Quantum matter without quasiparticles: graphene

ARO-AFOSR MURI Program Review
Chicago, September 26-28, 2016

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PHYSICS

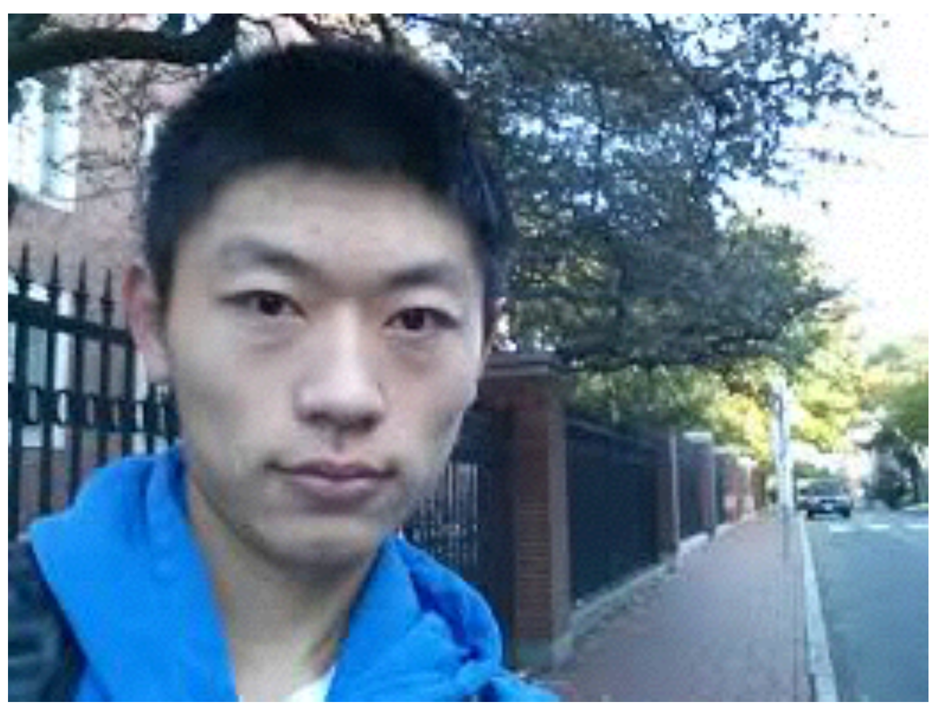
Army Research Office

Talk online: sachdev.physics.harvard.edu

HARVARD

William Witczak-Krempa
now at University of Montreal

Andrew Lucas
now at Stanford



Wenbo Fu, Harvard

Quantum matter without quasiparticles

- Quasiparticles are long-lived excitations which can be combined to yield the complete low-energy many-body spectrum

- Quasiparticles need not be electrons: they can be emergent excitations which involve non-local changes in the wave function of the underlying electrons *e.g.* Laughlin quasiparticles, visons . . .

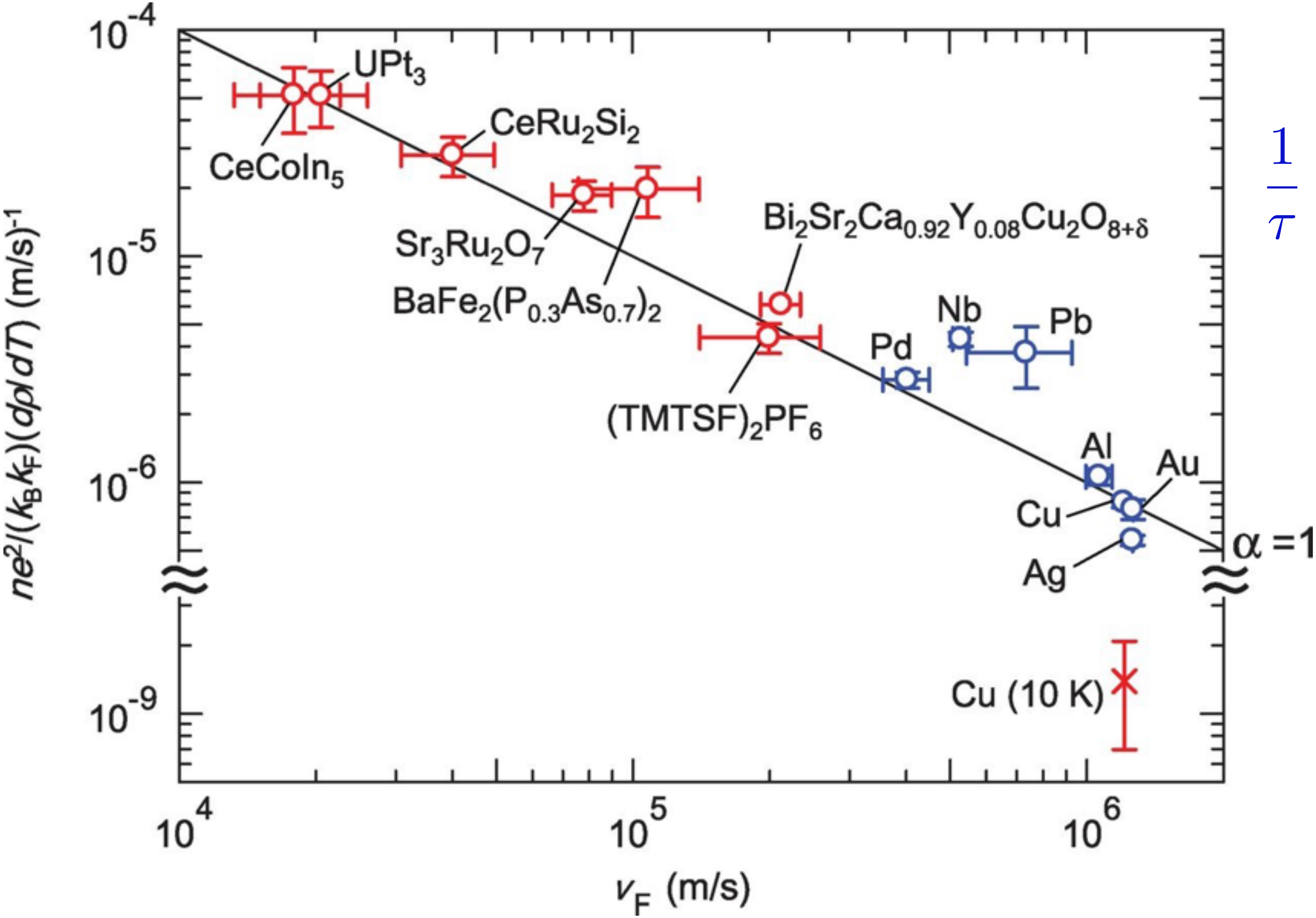
- How do we rule out quasiparticle excitations? Examine the time it takes to reach local thermal equilibrium. Equilibration takes a long time while quasiparticles collide (in Fermi liquids, $\tau \sim 1/T^2$; in gapped systems, $\tau \sim e^{\Delta/T}$). Systems *without* quasiparticles saturate a (conjectured) lower bound on the local-equilibration/de-phasing/ transition-to-quantum-chaos time

$$\tau_\varphi \quad \geq \quad C \frac{\hbar}{k_B T}$$

where C is a T-independent constant.

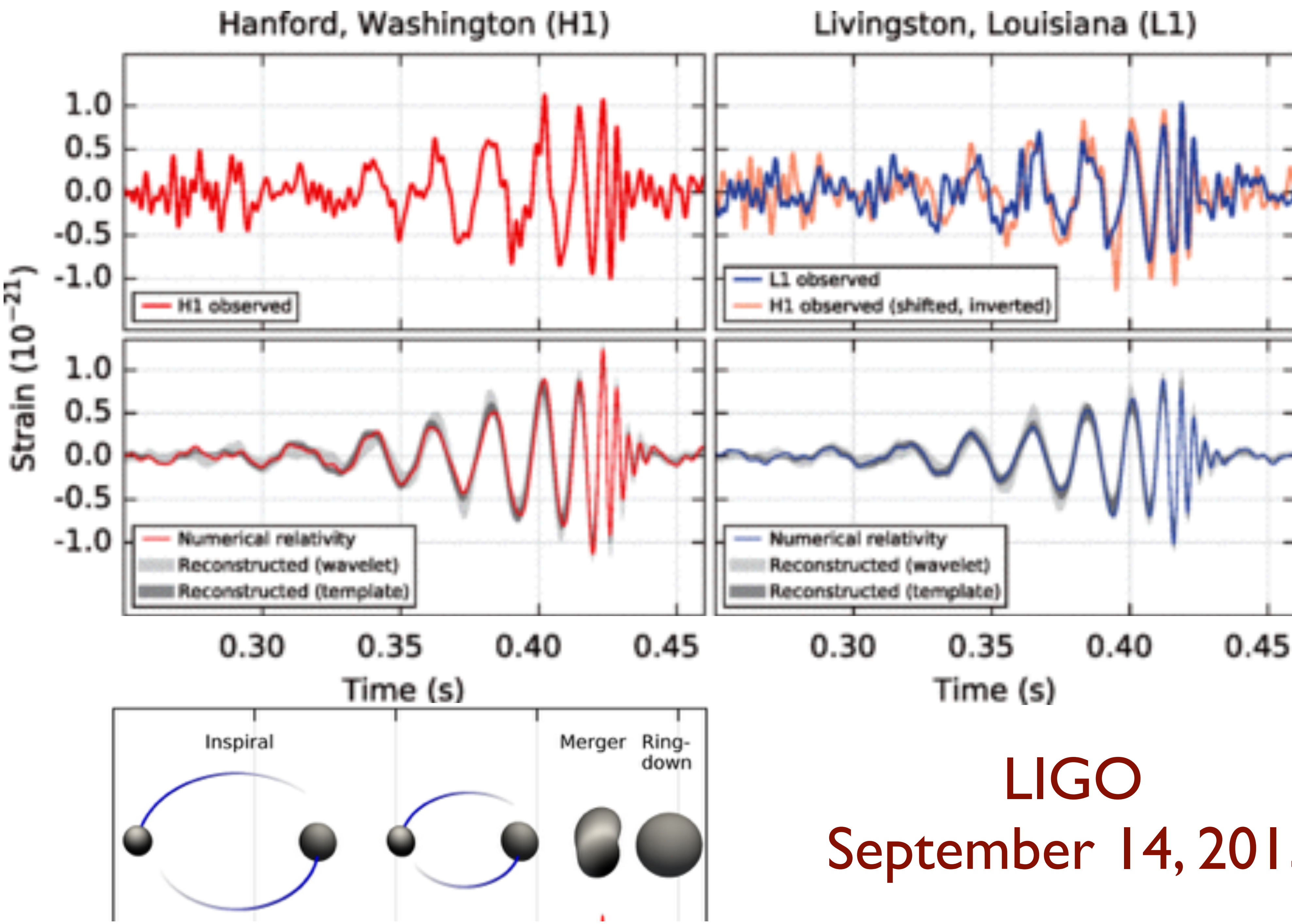
S. Sachdev, *Quantum Phase Transitions* (1999)
K. Damle and Sachdev, PRB **56**, 8714 (1997)

Strange metals



$$\frac{1}{\tau} = \alpha \frac{k_B T}{\hbar}$$

J. A. N. Bruin, H. Sakai, R. S. Perry, A. P. Mackenzie, *Science*. **339,** 804 (2013)



LIGO
September 14, 2015

- "Ring-down" time for black holes, $\tau_r = \hbar/(k_B T_H)$, where T_H is the Hawking temperature.

- For this black hole $T_H \approx 1$ nK, $\tau_r = 7.7$ milliseconds. (Radius of black hole = 183 km; Mass of black hole = 62 solar masses.)

Quantum matter without quasiparticles:

- Superfluid-insulator transition of ultracold bosonic atoms in an optical lattice

William Witczak-Krempa
Andrew Lucas

- Sachdev-Ye-Kitaev (SYK) model of a strange metal *and* a black hole in AdS_2

Wenbo Fu

- Graphene (and Weyl metals)

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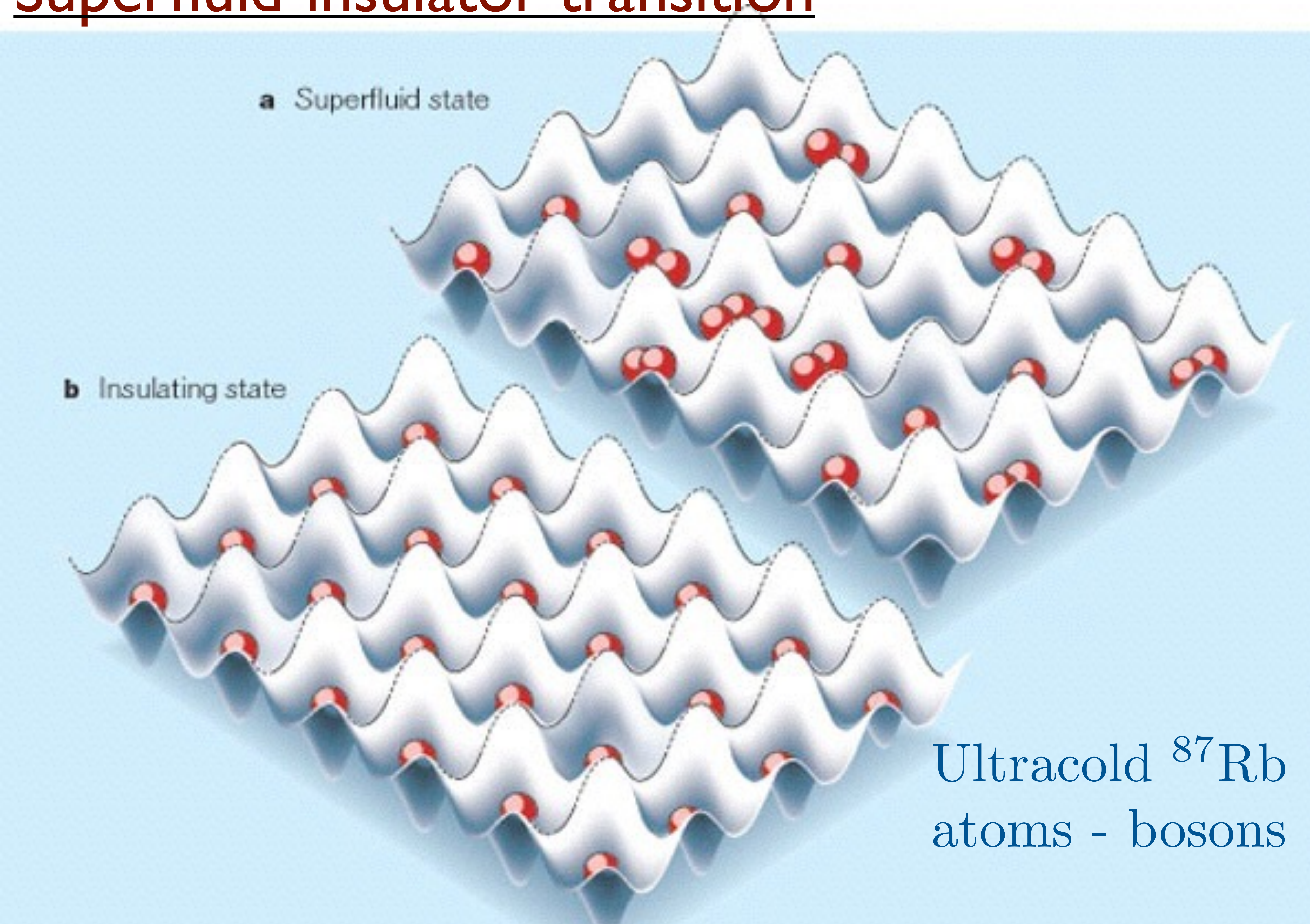
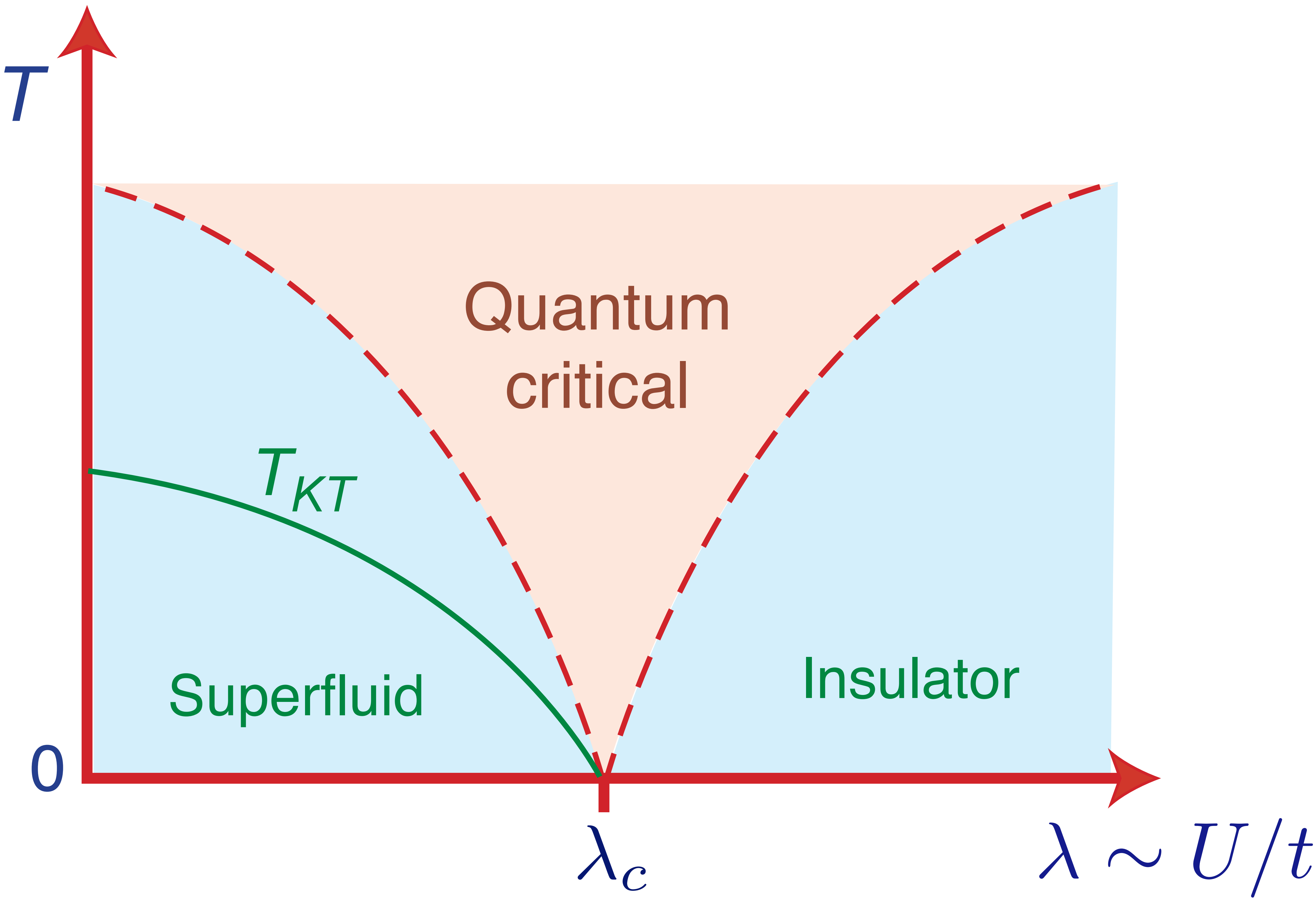
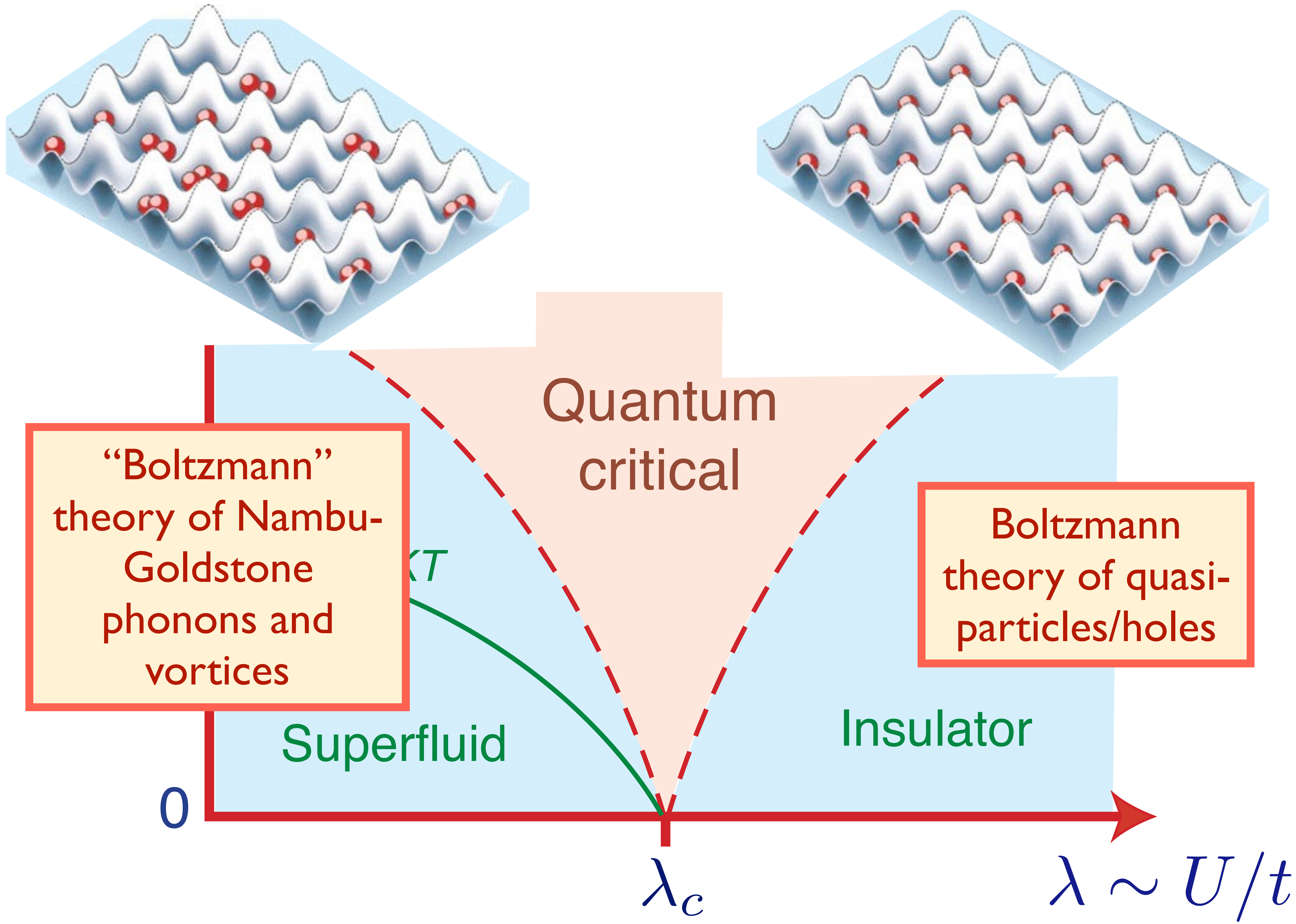
Superfluid-insulator transition



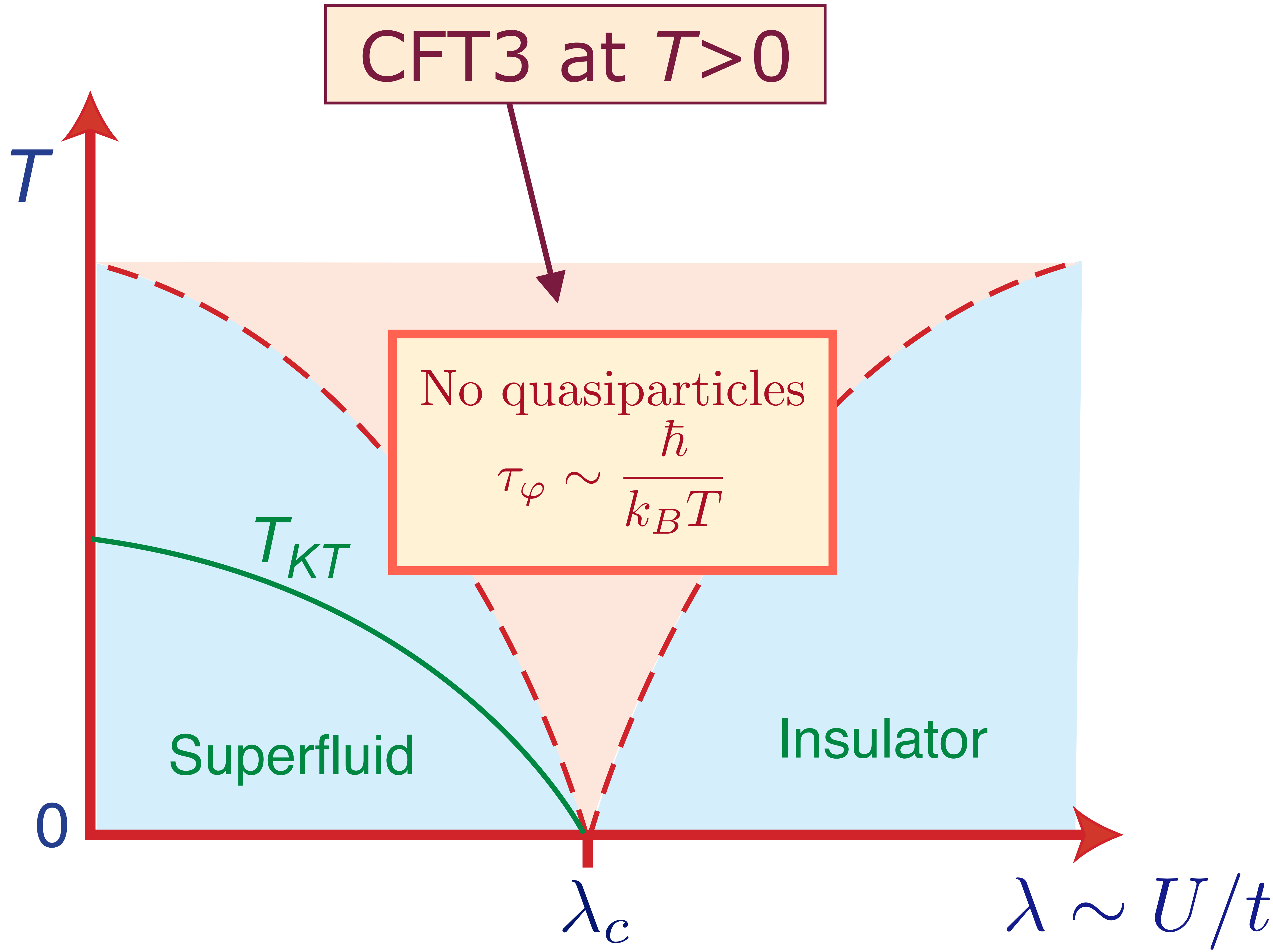
Ultracold ^{87}Rb atoms - bosons

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)


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



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



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)

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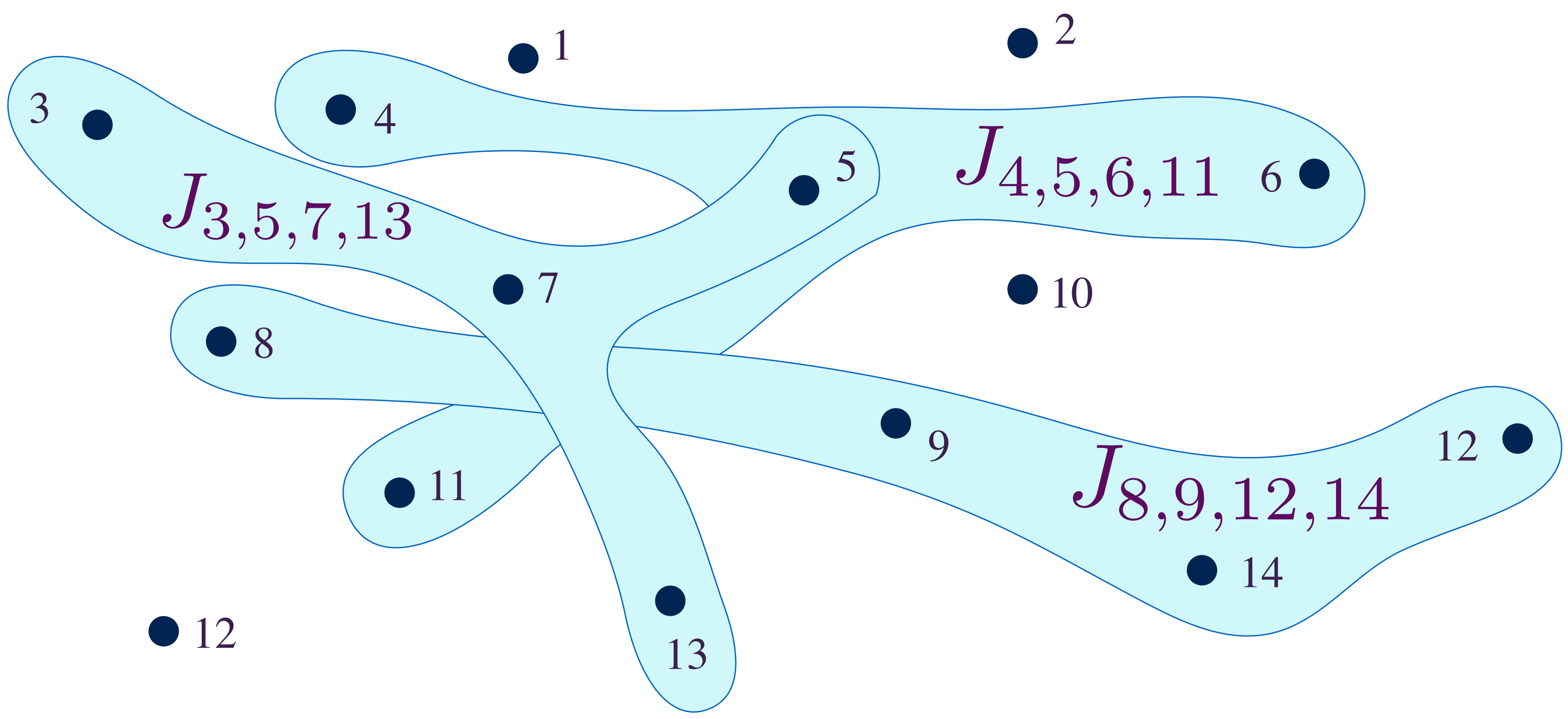
SYK model

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

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



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

Cold atom realization:
I. Danshita, M. Hanada, and M. Tezuka, arXiv:1606.02454

S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)
A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)

SYK model

- $T = 0$ Green's function $G \sim 1/\sqrt{\tau}$

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

- $T > 0$ Green's function implies conformal invariance $G \sim 1/(\sin(\pi T \tau))^{1/2}$

A. Georges and O. Parcollet PRB **59**, 5341 (1999)

- Non-zero entropy as $T \to 0$, $S(T \to 0) = NS_0 + \ldots$

A. Georges, O. Parcollet, and S. Sachdev, PRB **63**, 134406 (2001)

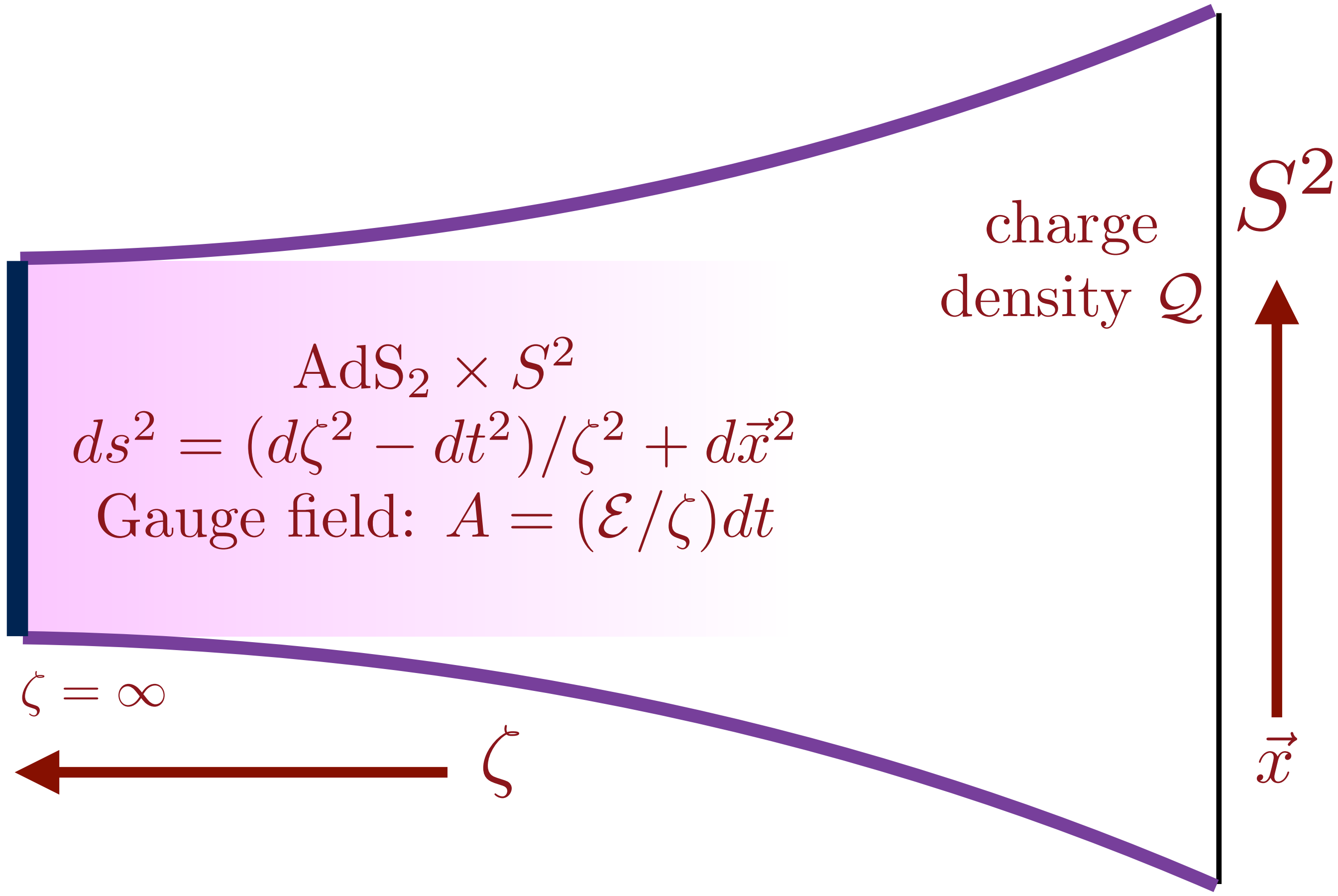
- These features indicate that the SYK model is dual to the low energy limit of a quantum gravity theory of black holes with AdS_2 near-horizon geometry. The Bekenstein-Hawking entropy is NS_0.

S. Sachdev, PRL **105**, 151602 (2010)

- Striking additional evidence for this duality in fermion bilinear correlations, which maps to the low energy dynamics of a graviton+dilaton in AdS_2. Both SYK and AdS_2 saturate the lower bound on the Lyapunov time to quantum chaos $= \hbar/(2\pi k_B T)$

A. Kitaev, unpublished; A. Almheiri and J. Polchinski, JHEP **1511** (2015) 014; J. Polchinski and V. Rosenhaus, arXiv: 1601.06768; J. Maldacena and D. Stanford, arXiv:1604.07818; K. Jensen, arXiv:1605.06098; J. Engelsoy, T.G. Mertens, and H. Verlinde, arXiv:1606.03438; A. Almheiri and B. Kang, arXiv: 1606.04108; A. Jevicki, K. Suzuki, and J. Yoon, arXiv:1603.06246; A. Jevicki and K. Suzuki, arXiv:1608.7567

SYK and AdS_2



PHYSICAL REVIEW LETTERS 105, 151602 (2010)

Holographic Metals and the Fractionalized Fermi Liquid

Subir Sachdev

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 23 June 2010; published 4 October 2010)

We show that there is a close correspondence between the physical properties of holographic metals near charged black holes in anti–de Sitter (AdS) space, and the fractionalized Fermi liquid phase of the lattice Anderson model. The latter phase has a "small" Fermi surface of conduction electrons, along with a spin liquid of local moments. This correspondence implies that certain mean-field gapless spin liquids are states of matter at nonzero density realizing the near-horizon, $AdS_2 \times R^2$ physics of Reissner-Nordström black holes.

In progress:

Non-equilibrium dynamics in the SYK model, black holes, and connections to the superfluid-insulator transition.

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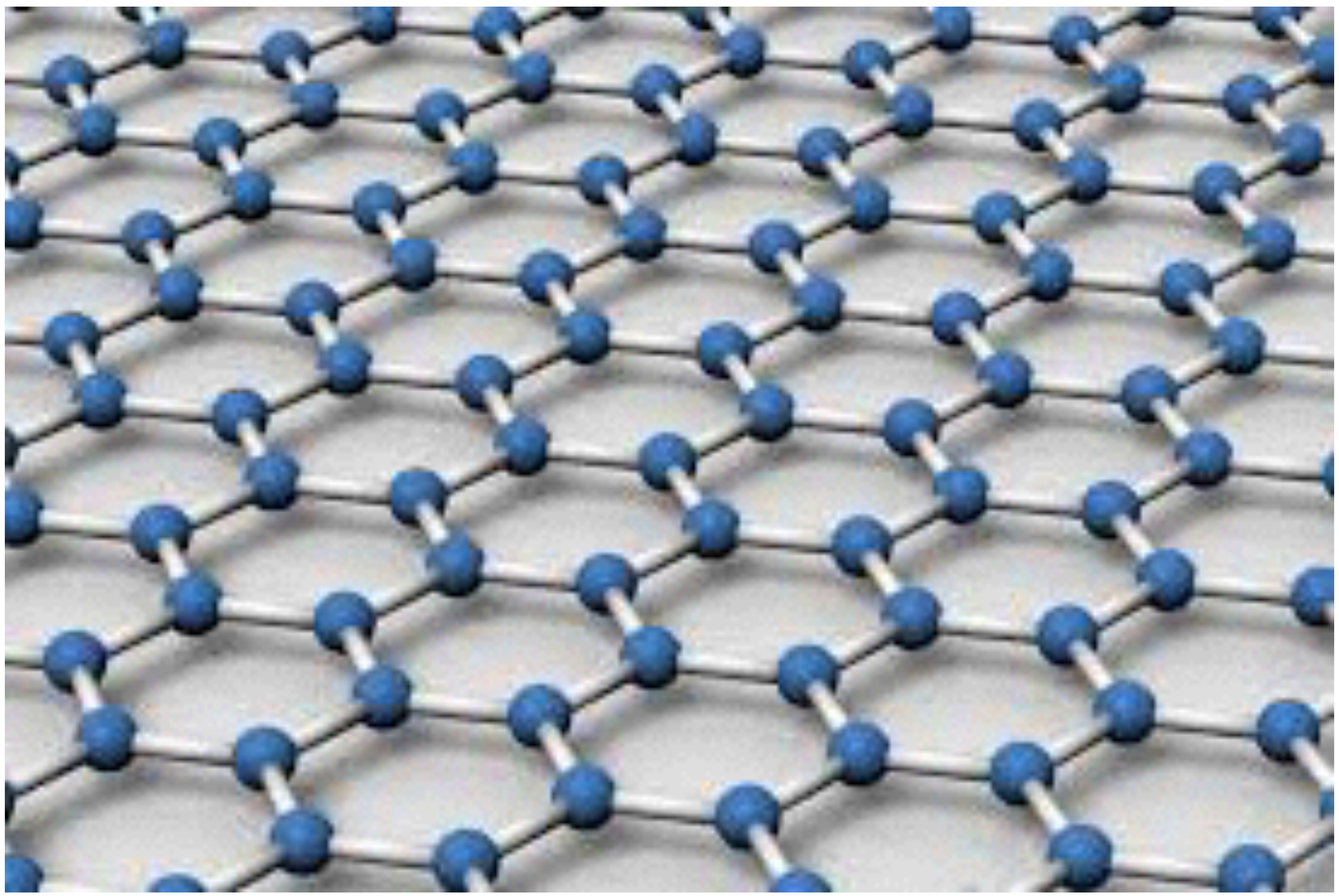
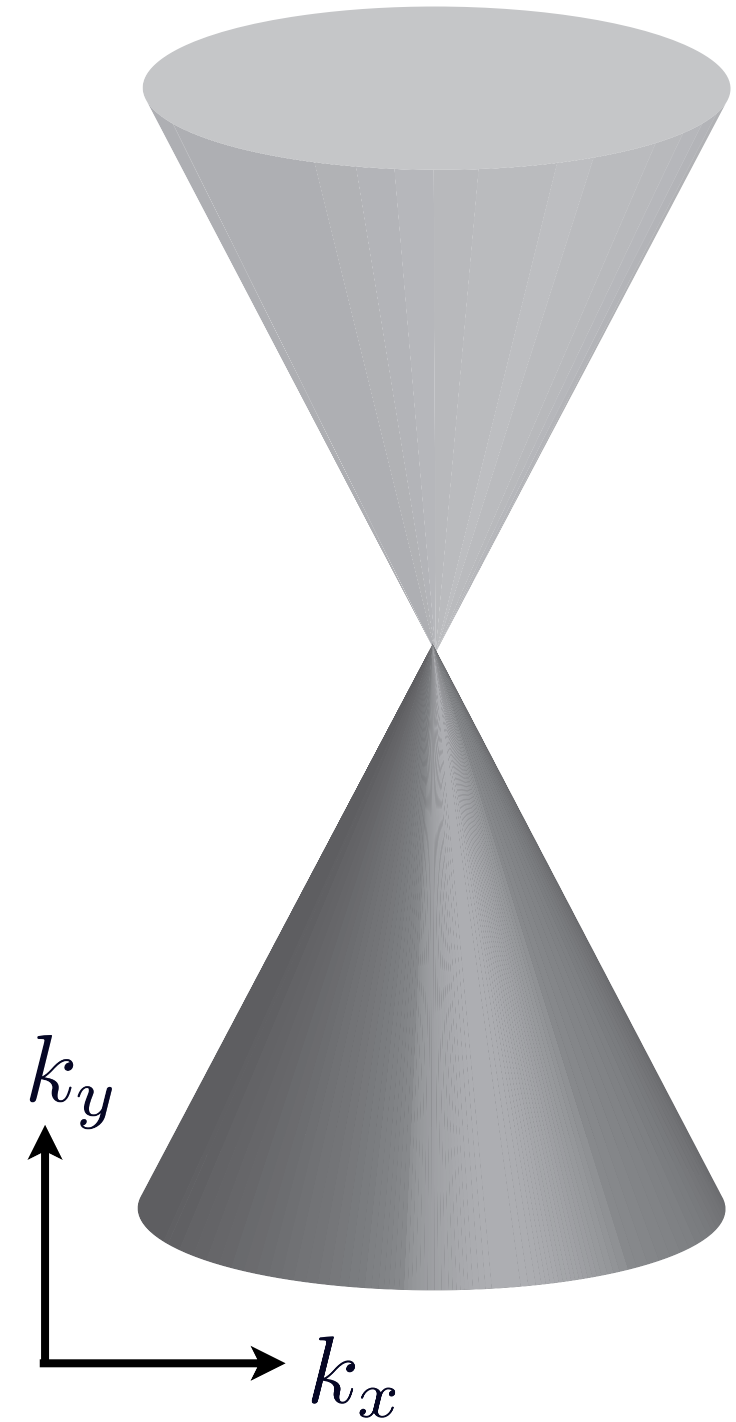
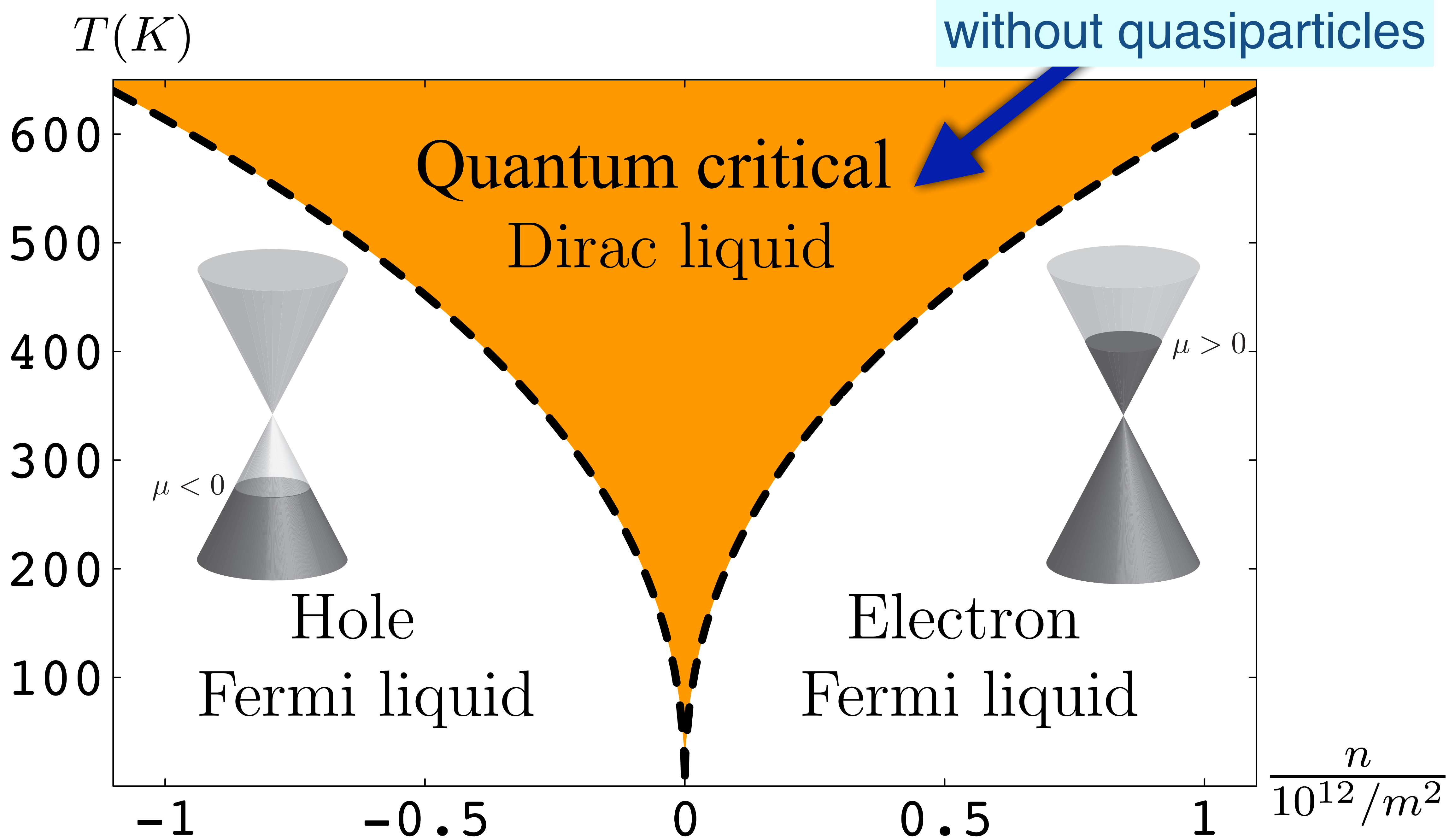
Graphene



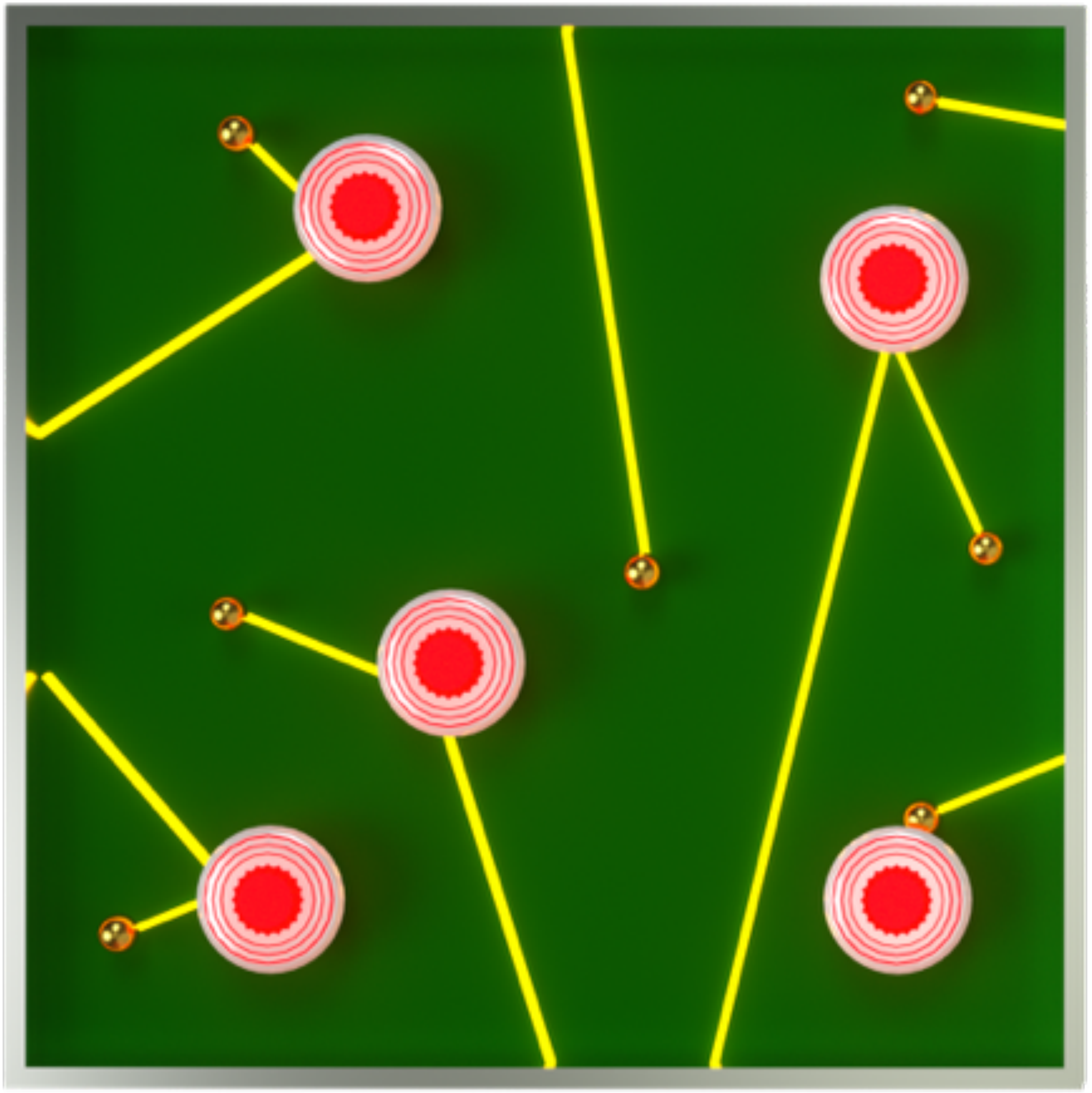


Graphene

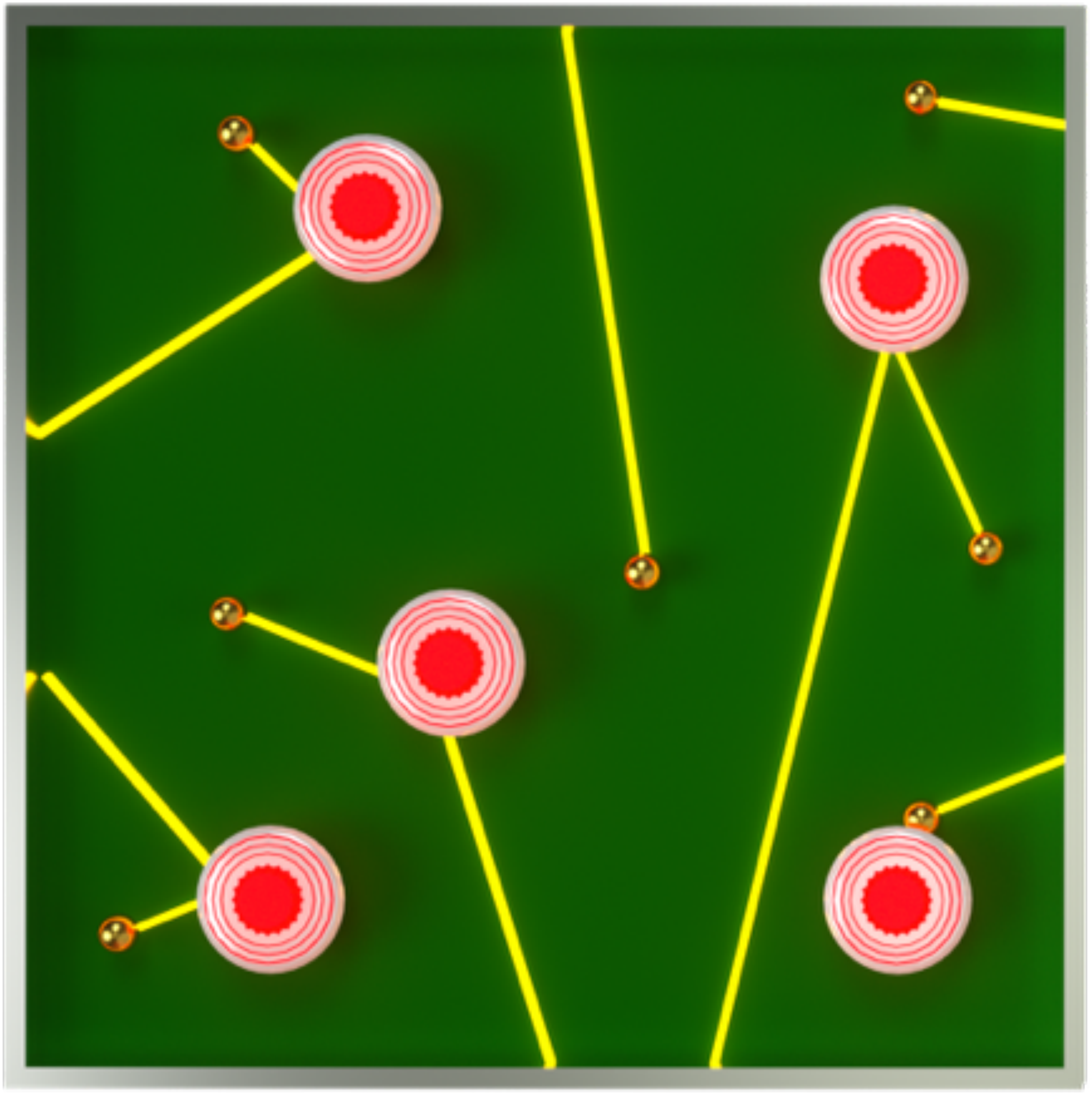
Predicted "strange metal" without quasiparticles



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



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



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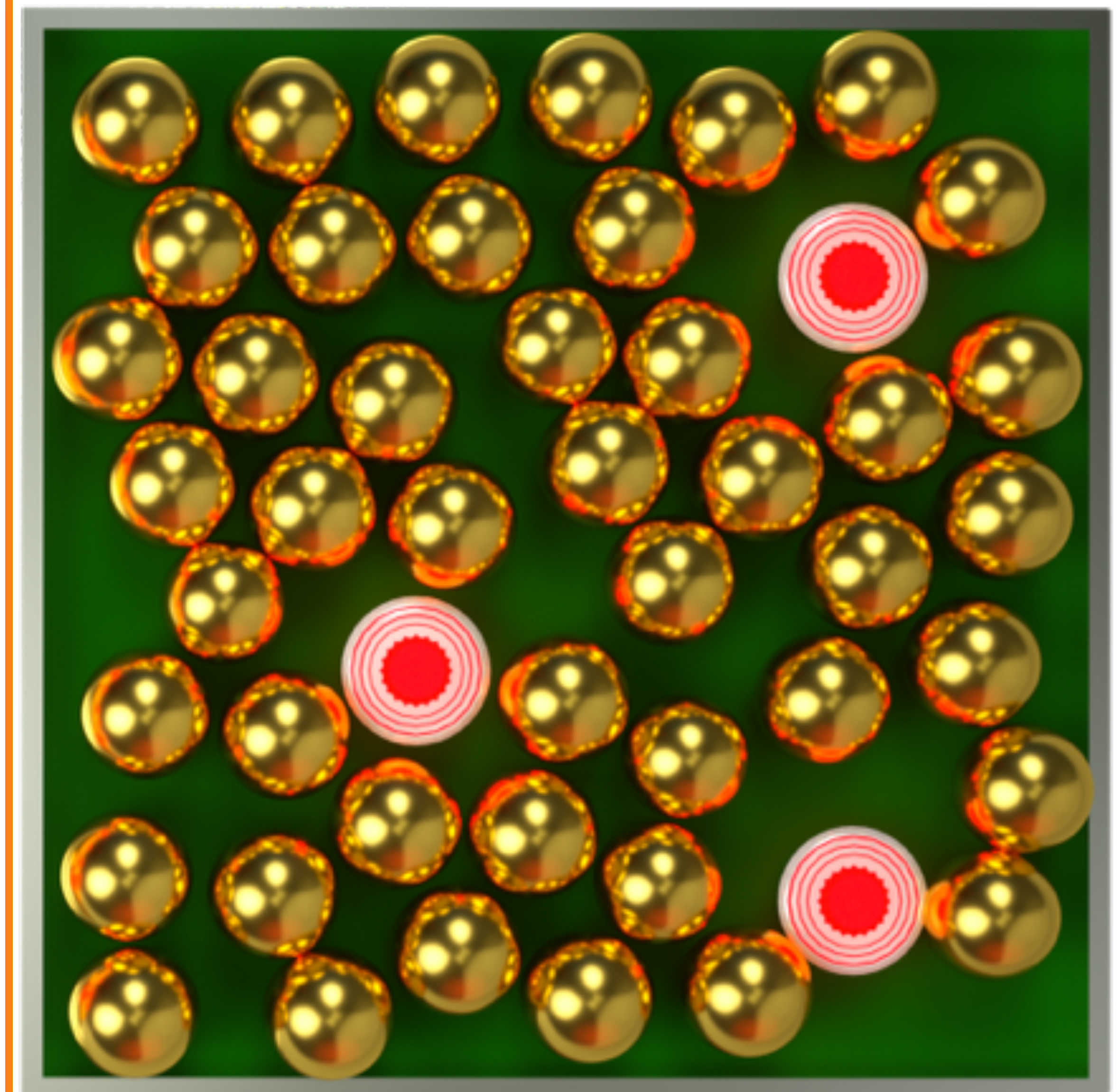
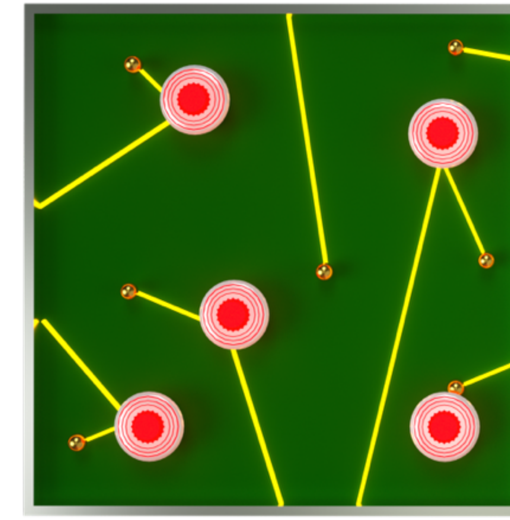


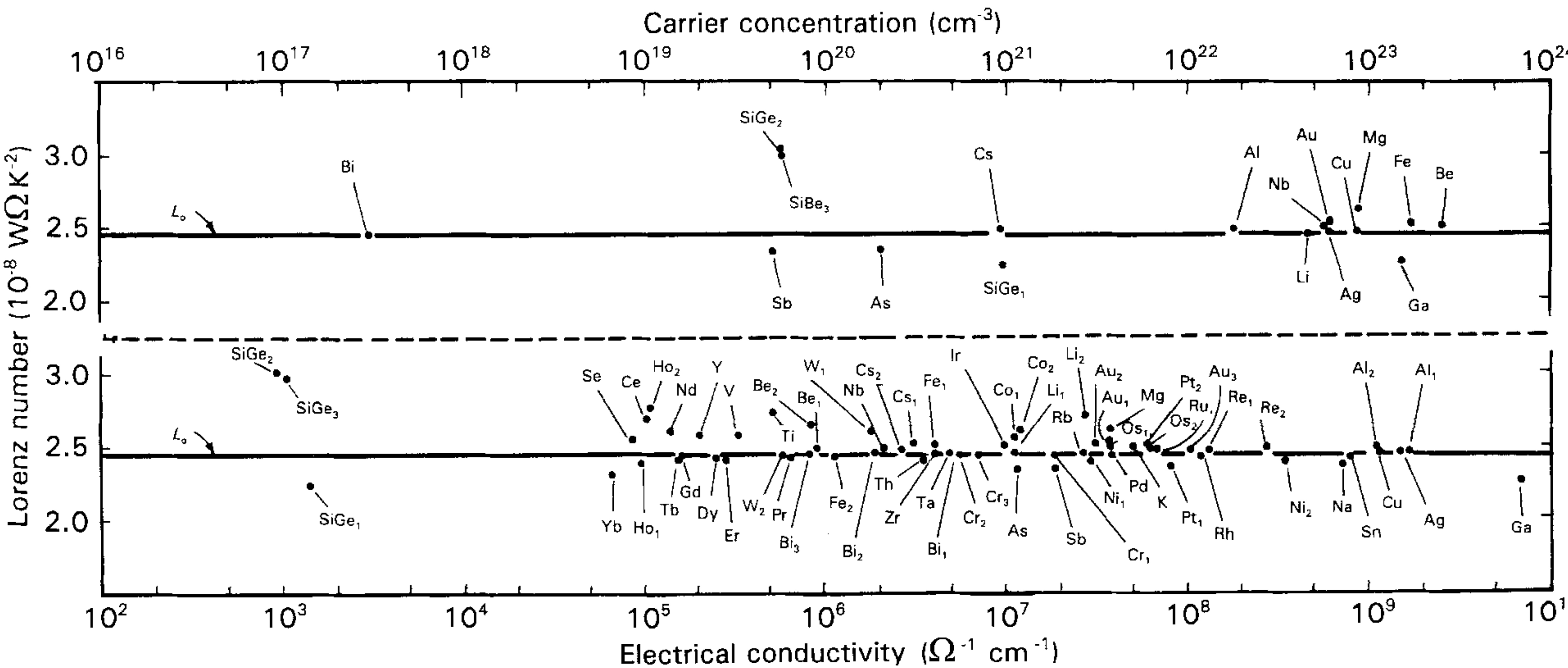
Strange metals: electrons scatter frequently off each other, so there is no regime of ballistic quasiparticle motion. The electron "liquid" then "flows" around impurities

Thermal and electrical conductivity with quasiparticles



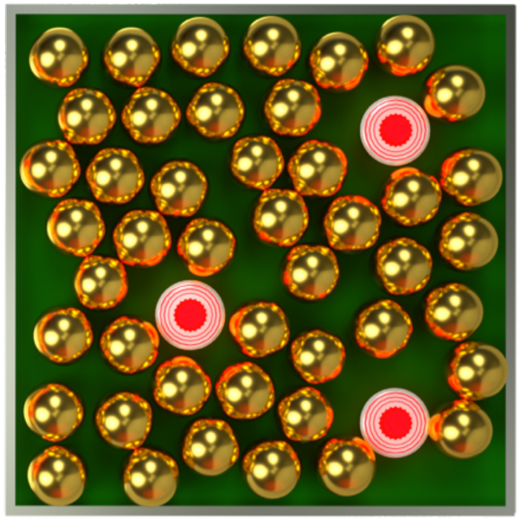
- Wiedemann-Franz law in a Fermi liquid:

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



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

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

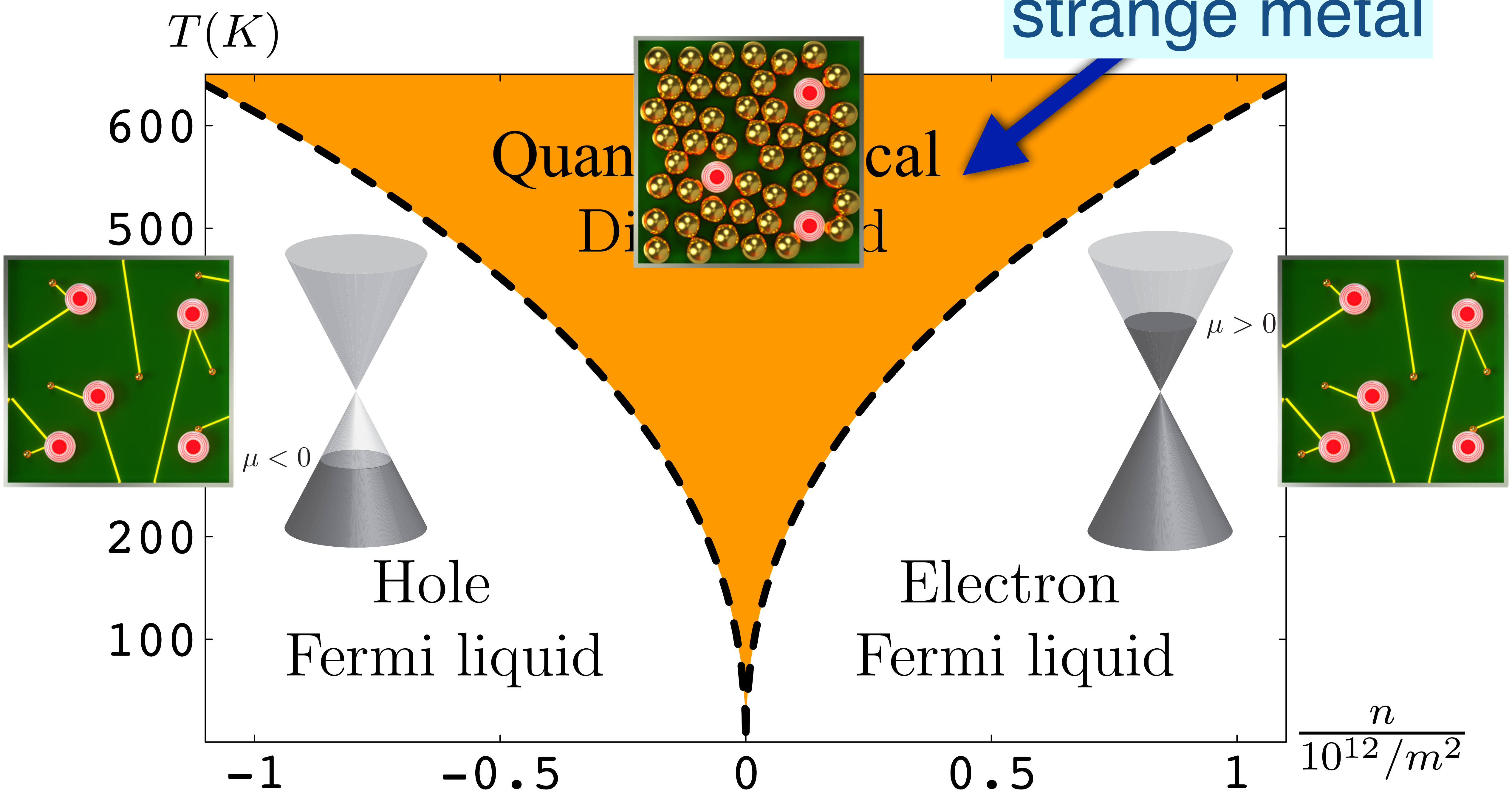
$\mathcal{Q} \rightarrow$ electron density; $\mathcal{H} \rightarrow$ enthalpy density
$\sigma_Q \rightarrow$ quantum critical conductivity
$\tau_{\rm imp} \rightarrow$ momentum relaxation time from impurities.

Note that for a clean system ($\tau_{\rm imp} \rightarrow \infty$ 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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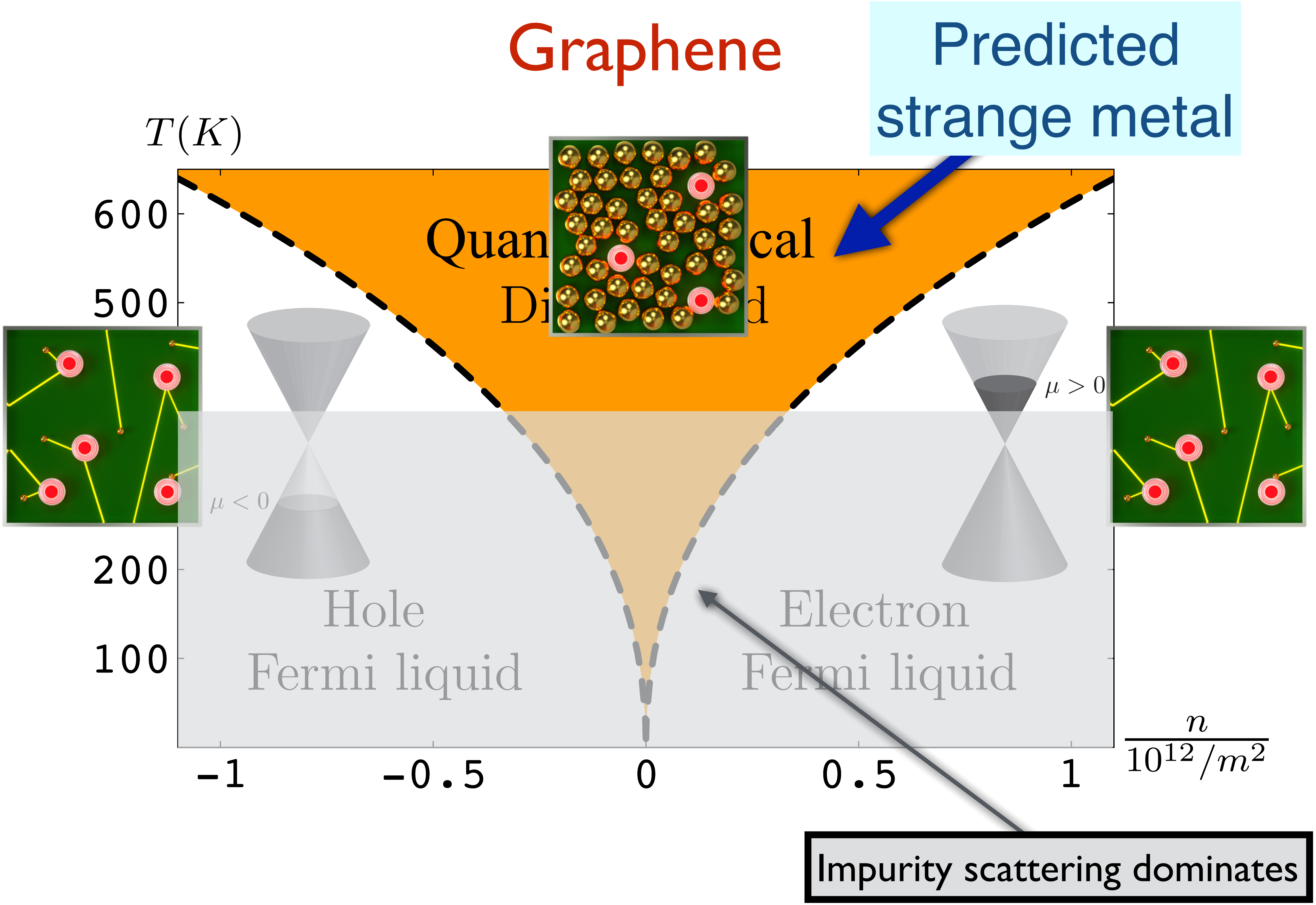

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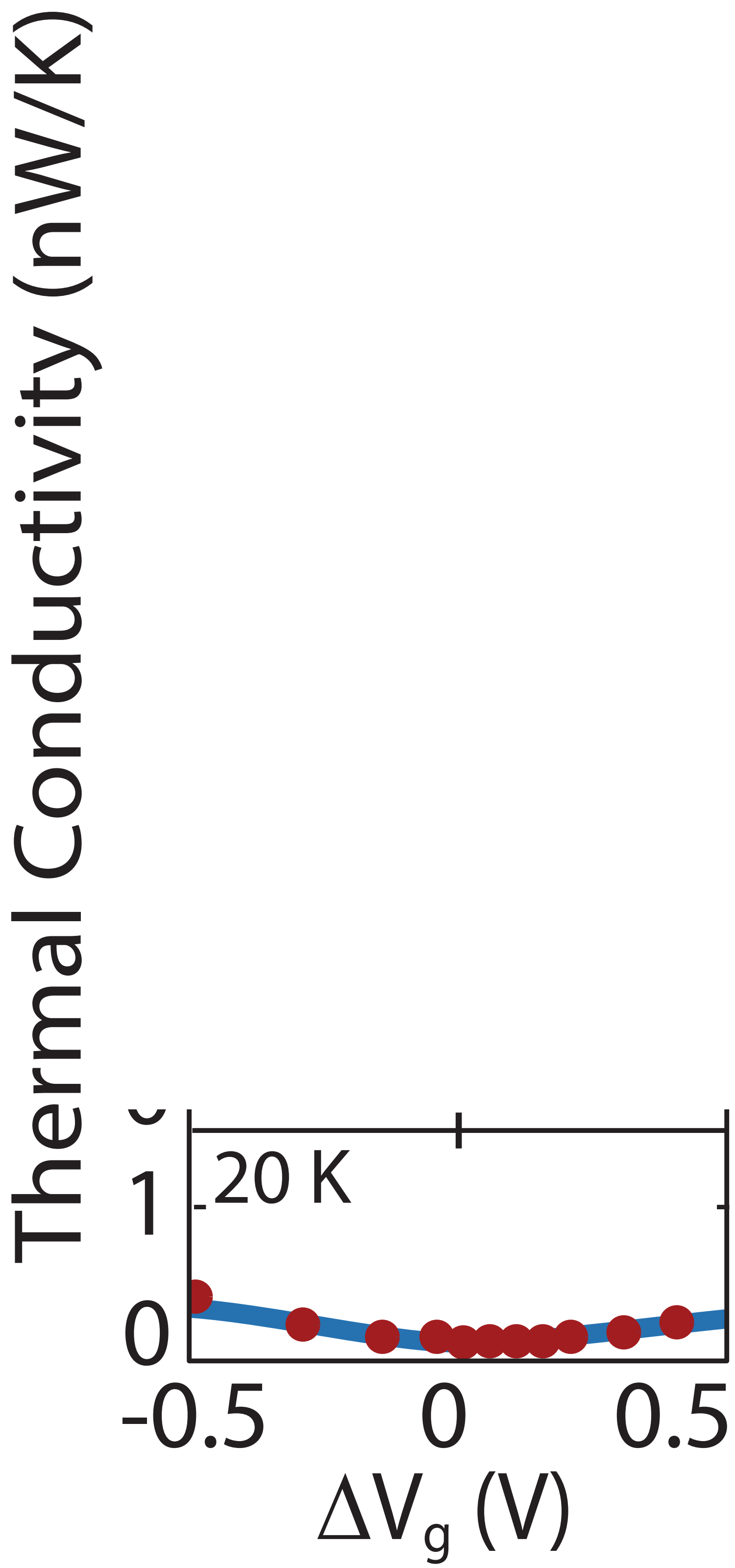
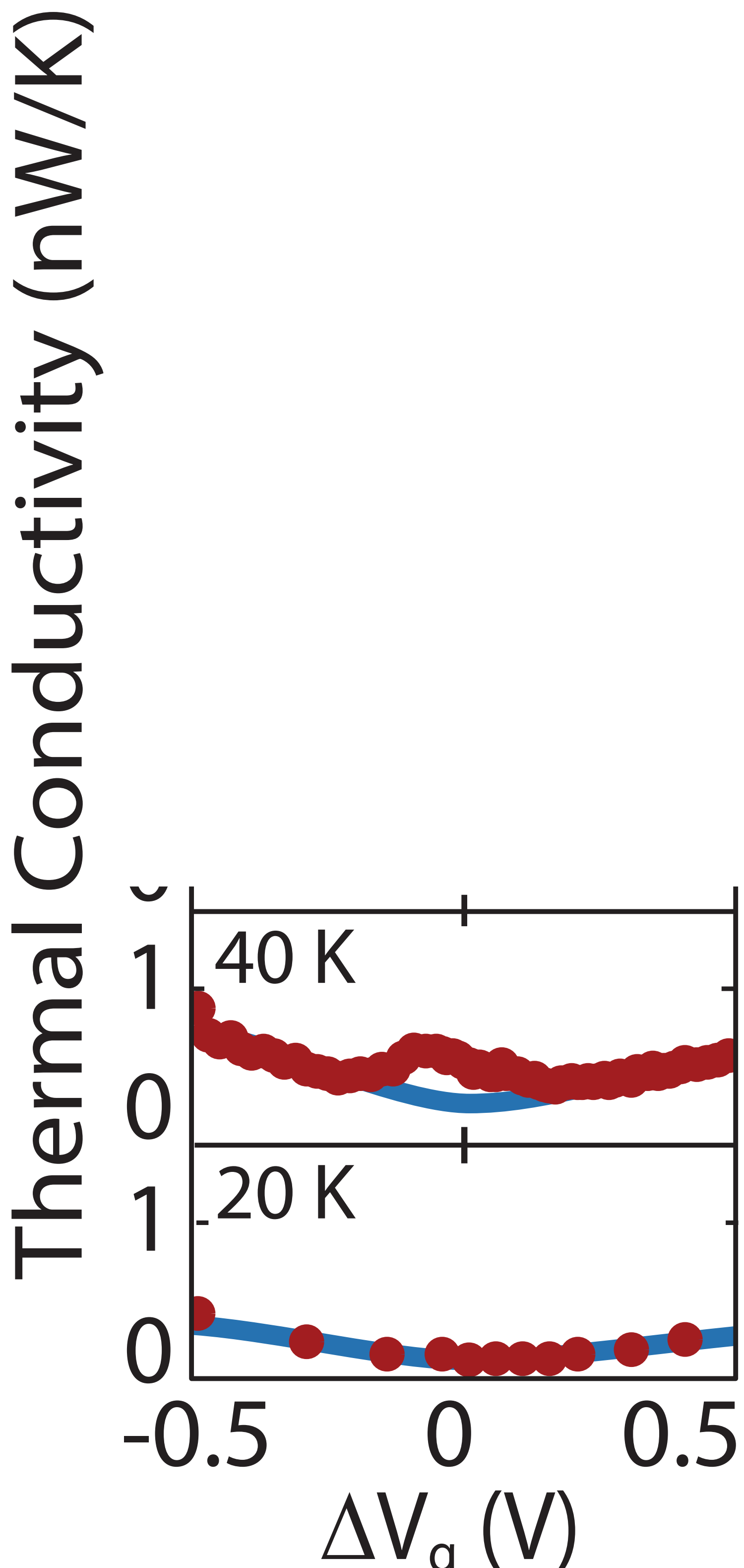
J. Crossno et al., Science **351**, 1058 (2016)



Red dots: data

Blue line: value for $L = L_0$

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



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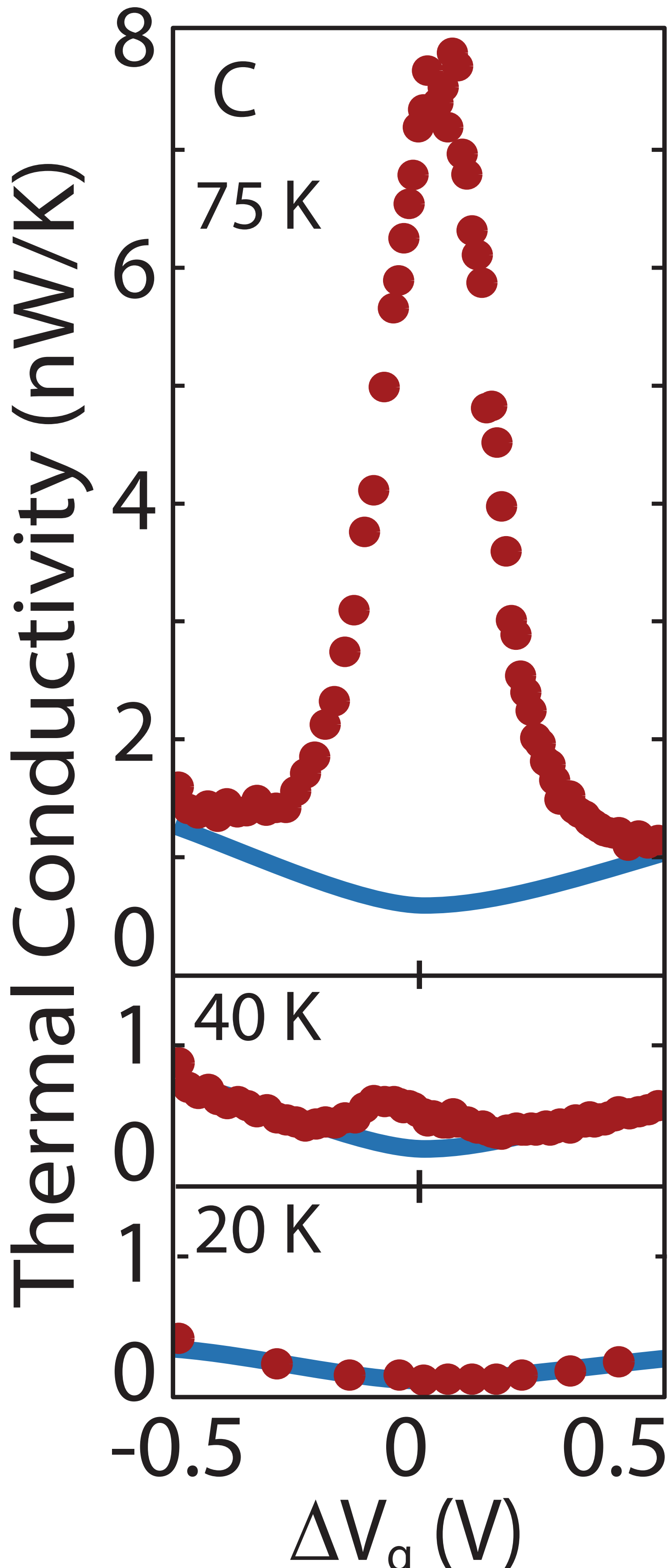
J. Crossno et al., Science **351**, 1058 (2016)



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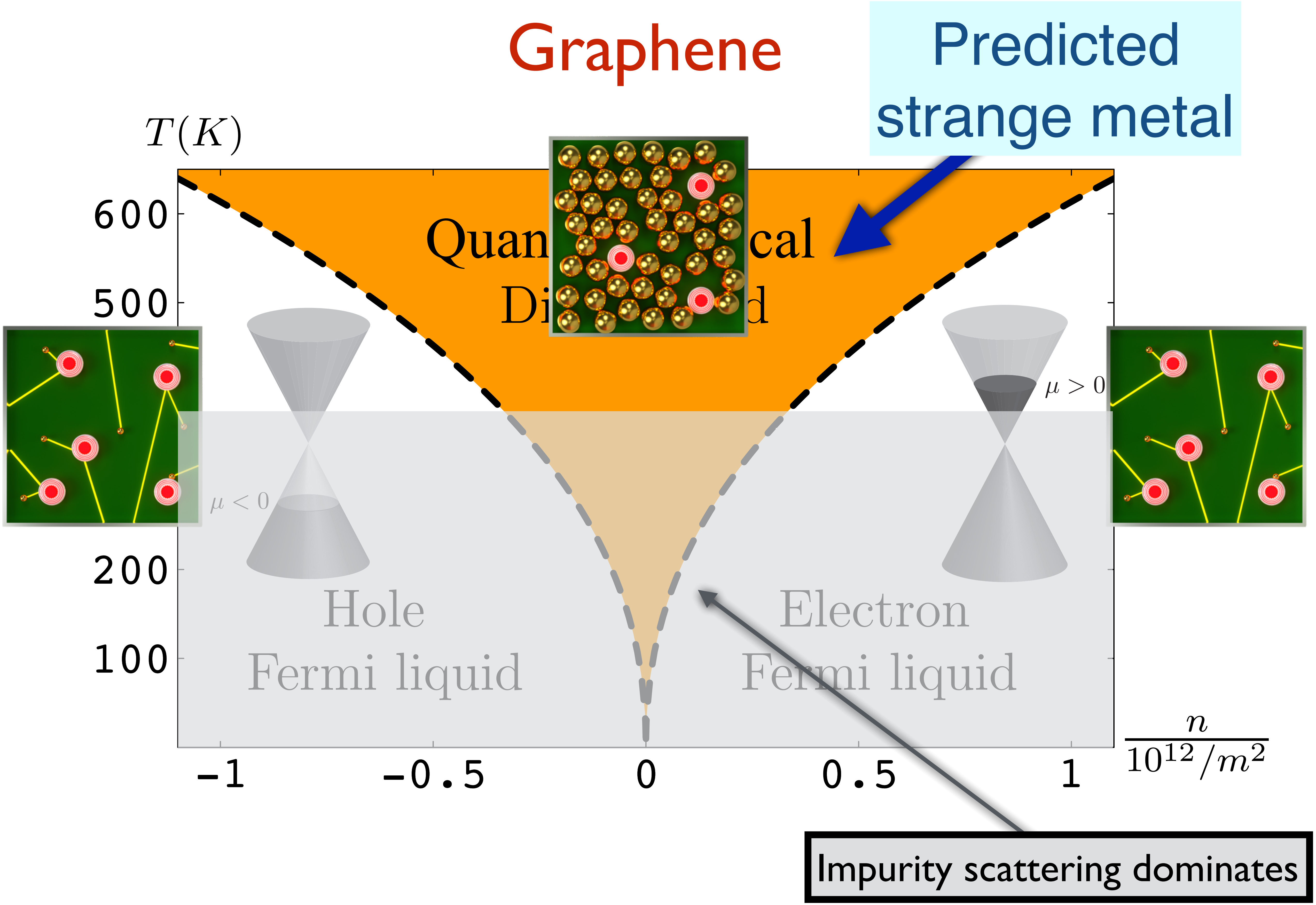

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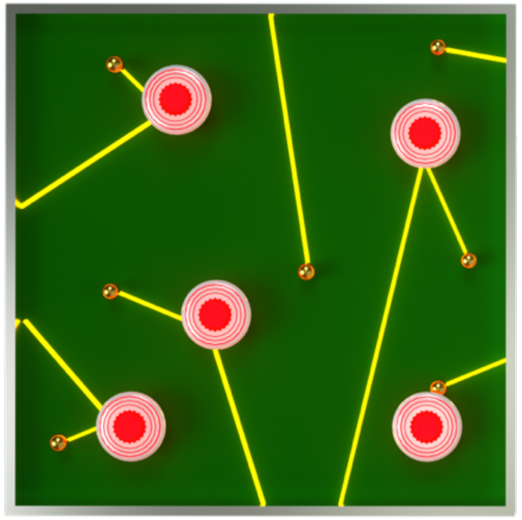
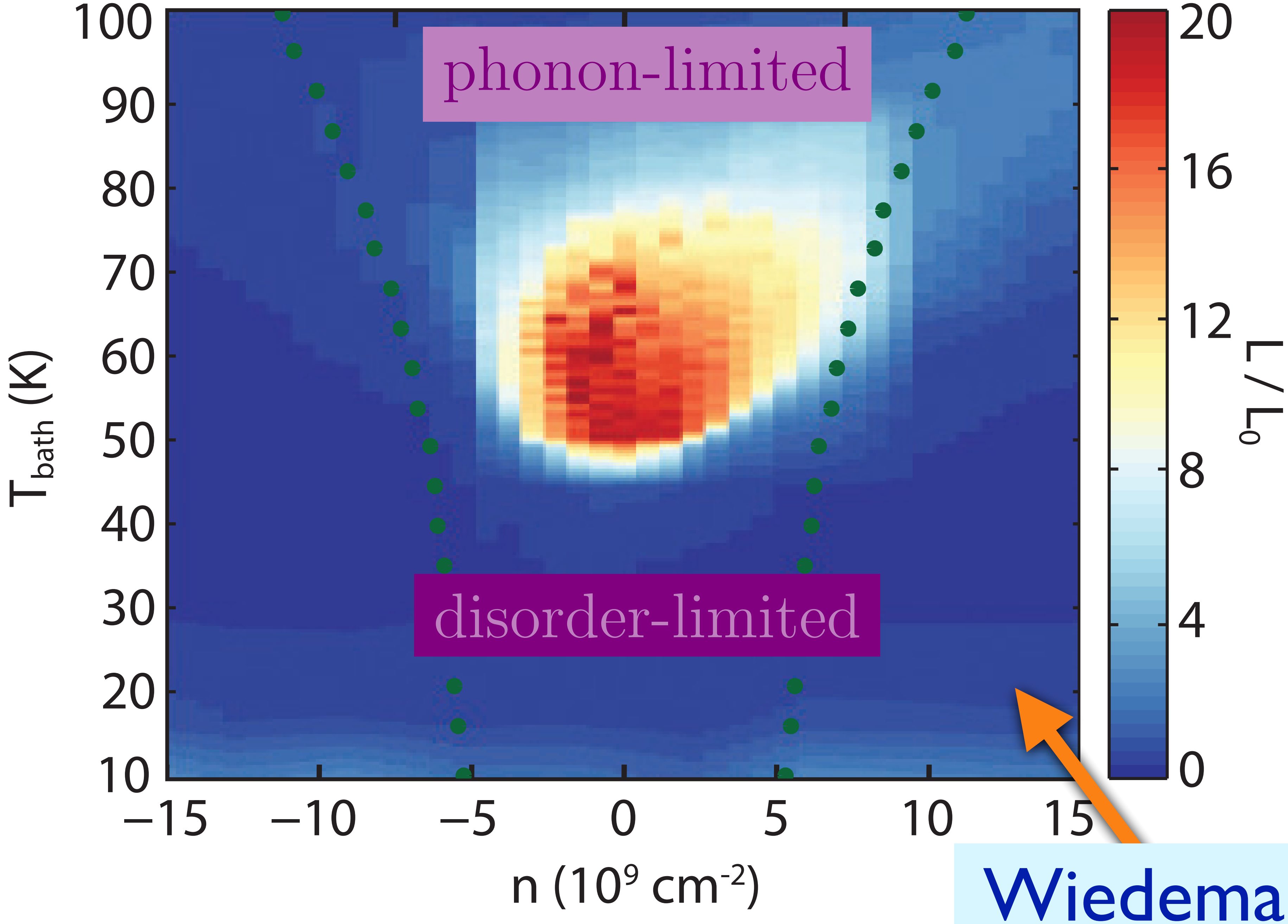
Strange metal in graphene





Wiedemann-Franz obeyed

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

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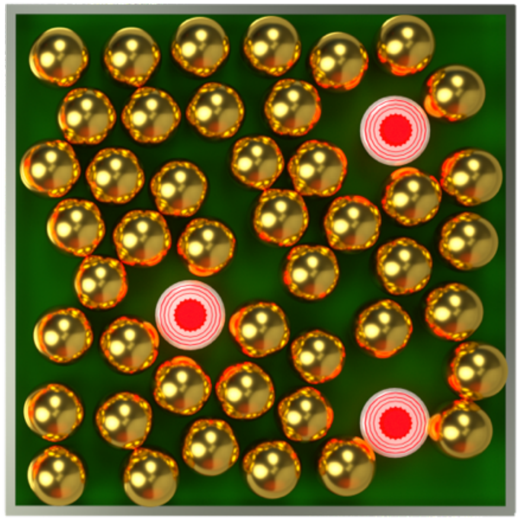
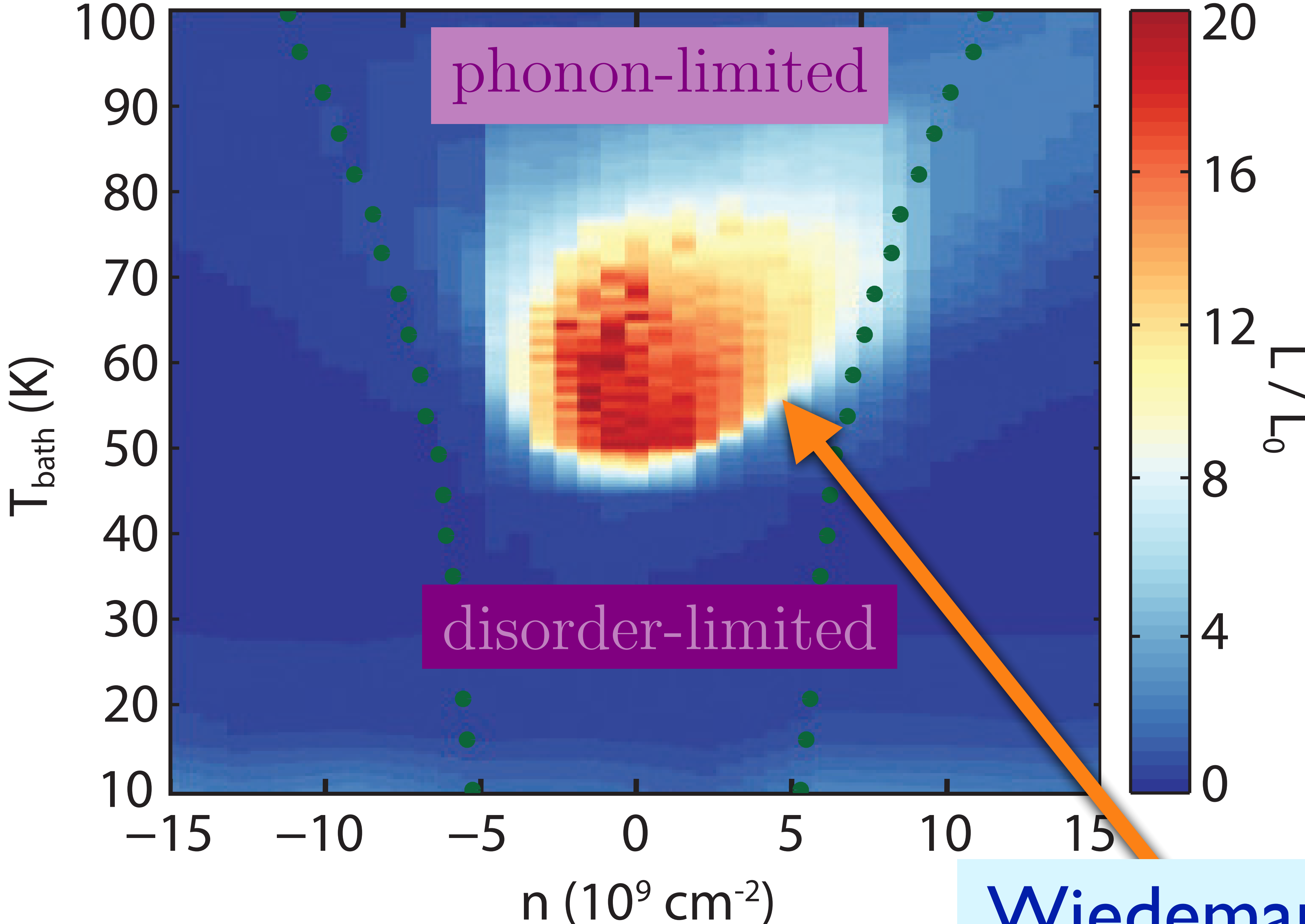
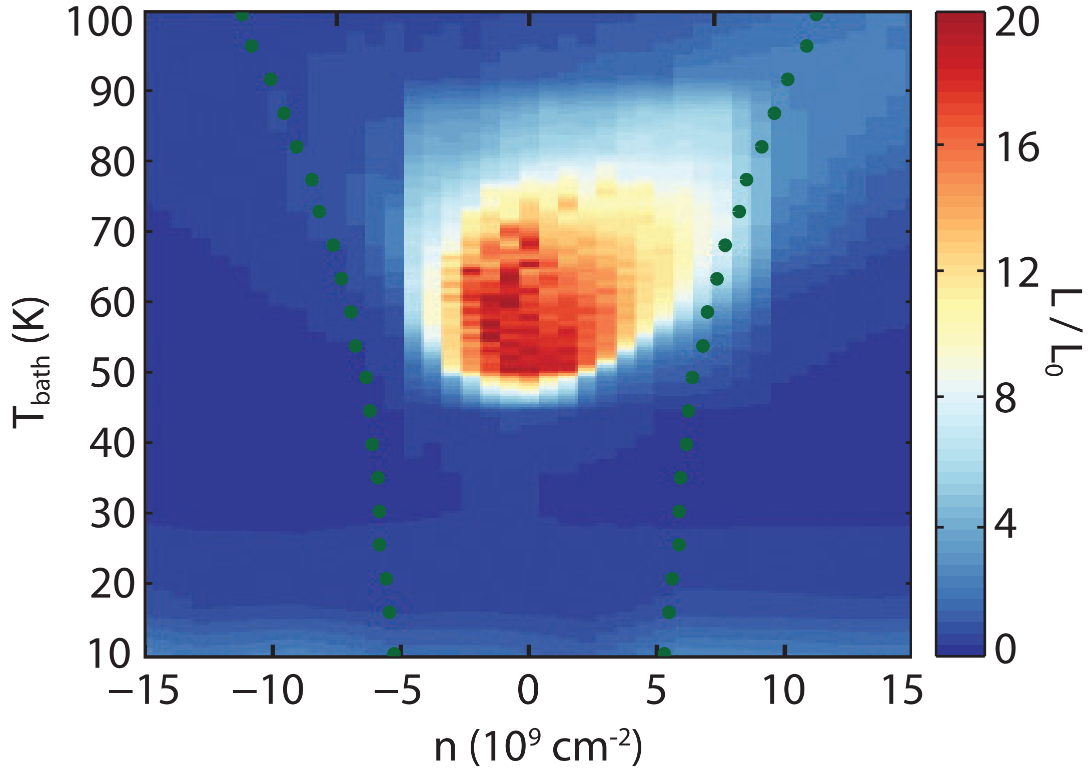
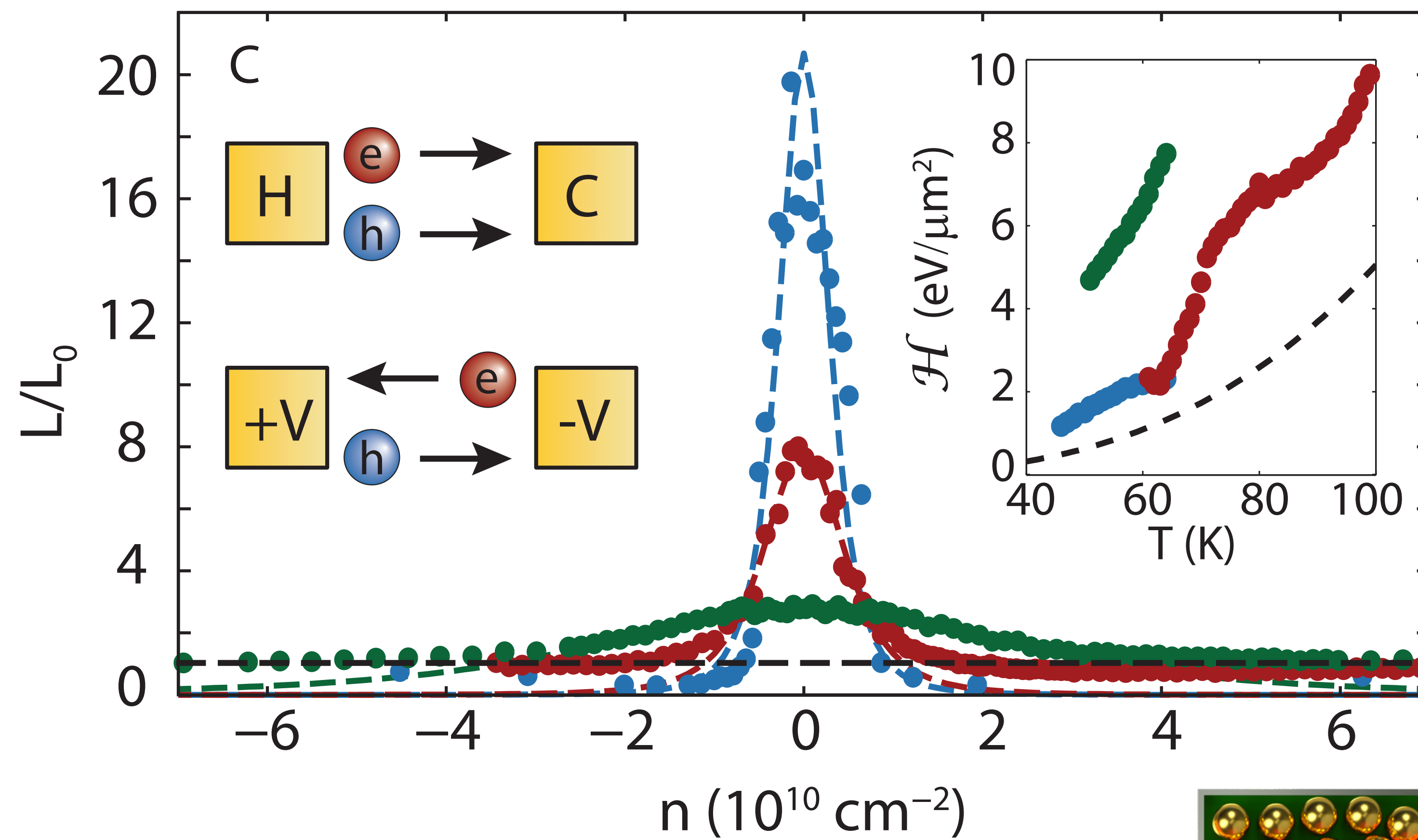
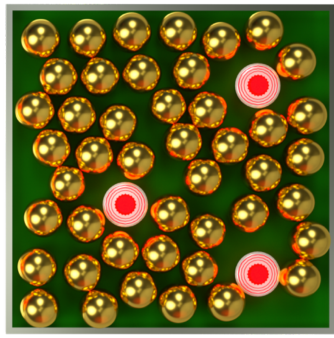


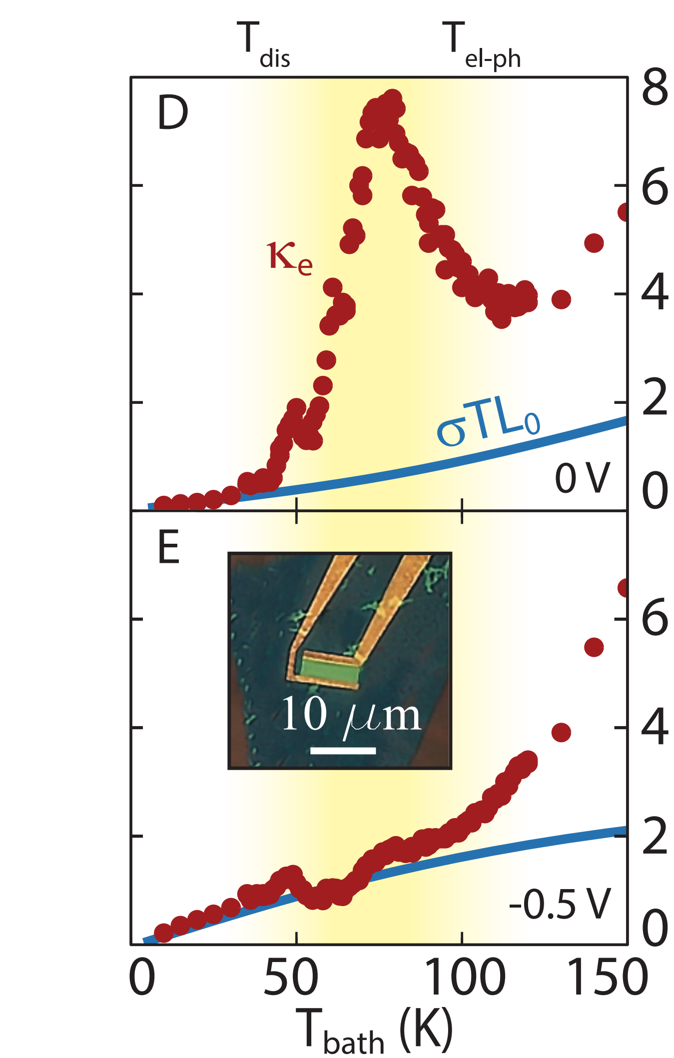


Wiedemann-Franz violated !









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

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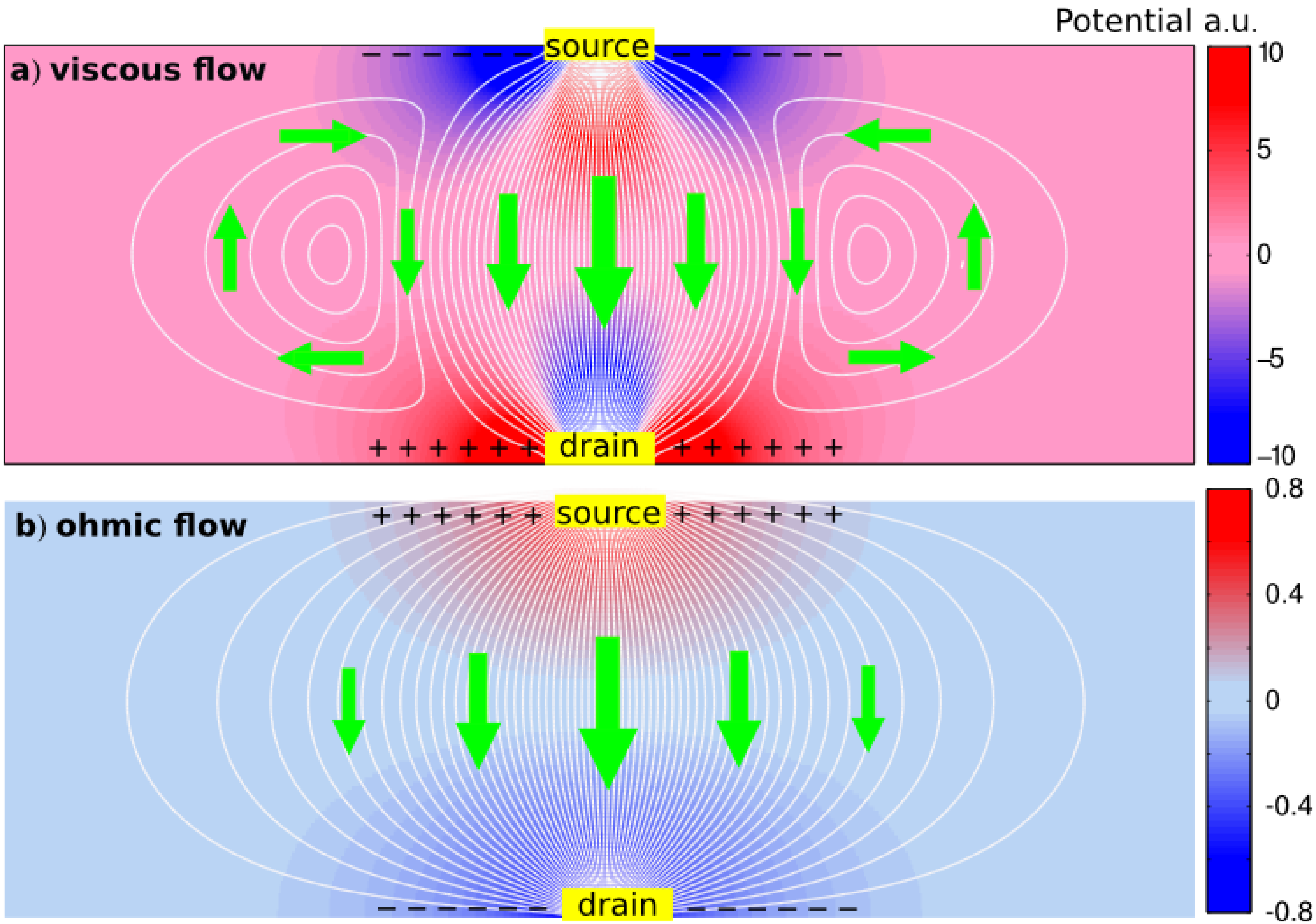
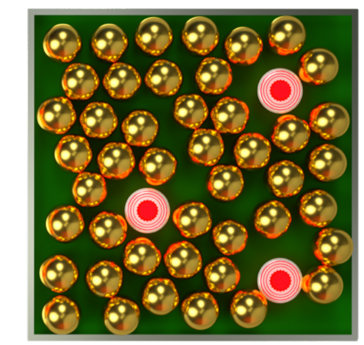
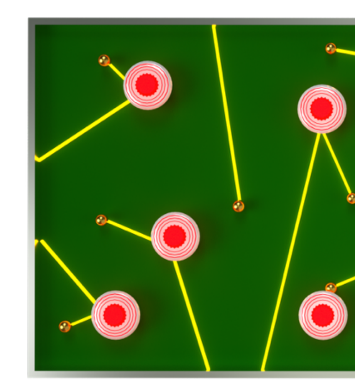
Strange metal in graphene

Negative local resistance due to viscous electron backflow in graphene







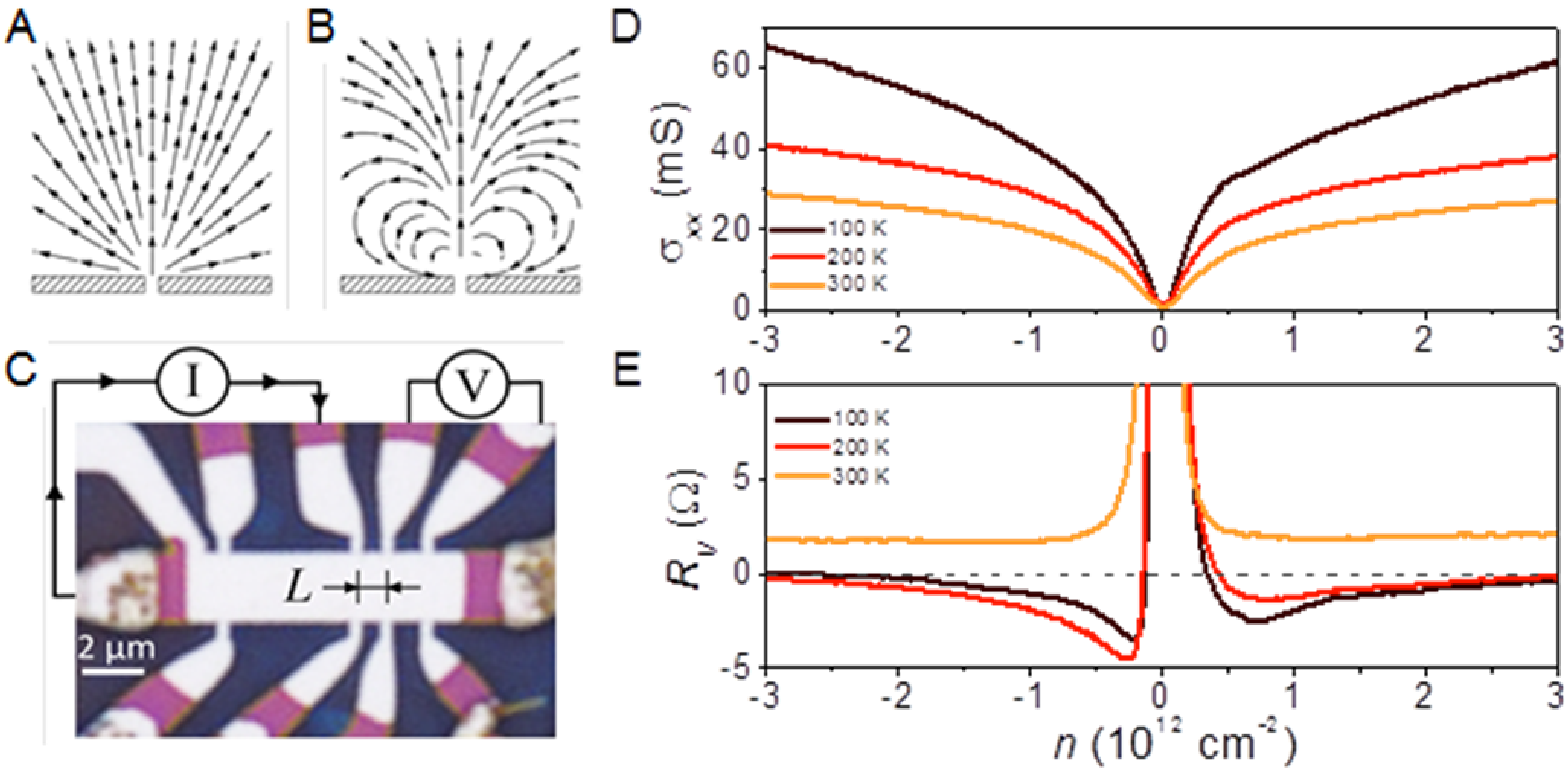
L. Levitov and G. Falkovich, arXiv:1508.00836, *Nature Physics online*

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]



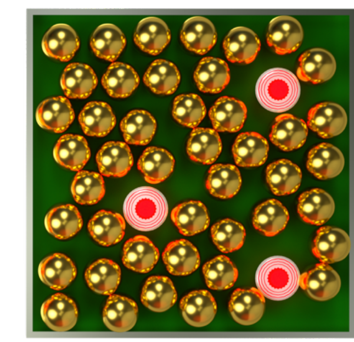


Figure 1. Viscous backflow in doped graphene. (**a,b**) Steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (a) and a viscous Fermi liquid (b). (**c**) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry 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. $I = 0.3$ μA; $L = 1$ μm. For more detail, see Supplementary Information.

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