Condensed matter physics
and
string theory

Talk online: sachdev.physics.harvard.edu

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Comfort zone of string theory

One, two, three.... particles

(quarks, gluons, gravitons....)

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Works at critical points where particle spectrum changes
(AdS/CFT correspondence)

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Infinite numbers of particles (non-zero density)
with weak interactions:
electrons, trapped cold atoms

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Quantum phases with universal
low energy properties, independent of
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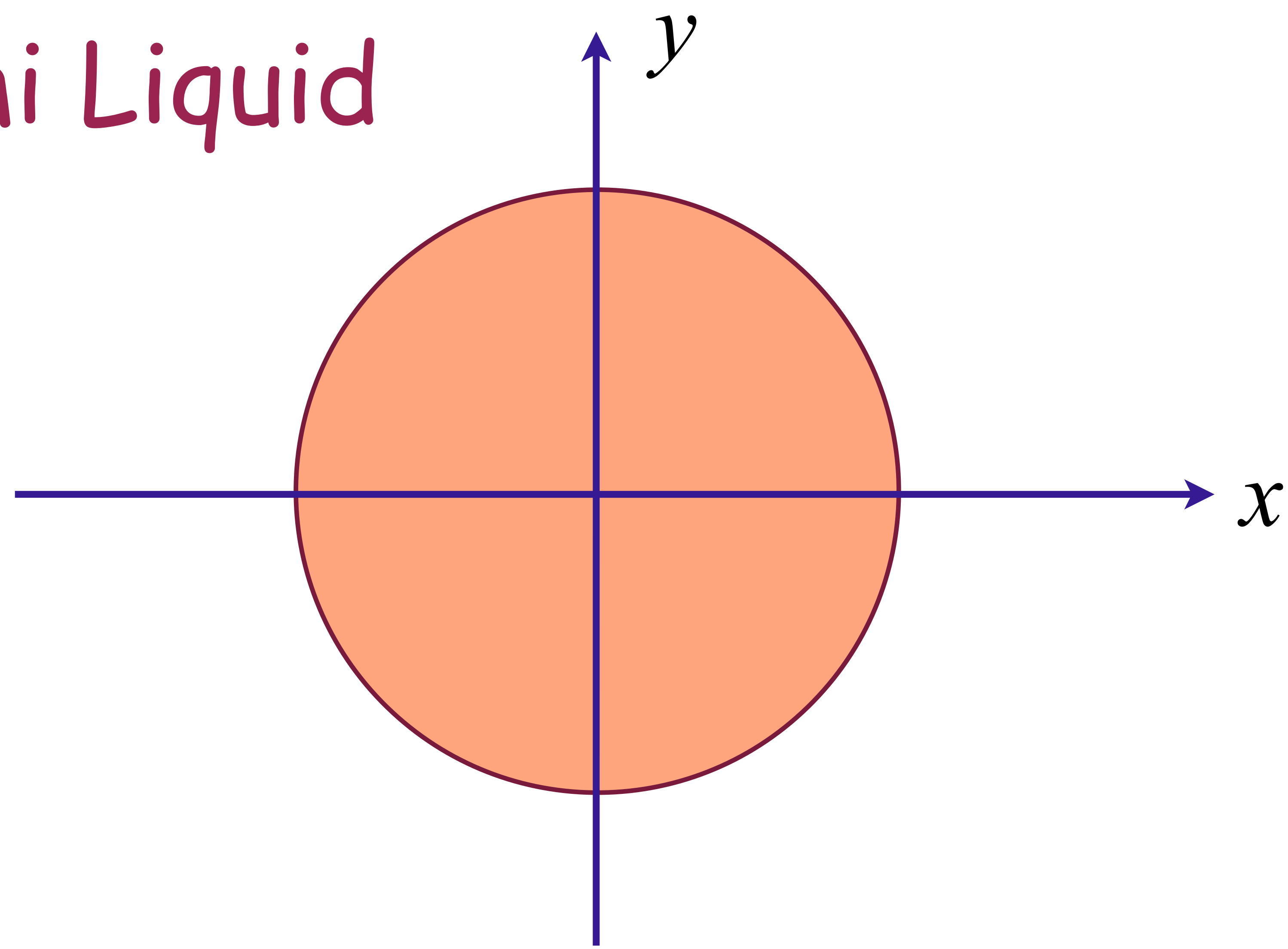
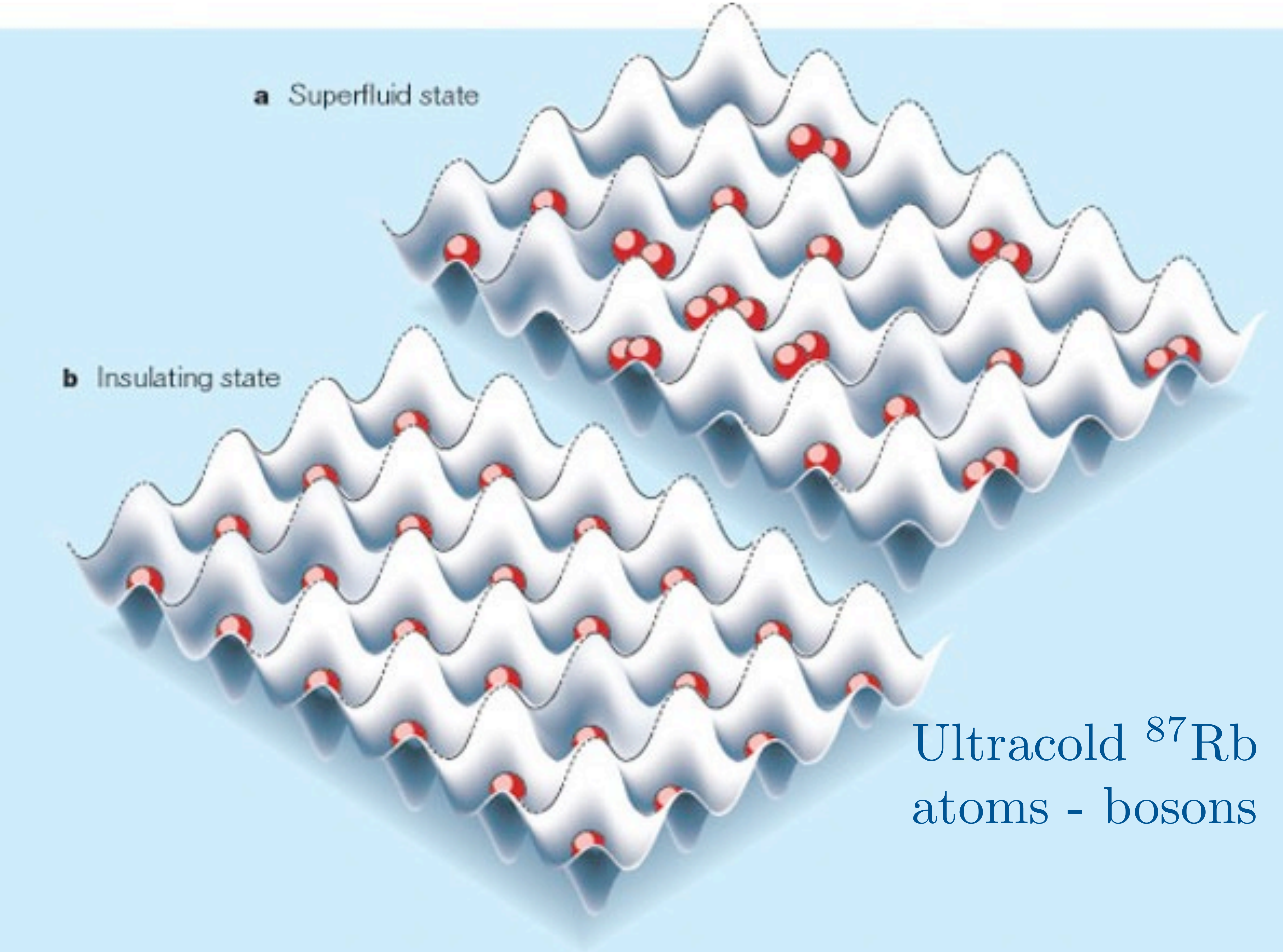
Fermi liquids, solids, superfluids

Fermi Liquid



In momentum space, Fermi surface separates occupied and empty electron states



Ultracold ^{87}Rb atoms - bosons

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Fermi liquid theory (and its cousins) allow
adiabatic continuation to
strong interaction regime

Move out of
comfort zones,
and use tools developed
in both fields

Strong coupling problems in condensed matter

1. Electrical resistance at non-zero temperature near quantum critical points

2. Zero temperature quantum phase transitions of Fermi liquids

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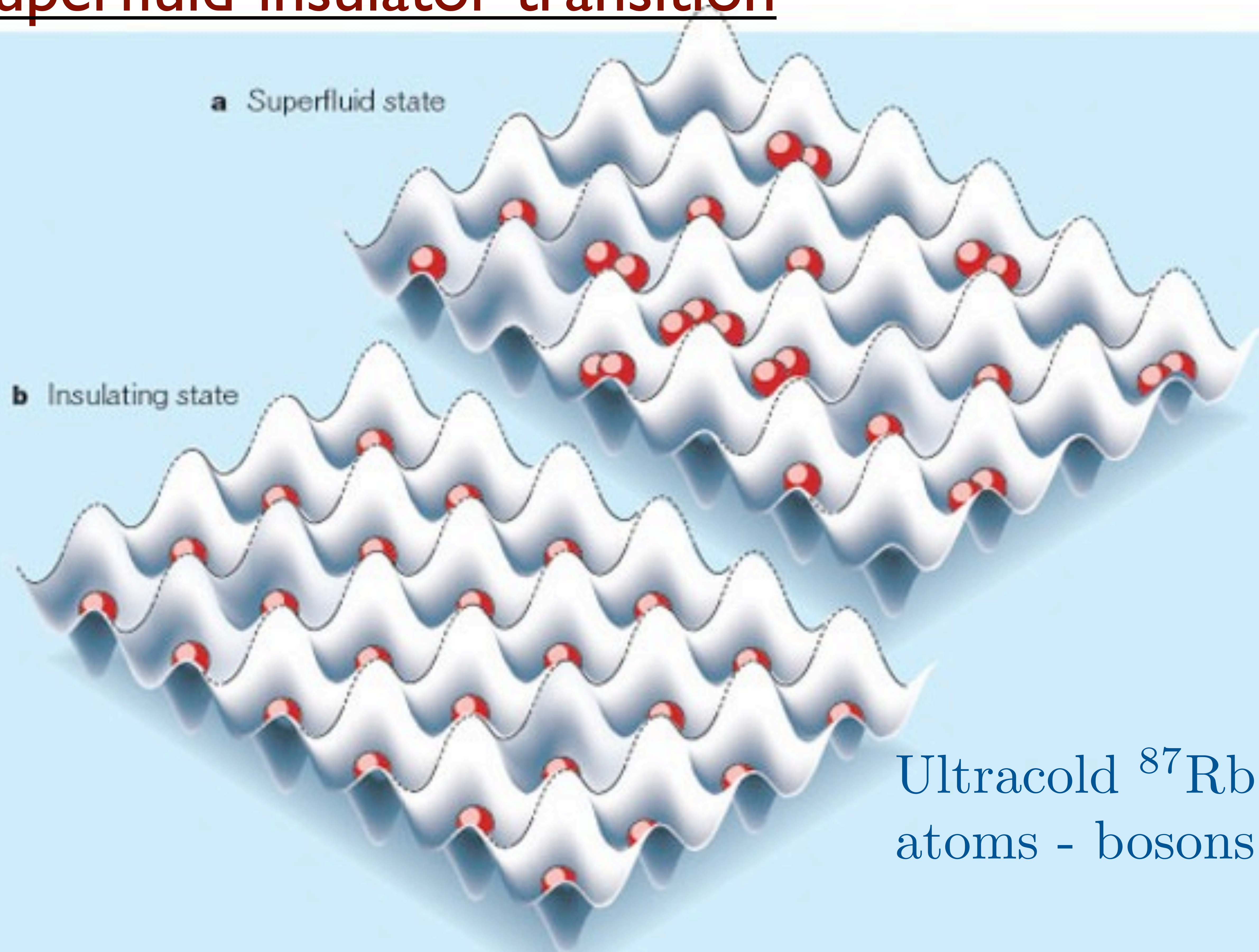
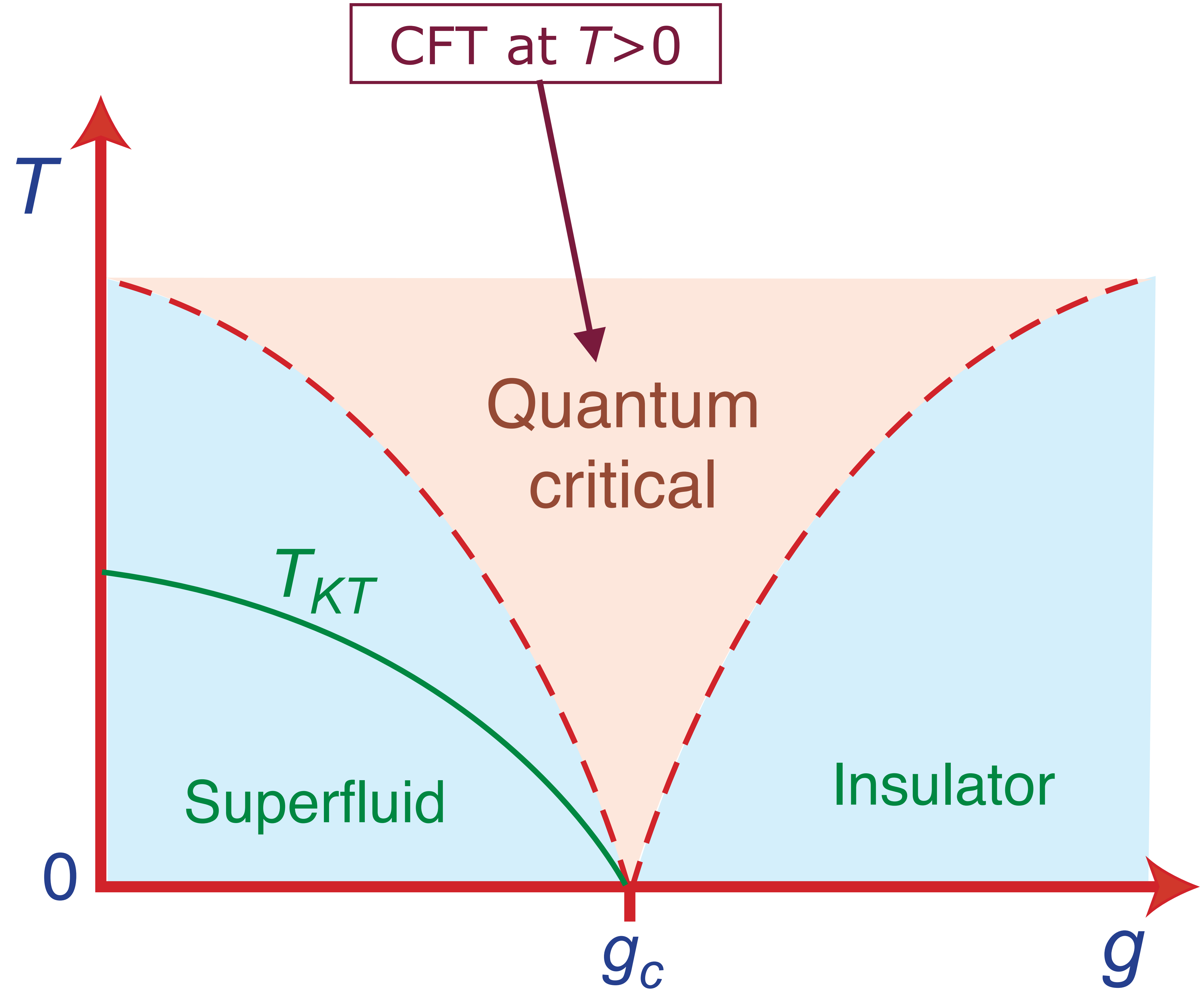
Superfluid-insulator transition



Ultracold ^{87}Rb
atoms - bosons

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


CFT at T>0
T
Quantum
critical
T_KT
Superfluid
Insulator
0
g_c
g

Quantum critical transport

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

$$\tau_R \gtrsim \frac{\hbar}{k_B T}$$

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

Electrical conductivity

$$\sigma = \frac{4e^2}{h} \times [\text{Universal constant } \mathcal{O}(1)\ ]$$

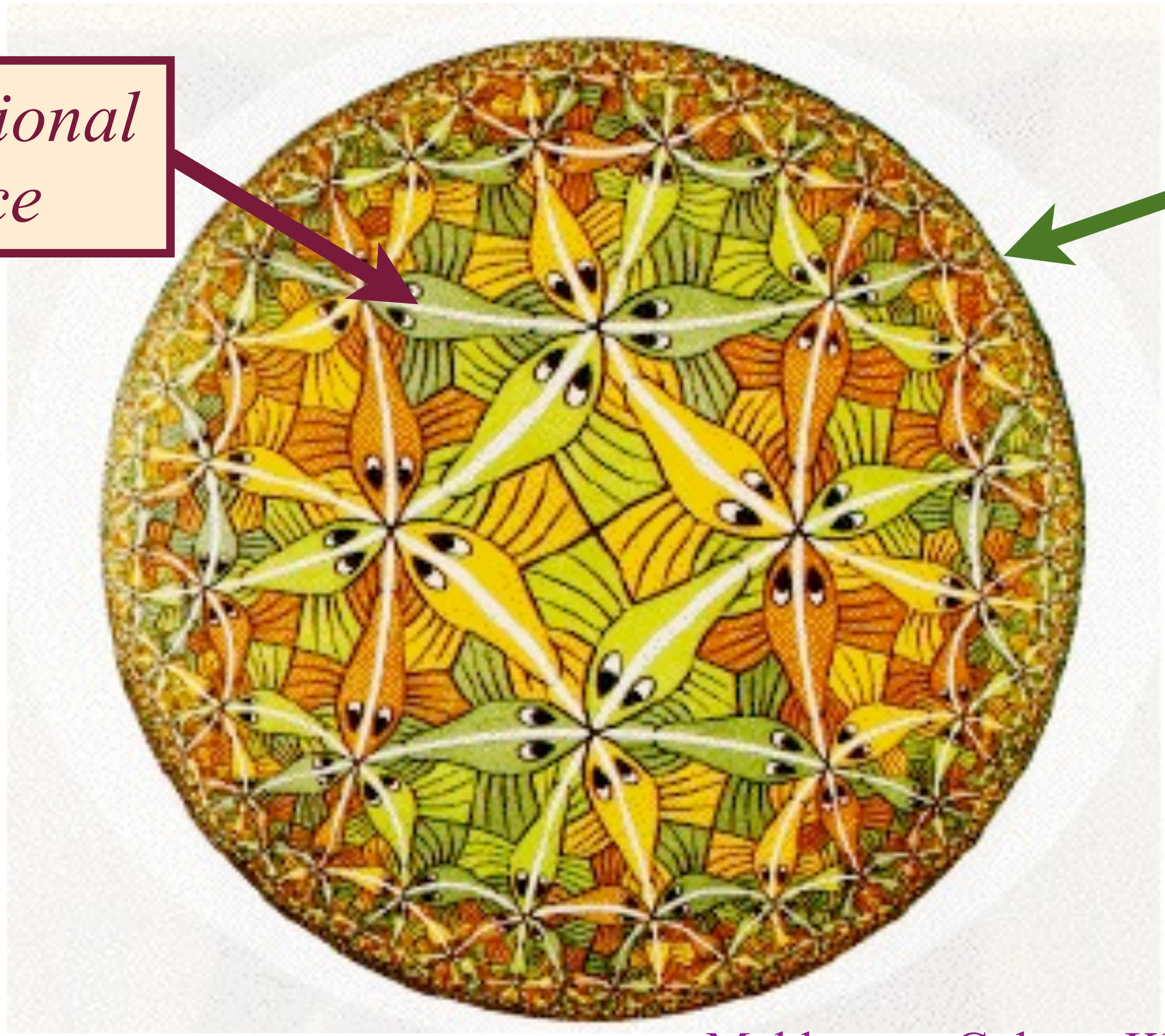
K. Damle and S. Sachdev, *Phys. Rev. B* **56**, 8714 (1997).

Requires long-time limit of correlations at non-zero temperature.

Cannot be obtained numerically by computers even for the simplest quantum problems. Is the sum of an exponentially large number of terms which oscillate in sign.

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



Maldacena, Gubser, Klebanov, Polyakov, Witten

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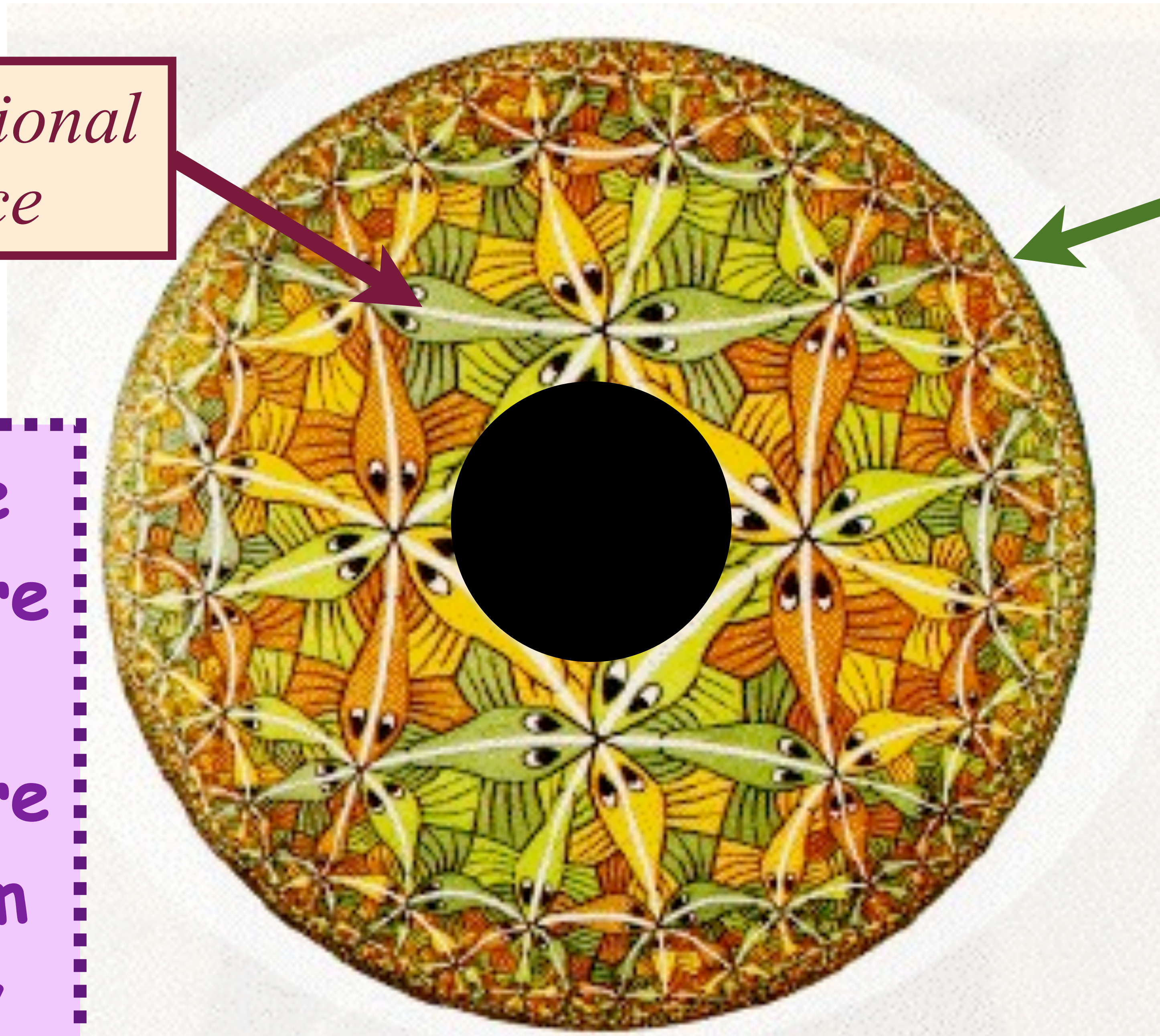
3+1 dimensional AdS space



Quantum criticality in 2+1 dimensions

Black hole temperature = temperature of quantum criticality

Maldacena, Gubser, Klebanov, Polyakov, Witten

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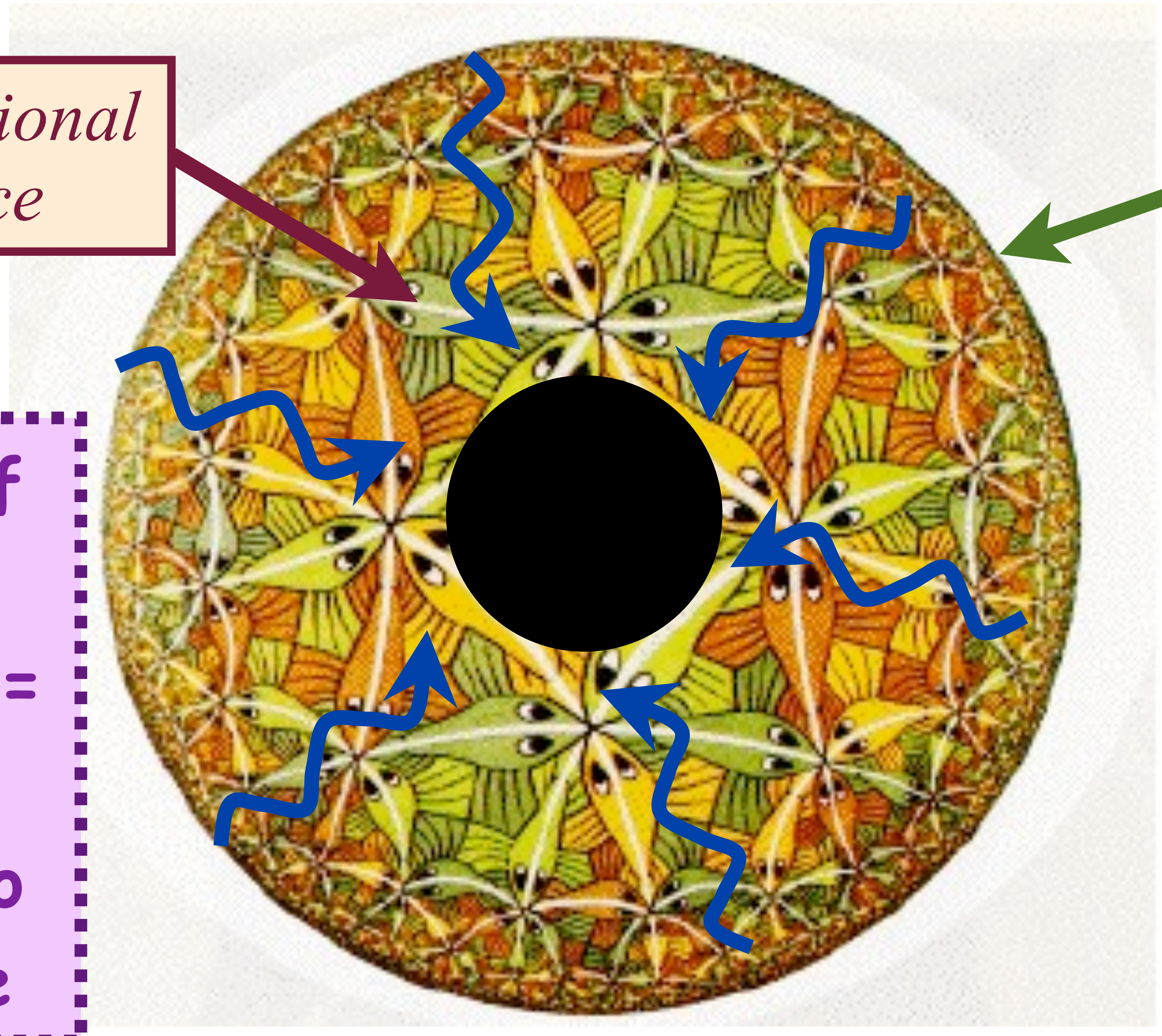

3+1 dimensional AdS space

Quantum criticality in 2+1 dimensions

Friction of quantum criticality = waves falling into black hole

Kovtun, Policastro, Son

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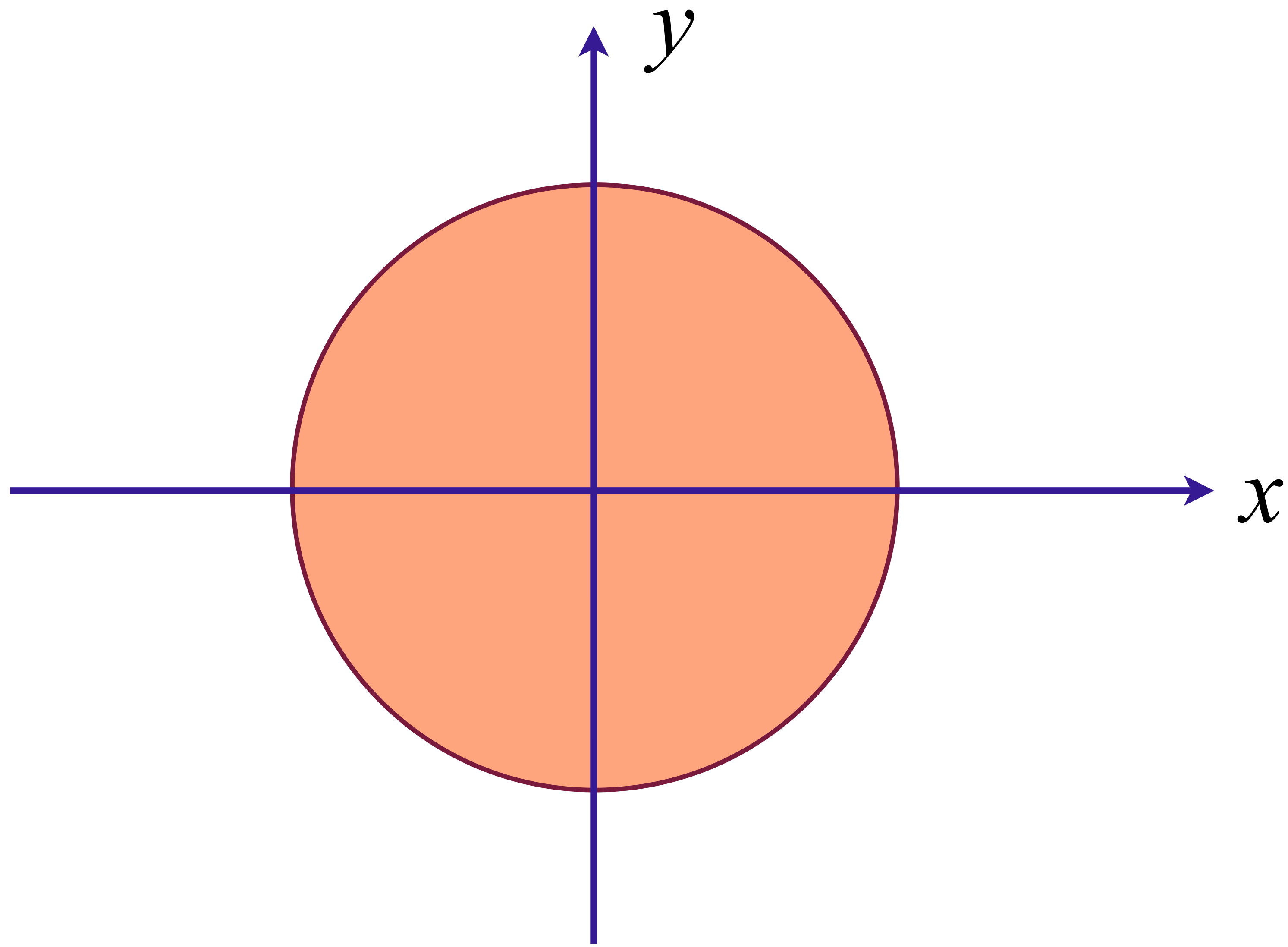
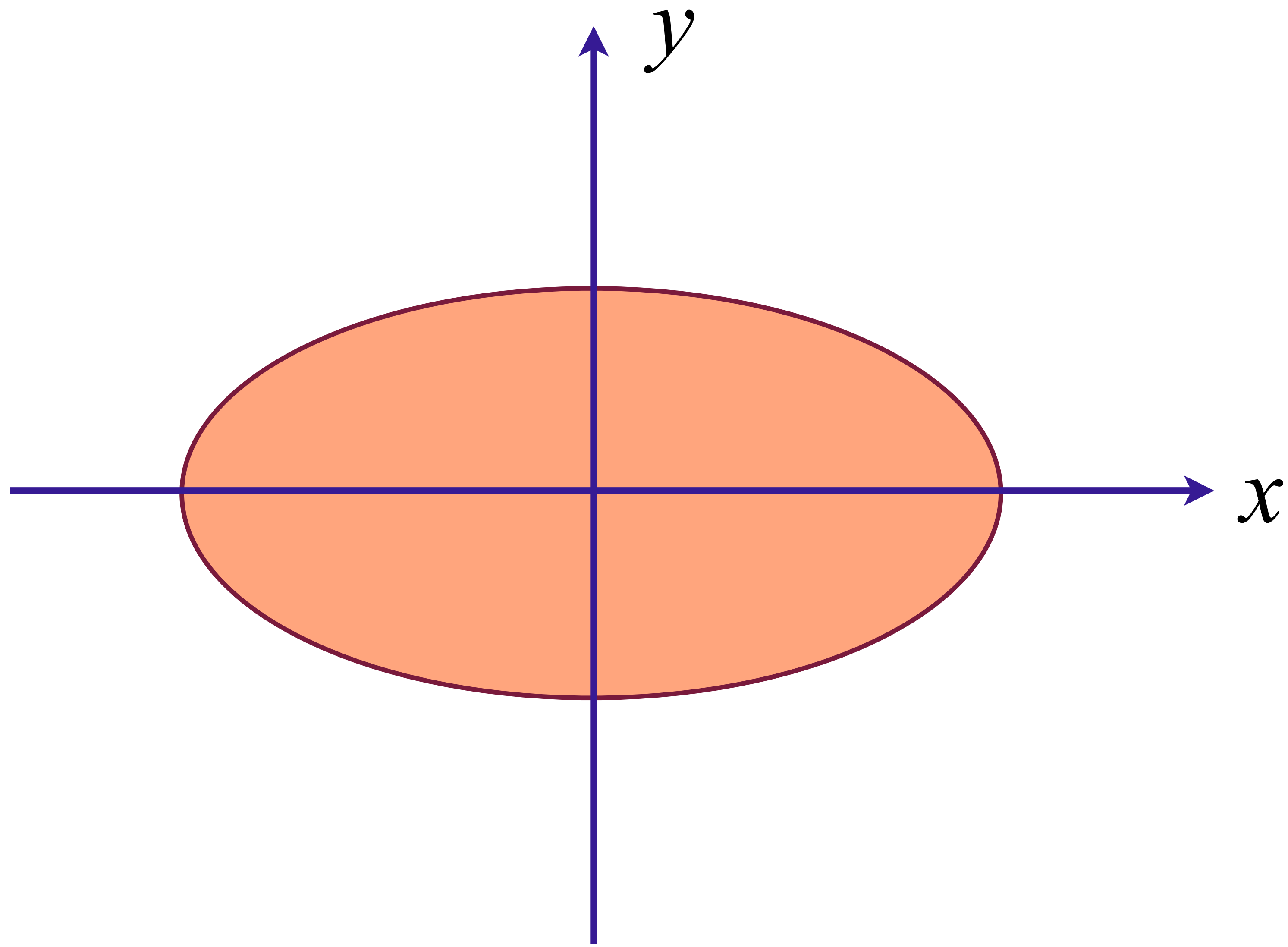
Quantum criticality of Pomeranchuk instability



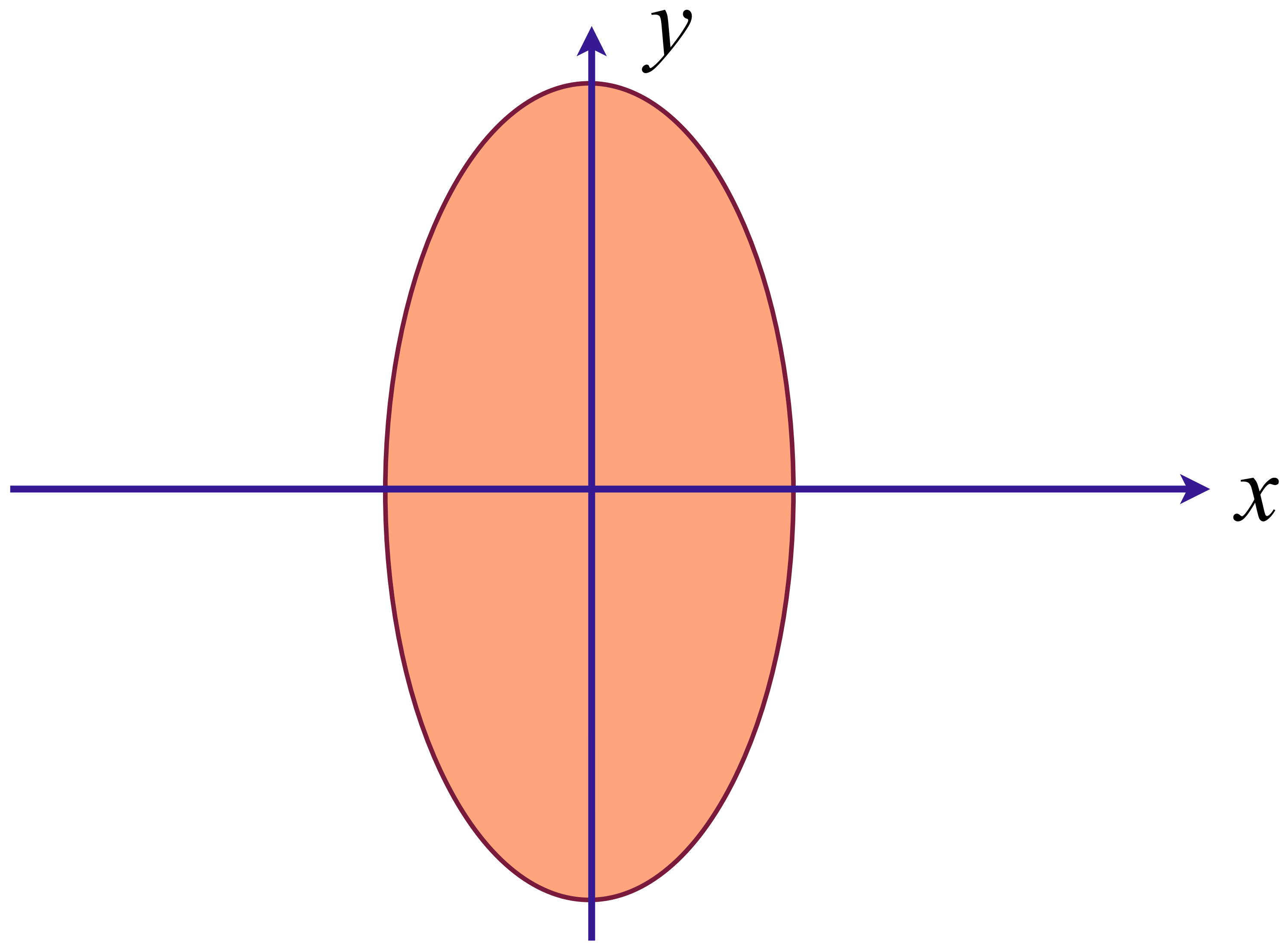
Fermi surface with full square lattice symmetry

Quantum criticality of Pomeranchuk instability



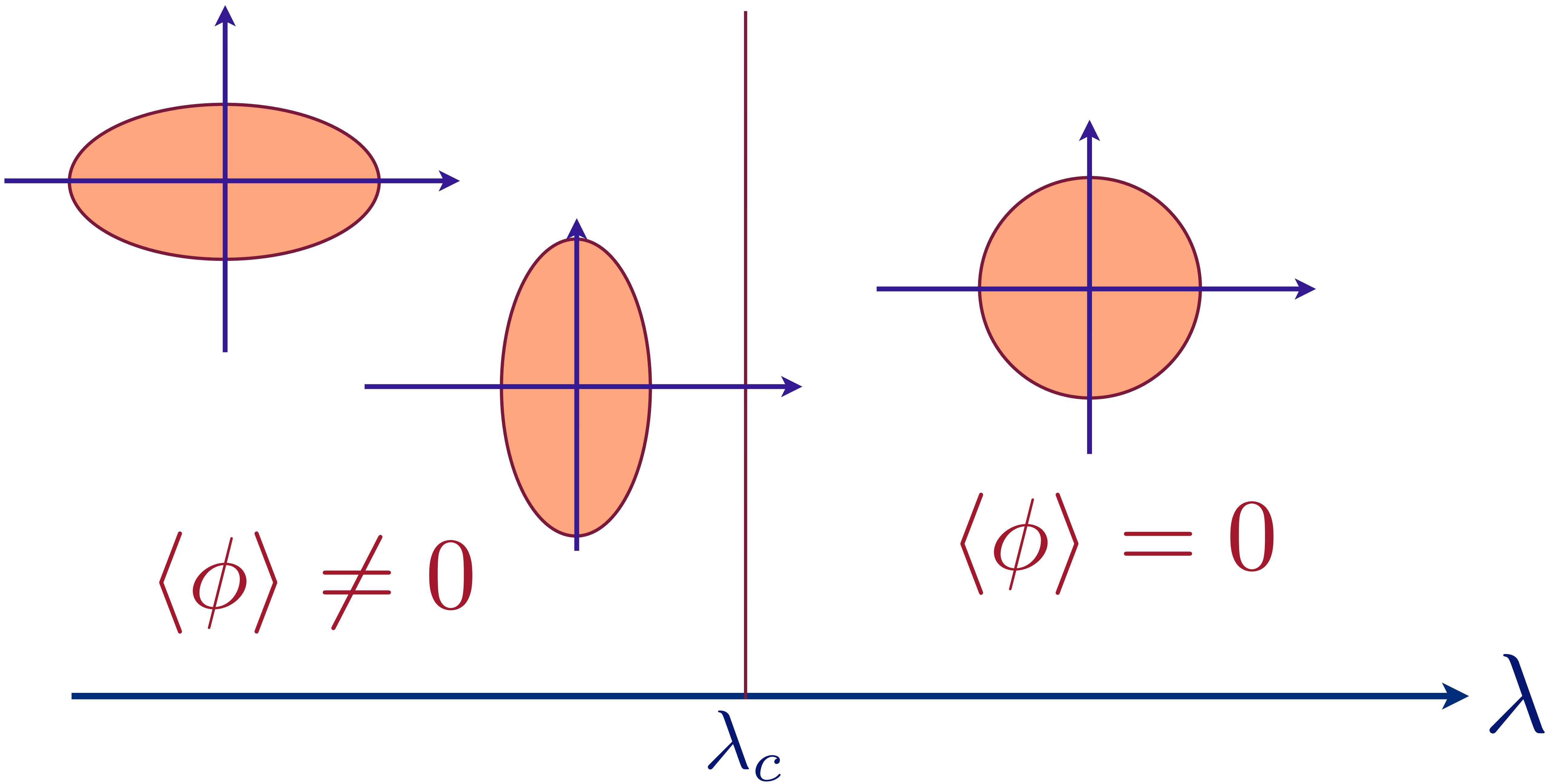
Spontaneous elongation along x direction:
Ising order parameter $\phi > 0$.

Quantum criticality of Pomeranchuk instability



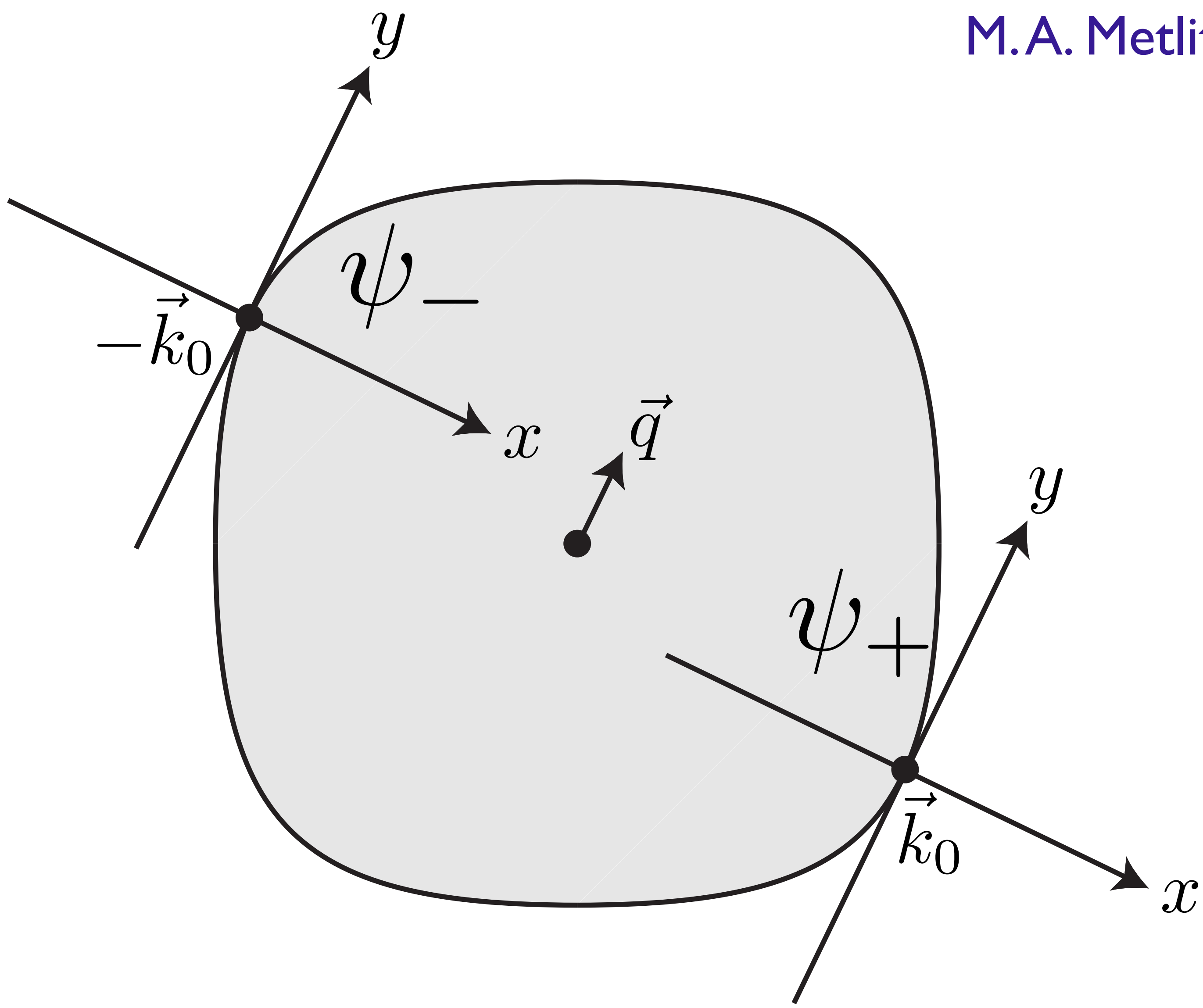
Spontaneous elongation along y direction:
Ising order parameter $\phi < 0$.

Quantum criticality of Pomeranchuk instability



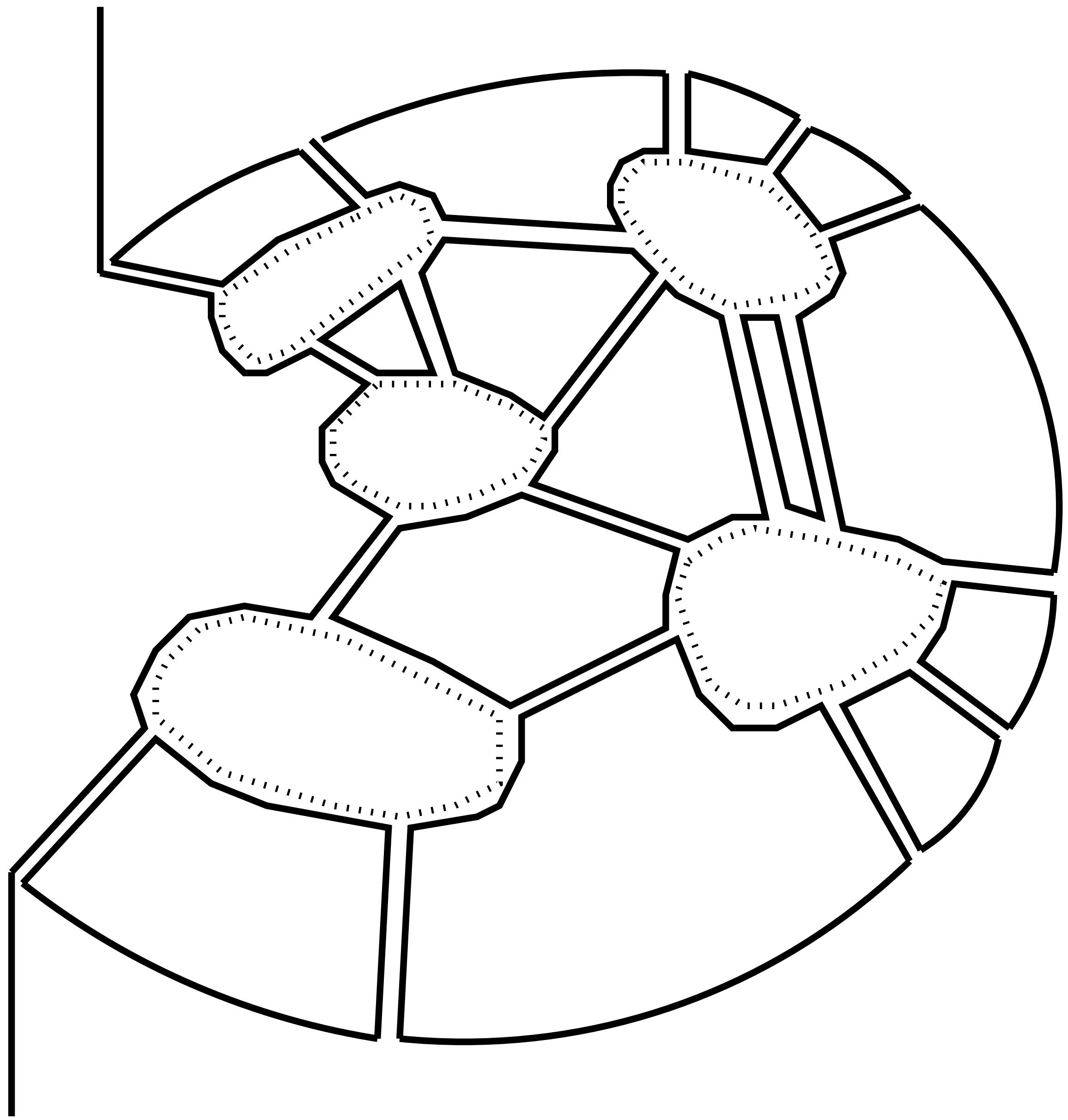
Pomeranchuk instability as a function of coupling λ

M.A. Metlitksi and S. Sachdev, to appear



A ϕ fluctuation at wavevector $\vec{q}$ couples most efficiently to fermions near $\pm\vec{k}_0$.

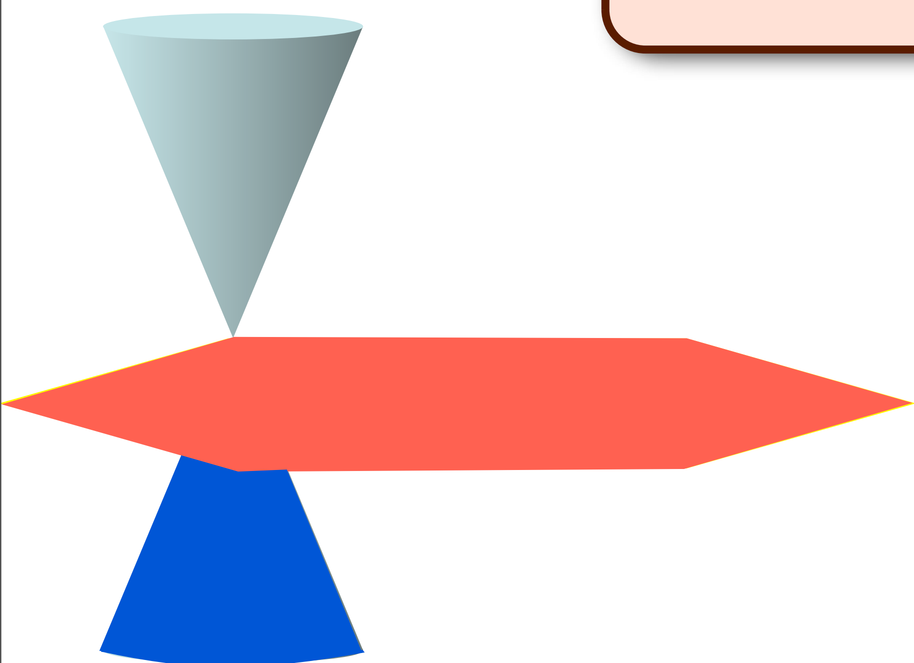
Infinite set of 2+1 dimensional quantum-critical field theories, one for each pair of points on the Fermi surface.
Ward identities ensure consistency of redundant description



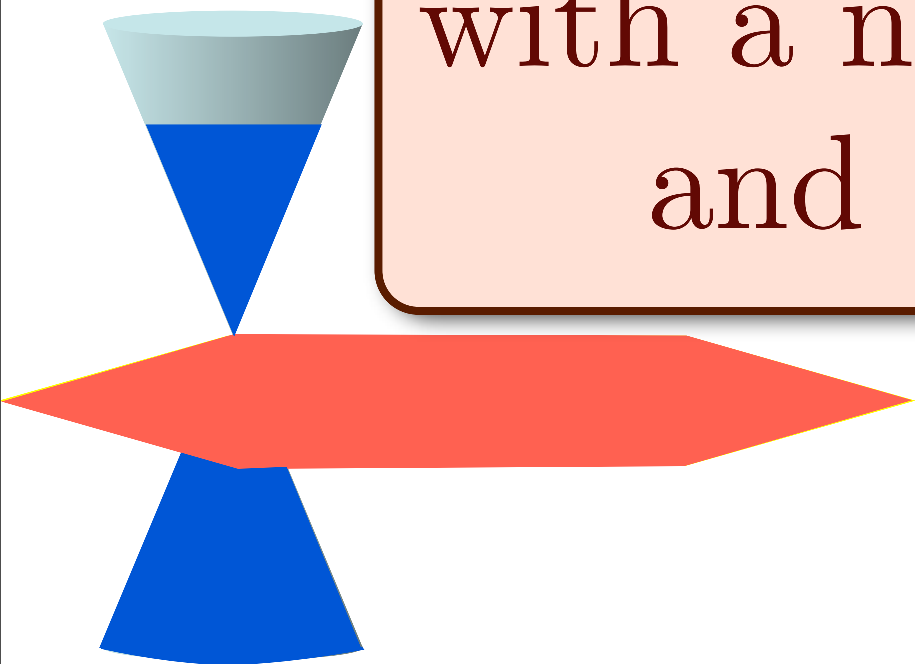
All planar graphs of ψ_+ alone are as important as the leading term

Sung-Sik Lee, *Physical Review* B **80**, 165102 (2009)

Conformal field theory
in 2+1 dimensions at $T = 0$

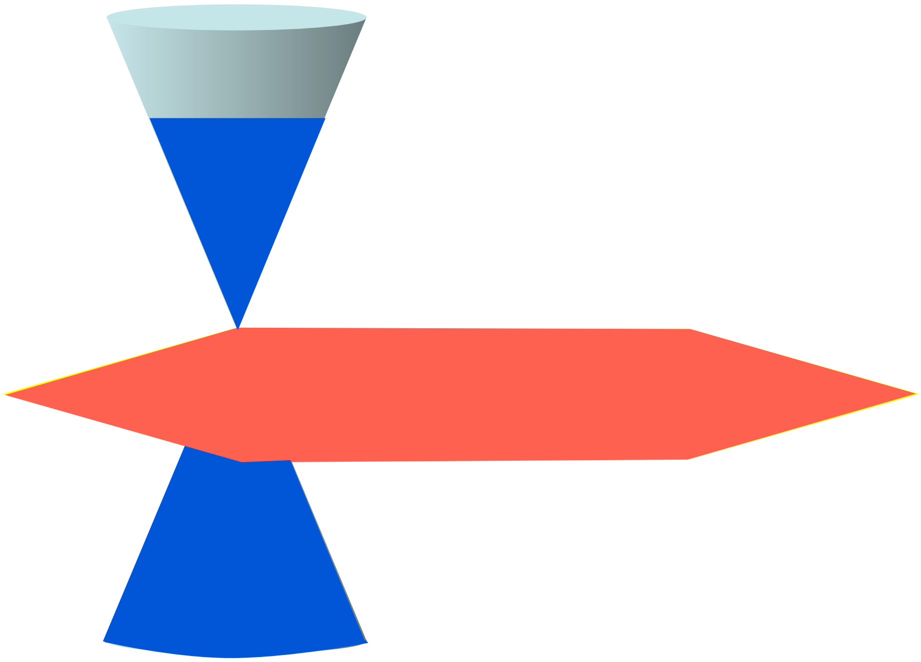


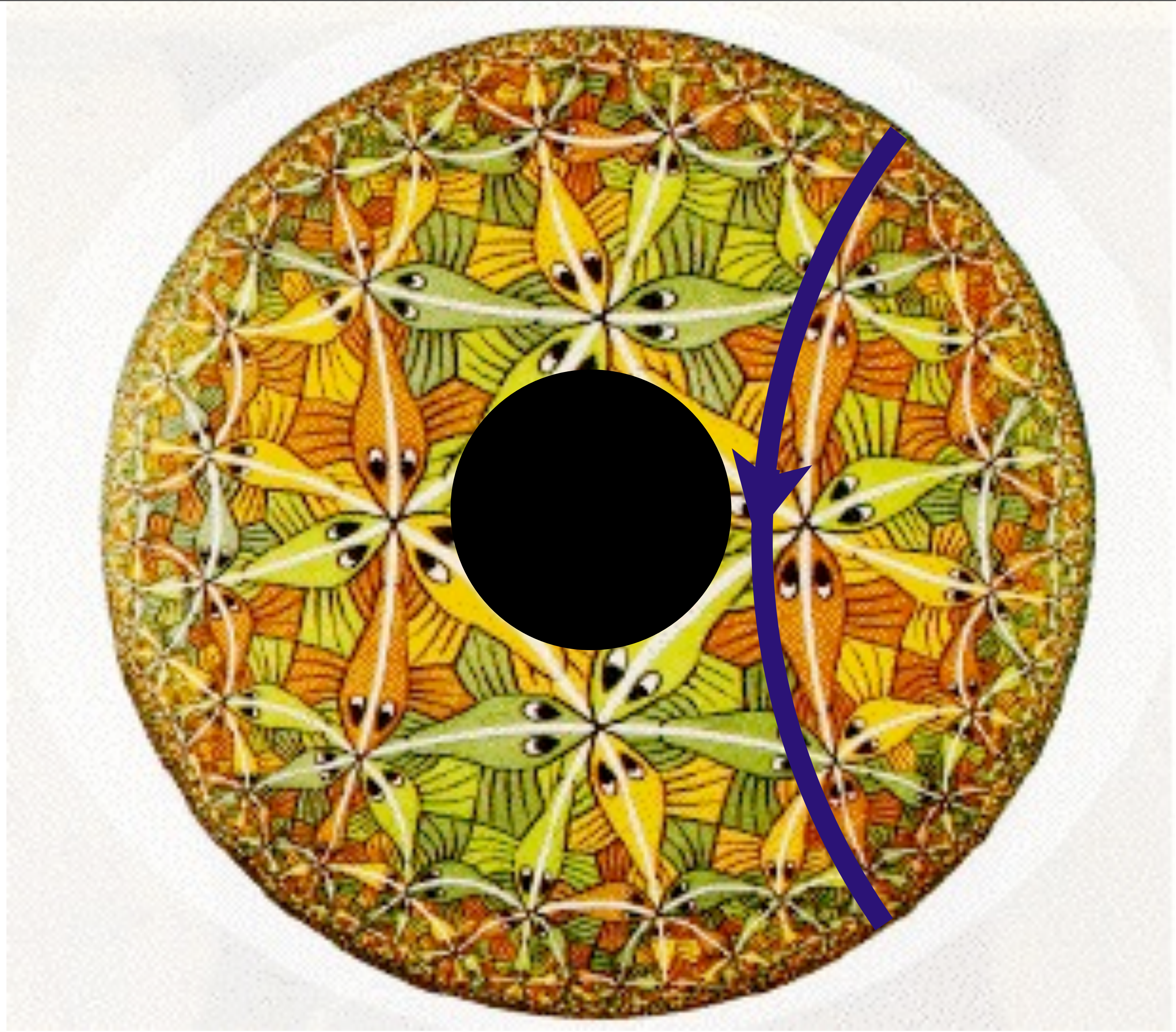
Einstein gravity
on AdS_4



Conformal field theory
in 2+1 dimensions at $T > 0$,
with a non-zero chemical potential, μ
and applied magnetic field, B

Einstein gravity on AdS_4
with a Reissner-Nordstrom
black hole carrying electric
and magnetic charges

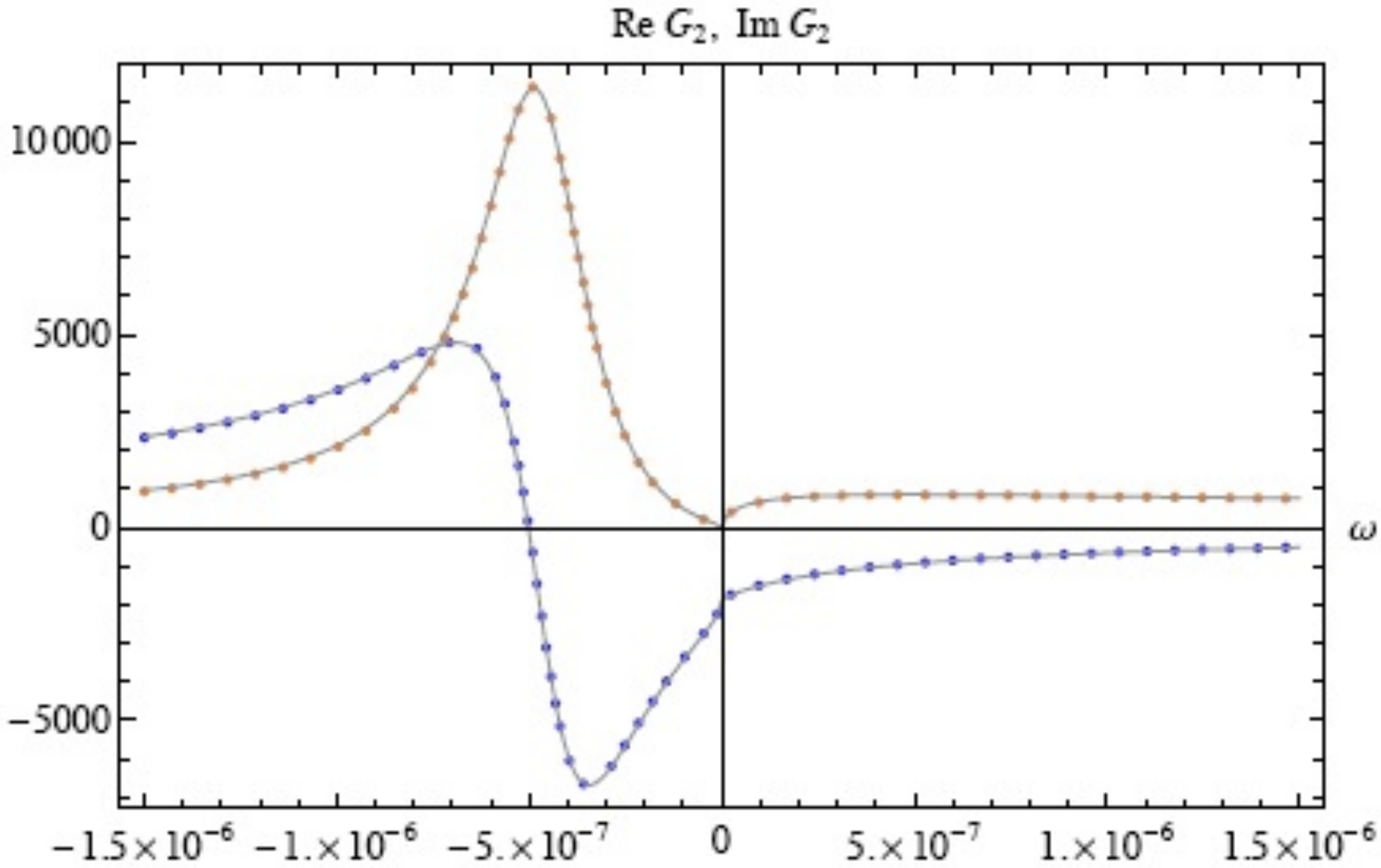




Examine free energy and Green's function of a probe particle

T. Faulkner, H. Liu, J. McGreevy, and D.Vegh, arXiv:0907.2694
F. Denef, S. Hartnoll, and S. Sachdev, arXiv:0908.1788

Green's function of a fermion



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

$$G(k,\omega) \approx \frac{1}{\omega - v_F(k-k_F) - i\omega^{\theta(k)}}$$

See also M. Cubrovic, J. Zaanen, and K. Schalm, arXiv:0904.1993

F. Denef, S. Hartnoll, and S. Sachdev, arXiv:0908.1788

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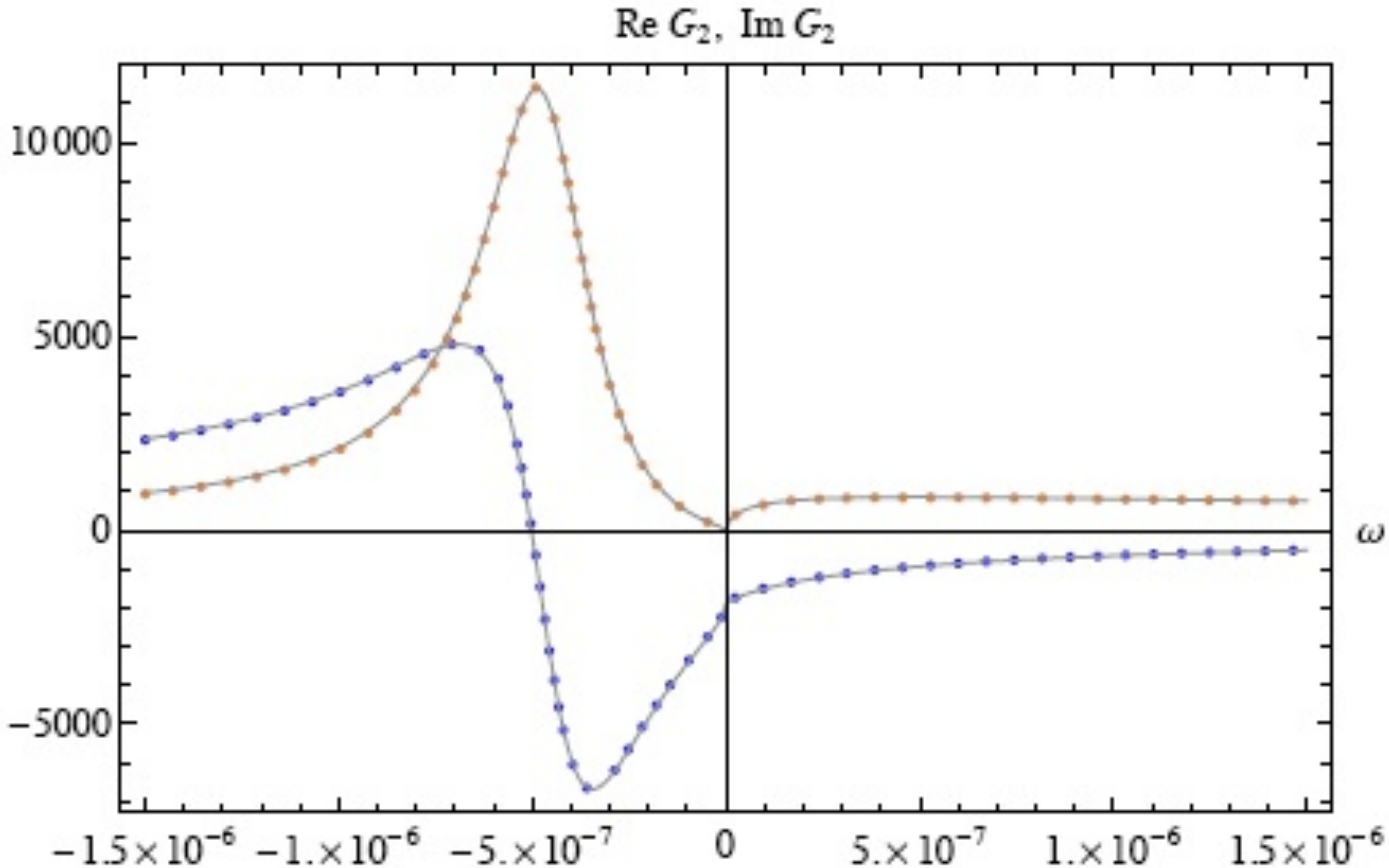

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$$G(k,\omega) \approx \frac{1}{\omega - v_F(k-k_F) - i\omega^{\theta(k)}}$$

Similar to non-Fermi liquid theories of Fermi surfaces coupled to gauge fields, and at quantum critical points