Universal, low temperature, *T*-linear resistivity in two-dimensional quantum-critical metals from spatially random interactions

A. A. P., H. Guo, I. Esterlis, and S. Sachdev, **arXiv:2203.04990**
See also: (i) I. Esterlis, H. Guo, A. A. P., and S. Sachdev, **Phys. Rev. B 103, 235129 (Editor's Suggestion, Featured in Physics)**, **arXiv:2103.08615**
(ii) E. E. Aldape, T. Cookmeyer, A. A. P., and E. Altman, **arXiv:2012:00763 (Phys. Rev. B, in press)**

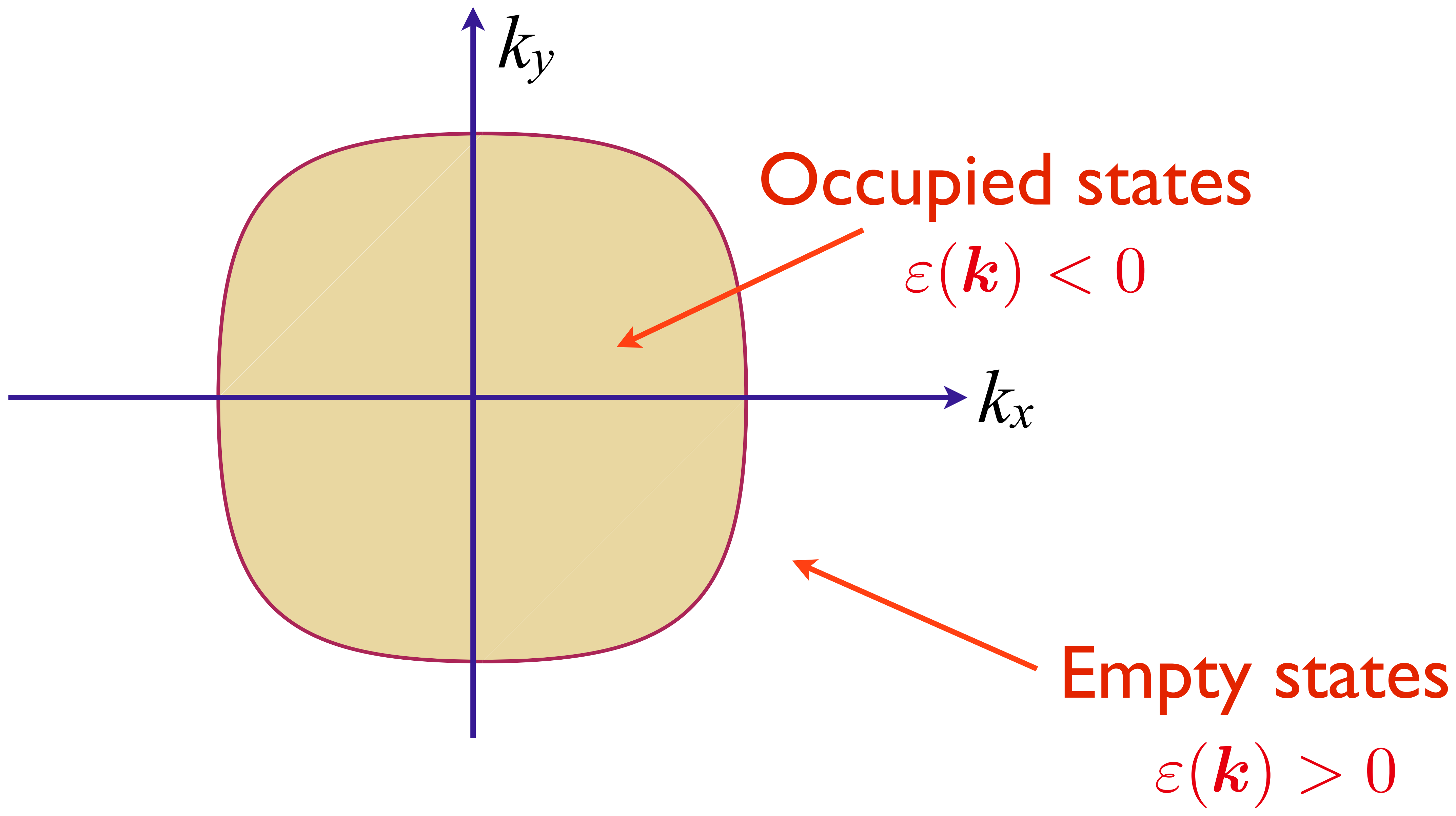
Aavishkar Patel

UCB Miller Institute → Flatiron Institute

Key to Strange Metals meeting: Strange metals from the Hubbard model to AdS/CFT, Cold atoms etc.

05/25/2022

Metals

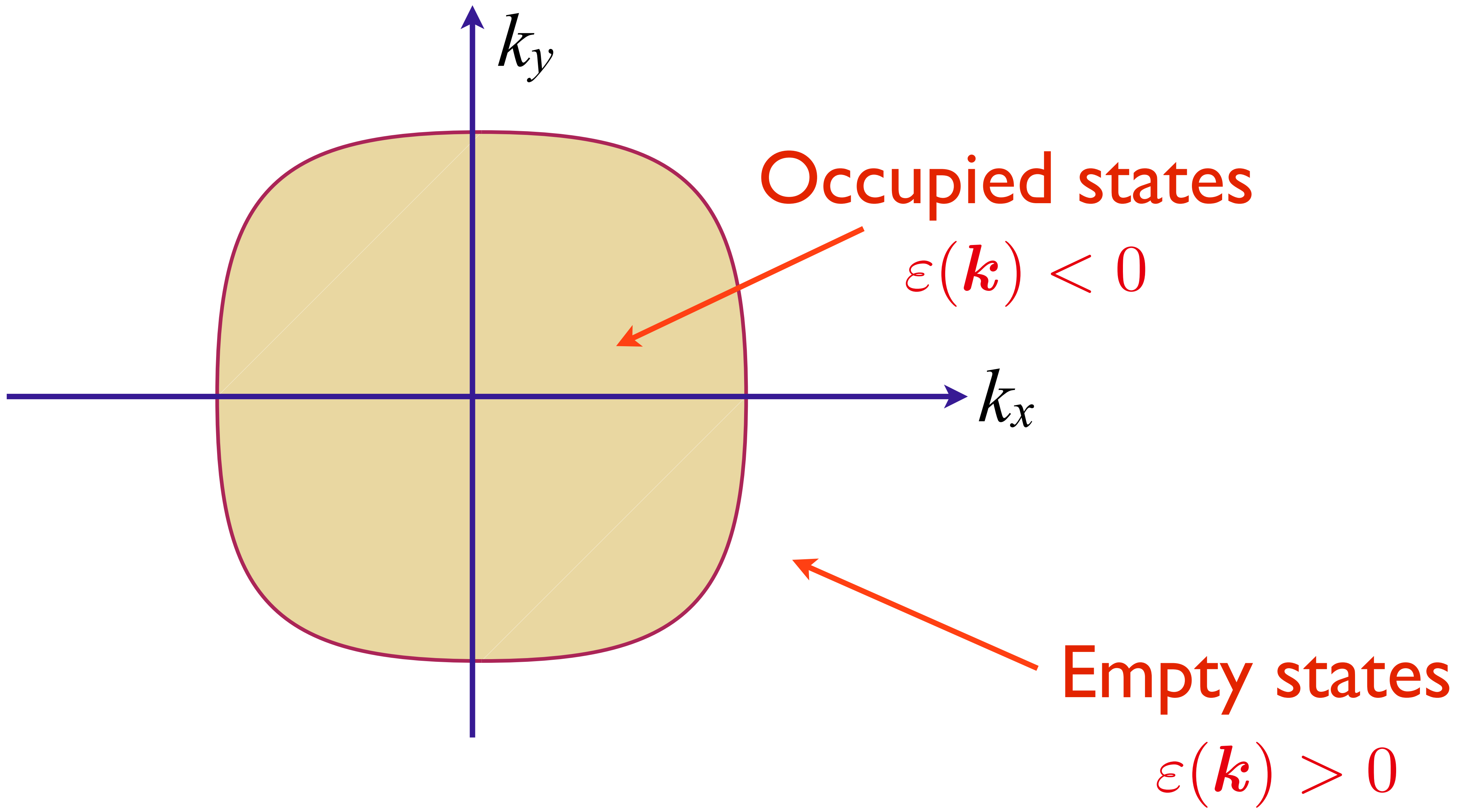


Momentum space picture:
Fermi surface
(due to Pauli's exclusion principle)

$$H = \sum_{\mathbf{k}} \varepsilon(\mathbf{k}) \psi_{\mathbf{k}}^\dagger \psi_{\mathbf{k}}$$

- States of fermionic matter at finite density.
- Compressible: $\partial \mathcal{Q}/\partial \mu \neq 0$ as $T \to 0$.
- Large number of gapless excitations.

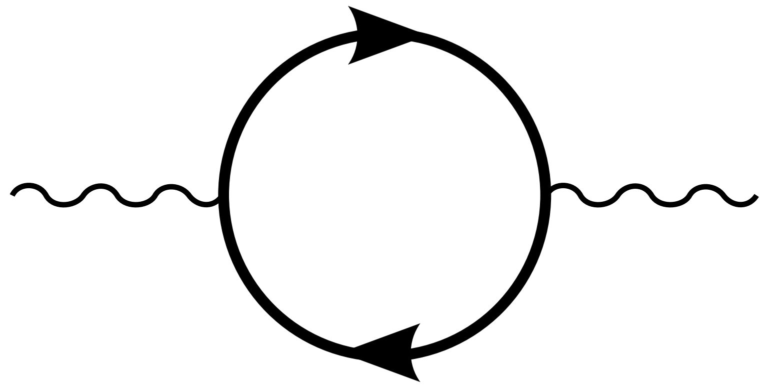
Fermi liquid theory



Fermi surface

$$H = \sum_{\mathbf{k}} \varepsilon(\mathbf{k}) \psi^\dagger_{\mathbf{k}} \psi_{\mathbf{k}} + \sum_{\mathbf{r},\mathbf{r}'} V(\mathbf{r}-\mathbf{r}') \psi^\dagger_{\mathbf{r}} \psi_{\mathbf{r}} \psi^\dagger_{\mathbf{r}'} \psi_{\mathbf{r}'}$$

$$\sum_{\mathbf{r}} \phi_{\mathbf{r}} V^{-1}(\mathbf{r}-\mathbf{r}') \phi_{\mathbf{r}'} \ + \ \sum_{\mathbf{r}} \phi_{\mathbf{r}} \psi^\dagger_{\mathbf{r}} \psi_{\mathbf{r}}$$

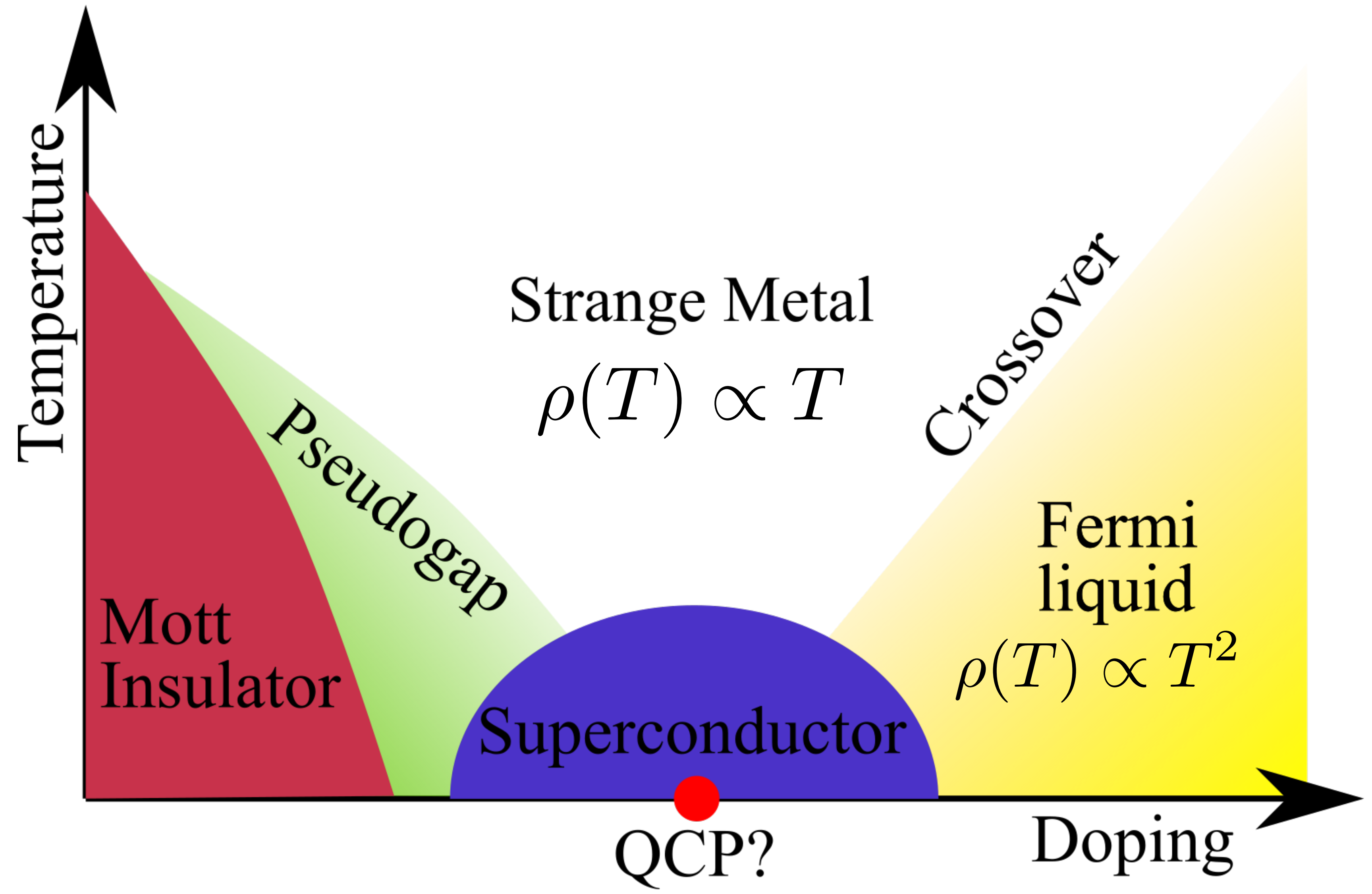


Screening leads to gapped (short-range) boson

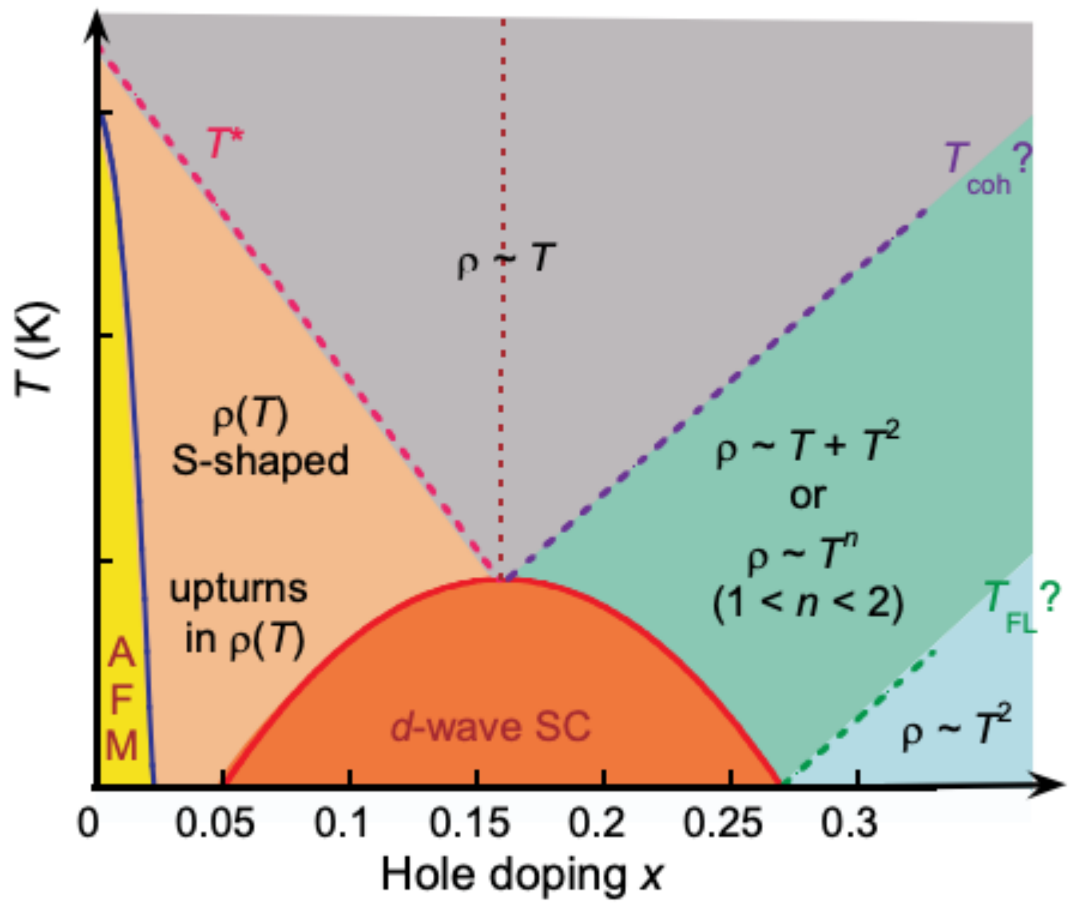
$$G_\psi(\mathbf{k}, i\omega) = \frac{Z}{i\omega - \varepsilon(\mathbf{k}) + i\Gamma} \qquad \Gamma \sim \max(\omega^2, T^2)$$

Fermions interact with gapped boson but just become renormalized quasiparticles (which are similar to the original non-interacting fermions).

Strange metals

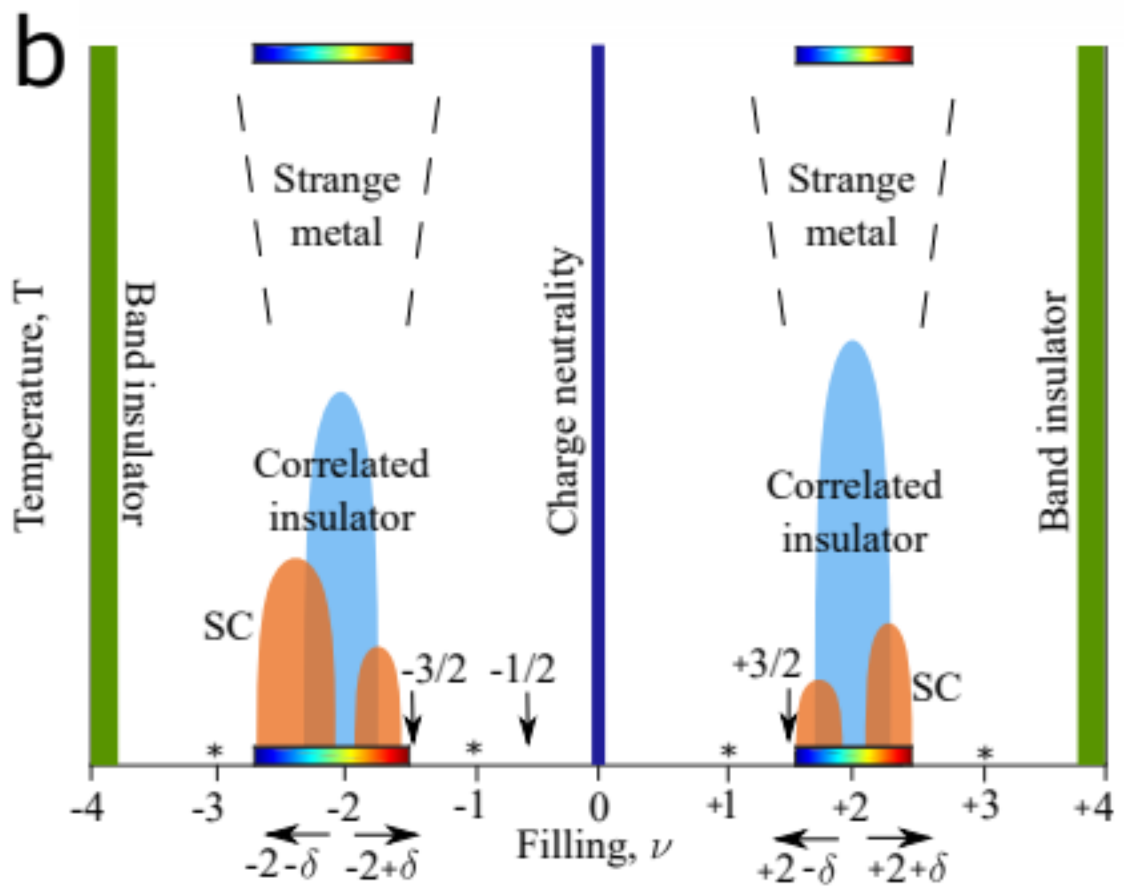


- Several quasi-two dimensional or layered materials with strongly correlated electrons display a ubiquitous and poorly understood metallic phase at intermediate values of carrier density.
- Unlike Landau Fermi liquids, which have a DC electrical resistivity that scales as T^2, these strange metals have a resistivity that scales as T. The exact mechanisms behind this are not (yet) known.
- This often occurs at finite T above a quantum critical point.



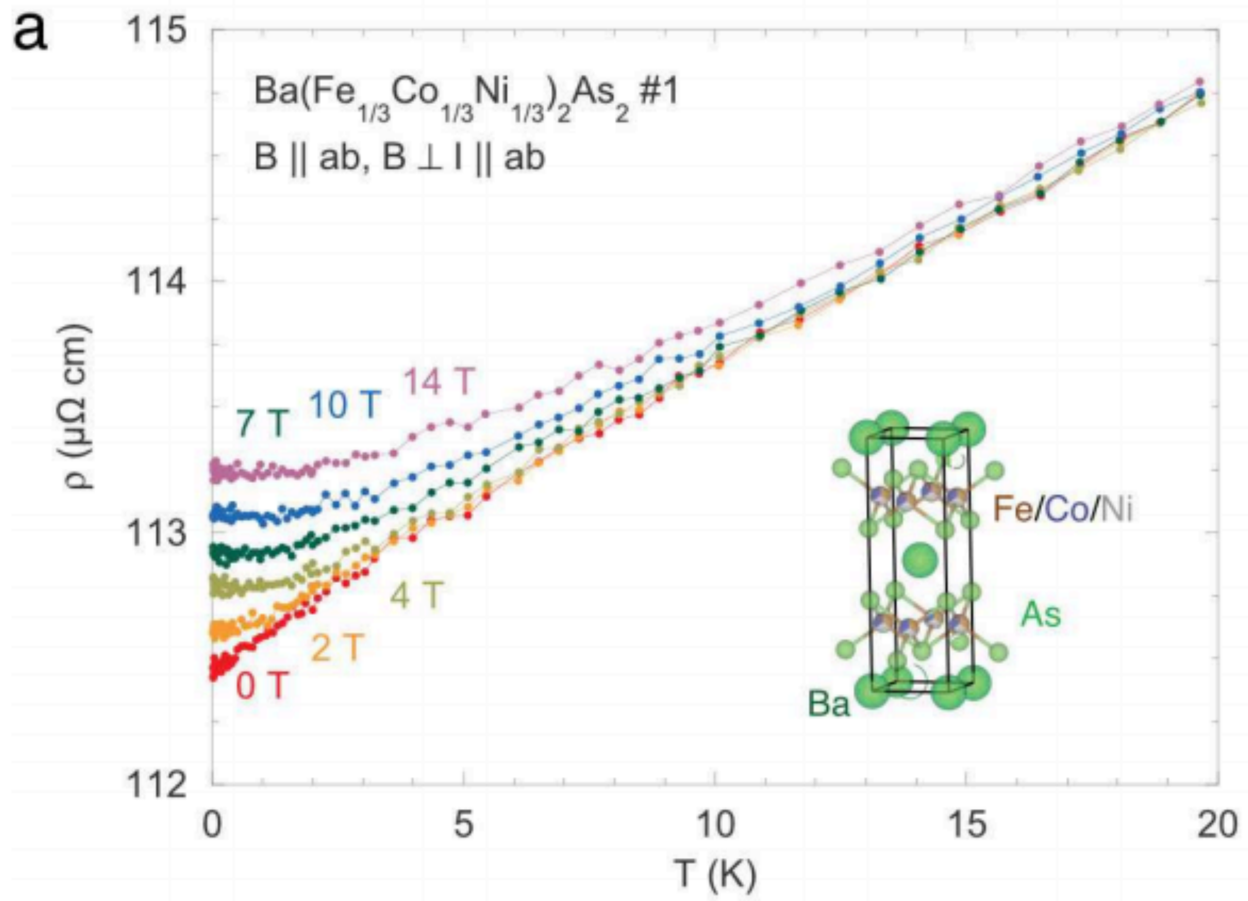
Cuprates

Hussey, J. Phys. Cond. Matt. **20** (2008) 123201



Twisted bilayer graphene

Cao et al, Phys. Rev. Lett. **124**, 076801 (2020)

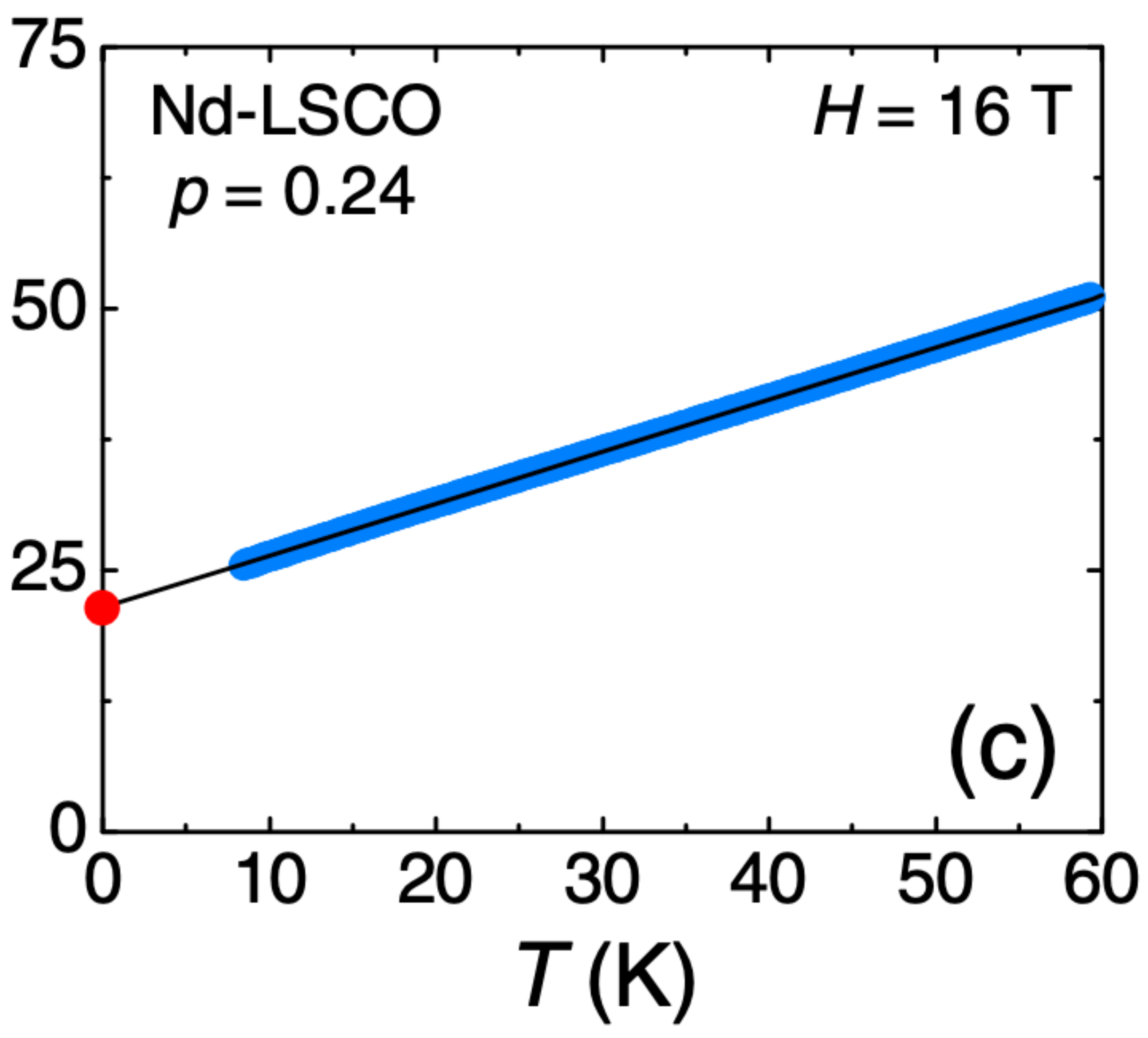


Pnictides

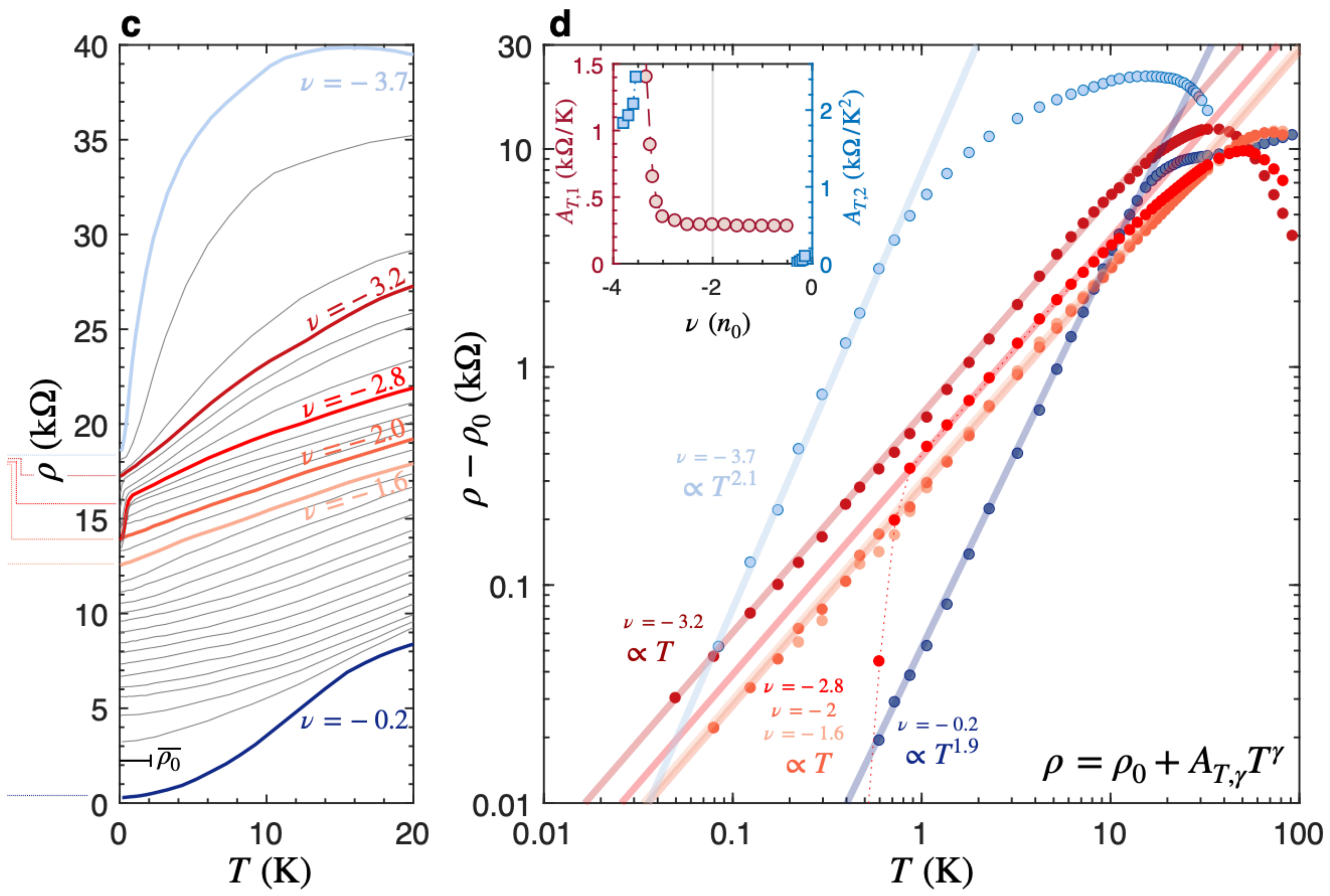
Nakajima et al, Comms. Phys. **3**, 181 (2020)

Strange metals

- While, at high temperatures, T-linear resistivity might putatively be explained by phonons, at low temperatures one expects $\rho(T) = \rho(0) + aT^2$ for weakly interacting Fermi liquids, with the temperature dependence arising from the parts of the quasiparticle decay process that involve momentum and current relaxing Umklapp scattering.
- This T-linear behavior is often accompanied by other signs of strong interactions - such as a large, T-dependent quasiparticle effective mass that shows up in specific heat measurements.

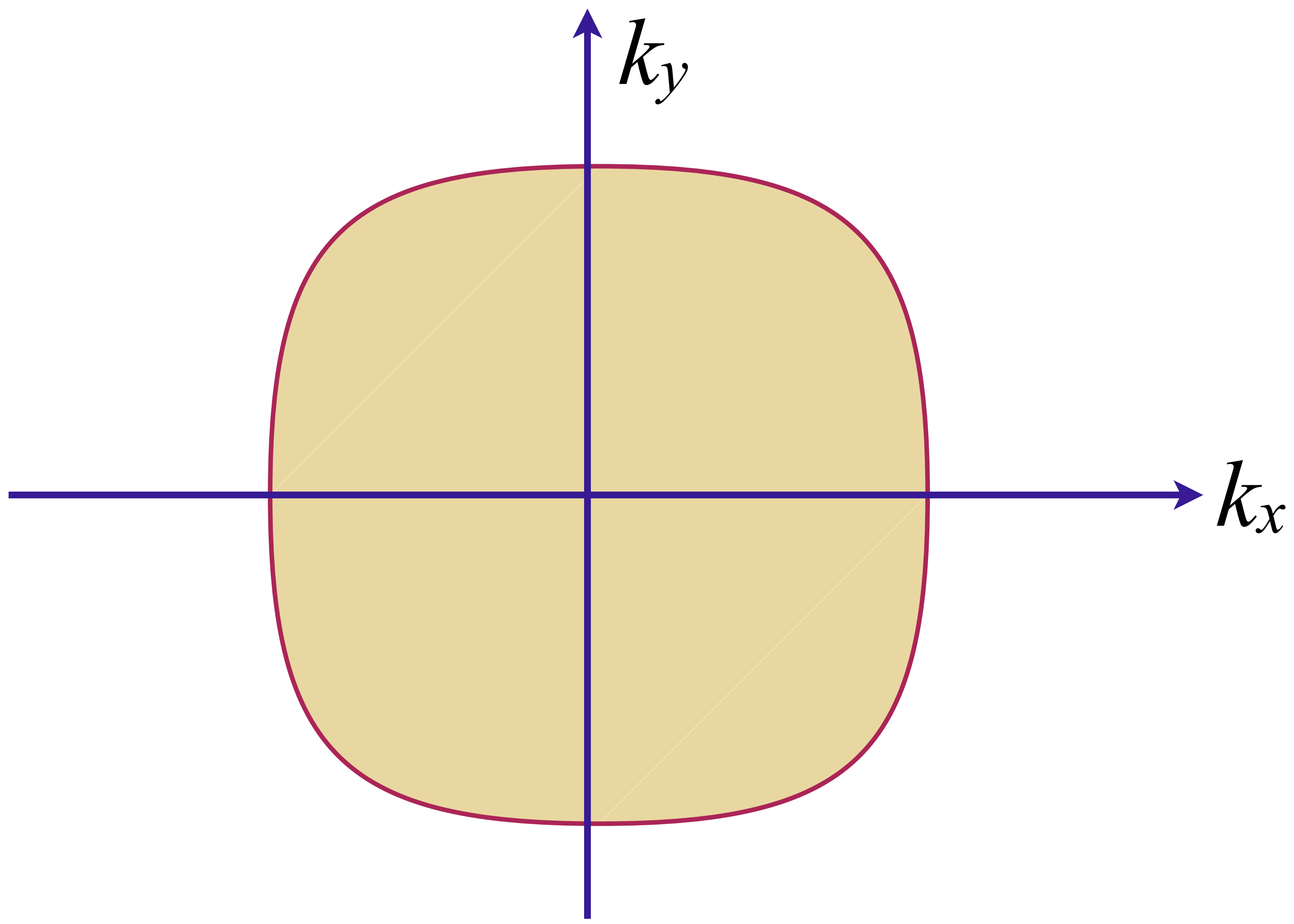


Michon et al, PRX **8**, 041010 (cuprate, SC suppressed by B field)



Jaoui et al, arXiv:2108.07753 (magic angle twisted bilayer graphene)

Non-Fermi liquid



Fermi surface

$$\{\mathbf{k} \mid G_\psi^{-1}(\mathbf{k}, i\omega = 0, T = 0) = 0\}$$

- Compressible: $\partial Q/\partial\mu \neq 0$ as $T \to 0$.
- Fermi surface is still well defined in translationally invariant systems.
- No quasiparticle excitations: the low-lying many-body energies **cannot** be identified in terms of a set $\{n_\mathbf{k}\}$ of quasiparticles with energies $\varepsilon(\mathbf{k})$ as

$$E = \sum_k \varepsilon(\mathbf{k}) n_\mathbf{k} + \sum_{\mathbf{k},\mathbf{k}'} F_{\mathbf{k},\mathbf{k}'} n_\mathbf{k} n_{\mathbf{k}'} + \ \ldots$$

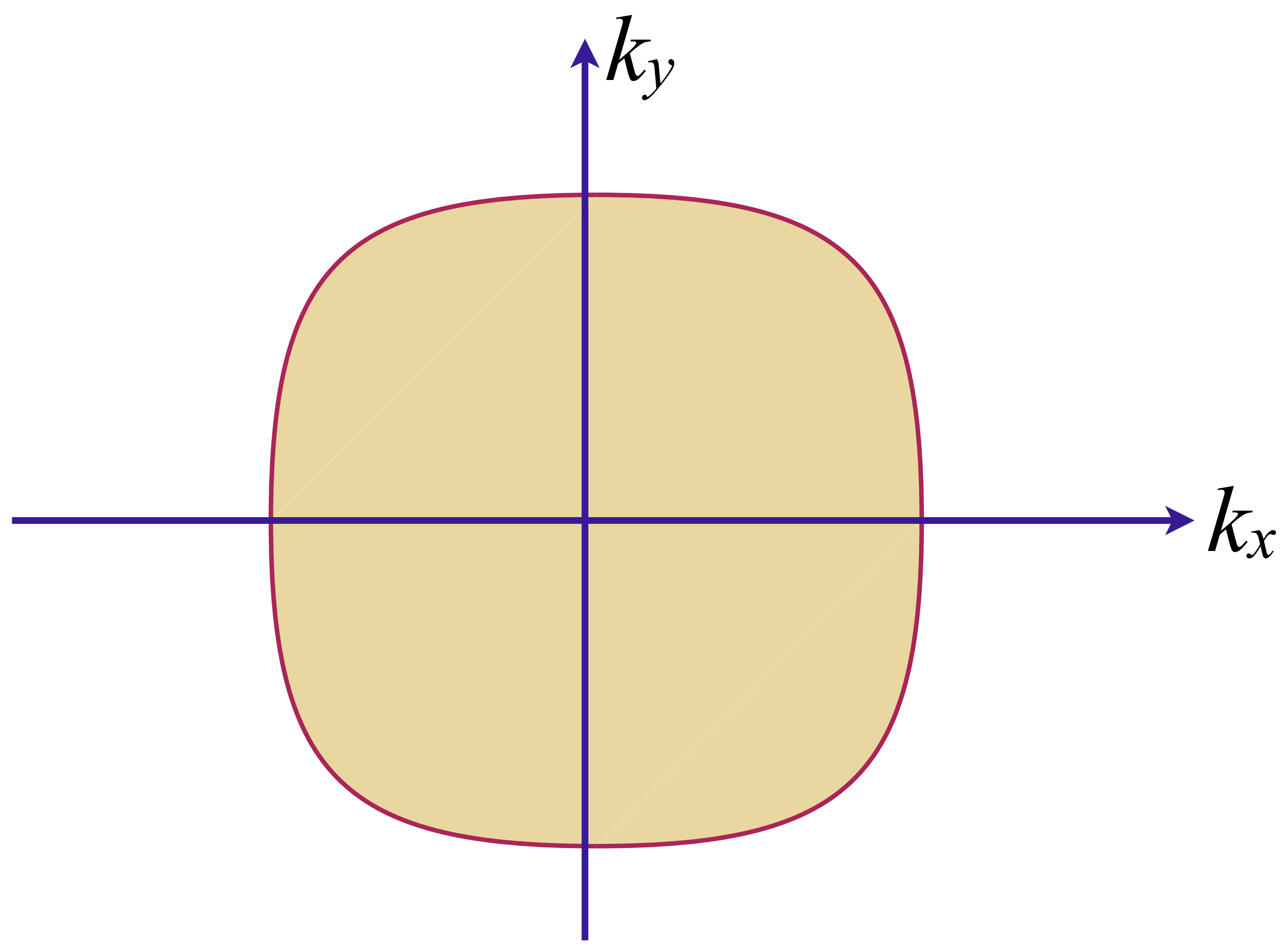
$$G_\psi(\mathbf{k}, i\omega) \sim \frac{1}{i\omega - \varepsilon(\mathbf{k}) + i\Gamma}, \quad \Gamma \gg \max(|\omega|, T).$$

Non-Fermi liquid

- Possible scenario: interactions between electrons are mediated by gapless bosonic fluctuations.

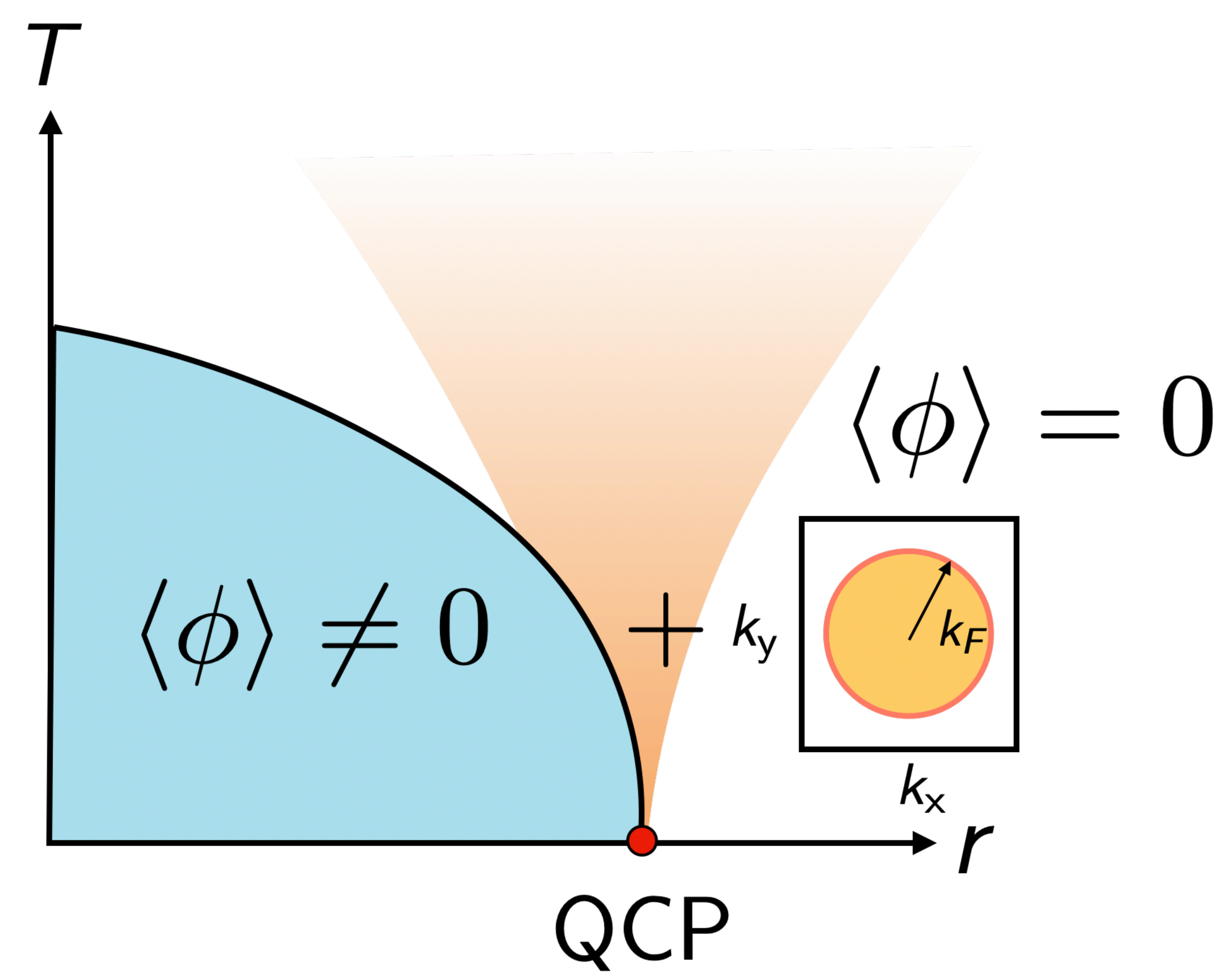
$$H = \sum_{\mathbf{k}} \varepsilon(\mathbf{k}) \psi^\dagger_{\mathbf{k}} \psi_{\mathbf{k}} + g \sum_{\mathbf{r}} \phi_{\mathbf{r}} \psi^\dagger_{\mathbf{r}} \psi_{\mathbf{r}}$$

- Such a situation can occur when excitations around a Fermi surface are coupled to fluctuations of a quantum critical order parameter, or an emergent gauge field, especially in two spatial dimensions. This is the effective low-energy field theory of many different models.



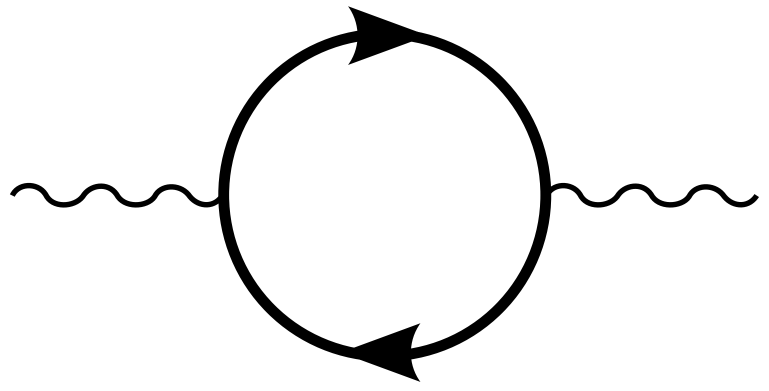
Fermi surface

$+$



Non-Fermi liquid

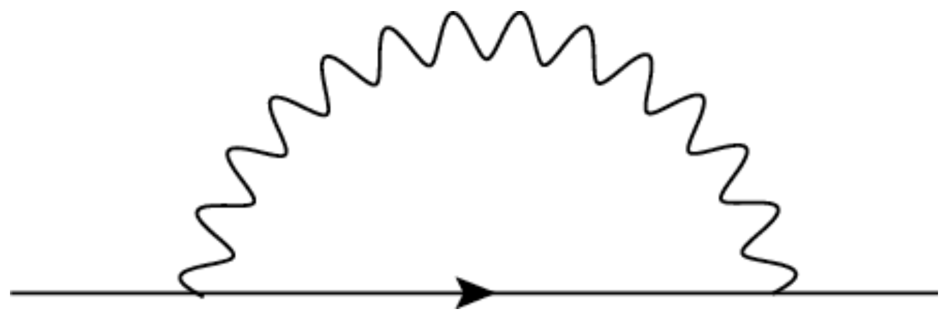
- The gapless ϕ field now means that the effective interactions between electrons are not screened and are long ranged. Further, the bosonic excitations are now heavily damped, and acquire non-trivial dynamics.



$$\Pi(\Omega, \mathbf{q}) \sim |\Omega|/q$$

- Interactions between fermions mediated by the damped bosons are strong, and lead to the destruction of fermion quasiparticles.

$$G_\psi(\mathbf{k}, i\omega) \sim \frac{1}{i\omega - \varepsilon(\mathbf{k}) + i\Gamma}, \quad \Gamma \gg \max(|\omega|, T).$$



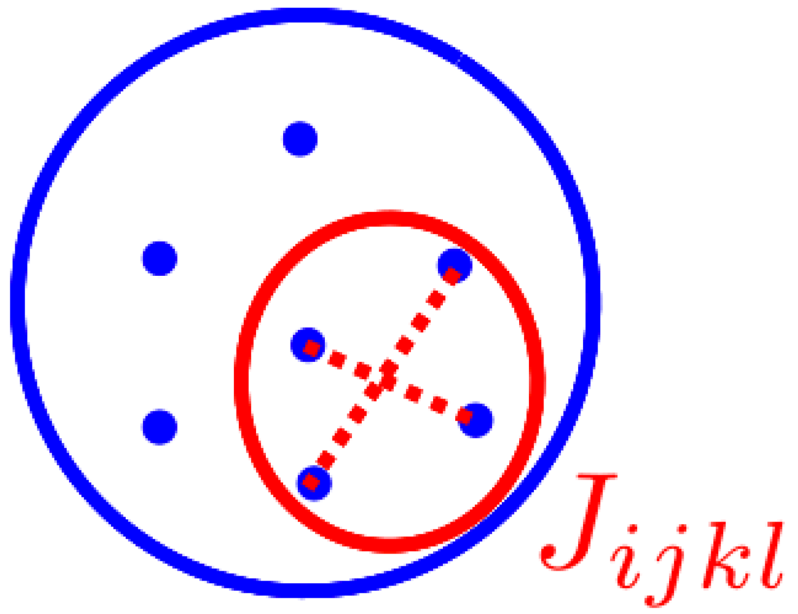
$$\Gamma \sim \max(\omega^{2/3}, T^{2/3}) \quad (d = 2)$$

1-loop fermion self energy is too large, this prevents a weak-coupling expansion in *g*.

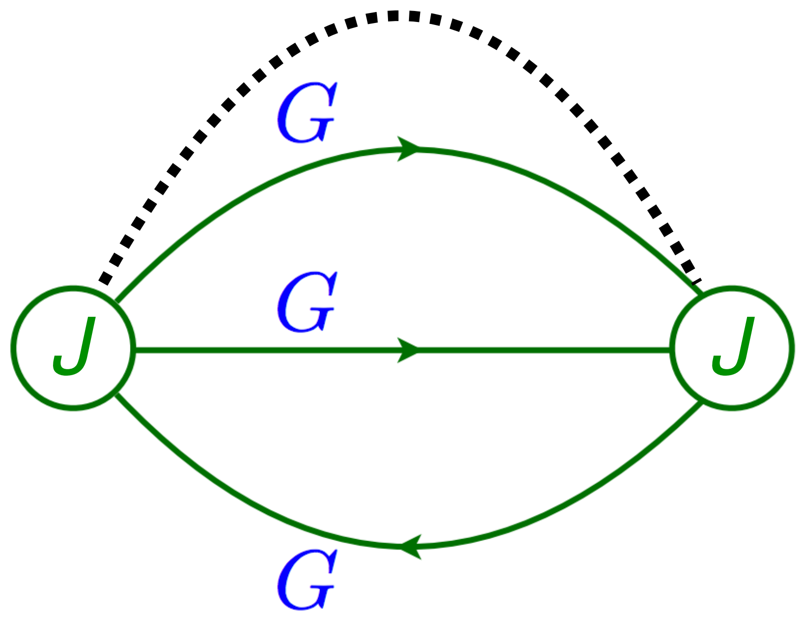
SYK Model: Solvable Non-Fermi liquid at a point

$$H = \sum_{i,j,k,l=1}^{N\to\infty} J_{ijkl} f_i^\dagger f_j^\dagger f_k f_l, \quad \{f_i^\dagger, f_j\} = \delta_{ij}$$

$$\ll J_{ijkl} \gg = 0, \quad \ll |J_{ijkl}|^2 \gg = J^2/(8N^3)$$



- Consists of large-N number of sites on a single "quantum dot", with random all-to-all interactions.
- The Hamiltonian has no quadratic kinetic terms.
- The randomness self-averages in the large-N limit, leading to a gapless non-Fermi liquid ground state.

$\Sigma =$ 

$$\Sigma(\tau) = -J^2 G^2(\tau) G(-\tau),$$

$$G(i\omega_n) = \frac{1}{i\omega_n - \Sigma(i\omega_n)}.$$

Strong coupling approach that systematically resums diagrams to all orders, leading to exact Schwinger-Dyson equations in the large-N limit.

S. Sachdev and J. Ye, PRL 70, 3339 (1993)
S. Sachdev, PRX 041025 (2015)
A. Kitaev, KITP Talks (2015)

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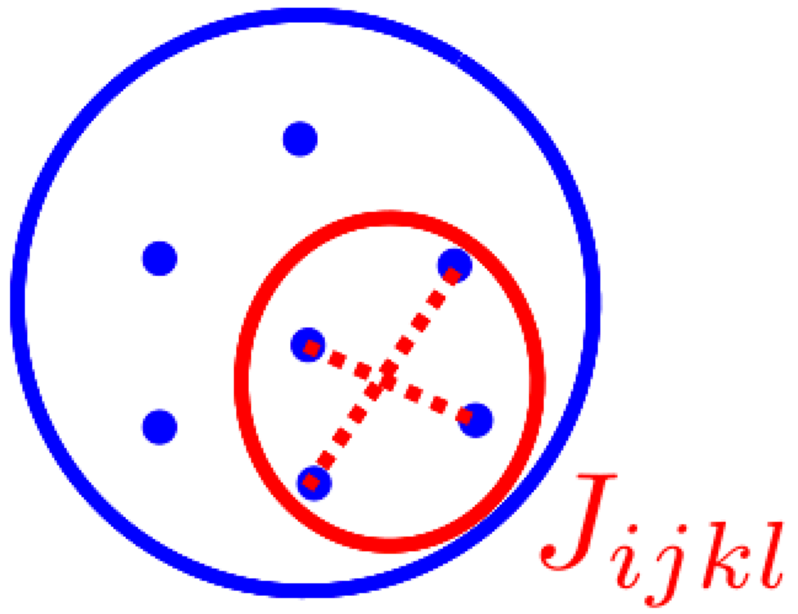

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$$G(i\omega_n) = \frac{1}{i\omega_n - \Sigma(i\omega_n)}.$$

$$\longrightarrow \quad G(i\omega_n \ll J) = \frac{C\,\mathrm{sgn}(\omega_n)}{\sqrt{J|\omega_n|}}.$$

(at T=0)

S. Sachdev and J. Ye, PRL 70, 3339 (1993)
S. Sachdev, PRX 041025 (2015)
A. Kitaev, KITP Talks (2015)

SYK fermion-boson models at a point

- The non-Fermi liquids at quantum critical points motivated earlier require fermions interacting with gapless bosons. So we need something like

$$H = \sum_{ijk} g_{ijk} f_i^\dagger f_j \phi_k$$

- Various works:

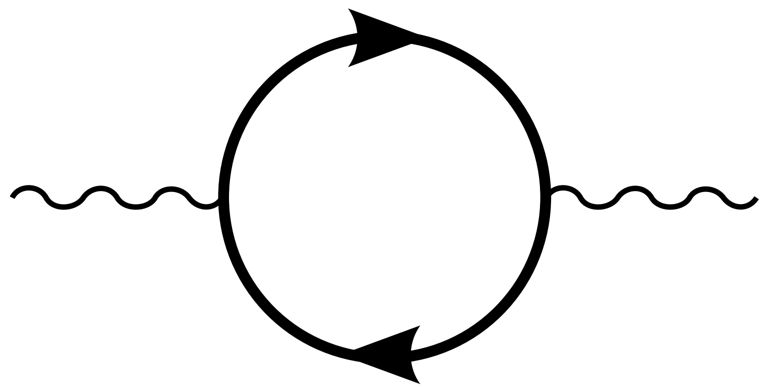
A. A. P. and S. Sachdev, PRB **98**, 125134 (2018) (0+1 dimensional fermions randomly Yukawa coupled to "gauge fields")

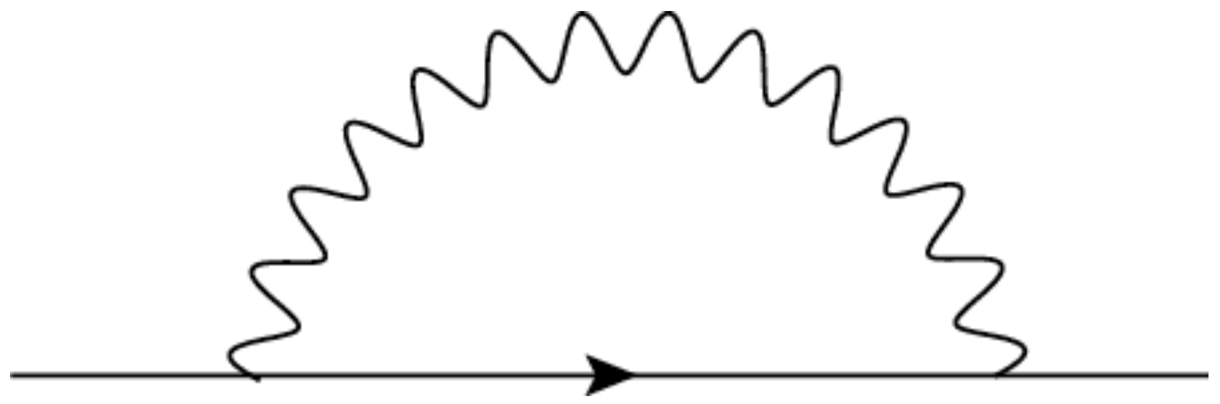
E. Marcus and S. Vandoren, JHEP **2019**, 166 (2019) (0+1 dimensional fermions randomly Yukawa coupled to scalars)

Y. Wang, PRL **124**, 017002 (2020) (Superconducting instability at $1/N$ order in 0+1 dimensions)

I. Esterlis and J. Schmalian PRB **100**, 115132 (2019) (Superconducting instability at large N for real g_{ijk} in 0+1 dimensions)

J. Kim, X. Cao, and E. Altman PRB **101**, 125112 (2020) (Different distributions of g_{ijk} instead of fully random in 0+1 dimensions)

$\Pi =$ 

$\Sigma =$ 

"RPA" Schwinger-Dyson equations

Non-Fermi liquid

We apply techniques from the SYK model...

- 2+1 dimensions: retain spatial translational invariance.
- Promote **both** fermions and bosons to large *N* flavors at every site: $\psi \to \psi_j, \quad \phi \to \phi_j$.
- Use flavor random complex gaussian couplings:

$$g \to g_{ijk}, \quad H_{\rm int} \sim \sum_{ijk} g_{ijk} \psi_i^\dagger \psi_j \phi_k \qquad \langle g_{ijk} \rangle = 0, \quad \langle |g_{ijk}|^2 \rangle = g^2/N^2, \quad g_{ijk}^* = g_{jik}.$$

- Average over random couplings using replicas like in SYK, which should be equivalent to self-averaging in the large *N* limit.

Note: like in SYK, the large *N* limit is now taken *before* the low energy limit.

I. Esterlis, H. Guo, A. A. P., and S. Sachdev, PRB 103, 235129 (2021)

Non-Fermi liquid

We apply techniques from the SYK model…

- 2+1 dimensions: retain spatial translational invariance.
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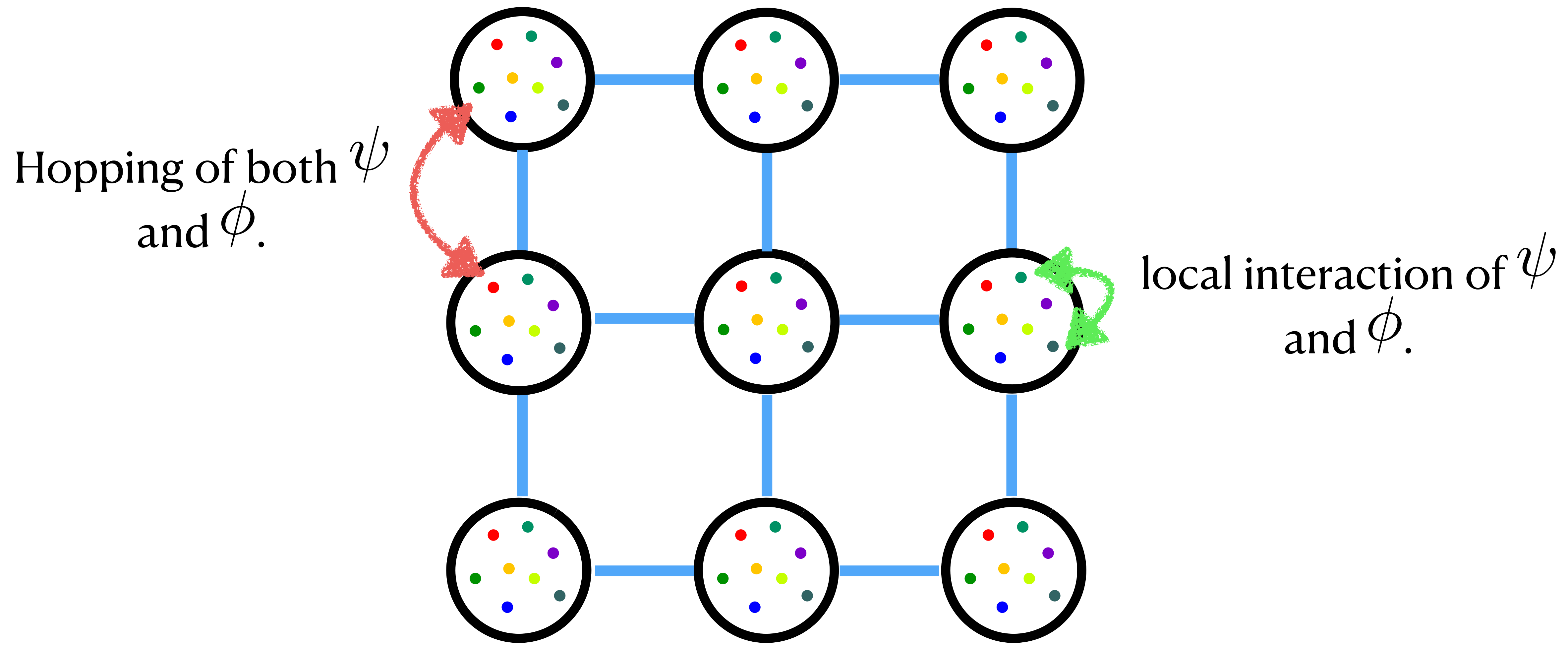


I. Esterlis, H. Guo, A. A. P., and S. Sachdev, PRB 103, 235129 (2021)

Non-Fermi liquid

We apply techniques from the SYK model...

- Large *N* saddle point just gives the "RPA" equations from "Eliashberg theory":

$$G(\mathbf{k}, i\omega) = \frac{1}{i\omega - \varepsilon(k) - \Sigma(\mathbf{k}, i\omega)}$$
$$D(\mathbf{q}, i\Omega) = \frac{1}{\Omega^2 + \mathbf{q}^2 - \Pi(\mathbf{q}, i\Omega) + M^2}$$

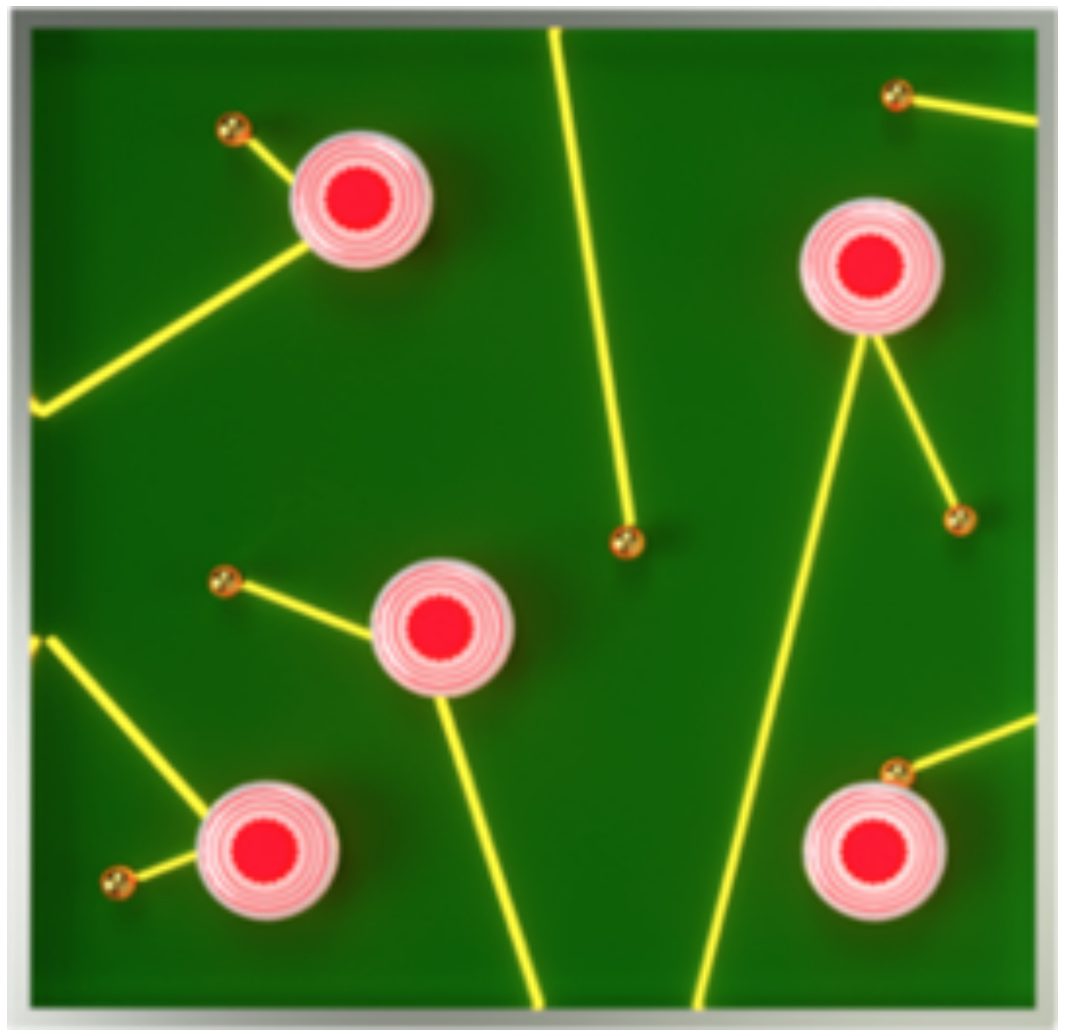
$$\Sigma(\mathbf{k}, i\omega) = g^2 \int d^2\mathbf{q} d\Omega D(\mathbf{q}, i\Omega) G(\mathbf{k}+\mathbf{q}, i\omega + i\Omega)$$
$$\Pi(\mathbf{q}, i\Omega) = g^2 \int d^2\mathbf{k} d\omega G(\mathbf{k}, i\omega) G(\mathbf{k}+\mathbf{q}, i\omega + i\Omega)$$

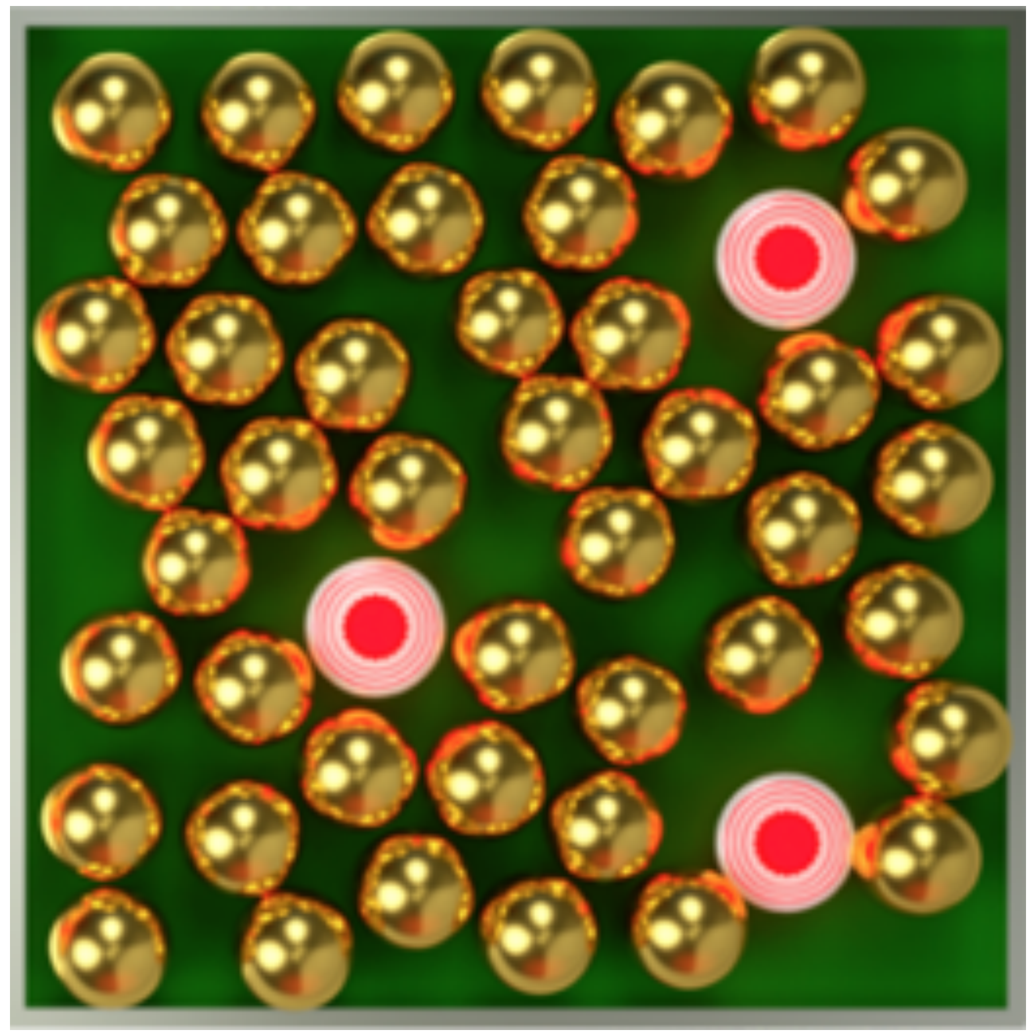
Exact low energy solution at $T=0$: $\Sigma(\mathbf{k}, i\omega) \sim -i\,\mathrm{sgn}(\omega)|\omega|^{2/3}, \quad \Pi(\mathbf{q}, i\Omega) \sim |\Omega|/|\mathbf{q}|.$

(at criticality, where *M*=0)

I. Esterlis, H. Guo, A. A. P., and S. Sachdev, **PRB 103, 235129 (2021)**

The theoretical models discussed so far are all translationally invariant. Because of the conserved total momentum, and a finite charge density that prevents excitation of currents without excitation of momentum, they have an infinite DC conductivity (up to some weak Umklapp processes on a lattice), as a finite DC conductivity requires current, and therefore momentum, to relax.



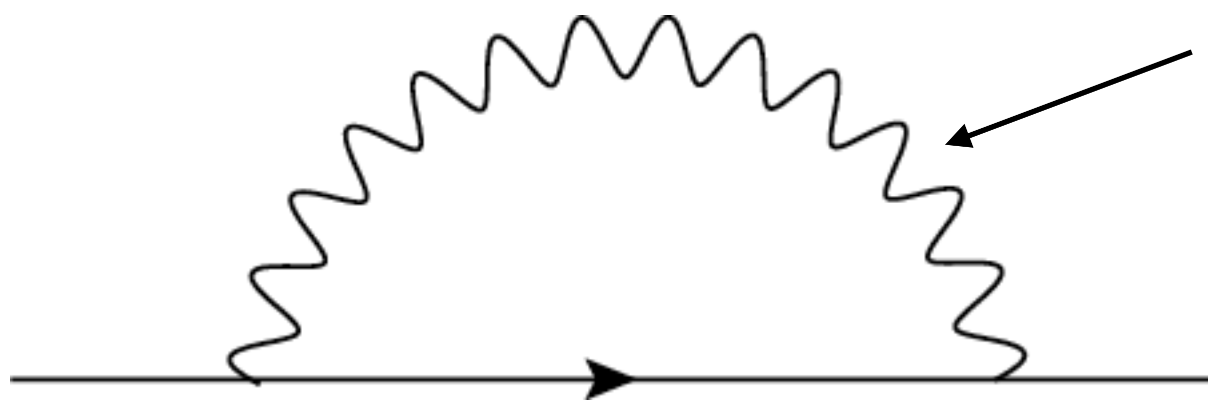


Presence of impurities (red bumpers) is required to degrade momentum and therefore current, irrespective of whether quasiparticles are well-defined or not.

We now move on to adapting such models of metallic quantum critical points to the experimentally observed problem of T-linear resistivity.

"Marginal Fermi liquid" phenomenology

- Varma et al (Phys. Rev. Lett. **63**, 1996 (1989)), proposed a phenomenological form of the electron self-energy representing the corrections to the motion of electronic quasiparticles coming from the scattering of electrons off a specific form of bosonic fluctuations:



$$\Sigma(k, \omega \gg T) \propto -i\omega \ln(\Lambda/|\omega|).$$

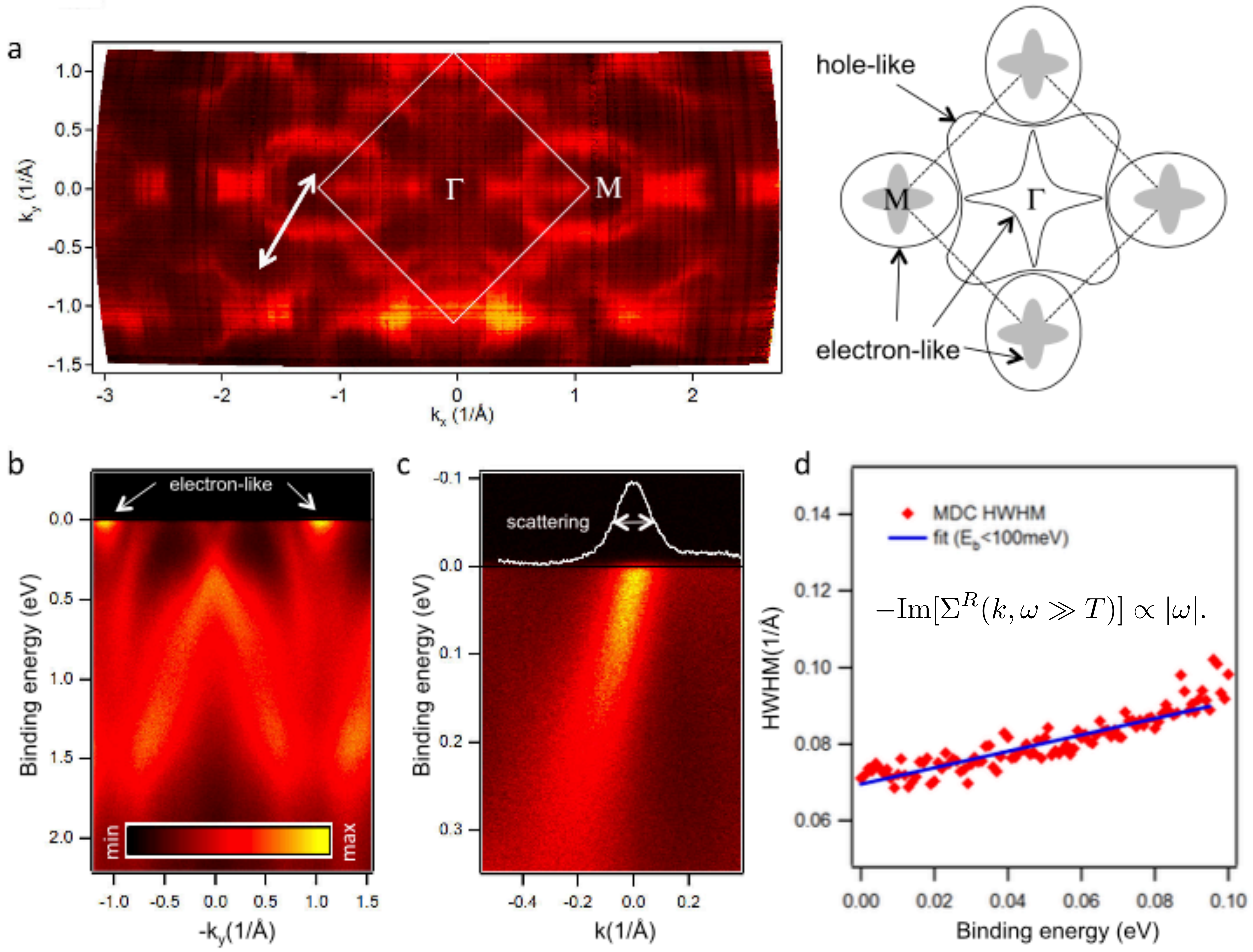
$$-\mathrm{Im}[\Sigma^R(k, \omega \gg T)] \propto |\omega|.$$

$$\frac{1}{\tau_{\mathrm{el}}} = -\mathrm{Im}[\Sigma^R(k, \omega \ll T)] \propto T.$$

- If the electron scattering rate $1/\tau_{\mathrm{el}}$ is interpreted as the transport scattering rate, this will lead to a T-linear resistivity. However, this requires the scattering to not conserve momentum.
- This is a phenomenological ansatz, and not a systematic strongly coupled field theory that provides a framework for non-perturbative effects of electron interactions.

"Marginal Fermi liquid" phenomenology

... works reasonably well in many cases.



Nakajima et al, Comms. Phys. 3, 181 (2020)

Disordered quantum critical metals

- The key to getting quantum critical T-linear resistivity, and near "Planckian" dissipation will be to include the effects of spatial disorder, in order to relax currents and momentum.
- One can naively just add a random potential term:

$$H_{\text{dis}} = \frac{1}{\sqrt{N}} \sum_{i,j} \int d^2\mathbf{r} \; v_{ij}(\mathbf{r}) \psi_i^\dagger(\mathbf{r}) \psi_j(\mathbf{r})$$

- At low energies at the quantum critical point, this leads to a diffusive boson propagator $D(\Omega, \mathbf{q}) = 1/(q^2 + \gamma|\Omega|)$, and a marginal Fermi liquid contribution to the fermion self energy (in addition to the residual impurity scattering).

- However, because the fermion-boson interactions largely represent forward scattering, the marginal Fermi liquid contribution does not contribute to the resistivity (which remains a constant at low T).

A. A. P., H. Guo, I. Esterlis, and S. Sachdev, **arXiv:2203.04990**

Disordered quantum critical metals

- We therefore consider the possibility of *disordered interactions*:

$$H_{\rm dis} = \frac{1}{\sqrt{N}} \sum_{i,j} \int d^2\mathbf{r} \; v_{ij}(\mathbf{r}) \psi_i^\dagger(\mathbf{r}) \psi_j(\mathbf{r}) \qquad H_{\rm int} = \frac{1}{N} \sum_{i,j,k} \int d^2\mathbf{r} \; (g_{ijk} + g'_{ijk}(\mathbf{r})) \psi_i^\dagger(\mathbf{r}) \psi_j(\mathbf{r}) \phi_k(\mathbf{r})$$

- At low energies at the quantum critical point, this leads to a diffusive boson propagator $D(\Omega, \mathbf{q}) = 1/(q^2 + \gamma|\Omega|)$, and a marginal Fermi liquid contribution to the fermion self energy (in addition to the residual impurity scattering).

- However, because the fermion-boson interactions now contain a significant non-forward scattering component, part of the marginal Fermi liquid contribution **contributes** to the resistivity (which gets a T-linear correction to the residual piece).

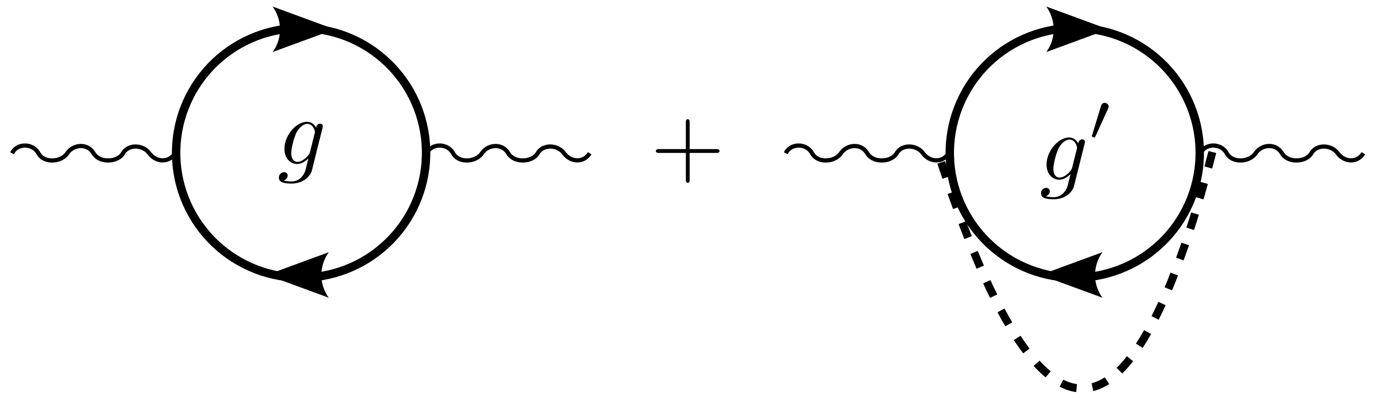
- The slope of the T-linear correction is **independent** of the residual resistivity.

A. A. P., H. Guo, I. Esterlis, and S. Sachdev, arXiv:2203.04990

How it works

$$\mathcal{L} = \psi_r^\dagger(\partial_\tau + \varepsilon(\nabla) - \mu + v(r))\psi_r + \phi_r(\partial_\tau^2 + \nabla^2 - m_b^2)\phi_r + (g + g'(r))\psi_r^\dagger\psi_r\phi_r.$$

- Non-interacting fermion propagator $G_0(i\omega,\mathbf{k}) = \left(i\frac{\Gamma}{2}\mathrm{sgn}(\omega) - v_F k\right)^{-1}$ is essentially local for $v_F k < \Gamma$, $G_0(i\omega,\mathbf{k}) = \left(i\frac{\Gamma}{2}\mathrm{sgn}(\omega) - \cancel{v_F k}\right)^{-1}$.
- This leads to $|\omega|$ boson damping and therefore $z = 2$ boson dynamics (giving a $T\ln(1/T)$ specific heat in $d = 2$).



$\sim |\omega|$

- At low (with respect to k_F) momentum scales, the essentially local fermion therefore couples to the *local* boson fluctuations, giving rise to marginal Fermi liquid behavior. The disorder g' actually couples the fermion to local bosonic fluctuations at all momentum scales.

$$\chi(\omega) \sim \langle\phi_r(\omega)\phi_r(-\omega)\rangle \sim \int \frac{d^2q}{q^2 + |\omega|} \sim \ln\left(\frac{\Lambda^2}{|\omega|}\right).$$

A. A. P., H. Guo, I. Esterlis, and S. Sachdev, **arXiv:2203.04990**

How it works

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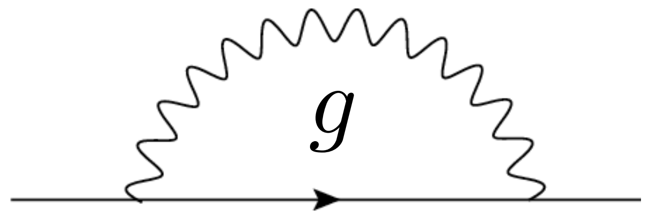
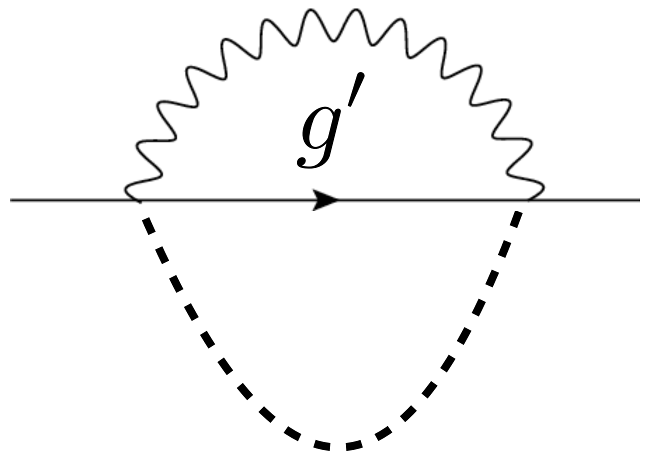


$$-i\omega \ln\left(\frac{\Lambda^2}{|\omega|}\right)$$

Forward scattering (boson q~0), no current relaxation.

$+$



$$-i\omega \ln\left(\frac{\Lambda^2}{|\omega|}\right)$$

Large angle disordered scattering (boson $q >> 0$), current + momentum relaxation: determines transport.

$$\sim -i\omega \ln\left(\frac{\Lambda^2}{|\omega|}\right)$$

Conductivity: $\sigma(\omega) \sim \tau_{\text{trans}}(\omega)$

$$\frac{1}{\tau_{\text{trans}}(\omega)} \sim v^2 + g'^2|\omega|$$

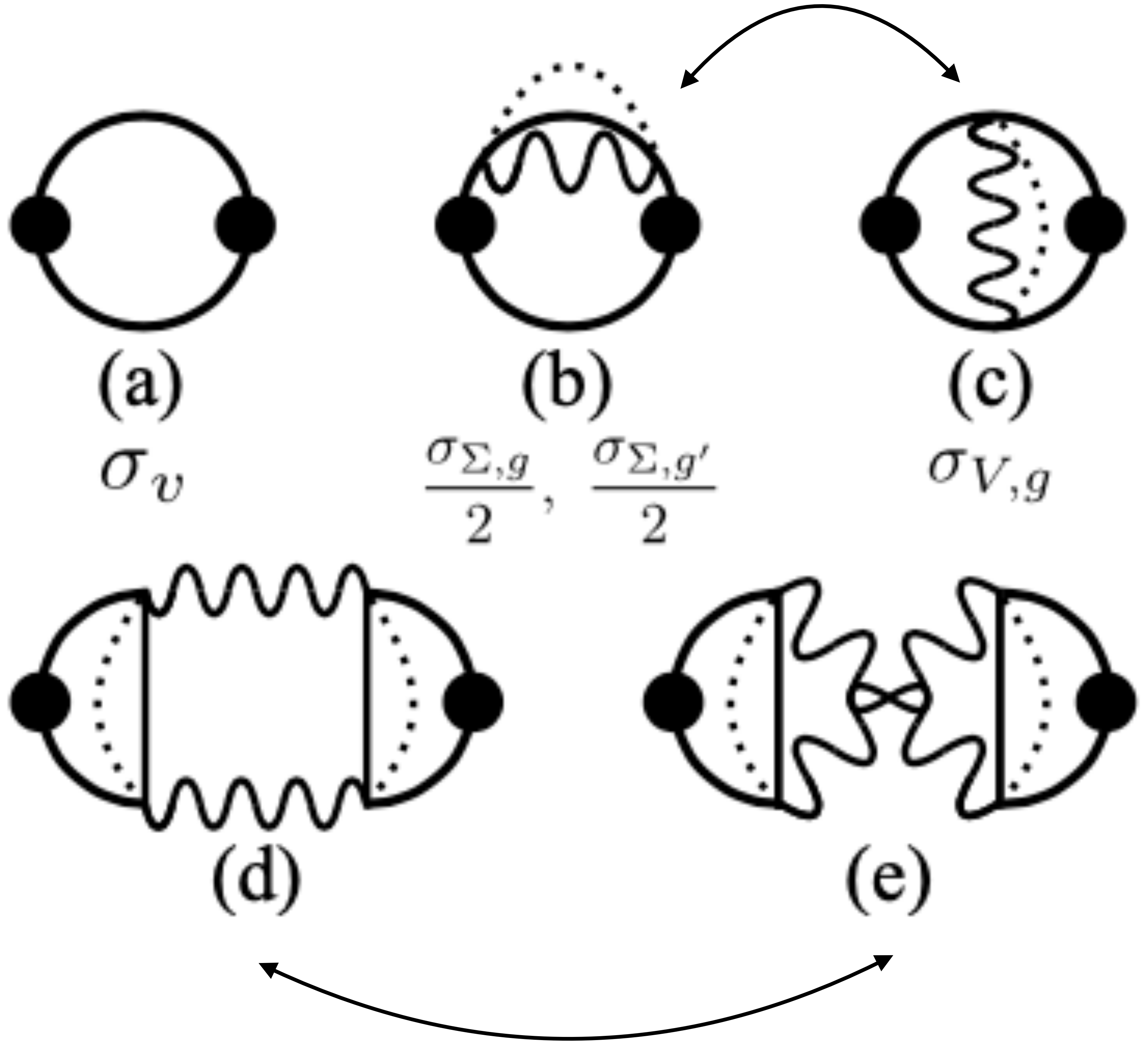
Residual resistivity is determined by v^2; Linear-in-T resistivity determined by g'^2.

A. A. P., H. Guo, I. Esterlis, and S. Sachdev, **arXiv:2203.04990**

How it works

These are the types of diagrams selected by the large-*N* construction; full summation of ladders agrees with perturbative computation.

Cancel for g but not g'.



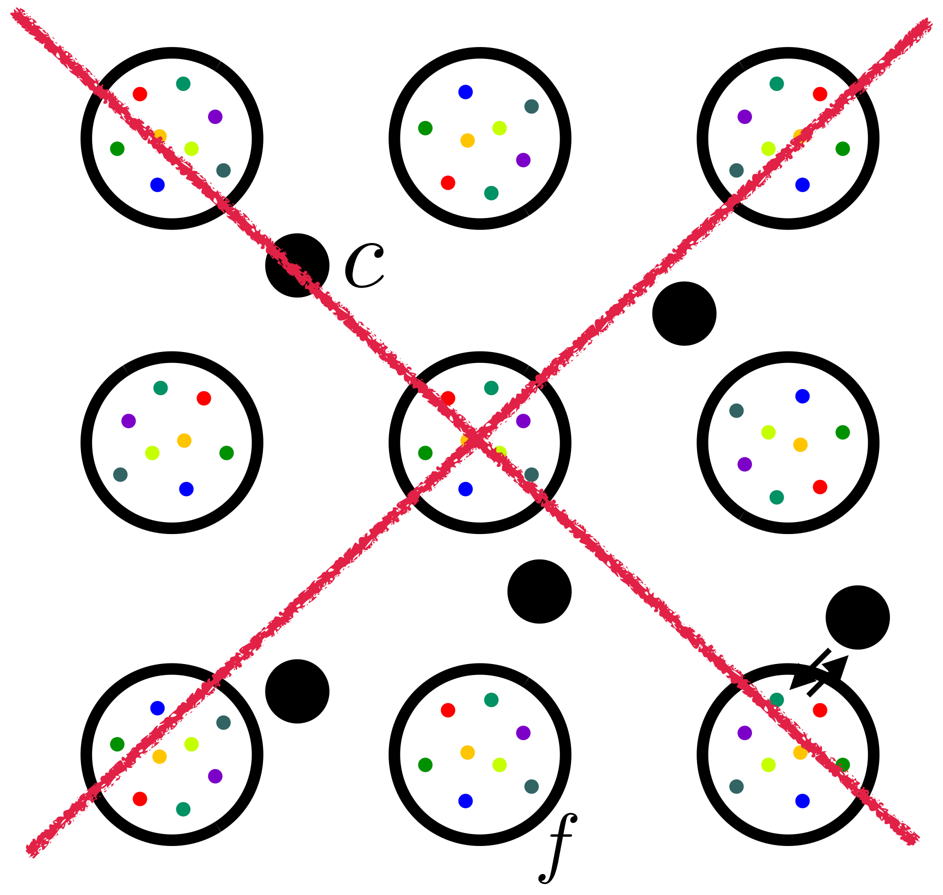
Leading contributions cancel in the large k_F limit; only sub-leading ω^2/E_F terms survive.

Vertex corrections only involve g couplings due to inversion symmetry, whereas self-energy corrections involve both g and g' couplings.

A. A. P., H. Guo, I. Esterlis, and S. Sachdev, **arXiv:2203.04990**

How it works

- Previous approaches towards constructing marginal Fermi liquids with T-linear resistivity (Patel et al, Phys. Rev. X. **8**, 021049 (2018) and Chowdhury et al, Phys. Rev. X. **7**, 031024 (2018)) involved local SYK criticality. Other DMFT-based approaches also involve locally critical impurities with marginal susceptibilities (besides also requiring $d = \infty$).



- Our new approach involves *no* local criticality. The boson is $d = 2$, but fermions can couple to fluctuations beyond just the long-wavelength ones.

$$\chi(\omega) \sim \langle \phi_r(\omega)\phi_r(-\omega)\rangle \sim \int \frac{d^2q}{q^2 + |\omega|} \sim \ln\left(\frac{\Lambda^2}{|\omega|}\right).$$

A. A. P., H. Guo, I. Esterlis, and S. Sachdev, **arXiv:2203.04990**

Planckian dissipation

In most strange metals, attempting to express the DC resistivity using the Drude formula,

$$\rho = \frac{m^*}{ne^2}\frac{1}{\tau},$$

where m^* is the effective electron mass measured in an adjoining Fermi liquid phase and n is the carrier density, gives a surprisingly universal transport scattering rate

$$\frac{1}{\tau} \approx C\frac{k_B T}{\hbar}, \quad C \sim \mathcal{O}(1),$$

independent of material parameters in very different materials. This phenomenon is termed “Planckian dissipation”.

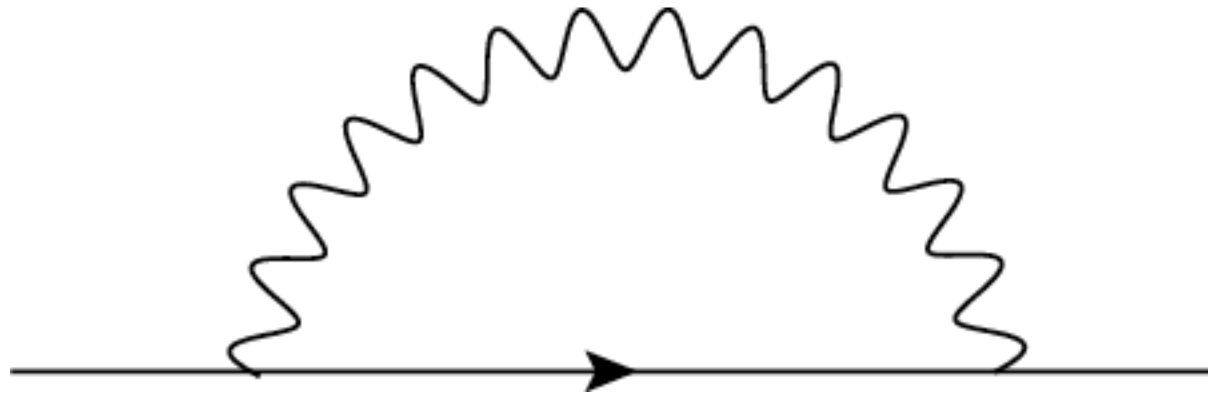
Fully disordered interactions - Planckian metal

$$S=\int d\tau\int d^2\mathbf{r}\sum_{i=1}^{N}\psi_i^\dagger(\mathbf{r},\tau)\left[\partial_\tau-\frac{\nabla^2}{2m}-\mu\right]\psi_i(\mathbf{r},\tau)+\frac{1}{2}\int d\tau\int d^2\mathbf{r}\sum_{i=1}^{N}\phi_i(\mathbf{r},\tau)\left[-\partial_\tau^2-\frac{\nabla^2}{2m_b}\right]\phi_i(\mathbf{r},\tau)$$
$$+\boxed{\int d\tau\int d^2\mathbf{r}\sum_{i,j,k=1}^{N}\left[\frac{g'_{ijk}(\mathbf{r})}{N}\psi_i^\dagger(\mathbf{r},\tau)\psi_j(\mathbf{r},\tau)\phi_k(\mathbf{r},\tau)\right]}+\frac{1}{2}\int d\tau\int d^2\mathbf{r}\; i\lambda(\mathbf{r},\tau)\left(\sum_{i=1}^{N}\phi_i(\mathbf{r},\tau)\phi_i(\mathbf{r},\tau)-\frac{N}{\gamma}\right).$$

- Consists of a large N number of strongly coupled electron and boson fields in 2+1 dimensions, with **fully random** local interactions $g'_{ijk}(\mathbf{r})$.
- large N limit leads to an exact set of Eliashberg equations for the electron and boson Green's functions and self energies.
- The model describes a metallic quantum critical point at $\gamma=\gamma_c$, when the boson is gapless at $T=0$, and a continuous phase transition as γ is tuned.
- Large N self-interaction for the bosons is added to sensibly account for their thermal fluctuations at $T\neq 0$.

I. Esterlis, H. Guo, A. A. P., and S. Sachdev, PRB 103, 235129 (2021)
E. E. Aldape, T. Cookmeyer, A. A. P., and E. Altman, arXiv:2012.00763 (PRB, in press)

Fully disordered interactions - Planckian metal



$$\Sigma(k,\omega \gg T) = -\frac{ig'^2 m m_b}{4\pi^2} i\omega \ln\left(\frac{\Lambda}{|\omega|}\right).$$

$$\frac{1}{\tau} = -\mathrm{Im}[\Sigma^R(k,\omega \ll T)] = \frac{g'^2 m m_b}{4\pi} T \ln\left(\ln\left(\frac{\Lambda}{T}\right)\right).$$

- Electrons couple to the *local* boson fluctuations instead of the long wavelength ones.
- The large N exact Eliashberg equations then yield a marginal Fermi liquid electron self energy at the QCP in 2+1 dimensions.
- Behavior beyond large N can be explored systematically in terms of the fluctuating bilocal G, Σ fields and constraint field λ enforcing the boson self interaction. marginal Fermi liquid likely to persist.
- Since the interaction is random in space and does not conserve momentum, the self energy also represents the transport scattering rate $1/\tau$, giving nearly T linear resistivity.

Fully disordered interactions - Planckian metal

- Away from the critical point, the boson is gapped, and the electrons then form a renormalized Fermi liquid, with a T^2 resistivity.

- However, the effective mass of the electrons is renormalized:

$$\frac{m^*}{m} \equiv 1 + i\frac{\partial\Sigma(i\omega)}{\partial\omega}\bigg|_{\omega\to 0, T\to 0} = 1 + \frac{g'^2 m m_b}{2\pi^2}\ln\left(\frac{\Lambda m_b}{g'^2 m^2}\sqrt{\frac{\gamma\gamma_c}{\gamma-\gamma_c}}\right) \approx \frac{g'^2 m m_b}{2\pi^2}\ln\left(\frac{\Lambda m_b}{g'^2 m^2}\sqrt{\frac{\gamma\gamma_c}{\gamma-\gamma_c}}\right).$$

$g'^2 m m_b \gg 1.$
(strong coupling)

- Then, the Drude transport scattering rate at low T is

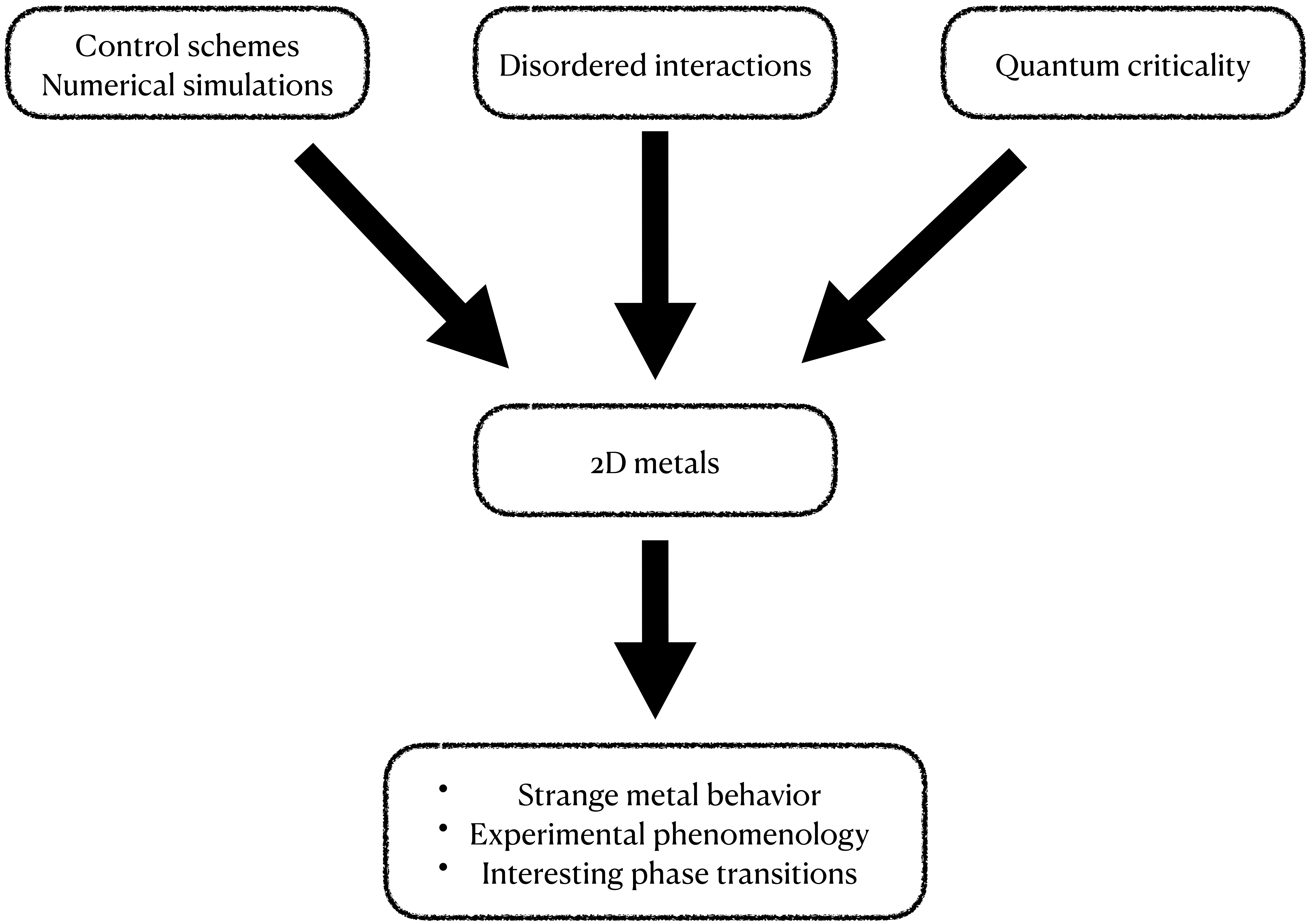
$$\frac{1}{\tau^*} = \frac{ne^2\rho}{m^*} = \frac{1}{\tau}\frac{m}{m^*} \approx \frac{\pi}{2}\frac{k_B T}{\hbar}\frac{\ln\ln\left(\frac{\Lambda}{T}\right)}{\ln\left(\frac{\Lambda m_b}{g'^2 m^2}\sqrt{\frac{\gamma\gamma_c}{\gamma-\gamma_c}}\right)}, \qquad \text{Or } \sim \frac{k_B T}{\hbar}\frac{\ln\ln\left(\frac{\Lambda}{T}\right)}{\ln\left(\frac{\Lambda}{T}\right)}$$

which is nearly universal, with all non-universalities pushed into slowly varying logs. This provides a simple explanation for the phenomenon of Planckian dissipation. **The fully random interactions ensure that exactly the same couplings contribute to both the mass renormalization and the transport scattering rate, yielding the Planckian behavior. This is not the case without full randomness.**

Summary and outlook

- Quantum critical points with *disordered interactions* provide routes to T-linear resistivity and "Planckian dissipation" in two spatial dimensions. They additionally realize $z = 2$ boson dynamics, and therefore also a $T \ln(1/T)$ specific heat. *There is no local criticality*.
- These results should even hold for disordered interactions with a finite q order parameter: $\mathcal{L}_{\text{int}} = (g + g'(r))e^{iQ\cdot r}\psi_r^\dagger \psi_r \phi_r + \text{H.c.}$, or in multi-band models (Aldape et al 2022), or for disordered pairing interactions.
- These can be described in a controlled manner at strong coupling using new large-N techniques, $1/N$ corrections can also be systematically computed. However, the main use of the new large-N method is to formally justify the RPA theory (which is also self-consistent at $N = 1$), and systematically compute possible corrections to it. The physics we described therefore also holds for RPA theory with $N = 1$.
- The experimental values of residual resistivity, ARPES energy dependence of single-particle lifetime, and slope of the linear resistivity, optical resistivity etc, can together (in conjunction with carrier density etc), be used to determine v, g, g'.
- Would be interesting to explore thermal transport: these models can possibly explain why $L = \kappa/(\sigma T) \approx L_0 = (\pi^2/3)(k_B/e)$ at low T even though $\rho = \rho_0 + aT$(Michon et al, Phys. Rev. X. **8**, 041010 (2018)).
- Determine microscopic origin of the new and essential ingredient: g'...

Summary and outlook



Thank you for your attention!