Quantum entanglement and the phases of matter

Physical Research Laboratory
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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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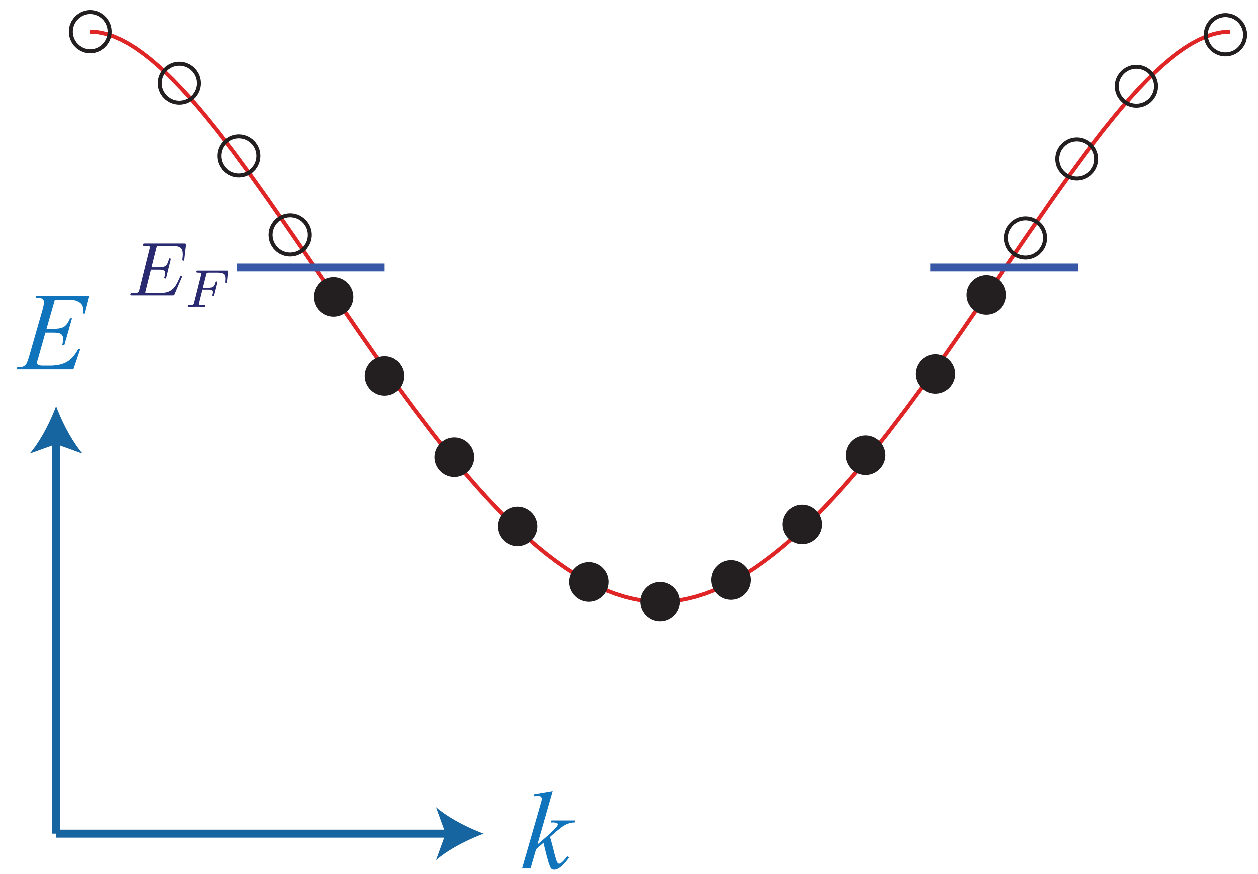
Foundations of quantum many body theory:

1. Ground states <u>connected</u> adiabatically to independent electron states

<u>Metals</u>



Foundations of quantum many body theory:

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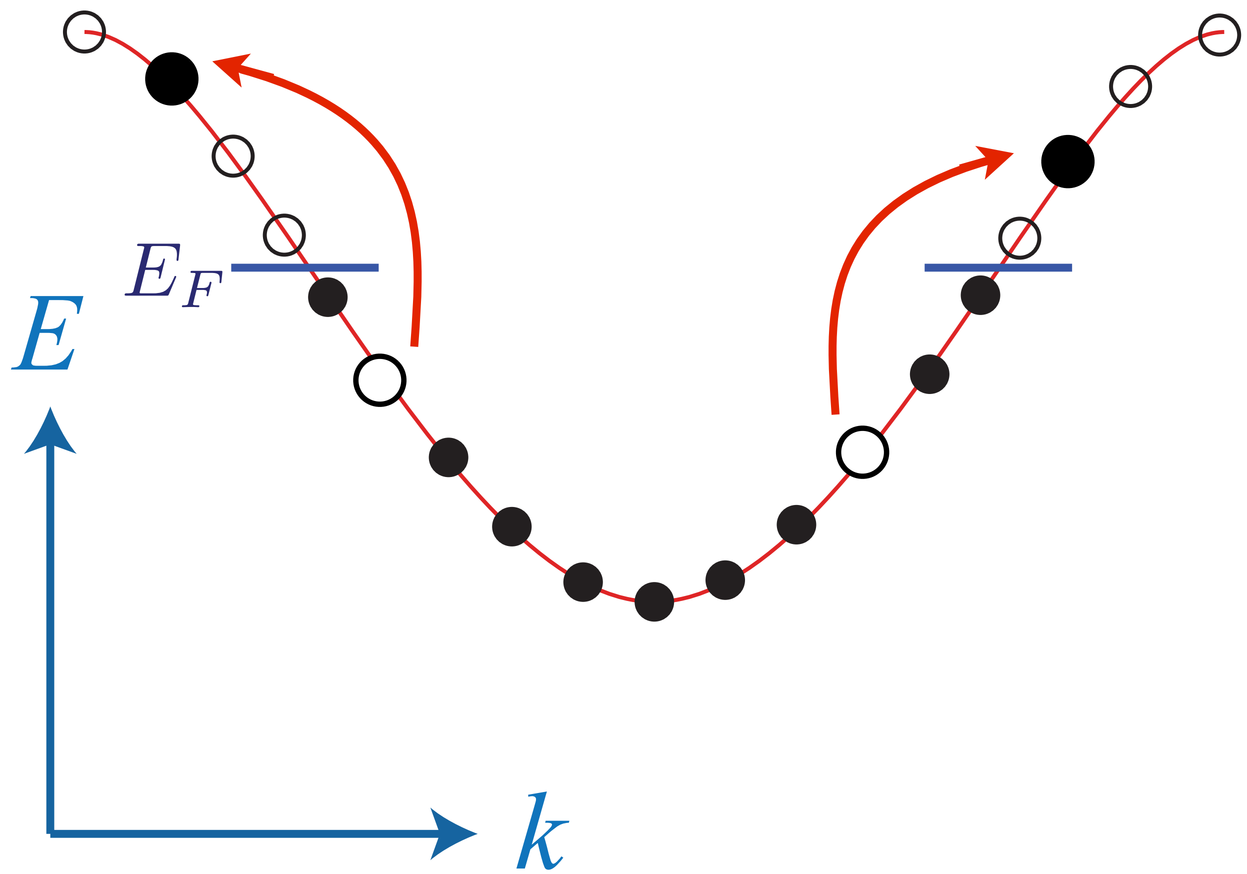
2. Boltzmann-Landau theory of quasiparticles

Metals



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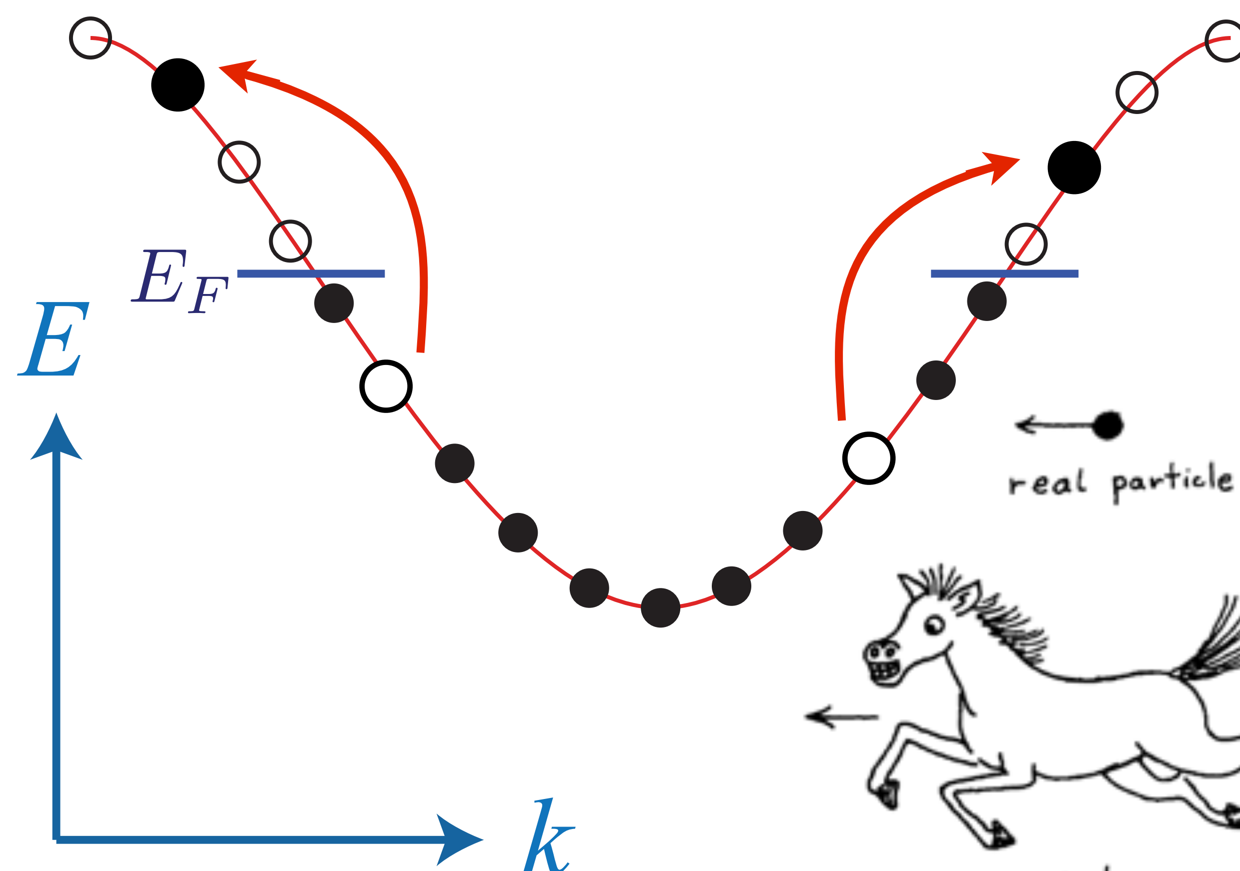
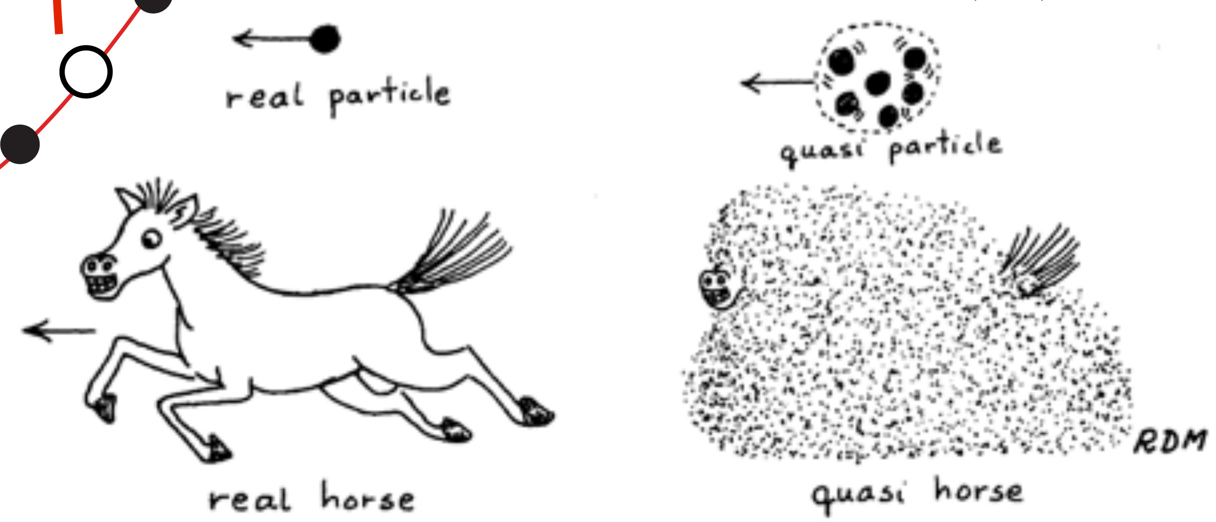
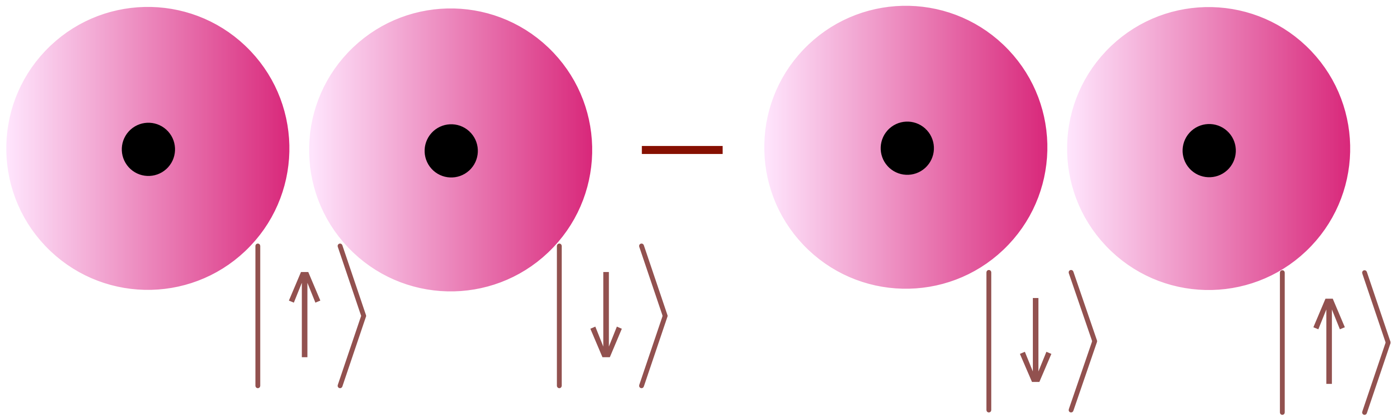


A Guide to Feynman Diagrams in the Many-body Problem, R.D. Mattuck, Dover (1992)



Quantum entanglement:

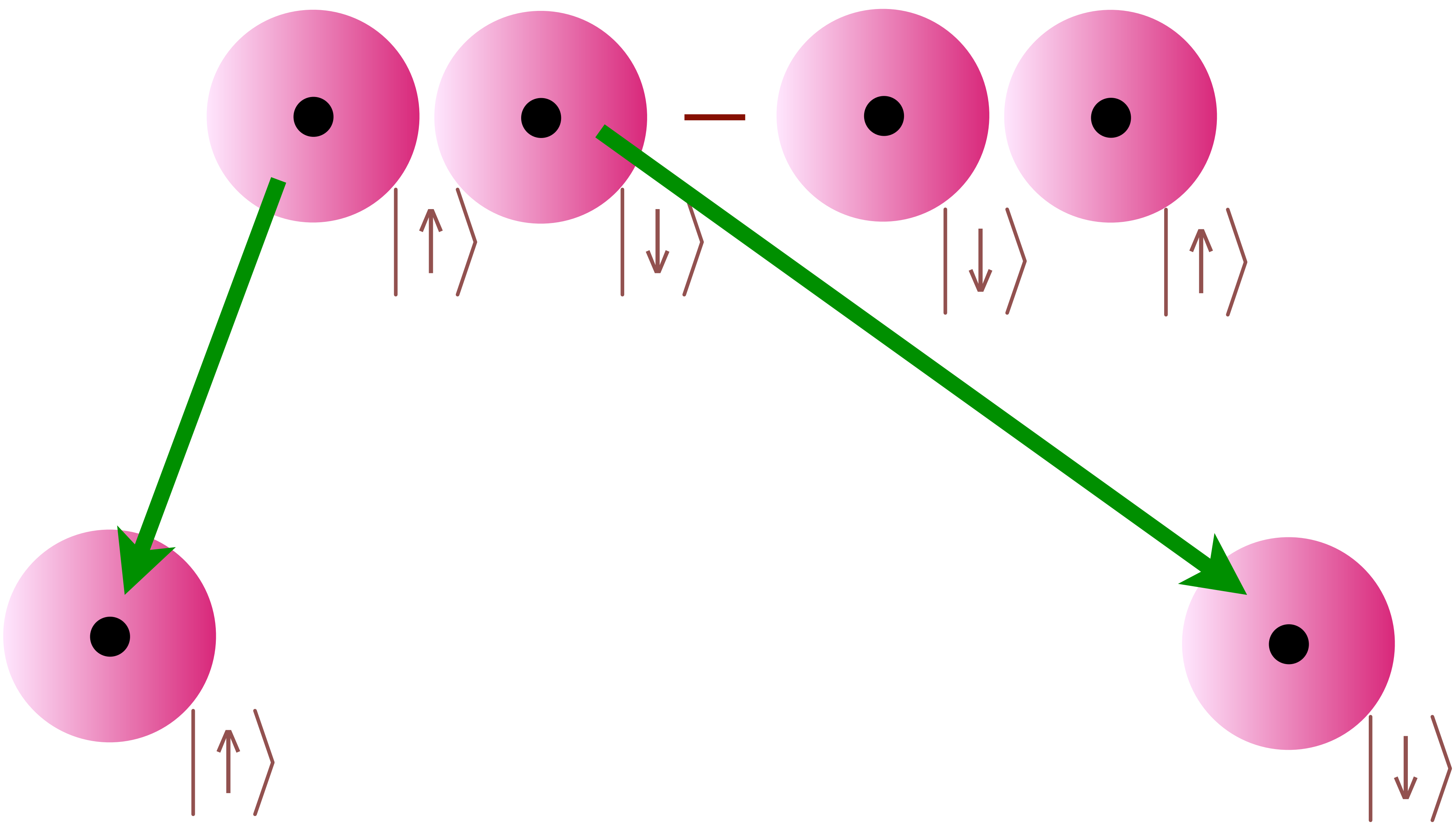
EPR pair: Non-local correlations between quantum measurements due to superposition between many-electron states



Hydrogen molecule

Quantum entanglement:

EPR pair: Non-local correlations between quantum measurements due to superposition between many-electron states



Quantum entanglement:

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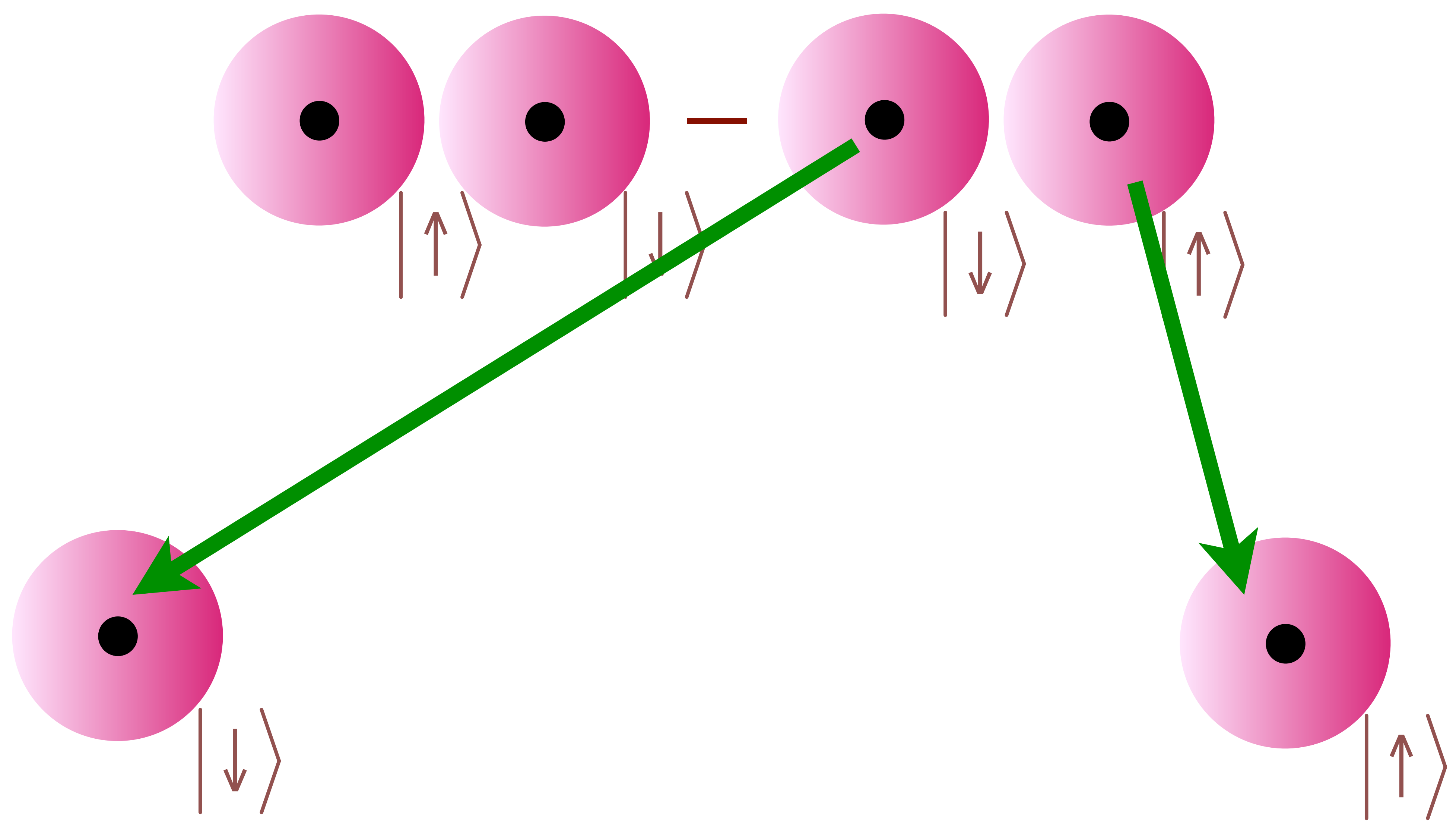

Modern phases of quantum matter:

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.

Modern phases of quantum matter:

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Field theory: topological quantum field theory

Modern phases of quantum matter:

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2. No quasiparticles

<u>Quantum matter without quasiparticles:</u>

1. Ground states <u>disconnected</u> 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*

Quantum matter without quasiparticles:

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Field theory example: conformal field theory

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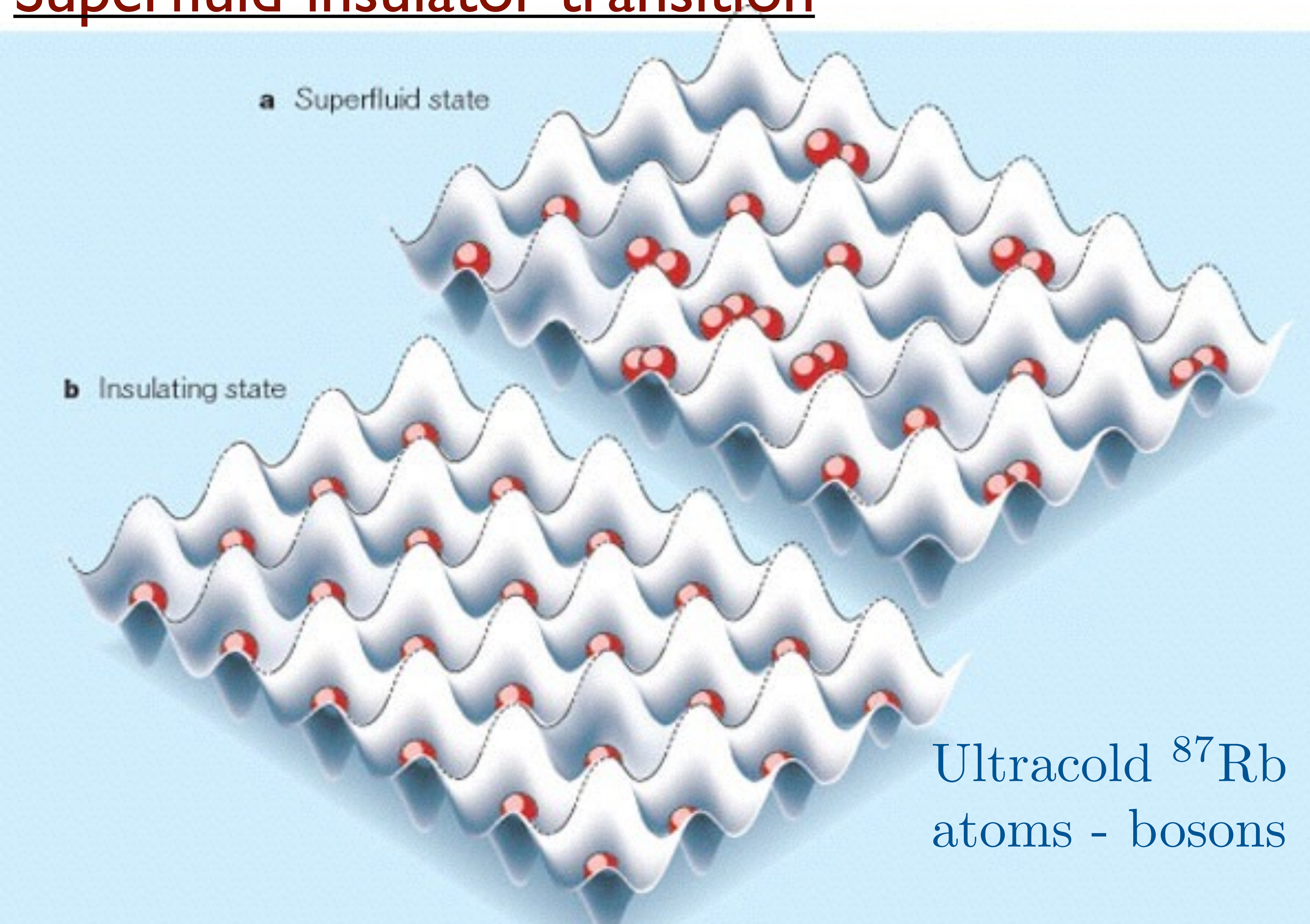
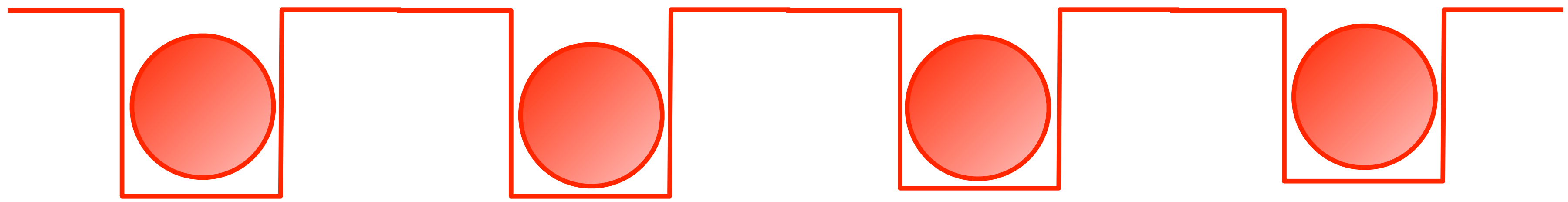
Superfluid-insulator transition



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)

$U \gg t$



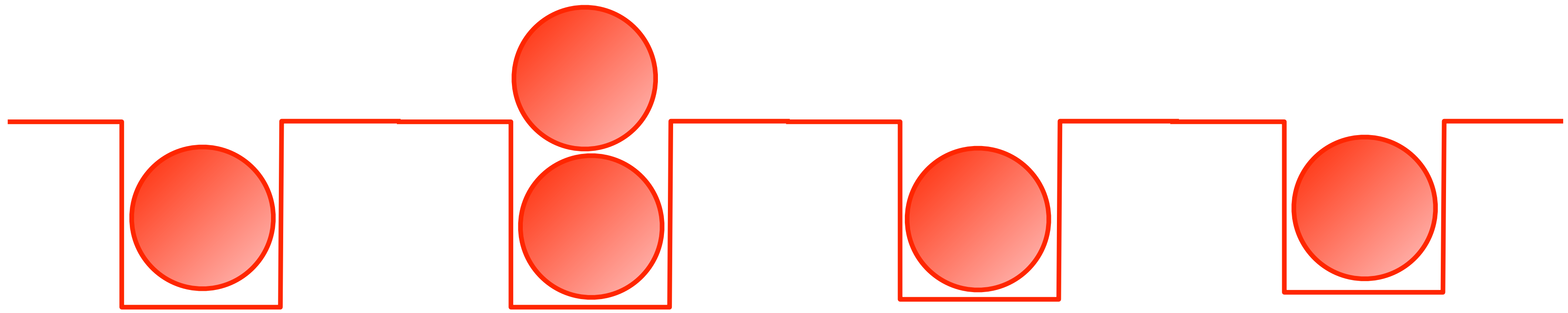
Insulator (the vacuum)
at large repulsion between bosons

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

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 $= U$
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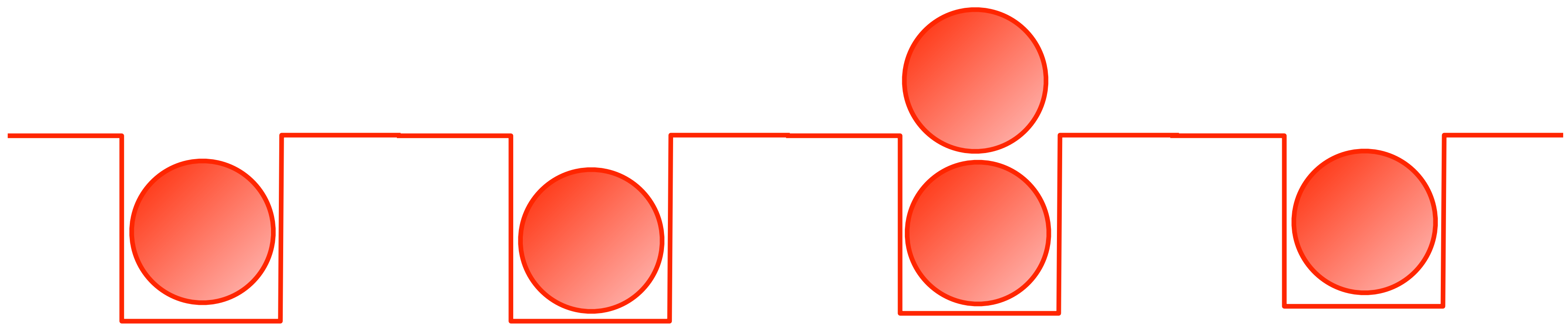
Excitations of the insulator:



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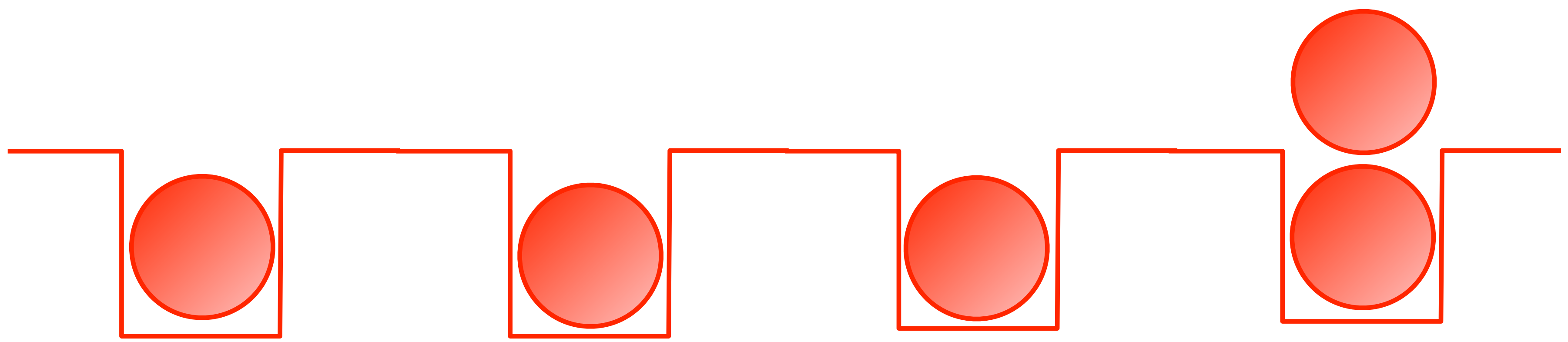

Particles $\sim \psi^{\dagger}$

On-site repulsion between bosons $= U$
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Excitations of the insulator:

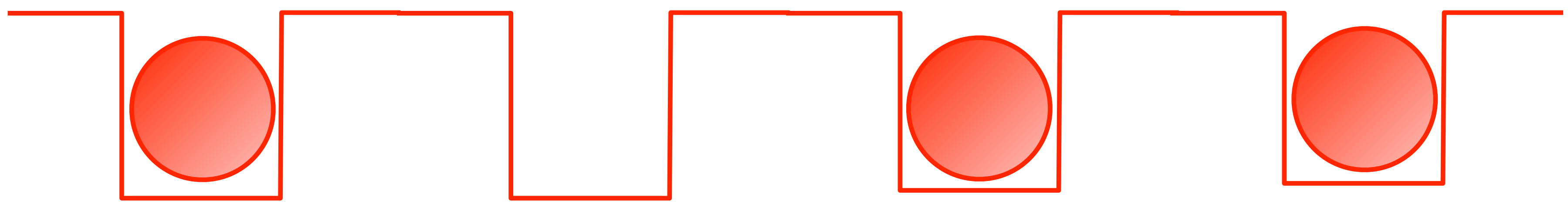
Holes $\sim \psi$

On-site repulsion between bosons $= U$

Tunneling amplitude between sites $= t$

$U \gg t$

Excitations of the insulator:



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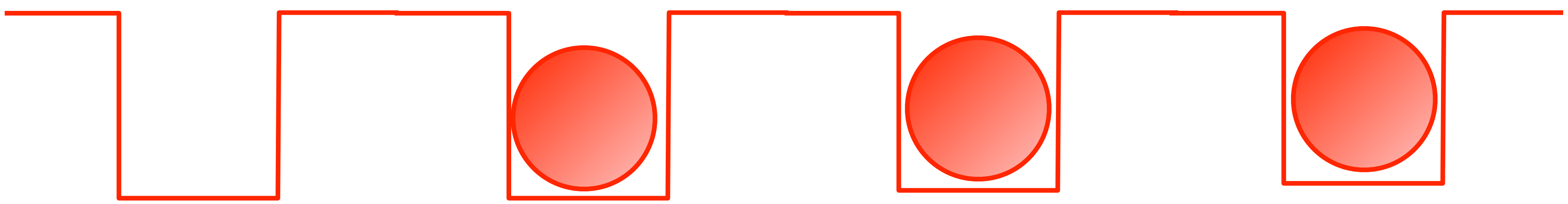
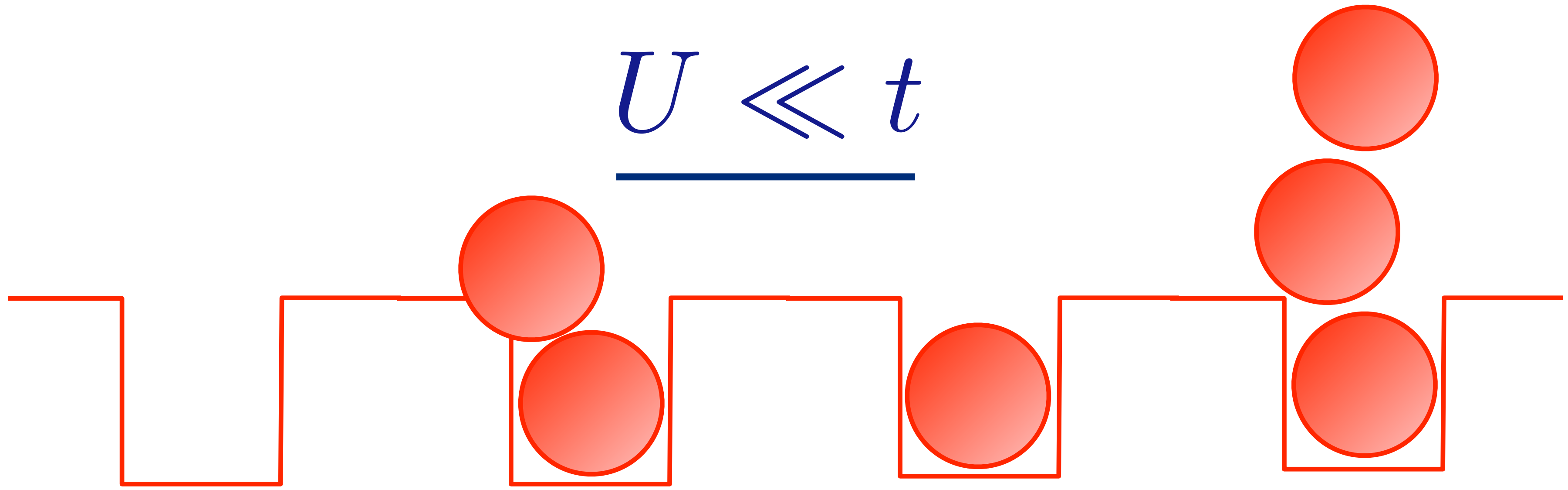
Excitations of the insulator:



Holes $\sim \psi$

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

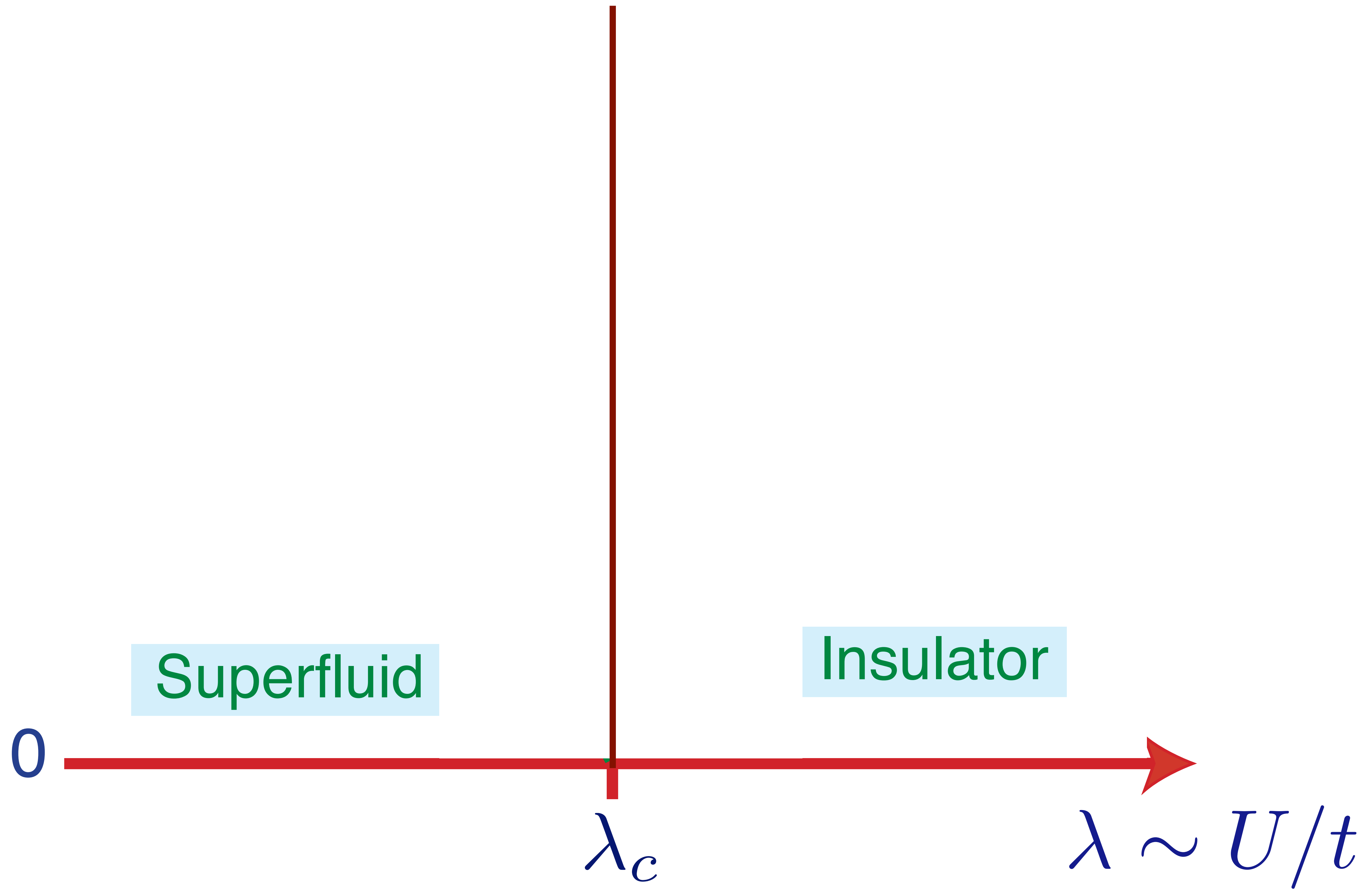
$$U \ll t$$



Superfluid
at small repulsion between bosons

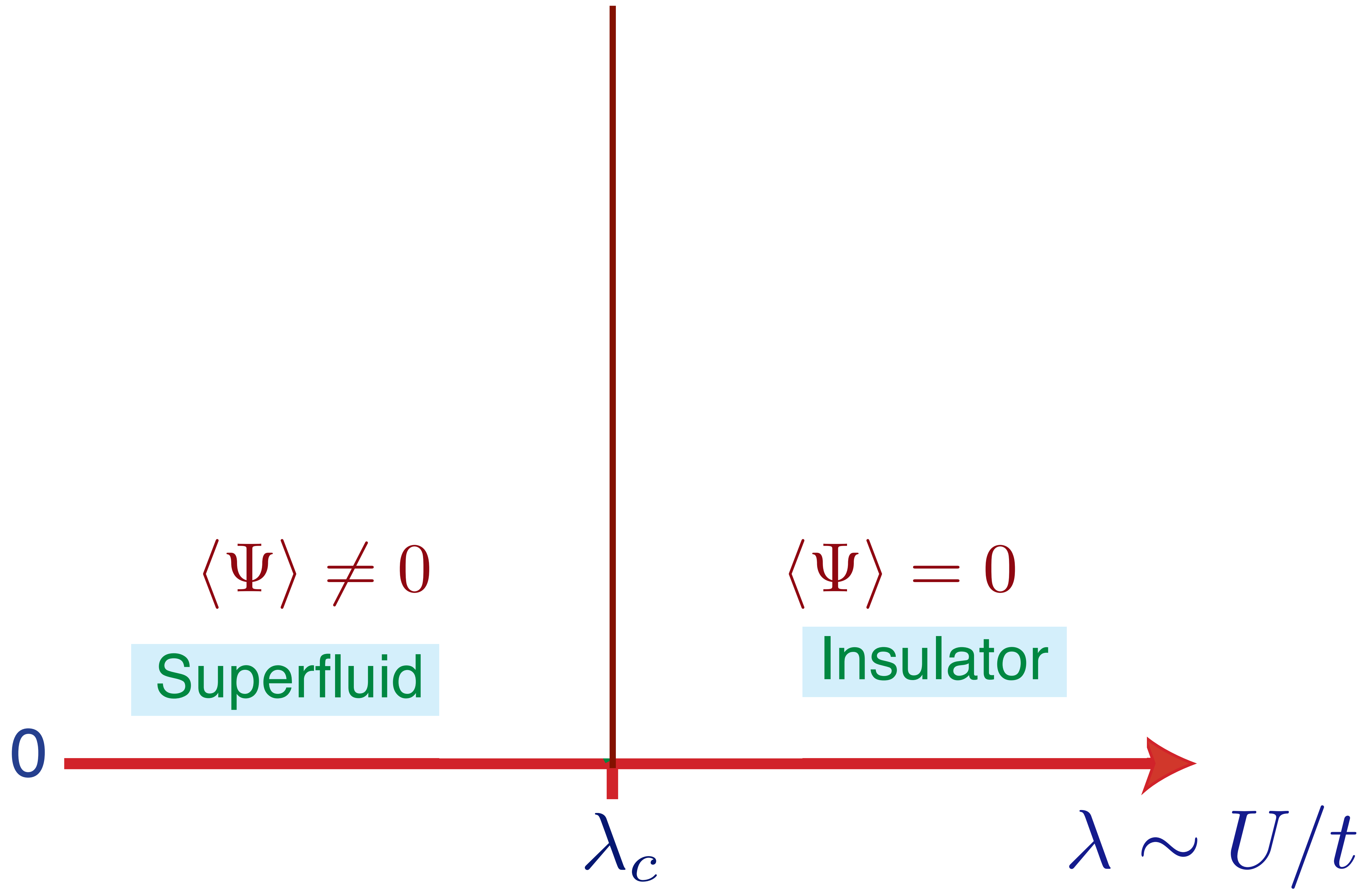
$$|\text{Ground state}\rangle = \left[\sum_i b_i^\dagger\right]^N |0\rangle$$

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



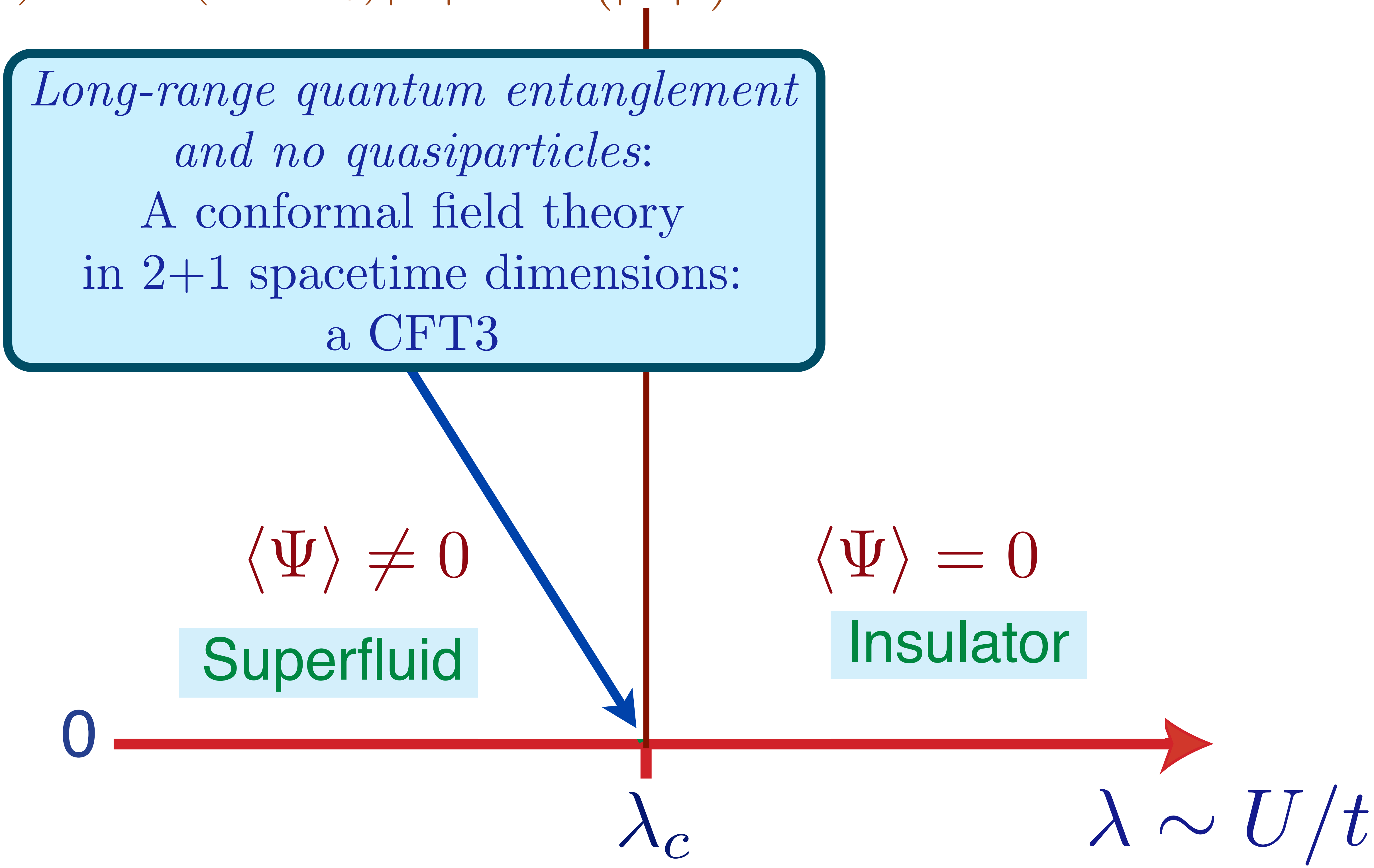
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$

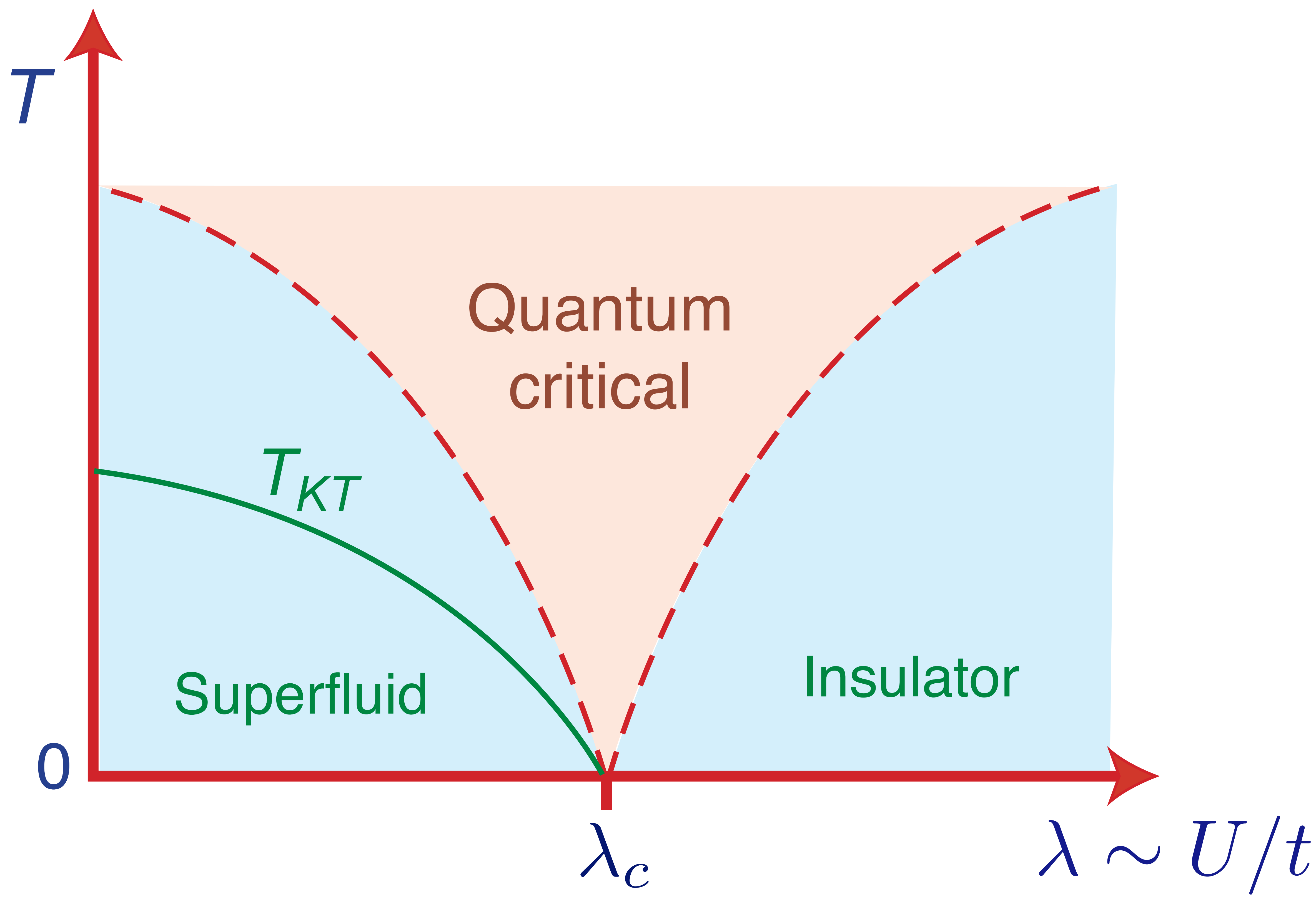
$\Psi \rightarrow$ a complex field representing the Bose-Einstein condensate of the superfluid



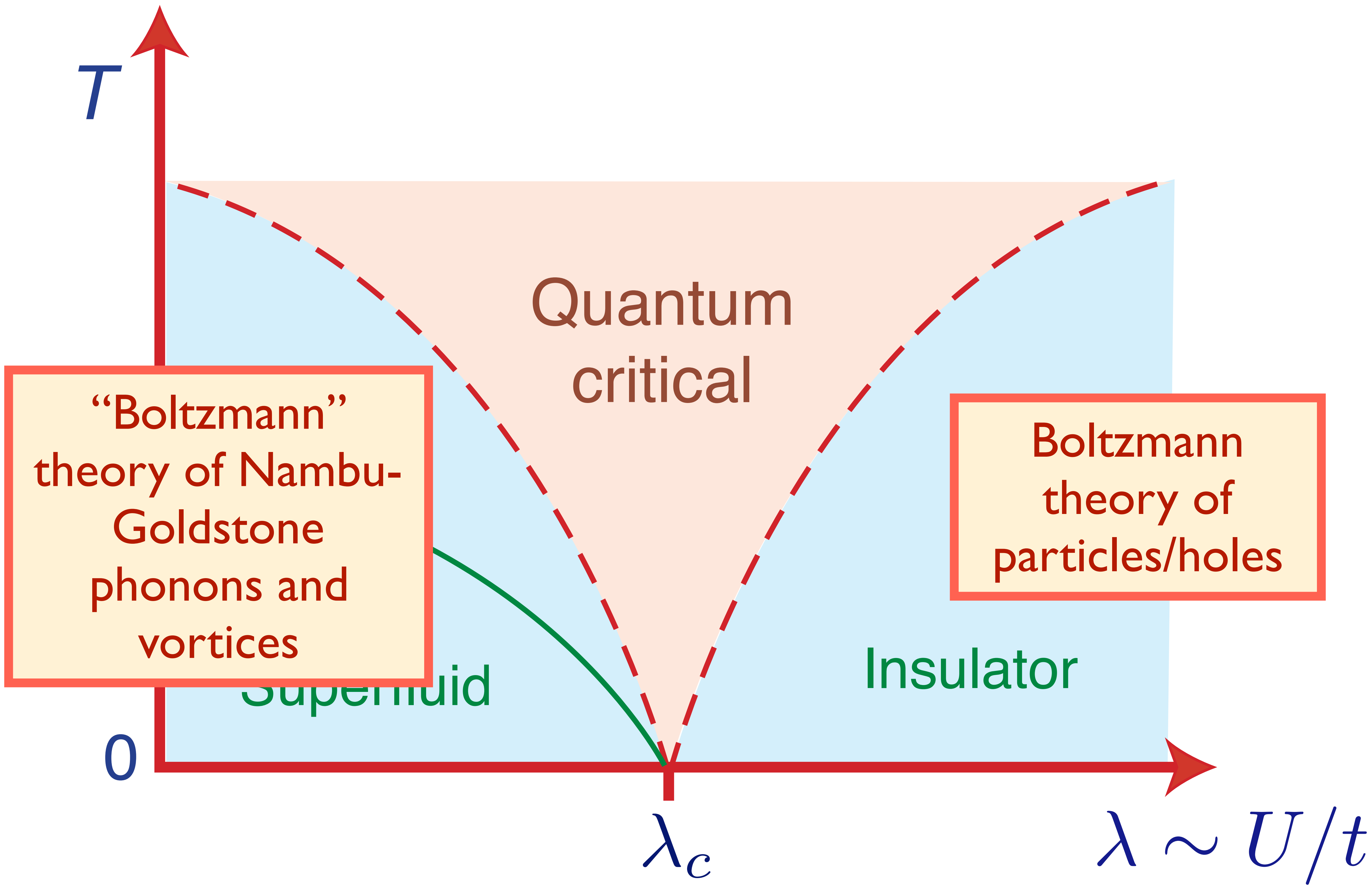
$$\mathcal{S} = \int d^2r dt \left[|\partial_t \Psi|^2 - c^2 |\nabla_r \Psi|^2 - V(\Psi) \right]$$

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

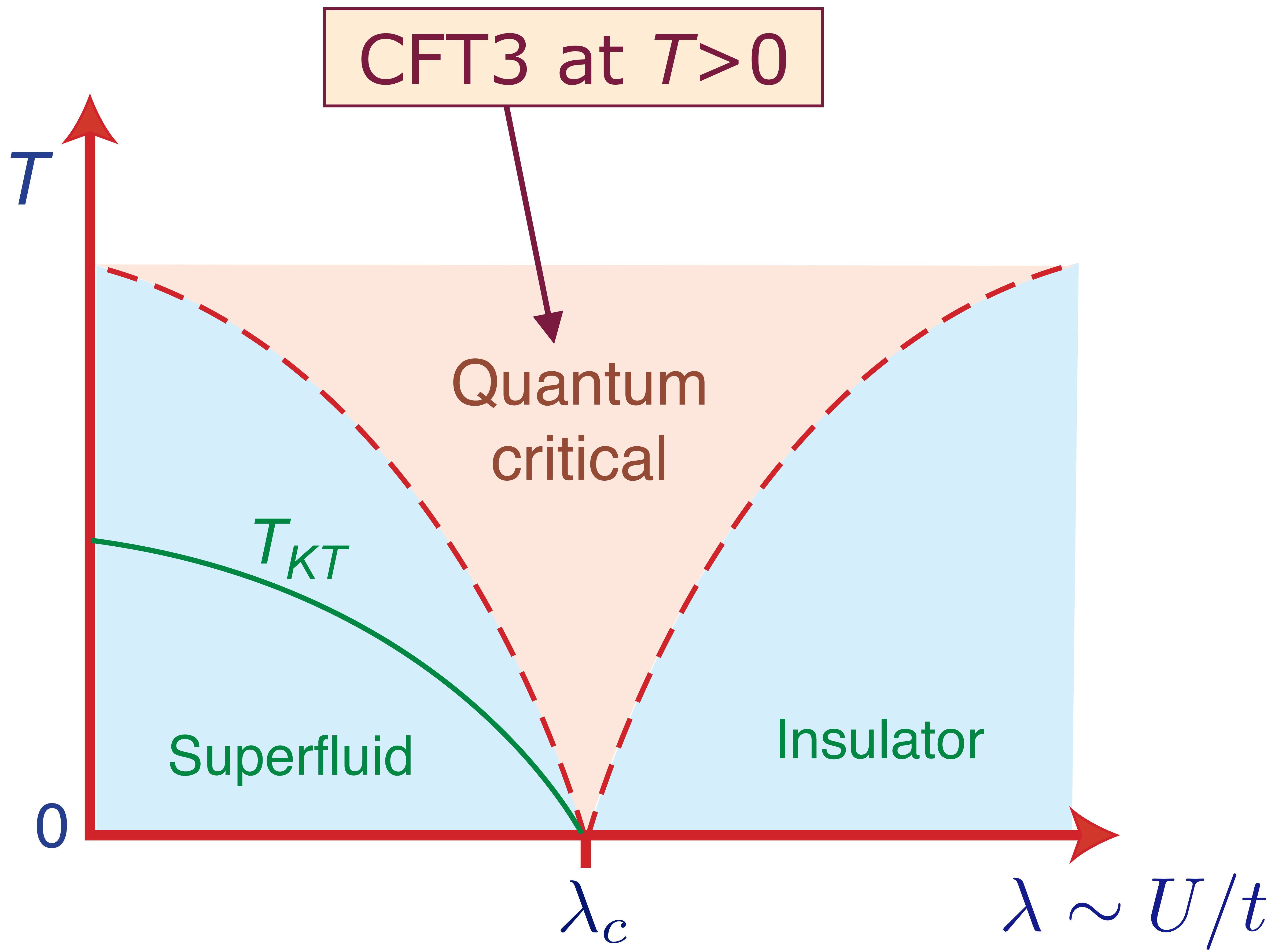




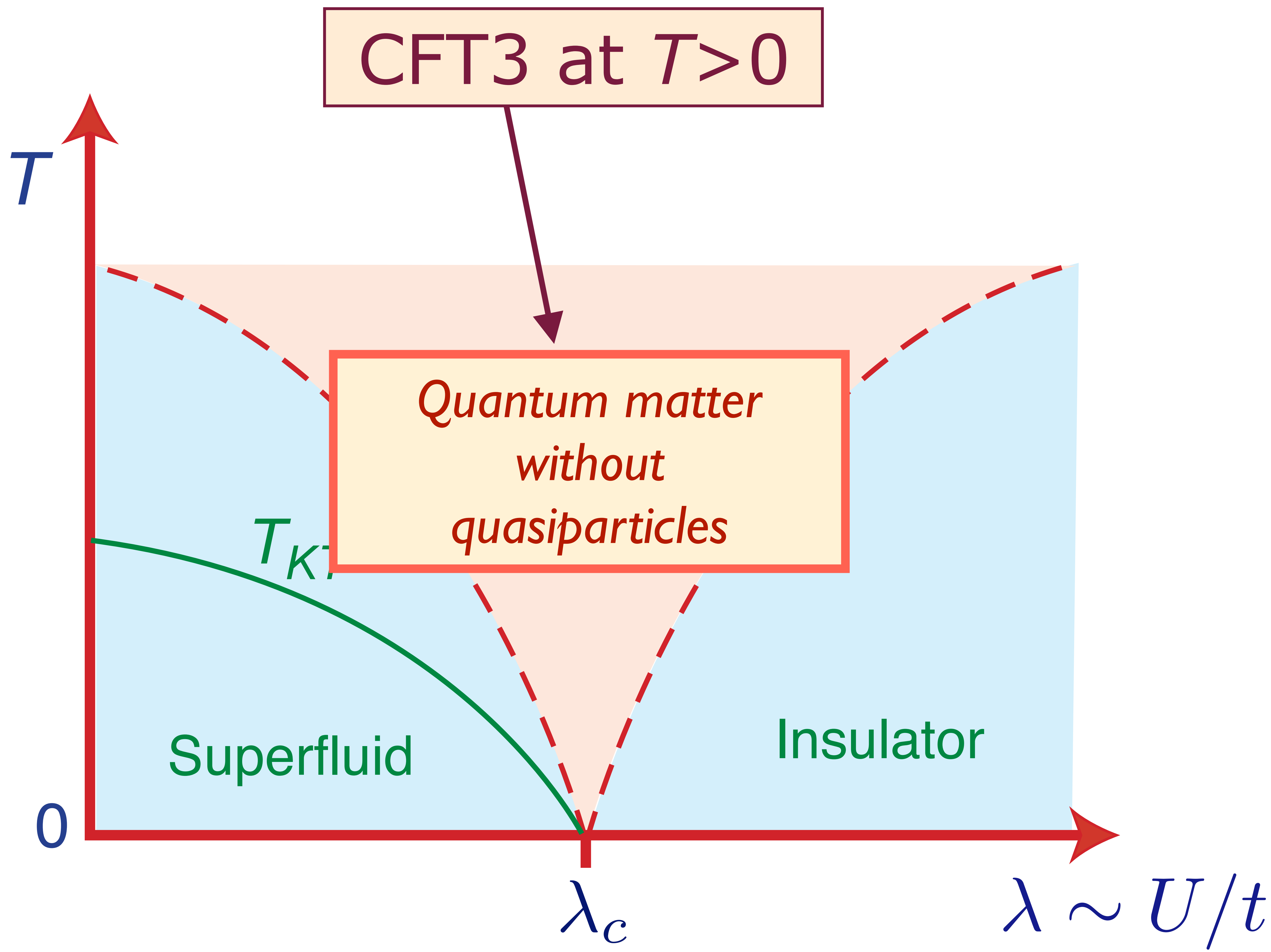
T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$



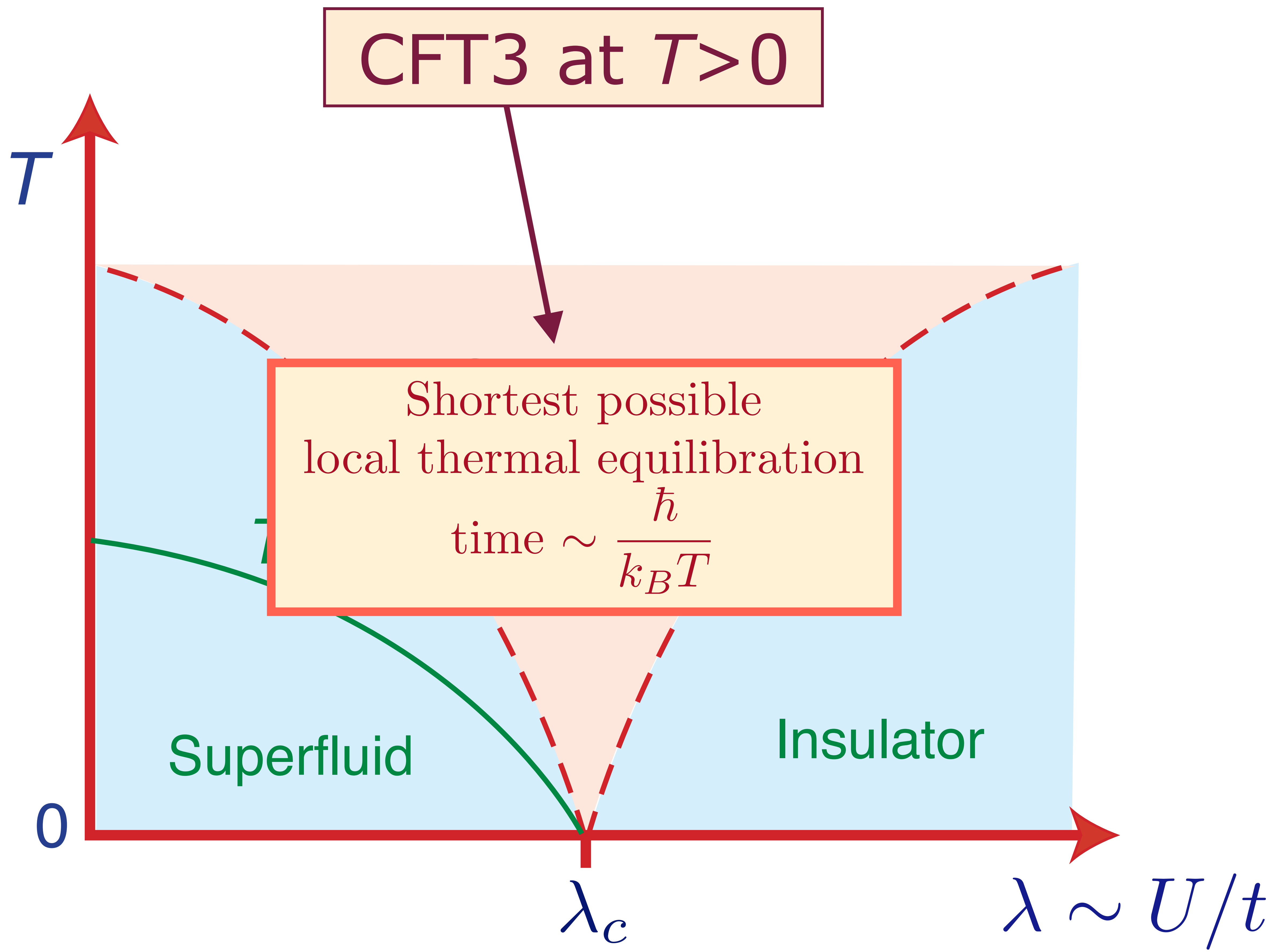
T
0
Quantum critical
"Boltzmann" theory of Nambu-Goldstone phonons and vortices
Superfluid
Boltzmann theory of particles/holes
Insulator
λ_c
$\lambda \sim U/t$



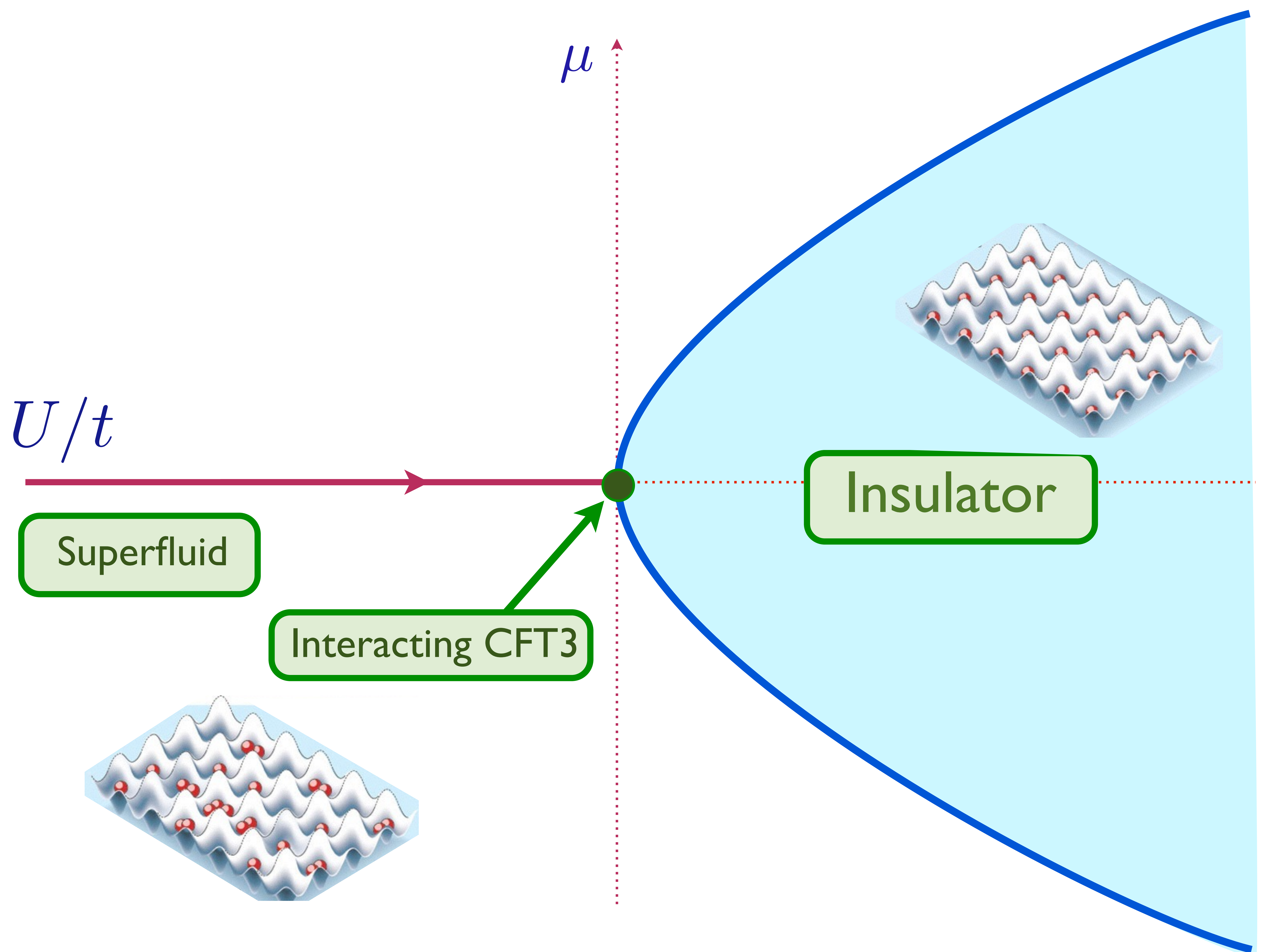
CFT3 at $T>0$
T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$



CFT3 at T>0
T
Quantum matter
without
quasiparticles
T_KT
Superfluid
Insulator
0
λ_c
λ ~ 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

Quantum matter without quasiparticles:

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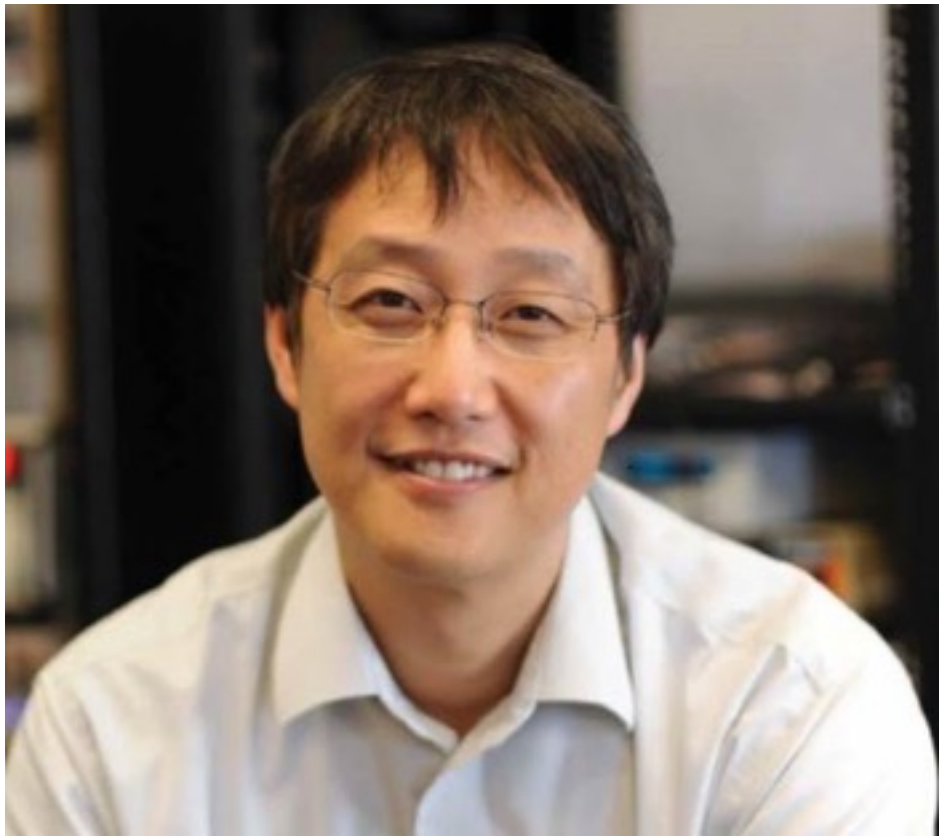
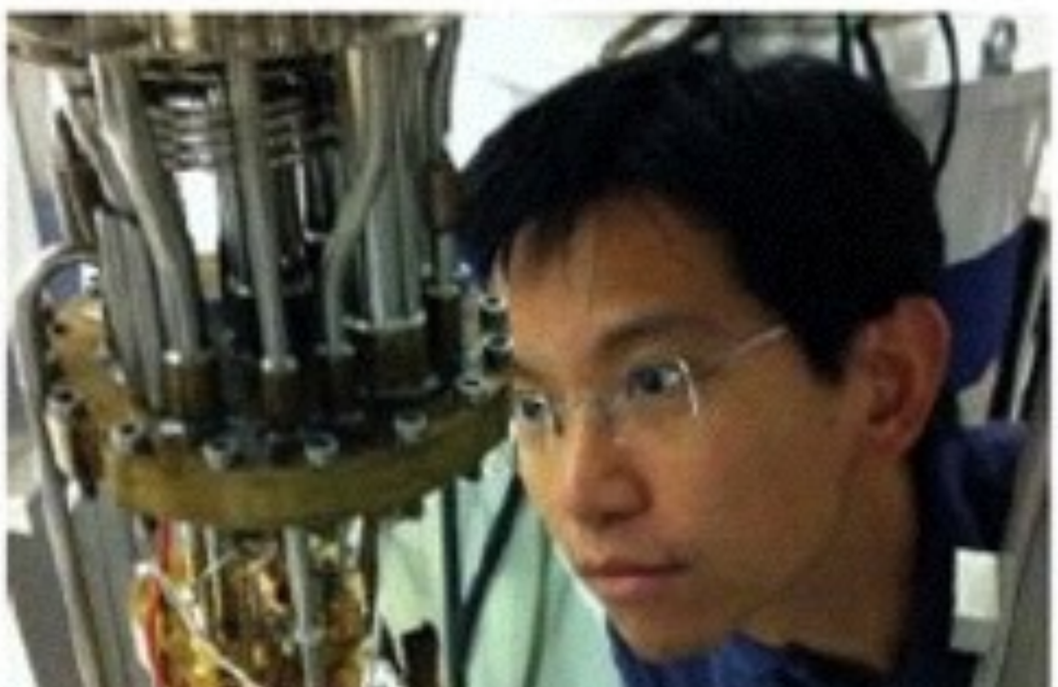
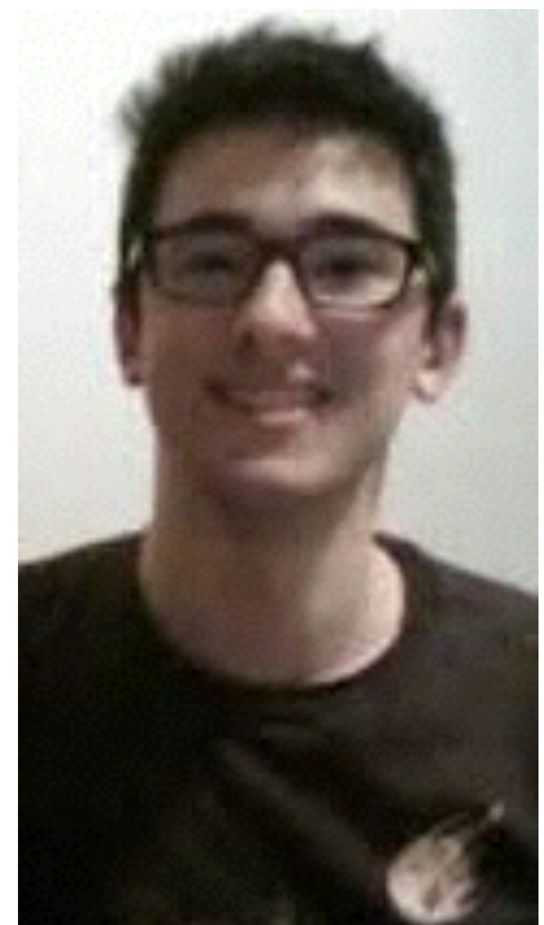


Philip Kim

Jesse Crossno

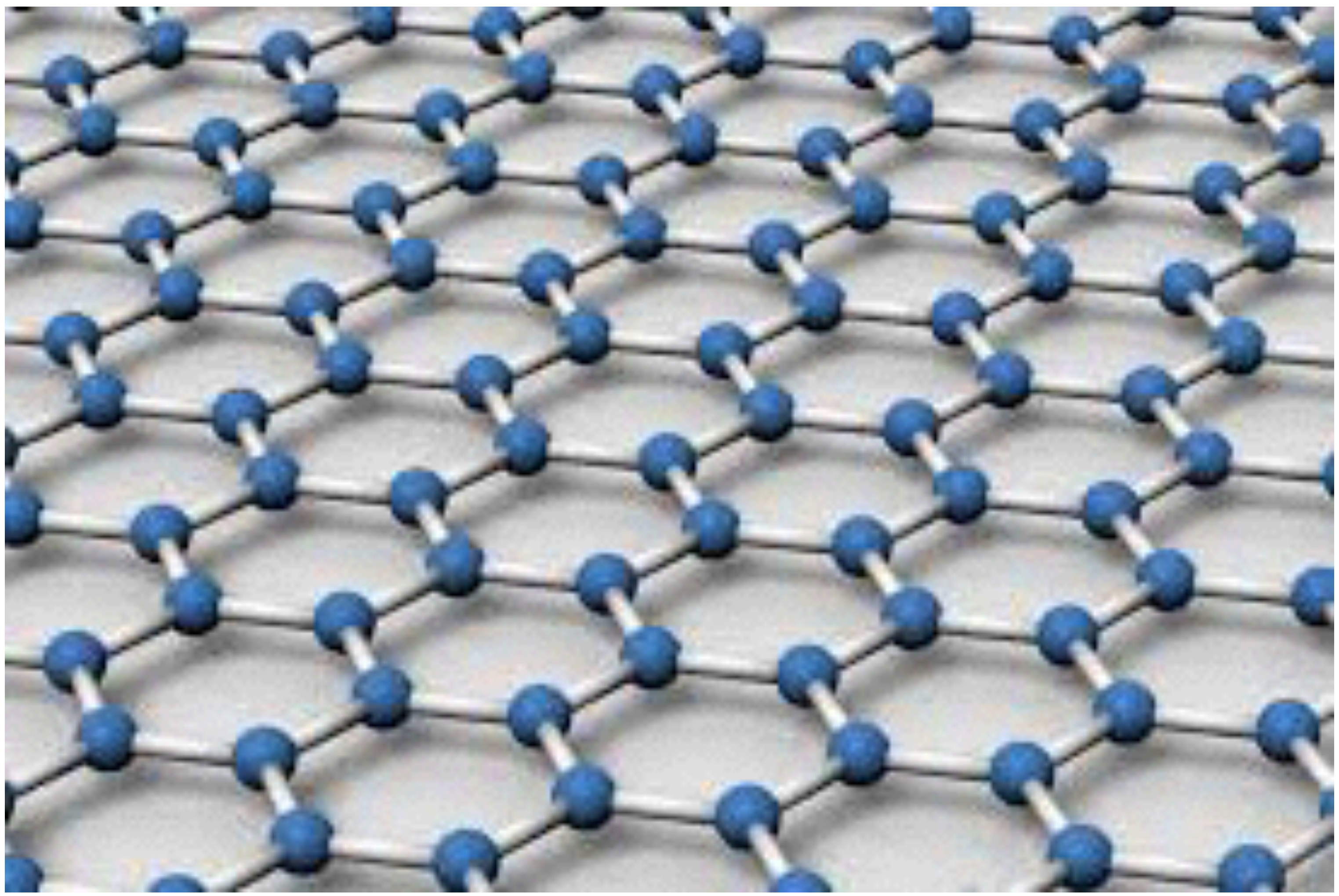


Kin Chung Fong

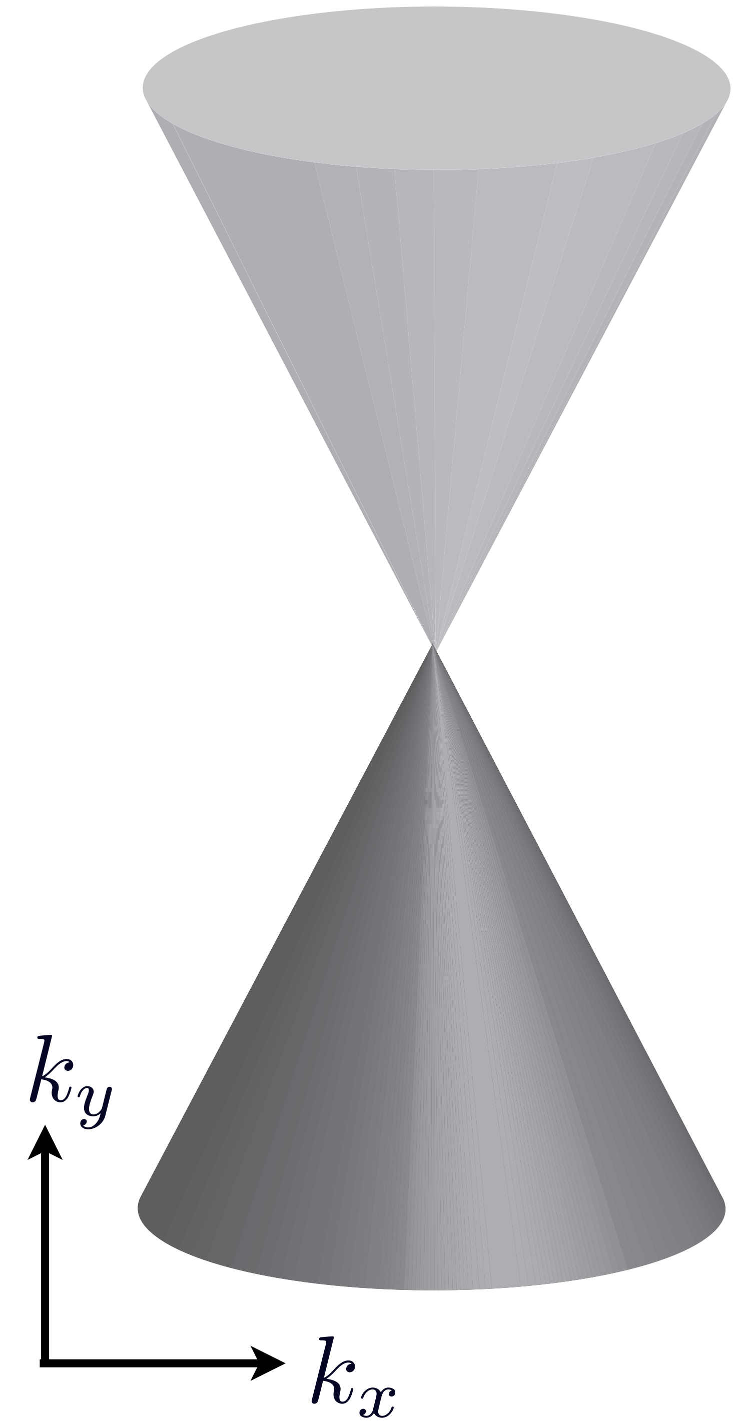


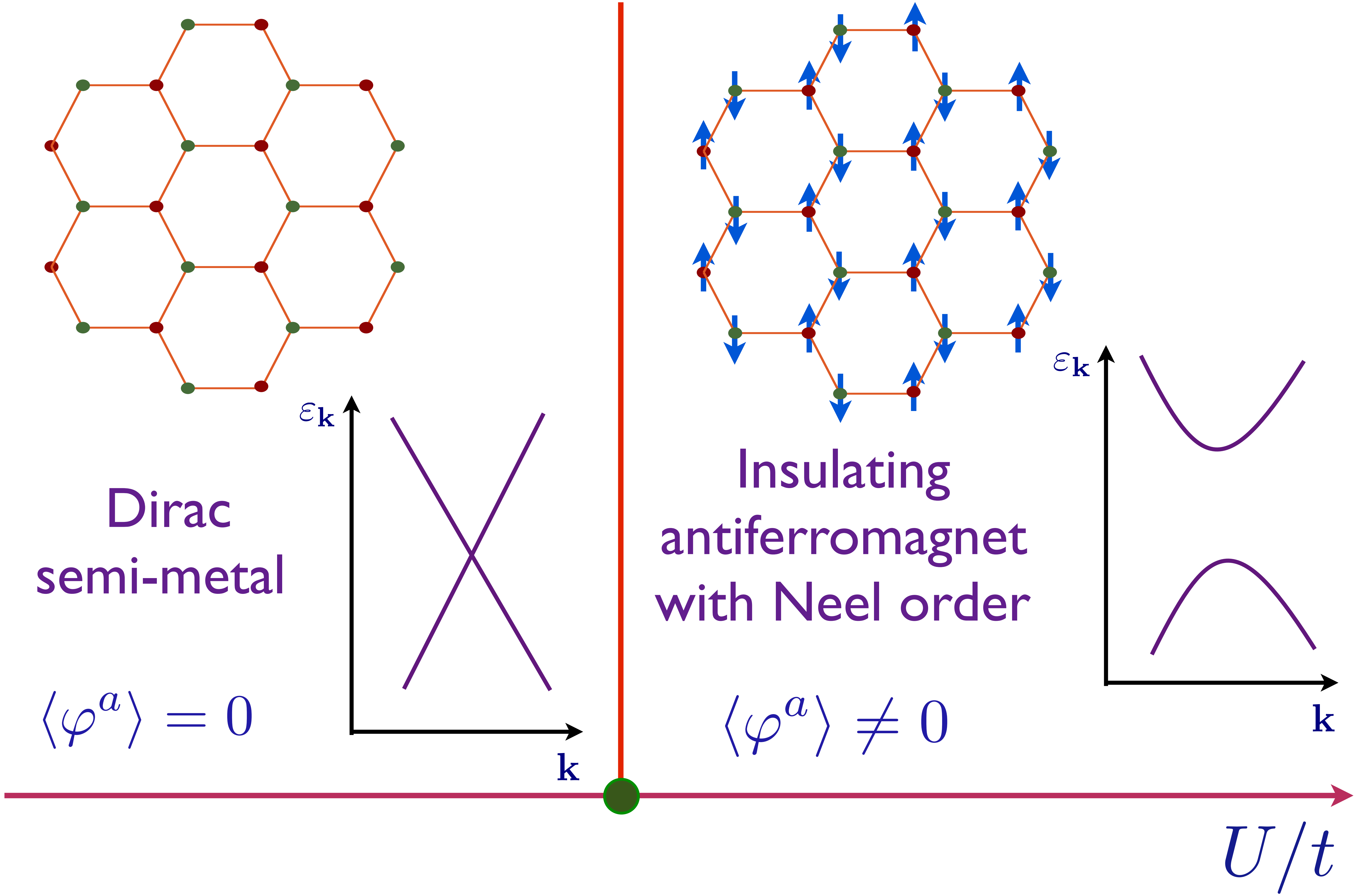
Andrew Lucas

Graphene

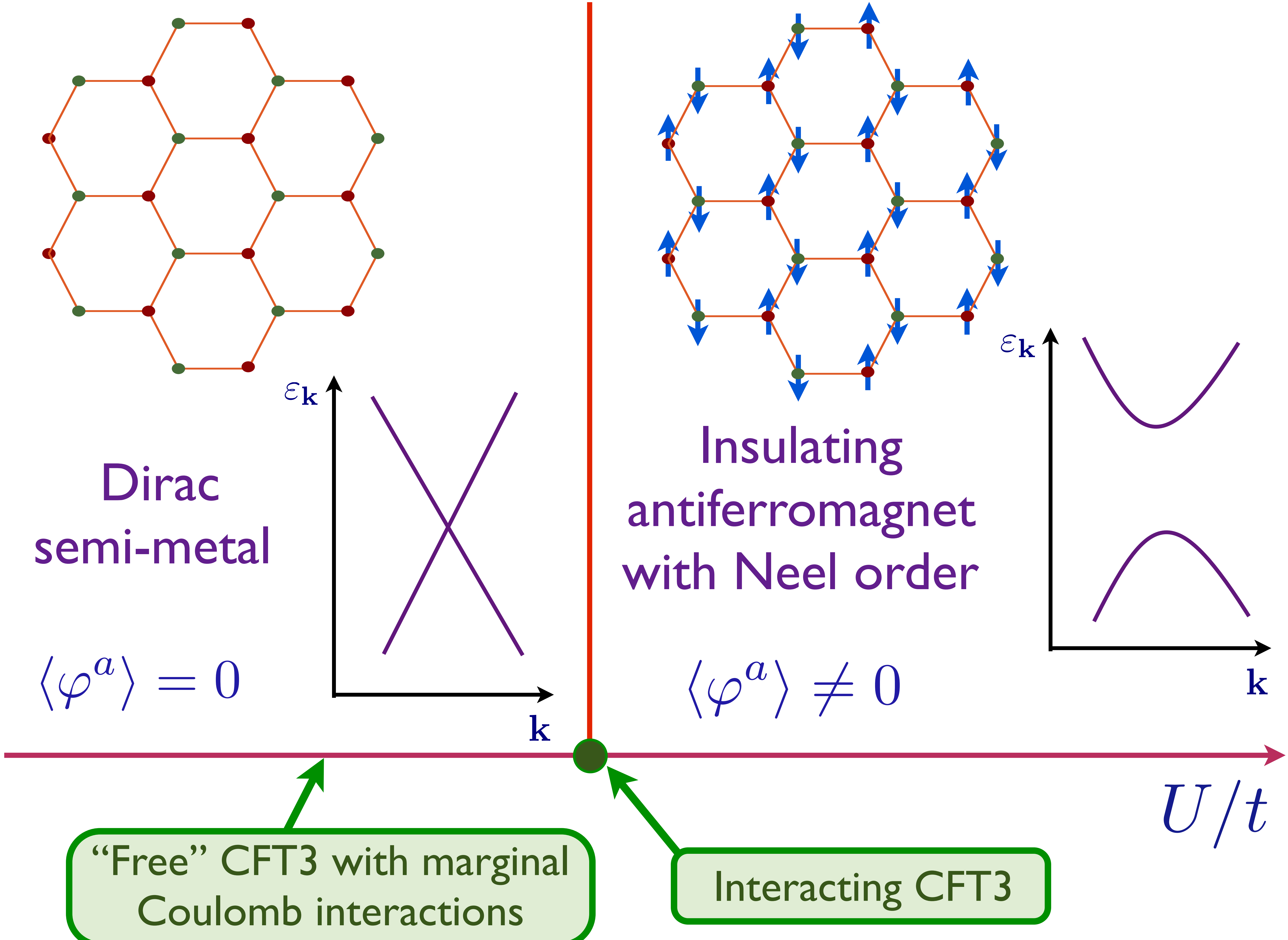


Same "Hubbard" model as for ultracold atoms, but for electrons on the honeycomb lattice





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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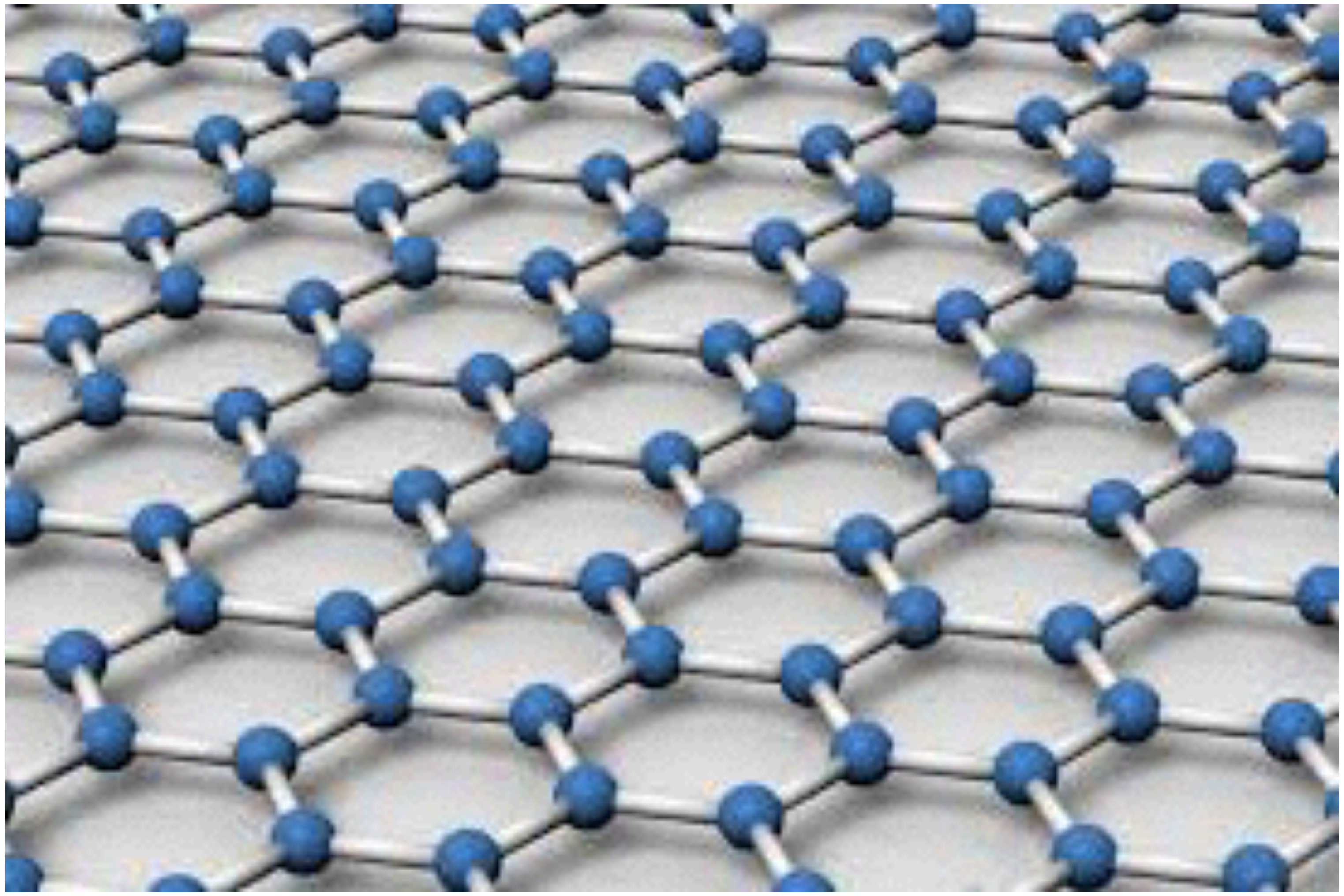
$\mathbf{k}$
U/t
"Free" CFT3 with marginal Coulomb interactions
Interacting CFT3

Graphene



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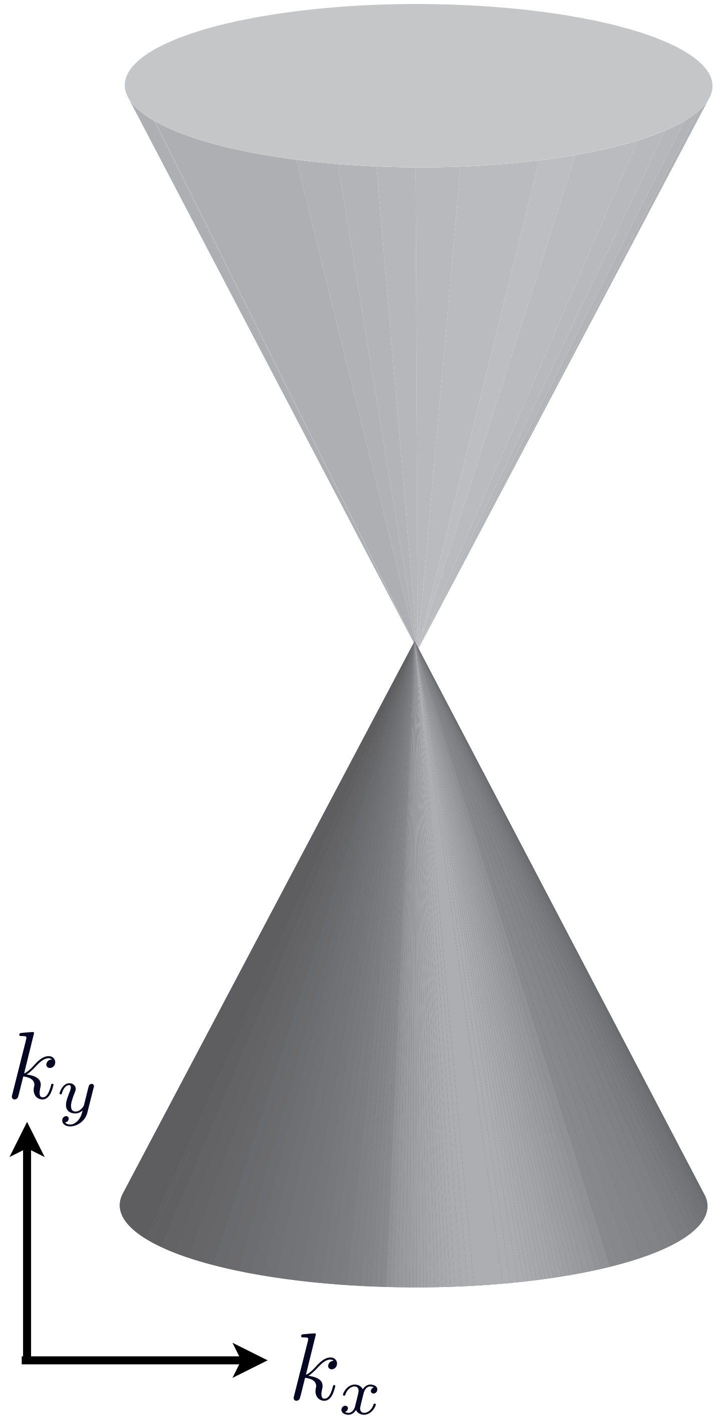
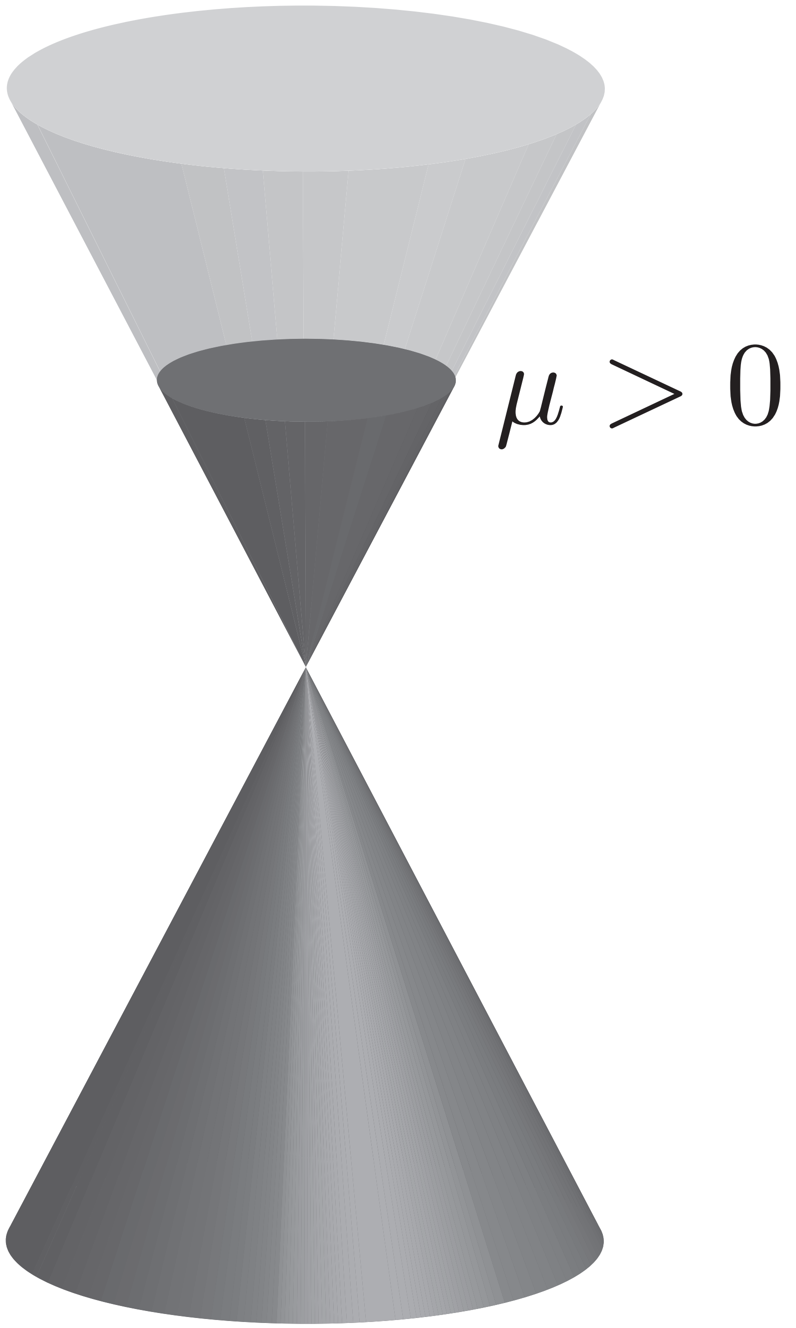
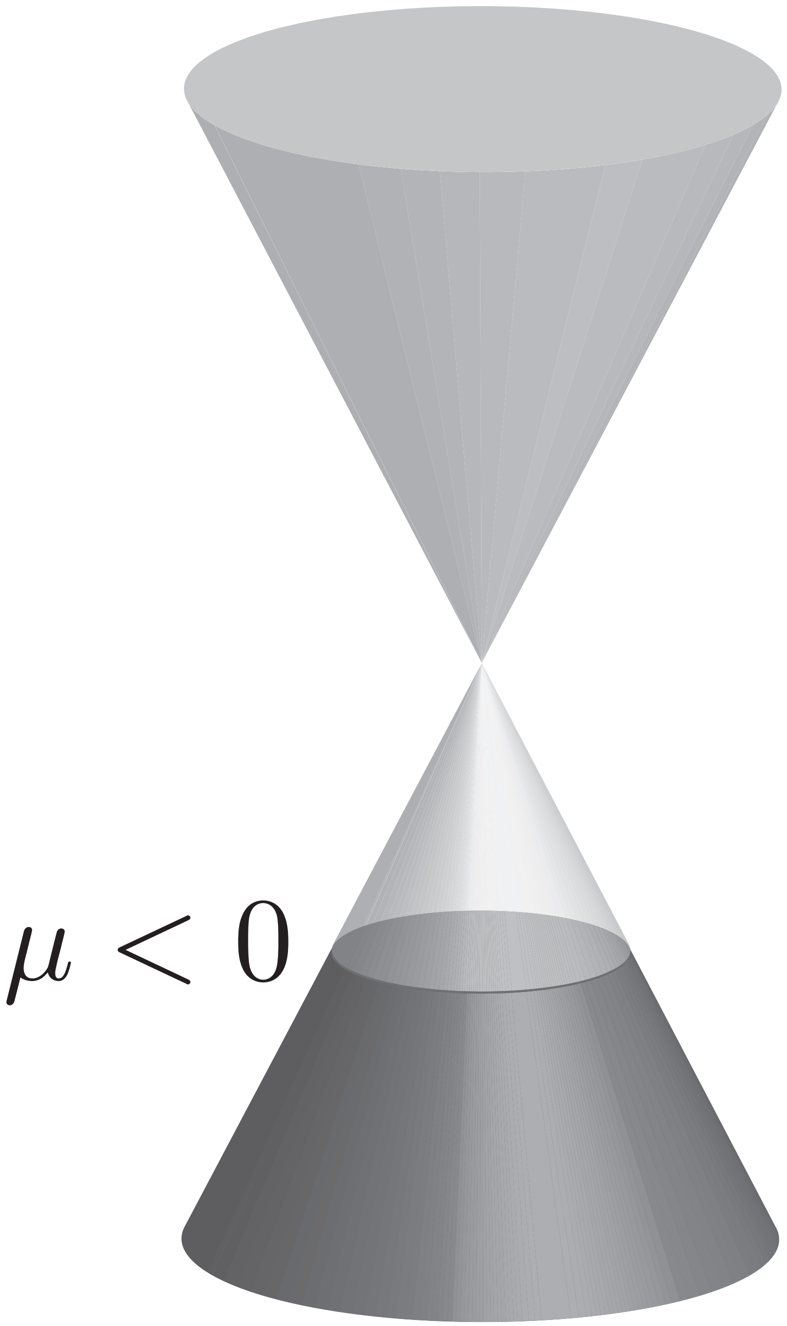


Graphene

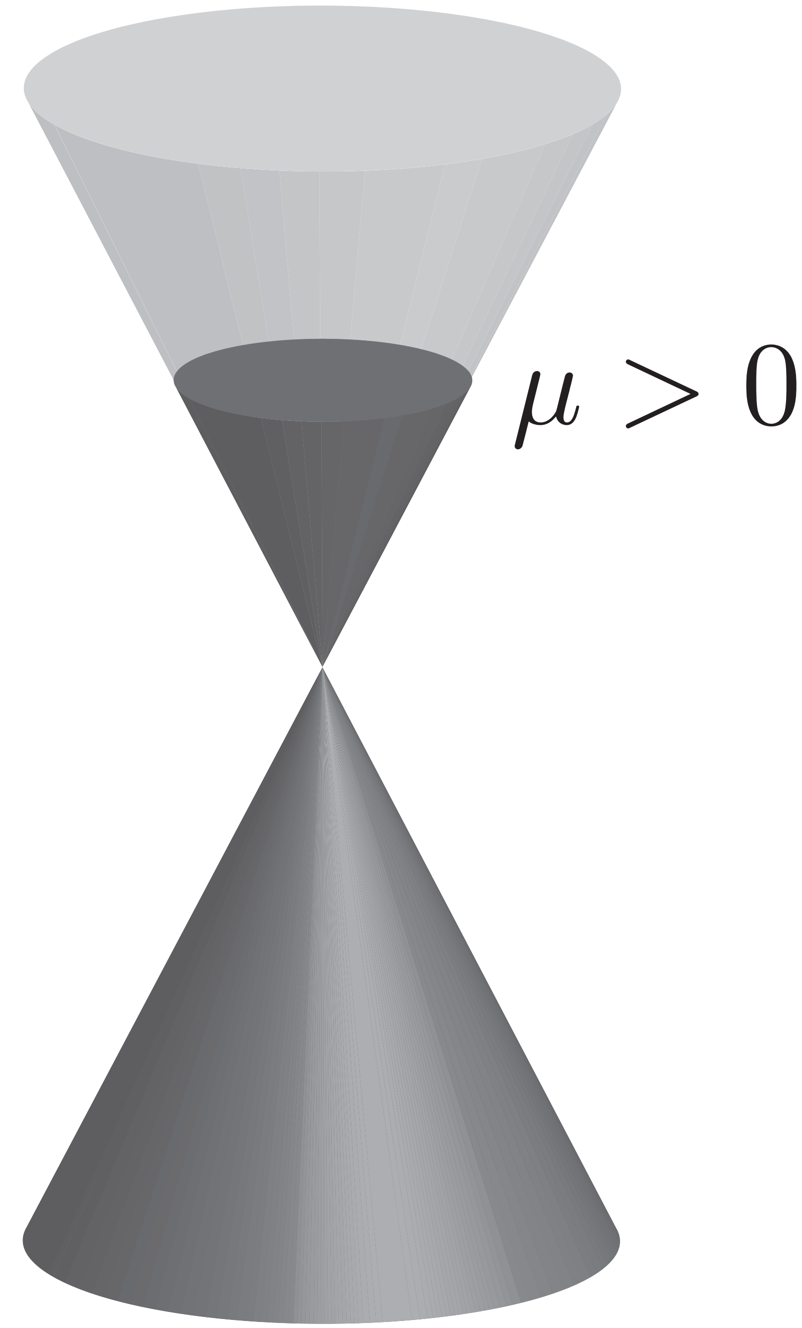


Electron
Fermi surface

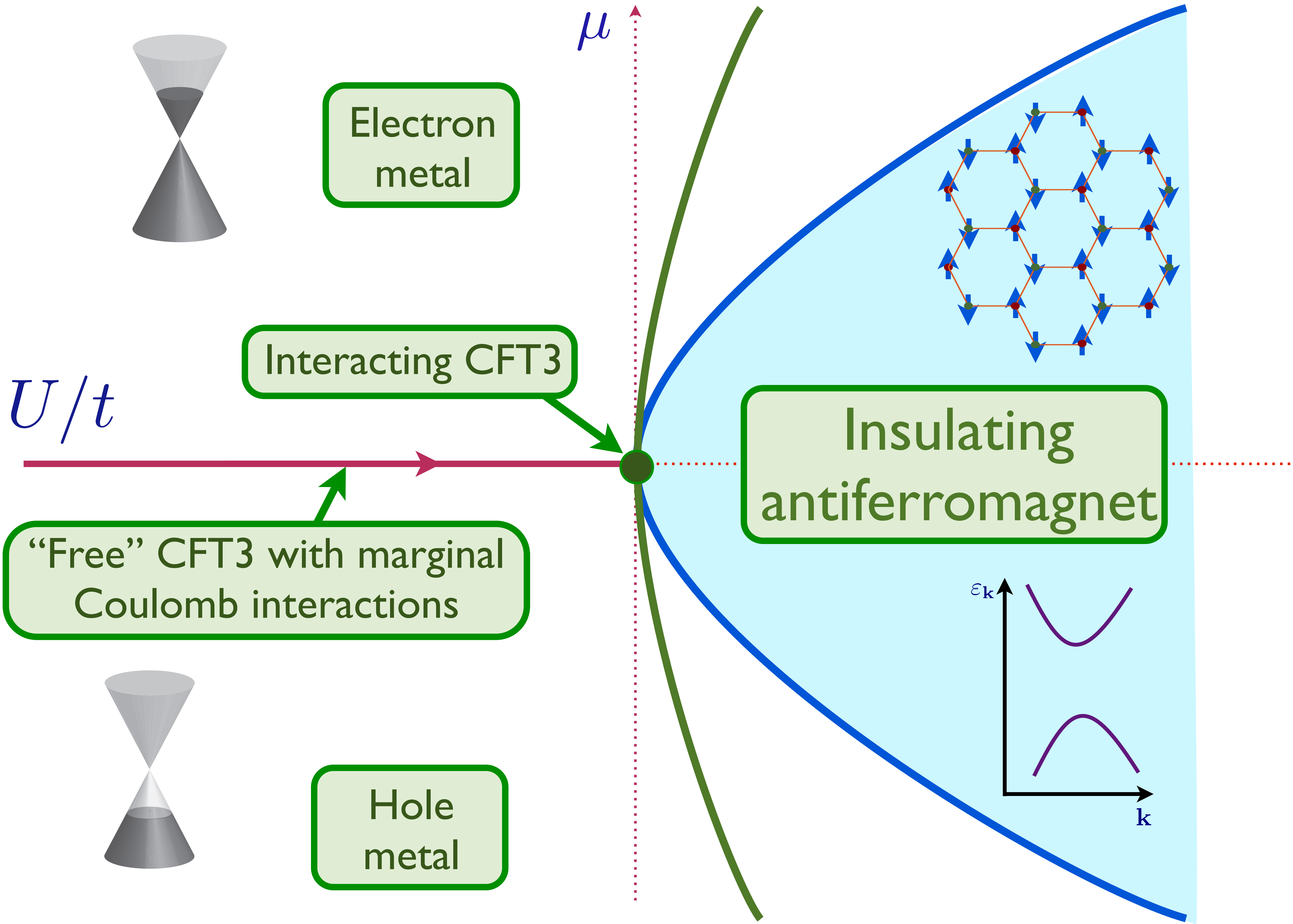
Graphene



Hole
Fermi surface



Electron
Fermi surface



μ
Electron metal
Interacting CFT3
U/t
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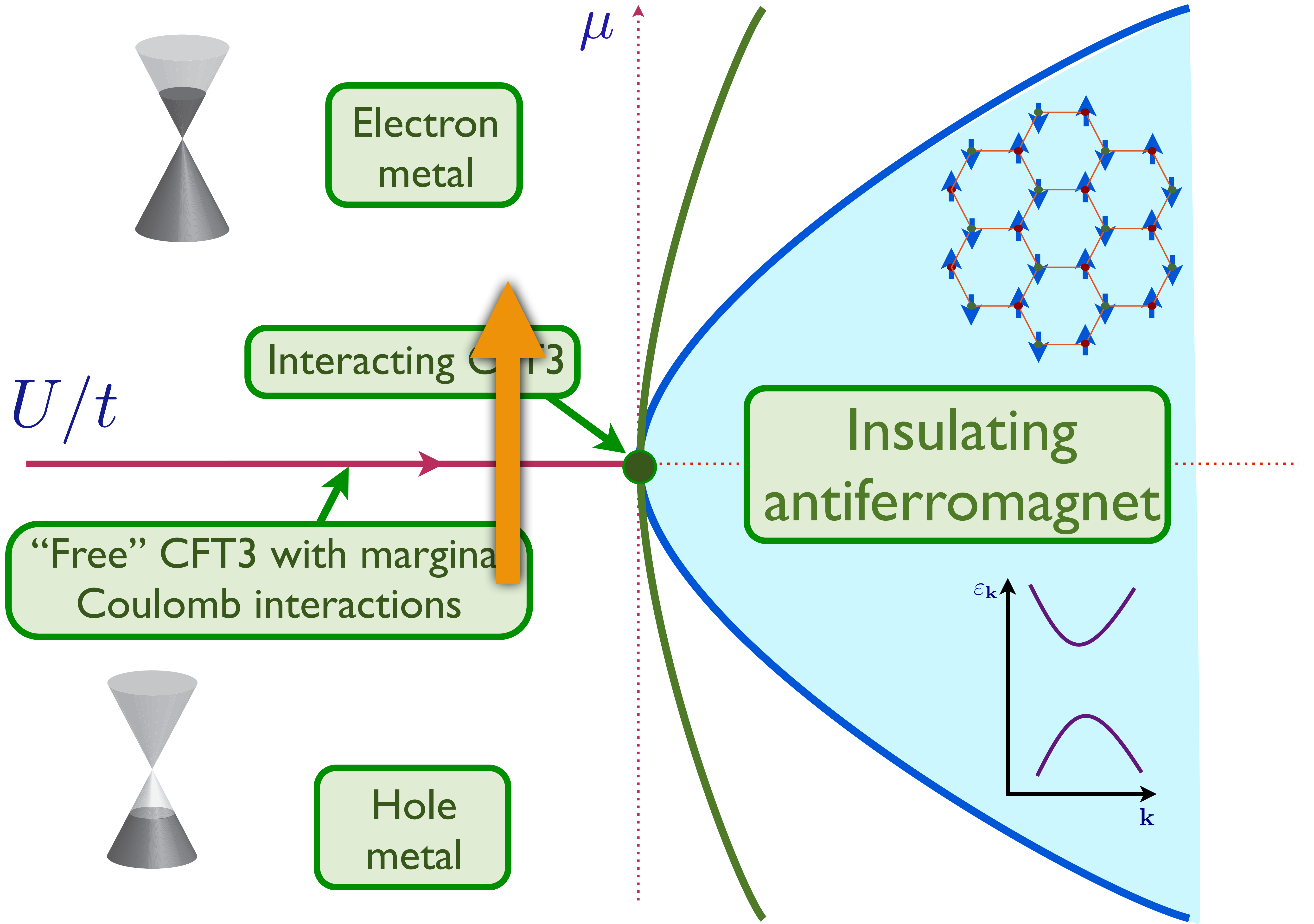
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
Hole metal



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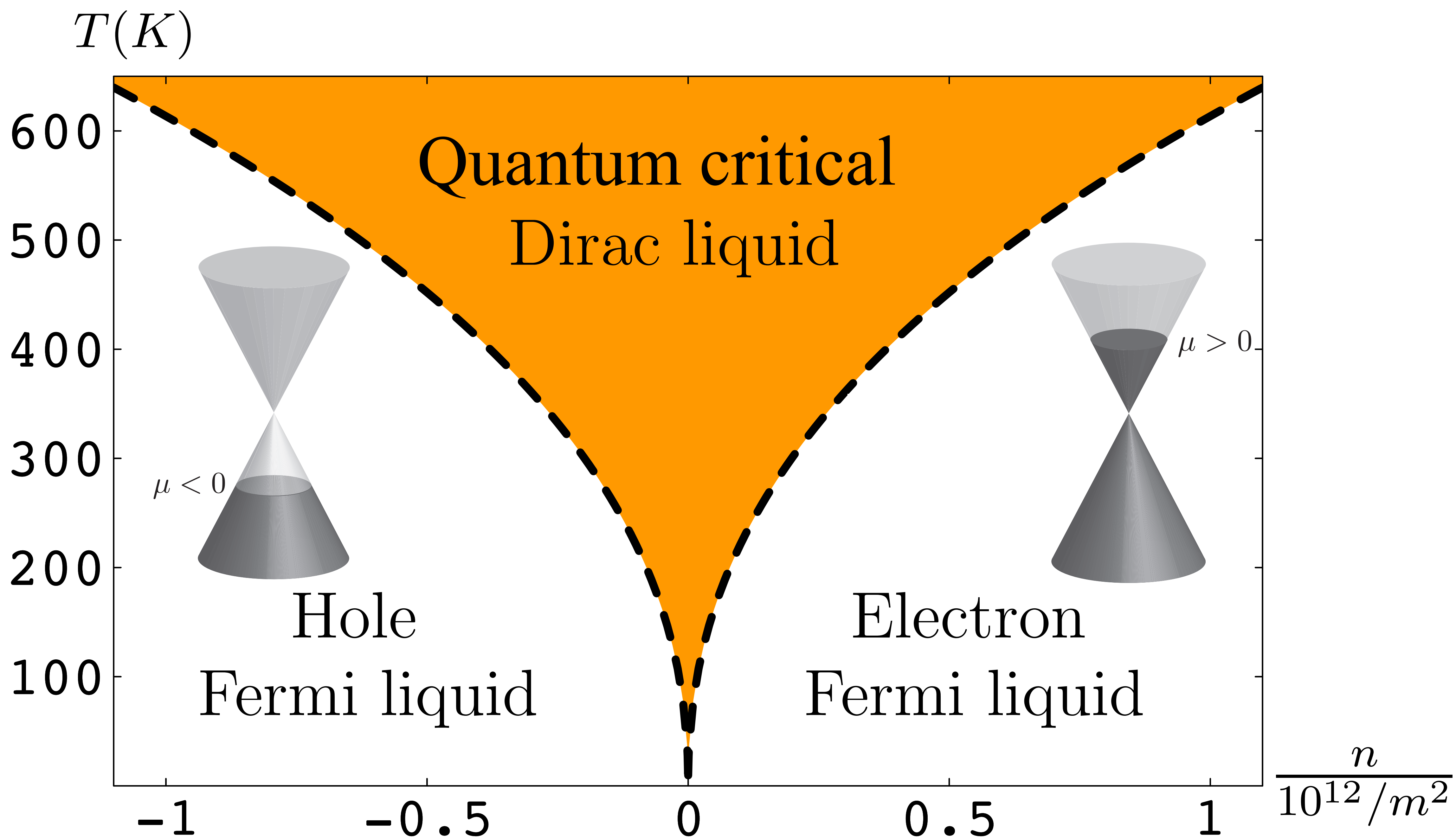
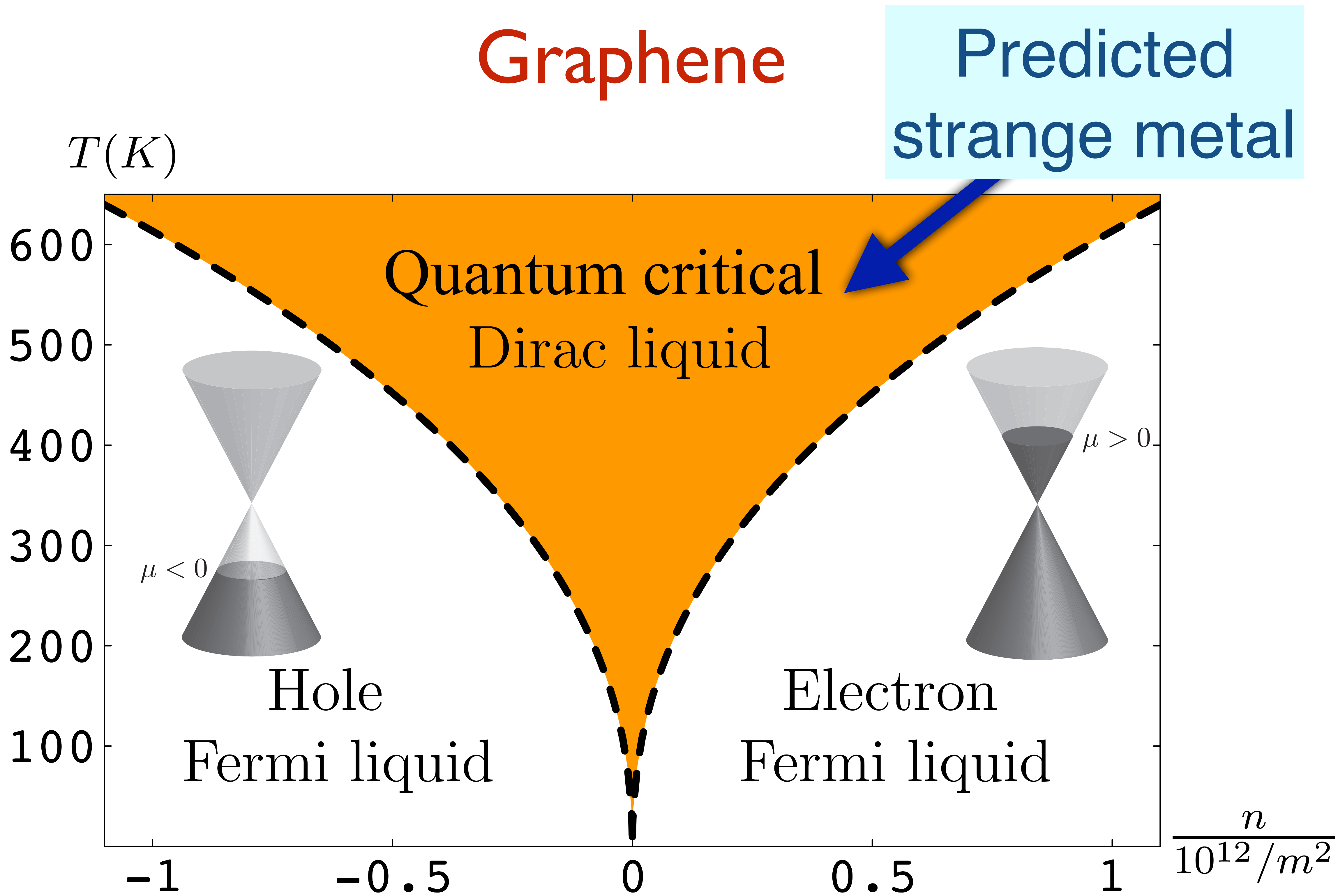


D. E. Sheehy and J. Schmalian, PRL **99**, 226803 (2007)
M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Graphene



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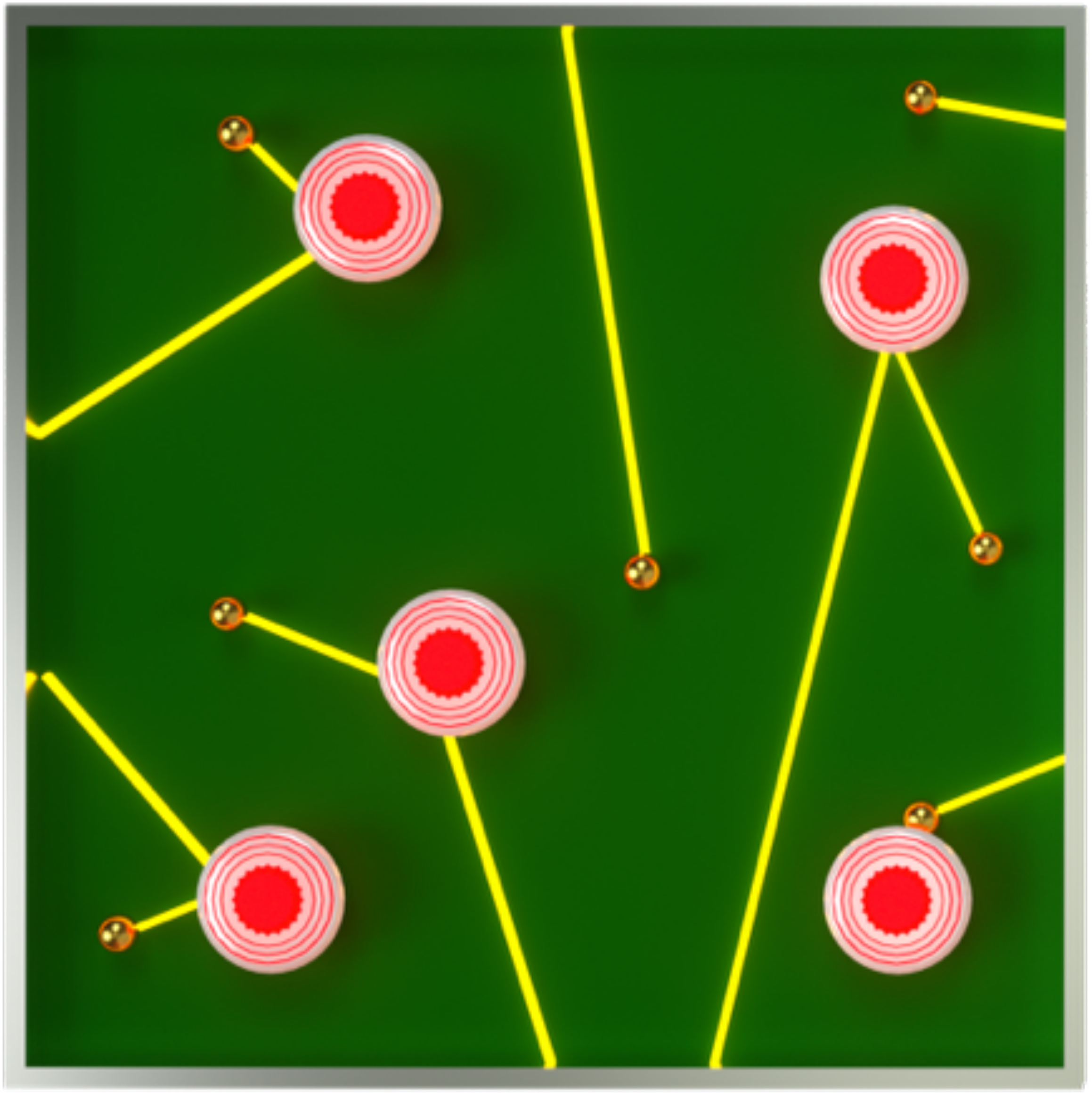
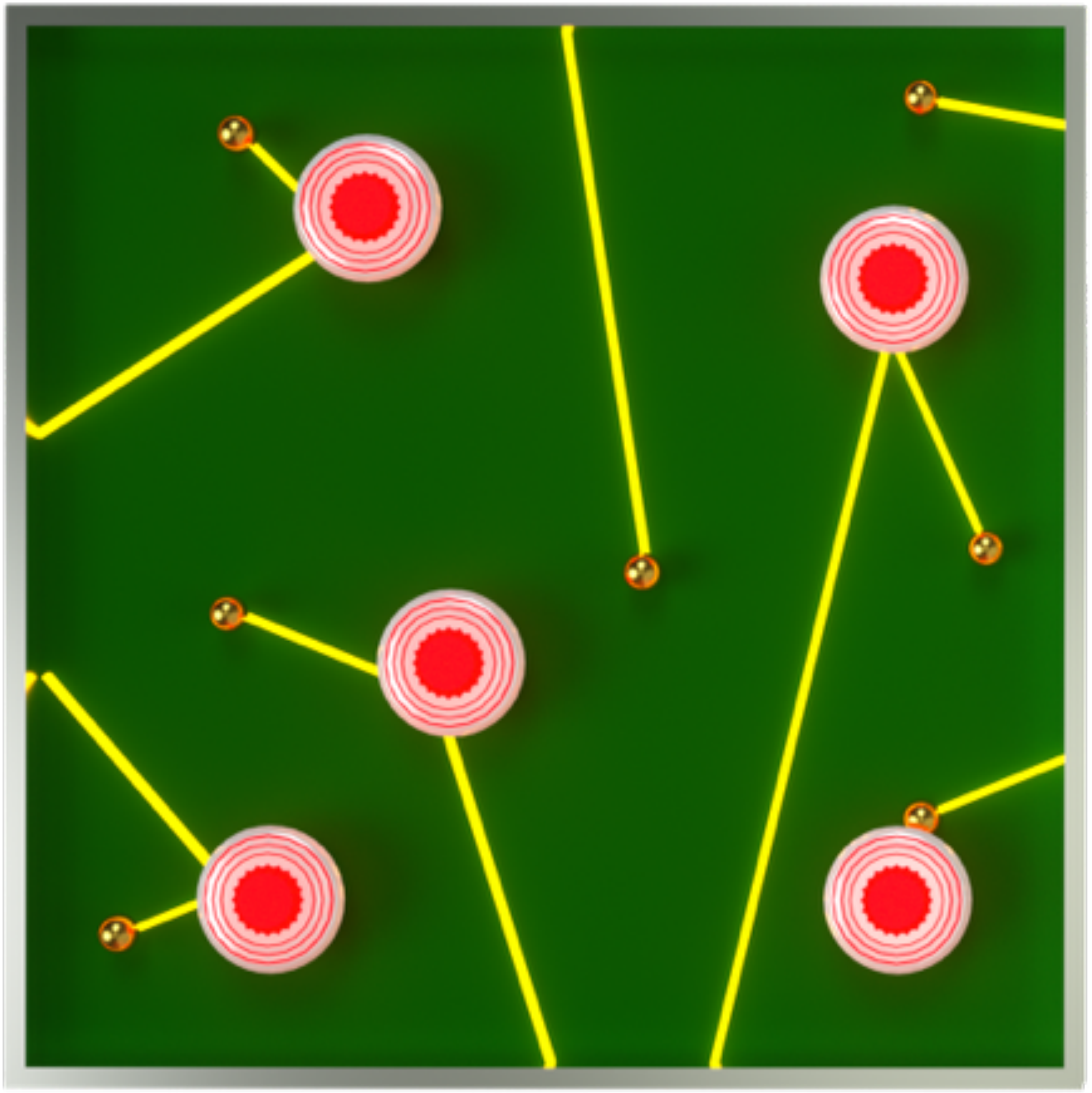


Fermi liquids: quasiparticles moving ballistically between impurity (red circles) scattering events



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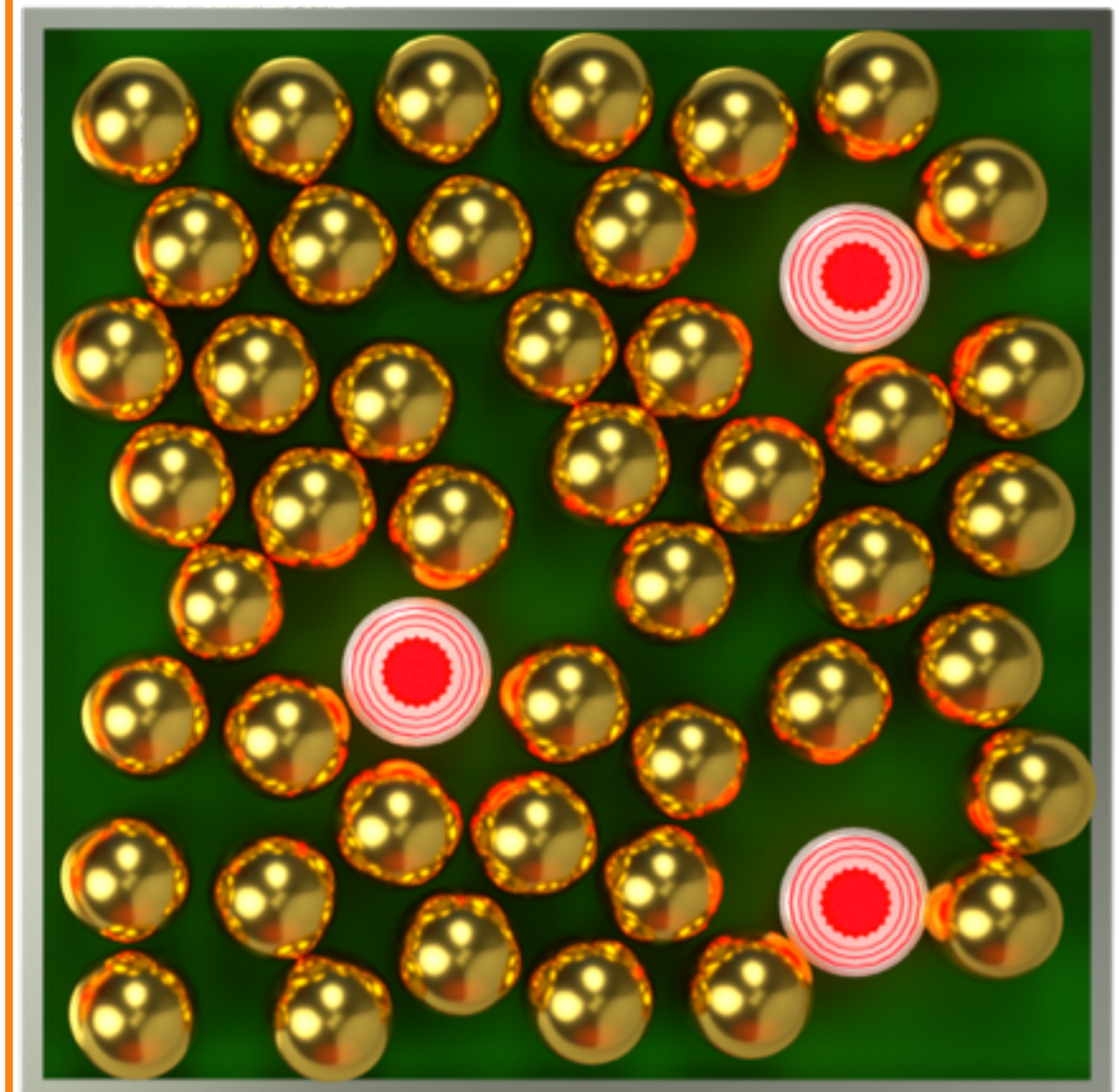
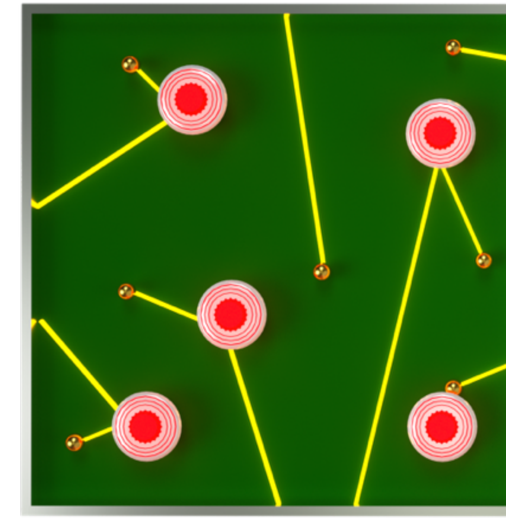


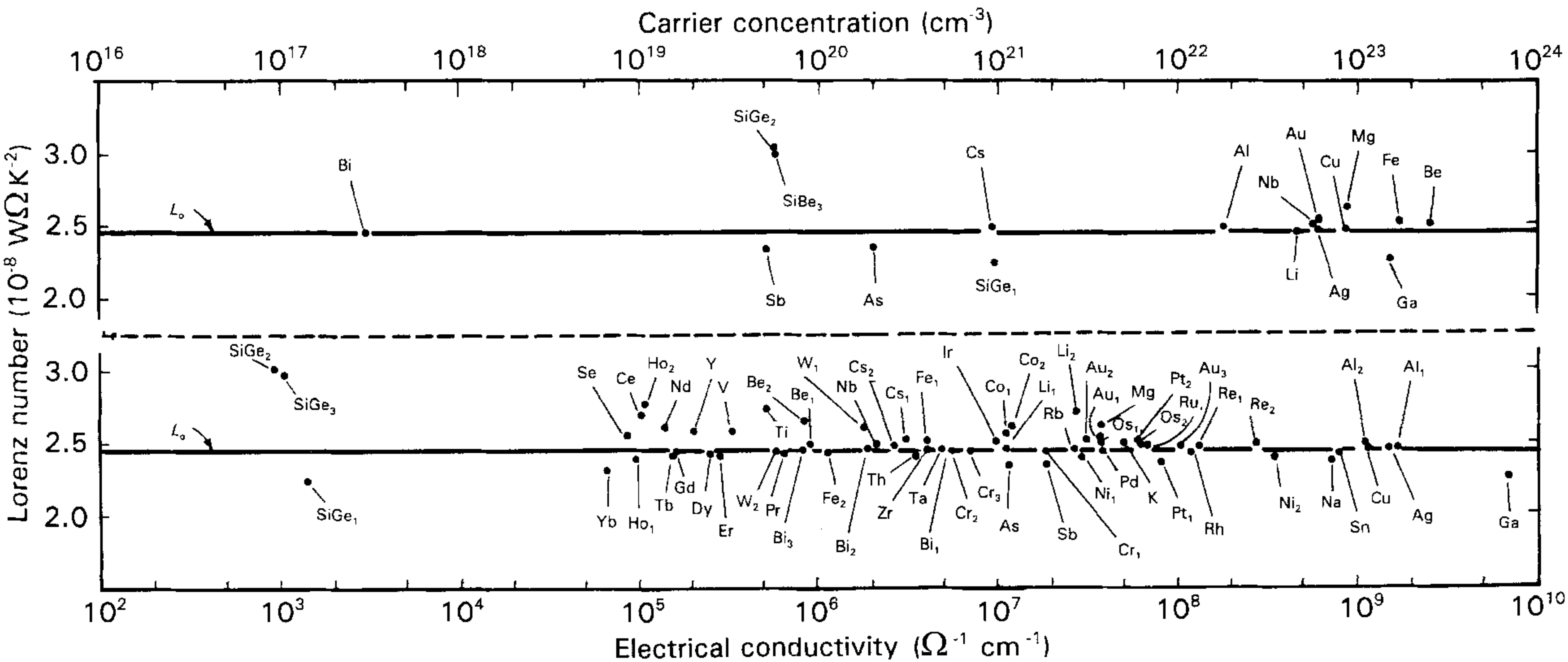
<u>Strange metals</u>: electrons scatter frequently off each other, so there is no regime of ballistic quasiparticle motion. The electron "liquid" then "flows" around impurities

Thermal and electrical conductivity with quasiparticles



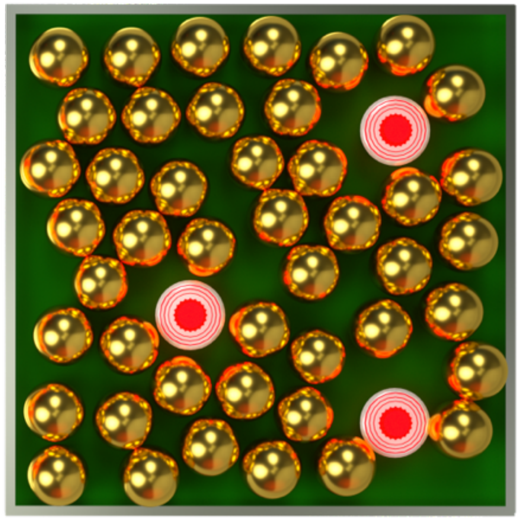
- Wiedemann-Franz law in a Fermi liquid:

$$L_0 = \frac{\kappa}{\sigma T} \approx \frac{\pi^2 k_B^2}{3e^2} \approx 2.45 \times 10^{-8} \, \frac{\mathrm{W} \cdot \Omega}{\mathrm{K}^2}.$$



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

Transport in Strange Metals



For a strange metal
with a "relativistic" Hamiltonian,
hydrodynamic, holographic,
and memory function methods yield
Lorentz ratio $L = \kappa/(T\sigma)$

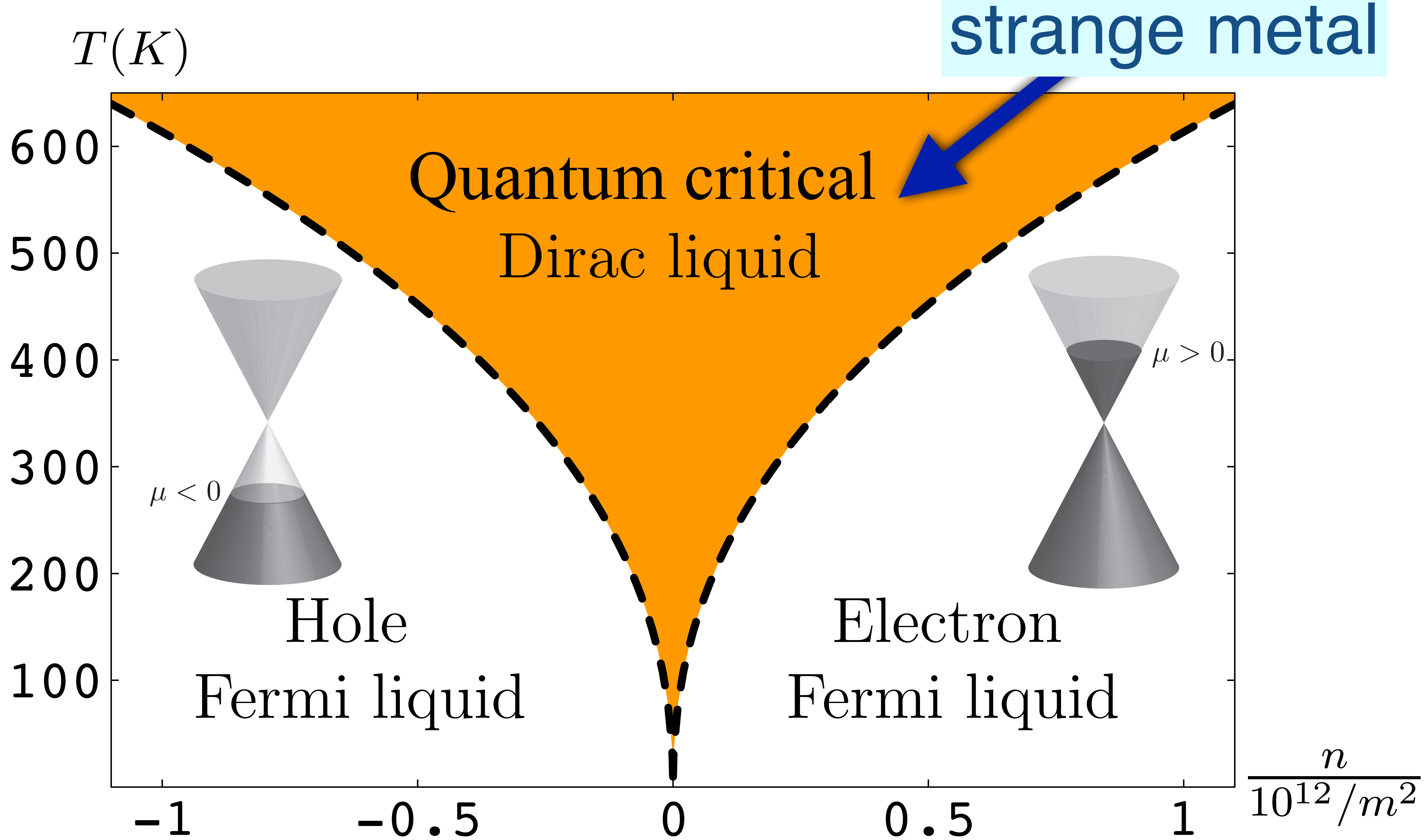
$$= \frac{v_F^2 \mathcal{H} \tau_{\rm imp}}{T^2 \sigma_Q} \frac{1}{\left(1 + e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}/(\mathcal{H}\sigma_Q)\right)^2}$$

$\mathcal{Q} \rightarrow$ electron density; $\mathcal{H} \rightarrow$ enthalpy density
$\sigma_Q \rightarrow$ quantum critical conductivity
$\tau_{\rm imp} \rightarrow$ momentum relaxation time from impurities.
Note that for $\mathcal{Q} \neq 0$, $L \rightarrow 0$ as $\tau_{\rm imp} \rightarrow \infty$,
while for $\mathcal{Q} = 0$, $L \rightarrow \infty$ as $\tau_{\rm imp} \rightarrow \infty$.

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Graphene

Predicted strange metal



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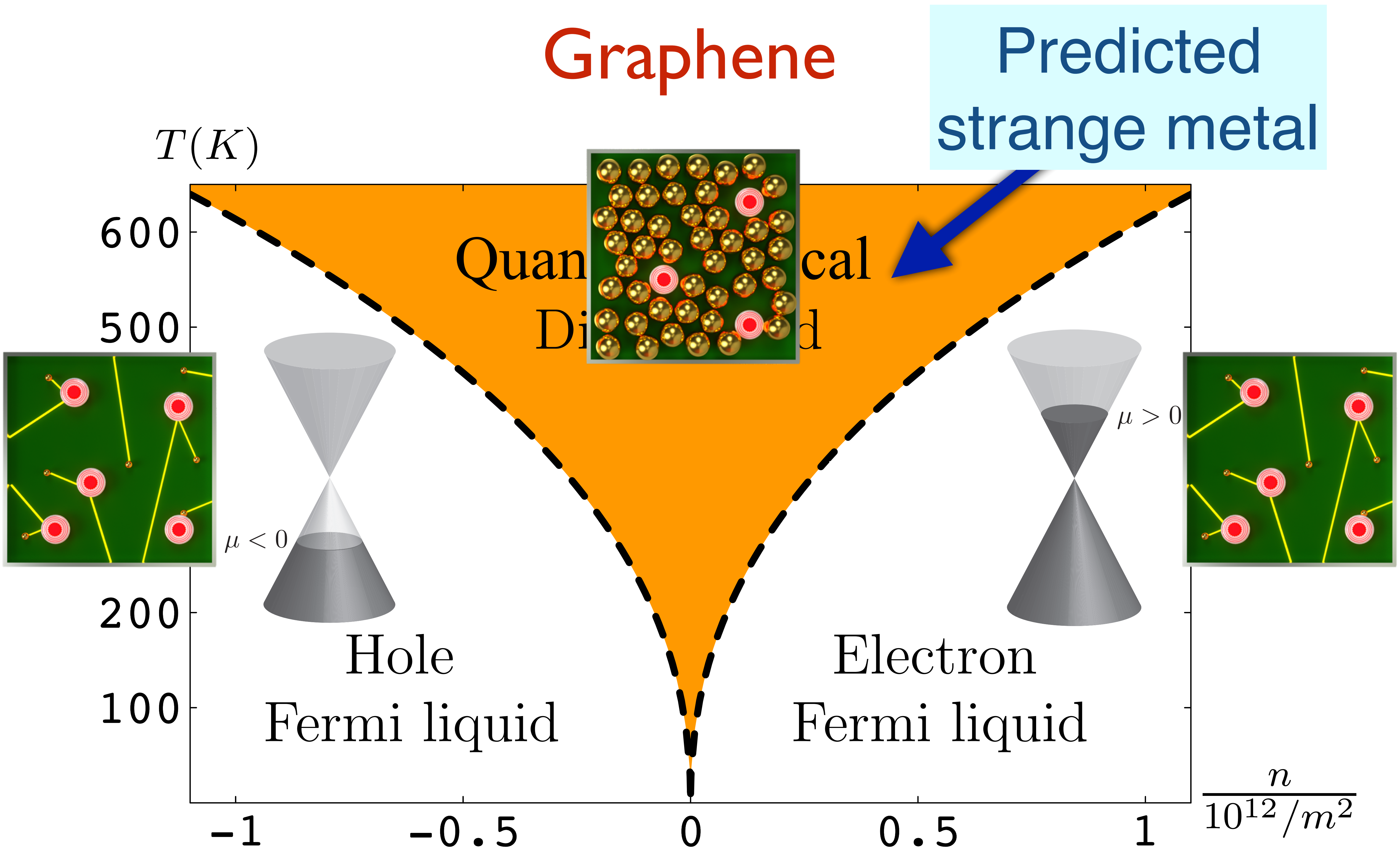
Graphene



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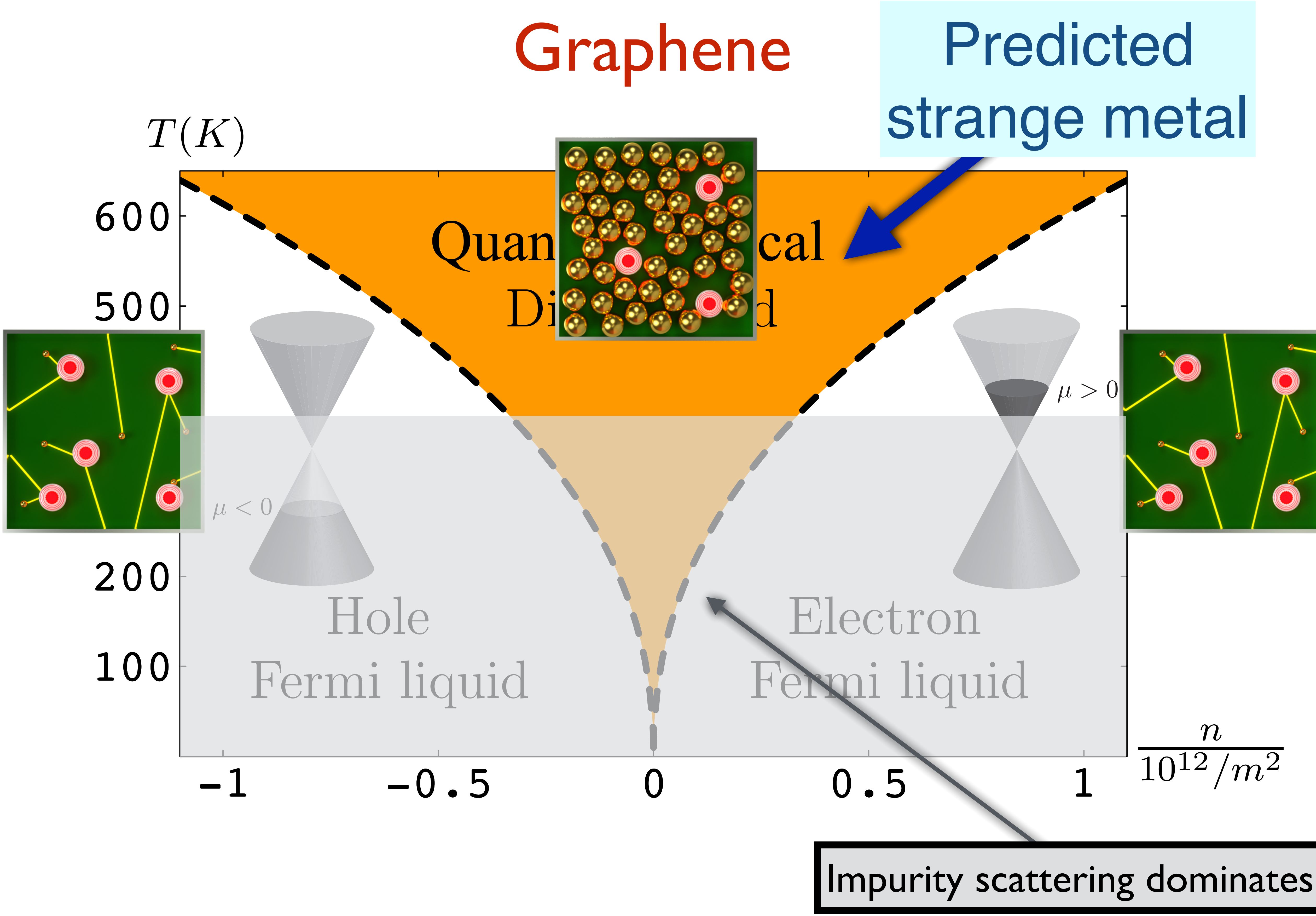
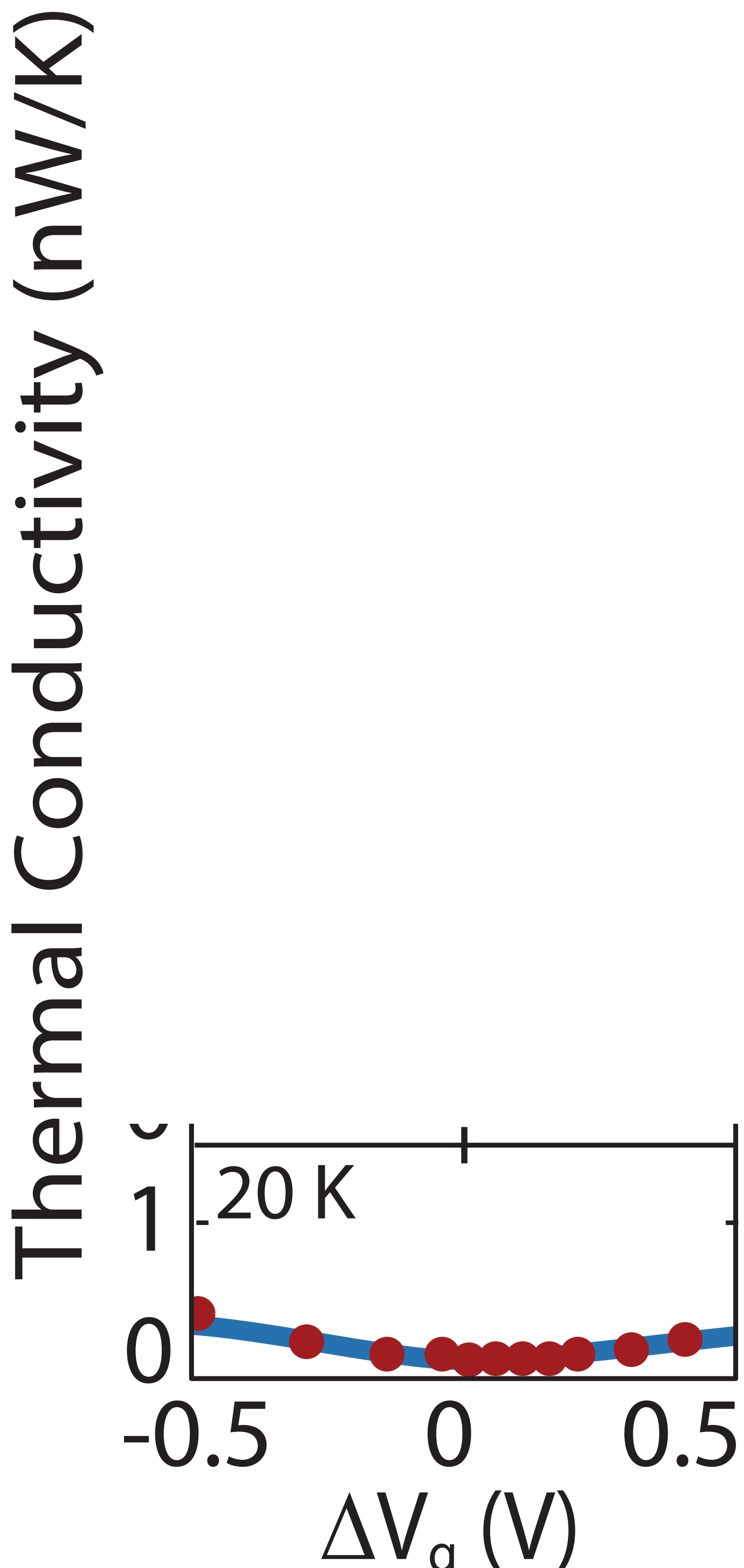
Graphene



M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

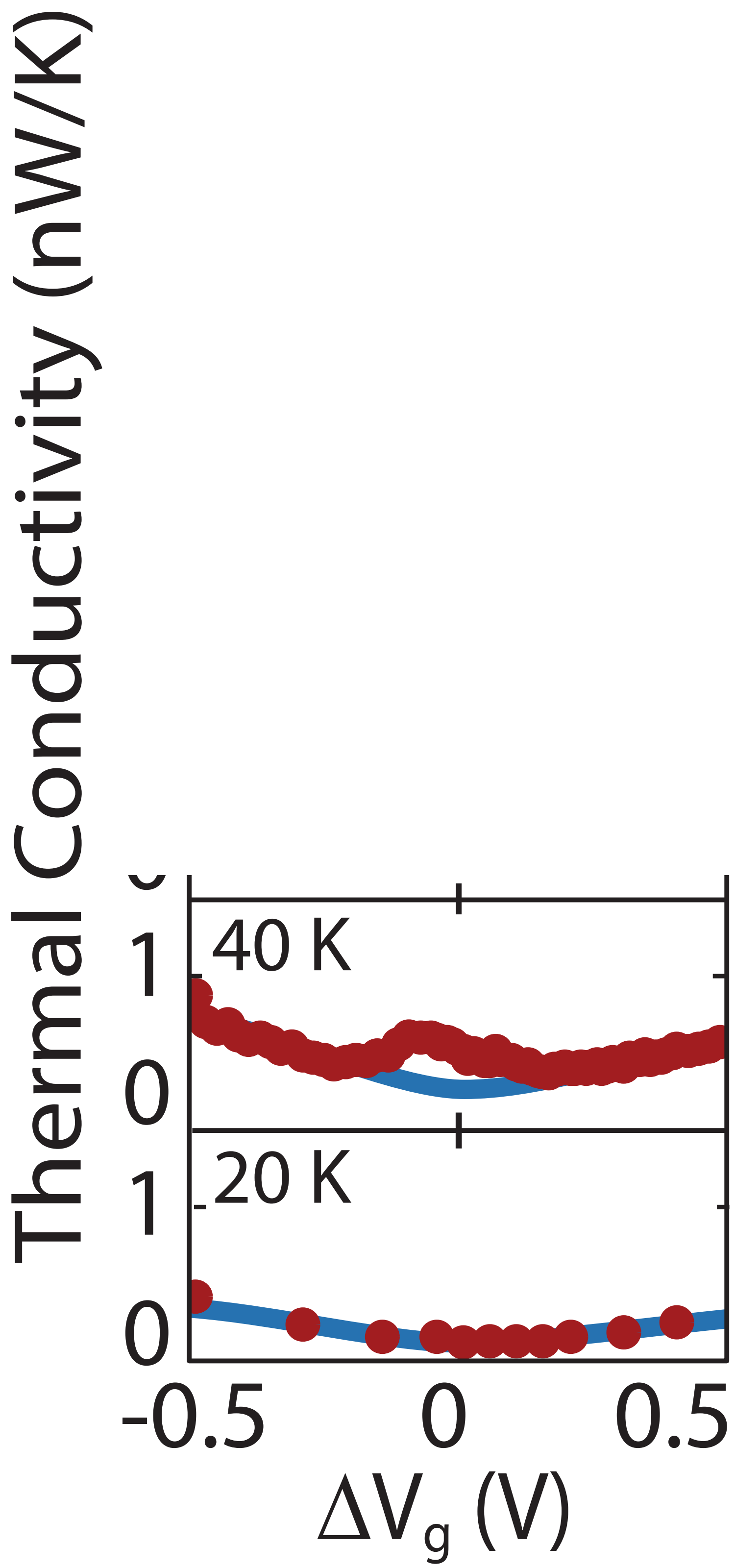
J. Crossno et al., Science **351**, 1058 (2016)



Red dots: data

Blue line: value for $L = L_0$

J. Crossno et al., Science **351**, 1058 (2016)



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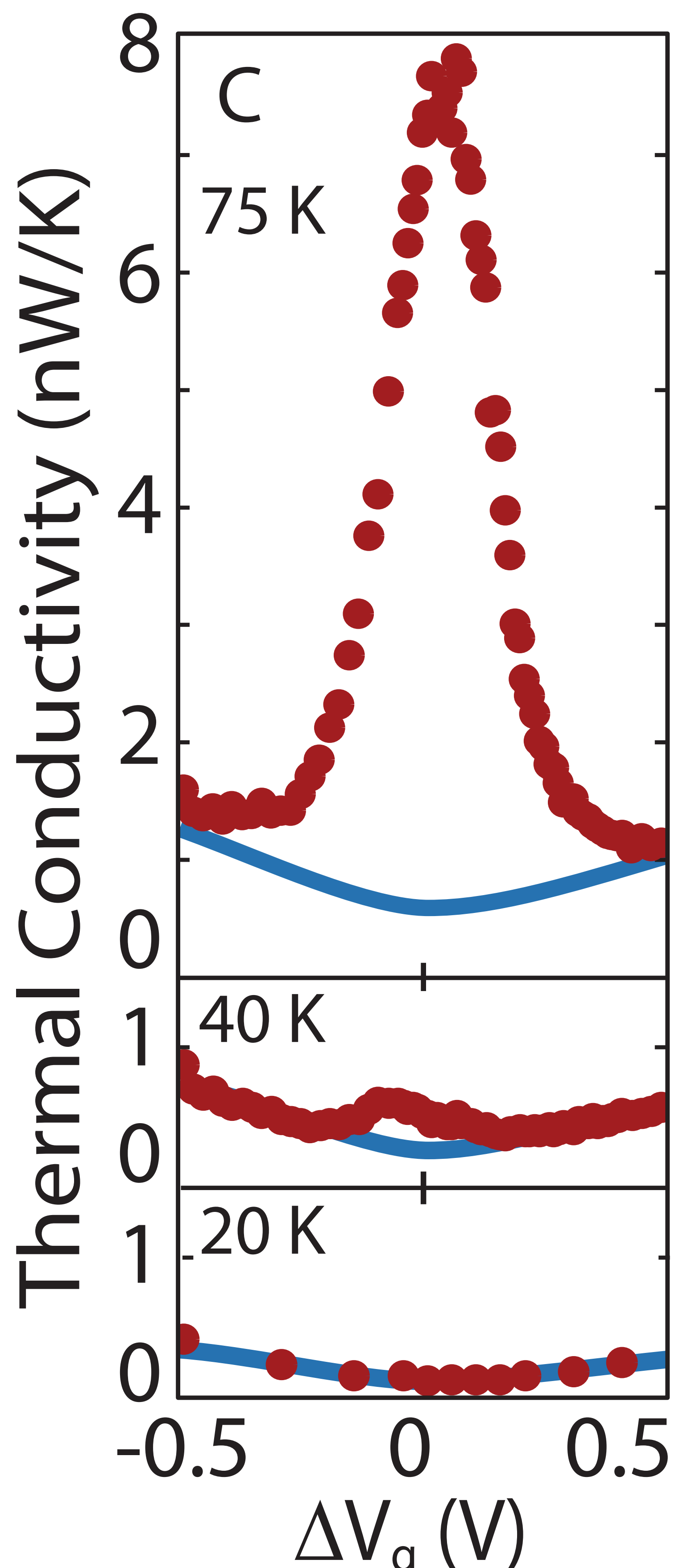
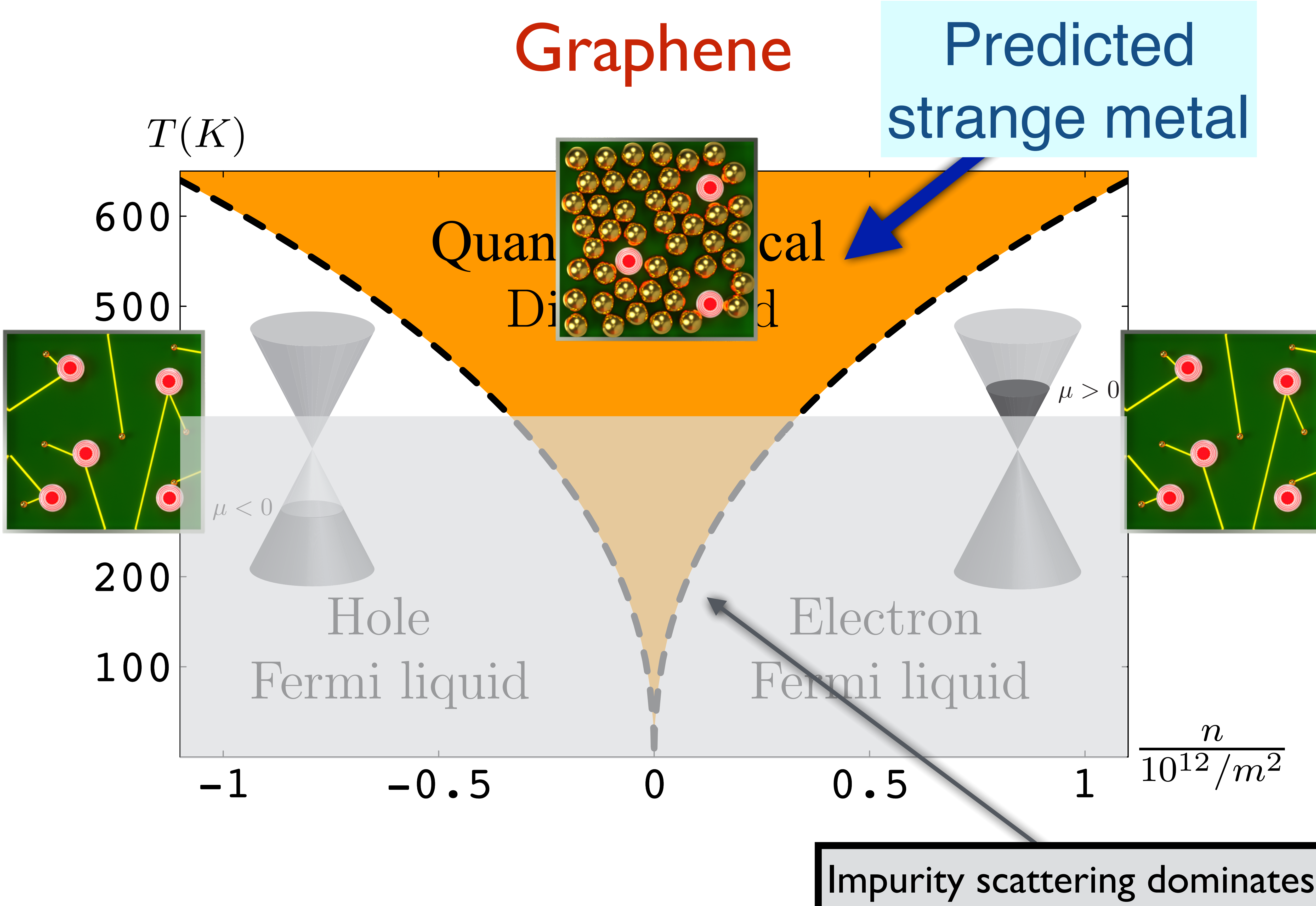
J. Crossno et al., Science **351**, 1058 (2016)



Red dots: data

Blue line: value for $L = L_0$

Graphene



M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
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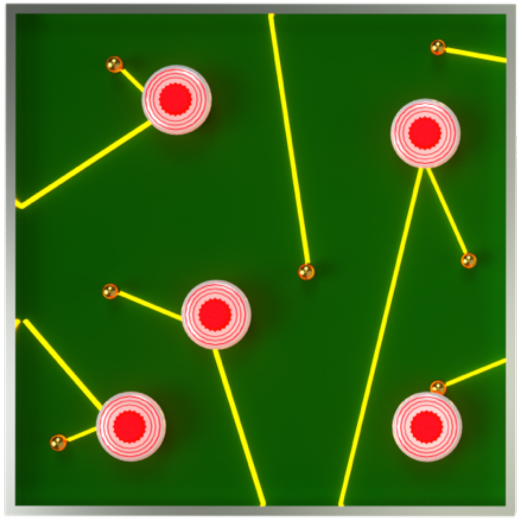
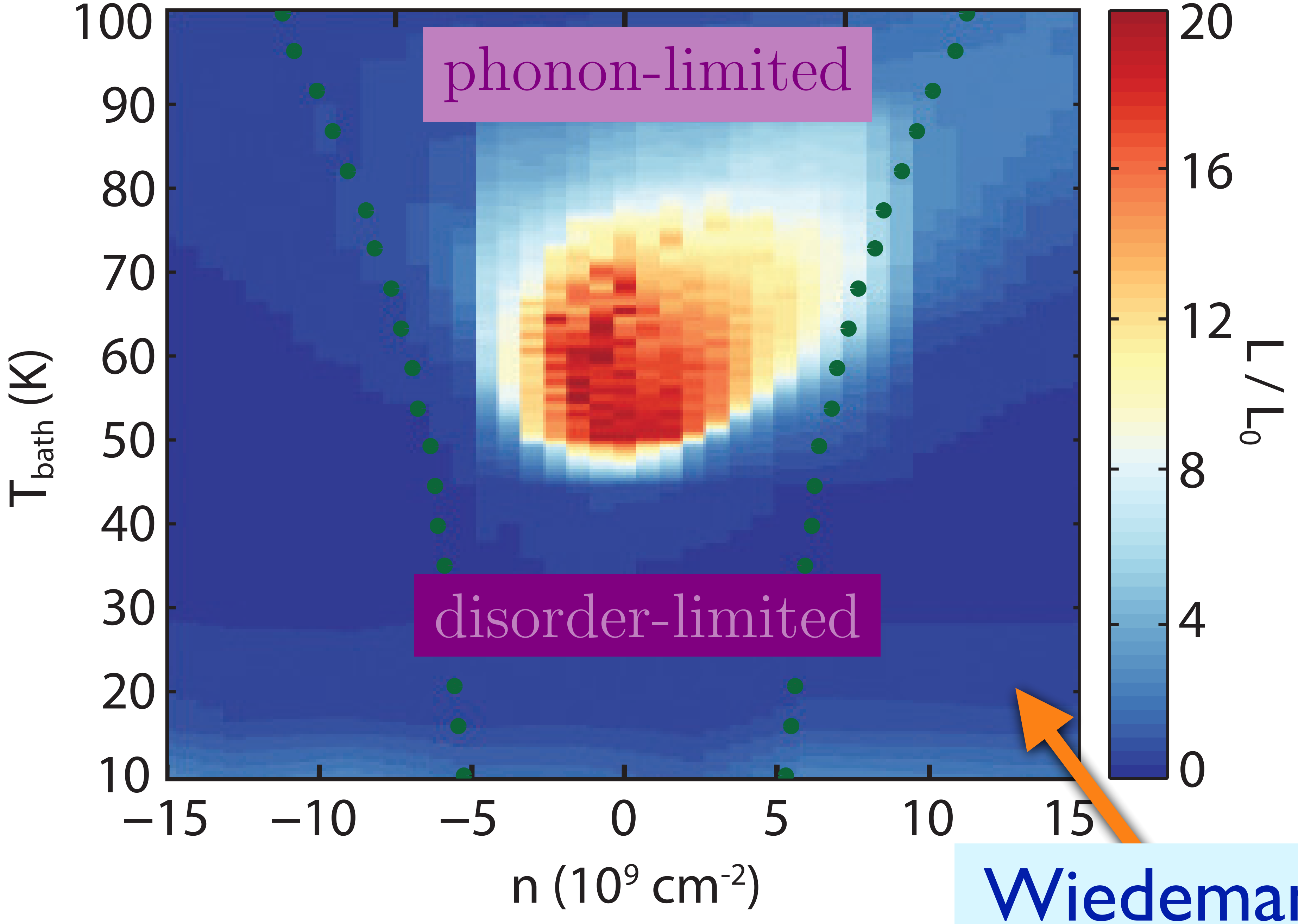
J. Crossno et al., Science **351**, 1058 (2016)

Strange metal in graphene

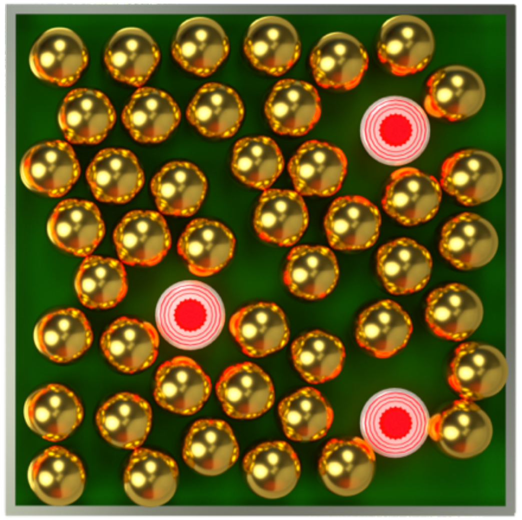


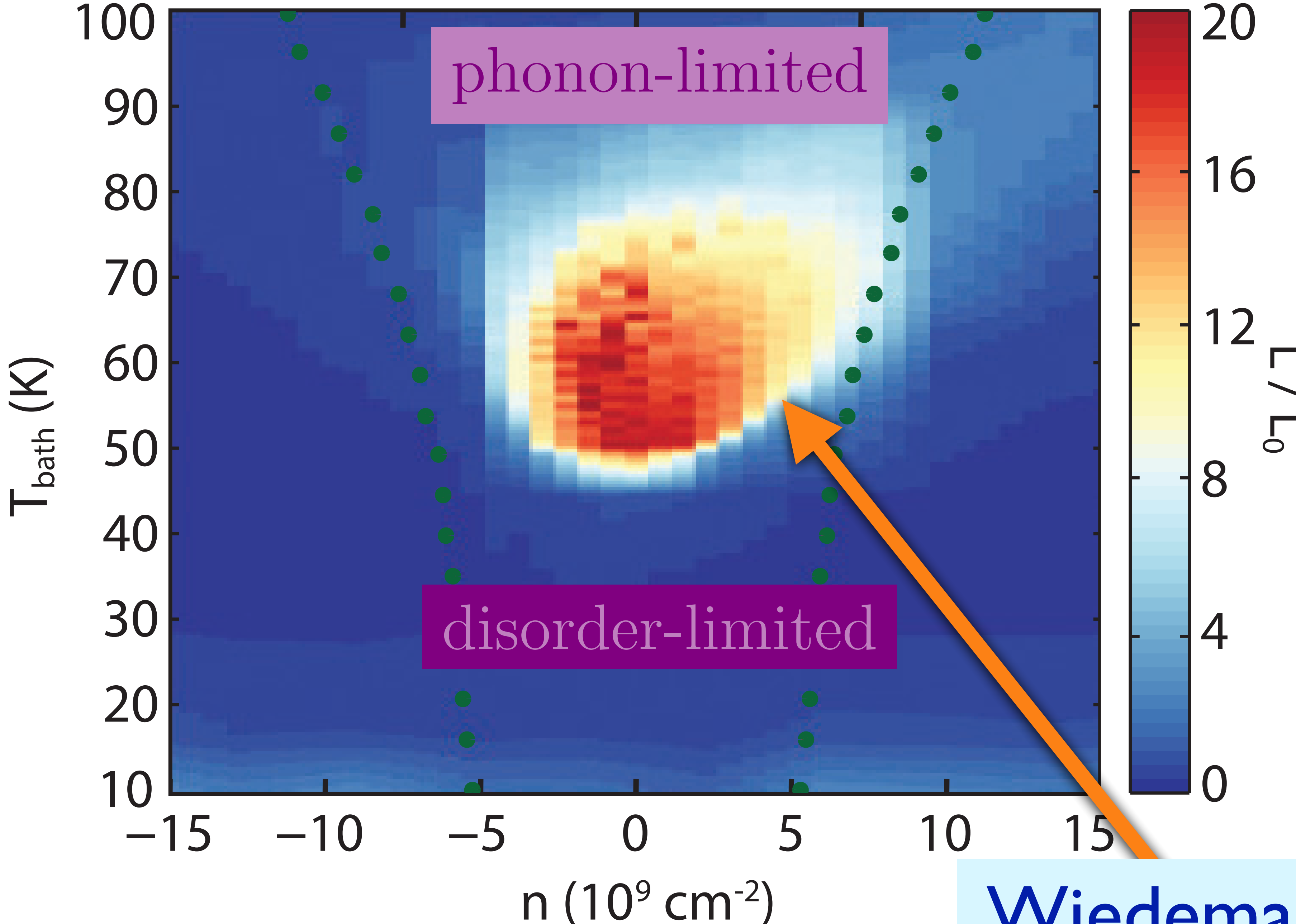


Wiedemann-Franz obeyed

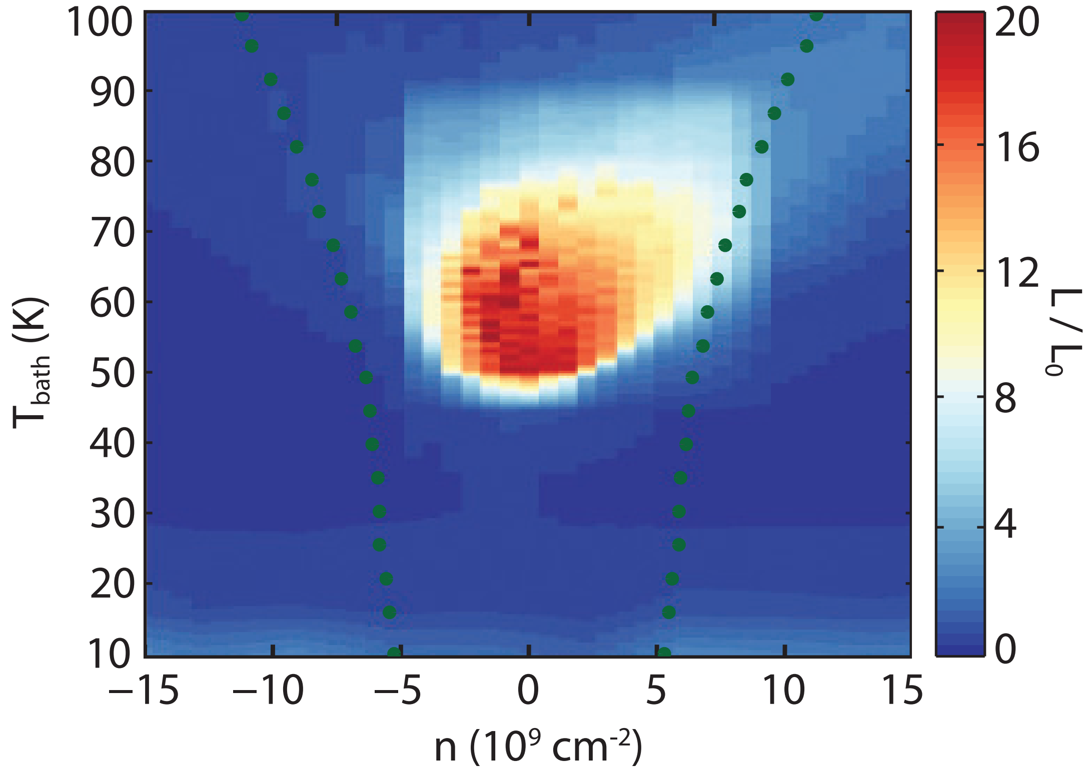
J. Crossno et al., Science **351**, 1058 (2016)

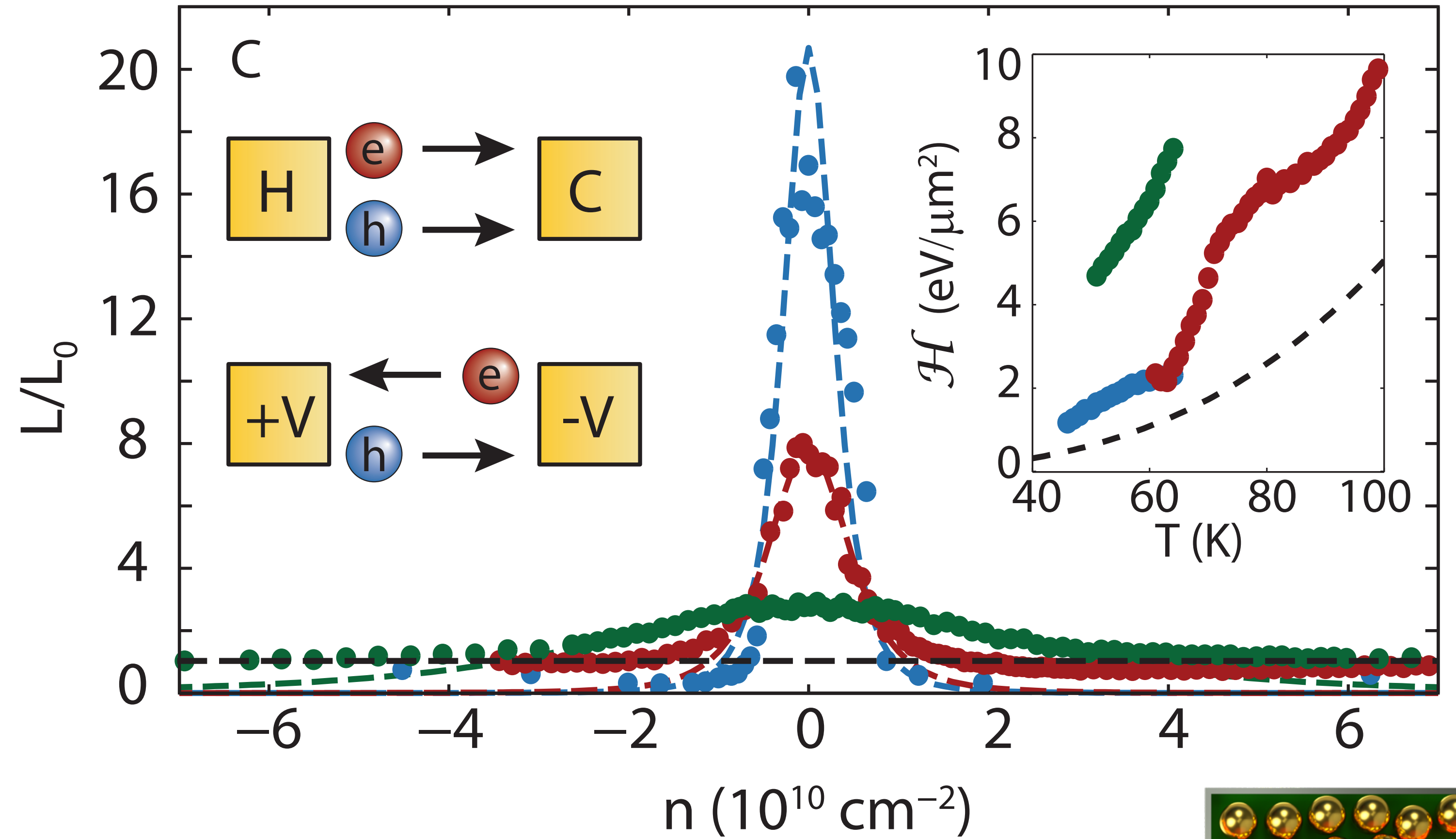
Strange metal in graphene

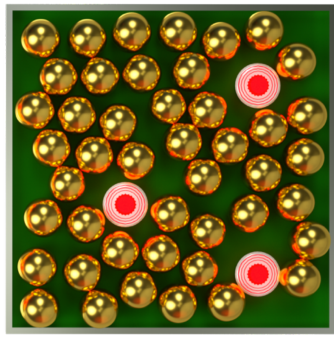


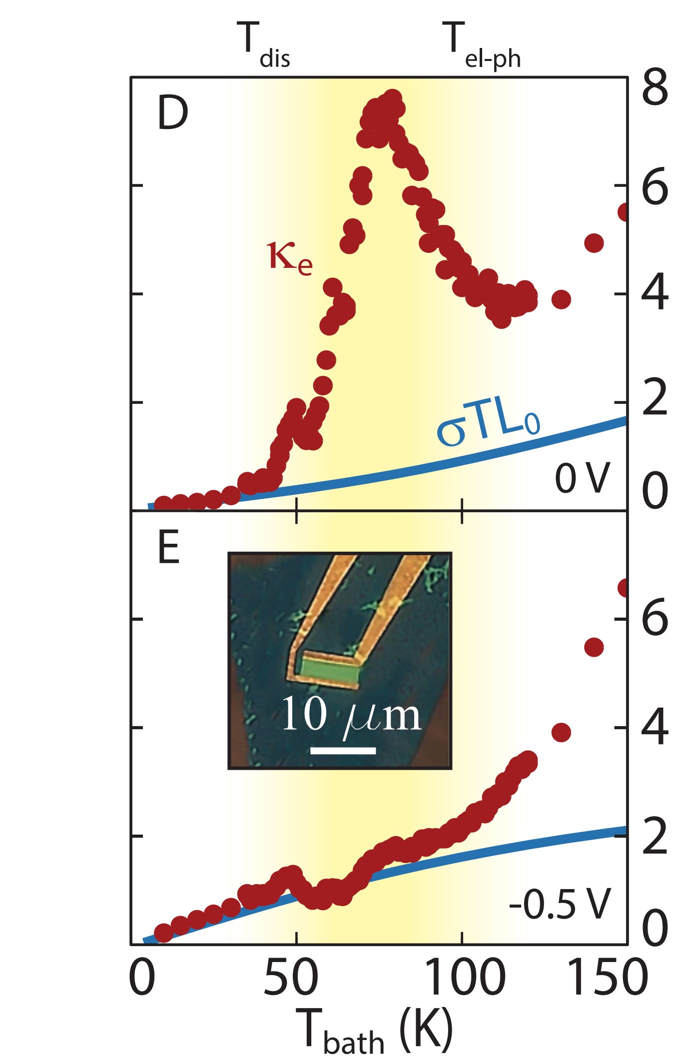


Wiedemann-Franz violated !









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

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

$\mathcal{Q} \rightarrow$ electron density; $\mathcal{H} \rightarrow$ enthalpy density

$\sigma_Q \rightarrow$ quantum critical conductivity

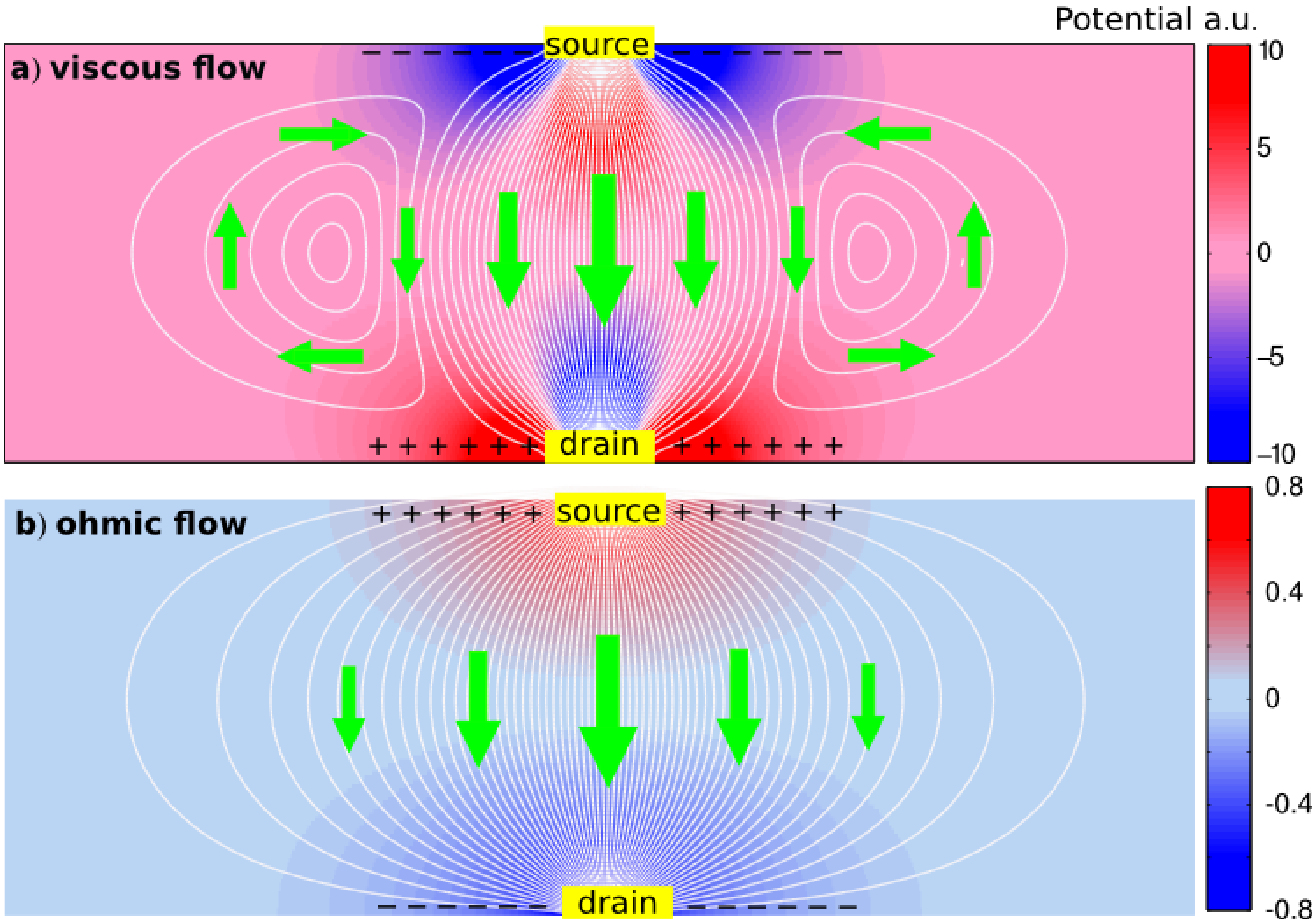
$\tau_{\rm imp} \rightarrow$ momentum relaxation time from impurities

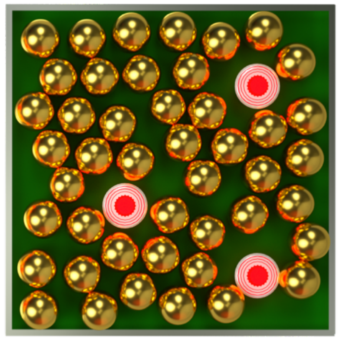
S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)

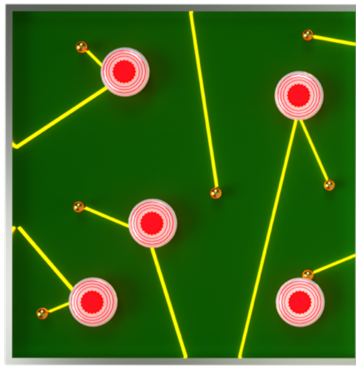
J. Crossno et al., Science **351**, 1058 (2016)

Strange metal in graphene

Negative local resistance due to viscous electron backflow in graphene







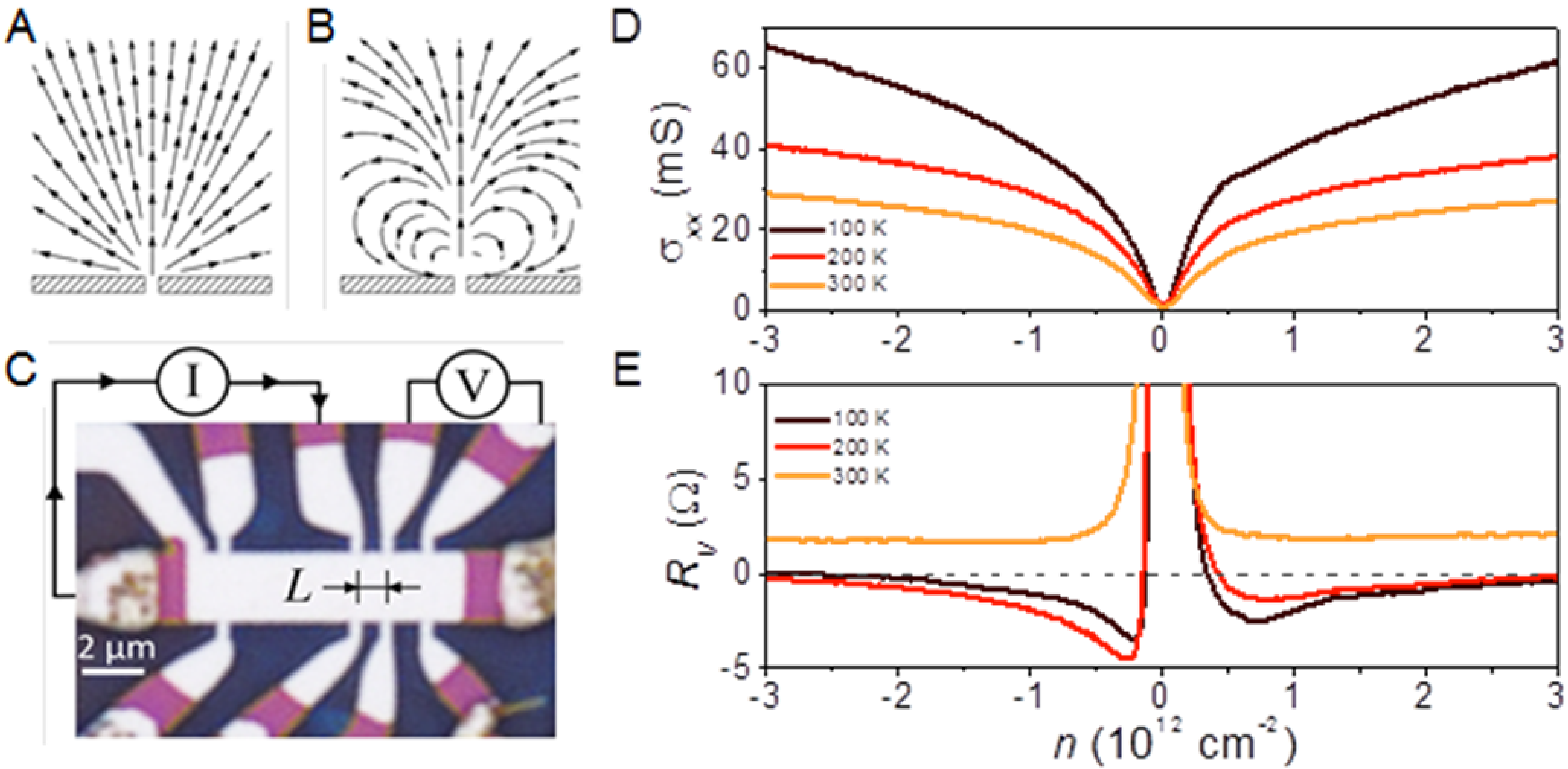
L. Levitov and G. Falkovich, arXiv:1508.00836, *Nature Physics online*

Strange metal in graphene

Science **351**, 1055 (2016)

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]



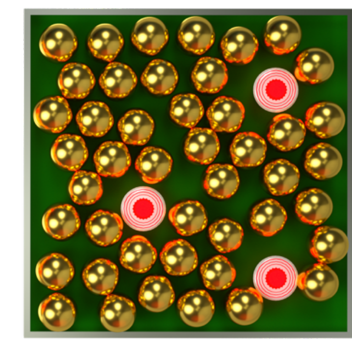
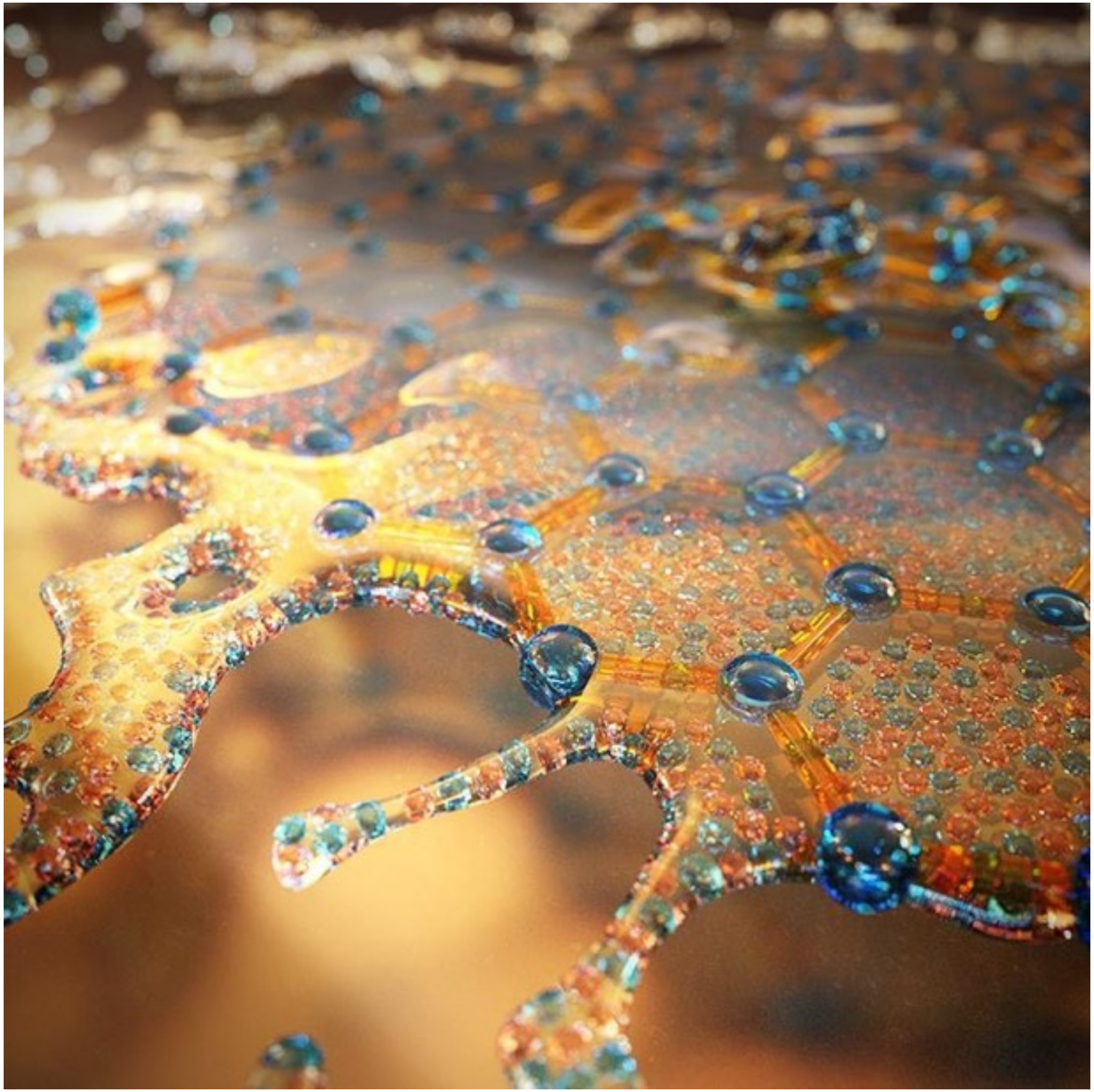


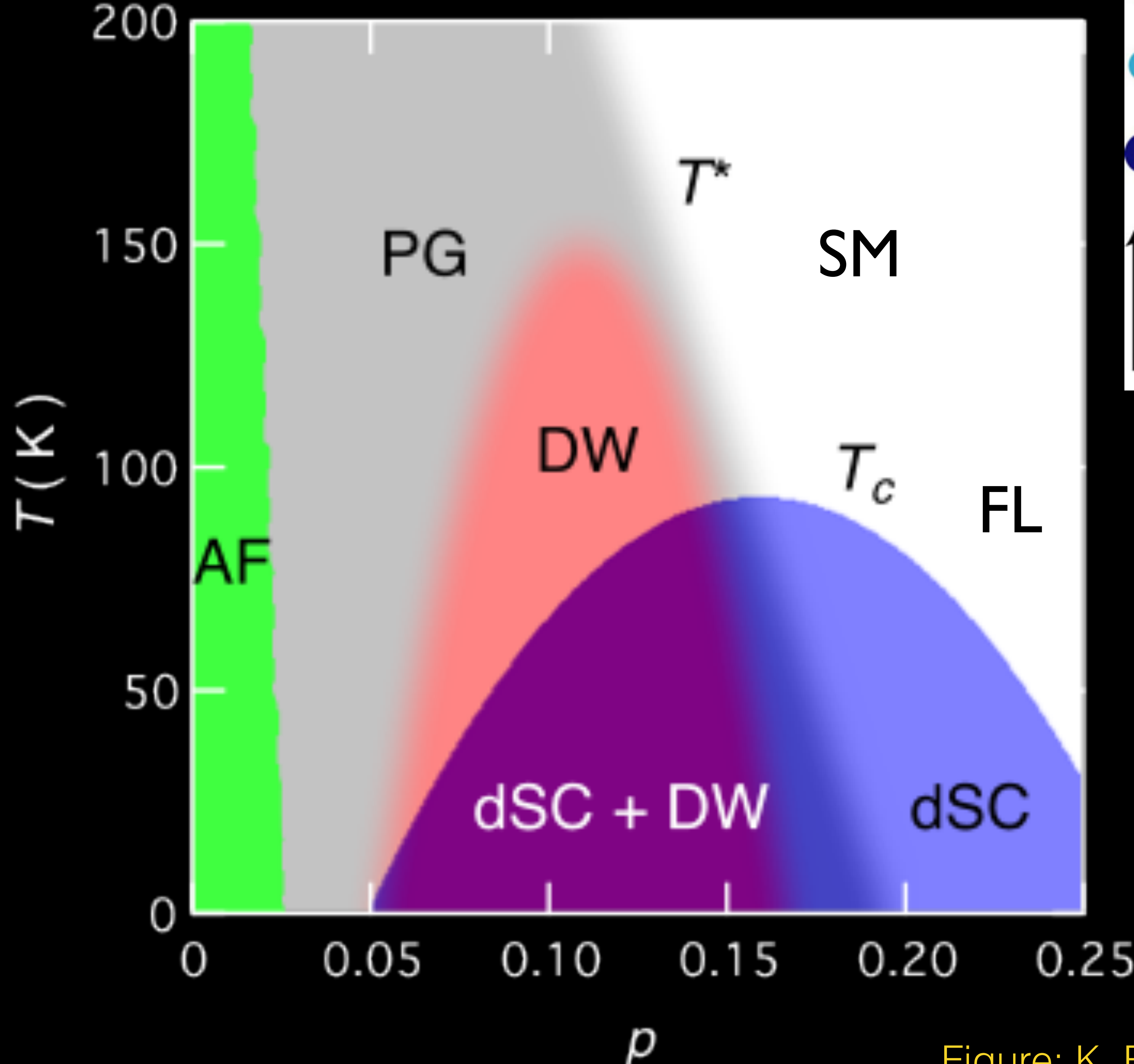
Figure 1. Viscous backflow in doped graphene. (**a,b**) Steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (a) and a viscous Fermi liquid (b). (**c**) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry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

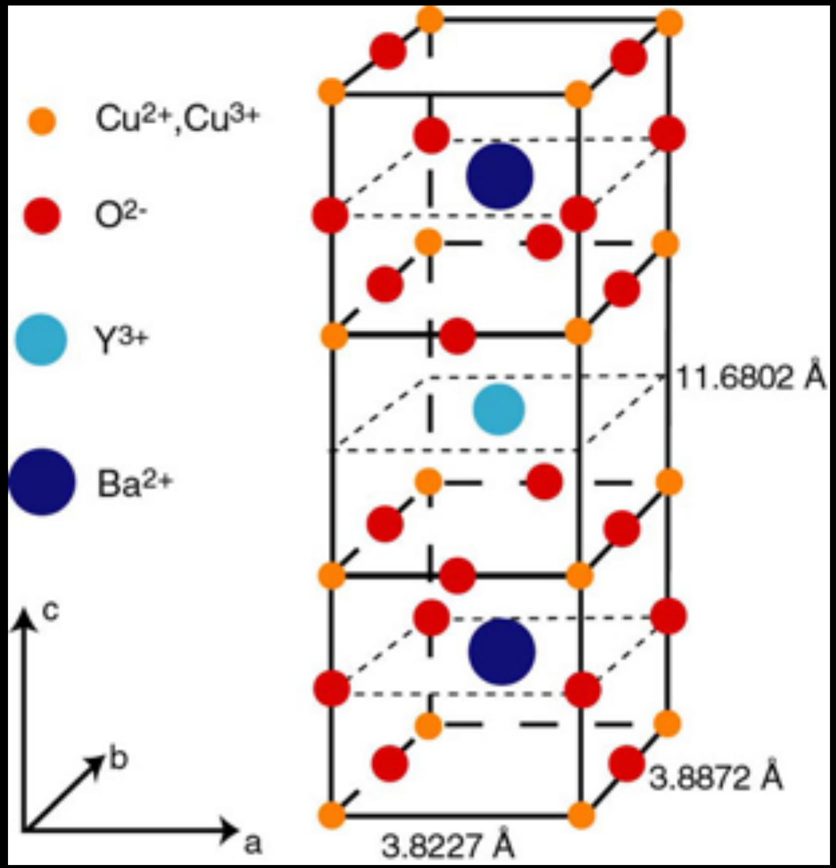
Graphene: "a metal that behaves like water"



Quantum matter without quasiparticles:

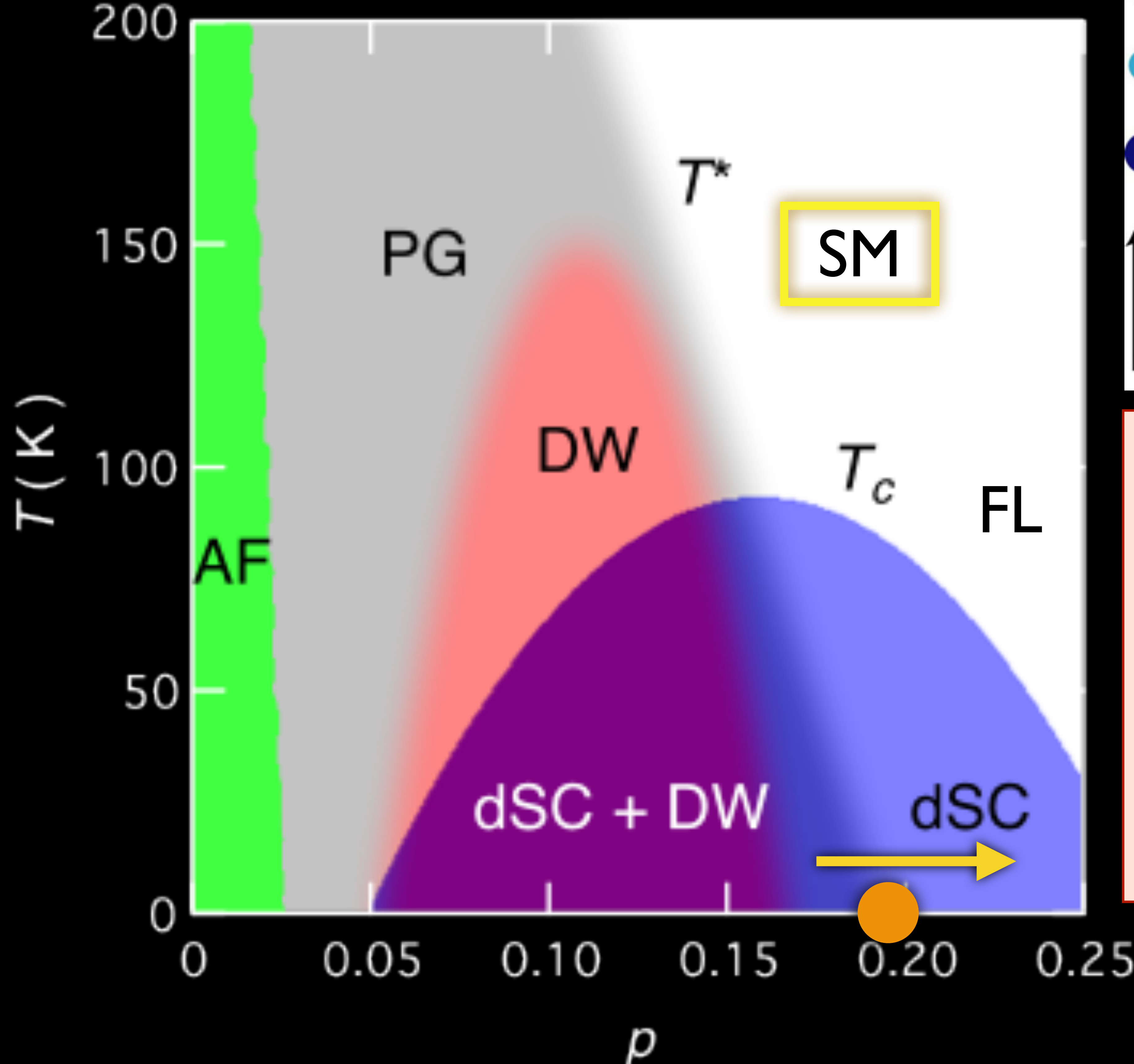
- Superfluid-insulator transition of ultracold bosonic atoms in an optical lattice
- Graphene
- Strange metals in high temperature superconductors
- Quark-gluon plasma
- *Charged black hole horizons in anti-de Sitter space*

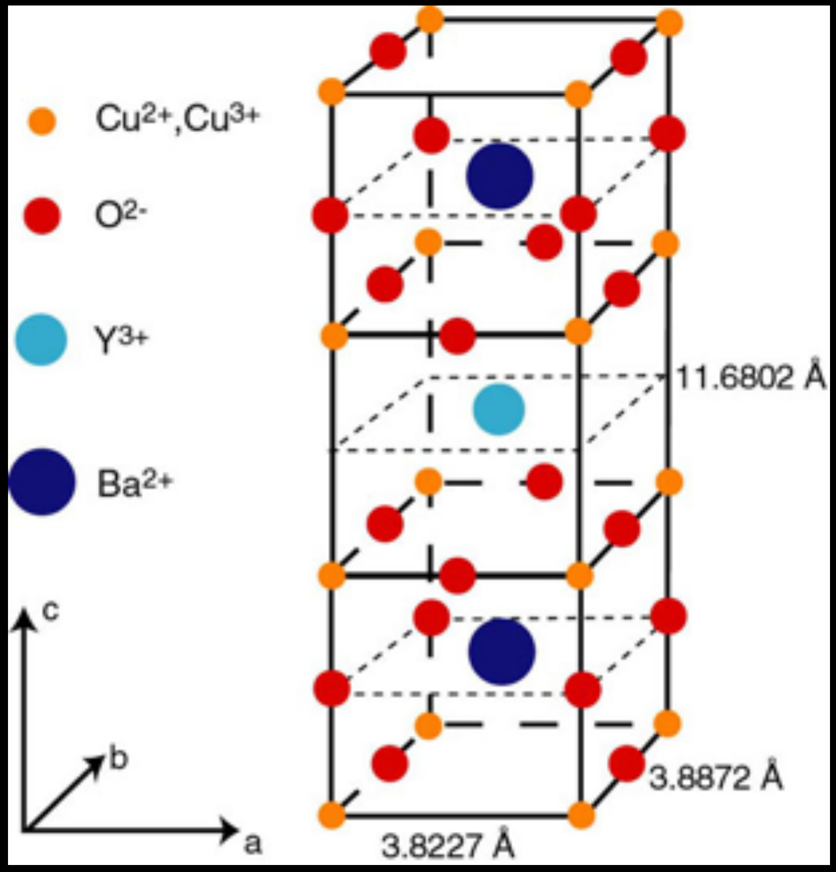




$\mathrm{YBa_2Cu_3O_{6+x}}$

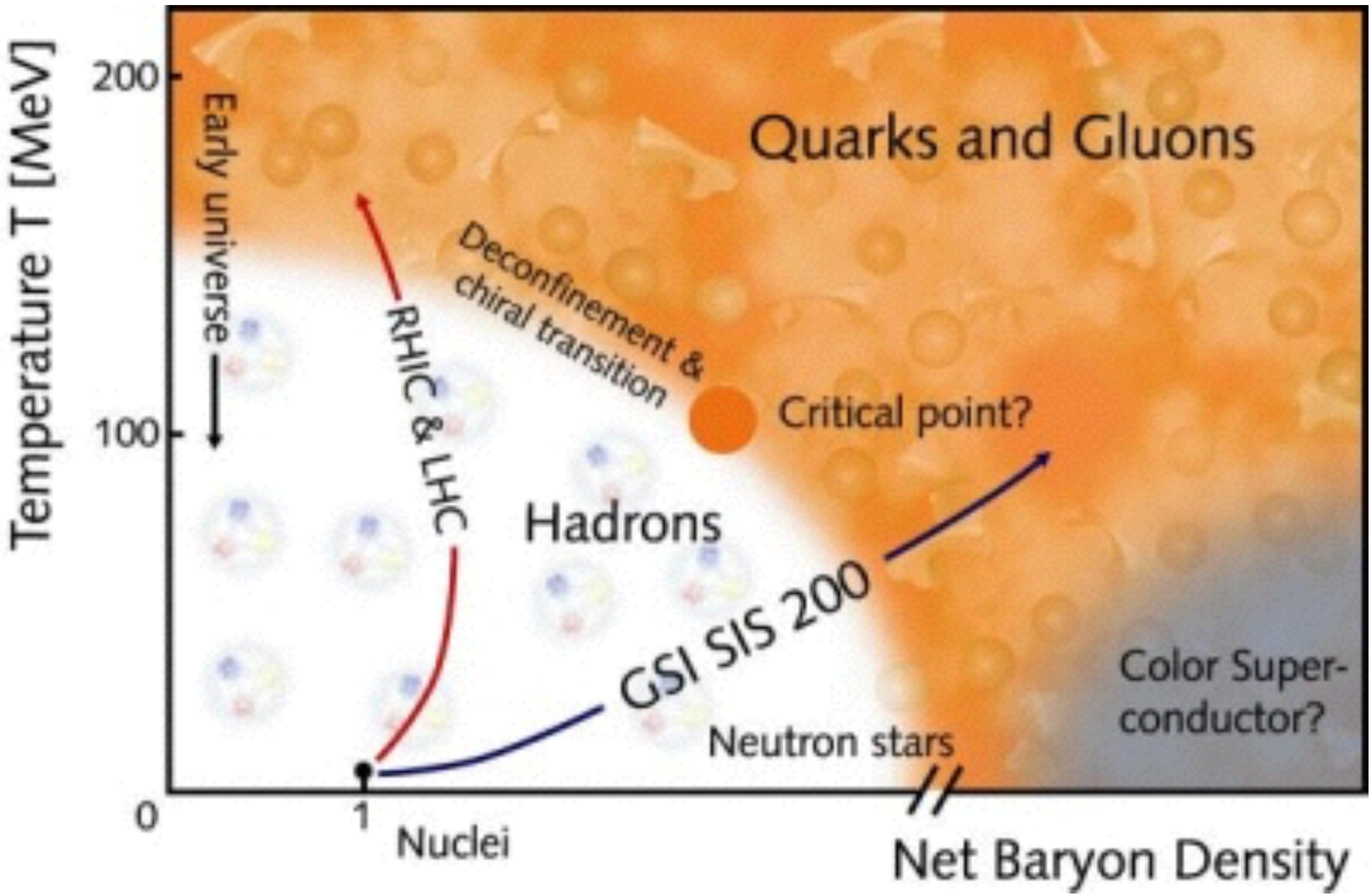
Figure: K. Fujita and J. C. Seamus Davis





Proposed a SU(2) gauge theory for transtion for quantum-criticality at optimal doping, as the origin of strange metal (SM) behavior at higher *T*

Quark-gluon plasma



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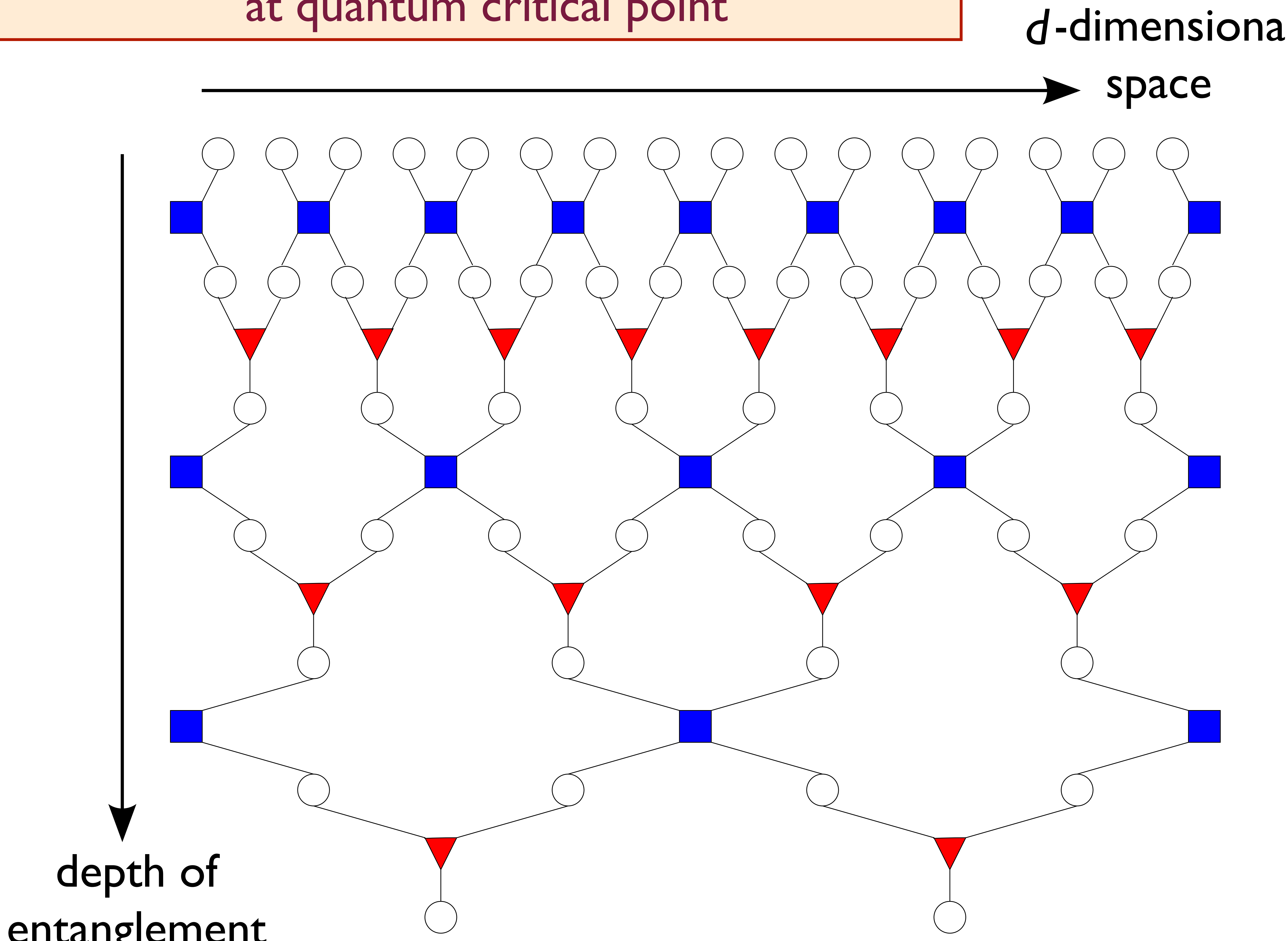
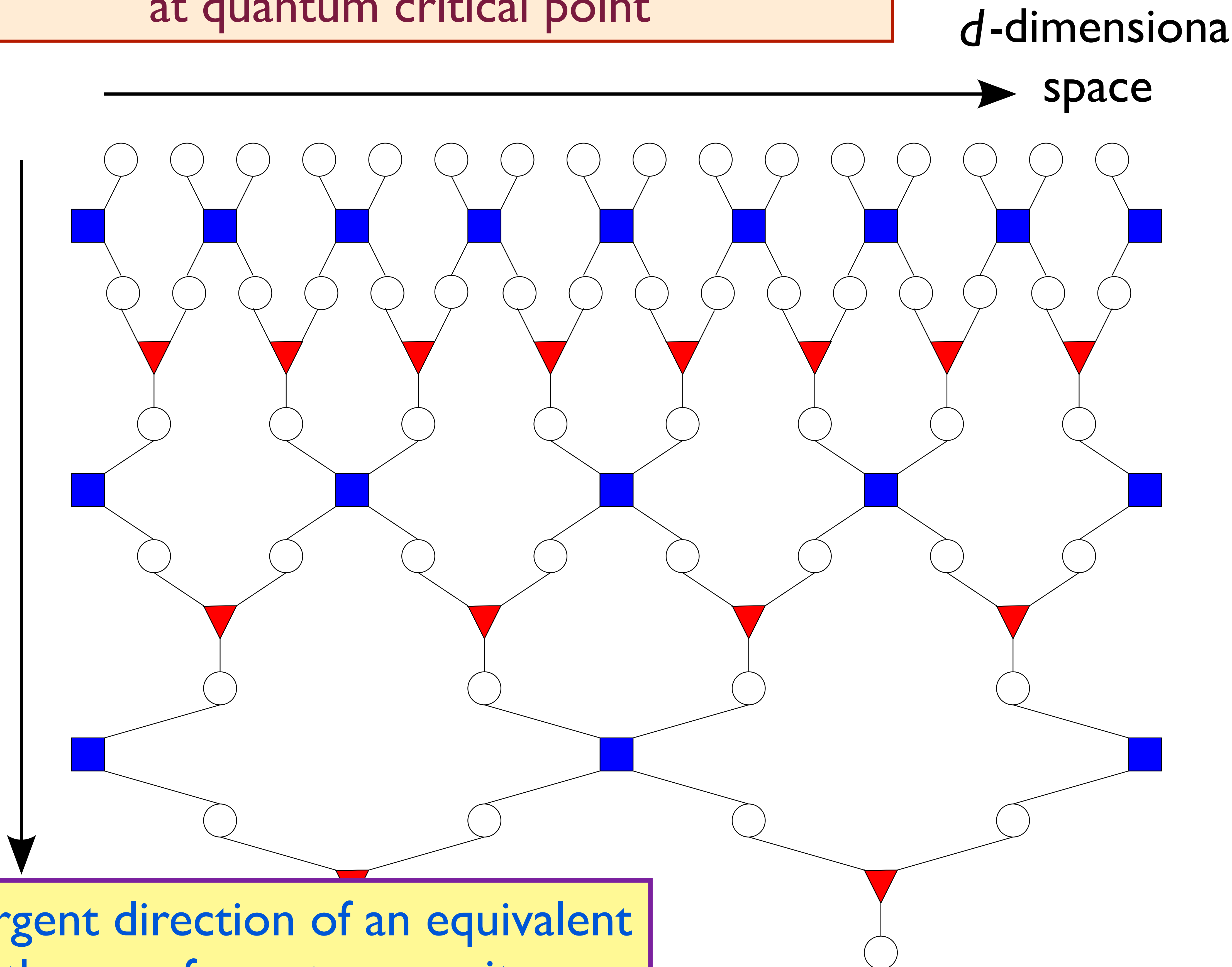
Tensor network representation of entanglement at quantum critical point



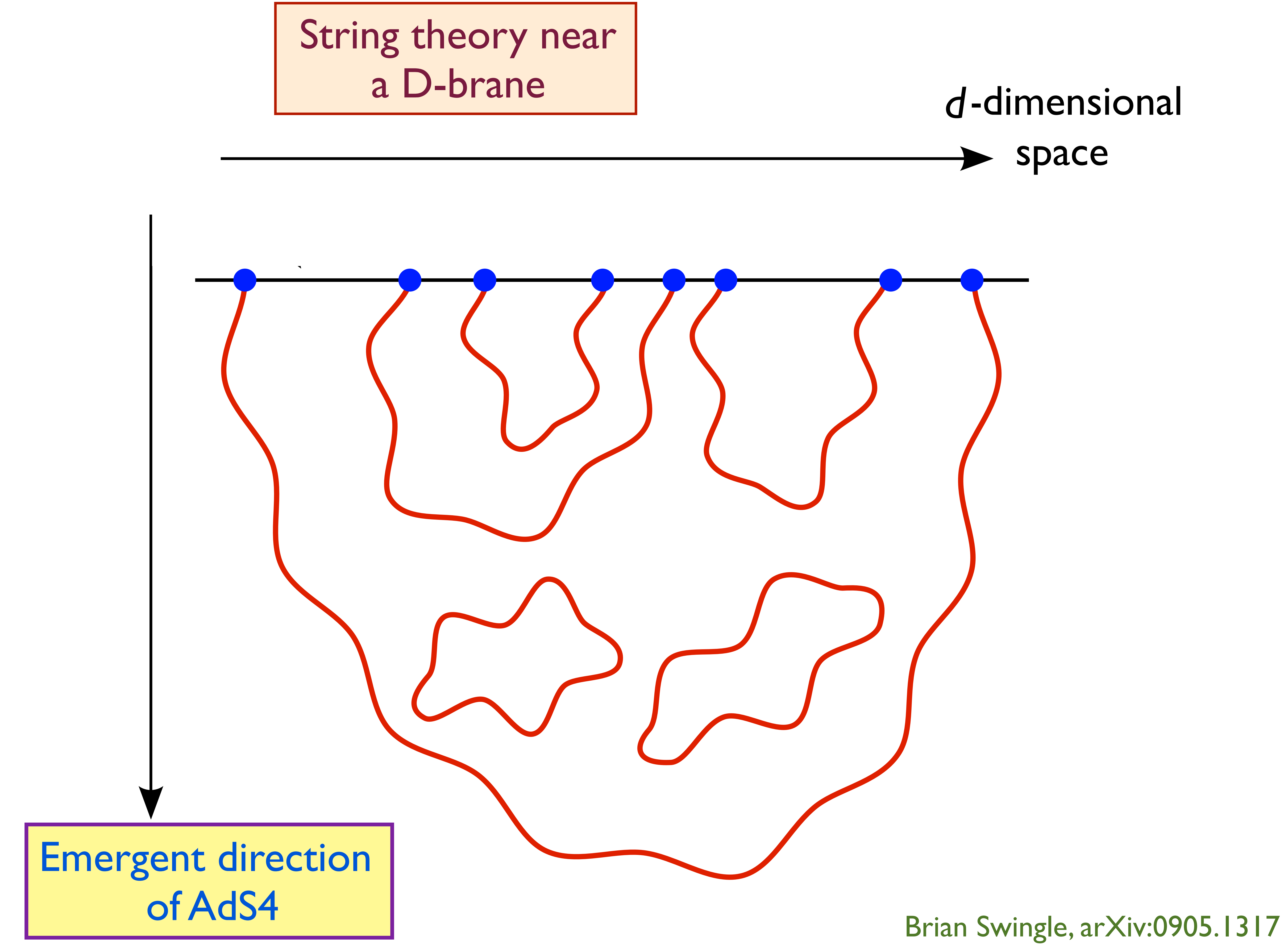
G.Vidal, Phys. Rev. Lett. 99, 220405 (2007)

Tensor network representation of entanglement at quantum critical point



Emergent direction of an equivalent theory of quantum gravity

Brian Swingle, arXiv:0905.1317


String theory near a D-brane
d-dimensional space
Emergent direction of AdS4
Brian Swingle, arXiv:0905.1317

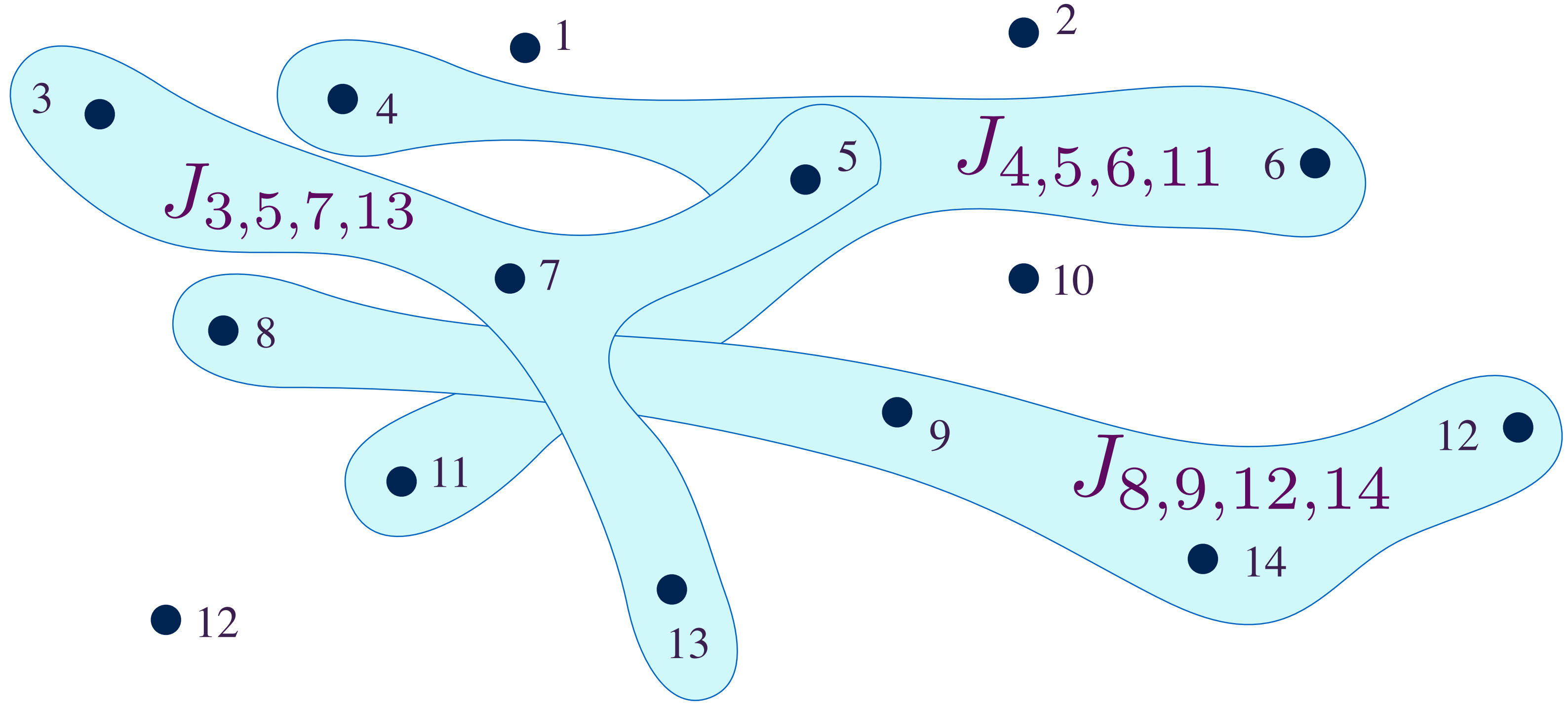
Infinite-range (SYK) model of a strange metal

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell - \mu \sum_i c_i^\dagger c_i$$

$$c_i c_j + c_j c_i = 0 \quad , \quad c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$$\mathcal{Q} = \frac{1}{N} \sum_i c_i^\dagger c_i$$

S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)



$J_{ij;k\ell}$ are independent random variables with $\overline{J_{ij;k\ell}} = 0$ and $\overline{|J_{ij;k\ell}|^2} = J^2$
$N \to \infty$ yields critical strange metal.

A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)

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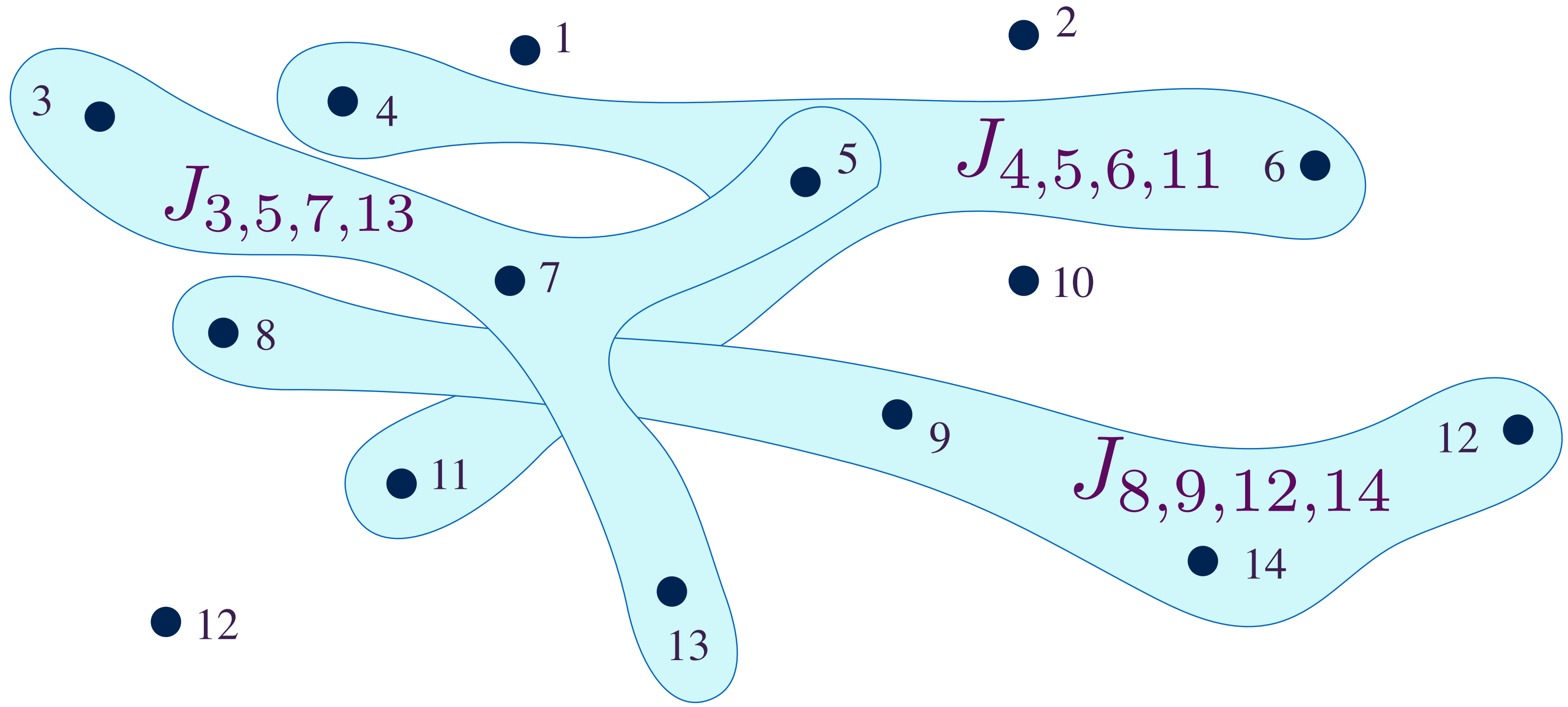


A fermion can move only by entangling with another fermion: the Hamiltonian has "nothing but entanglement".

A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)

Infinite-range strange metals

Local fermion density of states

$$\rho(\omega) = -\mathrm{Im}\, G(\omega) \sim \begin{cases} \omega^{-1/2} & , \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

$\boxed{\mathcal{E} \text{ encodes the particle-hole asymmetry}}$

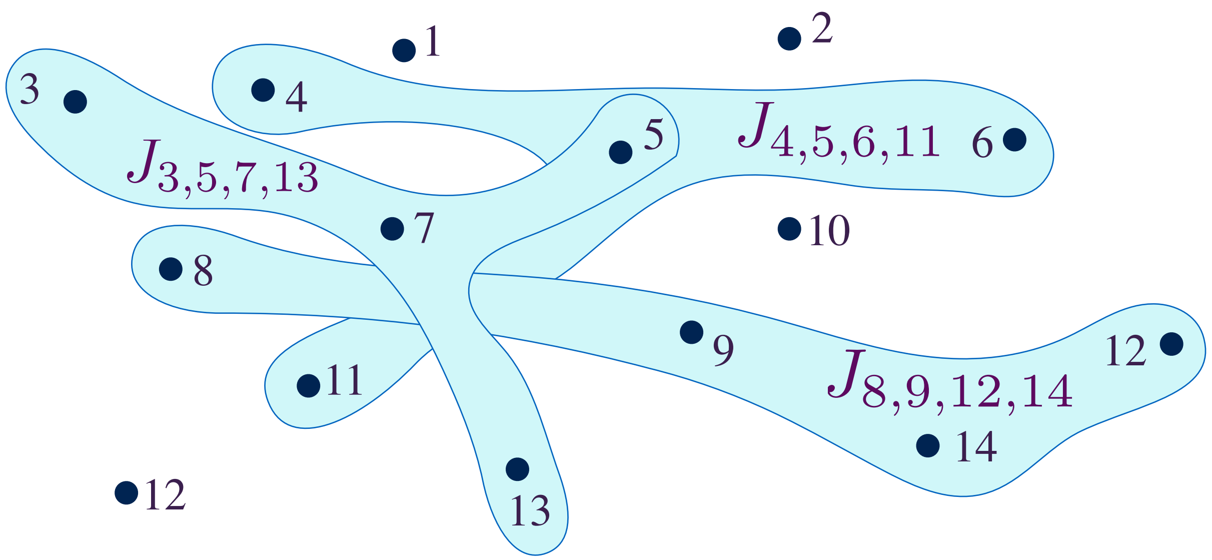
While $\mathcal{E}$ determines the *low* energy spectrum, it is determined by the *total* fermion density $\mathcal{Q}$:

$$\mathcal{Q} = \frac{1}{4}(3 - \tanh(2\pi\mathcal{E})) - \frac{1}{\pi} \tan^{-1}\left(e^{2\pi\mathcal{E}}\right).$$

Analog of the relationship between $\mathcal{Q}$ and k_F in a Fermi liquid.

S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)
A. Georges, O. Parcollet, and S. Sachdev Phys. Rev. B **63**, 134406 (2001)

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

$$\rho(\omega) \sim \left\{ \begin{array}{cc} \omega^{-1/2} & , \, \omega > 0 \\ e^{-2\pi\mathcal{E}} \, |\omega|^{-1/2} & , \, \omega < 0. \end{array} \right.$$

Known ‘equation of state’
determines $\mathcal{E}$ as a function of $\mathcal{Q}$

Microscopic zero temperature entropy density, $\mathcal{S}$, obeys

$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

Holographic gravity theory

Start with simplest theory of Einstein gravity and Maxwell electromagnetism

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

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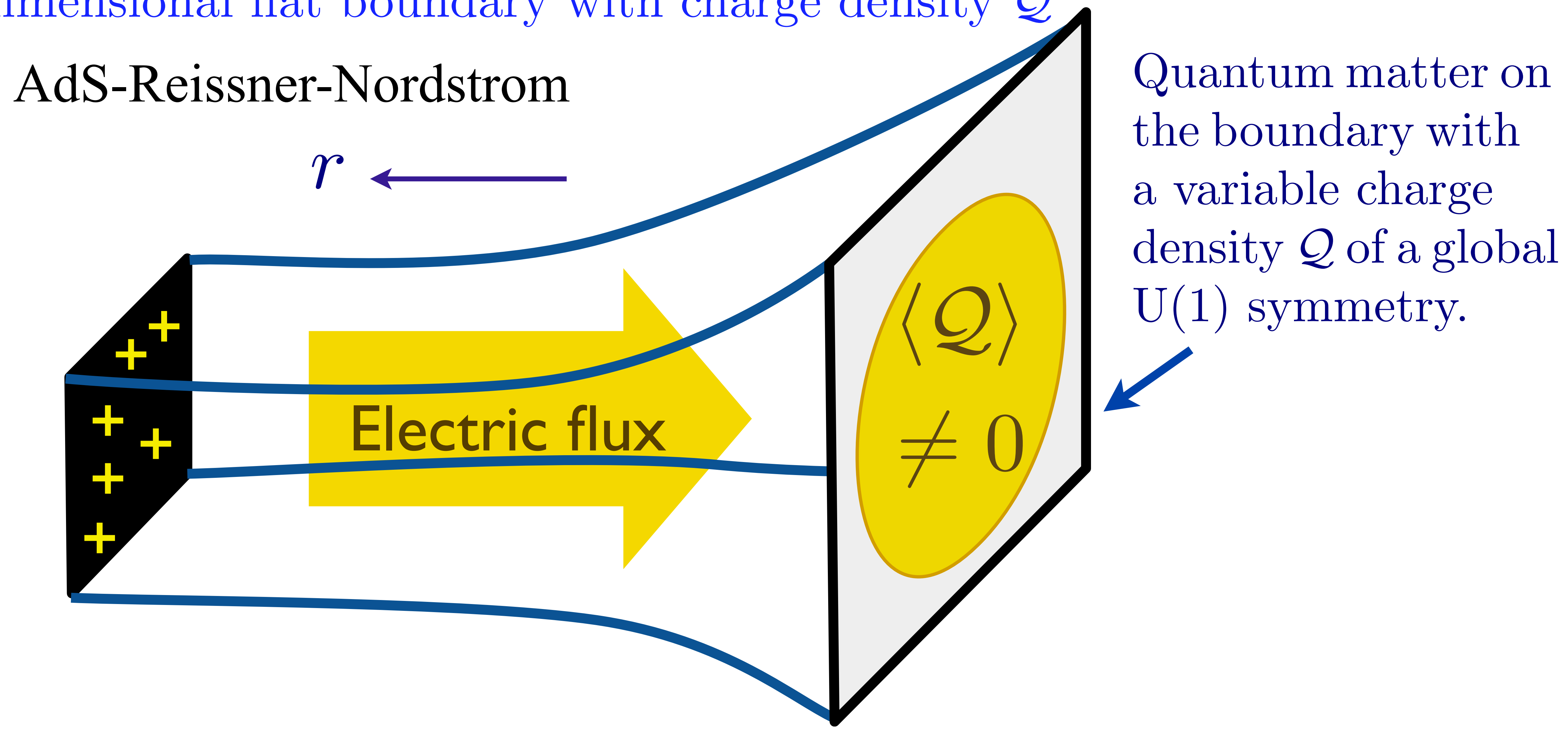
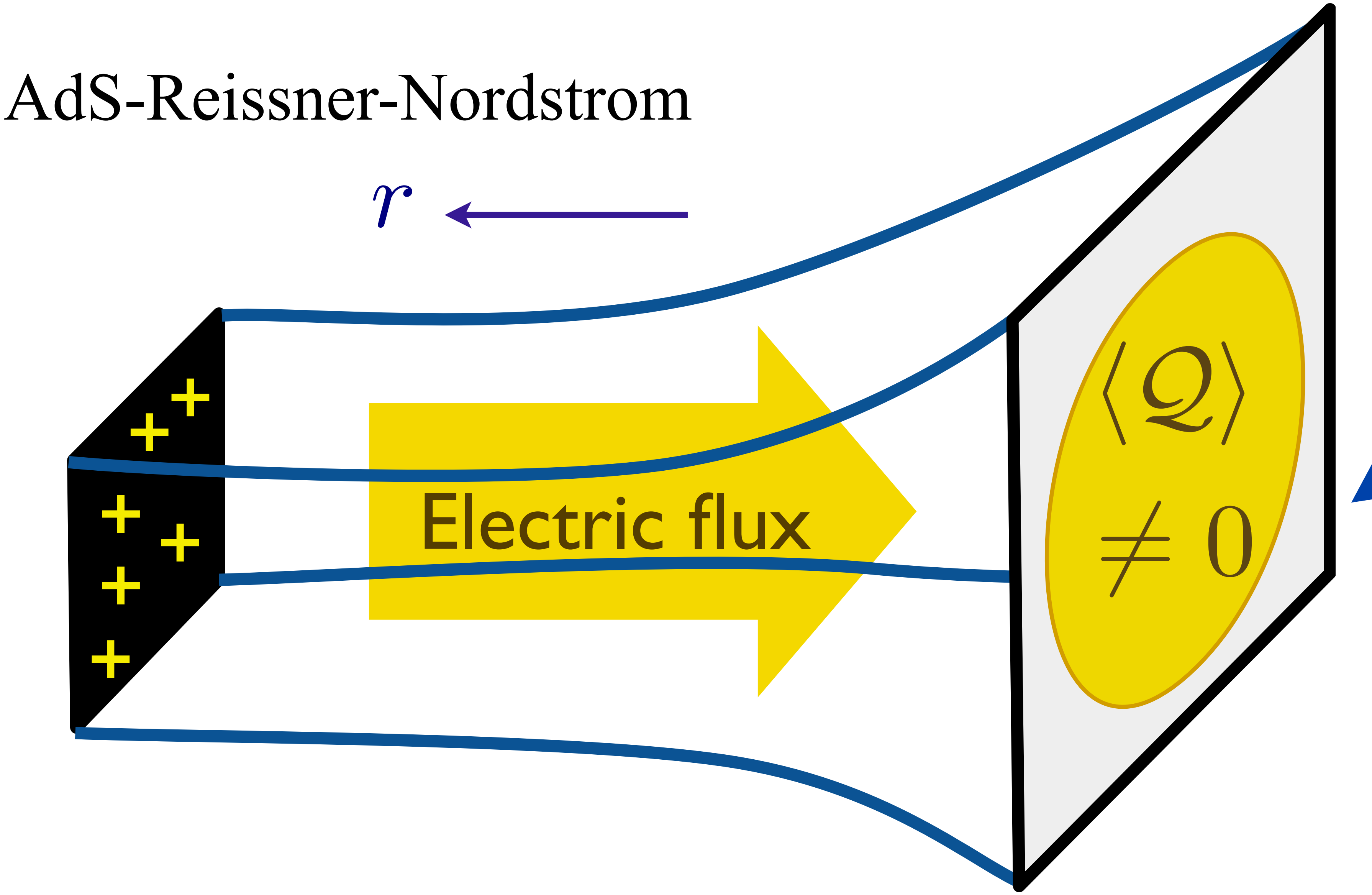
Solve equations of motion in the the presence of a d-dimensional flat boundary with charge density $\mathcal{Q}$



A. Chamblin, R. Emparan, C.V. Johnson, and R. C. Myers, PRD **60**, 064018 (1999)

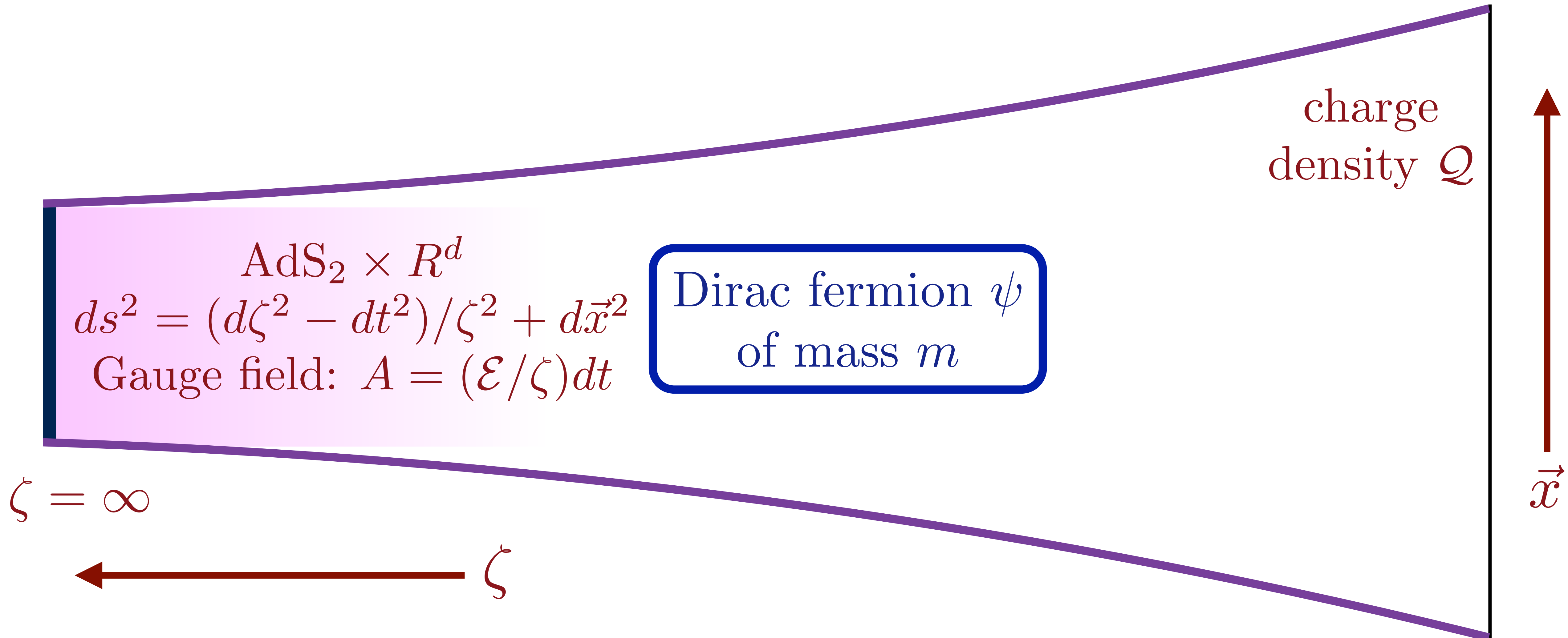
Charged black branes



Quantum matter on the boundary with a variable charge density $\mathcal{Q}$ of a global U(1) symmetry.

Realizes a strange metal: a state with an unbroken global U(1) symmetry with a continuously variable charge density, $\mathcal{Q}$, at $T = 0$ which does not have any quasiparticle excitations.

Quantum fields on charged black branes



AdS_2 boundary Green's function of ψ at $T = 0$

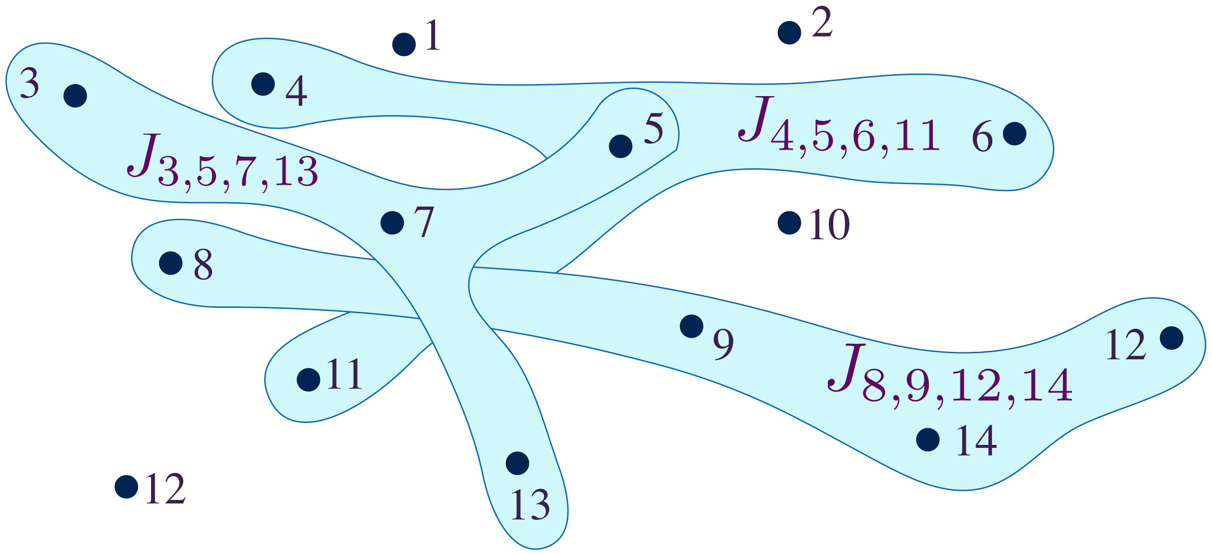
$$\mathrm{Im}G(\omega) \sim \begin{cases} \omega^{-(1-2\Delta)} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}}\,|\omega|^{-(1-2\Delta)} & , \ \omega < 0. \end{cases}$$

where the fermion scaling dimension Δ is a function of m

$\boxed{\mathcal{E} \text{ encodes the particle-hole asymmetry}}$

T. Faulkner, Hong Liu, J. McGreevy, and D. Vegh, PRD **83**, 125002 (2011)

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

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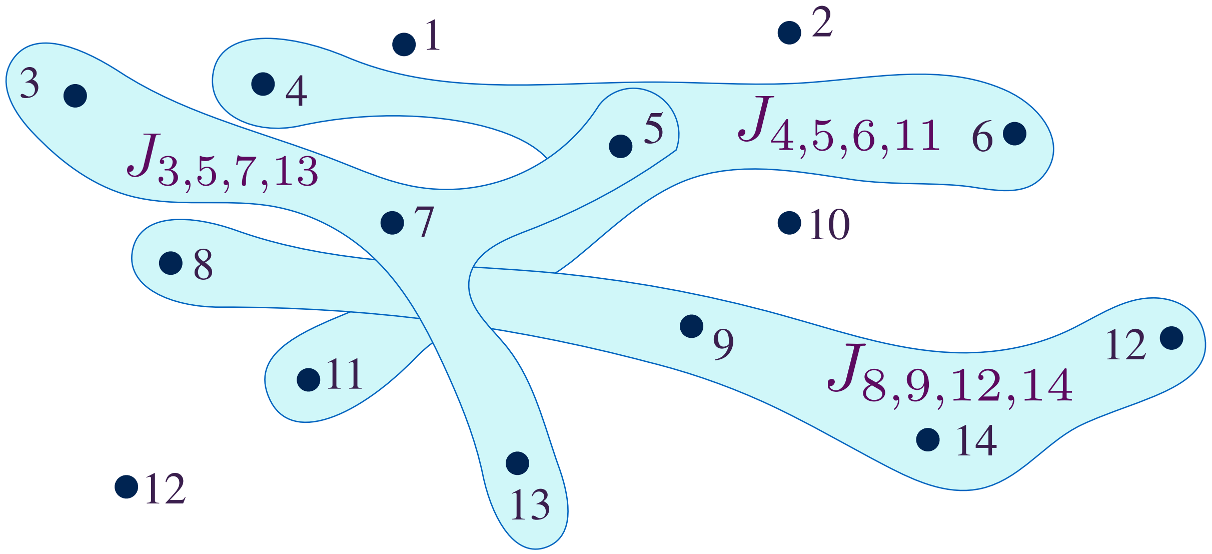

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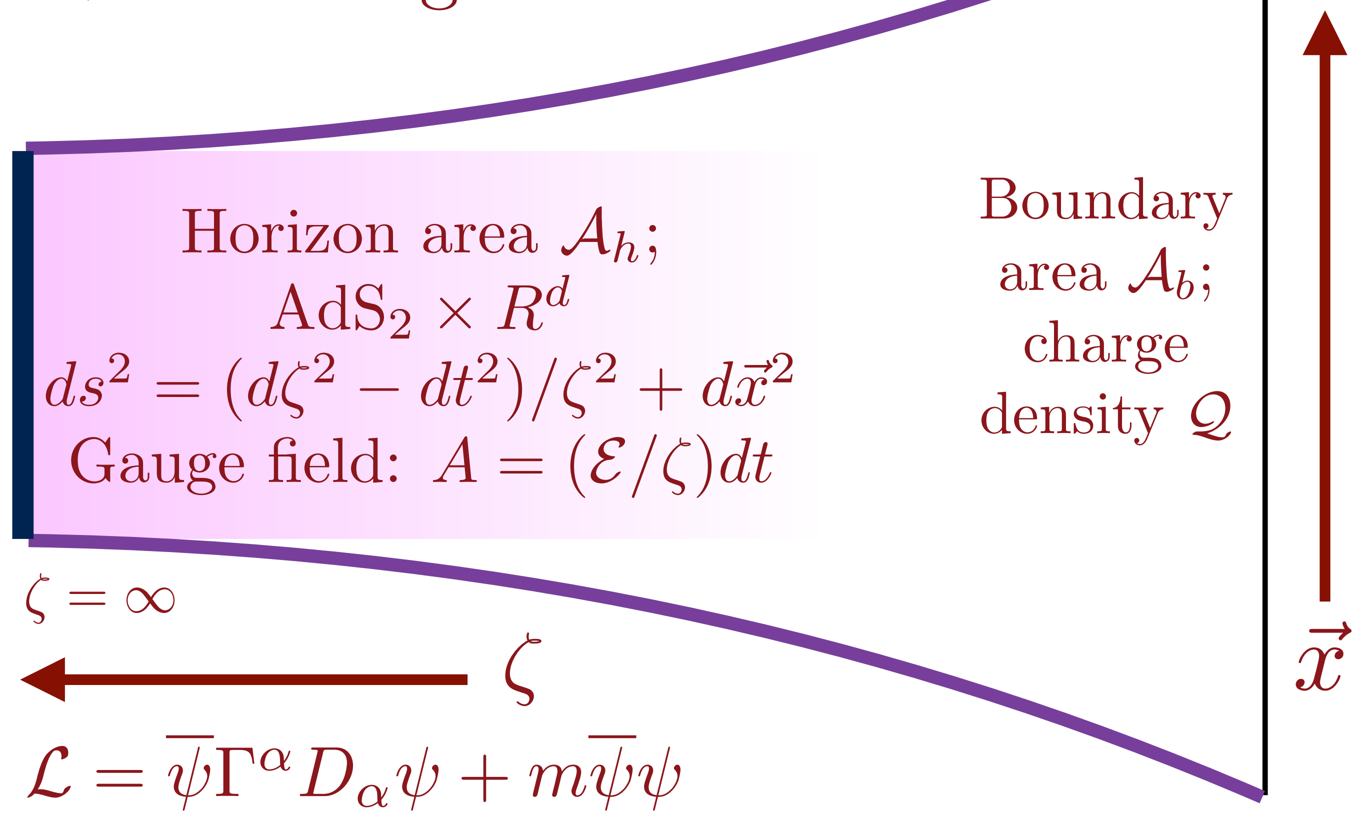
Einstein-Maxwell theory + cosmological constant



$$\mathcal{L} = \overline{\psi} \Gamma^\alpha D_\alpha \psi + m \overline{\psi} \psi$$

Local fermion density of states

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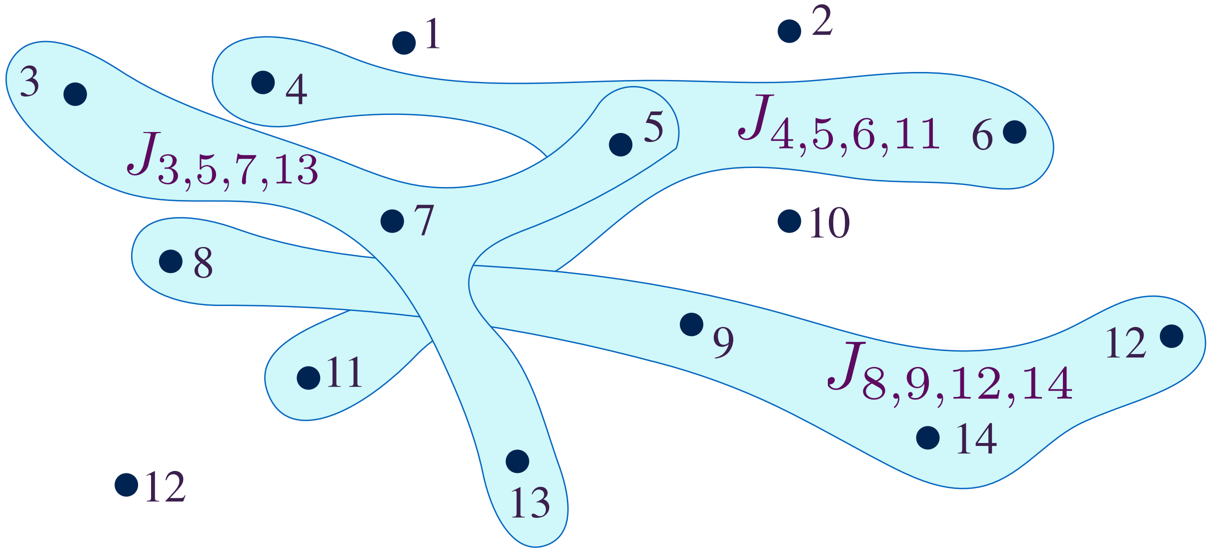
'Equation of state' relating $\mathcal{E}$ and $\mathcal{Q}$ depends upon the geometry of spacetime far from the AdS$_2$

Black hole thermodynamics (classical general relativity) yields

$$\frac{\partial \mathcal{S}_{\rm BH}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

A. Sen hep-th/0506177; S. Sachdev PRX **5**, 041025 (2015)

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$



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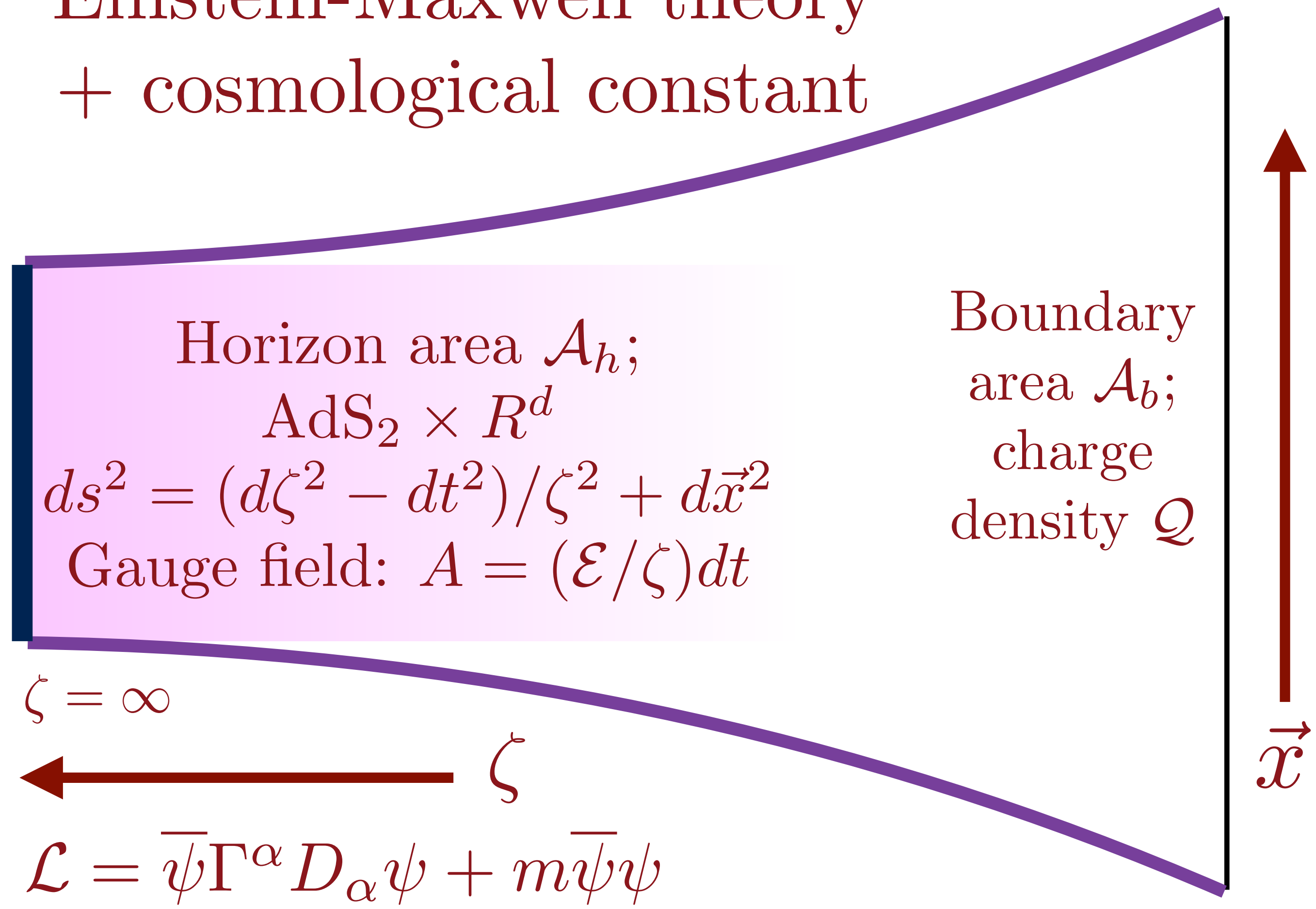
Einstein-Maxwell theory
+ cosmological constant



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Evidence for AdS_2 gravity dual of H

lack hole thermodynamics
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S. Sachdev, PRL **105**, 151602 (2010); PRX **5**, 041025 (2015)

A bound on quantum chaos:

- The "Lyapunov exponent" for chaos, λ_L, is given by out-of-time-order correlators, and for quantum systems near equilibrium, it obeys the bound $\lambda_L \leq 2\pi k_B T/\hbar$.

J. Maldacena, S. H. Shenker and D. Stanford, arXiv:1503.01409

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S. H. Shenker and D. Stanford, arXiv:1306.0622

- The bound is also saturated by the SYK model

A. Kitaev, unpublished
J. Polchinski and V. Rosenhaus, arXiv:1601.06768

Entangled 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*

Entangled 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.

- Future work: detection of hydrodynamic flow in other strange metals . . . . . .