Quantum matter without quasiparticles

Max-Planck-Institut für Physik komplexer Systeme
Dresden, May 22, 2016

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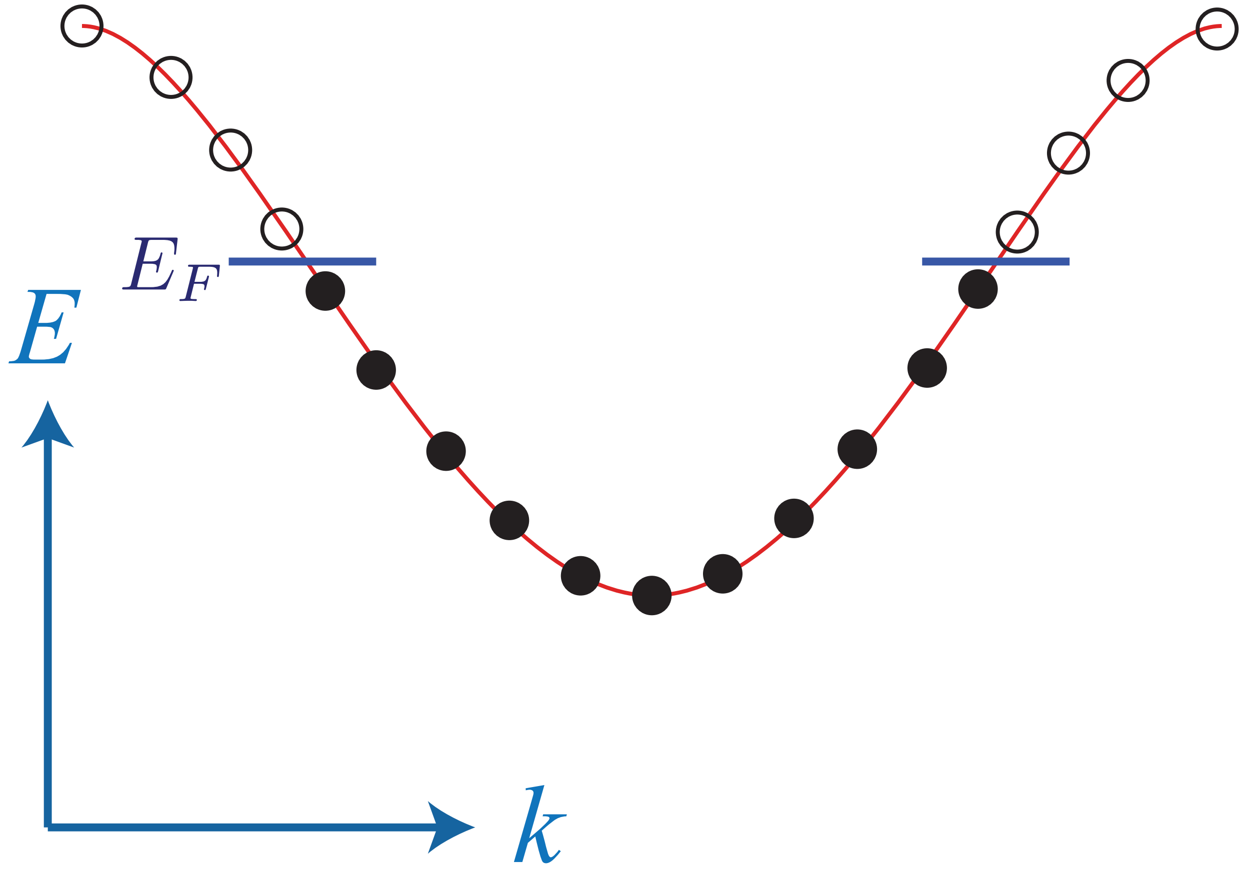
Foundations of quantum many body theory:

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

<u>Metals</u>

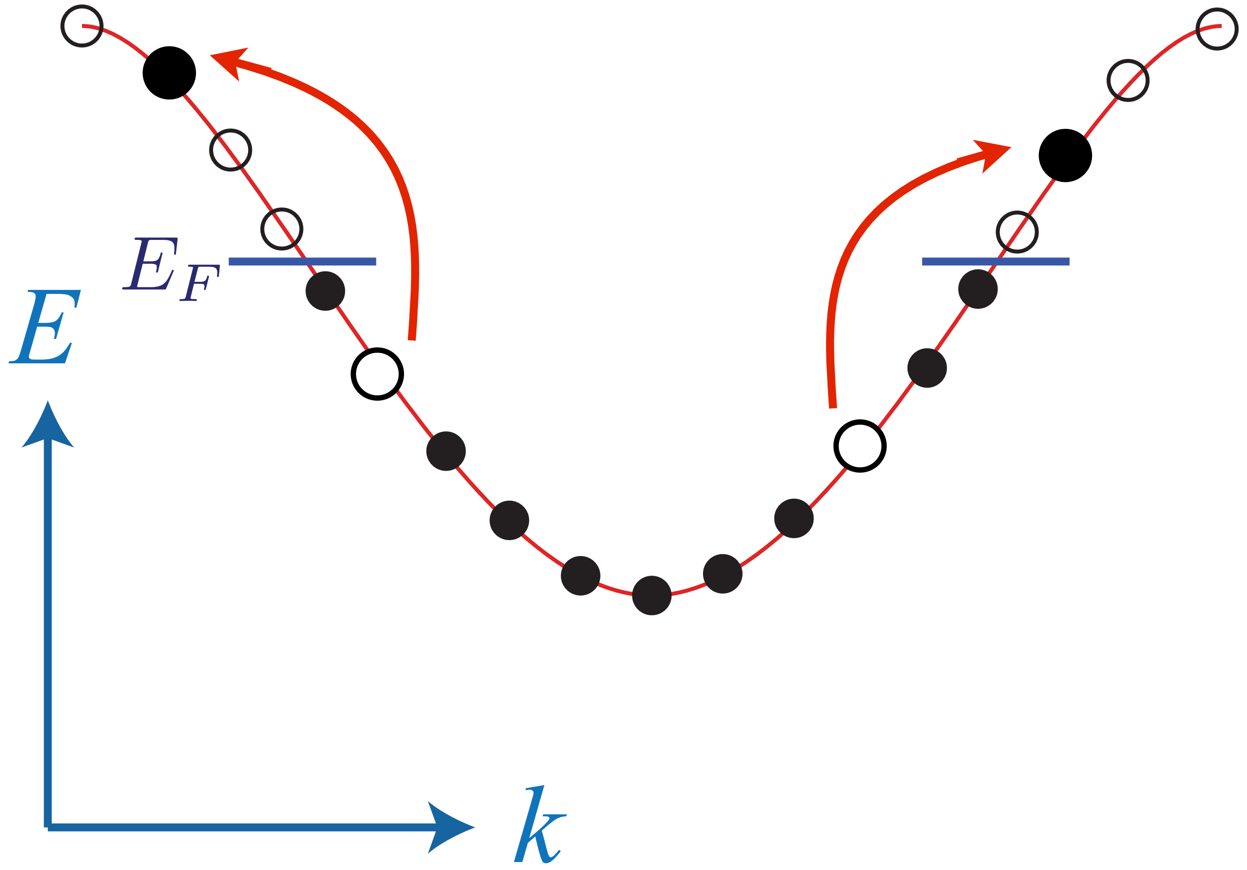


Foundations of quantum many body theory:

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

2. Boltzmann-Landau theory of quasiparticles

<u>Metals</u>



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:

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

2. No quasiparticles

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
- Solvable random fermion Sachdev-Ye-Kitaev (SYK) model
- Charged black hole horizons in anti-de Sitter space
- Strange metals in high temperature superconductors

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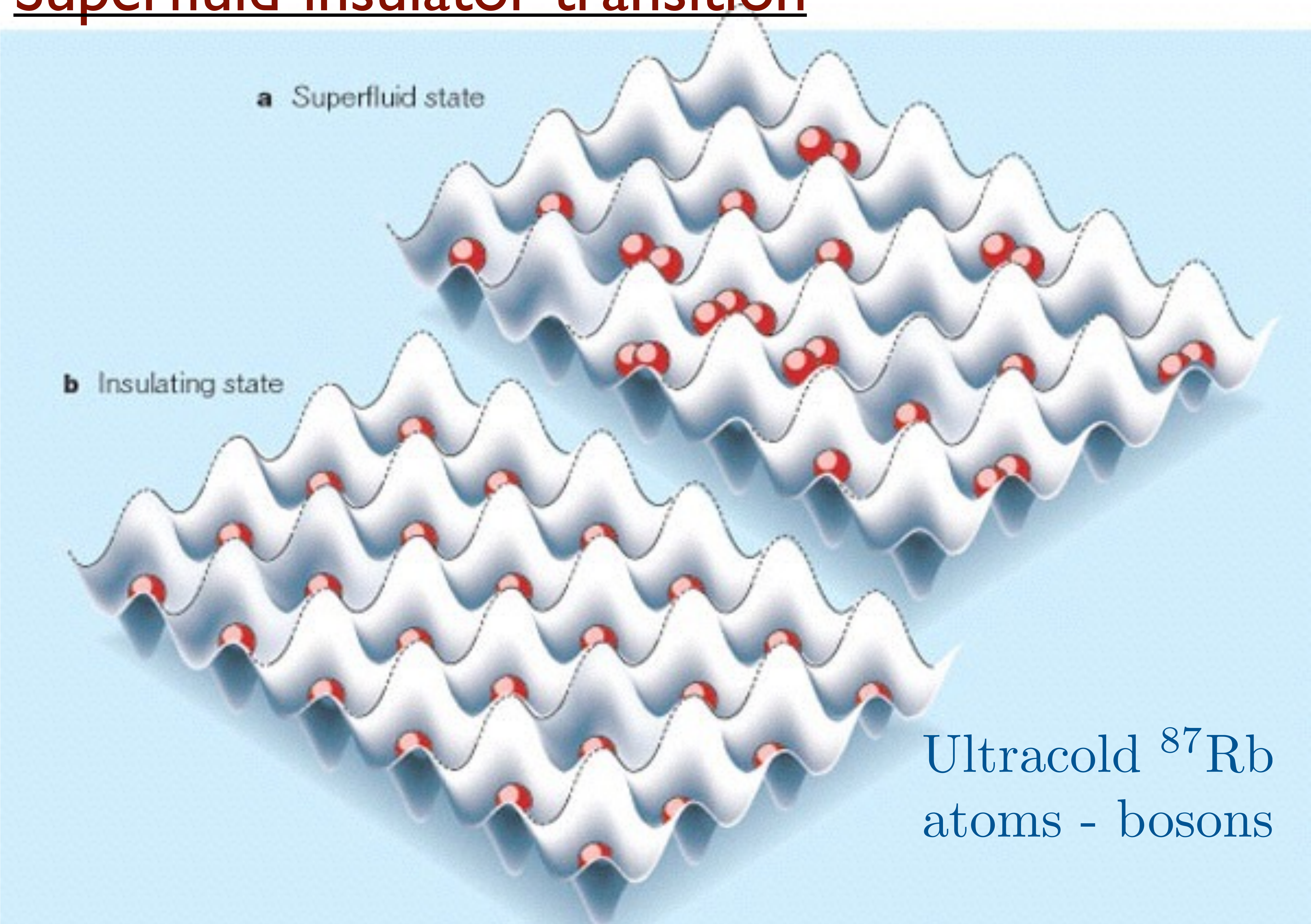
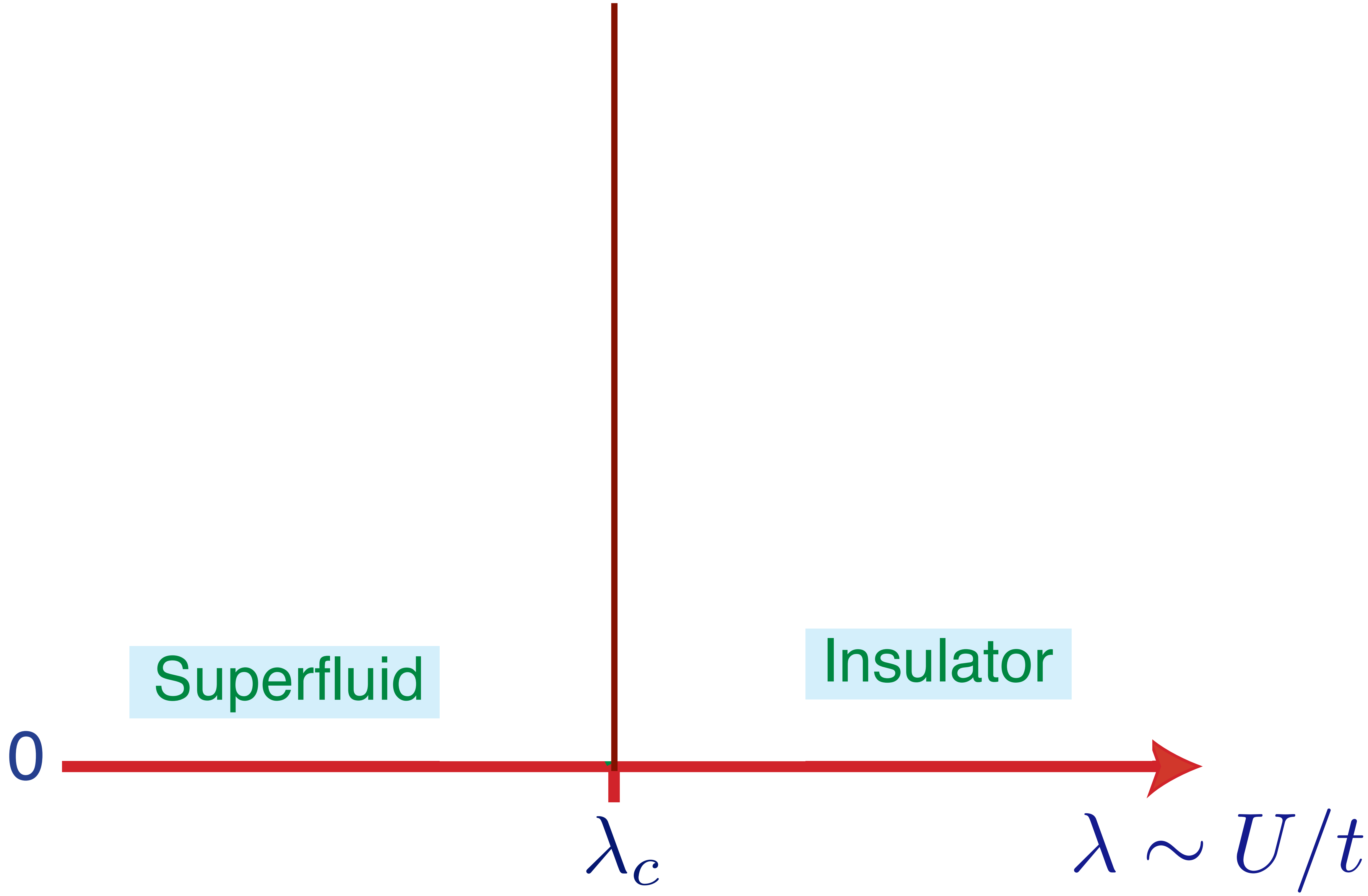
Superfluid-insulator transition

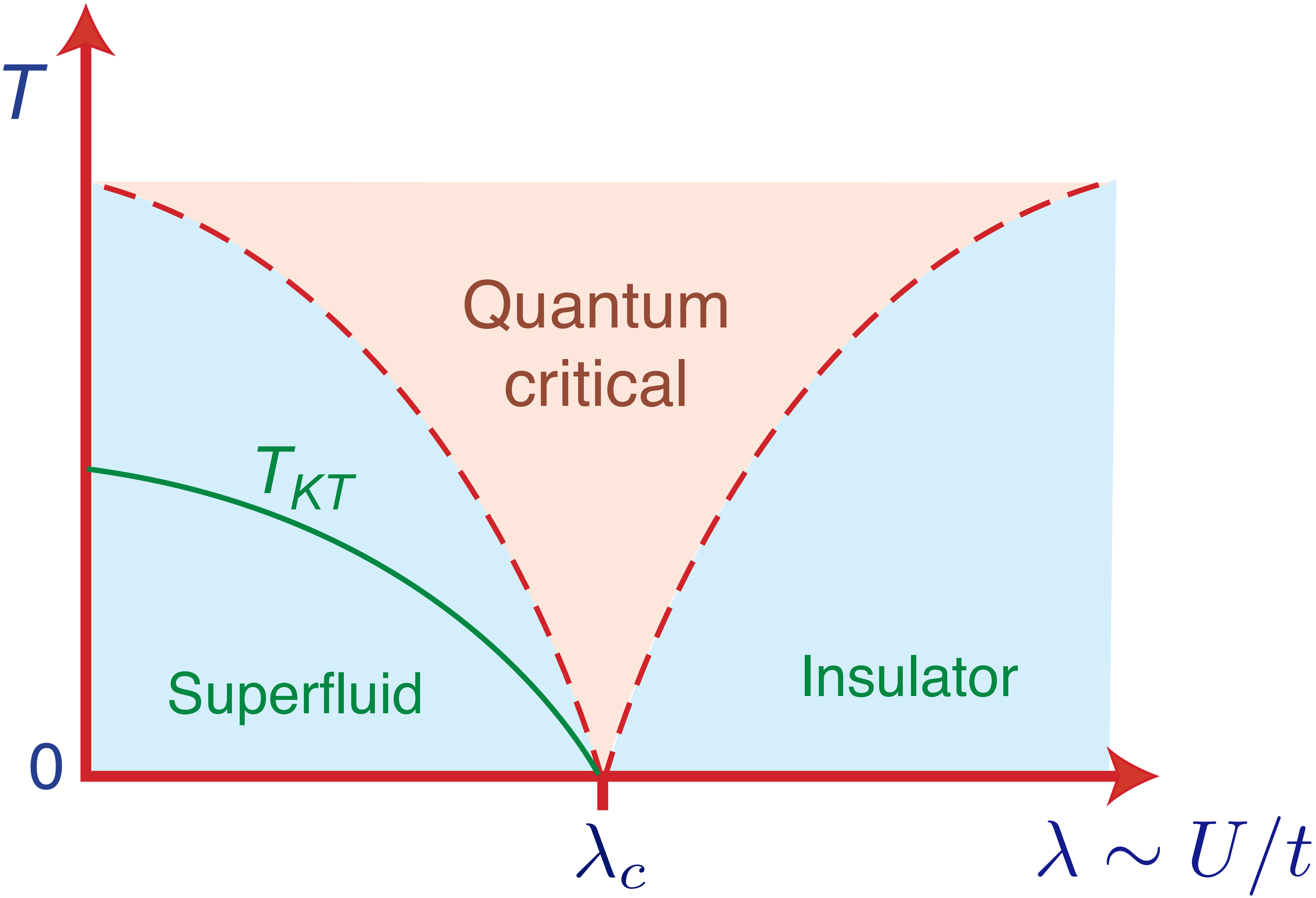


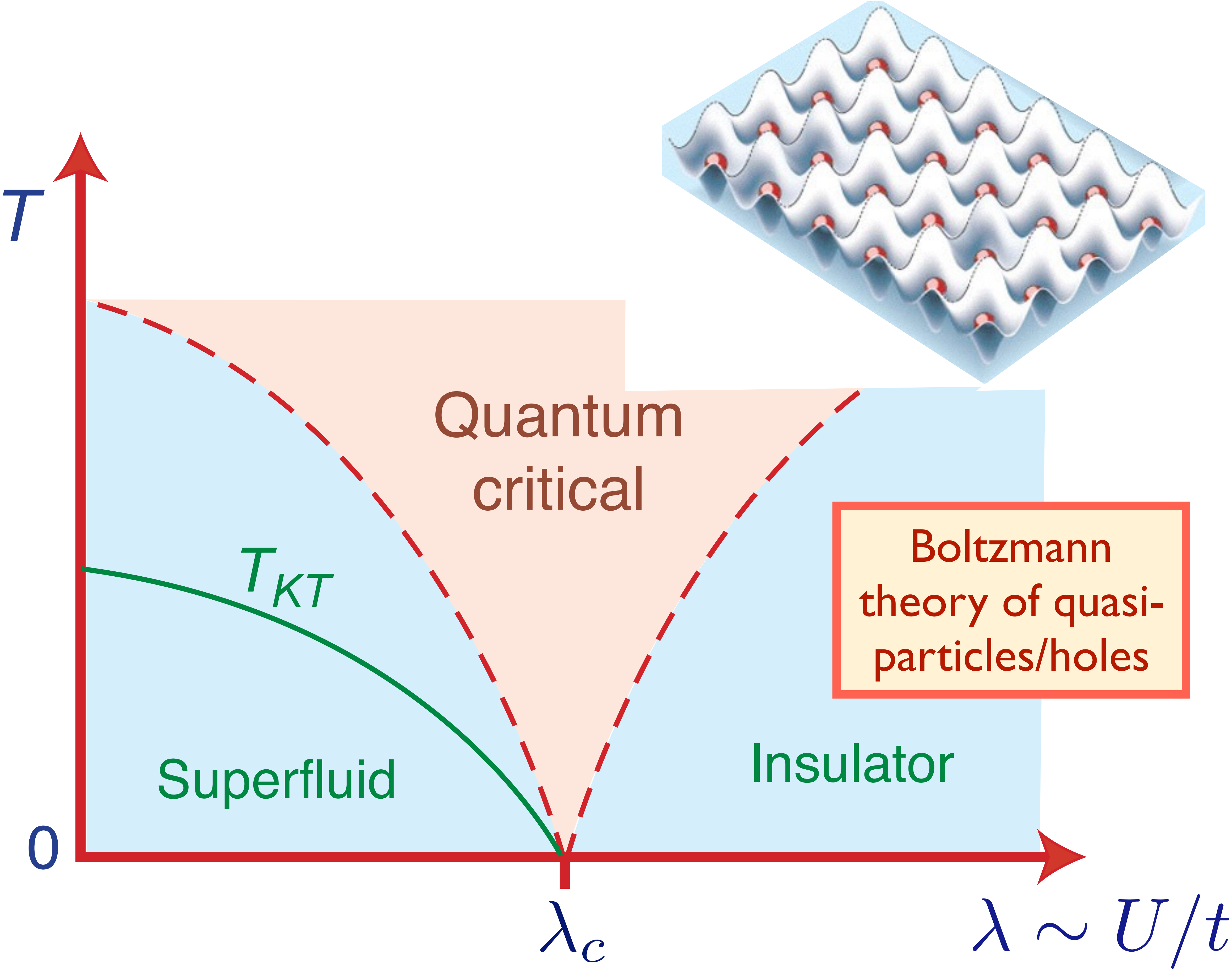
Ultracold ^{87}Rb atoms - bosons

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)

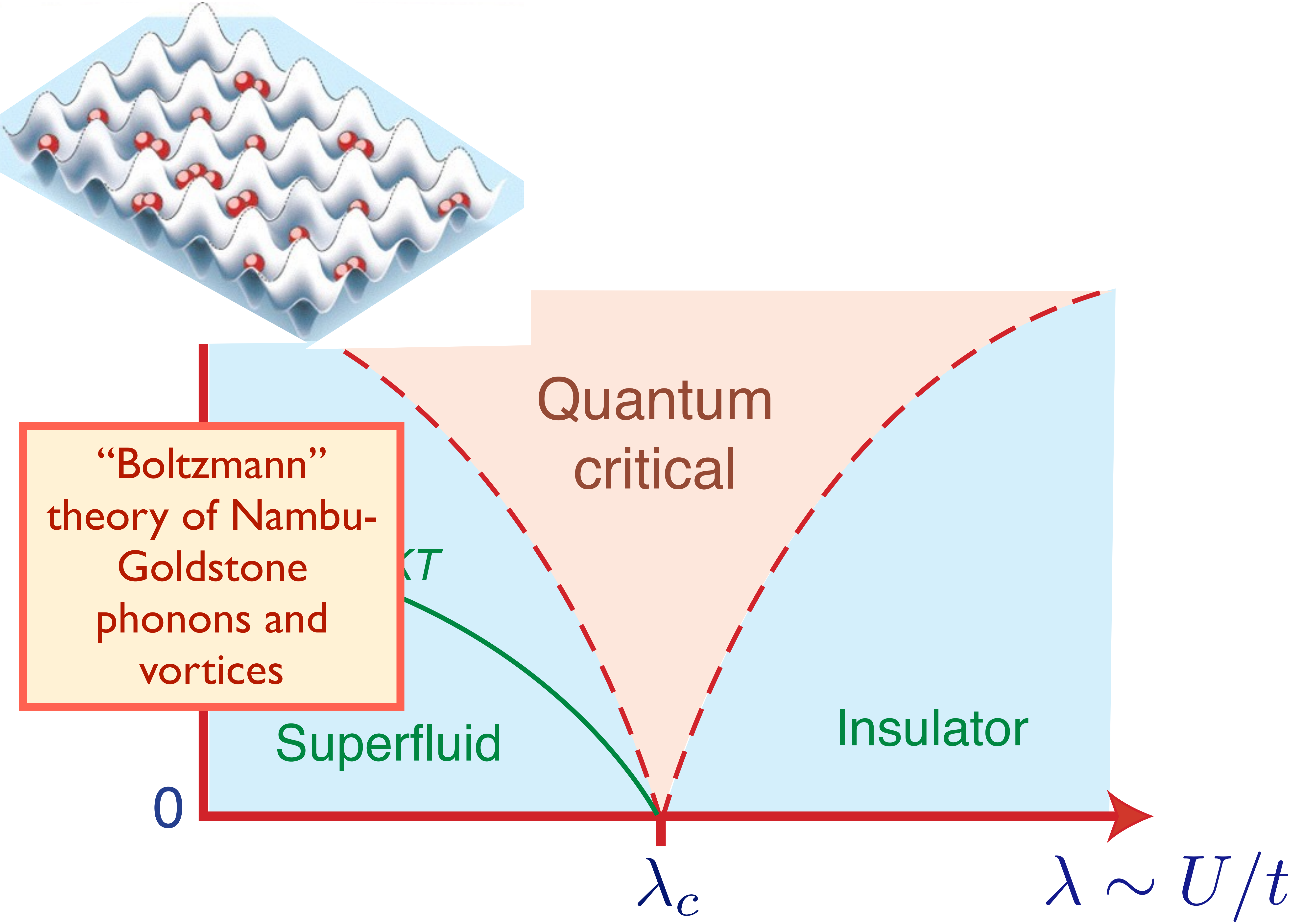
On-site repulsion between bosons $= U$
Tunneling amplitude between sites $= t$



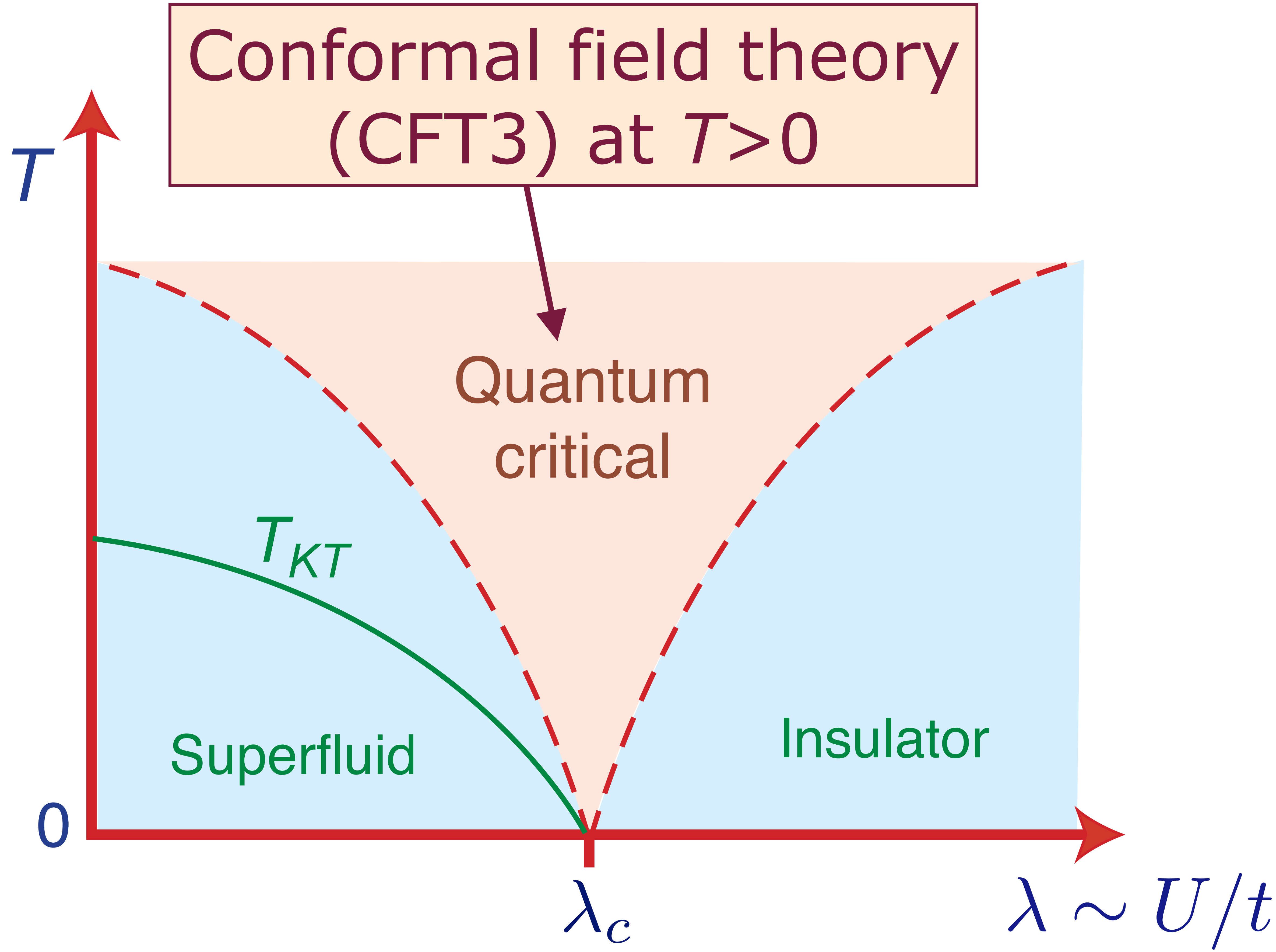

T
Quantum critical
T_{KT}
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$



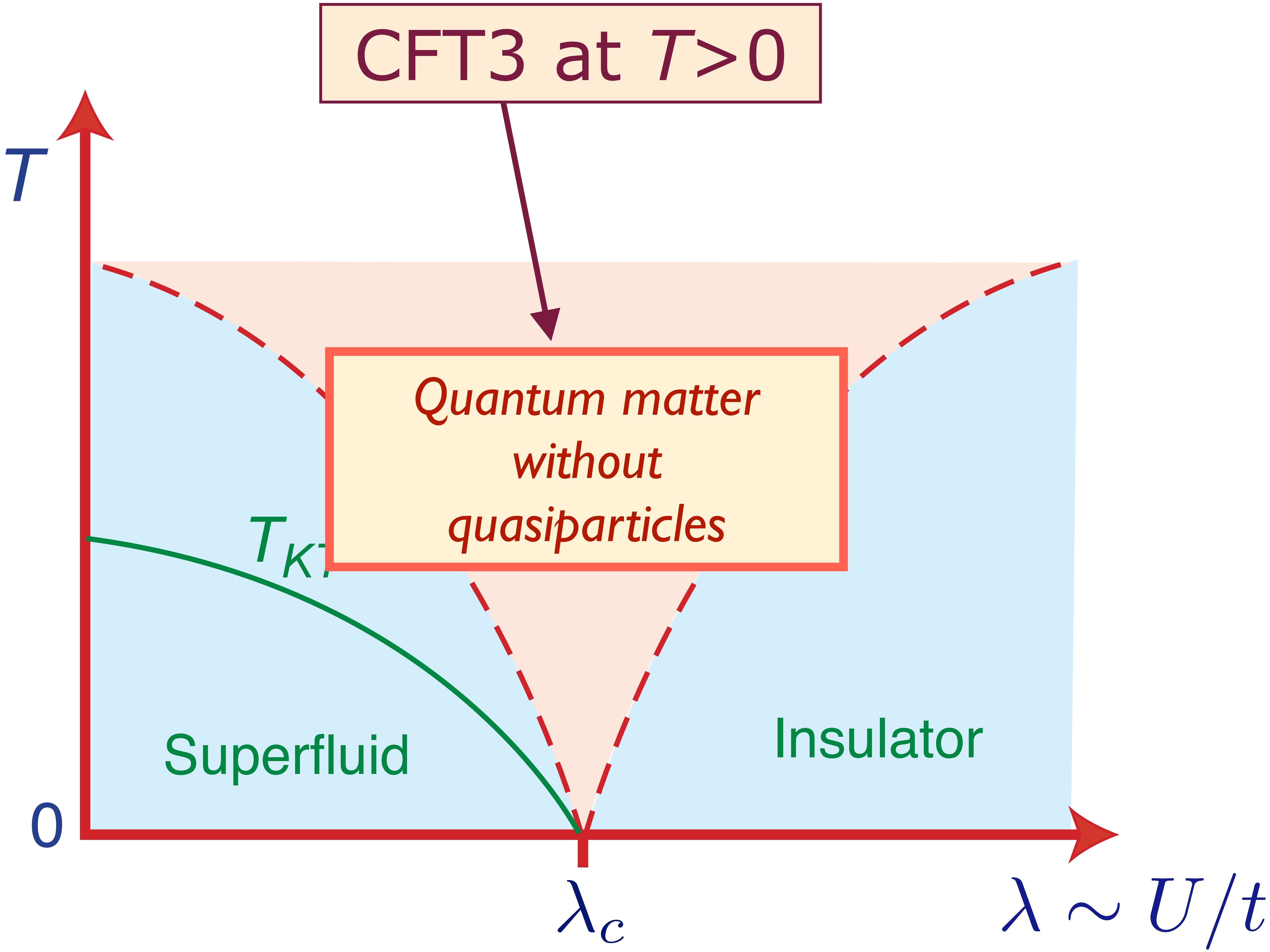
Boltzmann theory of quasi-particles/holes



“Boltzmann” theory of Nambu-Goldstone phonons and vortices

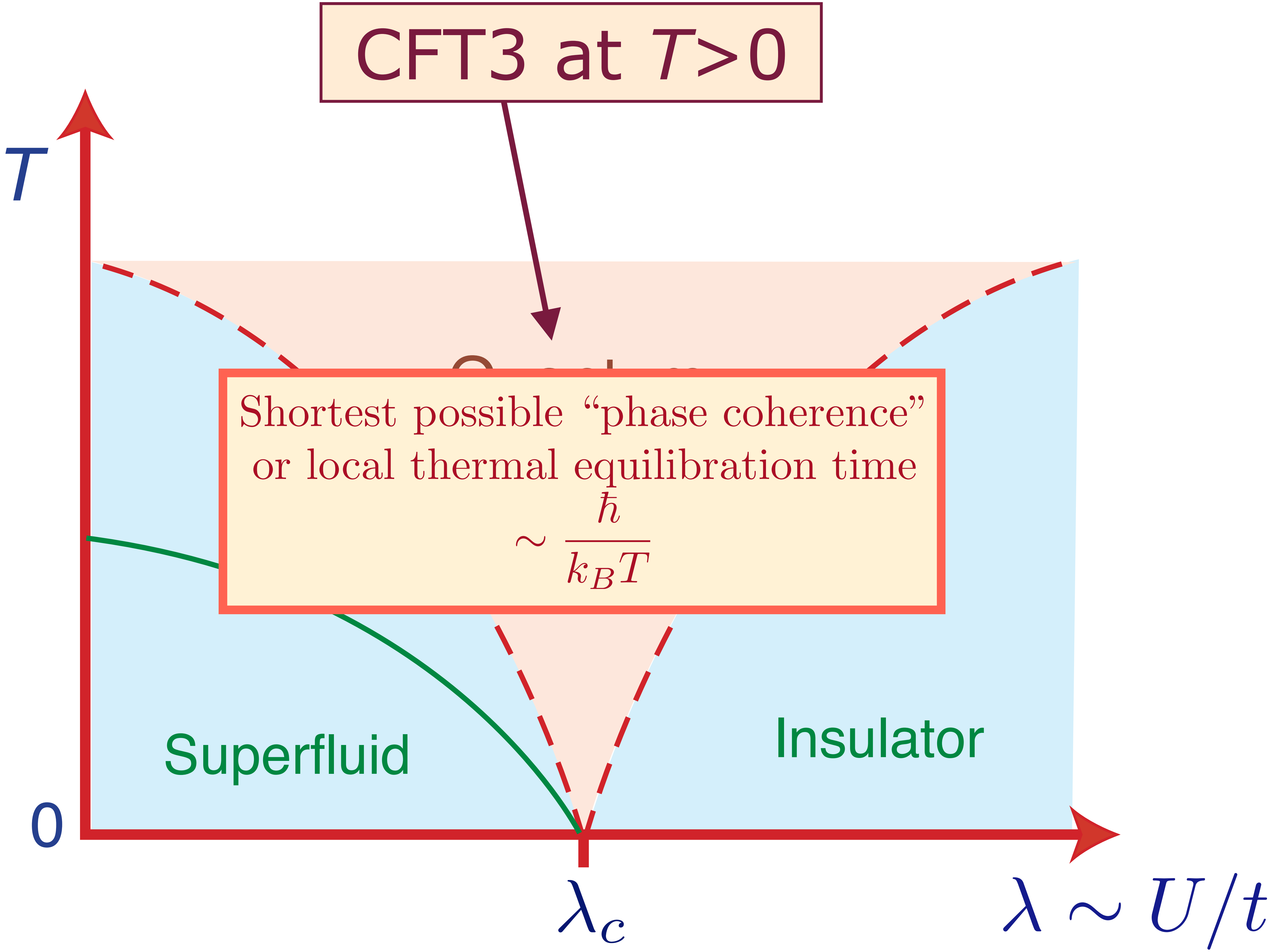


Conformal field theory (CFT3) at $T>0$



CFT3 at $T>0$

Quantum matter without quasiparticles



CFT3 at $T>0$

Shortest possible "phase coherence" or local thermal equilibration time

$$\sim \frac{\hbar}{k_B T}$$

A.V. Chubukov, S. Sachdev, and J. Ye, PRB **49**, 11919 (1994); K. Damle and S. Sachdev, PRB **56**, 8714 (1997);
S. Sachdev, *Quantum Phase Transitions*, Cambridge (1999)

Local thermal equilibration or phase coherence time, τ_φ:

- There is an *lower bound* on τ_φ in all many-body quantum systems of order $\hbar/(k_B T)$,

  $$\tau_\varphi > C \frac{\hbar}{k_B T},$$

  and the lower bound is realized by systems *without* quasiparticles.

- In systems *with* quasiparticles, τ_φ is parametrically larger at low T;
  e.g. in Fermi liquids $\tau_\varphi \sim 1/T^2$,
  and in gapped insulators $\tau_\varphi \sim e^{\Delta/(k_B T)}$ where Δ is the energy gap.

S. Sachdev, *Quantum Phase Transitions*, Cambridge (1999)

A bound on quantum chaos:

- The time over which a many-body quantum system becomes "chaotic" is given by $\tau_S = 1/\lambda_L$, where λ_L is the "Lyapunov exponent" determining memory of initial conditions. This SCRAMBLING TIME obeys the rigorous lower bound

$$\tau_S \geq \frac{1}{2\pi} \frac{\hbar}{k_B T}$$

A. I. Larkin and Y. N. Ovchinnikov, JETP **28**, 6 (1969)

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

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Quantum matter without quasiparticles
$\approx$ fastest possible many-body quantum chaos

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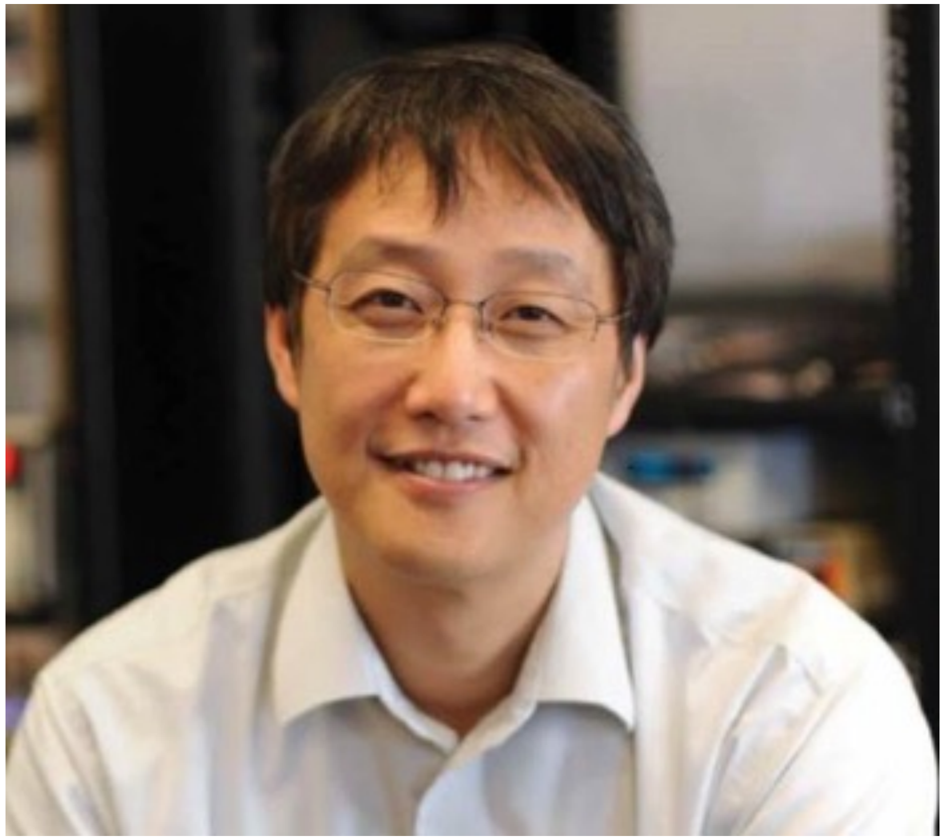
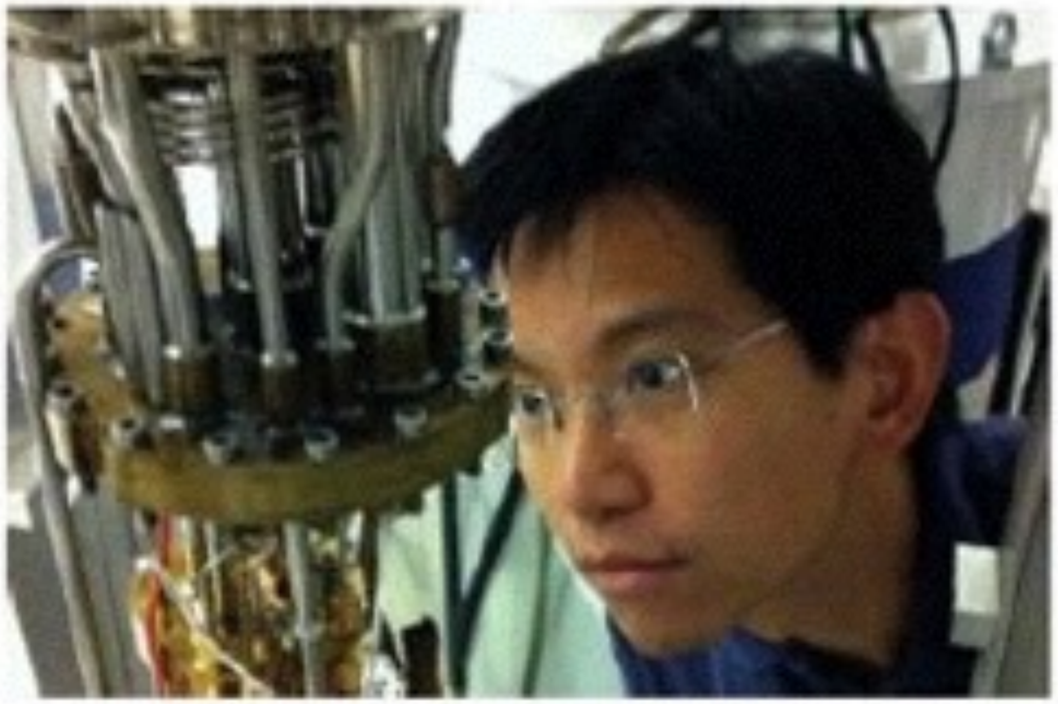
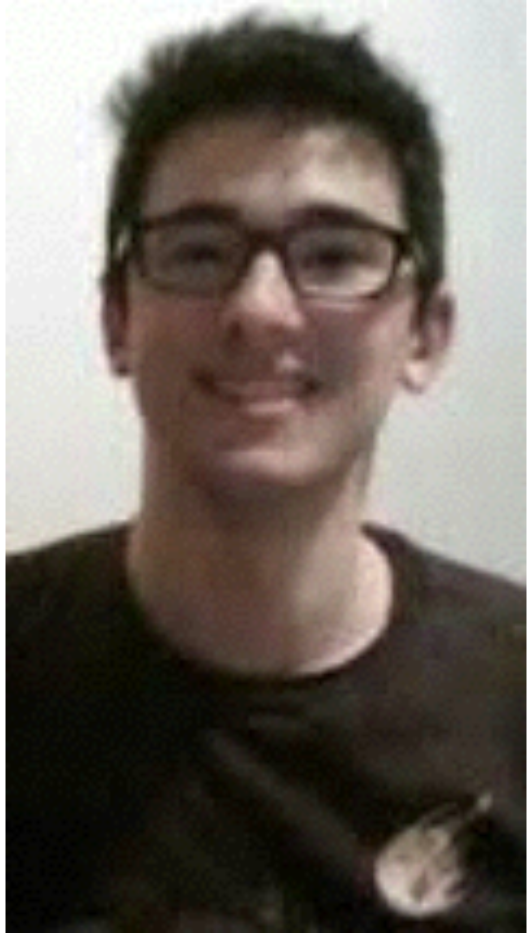


Philip Kim

Jesse Crossno

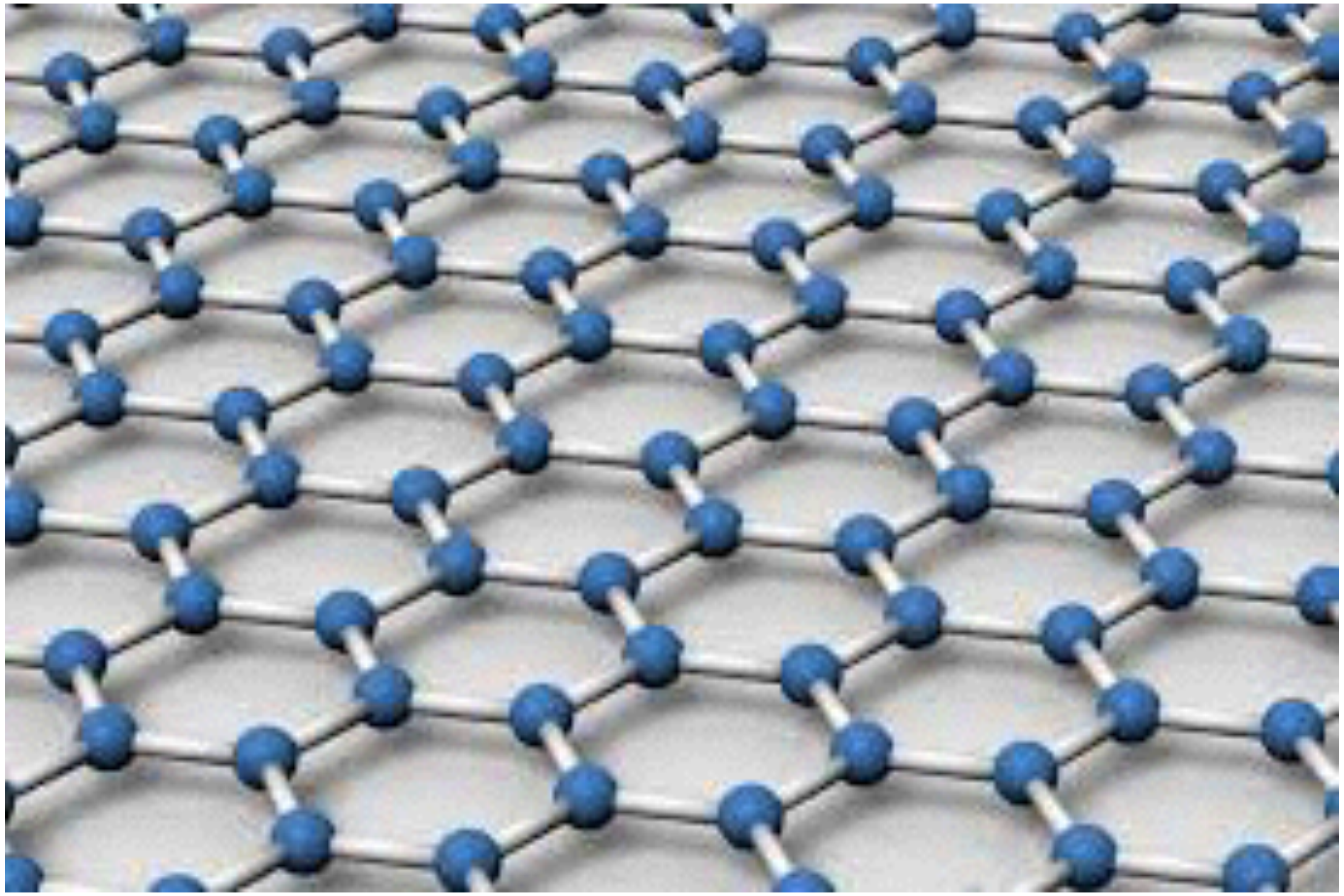


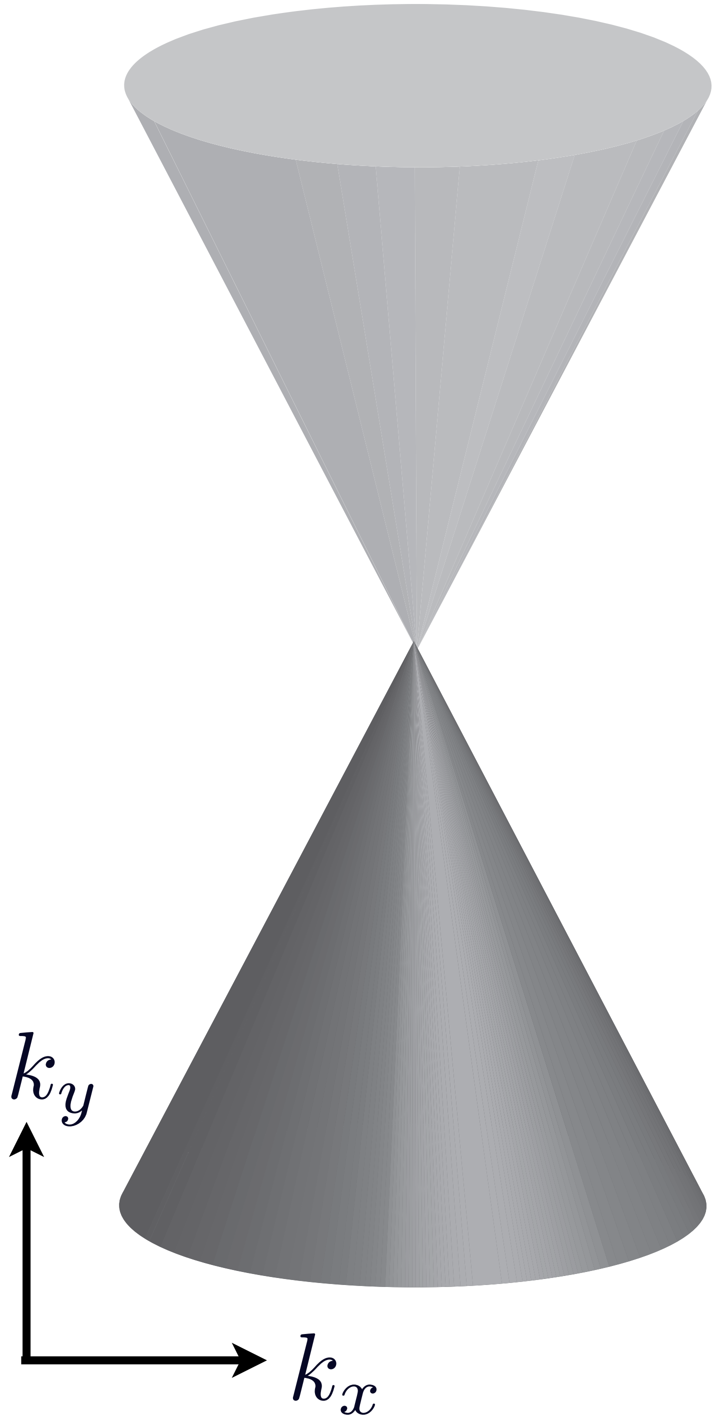
Kin Chung Fong



Andrew Lucas

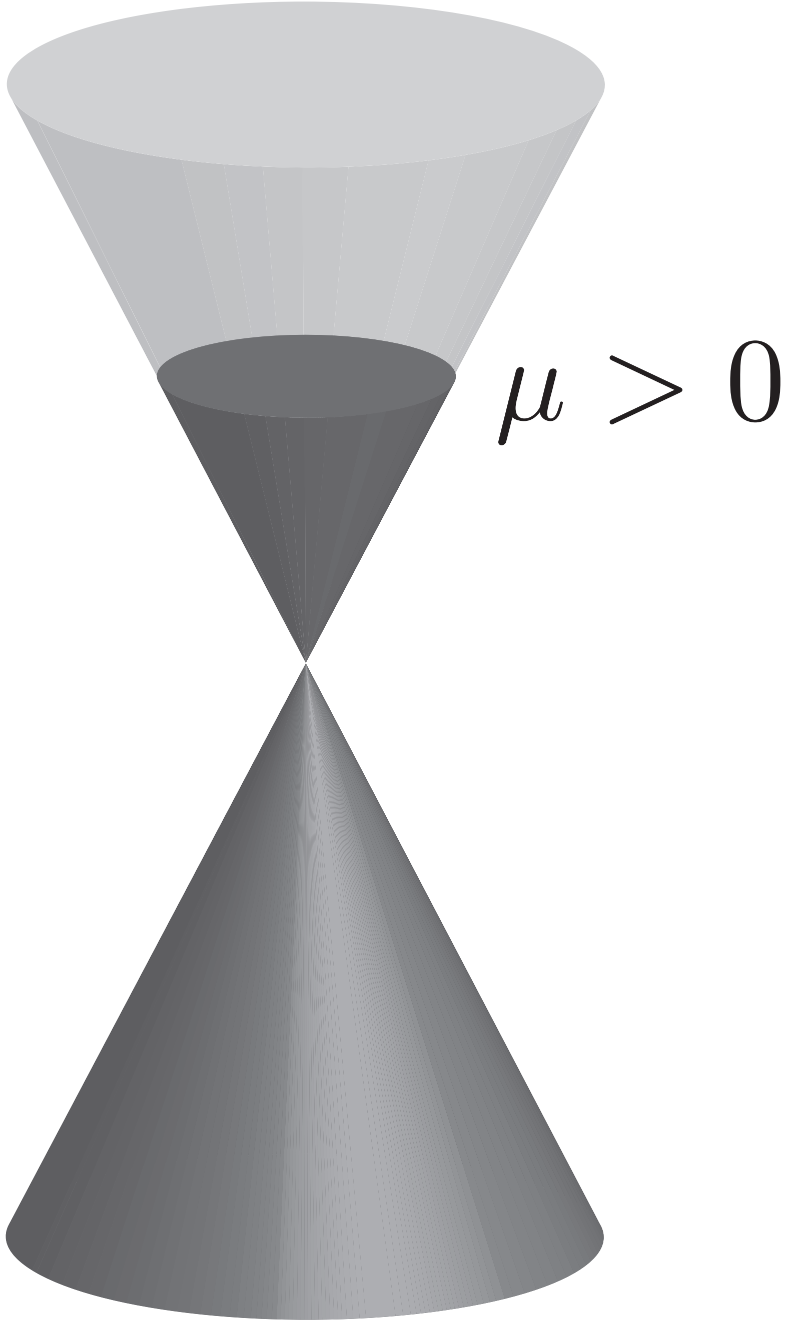
Graphene





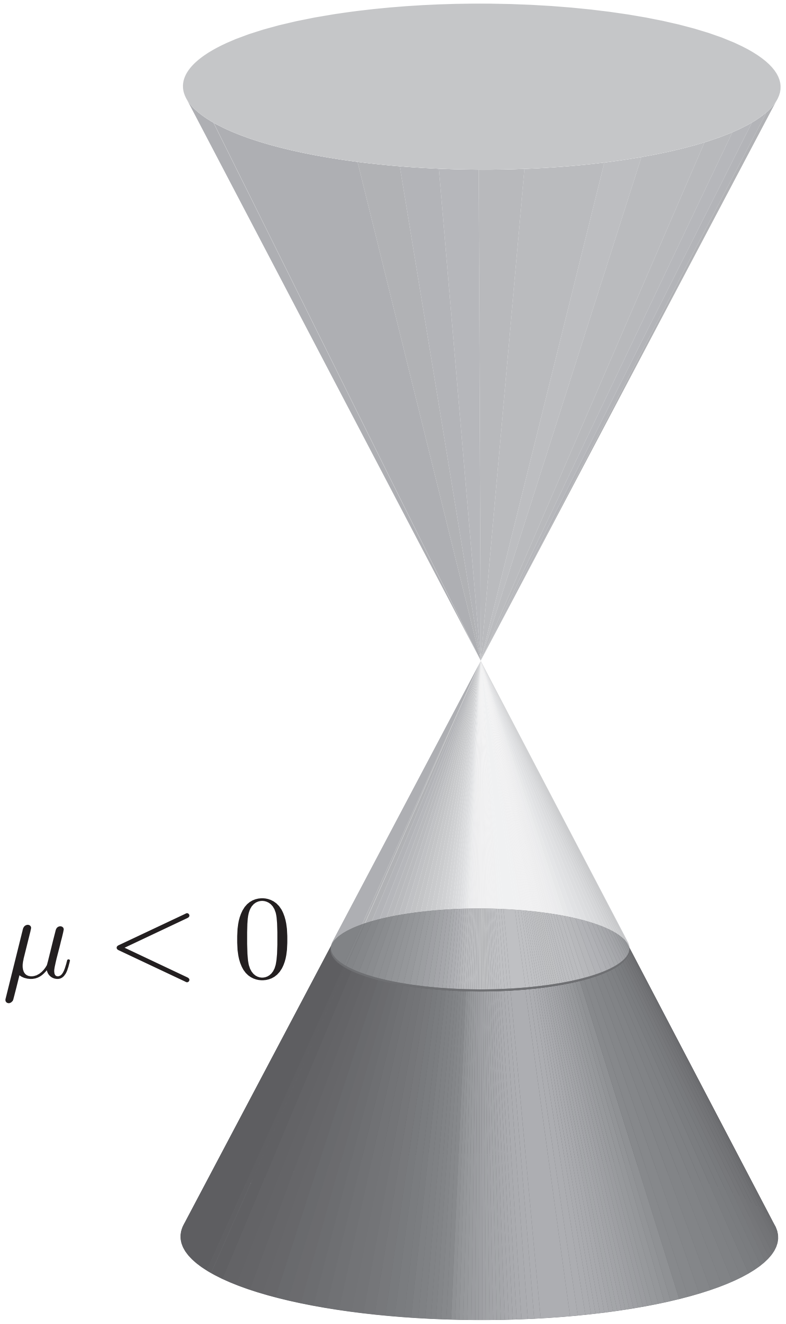
Same "Hubbard" model as for ultracold atoms, but for electrons on the honeycomb lattice

Graphene

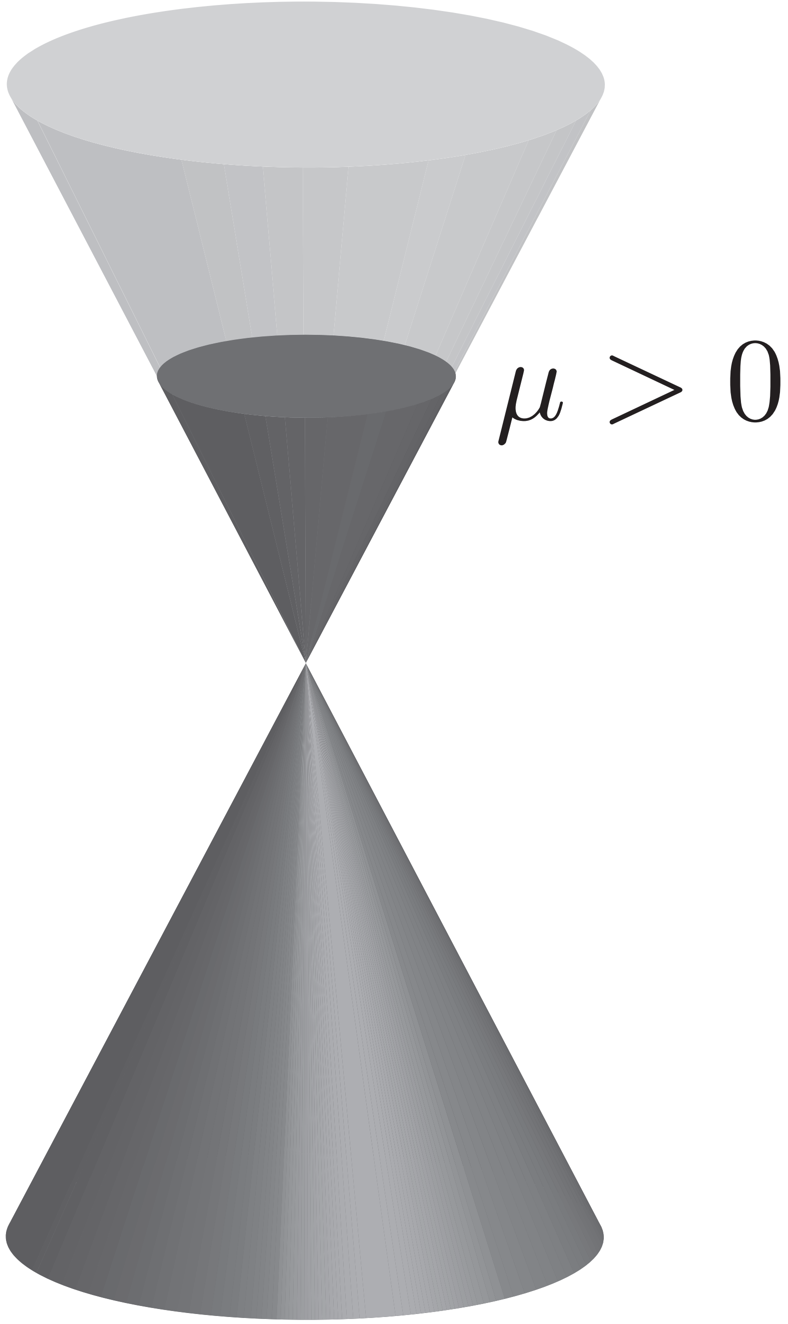


Electron
Fermi surface

Graphene

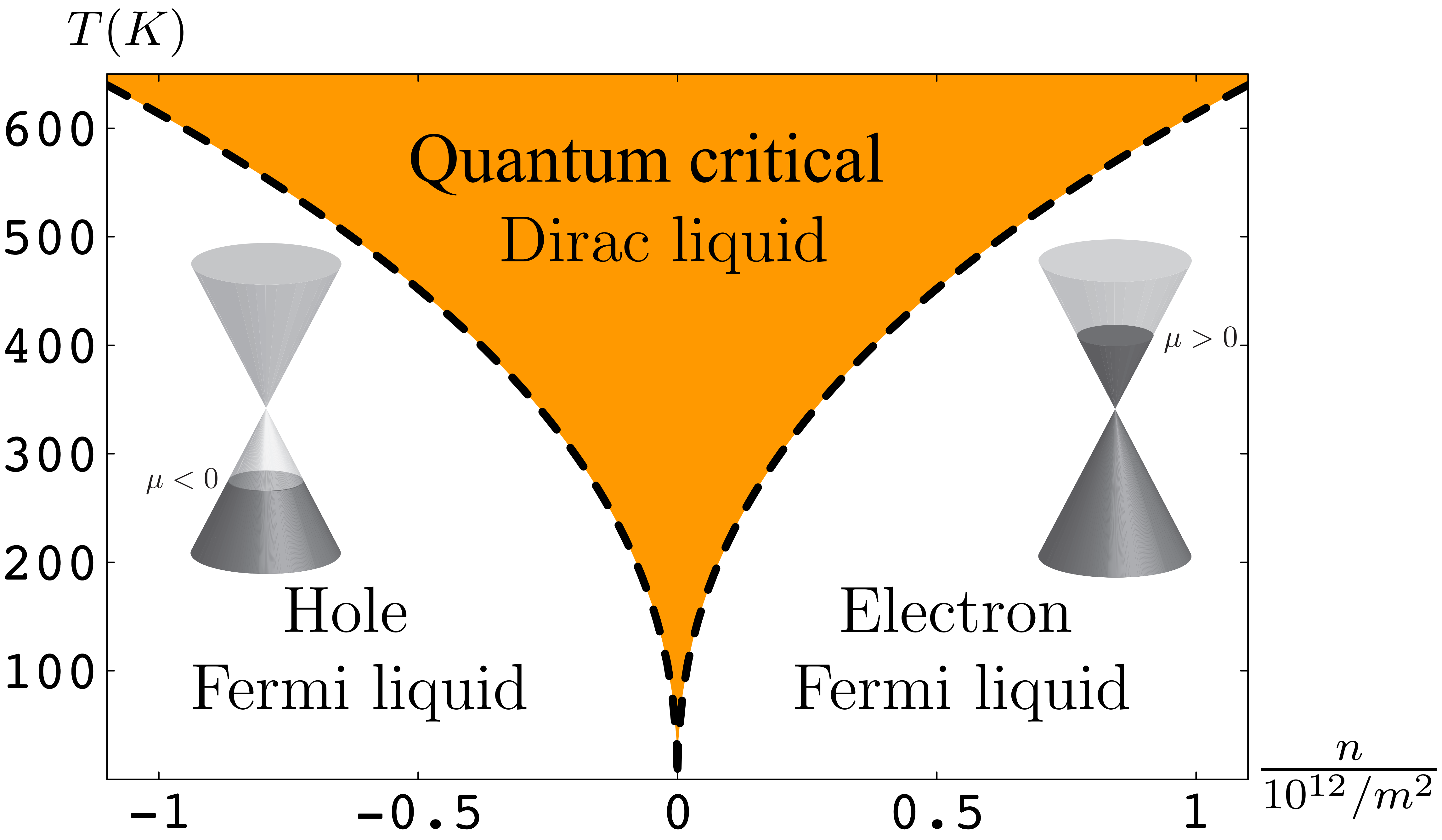


Hole
Fermi surface



Electron
Fermi surface

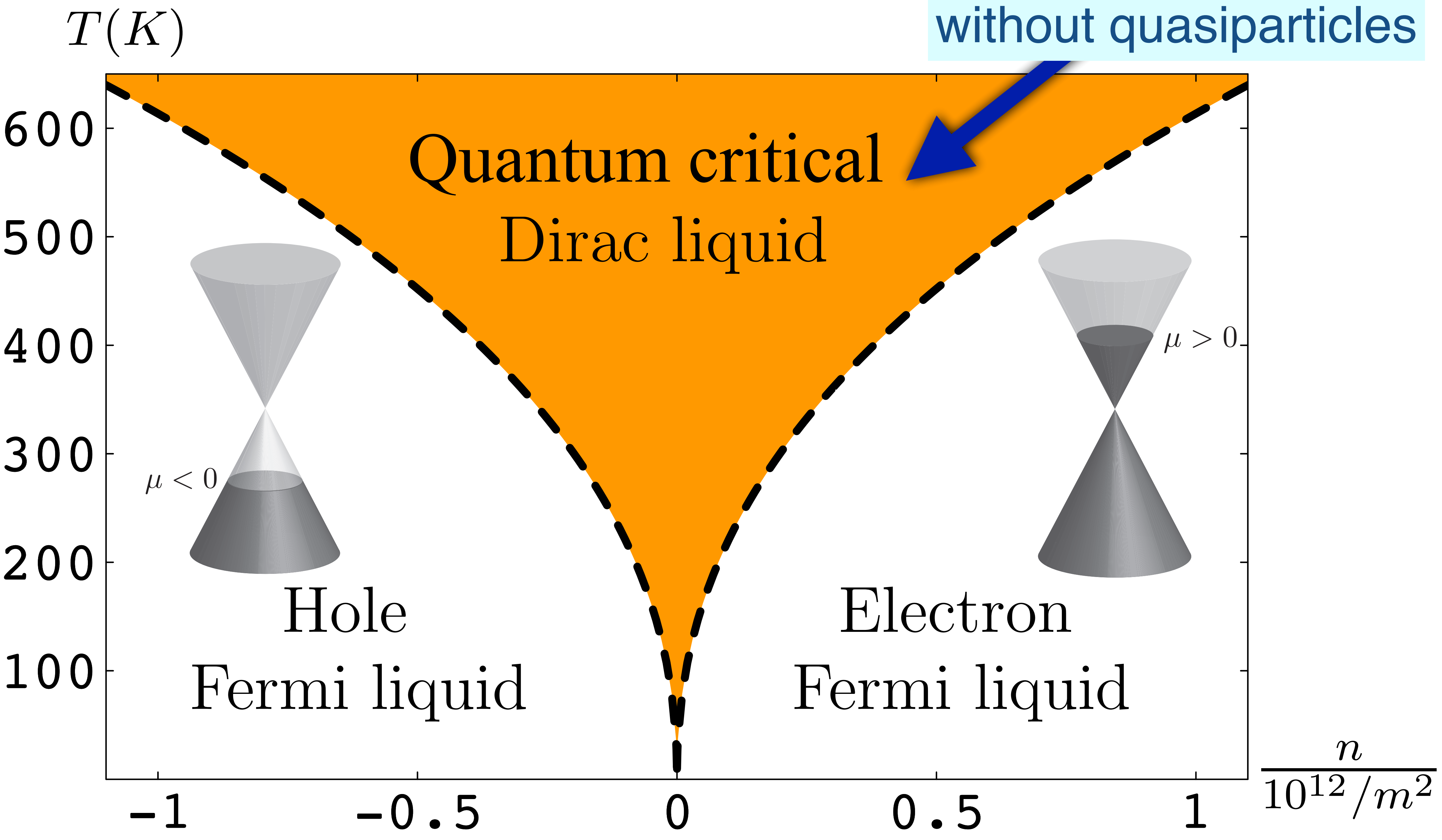
Graphene



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" without quasiparticles



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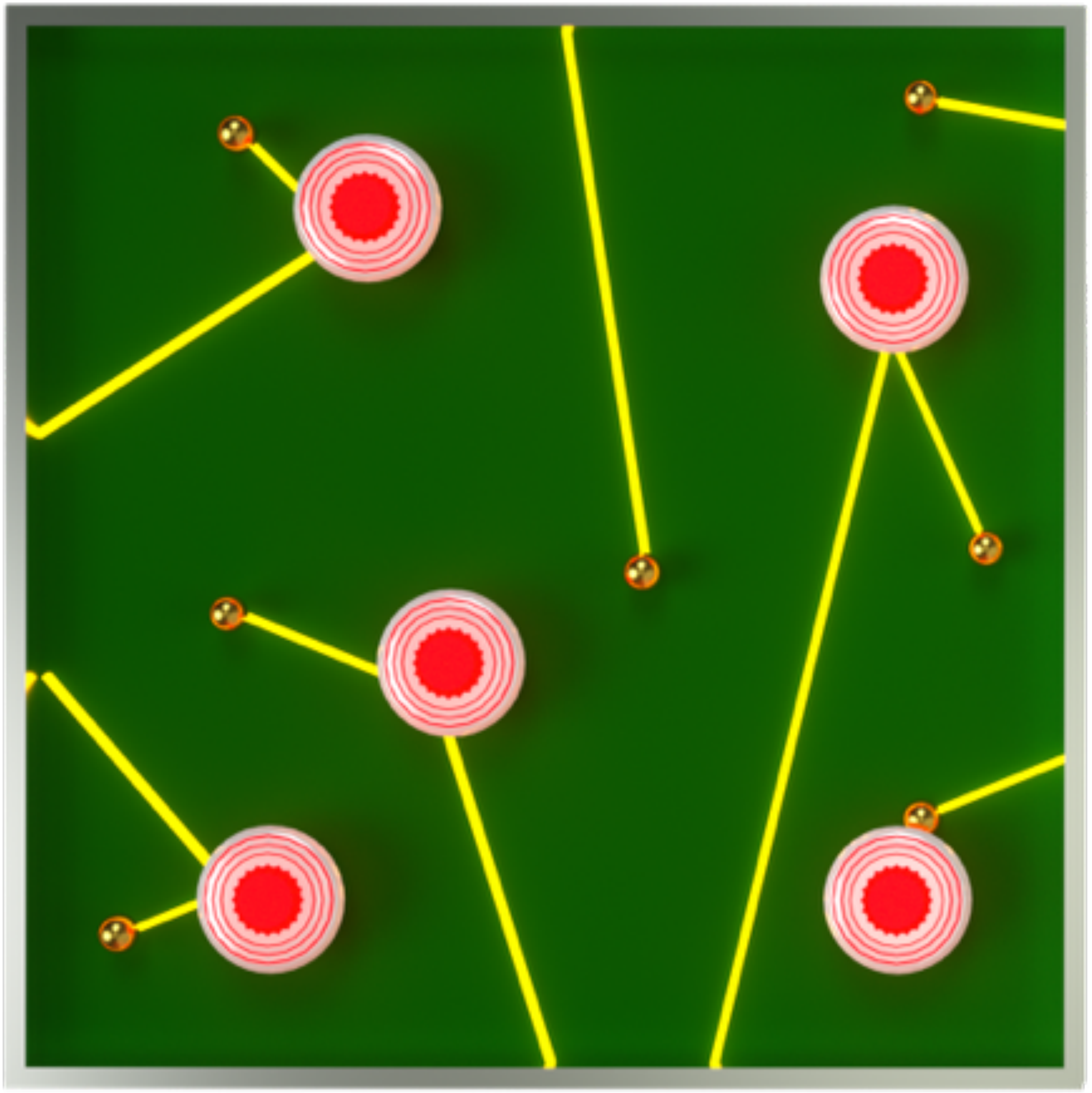
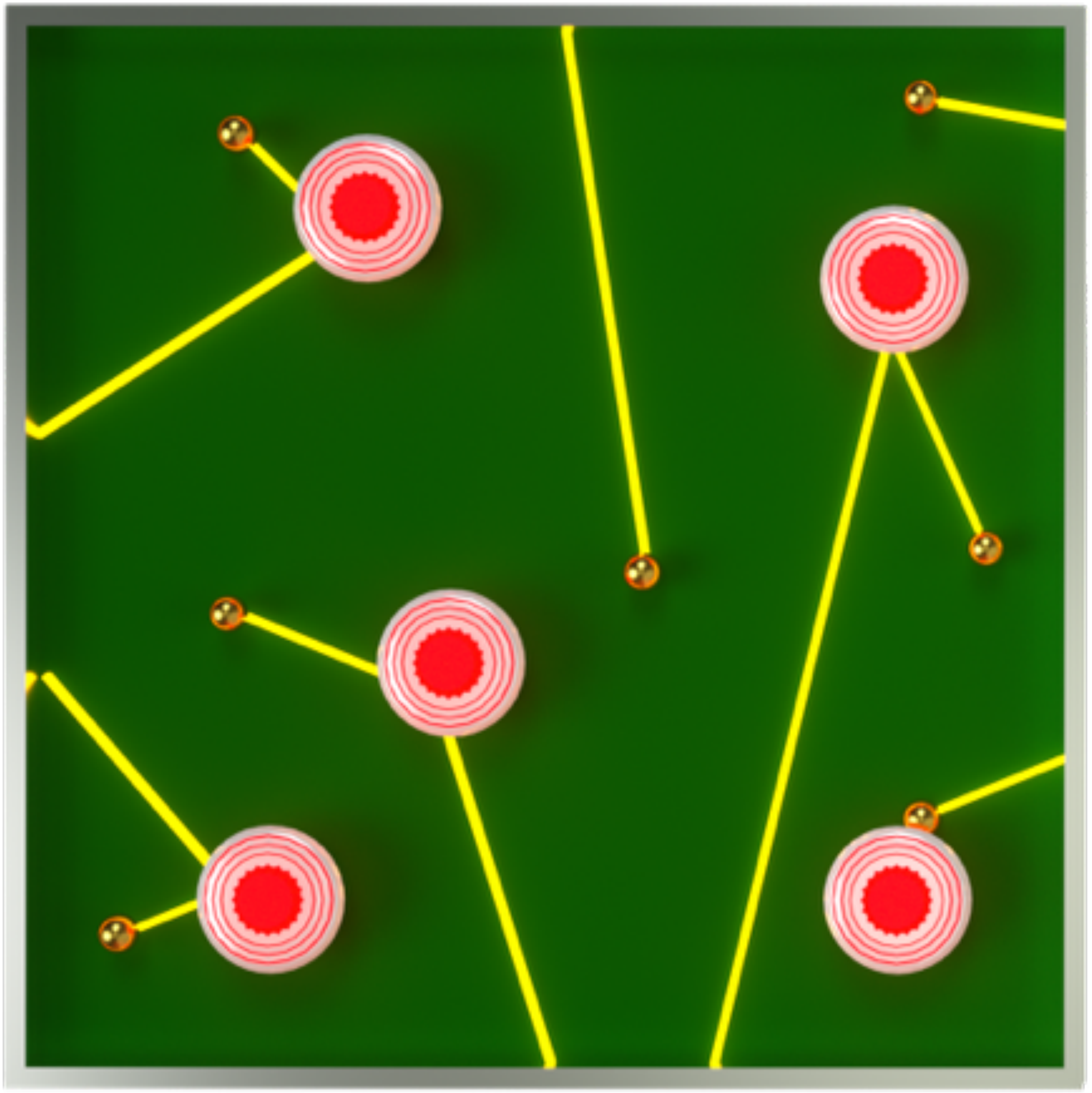


<u>Fermi liquids</u>: quasiparticles moving ballistically between impurity (red circles) scattering events



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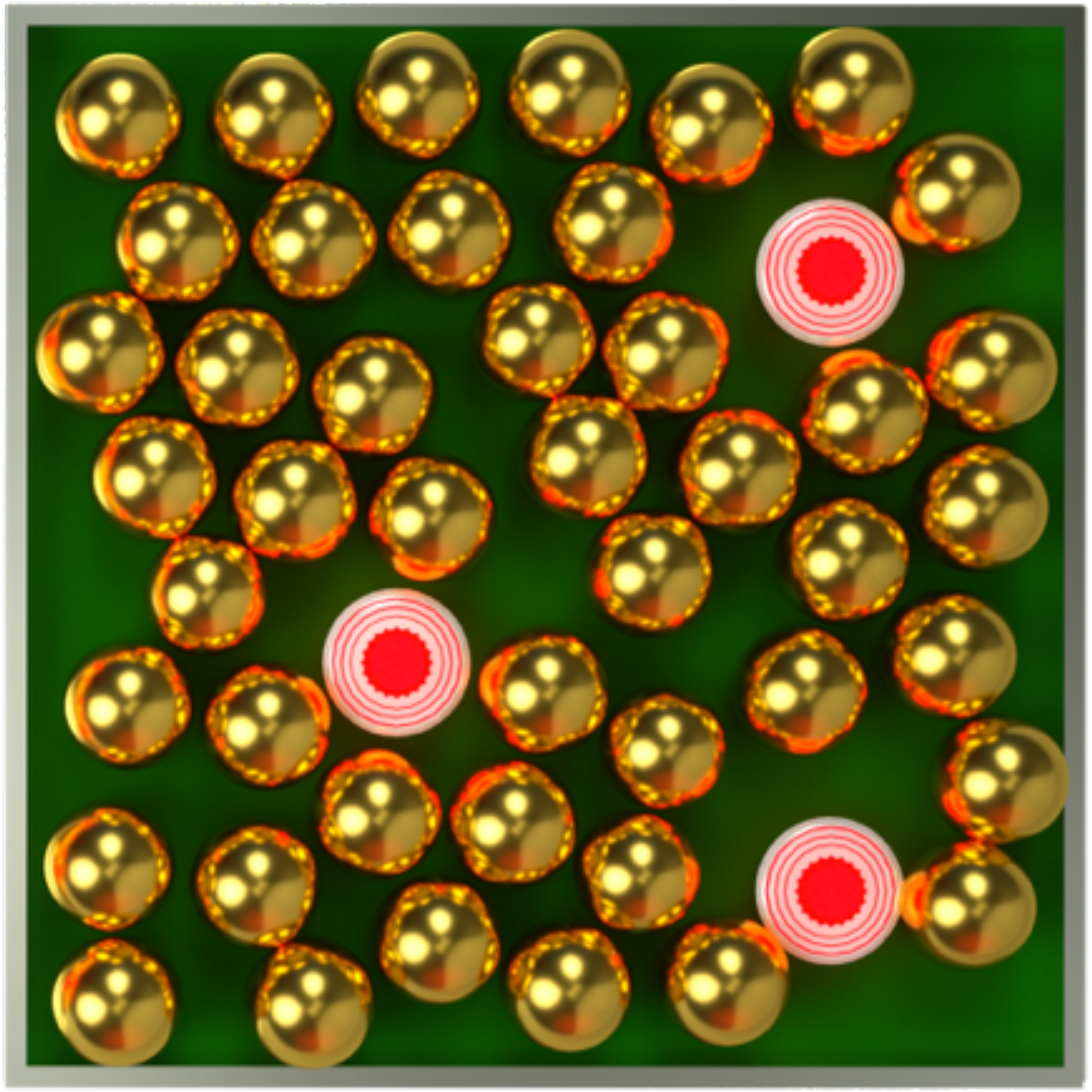
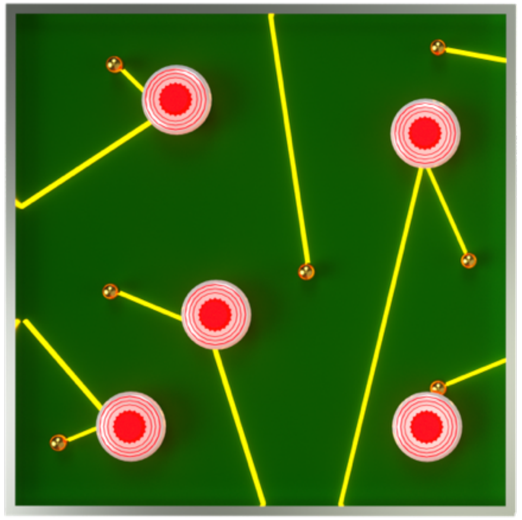


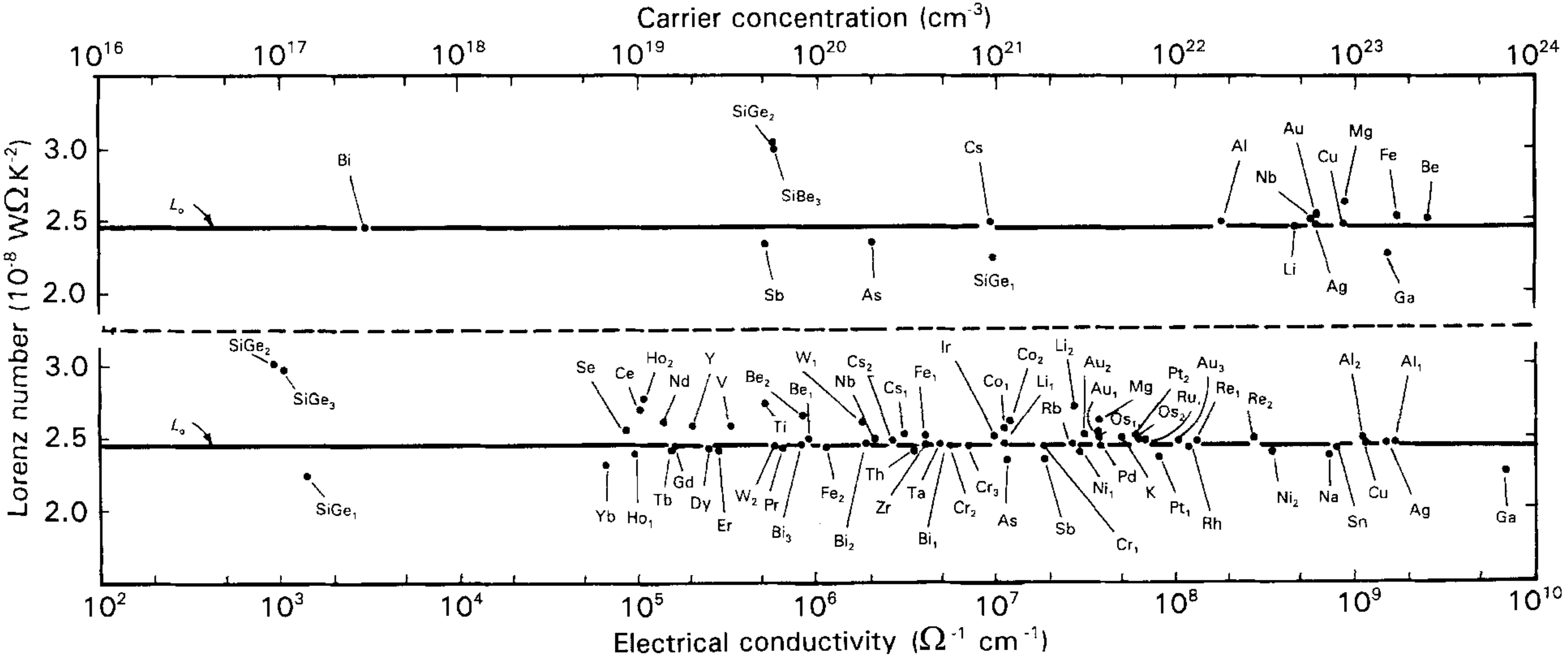
Strange metals: electrons scatter frequently off each other, so there is no regime of ballistic quasiparticle motion. The electron "liquid" then "flows" around impurities

Thermal and electrical conductivity with quasiparticles



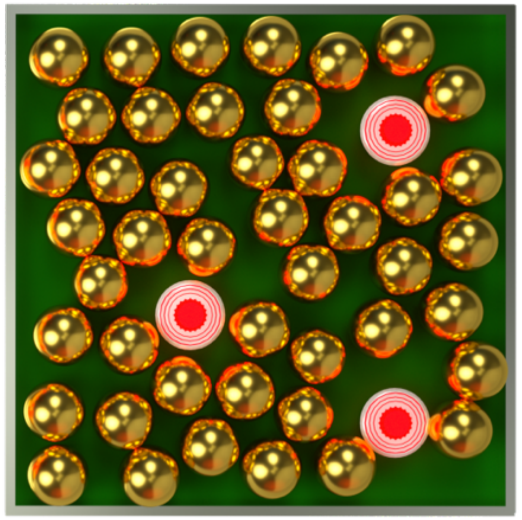
- Wiedemann-Franz law in a Fermi liquid:

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



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

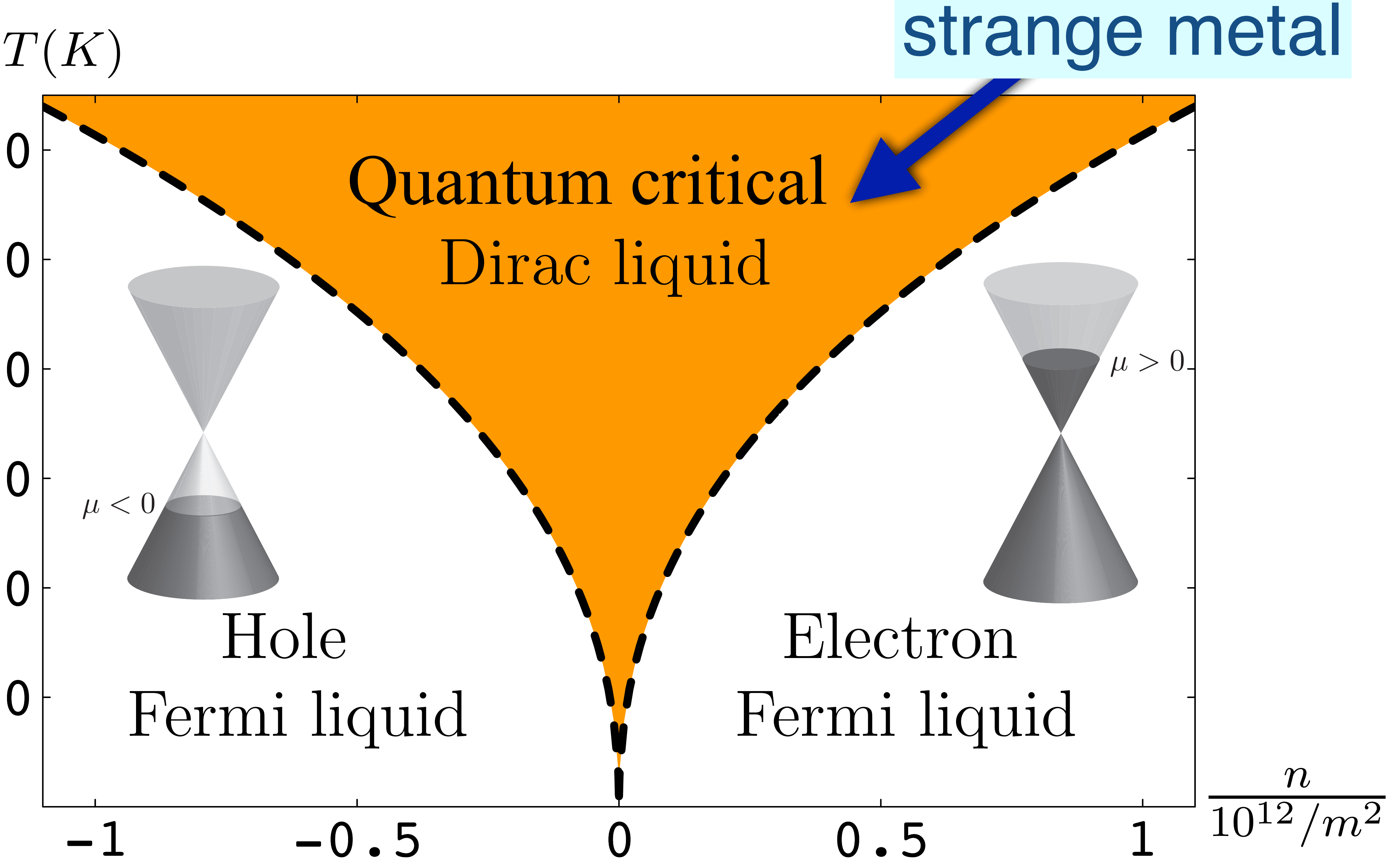
$$= \frac{v_F^2 \mathcal{H} \tau_{\rm imp}}{T^2 \sigma_Q} \frac{1}{\left(1 + e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}/(\mathcal{H}\sigma_Q)\right)^2}$$

$\mathcal{Q} \to$ electron density; $\mathcal{H} \to$ enthalpy density
$\sigma_Q \to$ quantum critical conductivity
$\tau_{\rm imp} \to$ momentum relaxation time from impurities.

Note that for a clean system ($\tau_{\rm imp} \to \infty$ first),
the Lorentz ratio diverges $L \sim 1/\mathcal{Q}^4$,
as we approach "zero" electron density at the Dirac point.

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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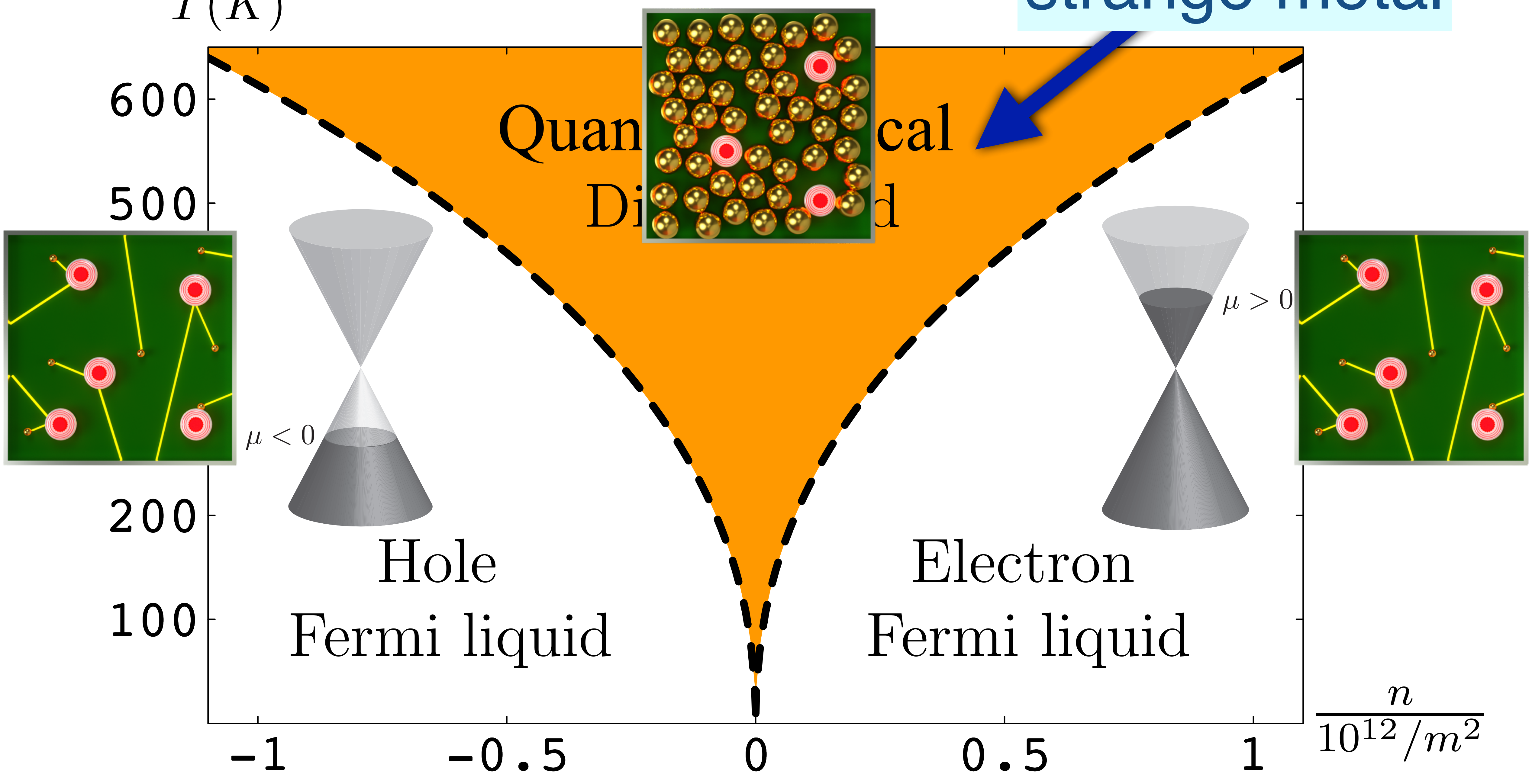

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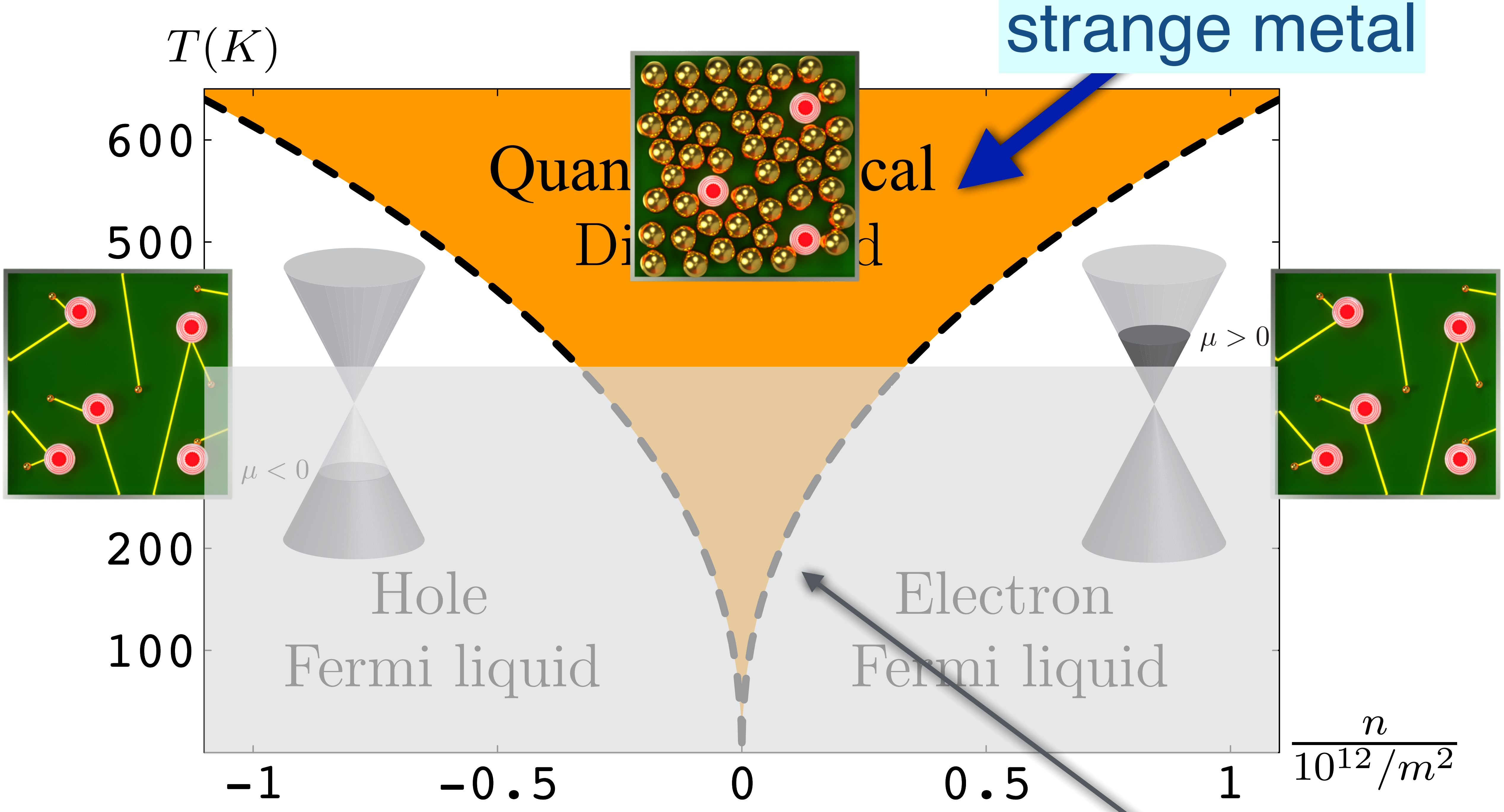

Impurity scattering dominates

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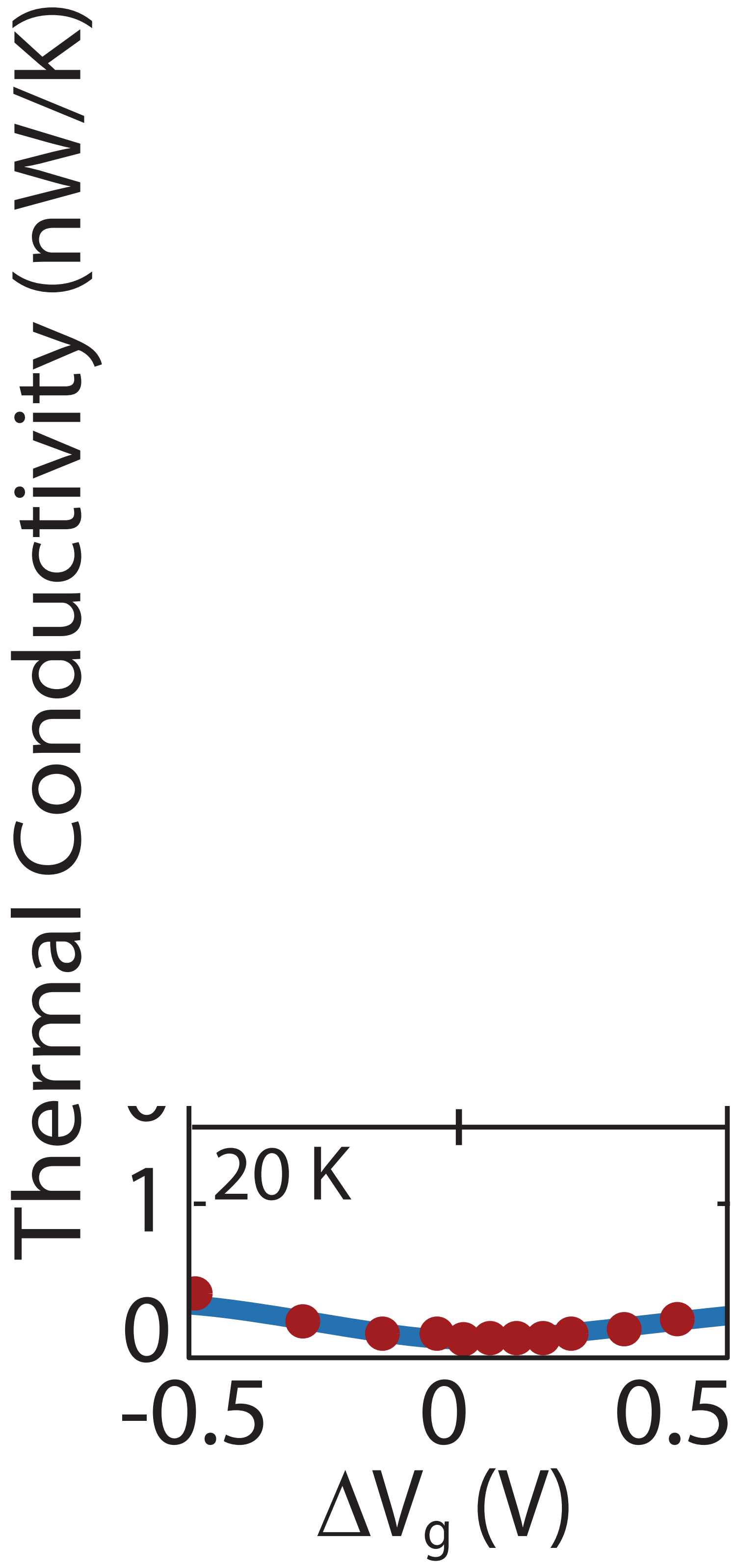
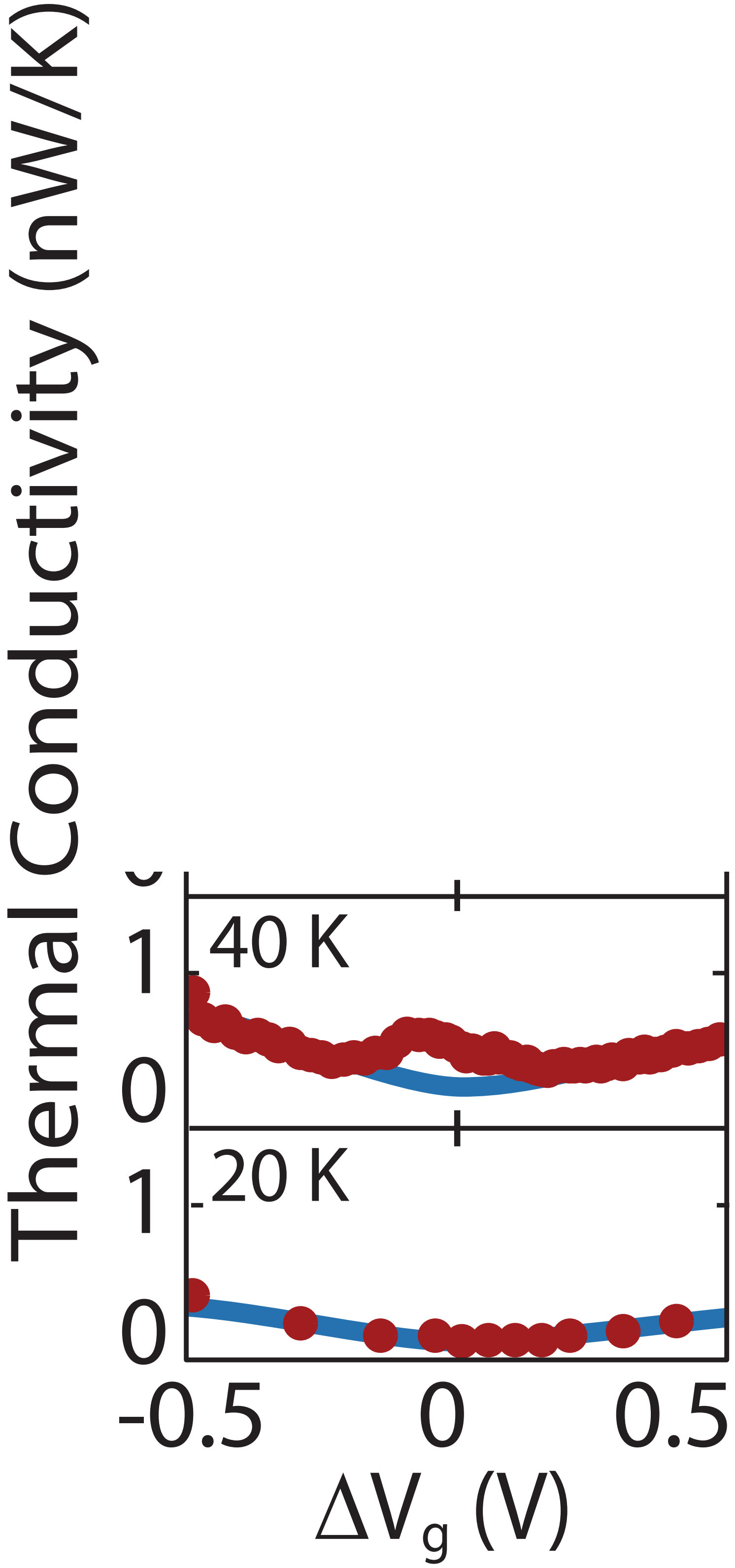
J. Crossno et al., Science **351**, 1058 (2016)



Red dots: data

Blue line: value for $L = L_0$

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



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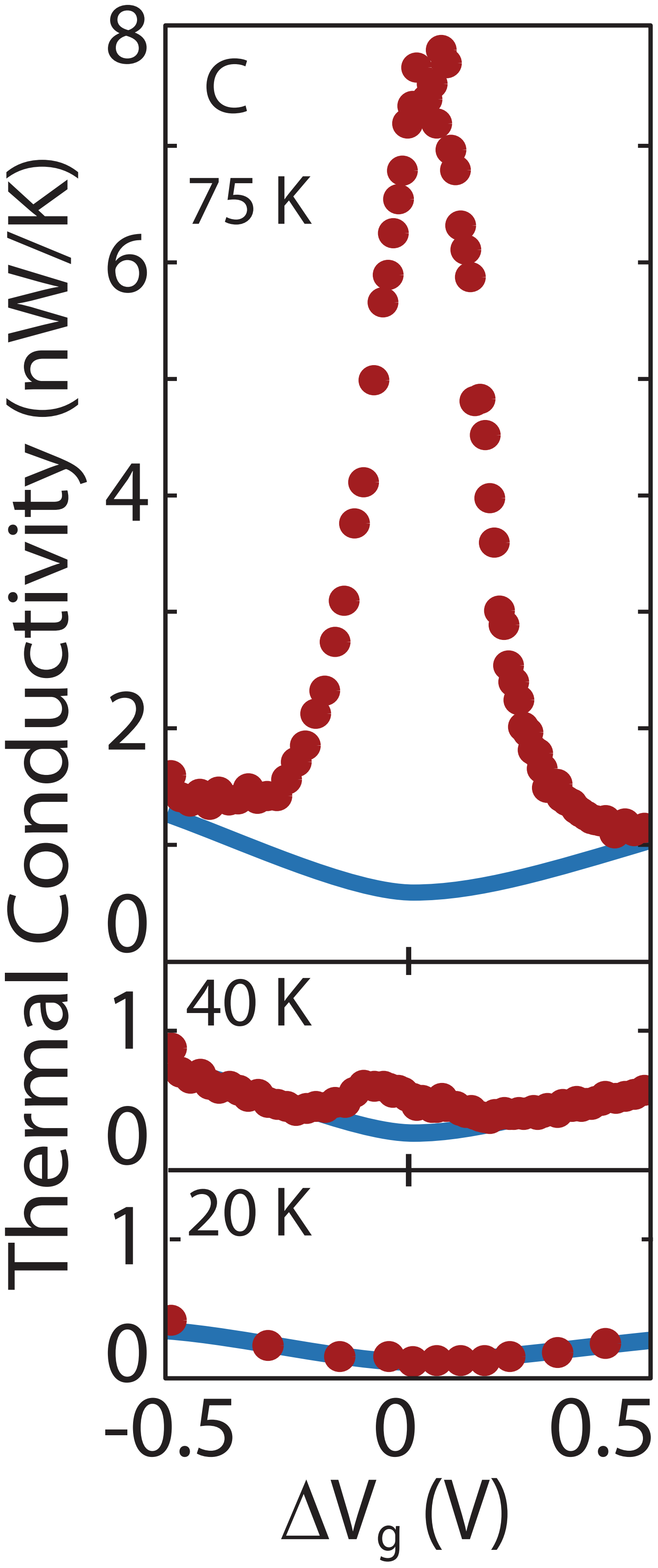

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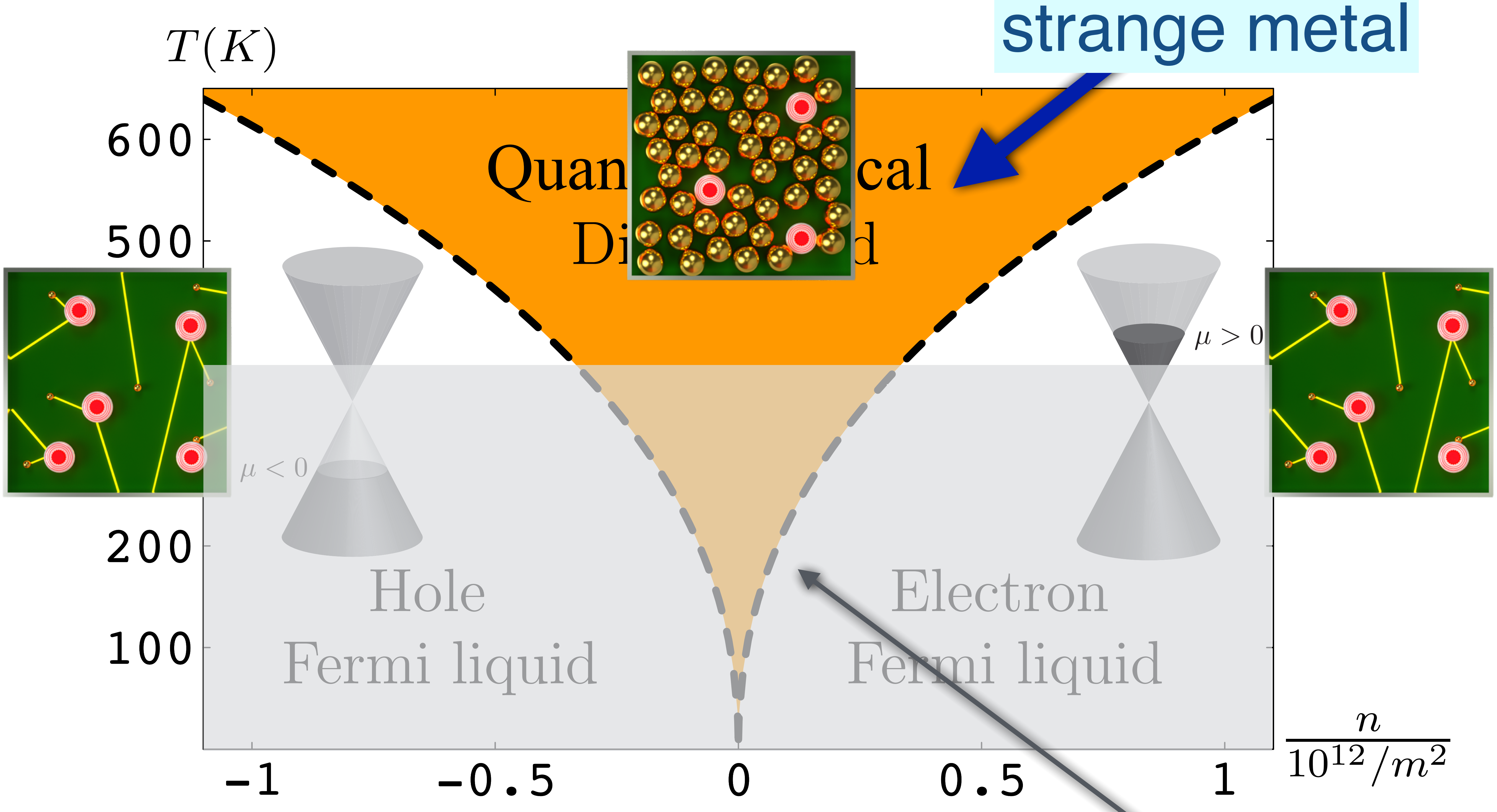

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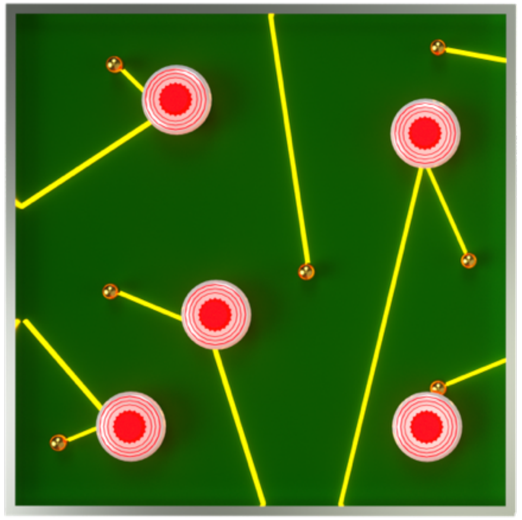
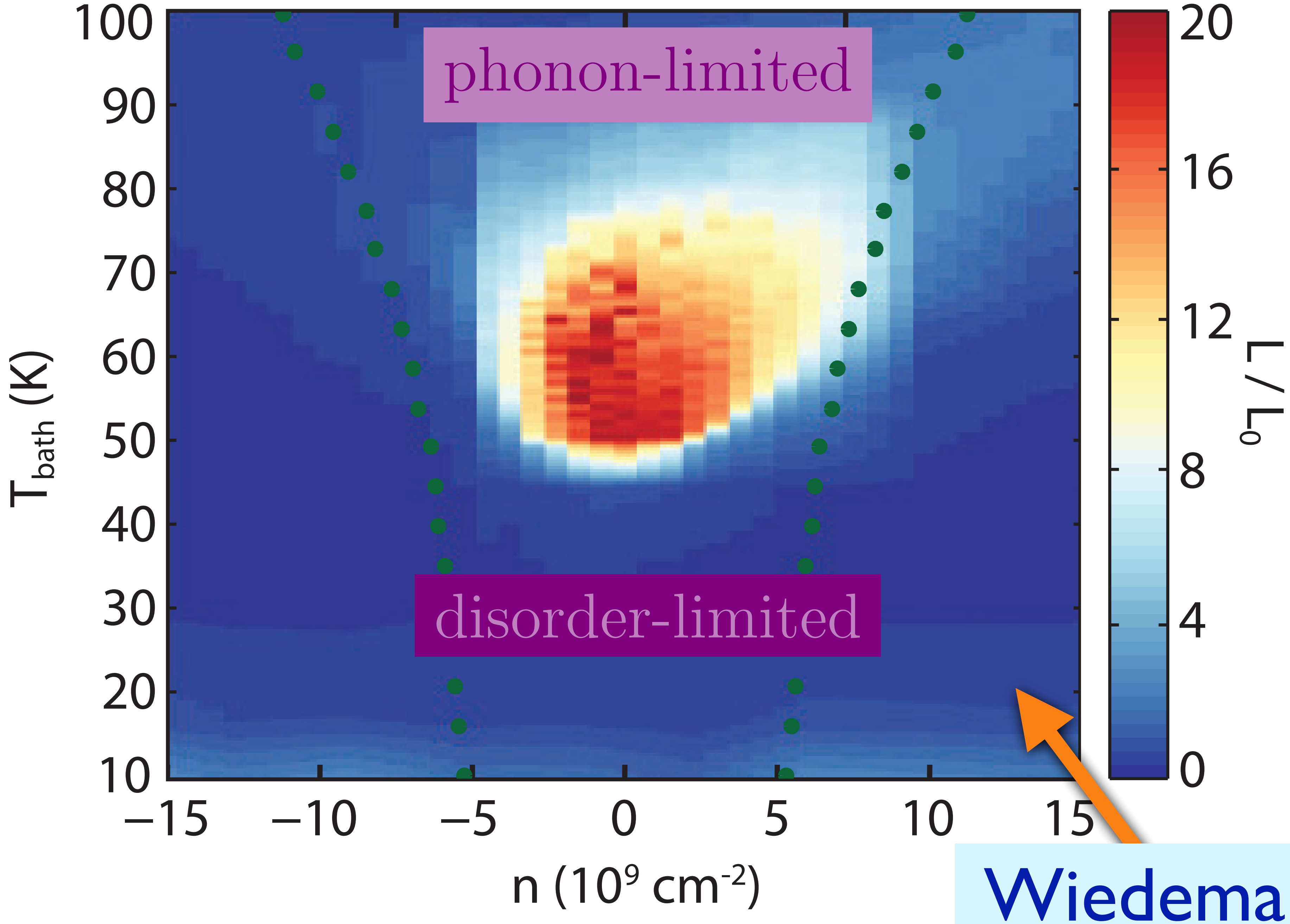
Strange metal in graphene

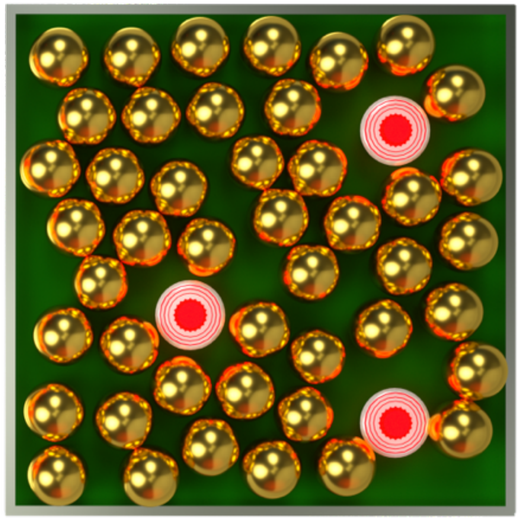


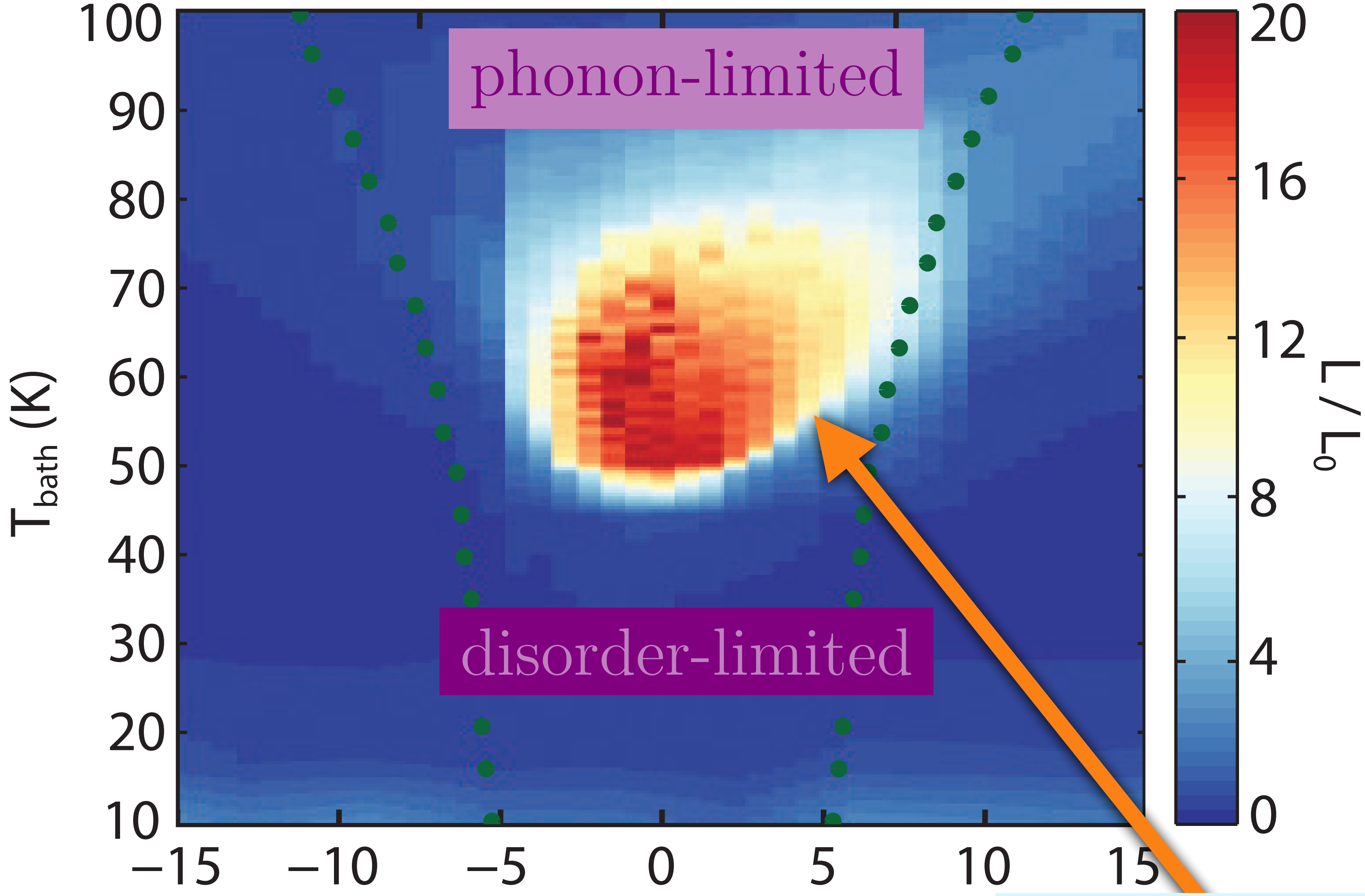


Wiedemann-Franz obeyed

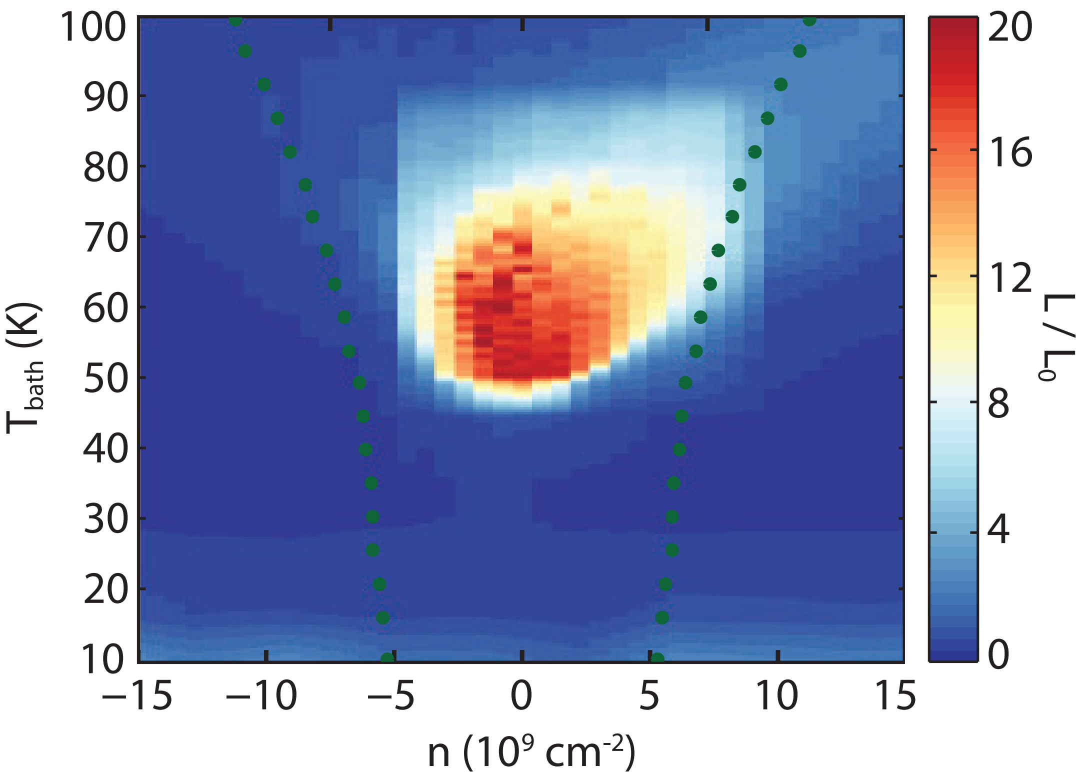
J. Crossno et al., Science **351**, 1058 (2016)

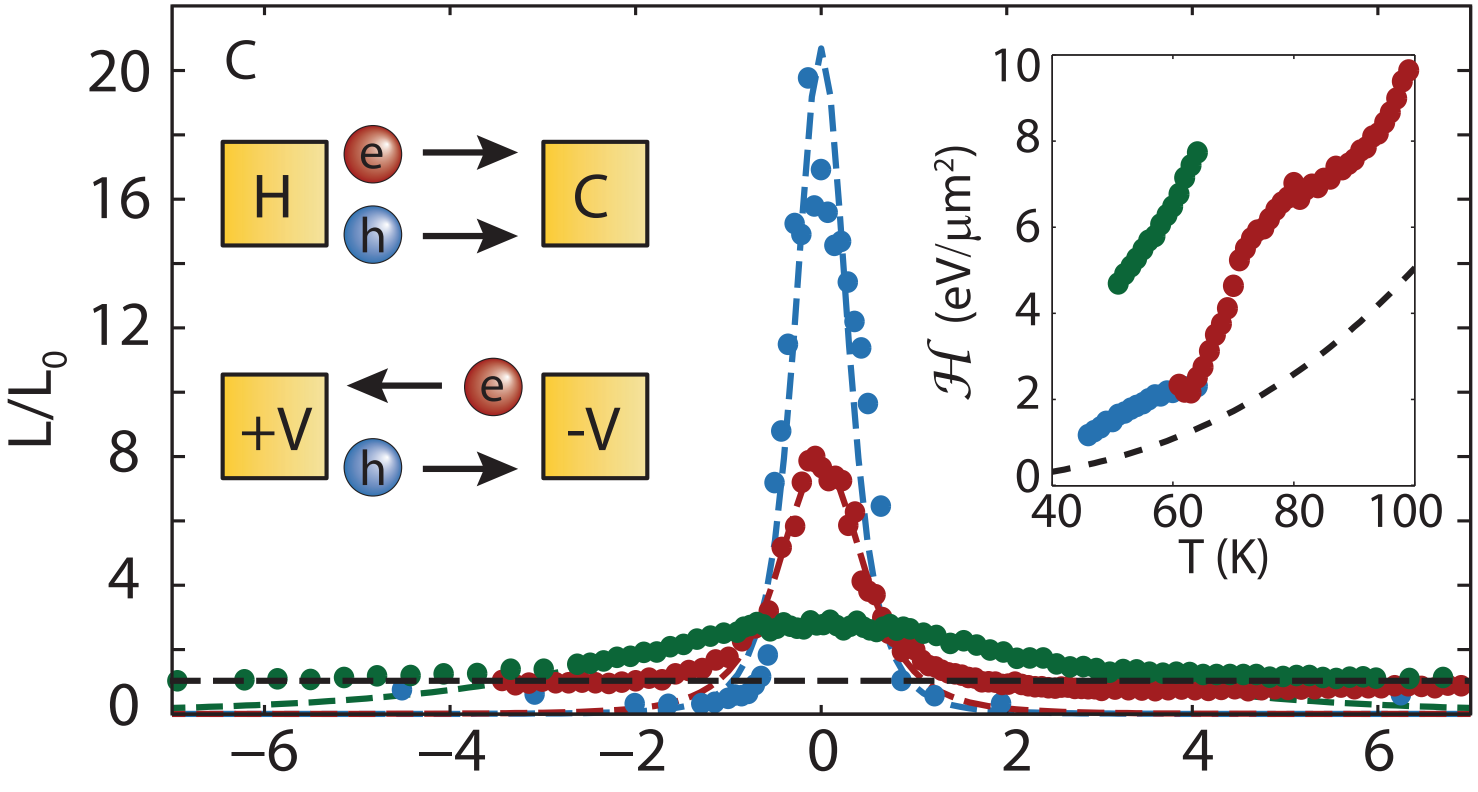
Strange metal in graphene

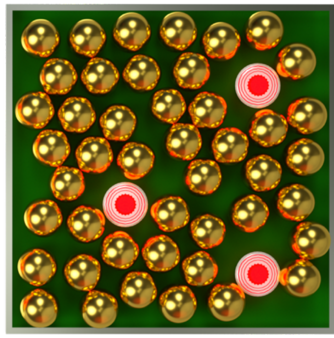


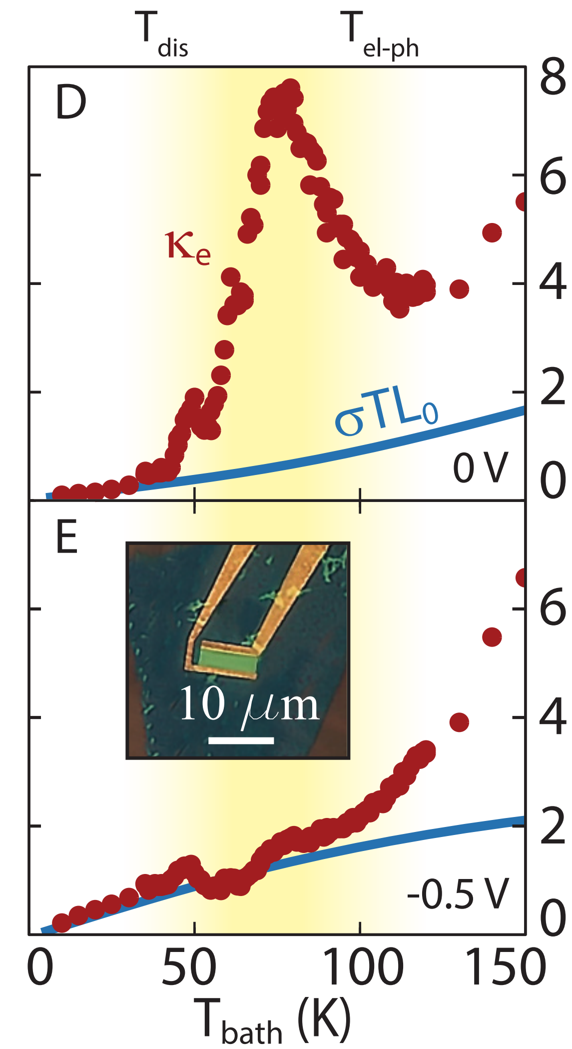


Wiedemann-Franz violated !









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

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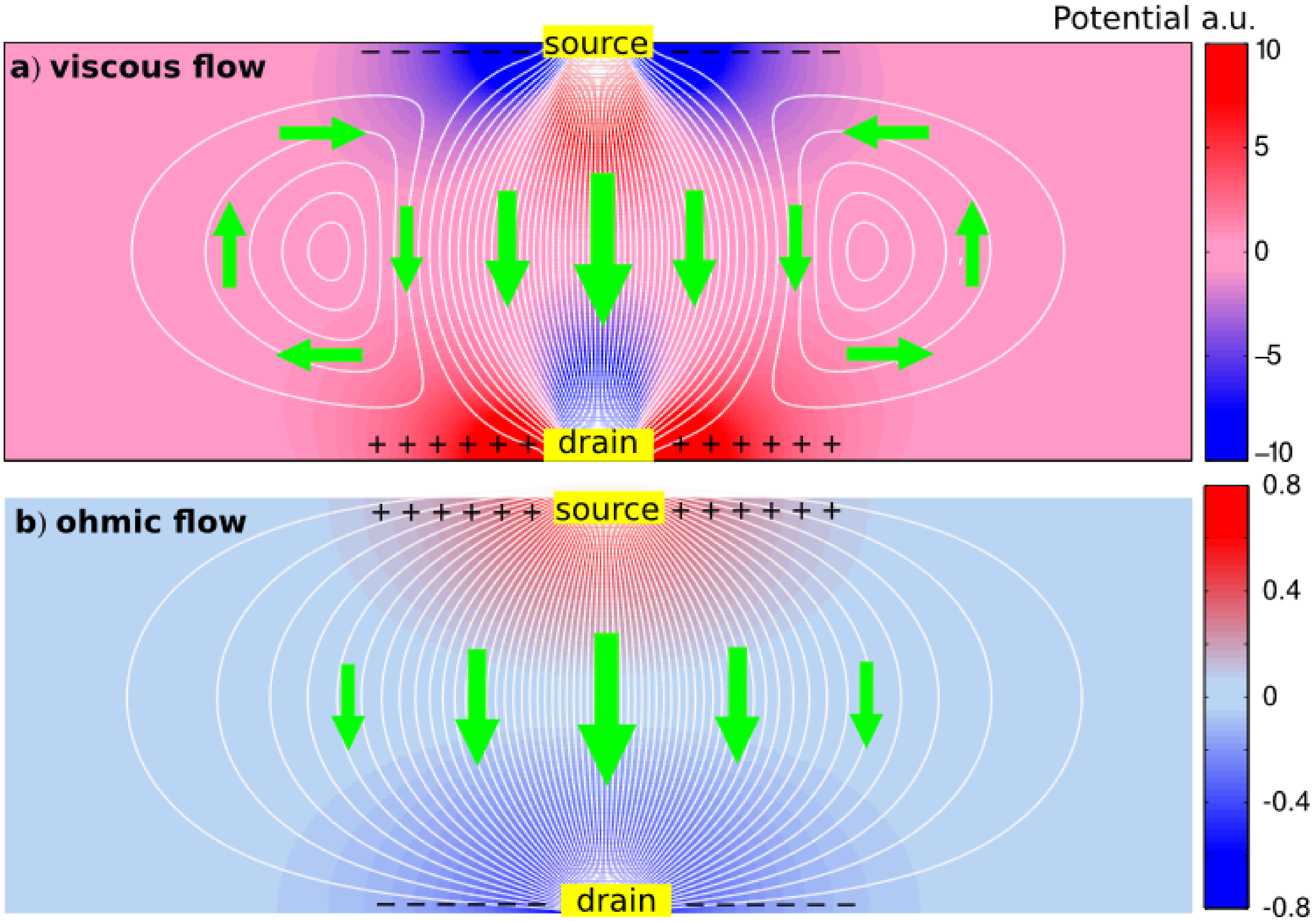
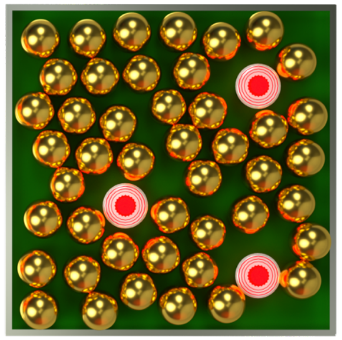
S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)

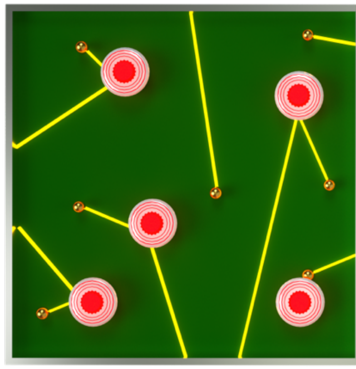
J. Crossno et al., Science **351**, 1058 (2016)

Strange metal in graphene

Negative local resistance due to viscous electron backflow in graphene







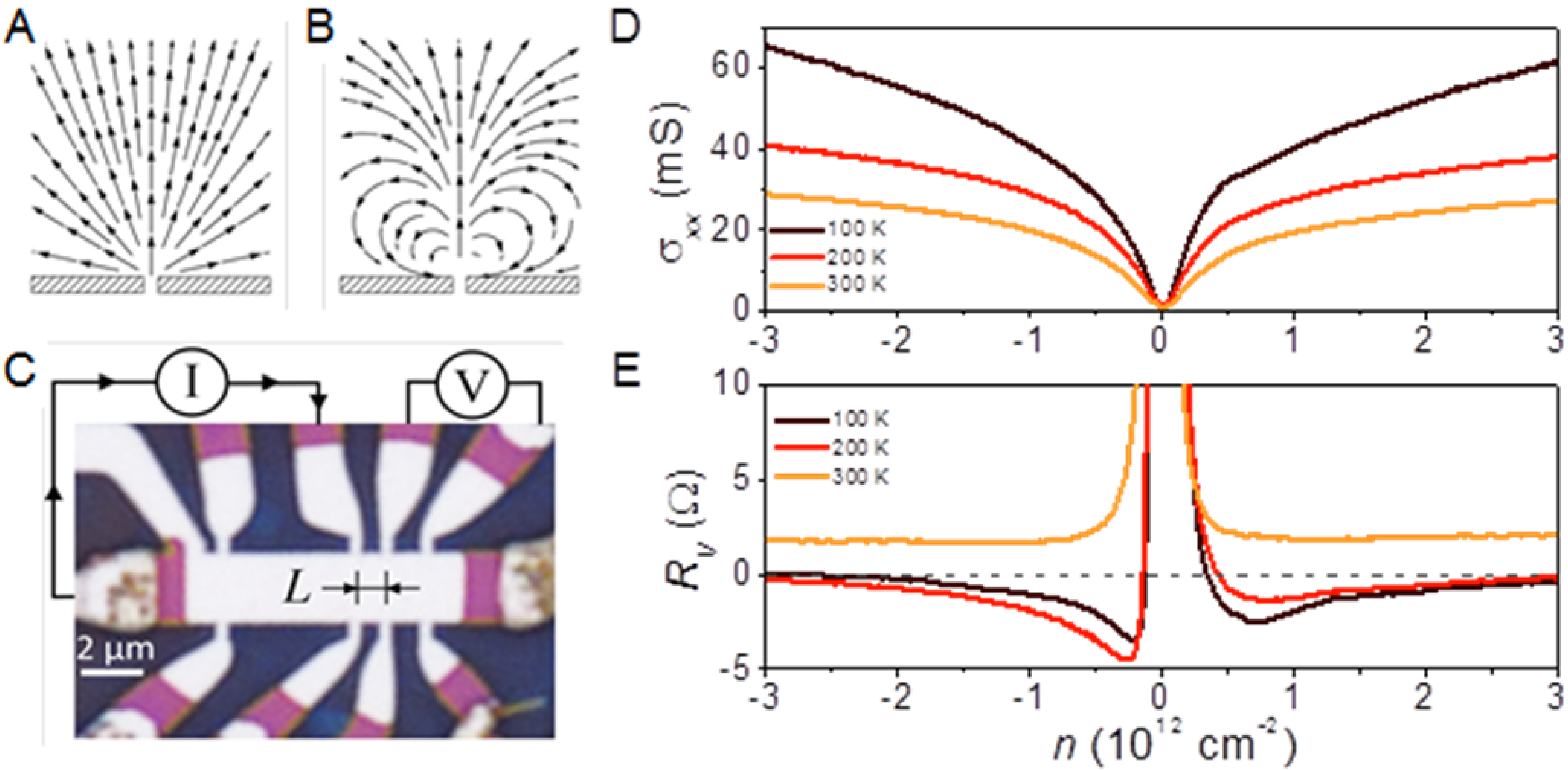
L. Levitov and G. Falkovich, arXiv:1508.00836, *Nature Physics online*

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]



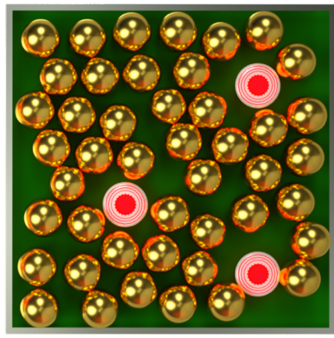
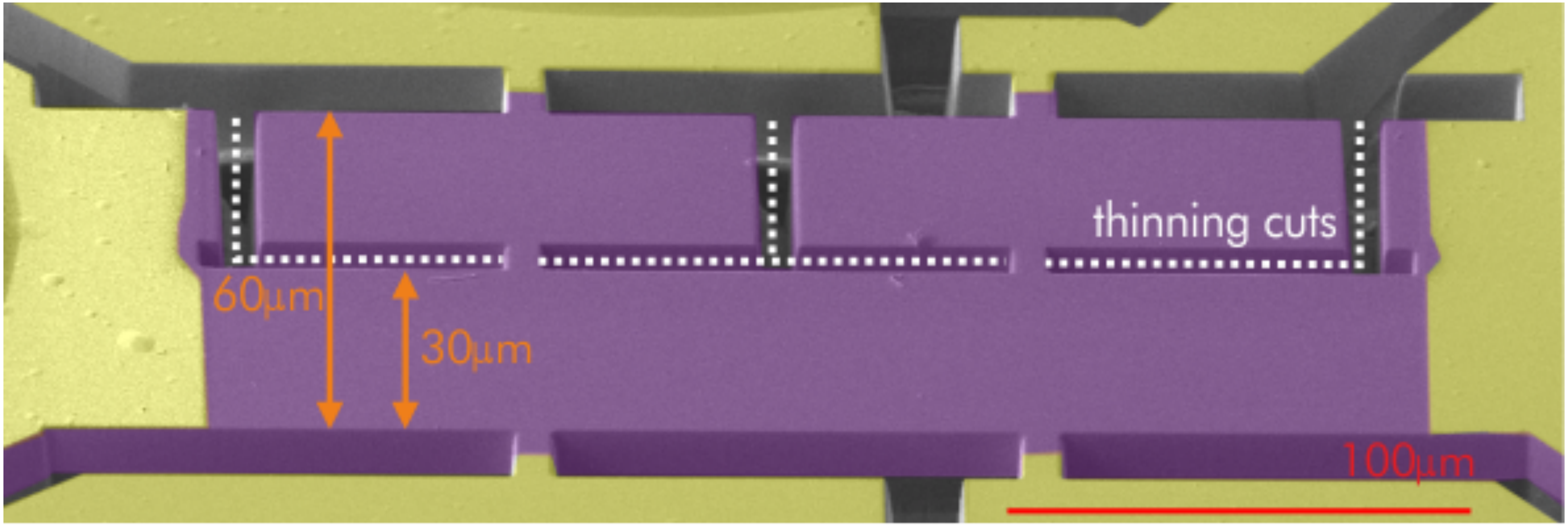


Figure 1. Viscous backflow in doped graphene. (**a,b**) Steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (a) and a viscous Fermi liquid (b). (**c**) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry for vicinity resistance. (**d,e**) Longitudinal conductivity σ_{xx} and $R_{\rm V}$ 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.

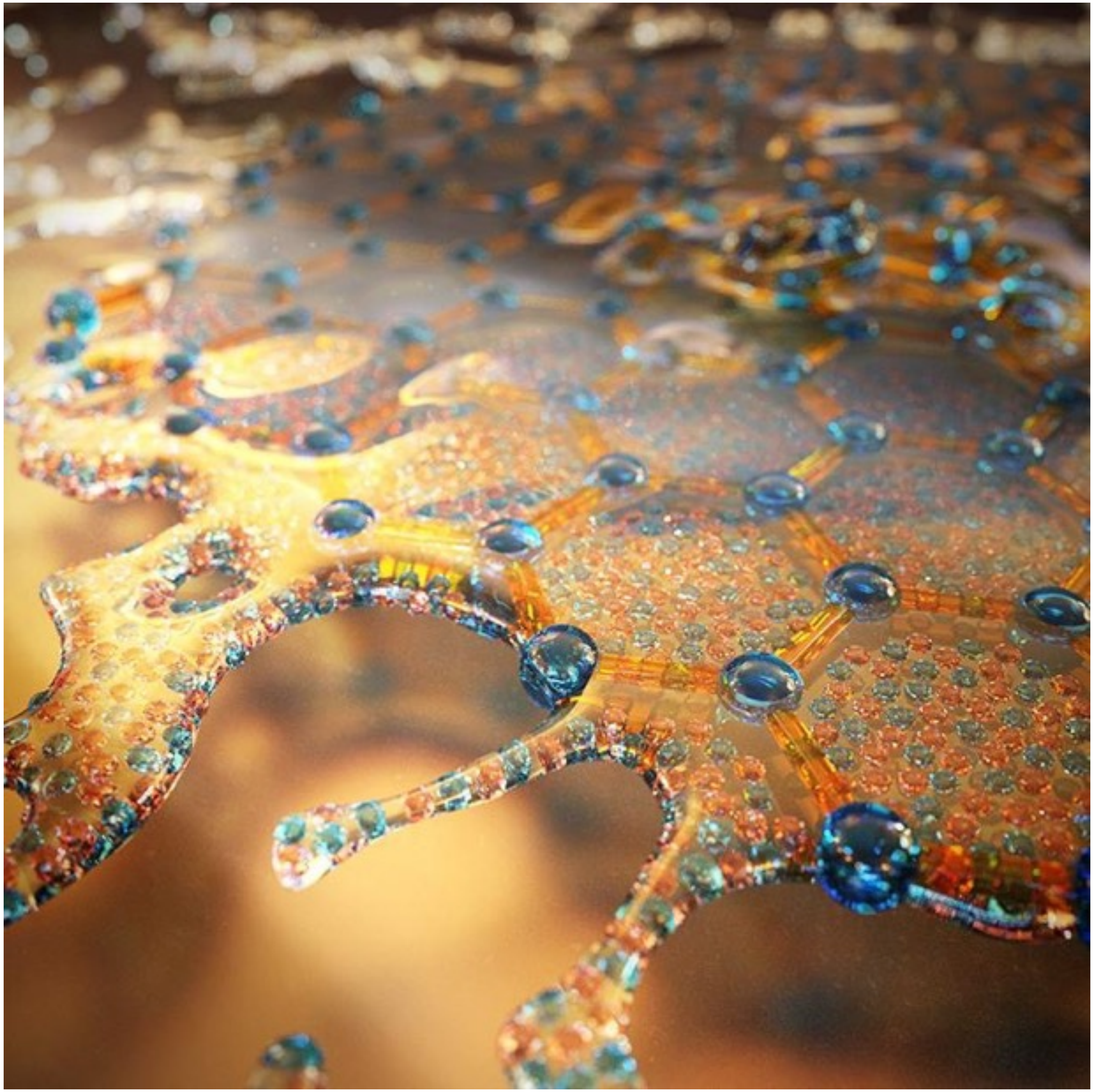
Signature of Navier-Stokes hydrodynamic flow in $PdCoO_2$



Experiment: Successively narrow the channel in factors of 2, measuring the resistance after every step.

P.J.W. Moll, P. Kushwaha, N. Nandi, B. Schmidt and A.P. Mackenzie, Science ***351****, 1061 (2016)*

Graphene: "a metal that behaves like water"



Quantum matter without quasiparticles:

- Superfluid-insulator transition of ultracold bosonic atoms in an optical lattice
- Graphene
- Solvable random fermion Sachdev-Ye-Kitaev (SYK) model
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Infinite-range model with quasiparticles

$$H = \frac{1}{(N)^{1/2}} \sum_{i,j=1}^{N} t_{ij} c_i^\dagger c_j + \ldots$$

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

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

t_{ij} are independent random variables with $\overline{t_{ij}} = 0$ and $\overline{|t_{ij}|^2} = t^2$

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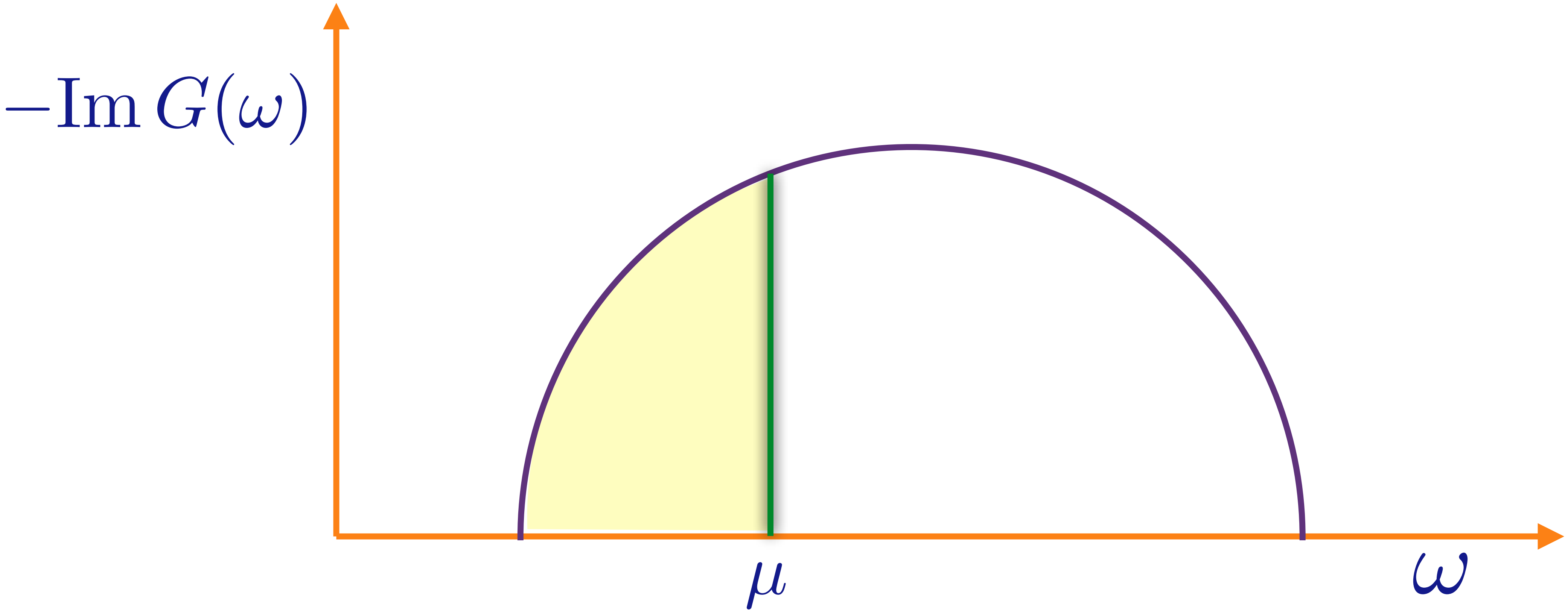

Fermions occupying eigenstates with a "semi-circular" density of states

Infinite-range (SYK) model of a strange metal

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

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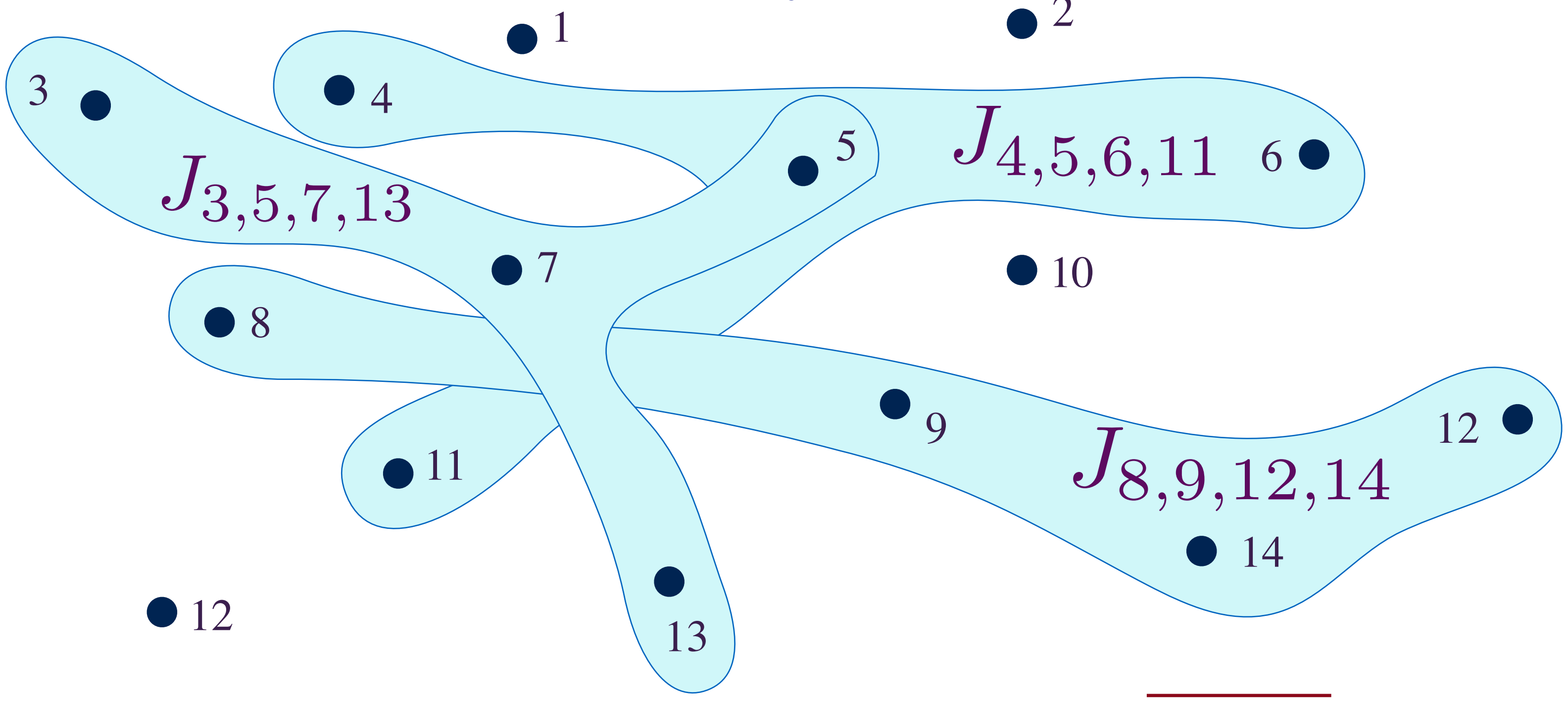

$J_{ij;k\ell}$ are independent random variables with $\overline{J_{ij;k\ell}} = 0$ and $\overline{|J_{ij;k\ell}|^2} = J^2$
$N \to \infty$ yields critical strange metal.

S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

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

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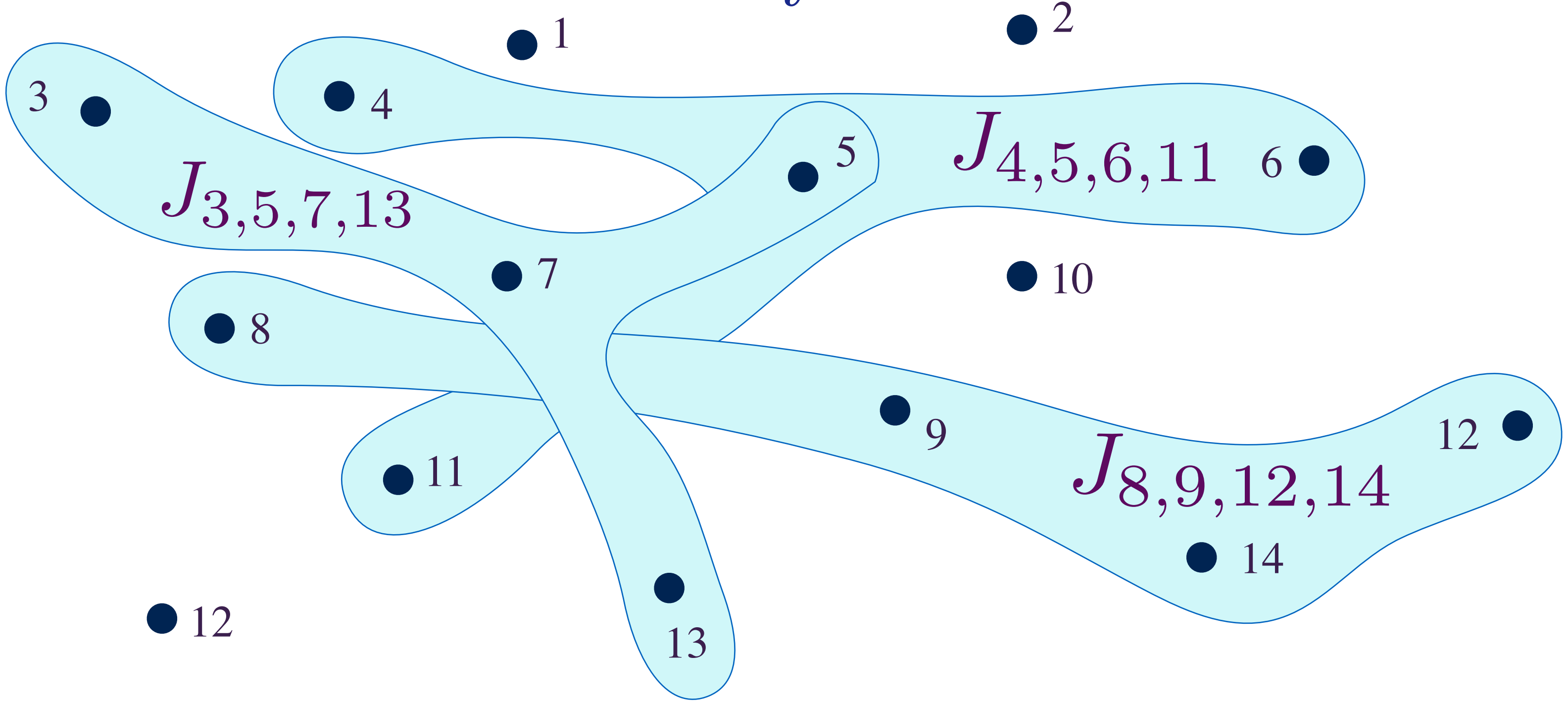

A fermion can move only by entangling with another fermion: the Hamiltonian has “nothing but entanglement”.

S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

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

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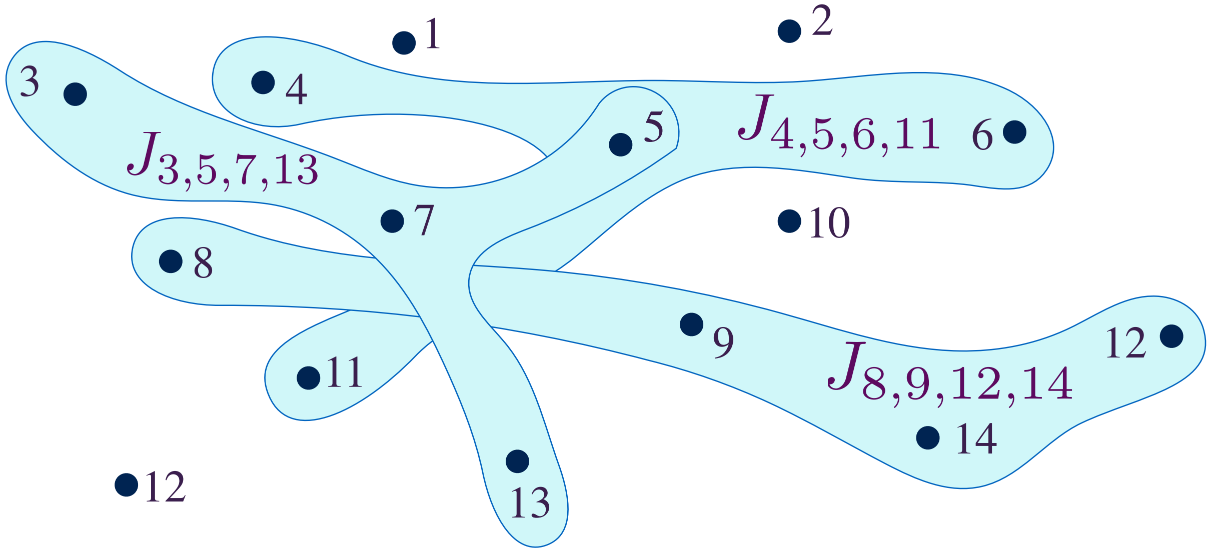

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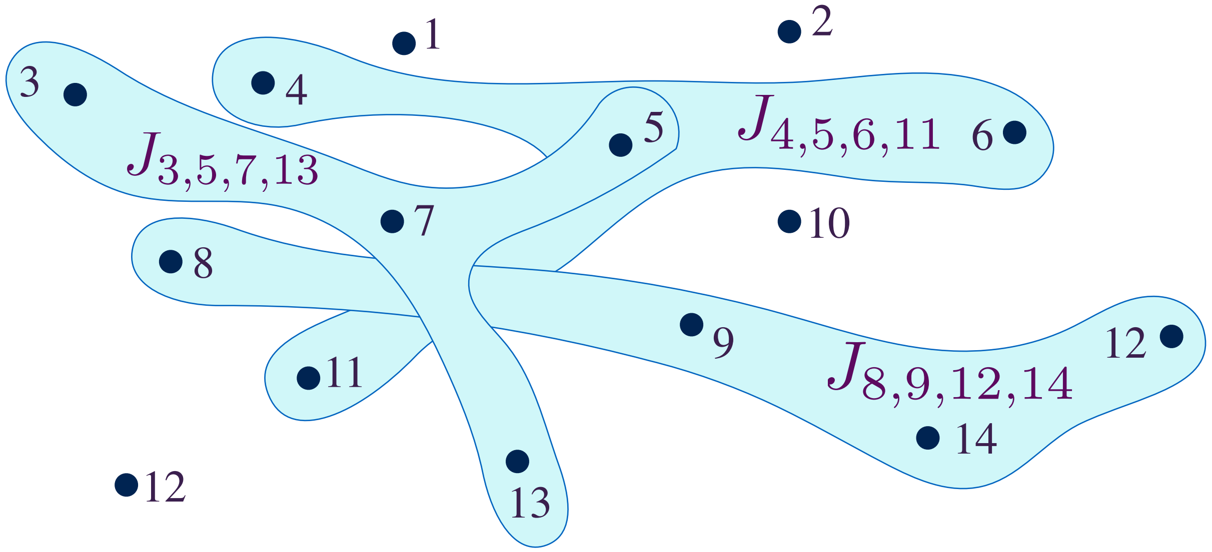

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Local fermion density of states

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

Known 'equation of state'
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A. Georges, O. Parcollet, and S. Sachdev PRB **63**, 134406 (2001)

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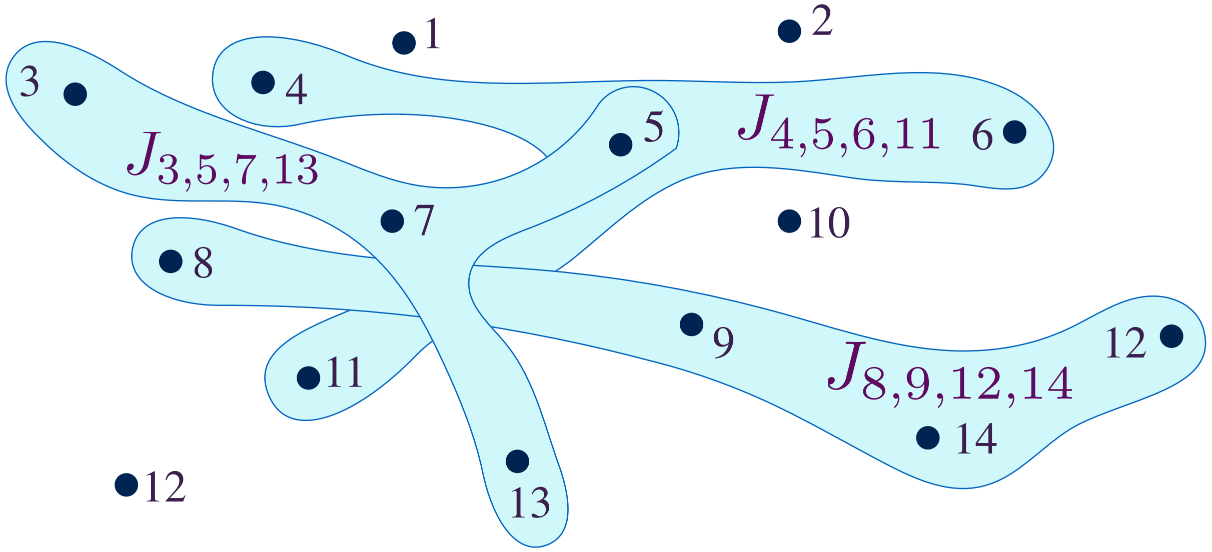

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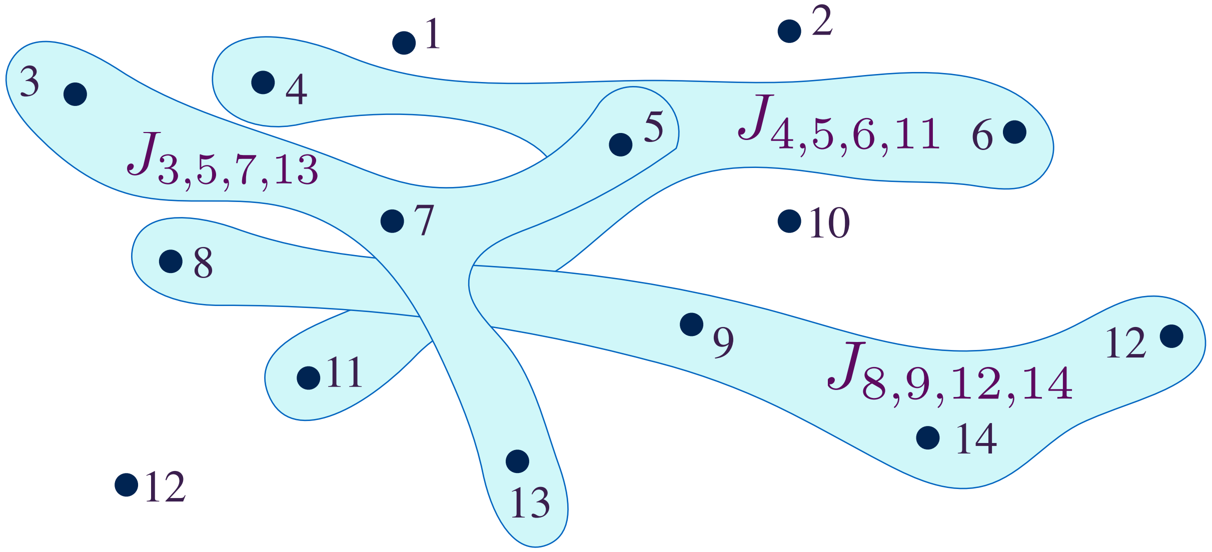

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A. Kitaev, unpublished
J. Polchinski and V. Rosenhaus, arXiv: 1601.06768
J. Maldacena and D. Stanford, arXiv:1604.07818
K. Jensen, arXiv:1605.06098.

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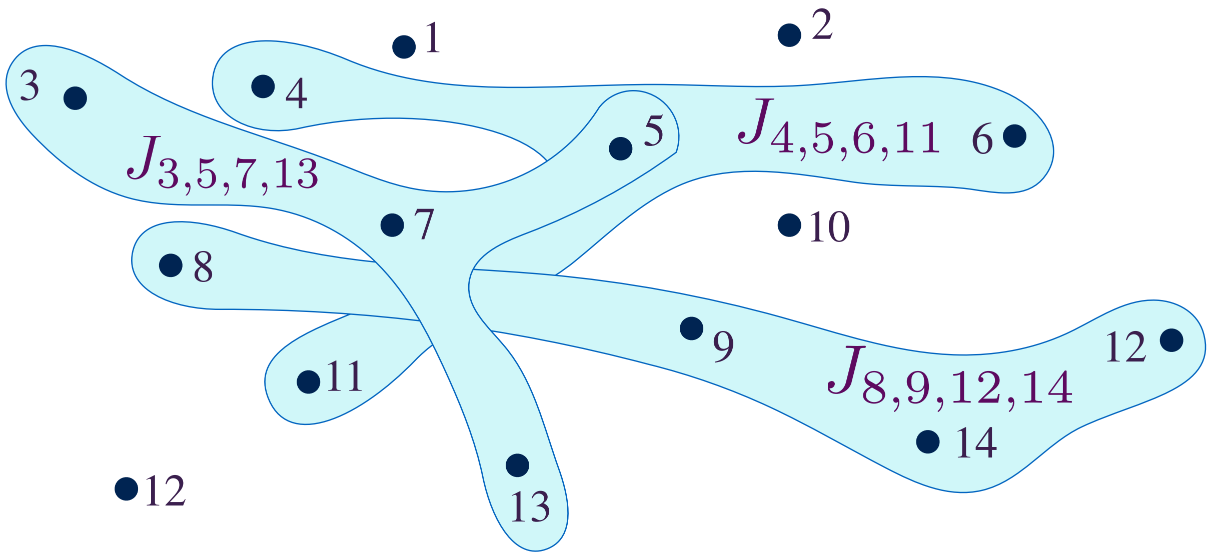

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The SYK strange metal is holographically dual to the gravity theory of the AdS$_2$ near-horizon geometry of charged black holes

S. Sachdev,
Phys. Rev. Lett. **105**, 151602 (2010)

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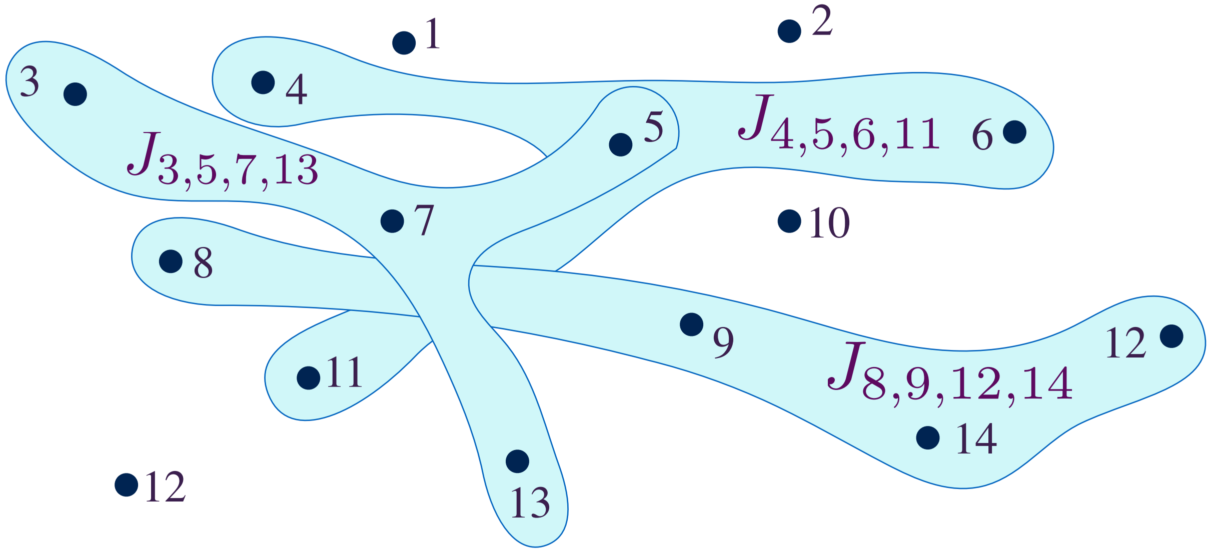

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Einstein-Maxwell theory
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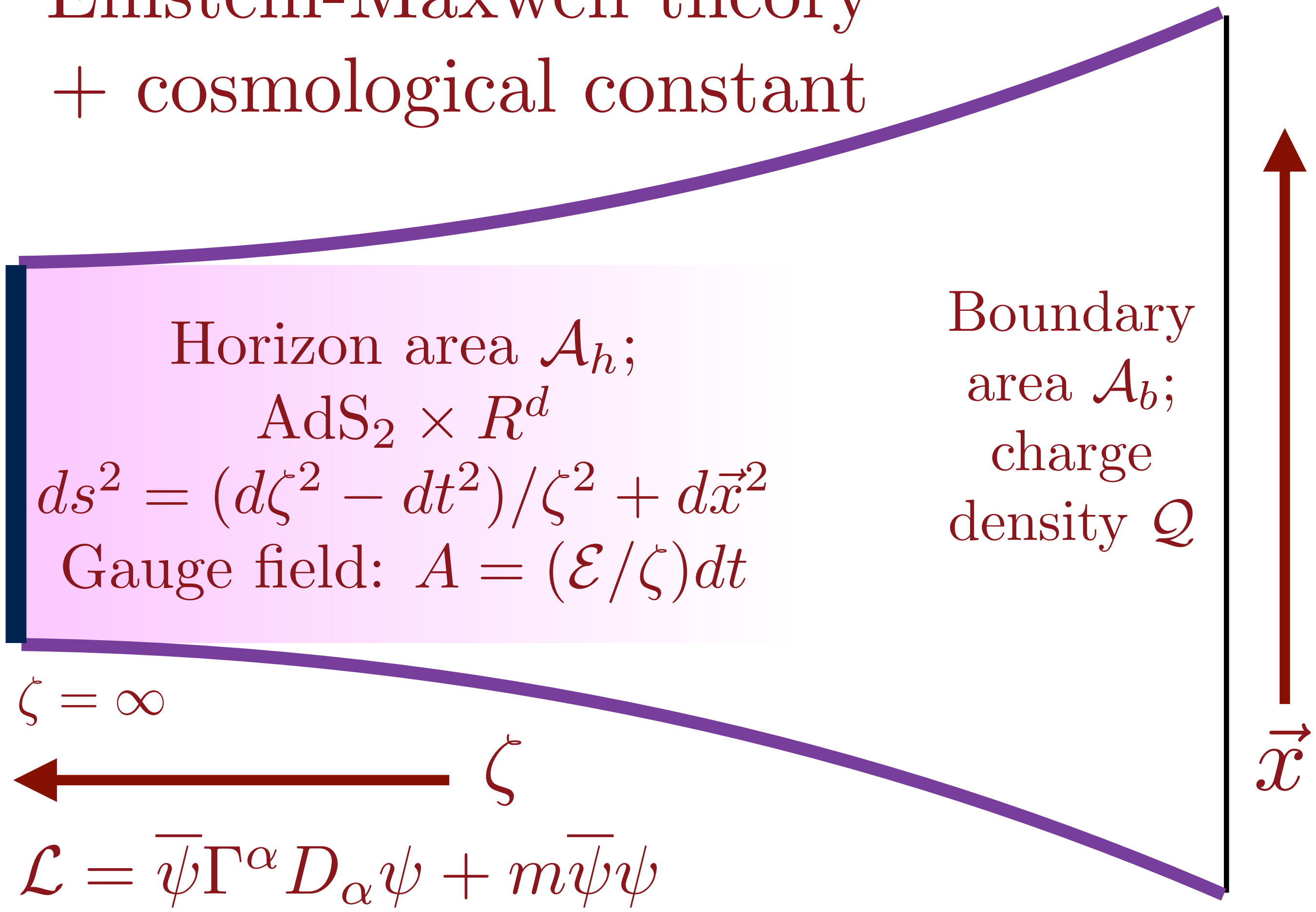

Horizon area $\mathcal{A}_h$;
AdS$_2 \times R^d$
$ds^2 = (d\zeta^2 - dt^2)/\zeta^2 + d\vec{x}^2$
Gauge field: $A = (\mathcal{E}/\zeta)dt$

Boundary area $\mathcal{A}_b$; charge density $\mathcal{Q}$

$\zeta = \infty$

ζ

$\vec{x}$

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

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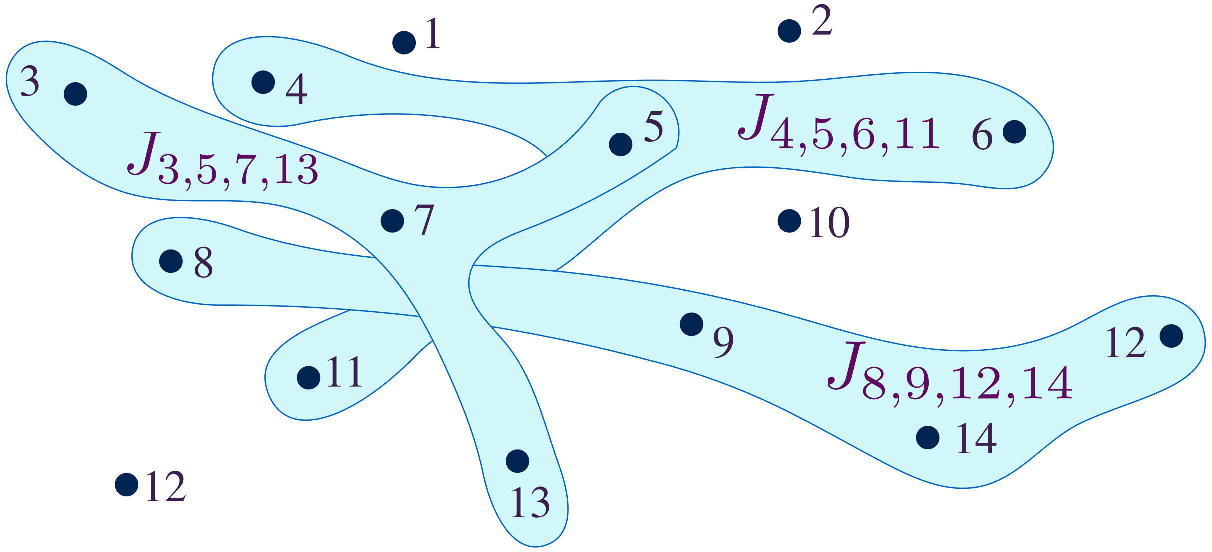

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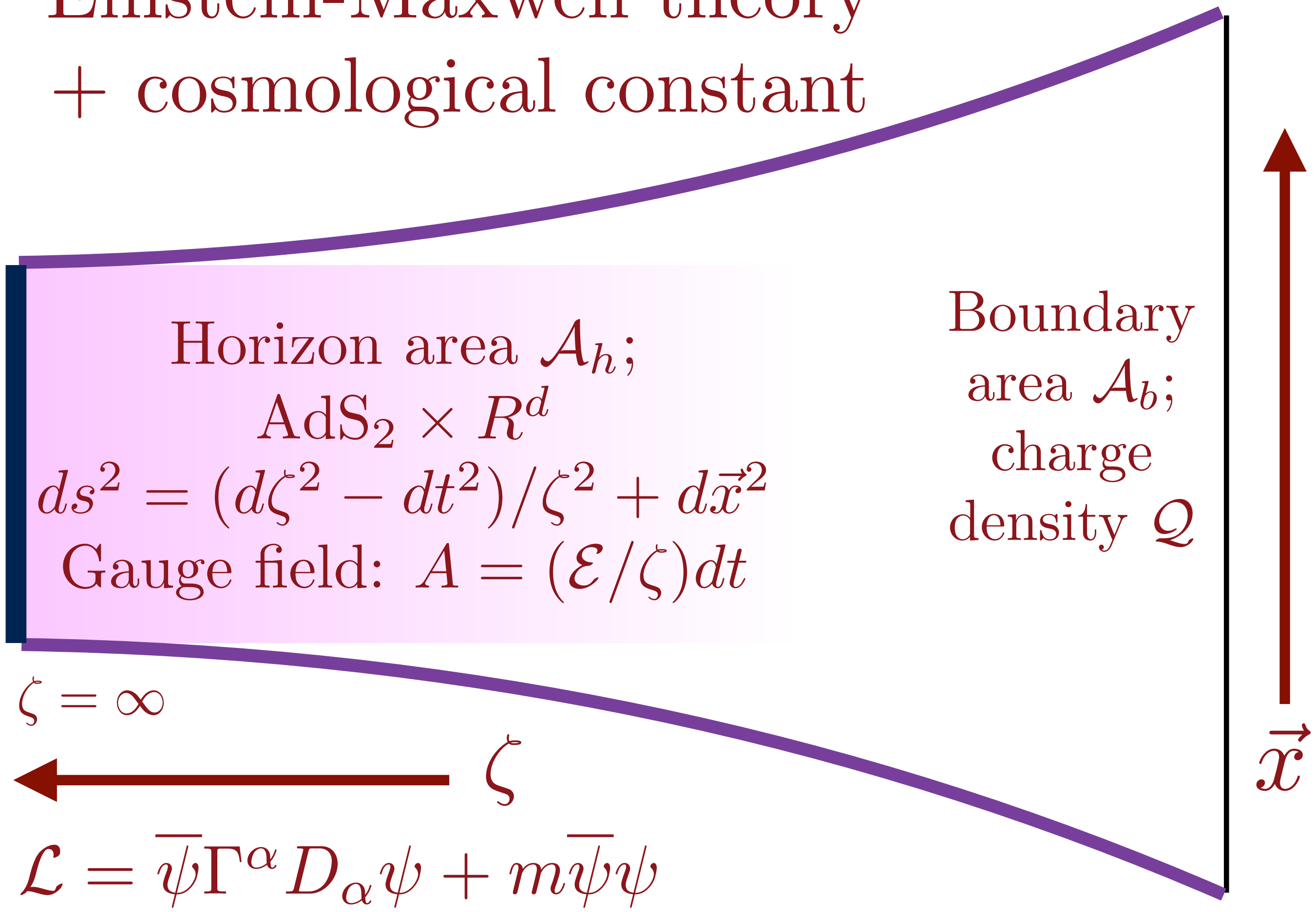

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Black hole thermodynamics (classical general relativity) yields

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

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

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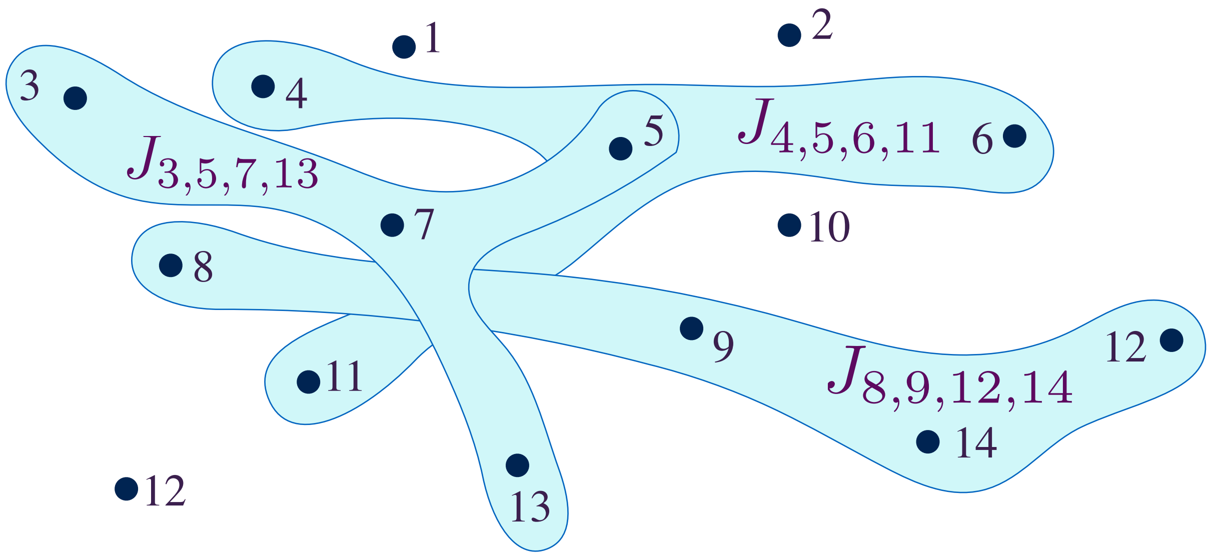

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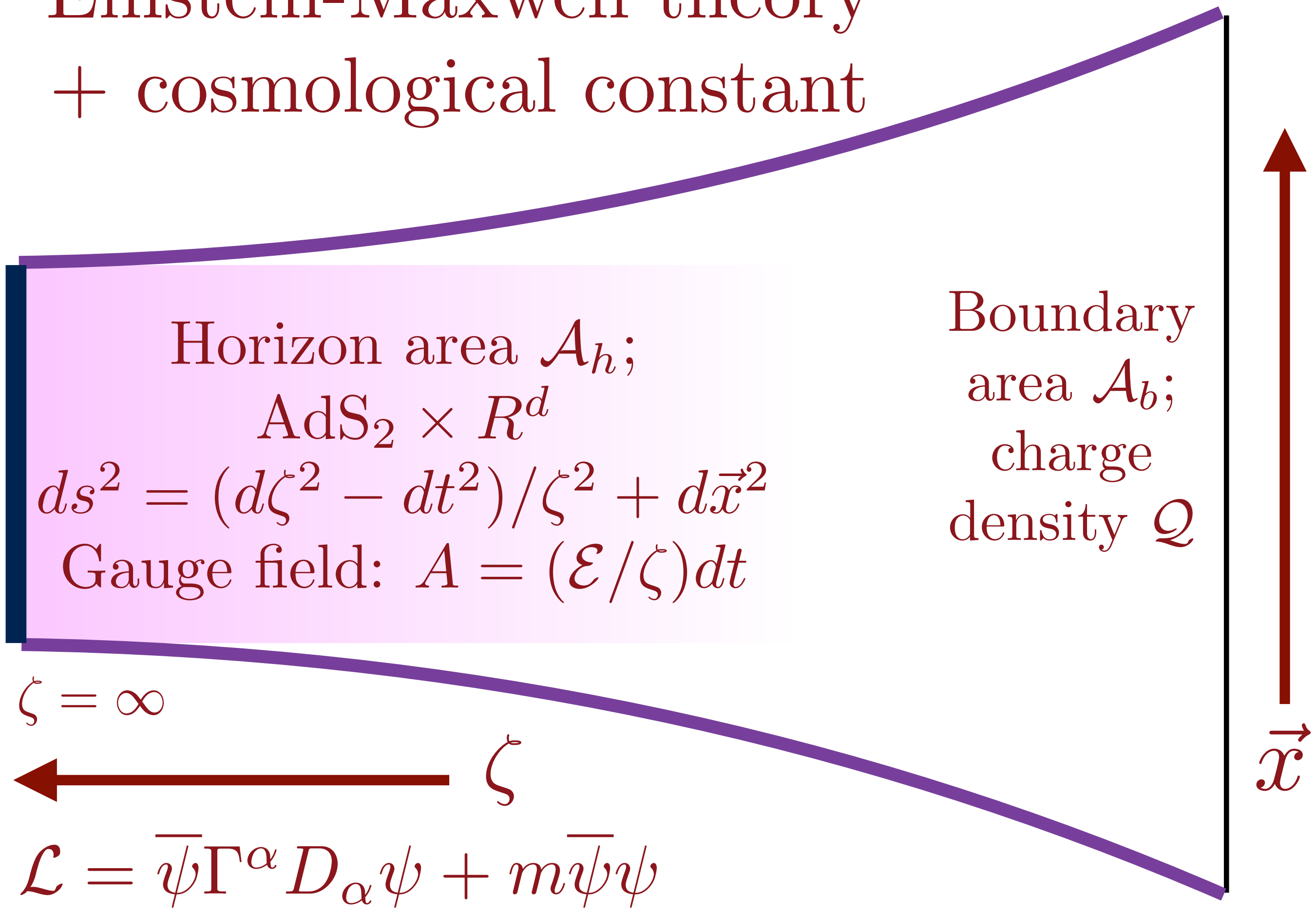
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S. Sachdev, PRL **105**, 151602 (2010); PRX **5**, 041025 (2015)

- The scrambling times of the SYK model and of black holes in Einstein gravity saturate the bound on quantum chaos

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S. Shenker and D. Stanford, arXiv: 1306.0622;
J. Maldacena, S. H. Shenker and D. Stanford, arXiv:1503.01409;
A. Kitaev, unpublished;
J. Polchinski and V. Rosenhaus, arXiv: 1601.06768;
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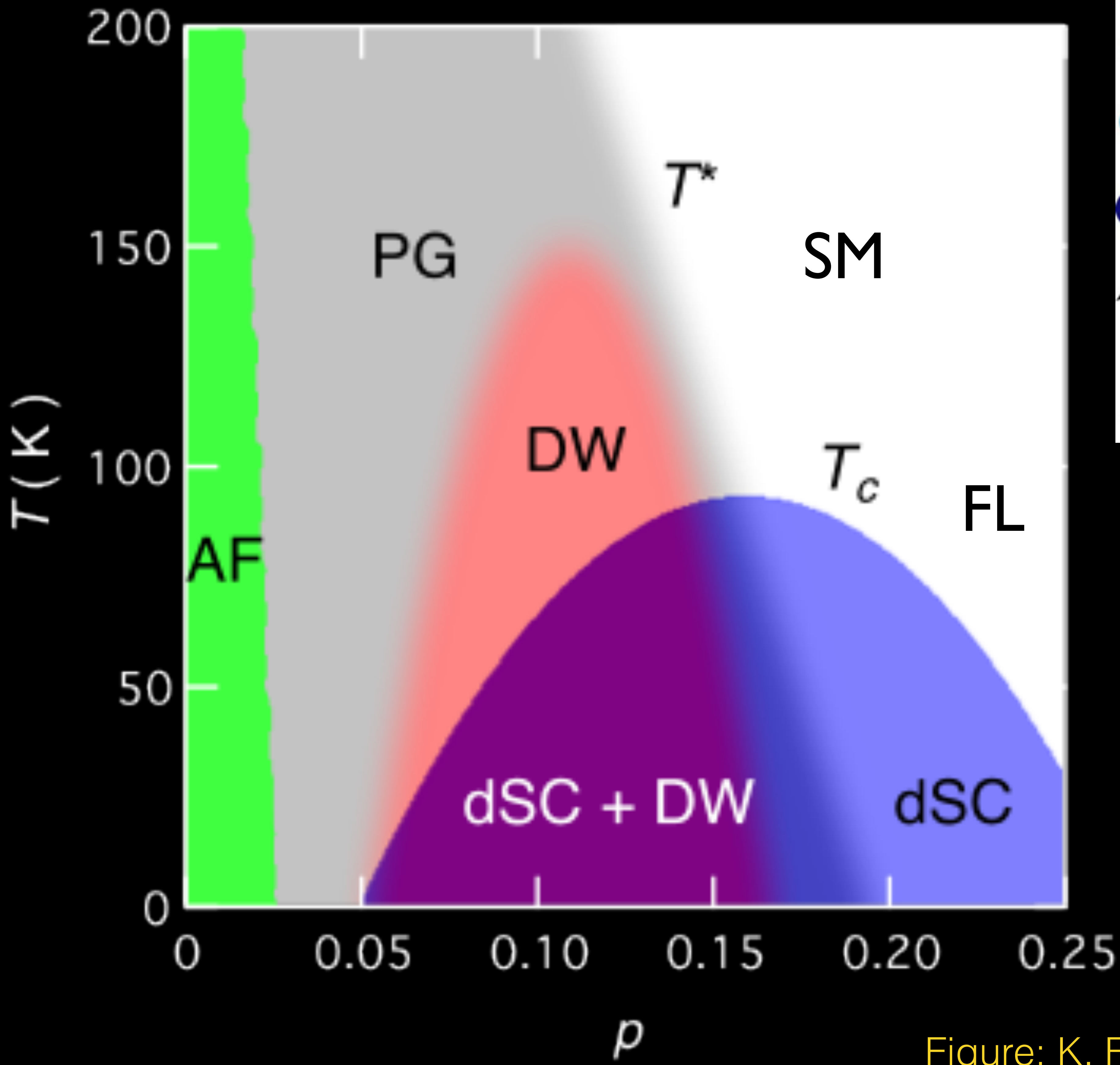
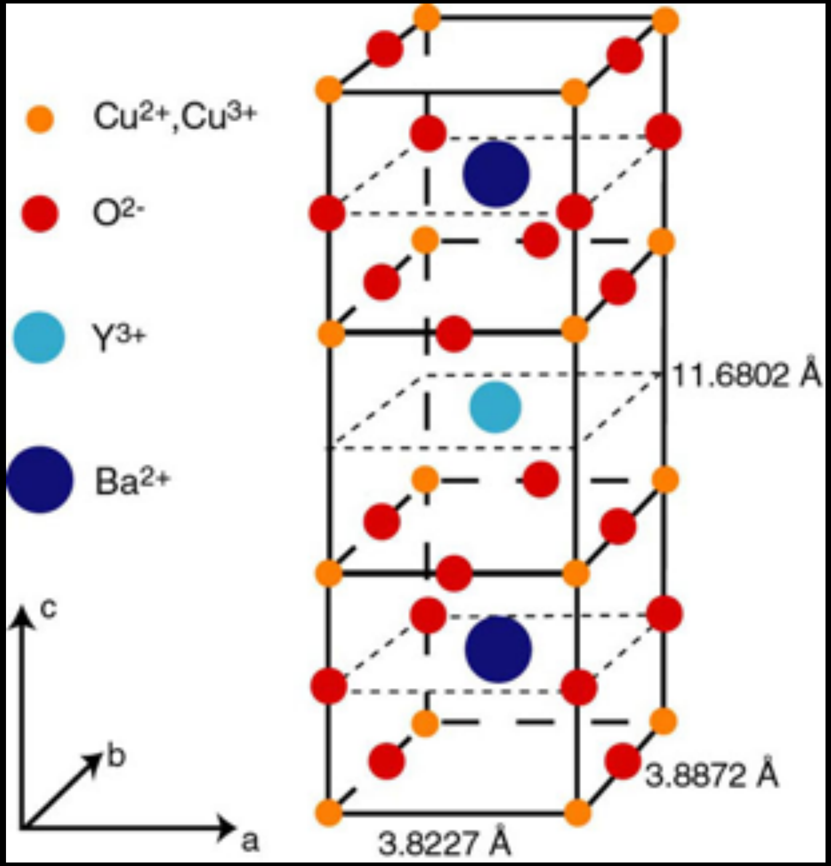
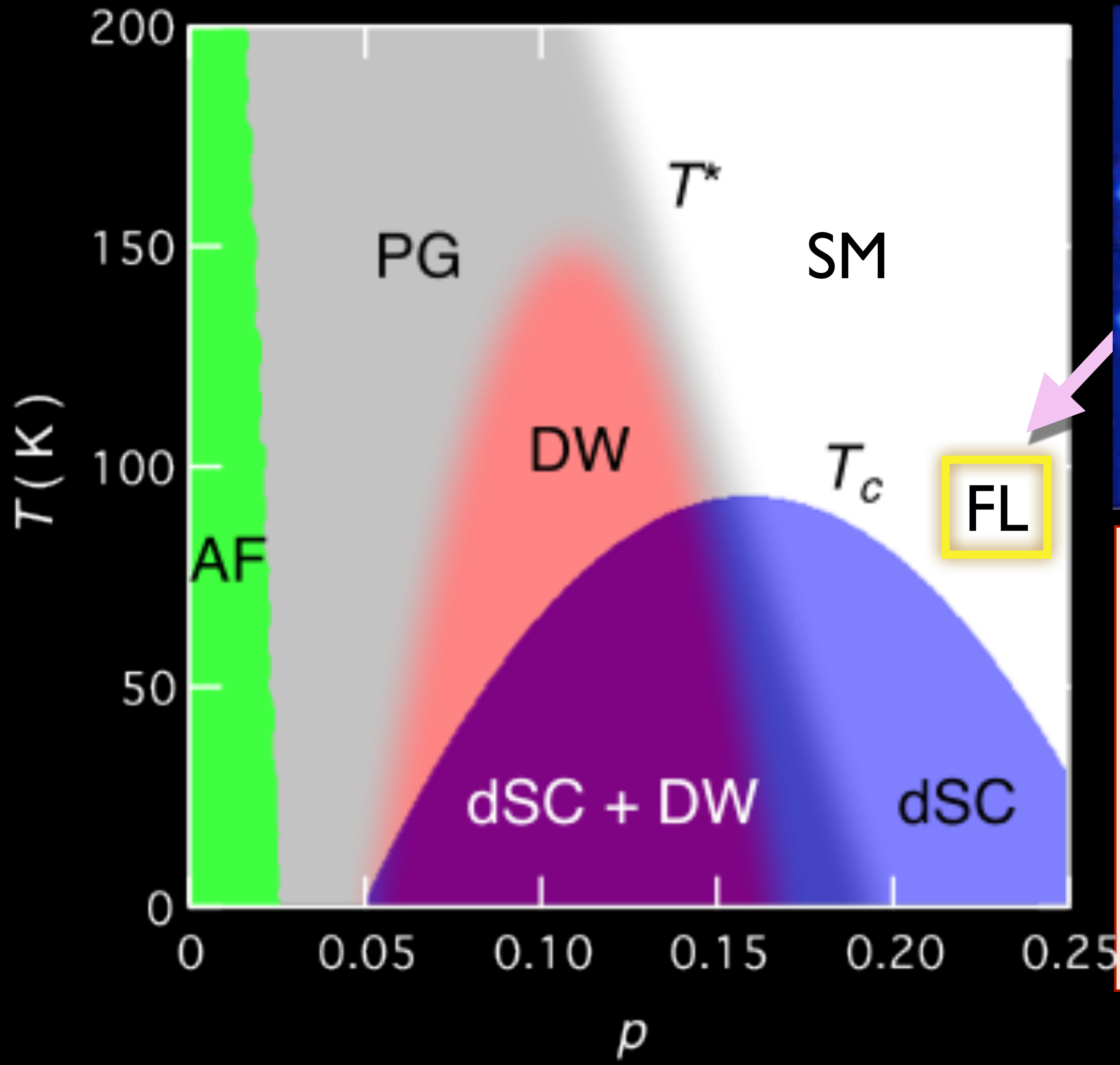


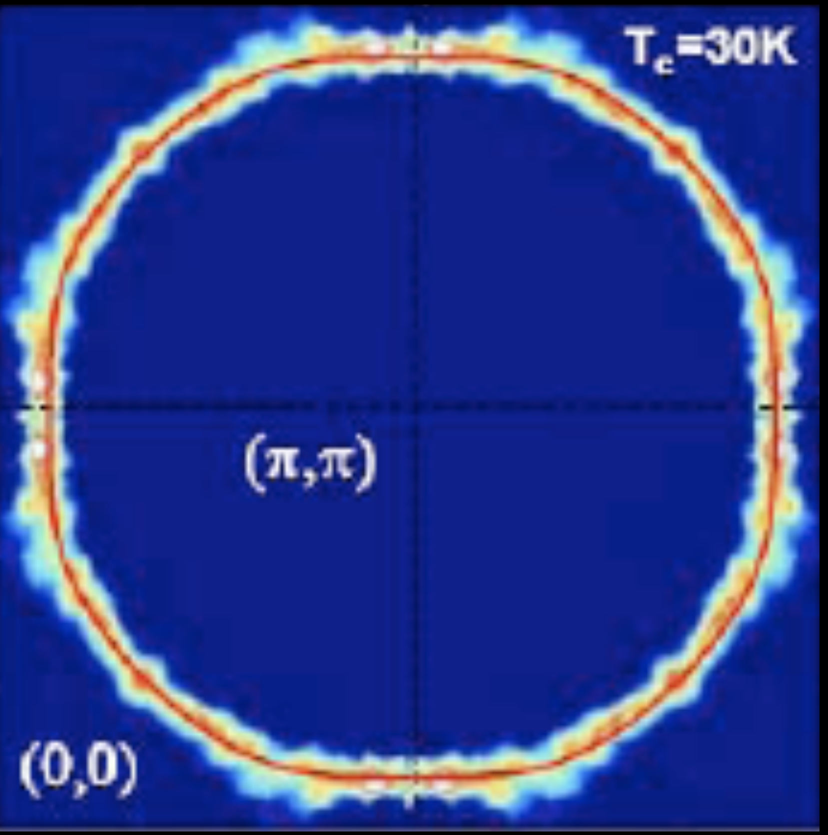


$YBa_2Cu_3O_{6+x}$

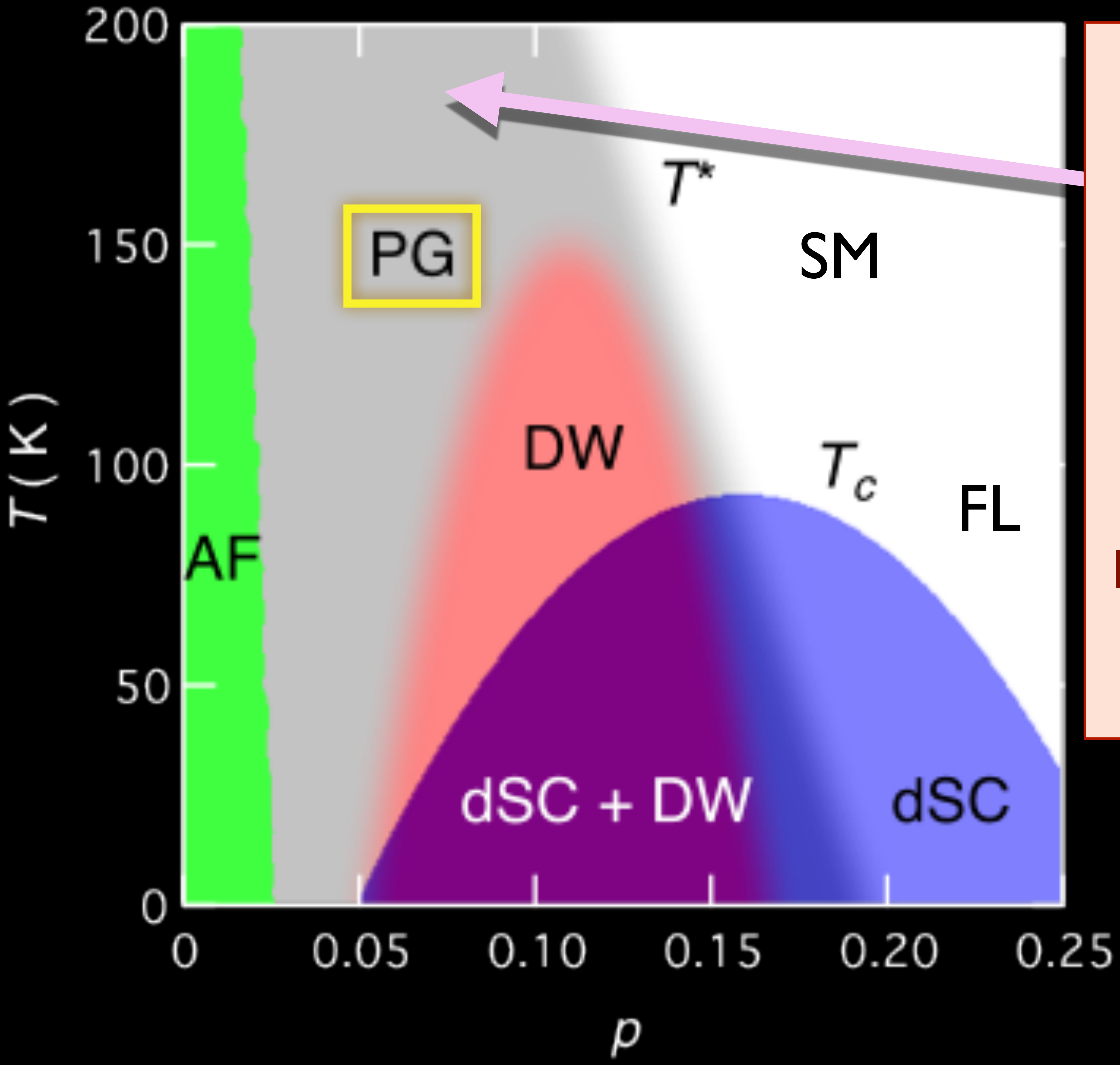
Figure: K. Fujita and J. C. Seamus Davis

M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)





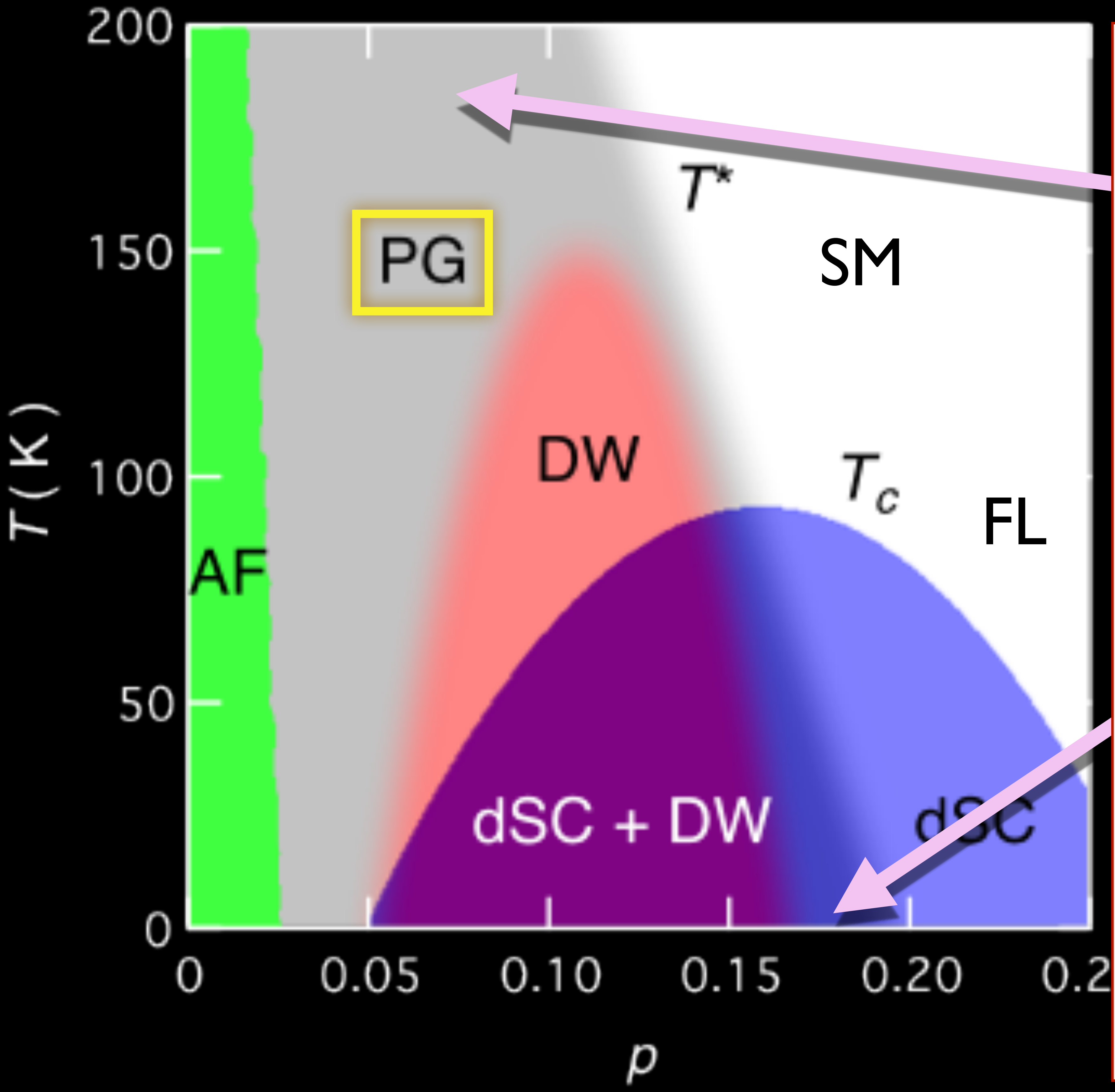
A conventional metal:
the Fermi liquid with Fermi surface of size $1+p$



Pseudogap metal at low p

Many experimental indications that this metal behaves like a Fermi liquid, but with Fermi surface size p and *not* $1+p$.

S. Badoux, W. Tabis, F. Laliberté, G. Grissonnanche, B. Vignolle, D. Vignolles, J. Béard, D.A. Bonn, W.N. Hardy, R. Liang, N. Doiron-Leyraud, L. Taillefer, and C. Proust, Nature **531**, 210 (2016).



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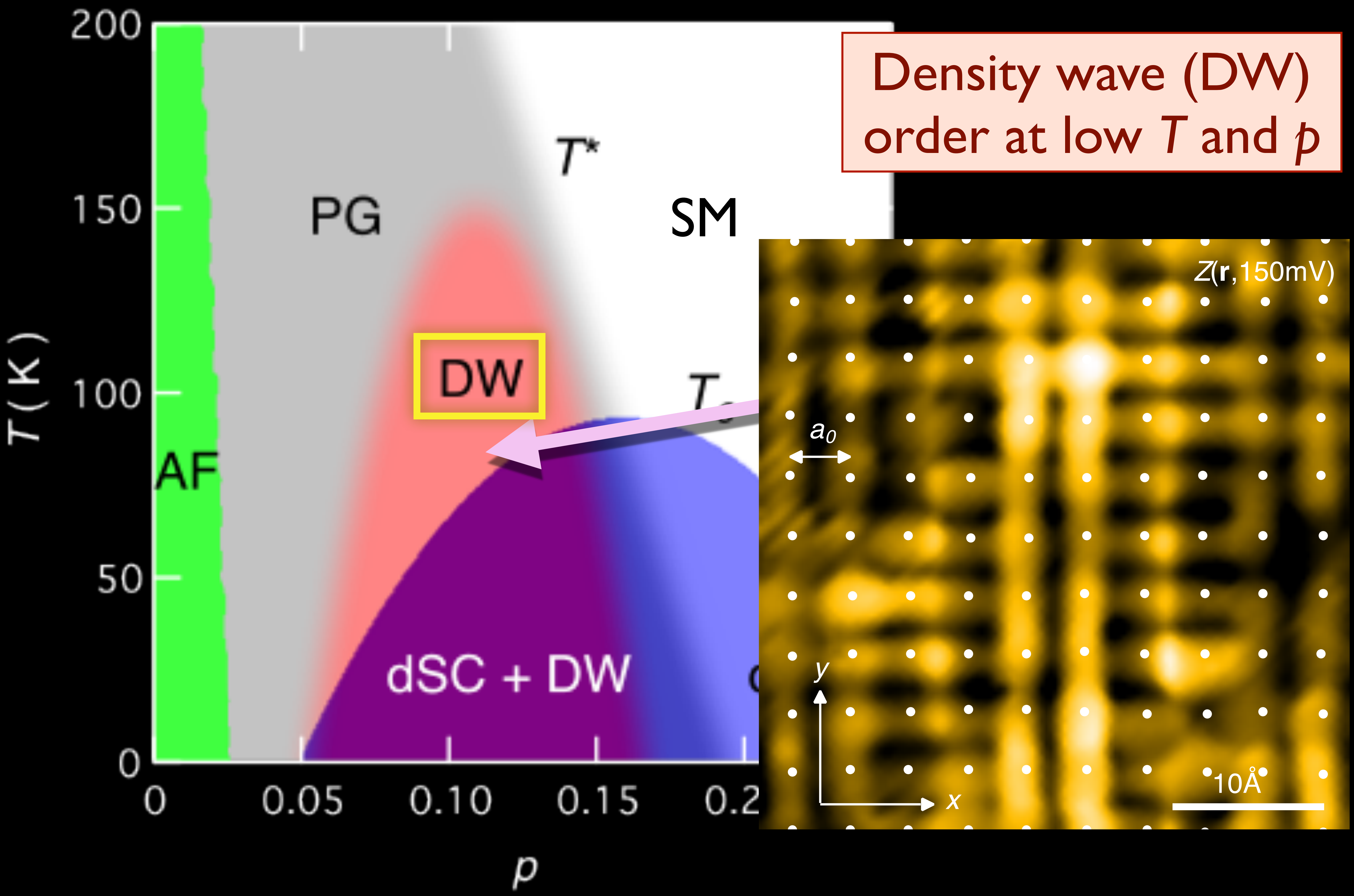
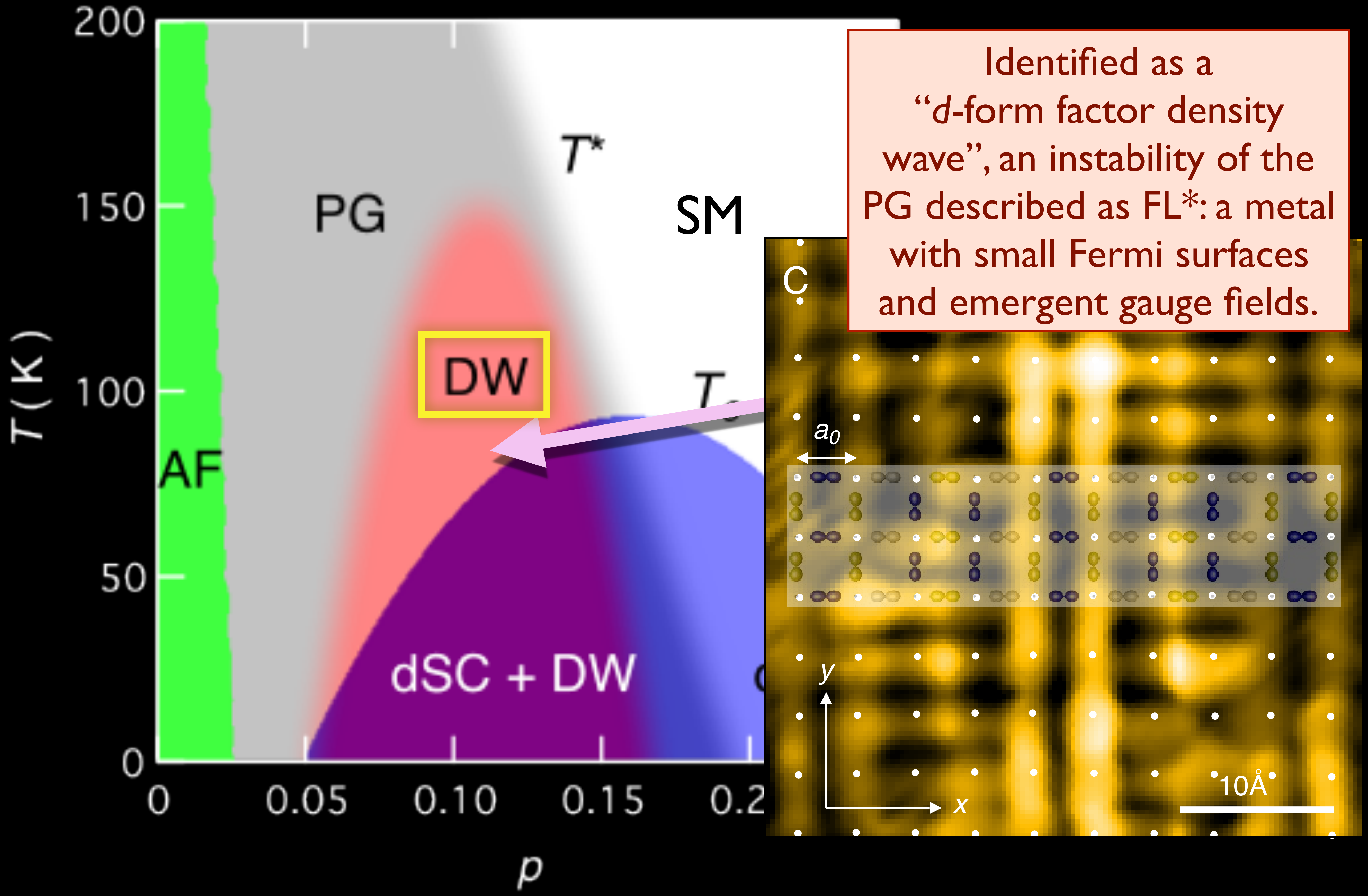
Recent experiments show the PG metal is also present at low T in high magnetic field

Y. Kohsaka *et al.*, Science **315**, 1380 (2007)
M. H. Hamidian *et al.*, Nature Physics **12**, 150 (2016)

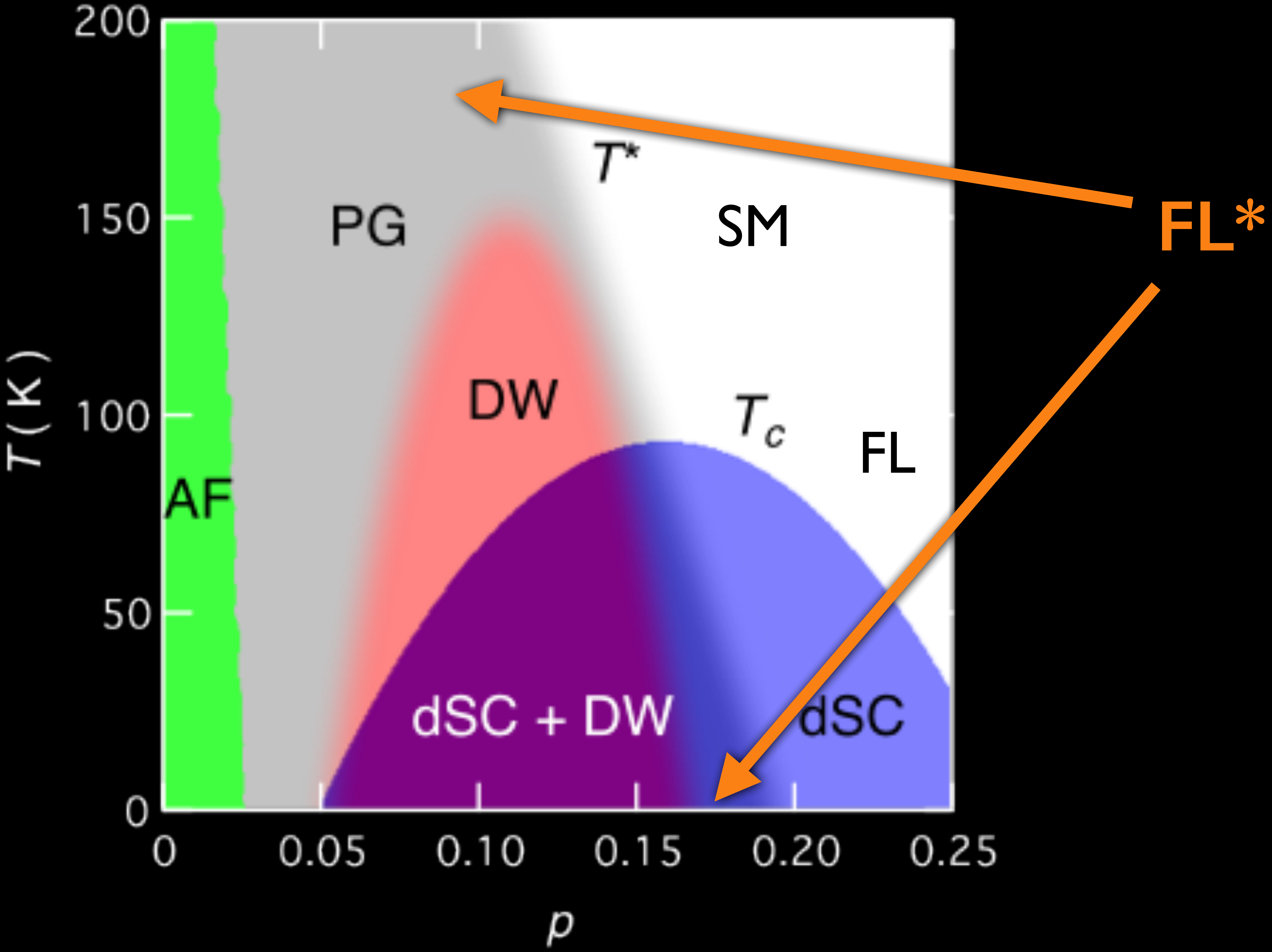


Density wave (DW) order at low T and p

M. A. Metlitski and S. Sachdev, PRB **82**, 075128 (2010). S. Sachdev R. La Placa, PRL **111**, 027202 (2013). K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

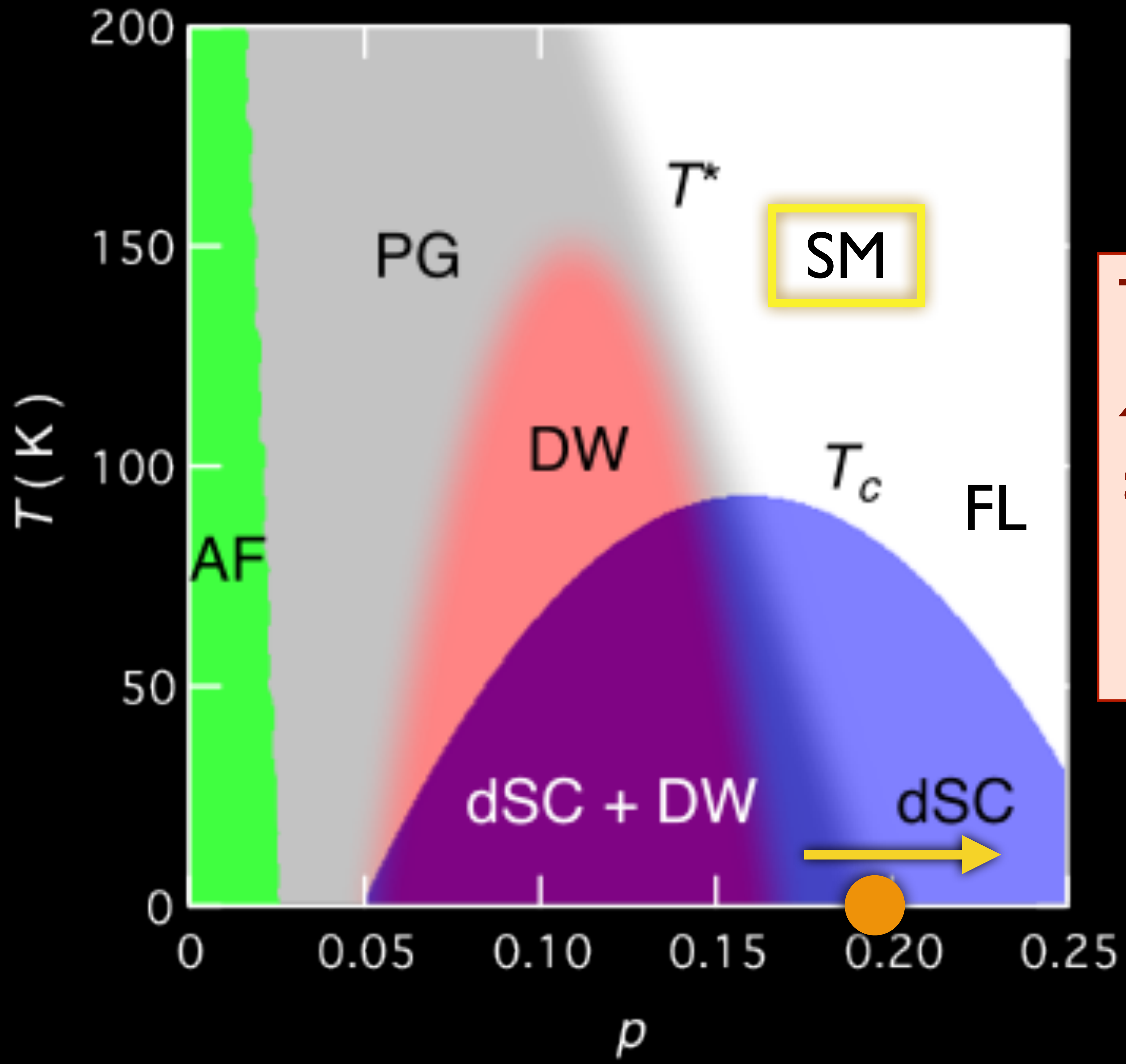


Identified as a “*d*-form factor density wave”, an instability of the PG described as FL*: a metal with small Fermi surfaces and emergent gauge fields.



200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
0.25
p
AF
PG
T^*
SM
DW
T_c
FL
dSC + DW
dSC

FL*



Transition from Z_2-FL* to FL as a theory of the strange metal (SM)

Quantum critical point at optimal doping

- Transition is primarily "topological". Main change is in the size of the Fermi surface.

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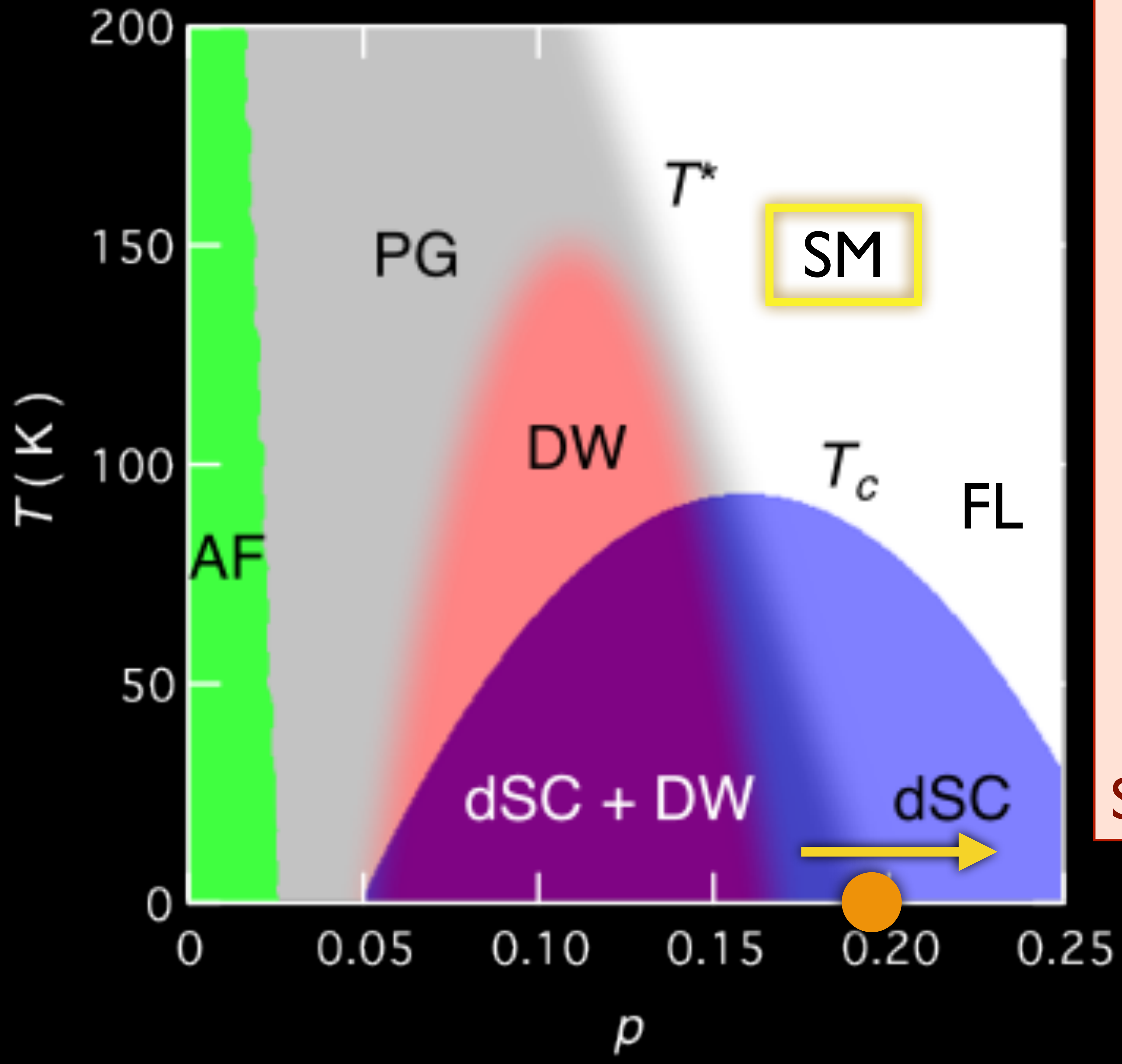
- The main symmetry breaking which appears co-incident with the transition is Ising-nematic ordering. But this symmetry cannot change the size of the Fermi surface; similar comments apply to time-reversal symmetry.
- Need a gauge theory for transition from "topological" to "confined" state.



Proposed a SU(2) gauge theory for transtion from Z_2-FL* to FL. This phase transition is beyond the Landau-Ginzburg-Wilson paradigm, and is instead a Higgs-confinement transition in a SU(2) gauge theory

Entangled quantum matter without quasiparticles

- No quasiparticle excitations

Entangled quantum matter without quasiparticles

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- Shortest possible “phase coherence” time, fastest possible local equilibration time, or fastest possible “scrambling” towards quantum chaos, all of order $\dfrac{\hbar}{k_B T}$

Entangled quantum matter without quasiparticles

- No quasiparticle excitations

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