What can string theory teach us about condensed matter physics?

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October 3, 2011

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Rob Myers

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Outline

1. Quantum critical points and string theory
   Entanglement and emergent dimensions

2. Some difficult condensed matter questions and answers from string theory
   "Nearly-perfect" quantum fluids near the superfluid-insulator transition

3. High temperature superconductors and strange metals
   Holography of compressible quantum phases

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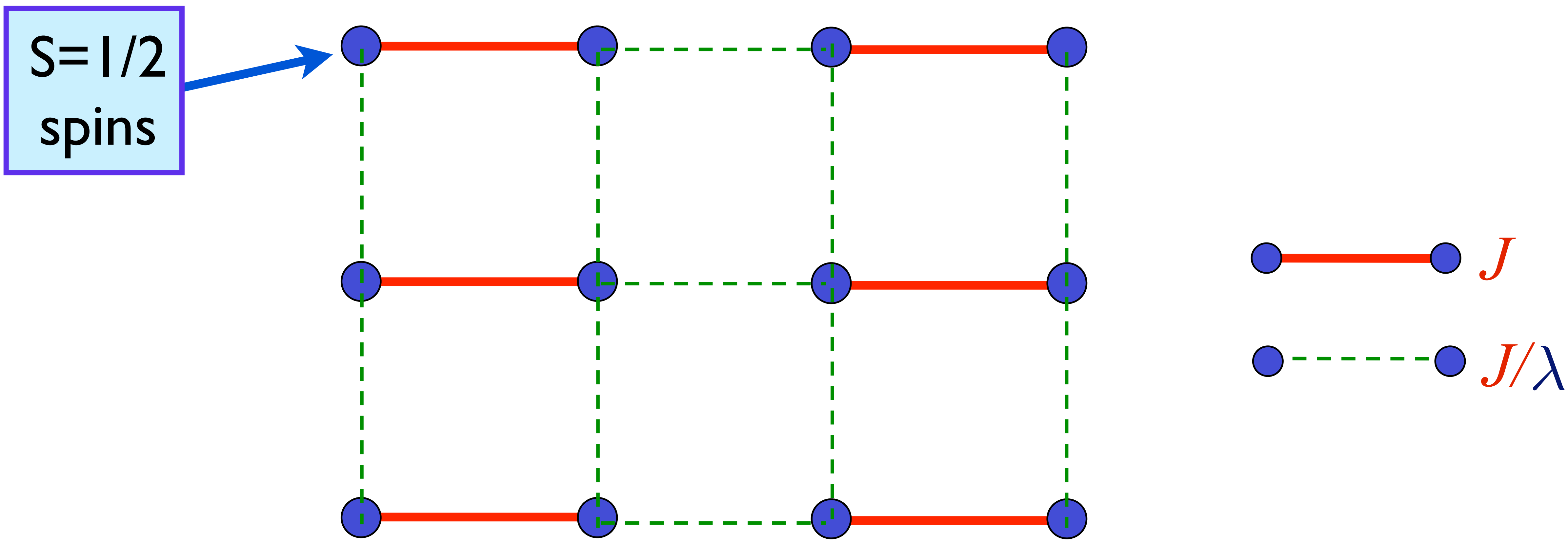
Square lattice antiferromagnet

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



Examine ground state as a function of λ

Square lattice antiferromagnet

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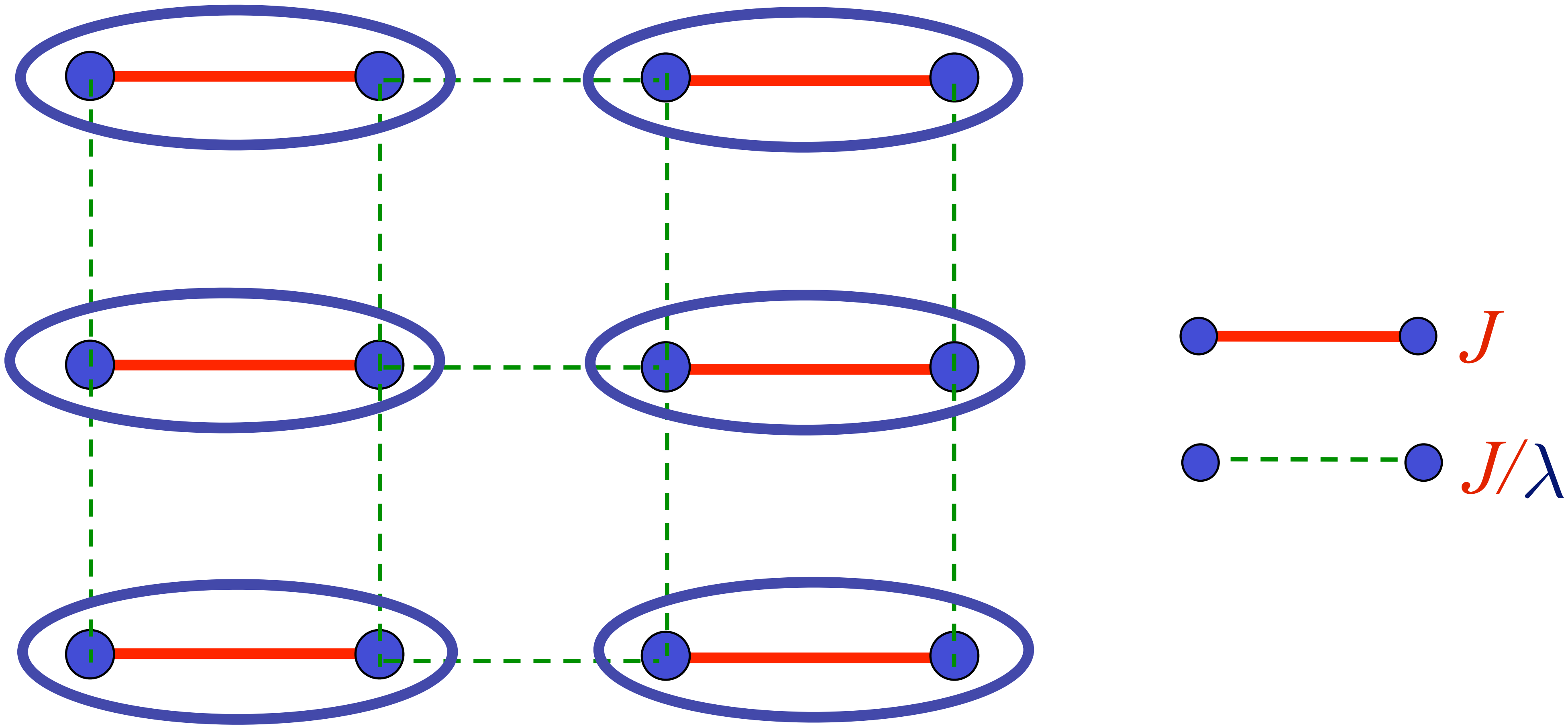

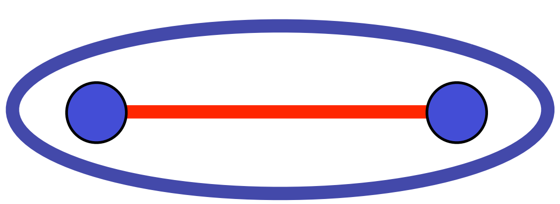 $= \frac{1}{\sqrt{2}} \Big(\big| \uparrow\downarrow \big\rangle - \big| \downarrow\uparrow \big\rangle \Big)$

At large λ ground state is a “quantum paramagnet” with spins locked in valence bond singlets

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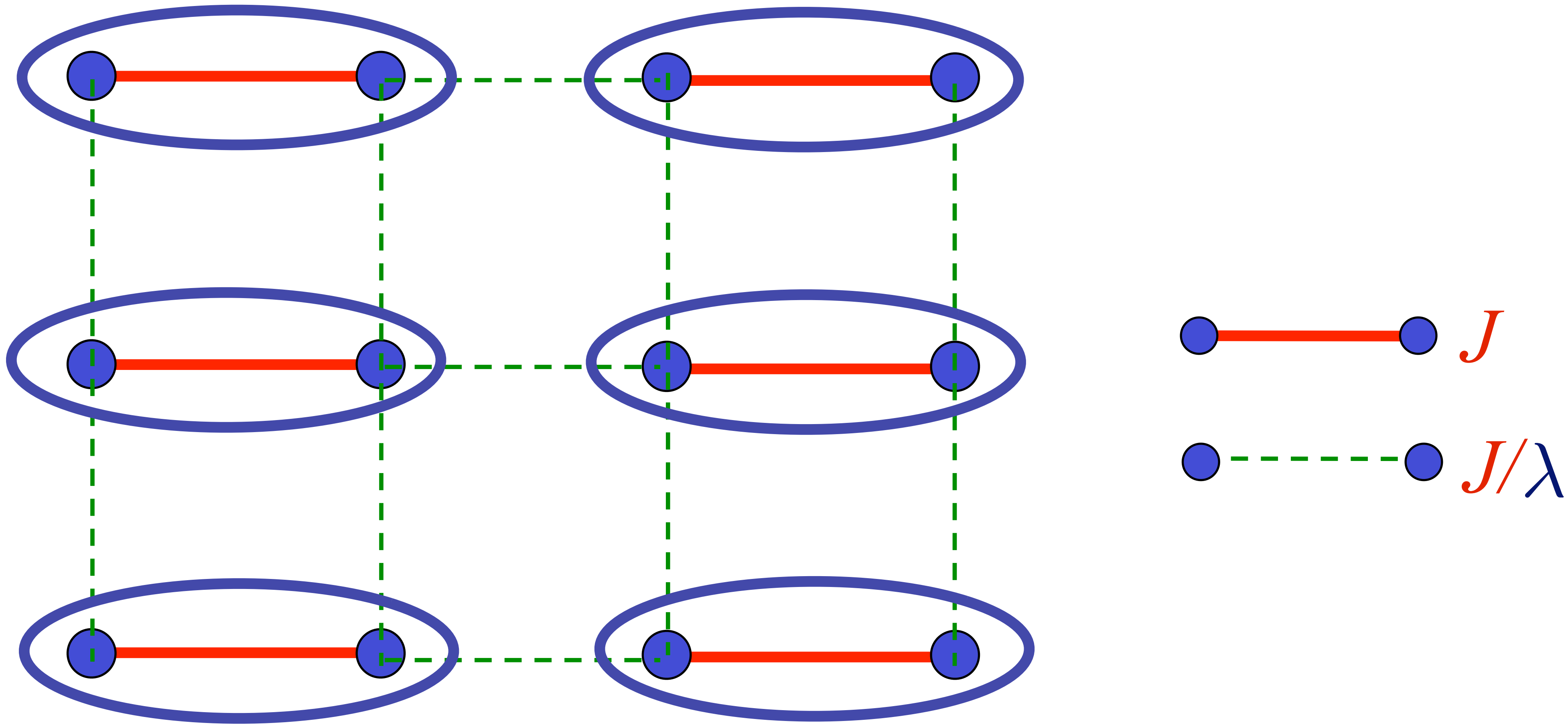

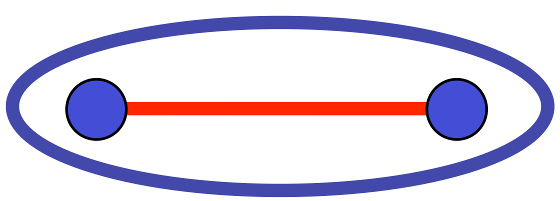

$$= \frac{1}{\sqrt{2}} \left(\left| \uparrow\downarrow \right\rangle - \left| \downarrow\uparrow \right\rangle \right)$$

Nearest-neighor spins are “entangled” with each other.
Can be separated into an Einstein-Podolsky-Rosen (EPR) pair.

Square lattice antiferromagnet

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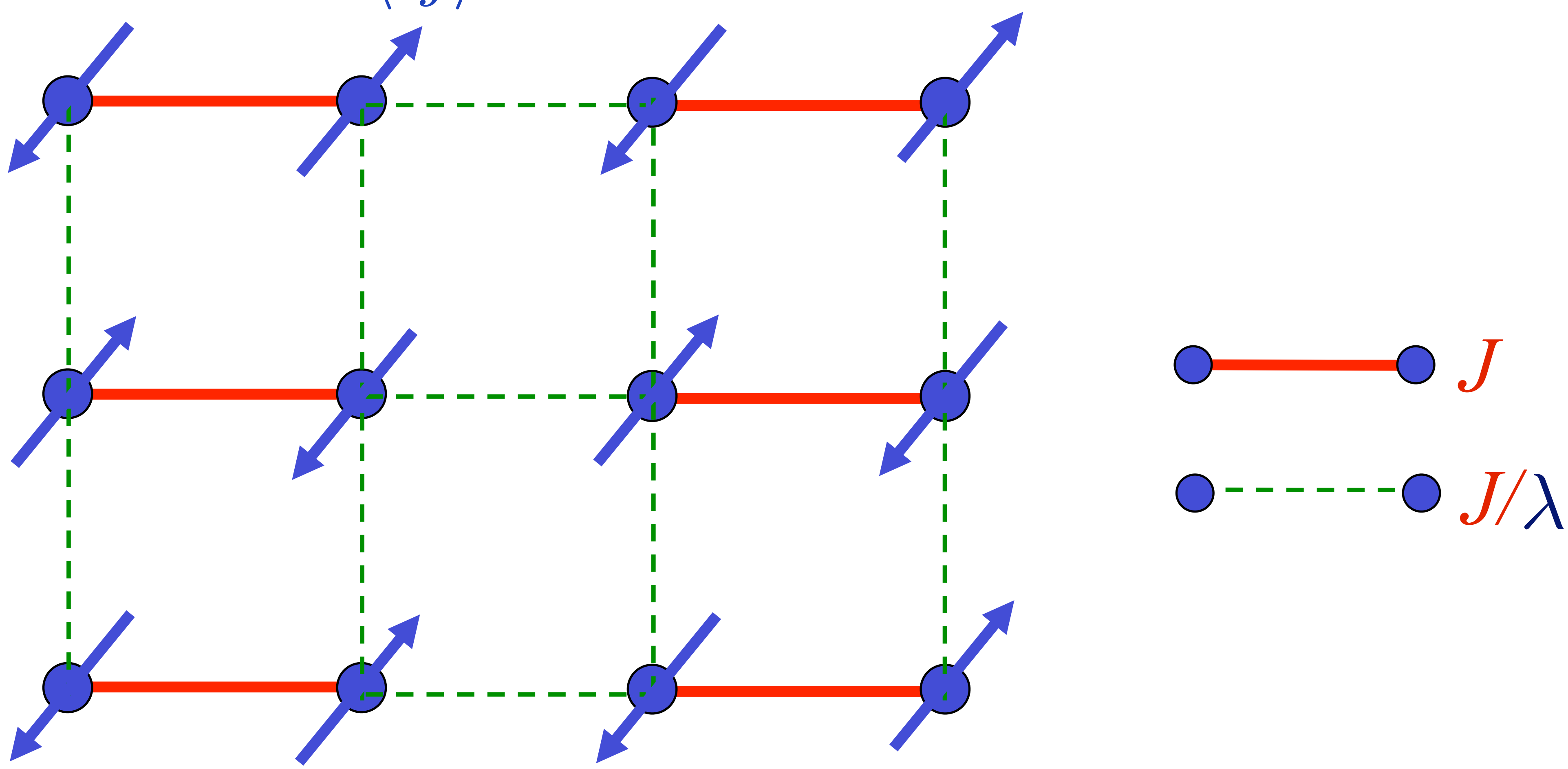

For $\lambda \approx 1$, the ground state has antiferromagnetic ("Néel") order, and the spins align in a checkerboard pattern

Square lattice antiferromagnet

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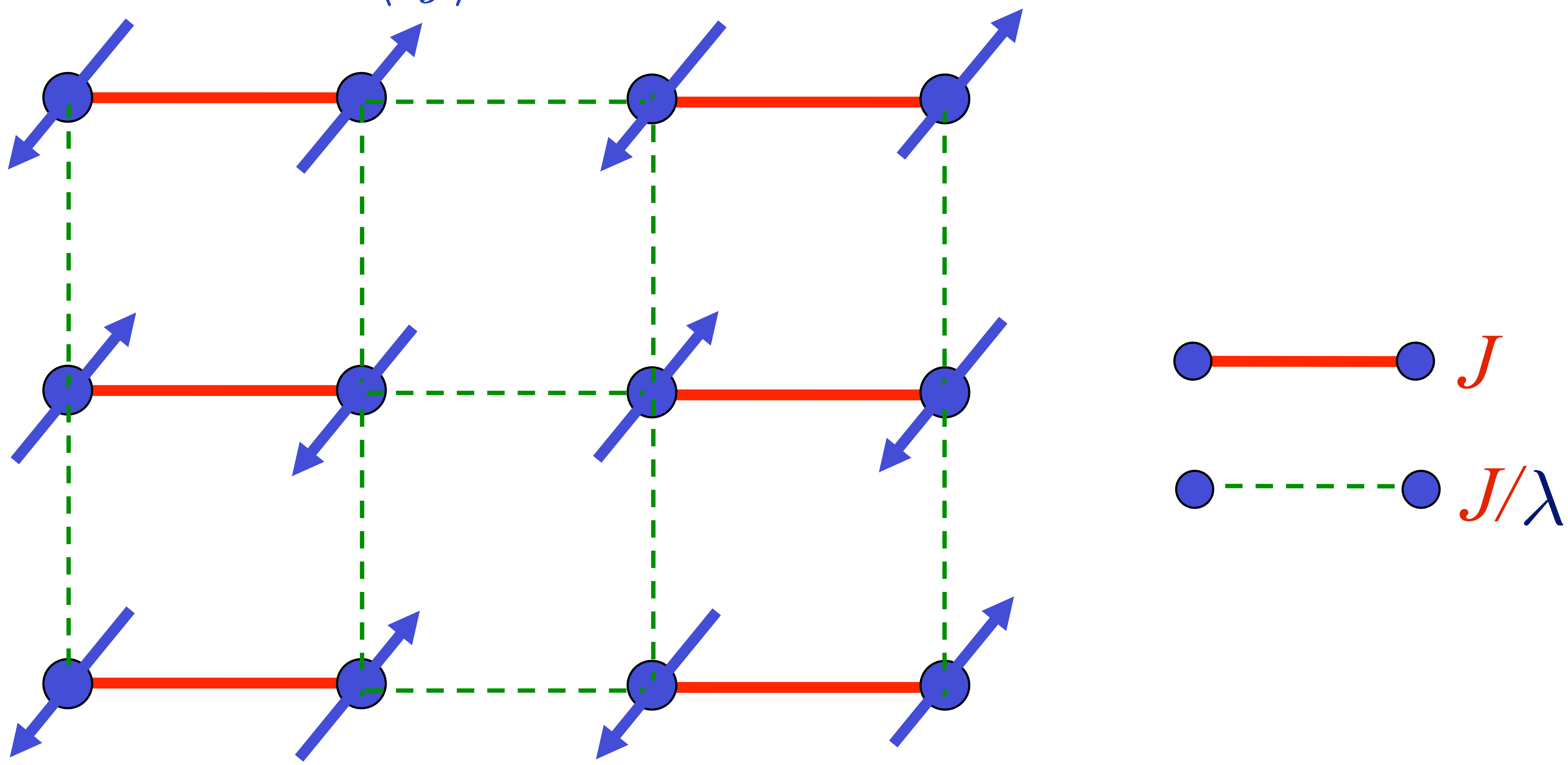

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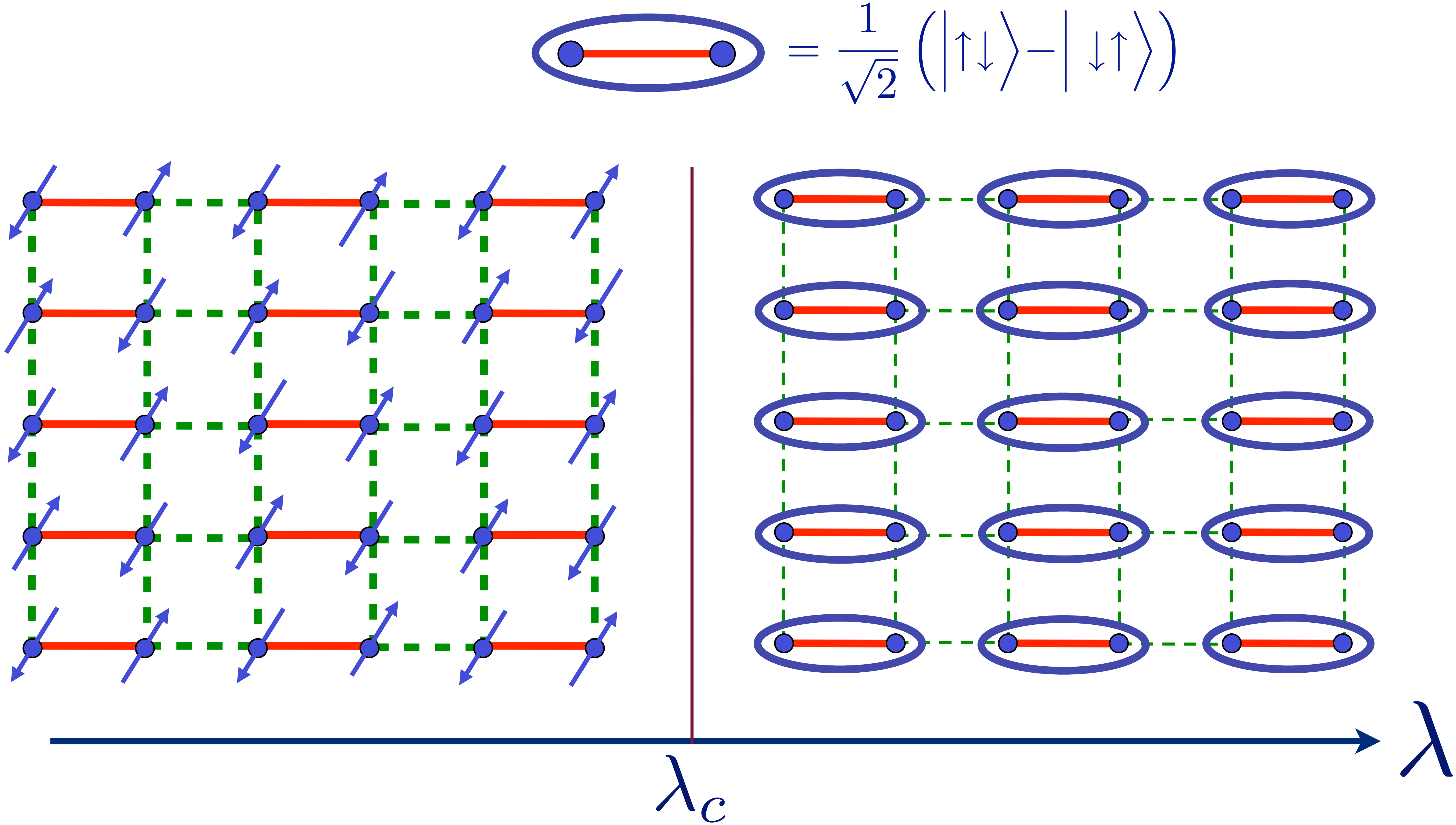
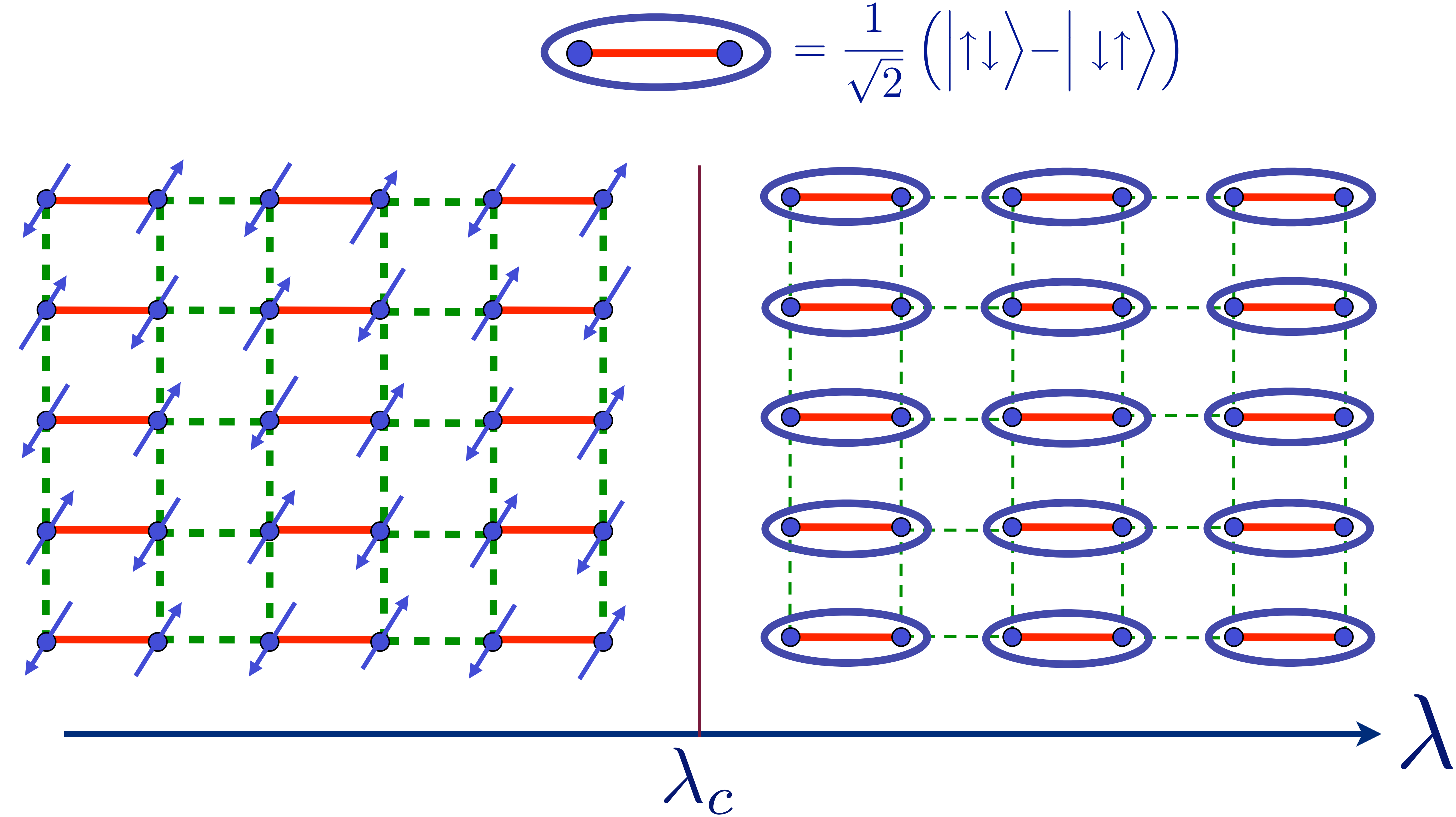
No EPR pairs

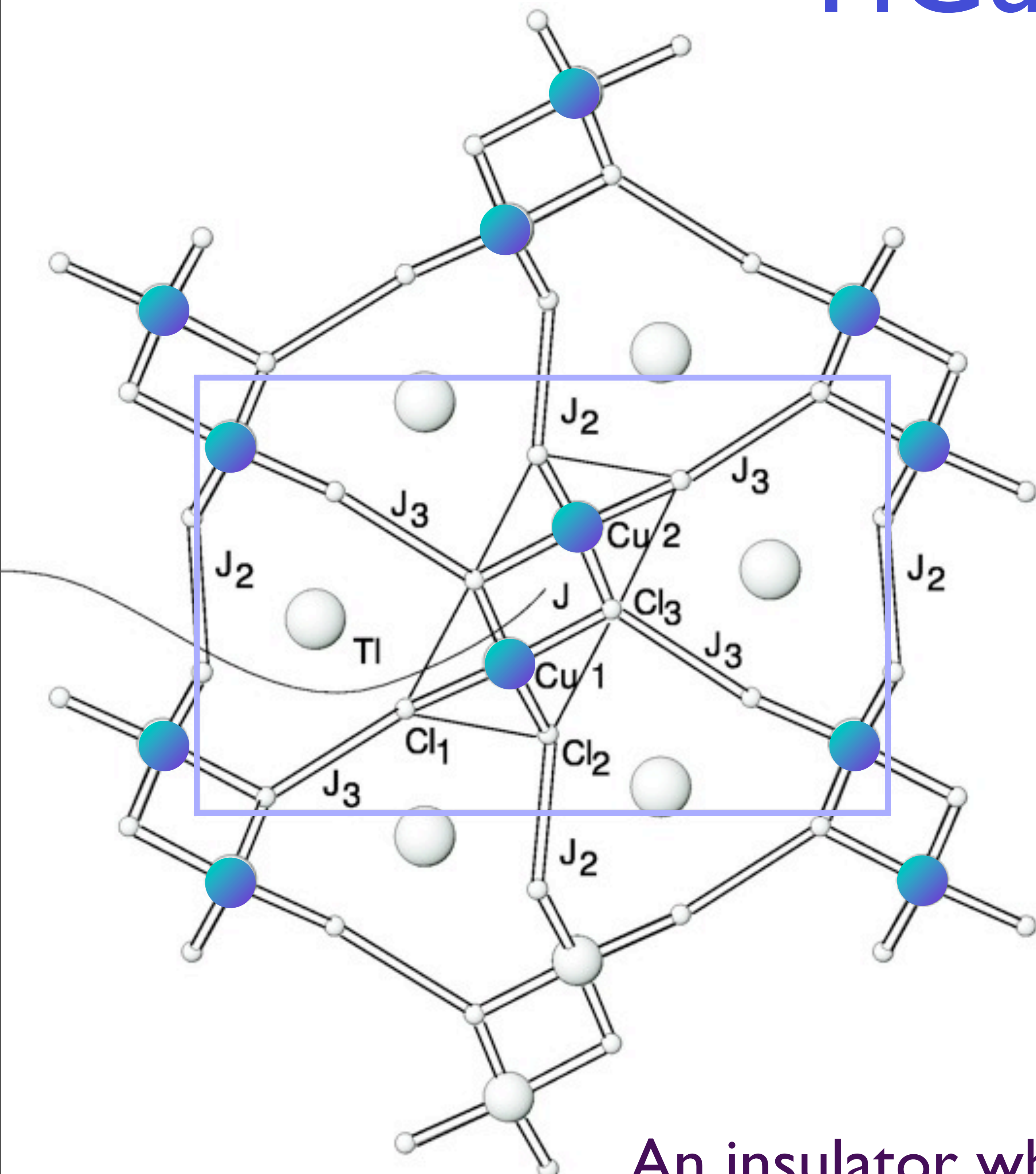

$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$
λ_c
λ

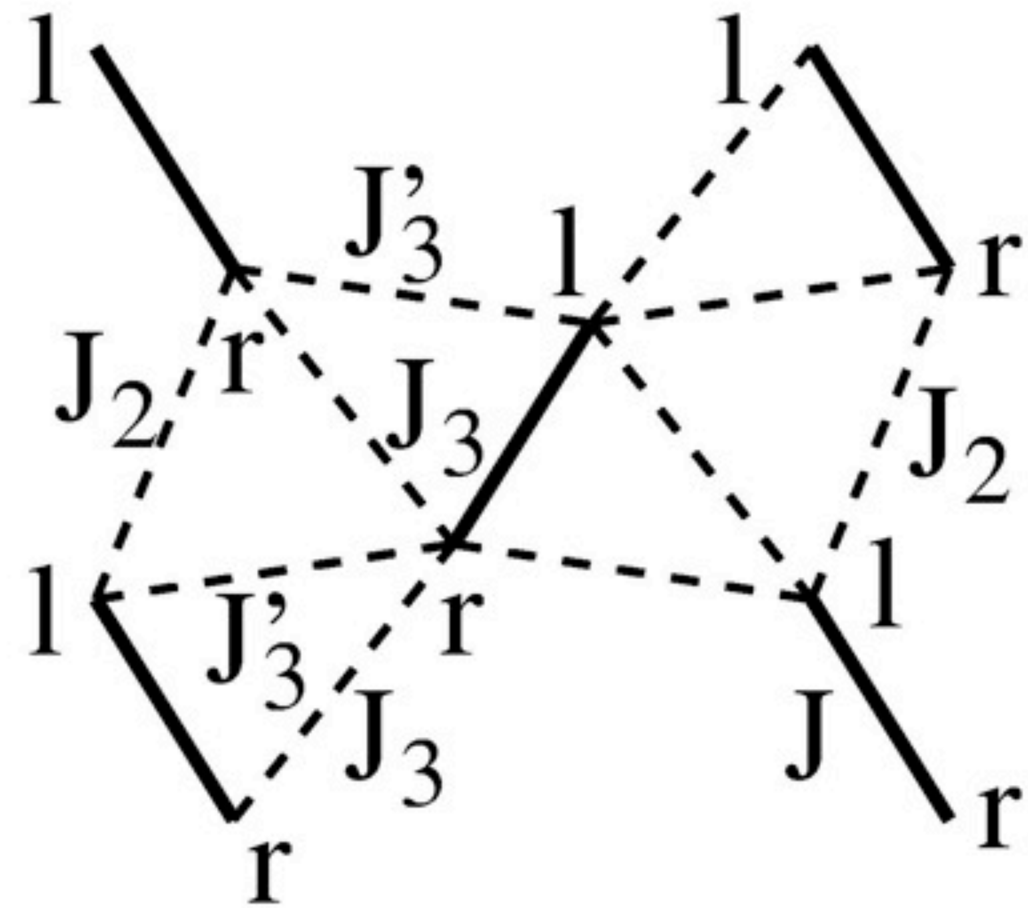


Pressure in $TlCuCl_3$

A. Oosawa, K. Kakurai, T. Osakabe, M. Nakamura, M. Takeda, and H. Tanaka, *Journal of the Physical Society of Japan*, **73**, 1446 (2004).

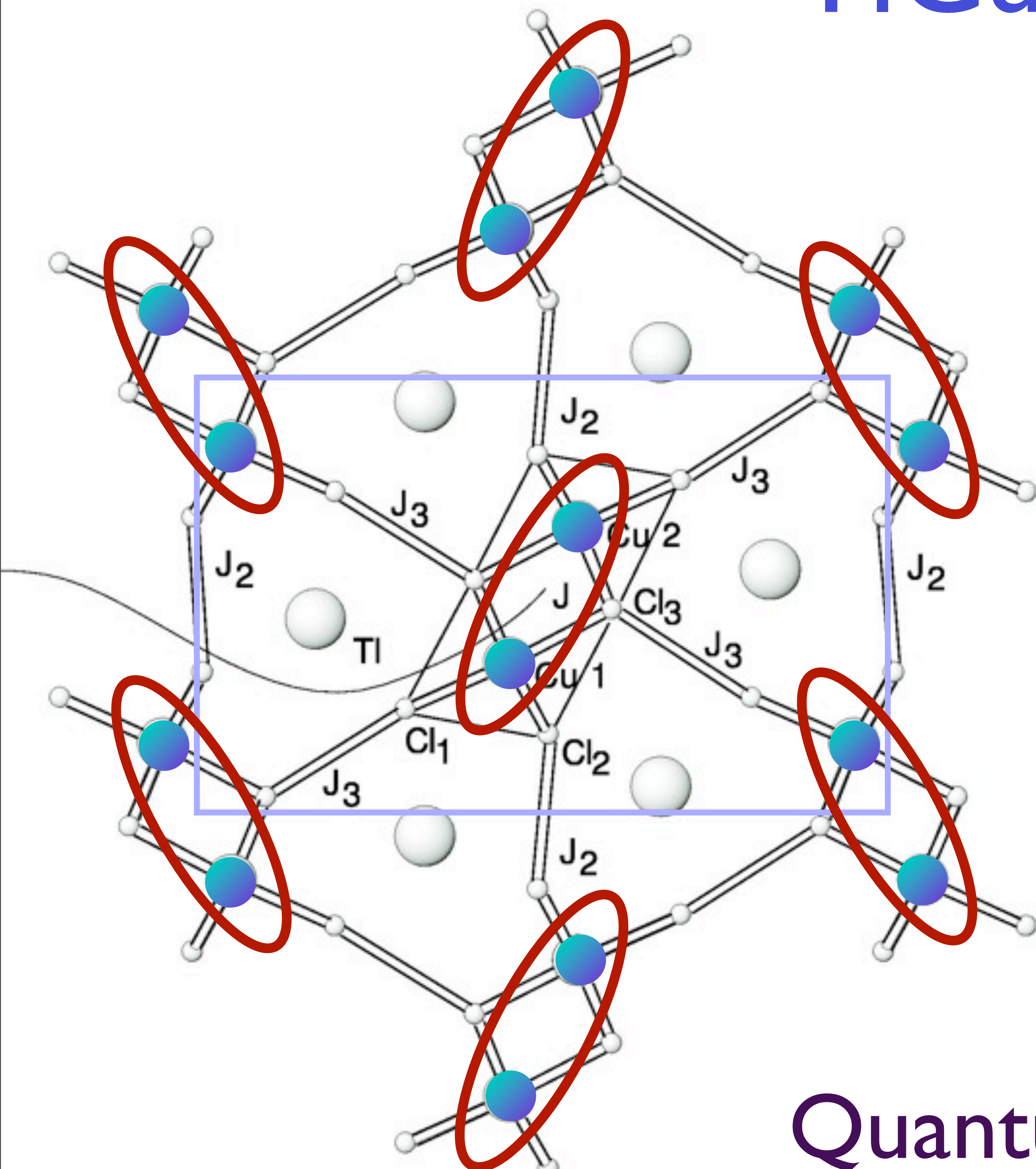
$TlCuCl_3$

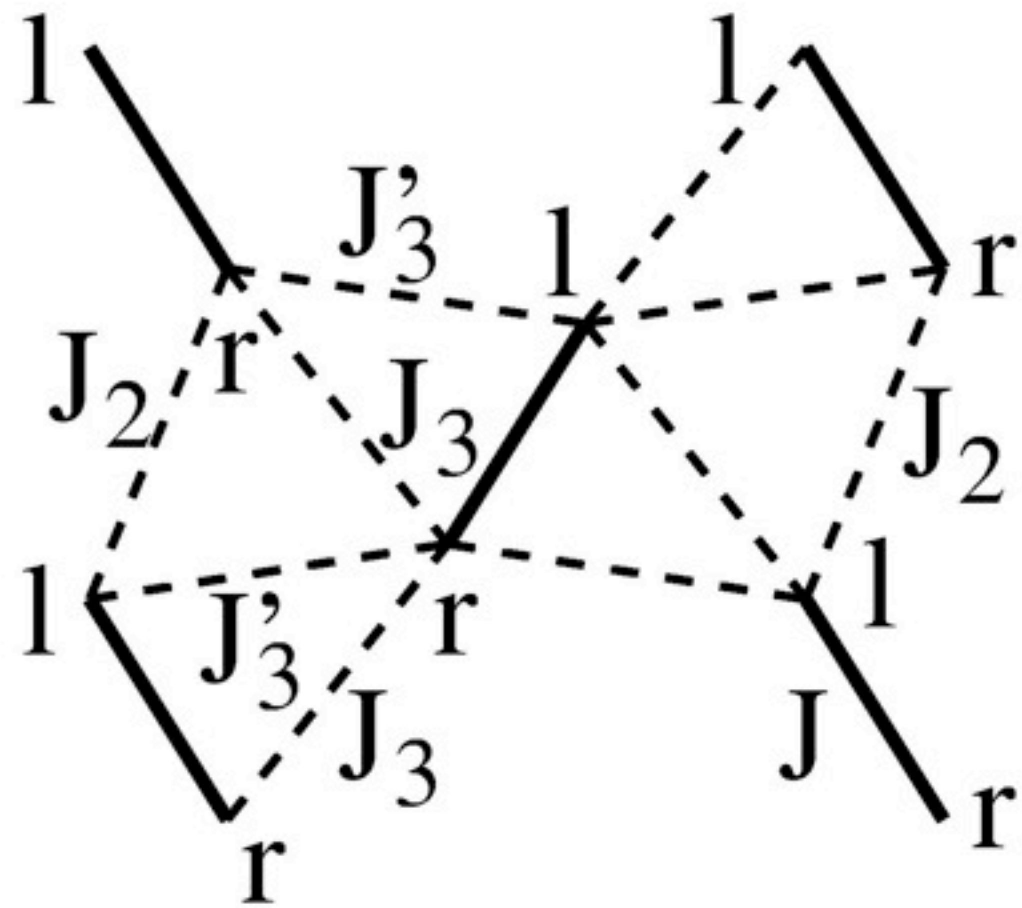




An insulator whose spin susceptibility vanishes exponentially as the temperature T tends to zero.

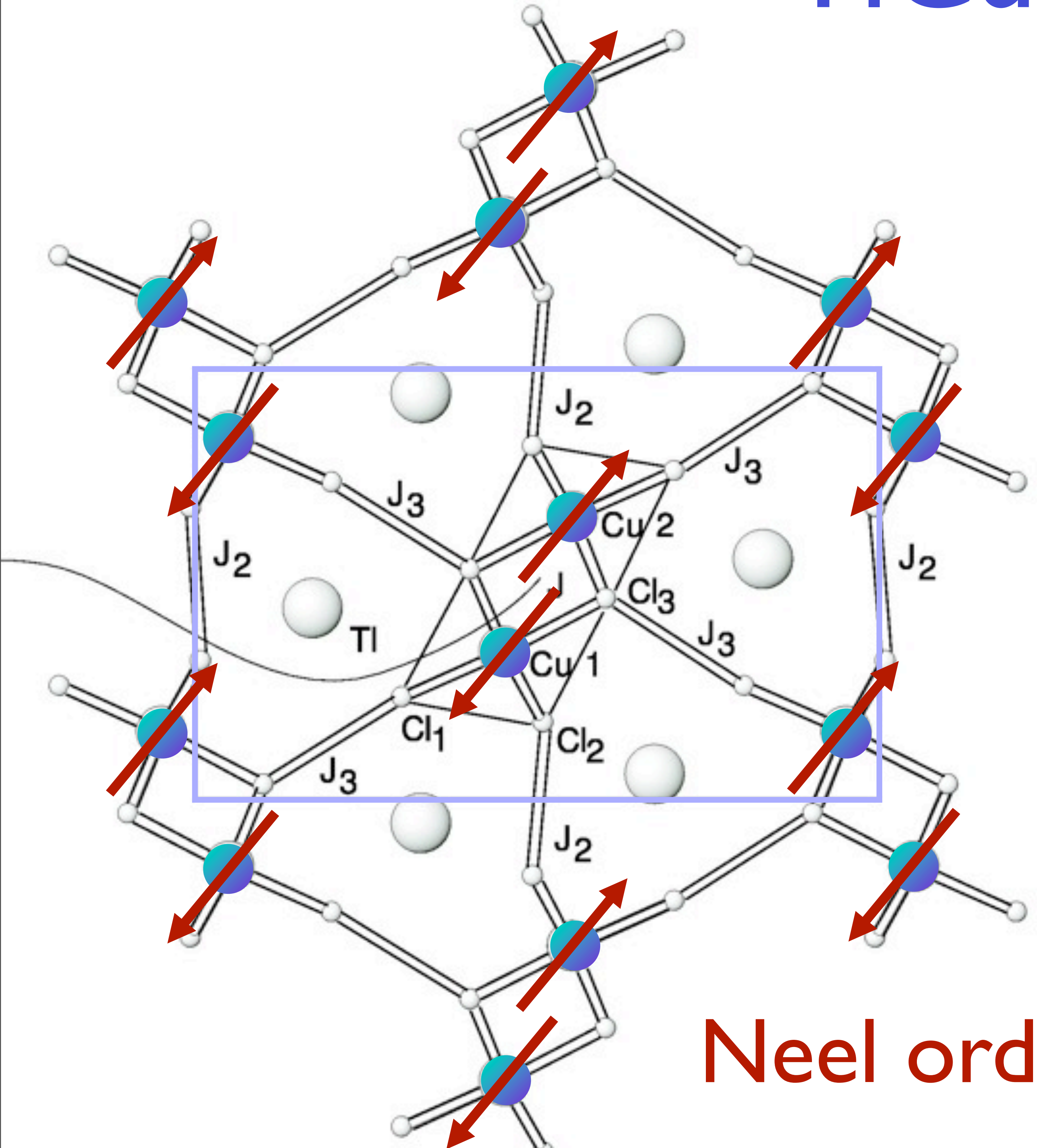
$TlCuCl_3$

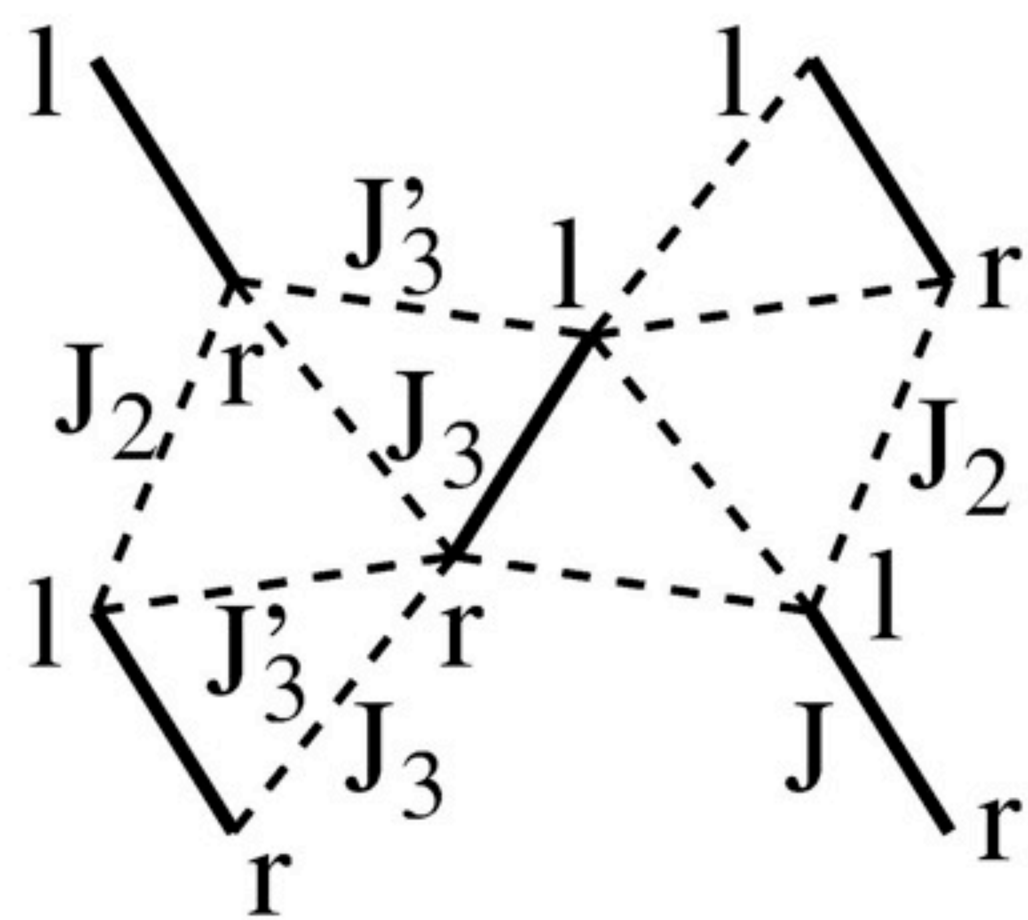




Quantum paramagnet at ambient pressure

$TlCuCl_3$

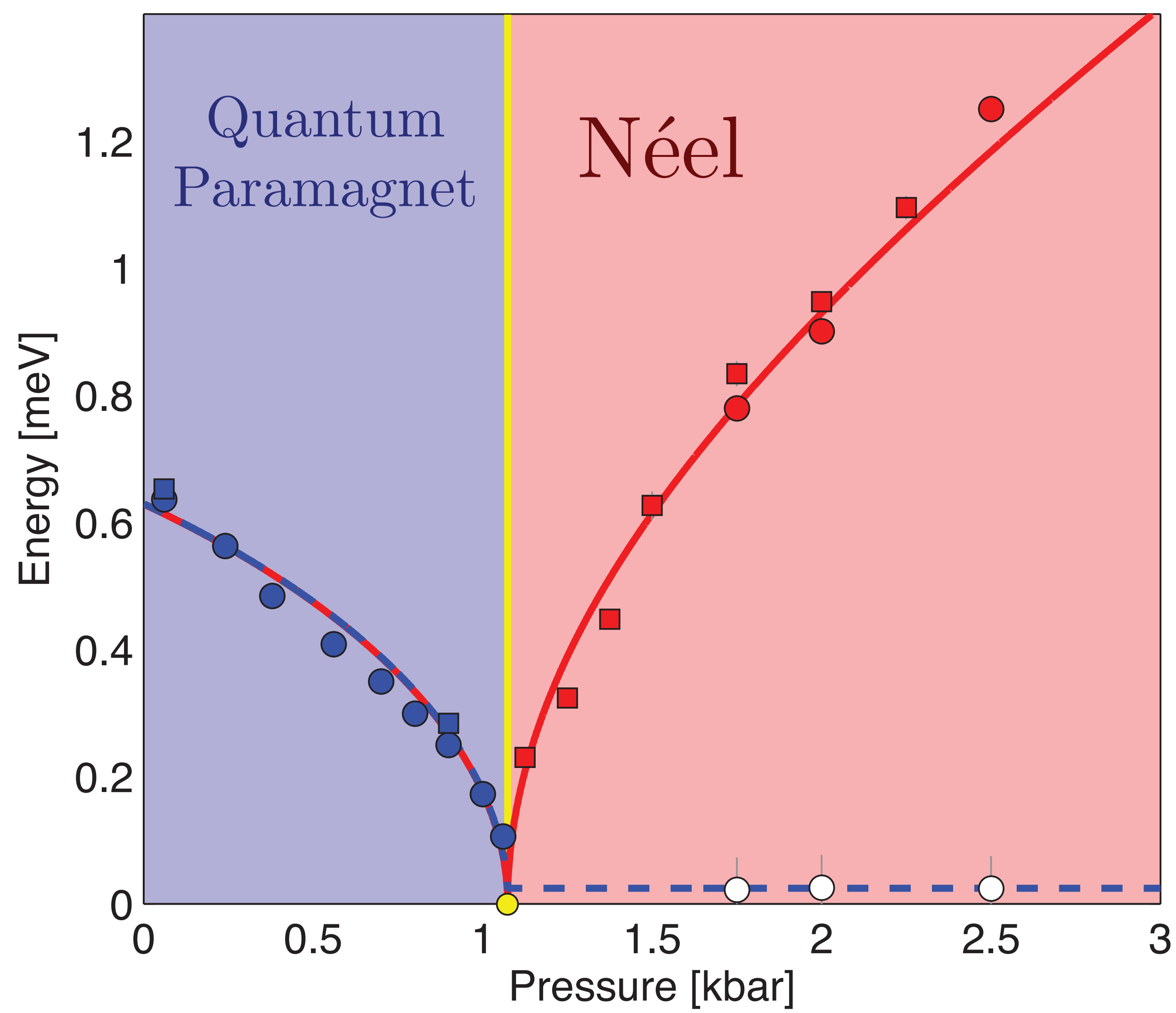




Neel order under pressure

A. Oosawa, K. Kakurai, T. Osakabe, M. Nakamura, M. Takeda, and H. Tanaka, *Journal of the Physical Society of Japan*, **73**, 1446 (2004).

Excitations of $TlCuCl_3$ with varying pressure



Christian Ruegg, Bruce Normand, Masashige Matsumoto, Albert Furrer, Desmond McMorrow, Karl Kramer, Hans-Ulrich Gudel, Severian Gvasaliya, Hannu Mutka, and Martin Boehm, *Phys. Rev. Lett.* **100**, 205701 (2008)

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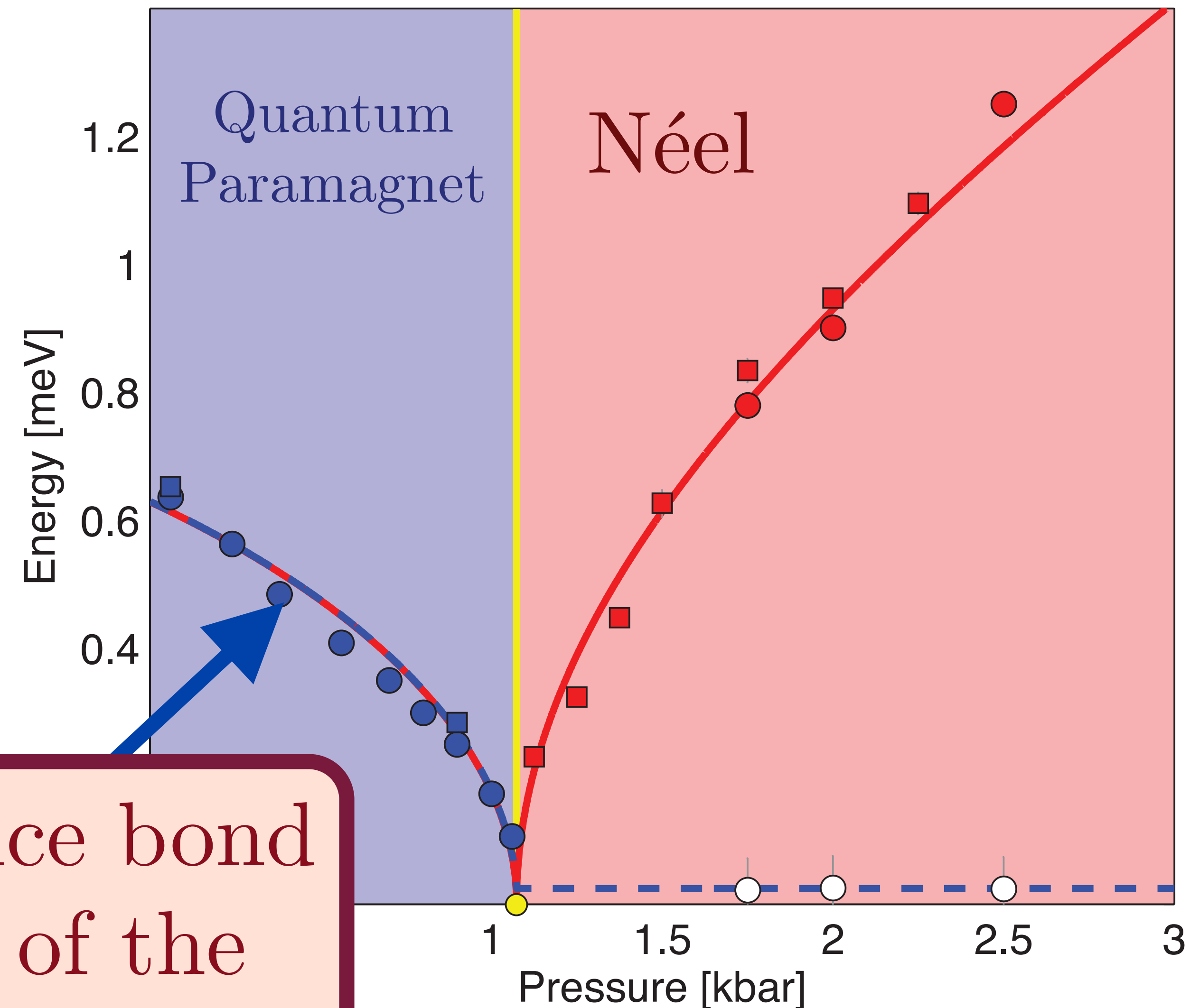

Broken valence bond excitations of the quantum paramagnet

Christian Ruegg, Bruce Normand, Masashige Matsumoto, Albert Furrer, Desmond McMorrow, Karl Kramer, Hans–Ulrich Gudel, Severian Gvasaliya, Hannu Mutka, and Martin Boehm, *Phys. Rev. Lett.* **100**, 205701 (2008)

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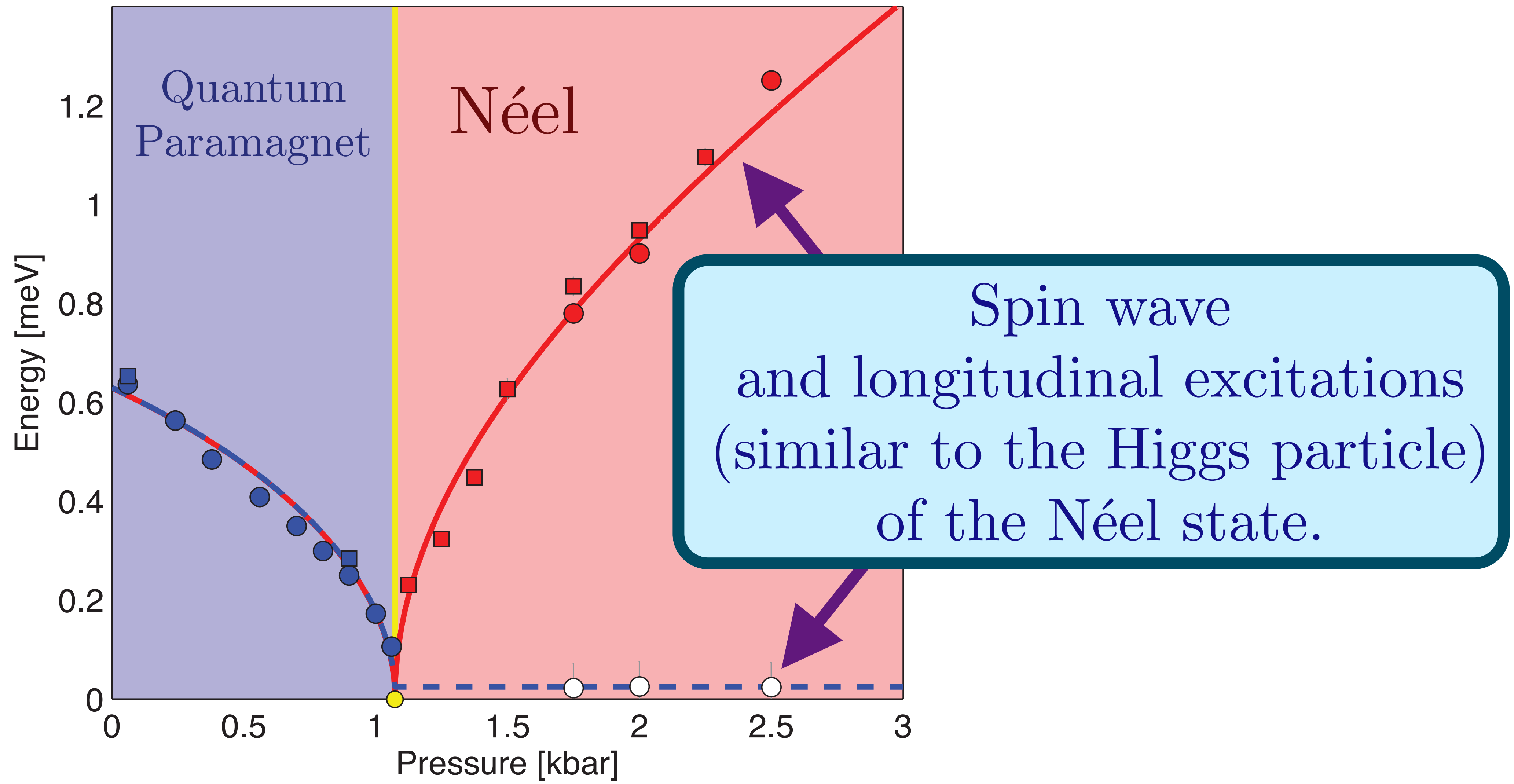

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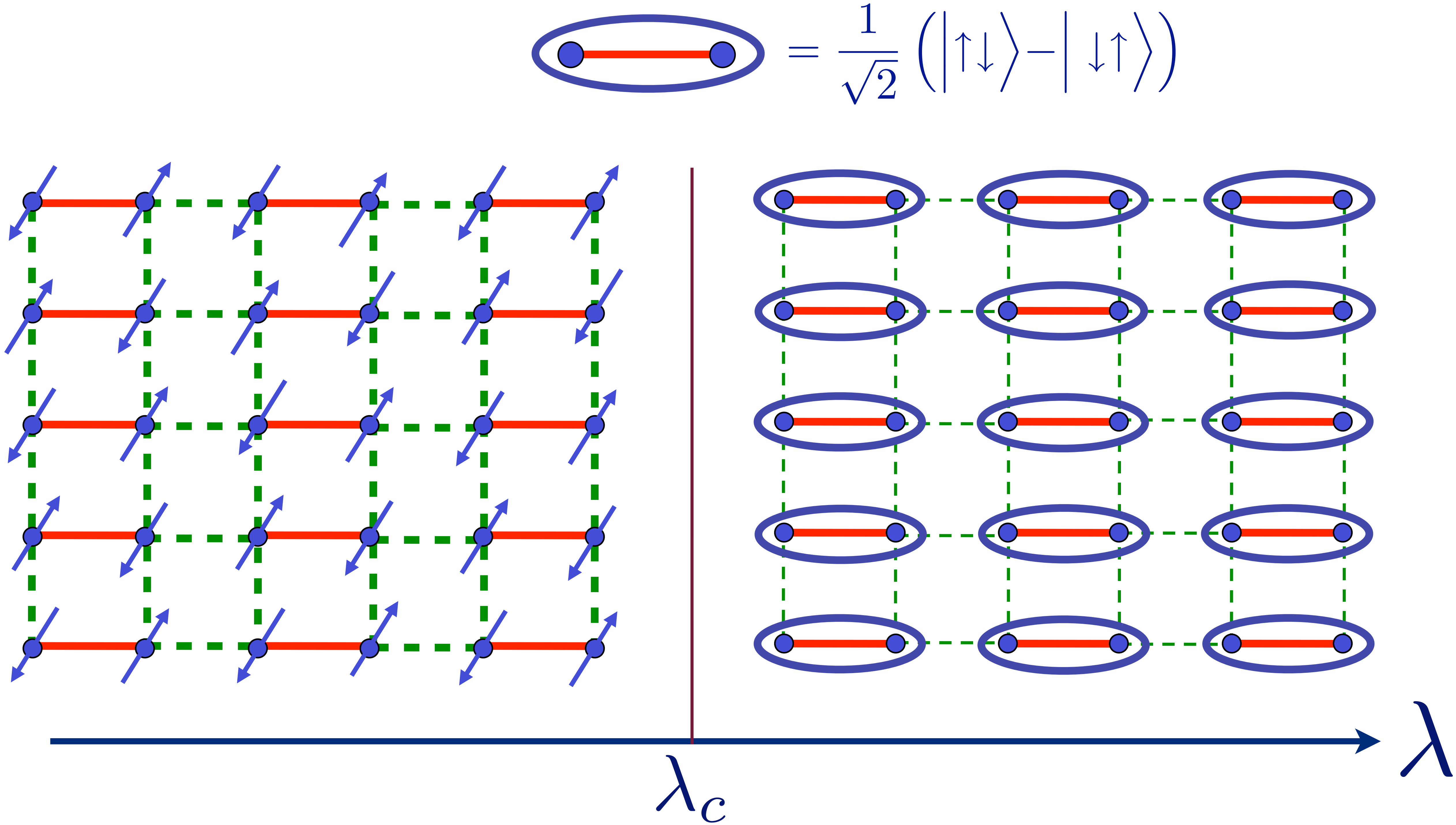

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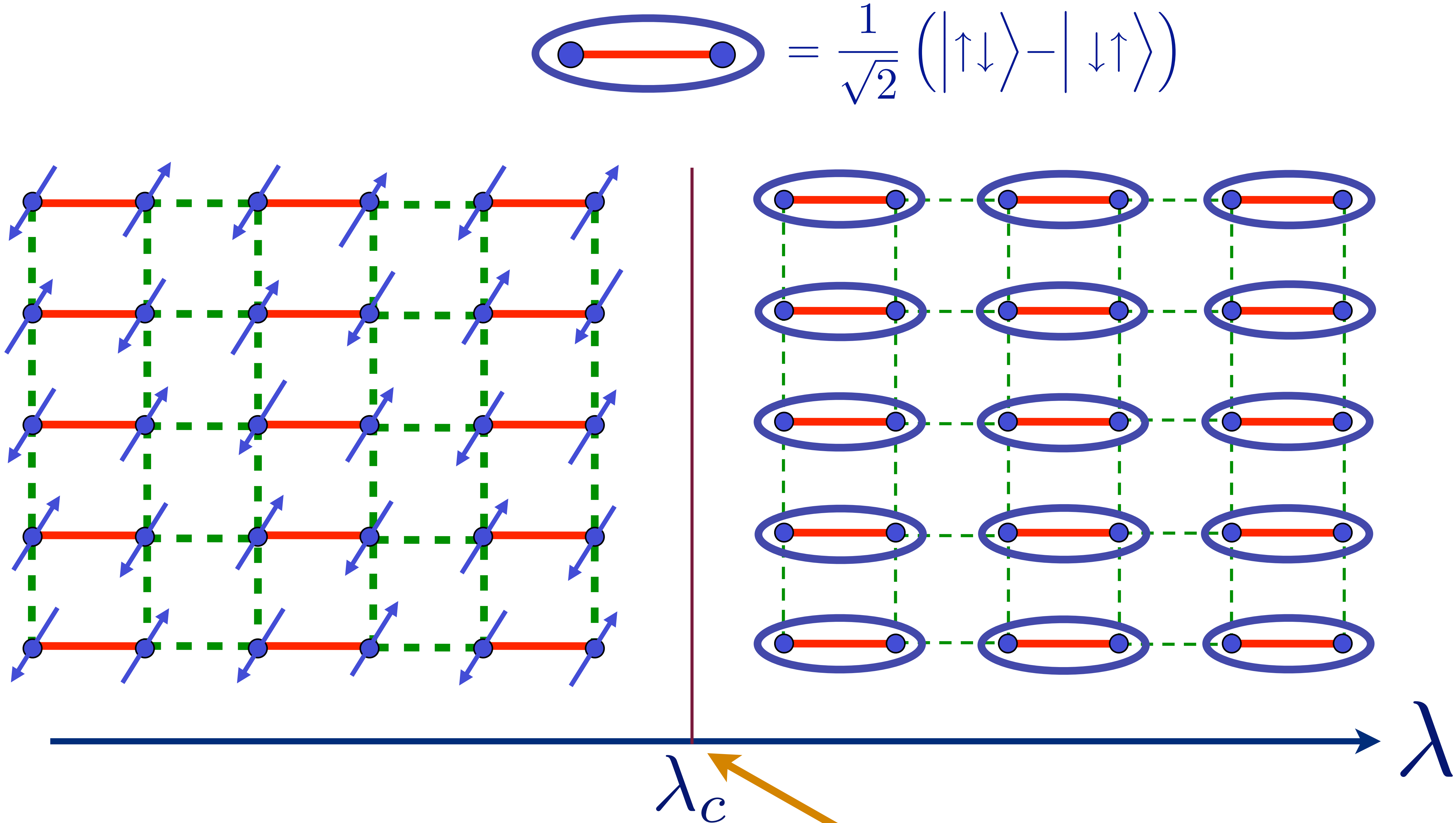
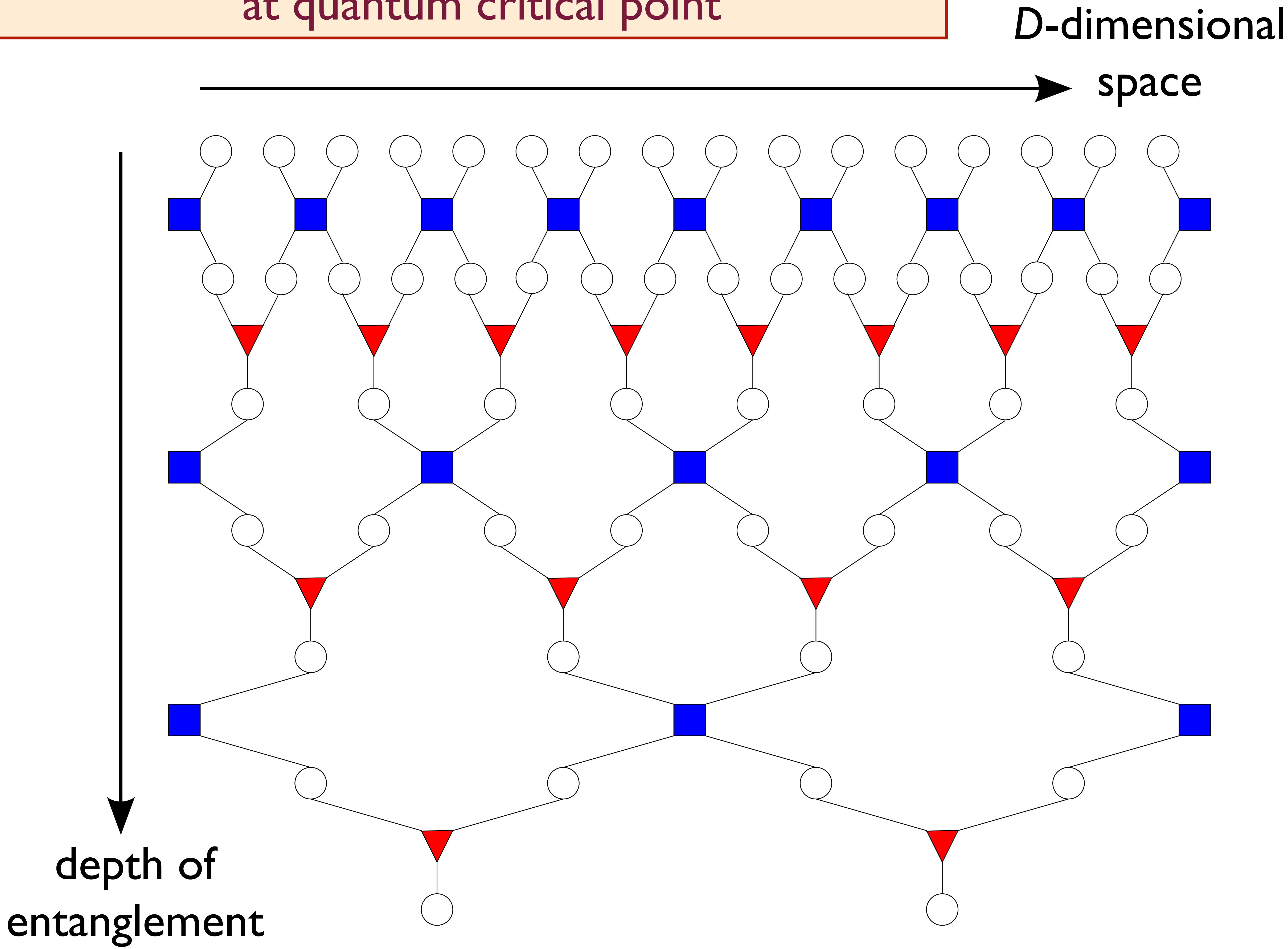
λ
λ_c



Quantum critical point with non-local entanglement in spin wavefunction

Tensor network representation of entanglement at quantum critical point



Characteristics of quantum critical point

- Long-range entanglement

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- Long distance and low energy correlations near the quantum critical point are described by a quantum field theory which is relativistically invariant (where the spin-wave velocity plays the role of the velocity of "light").

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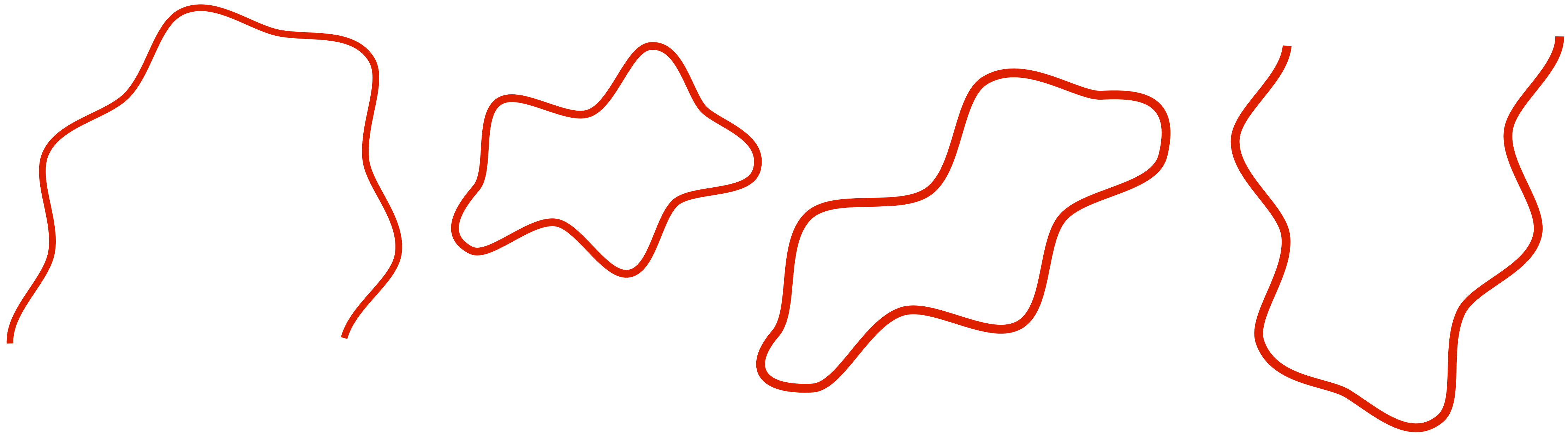
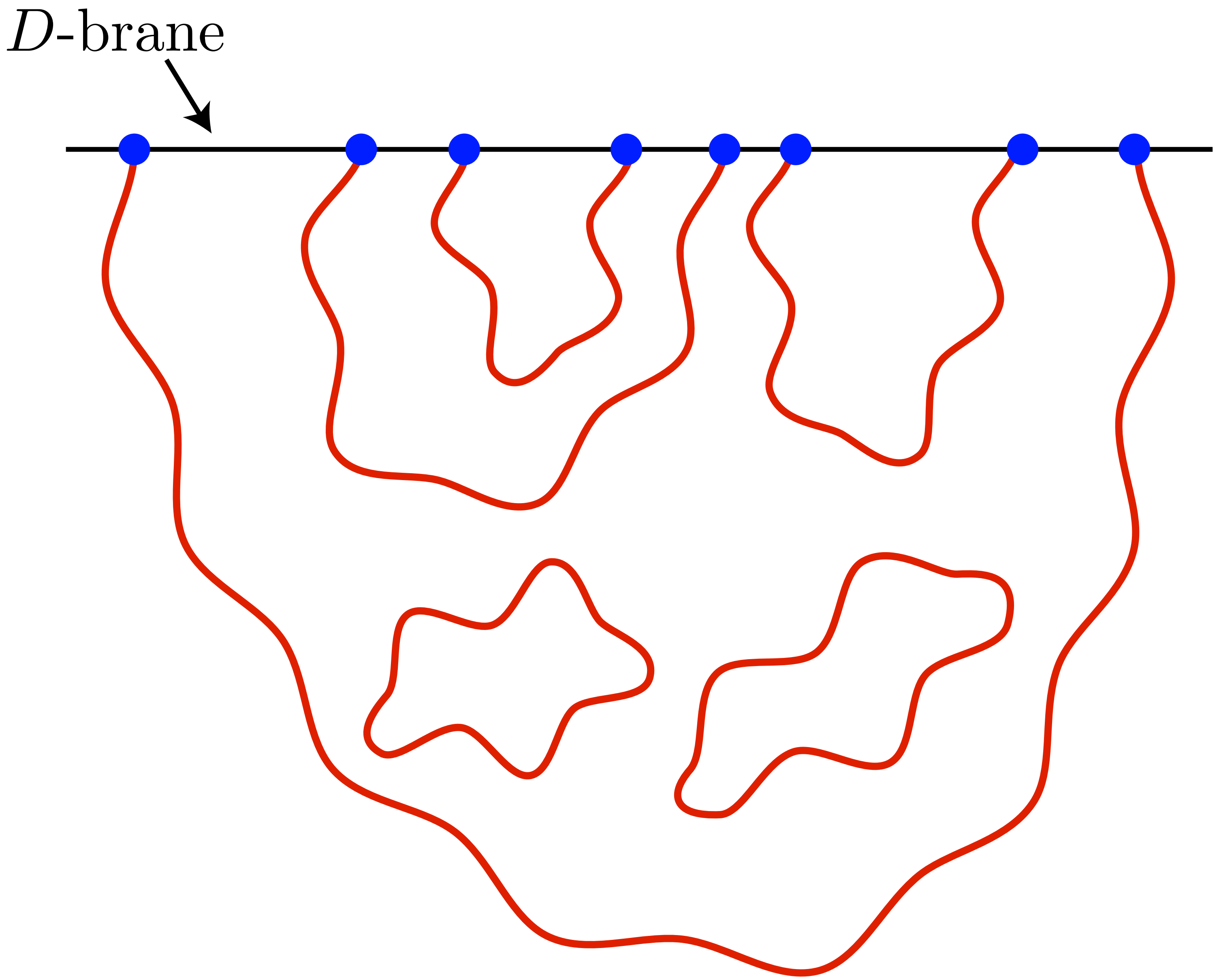
- Long-range entanglement
- Long distance and low energy correlations near the quantum critical point are described by a quantum field theory which is relativistically invariant (where the spin-wave velocity plays the role of the velocity of "light").
- The quantum field theory is invariant under scale and conformal transformations at the quantum critical point: a **CFT3**

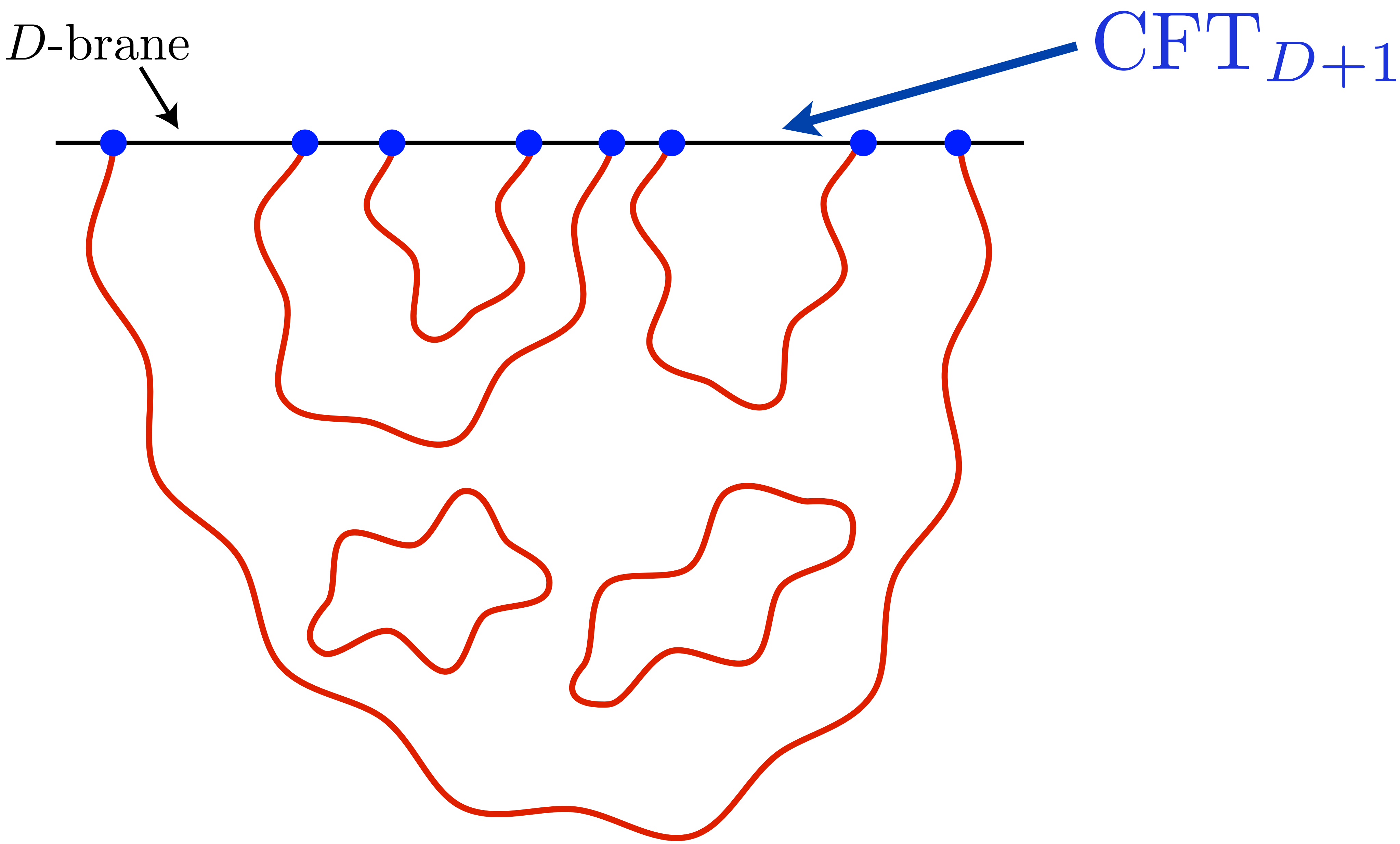
String theory



- Allows unification of the standard model of particle physics with gravity.
- Low-lying string modes correspond to gauge fields, gravitons, quarks ...

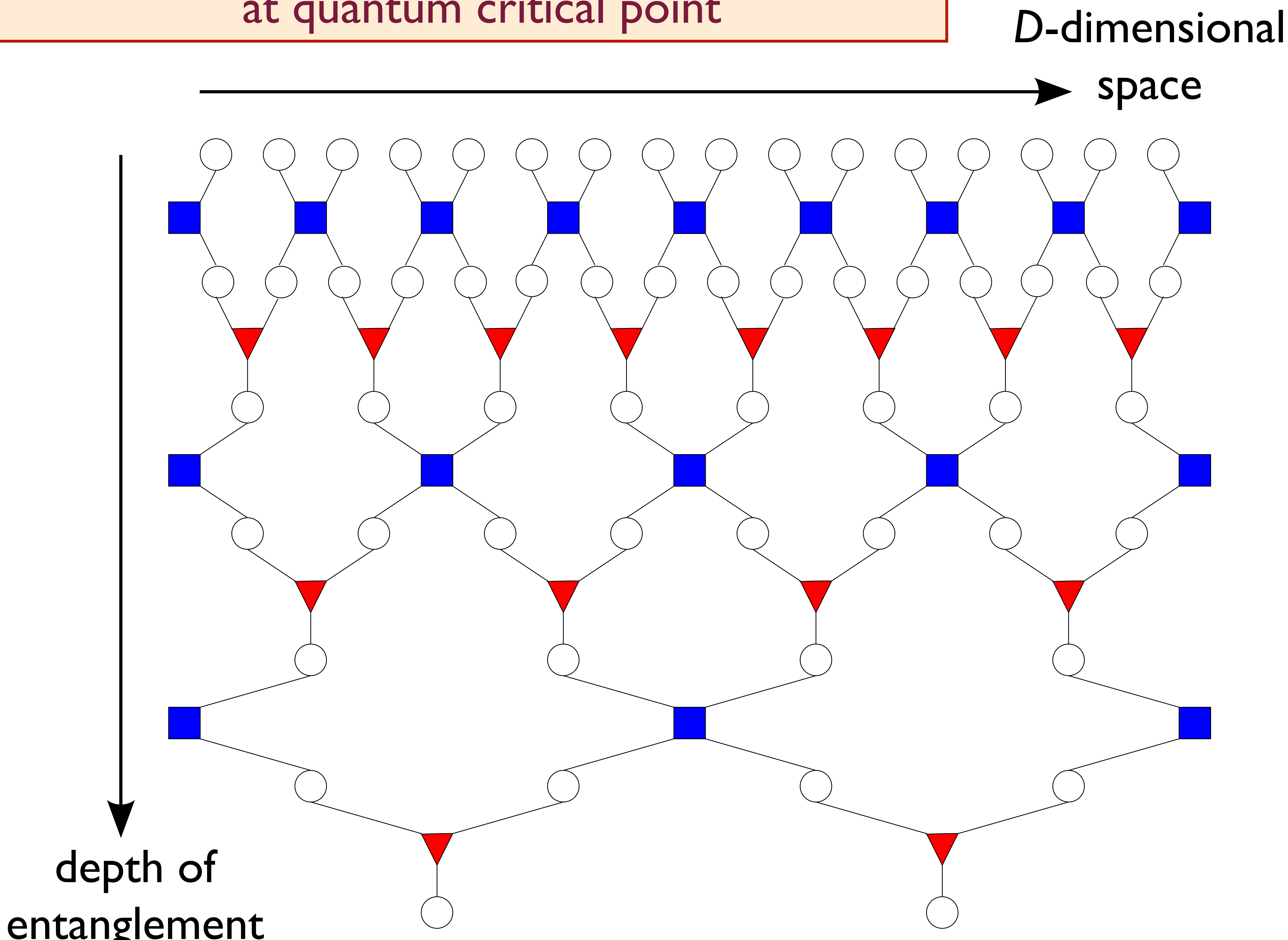


- A D-brane is a D-dimensional surface on which strings can end.
- The low-energy theory on a D-brane is an ordinary quantum field theory with no gravity.

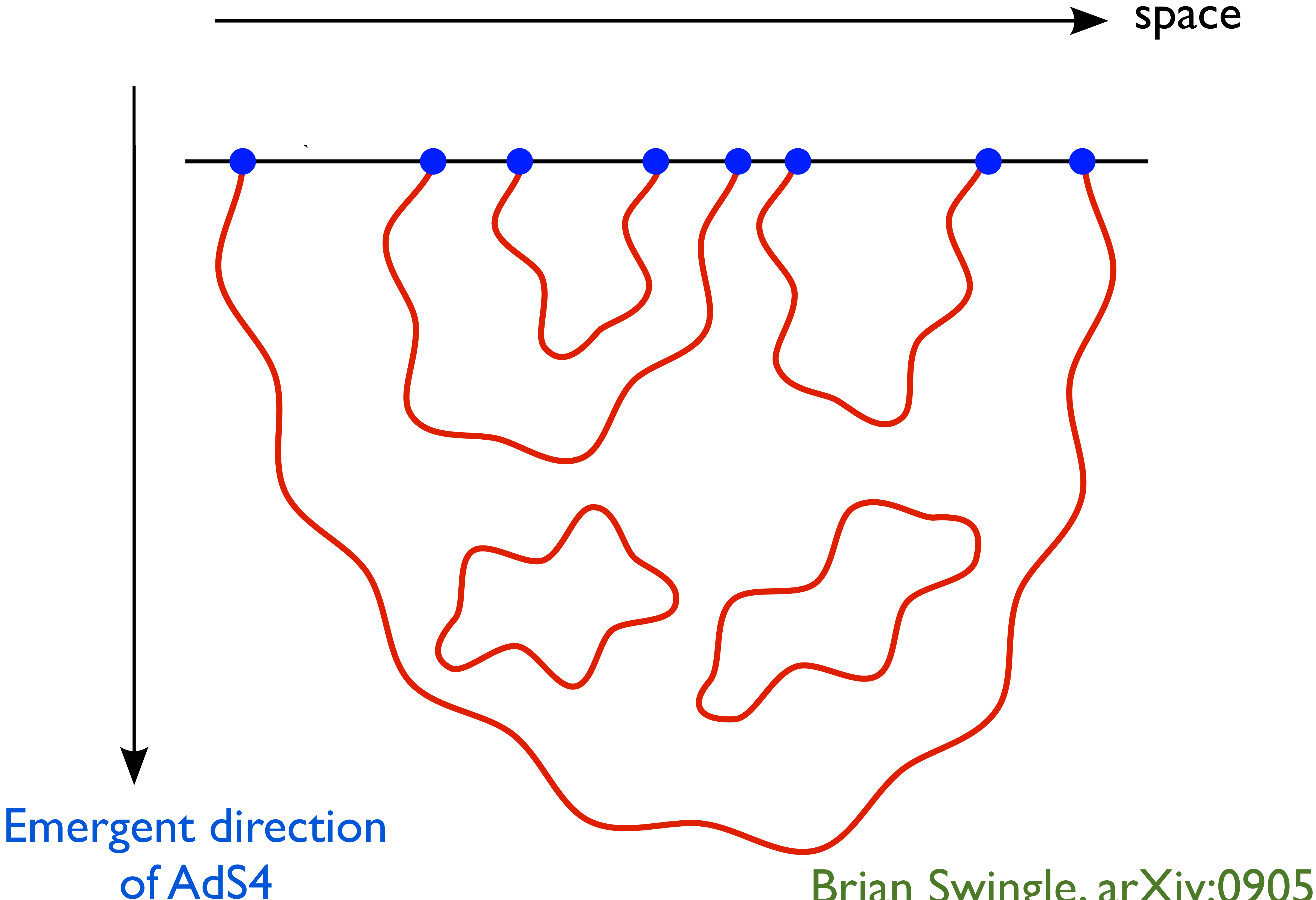


- A D-brane is a D-dimensional surface on which strings can end.
- The low-energy theory on a D-brane is an ordinary quantum field theory with no gravity.
- In $D = 2$, we obtain strongly-interacting **CFT3**s. These are "dual" to string theory on anti-de Sitter space: **AdS4**.

Tensor network representation of entanglement at quantum critical point

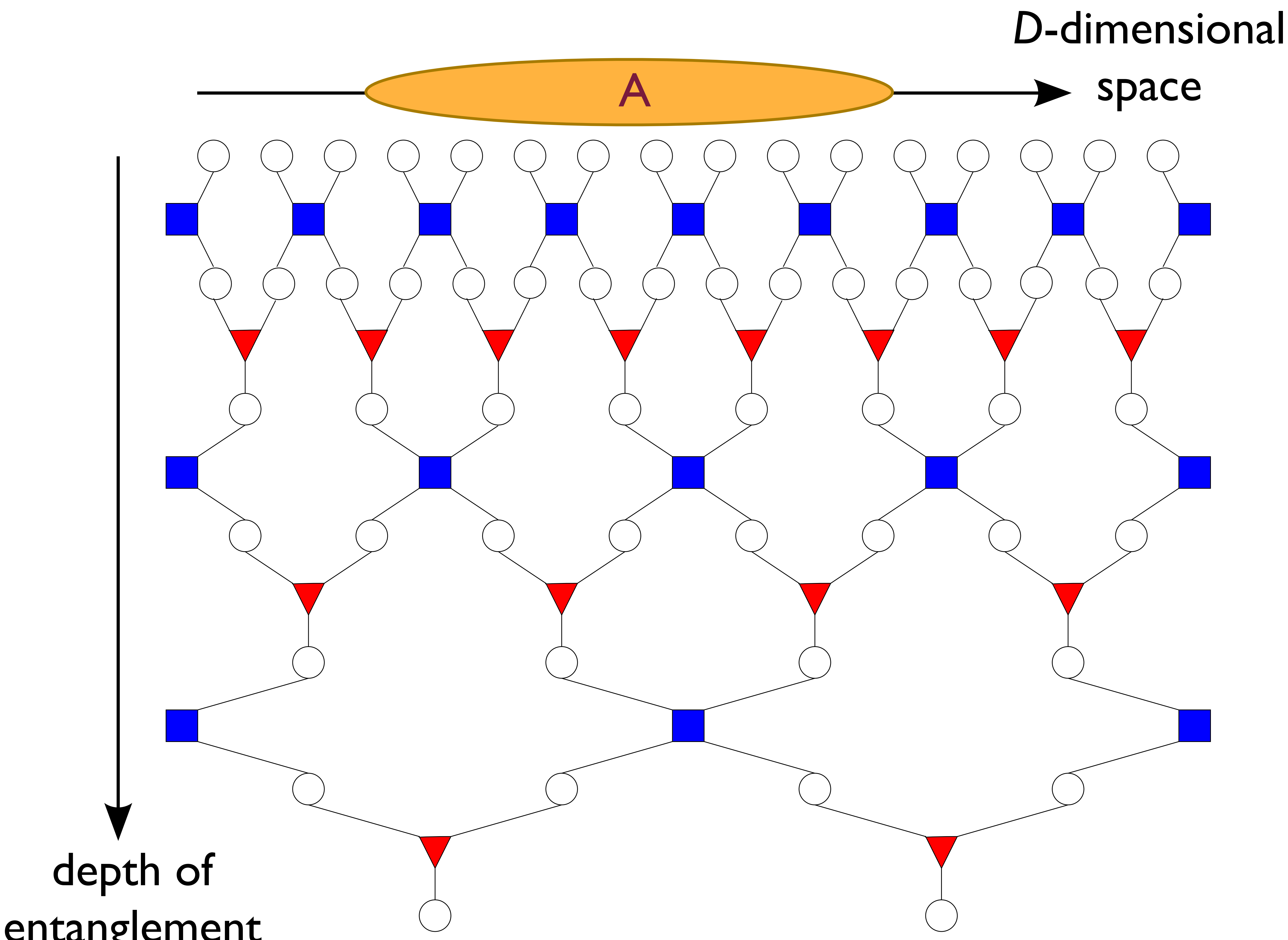


String theory near a D-brane

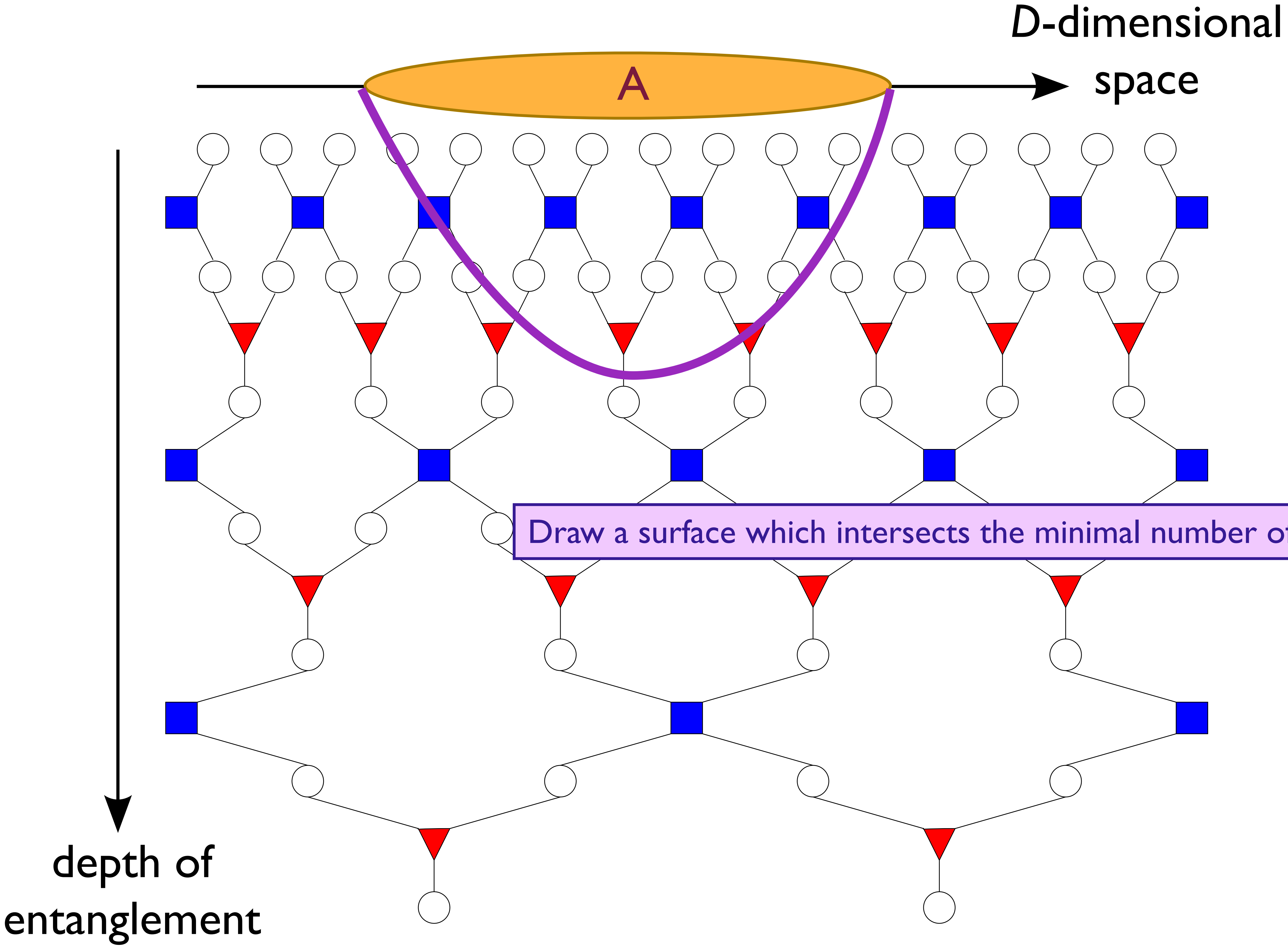


Brian Swingle, arXiv:0905.1317

Entanglement entropy



Entanglement entropy



Draw a surface which intersects the minimal number of links

Entanglement entropy

The entanglement entropy of a region A on the boundary equals the minimal area of a surface in the higher-dimensional space whose boundary co-incides with that of A.

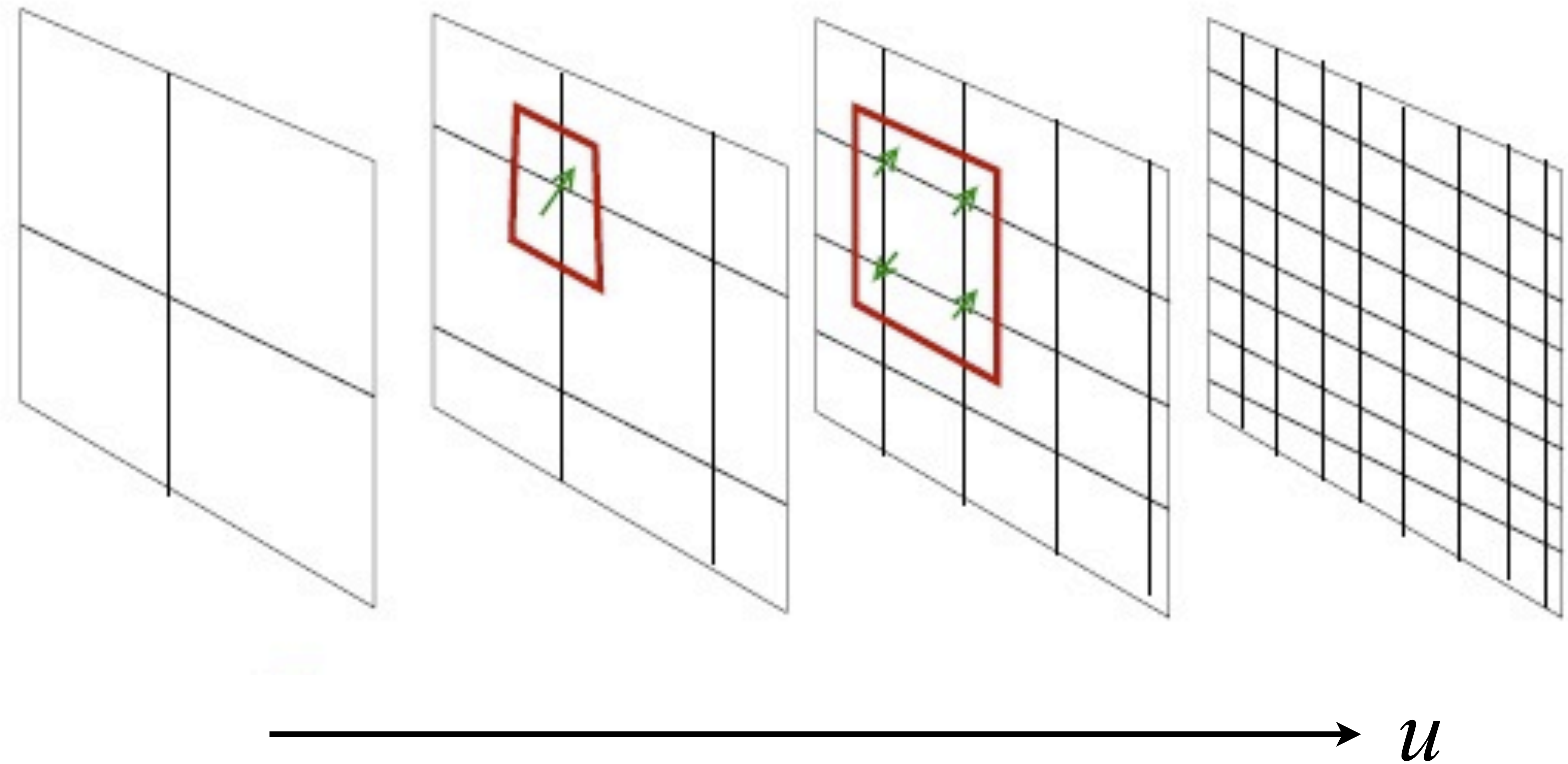
This can be seen both the string and tensor-network pictures

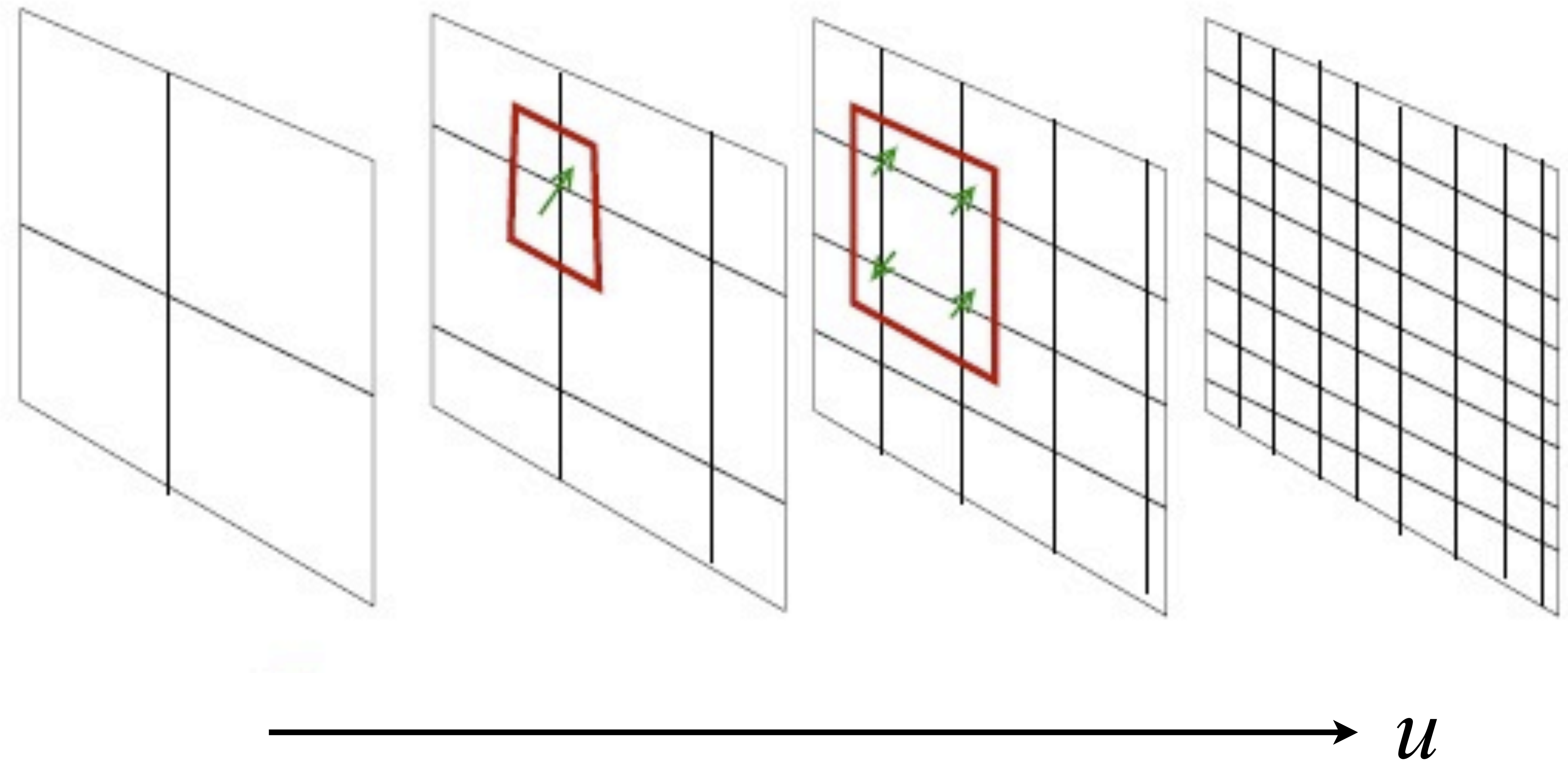
Swingle, Ryu, Takayanagi

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

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

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


u



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

At the RG fixed point, $\beta(g) = 0$, the $D+1$ 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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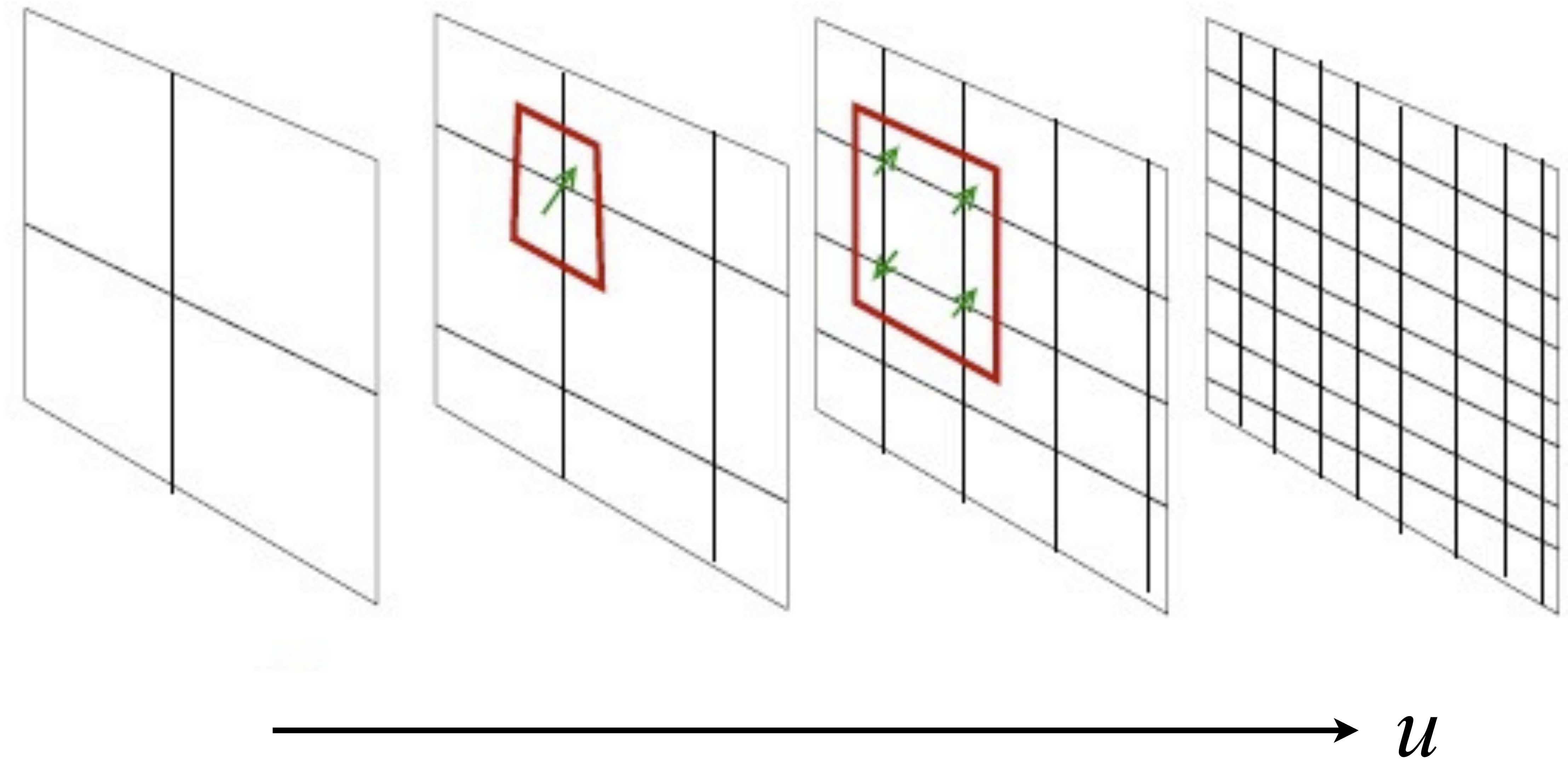
This is an invariance of the *metric* of the theory in $D+2$ dimensions. The unique solution is

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

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+2}, and L is the AdS radius.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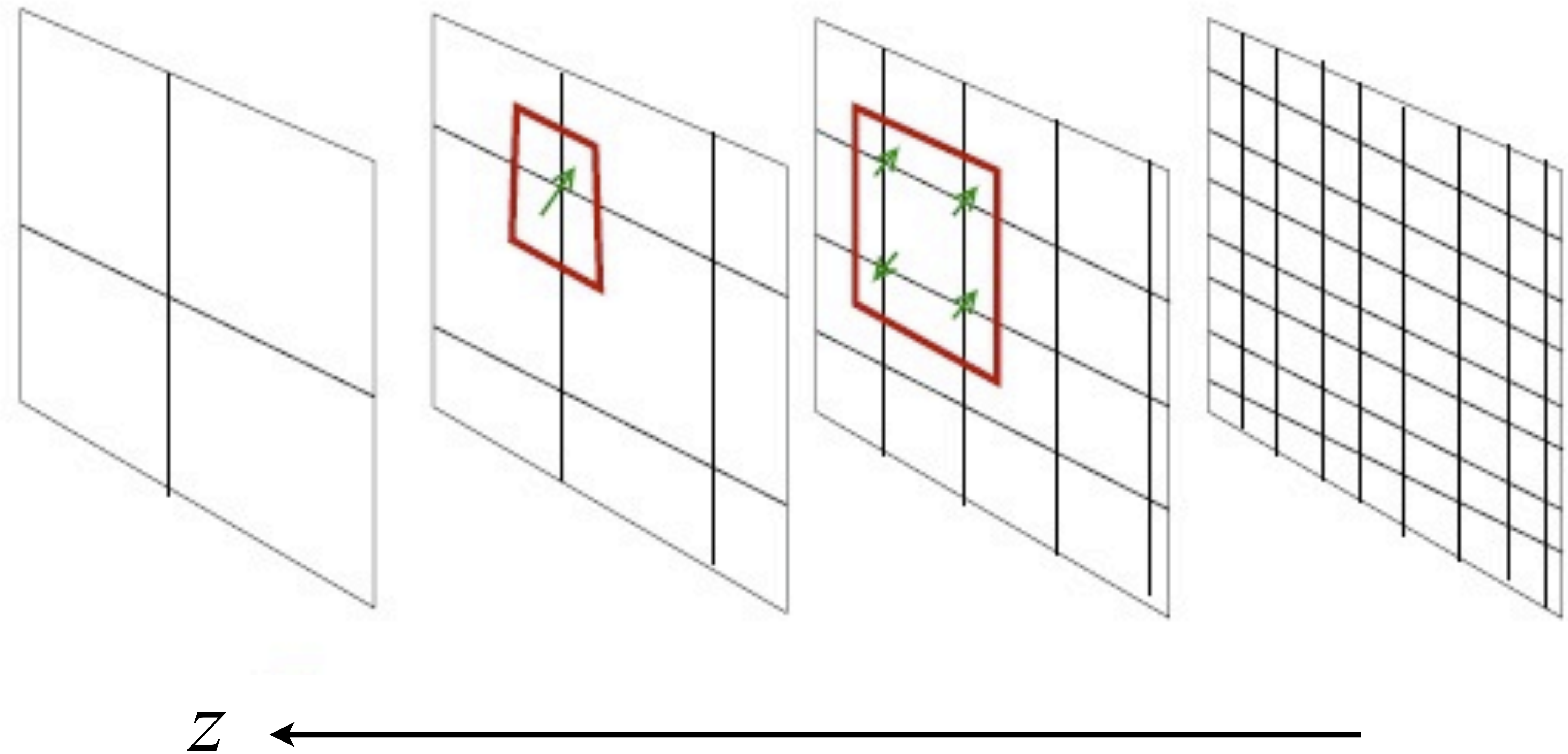
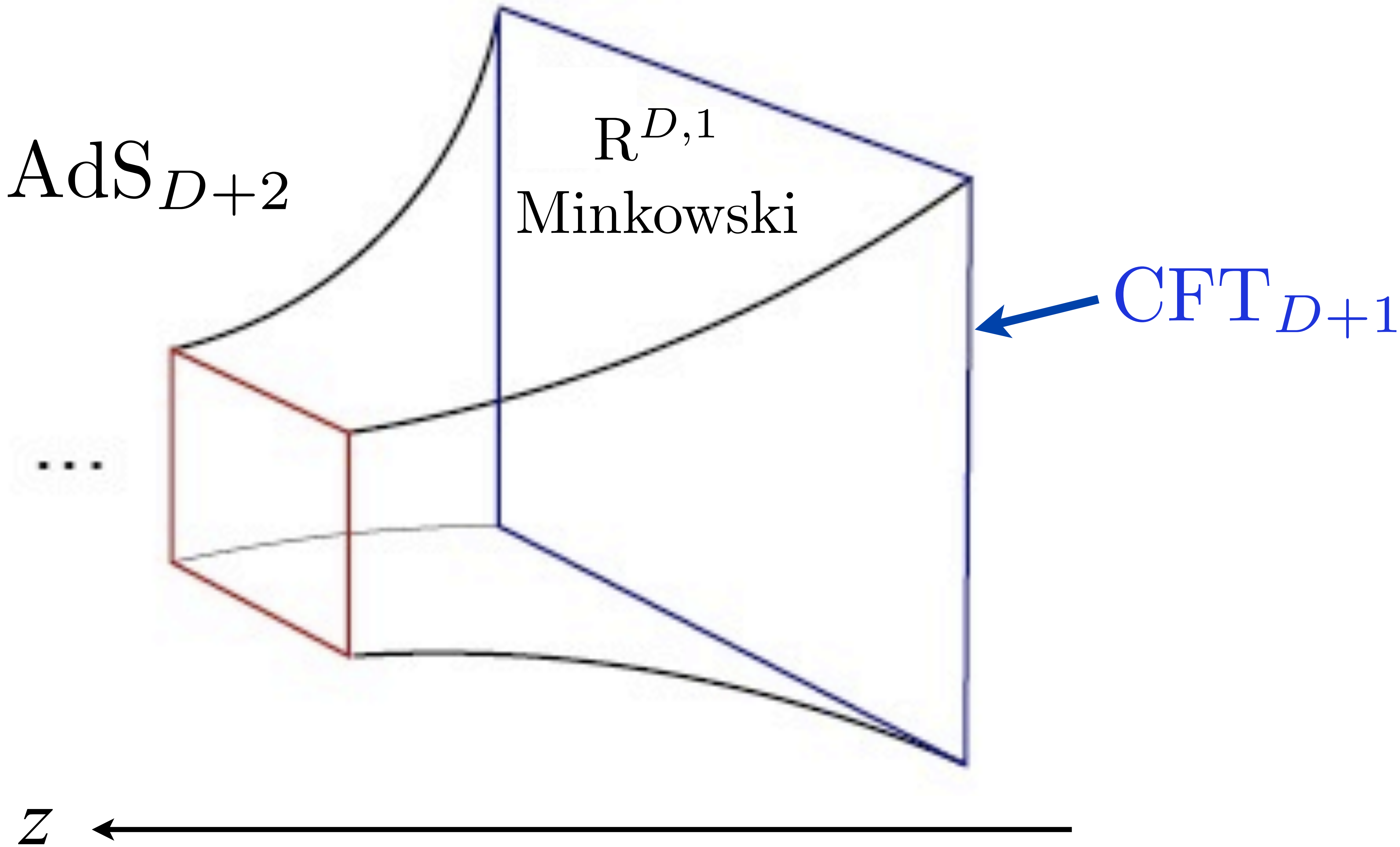


J. McGreevy, arXiv0909.0518



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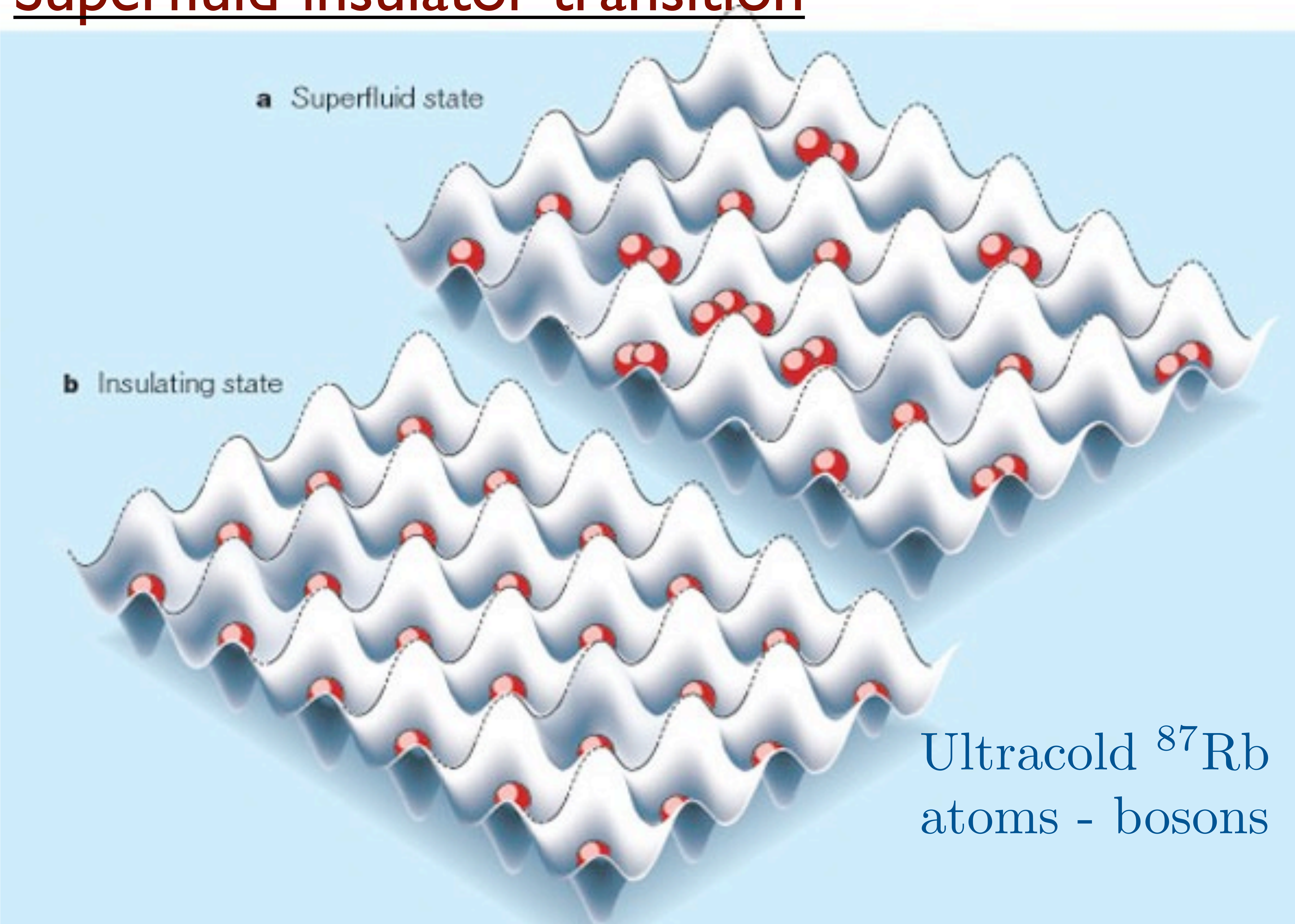
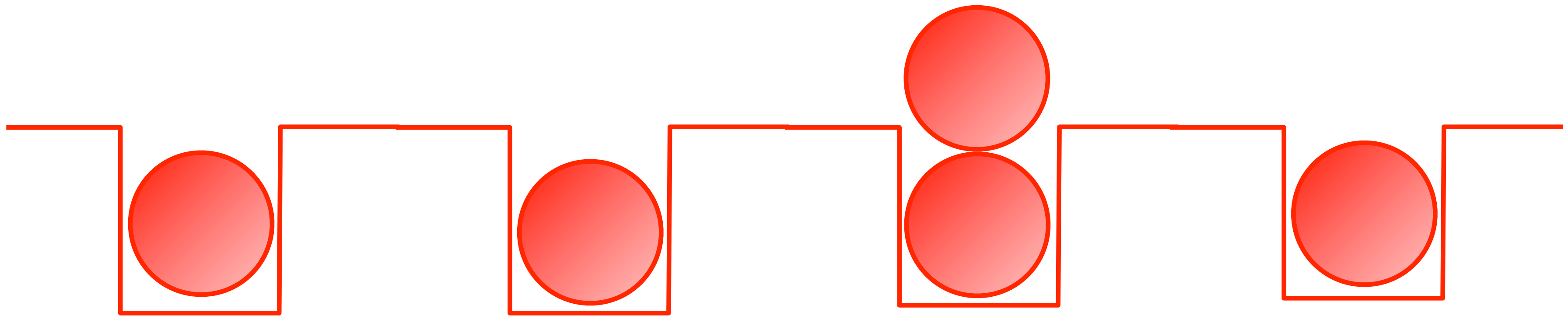
Superfluid-insulator transition



Ultracold ^{87}Rb
atoms - bosons

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

Excitations of the insulator:



Particles $\sim \psi^{\dagger}$

Holes $\sim \psi$

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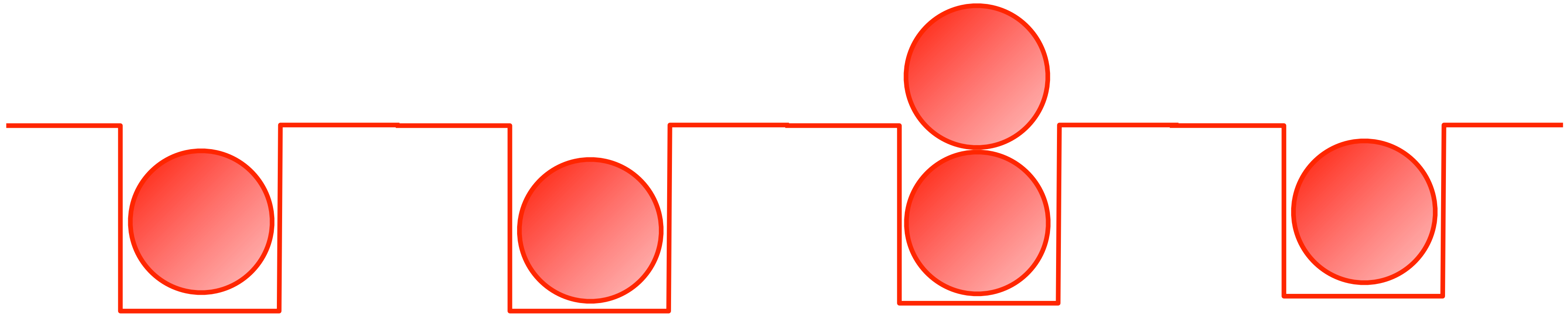

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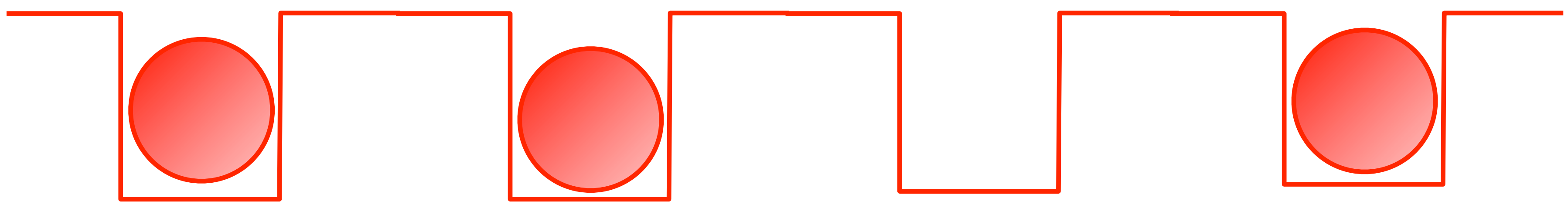

Holes $\sim \psi$

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

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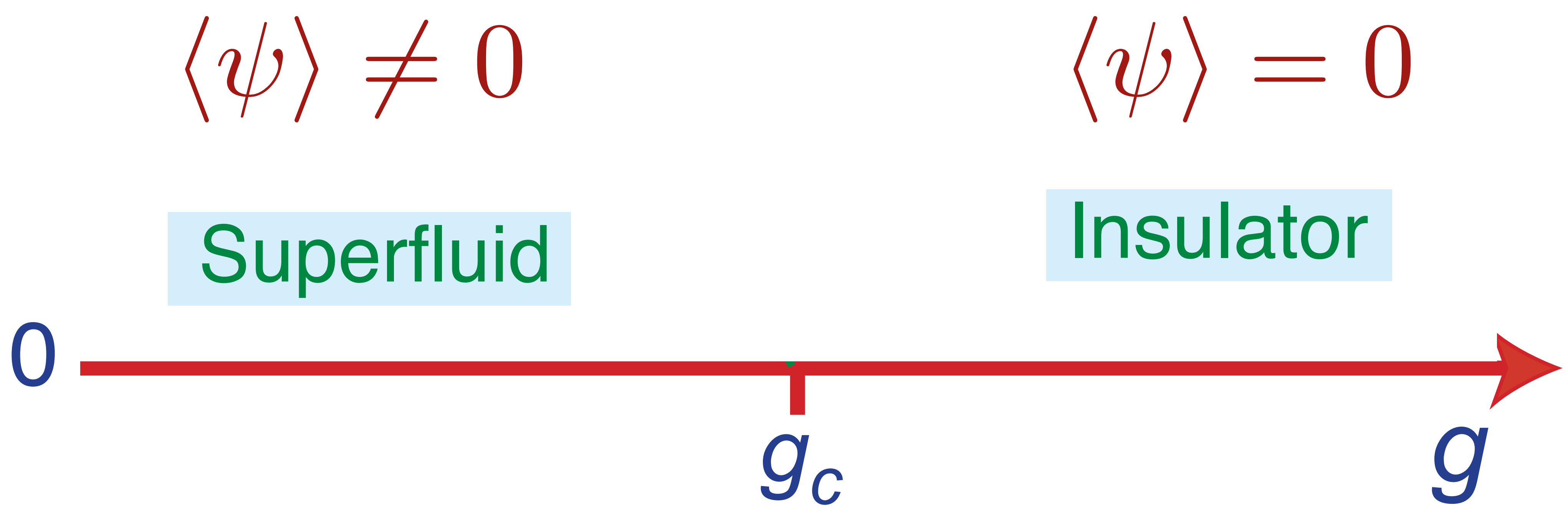
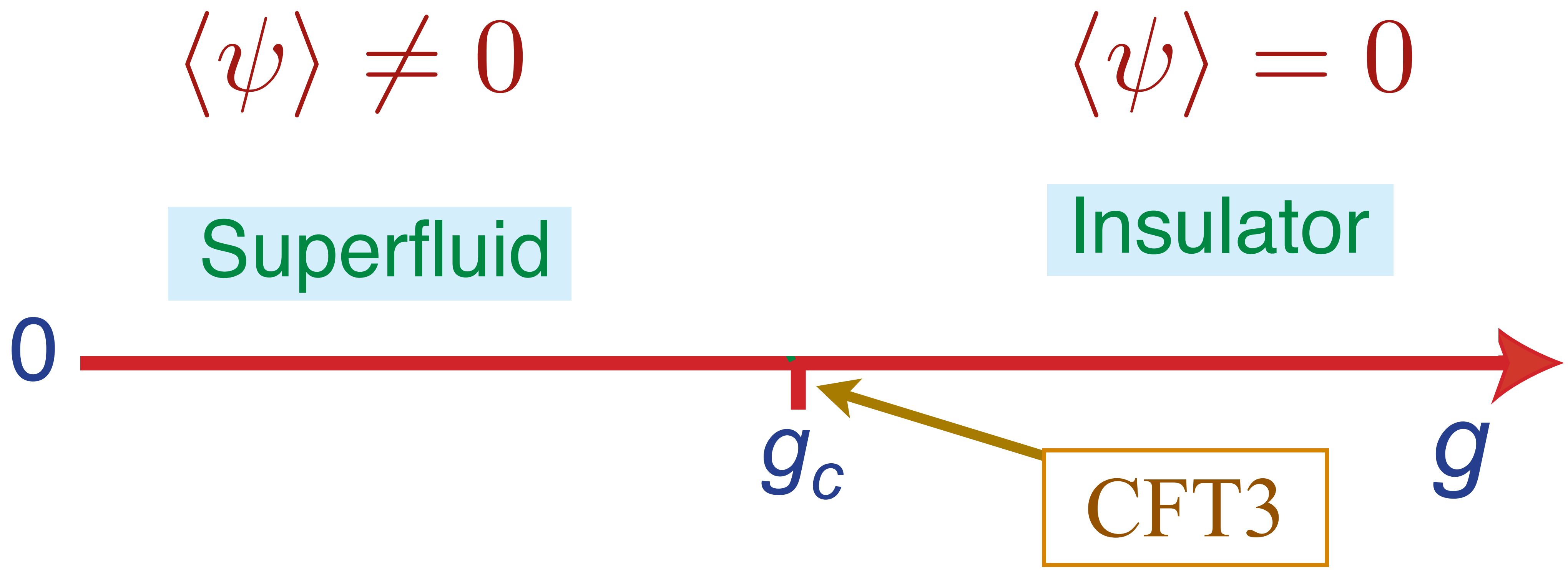
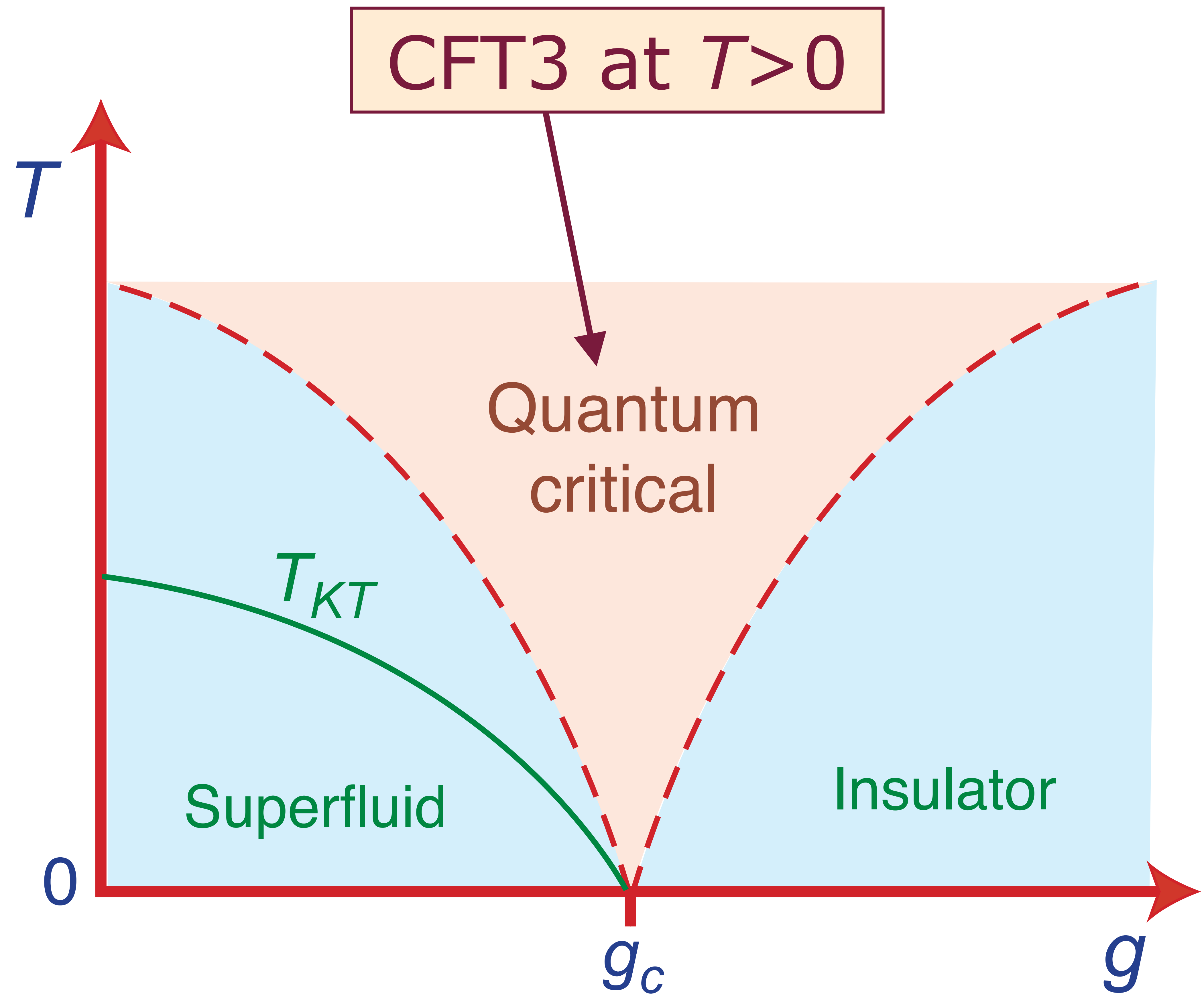
M.P. A. Fisher, P.B. Weichmann, G. Grinstein, and D.S. Fisher, *Phys. Rev. B* **40**, 546 (1989).


$\langle \psi \rangle \neq 0$
$\langle \psi \rangle = 0$
Superfluid
Insulator
0
g_c
g



$\langle \psi \rangle \neq 0$
$\langle \psi \rangle = 0$
Superfluid
Insulator
0
g_c
g
CFT3


CFT3 at $T>0$
T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
g_c
g

Quantum critical transport

Quantum *"nearly perfect fluid"*
with shortest possible
equilibration time, $\tau_{\rm eq}$

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

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 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).

Quantum critical transport

Describe charge transport using Boltzmann theory of interacting bosons:

$$\frac{dv}{dt} + \frac{v}{\tau_c} = F.$$

This gives a frequency (ω) dependent conductivity

$$\sigma(\omega) = \frac{\sigma_0}{1 - i\,\omega\,\tau_c}$$

where $\tau_c \sim \hbar/(k_B T)$ is the time between boson collisions.

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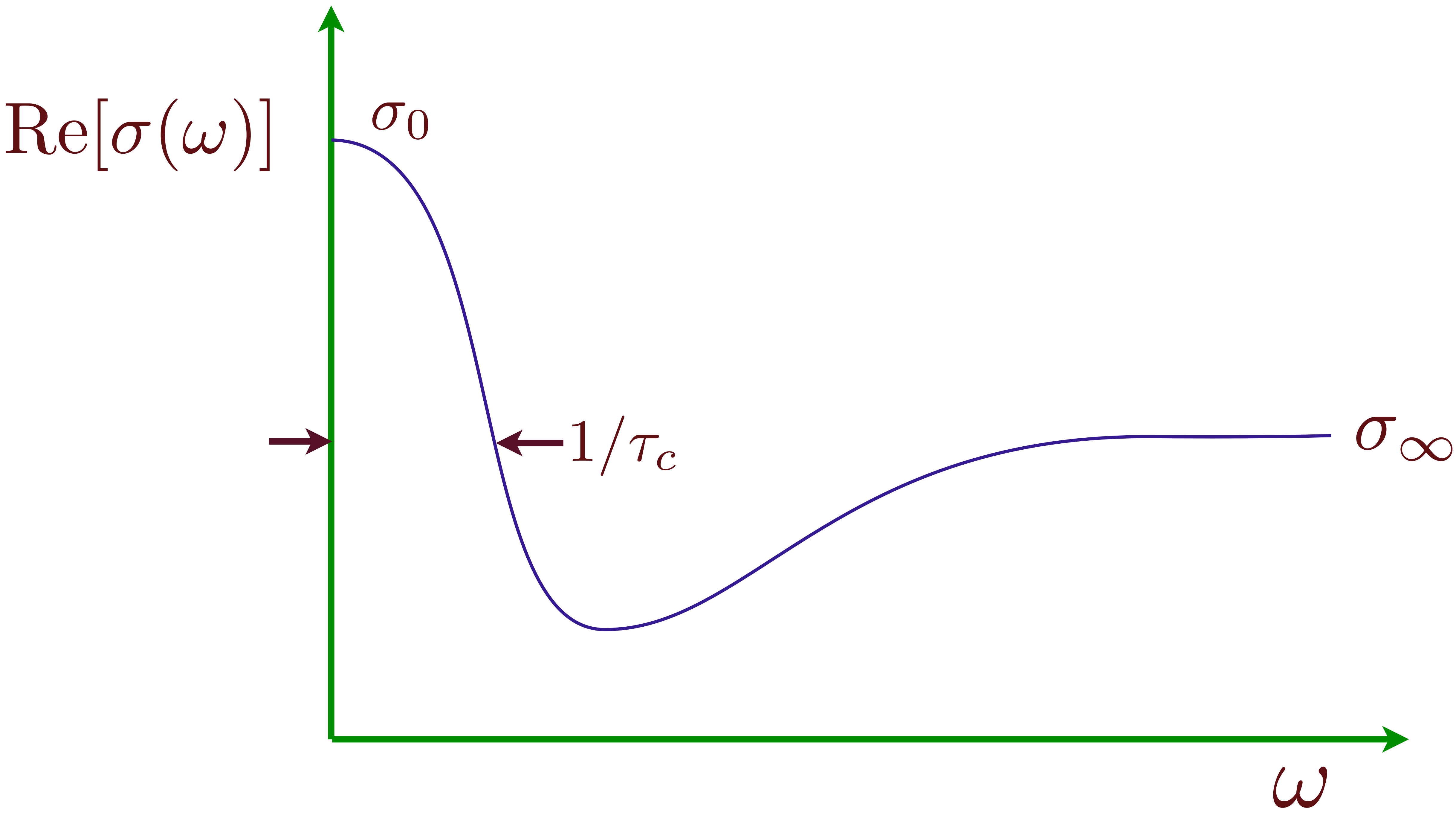
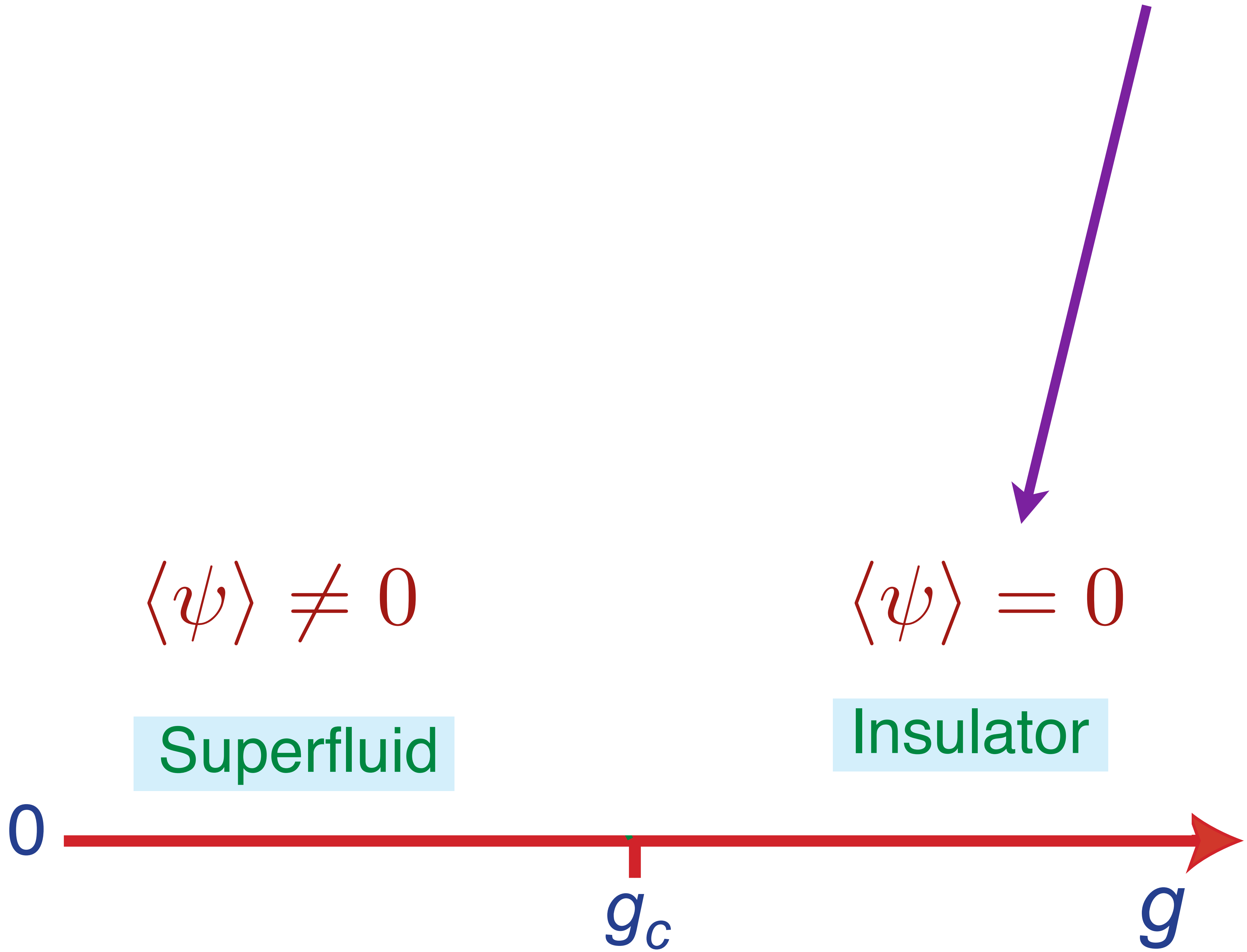
Also, we have $\sigma(\omega \to \infty) = \sigma_\infty$, associated with the density of states for particle-hole creation (the "optical conductivity") in the CFT3.

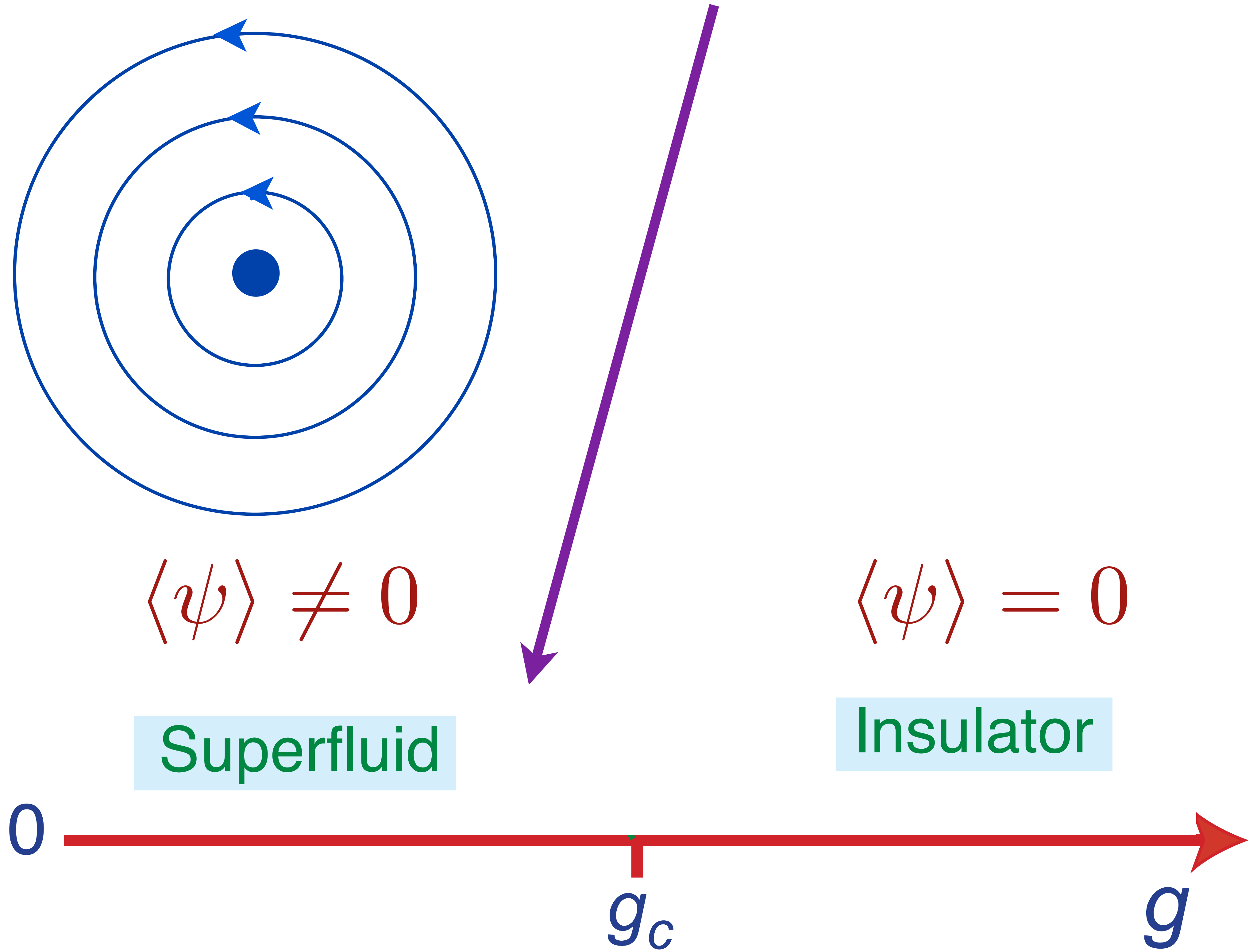
Boltzmann theory of bosons



So far, we have described the quantum critical point using the boson particle and hole excitations of the insulator.



However, we could equally well describe the conductivity using the excitations of the superfluid, which are *vortices*.



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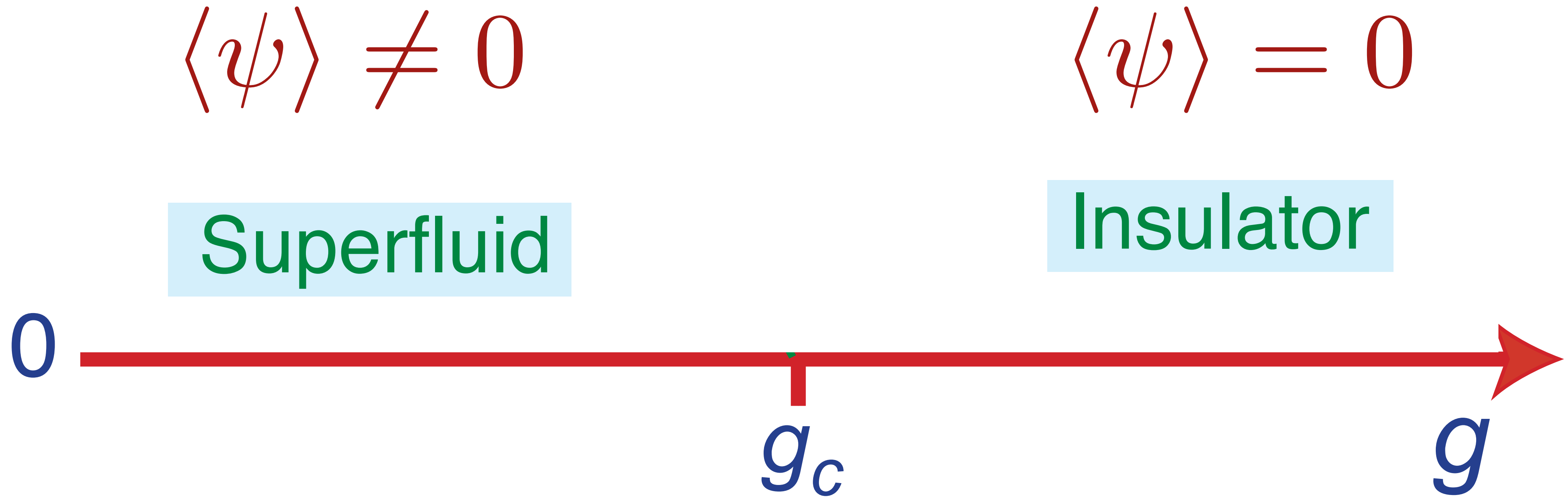
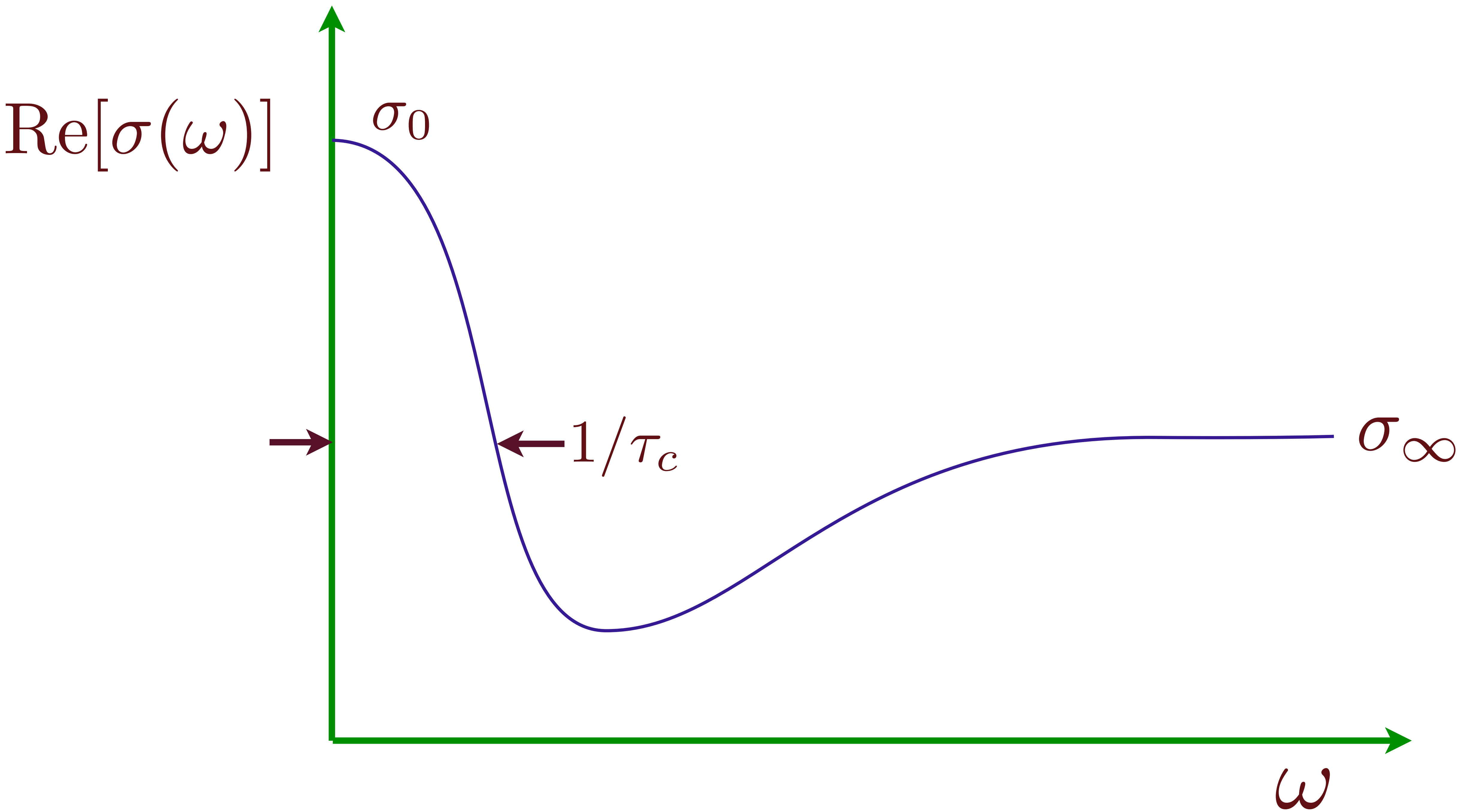
These are quantum particles (in 2+1 dimensions) which described by a (mirror/e.m.) "dual" CFT3 with an emergent U(1) gauge field. Their $T > 0$ dynamics can also be described by a Boltzmann equation:

$$\text{Conductivity} = \text{Resistivity of vortices}$$

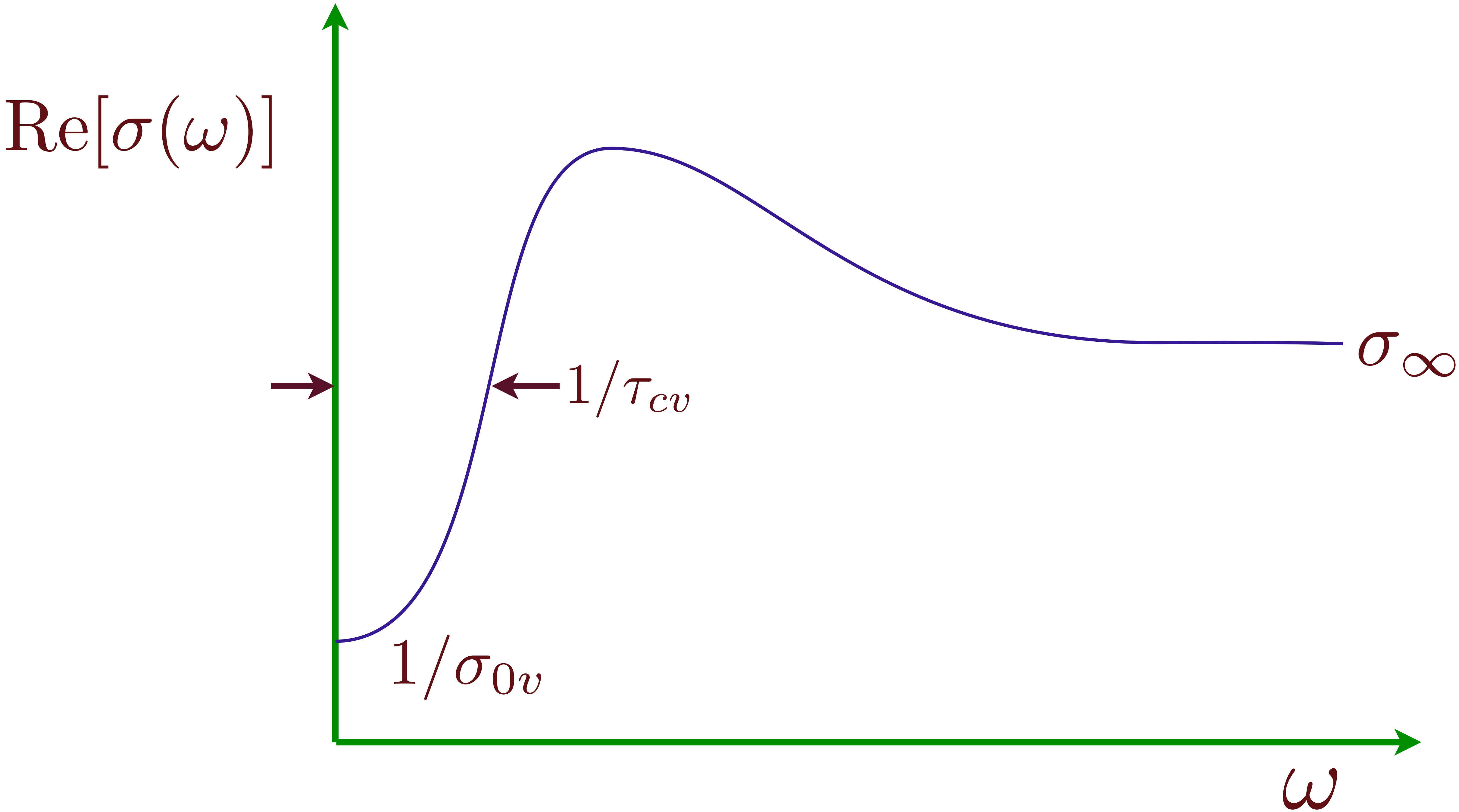


M.P.A. Fisher, *Physical Review Letters* **65**, 923 (1990)

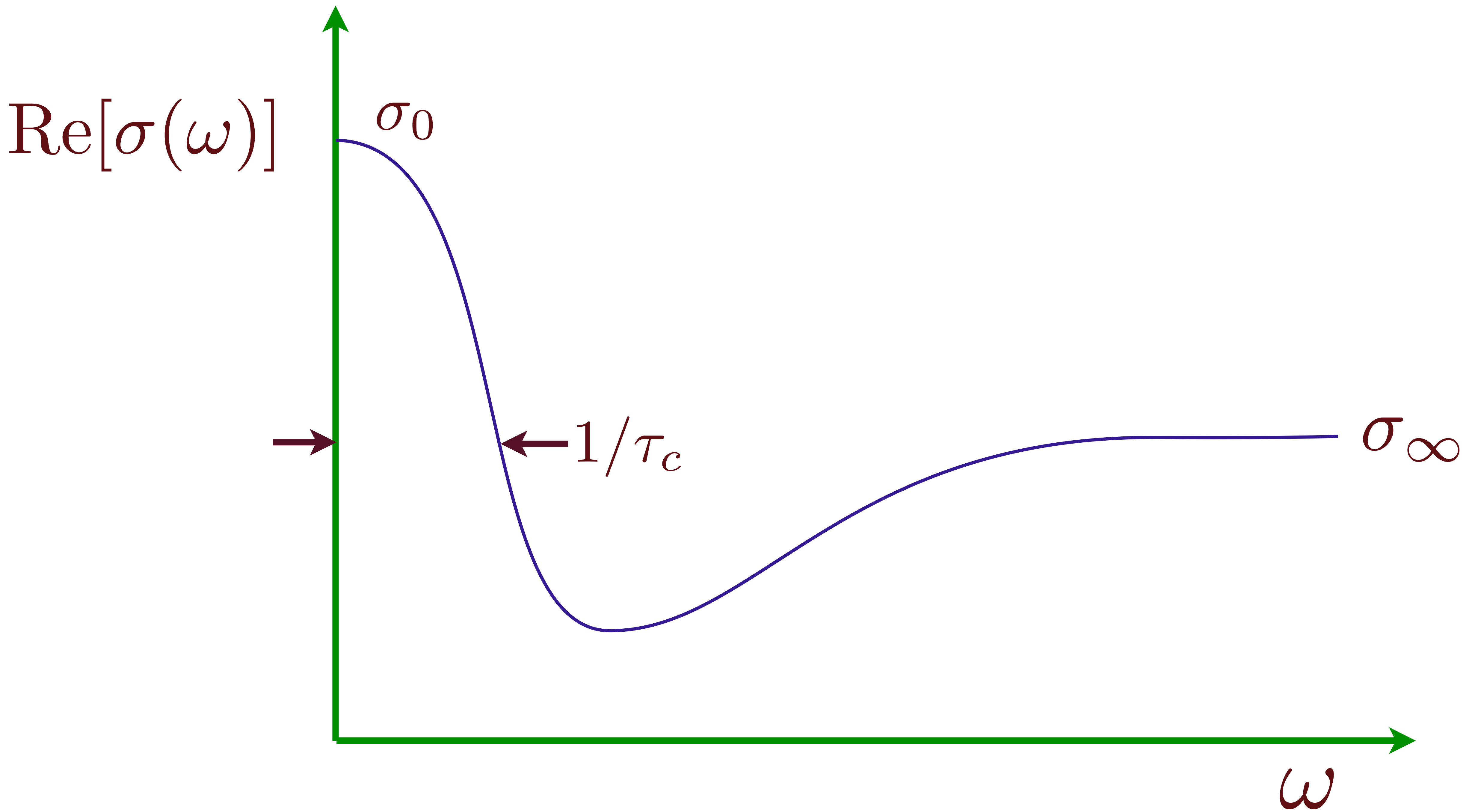
Boltzmann theory of bosons



Boltzmann theory of vortices



Boltzmann theory of bosons

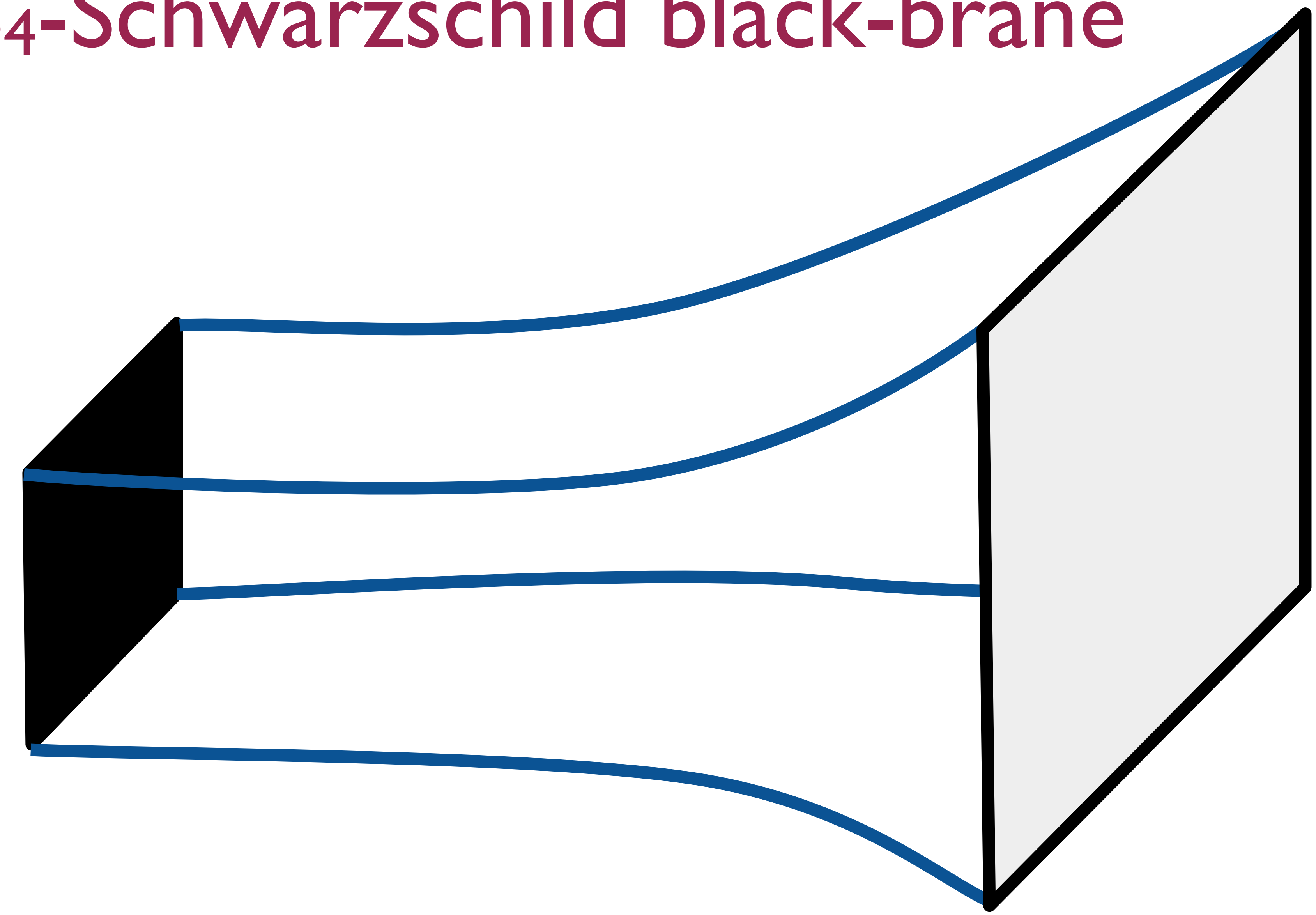


Answers from string theory

AdS/CFT correspondence at non-zero temperatures

AdS/CFT correspondence at non-zero temperatures

AdS_4-Schwarzschild black-brane



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

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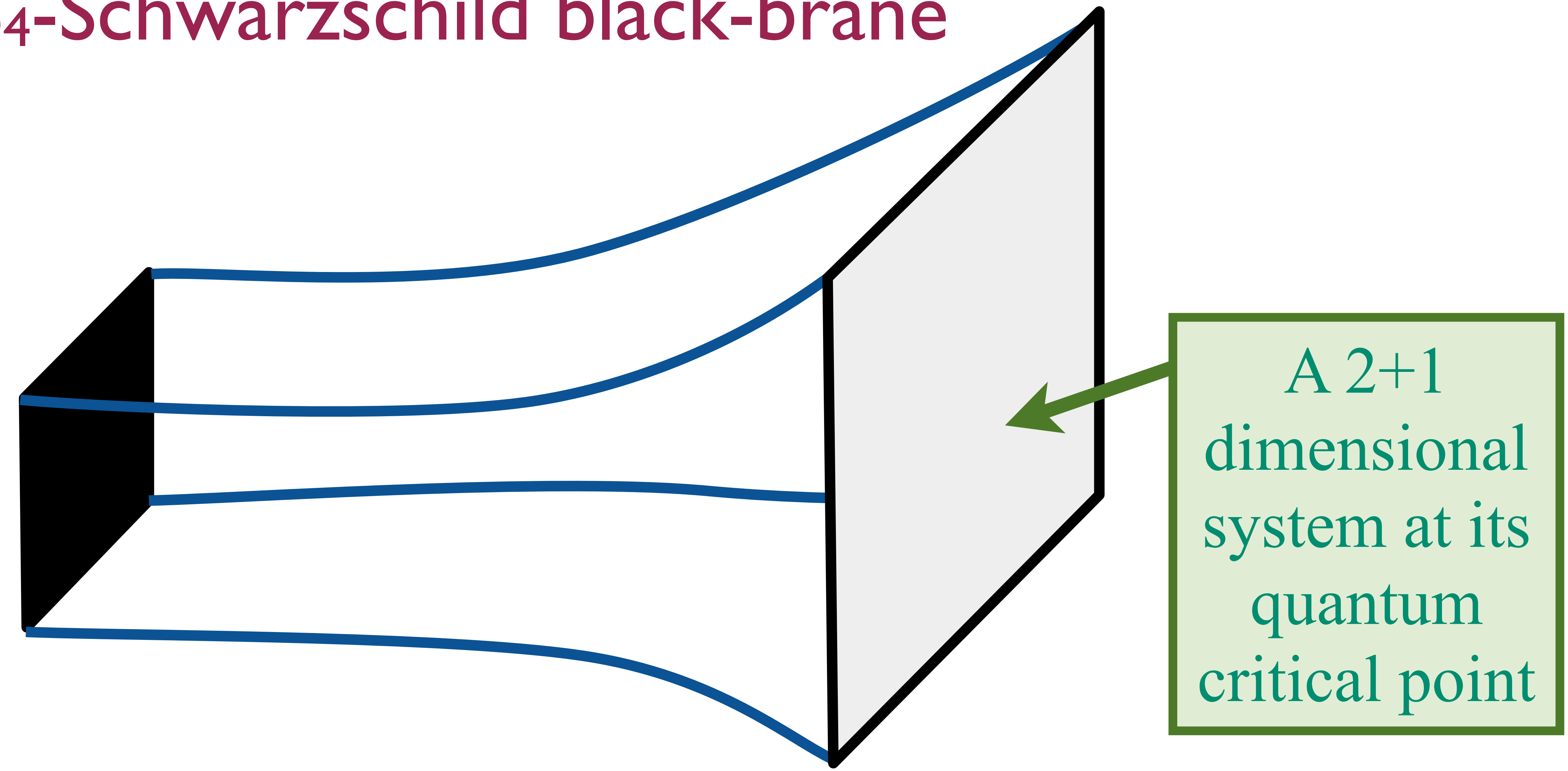

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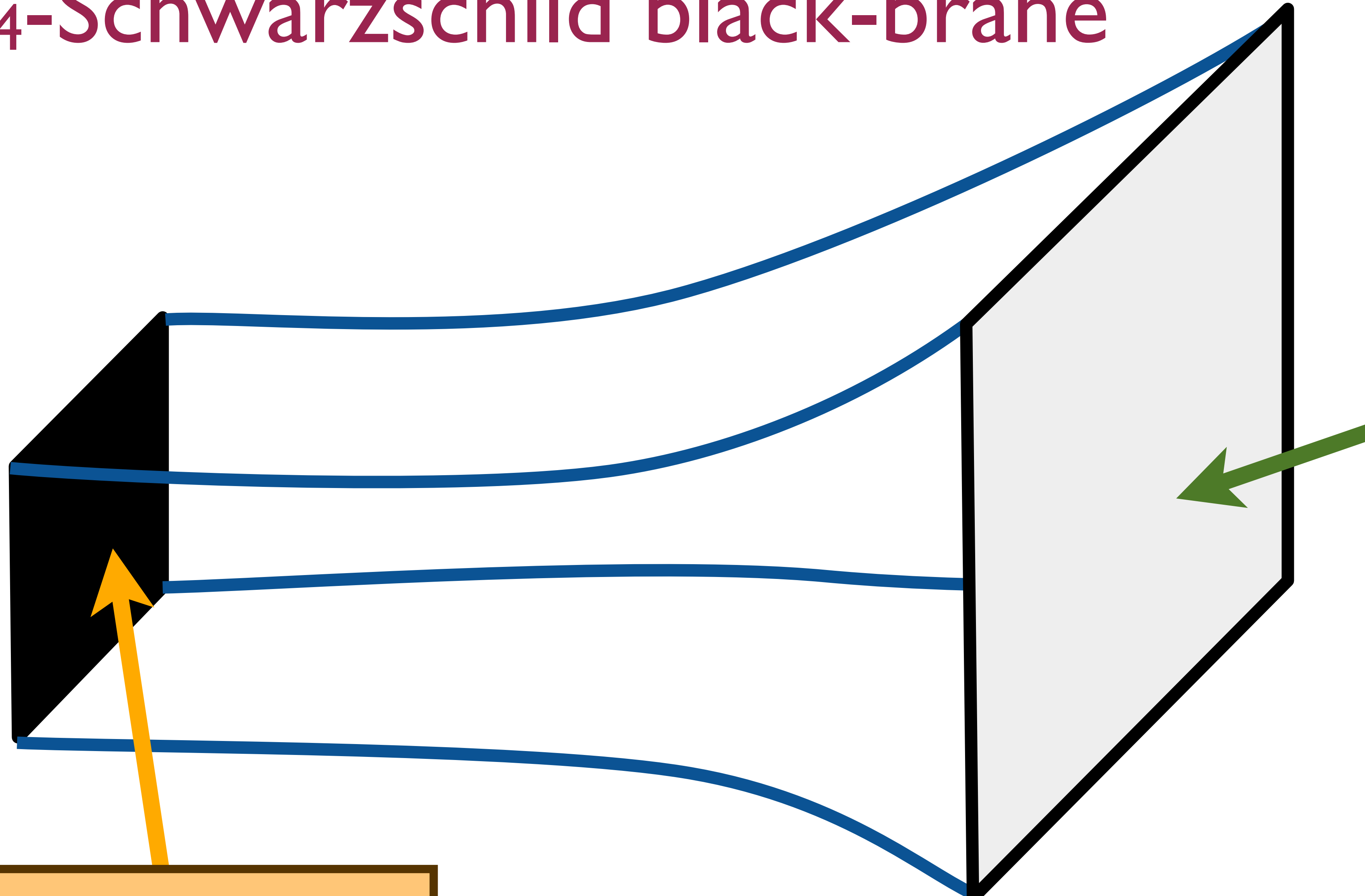

A 2+1 dimensional system at its quantum critical point

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

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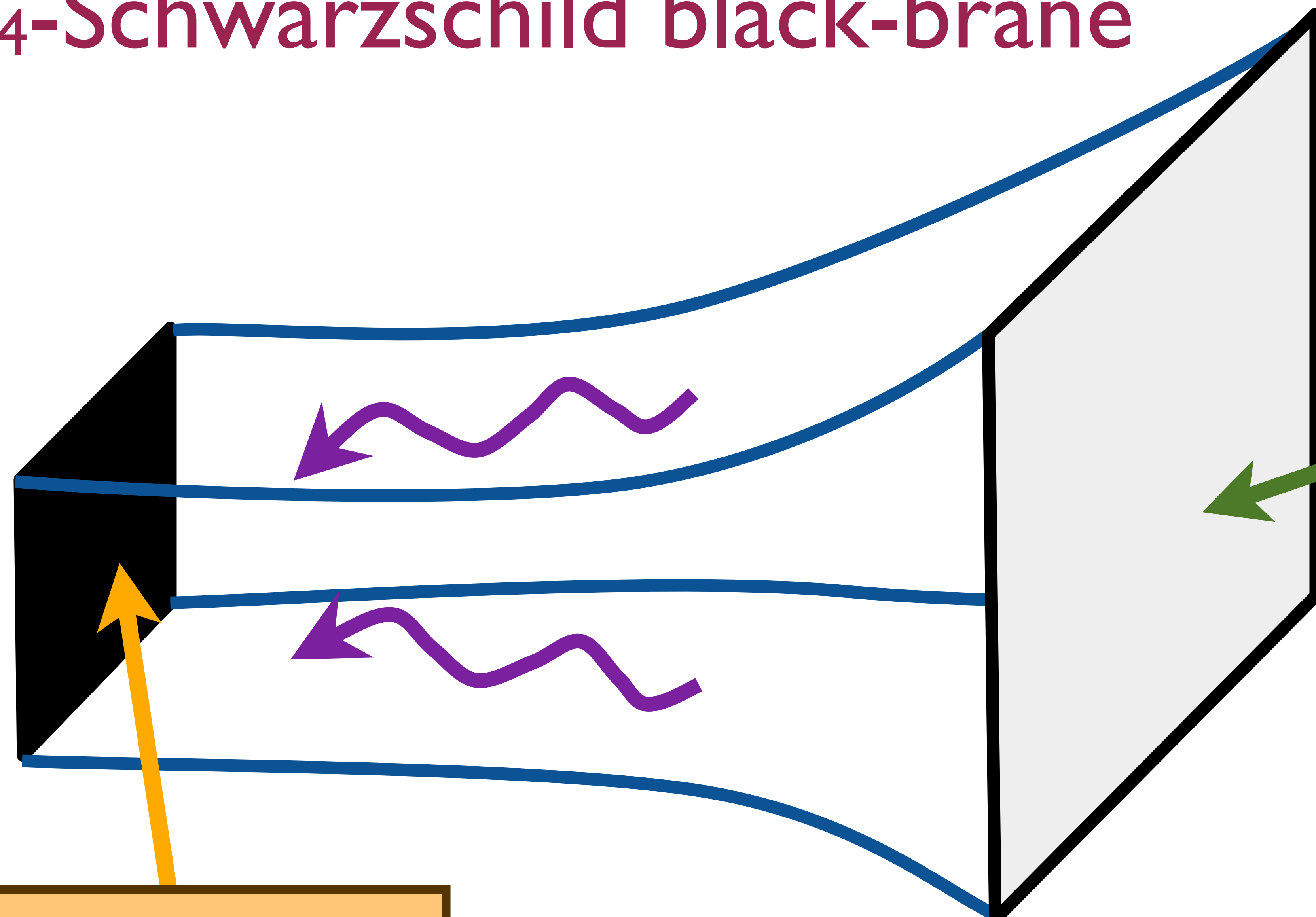


A 2+1 dimensional system at its quantum critical point

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

Friction of quantum criticality = waves falling into black brane

AdS$_4$ theory of "nearly perfect fluids"

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

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

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

AdS$_4$ theory of "nearly perfect fluids"

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

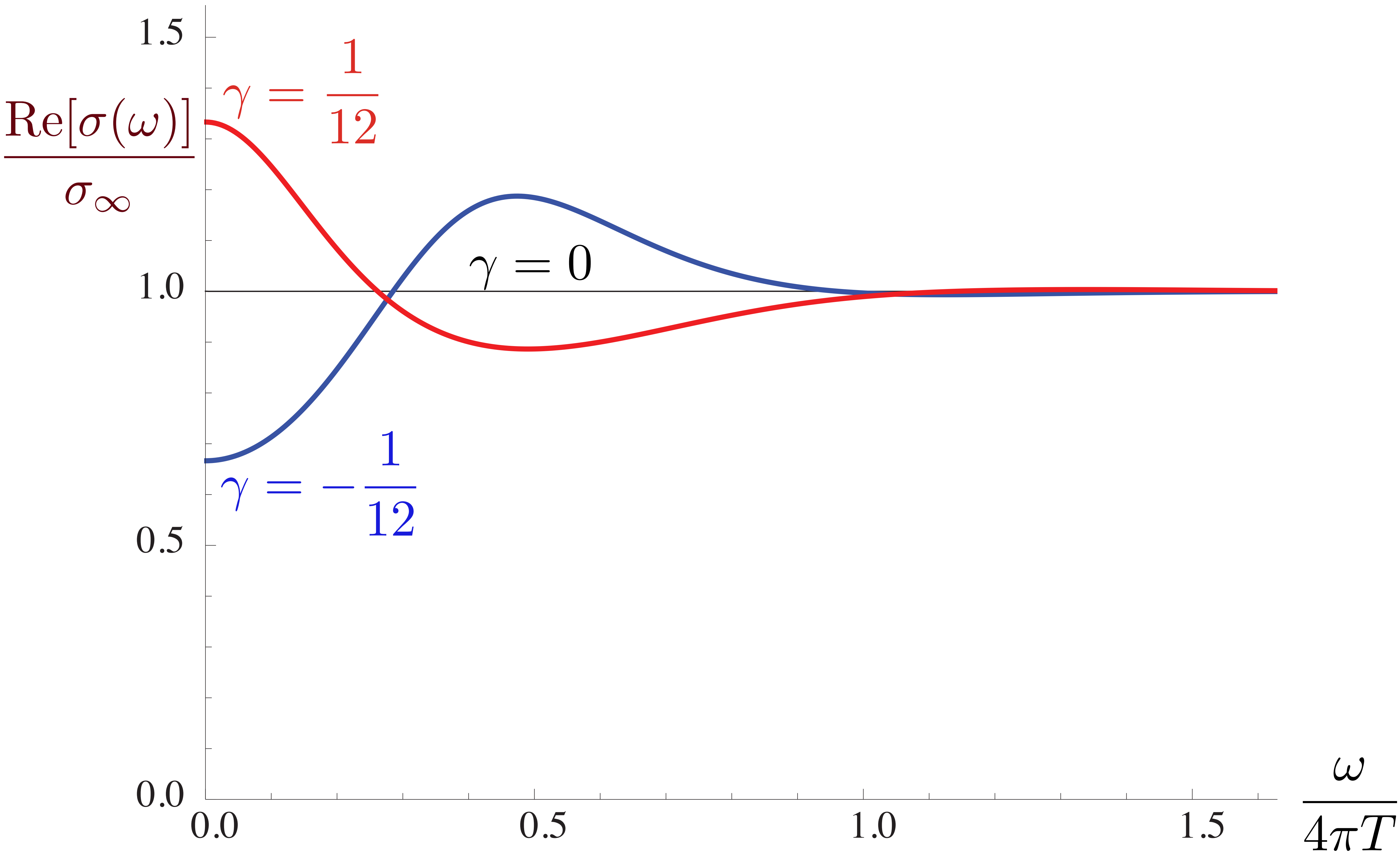
We include all possible 4-derivative terms: after suitable field redefinitions, the required theory has only *one* dimensionless constant γ (L is the radius of AdS$_4$):

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

where C_{abcd} is the Weyl curvature tensor.
Stability and causality constraints restrict $|\gamma| < 1/12$.
The value of γ can be fixed by matching to a direct computation in the CFT3 at $T = 0$.

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

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



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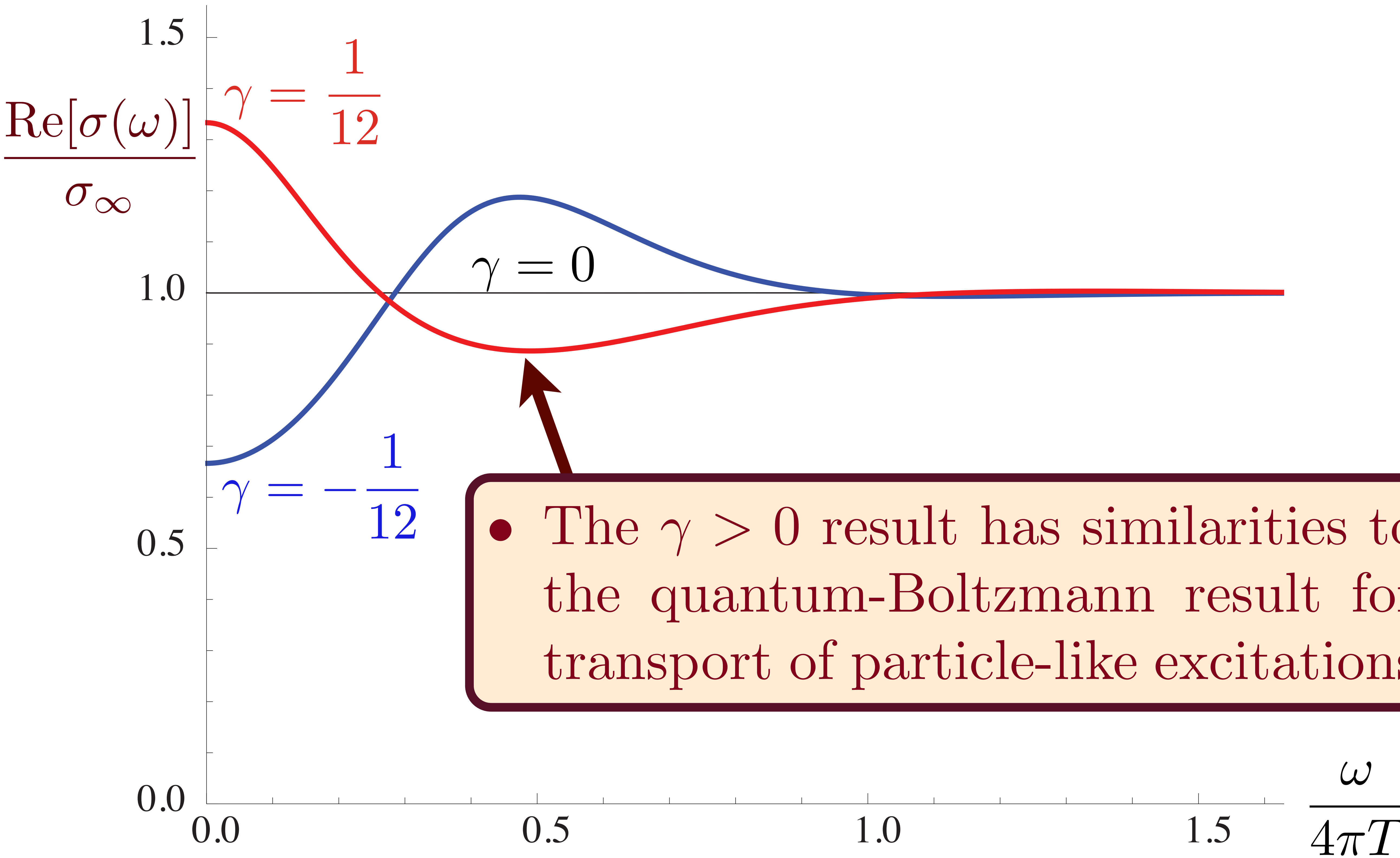

- The $\gamma > 0$ result has similarities to the quantum-Boltzmann result for transport of particle-like excitations

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

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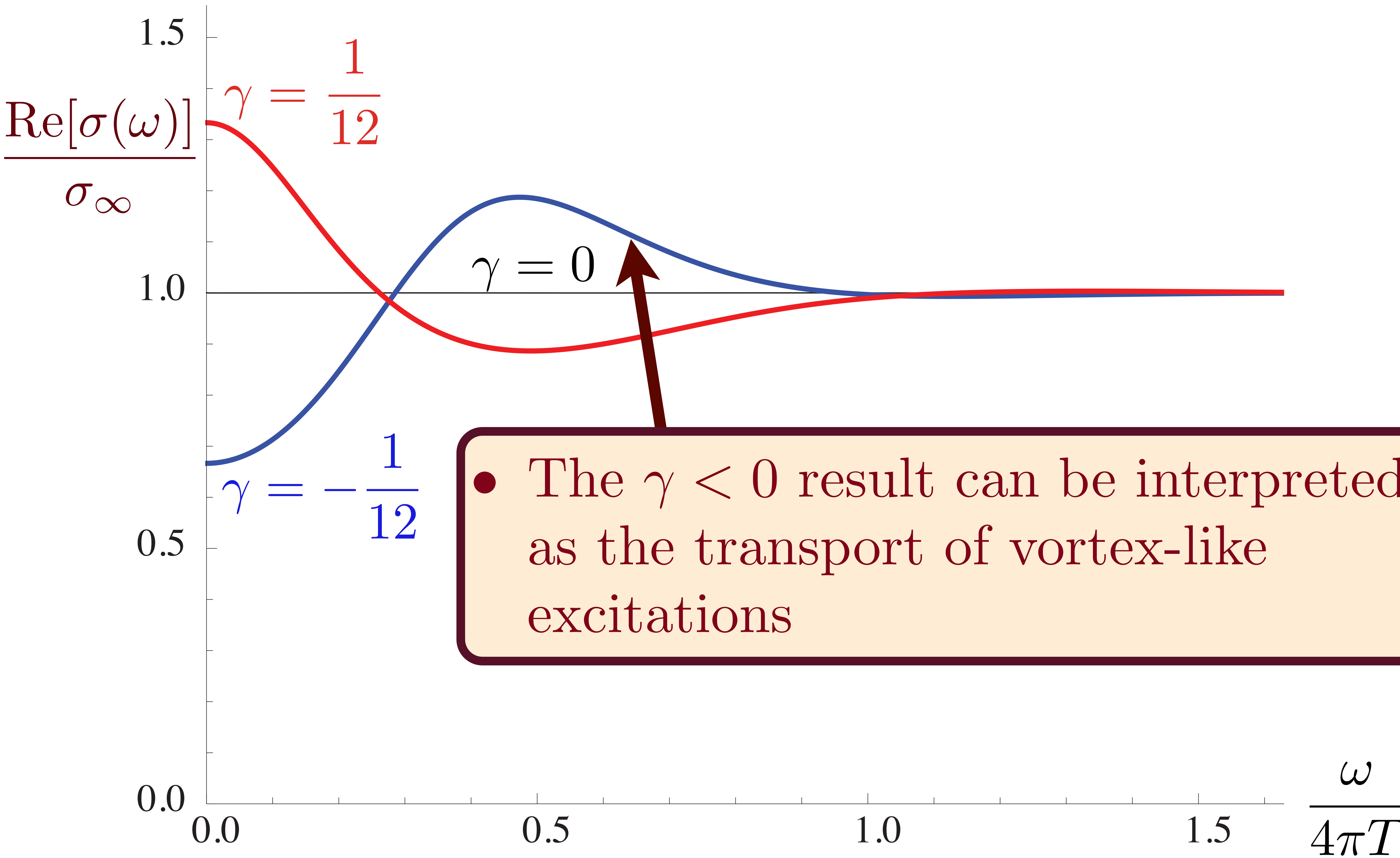
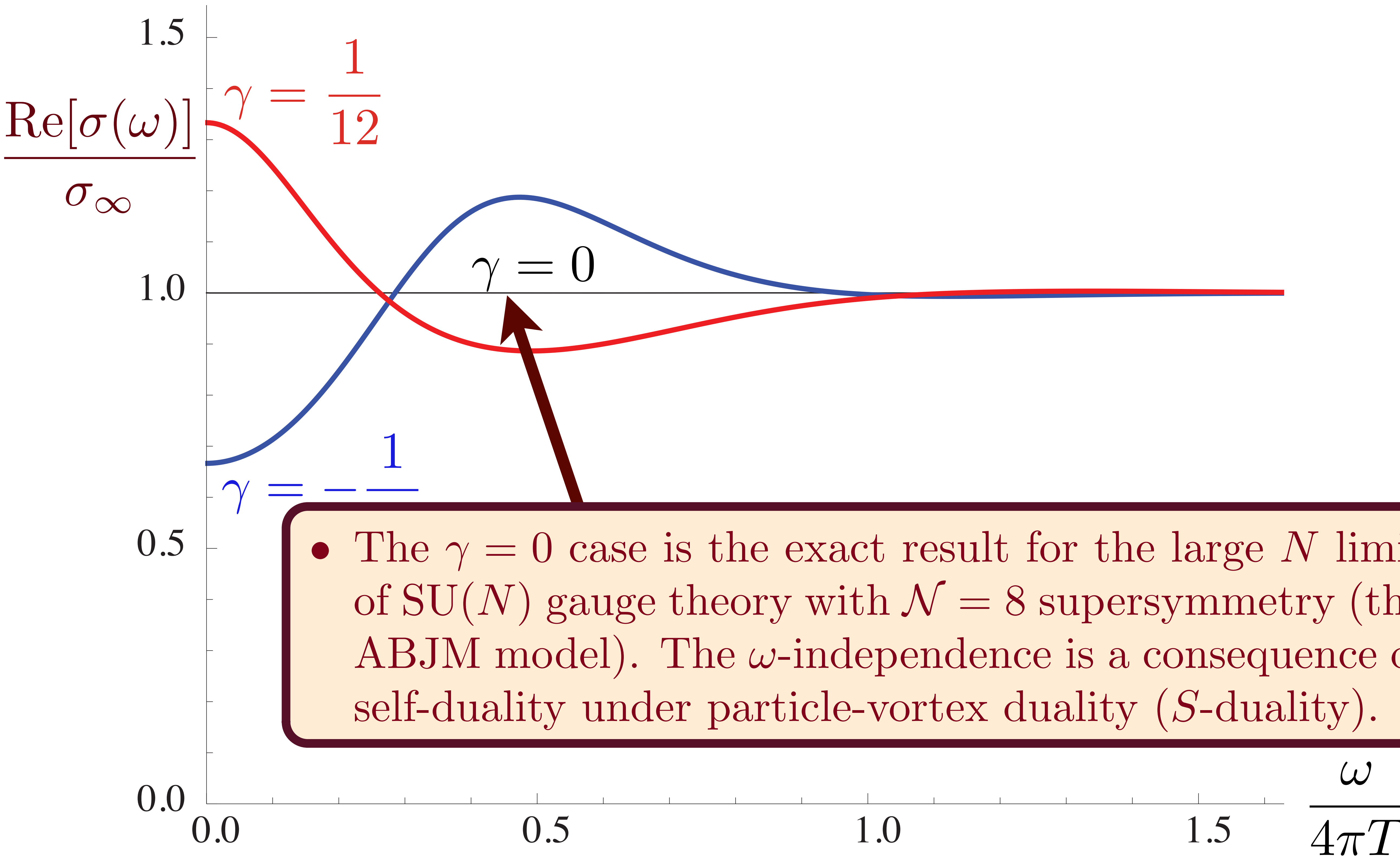


- The $\gamma < 0$ result can be interpreted as the transport of vortex-like excitations

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

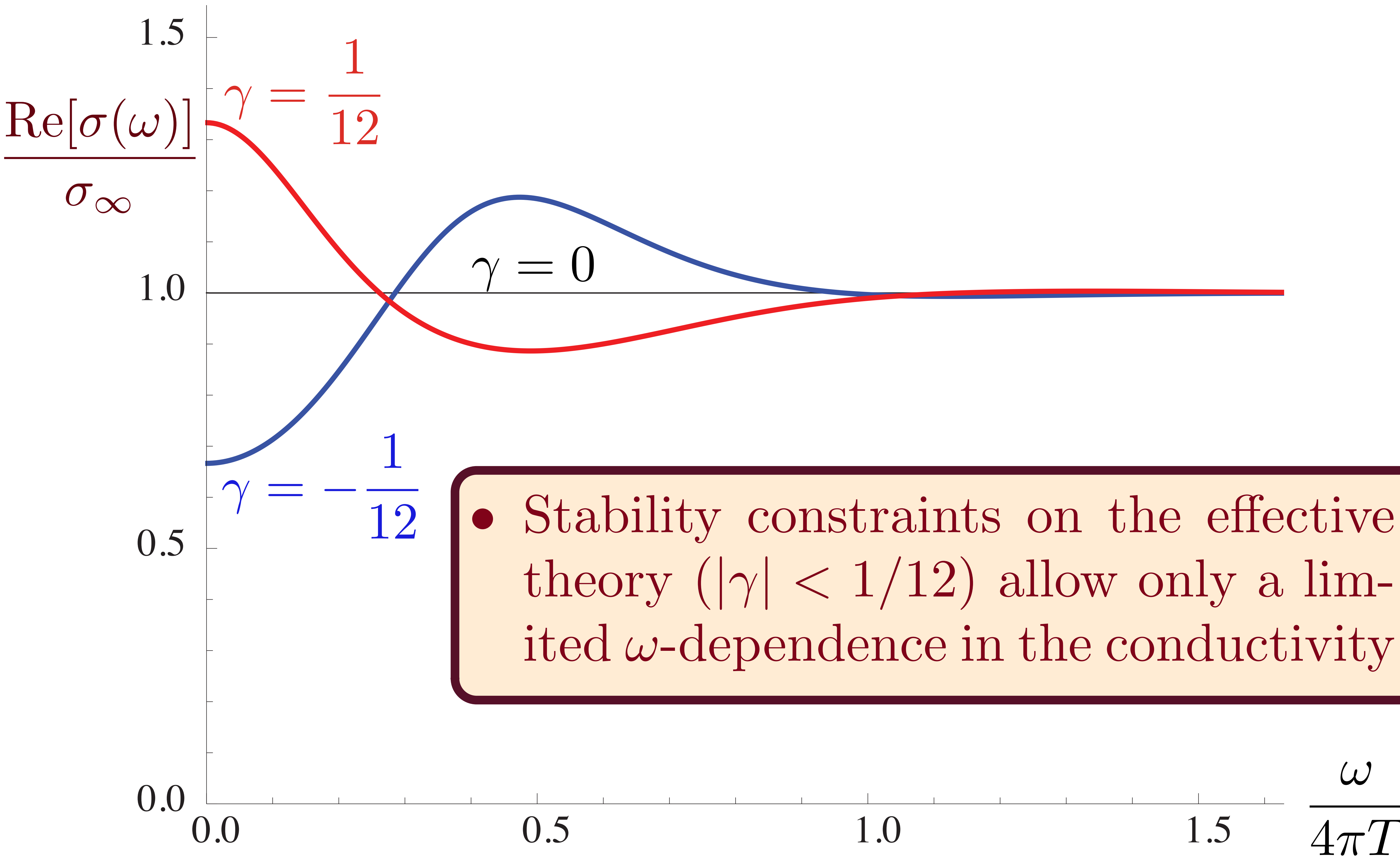
AdS$_4$ theory of strongly interacting "perfect fluids"



- 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 strongly interacting "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)

Outline

1. Quantum critical points and string theory
   Entanglement and emergent dimensions

2. Some difficult condensed matter questions and answers from string theory
   "Nearly-perfect" quantum fluids near the superfluid-insulator transition

3. High temperature superconductors and strange metals
   Holography of compressible quantum phases

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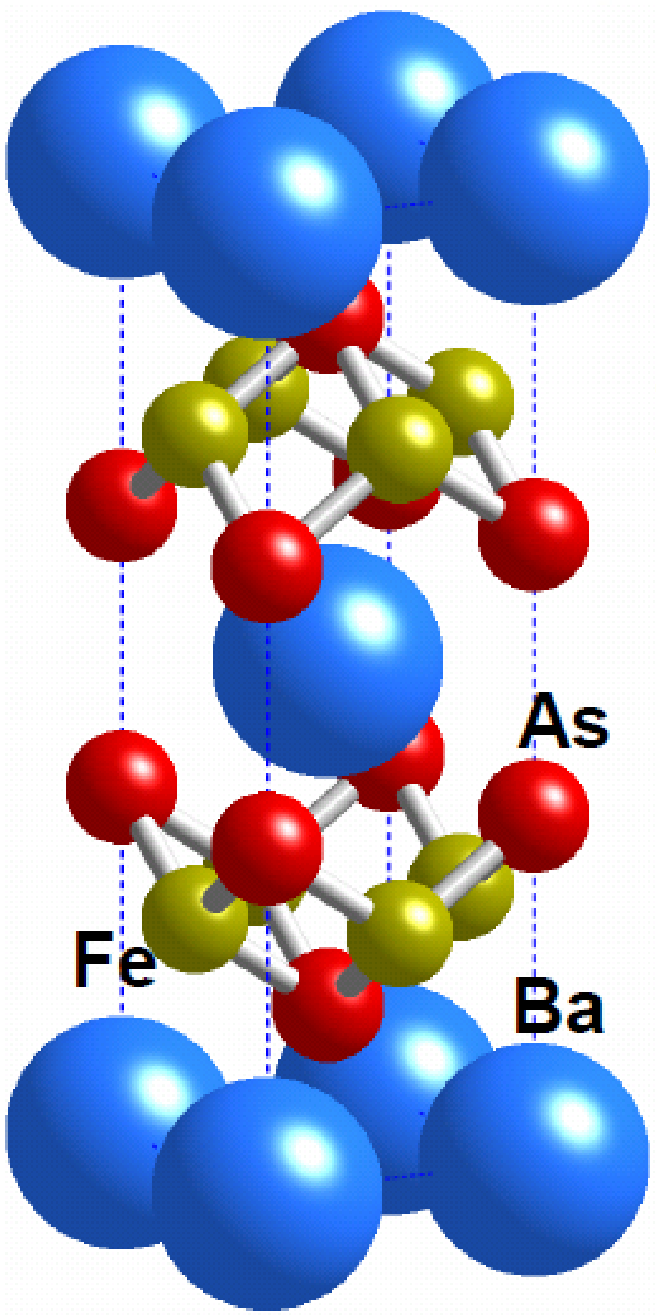
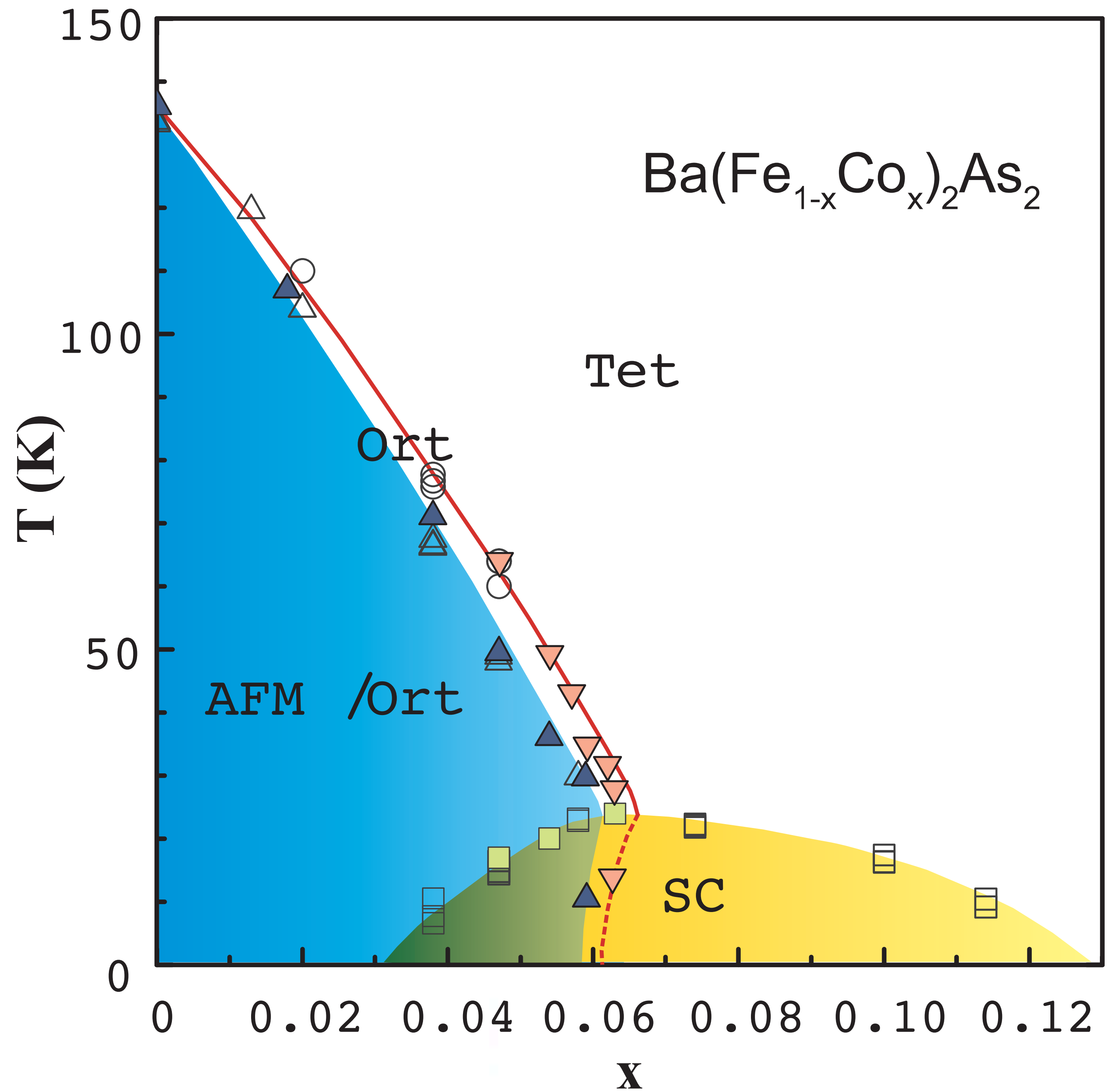
Iron pnictides:

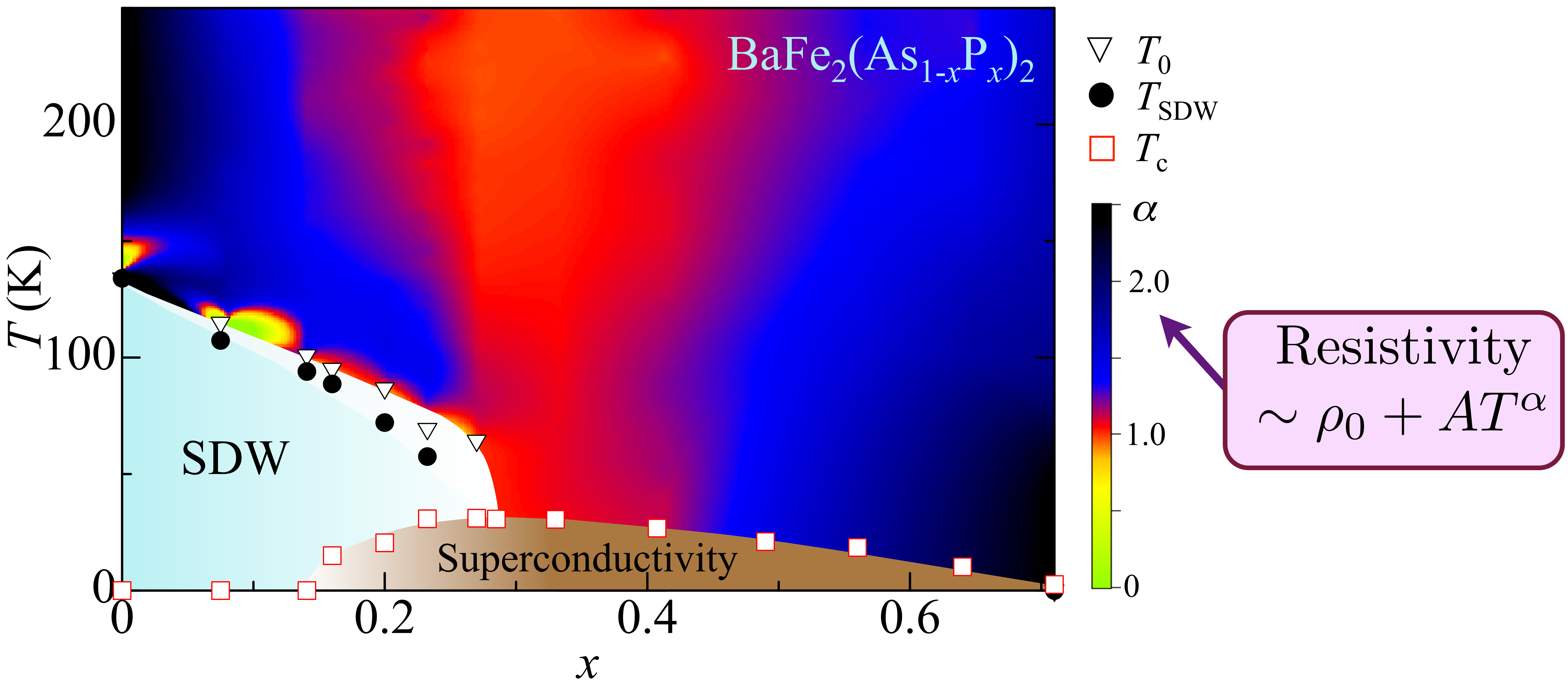
a new class of high temperature superconductors





S. Nandi, M. G. Kim, A. Kreyssig, R. M. Fernandes, D. K. Pratt, A. Thaler, N. Ni, S. L. Bud'ko, P. C. Canfield, J. Schmalian, R. J. McQueeney, A. I. Goldman, *Physical Review Letters* **104**, 057006 (2010).

Temperature-doping phase diagram of the iron pnictides:



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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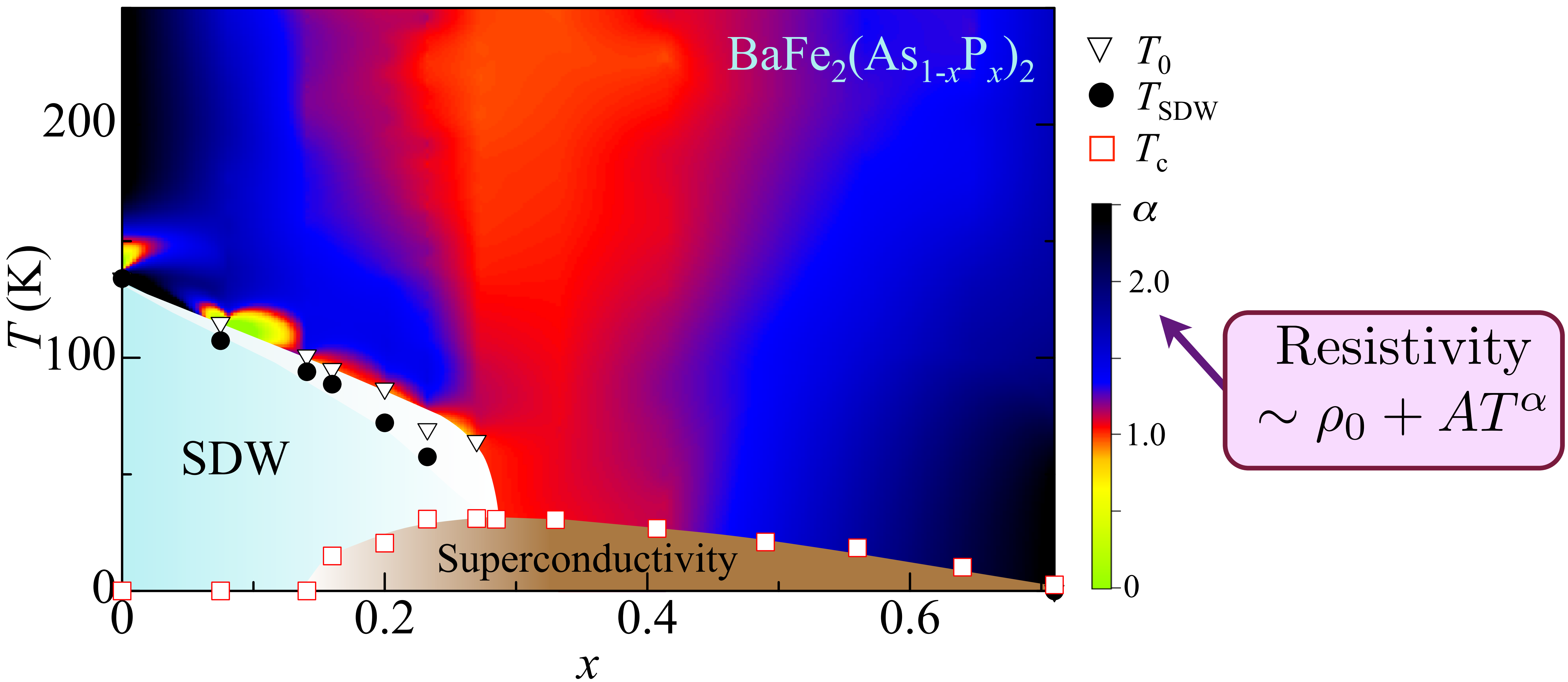

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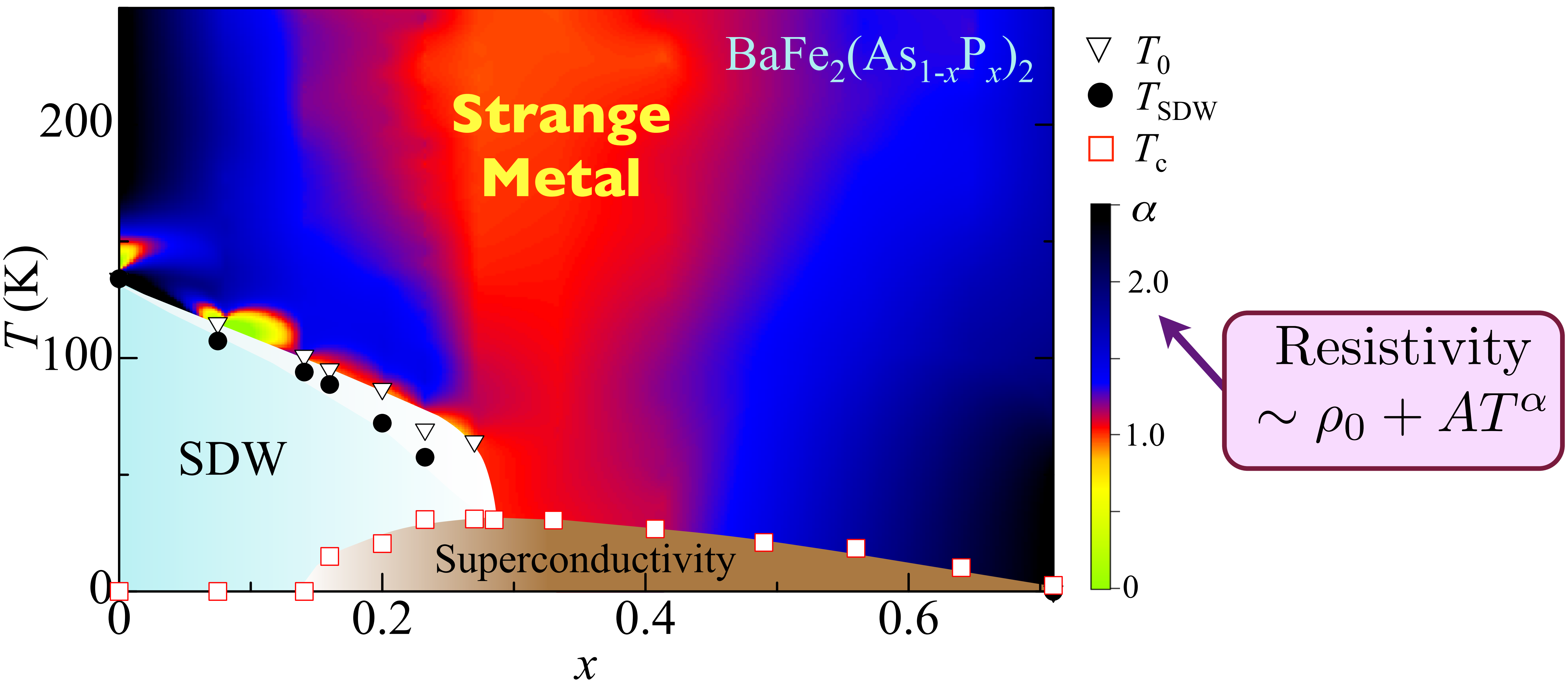

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None of these phases are CFTs

Their electron densities are variable,
i.e. they are compressible, and they are electrical conductors.

While finding such phases is simple at high temperatures,
there are only a few possible compressible quanutm phases...

Compressible quantum matter

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

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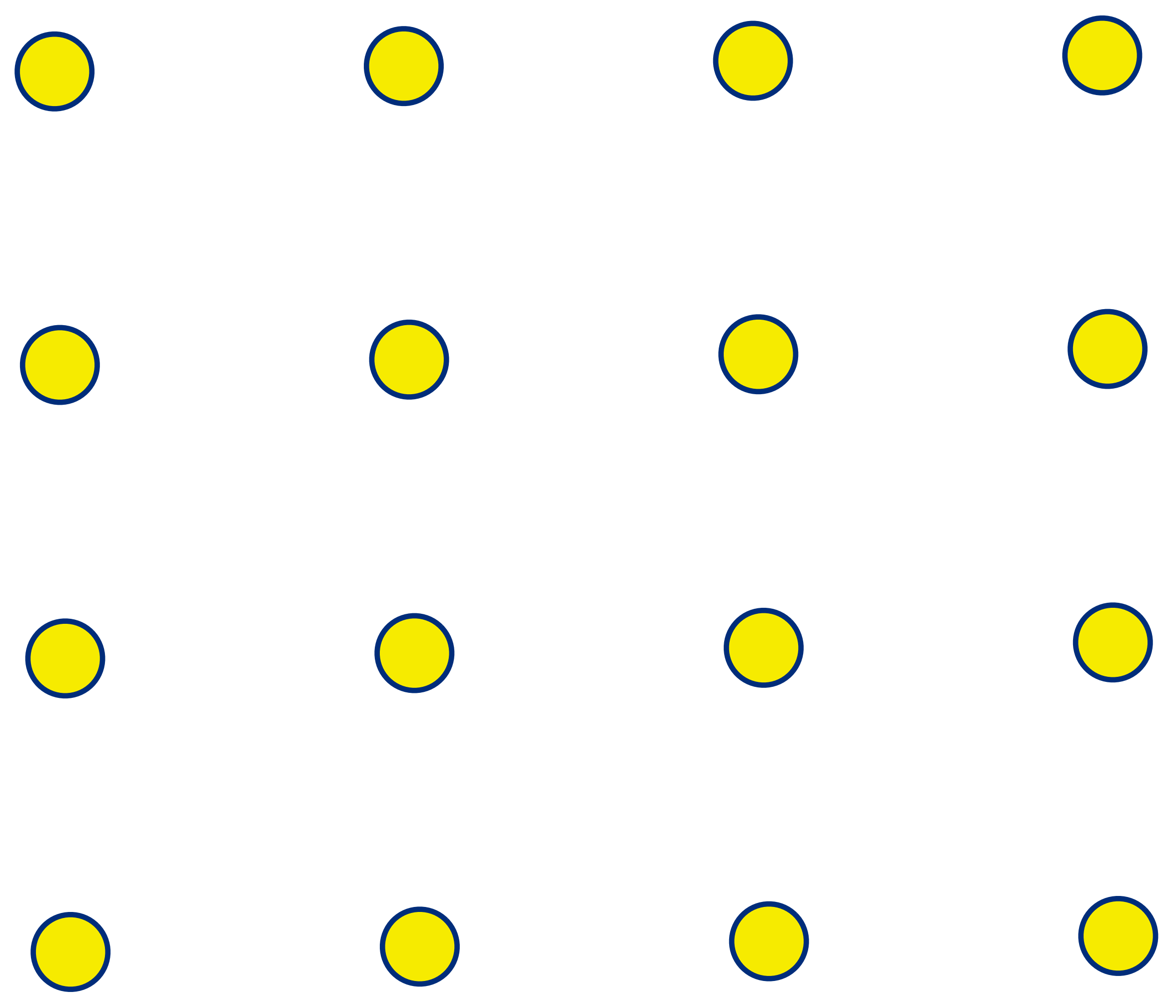
- Compressible systems must be gapless.

- Conformal systems are compressible in $d = 1$, but not for $d > 1$.

Compressible quantum matter

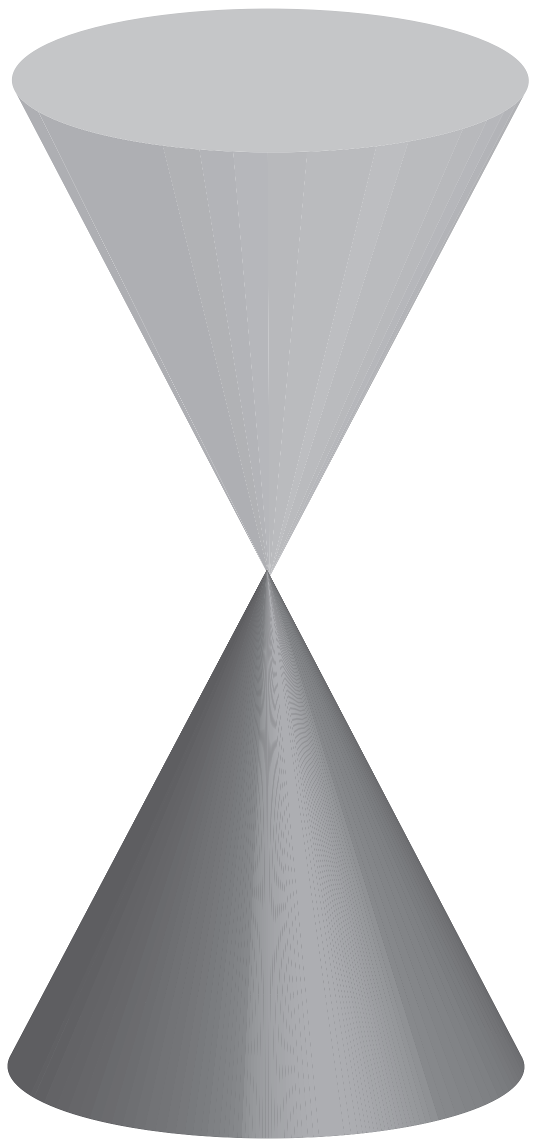
One compressible state is the **solid** (or "Wigner crystal" or "stripe").
This state breaks translational symmetry.



Compressible quantum matter

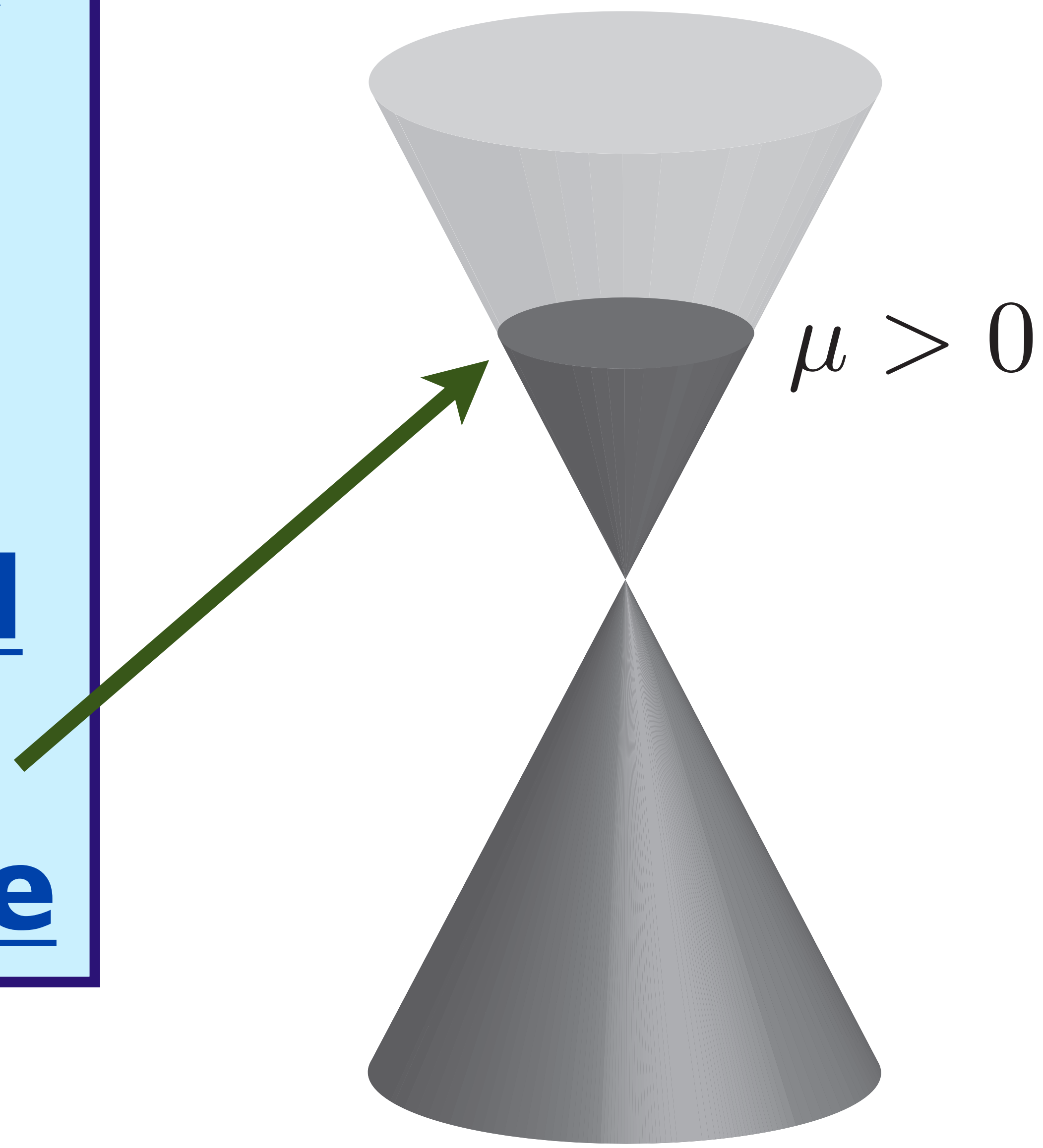
Another familiar compressible state is the **superfluid**.
This state breaks the global U(1) symmetry associated with $\mathcal{Q}$

Condensate of fermion pairs



Graphene

The only other familiar compressible phase is a **Fermi Liquid** with a **Fermi surface**



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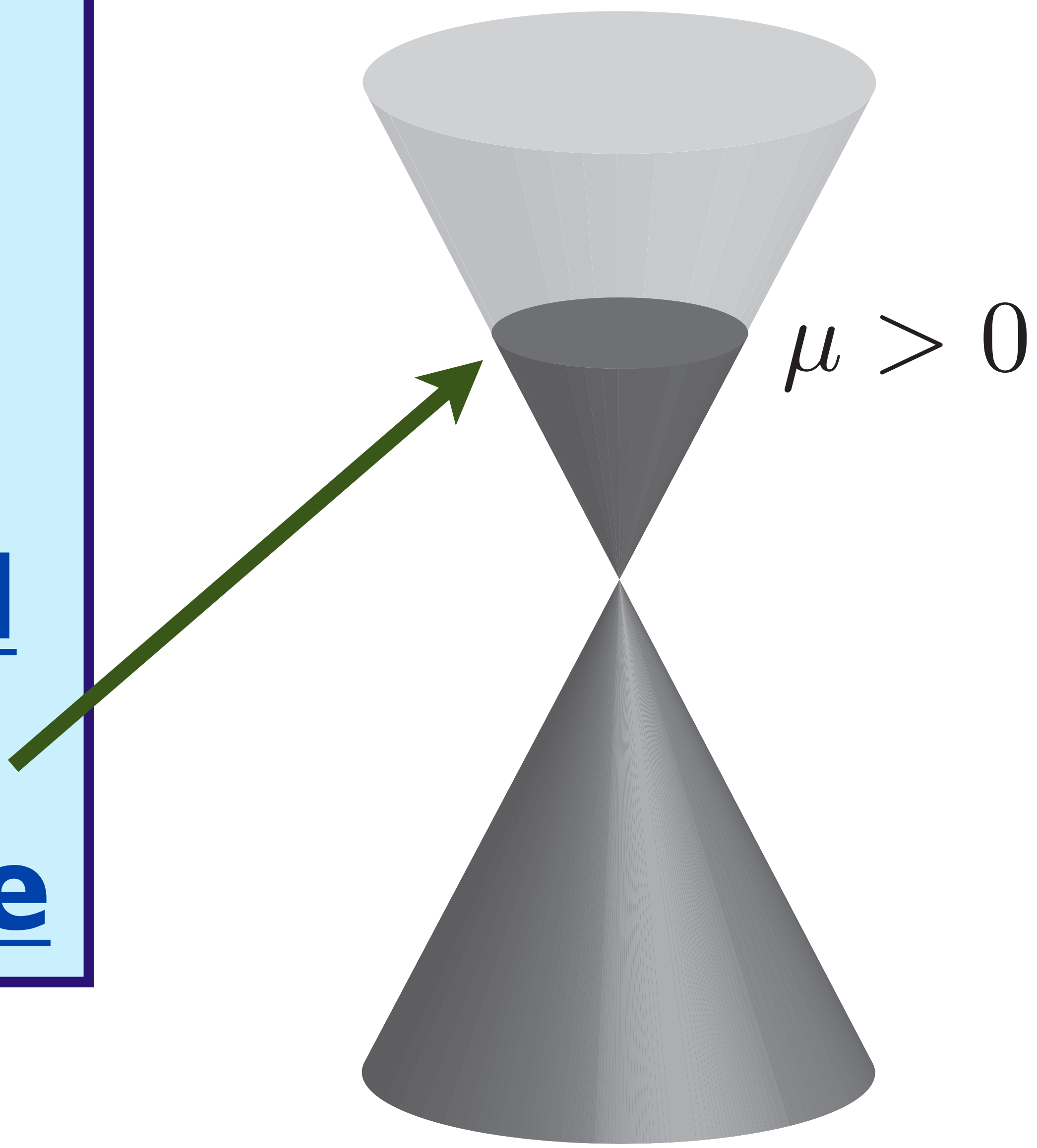
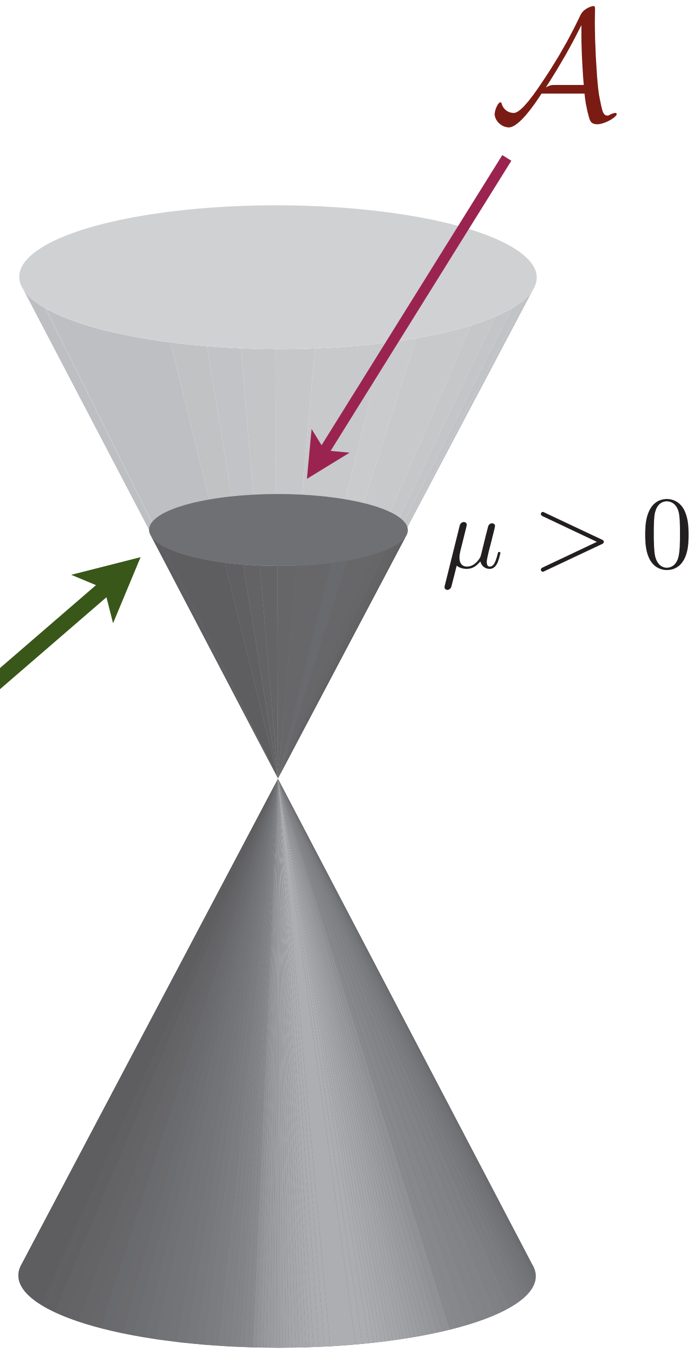


- The *only* low energy excitations are long-lived quasiparticles near the Fermi surface.

The only other familiar compressible phase is a **Fermi Liquid** with a **Fermi surface**



- **Luttinger relation:** The total "volume (area)" $\mathcal{A}$ enclosed by the Fermi surface is equal to $\langle \mathcal{Q} \rangle$.

Challenge to string theory:

Classify states of compressible quantum matter in continuum theories which preserve translational invariance.

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Can we obtain holographic theories of superfluids and Fermi liquids?

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Are there any other compressible phases?

Challenge to string theory:

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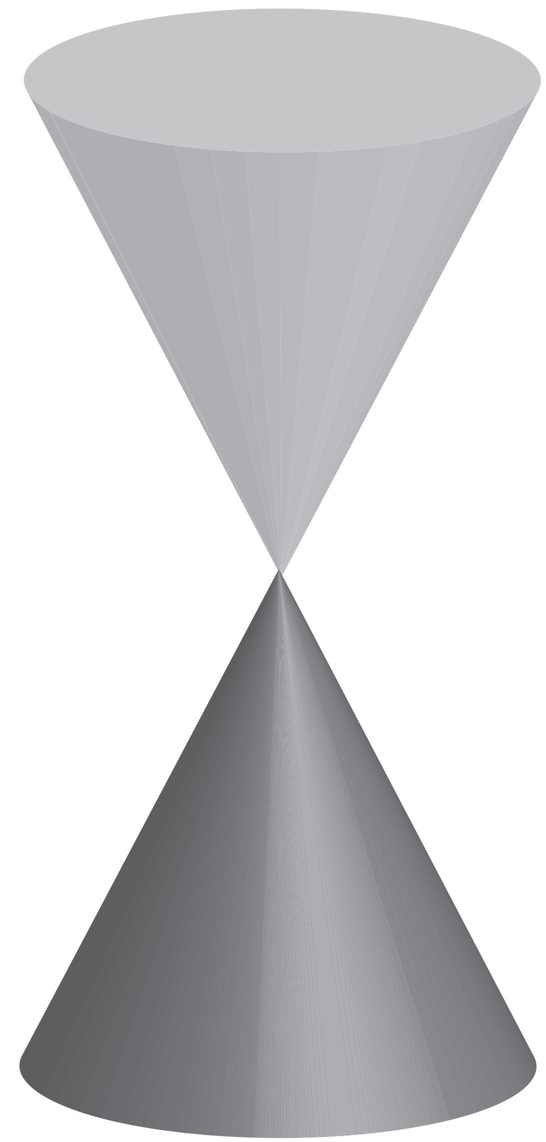
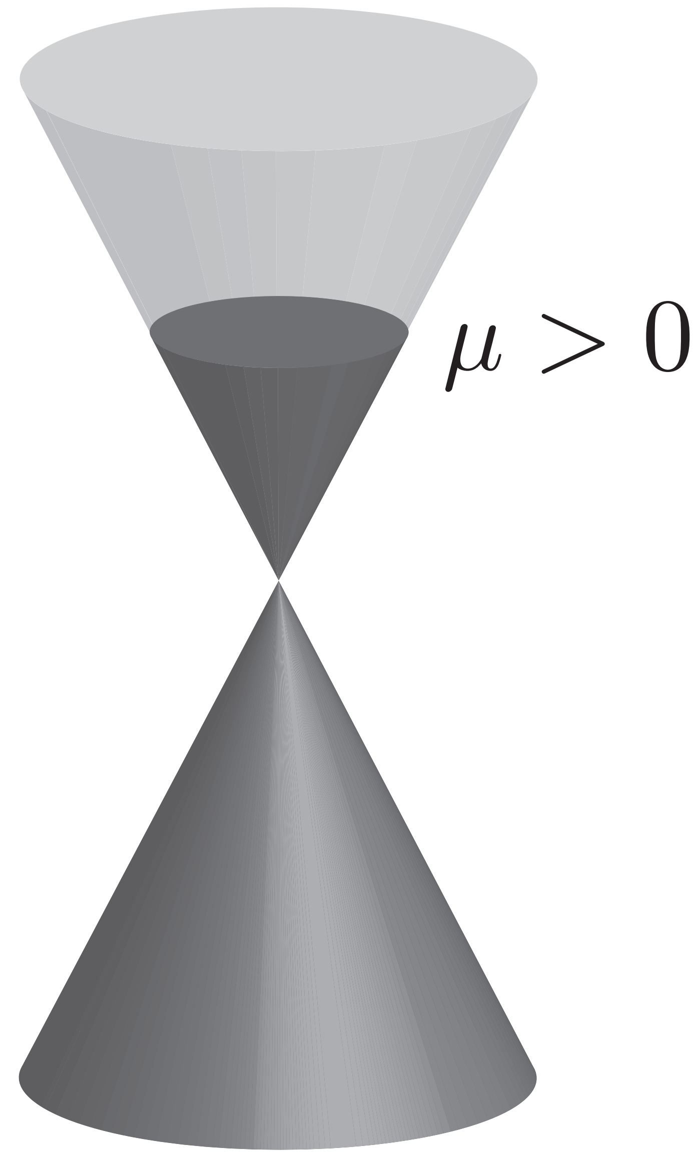
Are there any other compressible phases? Yes....

Begin with a strongly-coupled CFT

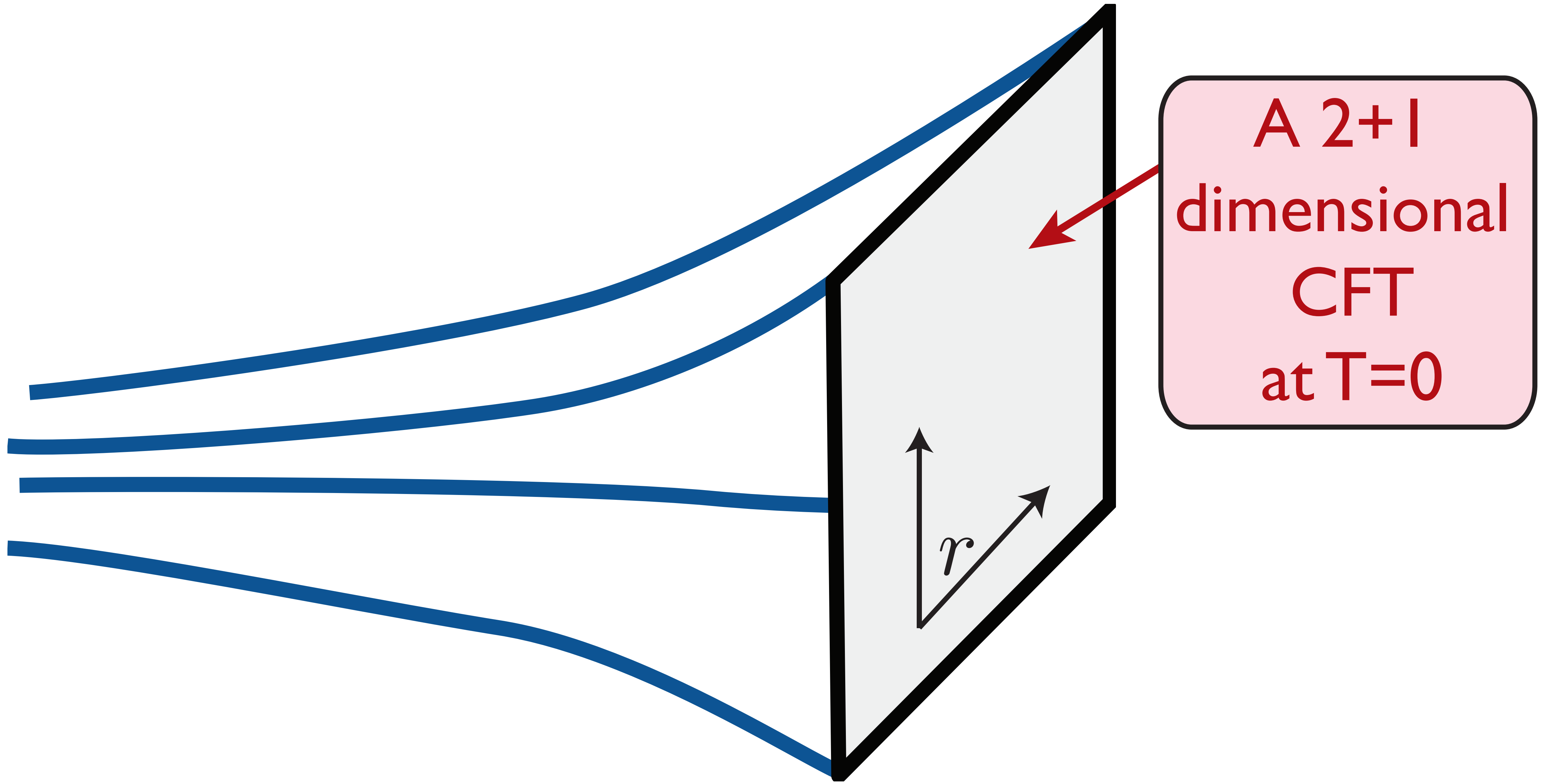


Dirac fermions + gauge field + ...

Are there holographic theories describing the appearance of superfluid or Fermi liquid ground states when a chemical potential is applied ?

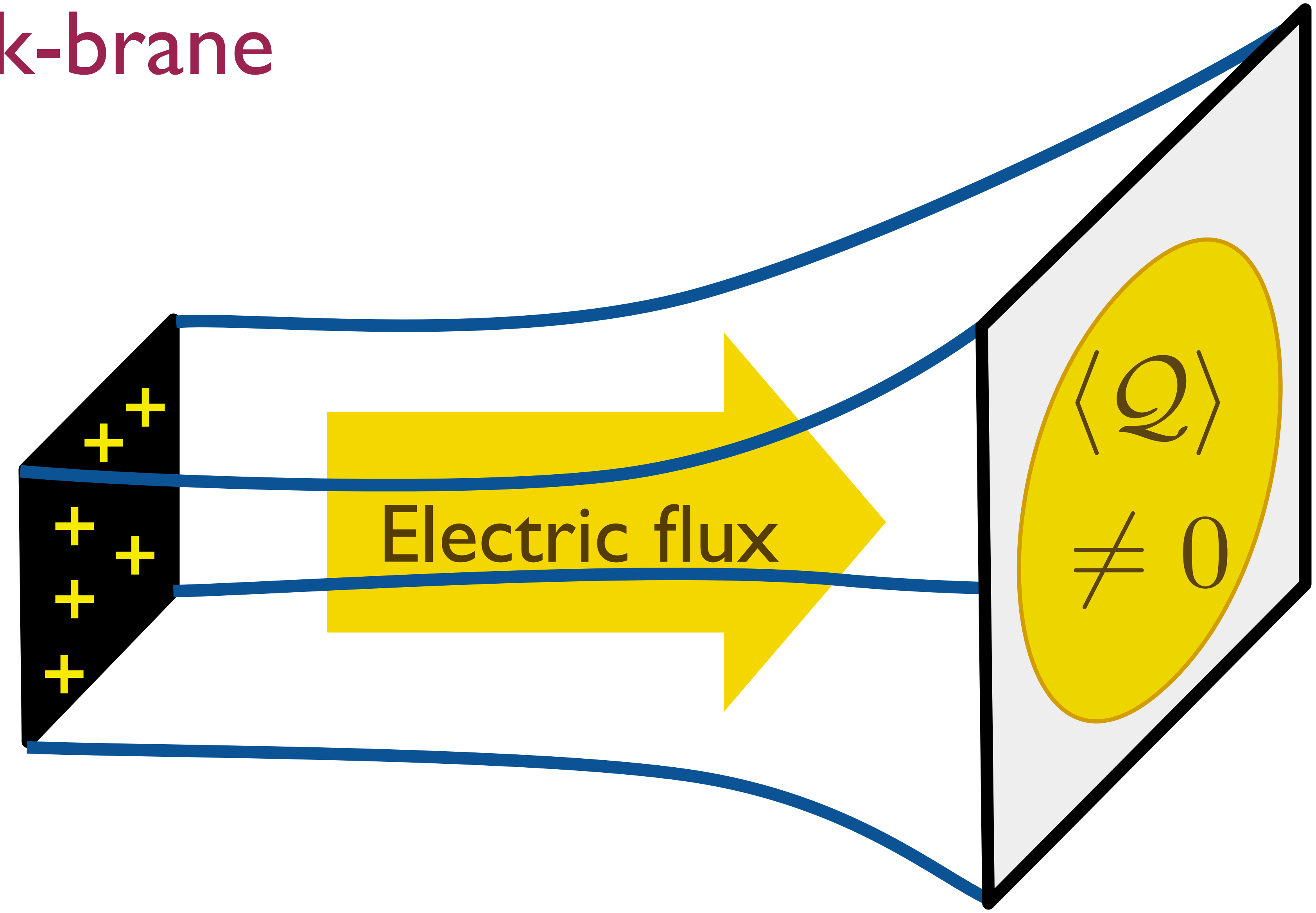


Holographic representation: AdS_4



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

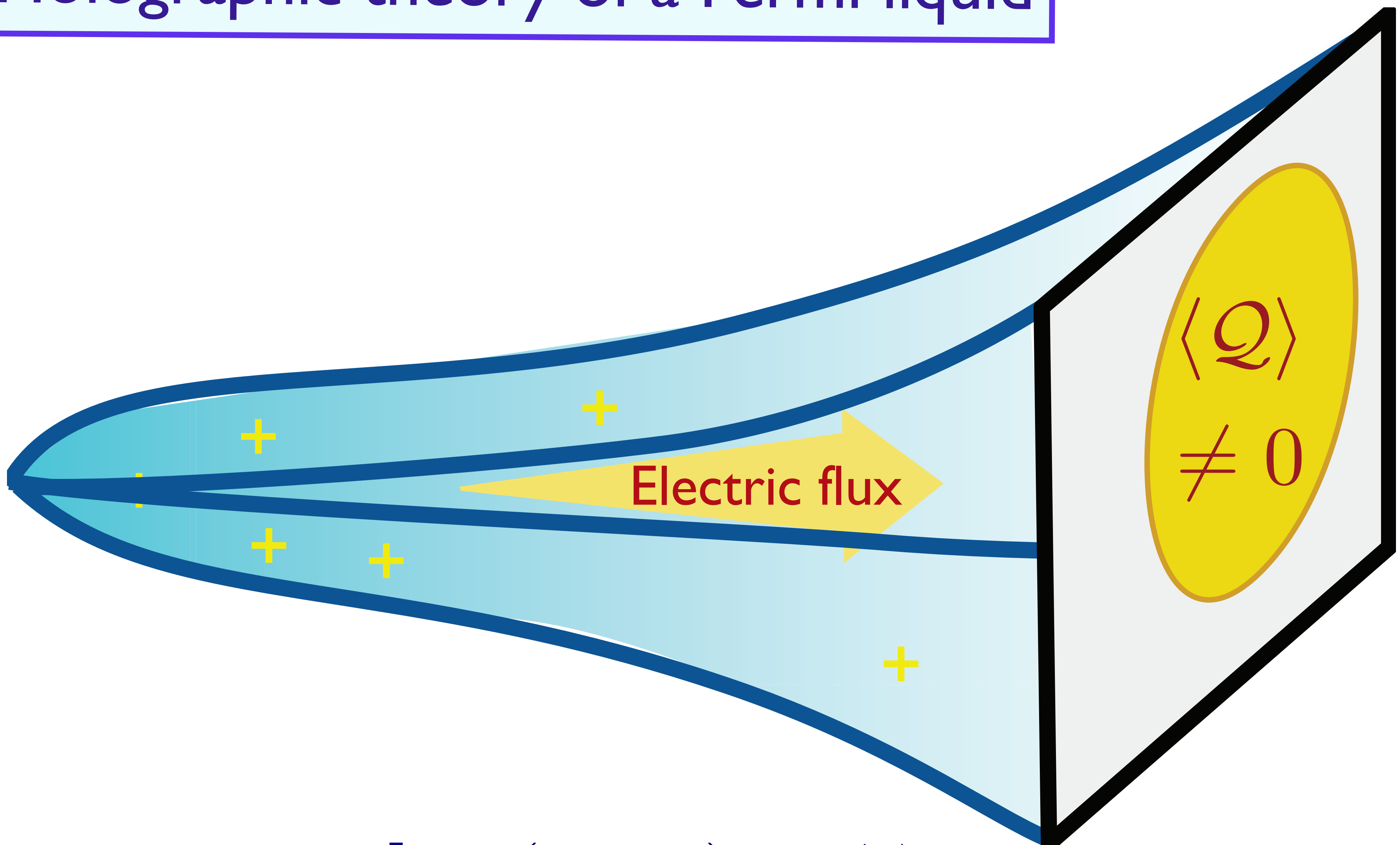
The Maxwell-Einstein theory of the applied chemical potential yields a AdS_4-Reissner-Nordtröm black-brane



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

Holographic theory of a Fermi liquid

S. Sachdev
arXiv:1107.5321



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

A Fermi liquid is a "confining" phase, in which all the low energy excitations are gauge-neutral.
In such a confining phase, the horizon disappears, there is charge density delocalized in the bulk spacetime.

Holographic theory of a Fermi liquid

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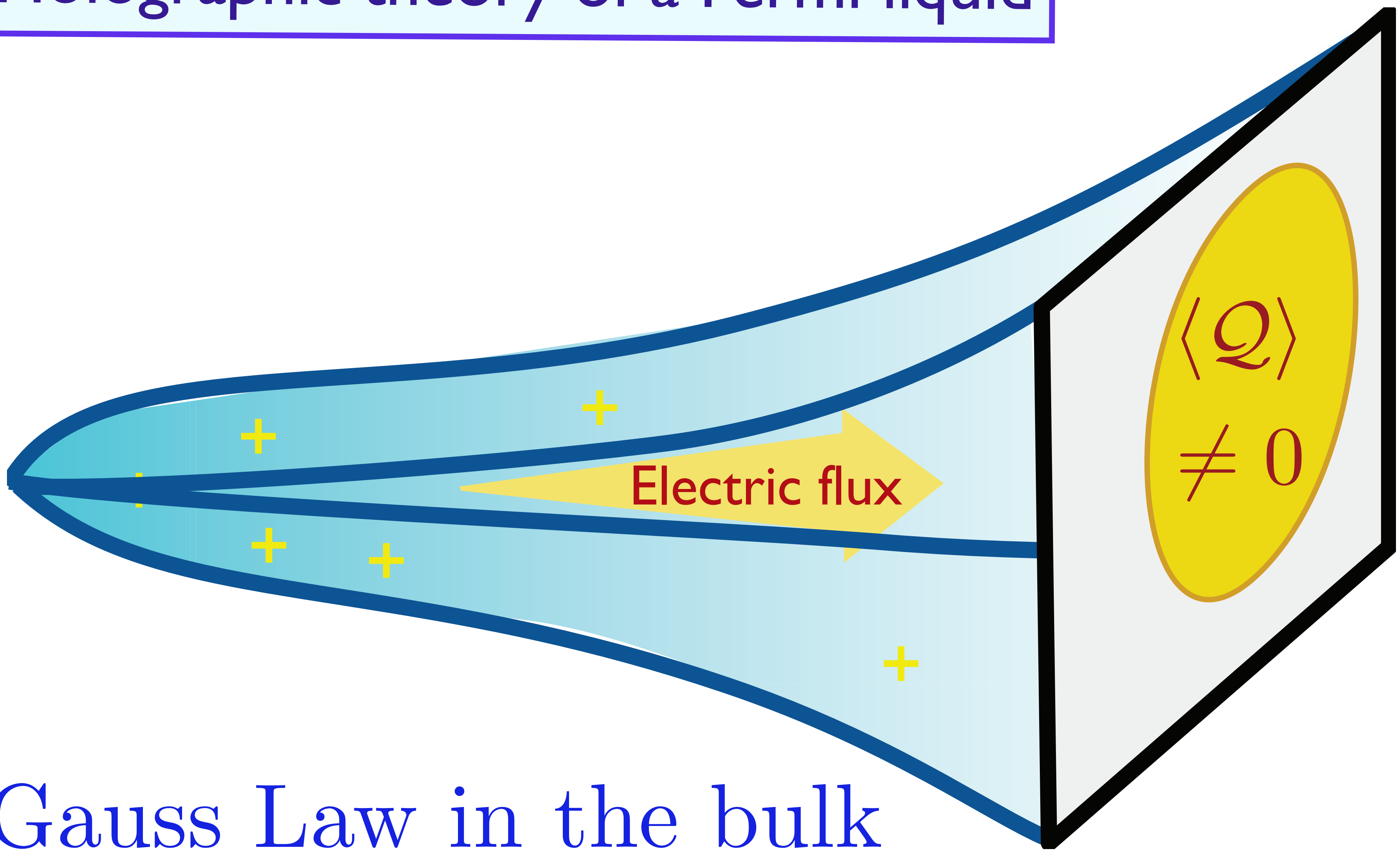

Gauss Law in the bulk
$\Leftrightarrow$ Luttinger theorem on the boundary

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In such a confining phase, the horizon disappears, there is charge density delocalized in the bulk spacetime.

Such a holographic theory describes a quantum state which agrees with Landau's Fermi liquid theory in all respects.

A similar description can be obtained for superfluids using bosonic matter in the bulk.

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How about more exotic compressible states (in the hopes of describing the strange metal) ?

Holographic theory of a Fermi liquid

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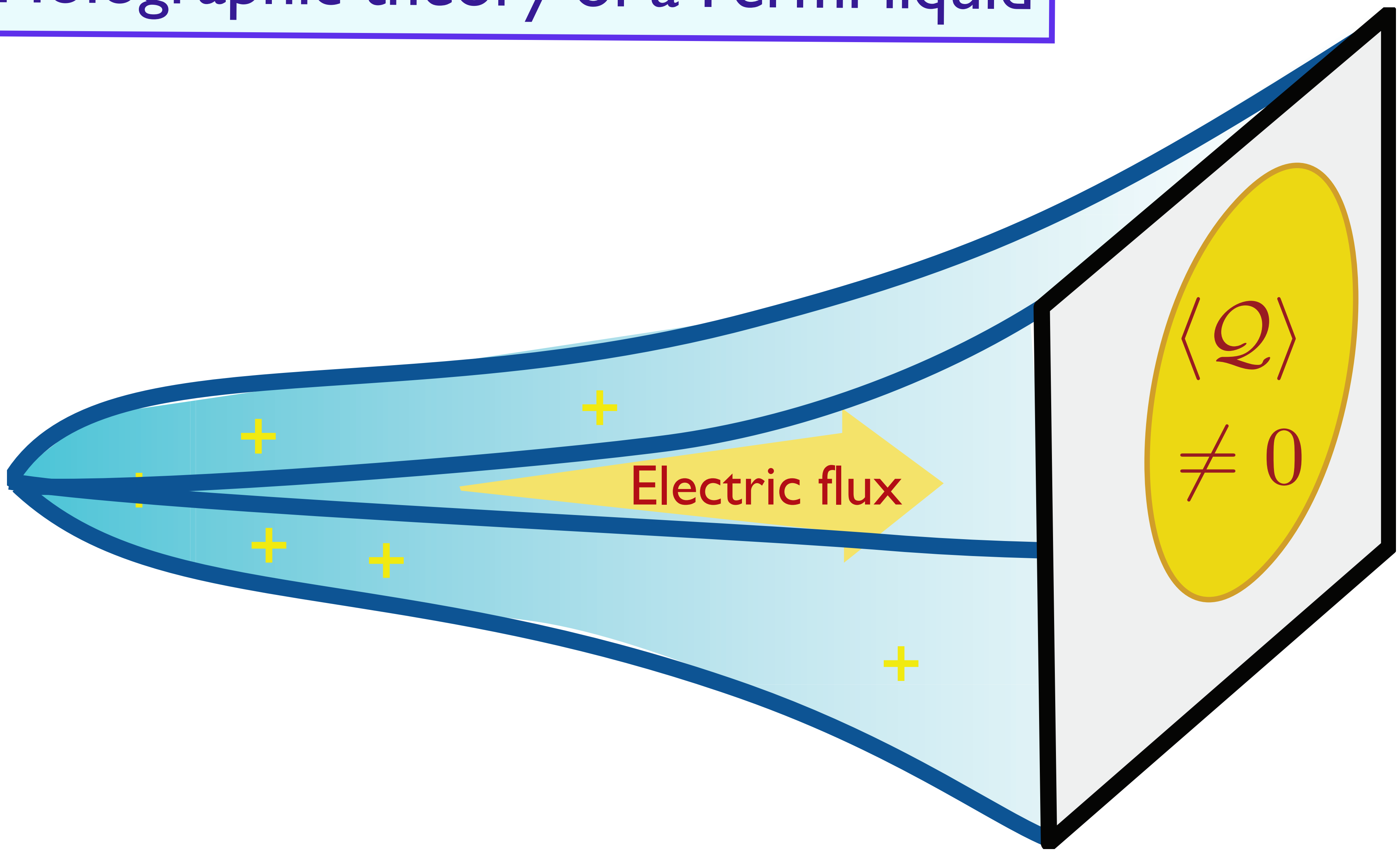
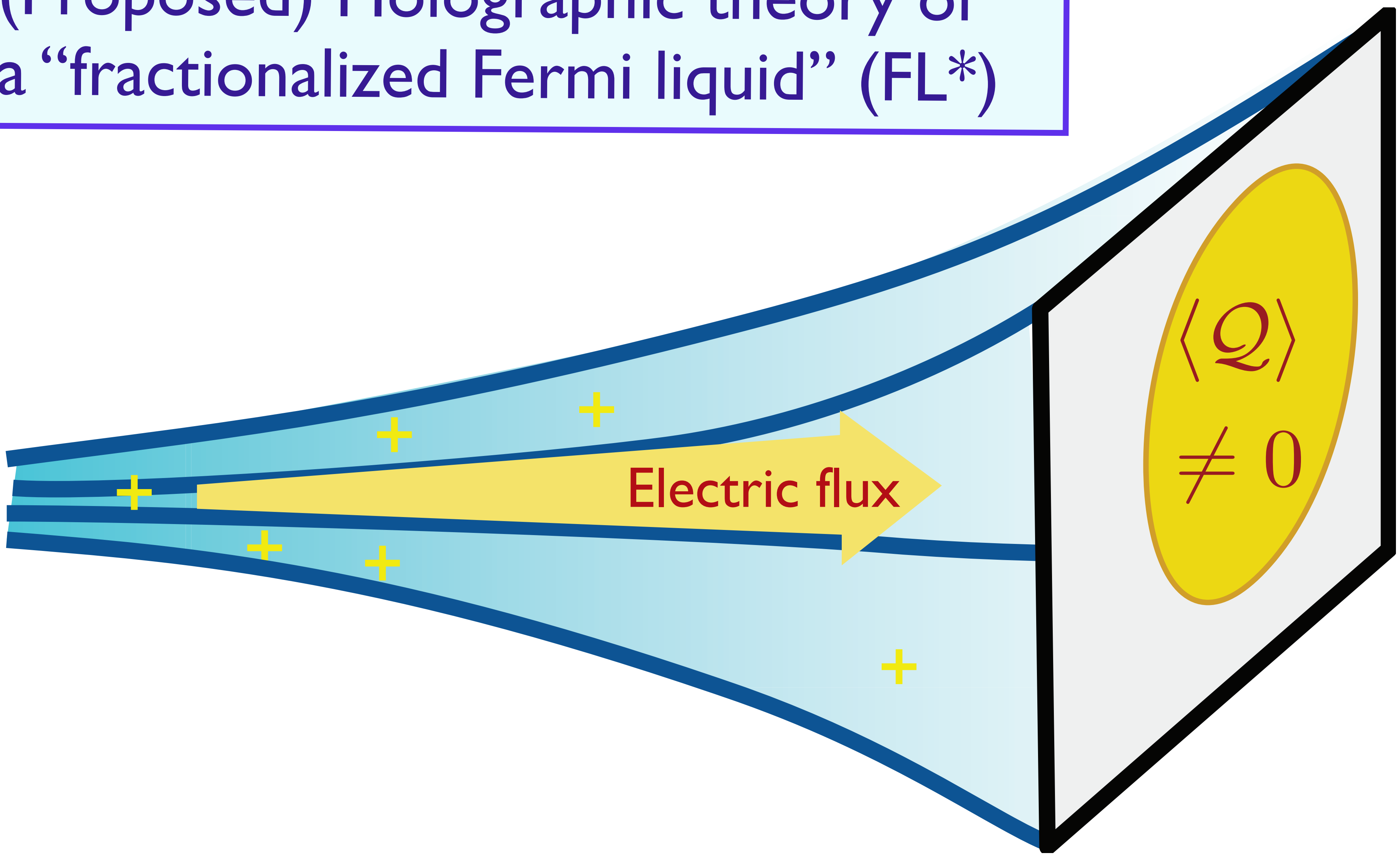


In a confining FL phase, the metric terminates, the bulk charge equals the boundary charge, and the electric flux vanishes in the IR.

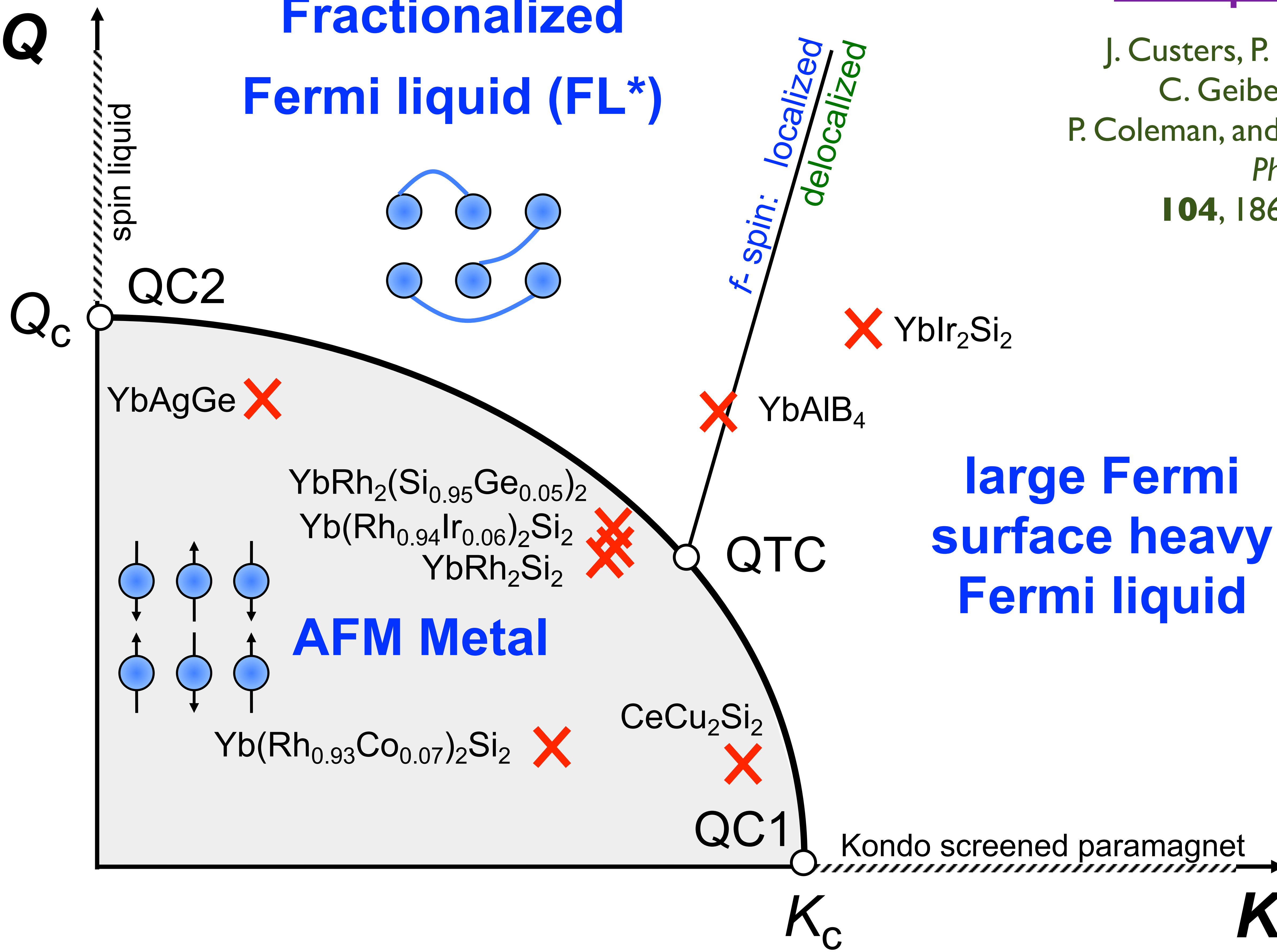
(Proposed) Holographic theory of a "fractionalized Fermi liquid" (FL*)



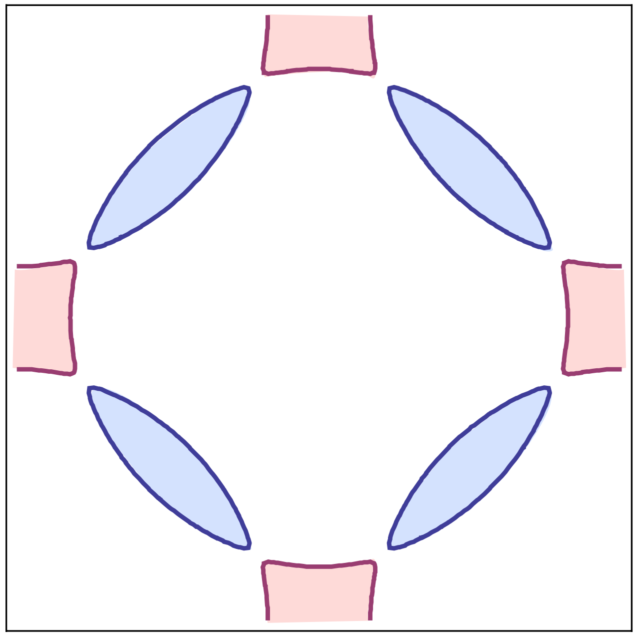
In a deconfined FL* phase, the metric extends to infinity
(representing critical IR modes),
and part of the electric flux "leaks out".

Experimental phase diagram of the heavy-fermion compounds

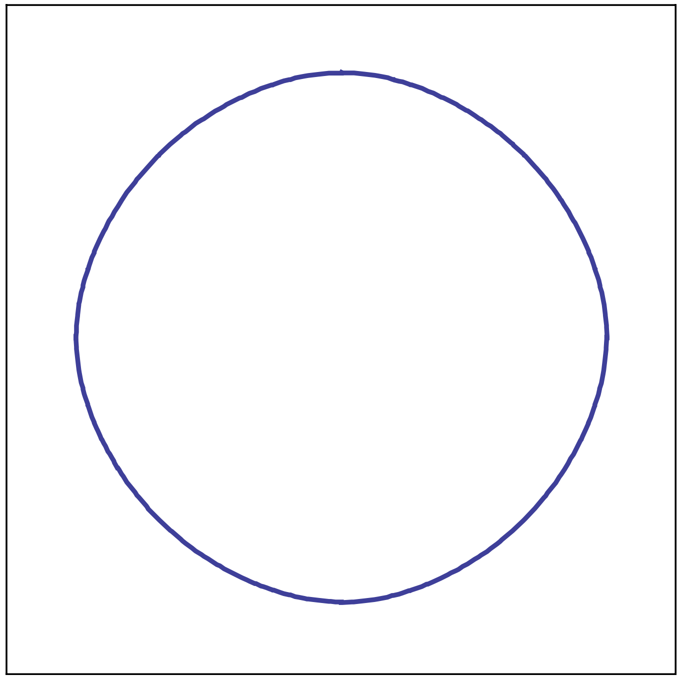
J. Custers, P. Gegenwart, C. Geibel, F. Steglich, P. Coleman, and S. Paschen, *Phys. Rev. Lett.* **104**, 186402 (2010)



Separating onset of SDW order and Fermi surface reconstruction in the cuprates



Electron and/or hole Fermi pockets form in "local" SDW order, but quantum fluctuations destroy long-range SDW order



$\langle \vec{\varphi} \rangle \neq 0$

$\langle \vec{\varphi} \rangle = 0$

$\langle \vec{\varphi} \rangle = 0$

Metal with electron and hole pockets

Fractionalized Fermi liquid (FL*) phase with no symmetry breaking and "small" Fermi surface

Metal with "large" Fermi surface

Y. Qi and S. Sachdev, *Physical Review B* **81**, 115129 (2010); M. Punk and S. Sachdev, to appear; see also T. C. Ribeiro and X.-G. Wen, *Physical Review B* **74**, 155113 (2006)

Conclusions

Quantum criticality and conformal field theories

- 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.

- Prospects non-linear, and non-equilibrium transport

Conclusions

Compressible quantum matter

- Presented a holographic model of a Fermi liquid

- Fractionalized Fermi liquid (FL*), appears in deconfined gauge theories, holographic models, and lattice theories of the heavy-fermion compounds and cuprates superconductors.

- Numerous plausible sightings of the FL* phase in recent experiments