Quantum matter without quasiparticles

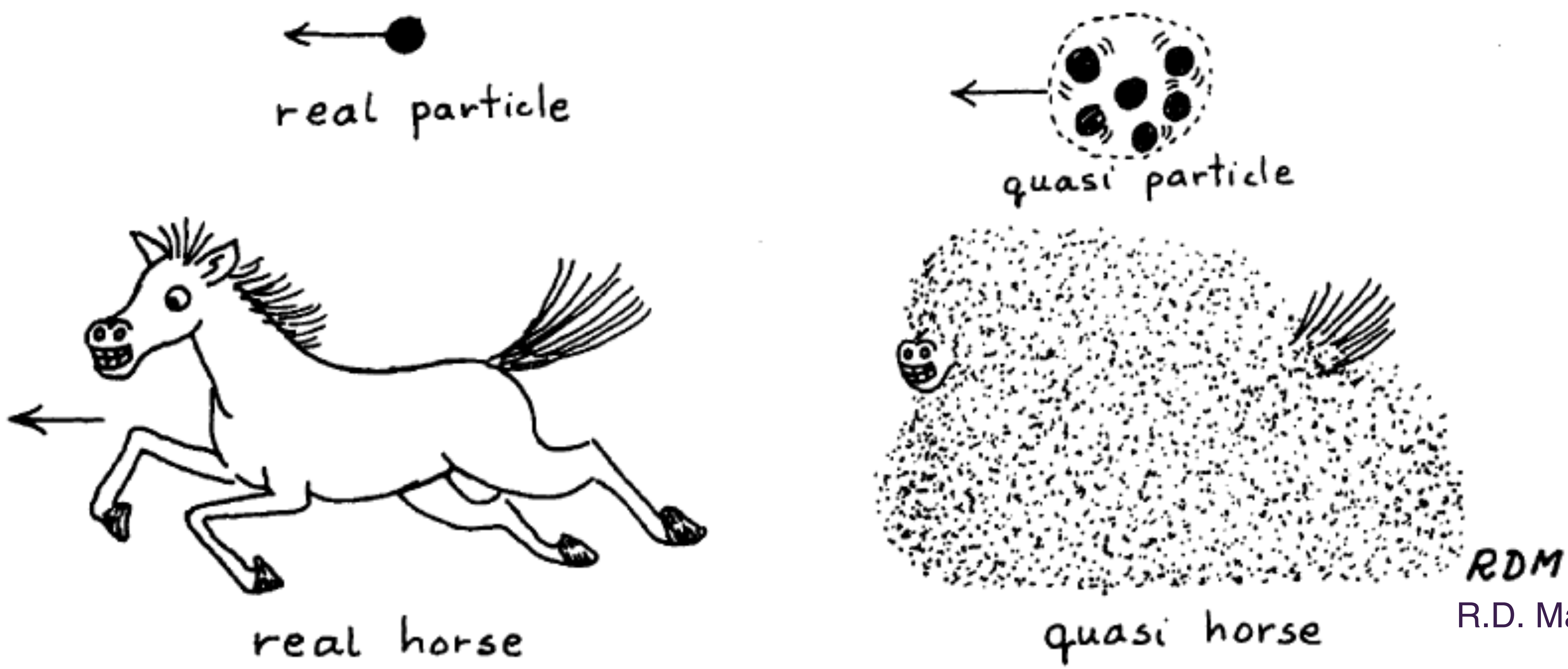
Electron-electron Interactions in Topological Materials,
Center for Advanced 2D Materials,
National University of Singapore, June 28-30, 2017

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

Quantum matter with quasiparticles:

A quasiparticle is an "excited lump" in the many-electron state which responds just like an ordinary particle.



R.D. Mattuck

Quantum matter with quasiparticles:

- **Quasiparticles are additive excitations:**
  The low-lying excitations of the many-body system can be identified as a set $\{n_\alpha\}$ of quasiparticles with energy ε_α

$$E = \sum_\alpha n_\alpha \varepsilon_\alpha + \sum_{\alpha,\beta} F_{\alpha\beta} n_\alpha n_\beta + \ldots$$

  - **Note:** The electron liquid in one dimension and the fractional quantum Hall state both have quasiparticles; however, the quasiparticles do not have the same quantum numbers as an electron.

Quantum matter with quasiparticles:

- Quasiparticles eventually collide with each other. Such collisions eventually leads to thermal equilibration in a chaotic quantum state, but the equilibration takes a long time. In a Fermi liquid, this time is of order $\hbar E_F/(k_B T)^2$ as $T \to 0$, where E_F is the Fermi energy.

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

- No quasiparticle decomposition of low-lying states
- Rapid thermalization

Local thermal equilibration or phase coherence time, τ_φ:

- There is an *lower bound* on τ_φ in all many-body quantum systems as $T \rightarrow 0$,

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

where C is a T-independent constant.

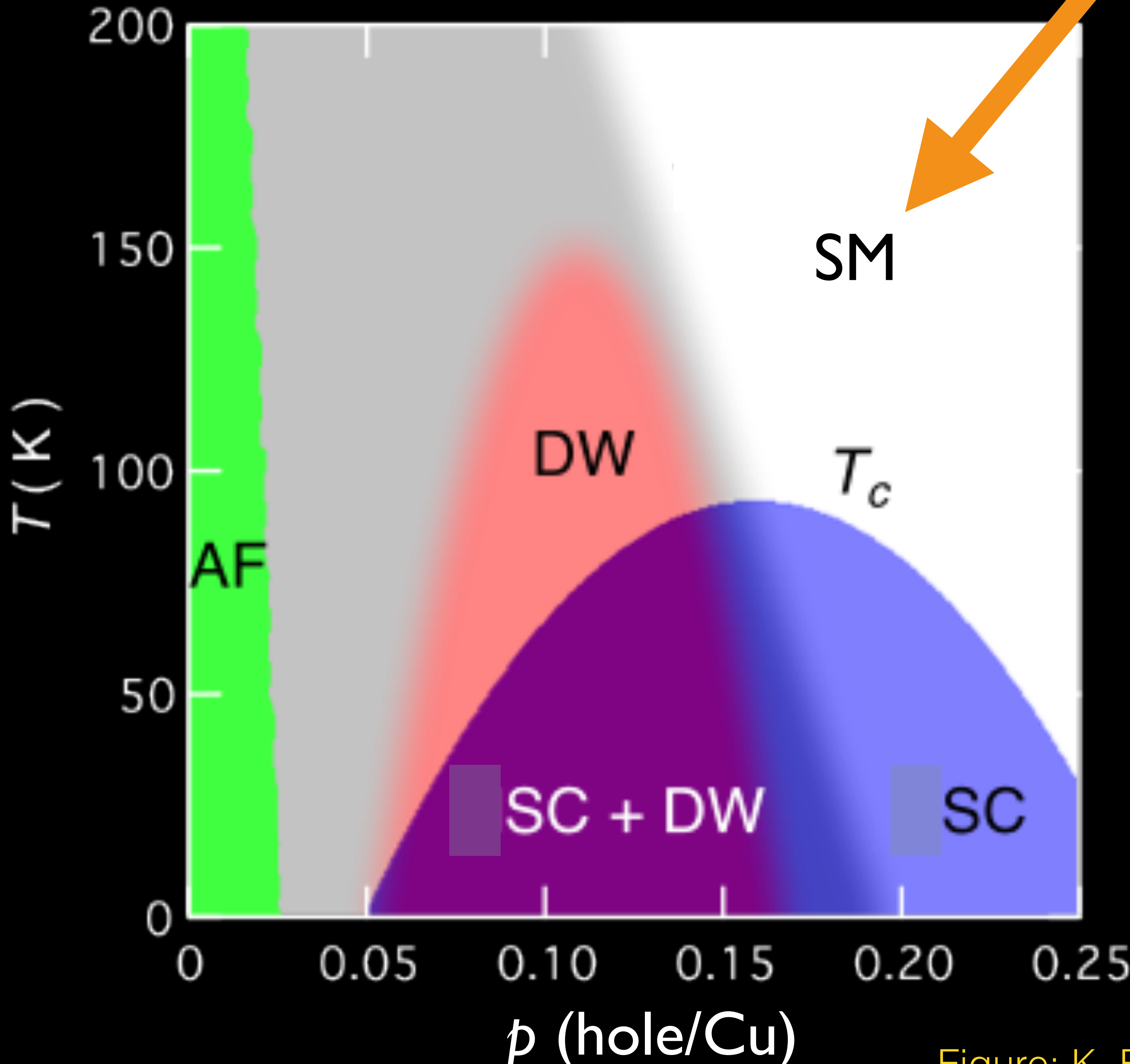
- Systems *without* quasiparticles have

$$\tau_\varphi \sim \frac{\hbar}{k_B T},$$

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

Strange metal

Entangled electrons lead to "strange" temperature dependence of resistivity and other properties



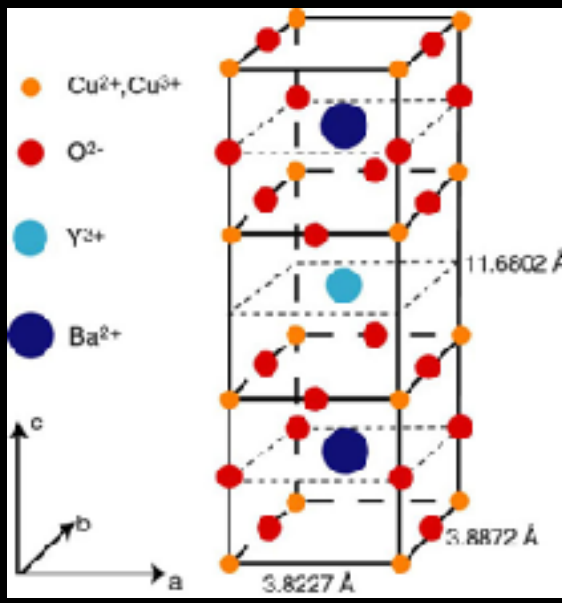
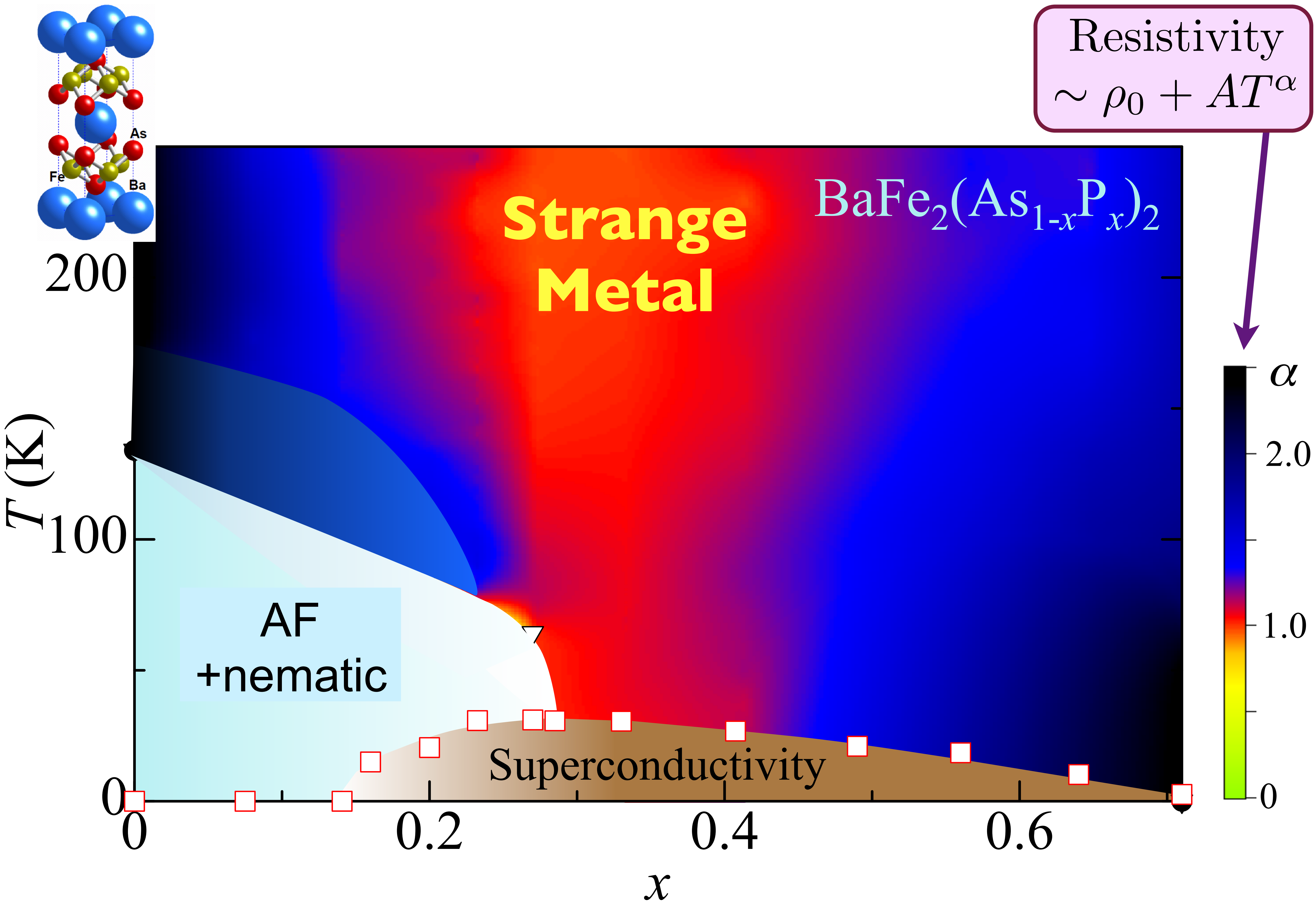
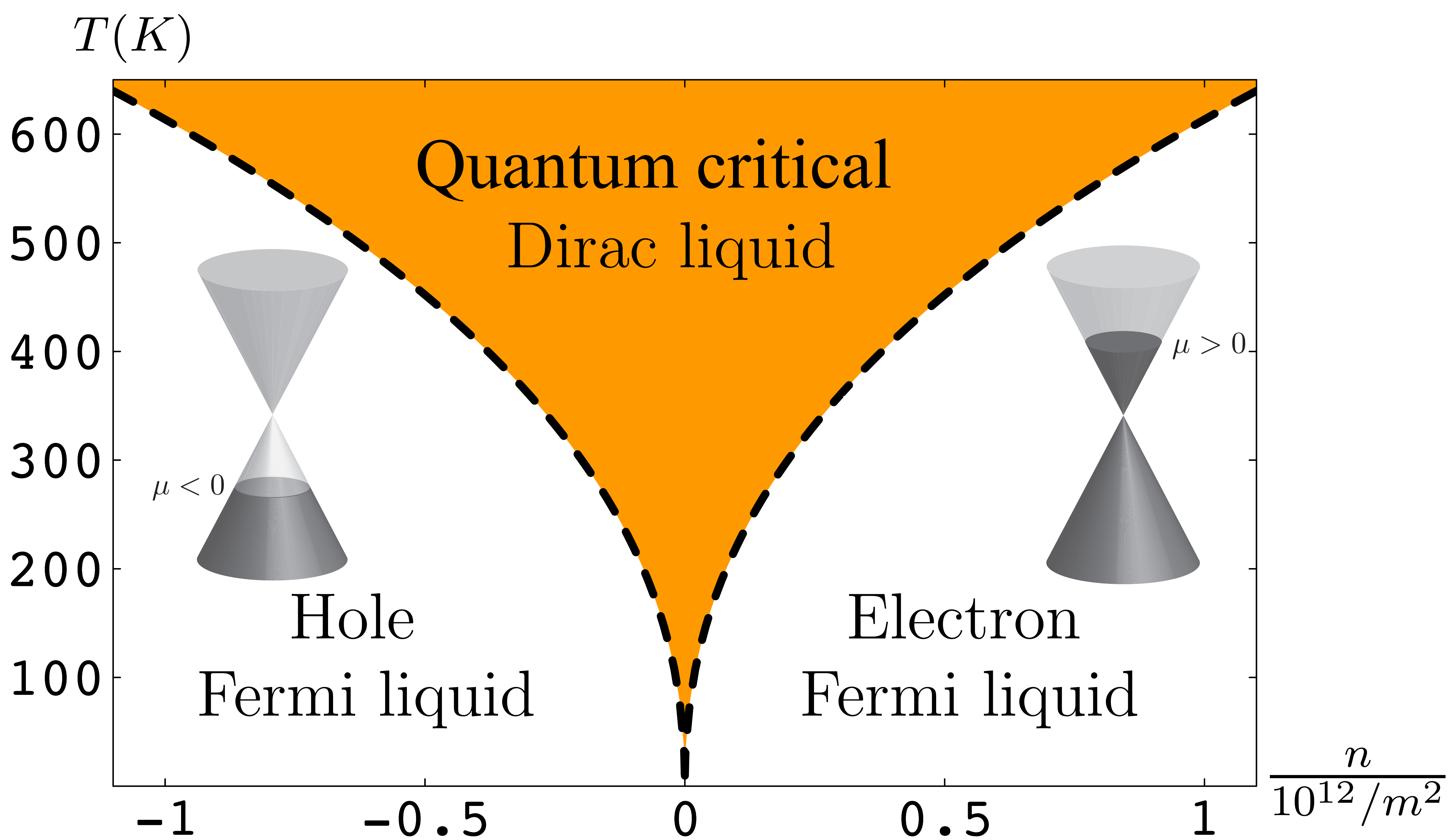


Figure: K. Fujita and J. C. Seamus Davis



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)

Graphene

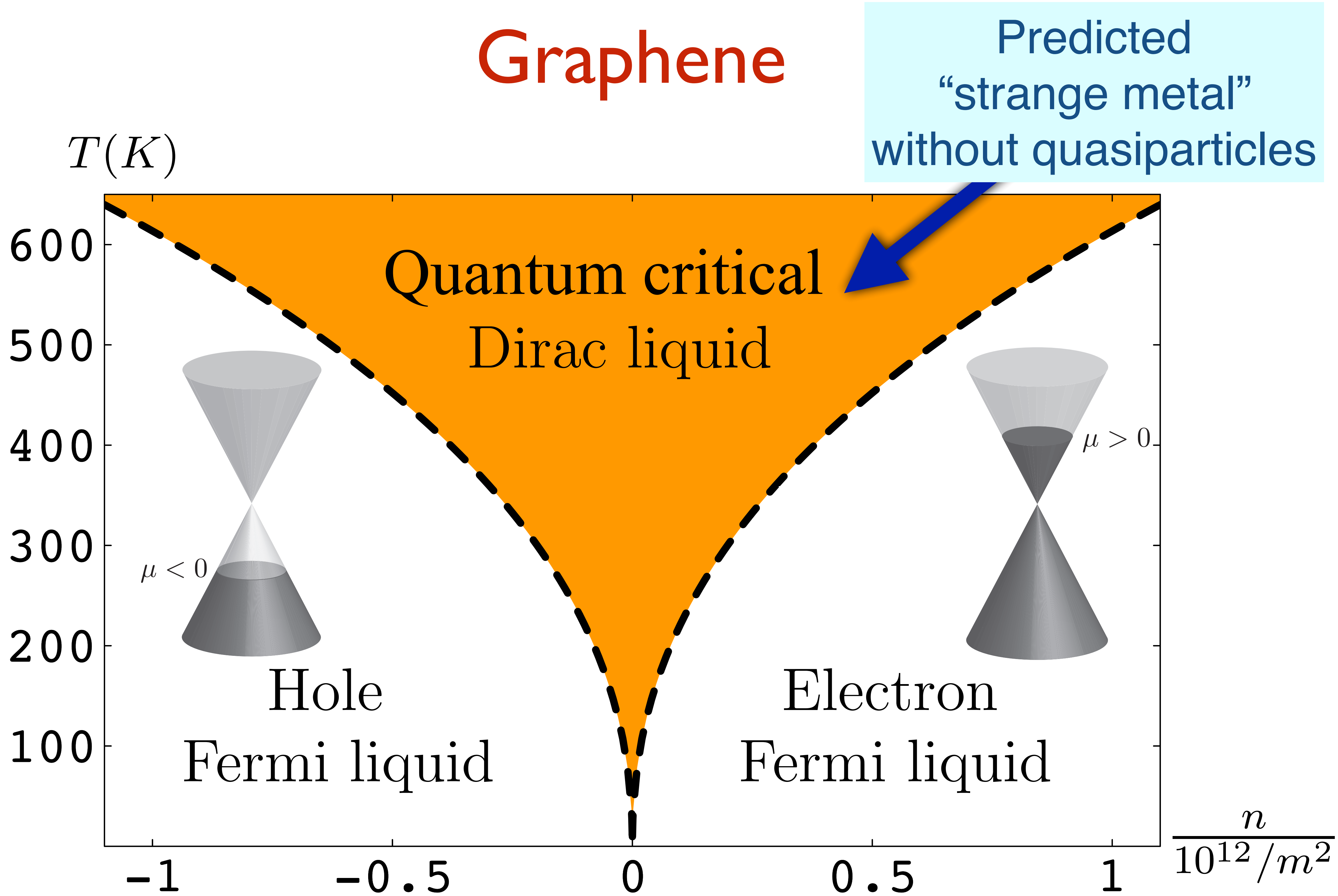


D. E. Sheehy and J. Schmalian, PRL **99**, 226803 (2007)

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

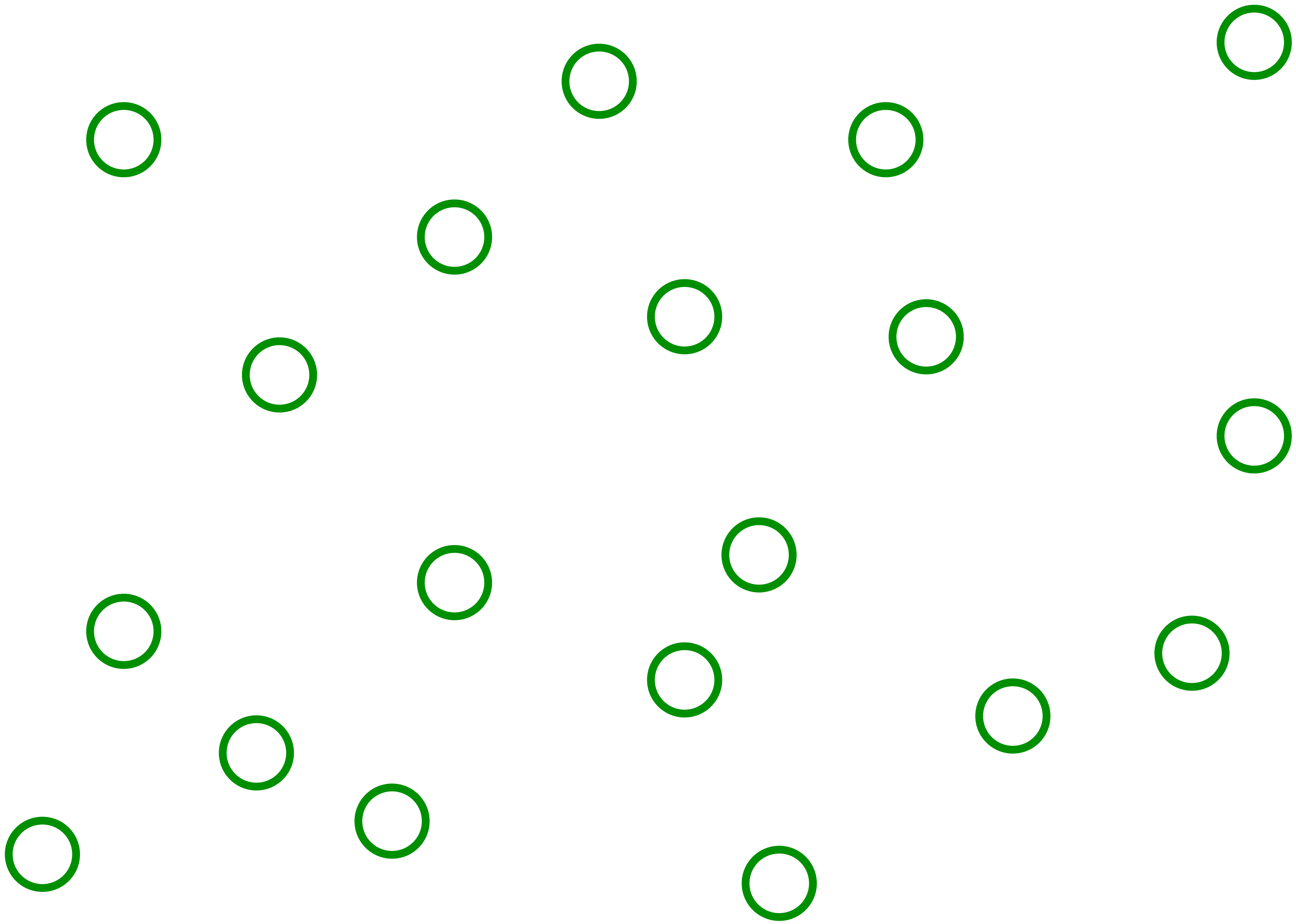
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Graphene



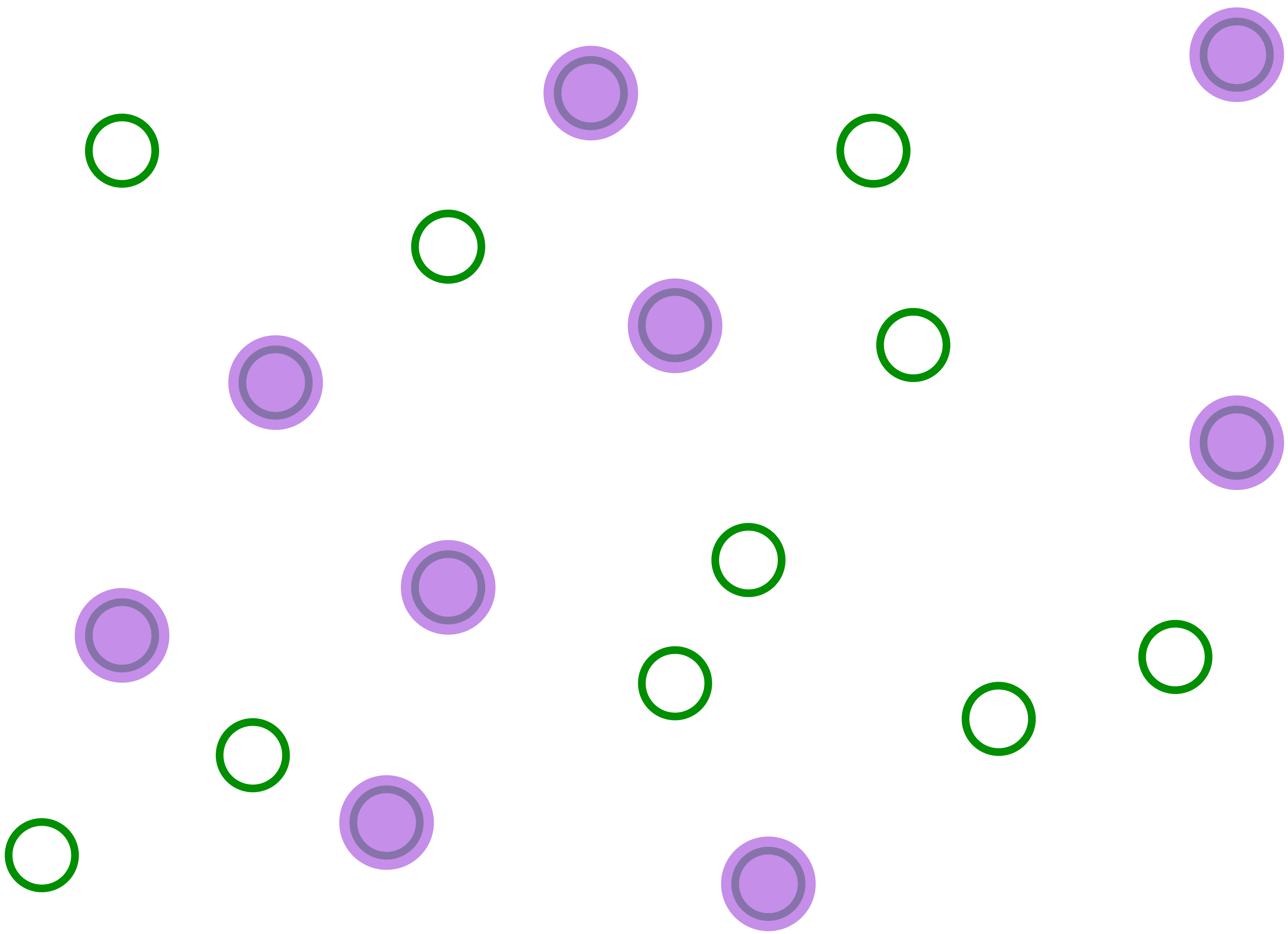
M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

A simple model of a metal with quasiparticles



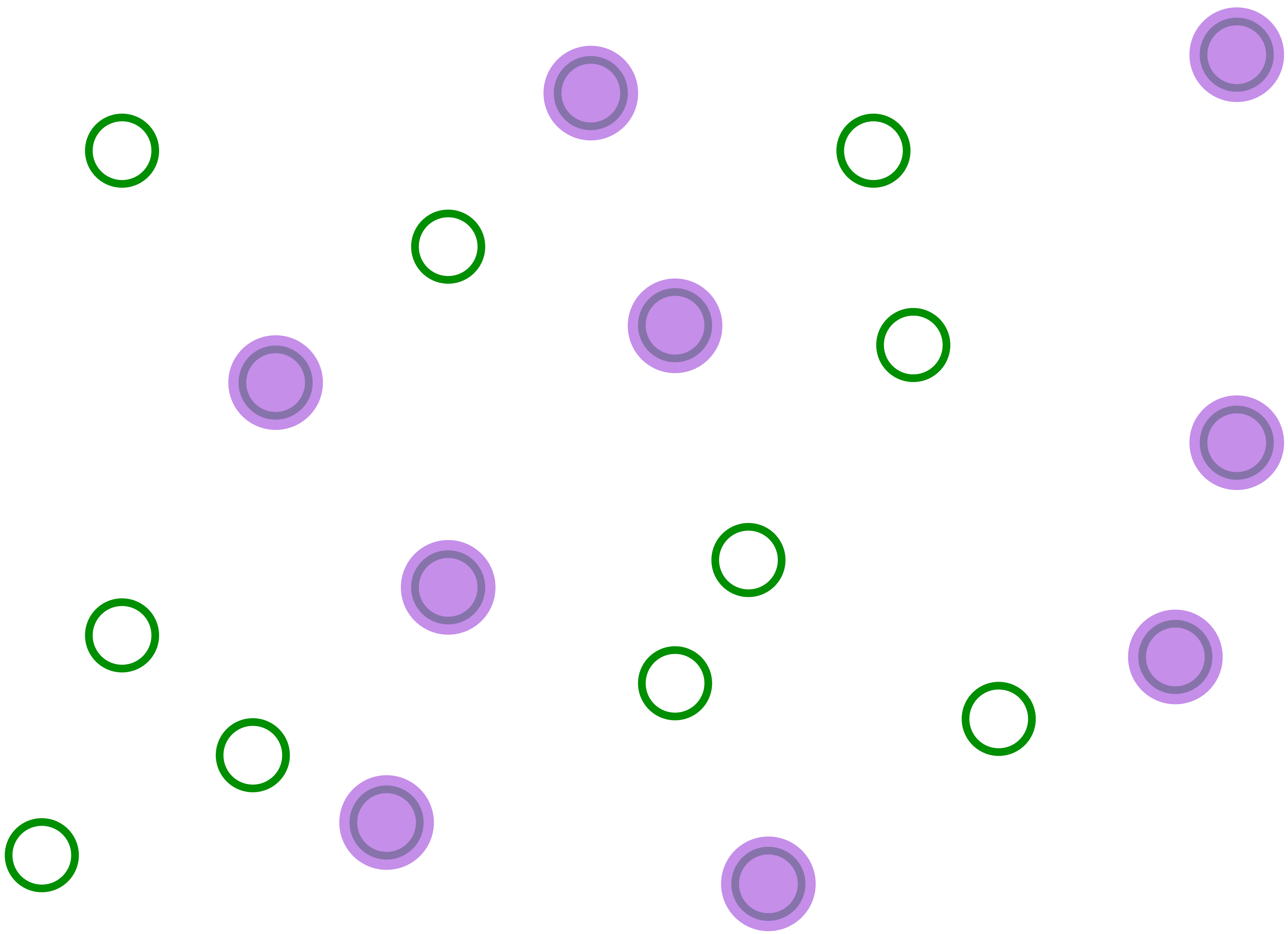
Pick a set of random positions

A simple model of a metal with quasiparticles



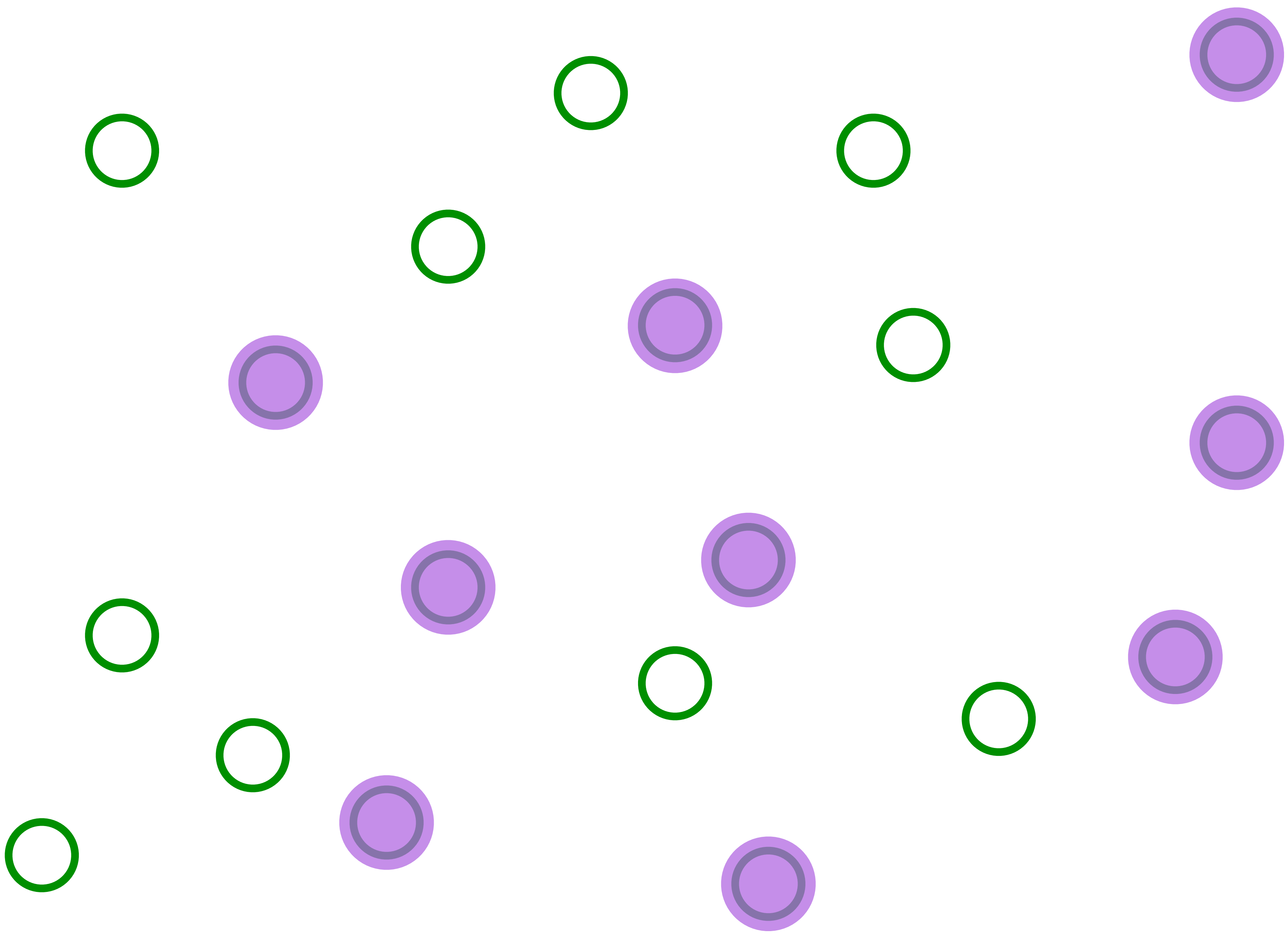
Place electrons randomly on some sites

A simple model of a metal with quasiparticles



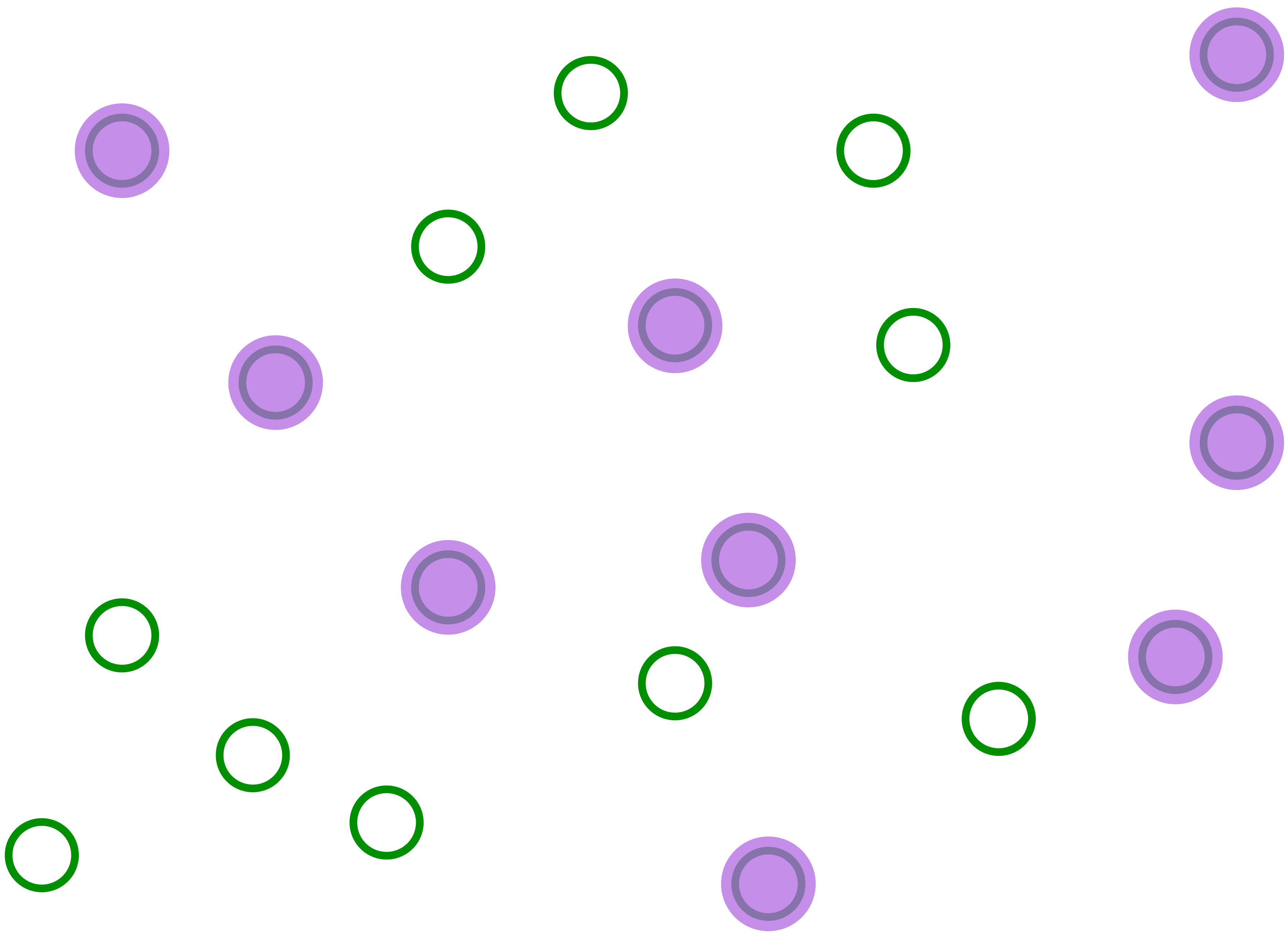
Electrons move one-by-one randomly

A simple model of a metal with quasiparticles



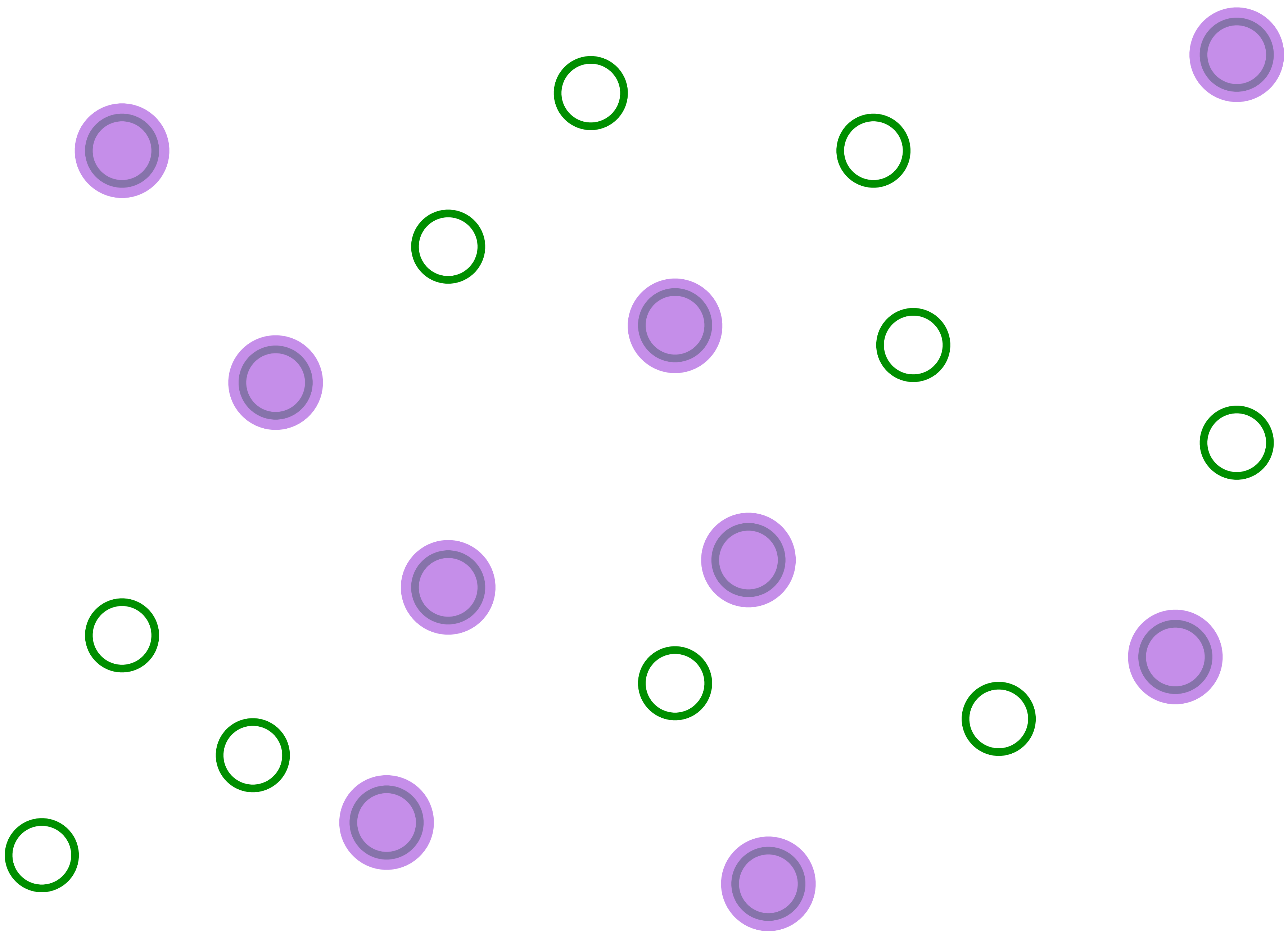
Electrons move one-by-one randomly

A simple model of a metal with quasiparticles



Electrons move one-by-one randomly

A simple model of a metal with quasiparticles



Electrons move one-by-one randomly

A simple model of a metal with quasiparticles

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

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

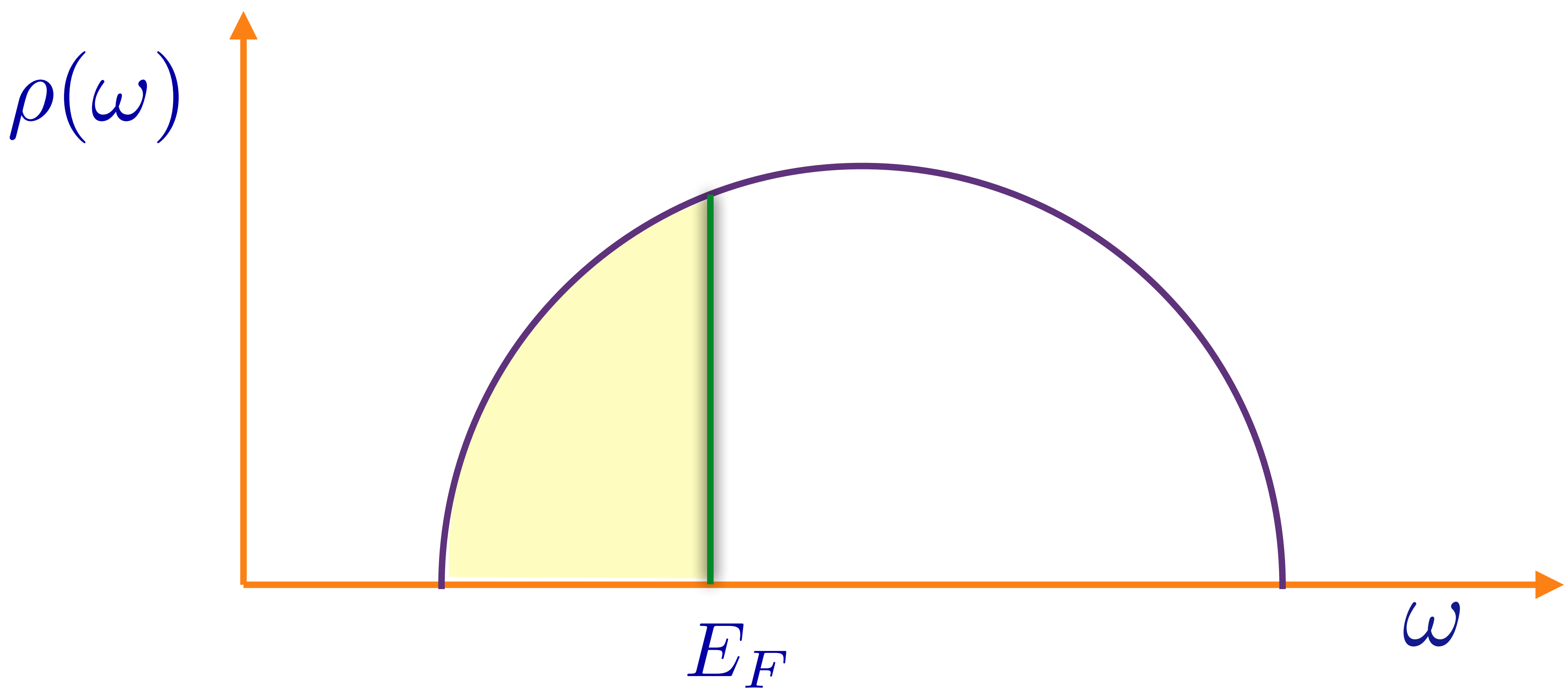
$$\frac{1}{N} \sum_i c_i^\dagger c_i = \mathcal{Q}$$

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

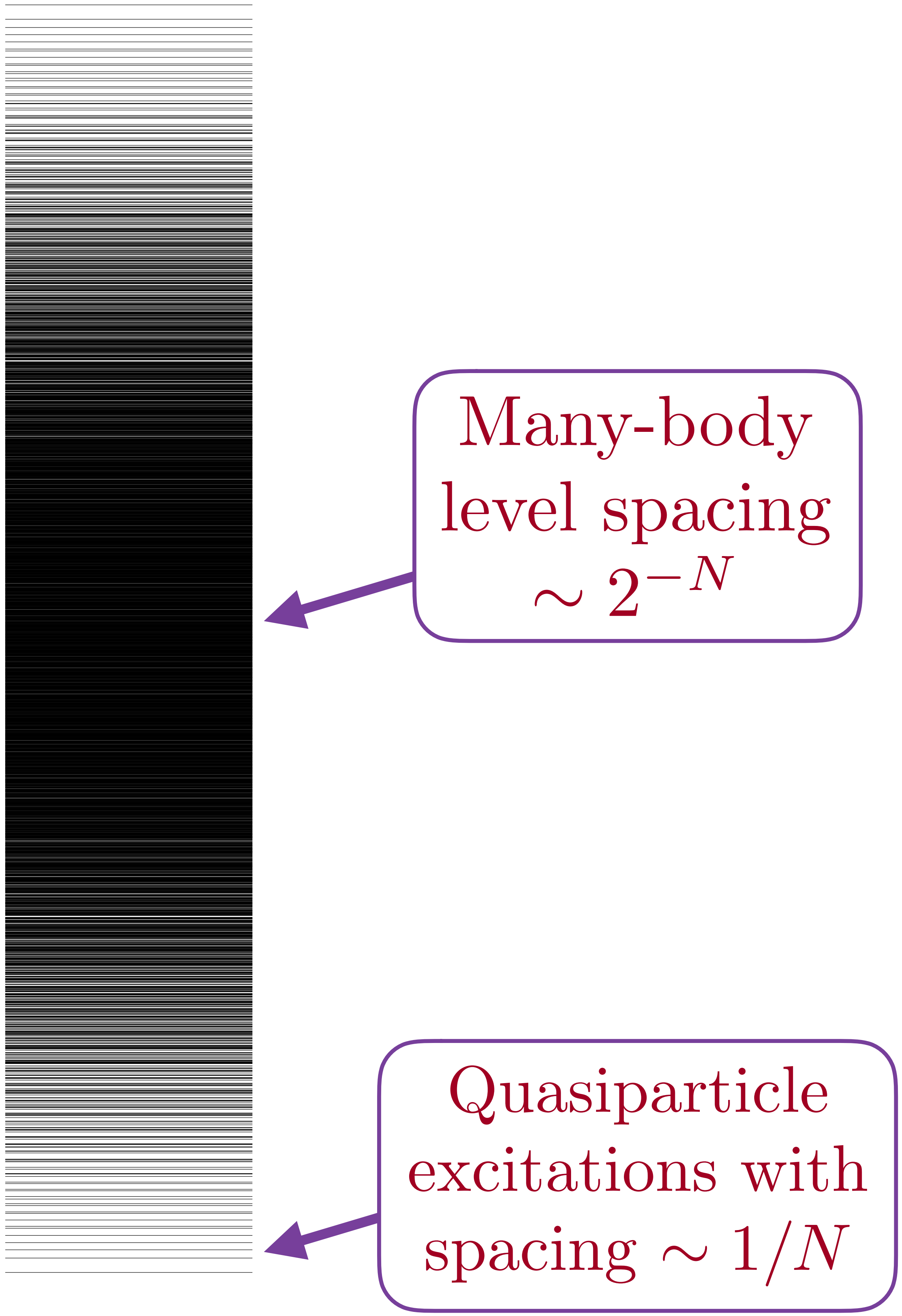
Fermions occupying the eigenstates of a *N* x *N* random matrix

A simple model of a metal with quasiparticles

Let ε_α be the eigenvalues of the matrix $t_{ij}/\sqrt{N}$. The fermions will occupy the lowest NQ eigenvalues, upto the Fermi energy E_F. The density of states is $\rho(\omega) = (1/N)\sum_\alpha \delta(\omega - \varepsilon_\alpha)$.



A simple model of a metal with quasiparticles

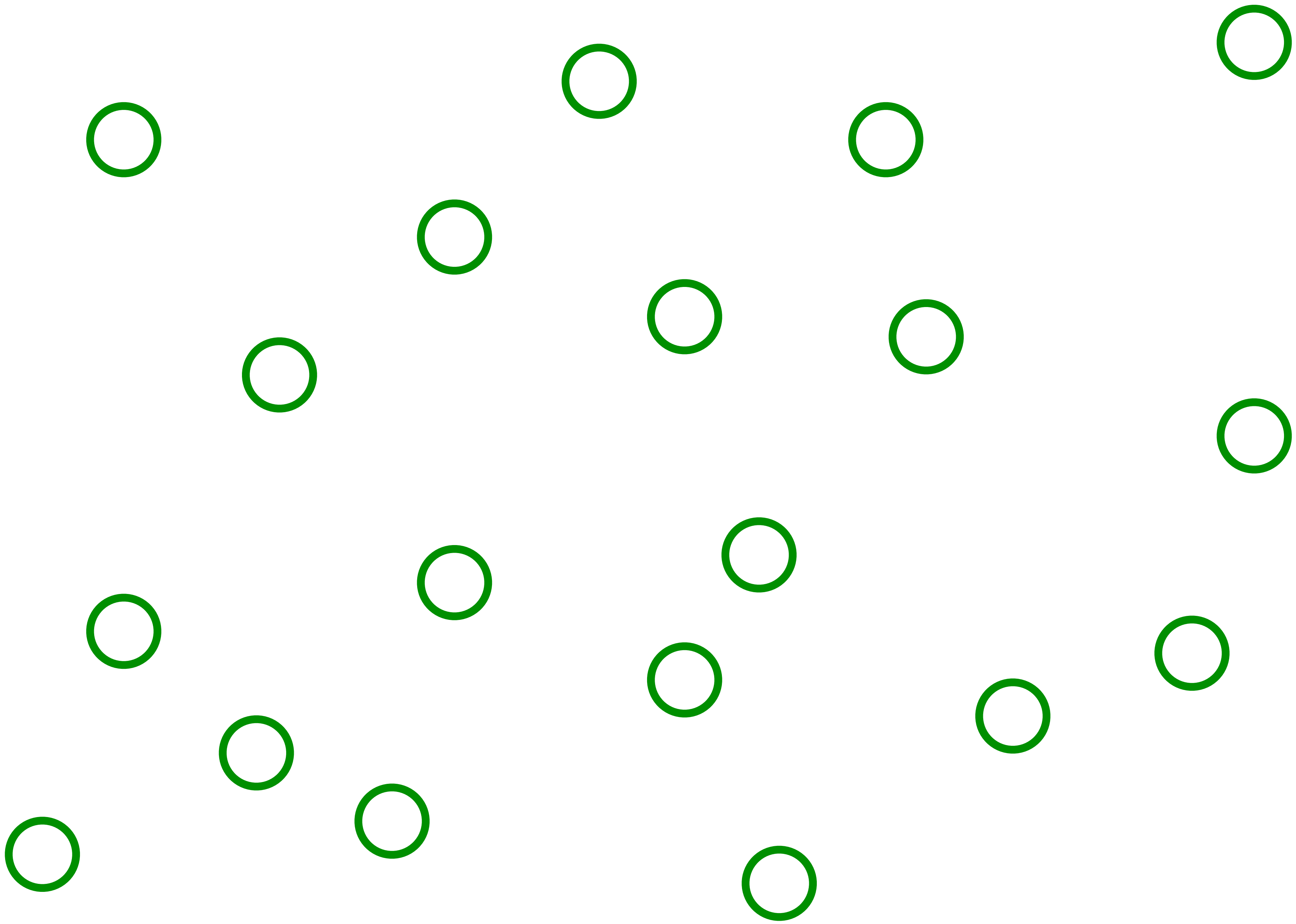


There are 2^N many body levels with energy

$$E = \sum_{\alpha=1}^{N} n_\alpha \varepsilon_\alpha,$$

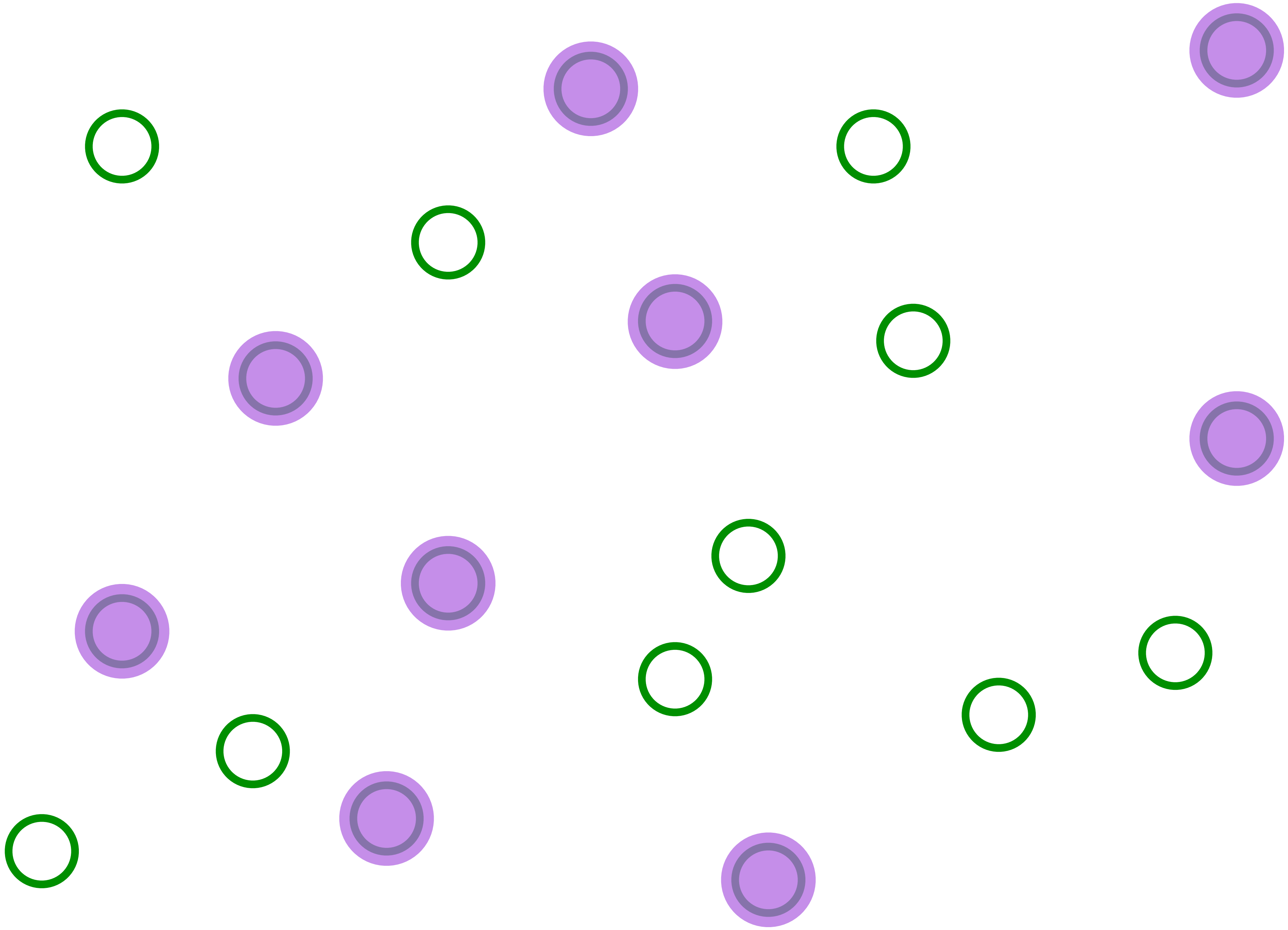
where $n_\alpha = 0, 1$. Shown are all values of E for a single cluster of size $N = 12$. The ε_α have a level spacing $\sim 1/N$.

The Sachdev-Ye-Kitaev (SYK) model



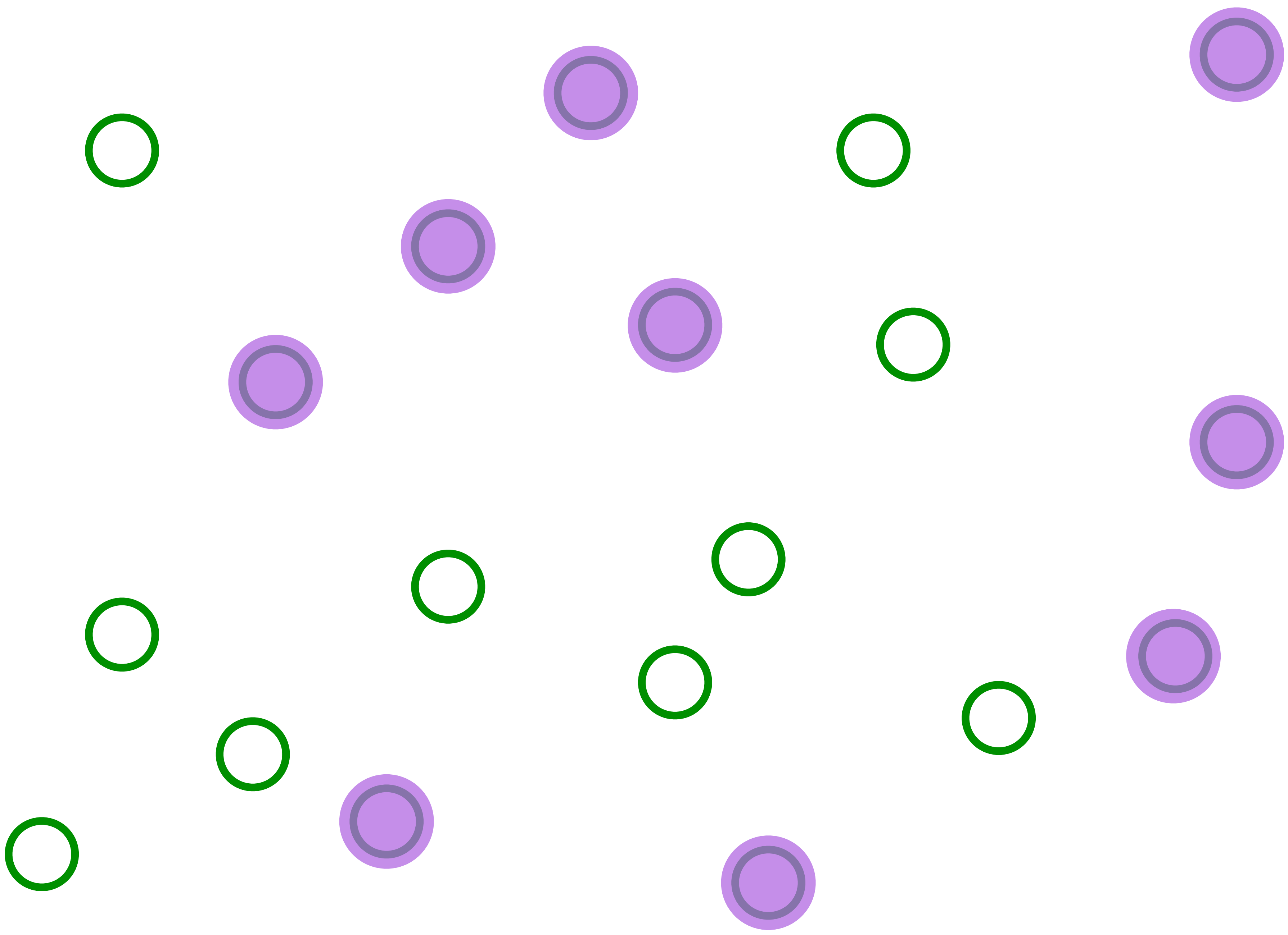
Pick a set of random positions

The Sachdev-Ye-Kitaev (SYK) model



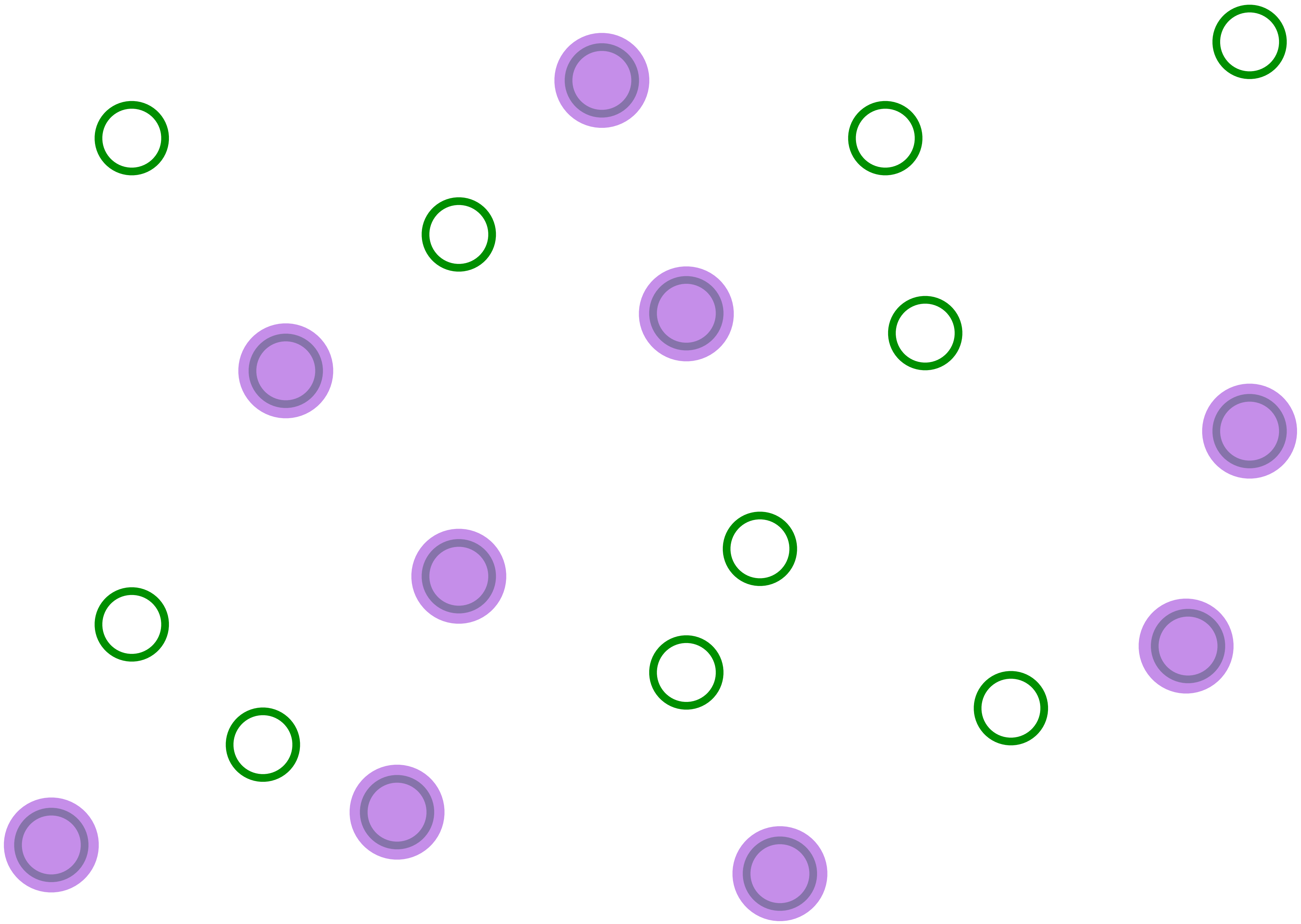
Place electrons randomly on some sites

The Sachdev-Ye-Kitaev (SYK) model



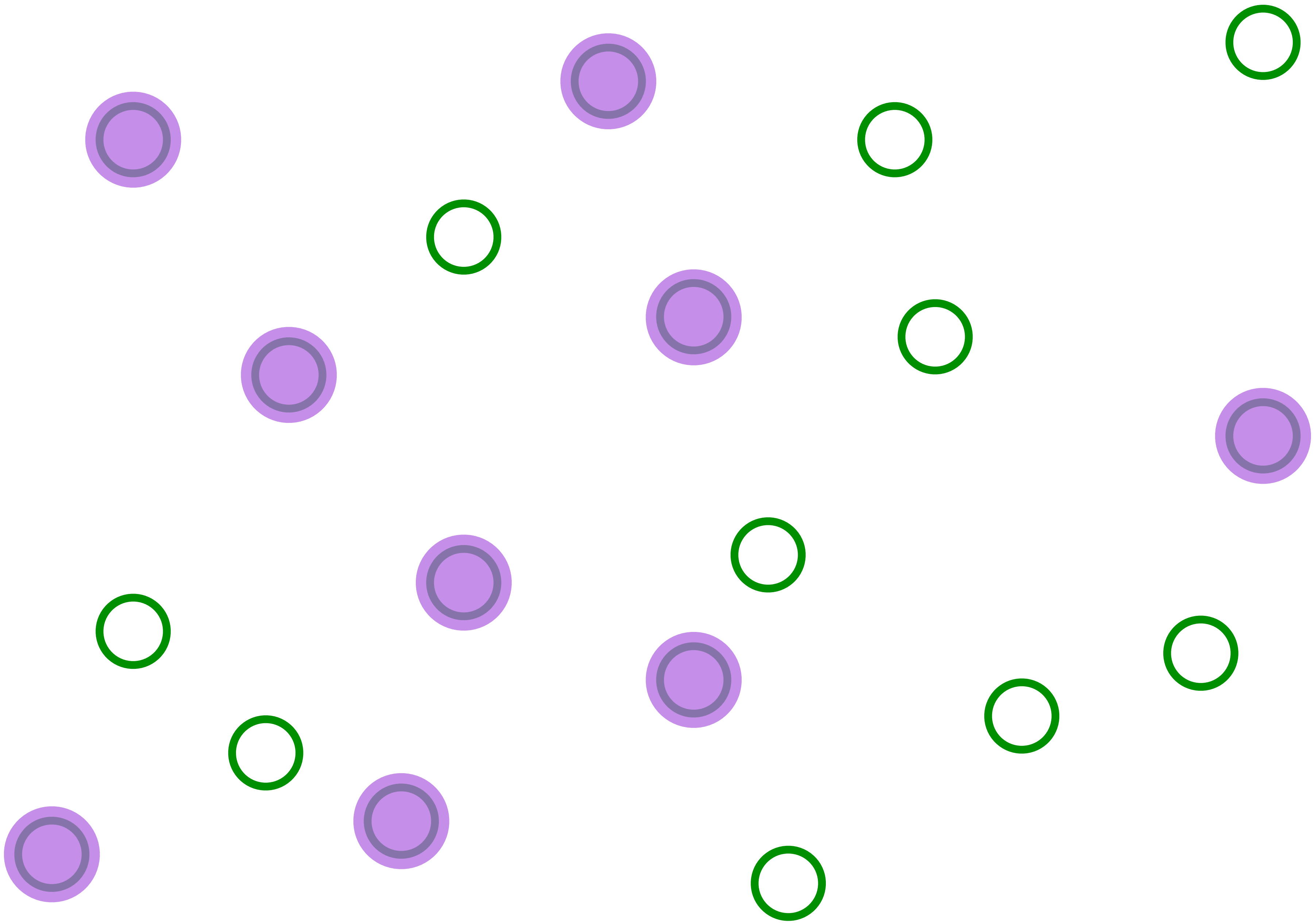
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



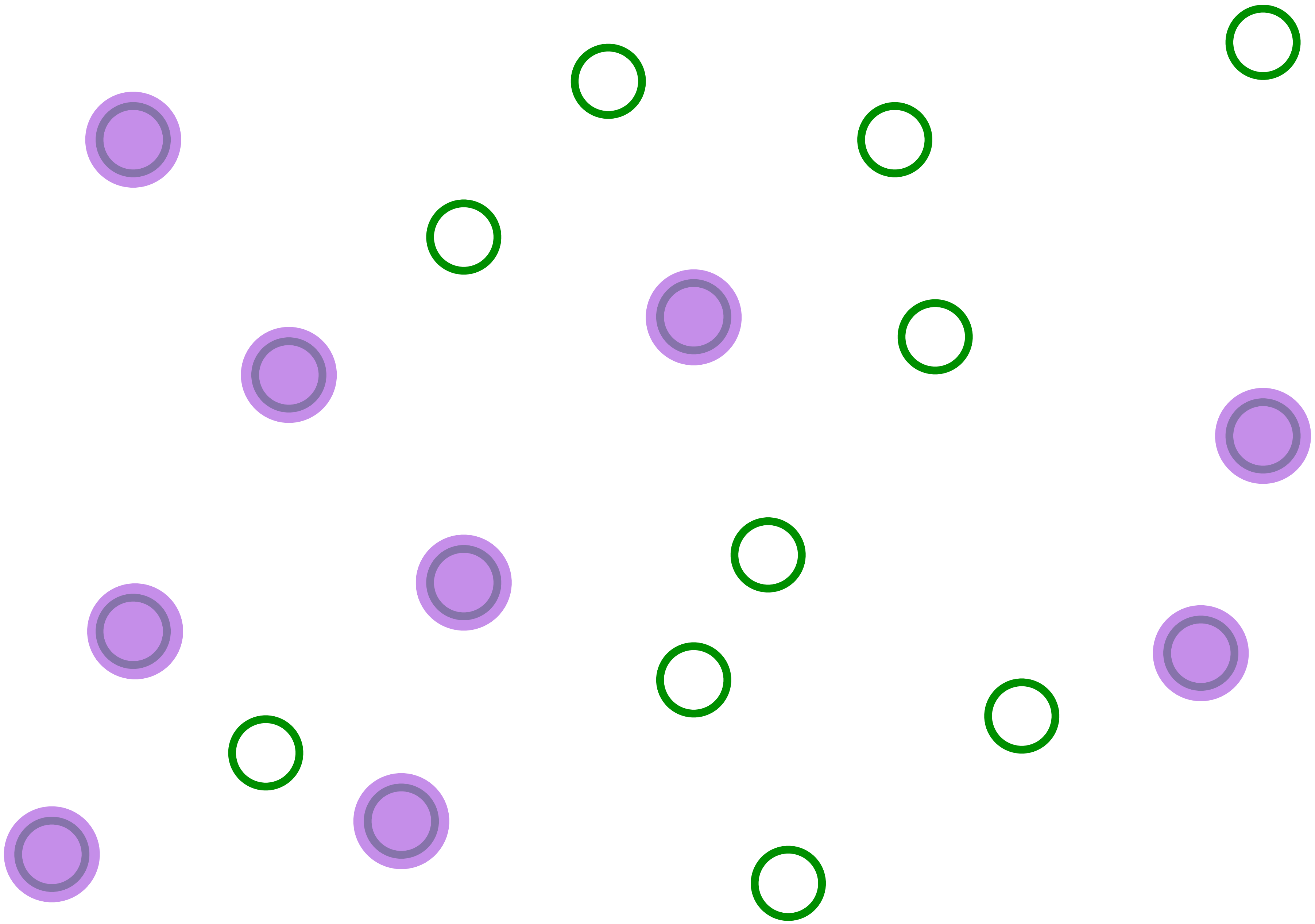
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



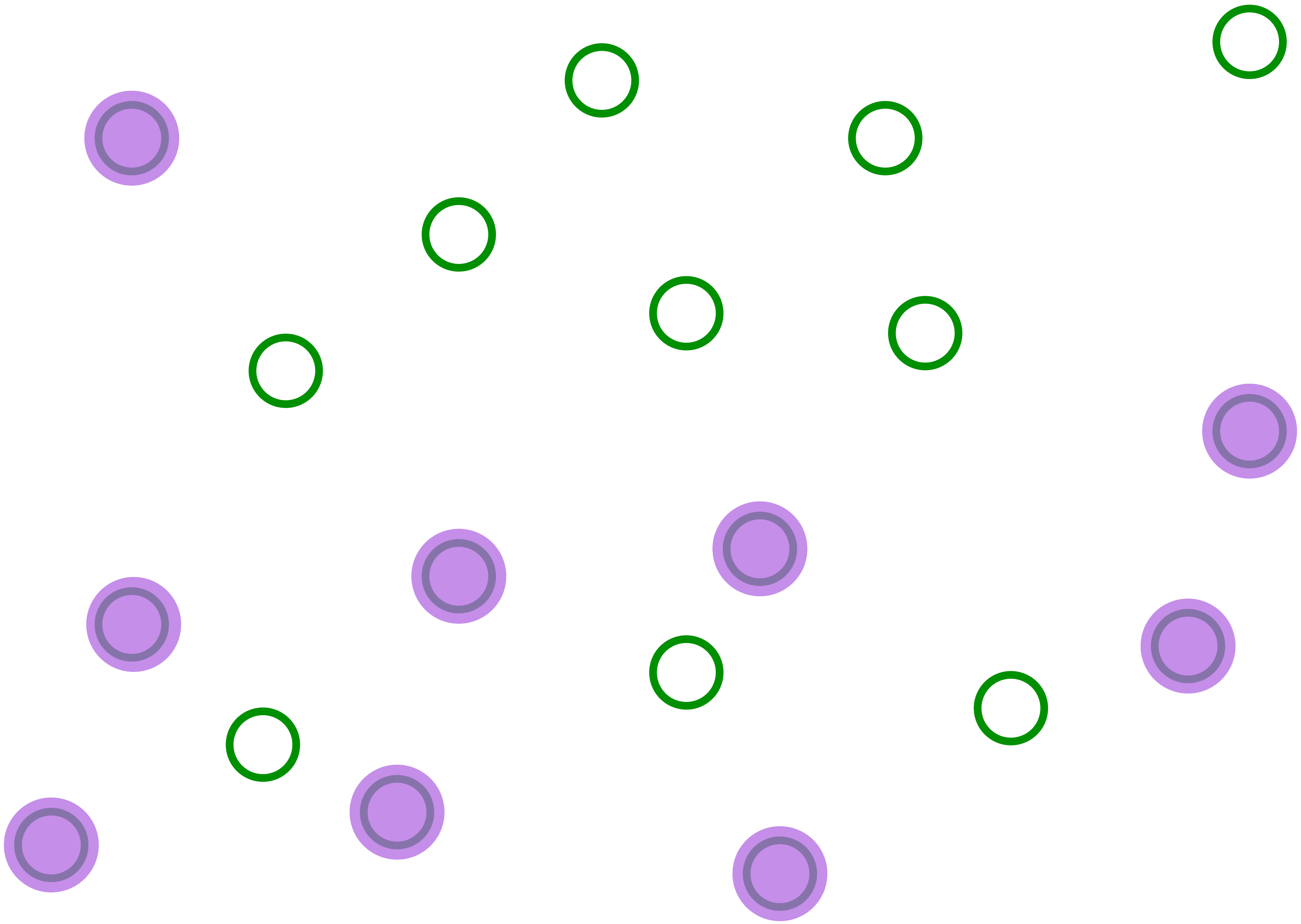
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



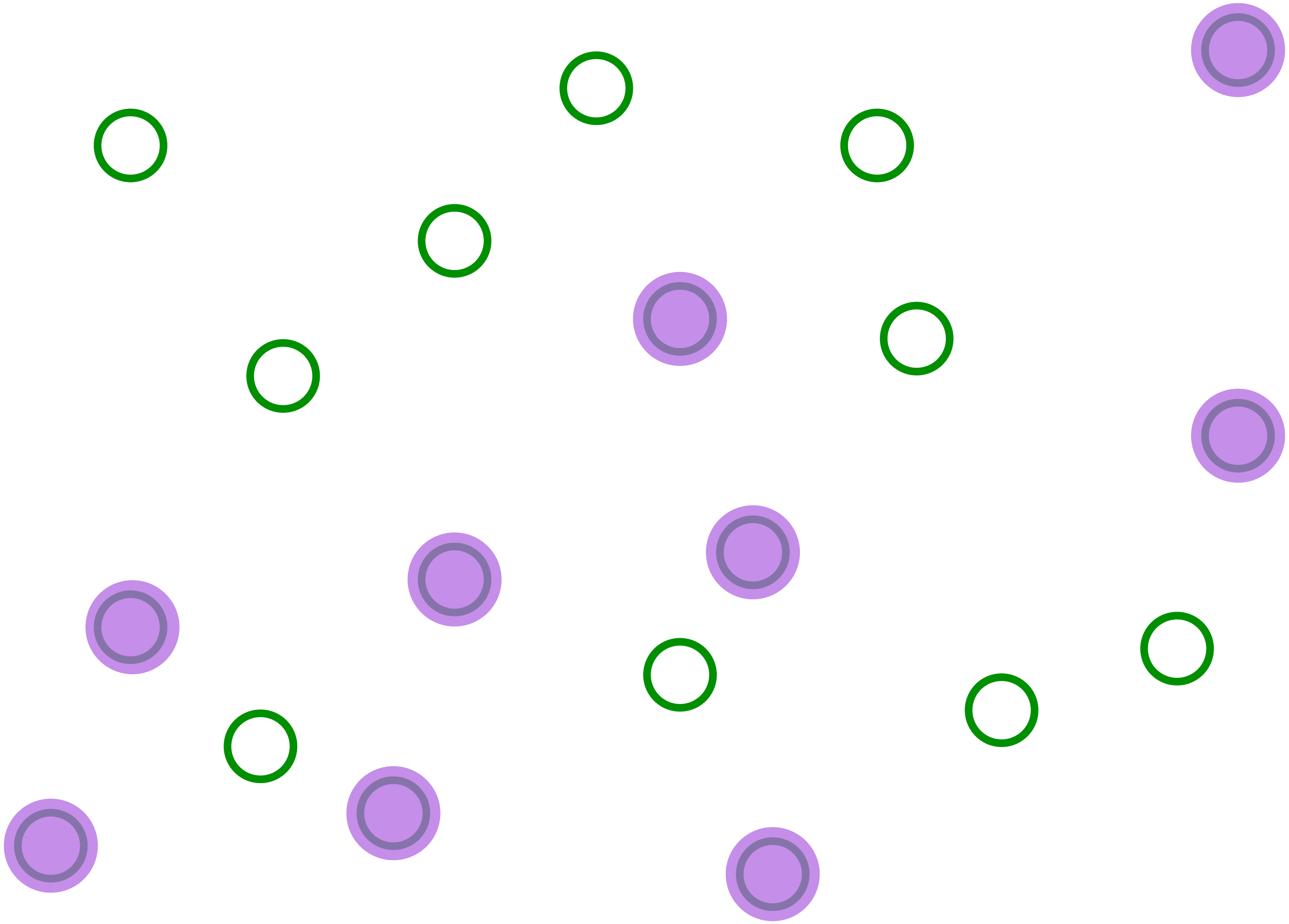
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



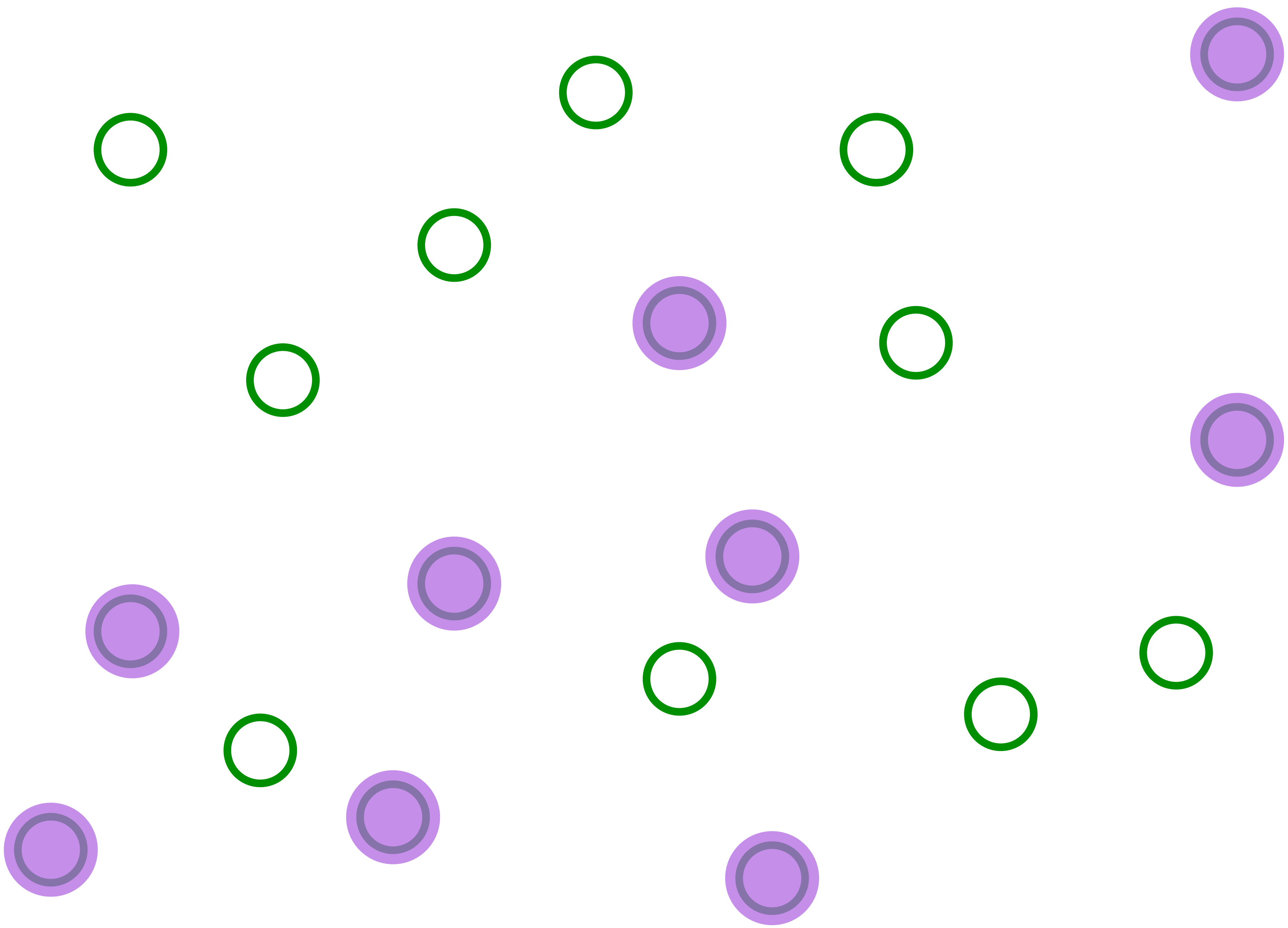
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



This describes both a strange metal and a black hole!

The Sachdev-Ye-Kitaev (SYK) model

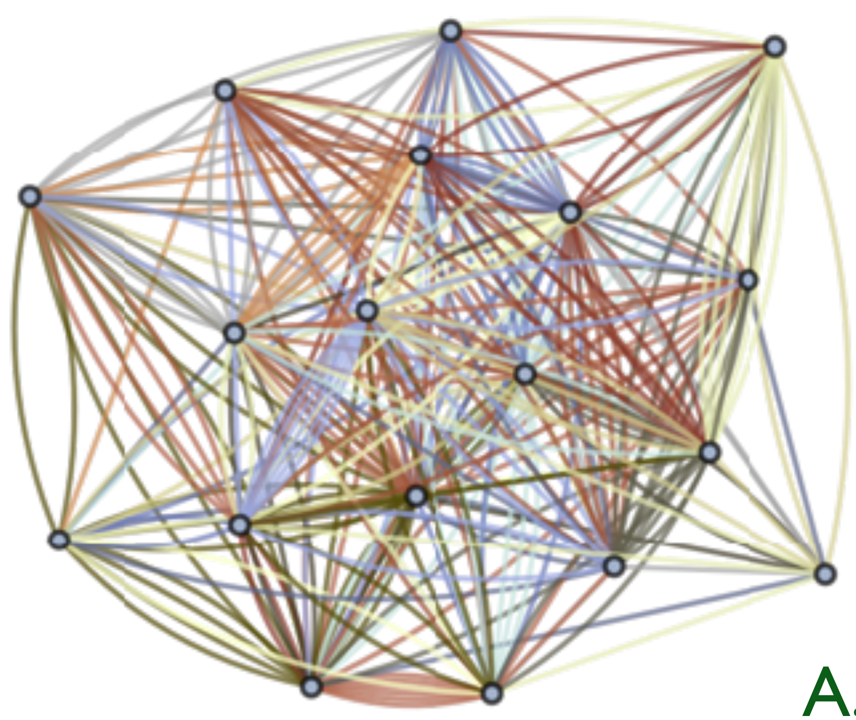
(See also: the "2-Body Random Ensemble" in nuclear physics; did not obtain the large N limit;
T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. **53**, 385 (1981))

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

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

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

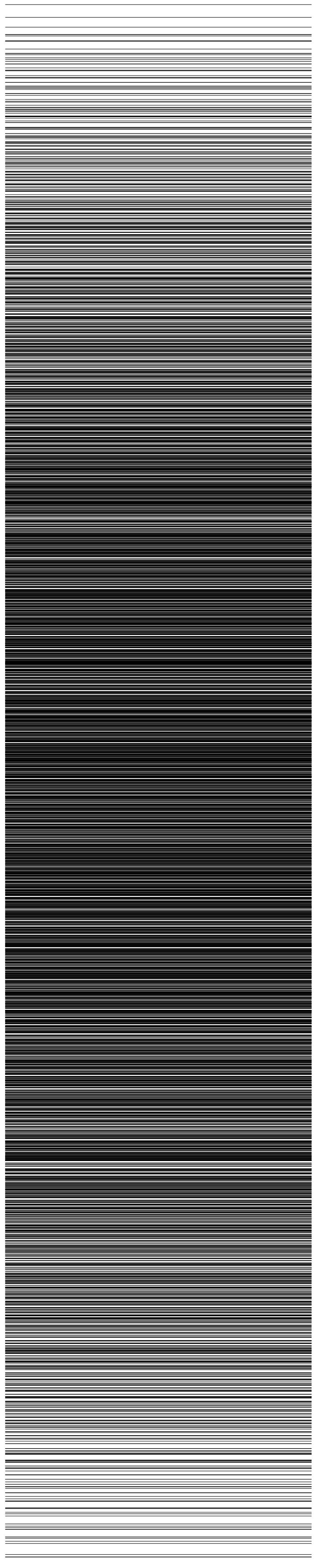
$J_{ij;k\ell}$ are independent random variables with $\overline{J_{ij;k\ell}} = 0$ and $\overline{|J_{ij;k\ell}|^2} = J^2$
$N \to \infty$ yields critical strange metal.



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

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

The Sachdev-Ye-Kitaev (SYK) model



Many-body level spacing $\sim 2^{-N} = e^{-N \ln 2}$

Non-quasiparticle excitations with spacing $\sim e^{-S_{GPS}}$

There are 2^N many body levels with energy E, which do not admit a quasiparticle decomposition. Shown are all values of E for a single cluster of size $N = 12$. The $T \to 0$ state has an entropy S_{GPS} with

$$\frac{S_{GPS}}{N} = \frac{G}{\pi} + \frac{\ln(2)}{4} = 0.464848\ldots$$
$$< \ln 2$$

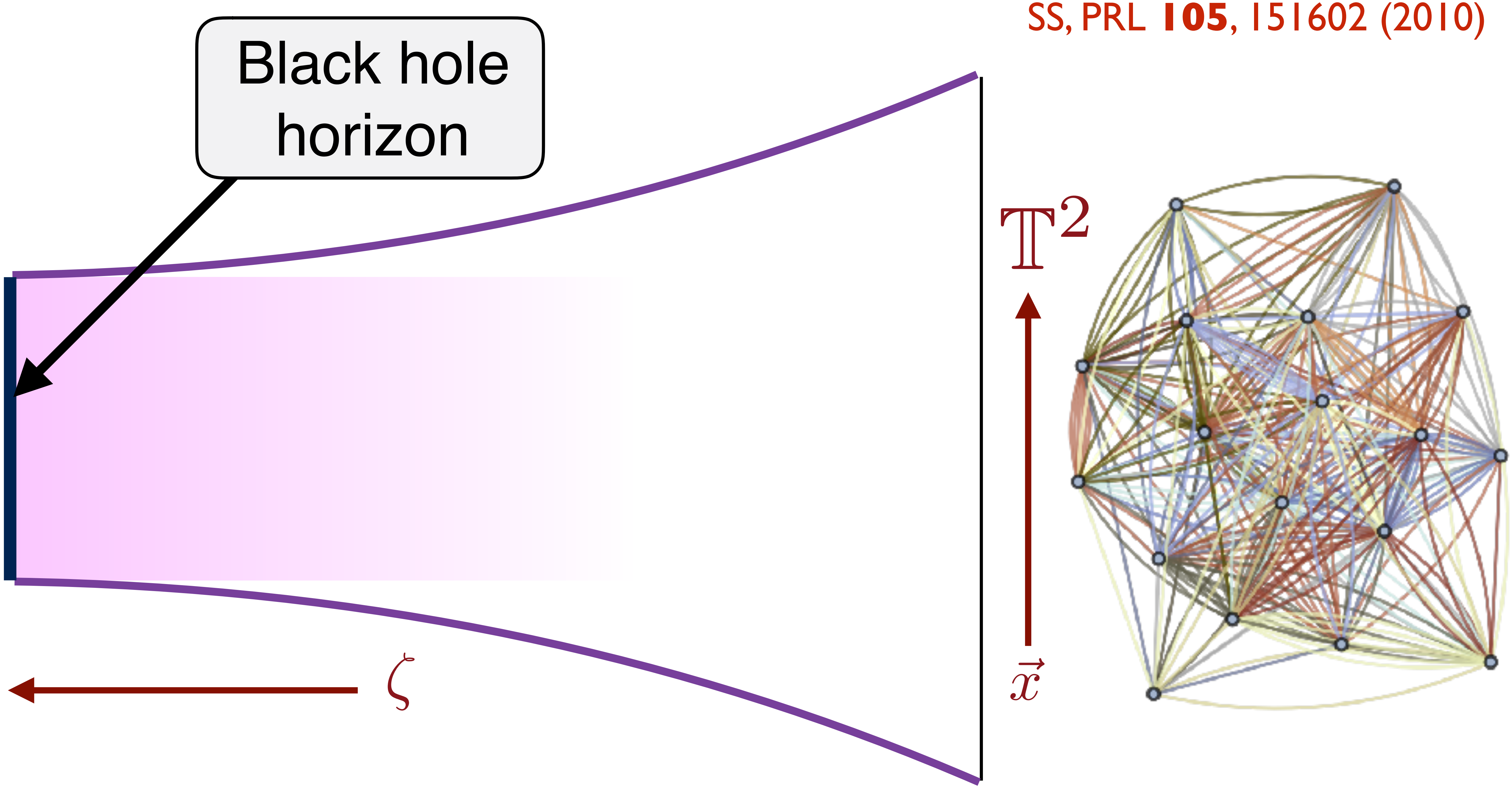
where G is Catalan's constant, for the half-filled case $Q = 1/2$.

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

W. Fu and S. Sachdev, PRB **94**, 035135 (2016)

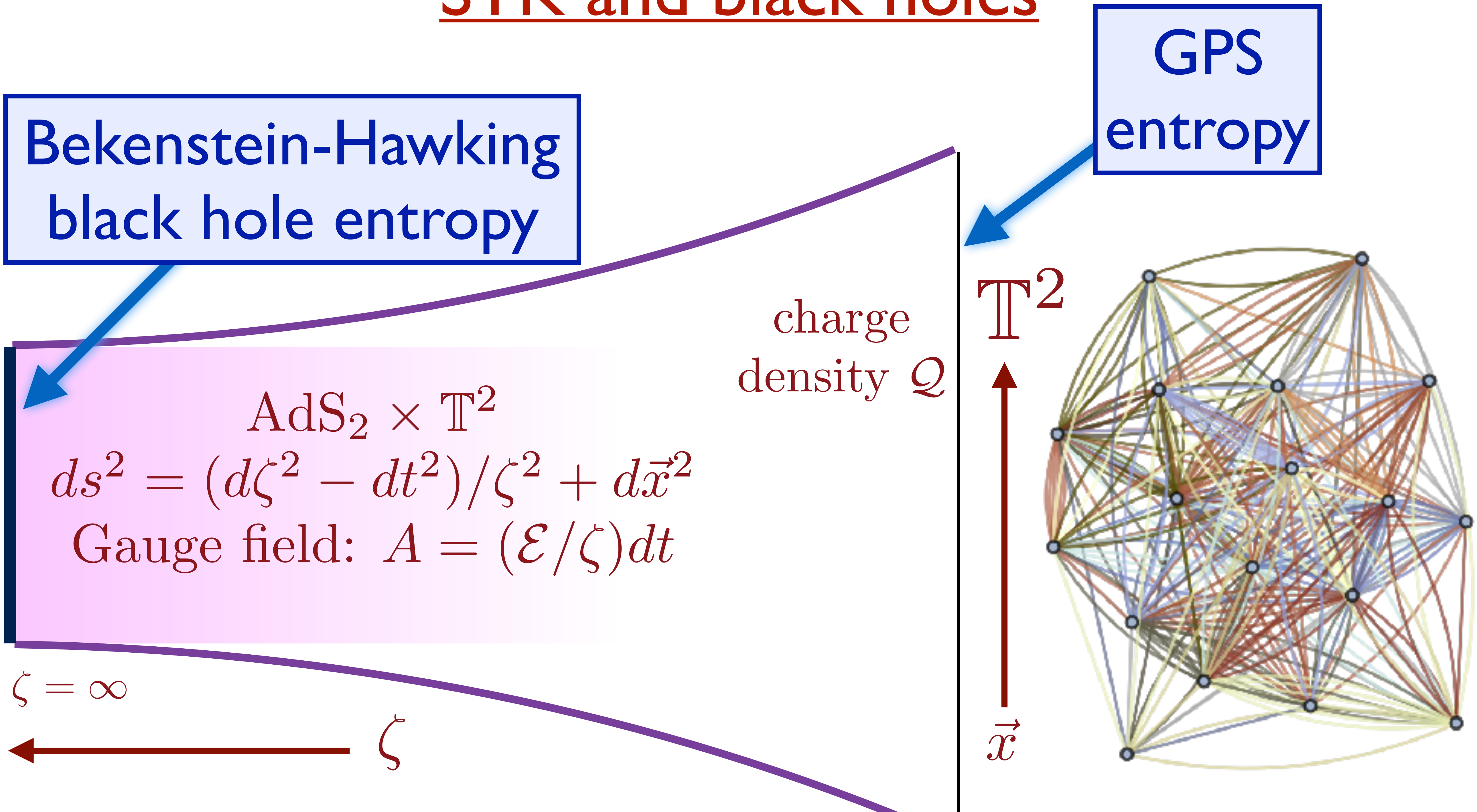
SYK and black holes

SS, PRL **105**, 151602 (2010)



The SYK model has "dual" description
in which an extra spatial dimension, ζ, emerges.
The curvature of this "emergent" spacetime is described
by Einstein's theory of general relativity

SYK and black holes

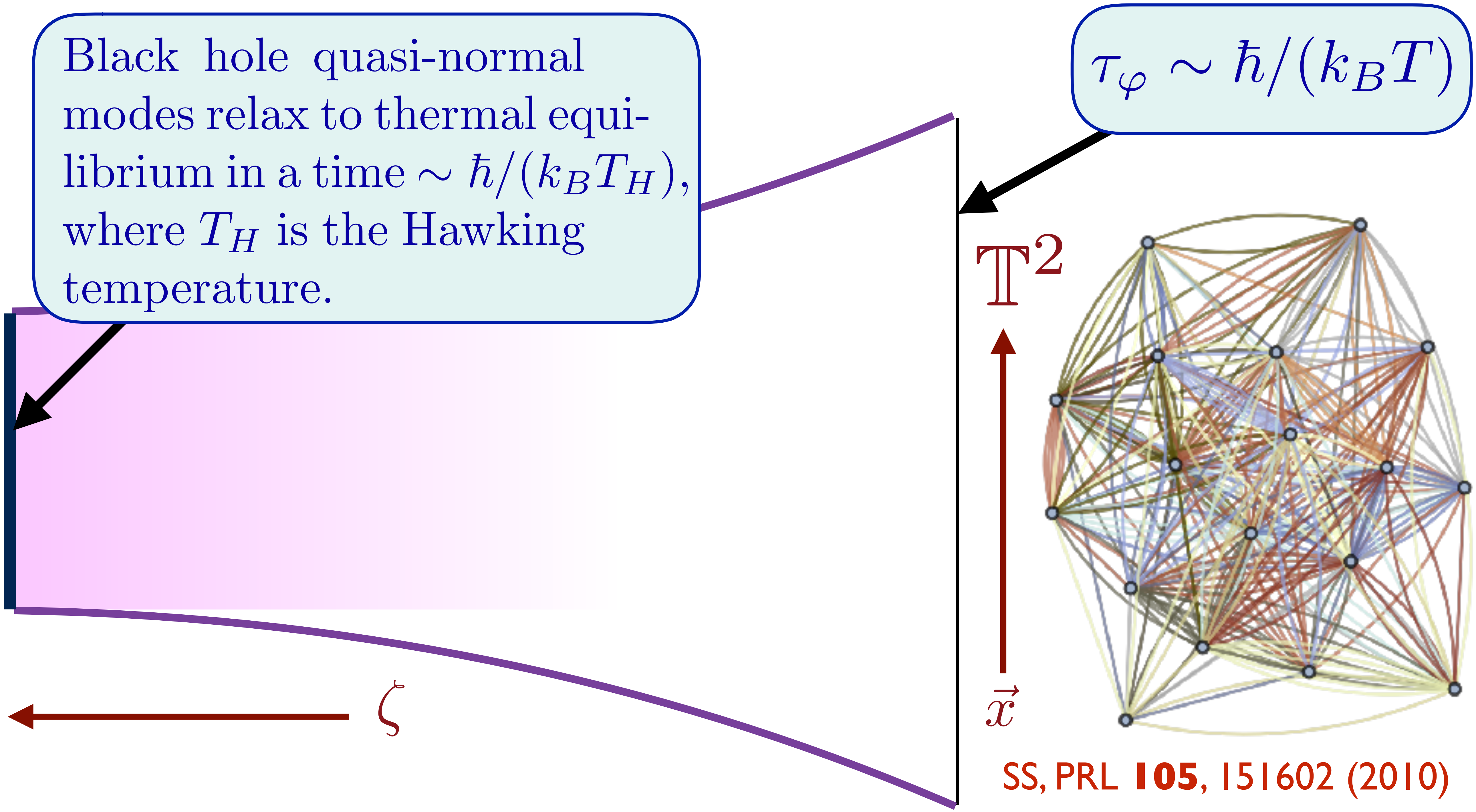


$$S = \int d^4x \sqrt{-\hat{g}} \left(\hat{\mathcal{R}} + 6/L^2 - \frac{1}{4} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} \right)$$

SS, PRL **105**, 151602 (2010)

The BH entropy is proportional to the size of $\mathbb{T}^2$, and hence the surface area of the black hole. Mapping to SYK applies when temperature $\ll 1/(\text{size of } \mathbb{T}^2)$.

SYK and black holes

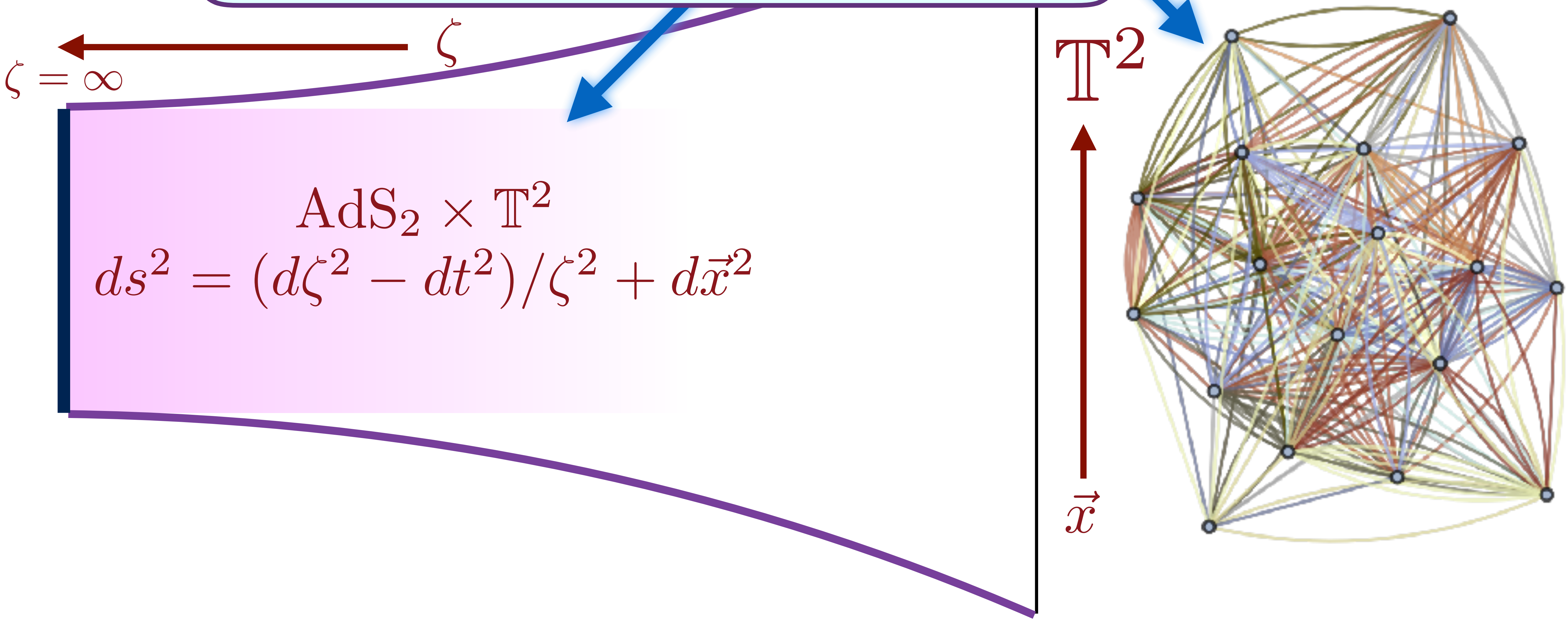


SS, PRL **105**, 151602 (2010)

The SYK model has "dual" description in which an extra spatial dimension, ζ, emerges. The curvature of this "emergent" spacetime is described by Einstein's theory of general relativity

SYK and AdS_2

Equilibrium and non-equilibrium* dynamics described by a theory with SL(2,R) invariance, and effective Schwarzian action, $S[h(\tau)]$, of a time reparameterization $\tau \to h(\tau)$.



J. Maldacena, D. Stanford, and Zhenbin Yang, arXiv:1606.01857;
K. Jensen, arXiv:1605.06098; J. Engelsoy, T.G. Mertens, and H. Verlinde, arXiv:1606.03438
*A. Eberlein, V. Kasper, S. Sachdev, and J. Steinberg, arXiv:1706.07803

SYK and AdS_2

Equilibrium and non-equilibrium* dynamics described by a theory with SL(2,R) invariance, and effective Schwarzian action, $S[h(\tau)]$, of a time reparameterization $\tau \to h(\tau)$.

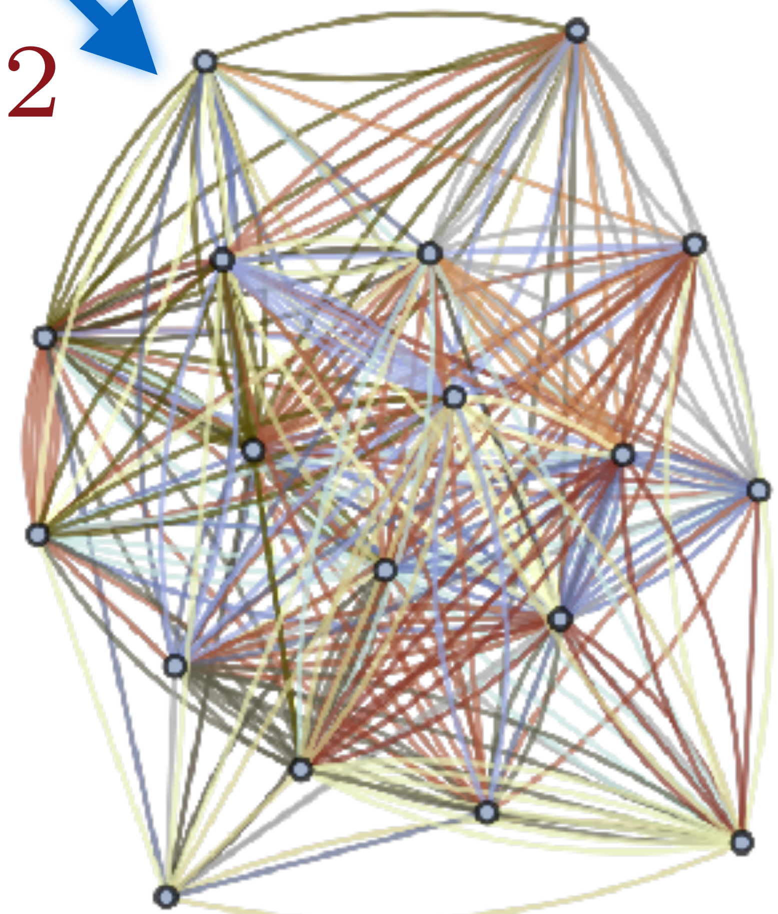
ζ

$\zeta = \infty$

$$\mathrm{AdS}_2 \times \mathbb{T}^2$$
$$ds^2 = (d\zeta^2 - dt^2)/\zeta^2 + d\vec{x}^2$$

$\mathbb{T}^2$

$\vec{x}$



SL(2,R) is the isometry group of AdS_2: $ds^2 = (d\tau^2 + d\zeta^2)/\zeta^2$ is invariant under

$$\tau' + i\zeta' = \frac{a(\tau + i\zeta) + b}{c(\tau + i\zeta) + d}$$

with $ad - bc = 1$.

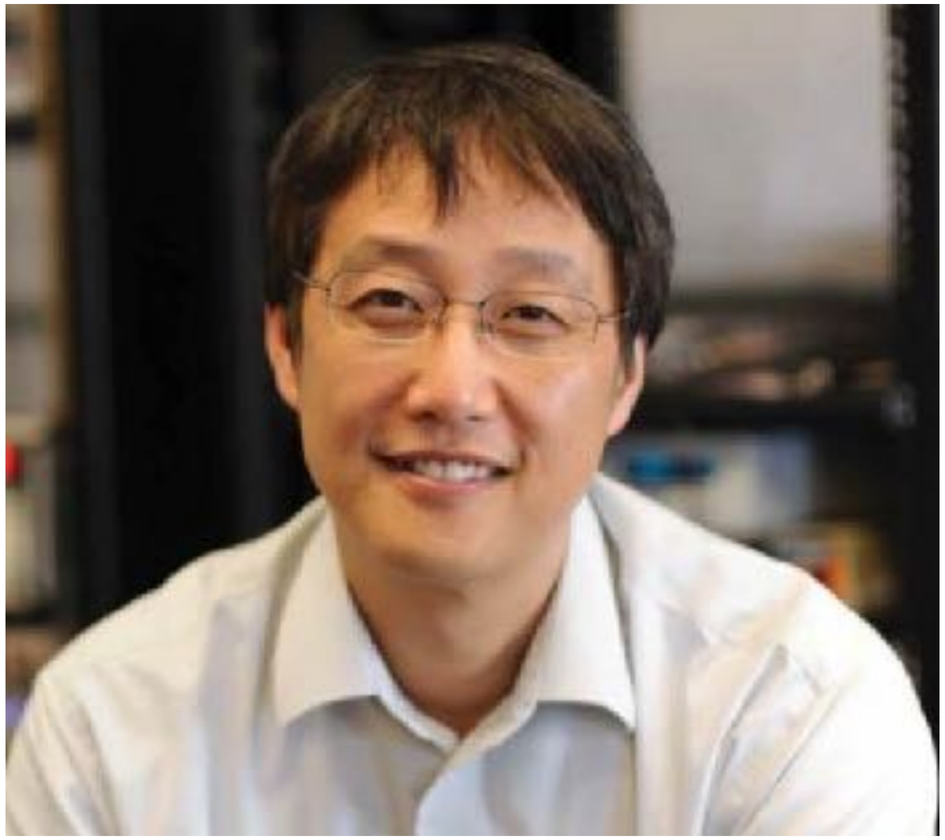
J. Maldacena, D. Stanford, and Zhenbin Yang, arXiv:1606.01857;
K. Jensen, arXiv:1605.06098; J. Engelsoy, T.G. Mertens, and H. Verlinde, arXiv:1606.03438
*A. Eberlein, V. Kasper, S. Sachdev, and J. Steinberg, arXiv:1706.07803

- Graphene

Non-quasiparticle "strange metal" transport

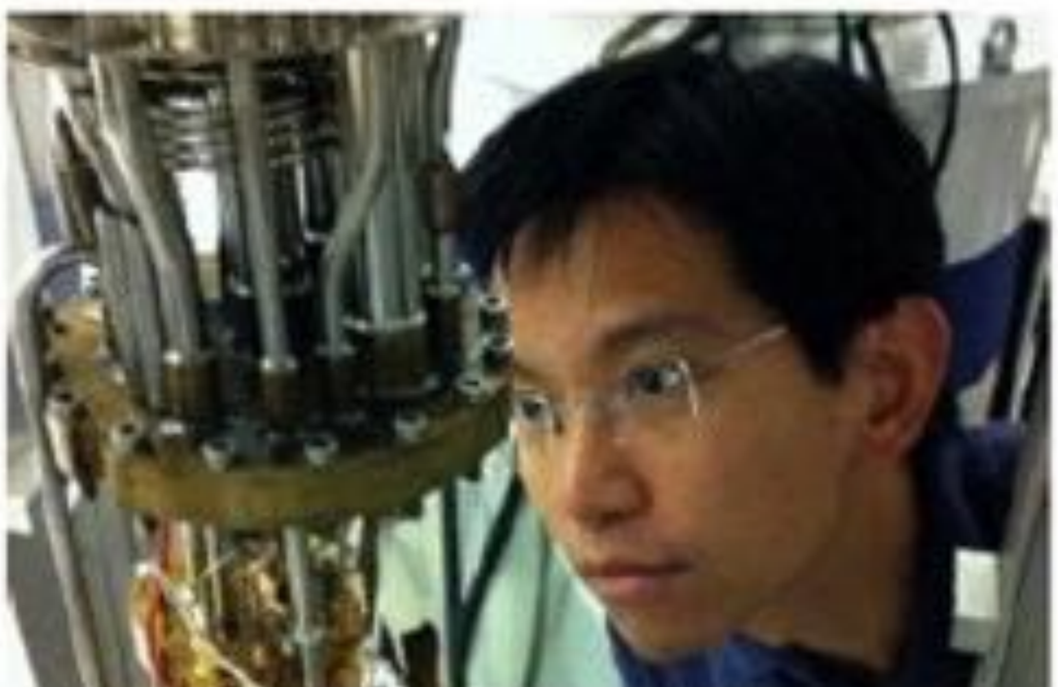
Theoretical predictions inspired by holography

Comparison with experiments



Philip Kim

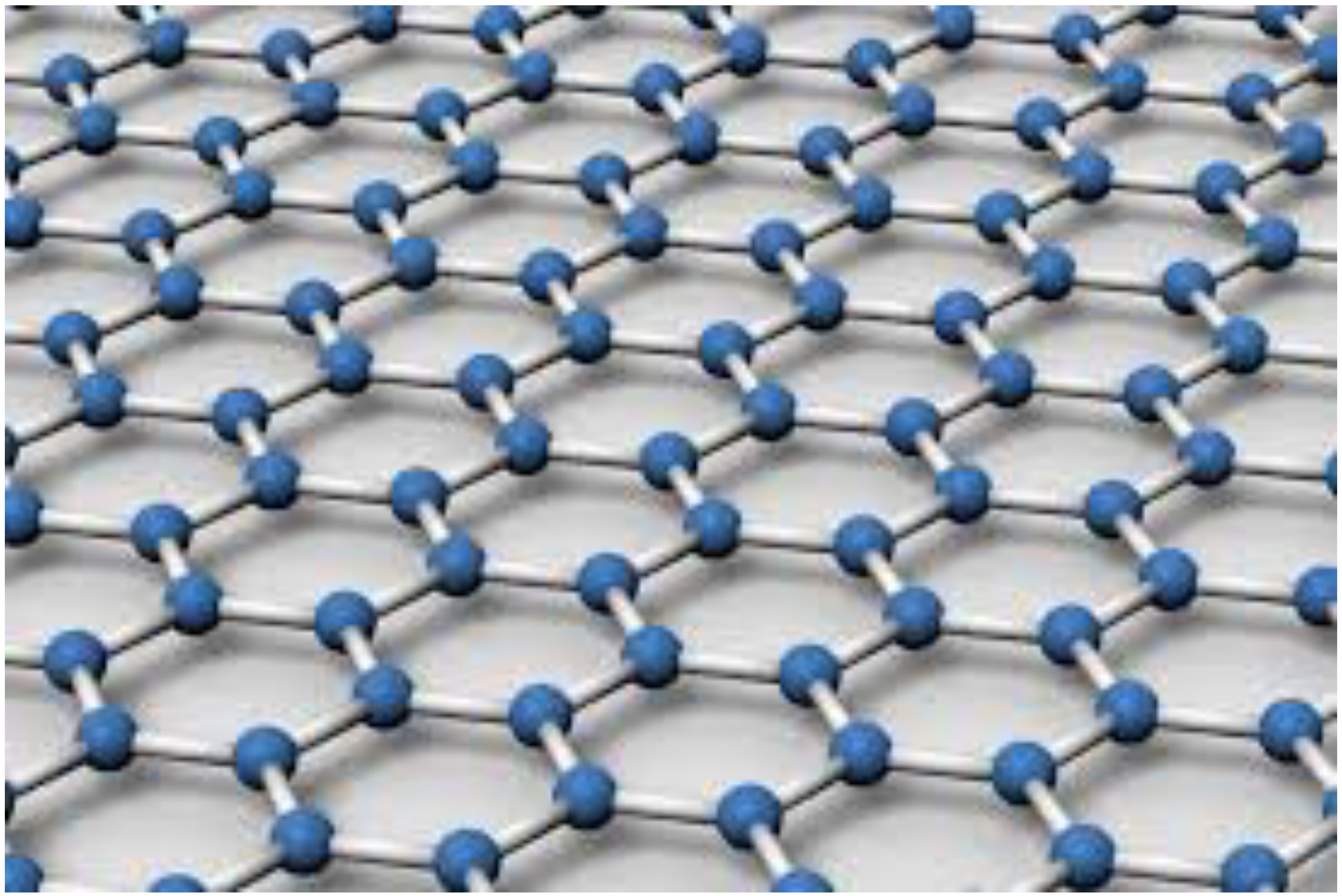
Jesse Crossno

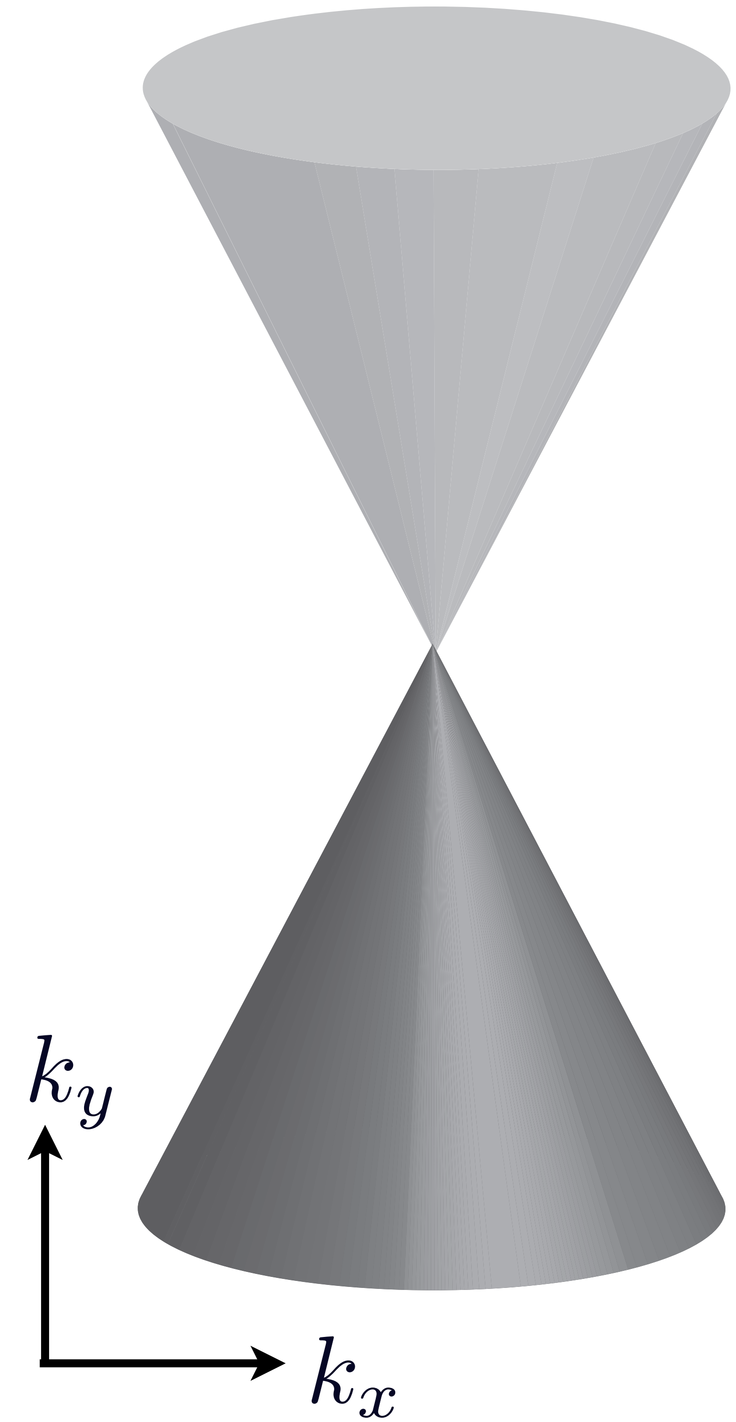


Kin Chung Fong

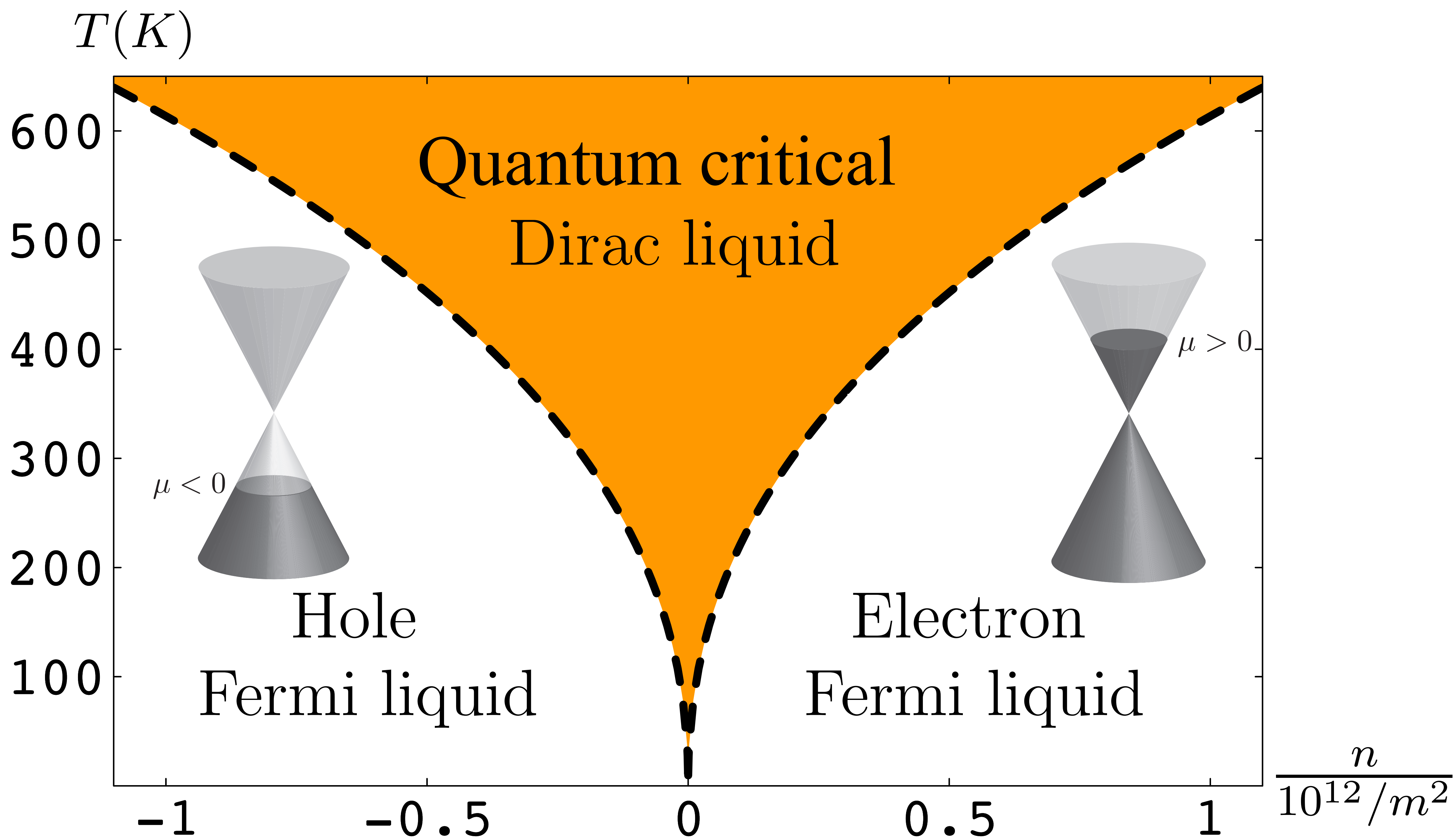
Andrew Lucas

Graphene





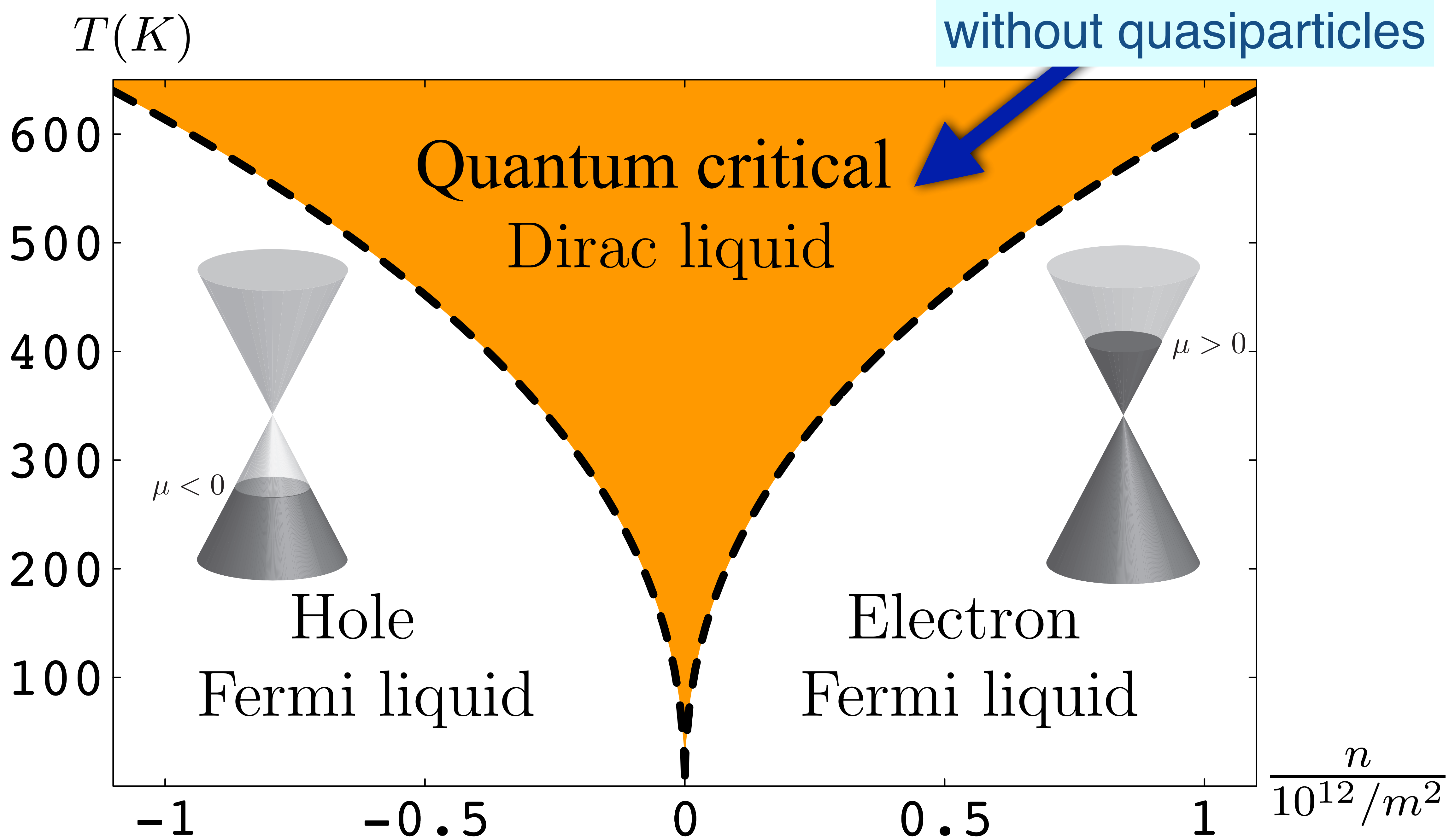
Graphene



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



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

Graphene at half-filling; no impurities

Low energy theory has 4 two-component Dirac fermions, ψ_σ, $\sigma = 1 \ldots 4$, interacting with a $1/r$ Coulomb interaction

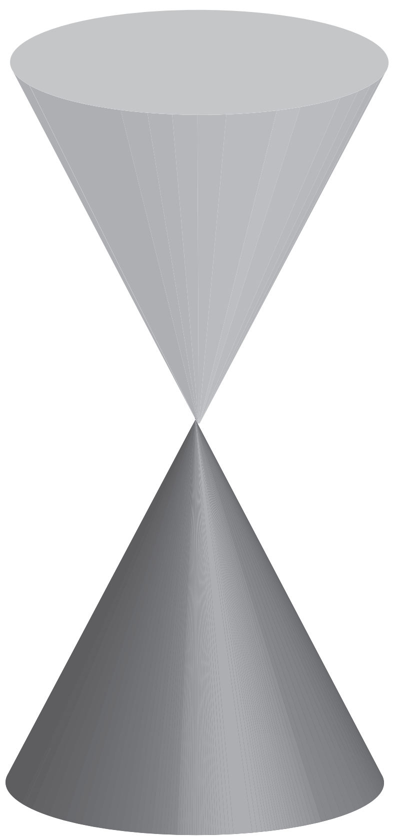
$$\mathcal{S} = \int d^2 r d\tau \psi_\sigma^\dagger \left(\partial_\tau - i v_F \vec{\sigma} \cdot \vec{\nabla} \right) \psi_\sigma + \frac{e^2}{2} \int d^2 r d^2 r' d\tau \psi_\sigma^\dagger \psi_\sigma(r) \frac{1}{|r - r'|} \psi_{\sigma'}^\dagger \psi_{\sigma'}(r')$$

Dimensionless "fine-structure" constant $\alpha = e^2/(\hbar v_F)$.
RG flow of α:

$$\frac{d\alpha}{d\ell} = -\alpha^2 + \ldots$$

Behavior is similar to a conformal field theory (CFT) in 2+1 dimensions with $\alpha \sim 1/\ln(\text{scale})$

Electrical conductivity is finite without impurities and with particle-hole symmetry



	Particles	Holes
Momentum	→	←
Electrical current	→	→

Collisionless-hydrodynamic crossover in graphene

$$\sigma_Q(\omega) = \begin{cases} \dfrac{e^2}{h}\left[\dfrac{\pi}{2} + \mathcal{O}\left(\dfrac{1}{\ln(\Lambda/\omega)}\right)\right] & , \quad \hbar\omega \gg k_B T \\ \dfrac{e^2}{h\alpha^2(T)}\left[0.760 + \mathcal{O}\left(\dfrac{1}{|\ln(\alpha(T))|}\right)\right] & , \quad \hbar\omega \ll k_B T \alpha^2(T) \end{cases}$$

I. Herbut, V. Juricic, and O. Vafek, *Phys. Rev. Lett.* **100**, 046403 (2008).

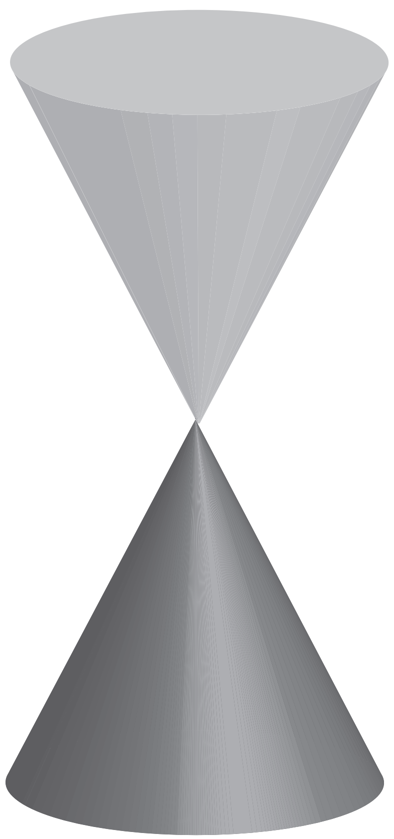
where $\alpha(T)$ is the T-dependent fine structure constant which obeys

$$\alpha(T) = \frac{\alpha}{1 + (\alpha/4)\ln(\Lambda/T)} \overset{T\to 0}{\sim} \frac{4}{\ln(\Lambda/T)}$$

Crossover takes place on a time scale $\sim \hbar/(\alpha^2 k_B T)$

L. Fritz, M. Mueller, J. Schmalian and S. Sachdev, PRB **78**, 085416 (2008)

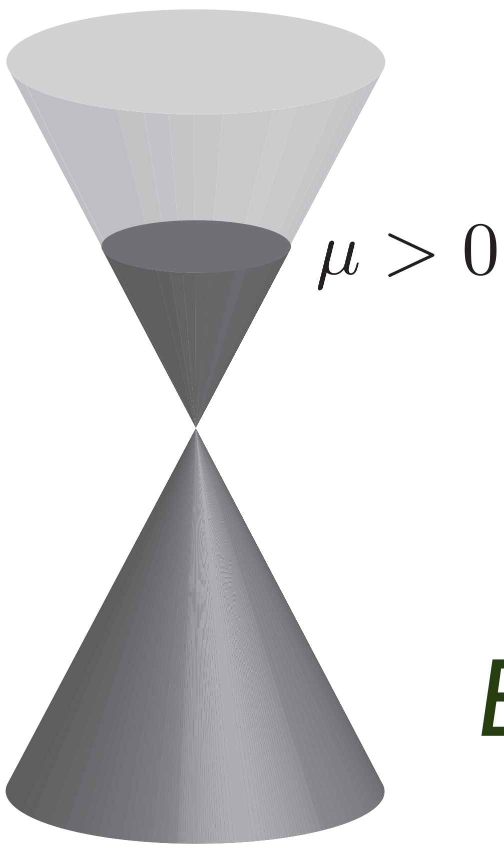
Electrical conductivity is finite
without impurities and
with particle-hole symmetry



	Particles	**Holes**
Momentum	→	←
Electrical current	→	→

And thermal conductivity is infinite
(stress-energy tensor is symmetric)

Electrical conductivity is infinite without impurities at non-zero doping

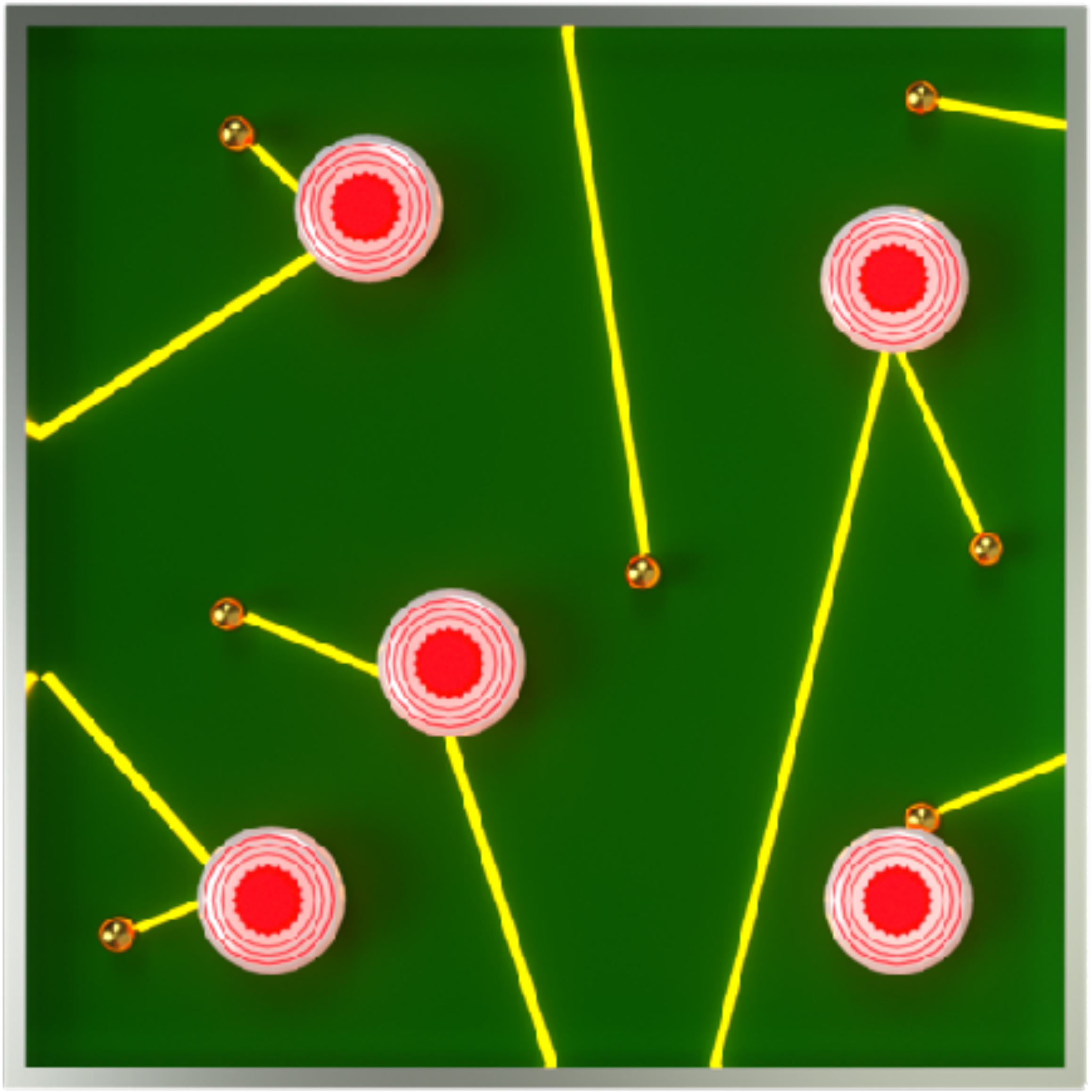


Particles

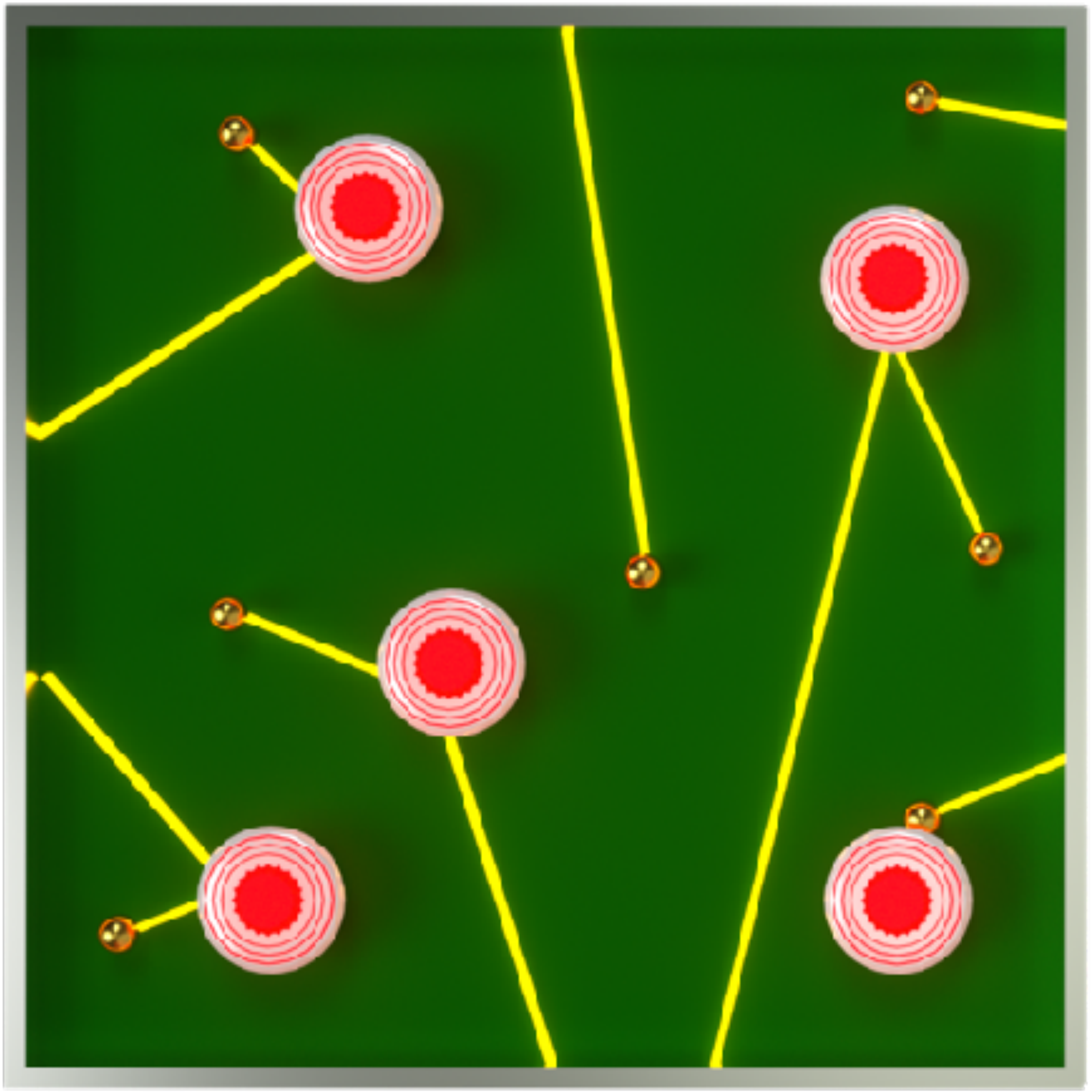
Momentum →

Electrical current →

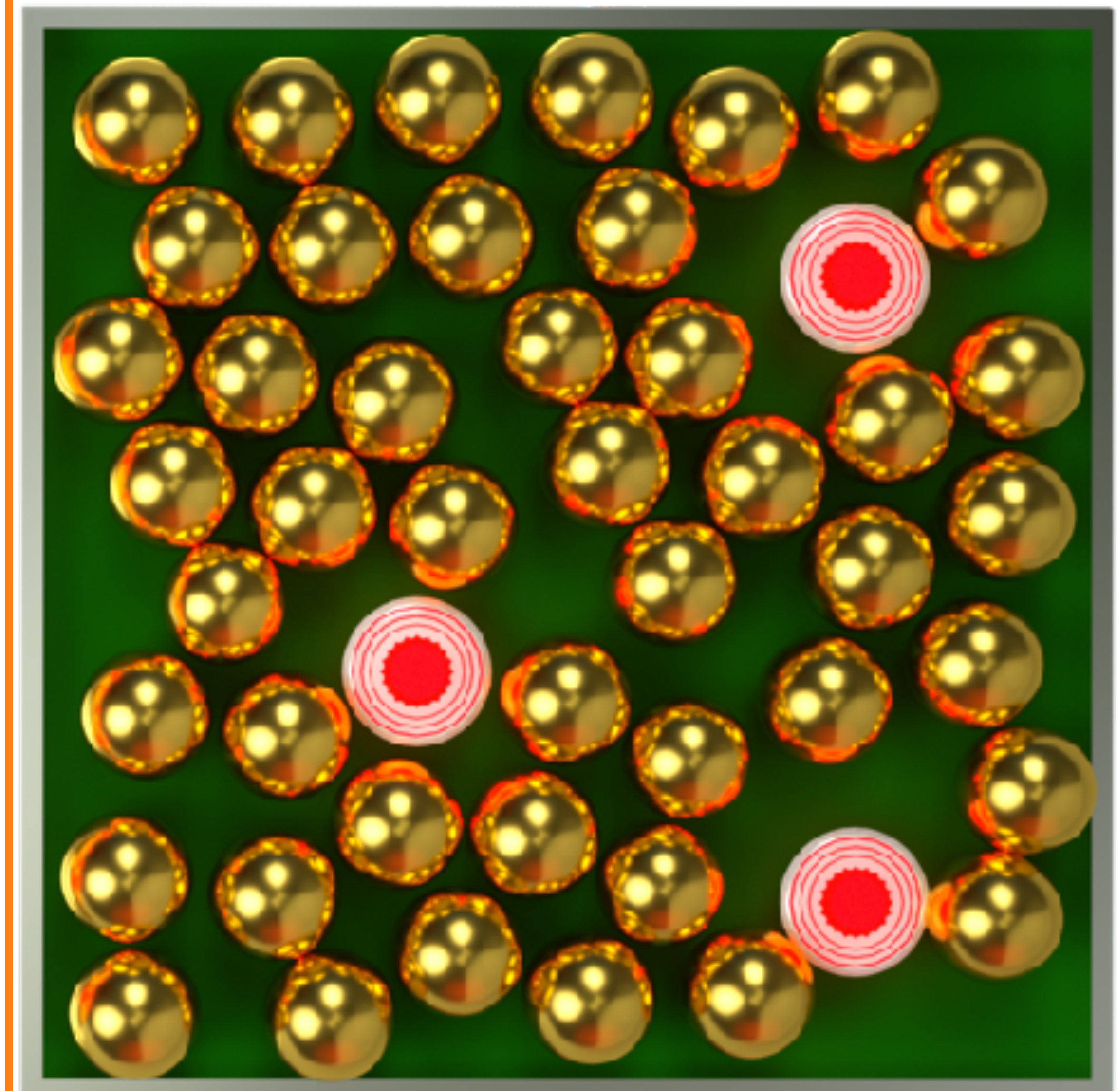
And thermal conductivity is finite



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

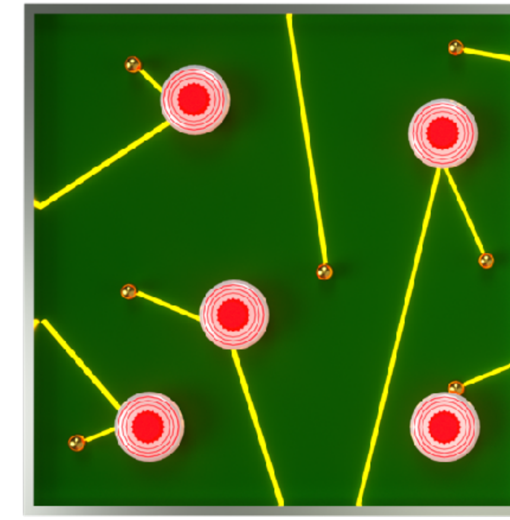


Fermi liquids: quasiparticles moving ballistically between impurity (red circles) scattering events



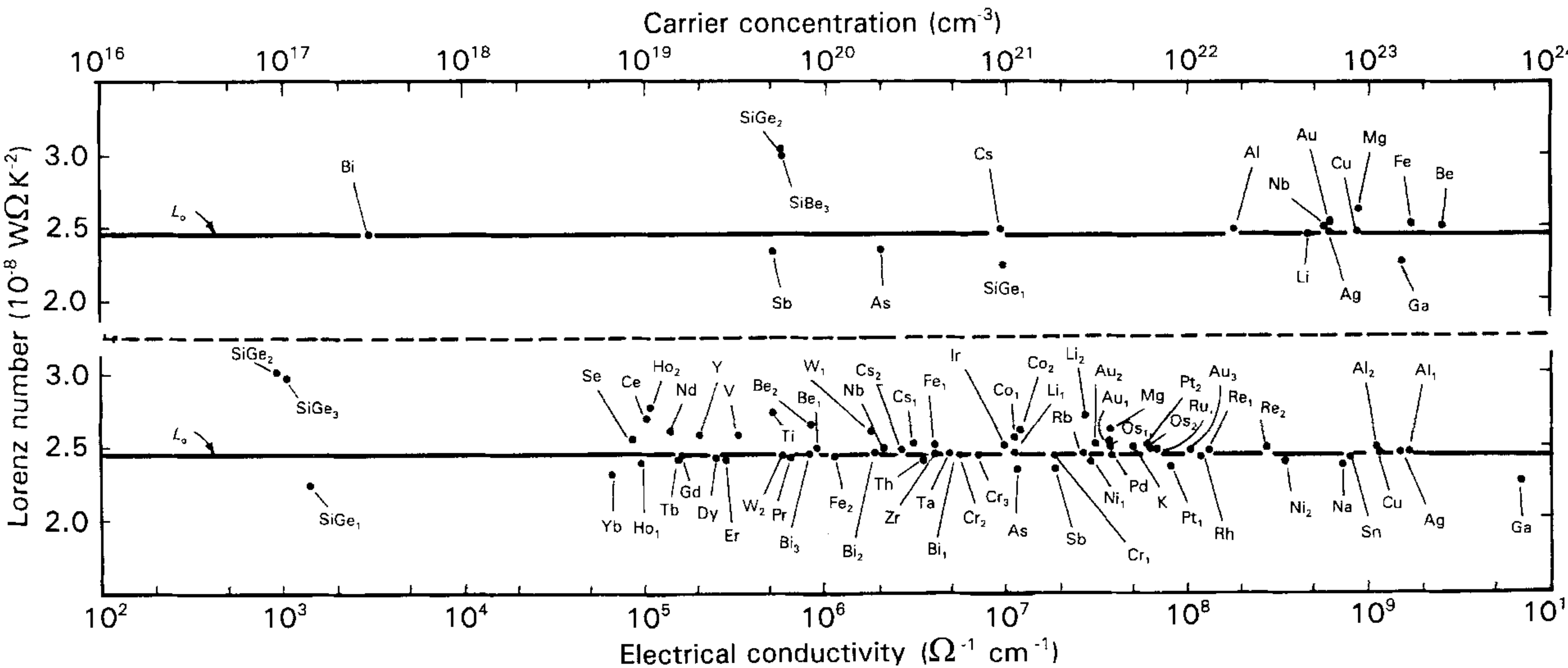
Strange metals: electrons scatter frequently off each other, so there is no regime of ballistic quasiparticle motion. The electron "liquid" then "flows" around impurities

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)

To understand a realistic strange metal, we use a hydrodynamic approach and include

- A bias voltage, leading to particle-hole asymmetry
- Dilute concentration of impurities
- A weak magnetic field

The variables entering the hydrodynamic theory are

- the external magnetic field $F^{\mu\nu}$,

$$F^{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & B \\ 0 & -B & 0 \end{pmatrix},$$

- $T^{\mu\nu}$, the stress energy tensor,
- J^{μ}, the current,
- ρ, the **difference** in density from undoped graphene.
- ε, the local energy
- P, the local pressure,
- u^{μ}, the local velocity, and
- σ_Q, a universal conductivity, which is the **single transport co-efficient**.

The dependence of ε, P, σ_Q on T and v follows from simple scaling arguments

Lorentz invariance and positivity of entropy production lead to the hydrodynamic equations of motion and constitutive relations:

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

Lorentz invariance and positivity of entropy production lead to the hydrodynamic equations of motion and constitutive relations:

$$\begin{aligned} \partial_\mu J^\mu &= 0 \\ \partial_\mu T^{\mu\nu} &= F^{\mu\nu} J_\nu \end{aligned}$$

Conservation laws/equations of motion

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

Lorentz invariance and positivity of entropy production lead to the hydrodynamic equations of motion and constitutive relations:

$$
\begin{aligned}
\partial_\mu J^\mu &= 0 \\
\partial_\mu T^{\mu\nu} &= F^{\mu\nu} J_\nu \\
T^{\mu\nu} &= (\varepsilon + P) u^\mu u^\nu + P g^{\mu\nu} \\
J^\mu &= \rho u^\mu
\end{aligned}
$$

Constitutive relations which follow from Lorentz transformation to moving frame

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

Lorentz invariance and positivity of entropy production lead to the hydrodynamic equations of motion and constitutive relations:

$$\begin{aligned} \partial_\mu J^\mu &= 0 \\ \partial_\mu T^{\mu\nu} &= F^{\mu\nu} J_\nu \\ T^{\mu\nu} &= (\varepsilon + P) u^\mu u^\nu + P g^{\mu\nu} \\ J^\mu &= \rho u^\mu + \sigma_Q (g^{\mu\nu} + u^\mu u^\nu) \left[(-\partial_\nu \mu + F_{\nu\lambda} u^\lambda) + \mu \frac{\partial_\mu T}{T} \right] \end{aligned}$$

New dissipative term allowed by requirement of positive entropy production. There is only one independent transport co-efficient

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

Lorentz invariance and positivity of entropy production lead to the hydrodynamic equations of motion and constitutive relations:

Momentum relaxation from impurities

$$\begin{aligned}
\partial_\mu J^\mu &= 0 \\
\partial_\mu T^{\mu\nu} &= F^{\mu\nu} J_\nu + \frac{1}{\tau_{\rm imp}} \left(\delta^\mu_\nu + u^\mu u_\nu\right) T^{\nu\gamma} u_\gamma \\
T^{\mu\nu} &= (\varepsilon + P) u^\mu u^\nu + P g^{\mu\nu} \\
J^\mu &= \rho u^\mu + \sigma_Q (g^{\mu\nu} + u^\mu u^\nu) \left[\left(-\partial_\nu \mu + F_{\nu\lambda} u^\lambda\right) + \mu \frac{\partial_\mu T}{T} \right]
\end{aligned}$$

Solve initial value problem and relate results to response functions (Kadanoff+Martin)

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

Prediction for transport in the graphene strange metal

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

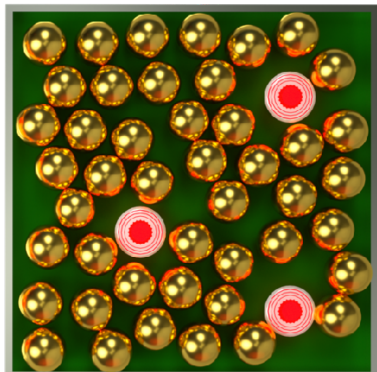
$$\sigma = \sigma_Q \left(1 + \frac{e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}}{\mathcal{H} \sigma_Q}\right) \quad , \quad \kappa = \frac{v_F^2 \mathcal{H} \tau_{\rm imp}}{T} \left(1 + \frac{e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}}{\mathcal{H} \sigma_Q}\right)^{-1}$$

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

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.

- For $\mathcal{Q} = 0$, as $\tau_{\rm imp} \to \infty$, σ remains finite, while $\kappa \to \infty$, and so $L \to \infty$.
- For $\mathcal{Q} \neq 0$, as $\tau_{\rm imp} \to \infty$, $\sigma \to \infty$, while κ remains finite, and so $L \to 0$.

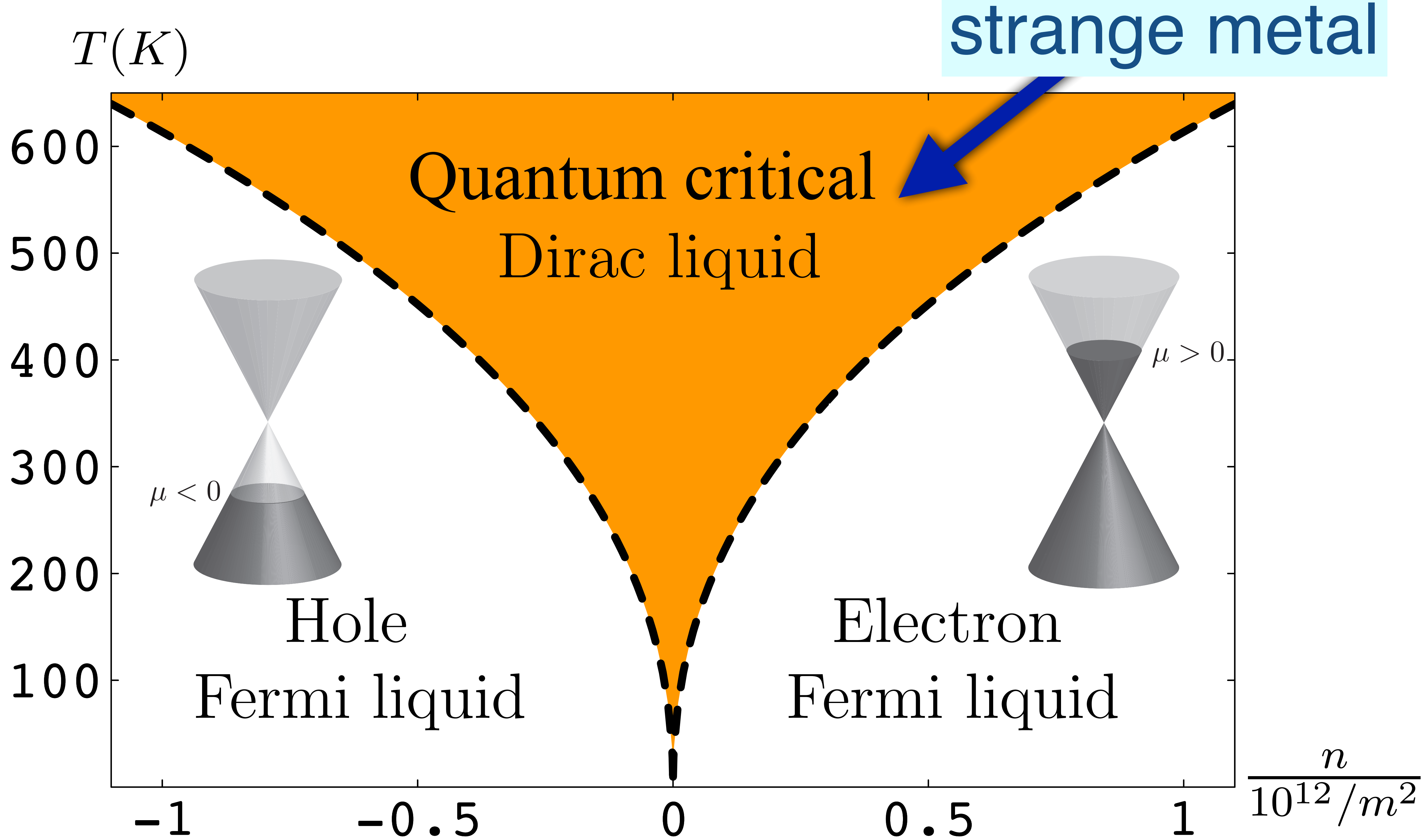
Prediction: L diverges as $1/\mathcal{Q}^4$ near $\mathcal{Q} = 0$ in clean graphene.



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

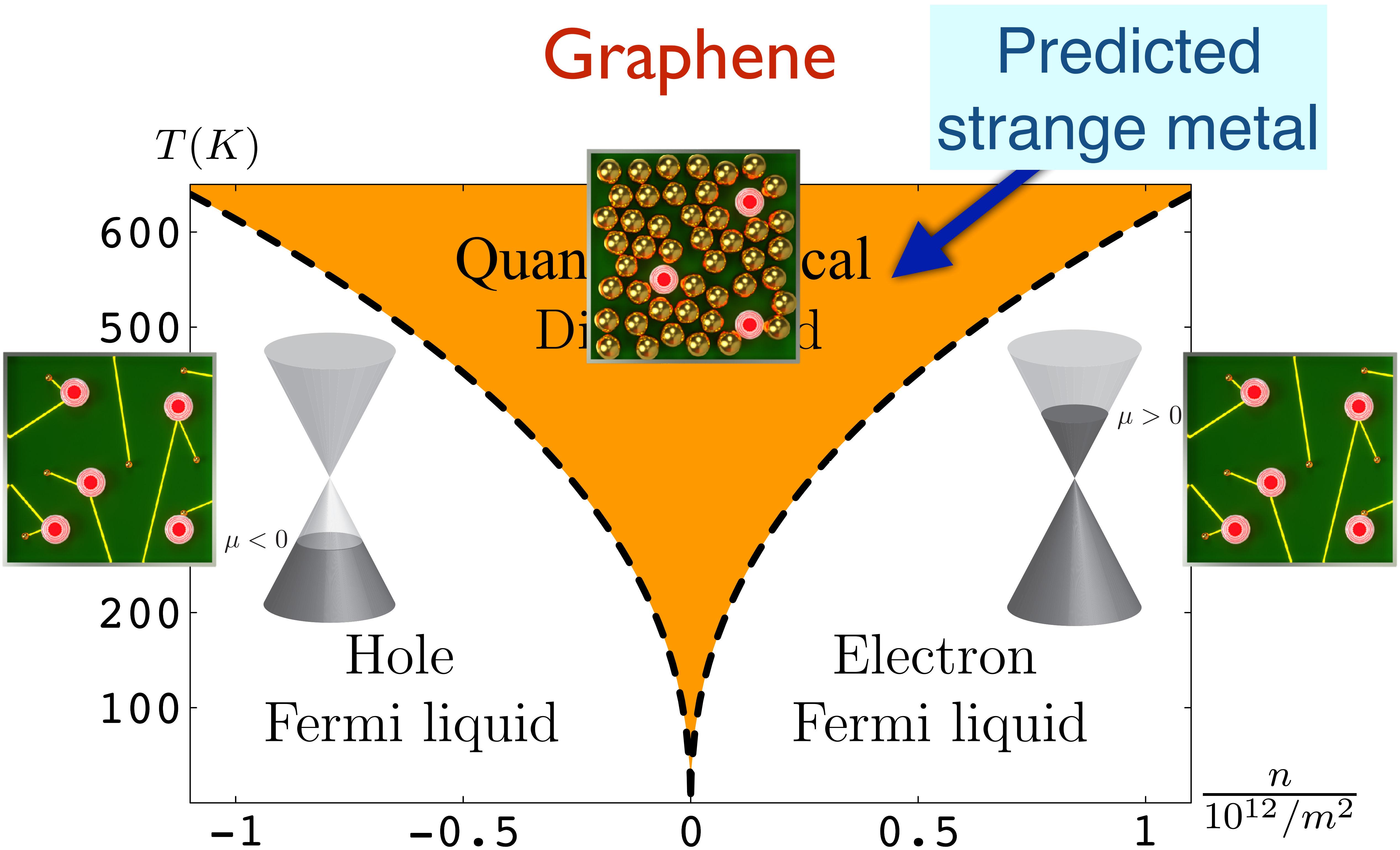
Graphene

Predicted strange metal



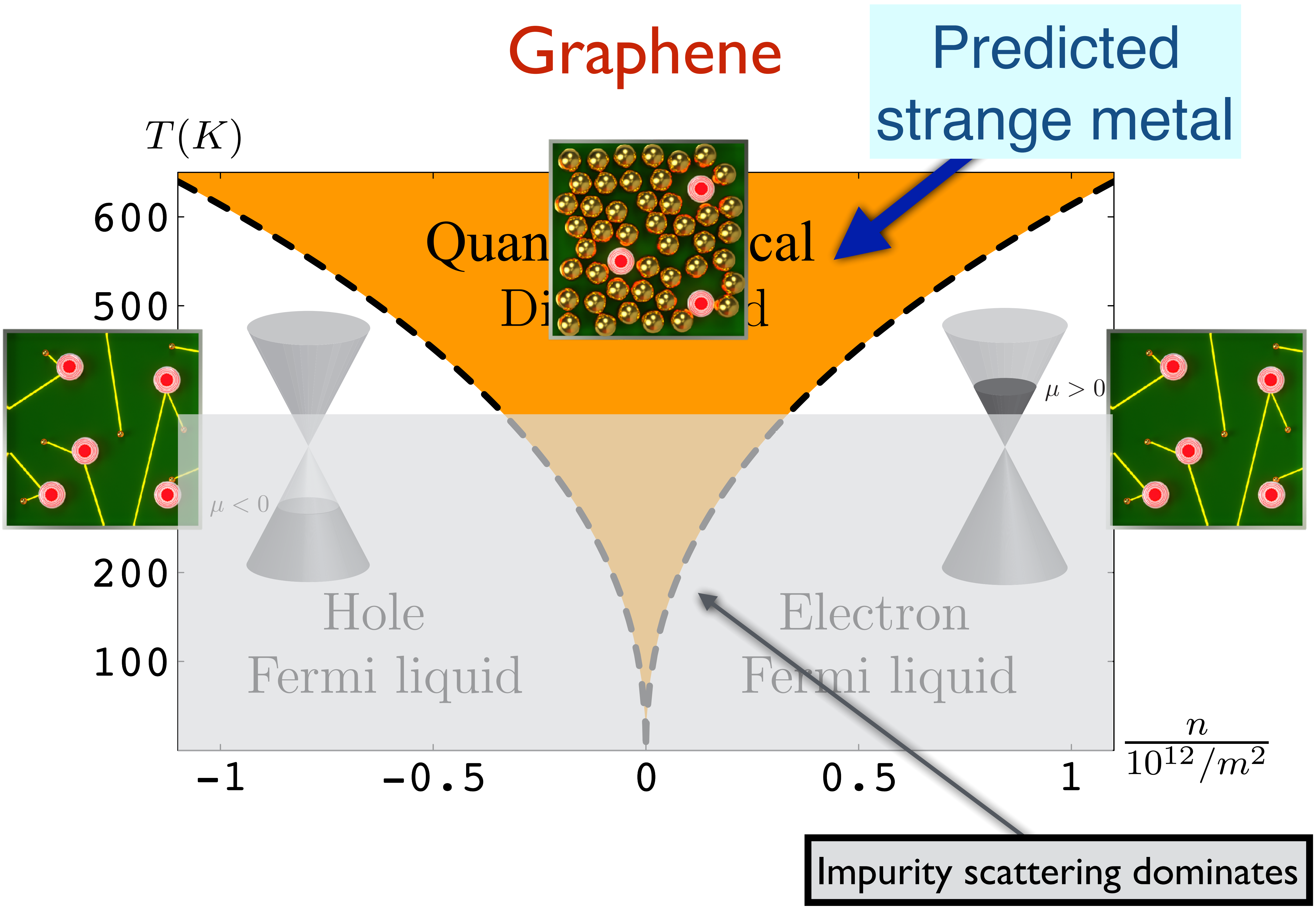
M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Graphene



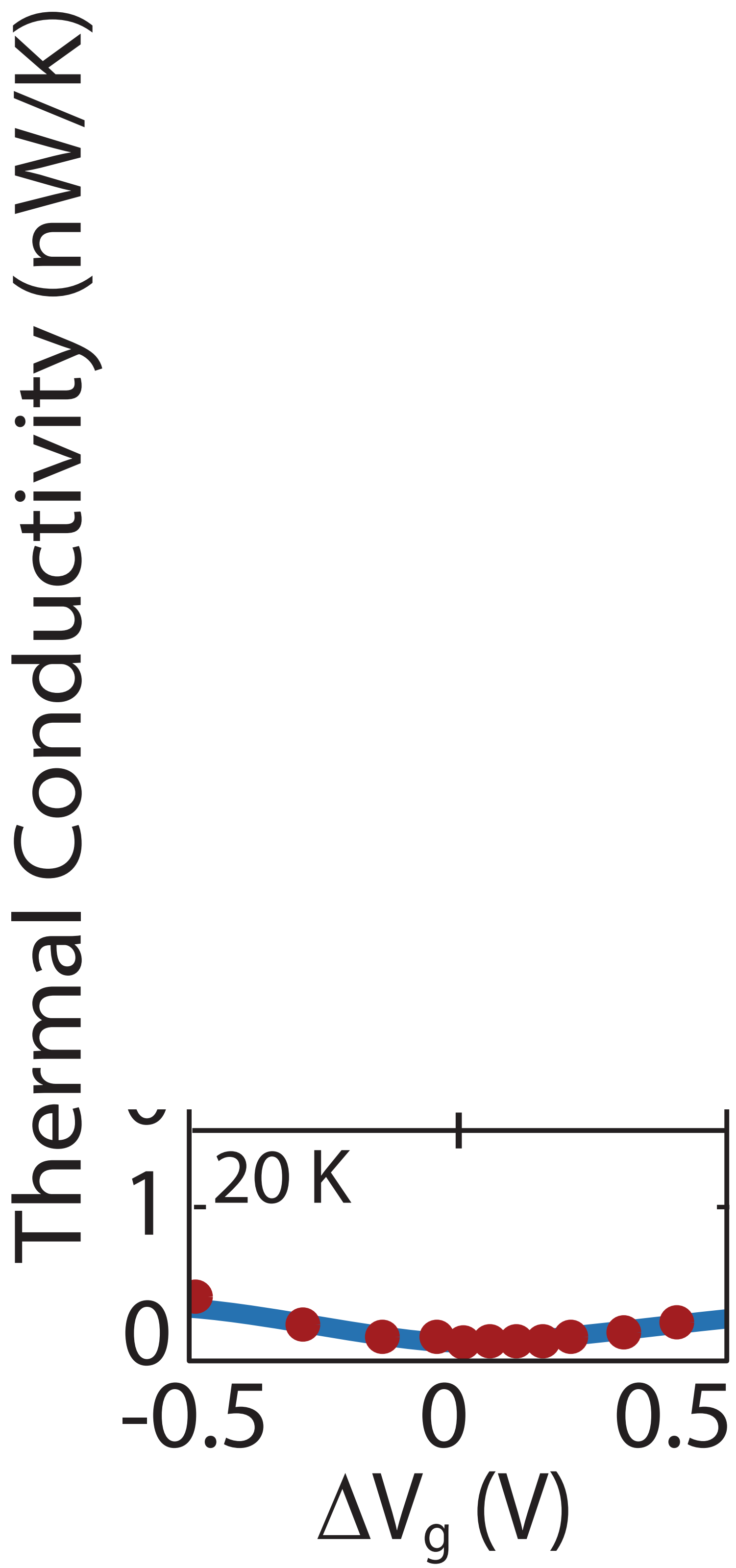
M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Graphene



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

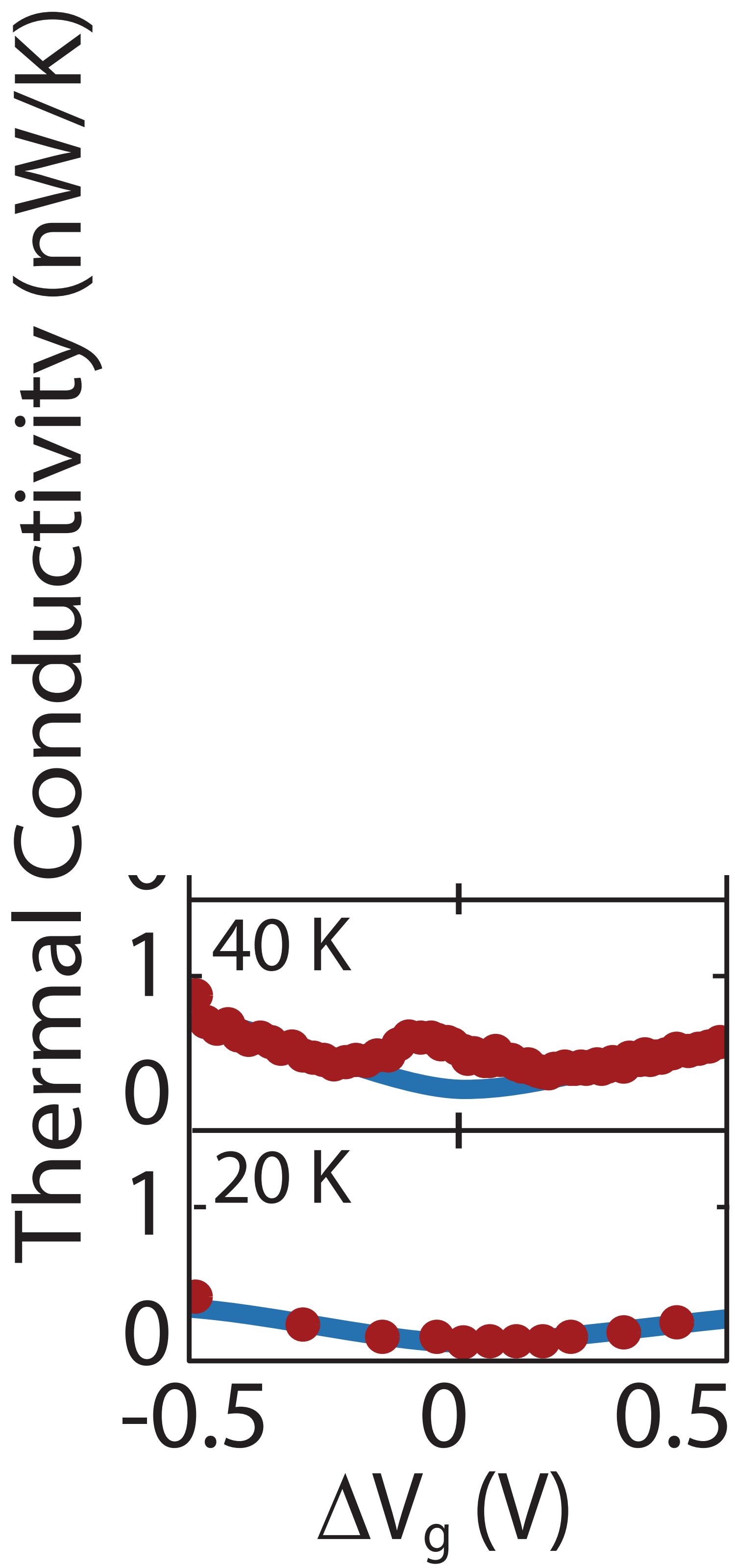
J. Crossno et al., Science **351**, 1058 (2016)



Red dots: data

Blue line: value for $L = L_0$

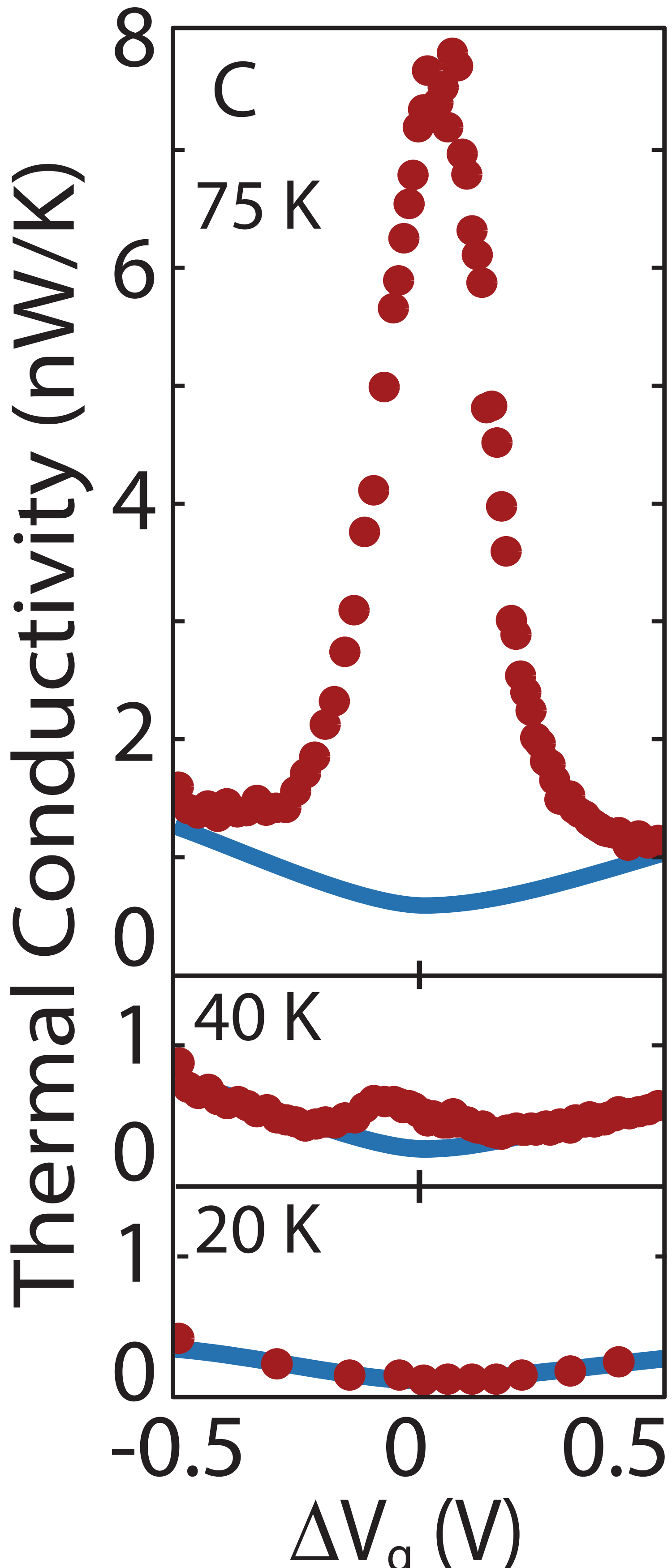
J. Crossno et al., Science **351**, 1058 (2016)



Red dots: data

Blue line: value for $L = L_0$

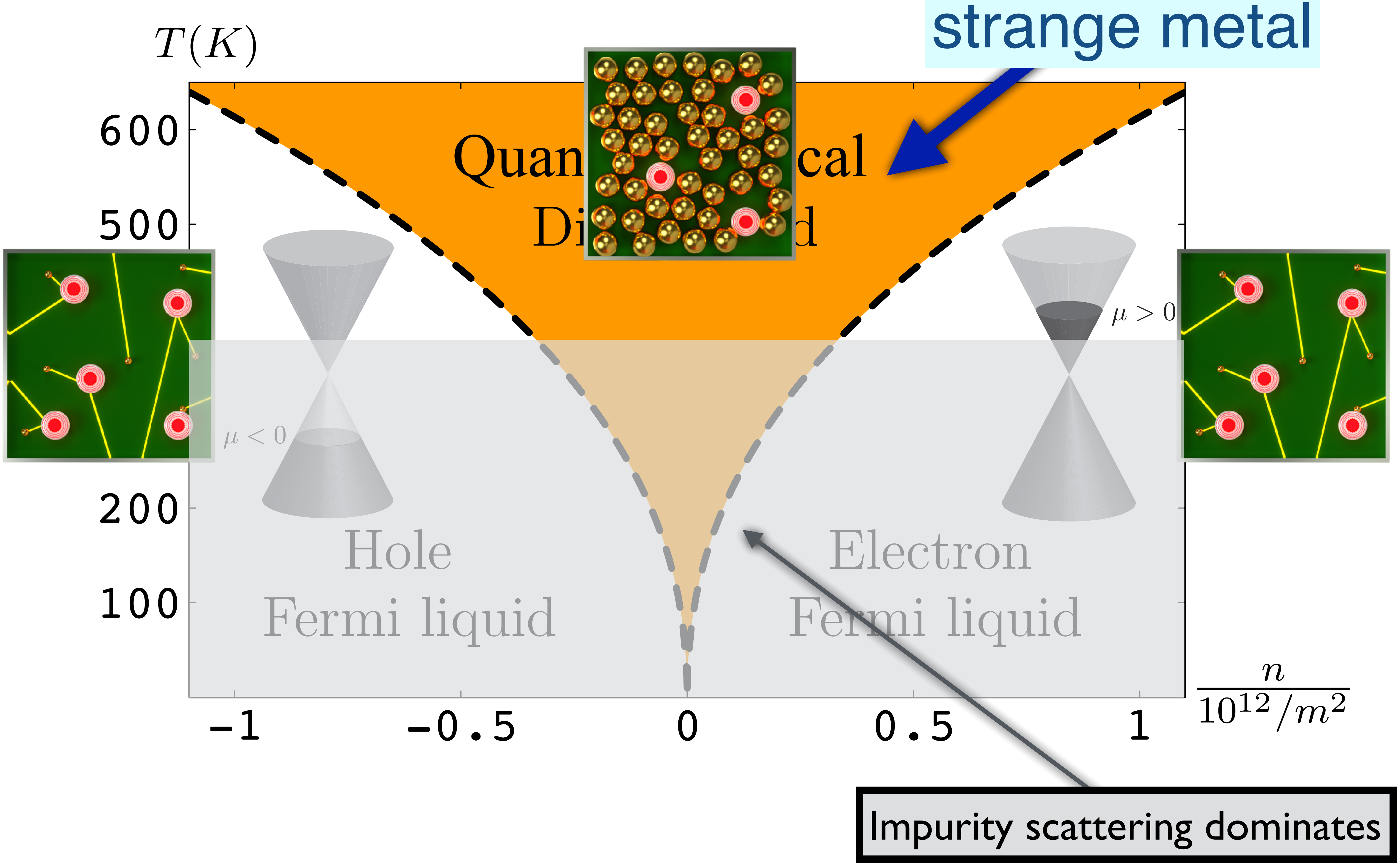
J. Crossno et al., Science **351**, 1058 (2016)



Red dots: data

Blue line: value for $L = L_0$

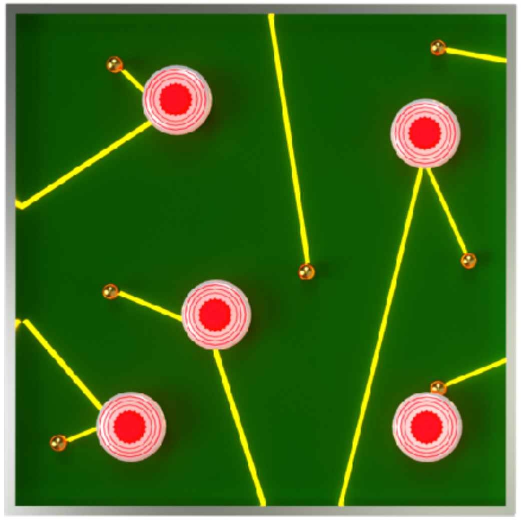
Graphene

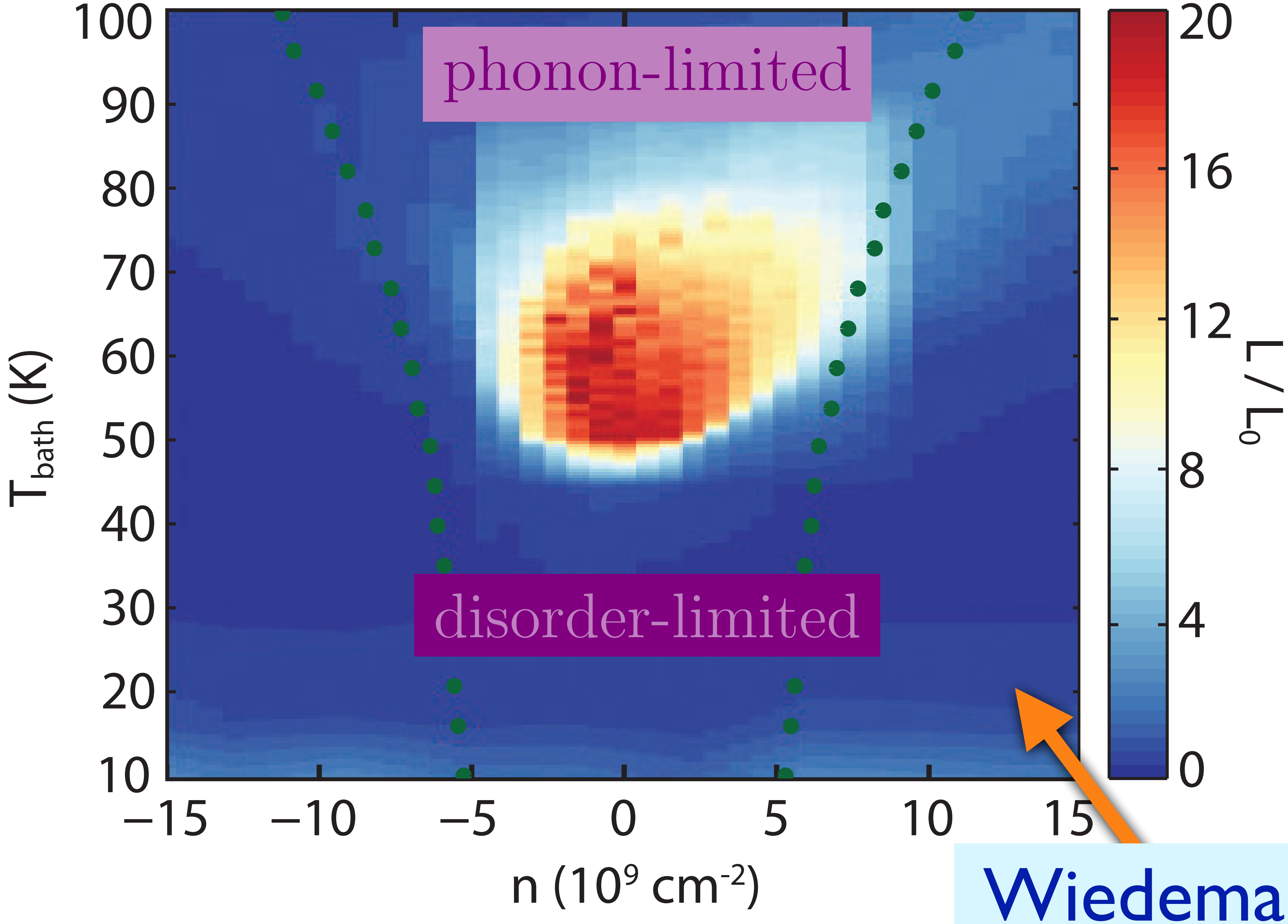


M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

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

Strange metal in graphene

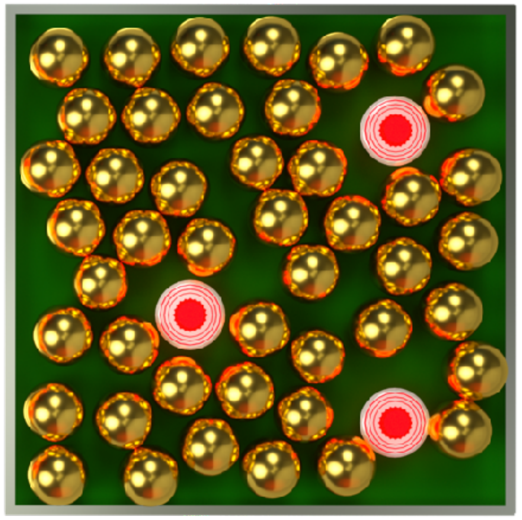


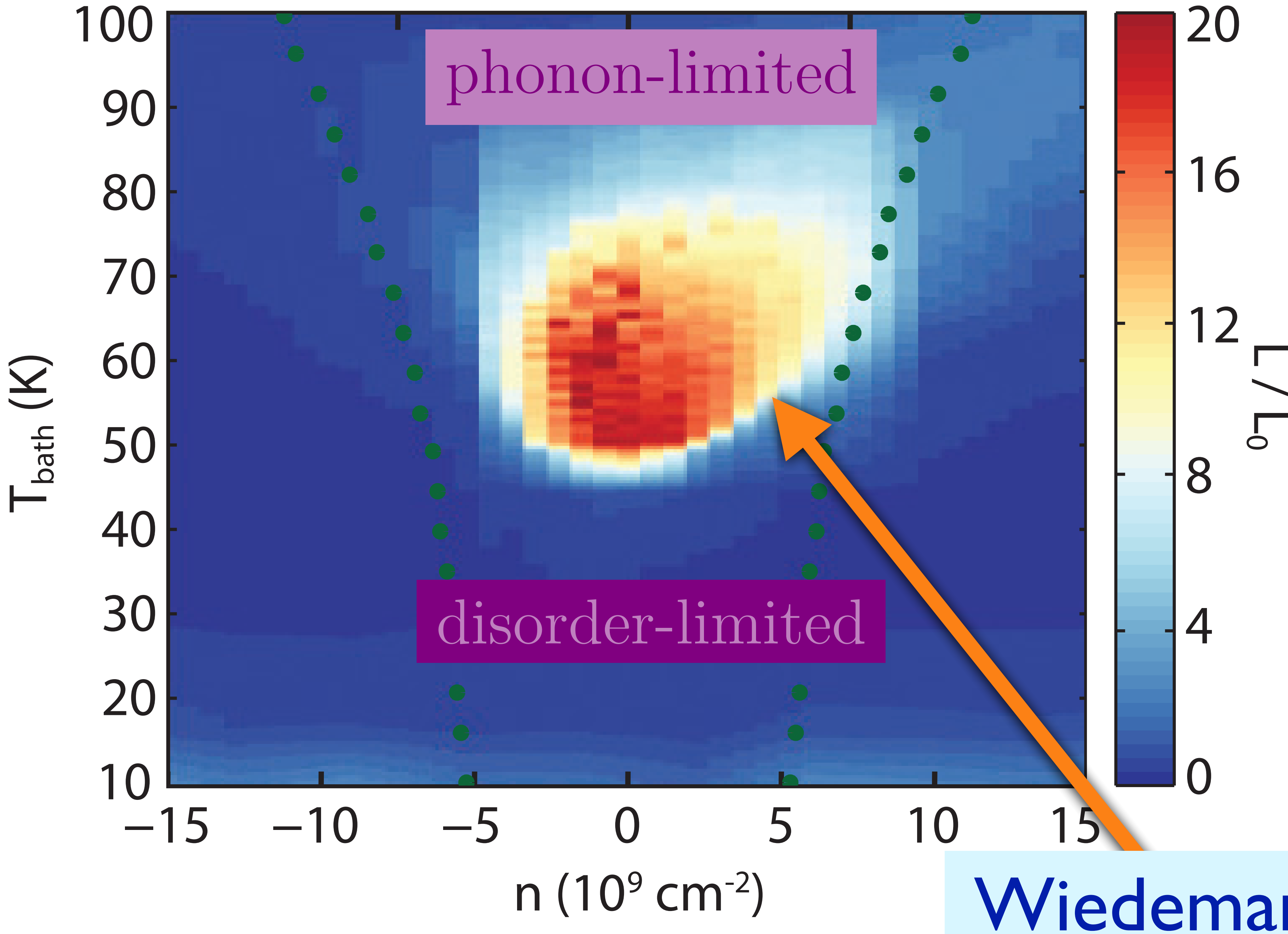


Wiedemann-Franz obeyed

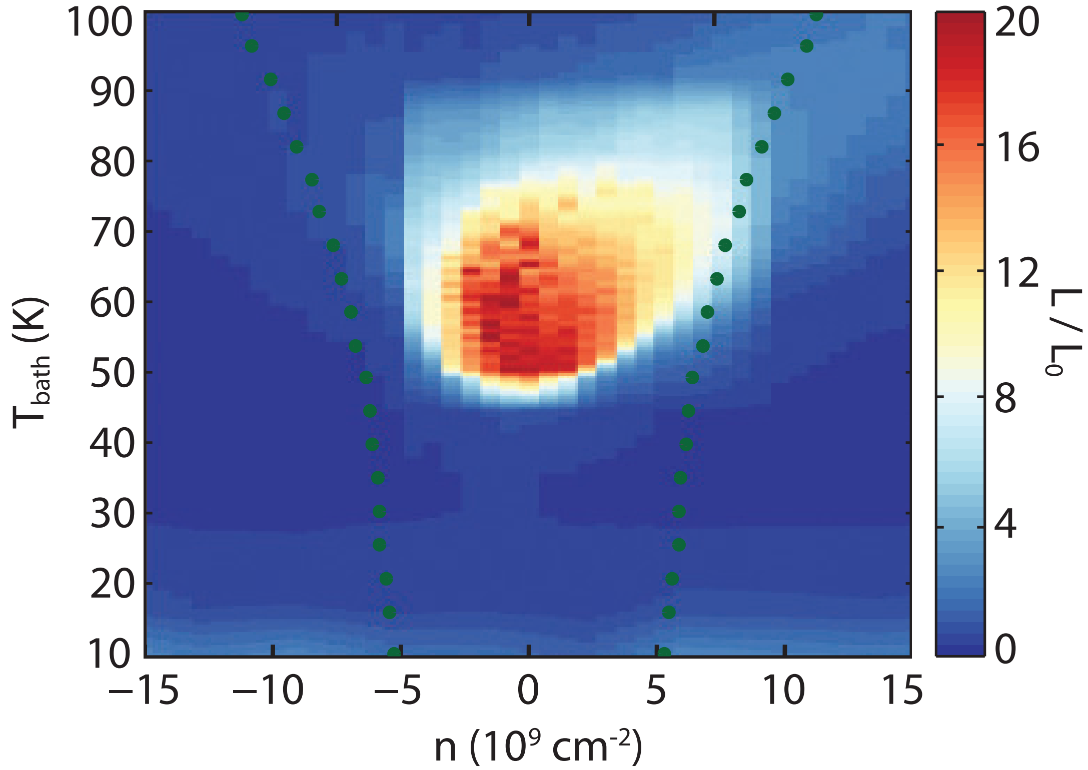
J. Crossno et al., Science **351**, 1058 (2016)

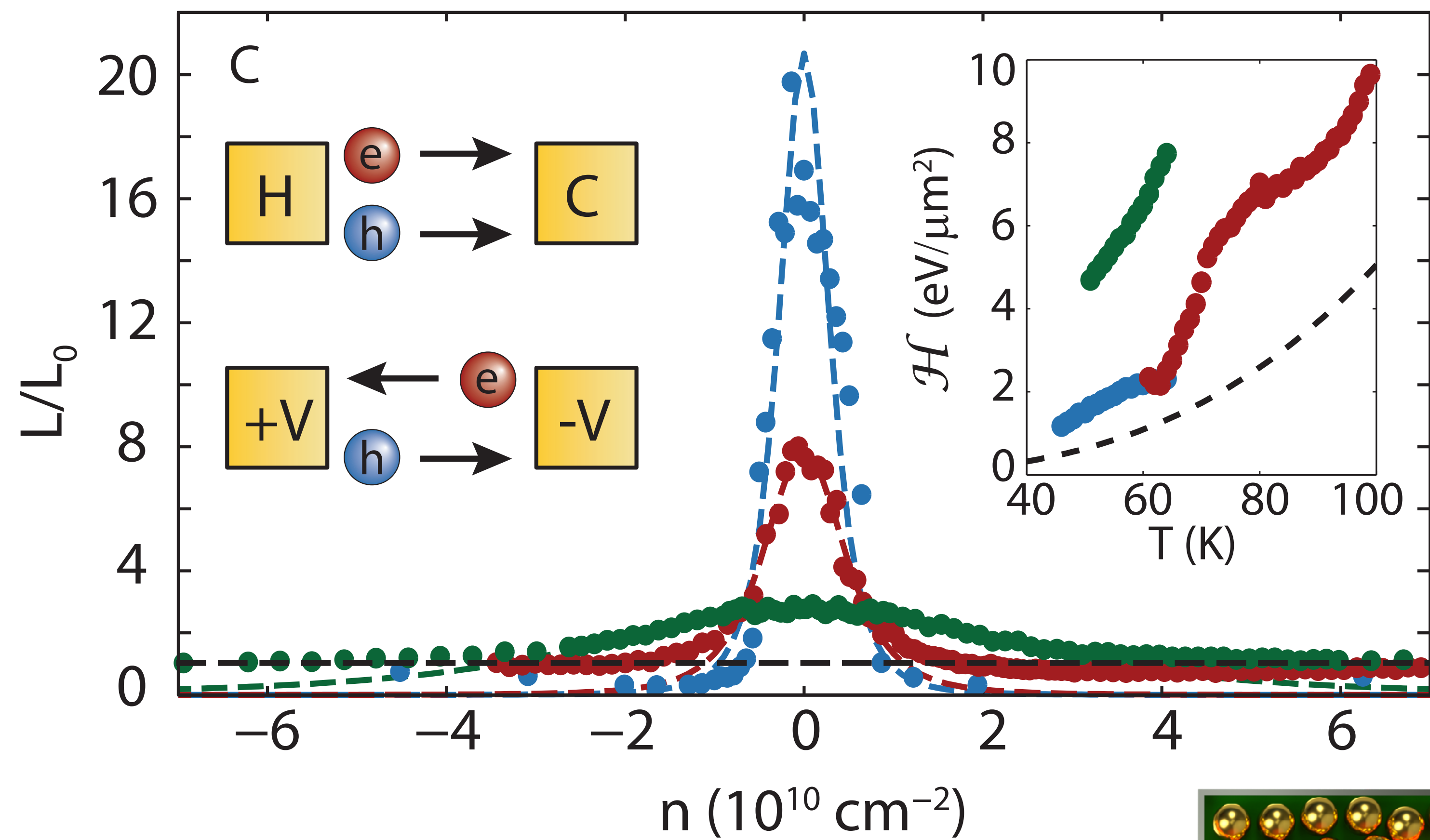
Strange metal in graphene

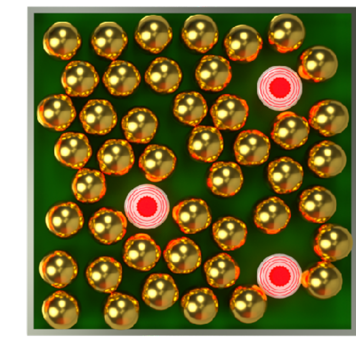


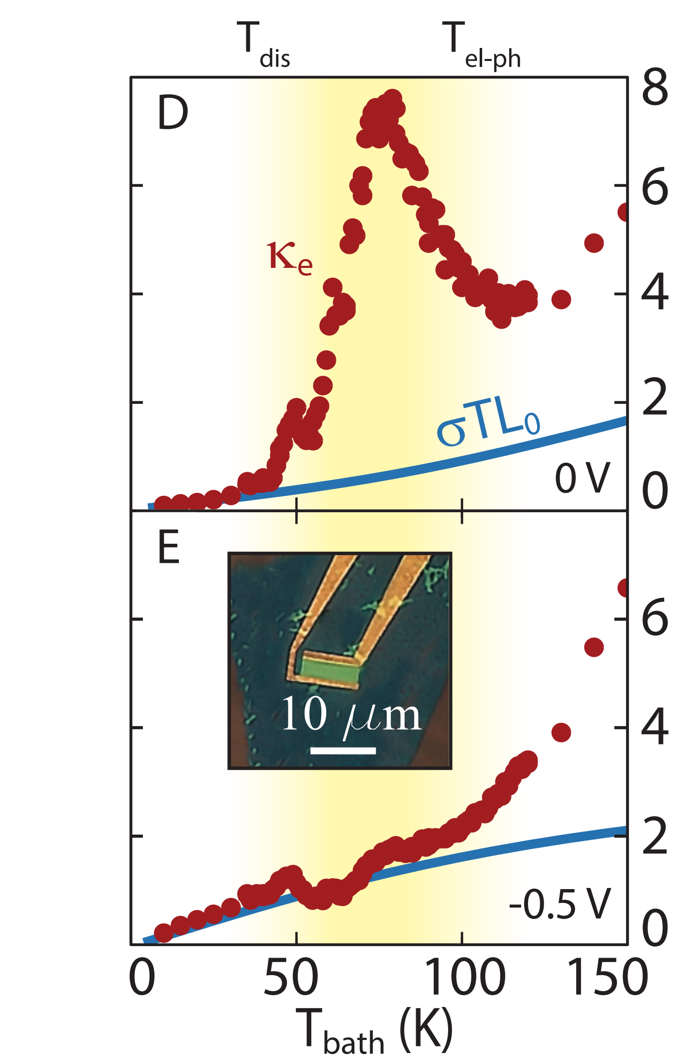


Wiedemann-Franz violated !









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

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

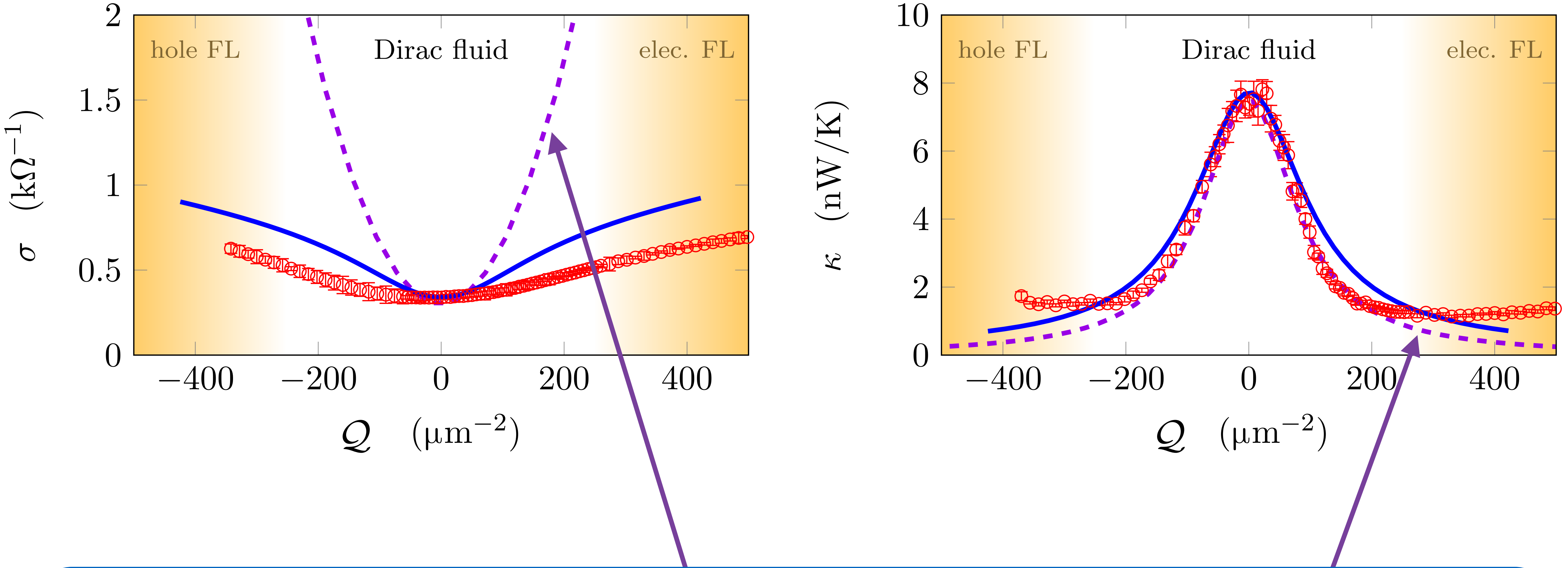
$\mathcal{Q} \rightarrow$ electron density; $\mathcal{H} \rightarrow$ enthalpy density

$\sigma_Q \rightarrow$ quantum critical conductivity

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

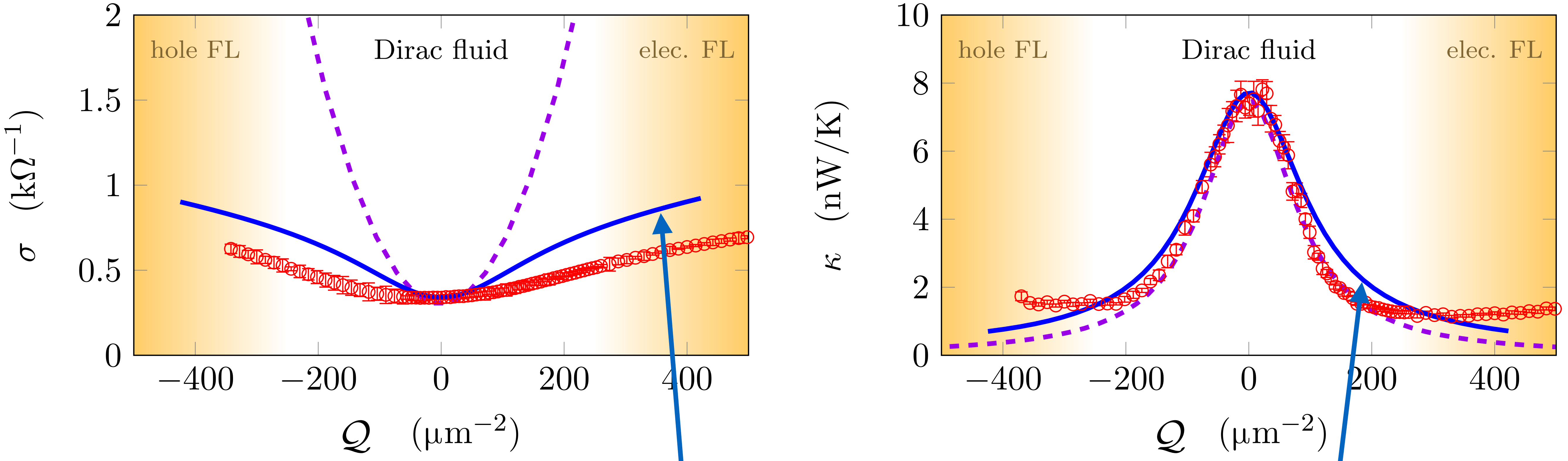
S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)

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



Comparison to theory with a single momentum relaxation time τ_{imp}. Best fit of density dependence to thermal conductivity does not capture the density dependence of electrical conductivity

A. Lucas, J. Crossno, K.C. Fong, P. Kim, and S. Sachdev, PRB **93**, 075426 (2016)

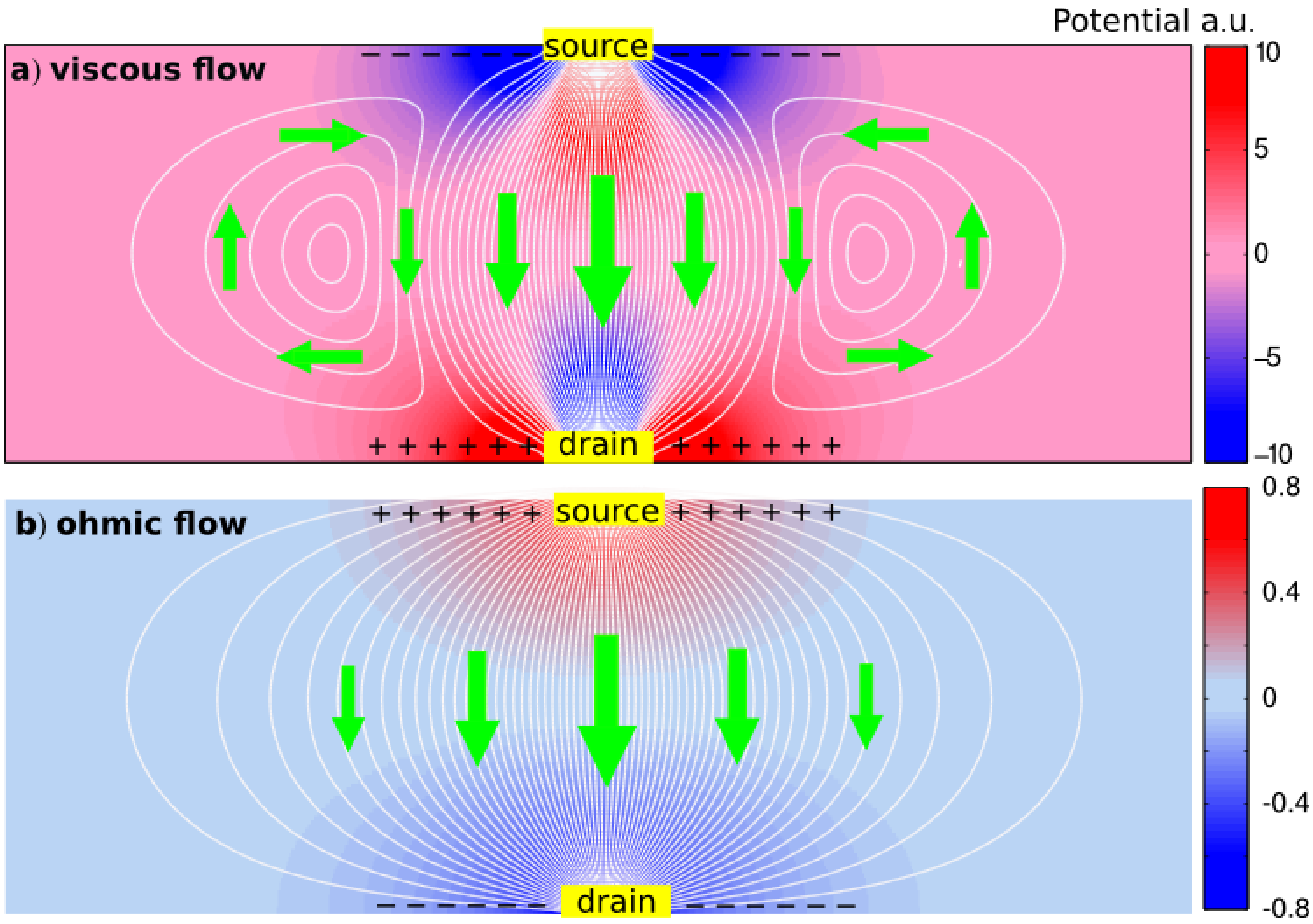


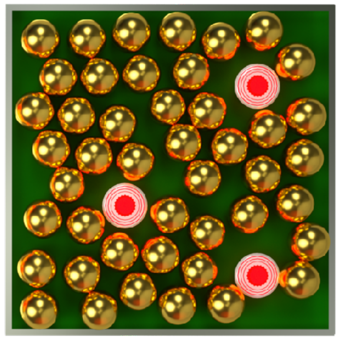
Solution of the hydrodynamic equations in the presence of a space-dependent chemical potential.
Best fit of density dependence to thermal conductivity now gives a better fit to the density dependence of the electrical conductivity (for $\eta/s \approx 10$). The T dependencies of other parameters also agree well with expectation.

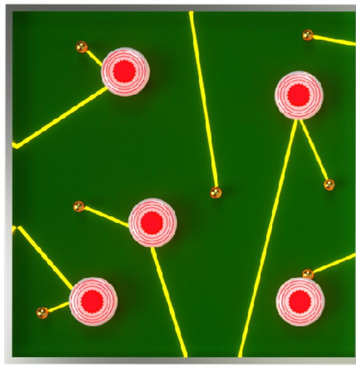
A. Lucas, J. Crossno, K.C. Fong, P. Kim, and S. Sachdev, PRB **93**, 075426 (2016)

Strange metal in graphene

Negative local resistance due to viscous electron backflow in graphene







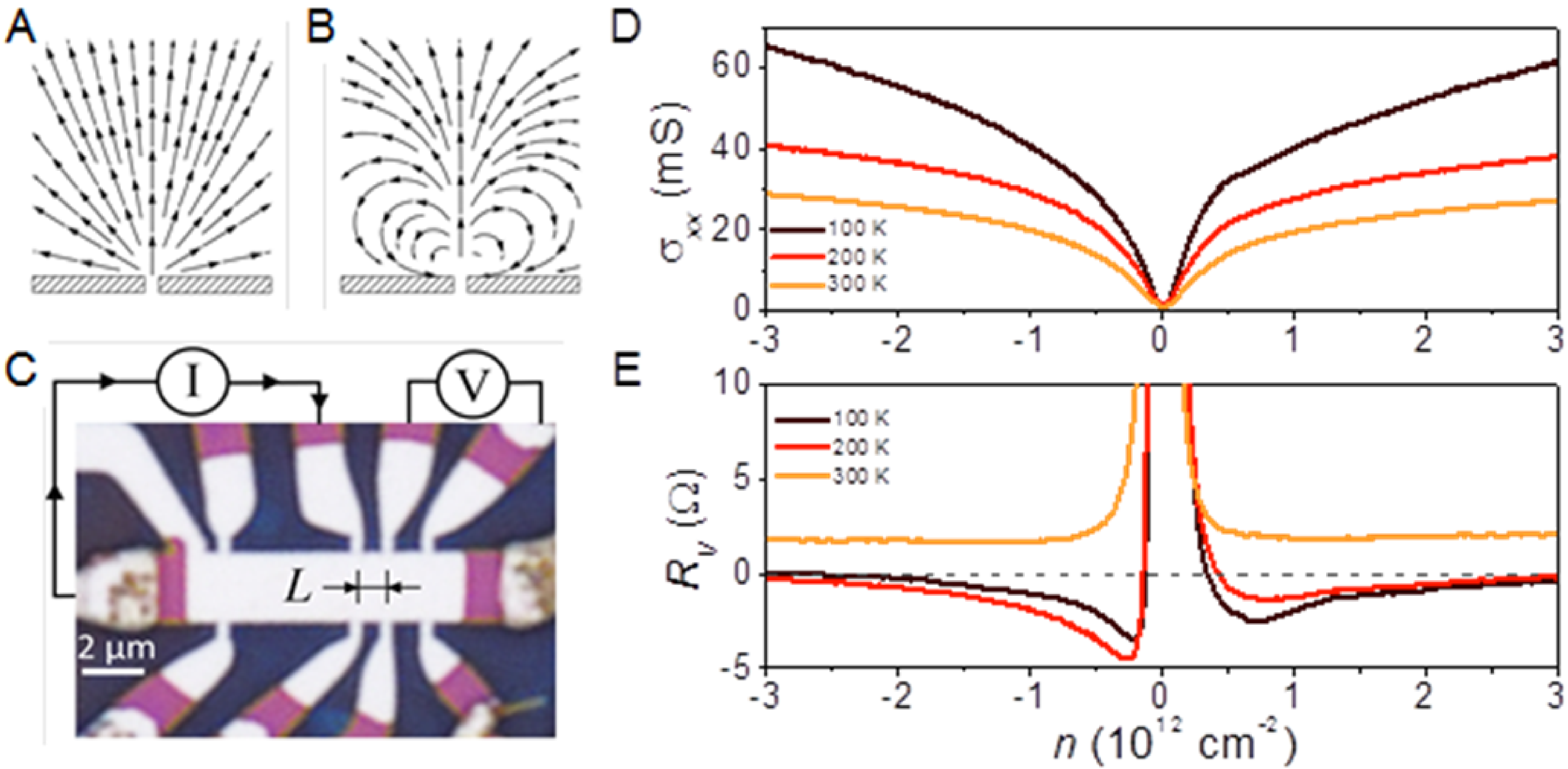
L. Levitov and G. Falkovich, arXiv:1508.00836, *Nature Physics online*

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]



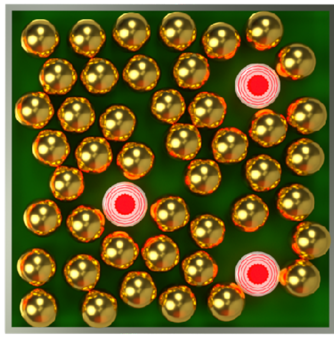


Figure 1. Viscous backflow in doped graphene. (**a,b**) Steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (a) and a viscous Fermi liquid (b). (**c**) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry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

Entangled quantum matter without quasiparticles

- Is there a connection between strange metals and black holes?
  Yes, the SYK model leads to an explicit duality mapping.

- Why do they have the same local equilibration time $\sim \hbar/(k_B T)$?
  Strange metals don't have quasiparticles and thermalize rapidly;
  General relativity leads to black hole quasi-normal modes, whose decay time $\sim \hbar/(k_B T_H)$, where T_H is the Hawking temperature".

- Theoretical predictions for strange metal transport in graphene agree well with experiments