Quantum matter without quasiparticles

University of Chicago
February 18, 2016

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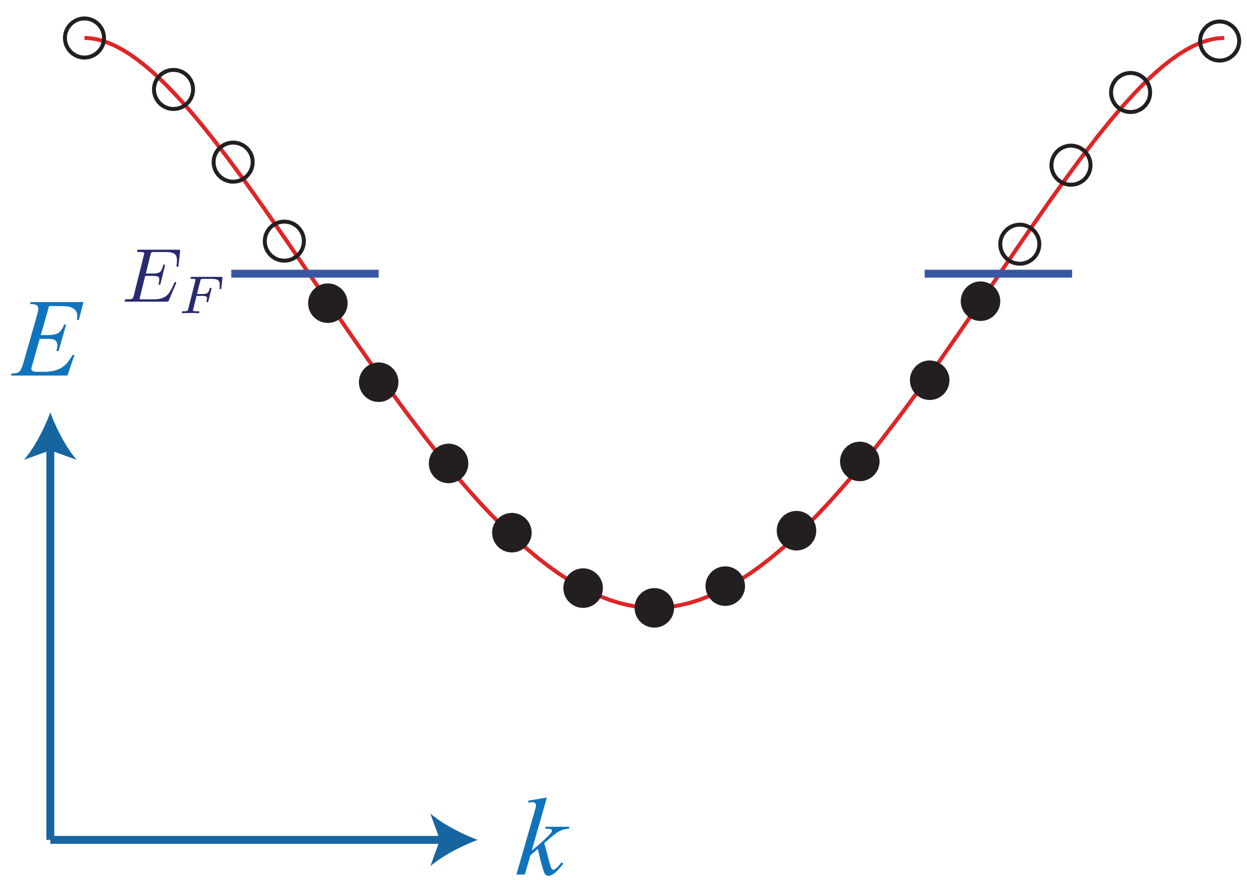
Foundations of quantum many body theory:

1. Ground states connected adiabatically to independent electron states

Metals

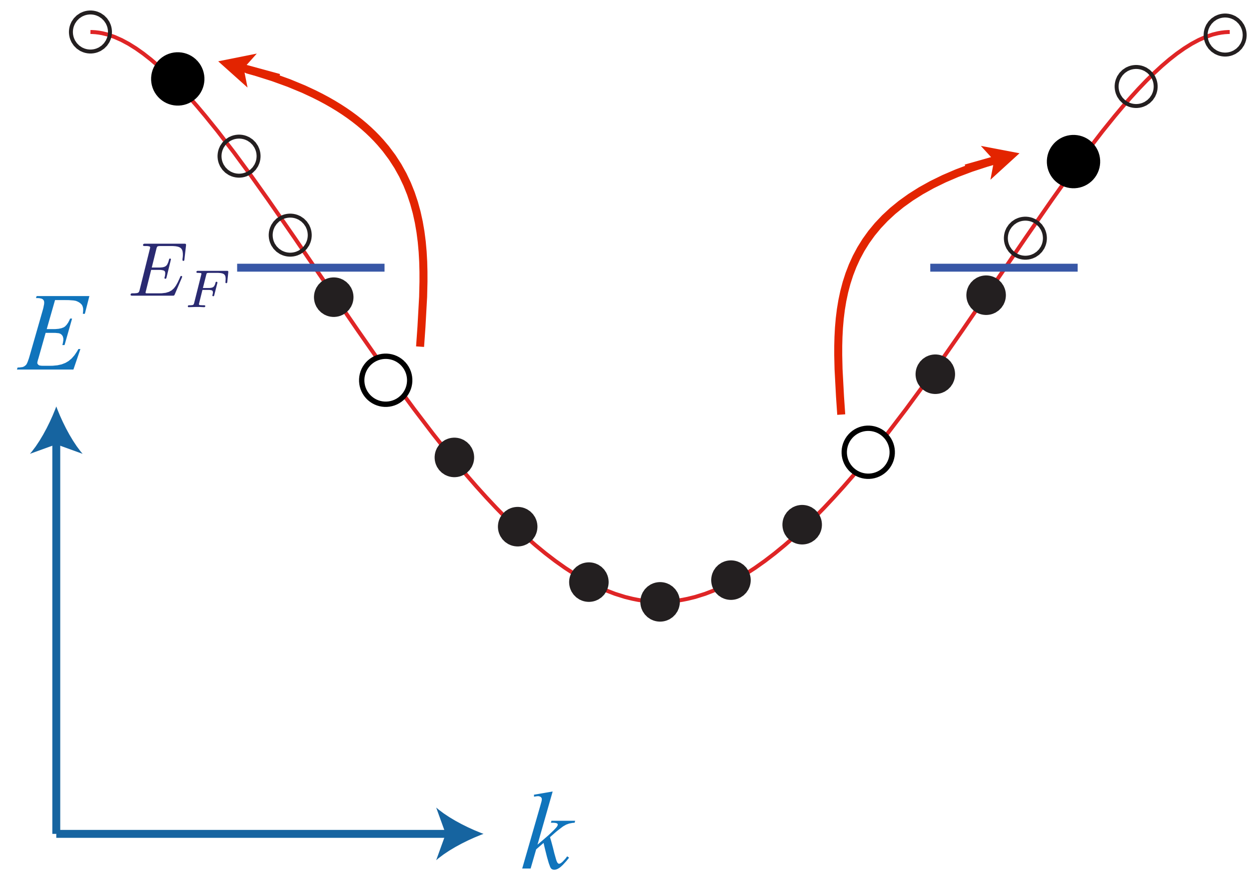


Foundations of quantum many body theory:

1. Ground states connected adiabatically to independent electron states

2. Boltzmann-Landau theory of quasiparticles

Metals



Modern phases of quantum matter:

1. *Ground states disconnected from independent electron states: many-particle entanglement*

2. *Boltzmann-Landau theory of quasiparticles*

Famous example:

The fractional quantum Hall effect of electrons in two dimensions (e.g. in graphene) in the presence of a strong magnetic field. The ground state is described by Laughlin's wavefunction, and the excitations are *quasiparticles* which carry fractional charge.

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Field theory: topological quantum field theory

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Quantum matter without quasiparticles:

1. Ground states disconnected from independent electron states: many-particle entanglement

2. No quasiparticles

- Superfluid-insulator transition of ultracold bosonic atoms in an optical lattice
- Graphene
- Strange metals in high temperature superconductors
- Quark-gluon plasma
- *Charged black hole horizons in anti-de Sitter space*

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Field theory example: conformal field theory

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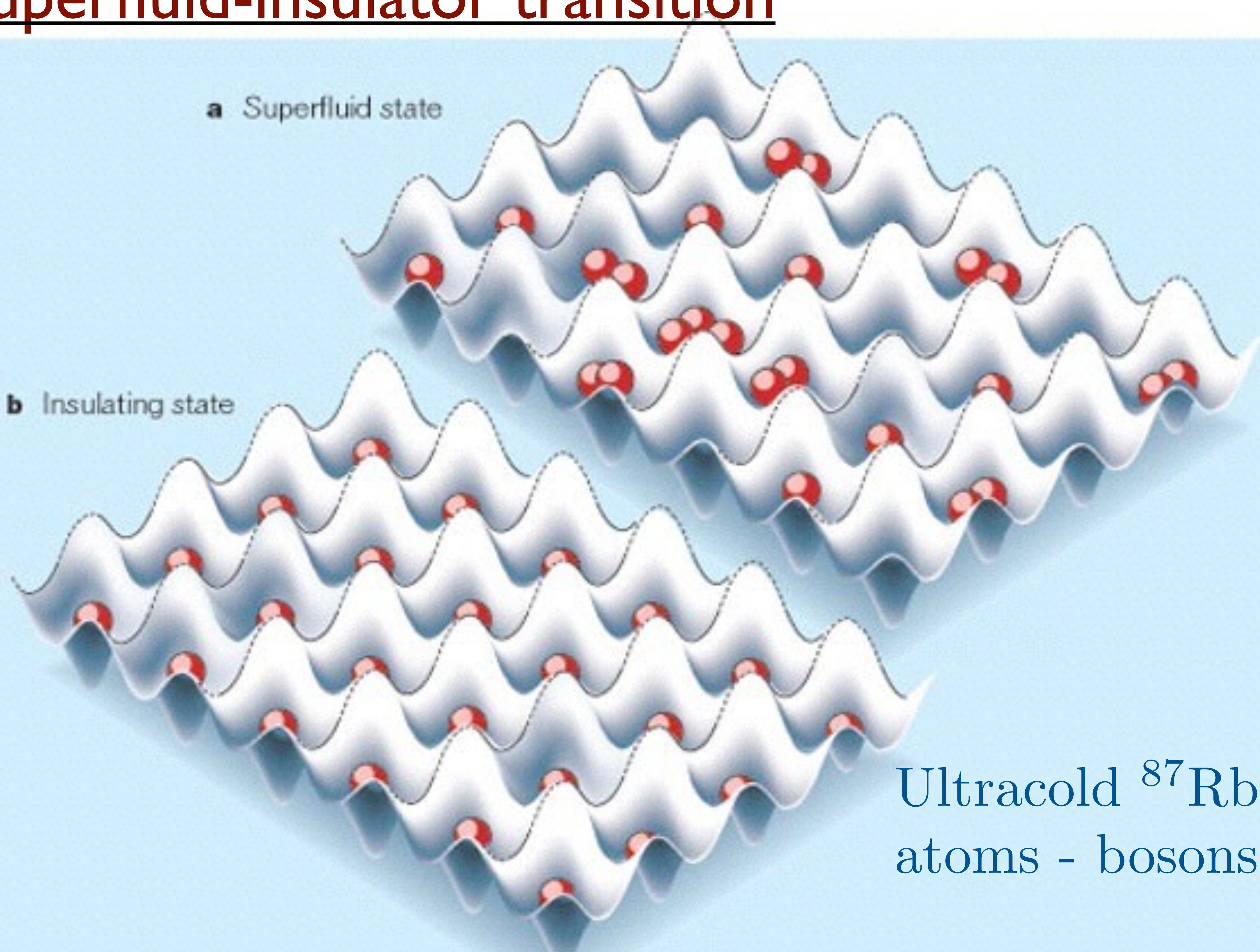
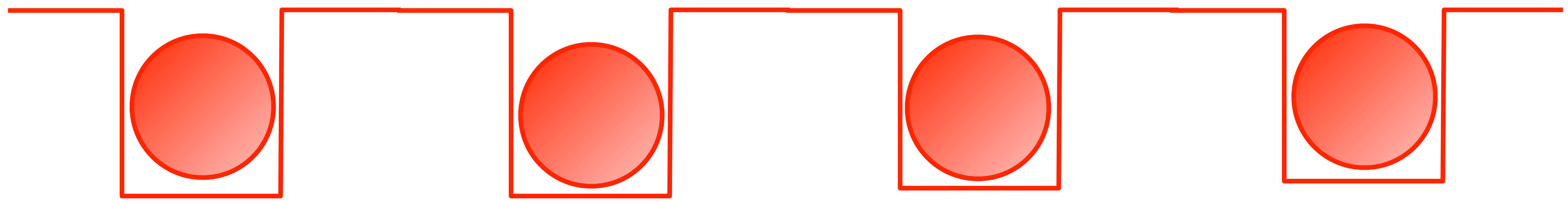
Superfluid-insulator transition



Ultracold ^{87}Rb
atoms - bosons

M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).
Xibo Zhang, Chen-Lung Hung, Shih-Kuang Tung, and Cheng Chin, *Science* **335**, 1070 (2012)

$U \gg t$



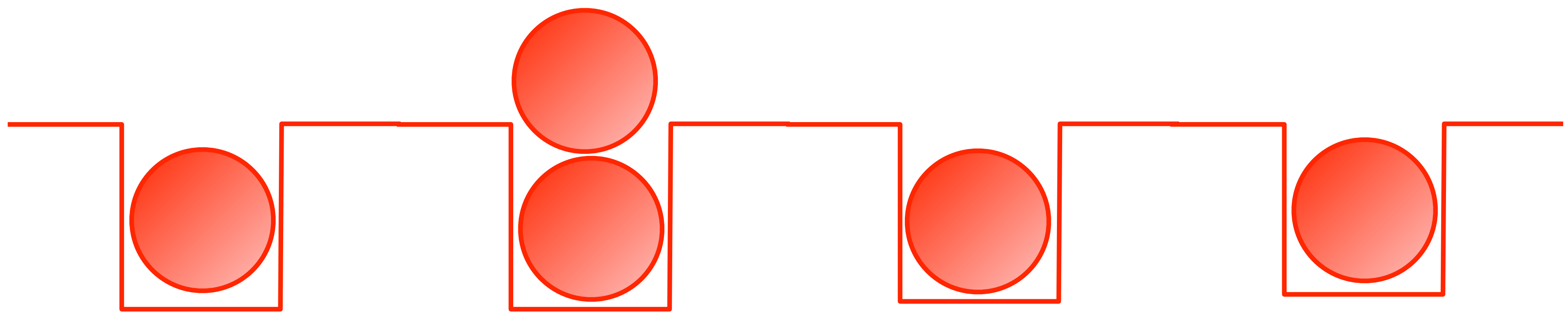
Insulator (the vacuum)
at large repulsion between bosons

$$|\text{Ground state}\rangle = \prod_i b_i^\dagger \, |0\rangle$$

On-site repulsion between bosons $= U$
Tunneling amplitude between sites $= t$

$U \gg t$

Excitations of the insulator:

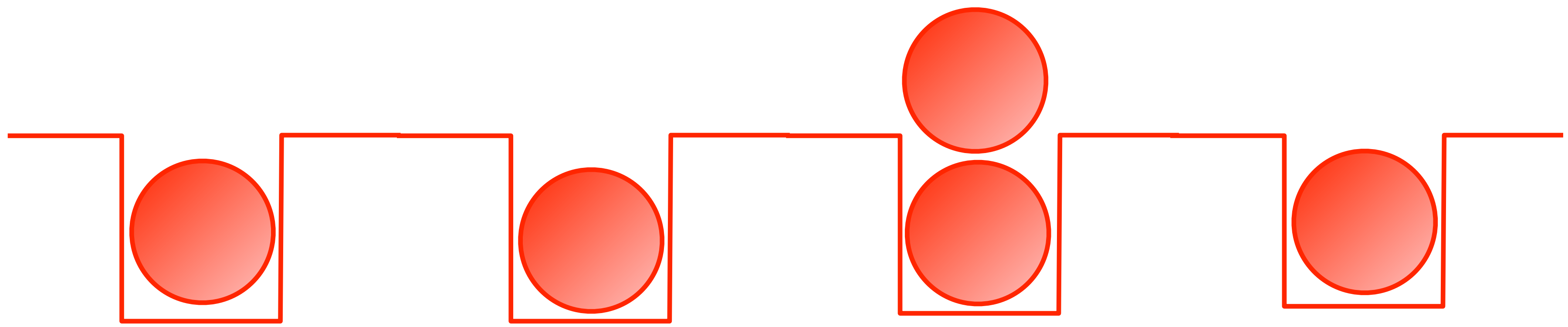


Particles $\sim \psi^\dagger$

On-site repulsion between bosons $= U$
Tunneling amplitude between sites $= t$

$U \gg t$

Excitations of the insulator:



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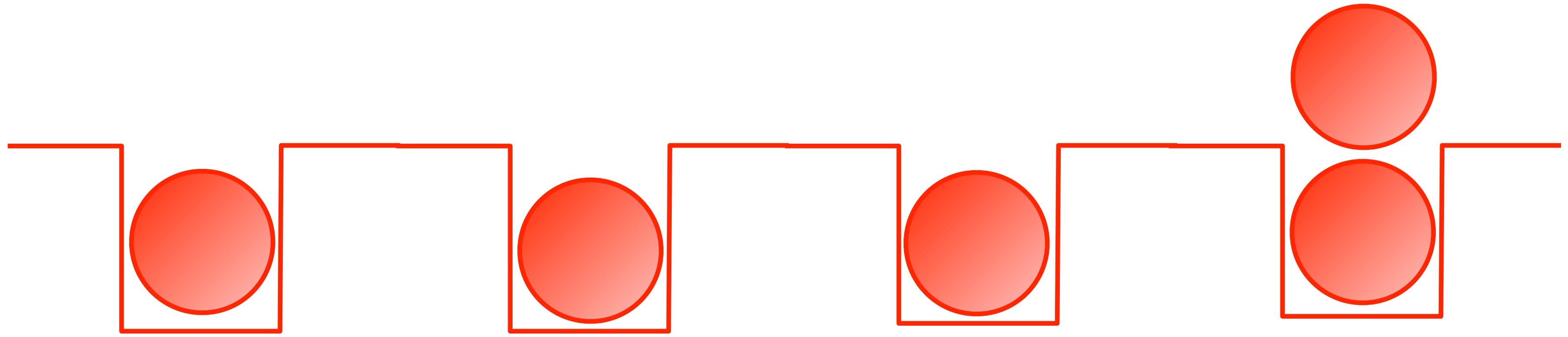

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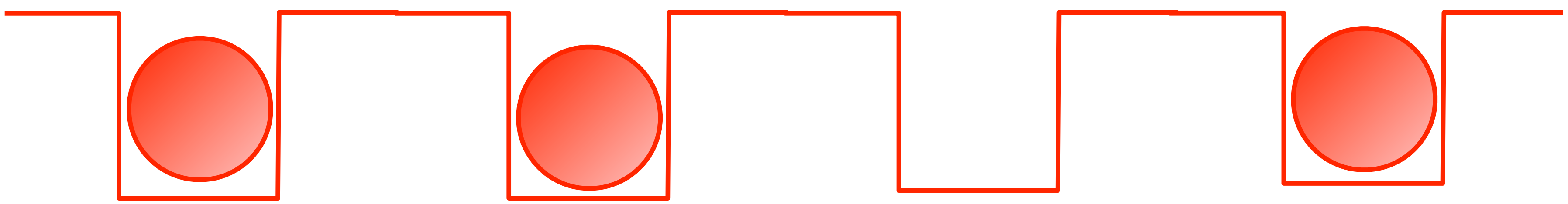


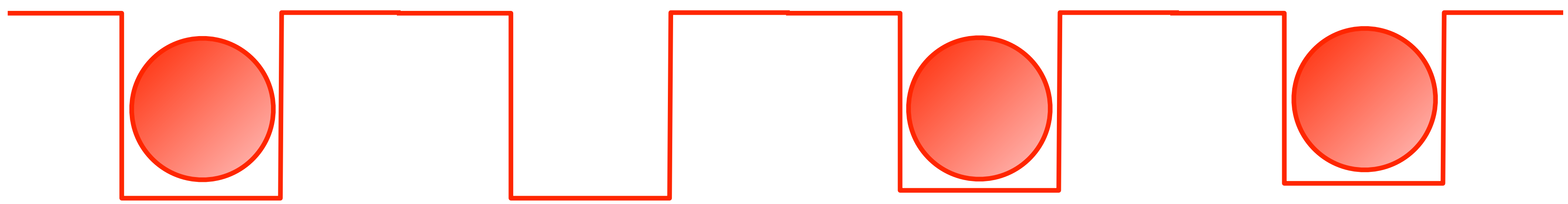
Holes $\sim \psi$

On-site repulsion between bosons $= U$

Tunneling amplitude between sites $= t$

$$U \gg t$$

Excitations of the insulator:



Holes $\sim \psi$

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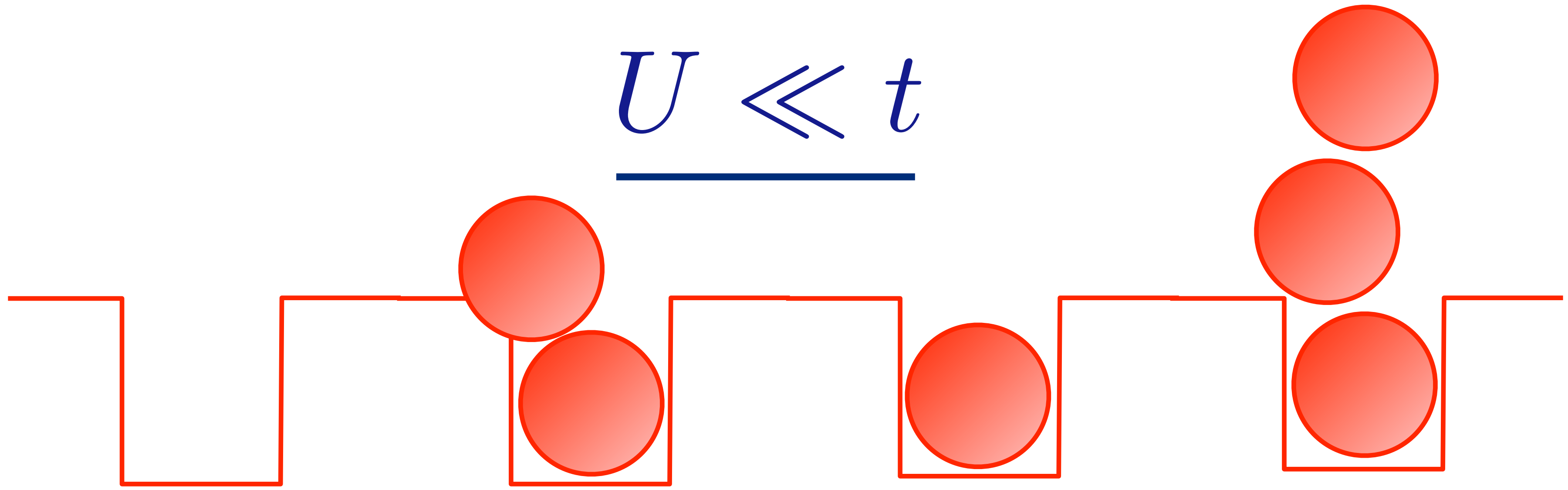
Excitations of the insulator:

Holes $\sim \psi$

On-site repulsion between bosons $= U$
Tunneling amplitude between sites $= t$

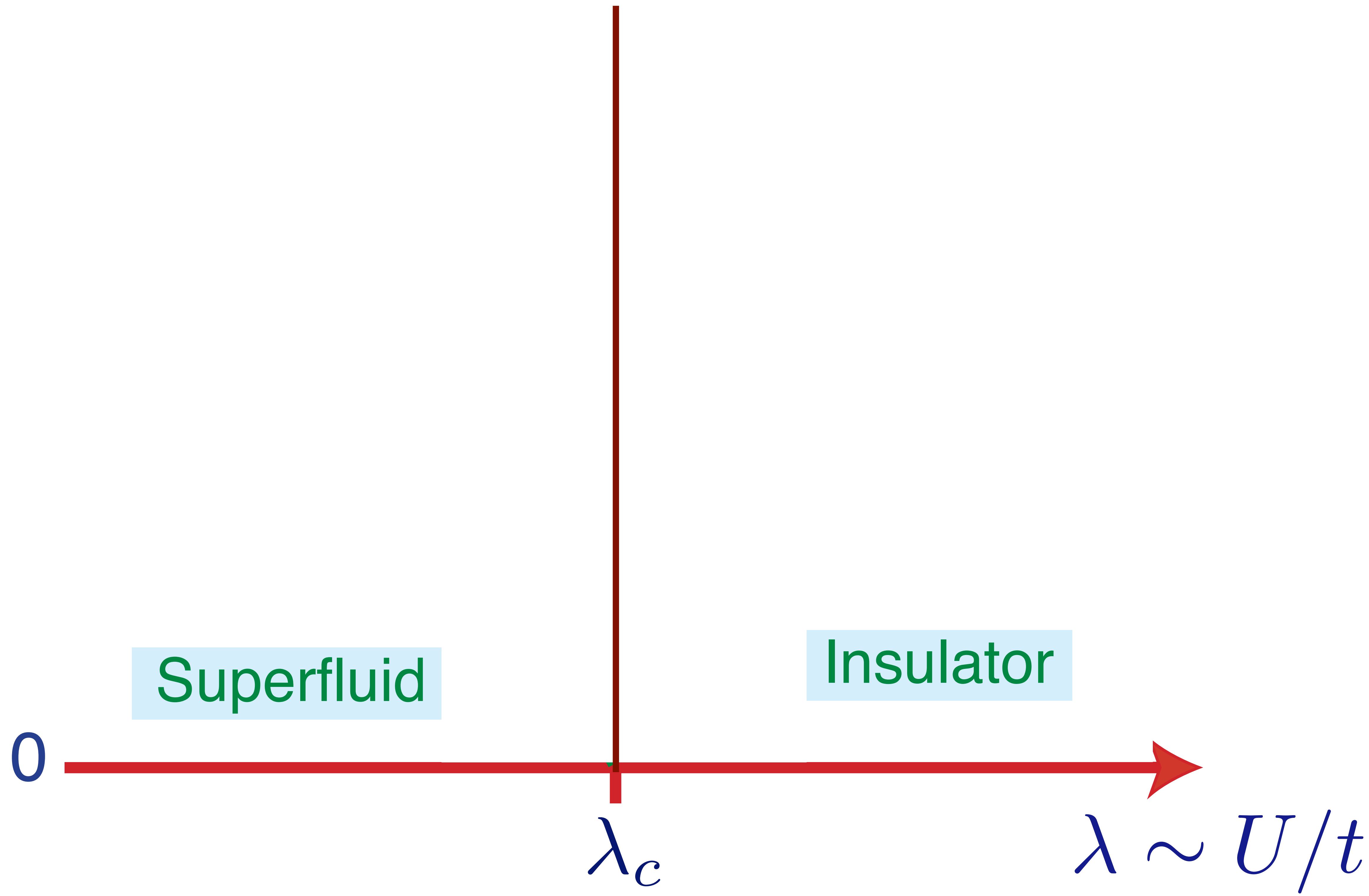
$U \ll t$



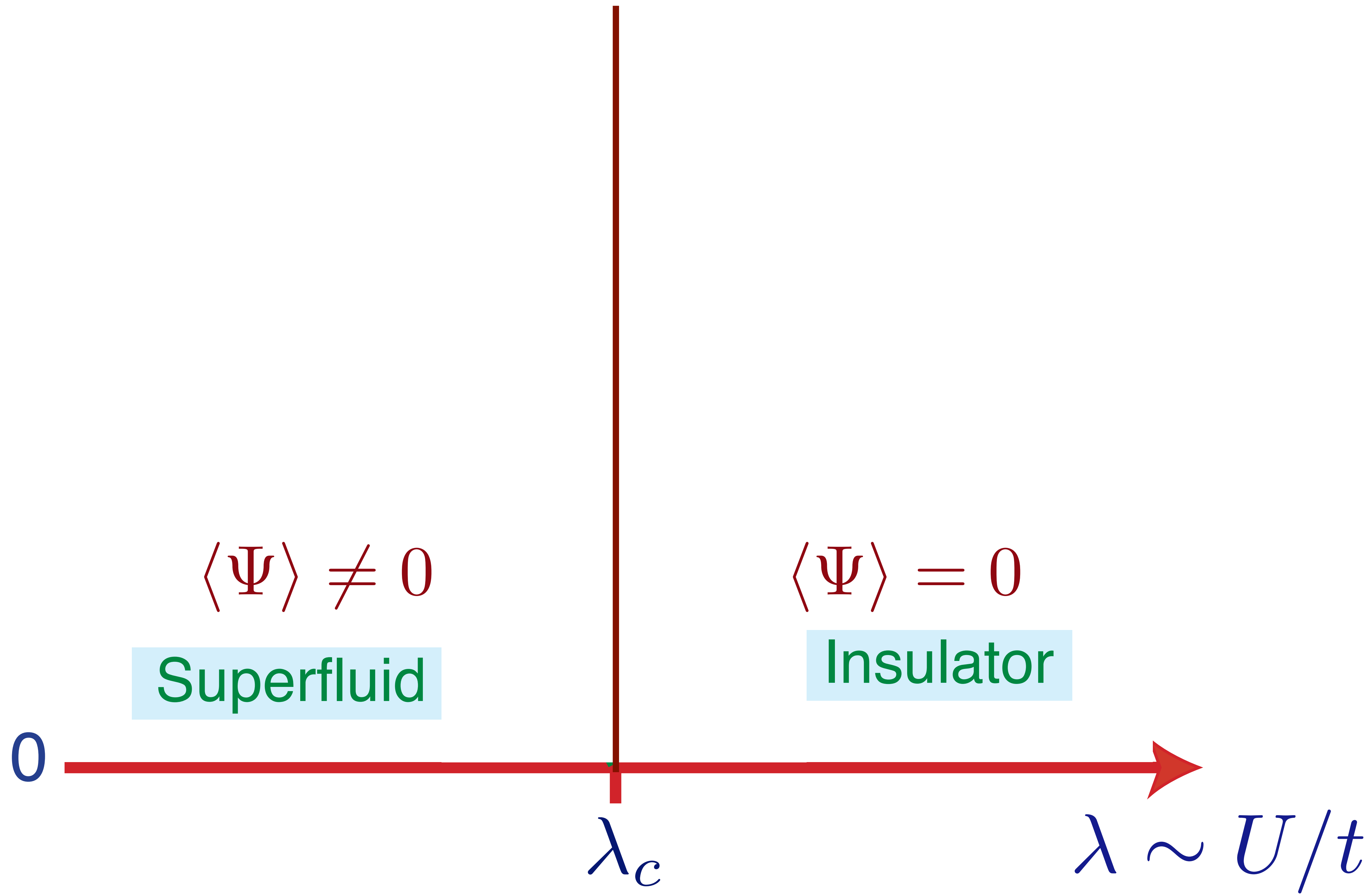
Superfluid
at small repulsion between bosons

$$|\text{Ground state}\rangle = \left[\sum_i b_i^\dagger\right]^N |0\rangle$$

On-site repulsion between bosons $= U$
Tunneling amplitude between sites $= t$

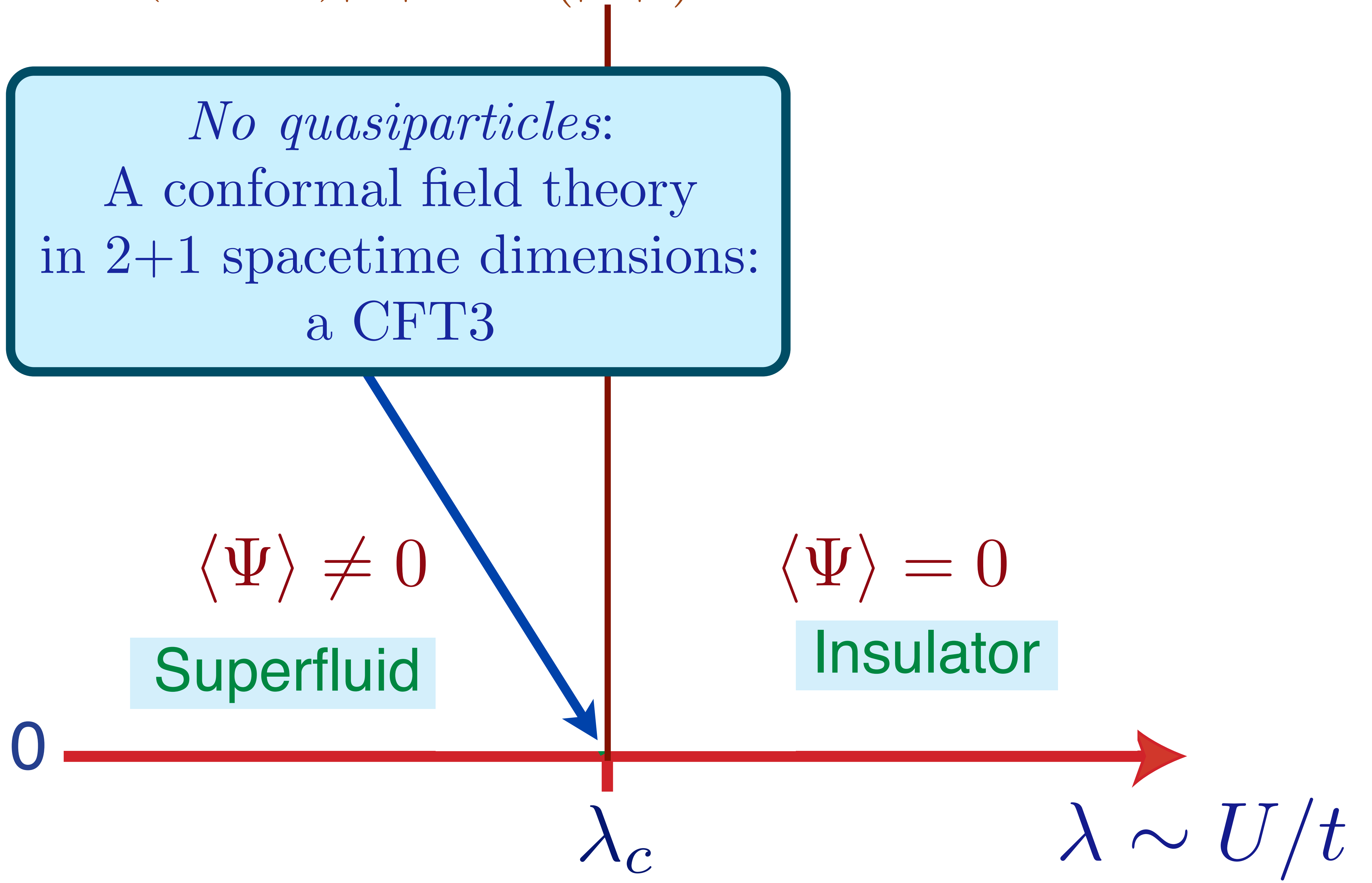

Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$

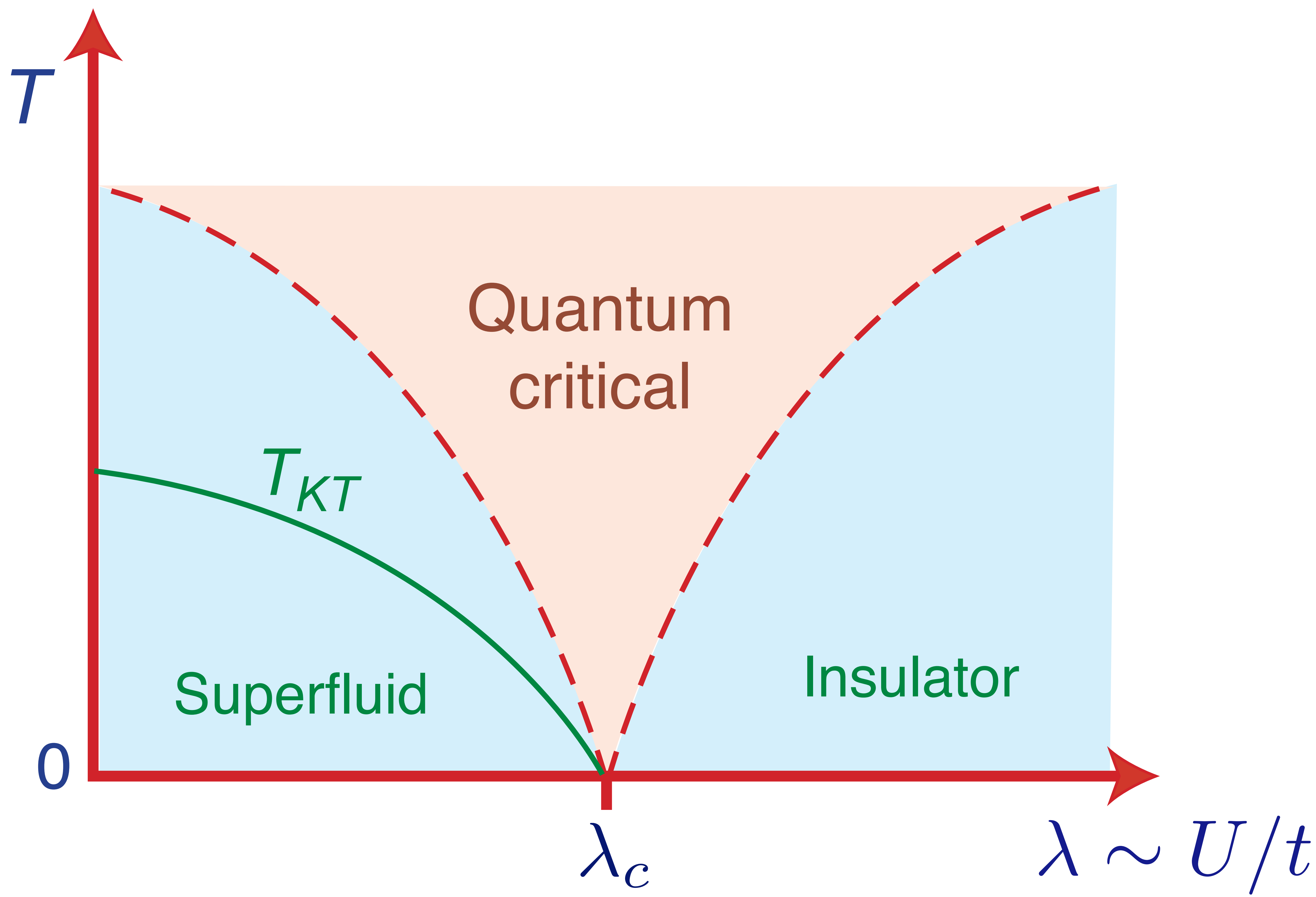
$\Psi \rightarrow$ a complex field representing the Bose-Einstein condensate of the superfluid



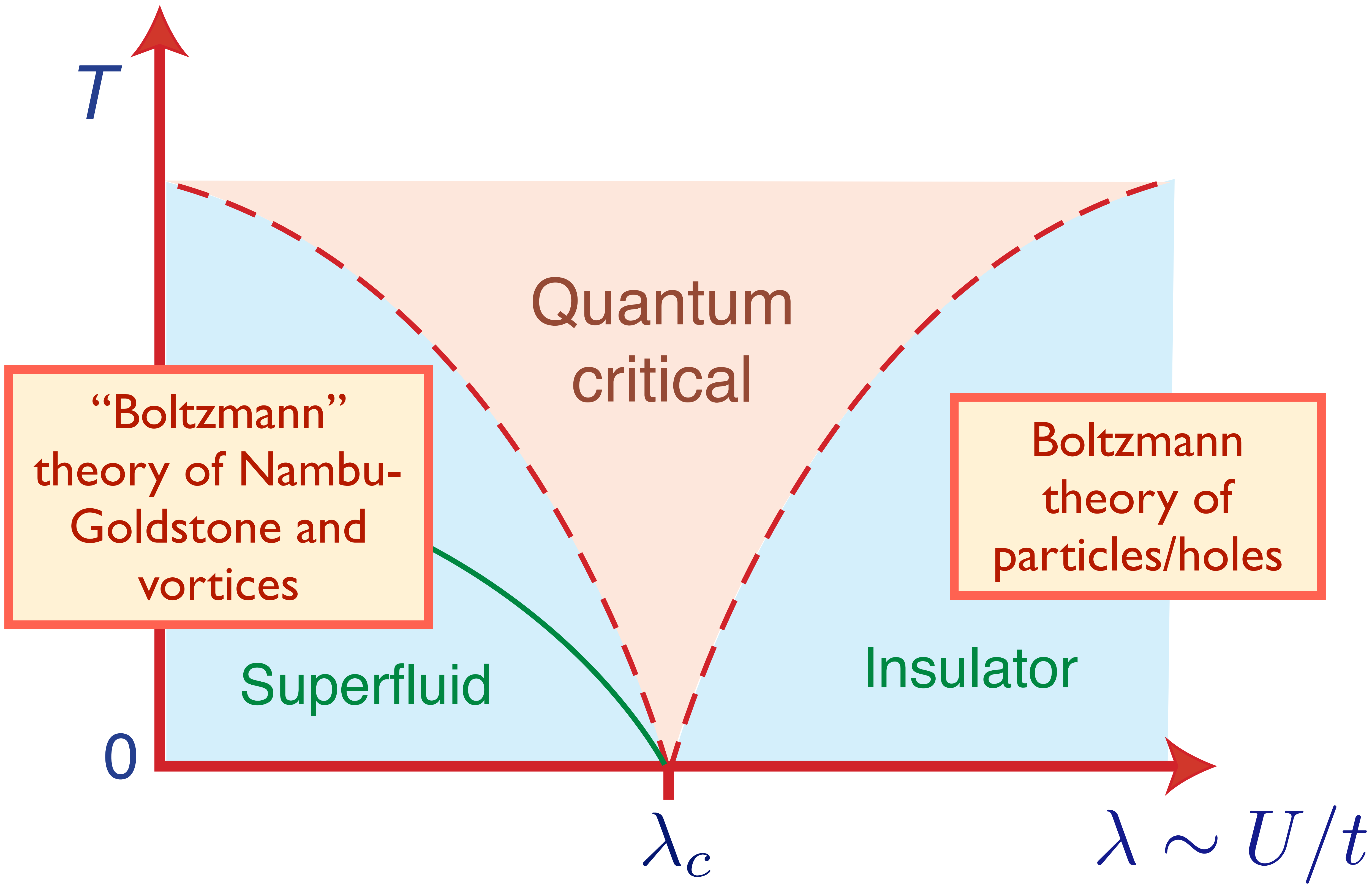
$$\mathcal{S} = \int d^2r dt \left[|\partial_t \Psi|^2 - c^2 |\nabla_r \Psi|^2 - V(\Psi) \right]$$

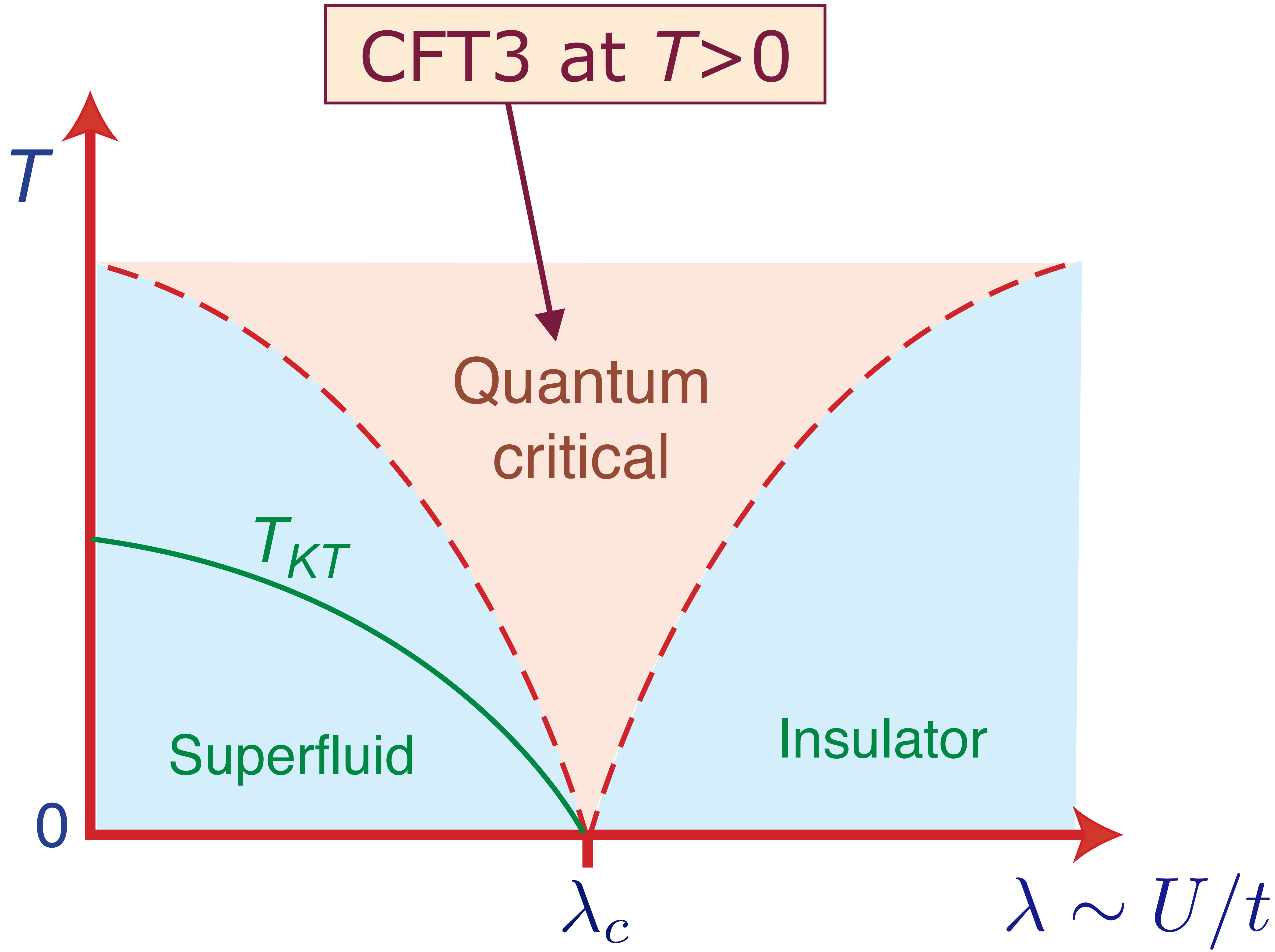
$$V(\Psi) = (\lambda - \lambda_c)|\Psi|^2 + u \left(|\Psi|^2 \right)^2$$



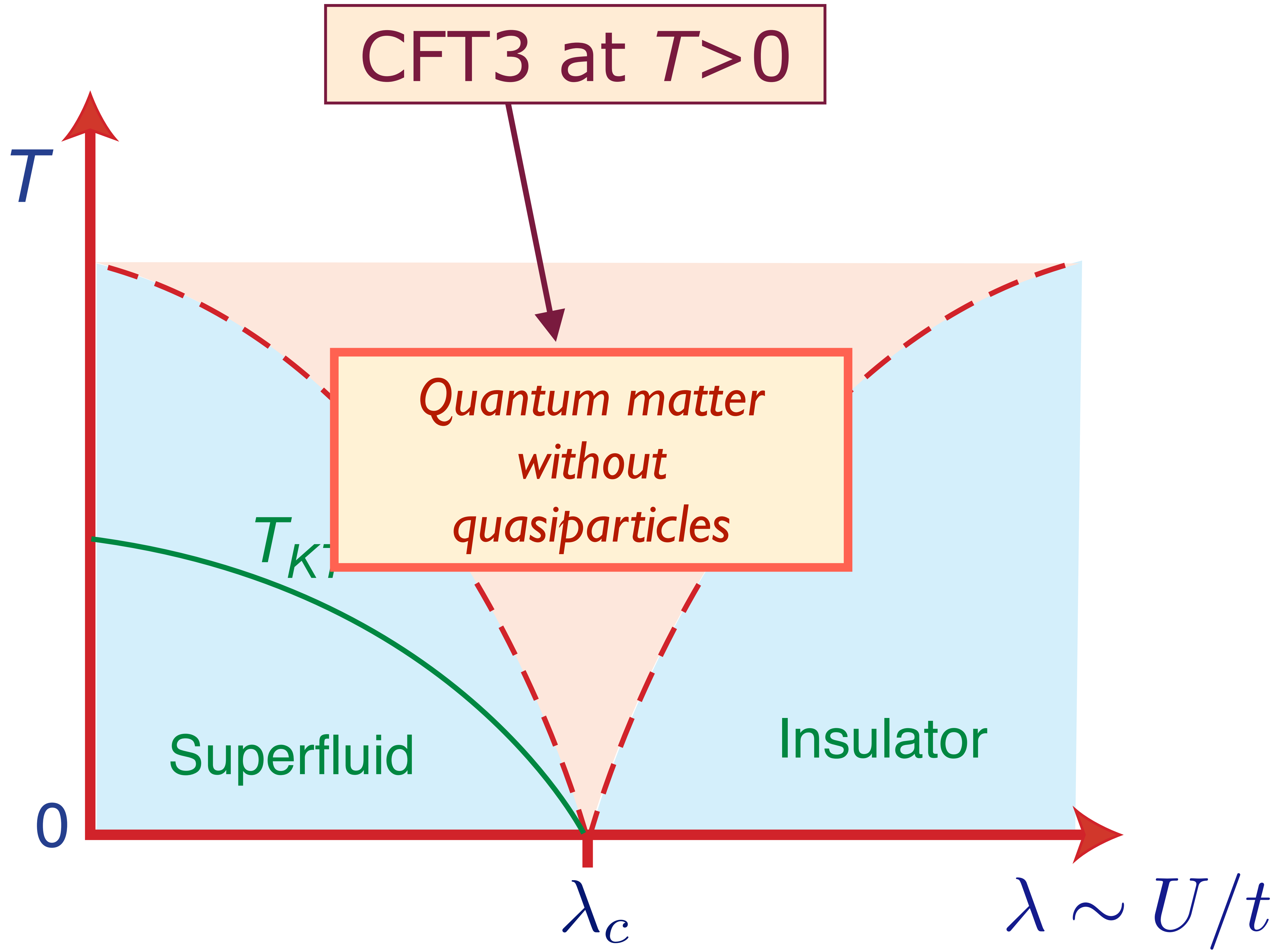


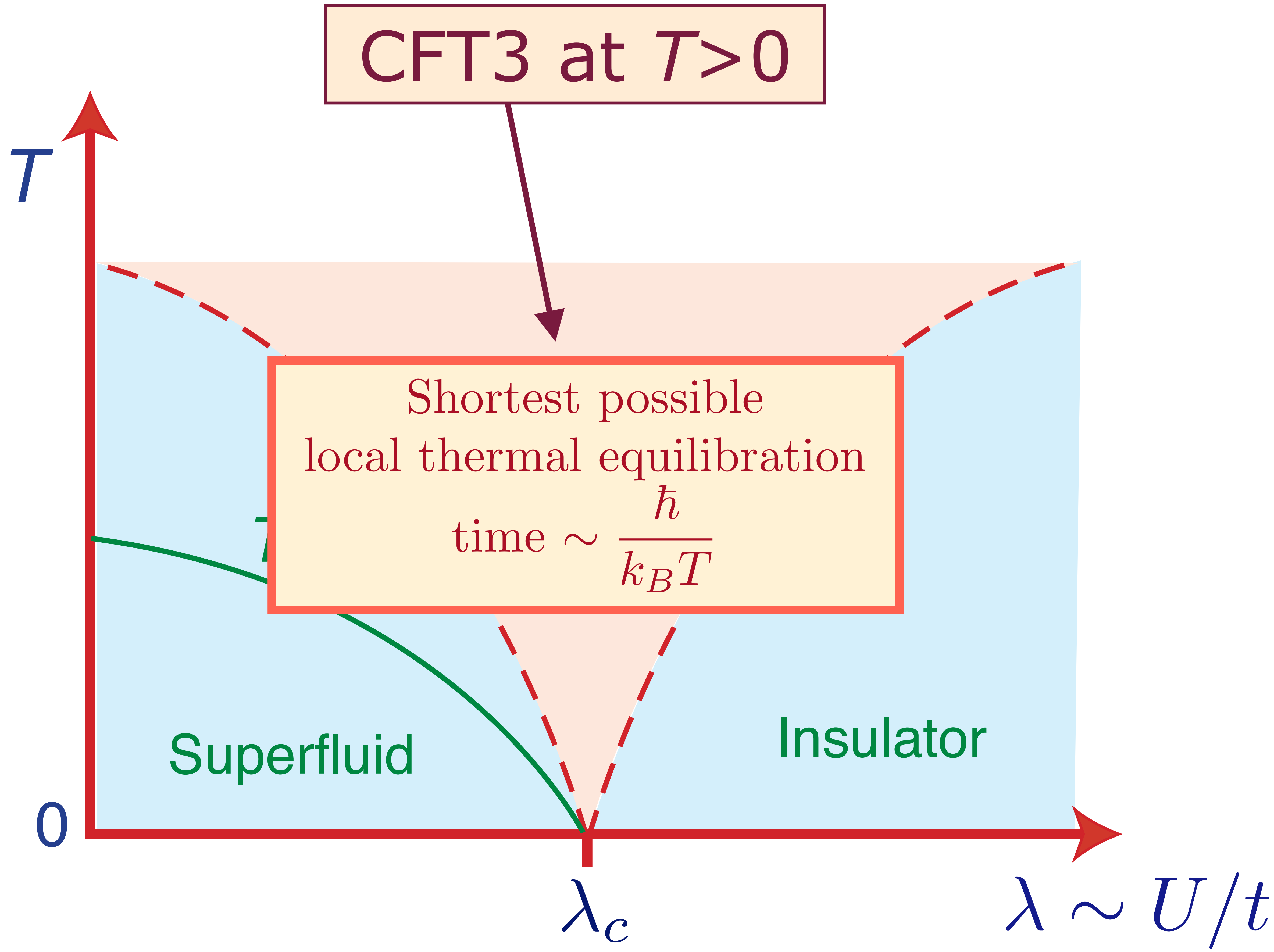
T
Quantum critical
T_{KT}
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$


T
Quantum critical
"Boltzmann" theory of Nambu-Goldstone and vortices
Boltzmann theory of particles/holes
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$

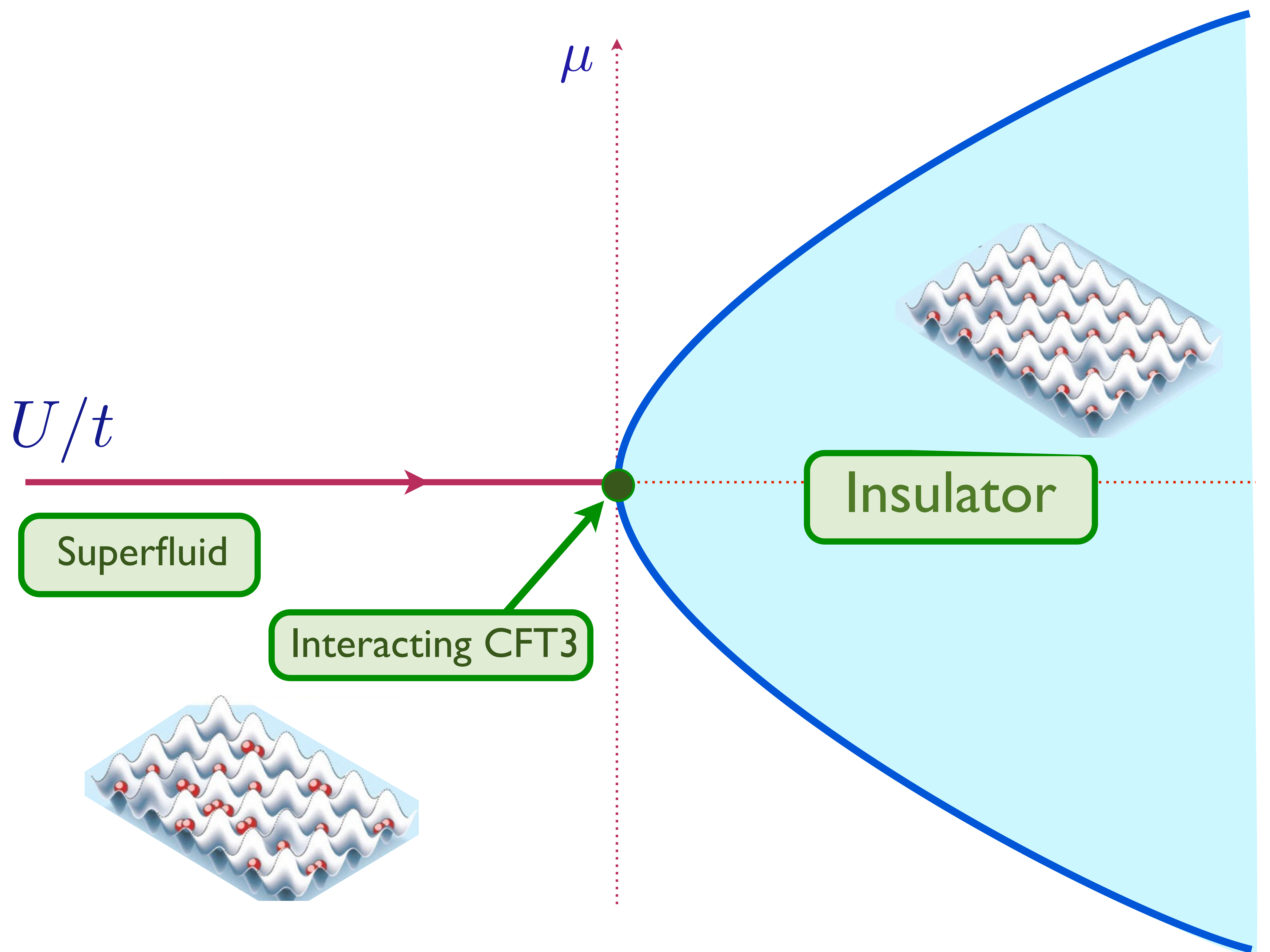


CFT3 at $T>0$
T
Quantum critical
T_{KT}
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$

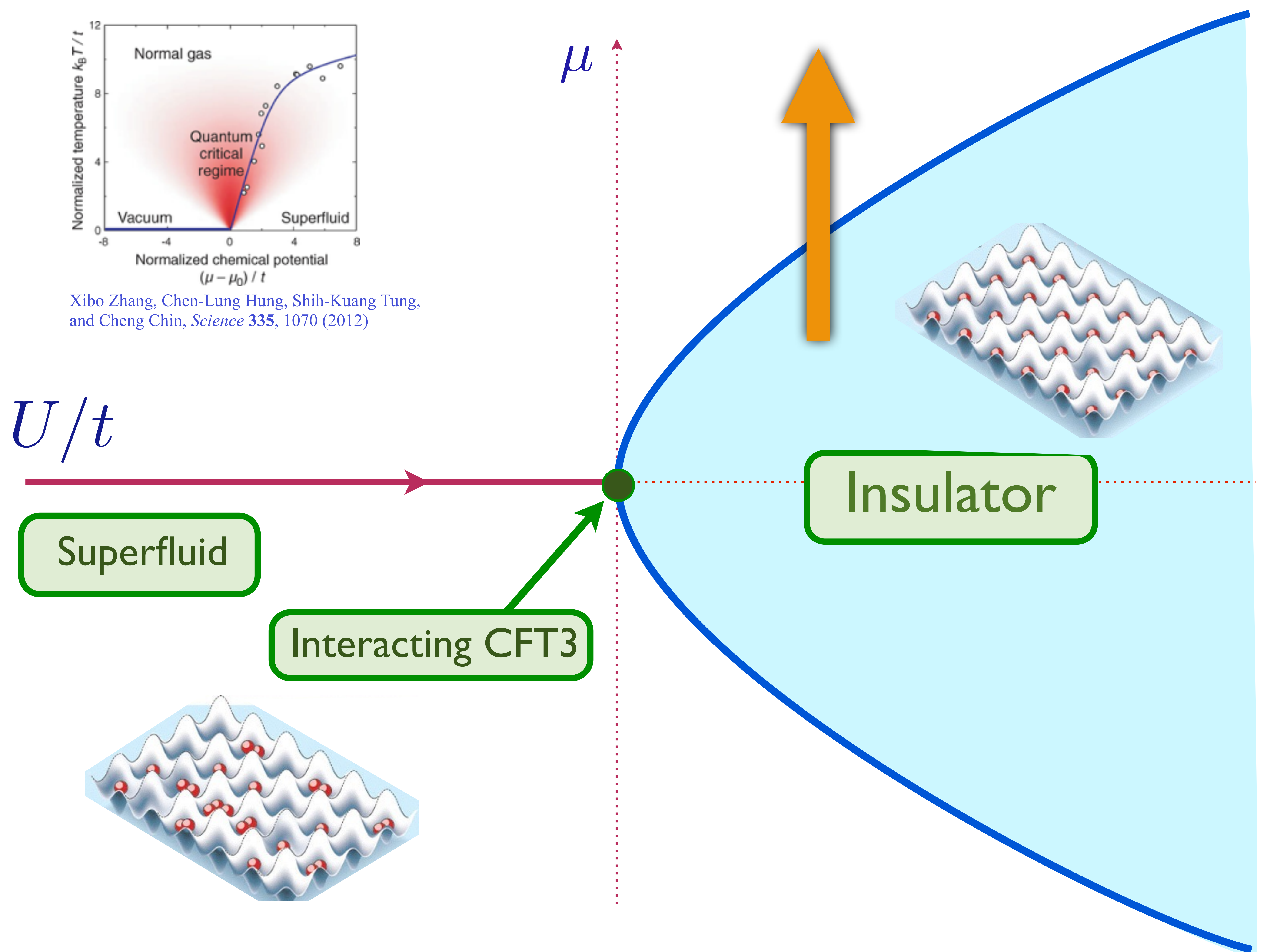

CFT3 at T>0
T
Quantum matter
without
quasiparticles
T_{KT}
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$



K. Damle and S. Sachdev, PRB **56**, 8714 (1997); S. Sachdev, *Quantum Phase Transitions*, Cambridge (1999)



μ
U/t
Superfluid
Interacting CFT3
Insulator



Normal gas
Quantum critical regime
Vacuum
Superfluid
Normalized temperature $k_B T / t$
Normalized chemical potential
$(\mu - \mu_0) / t$
12
8
4
0
-8
-4
0
4
8
Xibo Zhang, Chen-Lung Hung, Shih-Kuang Tung, and Cheng Chin, *Science* **335**, 1070 (2012)
μ
U/t
Superfluid
Interacting CFT3
Insulator

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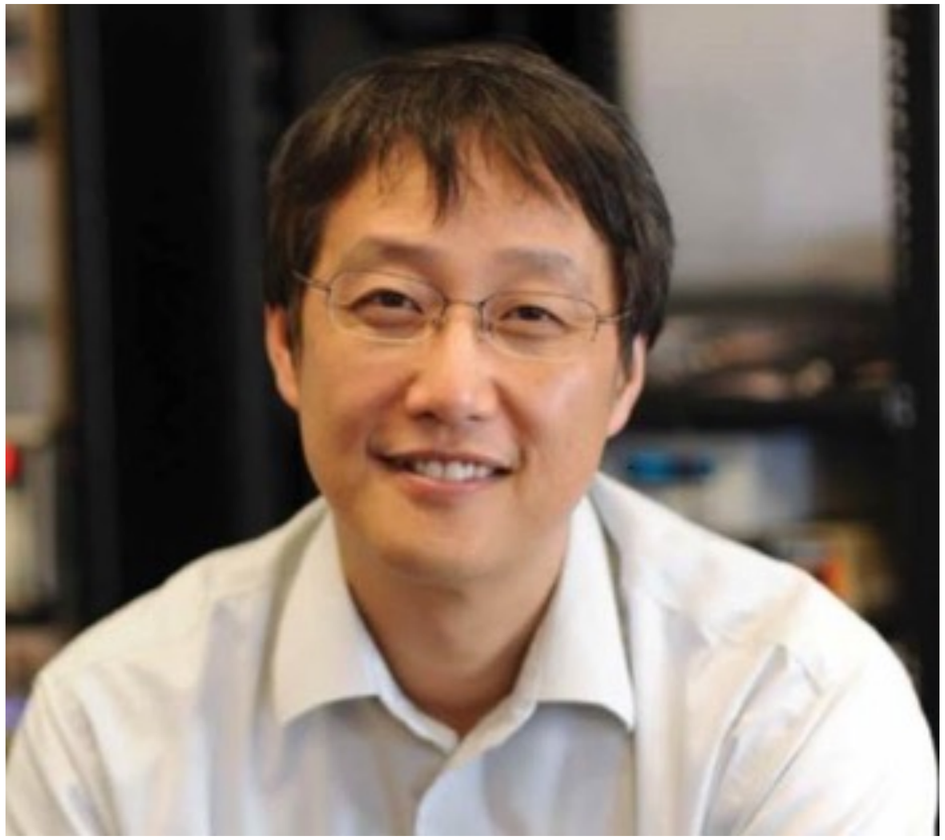
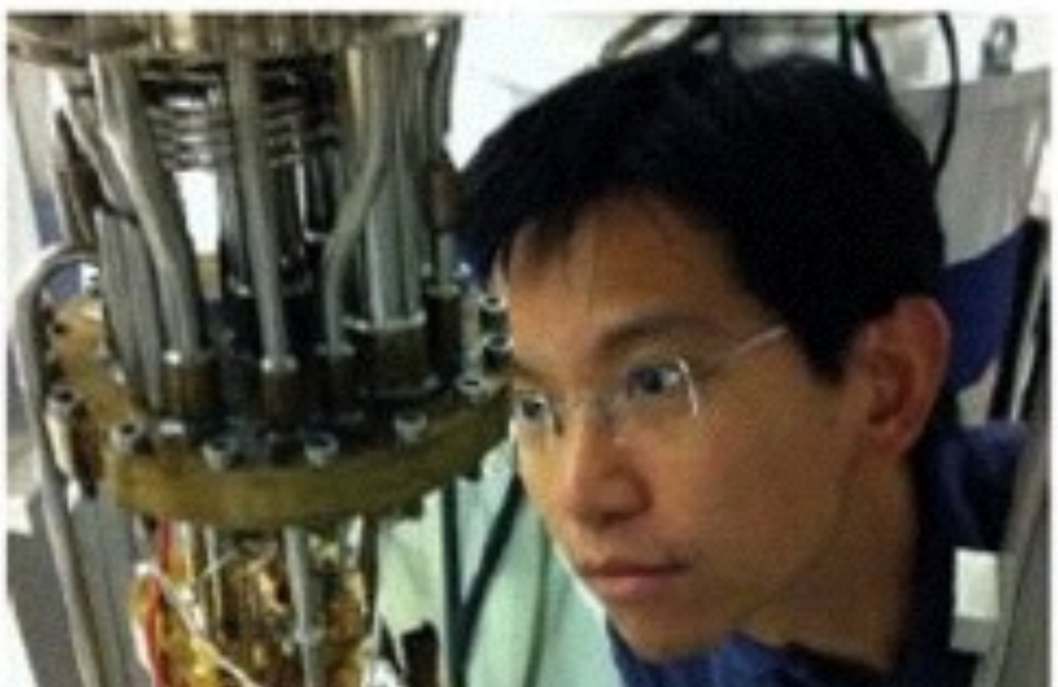
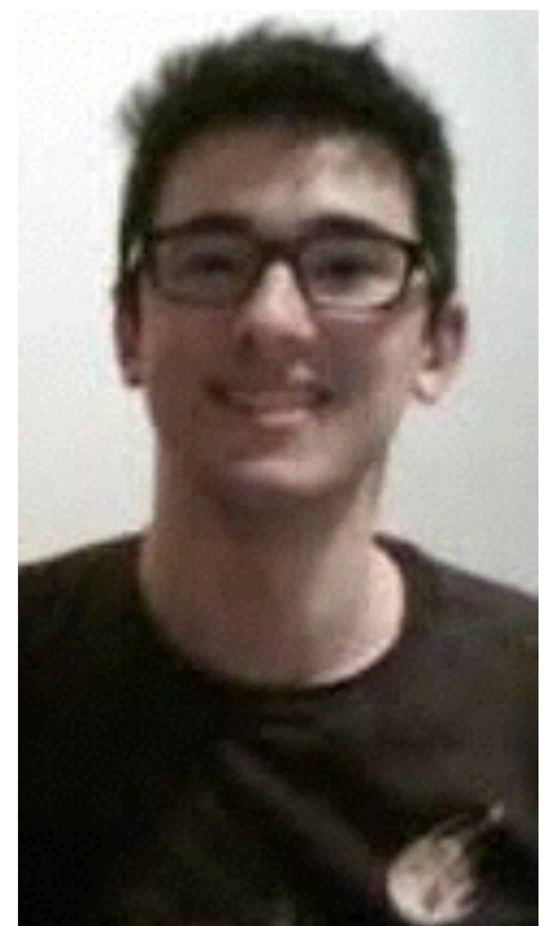


Philip Kim

Jesse Crossno

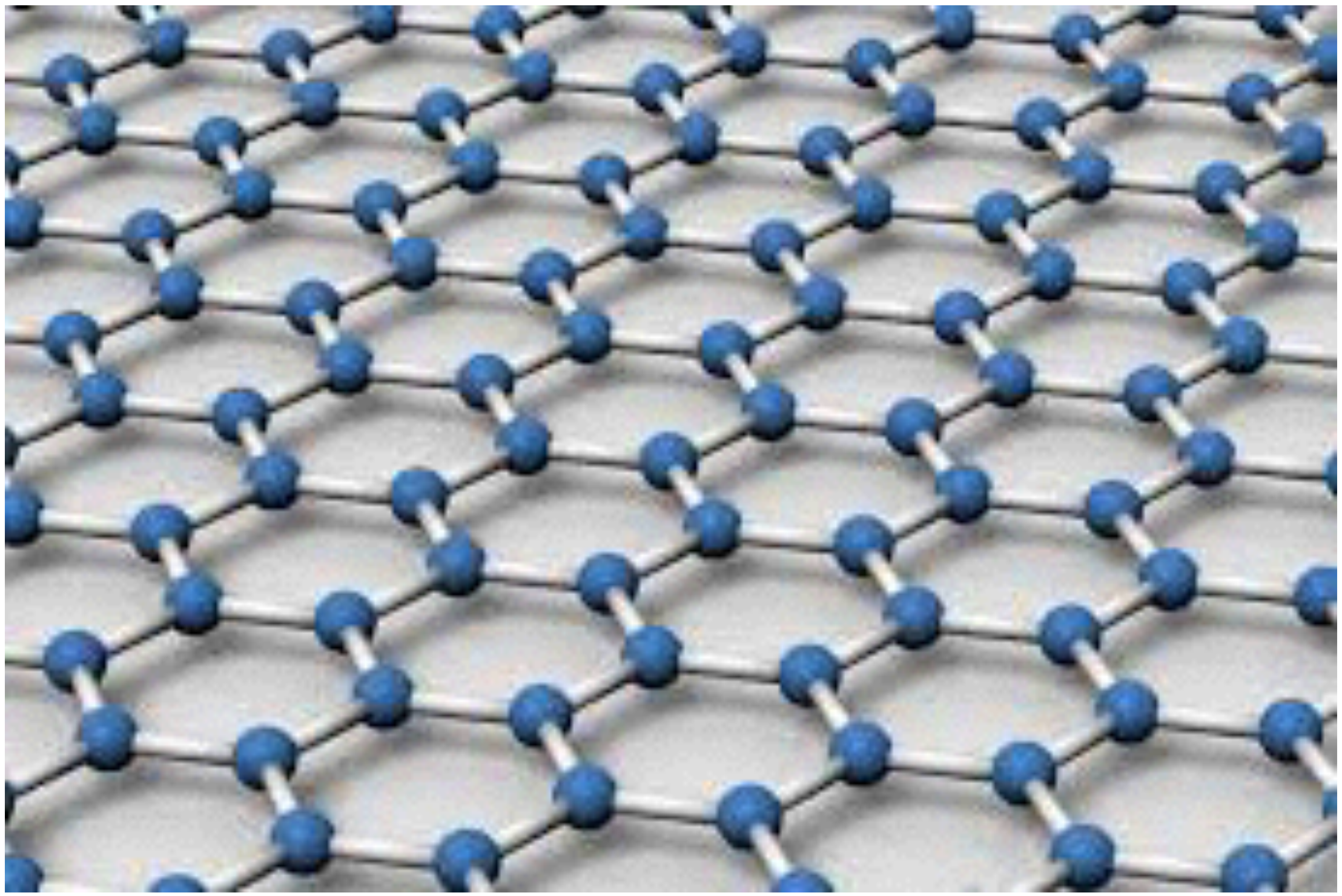


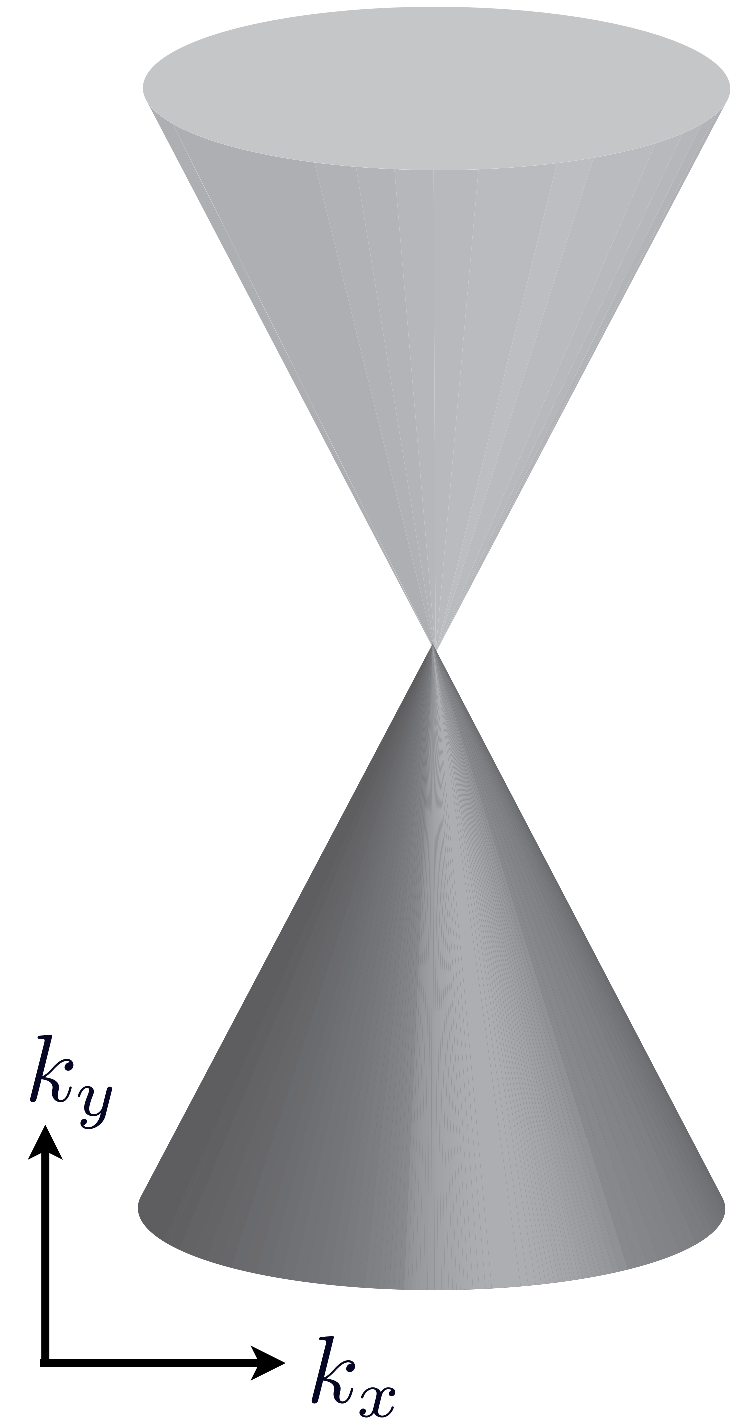
Kin Chung Fong



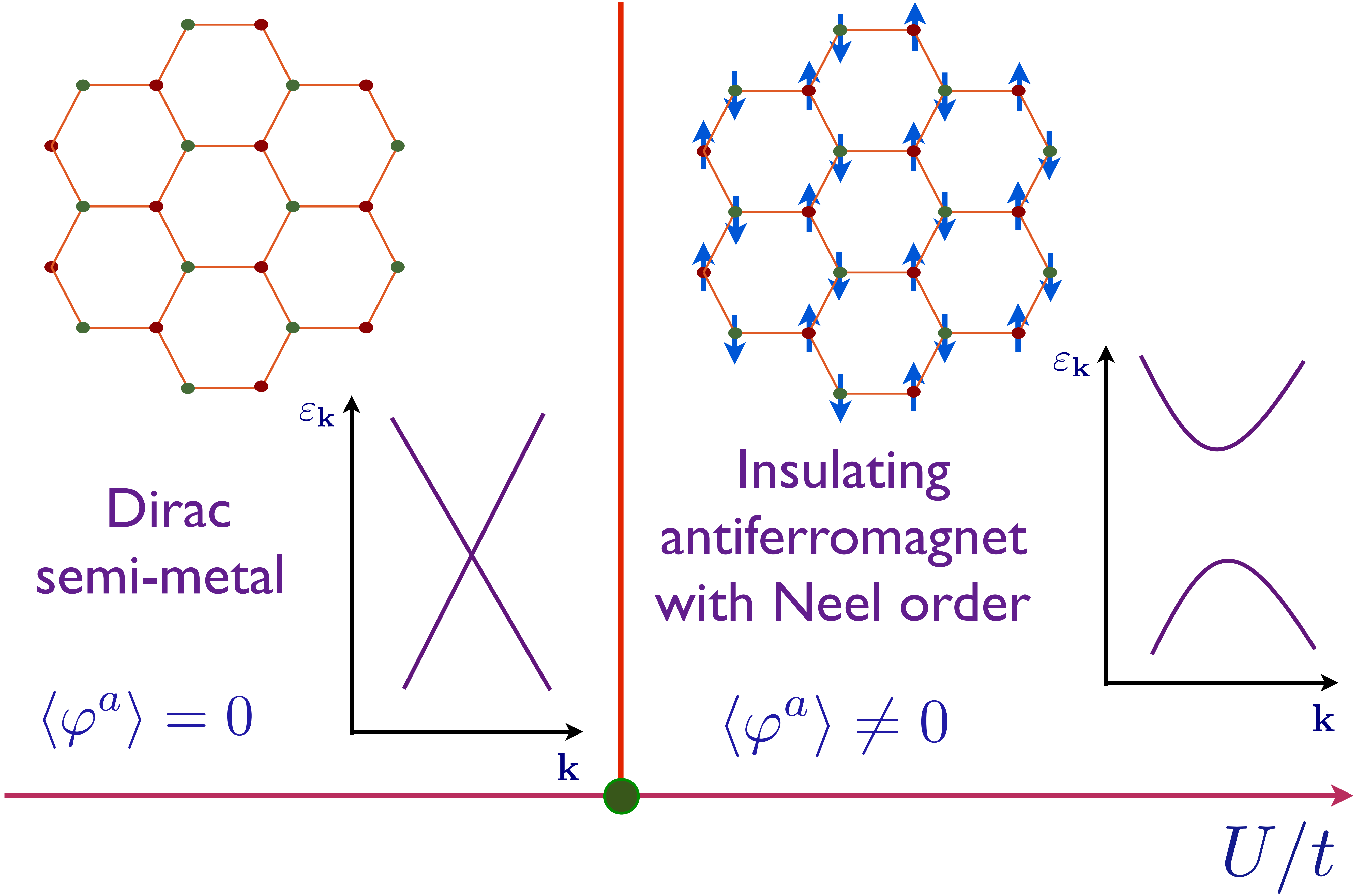
Andrew Lucas

Graphene

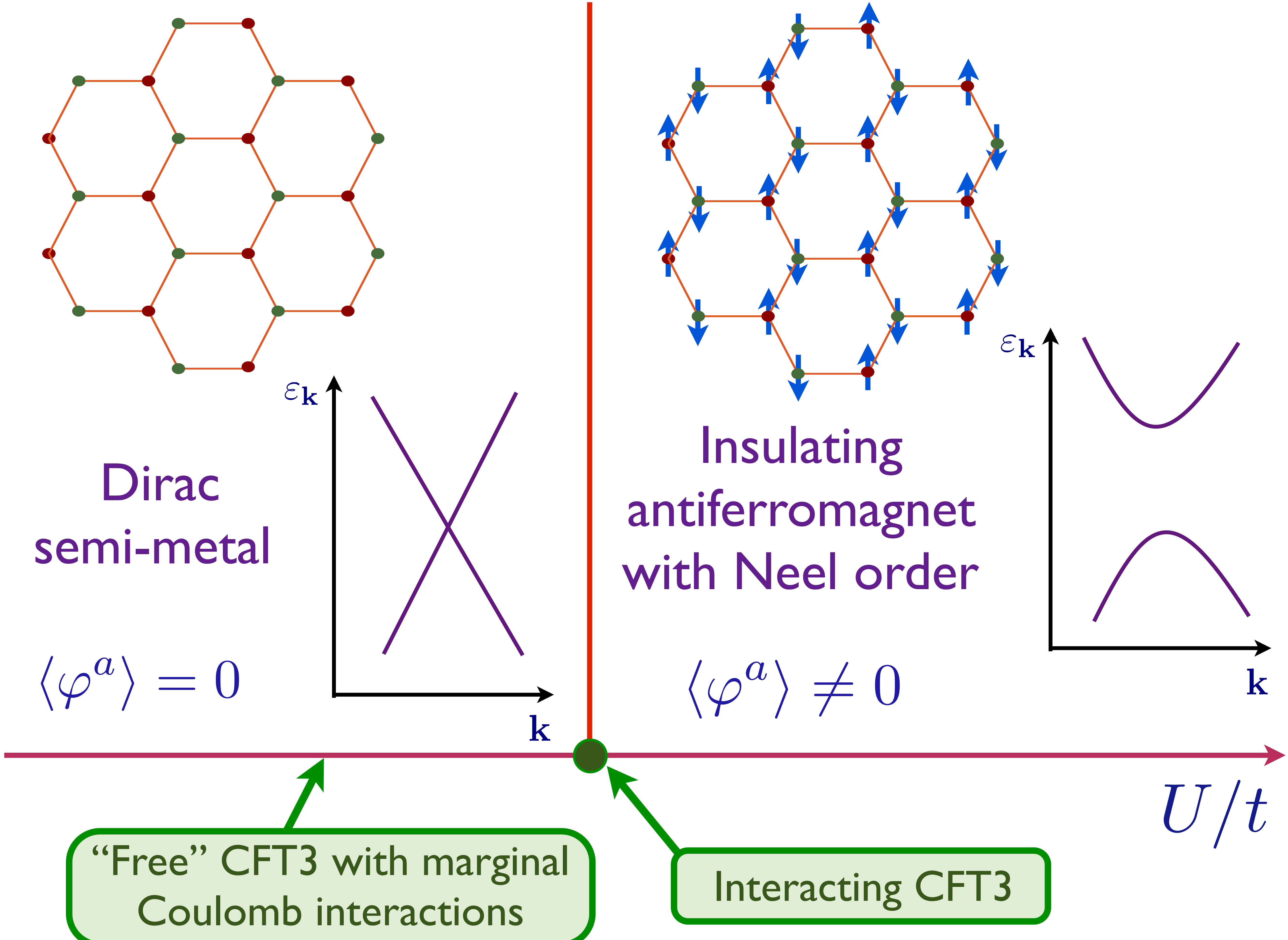




Same "Hubbard" model as for ultracold atoms, but for electrons on the honeycomb lattice

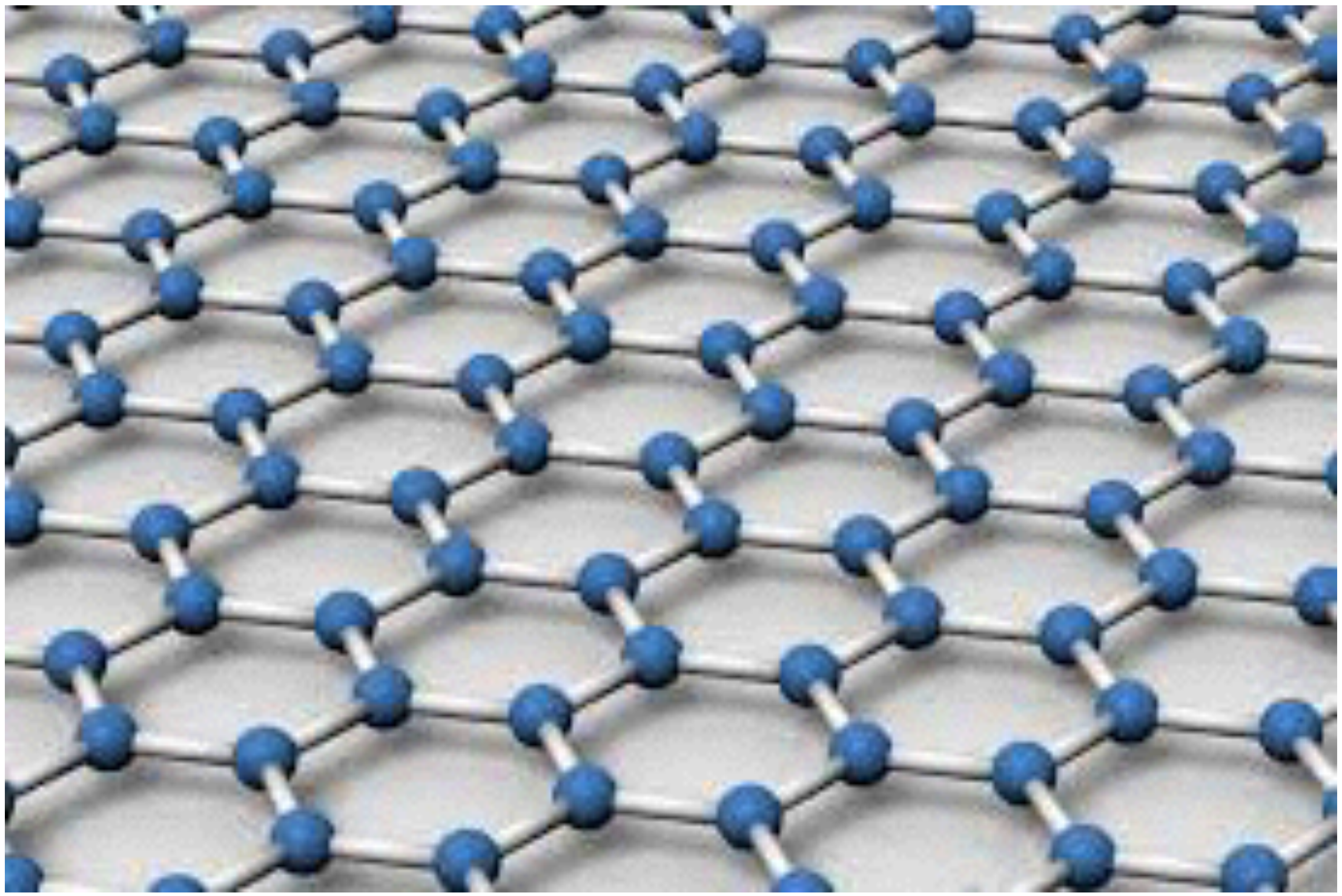


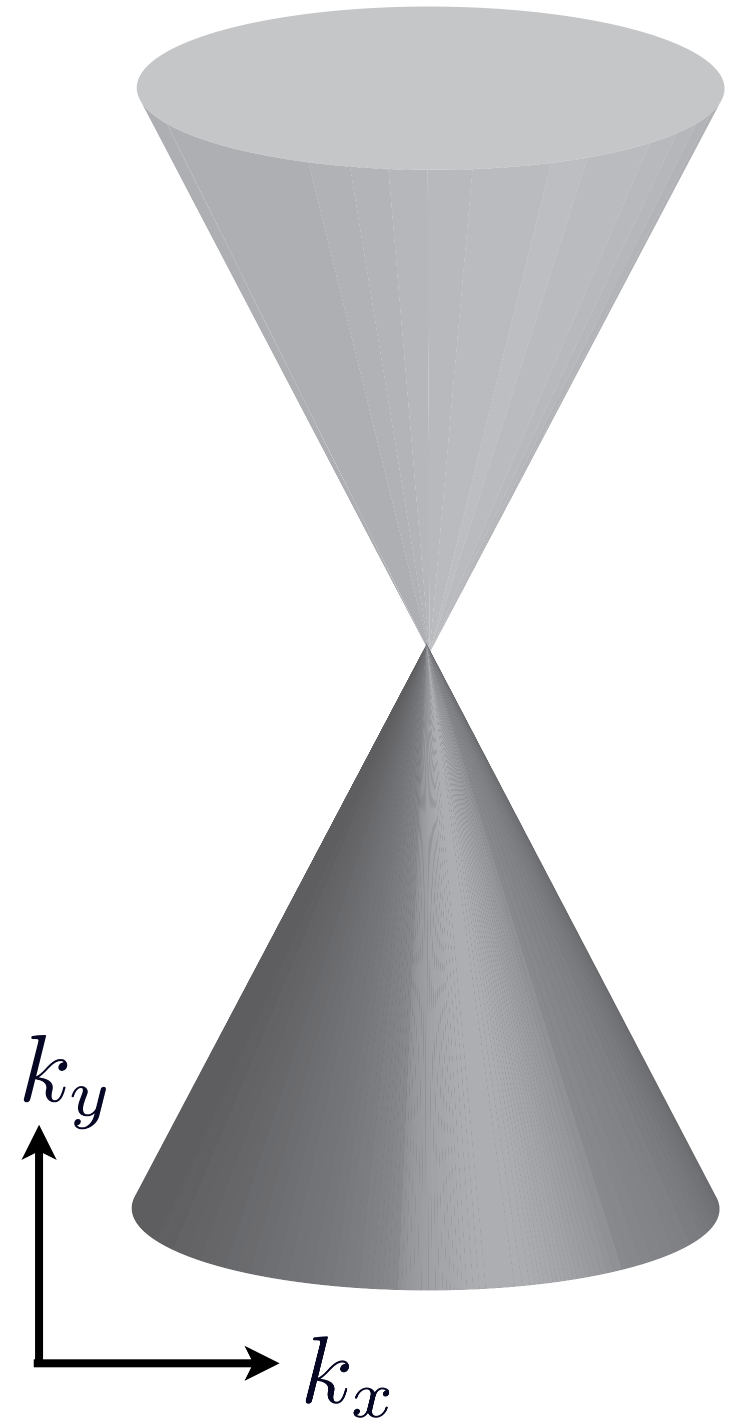
Dirac
semi-metal
$\langle \varphi^a \rangle = 0$
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
Insulating
antiferromagnet
with Neel order
$\langle \varphi^a \rangle \neq 0$
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
U/t



$\varepsilon_{\mathbf{k}}$
Dirac semi-metal
$\langle \varphi^a \rangle = 0$
$\mathbf{k}$
Insulating antiferromagnet with Neel order
$\varepsilon_{\mathbf{k}}$
$\langle \varphi^a \rangle \neq 0$
$\mathbf{k}$
U/t
"Free" CFT3 with marginal Coulomb interactions
Interacting CFT3

Graphene





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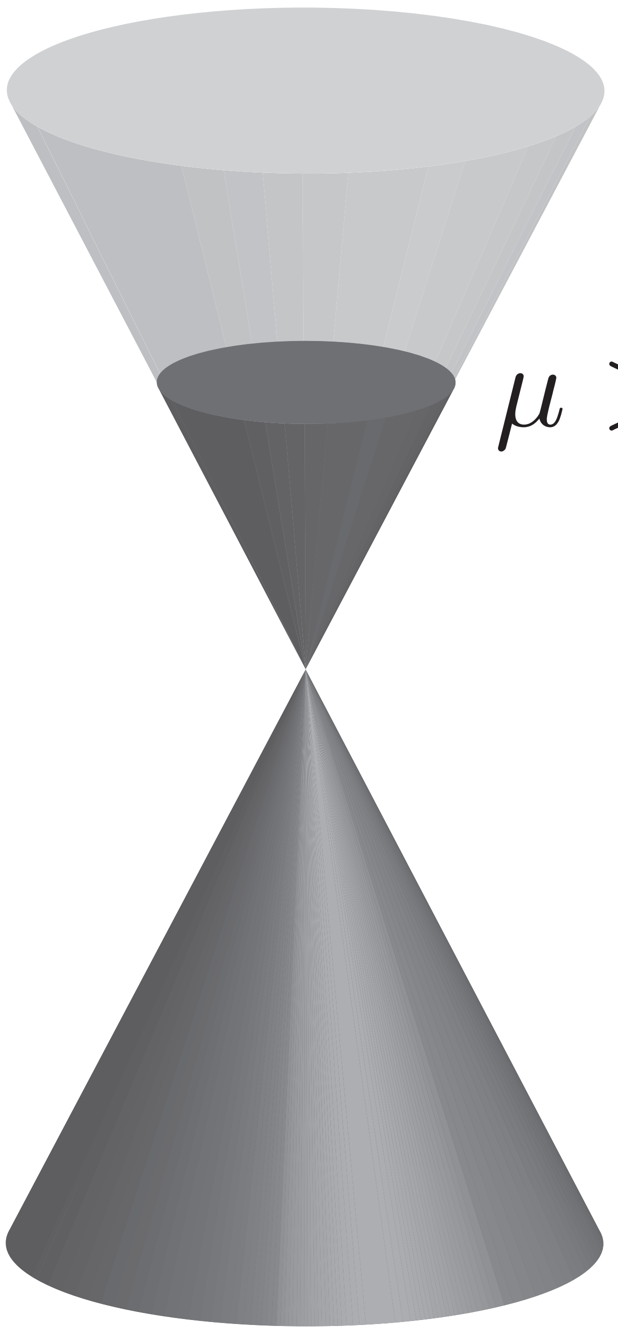
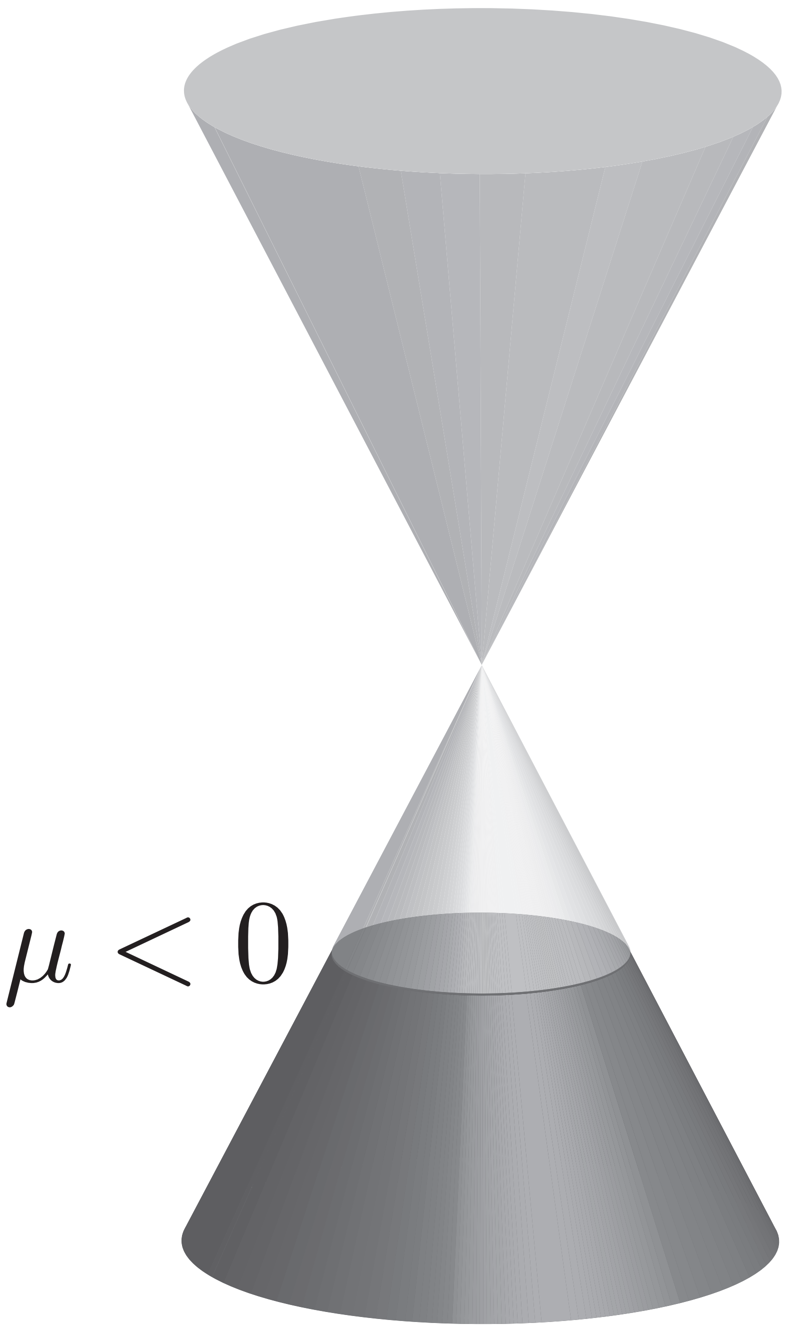
Graphene

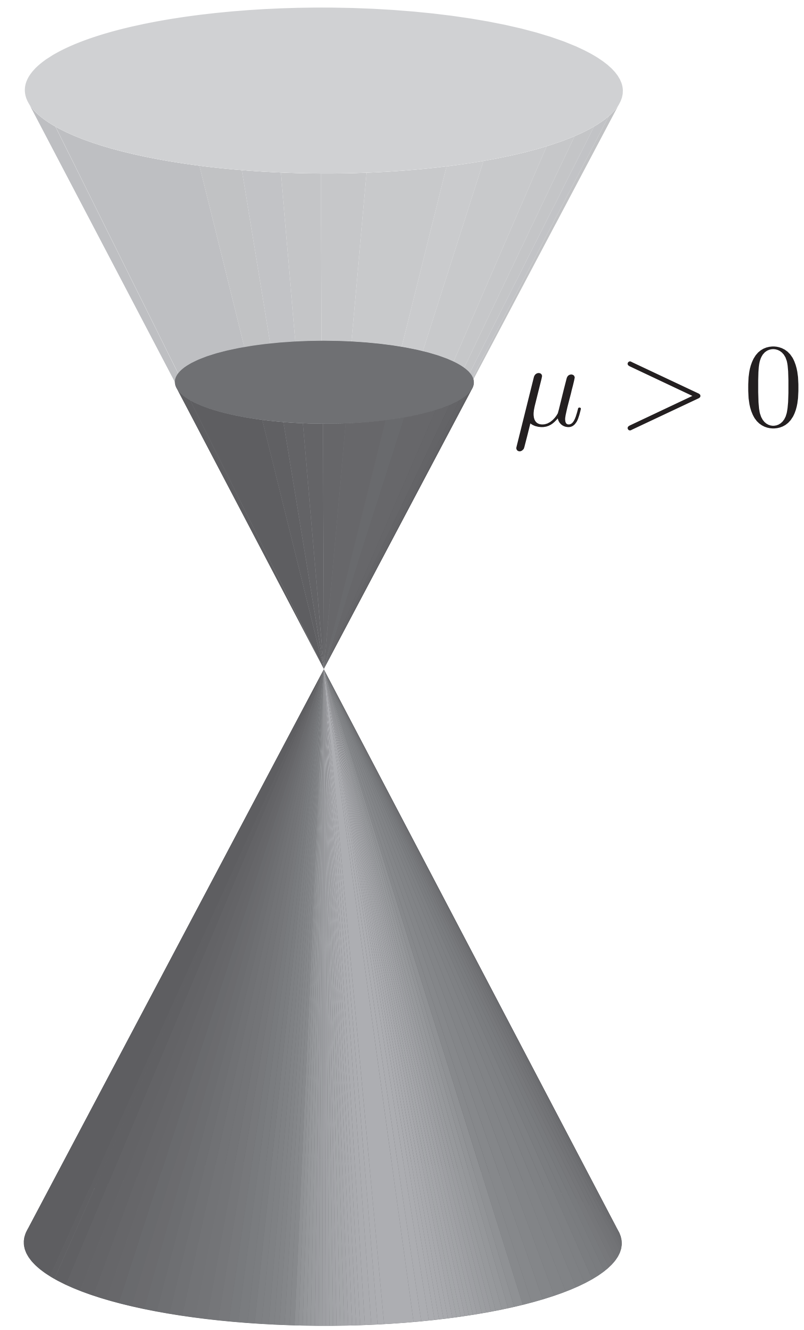


Electron
Fermi surface

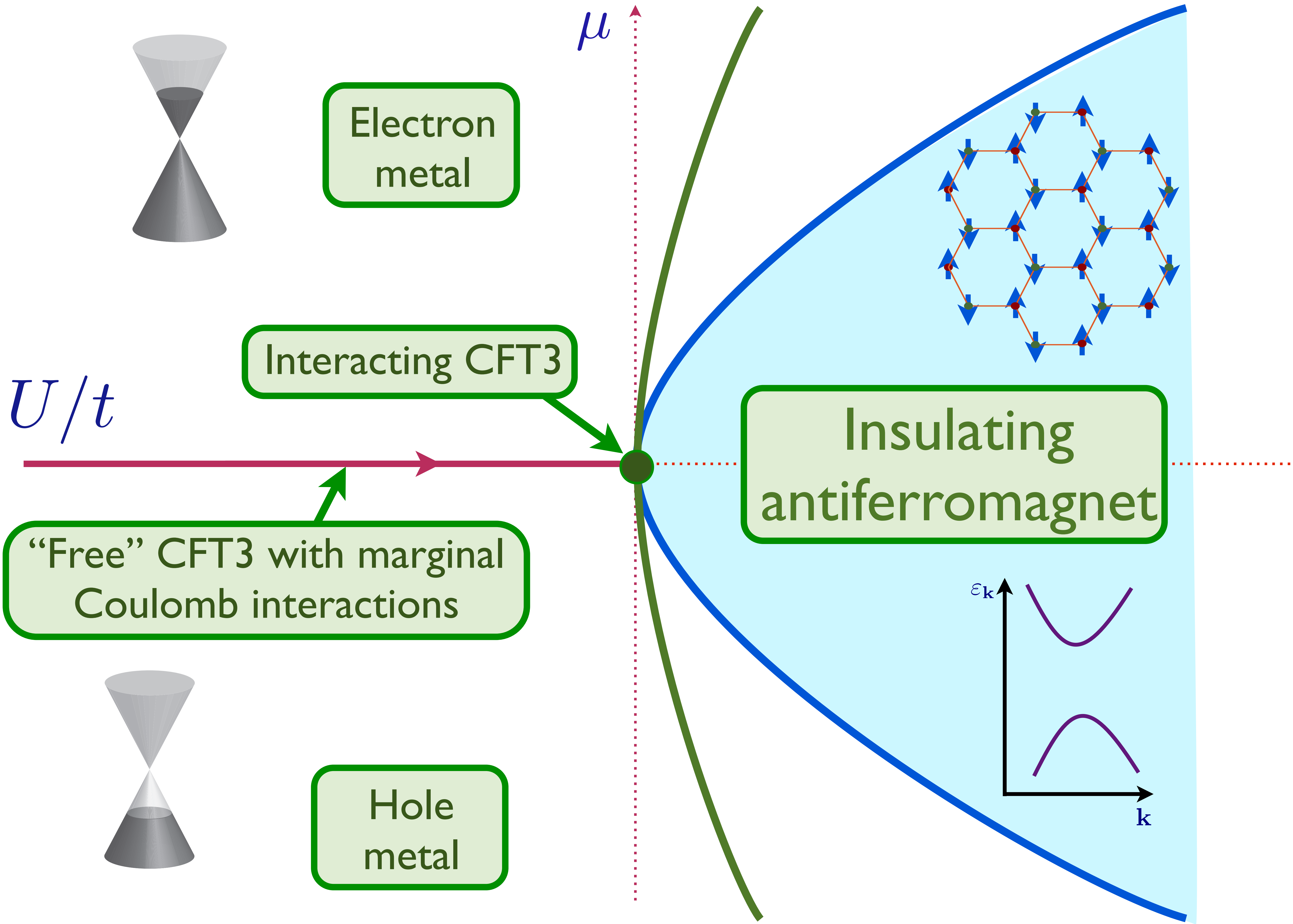
Graphene



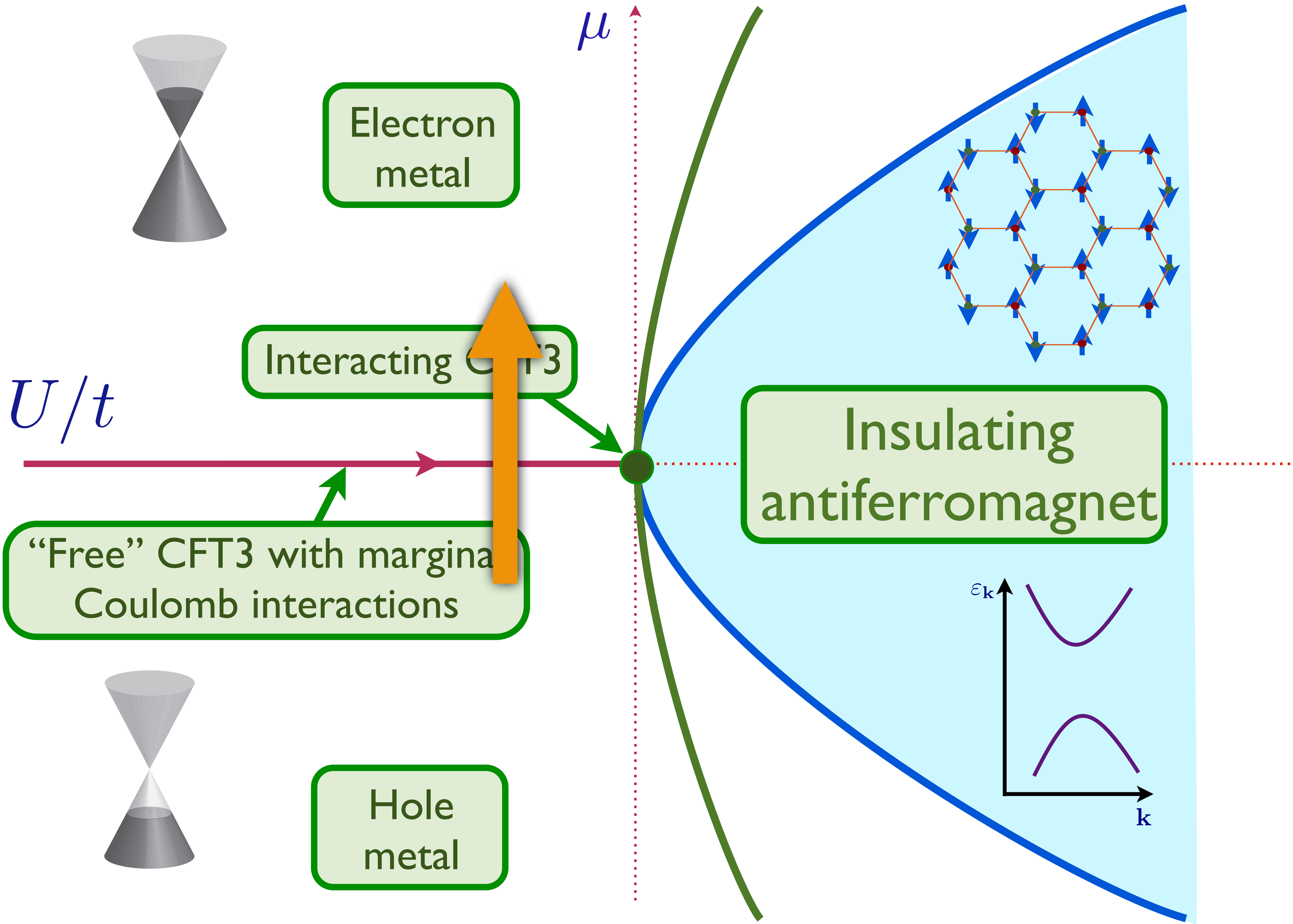
Hole
Fermi surface



Electron
Fermi surface



μ
Electron metal
Interacting CFT3
U/t
"Free" CFT3 with marginal Coulomb interactions
Insulating antiferromagnet
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
Hole metal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Hole metal
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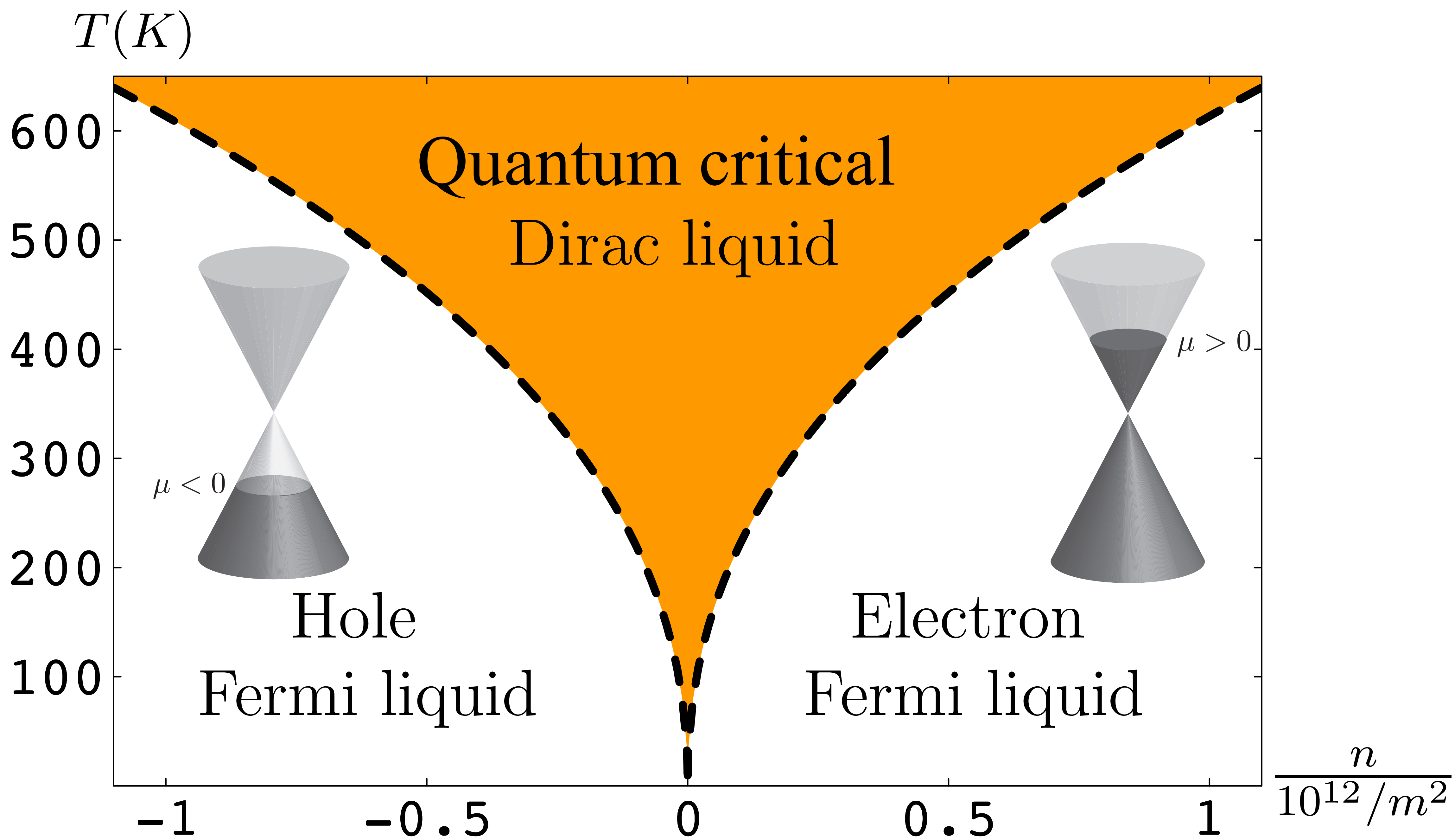
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$

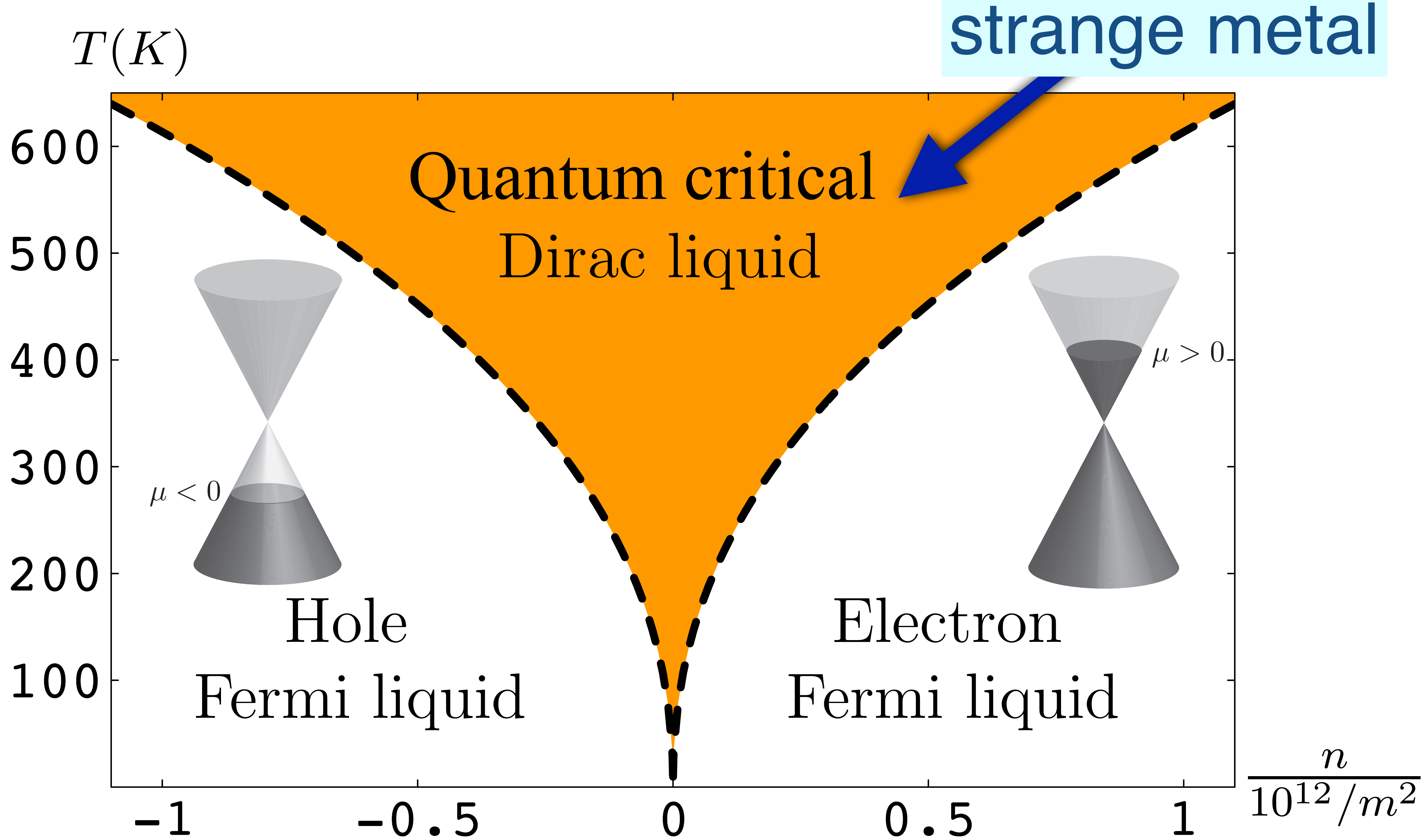
Graphene



D. E. Sheehy and J. Schmalian, PRL **99**, 226803 (2007)
M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Graphene

Predicted strange metal



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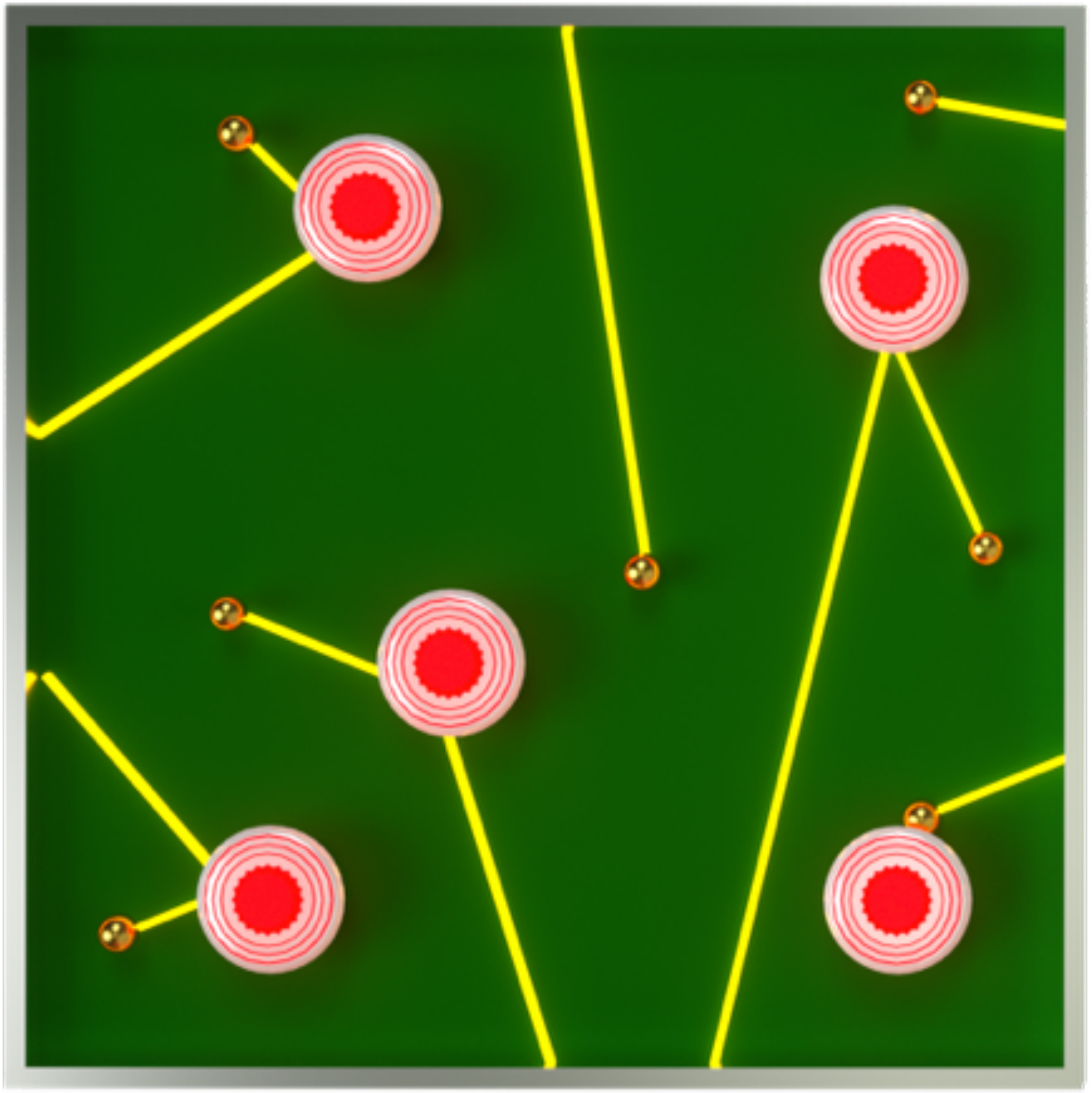
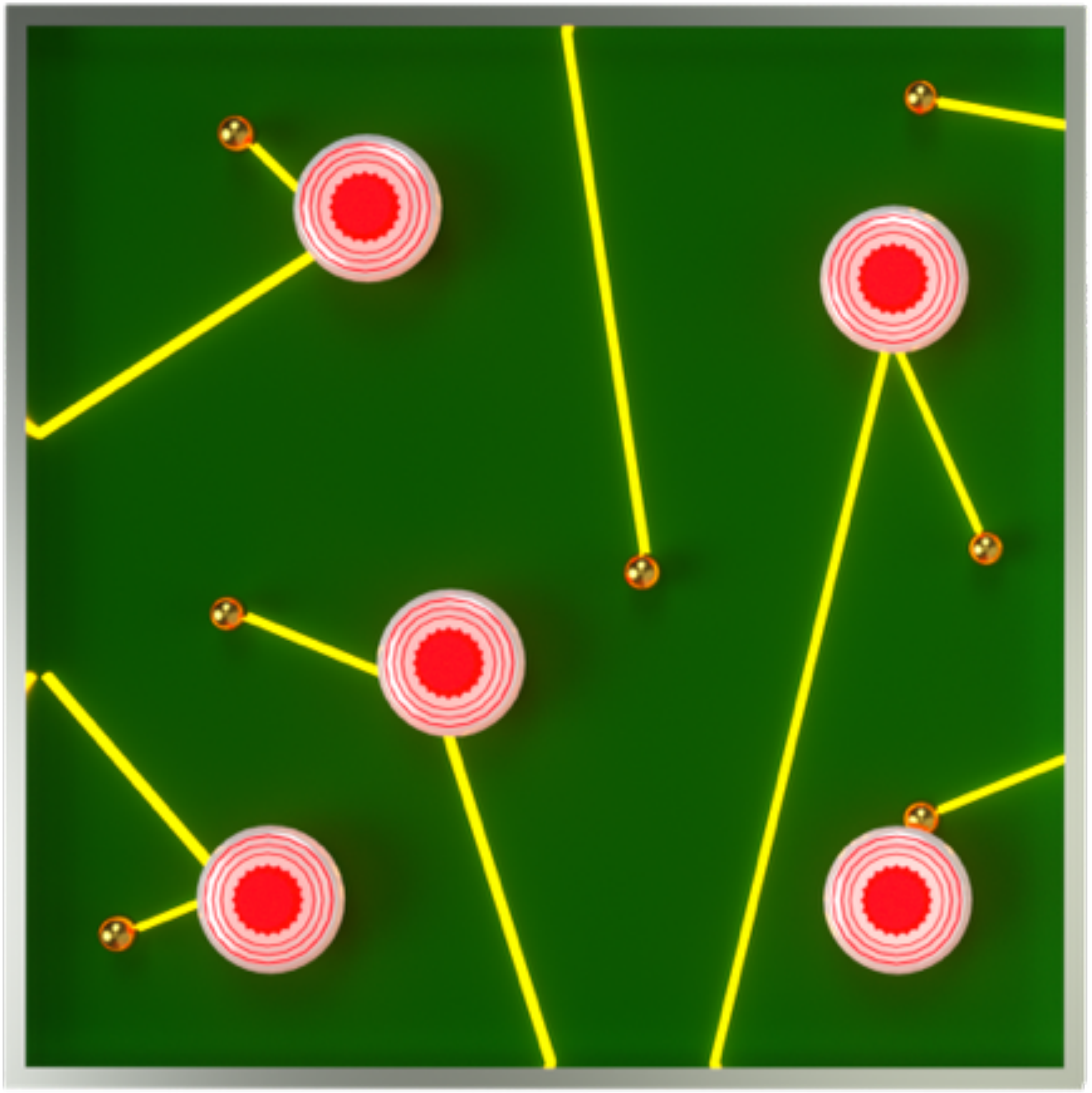


Fermi liquids: quasiparticles moving ballistically between impurity (red circles) scattering events



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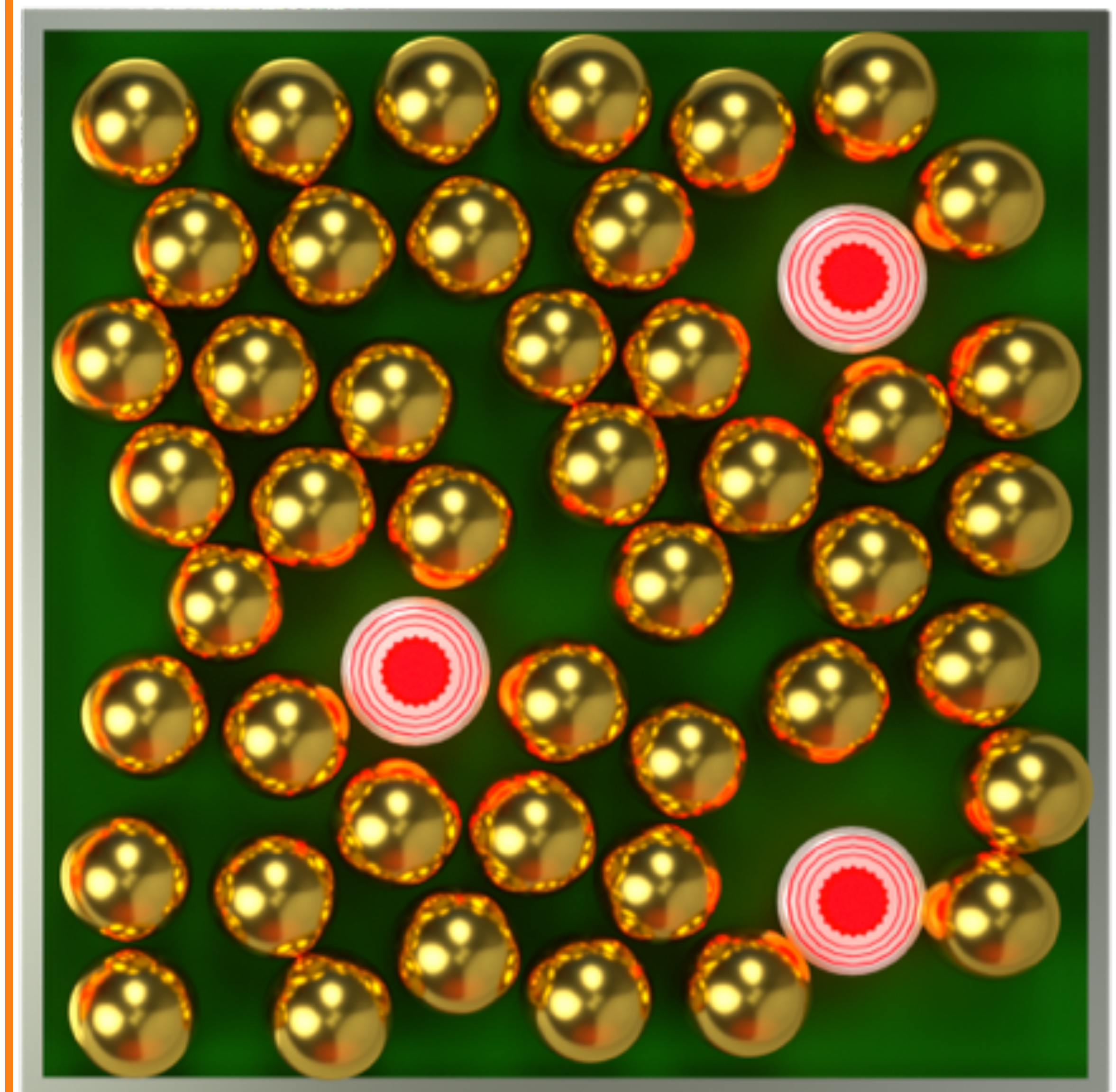
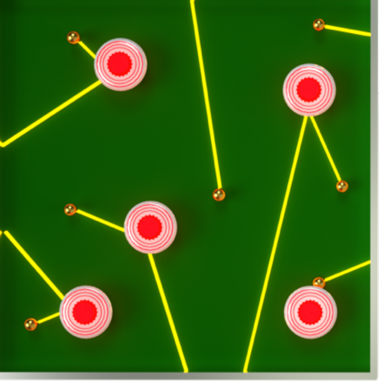
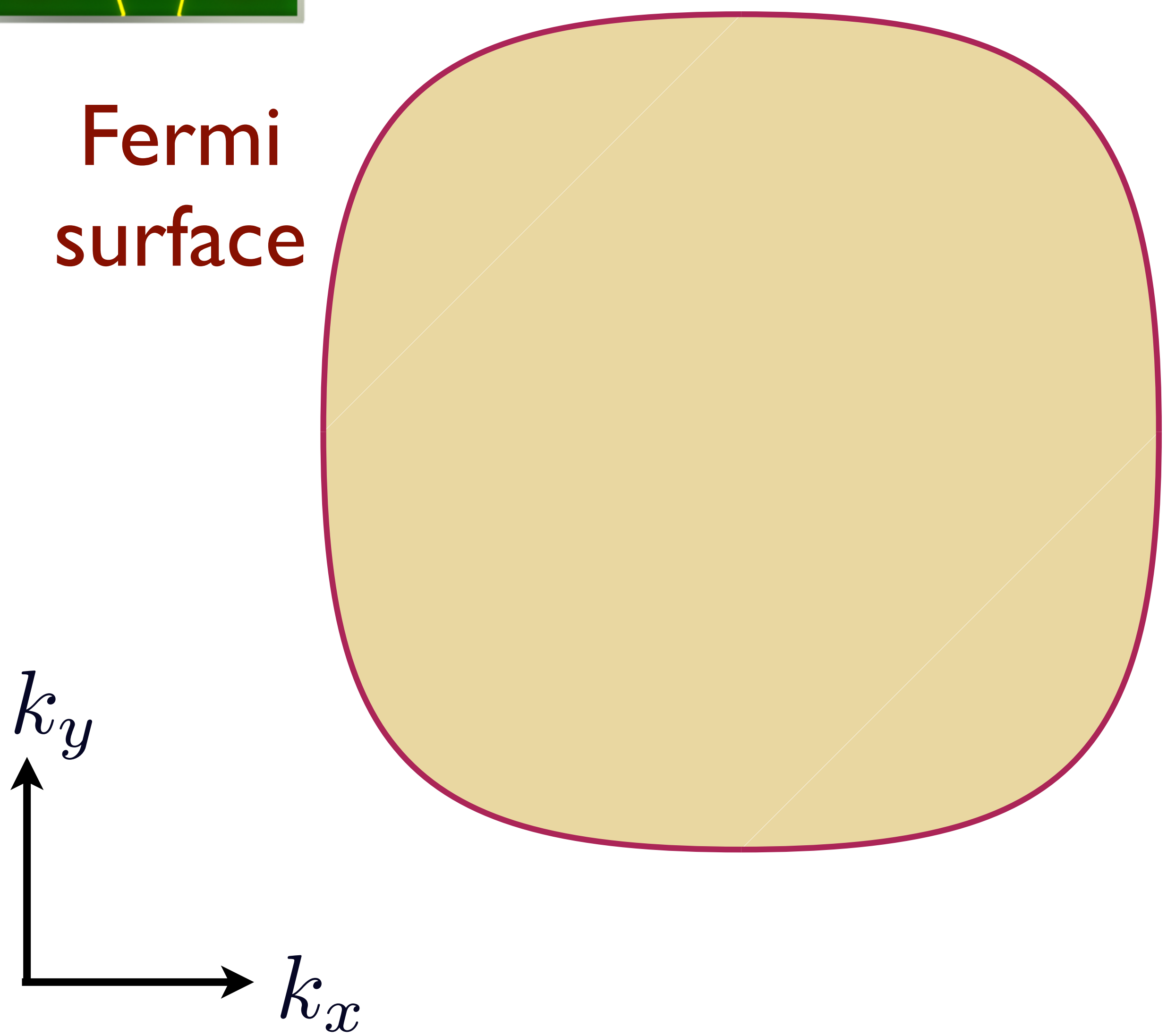


Strange metals: electrons scatter frequently off each other, so there is no regime of ballistic quasiparticle motion. The electron “liquid” then “flows” around impurities

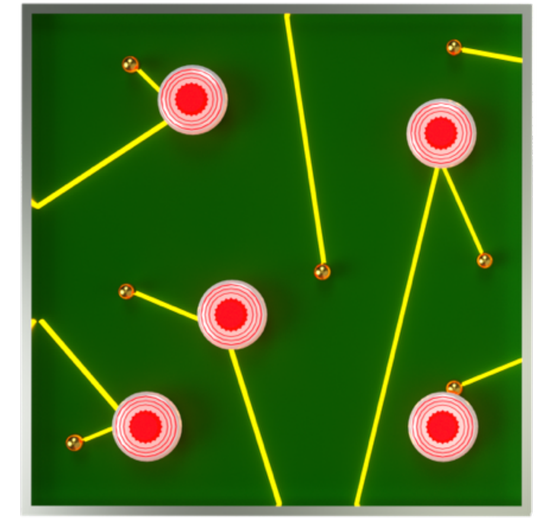


Ordinary metals: the Fermi liquid



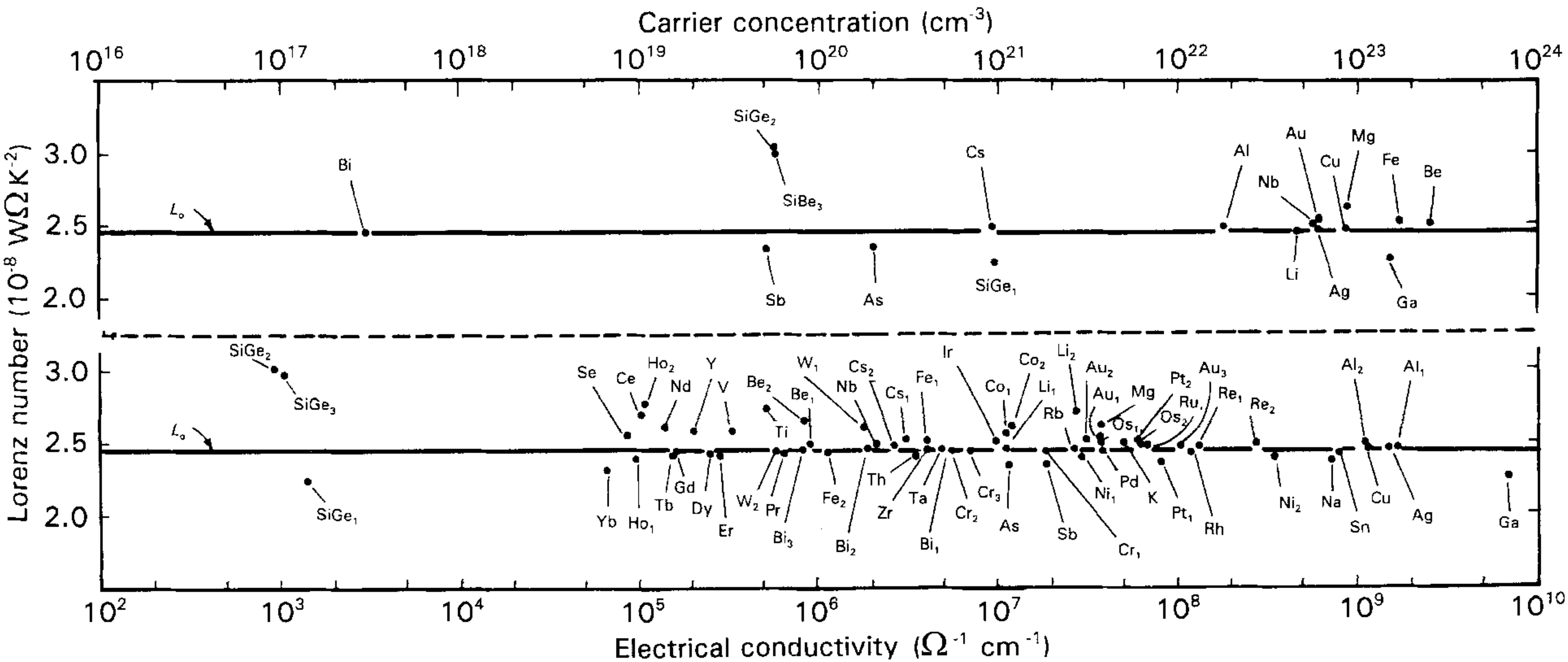
- Fermi surface separates empty and occupied states in momentum space.
- Area enclosed by Fermi surface = $\mathcal{Q}$. Momenta of low energy excitations fixed by density of *all* electrons.
- Long-lived electron-like quasiparticle excitations near the Fermi surface: lifetime of quasiparticles $\sim 1/T^2$.

- $$L \equiv \frac{\text{(Thermal conductivity)}}{T\,\text{(Electrical conductivity)}} = L_0 = \frac{\pi^2 k_B^2}{3e^2}$$



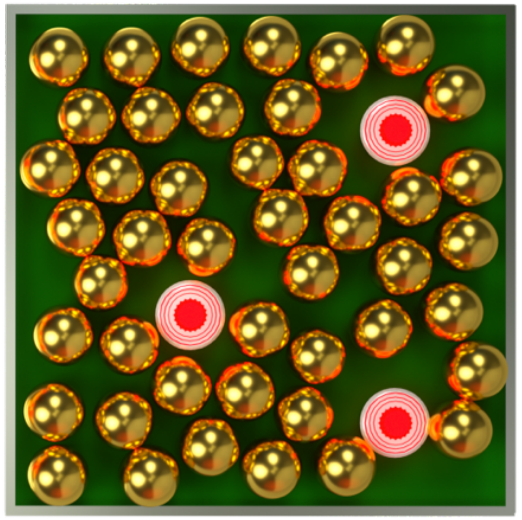
- Wiedemann-Franz law in a Fermi liquid:

$$\frac{\kappa}{\sigma T} \approx \frac{\pi^2 k_B^2}{3e^2} \approx 2.45 \times 10^{-8} \, \frac{\mathrm{W} \cdot \Omega}{\mathrm{K}^2}.$$



G. S. Kumar, G. Prasad, and R.O. Pohl, J. Mat. Sci. **28**, 4261 (1993)

Transport in Strange Metals



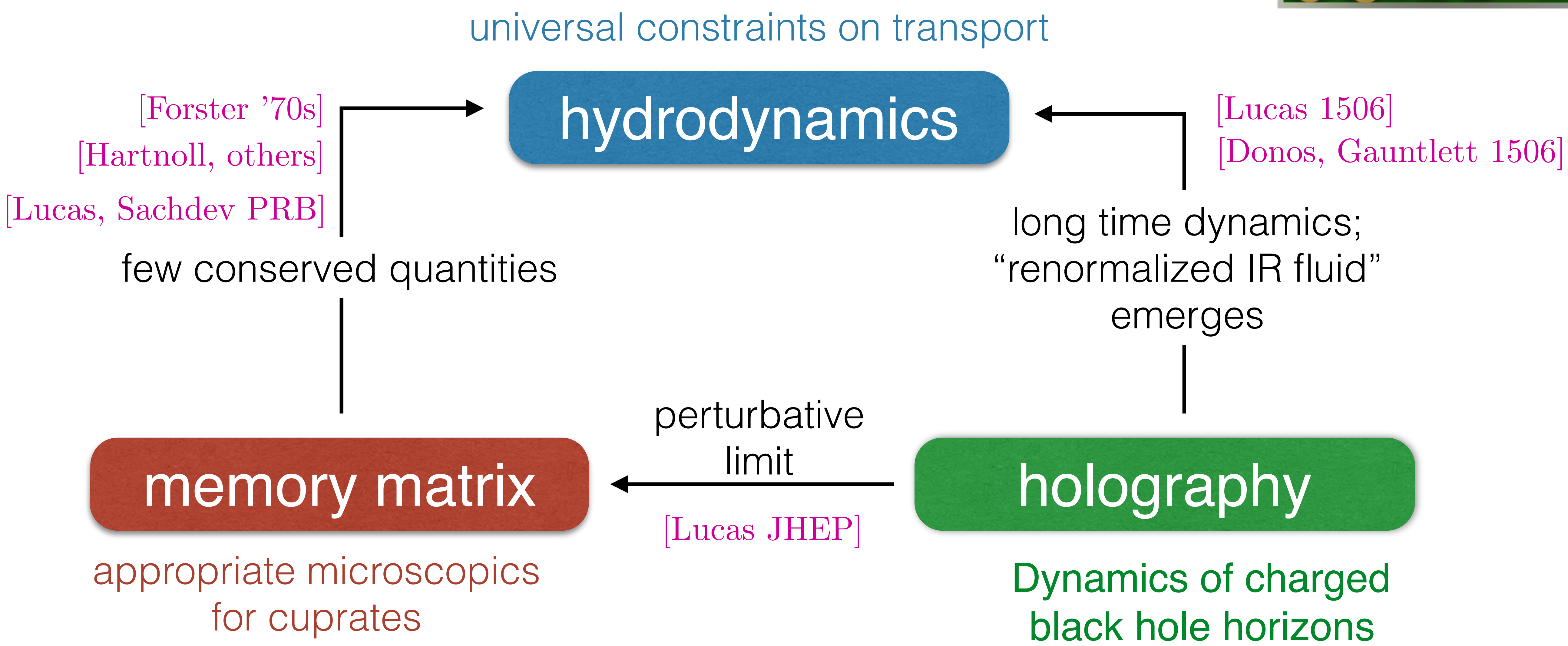
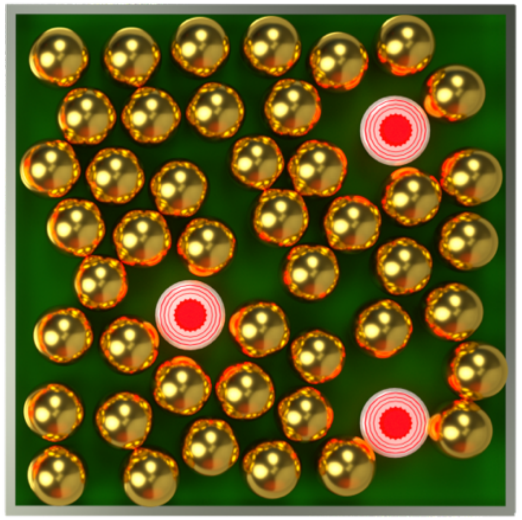


figure from [Lucas, Sachdev, *Physical Review* **B91** 195122 (2015)]

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)

Transport in Strange Metals



Recall that in a Fermi liquid, the Lorenz ratio $L = \kappa/(T\sigma)$, where κ is the thermal conductivity, and σ is the conductivity, is given by $L = L_0 = \pi^2 k_B^2/(3e^2)$.

For a strange metal with a "relativistic" Hamiltonian, hydrodynamic, holographic, and memory function methods yield

$$\sigma = \sigma_Q \left(1 + \frac{e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}}{\mathcal{H}\sigma_Q}\right) \quad , \quad \kappa = \frac{v_F^2 \mathcal{H} \tau_{\rm imp}}{T} \left(1 + \frac{e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}}{\mathcal{H}\sigma_Q}\right)^{-1}$$

$$L = \frac{v_F^2 \mathcal{H} \tau_{\rm imp}}{T^2 \sigma_Q} \left(1 + \frac{e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}}{\mathcal{H}\sigma_Q}\right)^{-2},$$

where $\mathcal{H}$ is the enthalpy density, $\tau_{\rm imp}$ is the momentum relaxation time (from impurities), while $\sigma = \sigma_Q$, an intrinsic, finite, "quantum critical" conductivity. Note that the limits $\mathcal{Q} \to 0$ and $\tau_{\rm imp} \to \infty$ do not commute.

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Graphene

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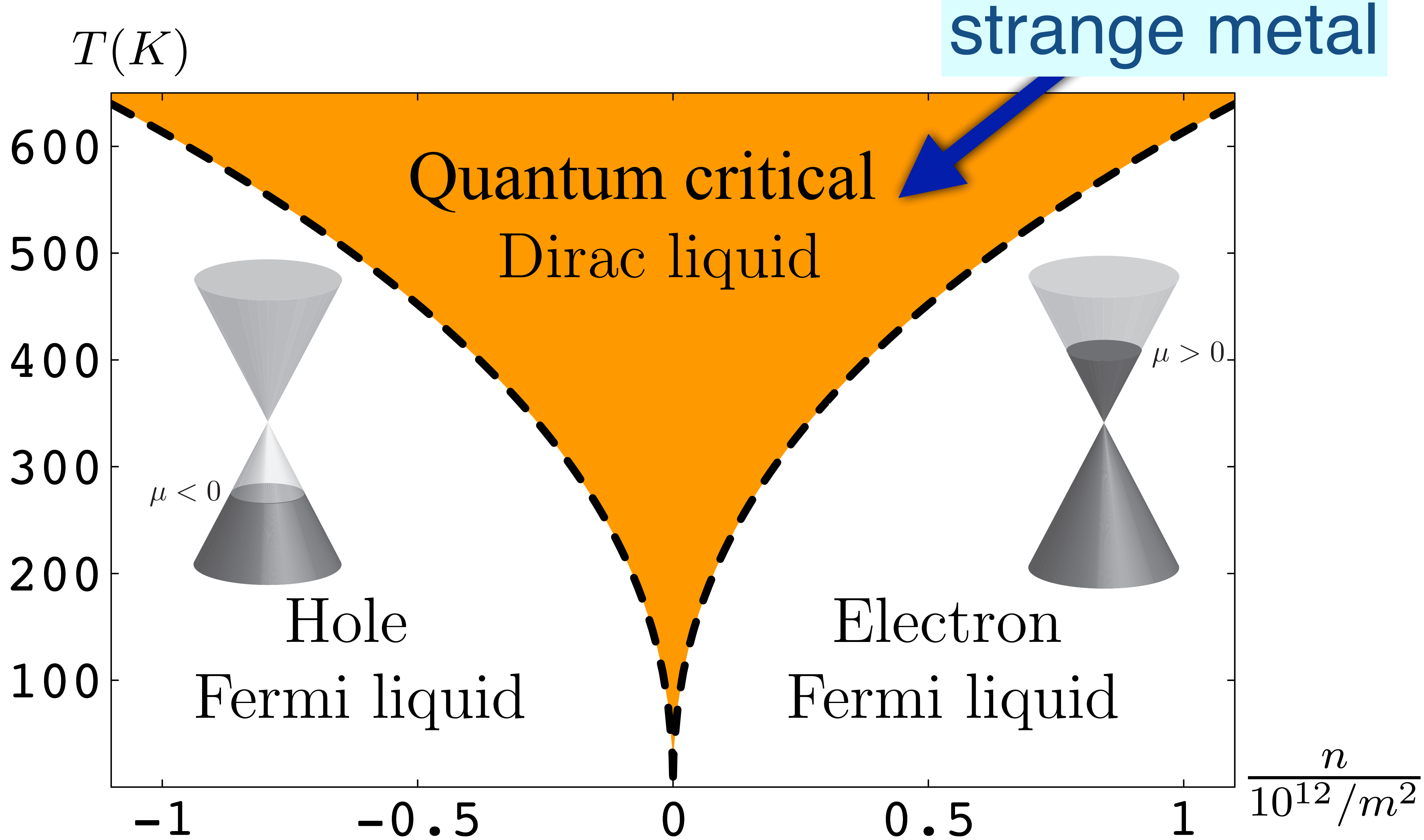

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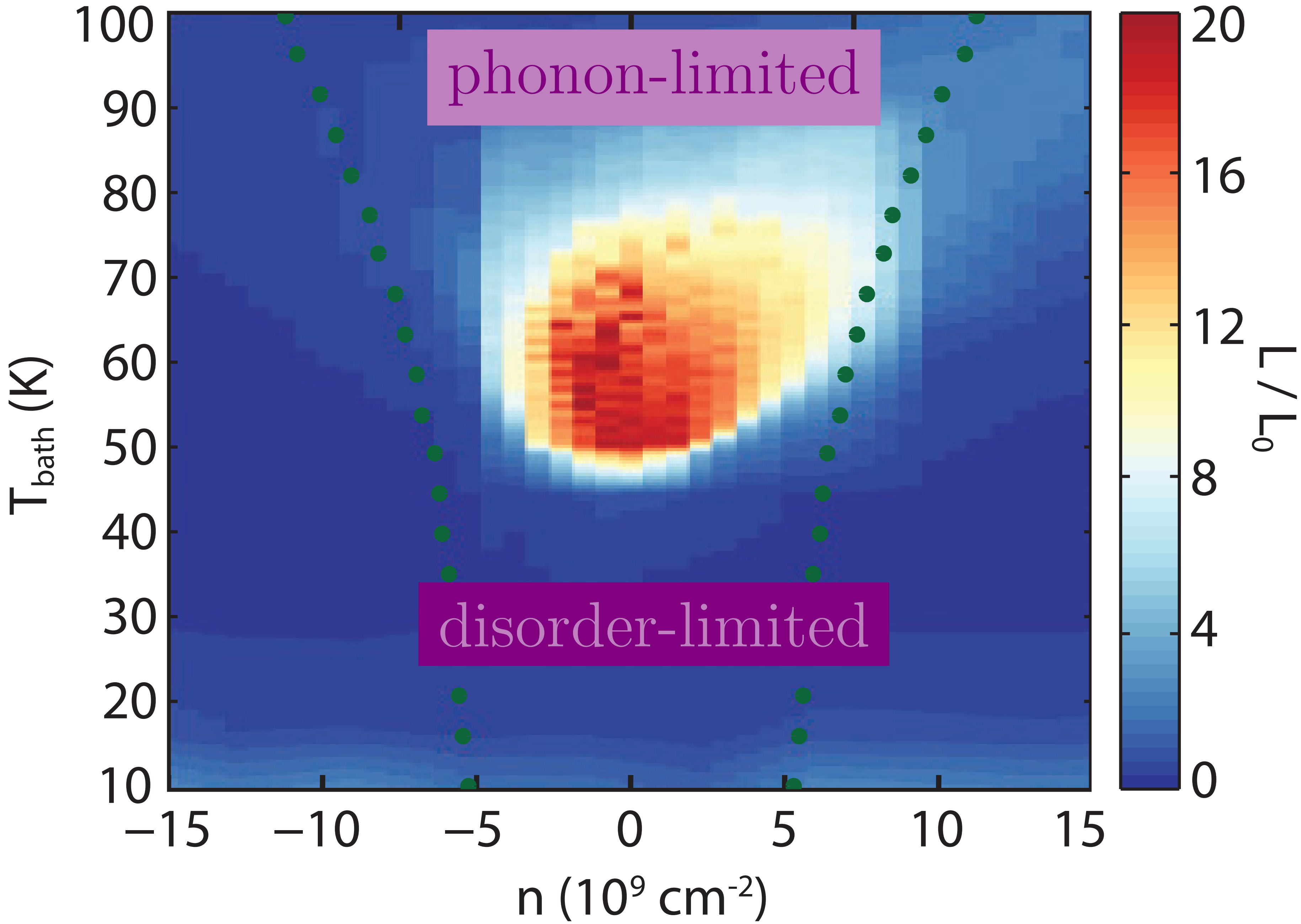
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

J. Crossno *et al.* arXiv:1509.04713; Science, to appear

Strange metal in graphene



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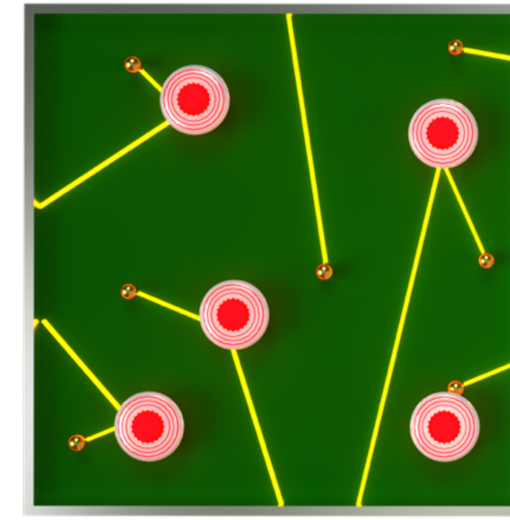
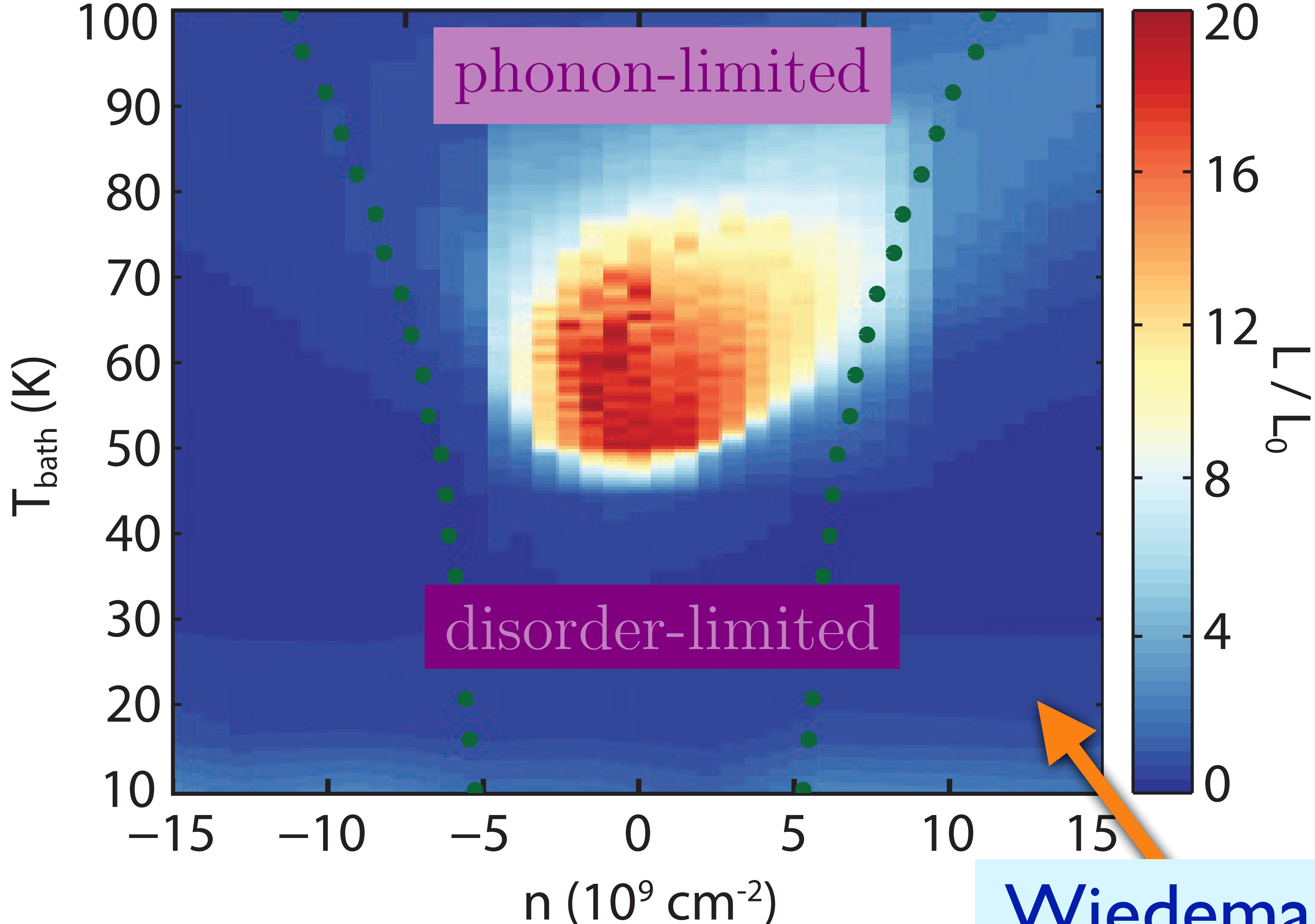
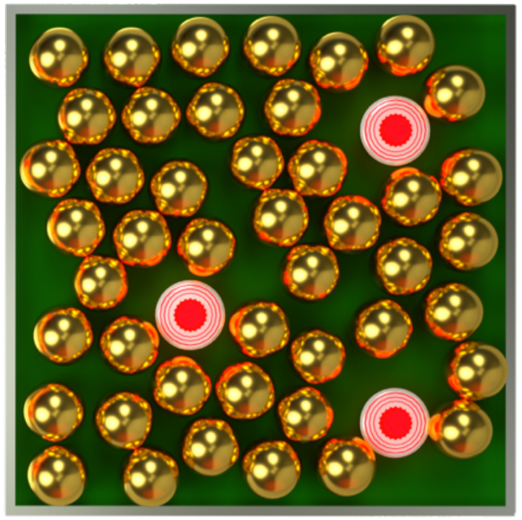


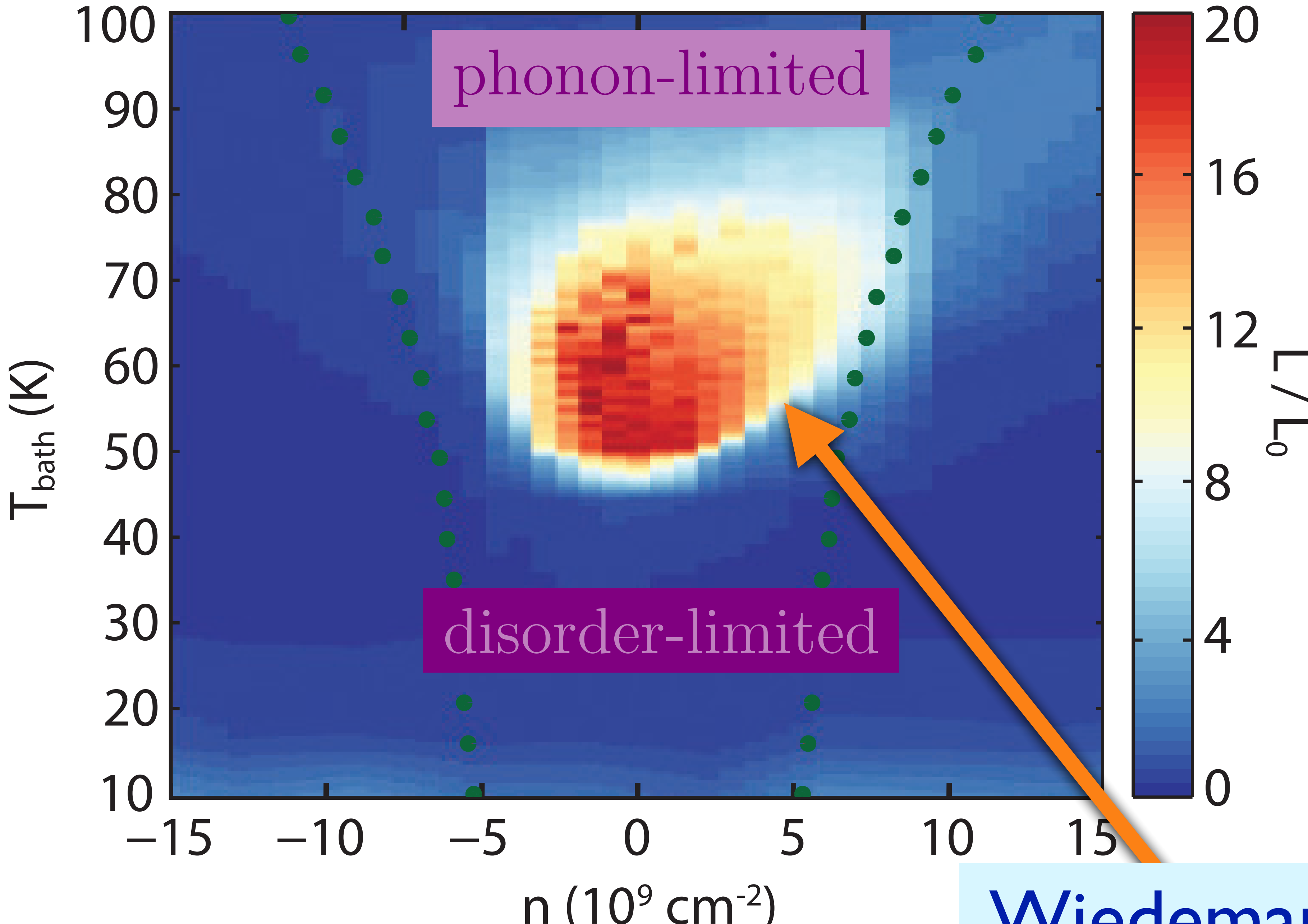


Wiedemann-Franz obeyed

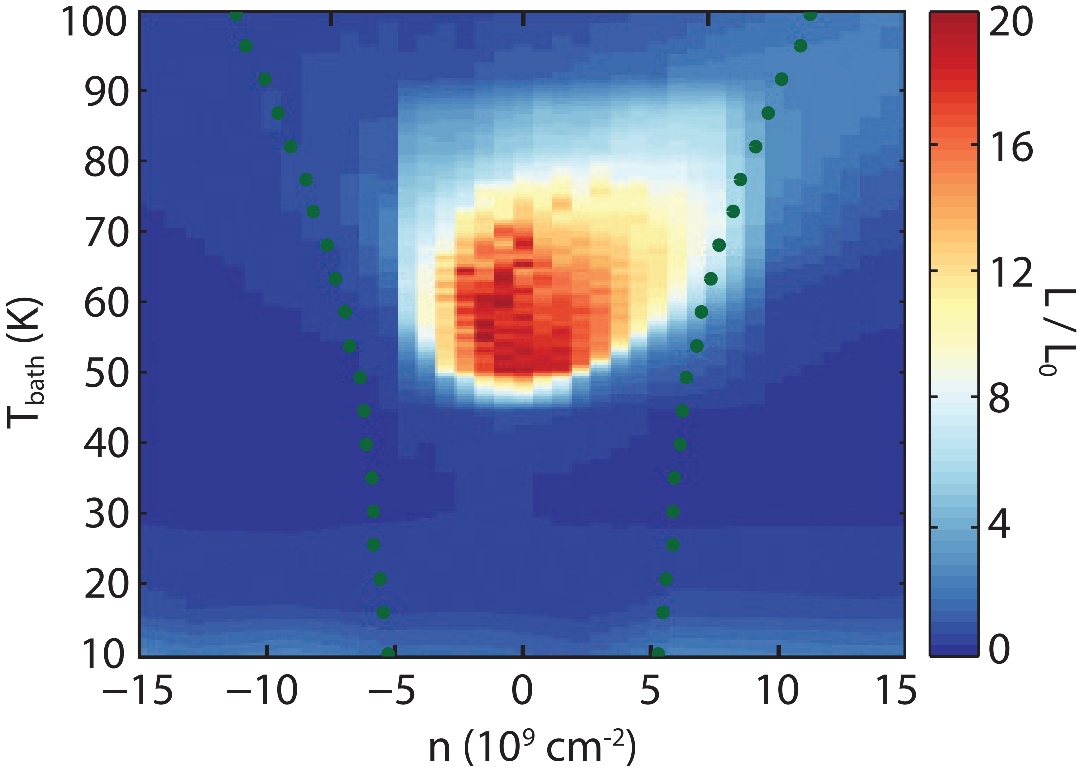
J. Crossno *et al.* arXiv:1509.04713; Science, to appear

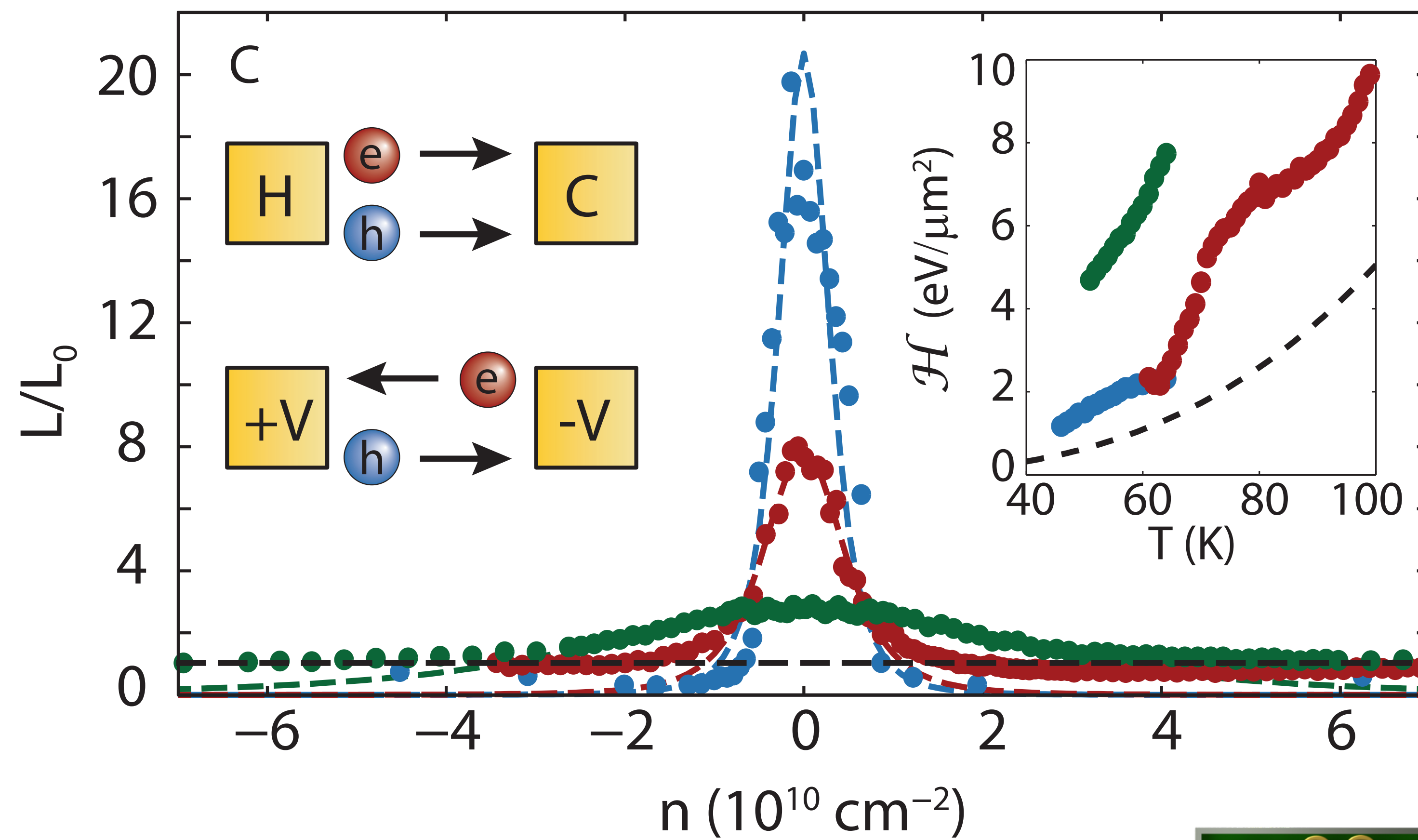
Strange metal in graphene

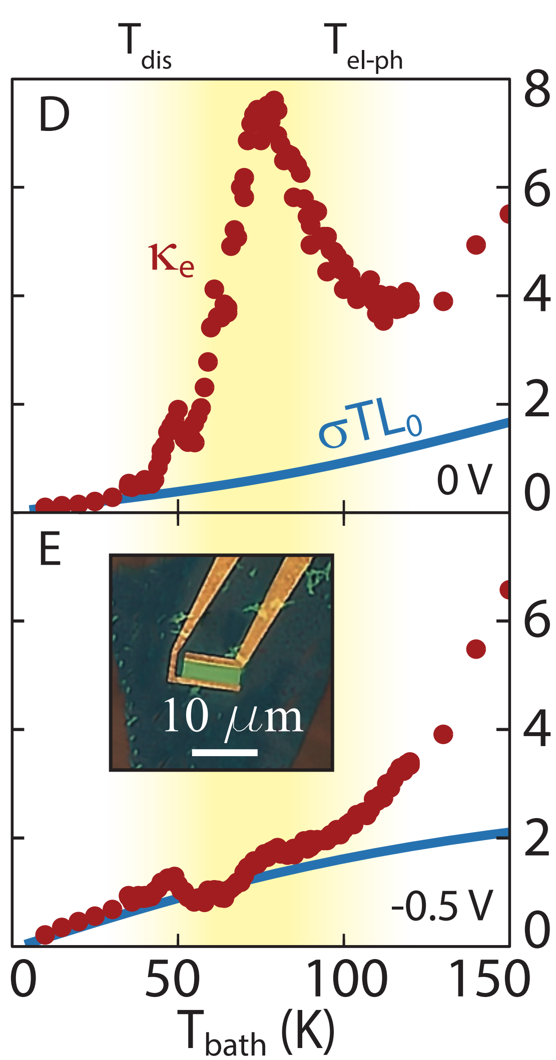


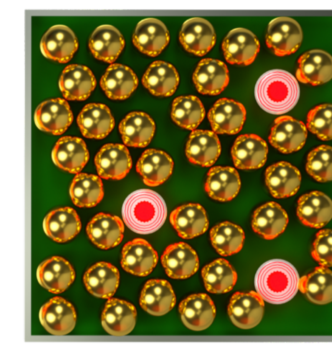


Wiedemann-Franz violated !









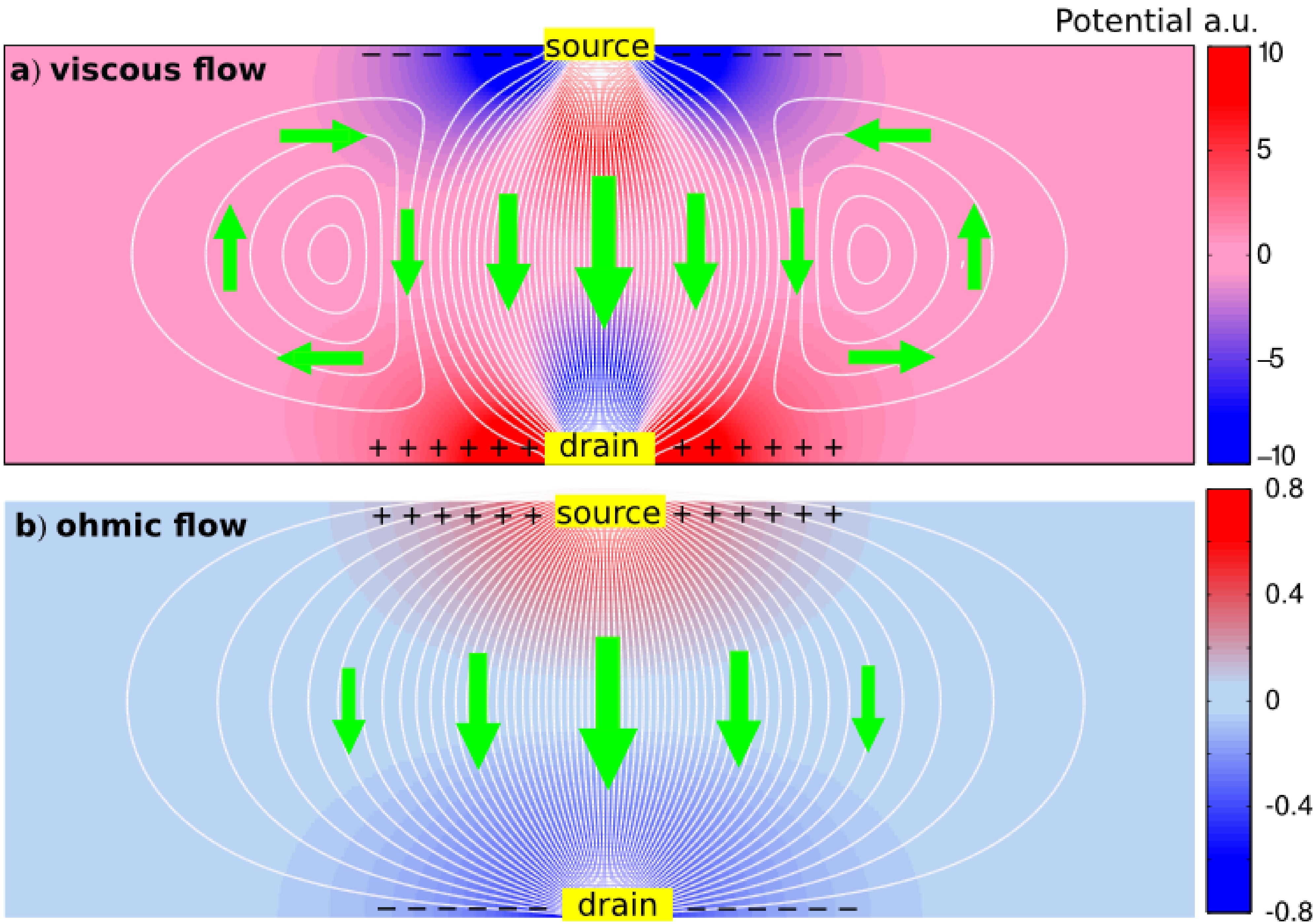
$$\text{Lorentz ratio } L = \kappa/(T\sigma)$$

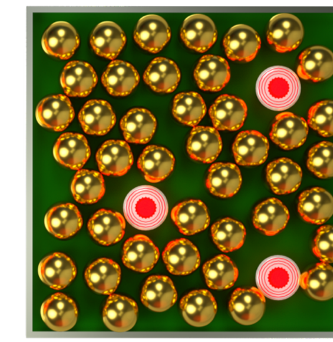
$$= \frac{v_F^2 \mathcal{H} \tau_{\rm imp}}{T^2 \sigma_Q} \frac{1}{\left(1 + e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}/(\mathcal{H}\sigma_Q)\right)^2}$$

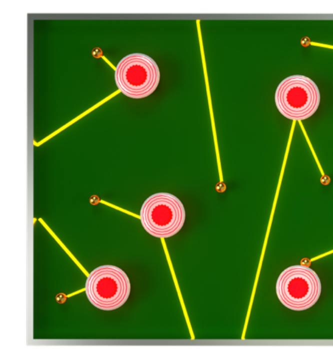
J. Crossno *et al.* arXiv:1509.04713; Science, to appear

Strange metal in graphene

Negative local resistance due to viscous electron backflow in graphene







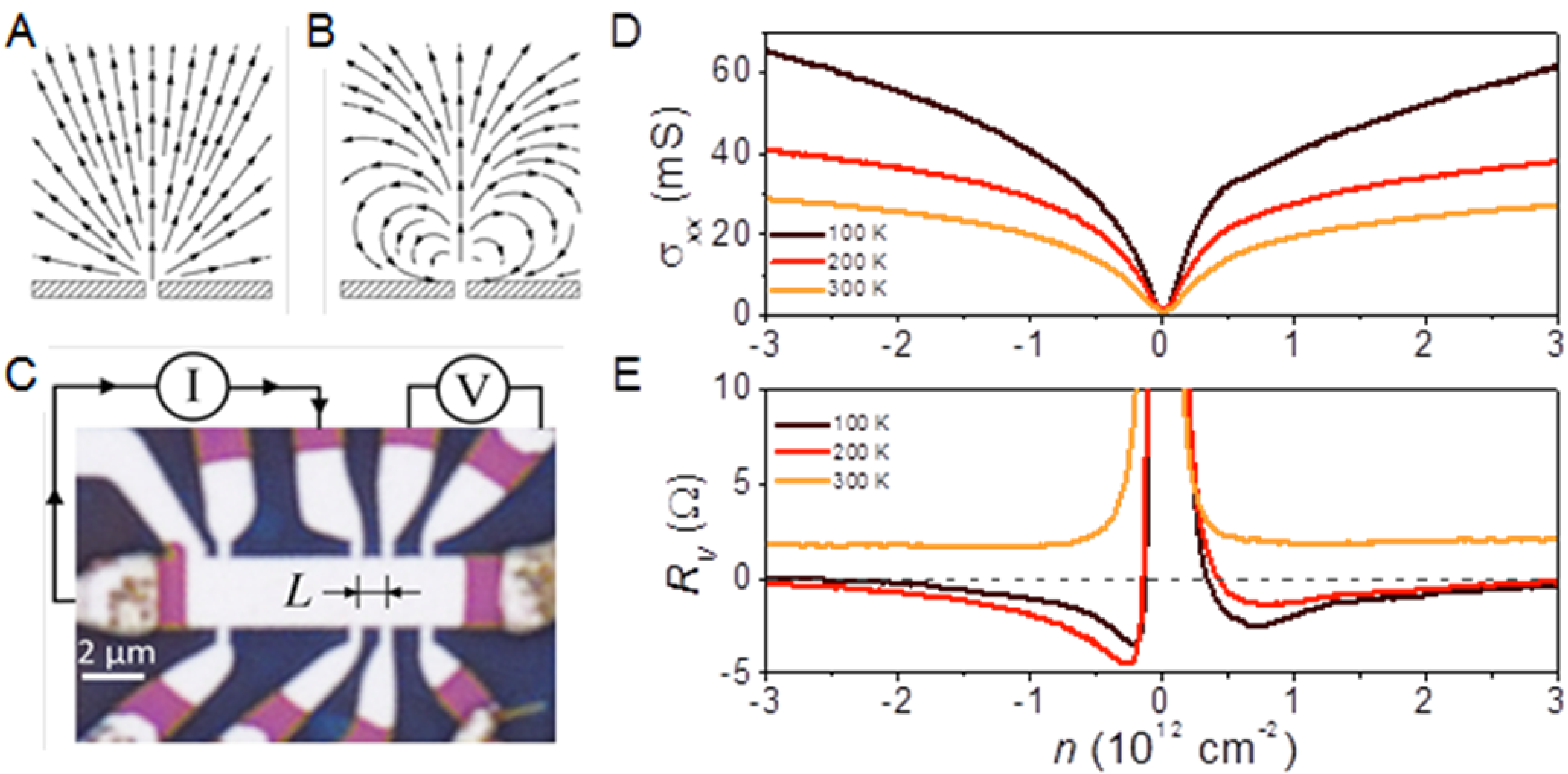
L. Levitov and G. Falkovich, arXiv:1508.00836, *Nature Physics*, to appear

Strange metal in graphene

arXiv:1509.04165
Science, to appear

Negative local resistance due to viscous electron backflow in graphene

D. A. Bandurin[1], I. Torre[2,3], R. Krishna Kumar[1,4], M. Ben Shalom[1,5], A. Tomadin[6], A. Principi[7], G. H. Auton[5], E. Khestanova[1,5], K. S. Novoselov[5], I. V. Grigorieva[1], L. A. Ponomarenko[1,4], A. K. Geim[1], M. Polini[3,6]



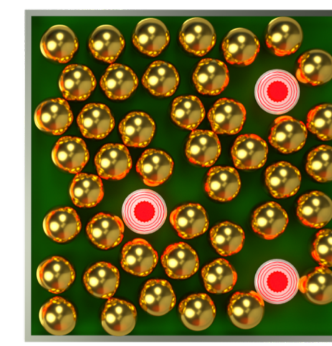
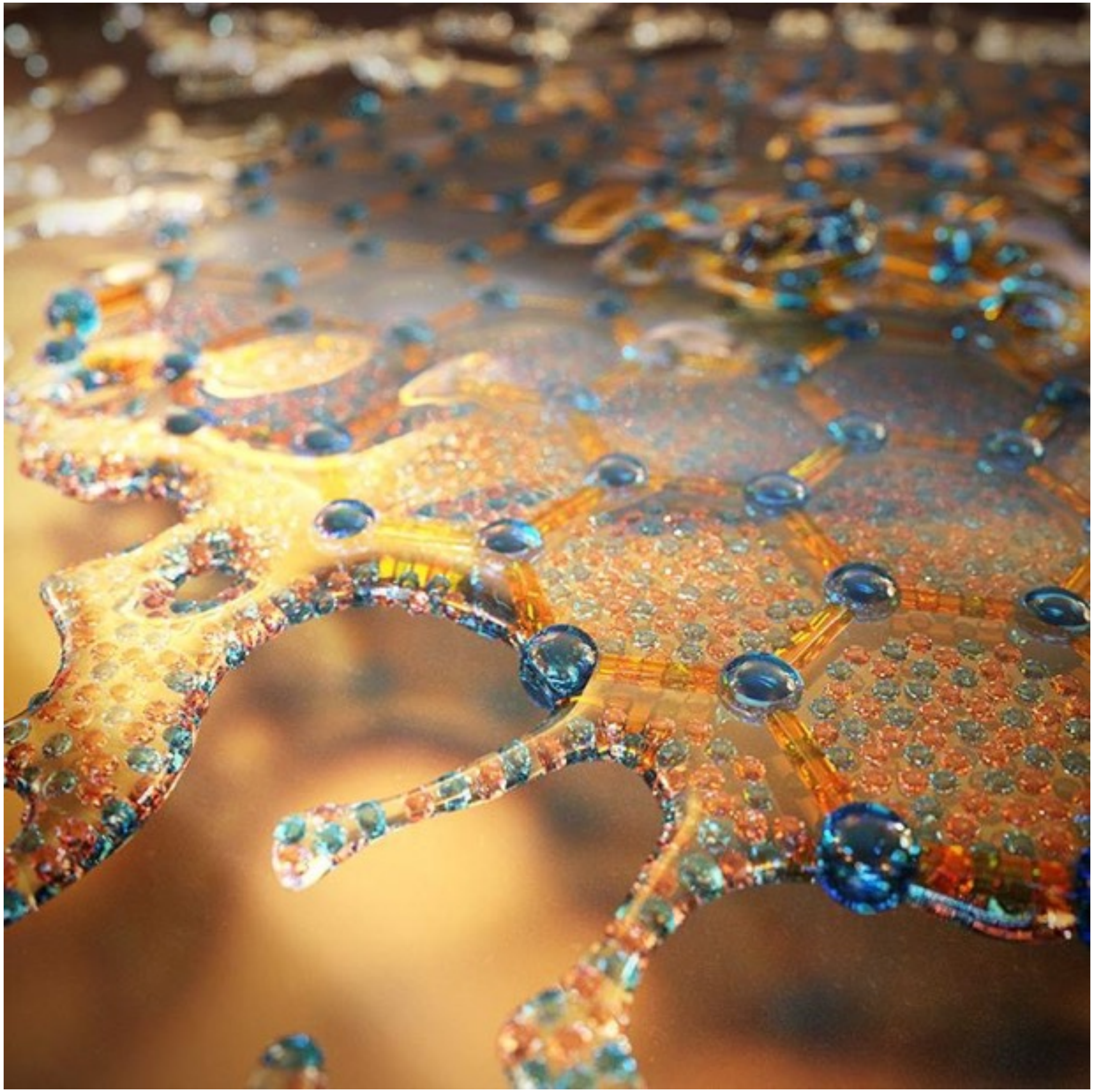


Figure 1. Viscous backflow in doped graphene. (**a,b**) Steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (a) and a viscous Fermi liquid (b). (**c**) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry for vicinity resistance. (**d,e**) Longitudinal conductivity σ_{xx} and $R_{\rm V}$ for this device as a function of n induced by applying gate voltage. $I = 0.3$ μA; $L = 1$ μm. For more detail, see Supplementary Information.

Graphene: "a metal that behaves like water"



Quantum matter without quasiparticles:

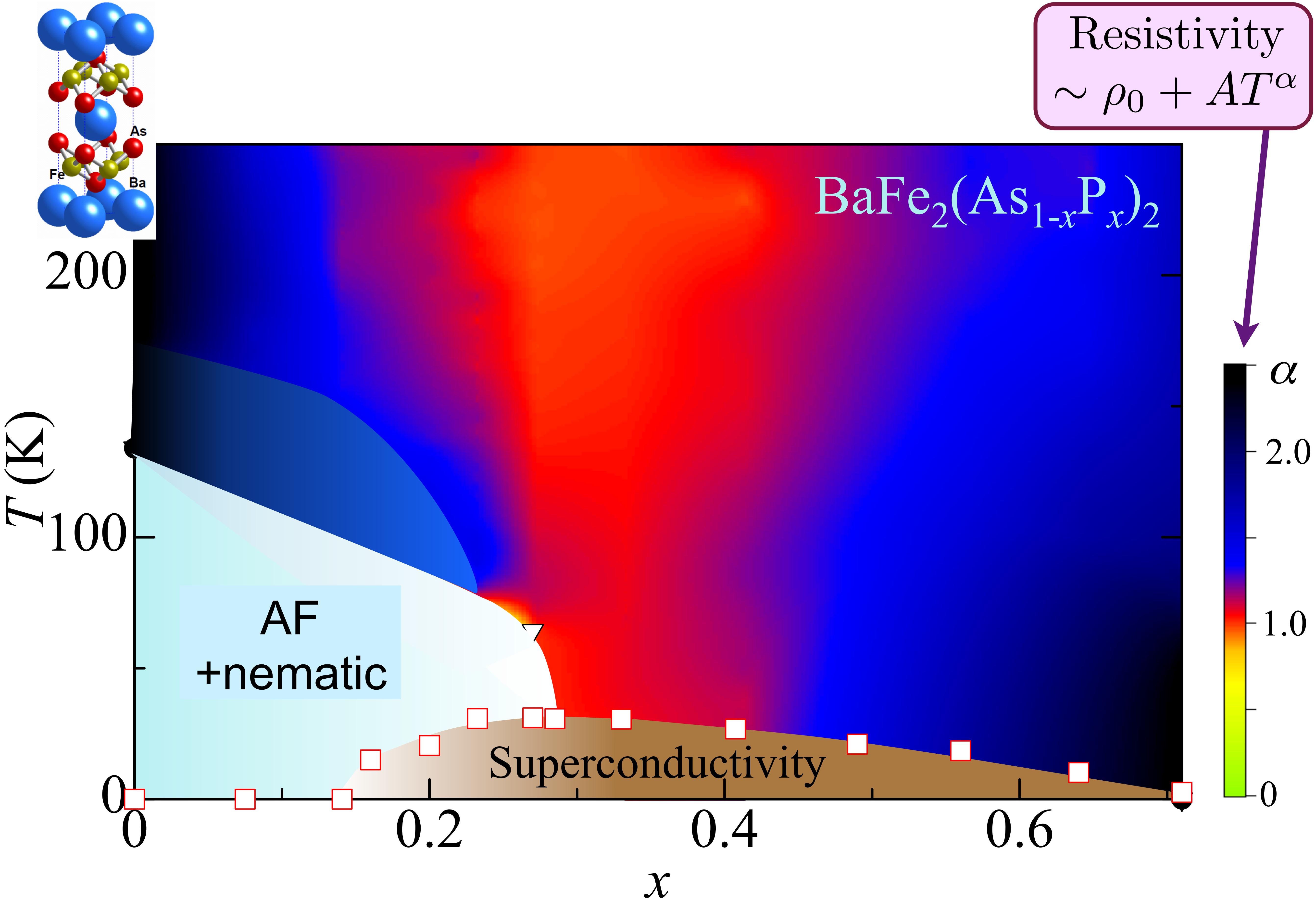
- Superfluid-insulator transition of ultracold bosonic atoms in an optical lattice
- Graphene
- Strange metals in high temperature superconductors
- Quark-gluon plasma
- *Charged black hole horizons in anti-de Sitter space*

Erez Berg

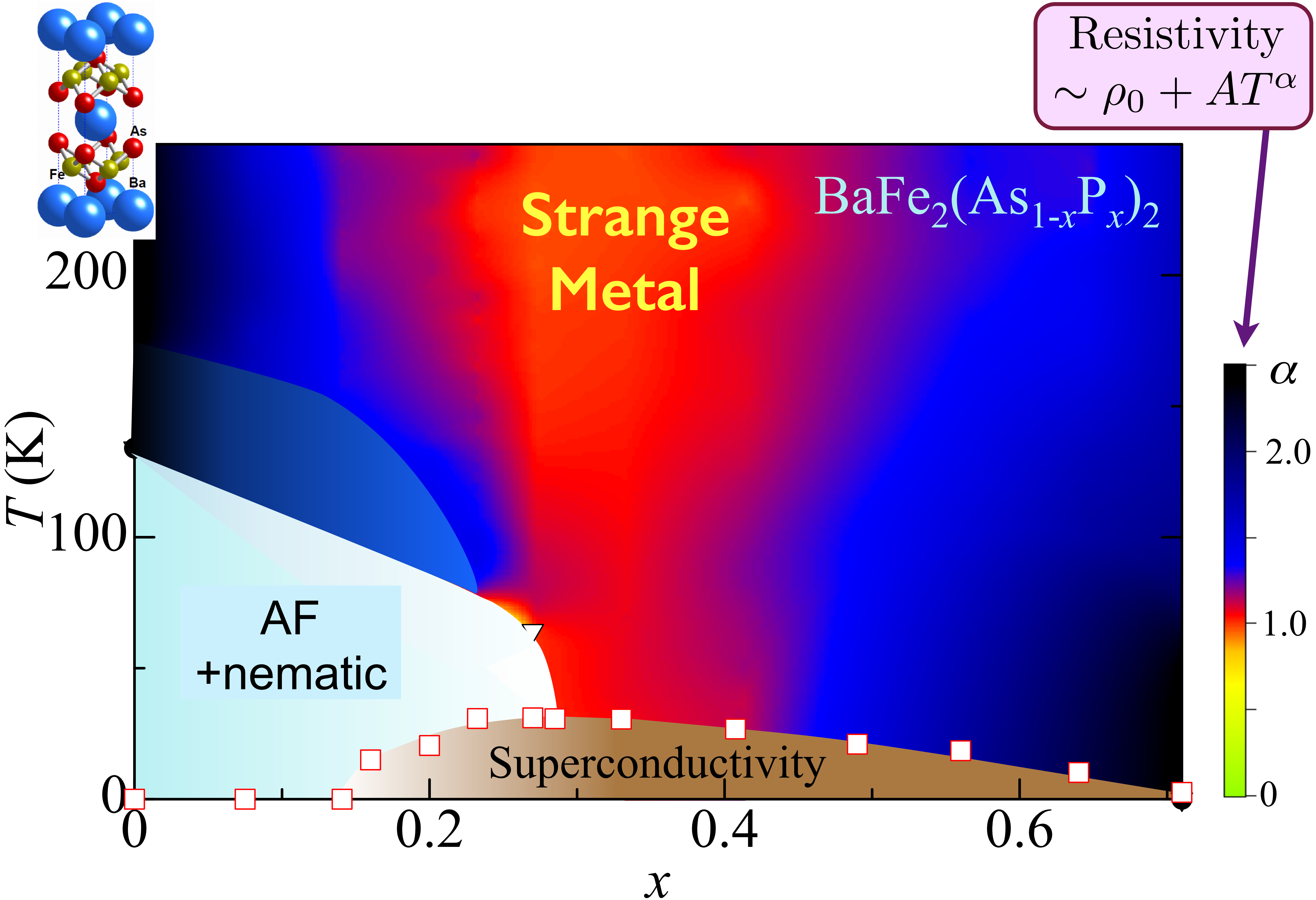
Max Metlitski

Aavishkar Patel

Philipp Strack



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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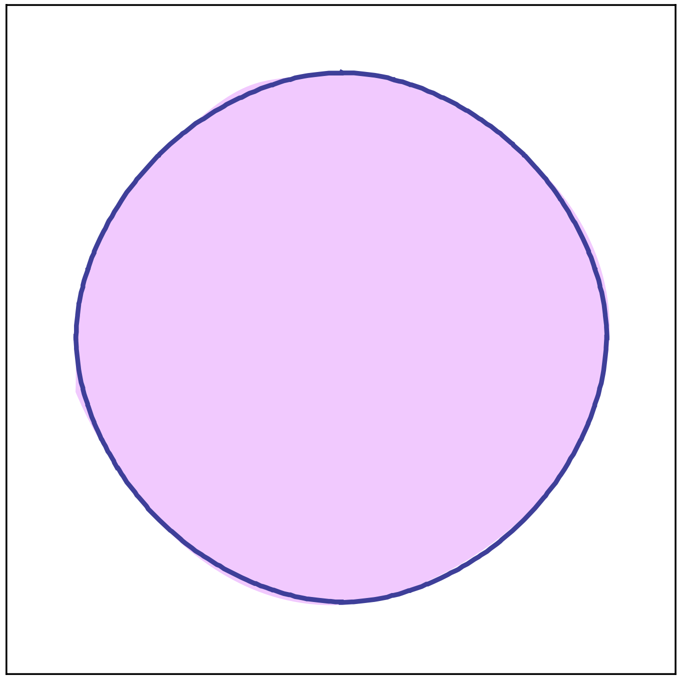
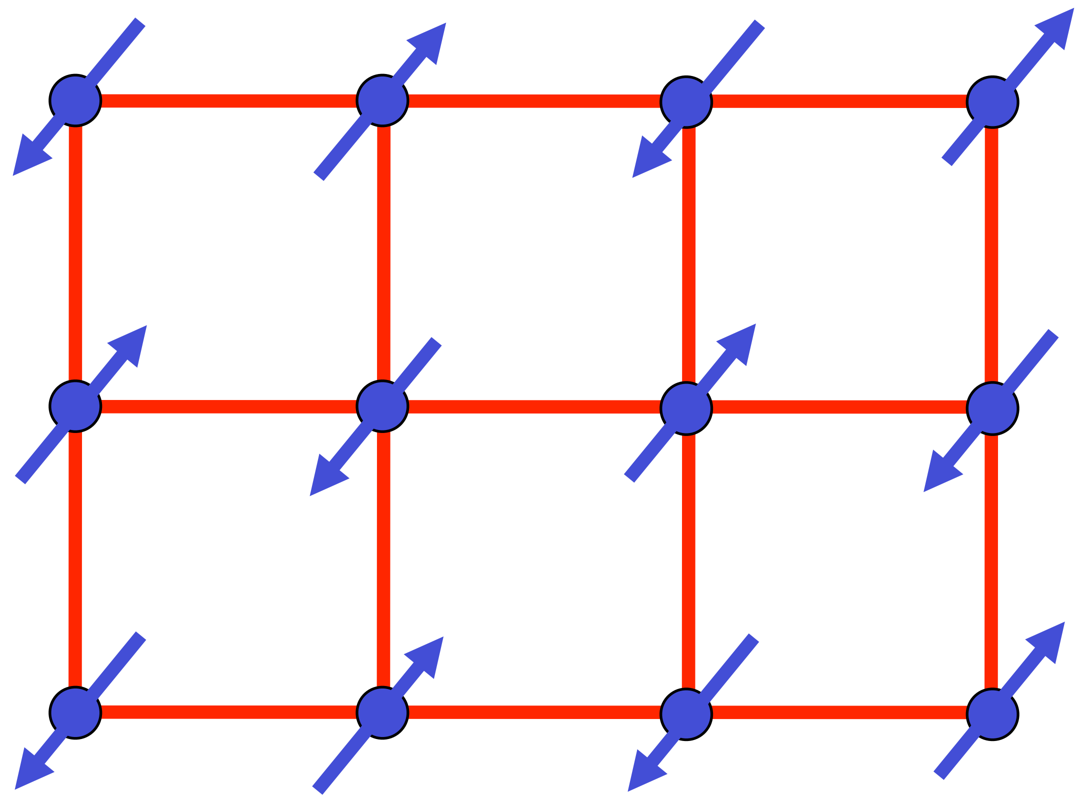
Fermi surface+antiferromagnetism

Metal with "large"
Fermi surface



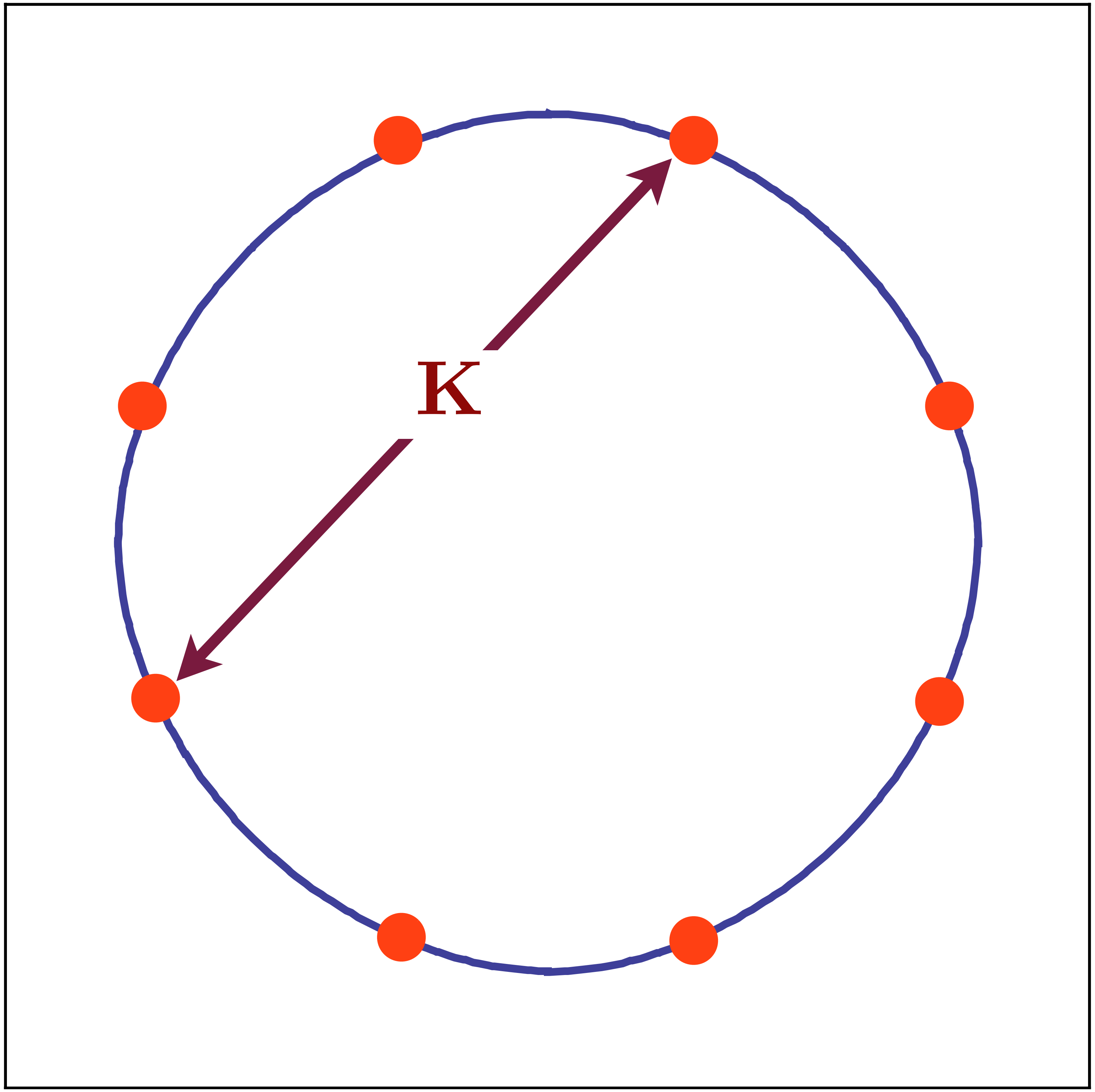


The electron spin polarization obeys

$$\left\langle \vec{S}(\mathbf{r},\tau) \right\rangle = \vec{\varphi}(\mathbf{r},\tau) e^{i\mathbf{K}\cdot\mathbf{r}}$$

where $\mathbf{K}$ is the ordering wavevector.

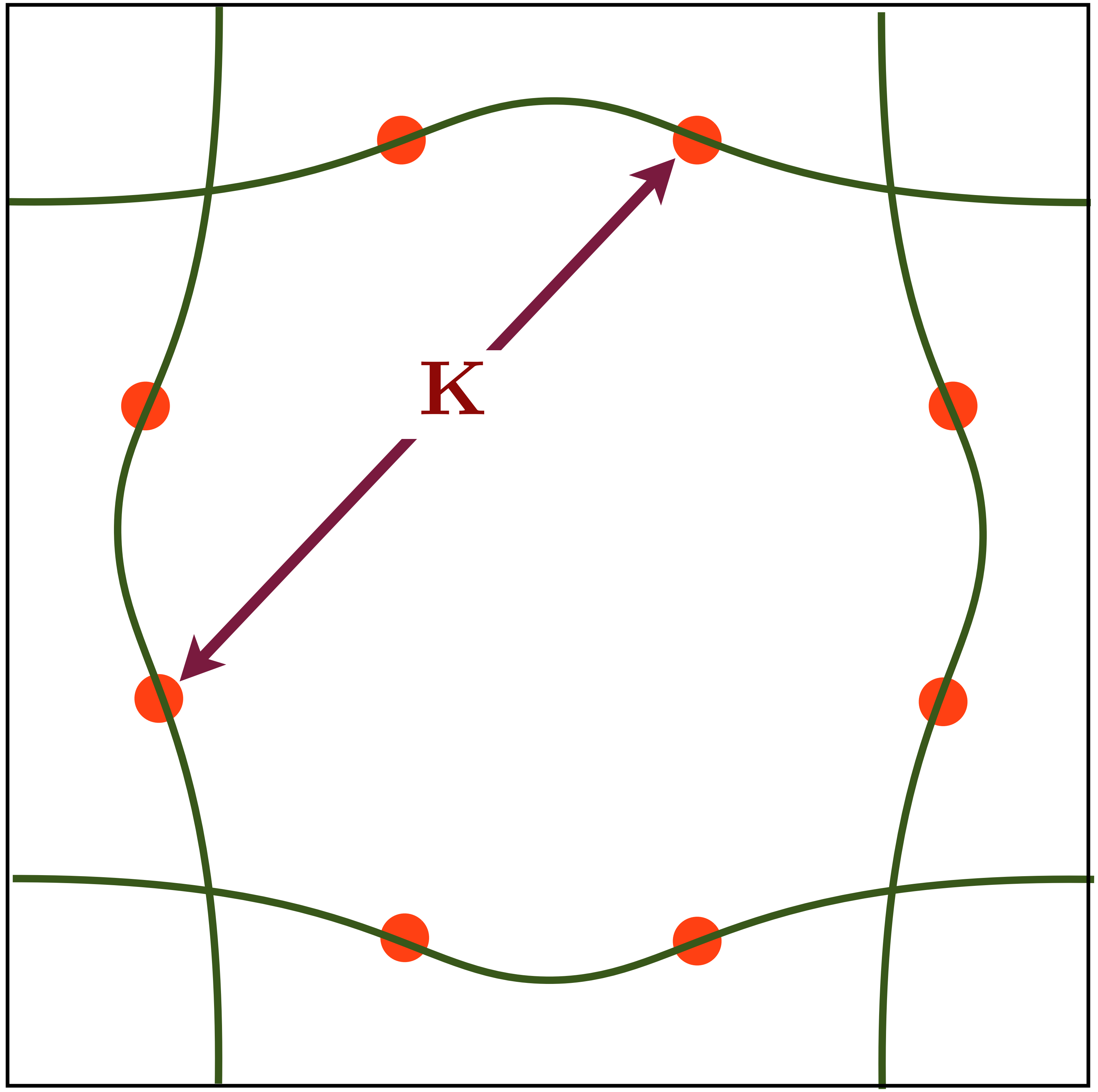
Fermi surface+antiferromagnetism



Hot spots in a single band model

QMC for the onset of antiferromagnetism

Faithful realization of the *generic* universal low energy theory for the onset of antiferromagnetism.

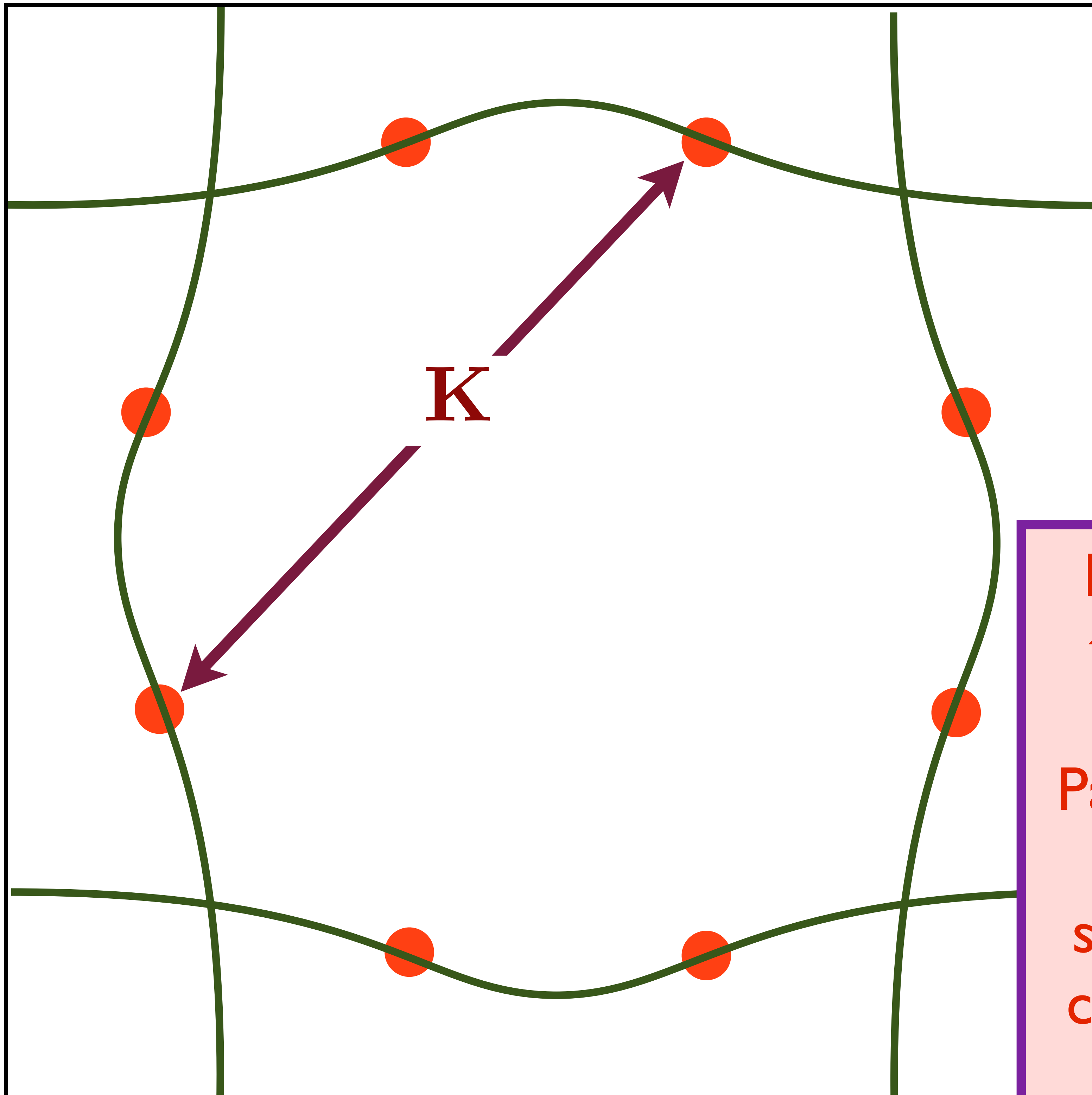


Hot spots in a two band model

E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

QMC for the onset of antiferromagnetism

Sign problem is absent as long as *K* connects hotspots in distinct bands

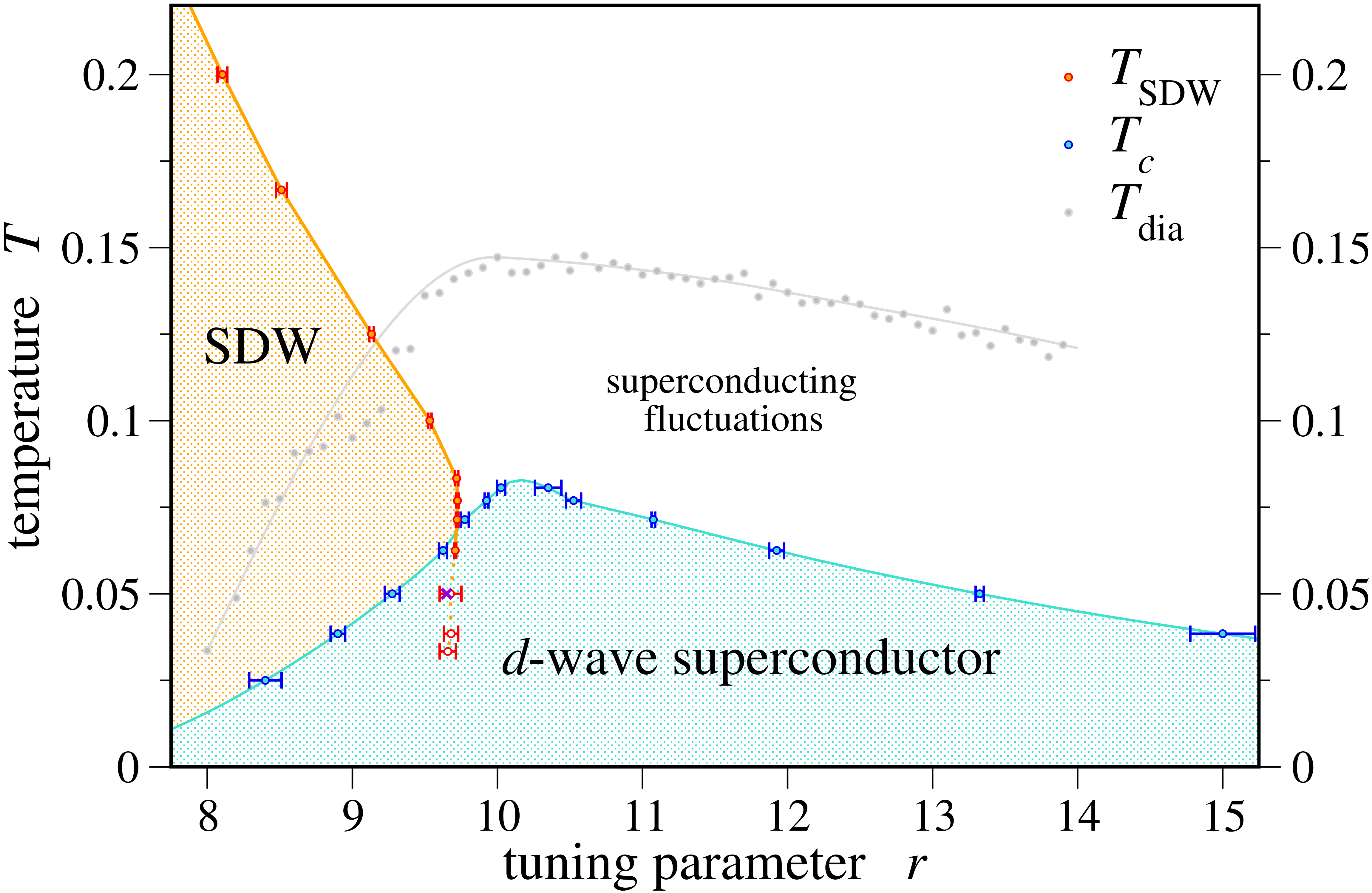


Hot spots in a two band mode

E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

Requires only time-reversal symmetry. Particle-hole or point-group symmetries or commensurate densities ***not*** required !

Sign-problem-free QMC for the onset of antiferromagnetism in a metal



E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).
Yoni Schattner, Max H. Gerlach, Simon Trebst, and Erez Berg, arXiv:1512.07257

Transport near SDW critical point

- Assume excitations around the full Fermi surface locally thermalize via interactions with excitations of the SDW boson φ_α. These interactions conserve a (suitably defined) total momentum.

S. A. Hartnoll, D. M. Hofman, M. A. Metlitski and S. Sachdev, PRB **84**, 125115 (2011)

A. A. Patel and S. Sachdev, PRB **90**, 165146 (2014)

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- Momentum relaxation occurs via disorder perturbations which change the local position of the quantum critical point.

$$\begin{aligned} H &= H_0 - \int d^d x \, h(x) \, \varphi_\alpha^2(x) \\ \overline{h(x) h(x')} &= h_0^2 \, \delta^d(x - x') \end{aligned}$$

A. A. Patel and S. Sachdev, PRB **90**, 165146 (2014)

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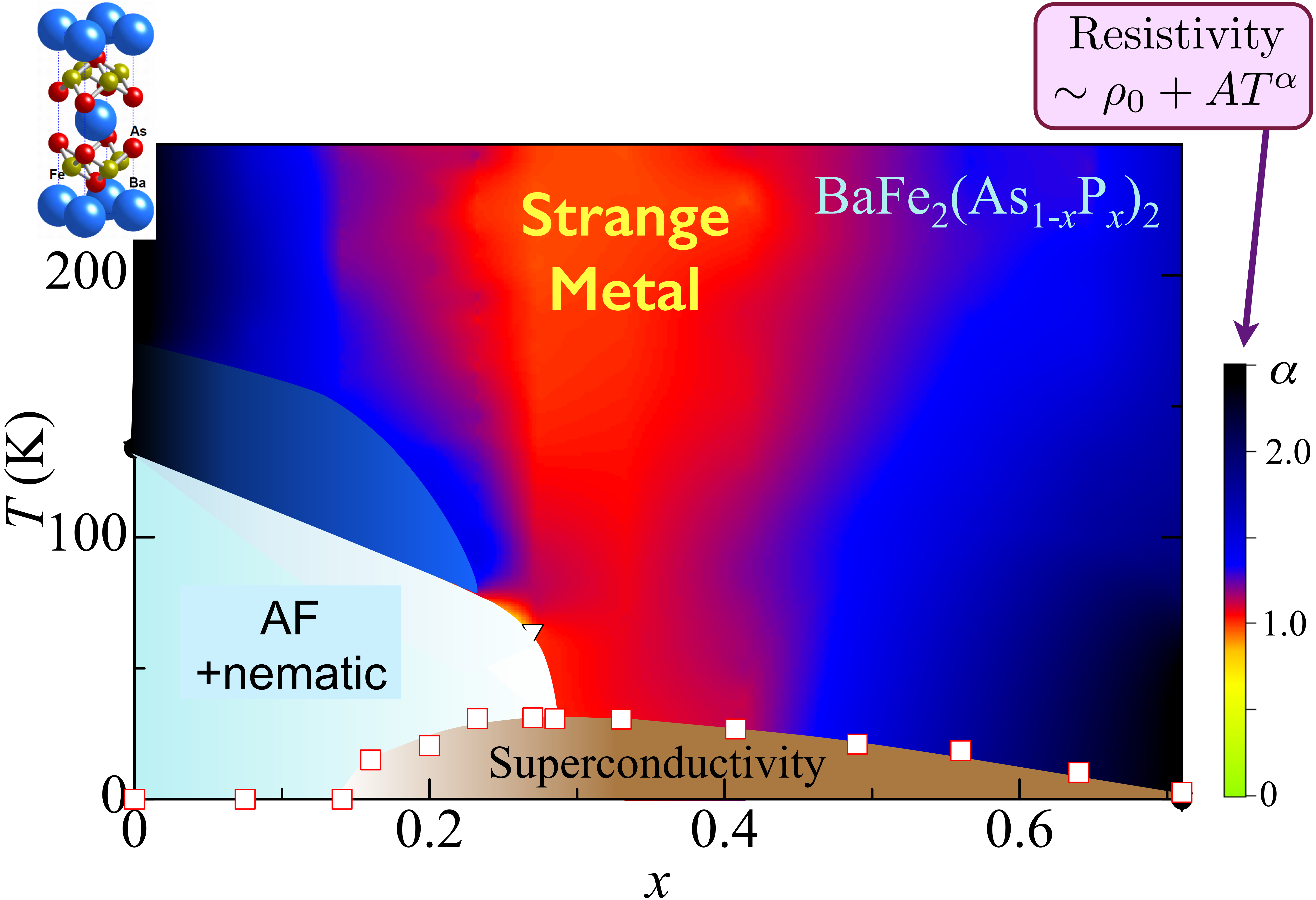
\overline{h(x) h(x')} &= h_0^2 \, \delta^d(x - x')
\end{aligned}
$$

- Memory function methods yield

$$
\begin{aligned}
\frac{1}{\tau_{\text{imp}}} &\sim \lim_{\omega \to 0} h_0^2 \int d^2 q \, q_x^2 \frac{\text{Im} \left(G^{\text{R}}_{\varphi_\alpha^2, \varphi_\alpha^2}(q, \omega) \right)_{H_0}}{\omega} \\
&\sim h_0^2 \, T \quad \text{(up to logarithms)}
\end{aligned}
$$

A. A. Patel and S. Sachdev, PRB **90**, 165146 (2014)



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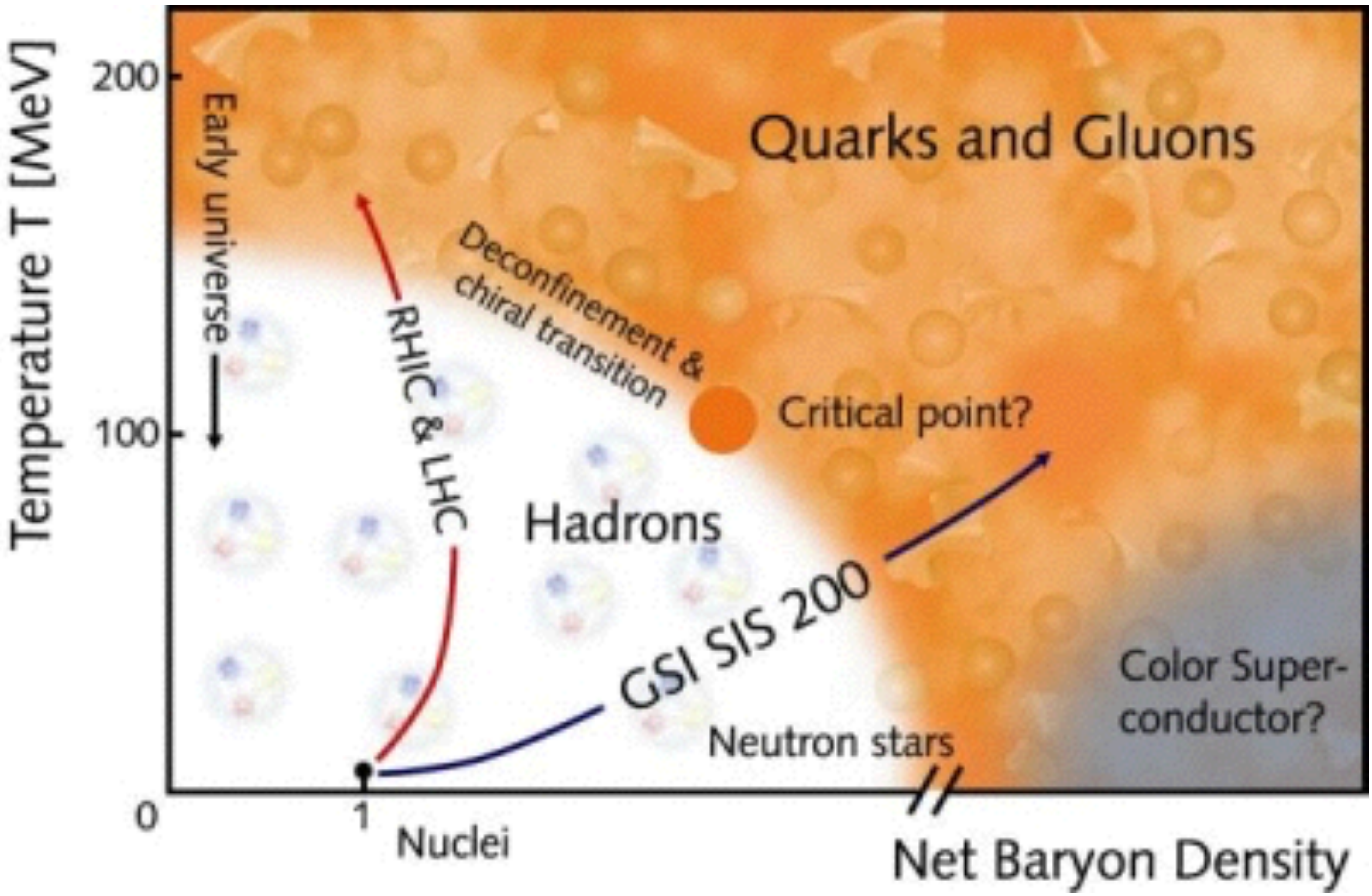
Quark-gluon plasma



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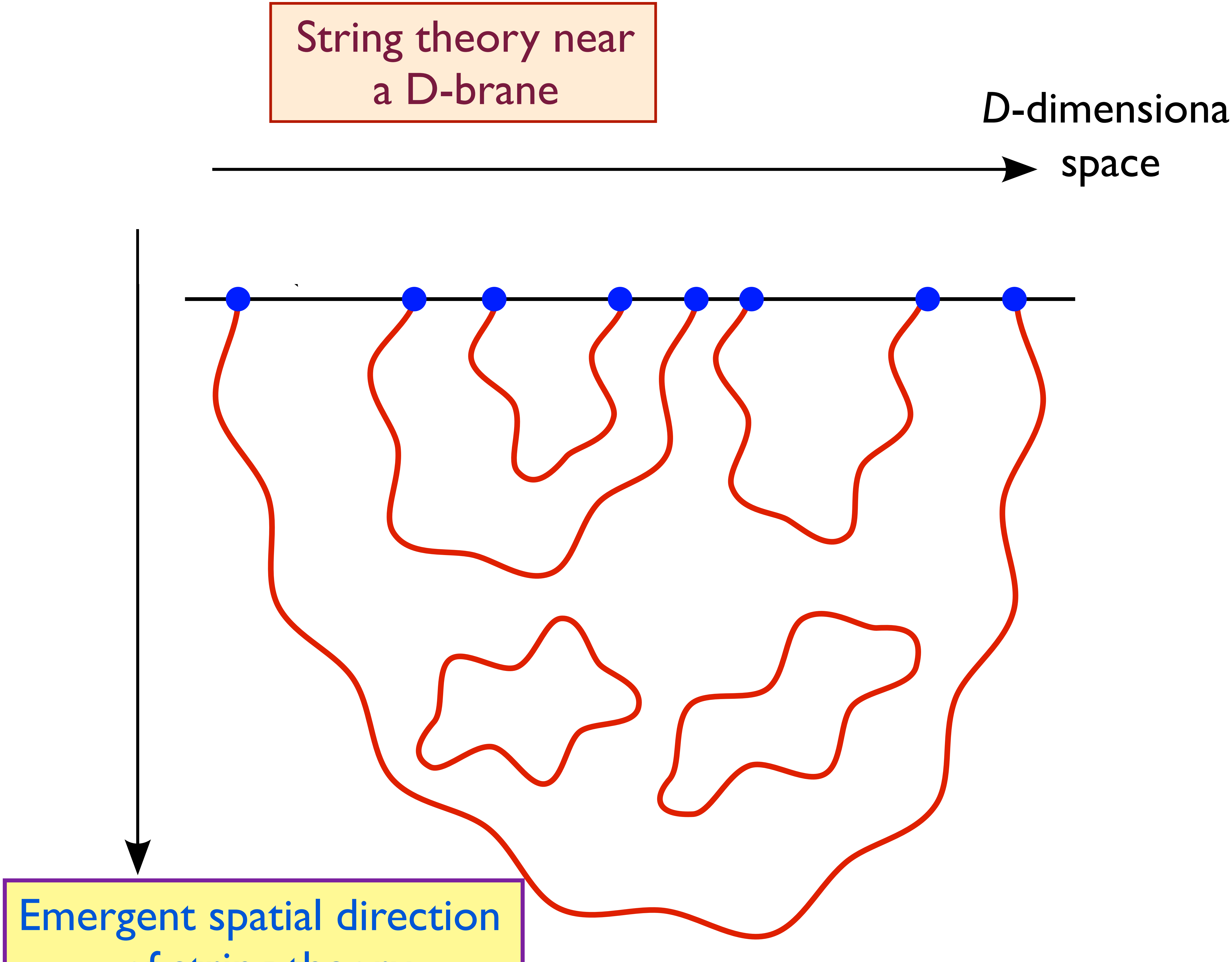

Brian Swingle, arXiv:0905.1317

Quantum matter without quasiparticles:

- No quasiparticle excitations
- Shortest possible "collision time", or more precisely, fastest possible local equilibration time $\sim \dfrac{\hbar}{k_B T}$
- Continuously variable density, $\mathcal{Q}$
  (conformal field theories are usually at fixed density, $\mathcal{Q} = 0$)
- Theory built from hydrodynamics/holography
  /memory-functions/strong-coupled-field-theory
- Exciting experimental realization in graphene.