Planckian metals from spatially random interactions

Open Challenges in the Theory of Strongly Correlated Electron Systems,
William I. Fine Theoretical Physics Institute,
University of Minnesota,
December 16, 2021

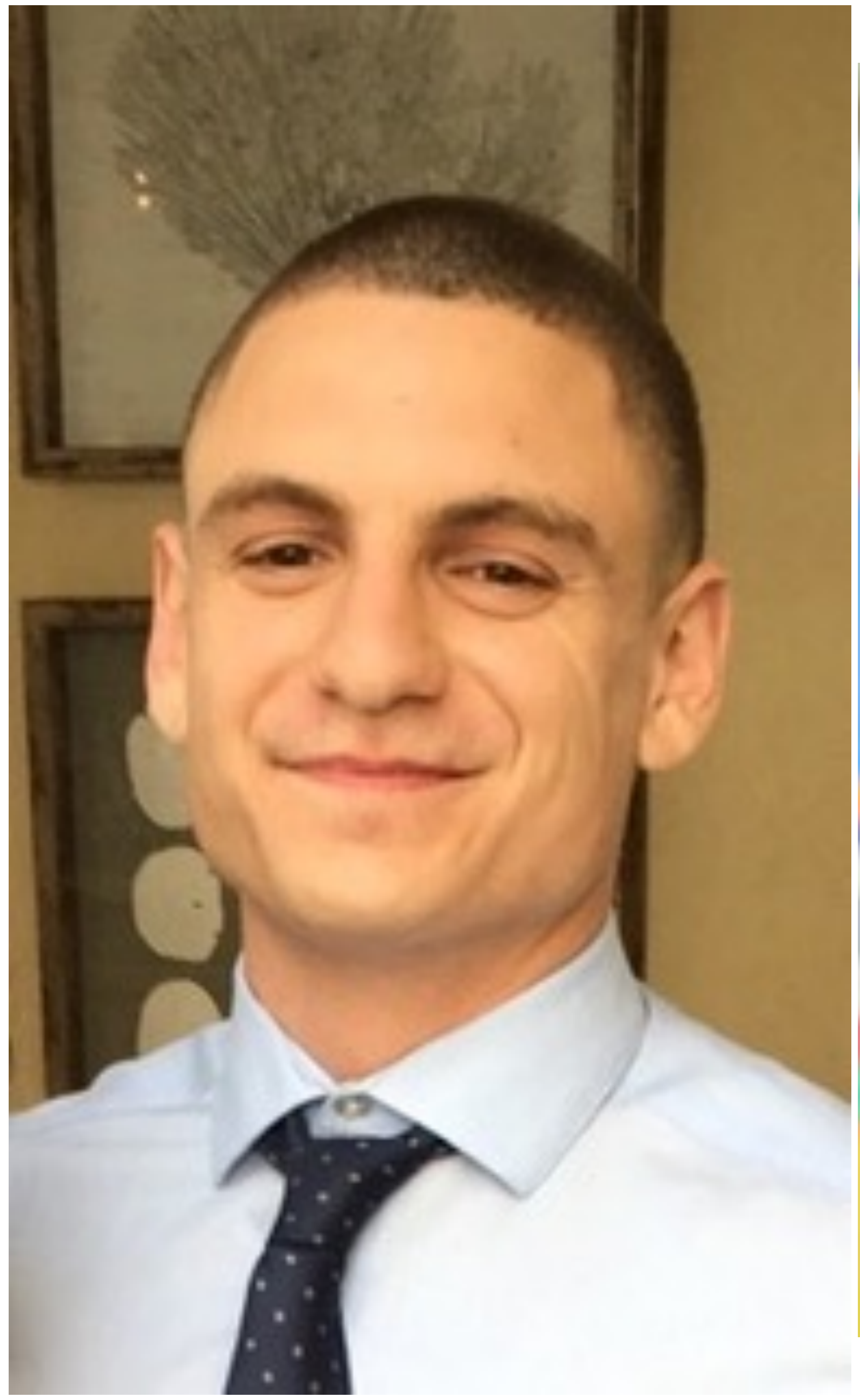
Subir Sachdev

Talk online: sachdev.physics.harvard.edu

INSTITUTE FOR ADVANCED STUDY

PHYSICS

HARVARD



Ilya Esterlis

Haoyu Guo

Aavishkar Patel
Berkeley

Maria Tikhanovskaya

1. The SYK model

2. Fermi surface coupled to a critical boson

3. Adding spatially random interactions to the critical Fermi surface

4. Random *t*-*J* model

The 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))

$$H = \frac{1}{(2N)^{3/2}} \sum_{\alpha,\beta,\gamma,\delta=1}^{N} U_{\alpha\beta;\gamma\delta}\, c_\alpha^\dagger c_\beta^\dagger c_\gamma c_\delta - \mu \sum_\alpha c_\alpha^\dagger c_\alpha$$

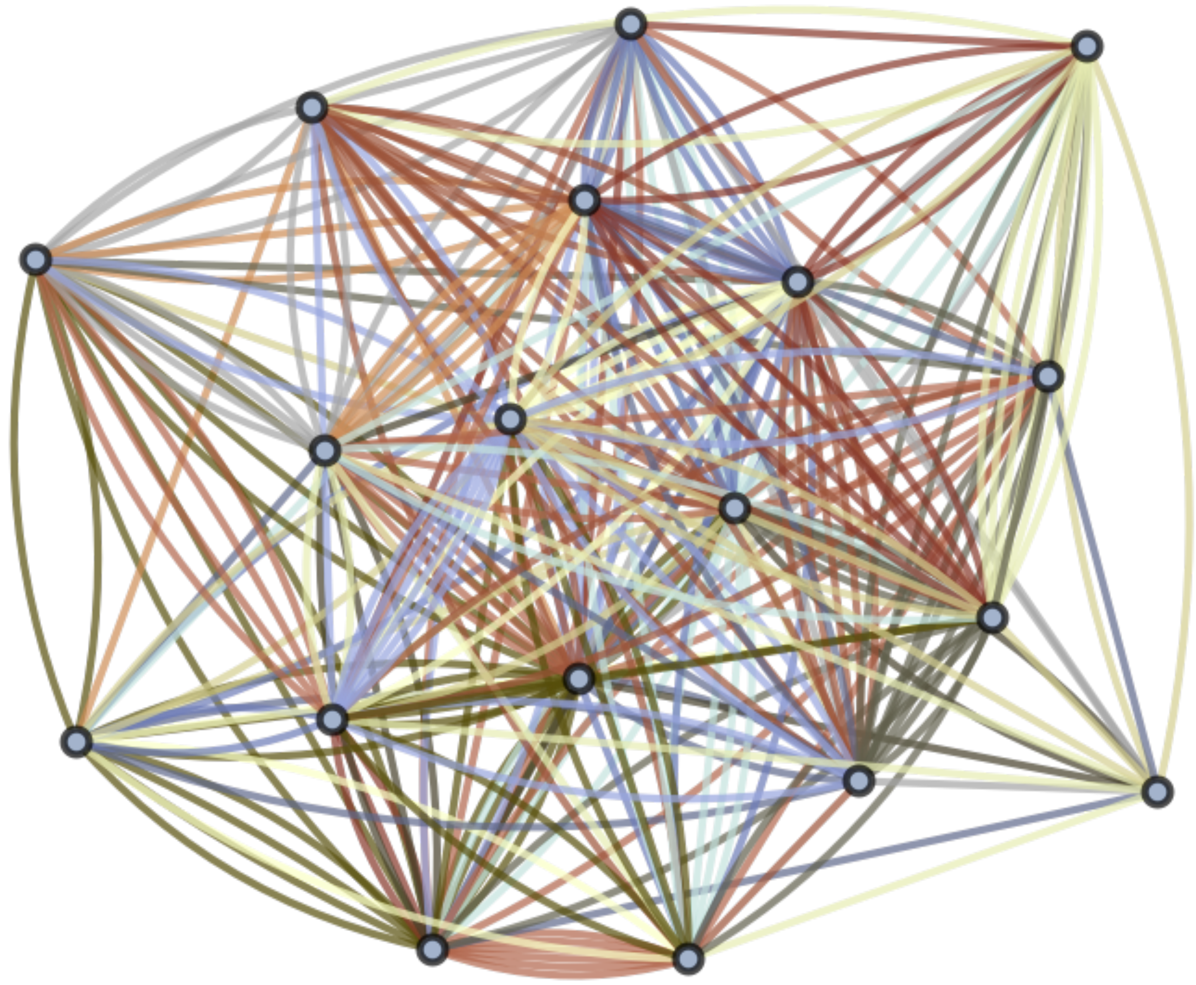
$$c_\alpha c_\beta + c_\beta c_\alpha = 0 \quad , \quad c_\alpha c_\beta^\dagger + c_\beta^\dagger c_\alpha = \delta_{\alpha\beta}$$

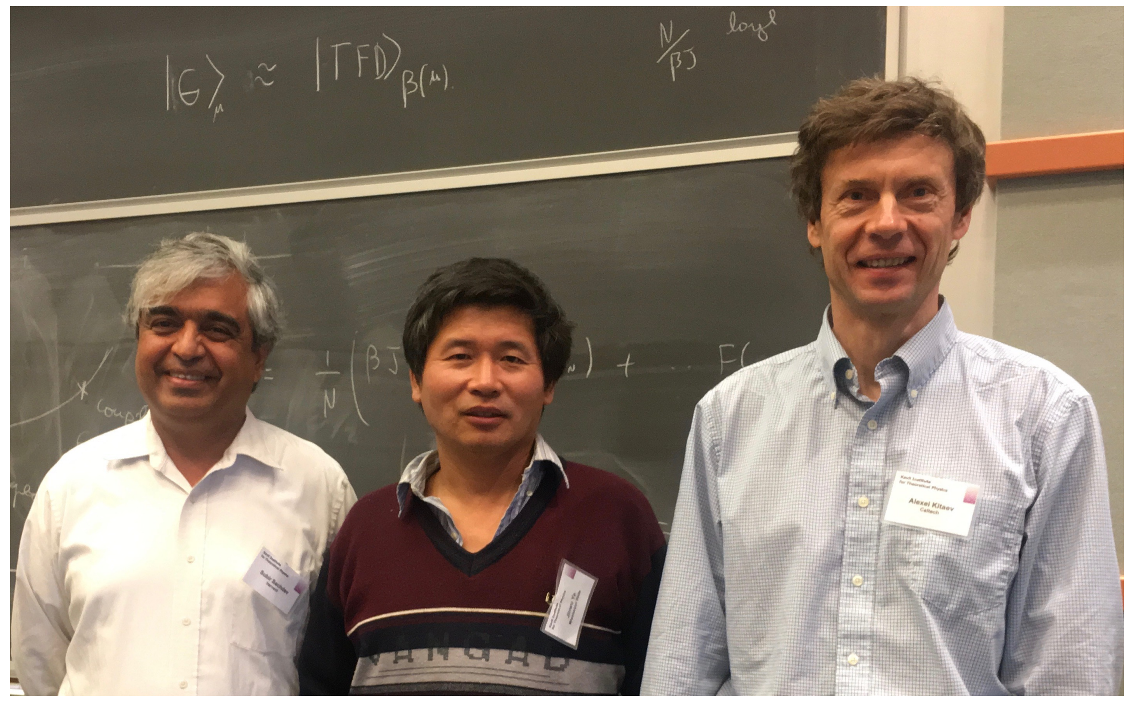
$$\mathcal{Q} = \frac{1}{N} \sum_\alpha c_\alpha^\dagger c_\alpha$$

$U_{\alpha\beta;\gamma\delta}$ are independent random variables with $\overline{U_{\alpha\beta;\gamma\delta}} = 0$ and $\overline{|U_{\alpha\beta;\gamma\delta}|^2} = U^2$
$N \to \infty$ yields critical strange metal.

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

A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)





G-Σ Theory

The theory self-averages, and the average partition function can be written exactly as a 'G-Σ' theory involving a path integral over *bilocal in time* Green's function $G(\tau_1, \tau_2)$ and self energy $\Sigma(\tau_1, \tau_2)$

$$\overline{Z} = \int \mathcal{D}G(\tau_1, \tau_2)\mathcal{D}\Sigma(\tau_1, \tau_2) \exp(-NS)$$

$$S = \ln\det\left[\delta(\tau_1 - \tau_2)(\partial_{\tau_1} + \mu) - \Sigma(\tau_1, \tau_2)\right] + \int d\tau_1 d\tau_2 \left[\Sigma(\tau_1, \tau_2)G(\tau_2, \tau_1) + (U^2/2)G^2(\tau_2, \tau_1)G^2(\tau_1, \tau_2)\right]$$

The large N saddle point yields $G(\tau_1 - \tau_2)$ and $\Sigma(\tau_1 - \tau_2)$ which obey

$$G(i\omega) = \frac{1}{i\omega + \mu - \Sigma(i\omega)} \quad ; \quad \Sigma(\tau) = -U^2 G^2(\tau) G(-\tau)$$

Exact Solution at small ω:

$$\Sigma(i\omega) \sim -i\,\text{sgn}(\omega)\sqrt{|\omega|}\,, \quad G(i\omega) = \frac{-1}{\Sigma(i\omega)}$$

where the co-efficient is known exactly.

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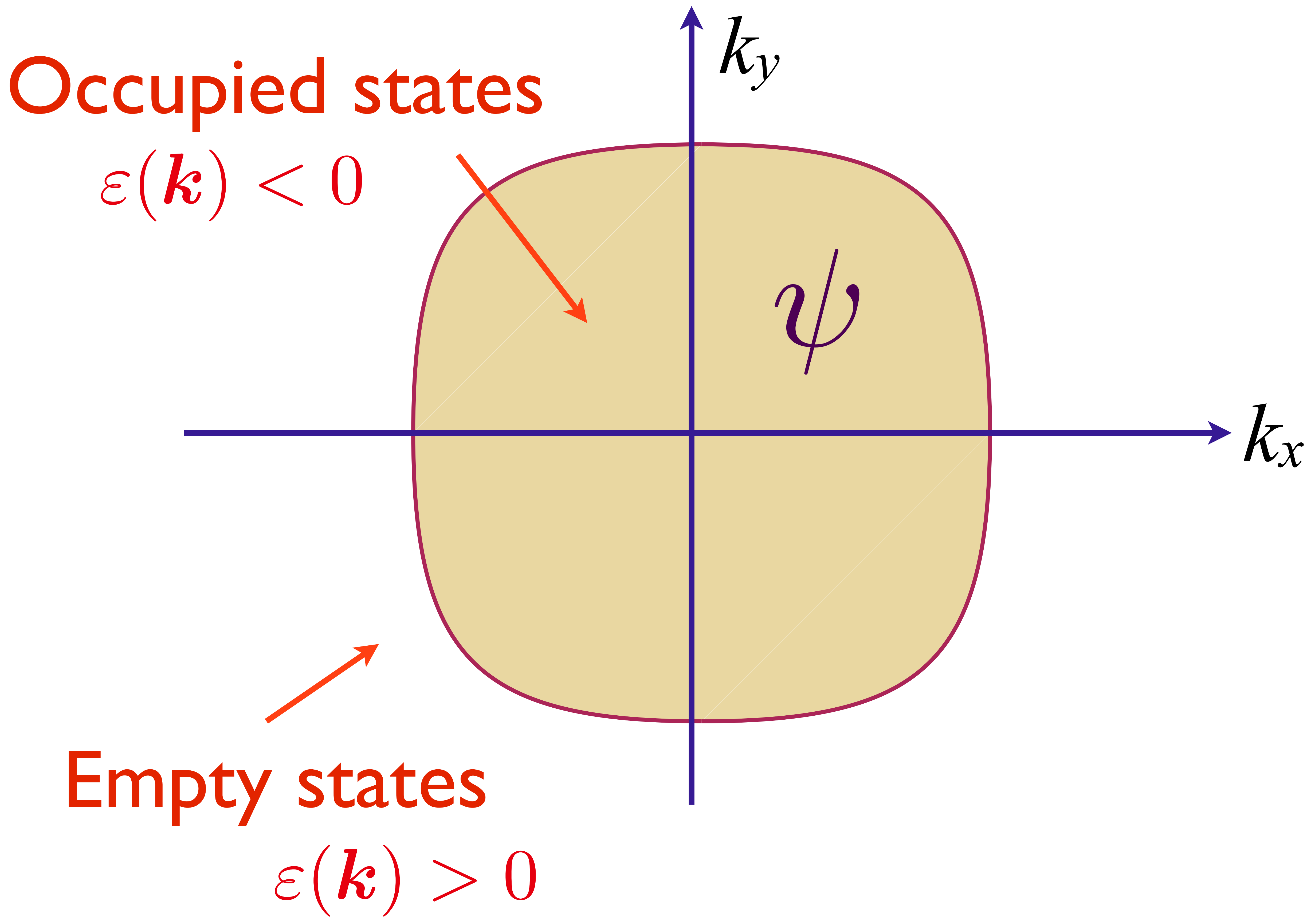
Fermi surface coupled to a critical boson



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Fermi surface coupled to a critical boson

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

Yields a state without quasiparticle excitations, but the theory is not systematic at large N

Sung-Sik Lee (2009)

Fermi surface coupled to a critical boson

"Yukawa" coupling: $$\frac{g_{ij\ell}}{N} \int d^2 r d\tau \, \psi_i^\dagger(r,\tau)\psi_j(r,\tau)\phi_l(r,\tau)$$

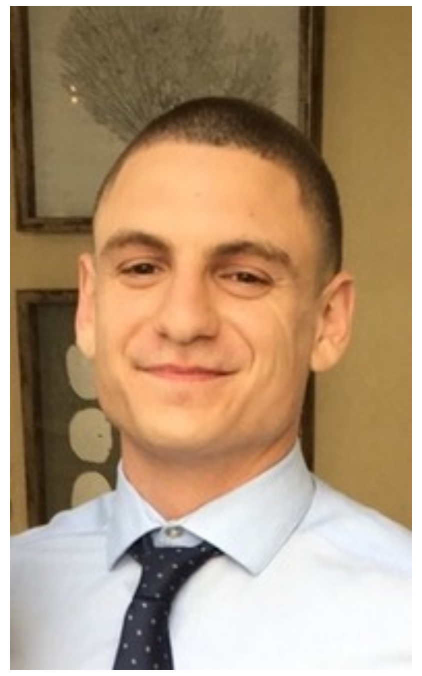
$$\overline{g_{ijl}} = 0 \quad , \quad \overline{|g_{ijl}|^2} = g^2$$

Main idea:

Introduce N flavors of fermions and bosons, and examine an *ensemble* of theories with different Yukawa couplings. In the large N limit, every member of the ensemble is expected to have the same critical properties, and so it is easier to study the average theory.

Ilya Esterlis, J. Schmalian, PRB **100**, 115132 (2019)
Yuxuan Wang and A.V. Chubukov, PRR **2**, 033084 (2020)
E. E. Aldape, T. Cookmeyer, A. A. Patel, and E. Altman, arXiv:2012.00763
Ilya Esterlis, Haoyu Guo, Aavishkar Patel, S.S. PRB **103**, 235129 (2021)

G-Σ-D-Π Theory



The theory self-averages, and the average partition function can be written exactly as a 'G-Σ' theory involving a path integral over *bilocal in spacetime*. We introduce the spacetime co-ordinate $X \equiv (\tau, x, y)$, and all Green's functions and self energies in the path integral are functions of two spacetime co-ordinates X_1 and X_2.

$$\overline{\mathcal{Z}} = \int \mathcal{D}G(X_1, X_2)\mathcal{D}\Sigma(X_1, X_2)\mathcal{D}D(X_1, X_2)\mathcal{D}\Pi(X_1, X_2) \exp\left[-N I(G, \Sigma, D, \Pi)\right] .$$

The G-Σ-D-Π action is now

$$\begin{aligned} I(G, \Sigma, D, \Pi) &= \frac{g^2}{2}\mathrm{Tr}\left(G \cdot [GD]\right) - \mathrm{Tr}(G \cdot \Sigma) + \frac{1}{2}\mathrm{Tr}(D \cdot \Pi) \\ &- \ln\det\left[(\partial_{\tau_1} + \varepsilon(-i\boldsymbol{\nabla}_1))\,\delta(X_1 - X_2) + \Sigma(X_1, X_2)\right] \\ &\quad + \frac{1}{2}\ln\det\left[\left(-\partial_{\tau_1}^2 - \boldsymbol{\nabla}_1^2 + s\right)\delta(X_1 - X_2) - \Pi(X_1, X_2)\right] . \end{aligned}$$

where we have introduced notation

$$\mathrm{Tr}\,(f \cdot g) \equiv \int dX_1 dX_2\, f(X_2, X_1) g(X_1, X_2) .$$

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G-Σ-D-Π Theory

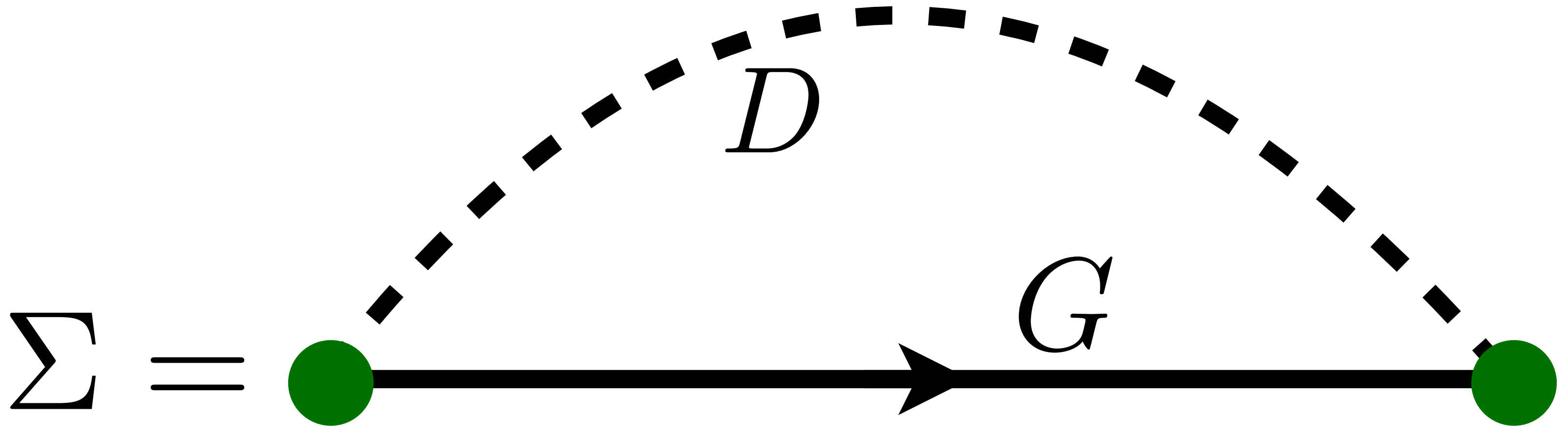
The saddle point equations are

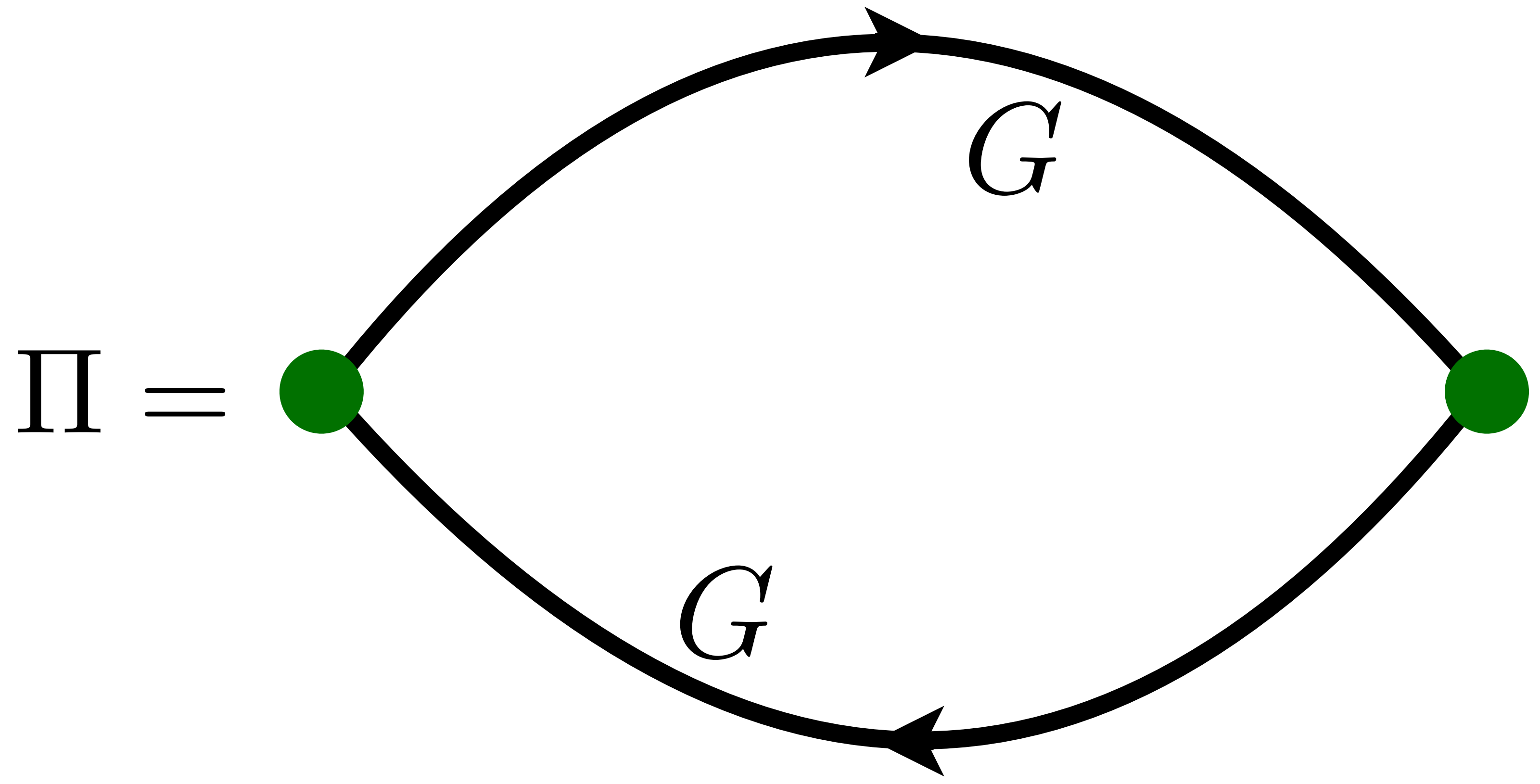
$$\Sigma(\boldsymbol{r},\tau) = g^2 \lambda D(\boldsymbol{r},\tau) G(\boldsymbol{r},\tau),$$

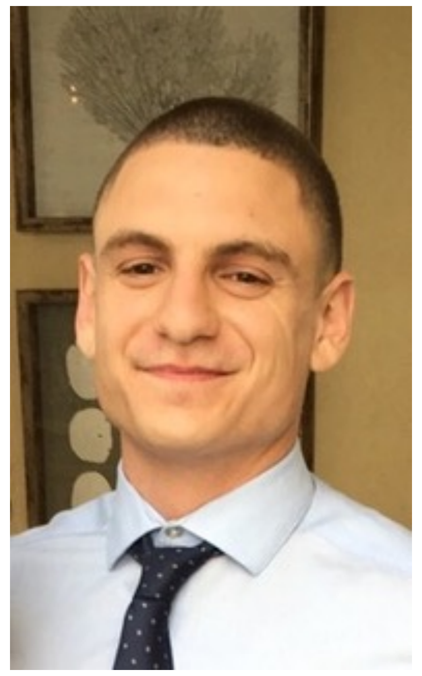
$$\Pi(\boldsymbol{r},\tau) = -g^2 G(-\boldsymbol{r},-\tau) G(\boldsymbol{r},\tau),$$

$$G(\boldsymbol{k}, i\omega_n) = \frac{1}{i\omega_n - \varepsilon(\boldsymbol{k}) - \Sigma(\boldsymbol{k}, i\omega_n)},$$

$$D(\boldsymbol{q}, i\Omega_m) = \frac{1}{\Omega_m^2 + q^2 + s - \Pi(\boldsymbol{q}, i\Omega_m)}.$$







Exact Solution at small ω:

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

where the co-efficient is known exactly in terms of the Fermi velocity and Fermi surface curvature at the Fermi surface point along the direction $\hat{\boldsymbol{k}}$.

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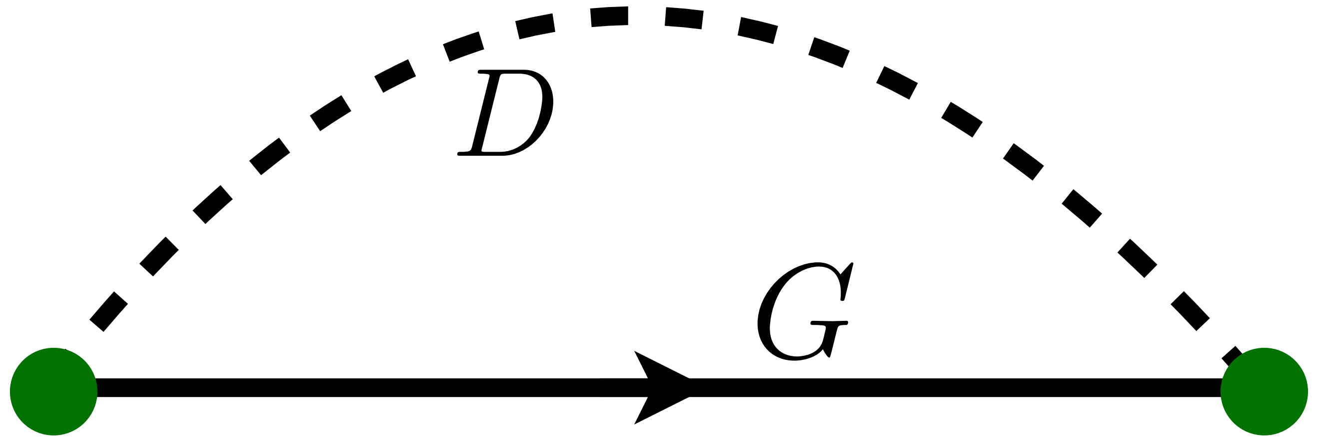
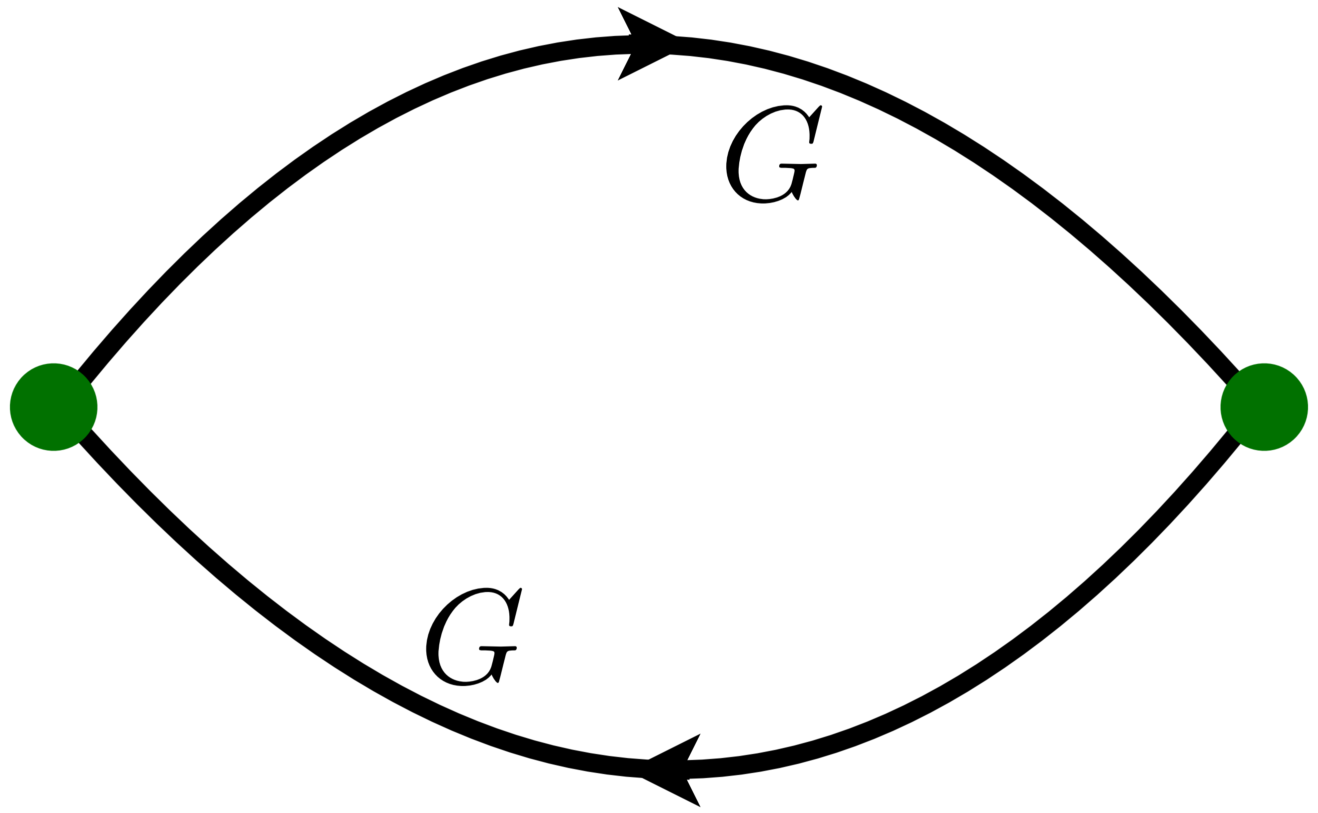
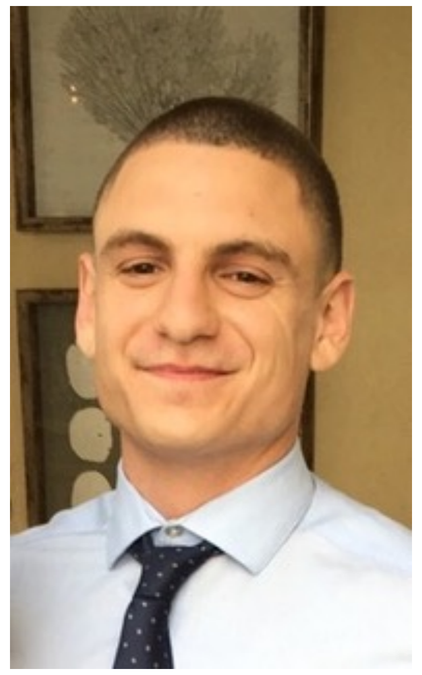
$\Sigma =$ 

$\Pi =$ 

- There is many-body quantum chaos in the out-of-time-order correlator (OTOC) with maximal Lyapunov exponent $\lambda_L = 2\pi k_B T/\hbar$.

M. Tikhanovskaya, Aavishkar Patel, S.S. to appear

Fermi surface coupled to a critical boson



"Yukawa" coupling: $$\frac{g_{ij\ell}}{N}\int d^2r d\tau\, \psi_i^\dagger(r,\tau)\psi_j(r,\tau)\phi_l(r,\tau)$$

$$\overline{g_{ijl}} = 0 \quad , \quad \overline{|g_{ijl}|^2} = g^2$$

Conservation of momentum implies the d.c. conductivity is infinite

S. A. Hartnoll, R. Mahajan, M. Punk, and S. Sachdev, PRB **89**, 155130 (2014)
A. Eberlein, I. Mandal, and S. S., PRB **94**, 045133 (2016)

$$\mathrm{Re}\,\sigma(\omega) = D\delta(\omega) + \mathrm{Re}\,\sigma_{\mathrm{reg}}(\omega)$$

$$\mathrm{Re}\,\sigma_{\mathrm{reg}}(\omega, T=0) \sim \frac{1}{\omega^{2/3}}$$

Yong Baek Kim, A. Furusaki, Xiao-Gang Wen, P. A. Lee, PRB **50**, 17917 (1994)

Aavishkar Patel, Haoyu Guo, Ilya Esterlis, S.S. to appear

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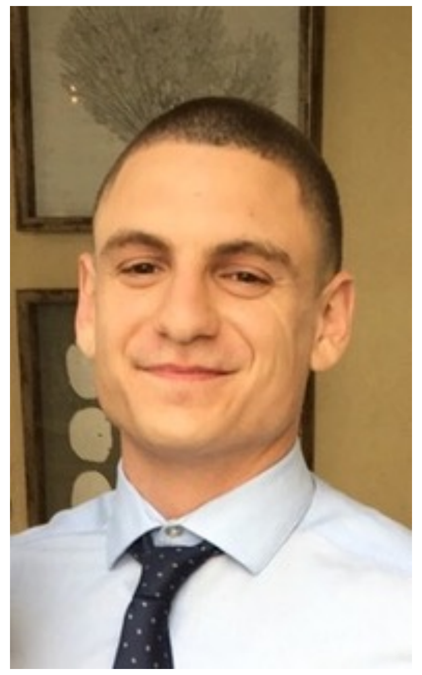


"Yukawa" coupling: $$\frac{g_{ij\ell}}{N}\int d^2r d\tau\, \psi_i^\dagger(r,\tau)\psi_j(r,\tau)\phi_l(r,\tau)$$

Random potential: $$+\frac{1}{\sqrt{N}}\int d^2r d\tau\, v_{ij}(r)\psi_i^\dagger(r,\tau)\psi_j(r,\tau)$$

$$\overline{g_{ijl}} = 0 \quad , \quad \overline{g^*_{ijl}g_{abc}} = g^2\,\delta_{ia}\delta_{jb}\delta_{lc} \quad , \quad \overline{v_{ij}(r)} = 0 \quad , \quad \overline{v^*_{ij}(r)v_{lm}(r')} = v^2\,\delta(r-r')\delta_{il}\delta_{jm}$$

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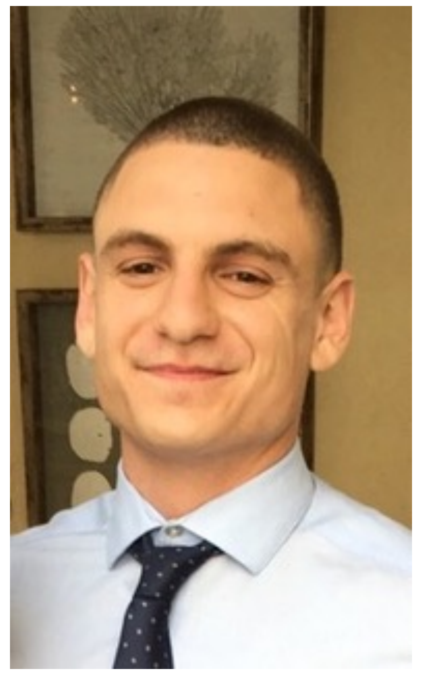
Fermi surface coupled to a critical boson with spatial disorder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Boson self energy: $\Pi \sim -\frac{g^2}{v^2}|\Omega|$, $\quad D(q, i\Omega) = \frac{1}{q^2 + \gamma|\Omega|}$

Fermion self energy: $\Sigma(i\omega) \sim -iv^2 \text{sgn}(\omega) - i\frac{g^2}{v^2}\omega\ln(1/|\omega|)$

Marginal Fermi liquid self energy and *T log T* specific heat

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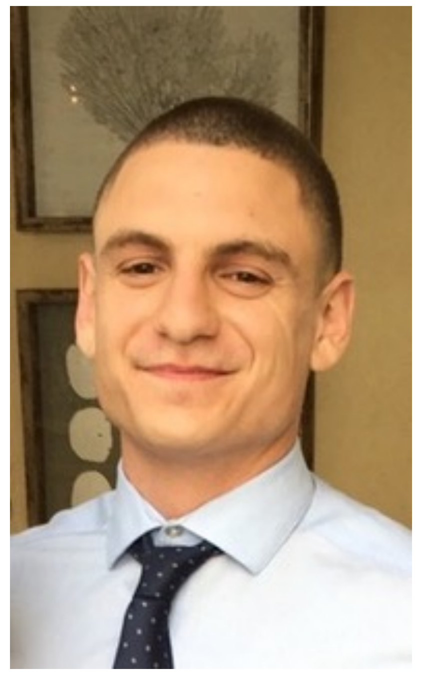

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The g^2 log term does not contribute to transport

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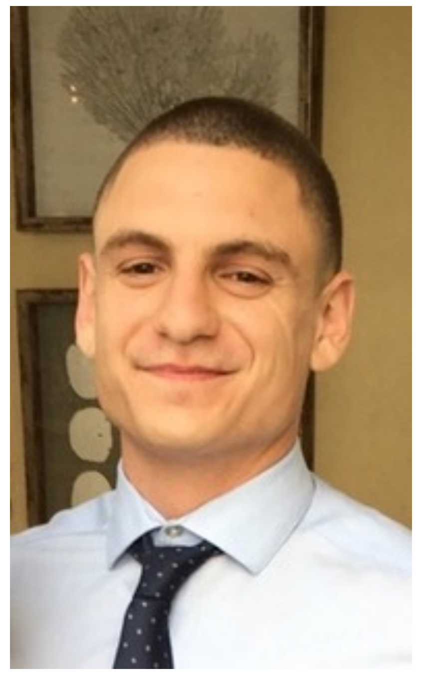
Fermi surface coupled to a critical boson with spatial disorder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With g and v non-zero, we obtain a non-zero residual resistivity and Fermi liquid like corrections

$$\rho(T) = \rho(0) + AT^2 + \ldots.$$

with $1/\rho(0) \sim 1/\tau_{\rm trans} \sim v^2$.

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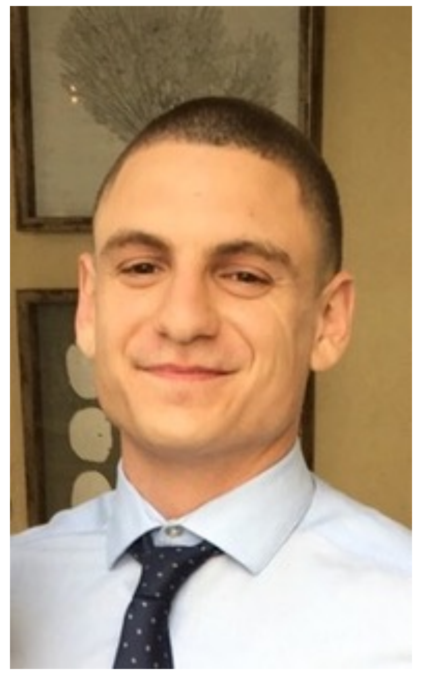


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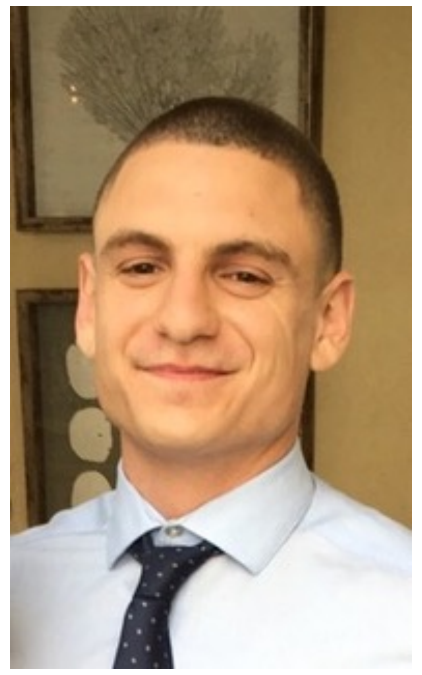
Fermi surface coupled to a critical boson with spatial disorder



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

$$\Pi_g(i\Omega) \sim -\frac{g^2}{v^2}|\Omega|, \qquad \Pi_{g'}(i\Omega) \sim -g'^2|\Omega|, \qquad D(q, i\Omega) = \frac{1}{q^2 + \gamma|\Omega|}$$

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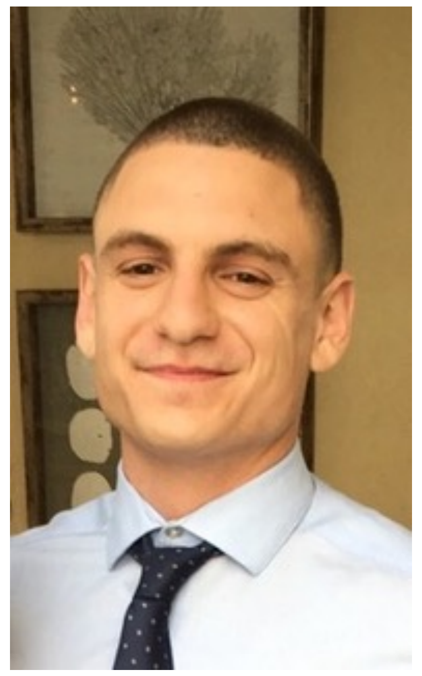

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Fermion self energy: $\Sigma = \Sigma_v + \Sigma_g + \Sigma_{g'}$

$$\Sigma_v(i\omega) \sim -iv^2 \mathrm{sgn}(\omega), \quad \Sigma_g(i\omega) \sim -i\frac{g^2}{v^2}\omega \ln(1/|\omega|), \quad \Sigma_{g'}(i\omega) \sim -ig'^2\omega \ln(1/|\omega|)$$

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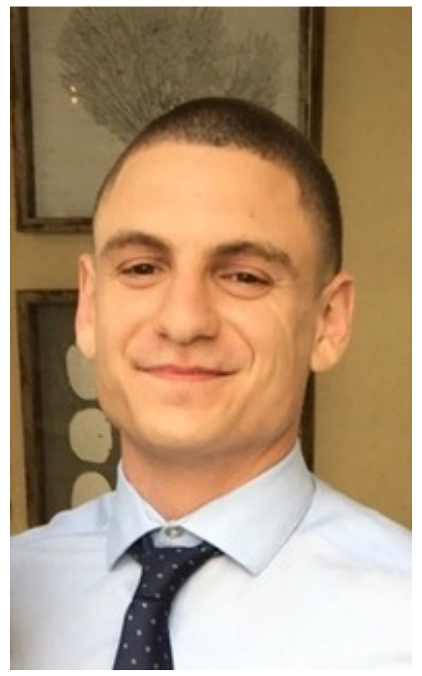

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The g^2 log term does not contribute to transport but the g'^2 log term does!

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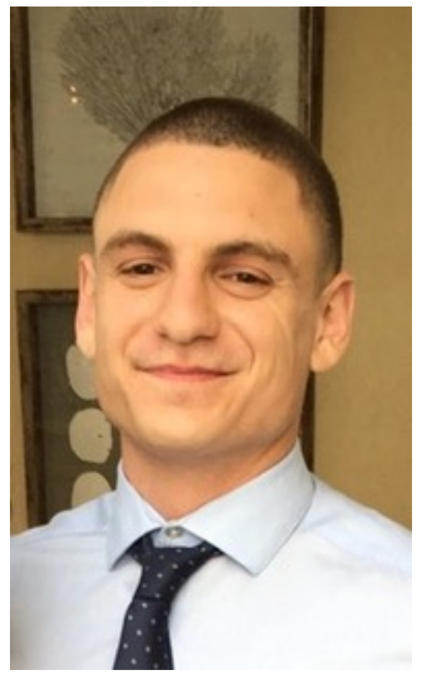
Fermi surface coupled to a critical boson with spatial disorder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Random potential: $+\dfrac{1}{\sqrt{N}}\int d^2r d\tau\, v_{ij}(r)\psi_i^\dagger(r,\tau)\psi_j(r,\tau)$

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

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

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

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4. Random t-J model

D. Chowdhury, A. Georges, O. Parcollet, S. Sachdev, arXiv: 2109.05037, review article

Random *t-J* model doped with hole density p

$$H = -\frac{1}{\sqrt{N}} \sum_{i,j=1}^{N} t_{ij}\, \mathcal{P}_d c_{i\alpha}^\dagger c_{j\alpha} \mathcal{P}_d + \frac{1}{\sqrt{N}} \sum_{i<j=1}^{N} J_{ij}\, \vec{S}_i \cdot \vec{S}_j$$

$$\vec{S}_i = \frac{1}{2} c_{i\alpha}^\dagger \vec{\sigma} c_{i\alpha}$$

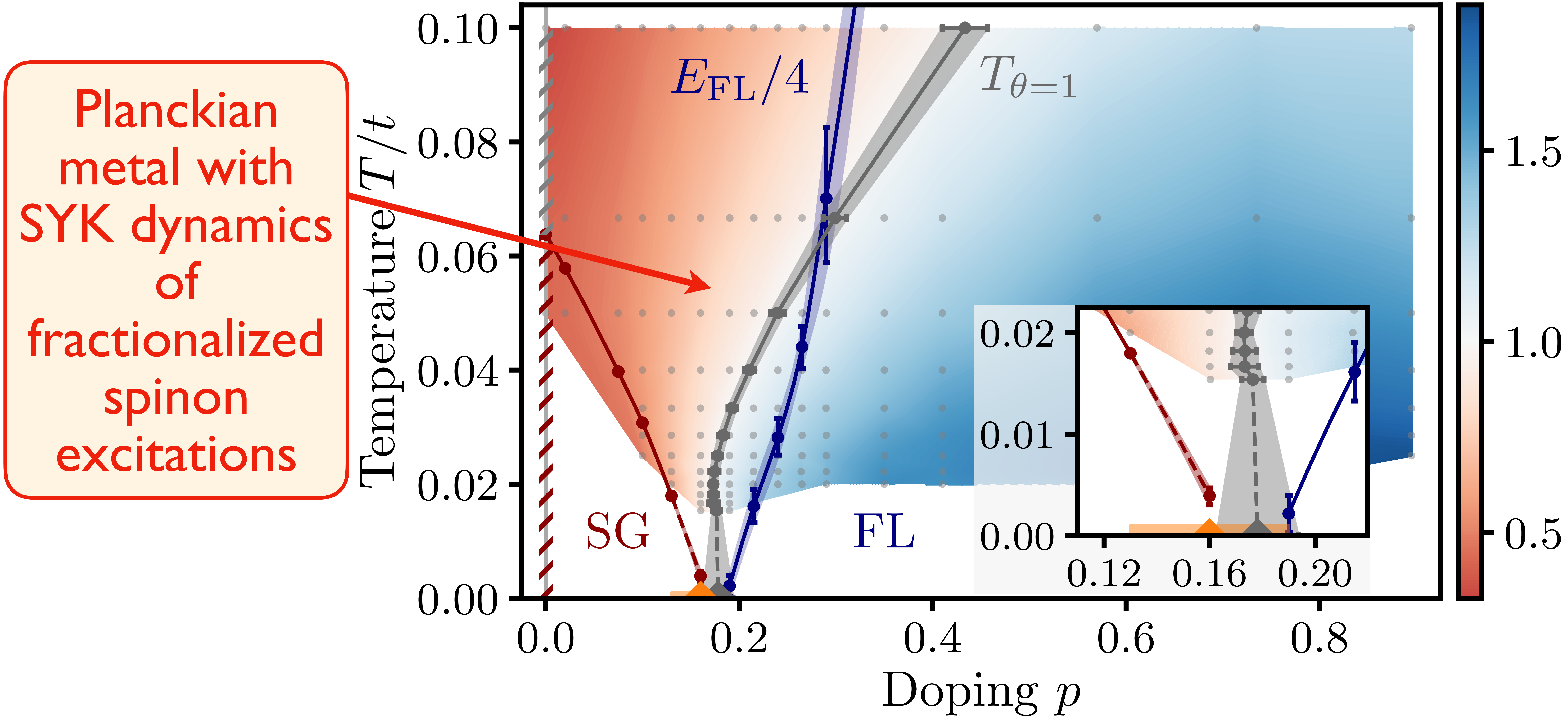
$\mathcal{P}_d$ projects out doubly-occupied sites.

J_{ij} random, $\overline{J_{ij}} = 0$, $\overline{J_{ij}^2} = J^2$

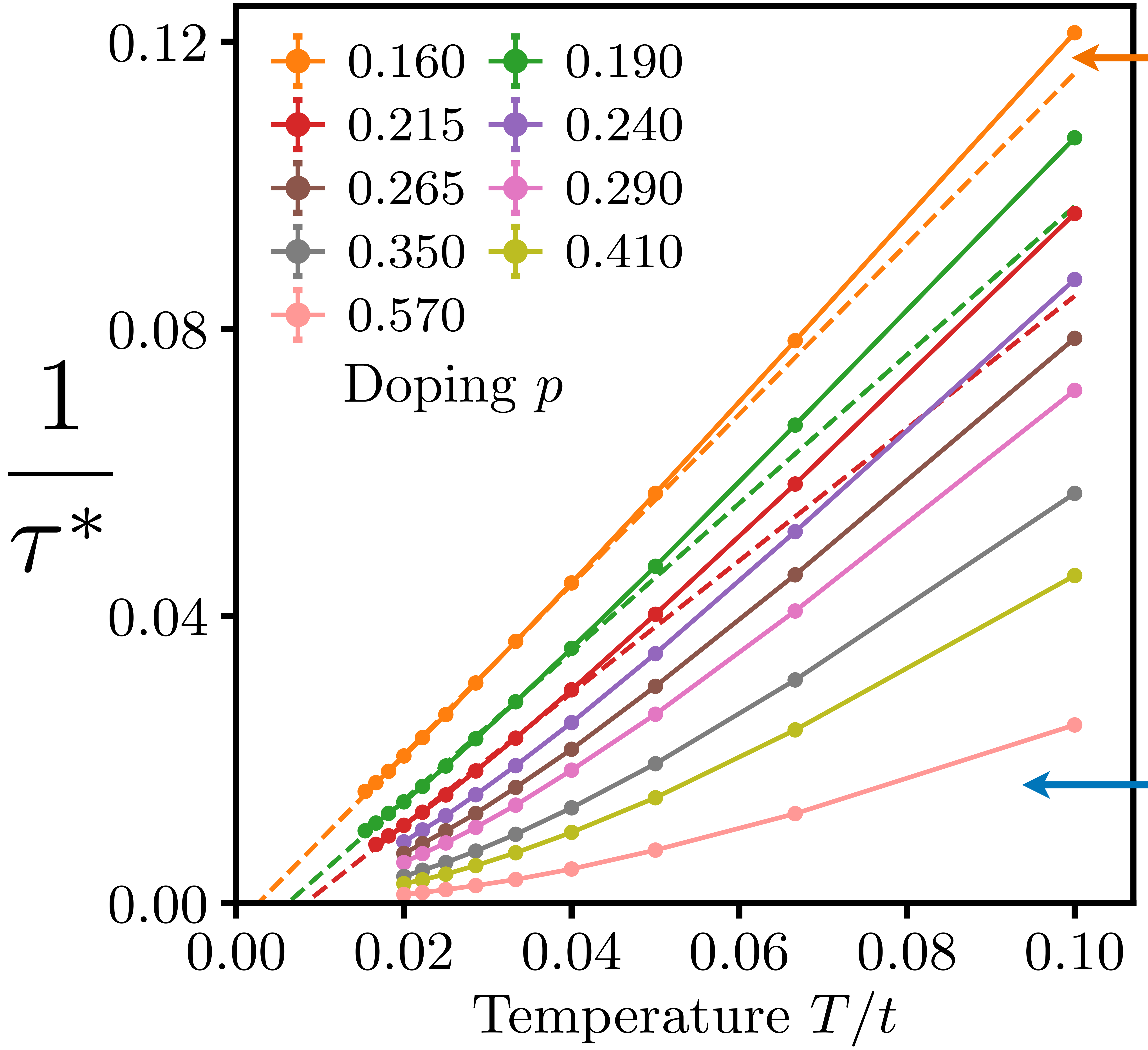
$J \quad \Rightarrow \quad$ two-particle interaction, similar to that in SYK

$t \quad \Rightarrow \quad$ one-particle hopping, can be regular or random

Numerical solution of t-J model on a fully-connected cluster with all-to-all and random t_{ij} and J_{ij}



P. T. Dumitrescu, N. Wentzell, A. Georges, O. Parcollet, arXiv:2103.08607
H. Shackleton, A. Wietek, A. Georges, and S. Sachdev, PRL **126**, 136602 (2021)



$$\frac{1}{\tau^*} \simeq c\frac{k_B T}{\hbar}$$

$$c \approx 1.0$$

Planckian metal
for $p \approx p_c$

Large M theory
Resistivity: $\rho(T) = \rho(0) + \tilde{c}\, T \ldots$
Linear T term is
correction to scaling
from time reparameterization mode.

Haoyu Guo, Yingfei Gu, and S. Sachdev 2020

$$\frac{1}{\tau^*} \propto T^2$$

Negligible residual resistivity
from random interactions J_{ij}

P. T. Dumitrescu, N. Wentzell, A. Georges, O. Parcollet, arXiv:2103.08607

Summary

- Two-dimensional Fermi surface coupled to a critical boson has no quasiparticle excitations, and exhibits Planckian time dynamics and maximal chaos with Lyapunov exponent $2\pi k_B T/\hbar$. In the presence of spatial disorder, linear-T resistivity arises from the first subleading operator of random interactions, while the leading operator of random potential leads to the residual resistivity. The spatial disorder theory also leads to a $T \ln T$ specific heat.

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