Inter-university Attraction Pole meeting

Vrije Universiteit Brussel, October 2nd, 2009

Strings *vs* Condensed Matter

An overview

Emiliano Imeroni

Université Libre de Bruxelles

Fundamental .be Interactions

Belgian Science Policy

Introduction

Can ***string theory*** be used to access ***experimentally testable systems*** ?

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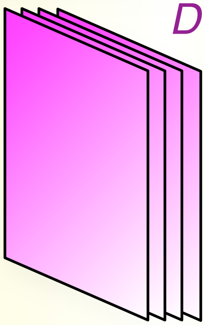

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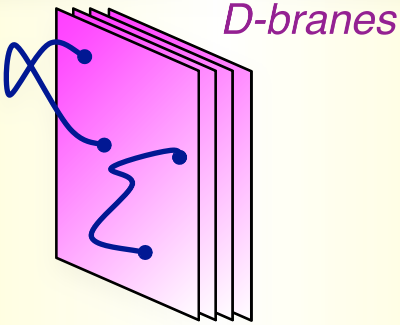

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LOW ENERGY

d-dimensional
Quantum Field Theory
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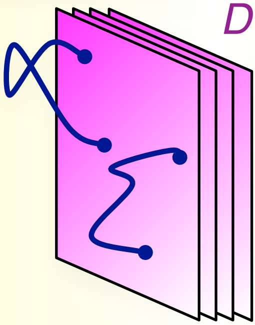

D-branes

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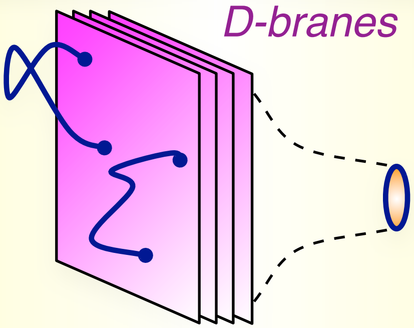

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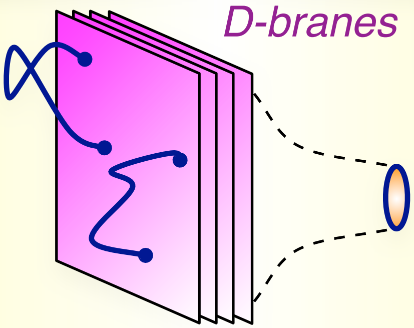

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Classical solution of a
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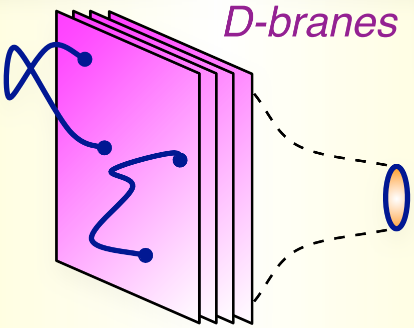

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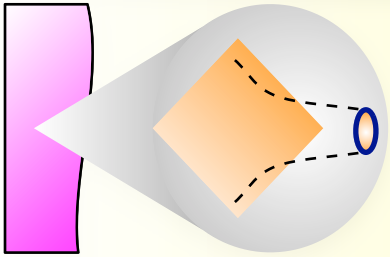

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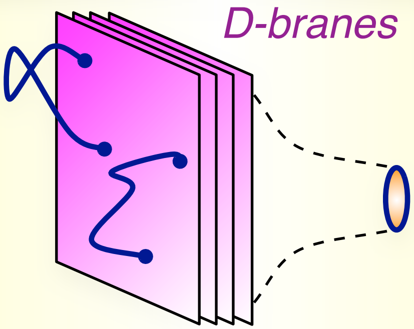

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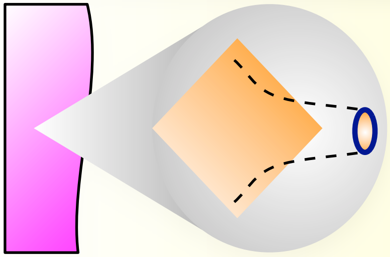

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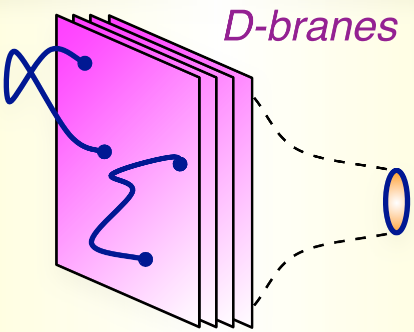

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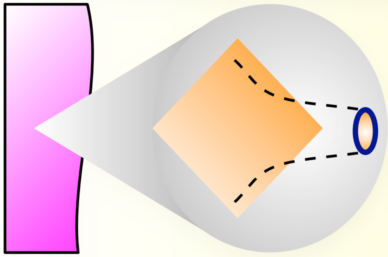

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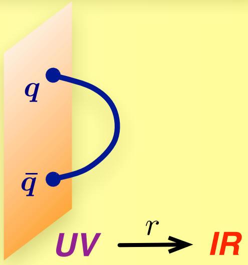

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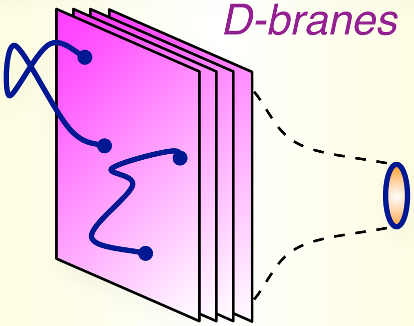

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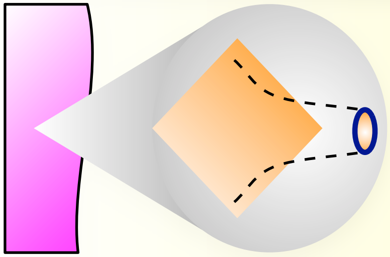

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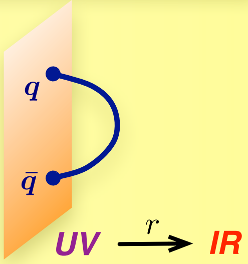

3d Conformal Field Theory ⟷ ***Strings in 4d Anti-de Sitter***

DUALITY

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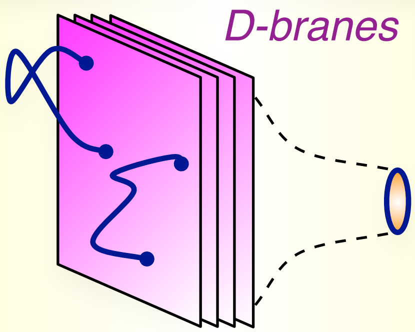

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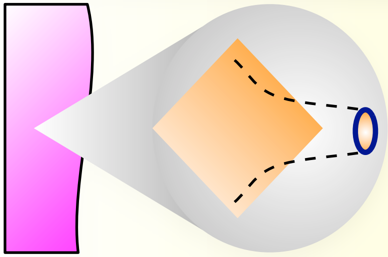

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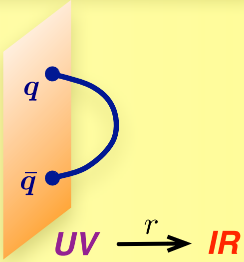

3d Conformal Field Theory ⟷ ***DUALITY*** ⟷ ***Strings in 4d Anti-de Sitter***

At ***large N*** and ***strong coupling***

the *radius of curvature* of the geometry is *large* $\frac{L^2}{l_s^2} \sim \sqrt{g^2 N}$

➡ ***Conformal field theory*** *described by **dual classical gravity***

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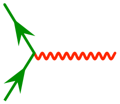
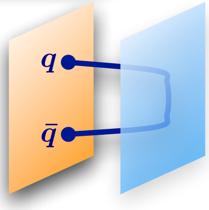
- Typical application of the duality: ***fundamental particle interactions*** described by ***quantum gauge theories*** (*confinement*, *χSB*, *quark-gluon plasma*, ...)





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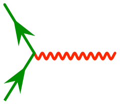

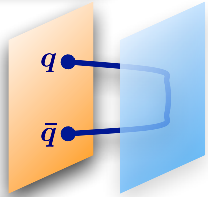

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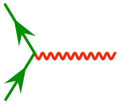

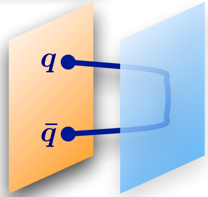

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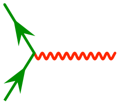

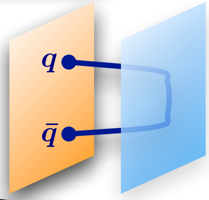

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WHY?

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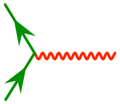

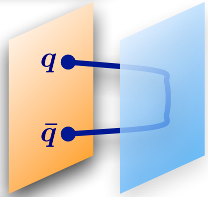

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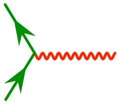

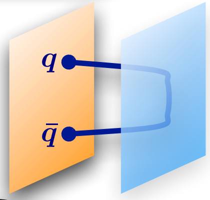

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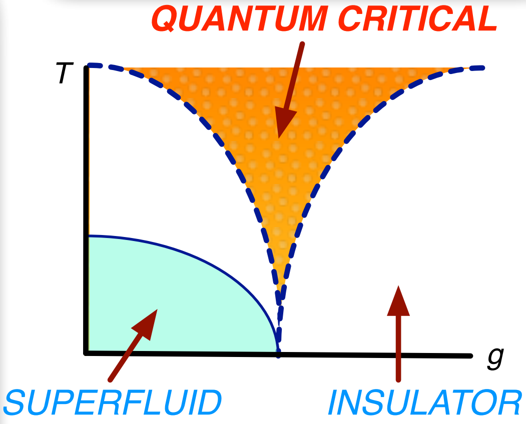
- ***High - T_c superconductors***
- ***Fermions at unitarity*** (***trapped cold atoms***)
- $\dots$

Quantum criticality



Outline

- Short review of *quantum critical systems*

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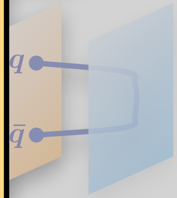

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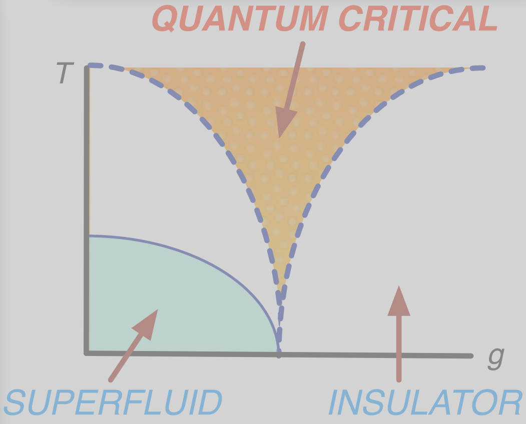

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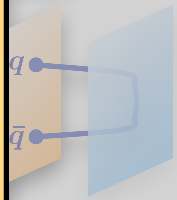

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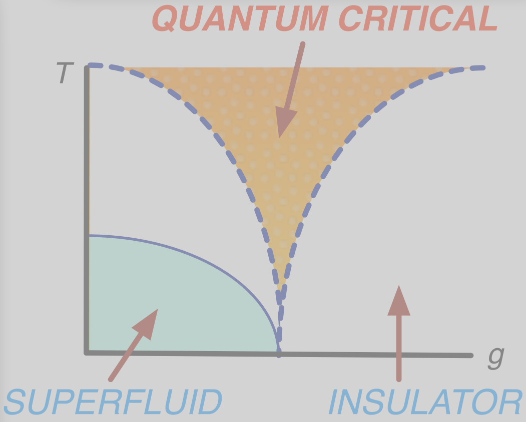

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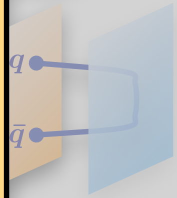

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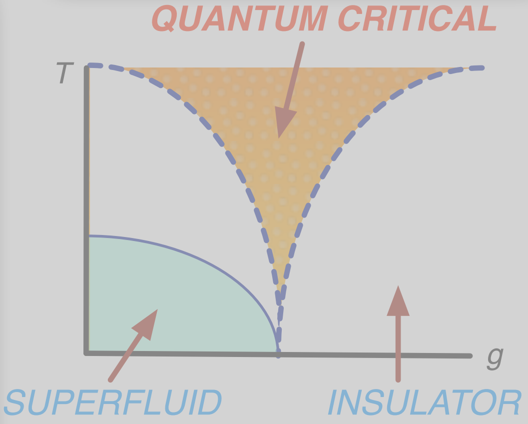

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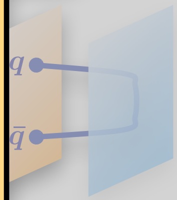

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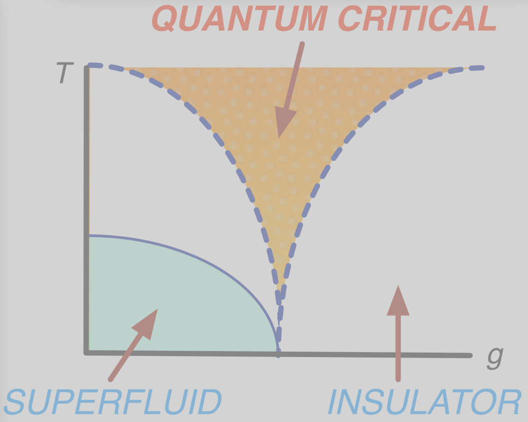

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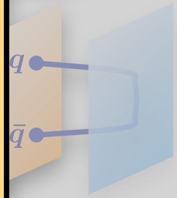

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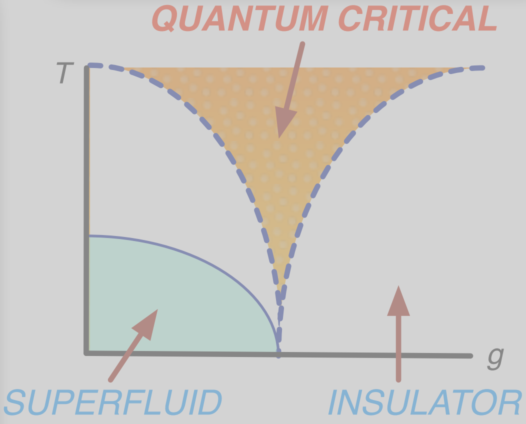

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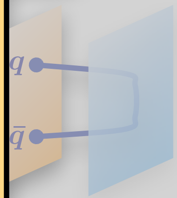

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SPIN

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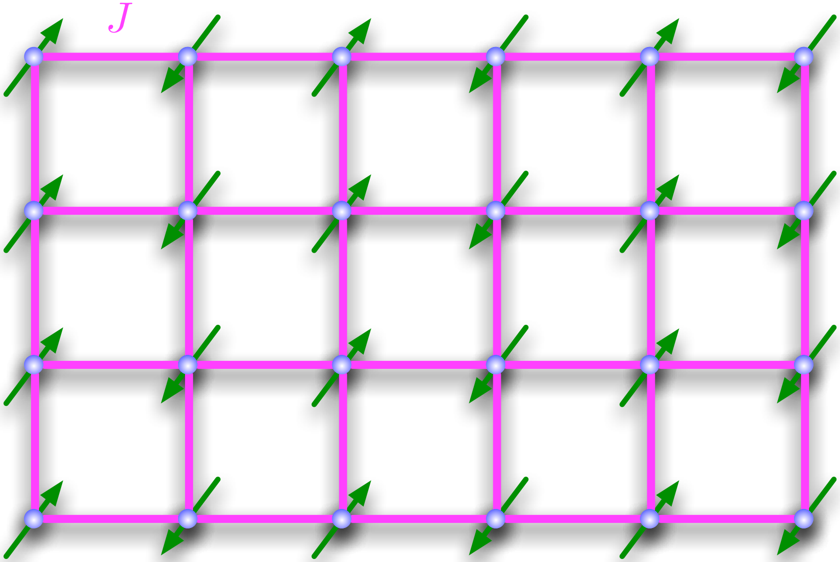

Quantum critical systems

Quantum critical point : continuous phase transition at *T = 0*
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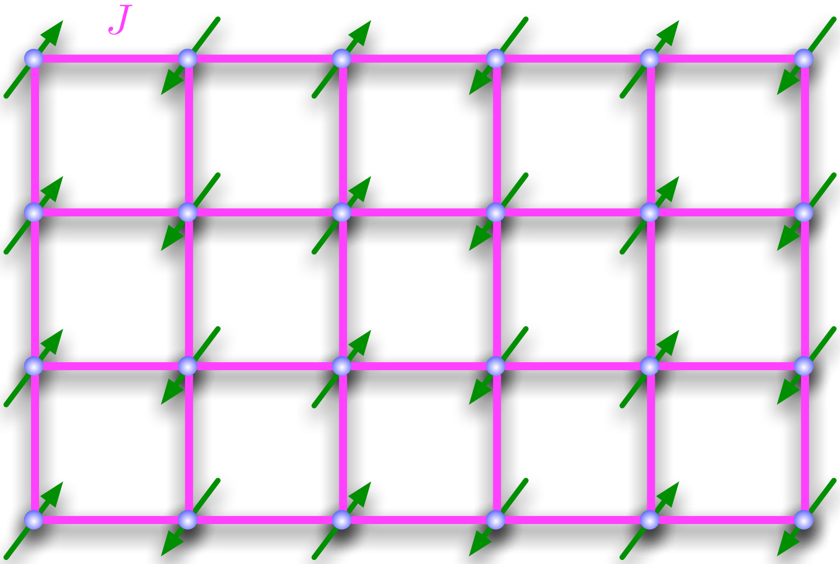

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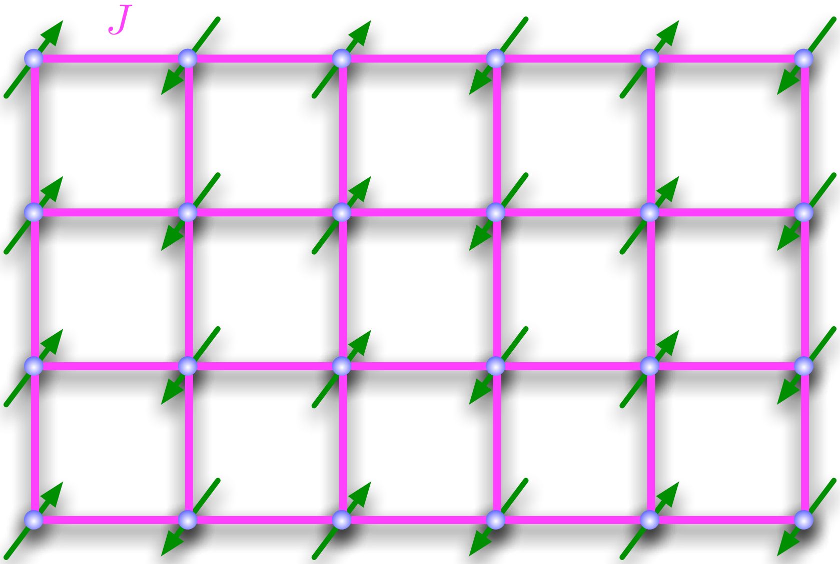

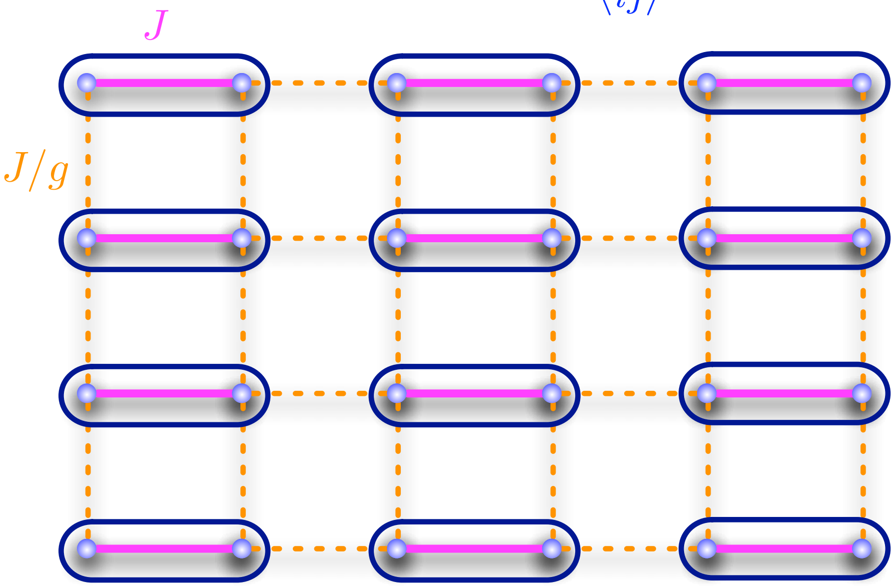

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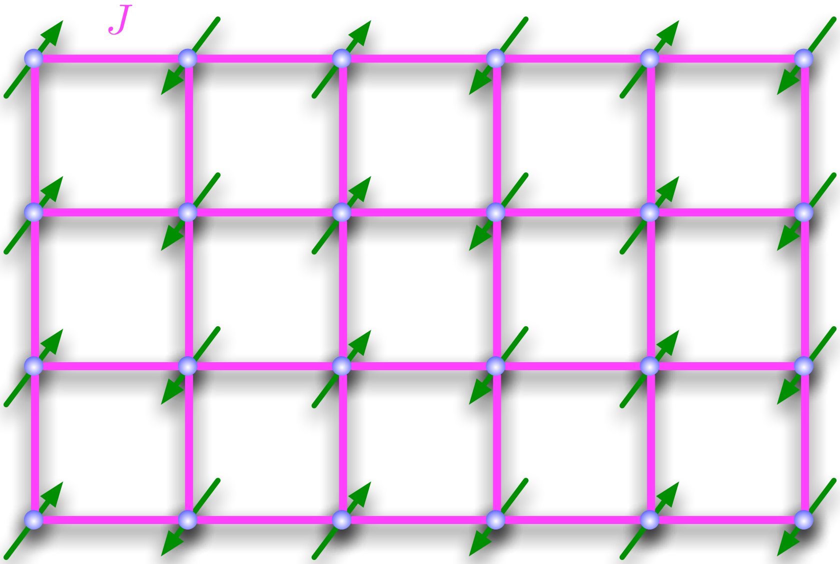

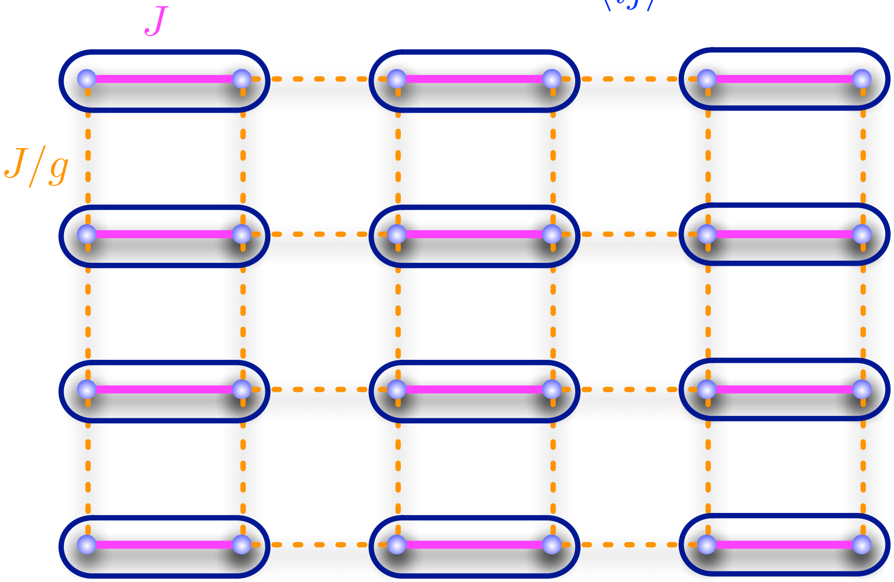

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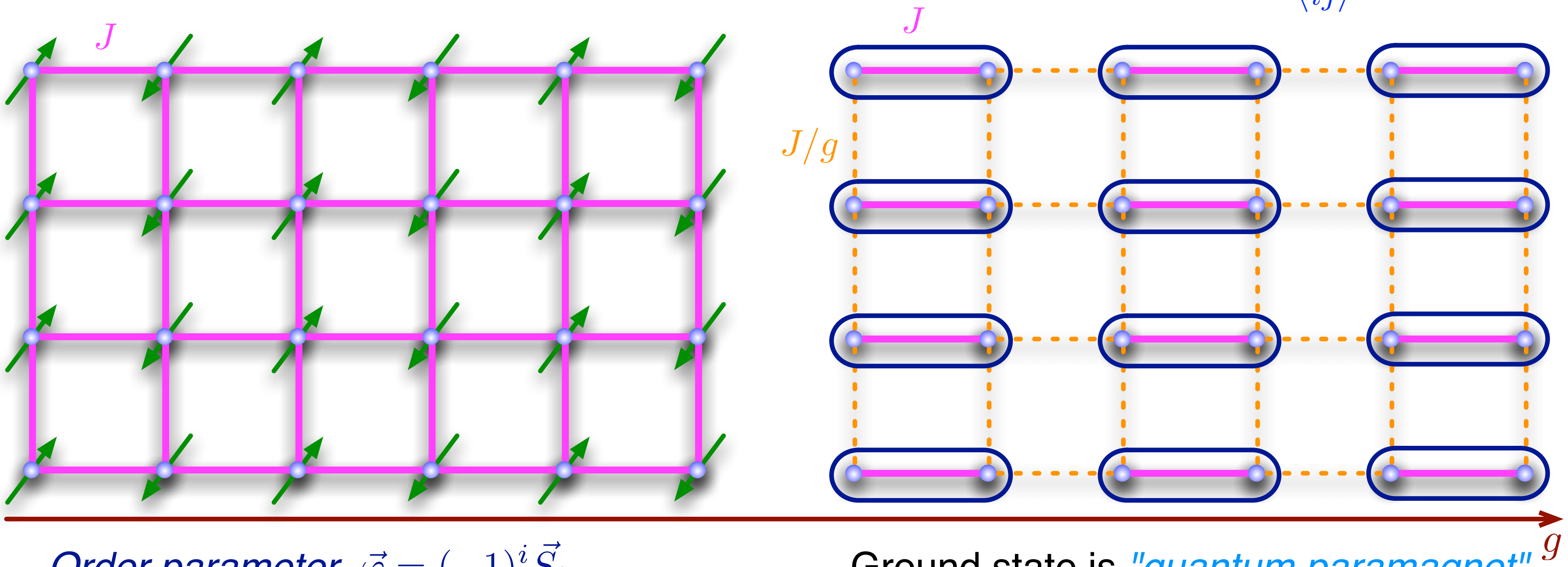

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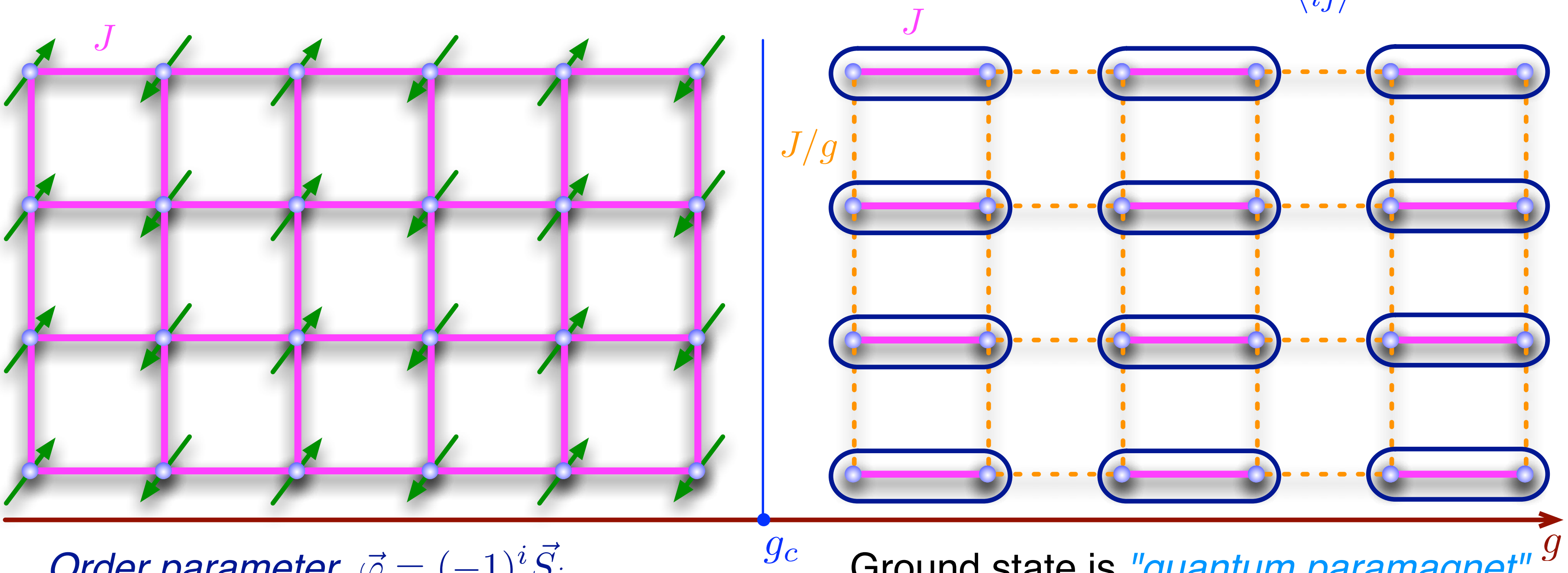

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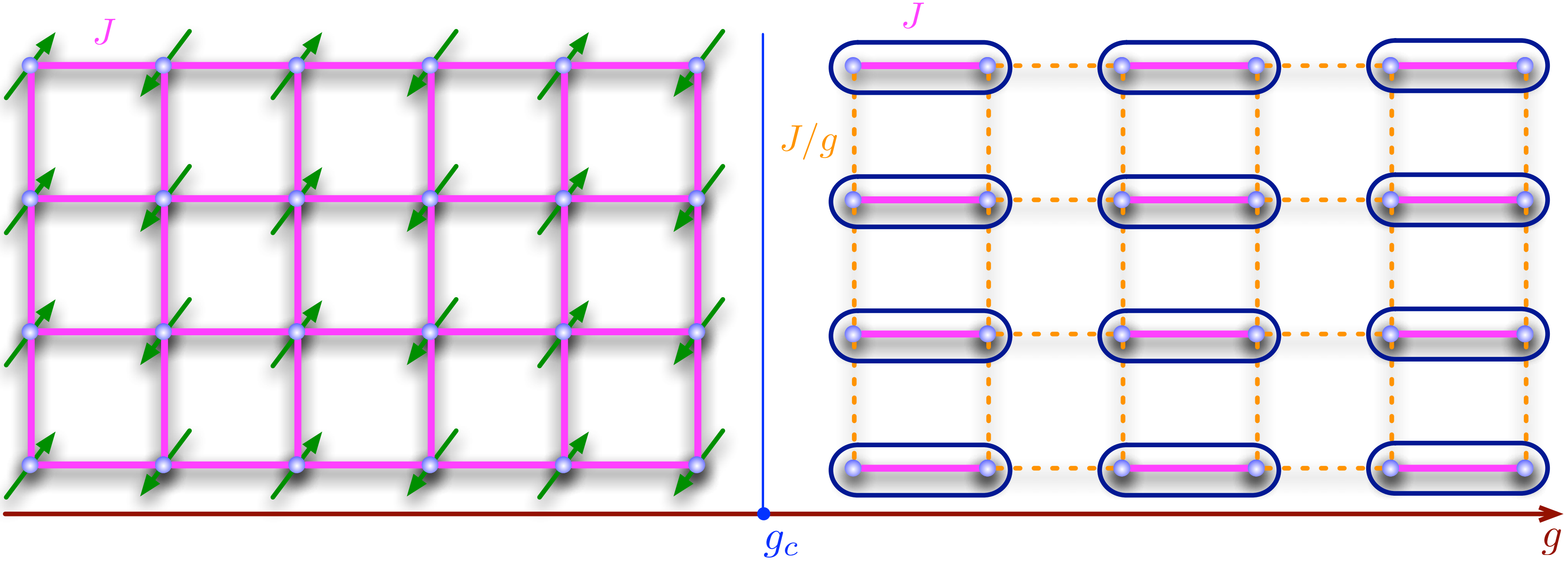
QUANTUM CRITICAL POINT

Quantum critical systems

O(3) order parameter $\vec{\varphi}$ described by QFT action

$$S = \int d\tau d^2x \left[(\partial_\tau \vec{\varphi}^2) + c^2 (\nabla_x \vec{\varphi})^2 + (g - g_c)\vec{\varphi}^2 + u(\vec{\varphi}^2)^2 \right]$$



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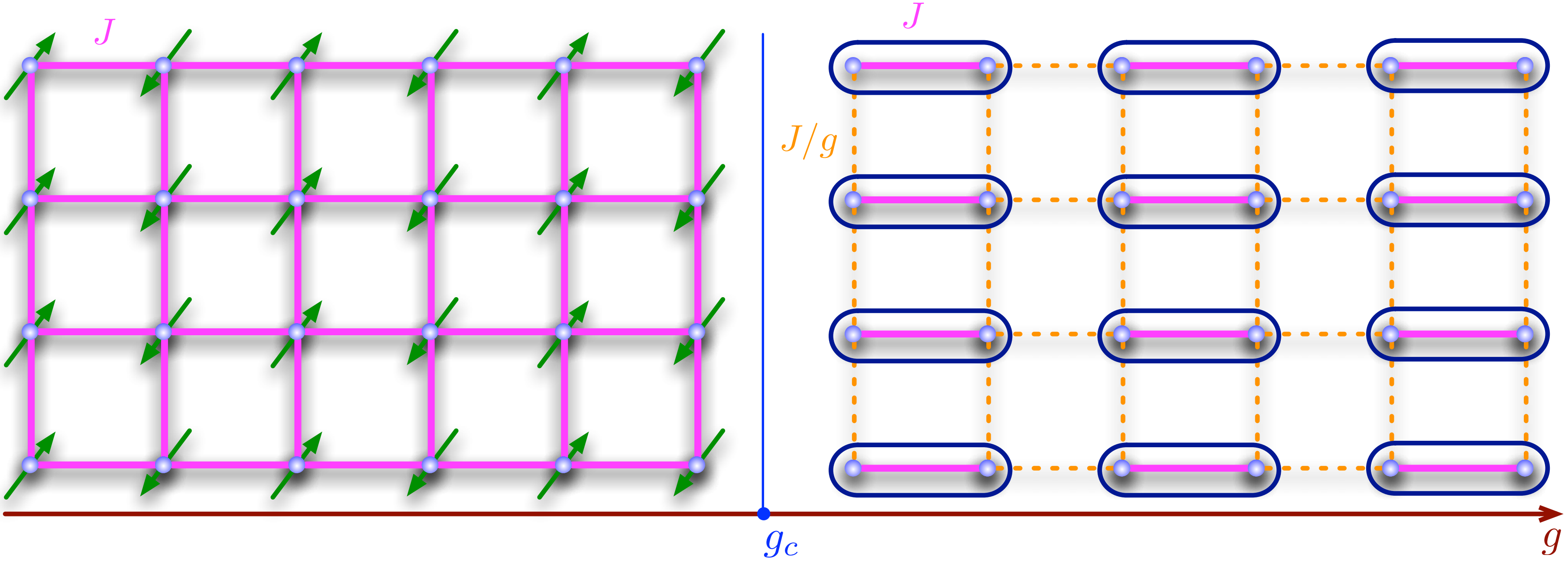

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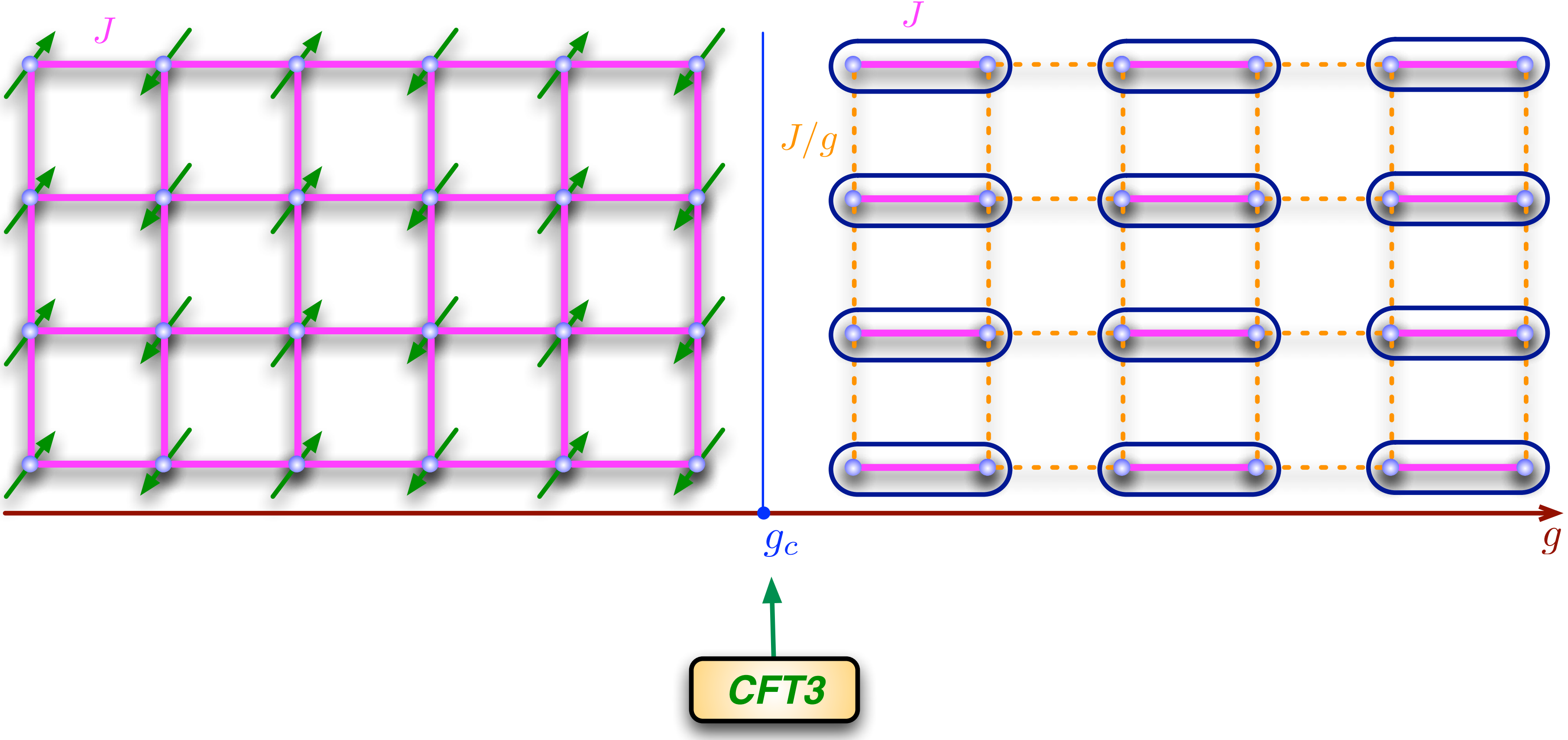

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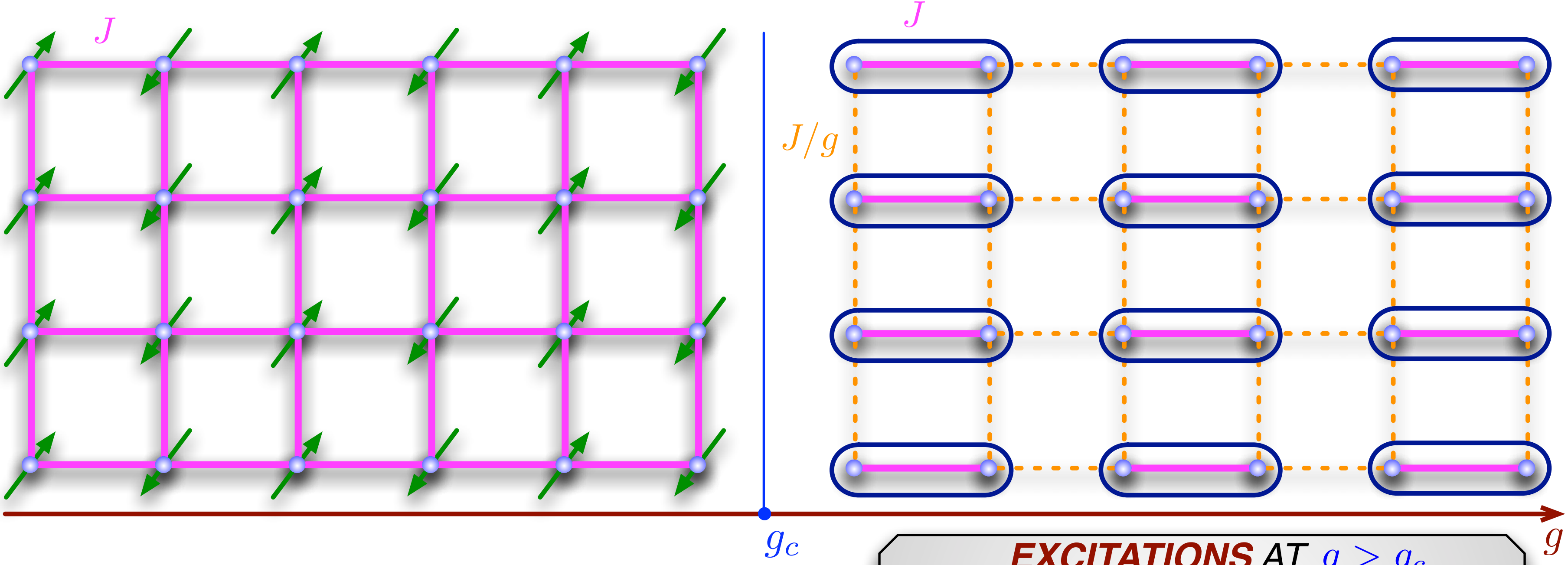

CFT3

***EXCITATIONS** AT* $g > g_c$

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SPIN 1 "TRIPLONS"

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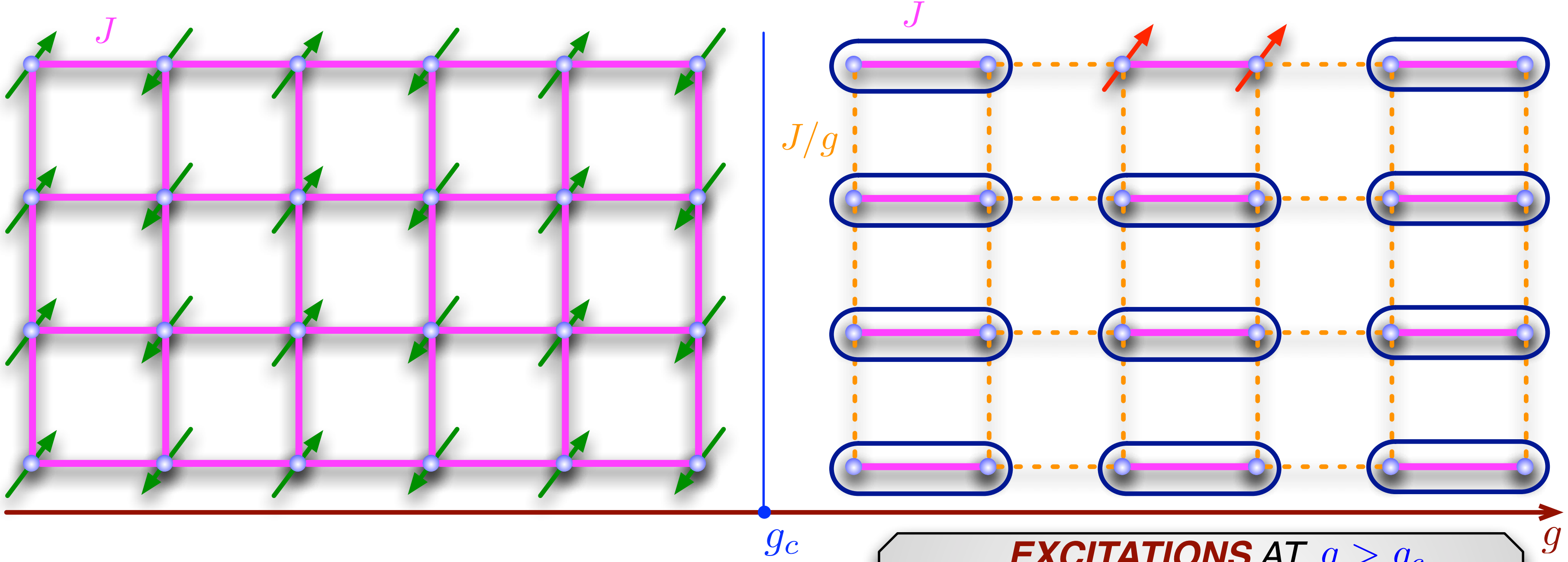

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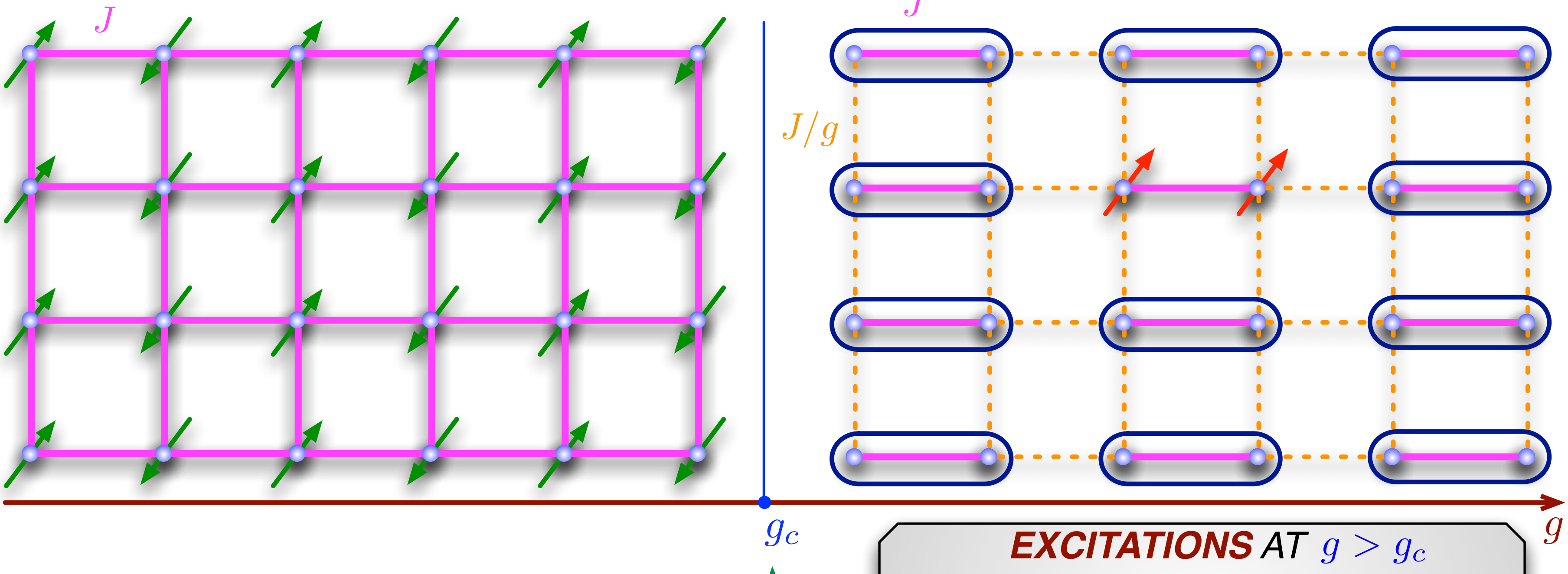

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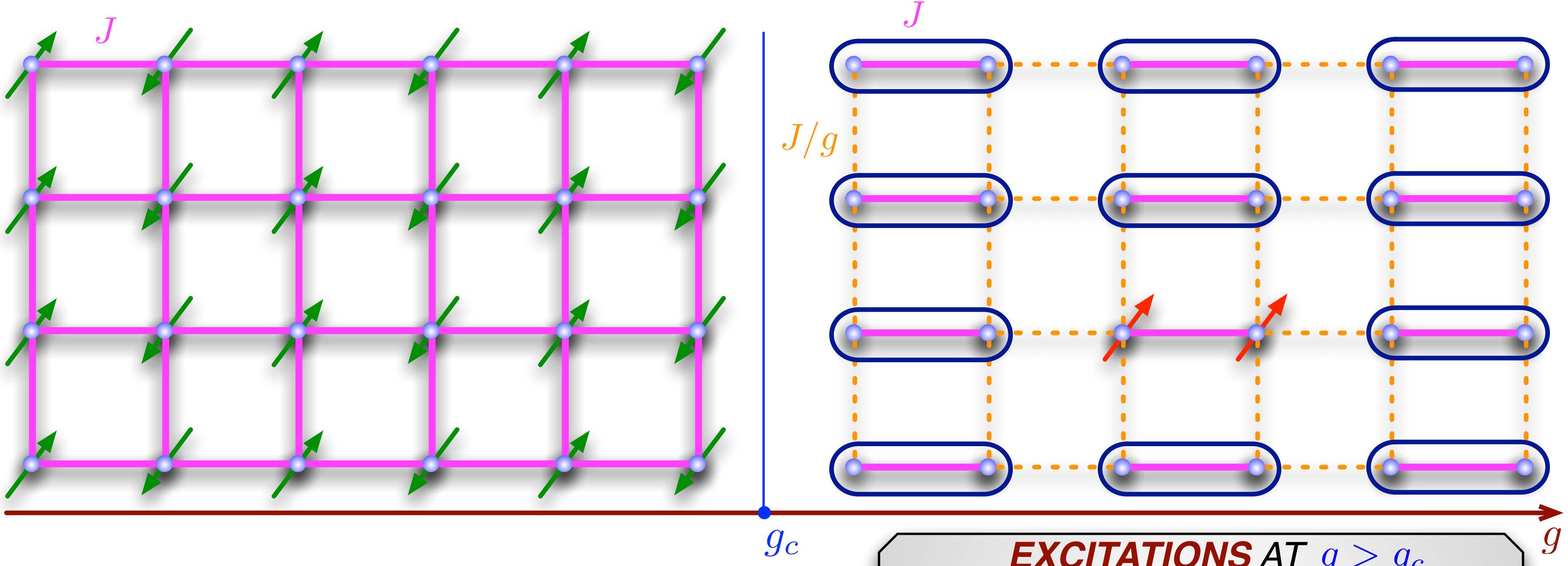

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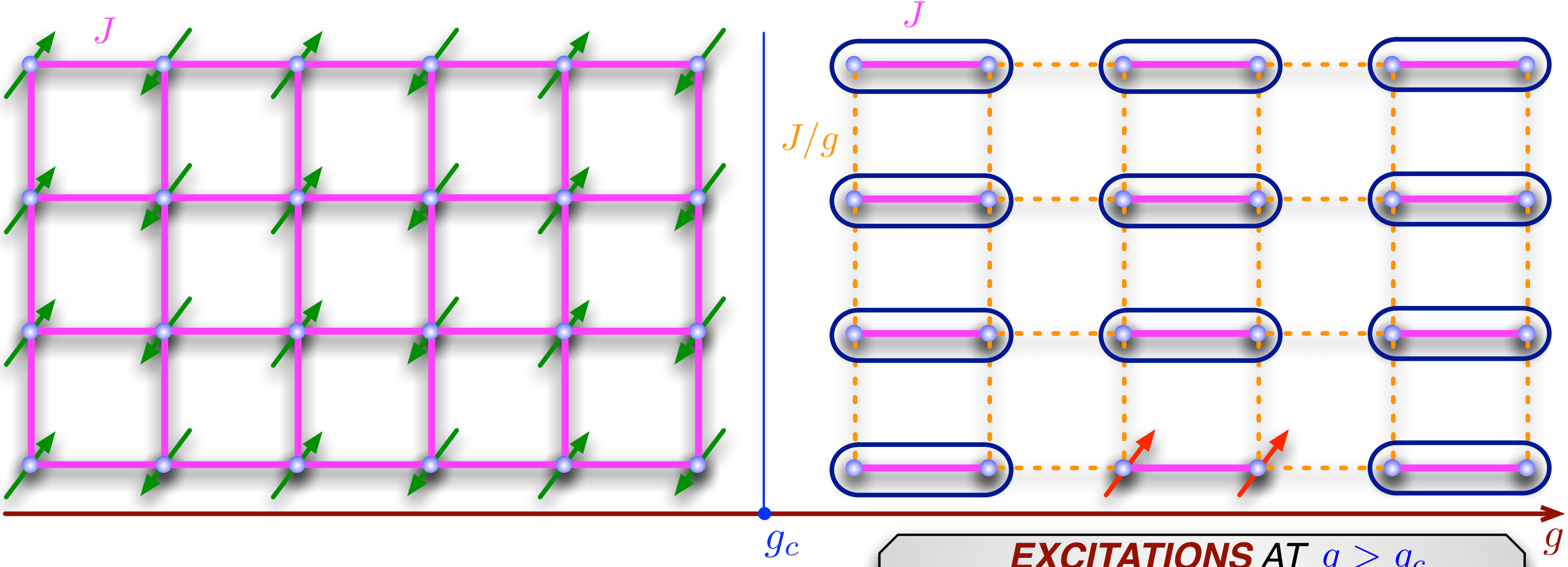

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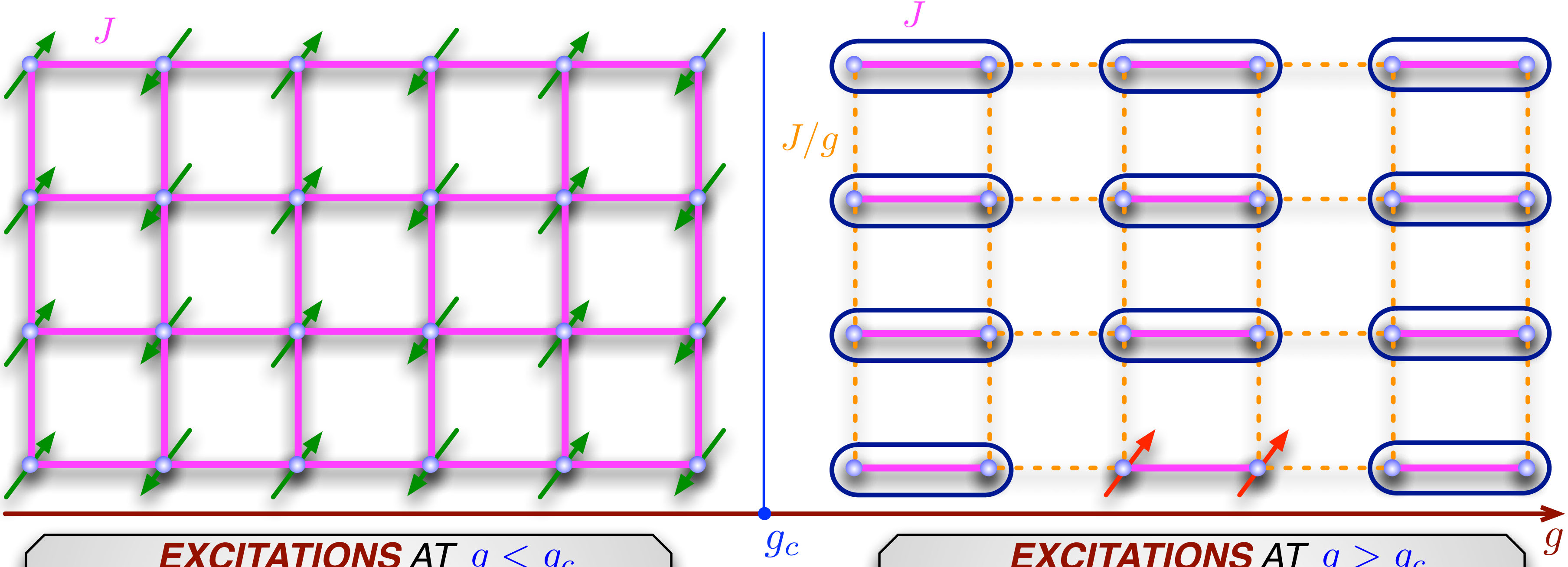

EXCITATIONS *AT* $g < g_c$

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

GOLDSTONE SPIN WAVES
+ "HIGGS" MODE

CFT3

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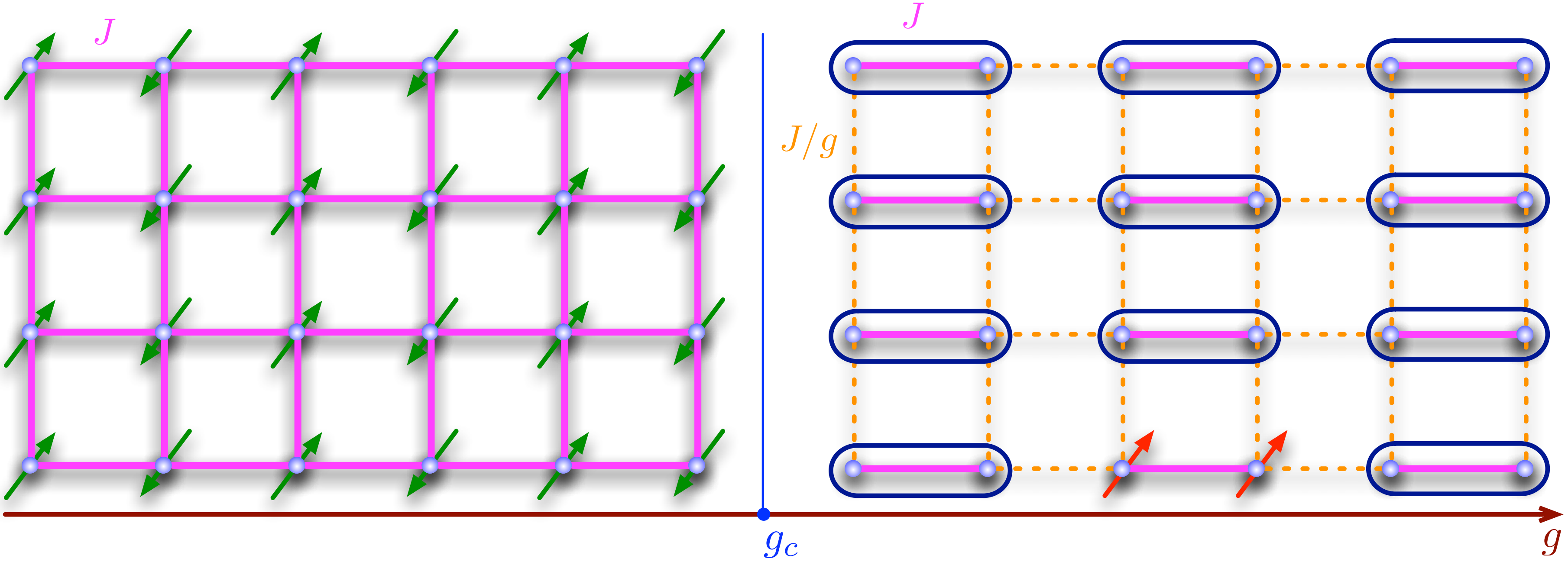
SPIN 1 "TRIPLONS"

Quantum critical systems

What happens if we add ***temperature*** to the system?



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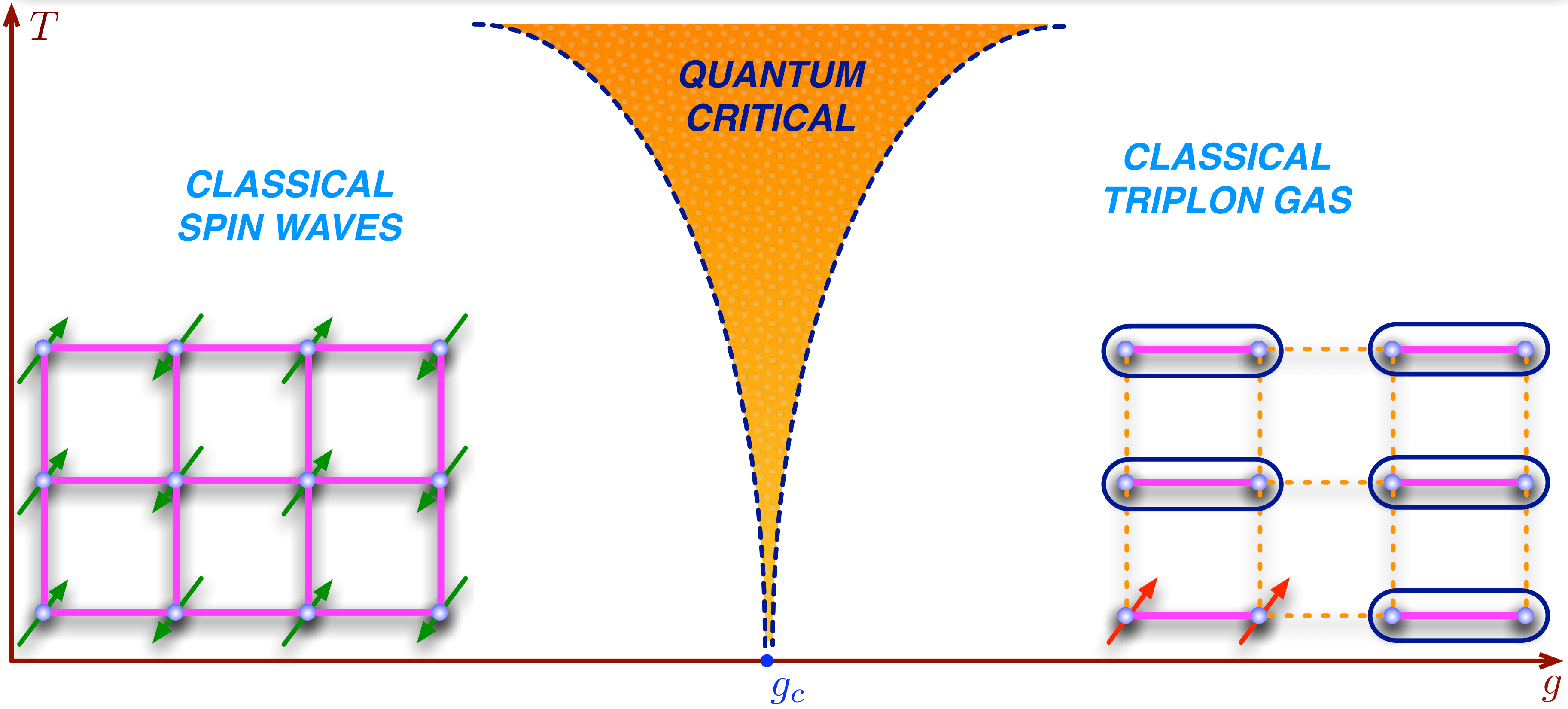

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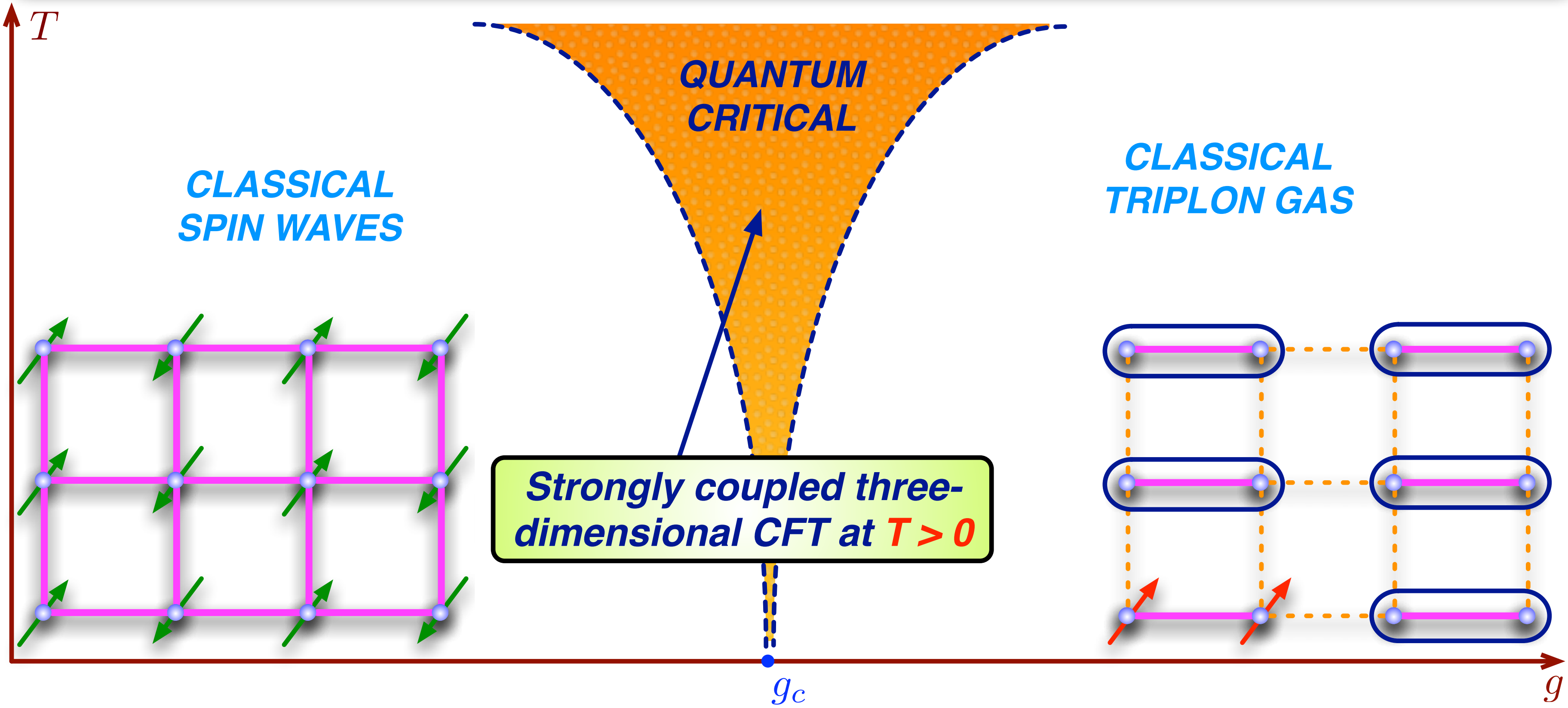

Strongly coupled three-dimensional CFT at $T > 0$

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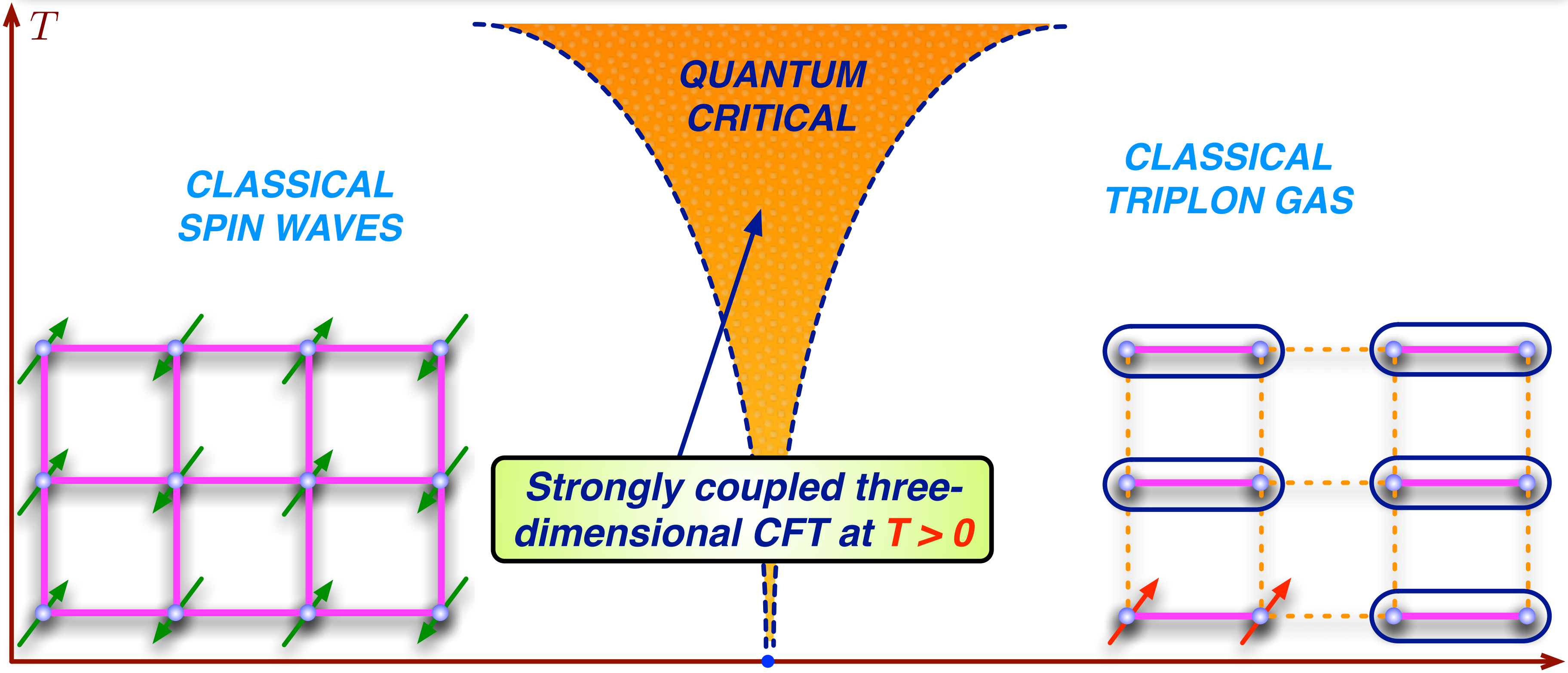

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Quantum ***"perfect fluid"***: ***transport coefficients*** depend only on ***universal constants***

Relaxation time

$$\tau \geq \frac{\hbar}{k_B T} \times [\text{universal } O(1)]$$

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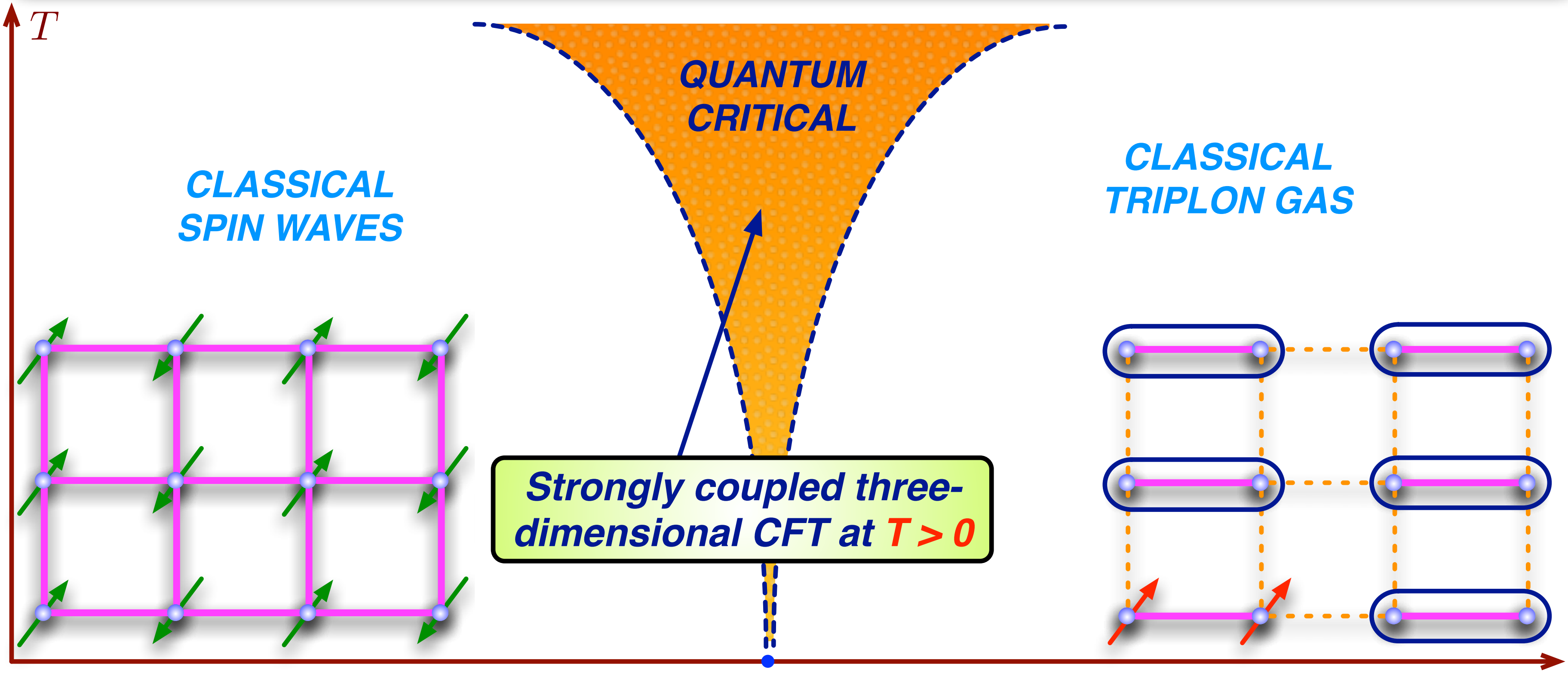

T

QUANTUM CRITICAL

CLASSICAL SPIN WAVES

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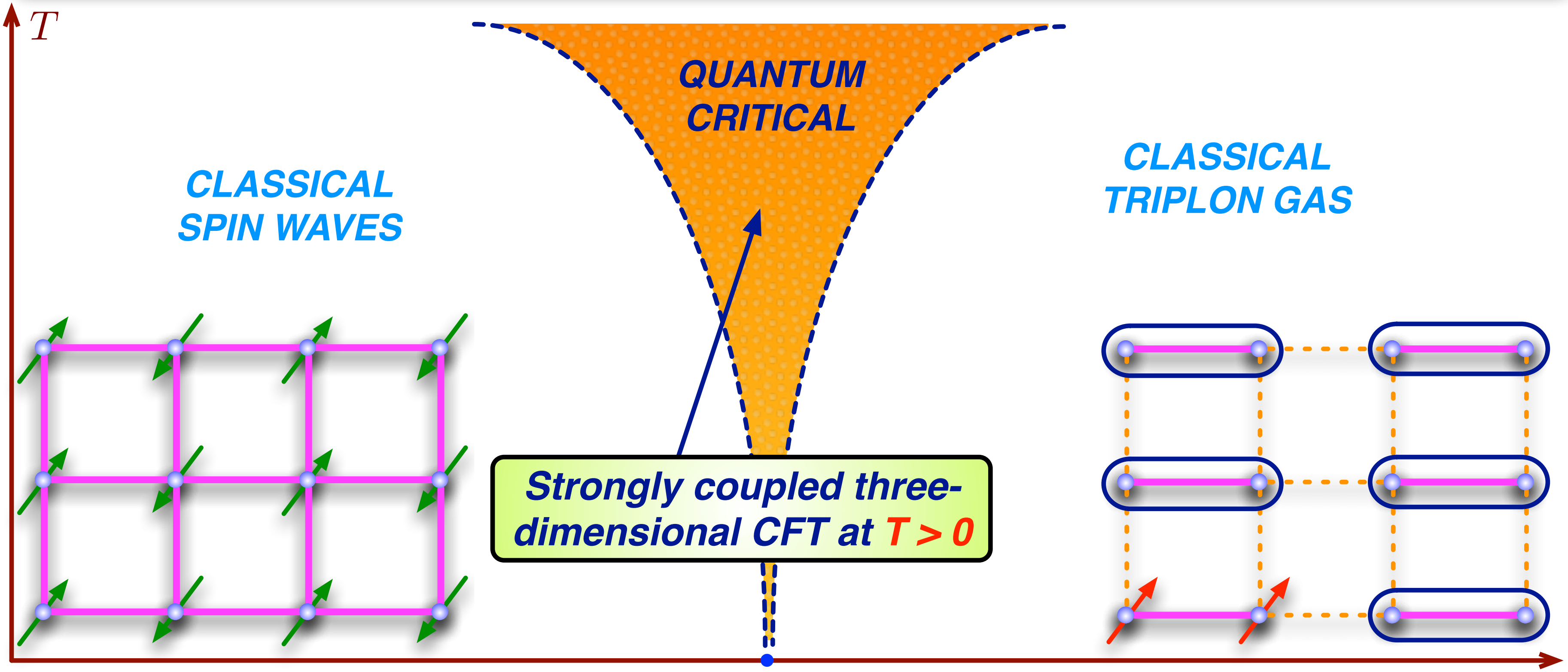

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Relaxation time	***Electrical conductivity***	***Viscosity / entropy density***
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Holography 1: temperature and black holes

Quantum critical region described by
conformal ***strongly coupled*** 3d QFT

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"GROUND STATE"

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HORIZON AREA

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Temperature T ⟷ **Black hole horizon** $r = r_H$

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Black hole Hawking ***temperature***, ***entropy***, ... are equal to the ones of the ***CFT***

Temperature	*Entropy density*
$T = \frac{3}{4\pi r_H}$	$\frac{S}{A} = \frac{1}{4G_N}$

In general compute *partition function* $Z \simeq e^{-S_E}$

Holography 1: temperature and black holes

Quantum critical region described by ***conformal strongly coupled*** 3d QFT ➡ Ideal set-up for ***holographic duality***

3d Conformal Field Theory ↔ ***Gravity in (Asymptotically) 4d Anti-de Sitter***

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Condensed matter systems are ***electron systems*** : add a ***U(1) symmetry***

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E.g. $g_{\mu\nu} \leftrightarrow T_{\mu\nu}$

$A_\mu \leftrightarrow J_\mu$

Holography 3: transport properties

Real time dynamics and ***transport*** *very sensitive* to interactions

➡ ***Holographic methods*** are often our ***only handle*** at strong coupling

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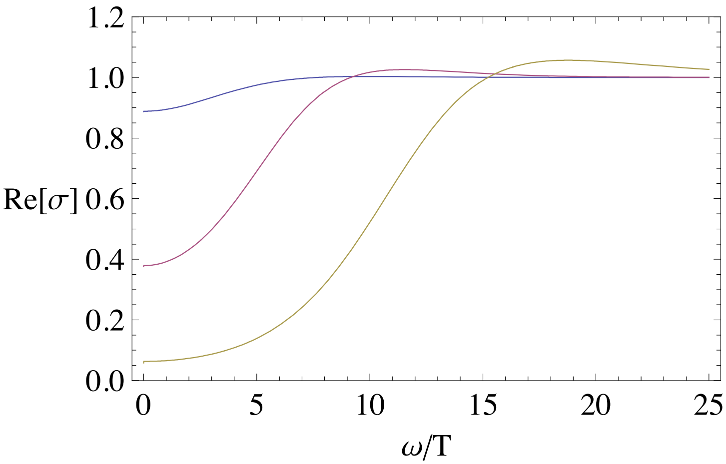

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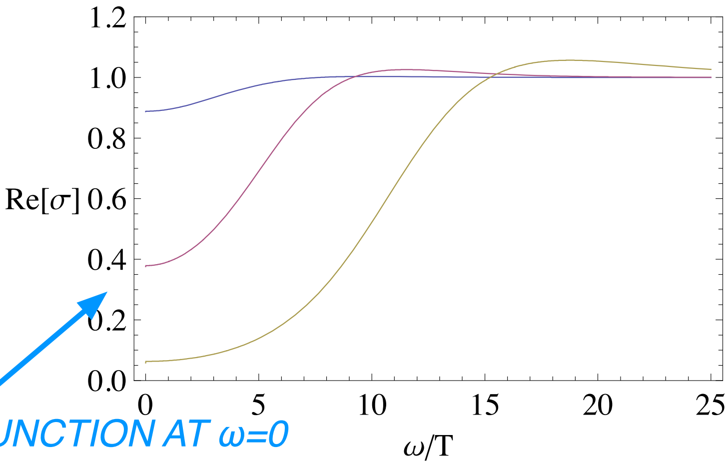

DELTA FUNCTION AT ω=0
(MOMENTUM CONSERVATION)

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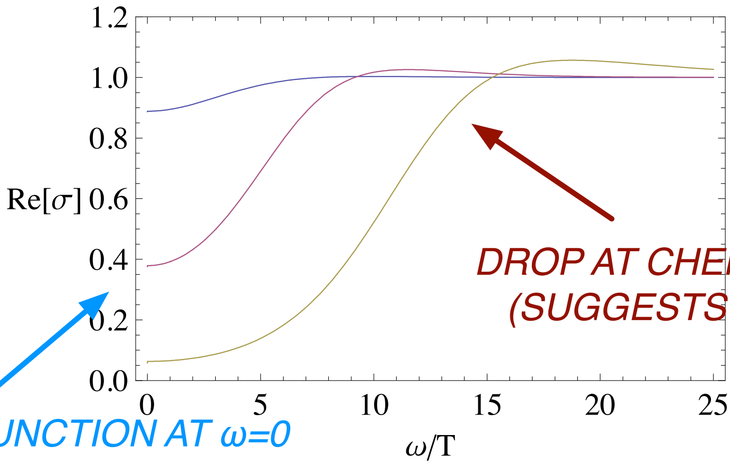

DROP AT CHEMICAL POTENTIAL μ (SUGGESTS ***FERMI SURFACE****)*

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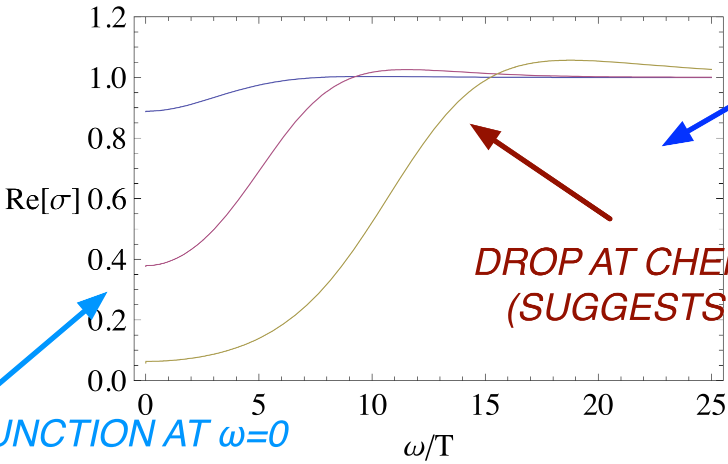

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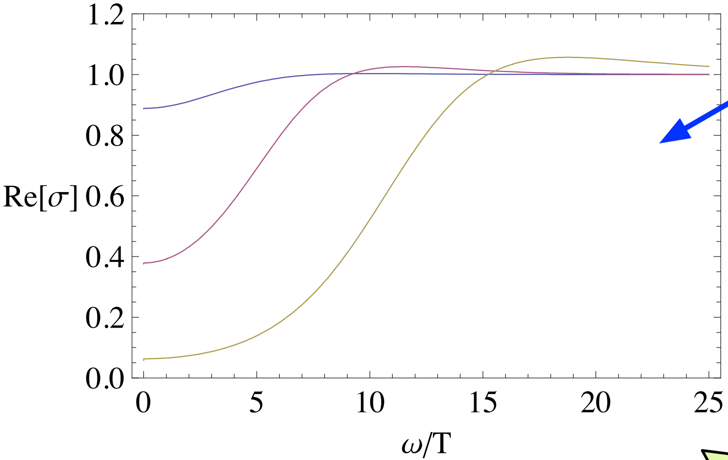


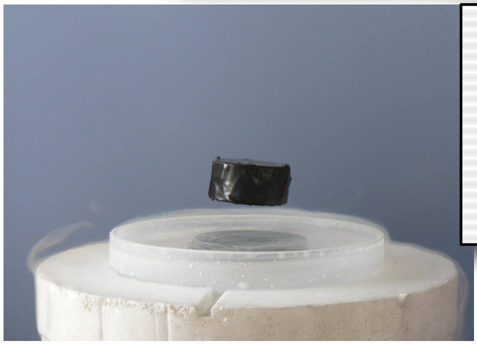
*VERY SIMILAR TO **GRAPHENE** !*

Viscosity

Holography gives *universal value* for *viscosity / entropy density*

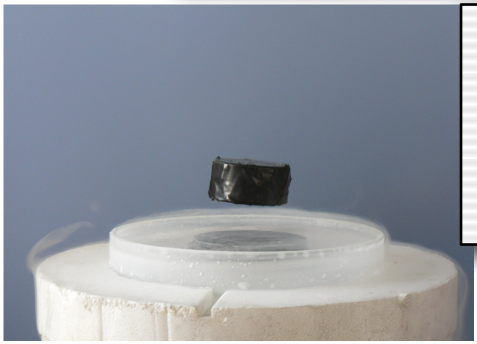
$$\frac{\eta}{s} = \frac{1}{4\pi}\frac{\hbar}{k_B}$$

Holographic superconductors



Superconductivity is spectacular application of
U(1) spontaneous symmetry breaking

Holographic superconductors



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➡ *Vanishing resistance at low temperatures*
➡ *Expulsion of magnetic field (Meissner effect)*

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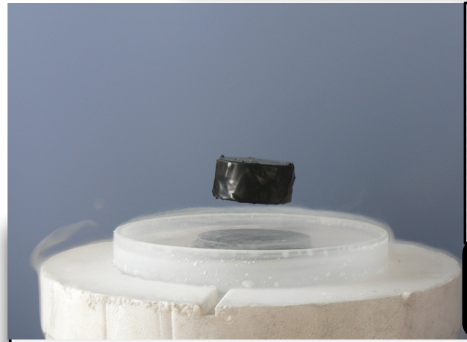

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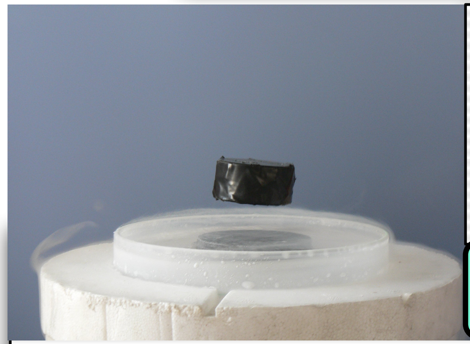

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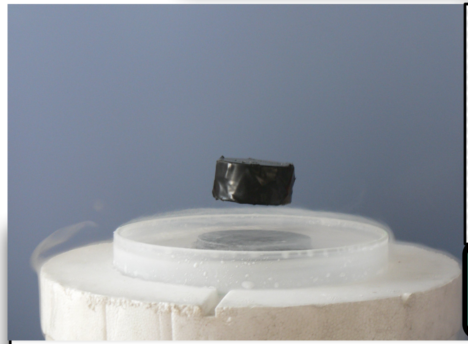

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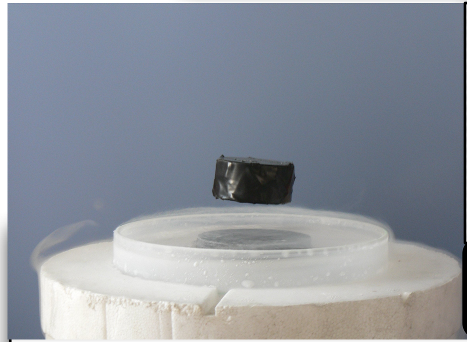

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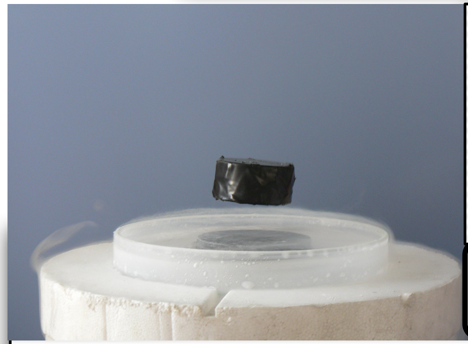

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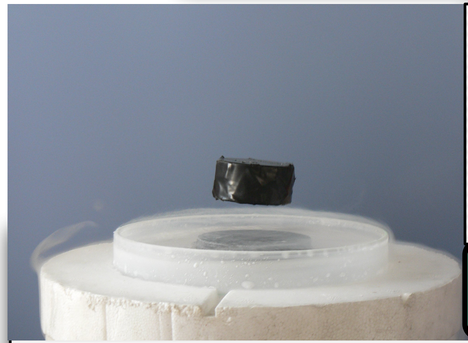

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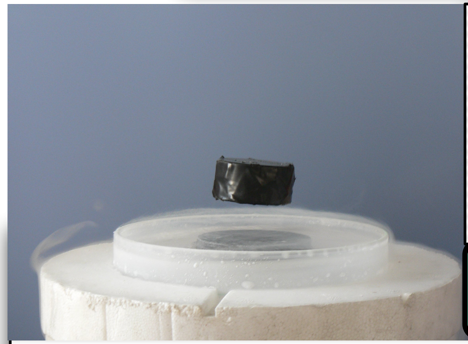

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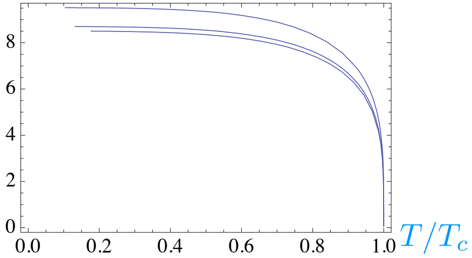

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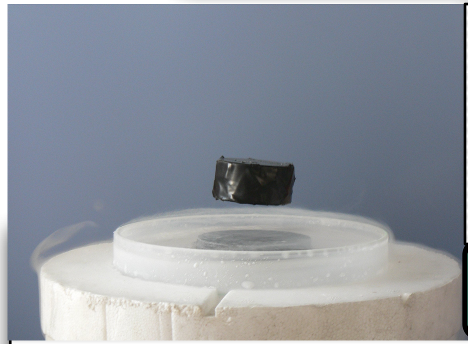

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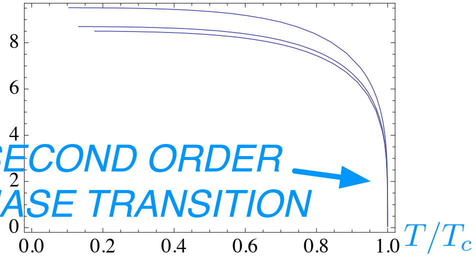
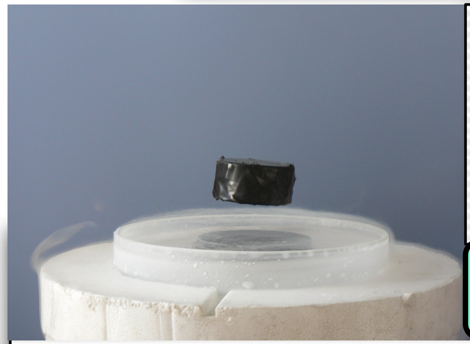


SECOND ORDER PHASE TRANSITION

Holographic superconductors



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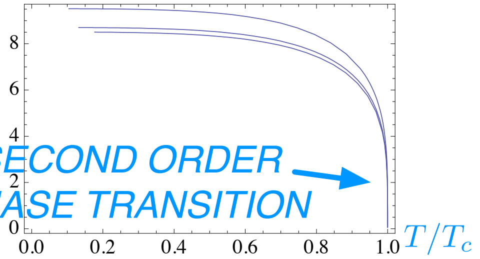

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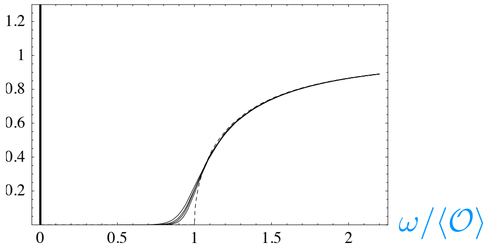

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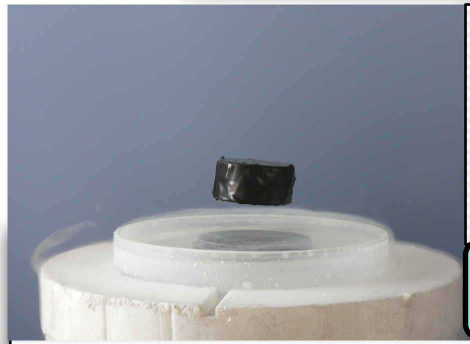

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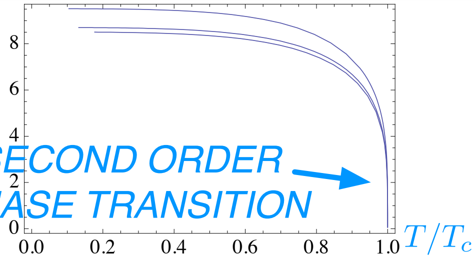

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ELECTRICAL CONDUCTIVITY
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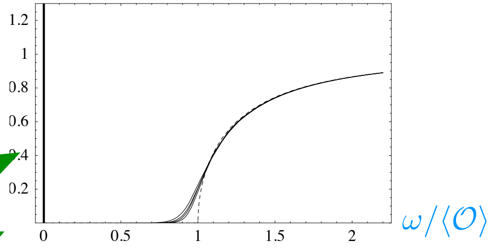
INFINITE DC CONDUCTIVITY



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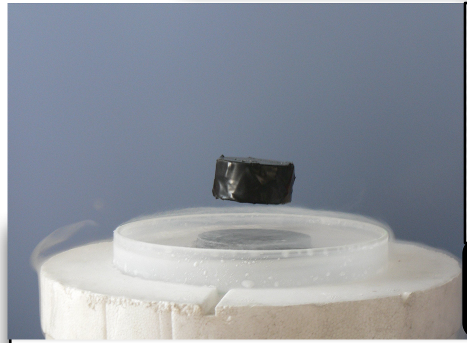

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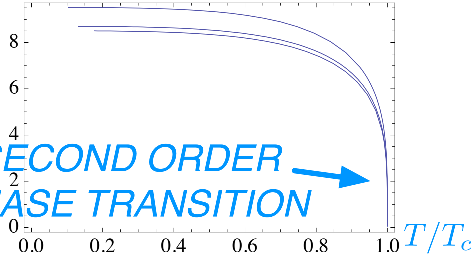

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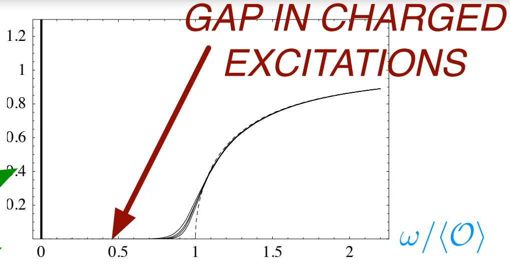
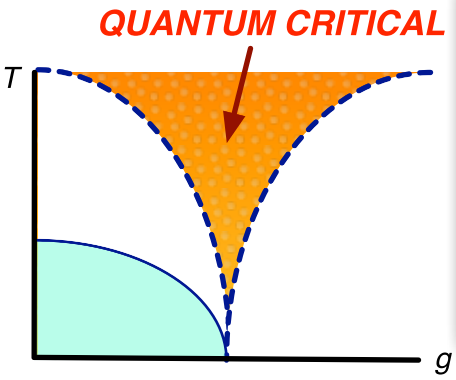
GAP IN CHARGED EXCITATIONS



INFINITE DC CONDUCTIVITY

Non-relativistic systems



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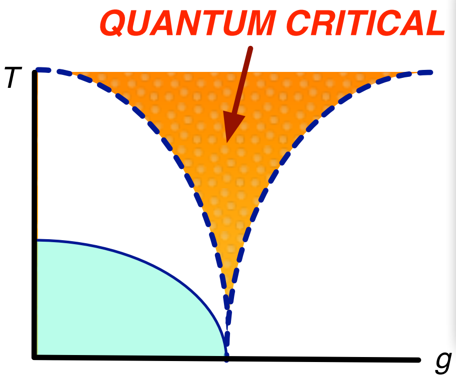

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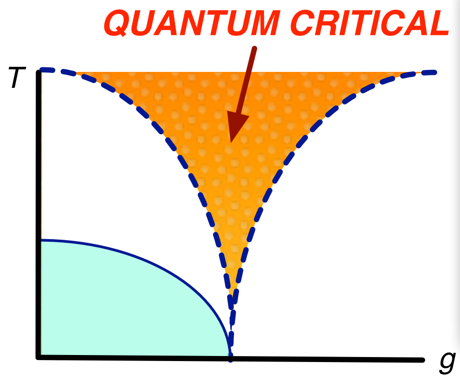

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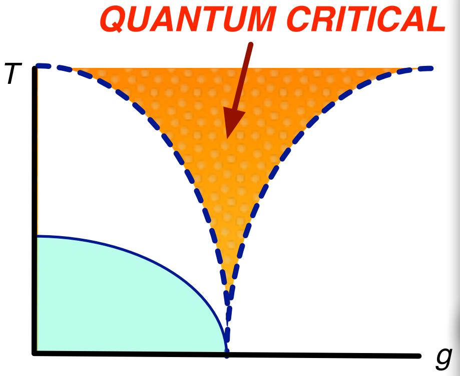

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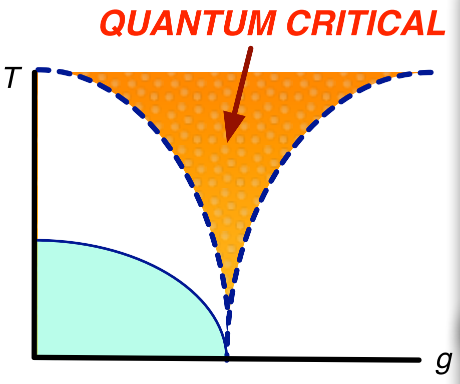

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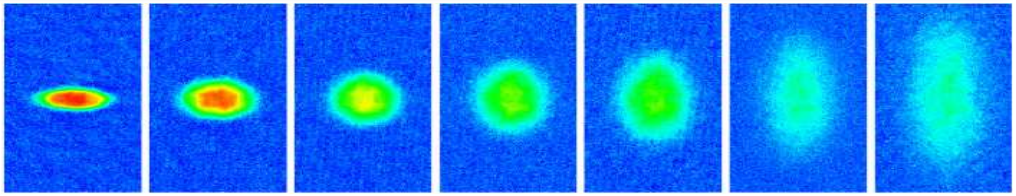

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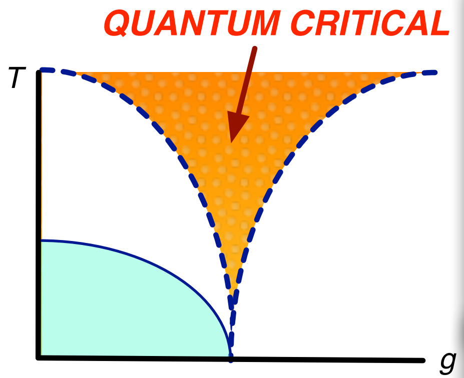

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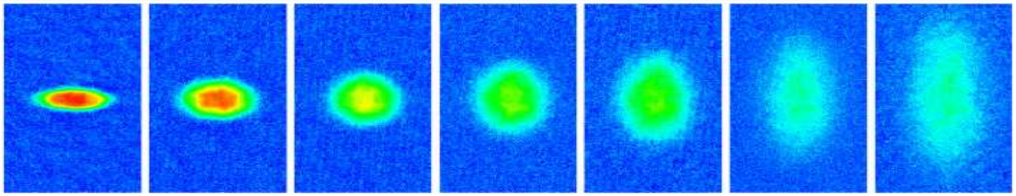

Algebra arises from *conformal algebra* in one higher dimension

Holographic dual obtained as ***transformation*** of (asymptotically) ***5d Anti-de Sitter space***

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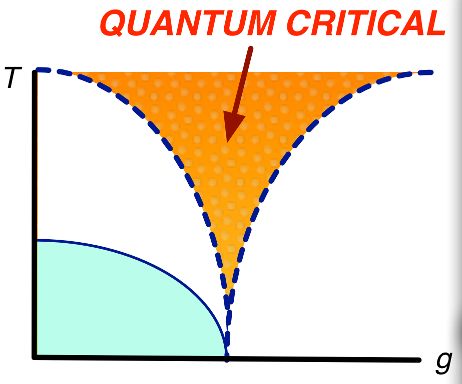

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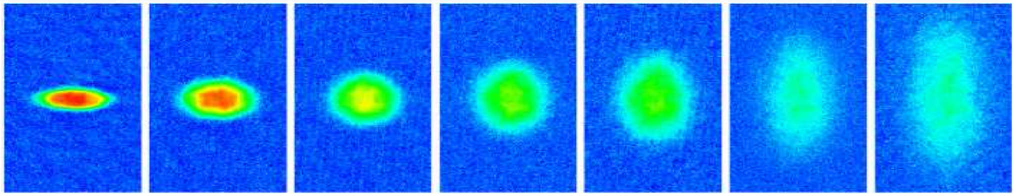

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SCHRÖDINGER SPACE-TIME

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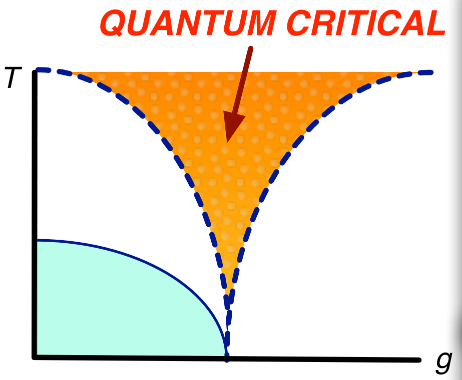

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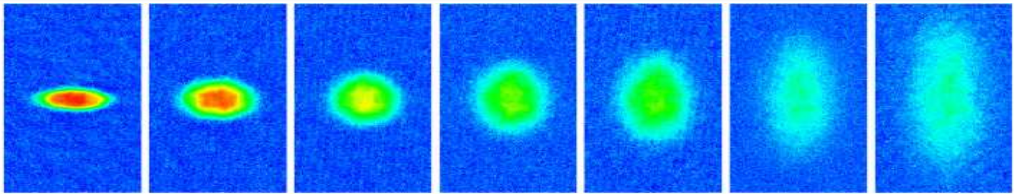

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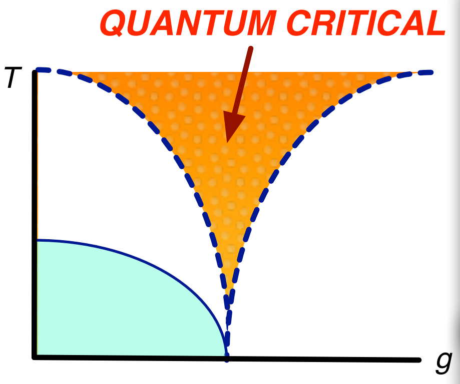

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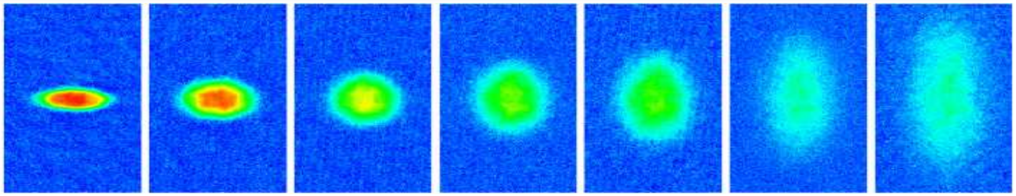

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E.g. $\frac{\eta}{s} = \frac{1}{4\pi}\frac{\hbar}{k_B}$

Conclusions

In summary...

- *Quantum critical systems* relevant for *condensed matter physics* are described by *strongly coupled conformal field theories*
- They *elude* the usual paradigms of *quasiparticles* and *order parameters*
- The *holographic gauge/string duality* can be used to study *equilibrium* and *real-time* dynamical properties of these systems
- *Holographic methods* may be relevant for the understanding of phenomena such as *superconductivity* and *fermions at unitarity* that have important *experimental applications*