DISORDER AND TRANSPORT IN STRANGE METALS - LESSONS FROM THEORY AND COMPUTATION

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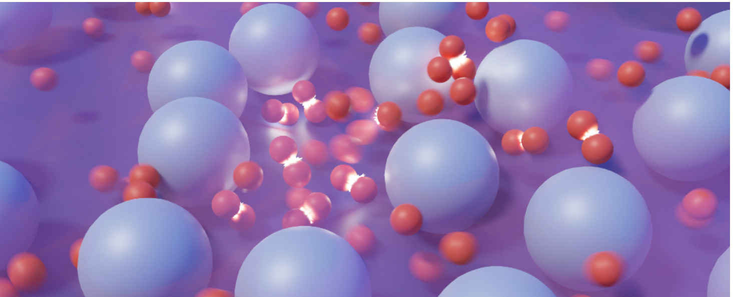
INTERNATIONAL CENTRE FOR THEORETICAL SCIENCES, July 26, 2024

A. A. P., P. Lunts, M. Albergo, **arXiv:2408.xxxxx**
A. Hardy, O. Parcollet, A. Georges and A. A. P, **arXiv:2407.21102**
A. A. P., H. Guo, I. Esterlis, and S. Sachdev **Science 381 (6659) 790-793 (2023)**
E. E. Aldape, T. Cookmeyer, A. A. P, and E. Altman, **Phys. Rev. B 105, 235111 (2022)**
C. Li, D. Valentinis, A. A. P., H. Guo, J. Schmalian, S. Sachdev, I. Esterlis **arXiv:2406.07608**



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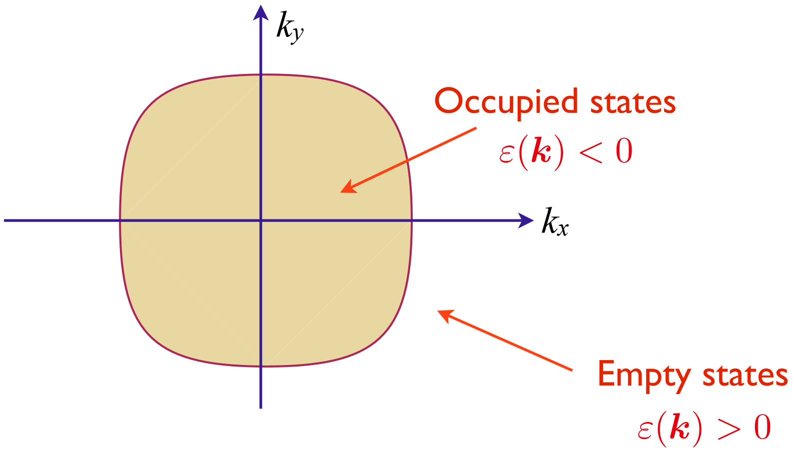
Principles and phenomenology

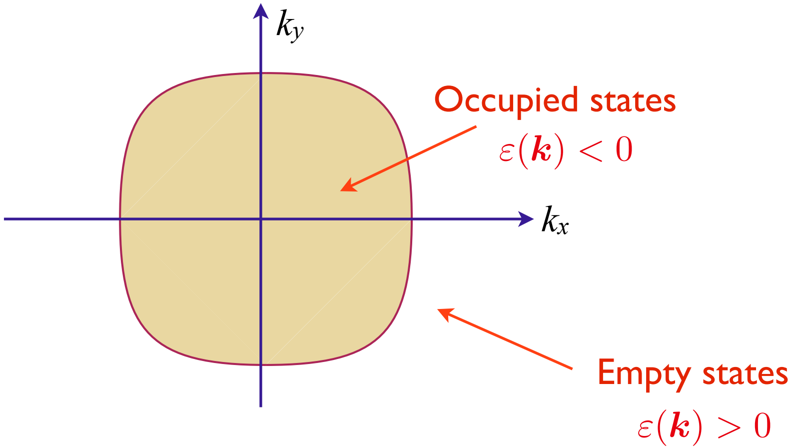
Metals



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

Fermi surface
(k-space: translationally invariant metals)

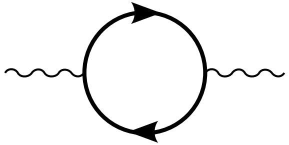
Fermi liquid theory



Fermi surface

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

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



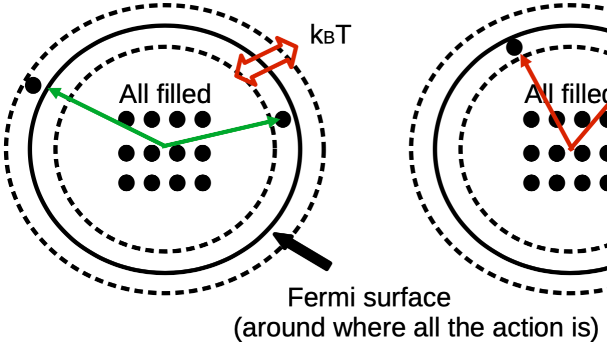
Screening leads to gapped boson

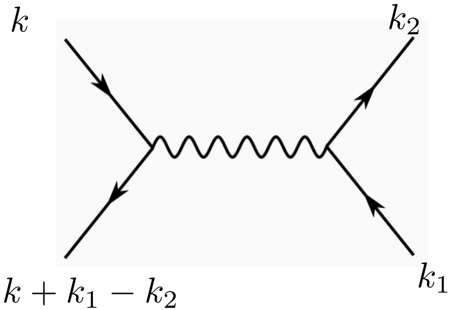
$$G_\psi(\mathbf{k}, i\omega) = \frac{Z}{i\omega - \varepsilon(\mathbf{k}) + i\Gamma} \qquad \Gamma \sim \max(\omega^2, T^2)$$

Fermions interact with gapped boson and become renormalized quasiparticles.

Fermi liquid theory

Screened interaction is similar to a weak contact interaction





$$k_3 = k + k_1 - k_2$$

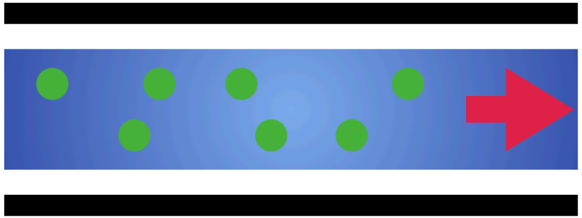
$$\Gamma \sim \int d\epsilon_{k_1} d\epsilon_{k_2} d\epsilon_{k_3} n_f(\epsilon_{k_1})(1 - n_f(\epsilon_{k_2}))(1 - n_f(\epsilon_{k_3}))$$
$$\times\, \delta(\omega + \epsilon_{k_1} - \epsilon_{k_2} - \epsilon_{k_3})$$

$$\Gamma \sim \max(\omega^2, T^2) \qquad \Gamma \ll \max(\omega, T)$$

The small damping rate means that fermion quasiparticles are well defined additive excitations in a Fermi liquid $(d > 1)$

The momentum bottleneck

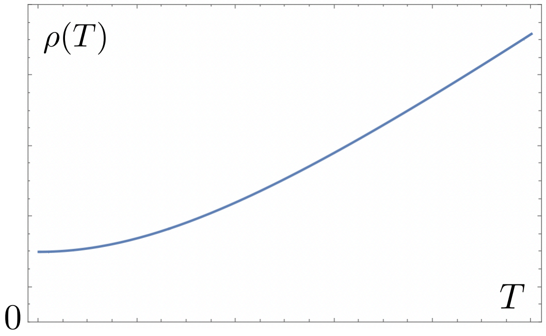
- Current carries momentum
- Resistance requires current relaxation —> momentum relaxation



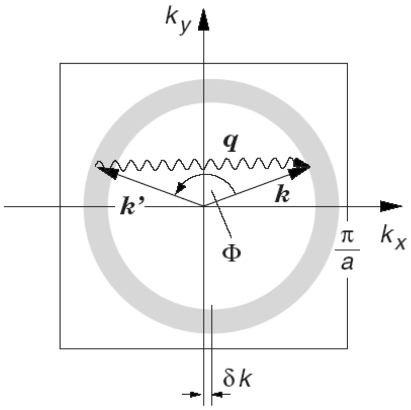
- Generic sources of momentum relaxation in solids: Umklapp, phonons, disorder. Translational invariance has to be broken.

Transport in conventional metals

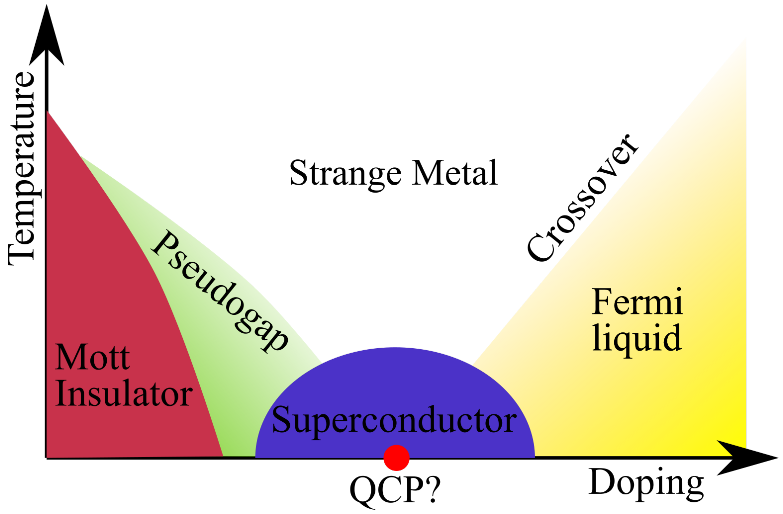
- Low T: $\rho(T) \sim T^2$ from Fermi liquid Umklapp processes.
- High T: $\rho(T) \sim T$ from phonons
- Residual resistivity $\rho(0) > 0$ from impurities



- Both Umklapp and phonons are "gapped" $2k_F$ processes that can't produce anything more than $\rho(T) \sim T^2$ at low T



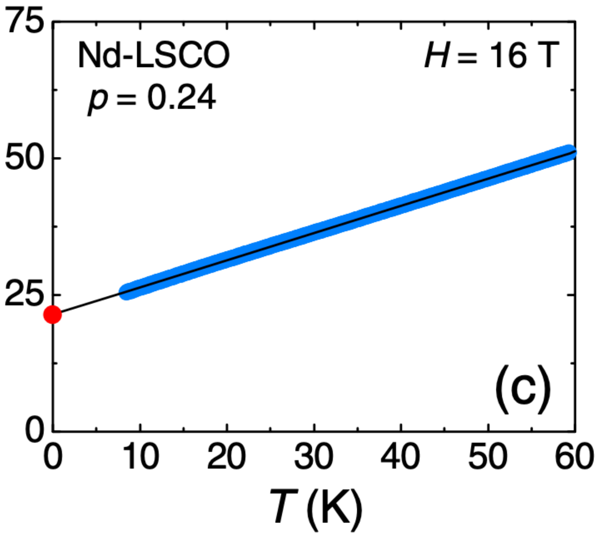
Strange metals



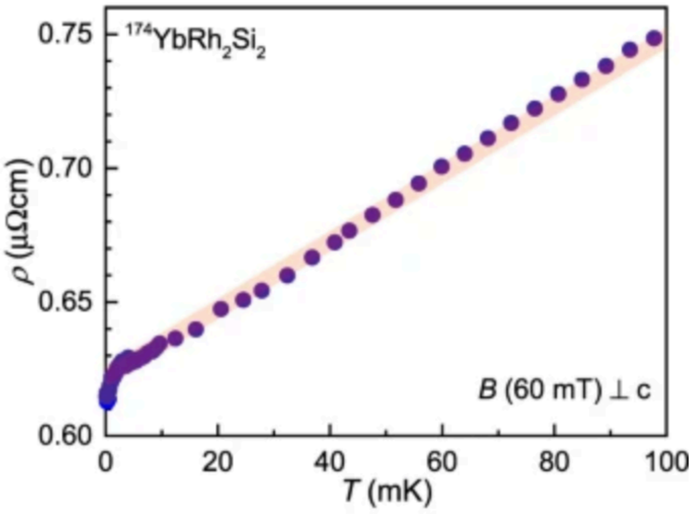
- 2D or quasi-2D (layered) materials.
- T-linear electrical resistivity
- Sometimes proximate to putative quantum critical points.

Transport in strange metals

T-linear resistivity down to $T \to 0$



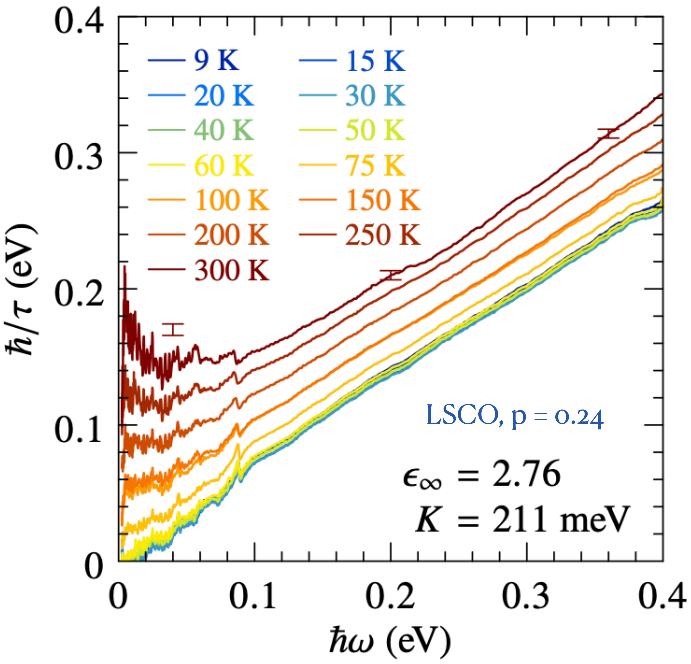
Michon et al, PRX **8**, 041010 (2018)
Cuprate



Nguyen et al, Nat. Comm **12**, 4341 (2021)
Heavy fermion

Transport in strange metals

Inelastic scattering from optical measurements



Michon et al, Nat. Comm. **14**, 3033 (2023)

$$\sigma(\omega) = \frac{K}{\frac{1}{\tau(\omega)} - i\omega\frac{m^*(\omega)}{m}}$$

$$\frac{1}{\tau(\omega)} \propto |\omega|\Phi\left(\frac{\hbar\omega}{k_B T}\right)$$

Large, frequency dependent (therefore inelastic) scattering rate in optical conductivity.

Also seen in photoemission

(Reber et al, Nat. Comm. **10**, 5737 (2019))

Transport constraints in strange metals

- Need T-linear DC resistivity at low T
- Finite DC resistivity requires momentum relaxation
- —> 3 generic options: Umklapp, phonons, disorder
- Finite activation gap for phonons and Umklapp —> weak scattering at low T, doesn't give T-linear as $T \to 0$

Transport constraints in strange metals

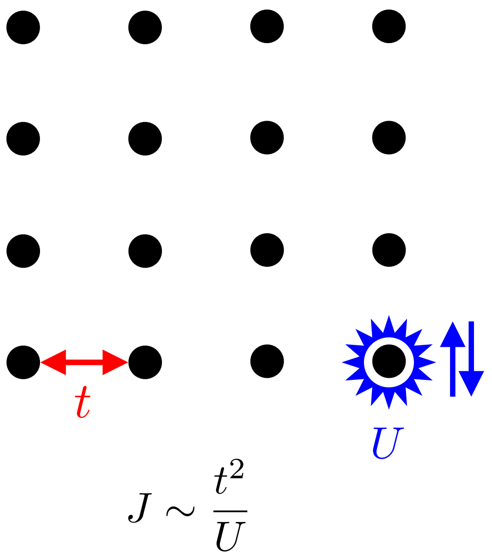
- Furthermore, ω-linear AC scattering rate
- —> Inelastic scattering
- Electron-phonon scattering is elastic in T-linear regime
- Electron-potential disorder scattering is also elastic

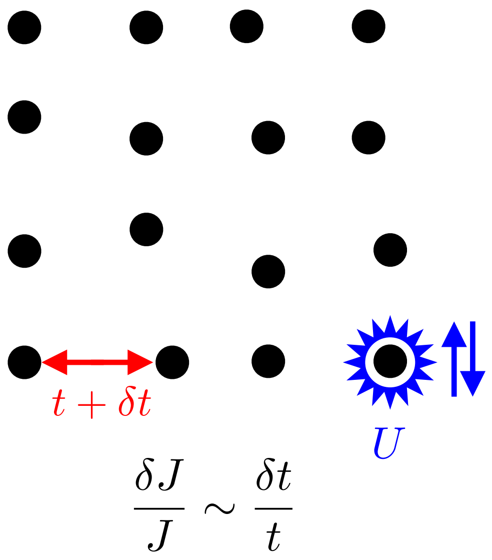
Transport constraints in strange metals

- None of phonons, Umklapp, potential disorder seem to work
- Disordered **interactions** can overcome inadequacies of these mechanisms, by providing momentum-relaxing inelastic scattering that can be strong at low T

Origin of Disordered Interactions

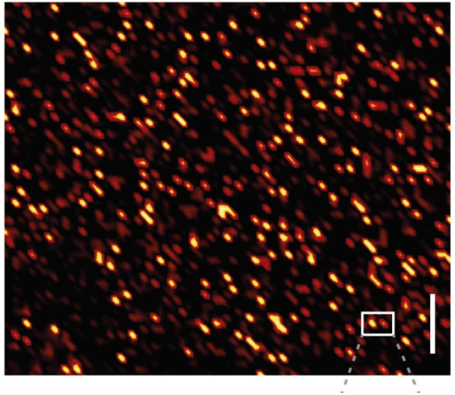
A simple example





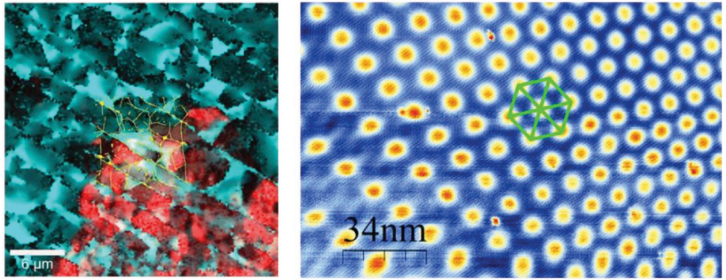
- Randomness in hopping strengths leads to randomness in exchange interactions.

Microscopic disorder in correlated electron materials



Randomness in dopant and charge density in cuprates

Campi et al, Nature **525**, 359–362 (2015)



Twist angle disorder in moiré materials

Andrei and MacDonald, Nat. Mater. **19**, 1265–1275 (2020)

- These can lead to randomness in hopping strengths (and also randomness in U itself) in effective Hubbard-type models

Zhou and Ceperley, Phys. Rev. A **81**, 013402 (2010)

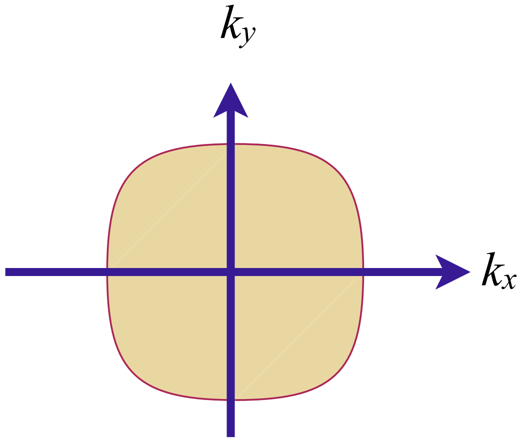
Theoretical models

non-Fermi Liquid Metal

Strong electron-electron interactions

$$\mathcal{L} = \psi^\dagger_{\boldsymbol{k}} \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}} \; + \; \frac{1}{2} \left[(\partial_\tau \phi)^2 + (\boldsymbol{\nabla} \phi)^2 + (\lambda - \lambda_c) \phi^2 \right]$$

“Yukawa” coupling: $g \int d^2 r d\tau \, \psi^\dagger(r,\tau) \psi(r,\tau) \phi(r,\tau)$



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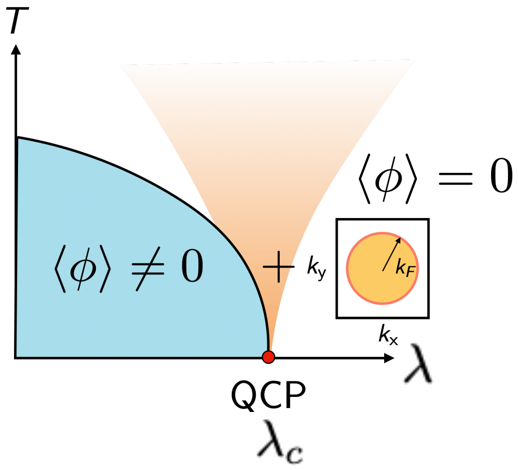


J. A. Hertz, Phys. Rev. B **14**, 1165 (1976)

A. J. Millis, Phys. Rev. B **48**, 7183 (1993)

Translationally invariant, $\rho_{DC}(T) = 0$.

non-Fermi Liquid Metal

$$\mathcal{L} = \psi_{\boldsymbol{k}}^\dagger \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}} + \frac{1}{2} \left[(\partial_\tau \phi)^2 + (\boldsymbol{\nabla} \phi)^2 + (\lambda - \lambda_c) \phi^2 \right]$$

$$\text{“Yukawa” coupling:} \quad g \int d^2 r d\tau \, \psi^\dagger(r,\tau) \psi(r,\tau) \phi(r,\tau)$$

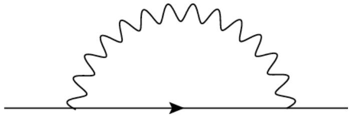
Eliashberg solution for electron (G) and boson (D) Green's functions at small ω:

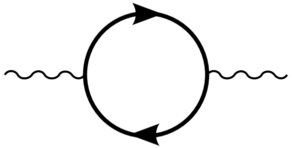
$$\Sigma(\hat{\boldsymbol{k}}, i\omega) \sim -i \text{sgn}(\omega) |\omega|^{2/3}, \quad G(\boldsymbol{k}, i\omega) = \frac{1}{i\omega - \varepsilon(\boldsymbol{k}) - \Sigma(\hat{\boldsymbol{k}}, i\omega)}, \quad D(\boldsymbol{q}, i\Omega) = \frac{1}{\Omega^2 + q^2 + \gamma |\Omega|/q}$$

P.A. Lee, Phys. Rev. Lett **63**, 680 (1989)

(in two spatial dimensions)

Strong inelastic forward scattering, no well-defined quasiparticles, but no momentum relaxation.





(Boson is massless but damped at QCP)

Translationally invariant, $\rho_{DC}(T) = 0$.

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

H. Guo, A. A. P., I. Esterlis and S. Sachdev, **Phys. Rev. B 106, 115151 (2022)**

non-Fermi Liquid Metal with Disordered Interactions

Strong and disordered electron-electron interactions

$$\mathcal{L} = \psi_{\boldsymbol{k}}^{\dagger}\left(\frac{\partial}{\partial\tau} + \varepsilon(\boldsymbol{k})\right)\psi_{\boldsymbol{k}} + \frac{1}{2}\left[(\partial_\tau\phi)^2 + (\nabla\phi)^2 + (\lambda-\lambda_c)\phi^2\right]$$

Random potential $\int d^2r d\tau\, v(r)\, \psi^\dagger(r,\tau)\psi(r,\tau)$

"Yukawa" coupling: $\int d^2r d\tau\, [g + g'(r)]\, \psi^\dagger(r,\tau)\psi(r,\tau)\phi(r,\tau)$

Spatially random Yukawa coupling $g'(r)$ with $\overline{g'(r)} = 0$, $\overline{g'(r)g'(r')} = g'^2\delta(r-r')$

- Hubbard-Stratonovich decomposition of random 4-Fermi term (such as exchange) produces random Yukawa coupling.

A. A. P., H. Guo, I. Esterlis and S. Sachdev,
Science 381 (6659) 790-793 (2023)

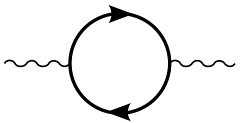
non-Fermi Liquid Metal with Disordered Interactions

Strong and disordered electron-electron interactions

Boson self energy: $\Pi = \Pi_g + \Pi_{g'}$

$$\Pi_g(i\Omega) \sim -\frac{g^2}{v^2}|\Omega|,$$

$$\boxed{\Pi_{g'}(i\Omega) \sim -g'^2|\Omega|,}$$



$$D(q, i\Omega) = \frac{1}{q^2 + \gamma|\Omega|}$$

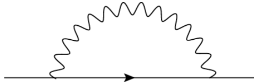
(in two spatial dimensions, at QCP)

Fermion self energy: $\Sigma = \Sigma_v + \Sigma_g + \Sigma_{g'}$

$$\Sigma_v(i\omega) \sim -iv^2 \mathrm{sgn}(\omega),$$

$$\Sigma_g(i\omega) \sim -i\frac{g^2}{v^2}\omega \ln(1/|\omega|),$$

$$\boxed{\Sigma_{g'}(i\omega) \sim -ig'^2\omega \ln(1/|\omega|)}$$

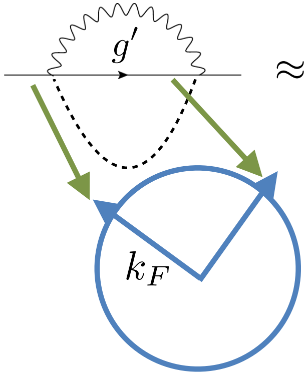


- Self-consistent 1-loop calculation (Eliashberg), equivalent to a large-N saddle point

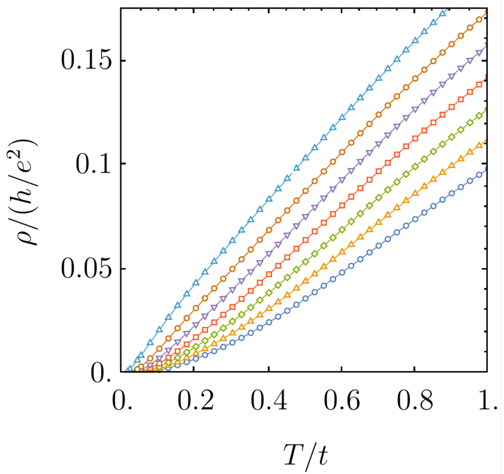
A. A. P., H. Guo, I. Esterlis and S. Sachdev,
Science 381 (6659) 790-793 (2023)

non-Fermi Liquid Metal with Disordered Interactions

$$\Sigma_{g'} = \text{[diagram]} \approx -i\omega \ln\left(\frac{\Lambda^2}{|\omega|}\right) g'^2$$



- Disordered interaction g' vertex does not conserve momentum
- —> Current and momentum relaxing scattering of fermions by critical bosons



Conductivity: $\sigma(\omega) \sim [1/\tau_{\text{trans}}(\omega) - i\omega\, m^*(\omega)/m]^{-1}$

$$\frac{1}{\tau_{\text{trans}}(\omega)} \sim v^2 + g'^2|\omega| \quad ; \quad \frac{m^*(\omega)}{m} \sim \frac{2g'^2}{\pi}\ln(\Lambda/\omega)$$

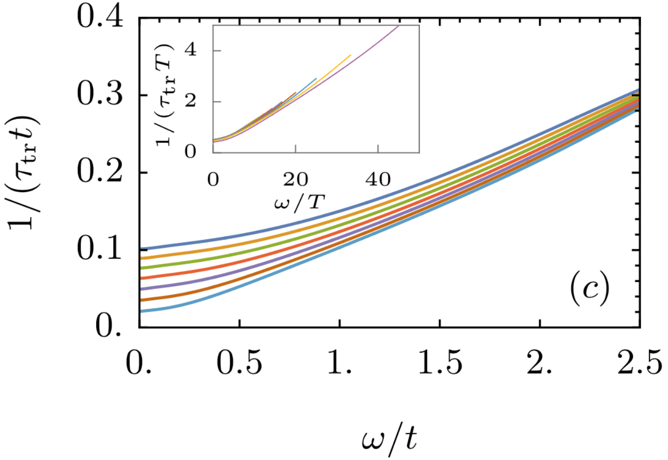
Residual resistivity is determined by v^2; Linear-in-T resistivity determined by g'^2.

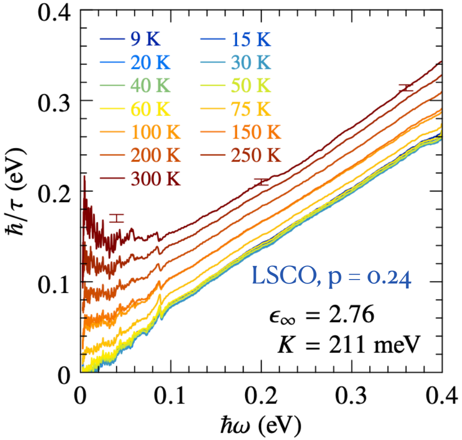
A. A. P., H. Guo, I. Esterlis, and S. Sachdev **Science 381 (6659) 790-793 (2023)**

E. E. Aldape, T. Cookmeyer, A. A. P, and E. Altman, **Phys. Rev. B 105, 235111 (2022)**

C. Li, D. Valentinis, A. A. P., H. Guo, J. Schmalian, S. Sachdev, I. Esterlis **arXiv:2406.07608**

non-Fermi Liquid Metal with Disordered Interactions





Michon et al, Nat. Comm. **14**, 3033 (2023)

Conductivity: $\sigma(\omega) \sim [1/\tau_{\text{trans}}(\omega) - i\omega\, m^*(\omega)/m]^{-1}$

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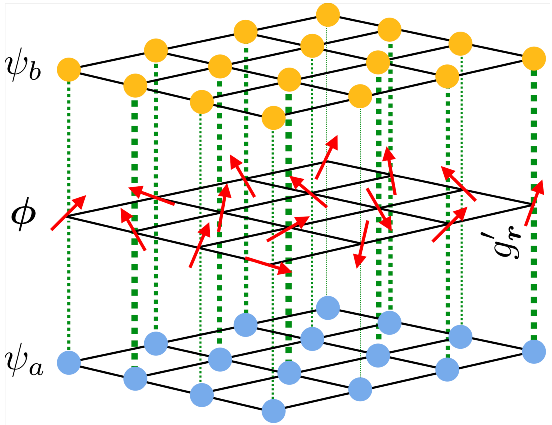
C. Li, D. Valentinis, A. A. P., H. Guo, J. Schmalian, S. Sachdev, I. Esterlis **arXiv:2406.07608**

Numerics beyond mean-field/Eliashberg

Model for sign-free Quantum Monte Carlo

$$\mathcal{S}[\boldsymbol{\phi},\psi,\psi^\dagger] = \int d\tau \sum_{\boldsymbol{r},\boldsymbol{r}'} \sum_{\alpha=a,b} \sum_{\sigma=\uparrow,\downarrow} \sum_{j=1}^{2} \psi^\dagger_{\alpha,\sigma,j,\boldsymbol{r}} \left[(\partial_\tau - \mu_\alpha)\delta_{\boldsymbol{r},\boldsymbol{r}'} - t_{\alpha,\boldsymbol{r},\boldsymbol{r}'}\right] \psi_{\alpha,\sigma,j,\boldsymbol{r}'}$$
$$+ \int d\tau \sum_{\boldsymbol{r}} \left[\frac{1}{2c^2}(\partial_\tau \boldsymbol{\phi}_{\boldsymbol{r}})^2 + \frac{1}{2}(\nabla \boldsymbol{\phi}_{\boldsymbol{r}})^2 + \frac{\lambda}{2}(\boldsymbol{\phi}_{\boldsymbol{r}})^2 + \frac{u}{4}(\boldsymbol{\phi}_{\boldsymbol{r}}\cdot\boldsymbol{\phi}_{\boldsymbol{r}})^2\right]$$
$$+ \frac{1}{\sqrt{2}} \sum_{\sigma,\sigma'=\uparrow,\downarrow} \sum_{j=1}^{2} \int d\tau \sum_{\boldsymbol{r}} g'_{\boldsymbol{r}}\, e^{i\boldsymbol{Q}_{\mathrm{AF}}\cdot\boldsymbol{r}}\, \boldsymbol{\phi}_{\boldsymbol{r}} \cdot \left[\psi^\dagger_{\alpha,\sigma,j,\boldsymbol{r}}\, \boldsymbol{\tau}_{\sigma,\sigma'}\, \psi_{b,\sigma',j,\boldsymbol{r}} + \mathrm{h.c.}\right].$$



Two-band structure: Berg, Metlitski, Sachdev, Science **338** 1606-1609 (2012).

A. A. P., P. Lunts, M. Albergo, **arXiv:2408.xxxxx**

Model for sign-free Quantum Monte Carlo

$$\mathcal{S}[\boldsymbol{\phi}, \psi, \psi^\dagger] = \int d\tau \sum_{\boldsymbol{r},\boldsymbol{r}'} \sum_{\alpha=a,b} \sum_{\sigma=\uparrow,\downarrow} \sum_{j=1}^{2} \psi^\dagger_{\alpha,\sigma,j,\boldsymbol{r}} \left[(\partial_\tau - \mu_\alpha)\delta_{\boldsymbol{r},\boldsymbol{r}'} - t_{\alpha,\boldsymbol{r},\boldsymbol{r}'}\right] \psi_{\alpha,\sigma,j,\boldsymbol{r}'}$$

$$+ \int d\tau \sum_{\boldsymbol{r}} \left[\frac{1}{2c^2}(\partial_\tau \boldsymbol{\phi}_{\boldsymbol{r}})^2 + \frac{1}{2}(\nabla \boldsymbol{\phi}_{\boldsymbol{r}})^2 + \frac{\lambda}{2}(\boldsymbol{\phi}_{\boldsymbol{r}})^2 + \frac{u}{4}(\boldsymbol{\phi}_{\boldsymbol{r}} \cdot \boldsymbol{\phi}_{\boldsymbol{r}})^2\right]$$

$$+ \frac{1}{\sqrt{2}} \sum_{\sigma,\sigma'=\uparrow,\downarrow} \sum_{j=1}^{2} \int d\tau \sum_{\boldsymbol{r}} g'_{\boldsymbol{r}}\, e^{i\boldsymbol{Q}_{\mathrm{AF}}\cdot\boldsymbol{r}}\, \boldsymbol{\phi}_{\boldsymbol{r}} \cdot \left[\psi^\dagger_{\alpha,\sigma,j,\boldsymbol{r}}\, \boldsymbol{\tau}_{\sigma,\sigma'}\, \psi_{b,\sigma',j,\boldsymbol{r}} + \mathrm{h.c.}\right].$$

- Integrate out fermions ψ: $\mathcal{Z} = \int \mathcal{D}[\boldsymbol{\phi}] e^{-S_B[\boldsymbol{\phi}]} \det[A(\boldsymbol{\phi})]$
- A is Hermitian positive definite, legitimate probability distribution.

A. A. P., P. Lunts, M. Albergo, arXiv:2408.xxxxx

Facing the determinant

- Need large system size to see enough disorder
- Lattice: L^2 sites, N_t imaginary time points.
- Compute $\det[A]$ directly: $O(L^6 N_t^3)$ cost, very bad.
- Usual determinant QMC method with low-rank updates: $O(L^6 N_t)$.
- Requires storing and applying an extensively-sized dense matrix A^{-1}, prohibitive memory and bandwidth costs for large L, N_t.

Hybrid Monte Carlo

$$\mathcal{Z} = \int \mathcal{D}[\vec{\phi}] e^{-S_B[\vec{\phi}]} \det[A(\vec{\phi})]$$

$$\mathcal{Z} = \int \mathcal{D}[\vec{\phi}] \mathcal{D}[\varphi, \varphi^*] e^{-S_B[\vec{\phi}]} e^{-\varphi^* A^{-1}(\vec{\phi})\varphi}$$

- Avoid evaluating det by sampling over φ.
- Solve linear system with A at each step to determine $A^{-1}(\vec{\phi})\varphi$.
- Cost of the (iterative) linear solve depends upon the condition number of A which can become large at low T, preconditioning is generally required.
- Uses far less memory and bandwidth, GPU friendly, $O(L^2 N_t^{a \gtrsim 1})$, scales to large sizes
- We go up to $L = 40, \quad N_t = 800 \quad (\beta = 80)$.

S. Duane et al, Phys. Lett. B **195**, 216-222 (1987)

Hybrid Monte Carlo

$$\mathcal{Z} = \int \mathcal{D}[\vec{\phi}]\mathcal{D}[\varphi, \varphi^*]e^{-S_B[\vec{\phi}]}e^{-\varphi^* A^{-1}(\vec{\phi})\varphi}$$

- Sample φ from distribution, use fictitious Hamiltonian dynamics to update ϕ, repeat iteratively.

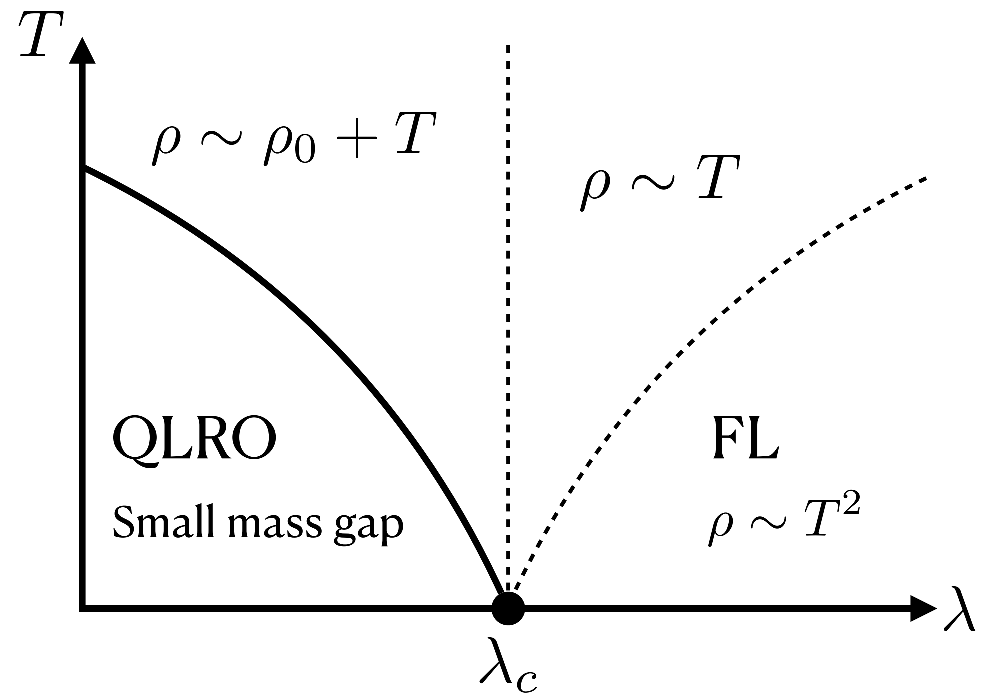
$$\frac{d\phi}{dt} = M^{-1}\pi \quad \text{and} \quad \frac{d\pi}{dt} = -\frac{\partial \mathcal{S}(\phi, \varphi)}{\partial \phi}$$ (randomly sampled fictitious momentum π)

- Integrator time step size and number of steps are chosen in a warmup phase to maximize change in ϕ. (P. Lunts et al, Nat. Comm. **14**, 2547 (2023)).

- M^{-1} is set equal to a running estimate of the $\vec{\phi}$ propagator for optimal updates (P. Lunts et al, Nat. Comm. **14**, 2547 (2023)).

S. Duane et al, Phys. Lett. B **195**, 216-222 (1987)
P. Lunts et al, Nat. Comm. **14**, 2547 (2023)

Mean-field (Eliashberg) phase diagram



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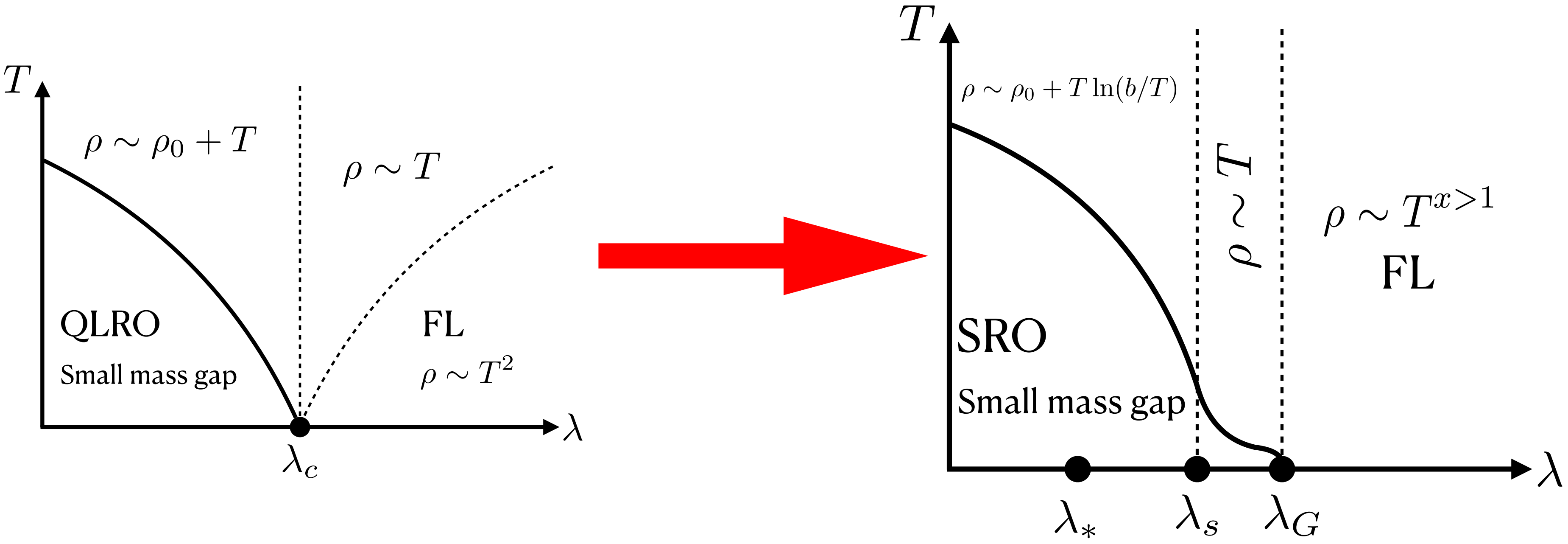
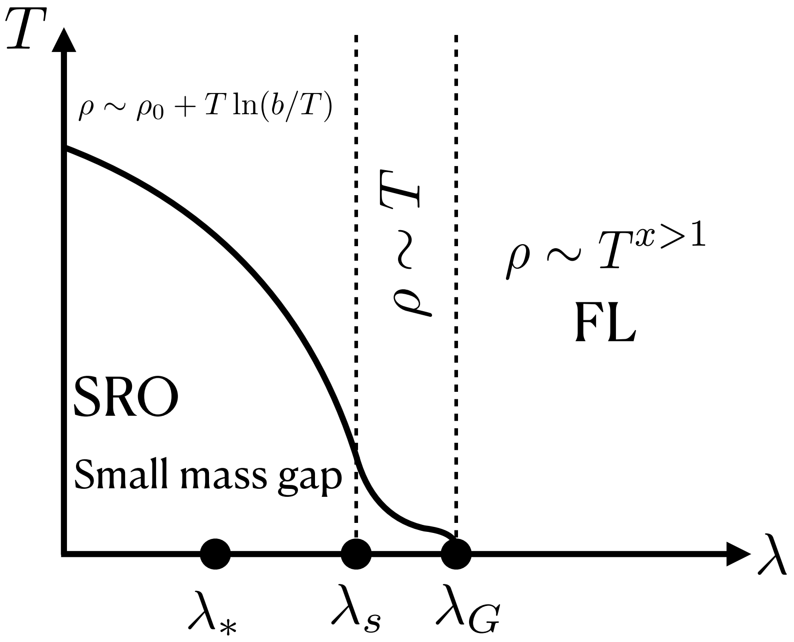
C. Li, D. Valentinis, A. A. P., H. Guo, J. Schmalian, S. Sachdev, I. Esterlis, **arXiv:2406.07608**

Non-perturbative phase diagram



A. A. P., P. Lunts, M. Albergo, **arXiv:2408.xxxxx**

Non-perturbative phase diagram



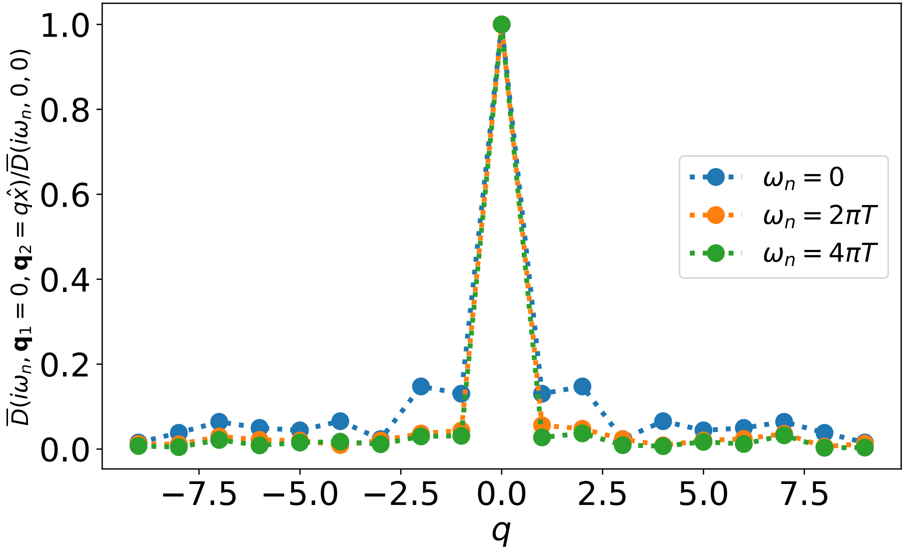
- Extended region of T-linear resistivity ($\lambda_s < \lambda < \lambda_G$)
- Gapless SRO boson phase, eventual crossover to LRO for $\lambda < \lambda_*$, no sharp QPT to LRO.

A. A. P., P. Lunts, M. Albergo, **arXiv:2408.xxxxx**

Dirty bosons

- Key to new physics: strongly disordered bosons at low energies

$$D(i\omega_n = 0, \mathbf{q}_1, \mathbf{q}_2 \neq \mathbf{q}_1) \neq 0$$



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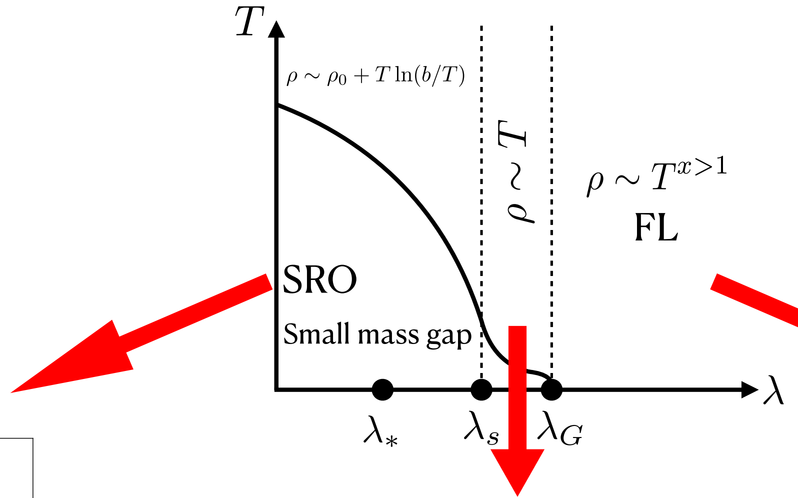
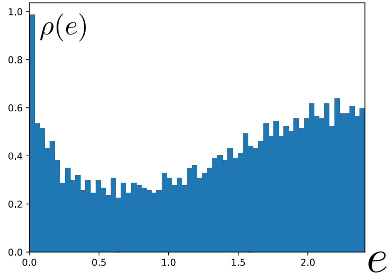
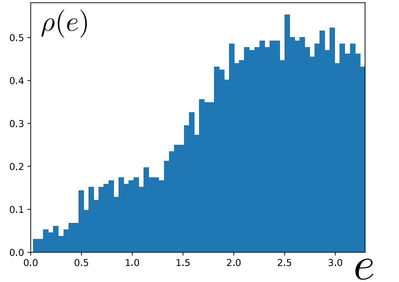
Boson density of states

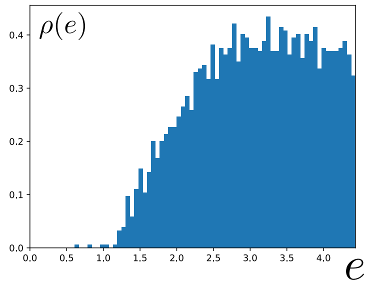




$\rho(e \to 0) > 0,\ \rho'(e \to 0) < 0$



$\rho(e \to 0) > 0,\ \rho'(e \to 0) = 0$



$\rho(e \to 0) = 0,\ \rho'(e \to 0) = 0$

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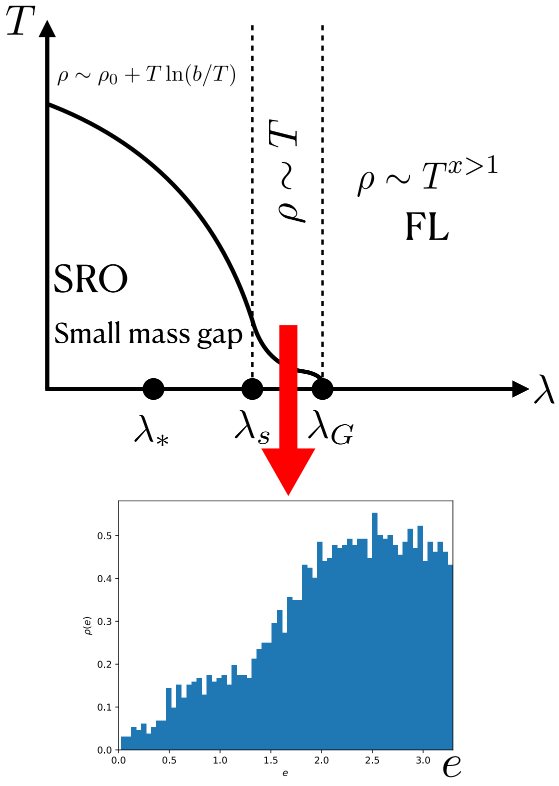
Boson density of states



$$\rho(e \to 0) > 0, \ \ \rho'(e \to 0) = 0$$

- Gapless constant low-energy DOS for $\lambda_s < \lambda < \lambda_G$ similar to $\lambda = \lambda_c$ in mean field (quadratic dispersion in 2D)
- But, boson eigenmodes are not plane-wave states
- Spatial correlation length is **not** large
- Not a QCP

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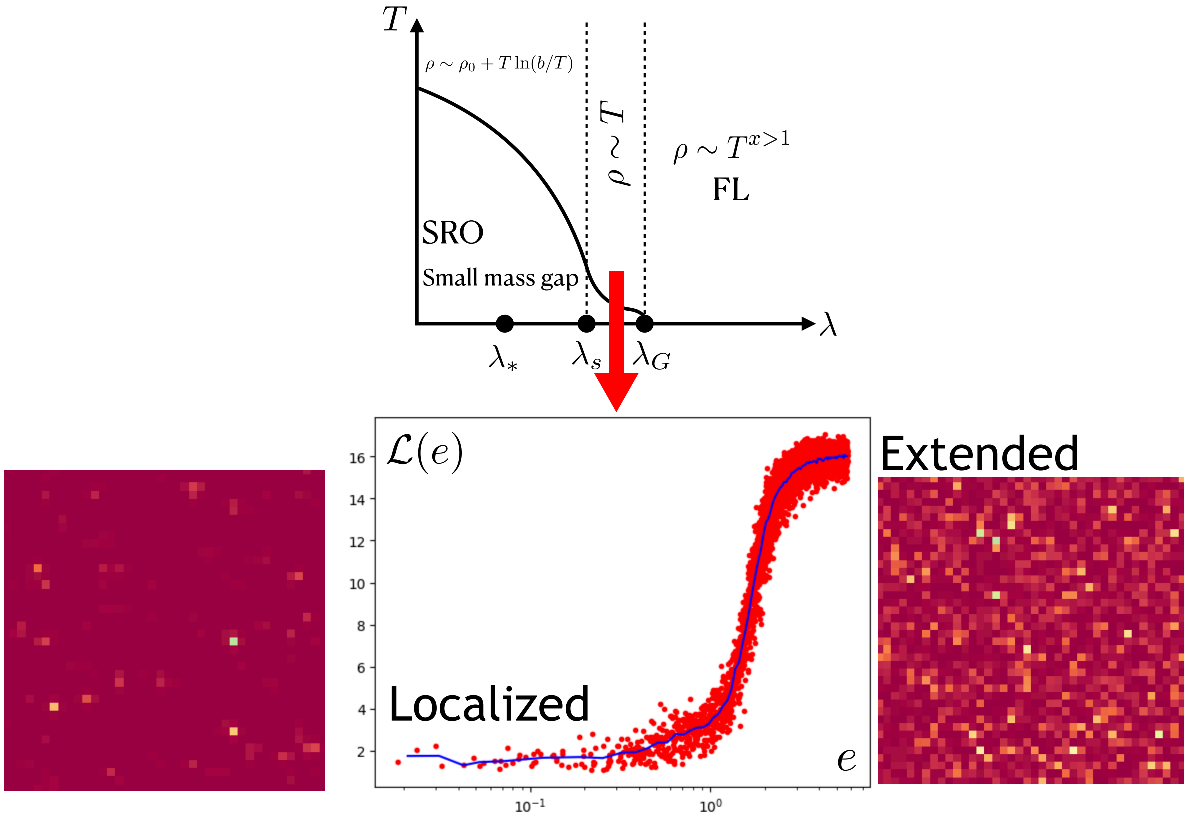
Boson eigenmodes



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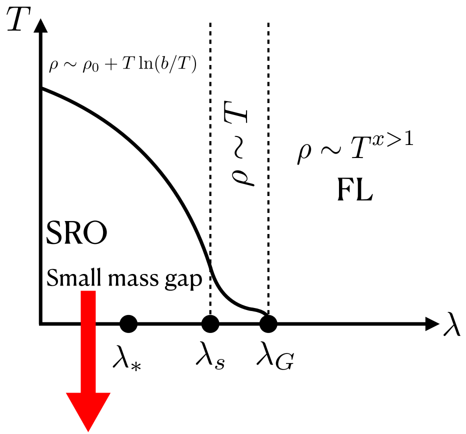
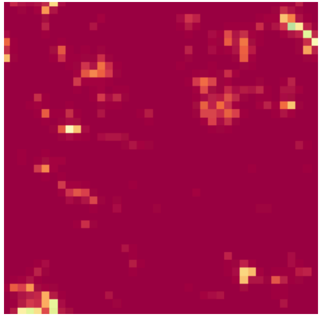
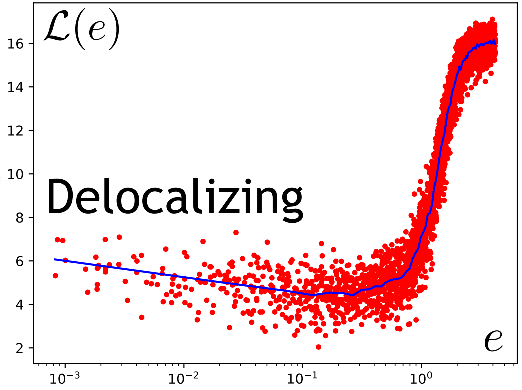
Boson eigenmodes







- Gradual crossover to LRO for $\lambda < \lambda_*$ associated with localized low-energy modes slowly delocalizing again

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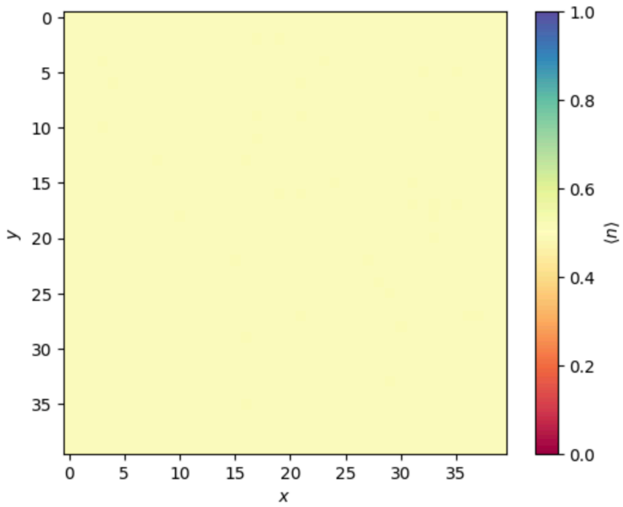
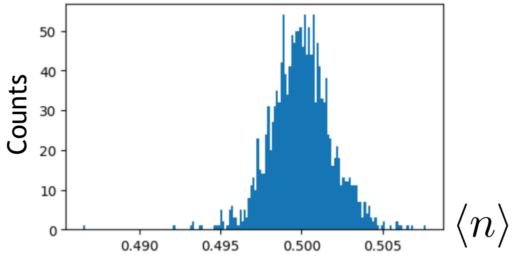
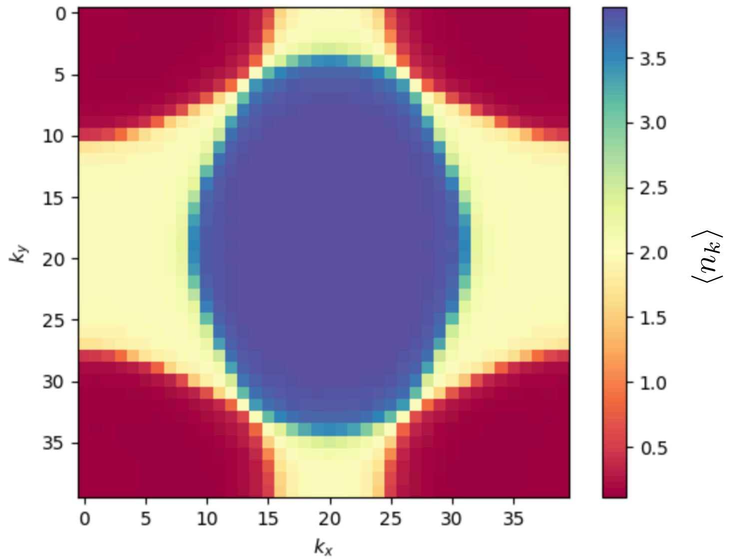
Dirty bosons, clean fermions



Uniform real-space occupation





Fermi surface in momentum-space occupation

$$\lambda = \lambda_s$$

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Transport

- Measure $\sigma(i\omega_n)$ from Kubo formula
- Reparametrize $\sigma(i\omega_n) = \dfrac{\tilde{D}}{|\omega_n| + \Gamma(\omega_n, T)}$

  $\tilde{D} =$ non-interacting Drude weight

- Analyze functional form of $\Gamma(\omega_n, T)$
- Extrapolation $\Gamma(\omega_n \to 0, T)$ gives DC scattering rate

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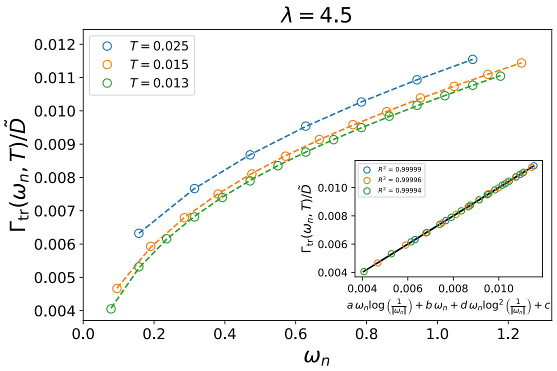
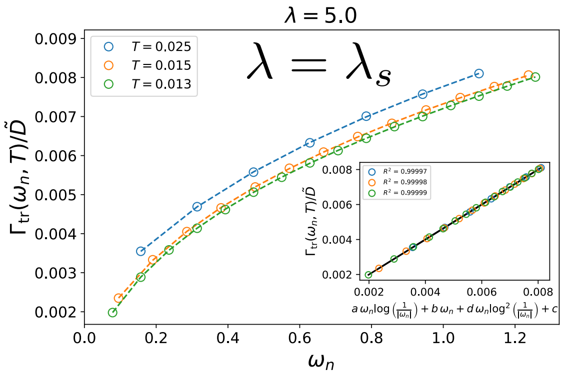
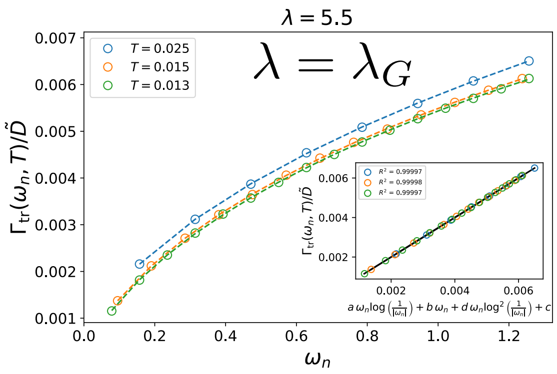
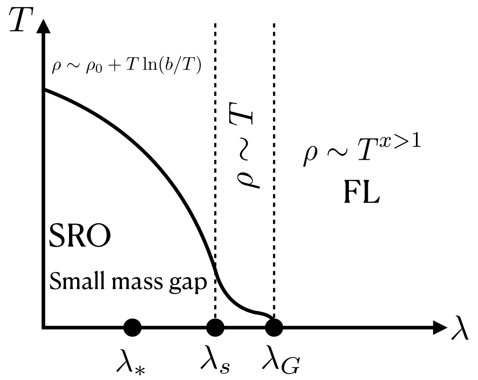
Transport







- Universal form $\Gamma(i\omega_n \geq 2\pi T) = -a\omega_n \ln \omega_n + b\omega_n + d\omega_n \ln^2 \omega_n + c$ for $\lambda \leq \lambda_G$
- "Marginal Fermi liquid" with extra $\omega \ln^2 \omega$ correction that becomes significant for $\lambda < \lambda_s$



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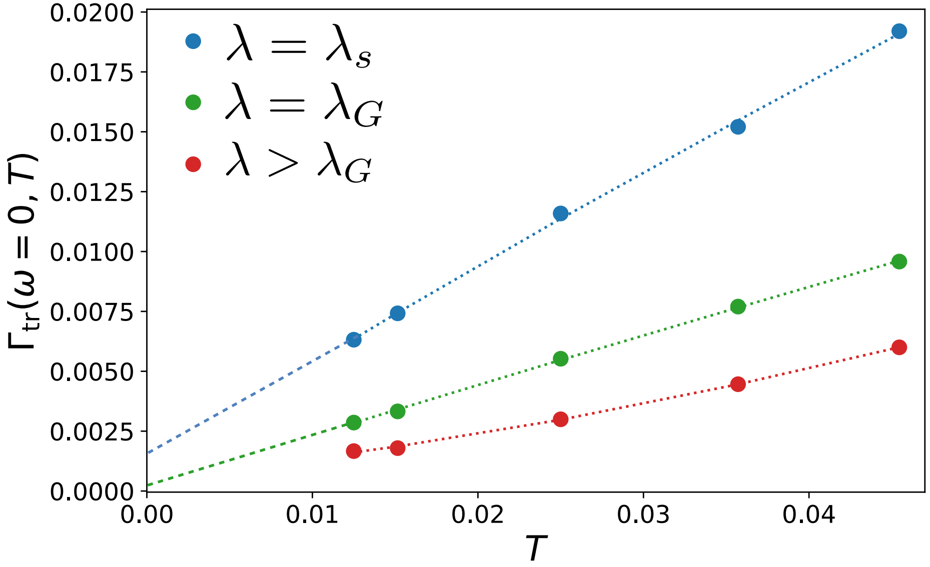
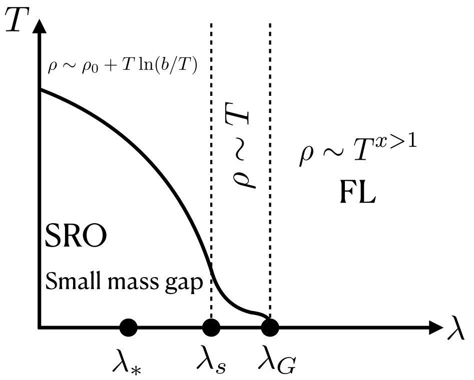
Transport



- Polynomial spline extrapolation of $\Gamma(\omega_n \to 0, T)$
- Largest slope of T-linear at $\lambda = \lambda_s$
- Planckian $\Gamma \approx 0.4 k_B T/\hbar$, large RRR (clean fermions)



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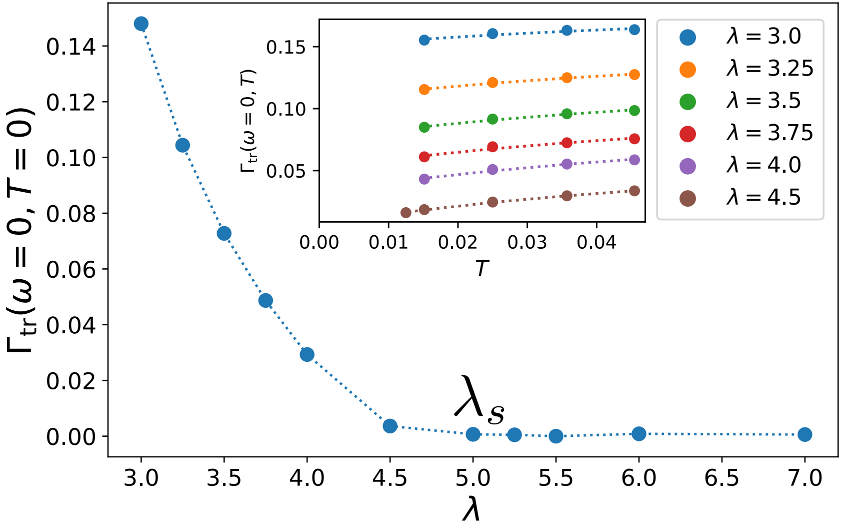
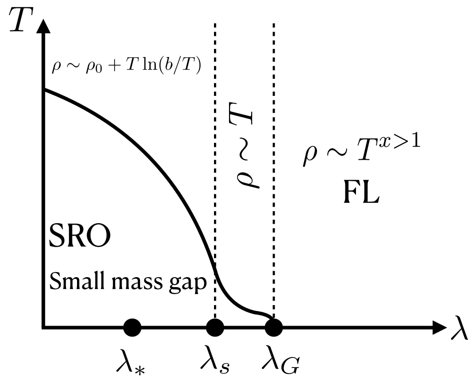
Transport





- Residual resistivity onsets for $\lambda < \lambda_s$, associated with SRO
- T-dependence changes to $T\ln(b/T)$ (recall extra log term in ω-dependence). RRR becomes small(er)

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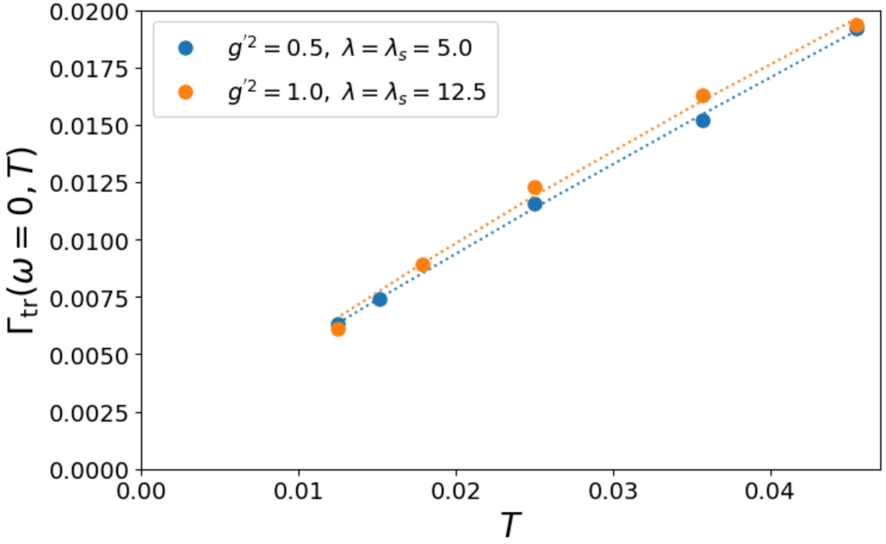
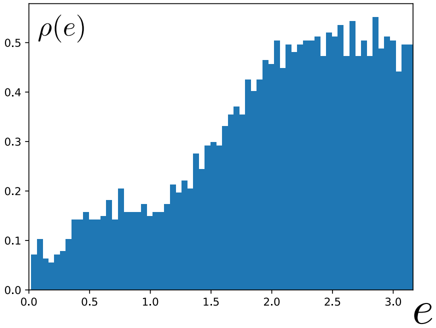
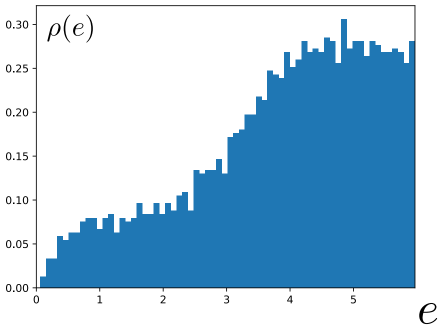
Transport universality



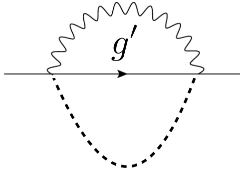


$\lambda = \lambda_s,\ g'^2 = 0.5$



$\lambda = \lambda_s,\ g'^2 = 1.0$

- At $\lambda = \lambda_s$, slope of T-linear is independent of interaction disorder g'
- Boson DOS $\rho(e) \sim f(e/g'^2)/g'^2$, $\rho(e \to 0) \sim 1/g'^2$
- Compatible with $\Gamma \sim \text{fermion DOS} \times \text{boson DOS} \times g'^2 \times T$



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Transport universality

Material		n (10^{27} m^{-3})	m^* (m_0)	A_1 / d (Ω / K)	$h / (2e^2 T_F)$ (Ω / K)	α
Bi2212	$p = 0.23$	6.8	8.4 ± 1.6	8.0 ± 0.9	7.4 ± 1.4	1.1 ± 0.3
Bi2201	$p \sim 0.4$	3.5	7 ± 1.5	8 ± 2	8 ± 2	1.0 ± 0.4
LSCO	$p = 0.26$	7.8	9.8 ± 1.7	8.2 ± 1.0	8.9 ± 1.8	0.9 ± 0.3
Nd-LSCO	$p = 0.24$	7.9	12 ± 4	7.4 ± 0.8	10.6 ± 3.7	0.7 ± 0.4
PCCO	$x = 0.17$	8.8	2.4 ± 0.1	1.7 ± 0.3	2.1 ± 0.1	0.8 ± 0.2
LCCO	$x = 0.15$	9.0	3.0 ± 0.3	3.0 ± 0.45	2.6 ± 0.3	1.2 ± 0.3
TMTSF	$P = 11$ kbar	1.4	1.15 ± 0.2	2.8 ± 0.3	2.8 ± 0.4	1.0 ± 0.3

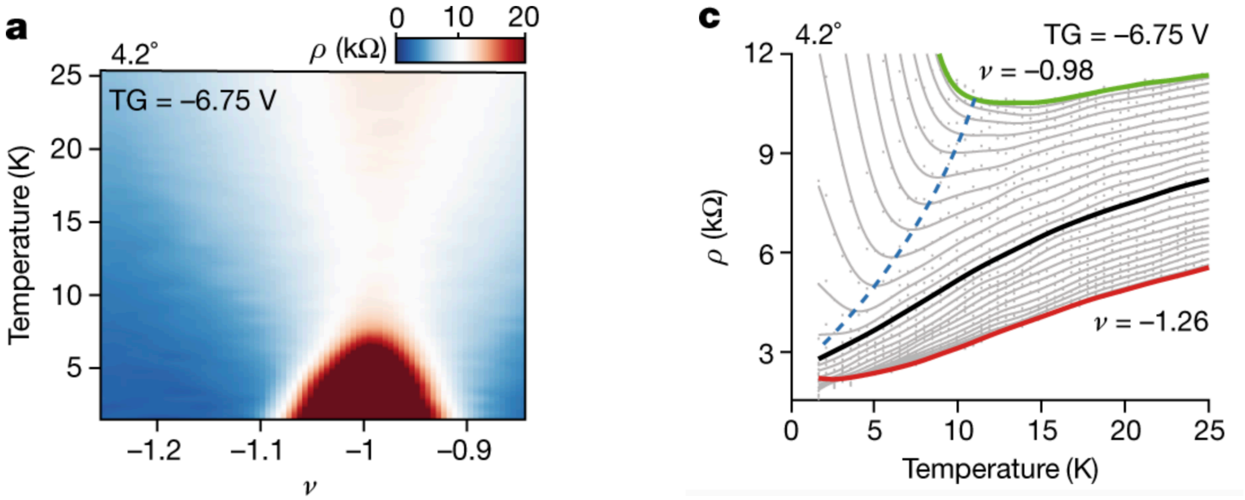
$$\Gamma = \alpha k_B T / \hbar$$

Legros et al al, Nat. Phys. **15**, 142 (2019)

Table 1 | Slope of *T*-linear resistivity vs Planckian limit in seven materials.

- Universality of α is a non-perturbative phenomenon

Strange metals near Mott transitions



Ghiotto et al, Nature **597**, 345–349 (2021)

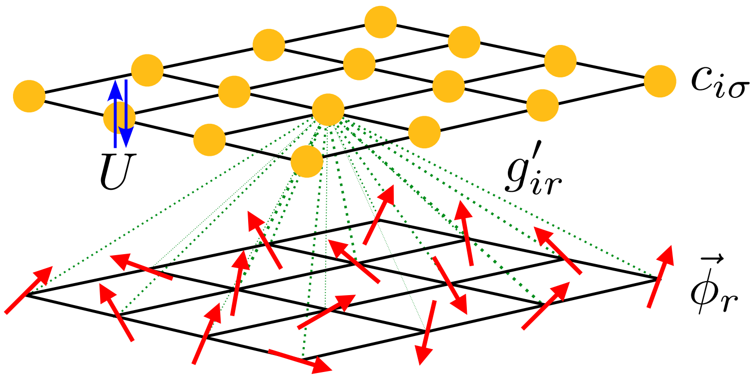
- Twisted WSe_2 has a metal-insulator (Mott) transition, near which a strange metal is observed
- Need to include Coulomb repulsion (Hubbard U) in model of strange metals…

Effects of Hubbard U

- Use EDMFT to study SU(2) fermions with spatially-random Yukawa coupling to a 2D constant DOS bosonic bath and Hubbard U
- Disorder average over random Yukawa coupling g' yields impurity problem with dynamical spin interactions. Solve coupled fermion and boson problems.

$$H_c = -\sum_{ij,\sigma} (t_{ij} + \mu\delta_{ij})\, c^\dagger_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow},$$

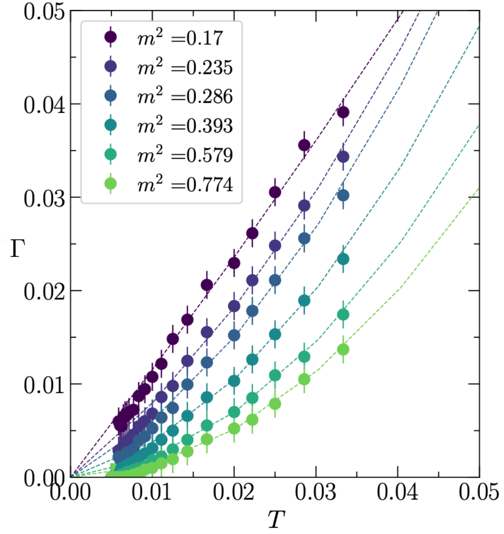
$$H_Y = \sum_{ir} \frac{g'_{ir}}{\sqrt{V}} (-1)^i \vec{S}_i \cdot \vec{\phi}_r, \quad \ll g'_{ir} g'_{jr'} \gg = g'^2 \delta_{ij} \delta_{rr'}.$$

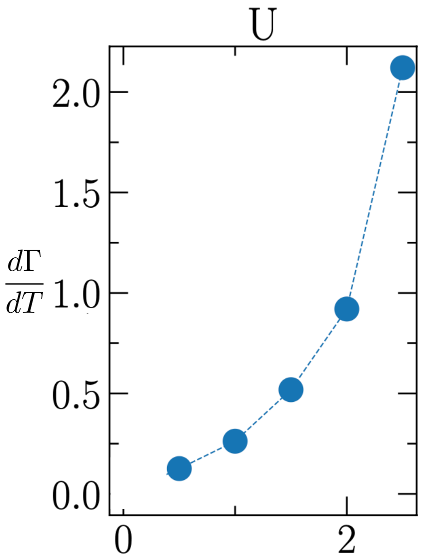


A. Hardy, O. Parcollet, A. Georges and A. A. P, **arXiv:2407.21102**

Effects of Hubbard U

- Hubbard U enhances marginal Fermi liquid and T-linear scattering rate Γ
- The effects of a weak random Yukawa coupling can therefore be amplified by Coulomb repulsion





A. Hardy, O. Parcollet, A. Georges and A. A. P, **arXiv:2407.21102**

Conclusions

- 2D metallic quantum criticality with disordered Yukawa interactions leads to strange metal behavior in both DC and AC transport in a disorder-averaged mean-field (Eliashberg) description
- Without mean-field and disorder-averaging, exact QMC shows strong disorder in the bosonic sector, which still leads to robust strange metal behavior not associated with a QCP
- Even though the bosonic sector is disordered, the fermions in the strange metal are clean, with large mean free path and a clear FS
- Strongly disordered bosonic sector produces localized overdamped bosonic modes that serve as microscopic inelastic scatterers of electrons
- T-linear transport scattering rate in the non-perturbative strange metal is universal (Planckian) and independent of the interaction disorder strength
- Hubbard U strongly amplifies the effects of disordered Yukawa interactions, important near Mott transitions