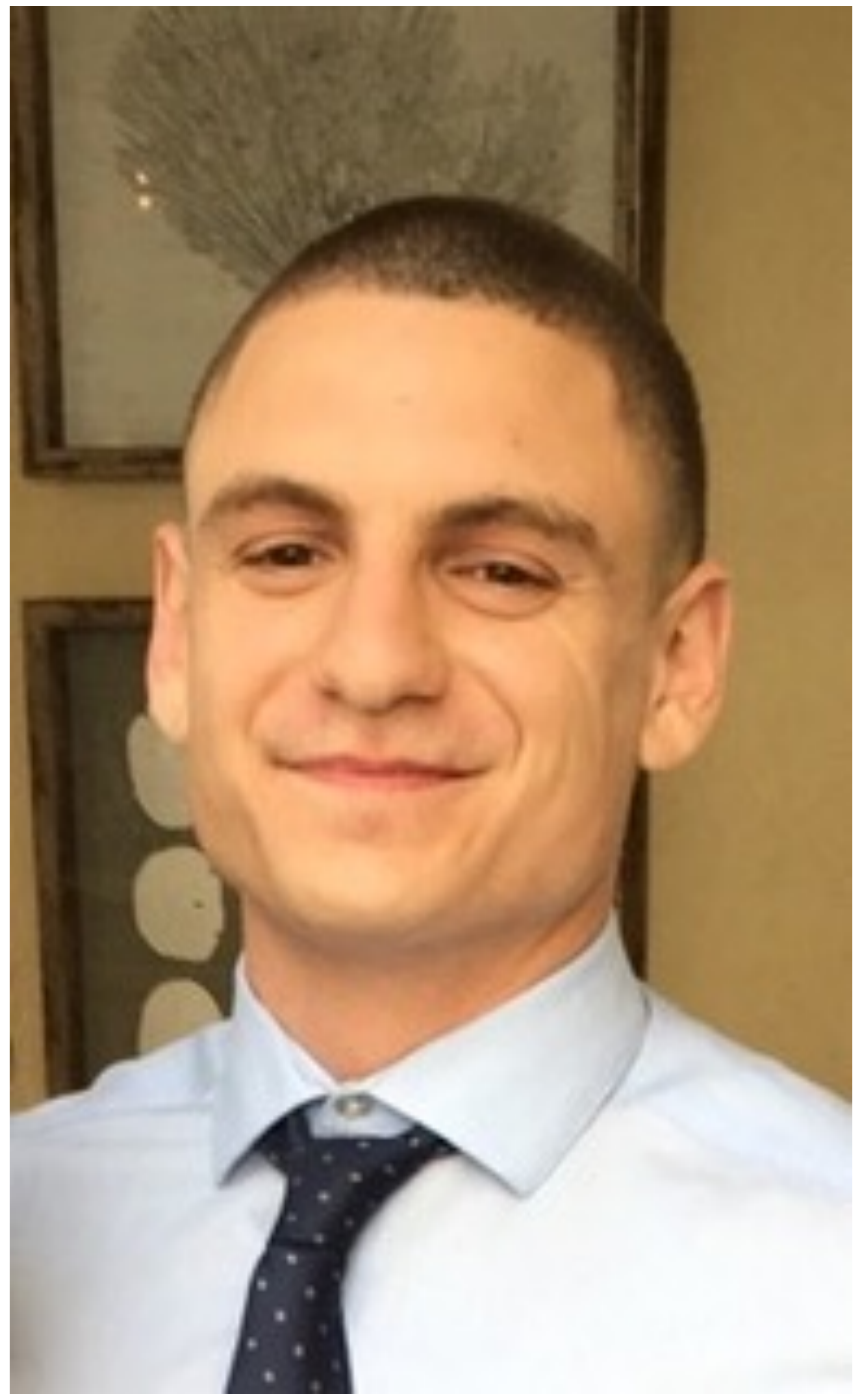
Future of gapless UQM

UQM meeting
Caltech
September 20, 2022

Subir Sachdev

PHYSICS
HARVARD

Talk online: sachdev.physics.harvard.edu



Aavishkar Patel
Flatiron Institute, NYC

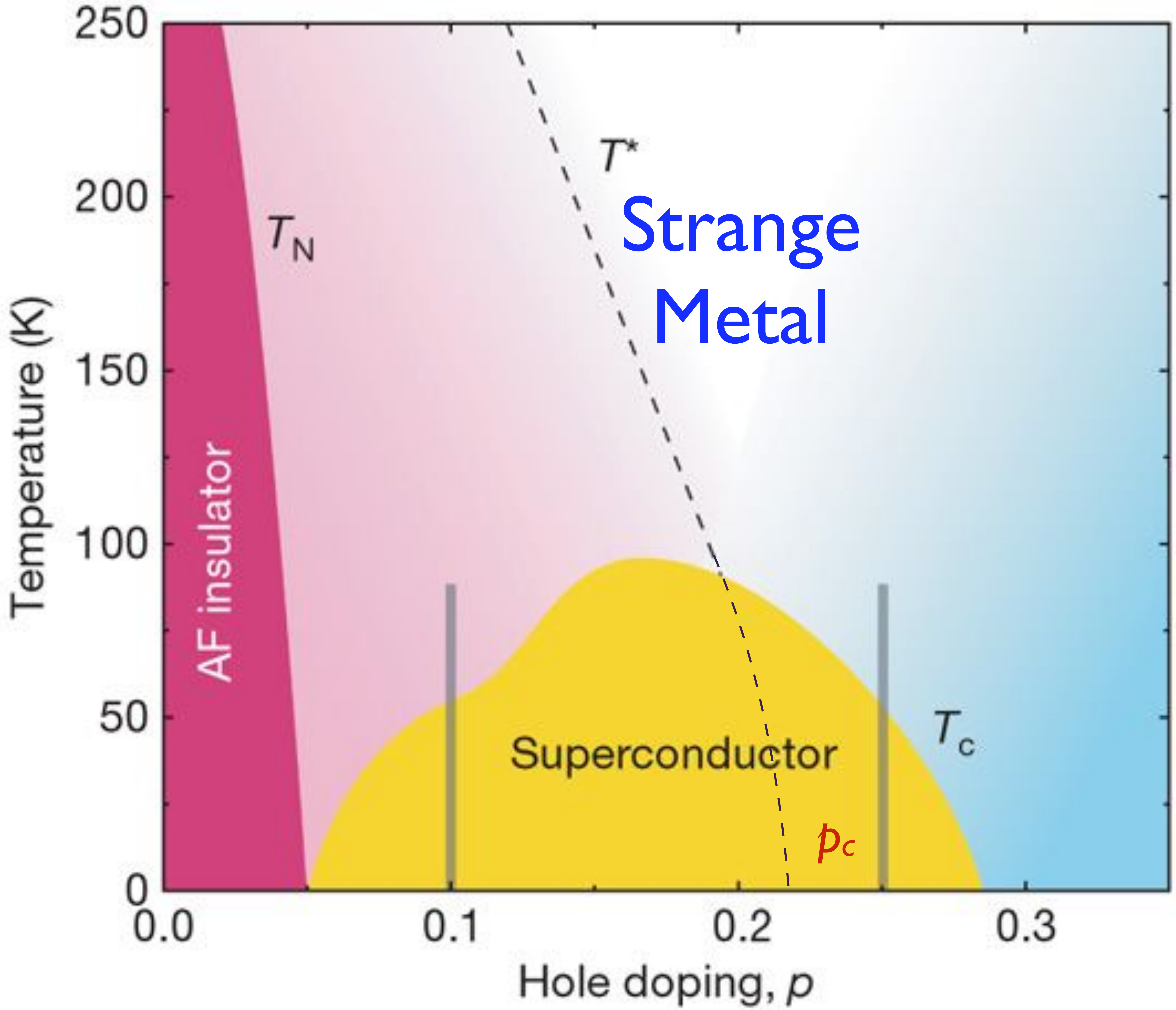
Haoyu Guo
Harvard

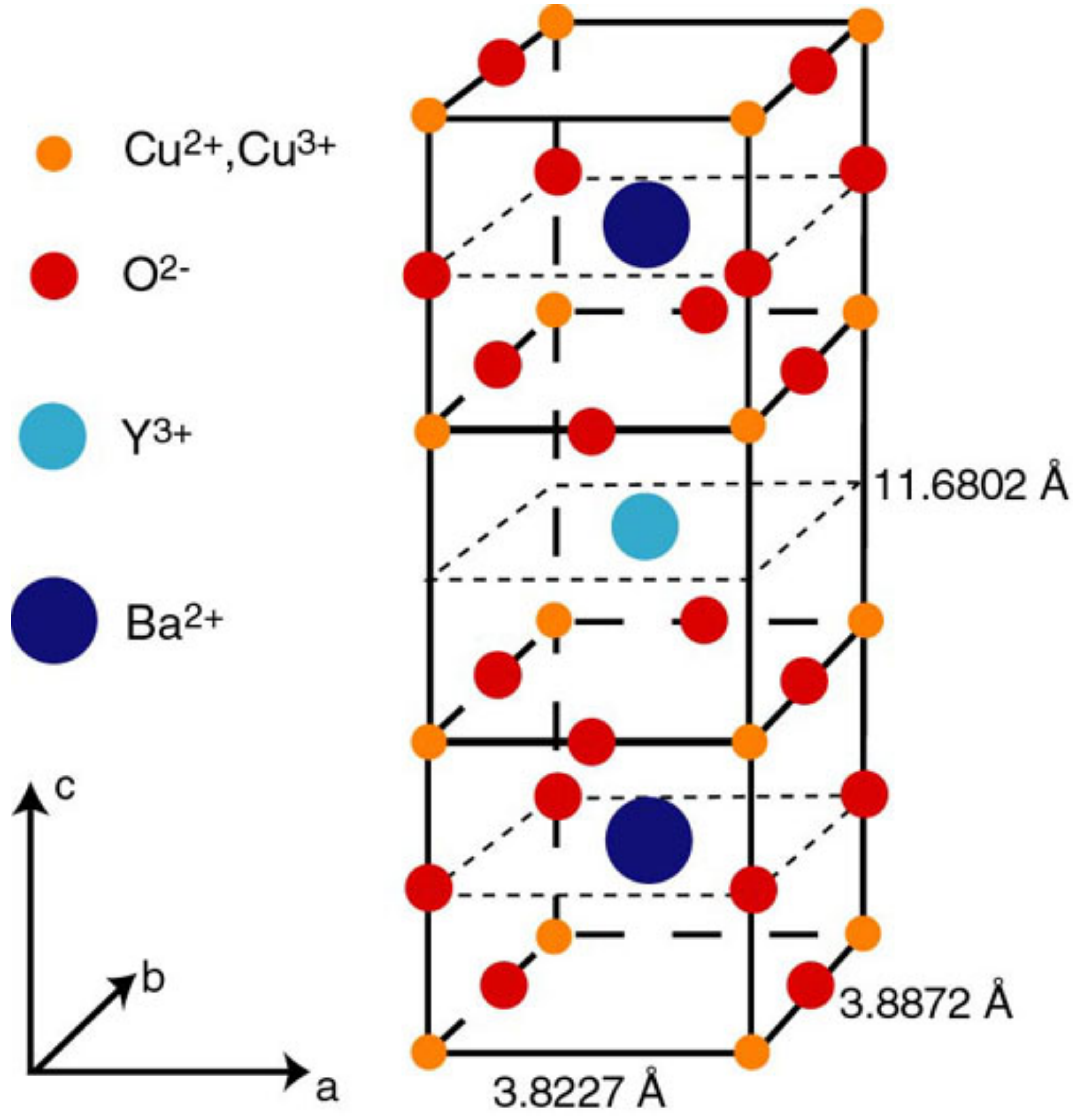
Ilya Esterlis
Harvard → Wisconsin

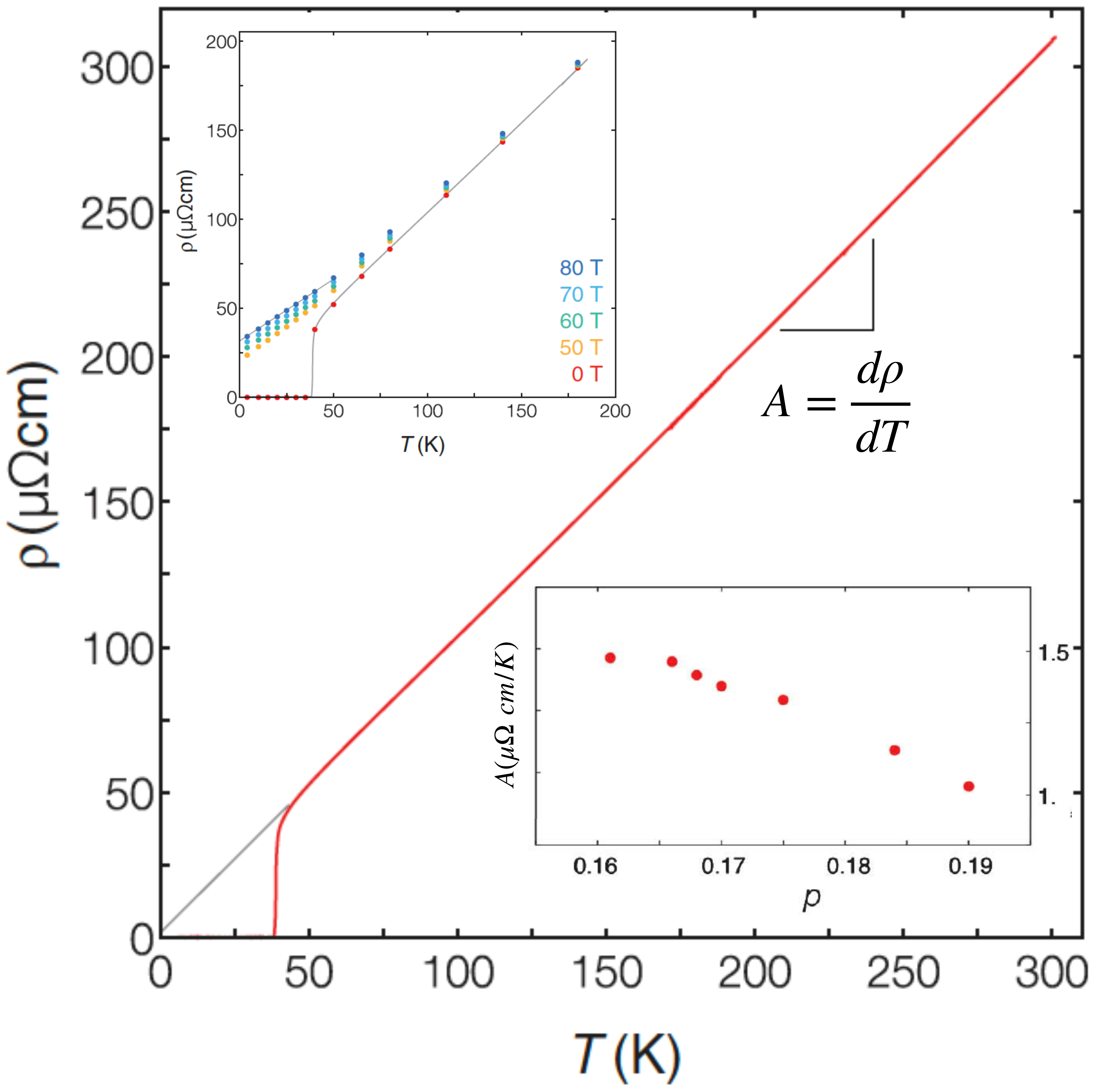
arXiv: 2103.08615, 2203.04990, 2207.08841

E. E. Aldape, T. Cookmeyer, Aavishkar A. Patel, and Ehud Altman, arXiv:2012.00763

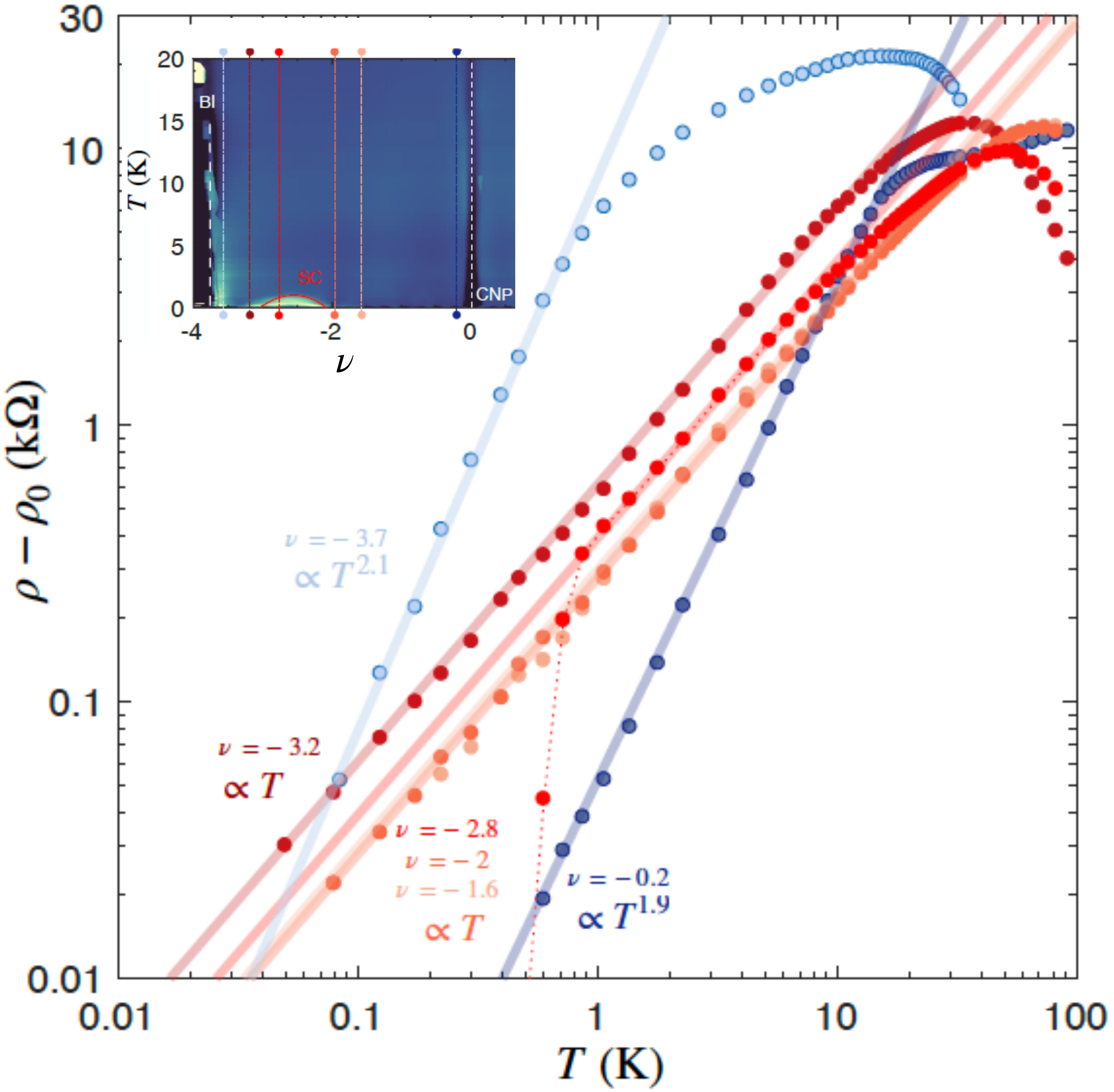
Strange metals


250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T*
Strange
Metal
Superconductor
T_c
p_c


Cu2+,Cu3+
O2-
Y3+
Ba2+
c
b
a
11.6802 Å
3.8872 Å
3.8227 Å



LSCO: Giraldo-Gallo et al. 2018



MATBG: Jaoui et al. 2021

Properties of a strange metal:

- Resistivity $\rho(T) = \rho_0 + AT + \ldots$ as $T \to 0$
  and $\rho(T) < h/e^2$ (in $d = 2$).
  Metals with $\rho(T) > h/e^2$ are bad metals.

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- Specific heat $\sim T \ln(1/T)$ as $T \to 0$.

S.A. Hartnoll and A.P. MacKenzie, arXiv:2107.07802

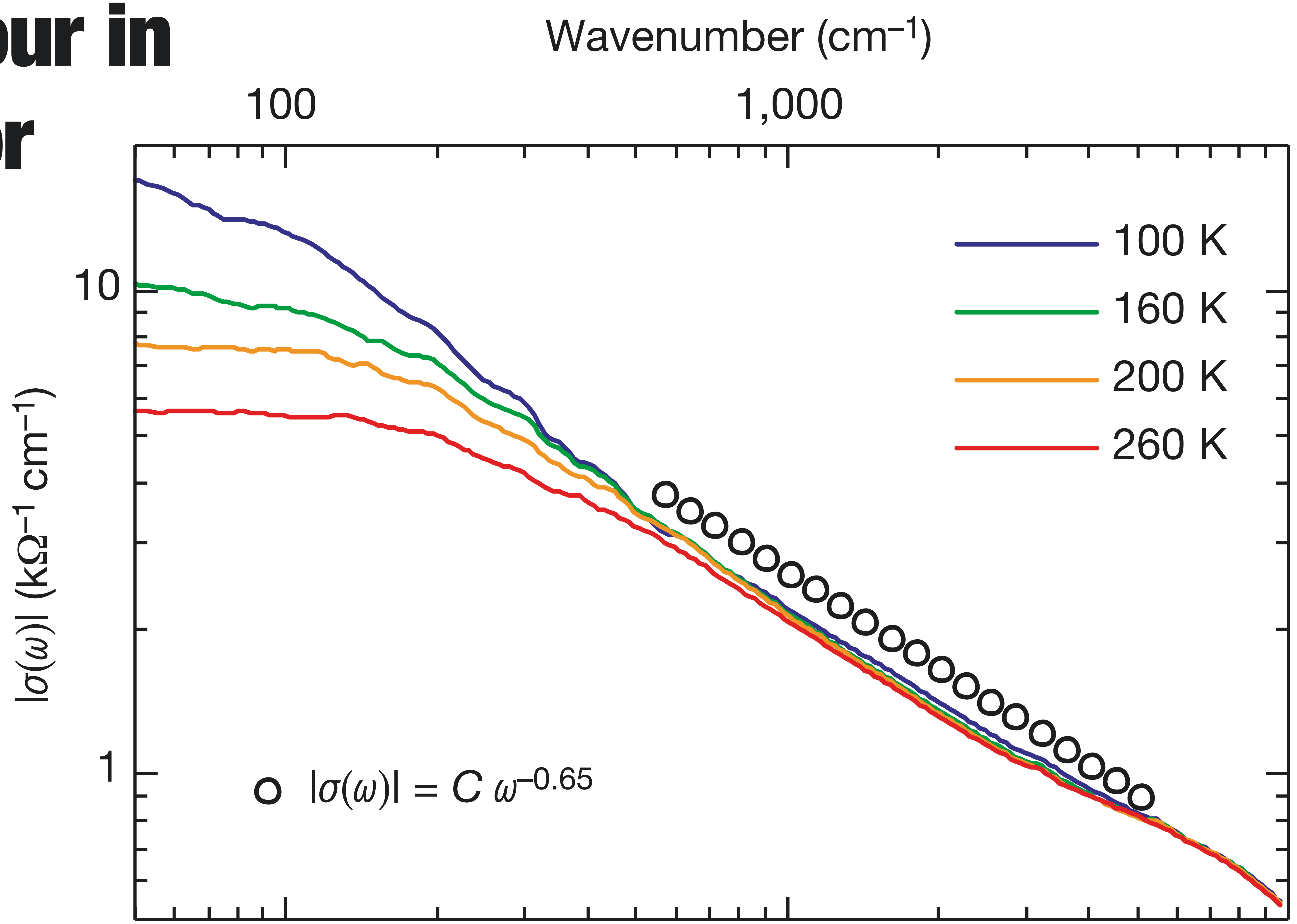
Properties of a strange metal:

- Optical conductivity

Nature **425**, 271 (2003)

D. van der Marel[1*], H. J. A. Molegraaf[1*], J. Zaanen[2], Z. Nussinov[2*], F. Carbone[1*], A. Damascelli[3*], H. Eisaki[3*], M. Greven[3], P. H. Kes[2] & M. Li[2]

Quantum critical behaviour in a high-T_c superconductor



But no $\hbar\omega/(k_B T)$ scaling.

Properties of a strange metal:

arXiv:2205.04030

- Optical conductivity

B. Michon,[1,2,3] C. Berthod,[3] C. W. Rischau,[3] A. Ataei,[4] L. Chen,[4]
S. Komiya,[5] S. Ono,[5] L. Taillefer,[4,6] D. van der Marel,[3] and A. Georges[7,8,3,]

Planckian Behavior of Cuprate Superconductors: Reconciling the Scaling of Optical Conductivity with Resistivity and Specific Heat

$$\sigma(\omega) = \frac{K}{\frac{1}{\tau_{\text{trans}}(\omega)} - i\omega\frac{m^*(\omega)}{m}} \quad ; \quad \frac{1}{\tau_{\text{trans}}(\omega)} \sim |\omega|\Phi_\sigma\left(\frac{\hbar\omega}{k_B T}\right)$$

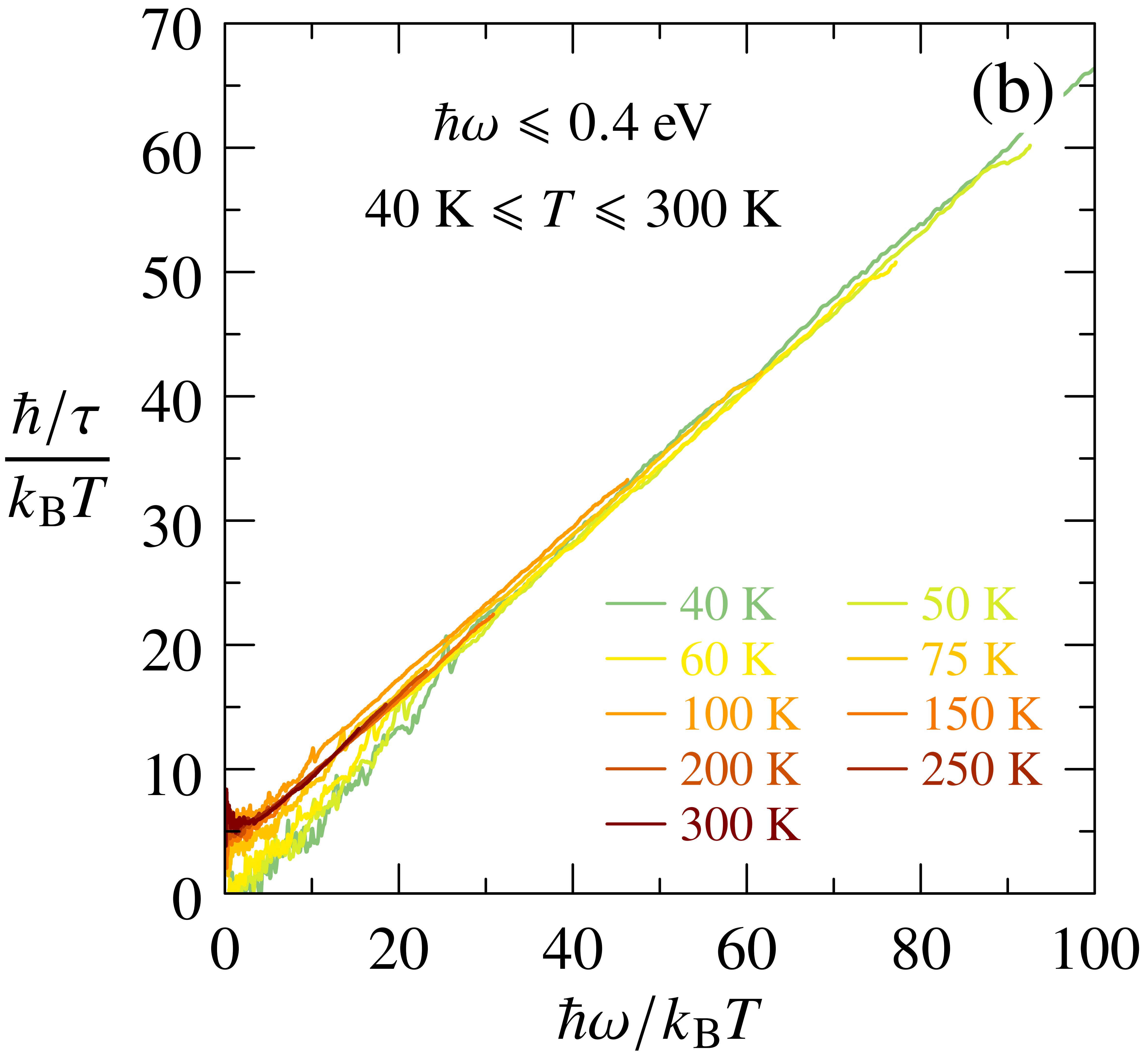
$$\text{Causality:} \quad \frac{m^*(\omega)}{m} \sim \ln\left(\frac{\Lambda}{\text{Max}(\hbar\omega, k_B T)}\right)$$

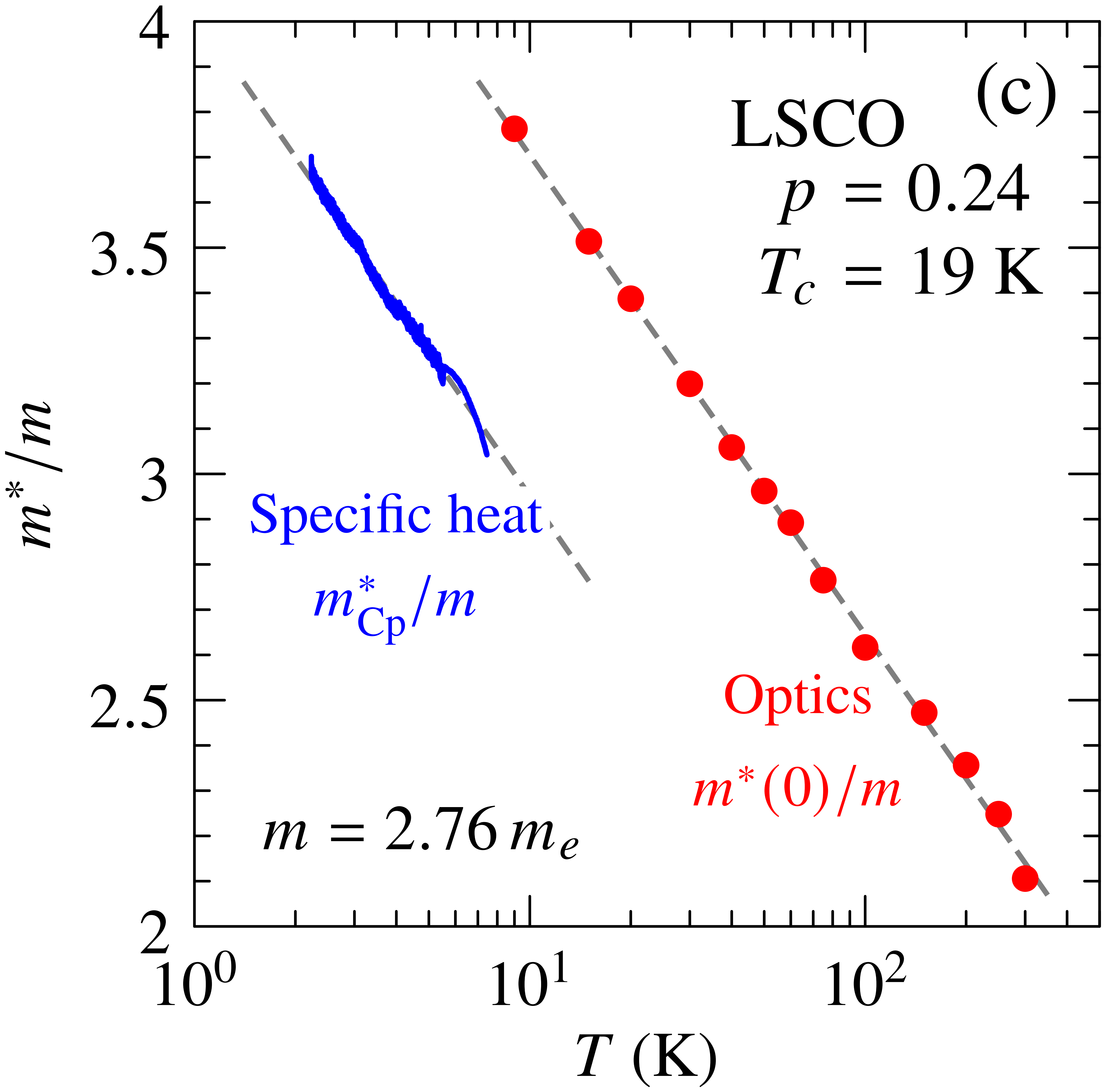
Properties of a strange metal:

arXiv:2205.04030

- Optical conductivity

B. Michon,[1,2,3] C. Berthod,[3] C. W. Rischau,[3] A. Ataei,[4] L. Chen,[4] S. Komiya,[5] S. Ono,[5] L. Taillefer,[4,6] D. van der Marel,[3] and A. Georges[7,8,3,





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S.A. Hartnoll and A.P. MacKenzie, arXiv:2107.07802

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B. Michon……A. Georges, arXiv:2205.04030

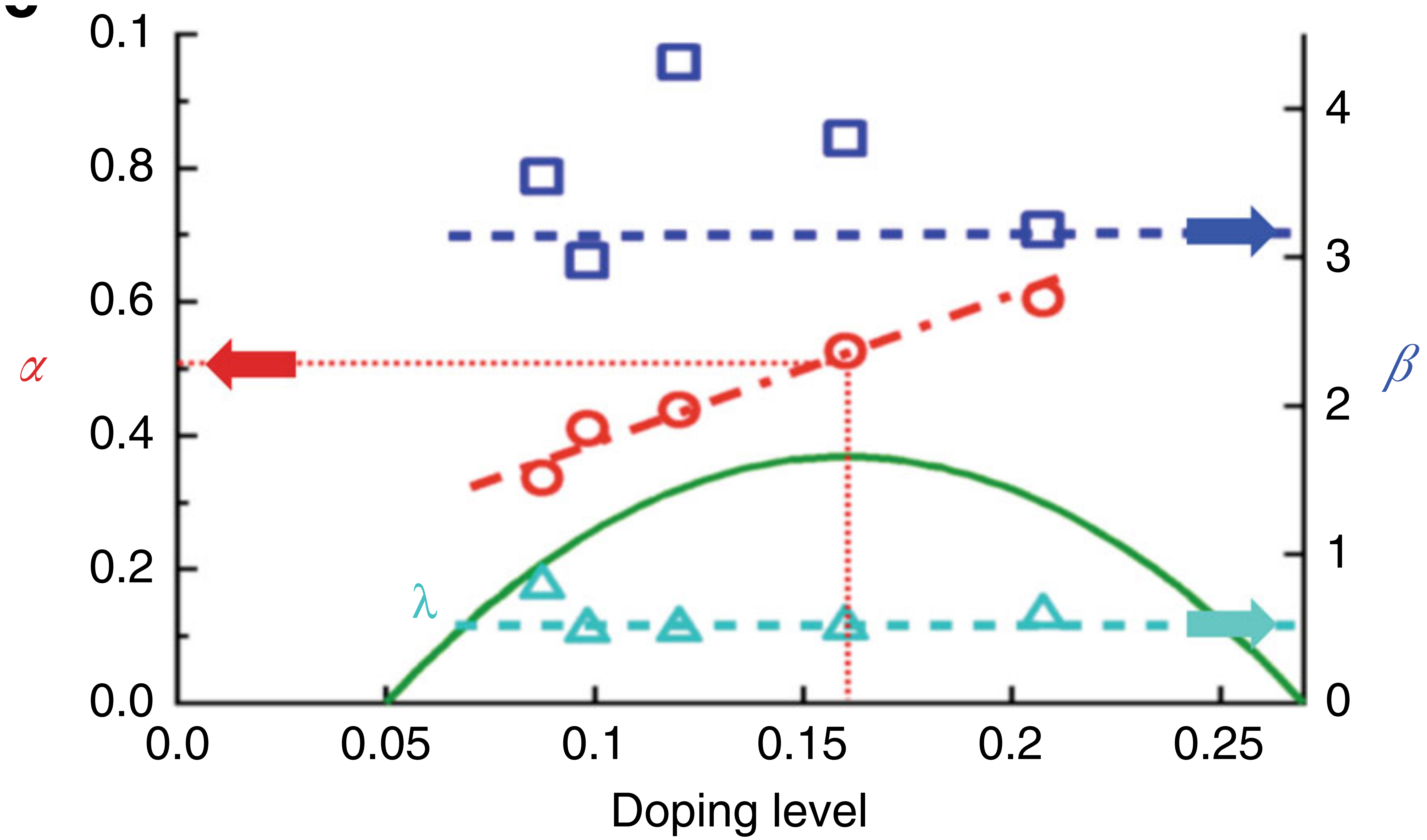
Properties of a strange metal:

Nature Communications **10**, 5737 (2019)

- Photoemission

A unified form of low-energy nodal electronic interactions in hole-doped cuprate superconductors

T.J. Reber[1,5*], X. Zhou[1*], N.C. Plumb[1,6], S. Parham[1], J.A. Waugh[1], Y. Cao[1], Z. Sun[1,7], H. Li[1], Q. Wang[1], J.S. Wen[2], Z.J. Xu[2], G. Gu[2], Y. Yoshida[3], H. Eisaki[3], G.B. Arnold[1] & D.S. Dessau[1,4*]



$$\Sigma''_{\mathrm{PLL}}(\omega) = \Gamma_0 + \lambda \frac{\left[(\hbar\omega)^2 + (\beta k_{\mathrm{B}} T)^2\right]^{\alpha}}{(\hbar\omega_N)^{2\alpha-1}}$$

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B. Michon……A. Georges, arXiv:2205.04030

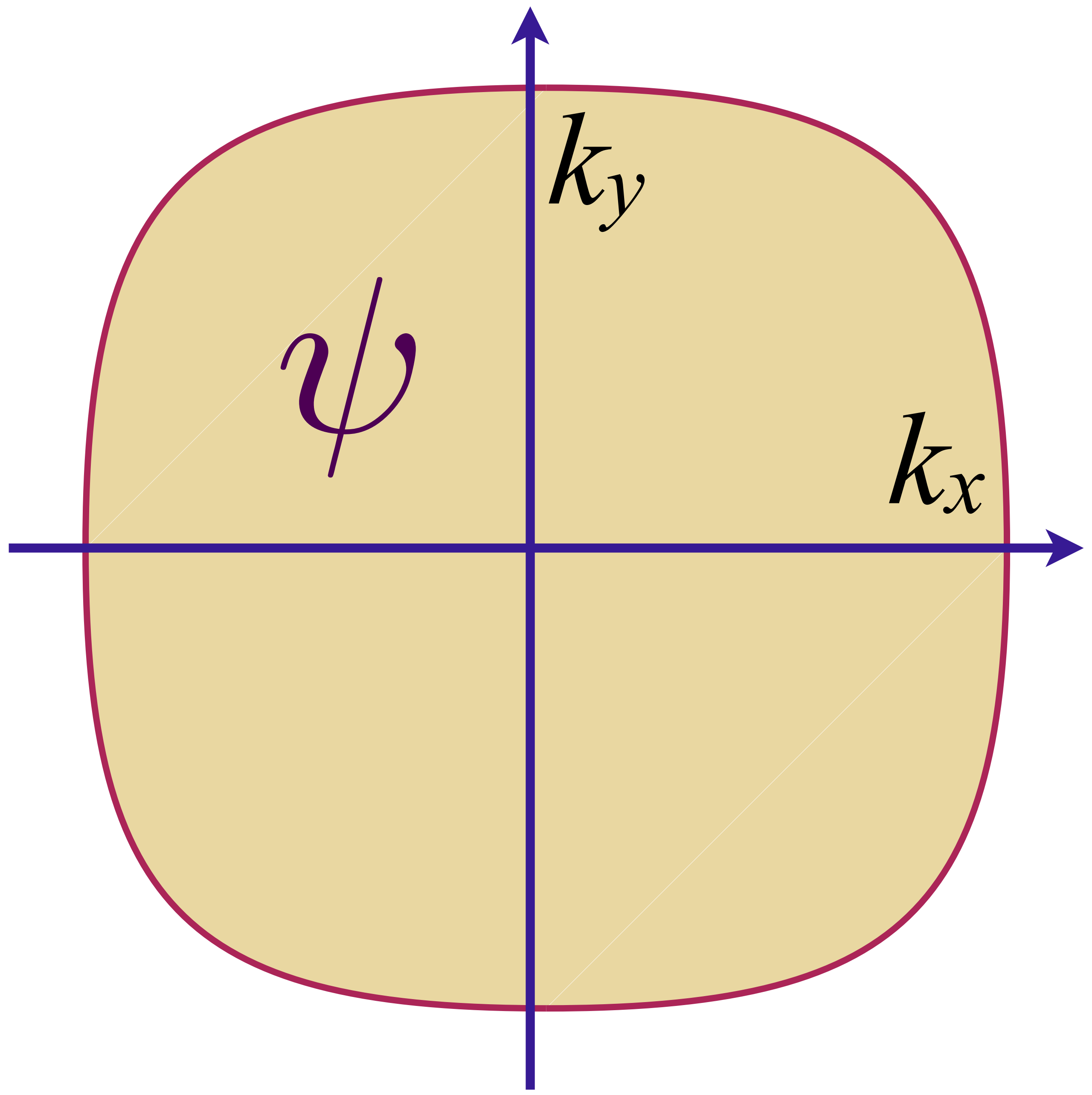
- Photoemission: nearly "marginal Fermi liquid" electron spectral density:

$$\text{Im}\Sigma(\omega) \sim |\omega|^{2\alpha} \Phi_\Sigma \left(\frac{\hbar\omega}{k_B T} \right) \quad \text{with } \alpha \approx 1/2$$

T.J. Reber….D. Dessau, Nature Communications **10**, 5737 (2019)

Fermions
and
critical bosons

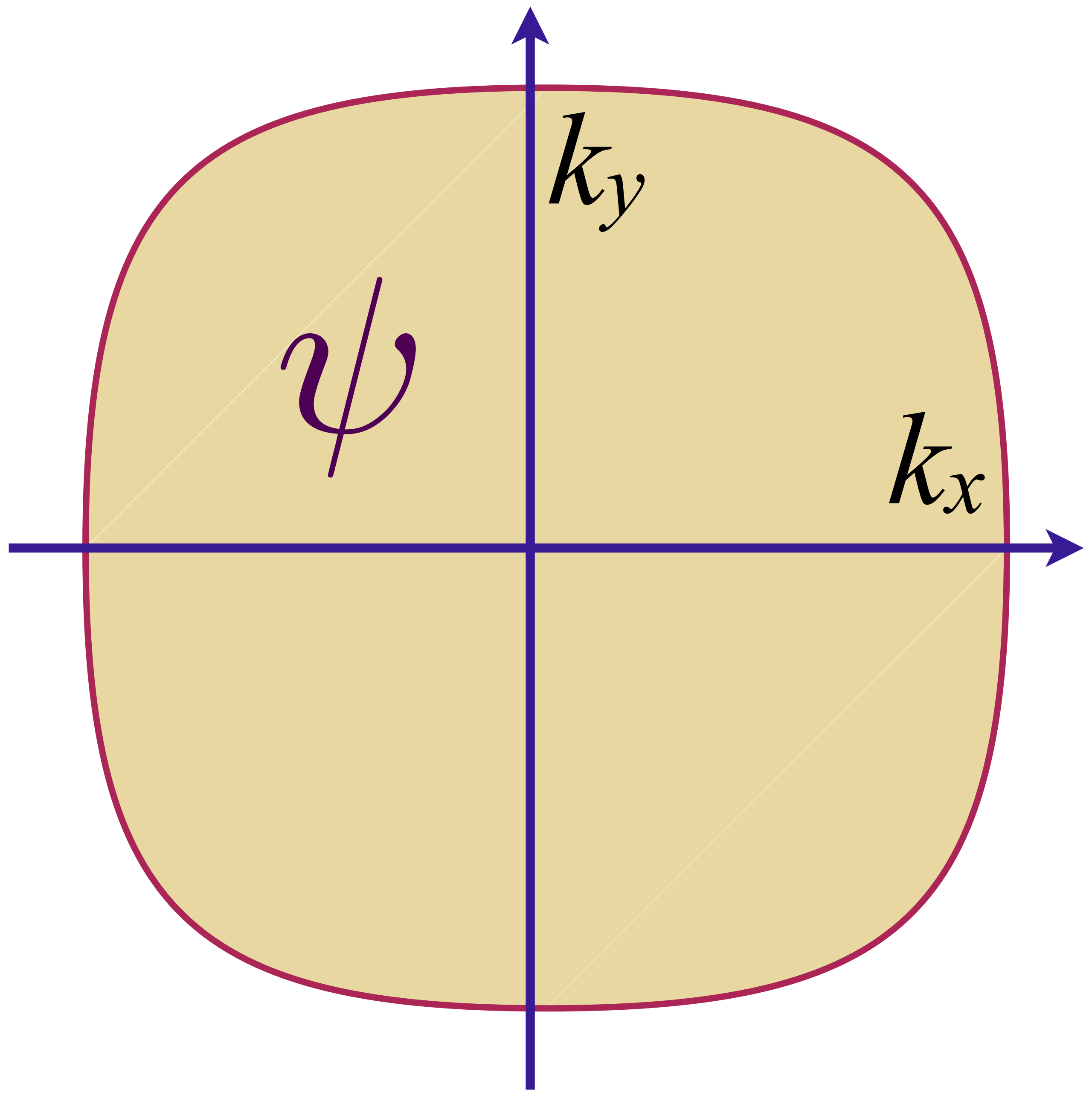
$$\mathcal{L}_\psi = \psi_{\boldsymbol{k}}^\dagger \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}}$$



$$-J\,\psi^\dagger \psi^\dagger \psi \psi$$

Fermi surface coupled to a critical boson

$$\mathcal{L}_\psi = \psi_{\boldsymbol{k}}^\dagger \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}}$$



a critical boson ϕ

e.g. Ising-nematic order

$$\frac{\phi^2}{J} + \psi^\dagger \psi \, \phi$$

Fermi surface coupled to a critical boson

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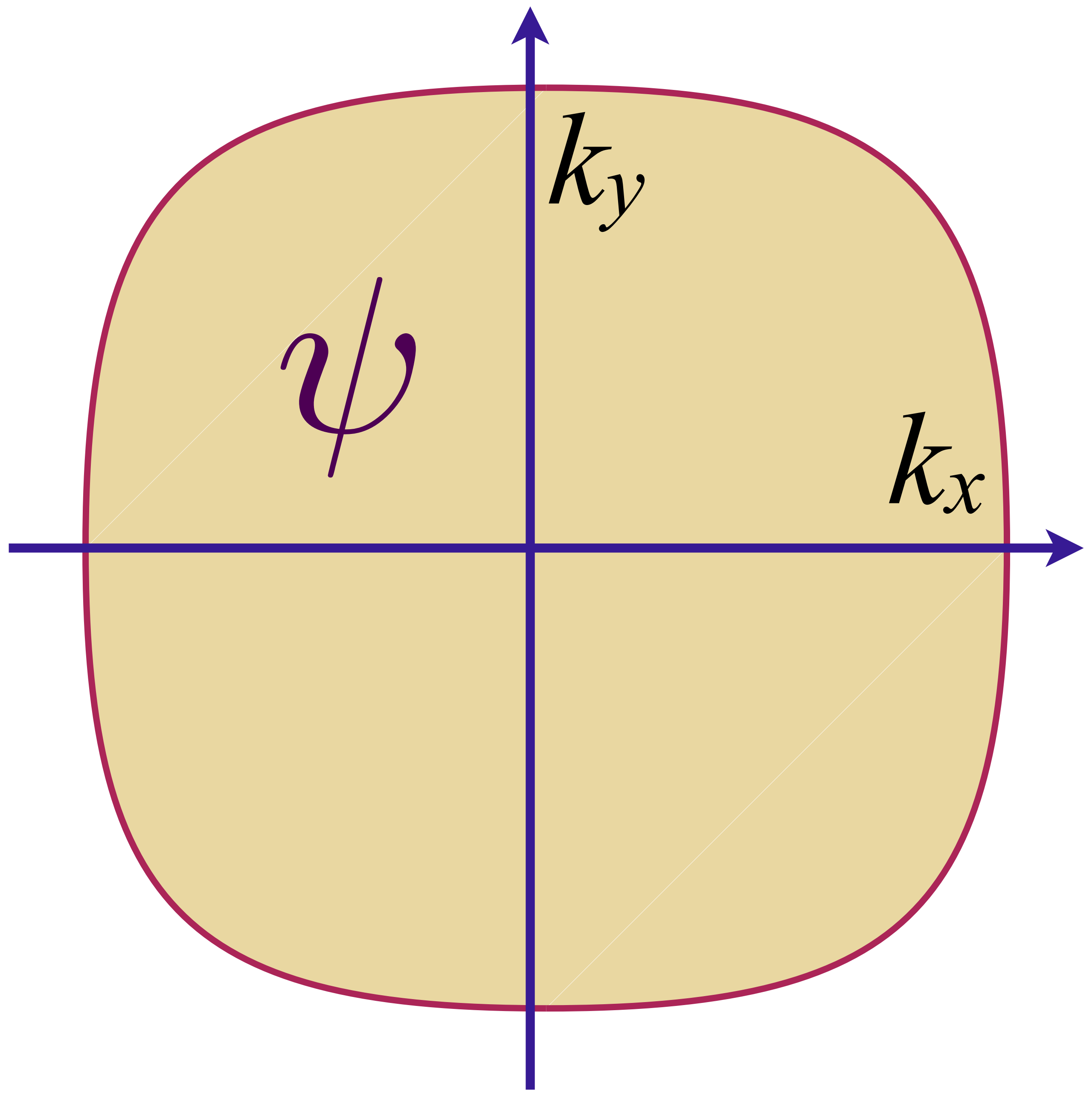


a critical boson ϕ
e.g. Ising-nematic order

$$\frac{\phi^2}{J} + \psi^\dagger \psi \, \phi$$

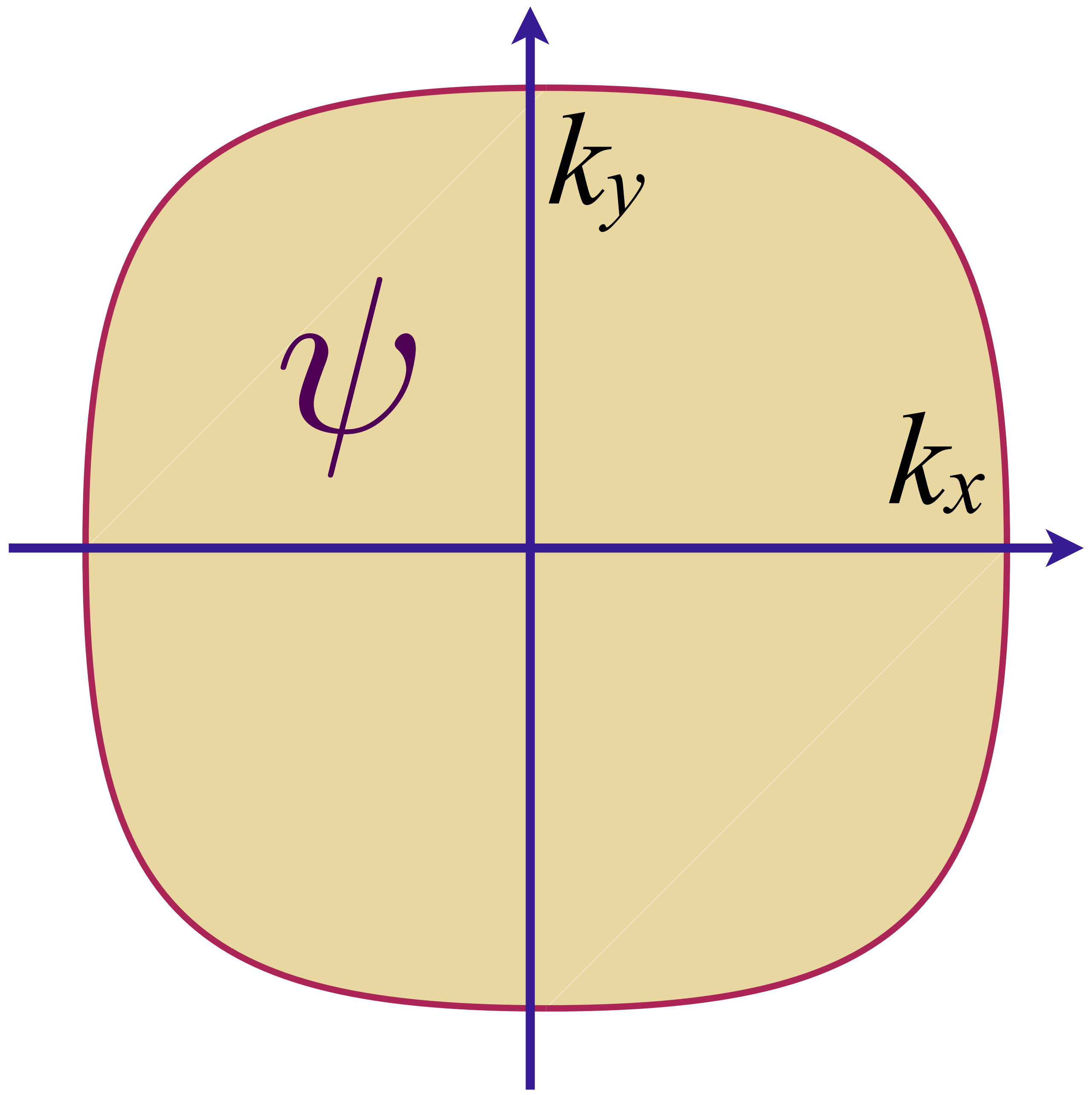
Eliashberg solution for electron (G) and boson (D) Green's functions at small ω:

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

P.A. Lee (1989)

Fermi surface coupled to a critical boson

$$\mathcal{L}_\psi = \psi^\dagger_{\boldsymbol{k}} \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}}$$



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$$\frac{\phi^2}{J} + \psi^\dagger \psi \, \phi$$

S. A. Hartnoll, P. K. Kovtun, M. Muller, and S.S. PRB **76**, 144502 (2007)
D. L. Maslov, V. I. Yudson, and A. V. Chubukov PRL **106**, 106403 (2011)
S. A. Hartnoll, R. Mahajan, M. Punk, and S.S. PRB **89**, 155130 (2014)
A. Eberlein, I. Mandal, and S.S. PRB **94**, 045133 (2016)
Aavishkar Patel, Haoyu Guo, Ilya Esterlis, S.S. arXiv:2203.04990
Zhengyan Darius Shi, Hart Goldman, Dominic V. Else, T. Senthil arXiv:2204.07585

Transport—a perfect metal!
Conservation of momentum and fermion-boson drag imply:

$$\mathrm{Re}\left[\sigma(\omega)\right] = D\delta(\omega) + \ldots$$

Fermi surface coupled to a critical boson:
No spatial disorder

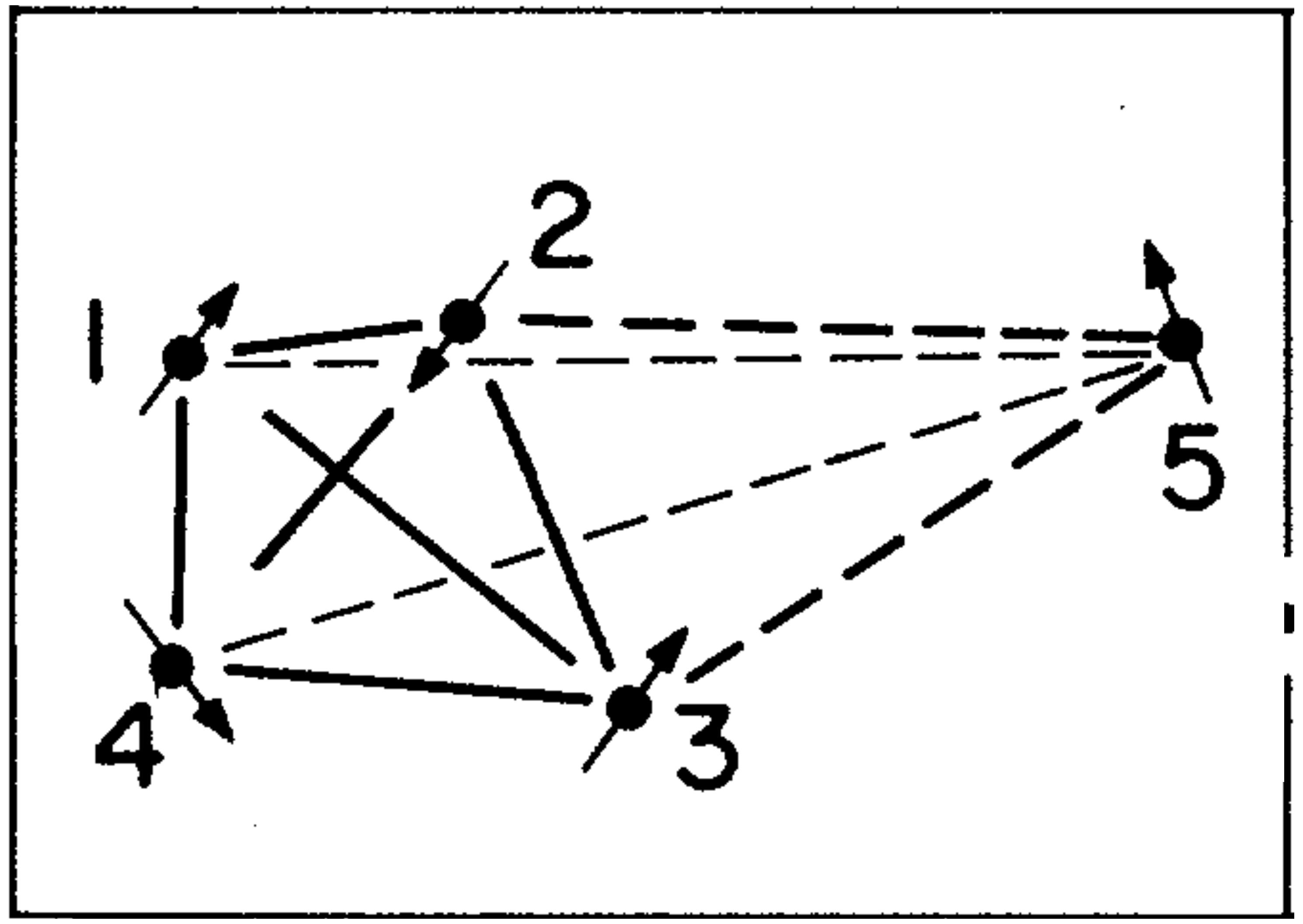
A non-Fermi liquid but NOT a strange metal

Fermions and critical bosons with spatial disorder

Scaling Studies of Highly Disordered Spin-$\frac{1}{2}$ Antiferromagnetic Systems

R. N. Bhatt and P. A. Lee
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 6 May 1981; revised manuscript received 16 November 1981)
Physical Review Letters **48**, 344 (1982)

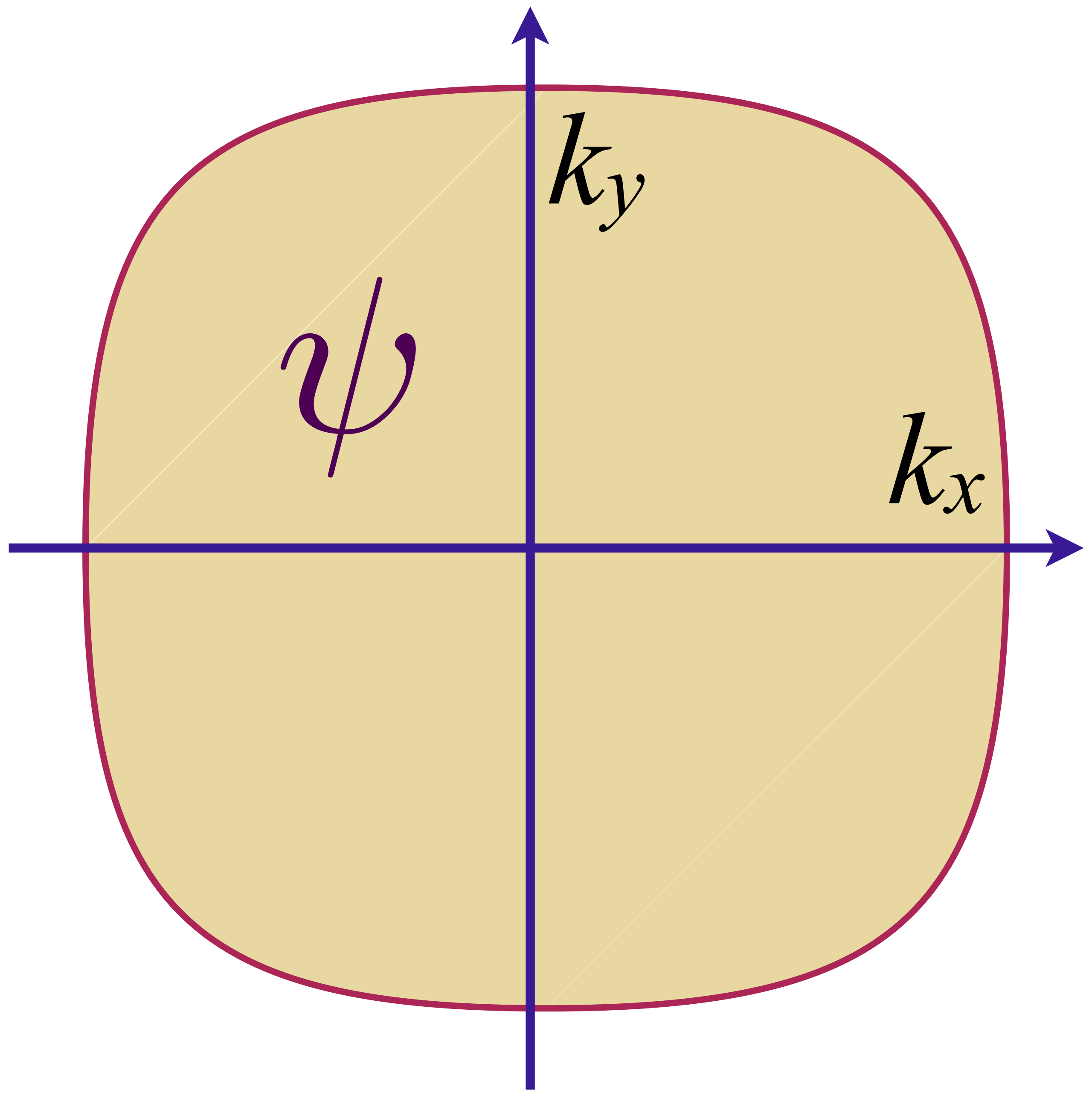
$$H = \frac{1}{2} \sum_{i \neq j} J(\vec{r}_i - \vec{r}_j) \vec{S}_i \cdot \vec{S}_j, \qquad J(\vec{r}) \sim \exp\left(-2\left|\vec{r}\right|/a_0\right)$$



Strong disorder fixed point ⇒ Random singlet phase

Fermi surface coupled to a critical boson with disorder

$$\mathcal{L}_\psi = \psi_{\boldsymbol{k}}^\dagger \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}}$$



a critical boson ϕ
e.g. Ising-nematic order

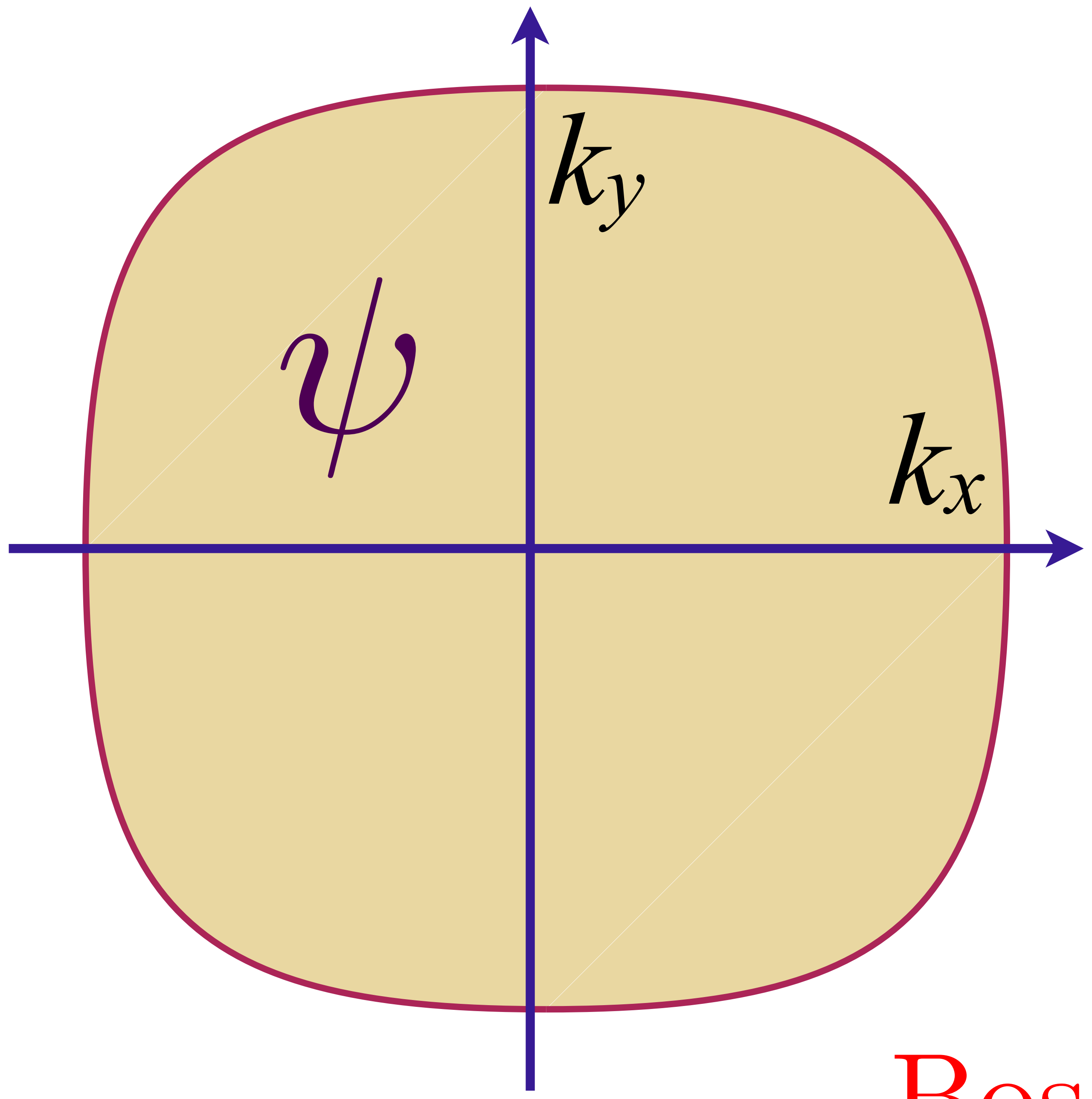
$$\frac{\phi^2}{J} + \psi^\dagger \psi \, \phi$$

$$+ v(\boldsymbol{r}) \psi^\dagger \psi$$

Spatially random potential $v(r)$ with $\overline{v(r)} = 0$, $\overline{v(r) v(r')} = v^2 \delta(r - r')$

Fermi surface coupled to a critical boson with disorder

$$\mathcal{L}_\psi = \psi^\dagger_{\boldsymbol{k}} \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}}$$



a critical boson ϕ
e.g. Ising-nematic order

$$\frac{\phi^2}{J} + \psi^\dagger \psi \, \phi$$

$$+ v(\boldsymbol{r}) \psi^\dagger \psi$$

Boson Green's function: $D(q, i\Omega) \sim 1/(q^2 + \gamma|\Omega|)$

Fermion self energy: $\Sigma(i\omega) \sim -iv^2 \mathrm{sgn}(\omega) - i\dfrac{g^2}{v^2} \omega \ln(1/|\omega|)$; $\quad \dfrac{1}{\tau(\varepsilon)} \sim |\varepsilon|$

Marginal Fermi liquid self energy and $T \ln(1/T)$ specific heat

HLR (1993)

Fermi surface coupled to a critical boson with disorder

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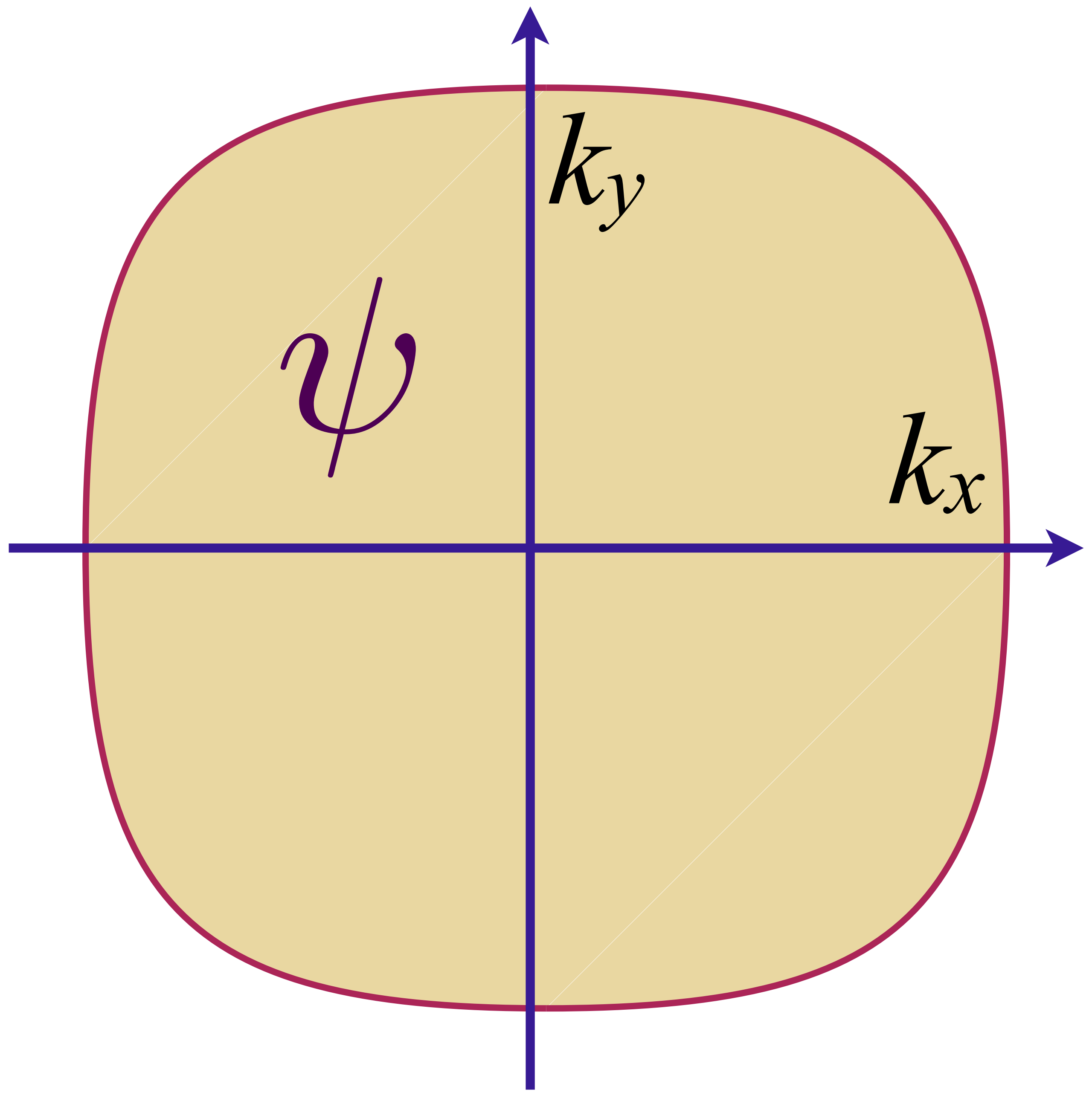


a critical boson ϕ
e.g. Ising-nematic order

$$\frac{\phi^2}{J} + \psi^\dagger \psi \, \phi$$

$$+ v(\boldsymbol{r}) \psi^\dagger \psi$$

But resistivity and optical conductivity are like a Fermi liquid, with residual resistivity $\sim 1/v^2$.

Aavishkar Patel, Haoyu Guo, Ilya Esterlis, S.S. arXiv:2203.04990; T. C. Wu, Y. Liao, and M. S. Foster, arXiv:2206.01762

Fermi surface coupled to a critical boson:

No spatial disorder

A non-Fermi liquid but NOT a strange metal

Fermi surface coupled to a critical boson:

Potential disorder v

A marginal Fermi liquid but NOT a strange metal

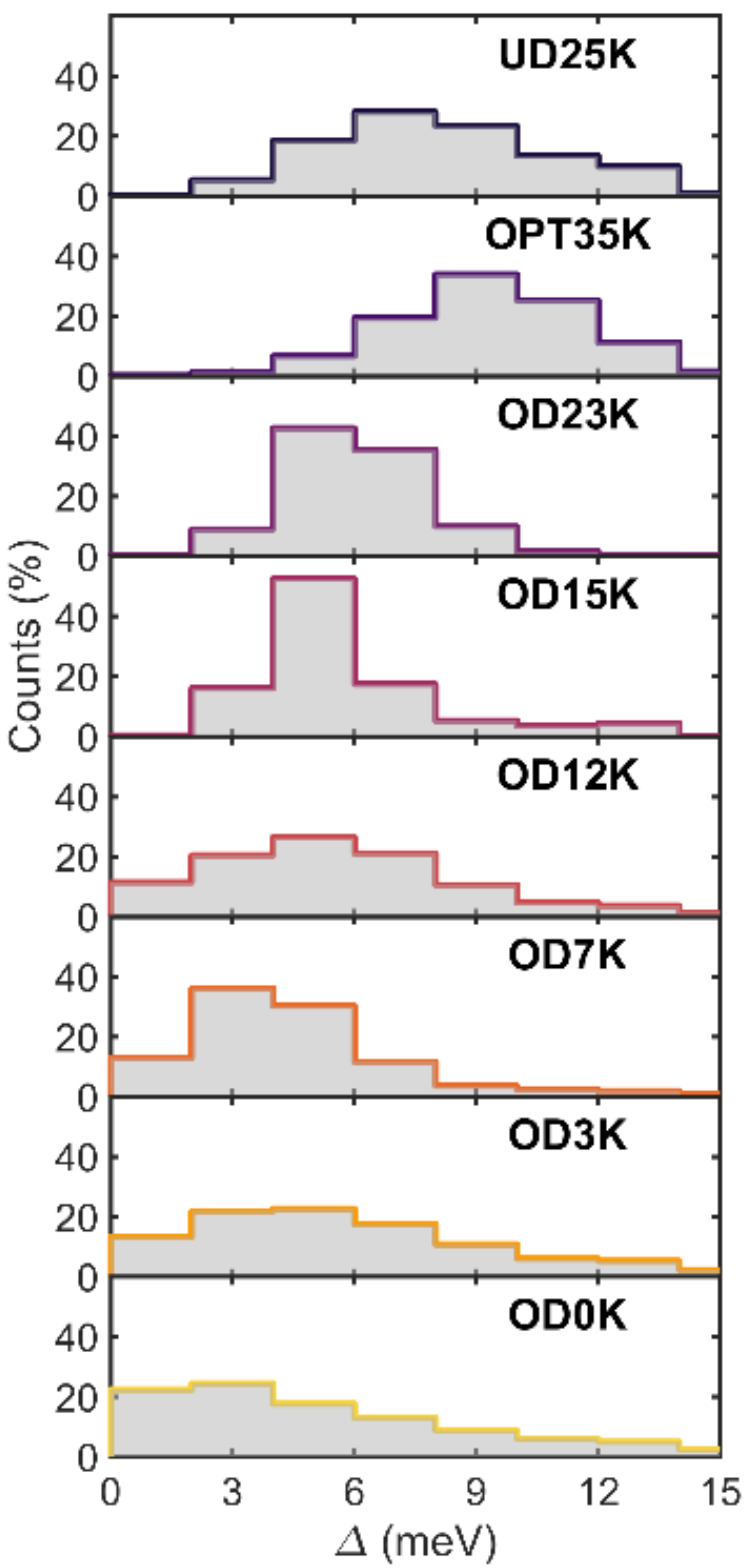
Spatially random interactions!

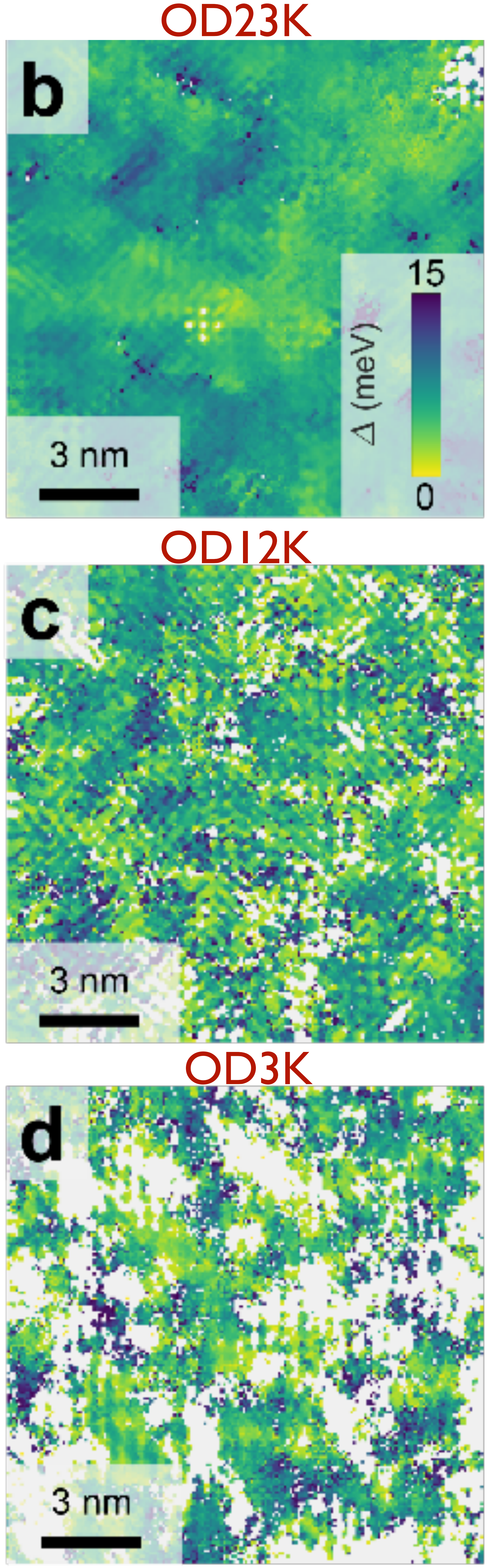
Puddle formation, persistent gaps, and non-mean-field breakdown of superconductivity in overdoped $(Pb,Bi)_2Sr_2CuO_{6+\delta}$

Willem O. Tromp, Tjerk Benschop, Jian-Feng Ge, Irene Battisti, Koen M. Bastiaans, Damianos Chatzopoulos, Amber Vervloet, Steef Smit, Erik van Heumen, Mark S. Golden, Yinkai Huang, Takeshi Kondo, Yi Yin, Jennifer E. Hoffman, Miguel Antonio Sulangi, Jan Zaanen, Milan P. Allan

Our scanning tunneling spectroscopy measurements in the overdoped regime of the $(Pb,Bi)_2Sr_2CuO_{6+\delta}$ high-temperature superconductor show the emergence of puddled superconductivity, featuring nanoscale superconducting islands in a metallic matrix

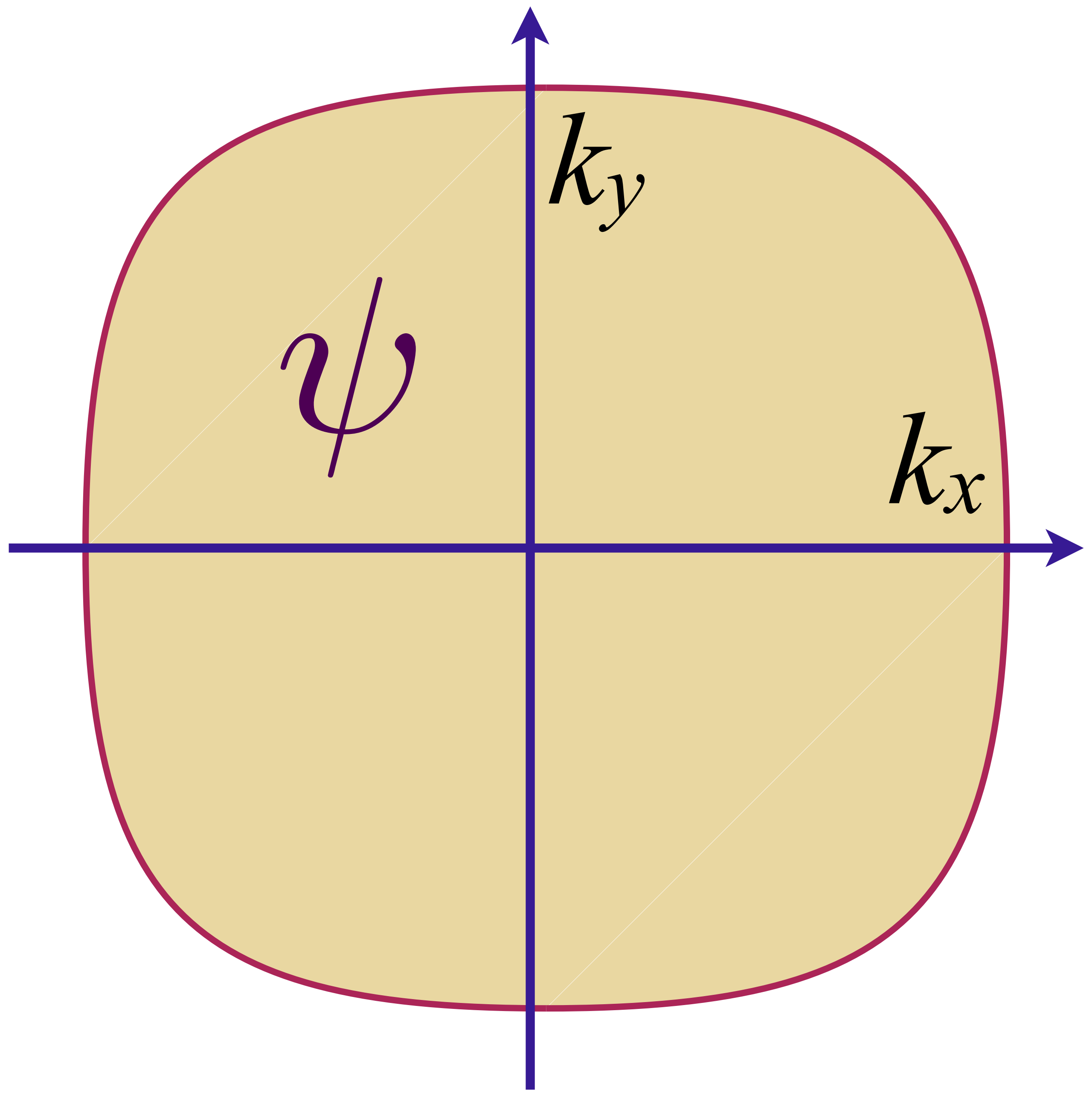
arXiv:2205.09740





Fermi surface coupled to a critical boson with disorder

$$\mathcal{L}_\psi = \psi_{\boldsymbol{k}}^\dagger \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}}$$



a critical boson ϕ

e.g. Ising-nematic order

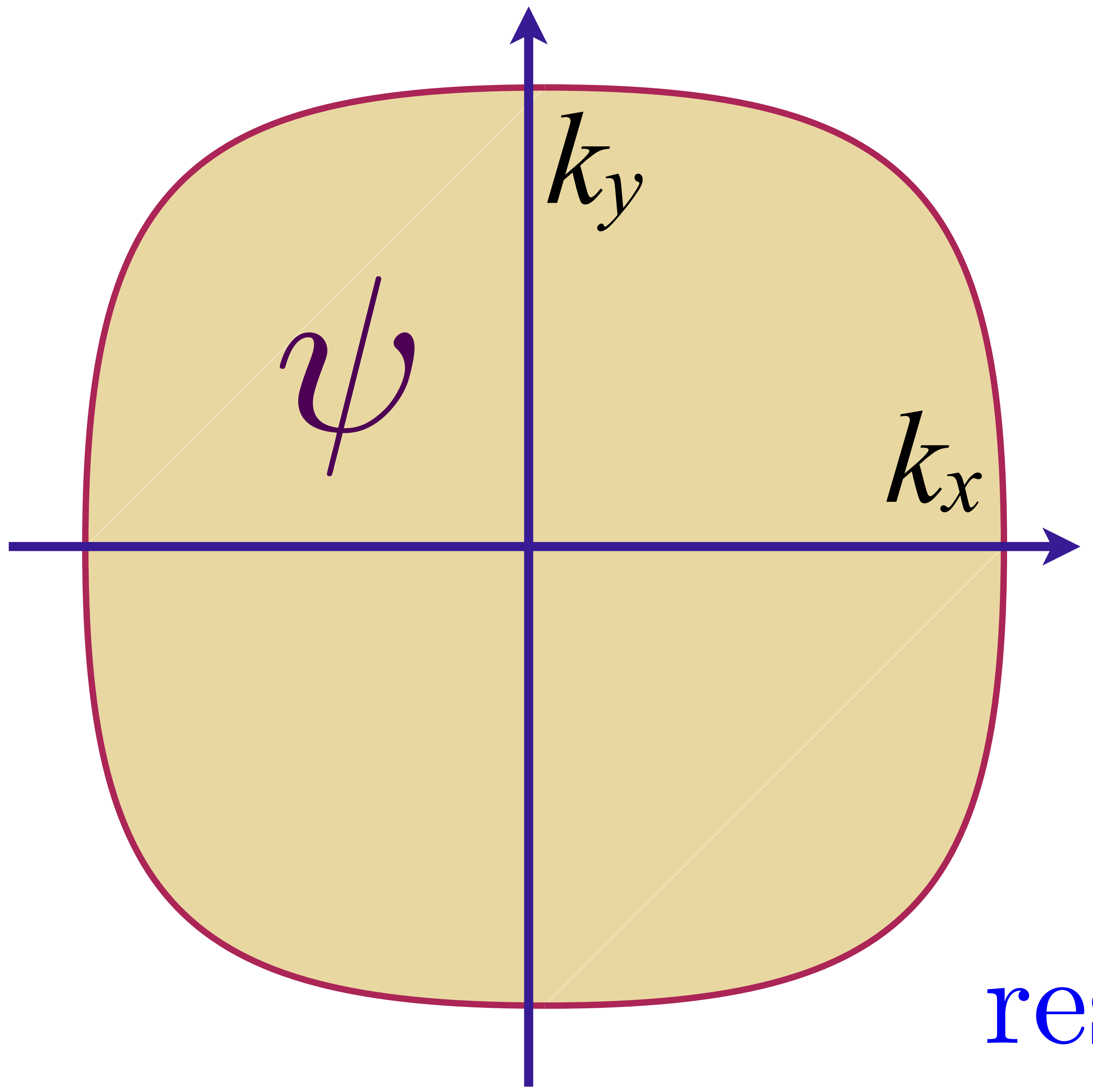
$$\frac{\phi^2}{J + J'(\boldsymbol{r})} + \psi^\dagger \psi \, \phi$$

$$+ v(\boldsymbol{r}) \psi^\dagger \psi$$

Fermi surface coupled to a critical boson with disorder

$$\mathcal{L}_\psi = \psi^\dagger_{\boldsymbol{k}} \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}}$$

a critical boson ϕ
e.g. Ising-nematic order



$$\phi^2 + \; [g + g'(\boldsymbol{r})]\psi^\dagger \psi \, \phi$$

$$+v(\boldsymbol{r})\psi^\dagger \psi$$

ϕ^2 "mass" disorder $J'(\boldsymbol{r})$ is strongly relevant;
rescale ϕ to move disorder to the Yukawa coupling;
can then be controlled in a SYK-like large N limit of 'flavor' indices,
leading to a G-Σ-D-Π bi-local field theory.

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

Fermi surface coupled to a critical boson with disorder

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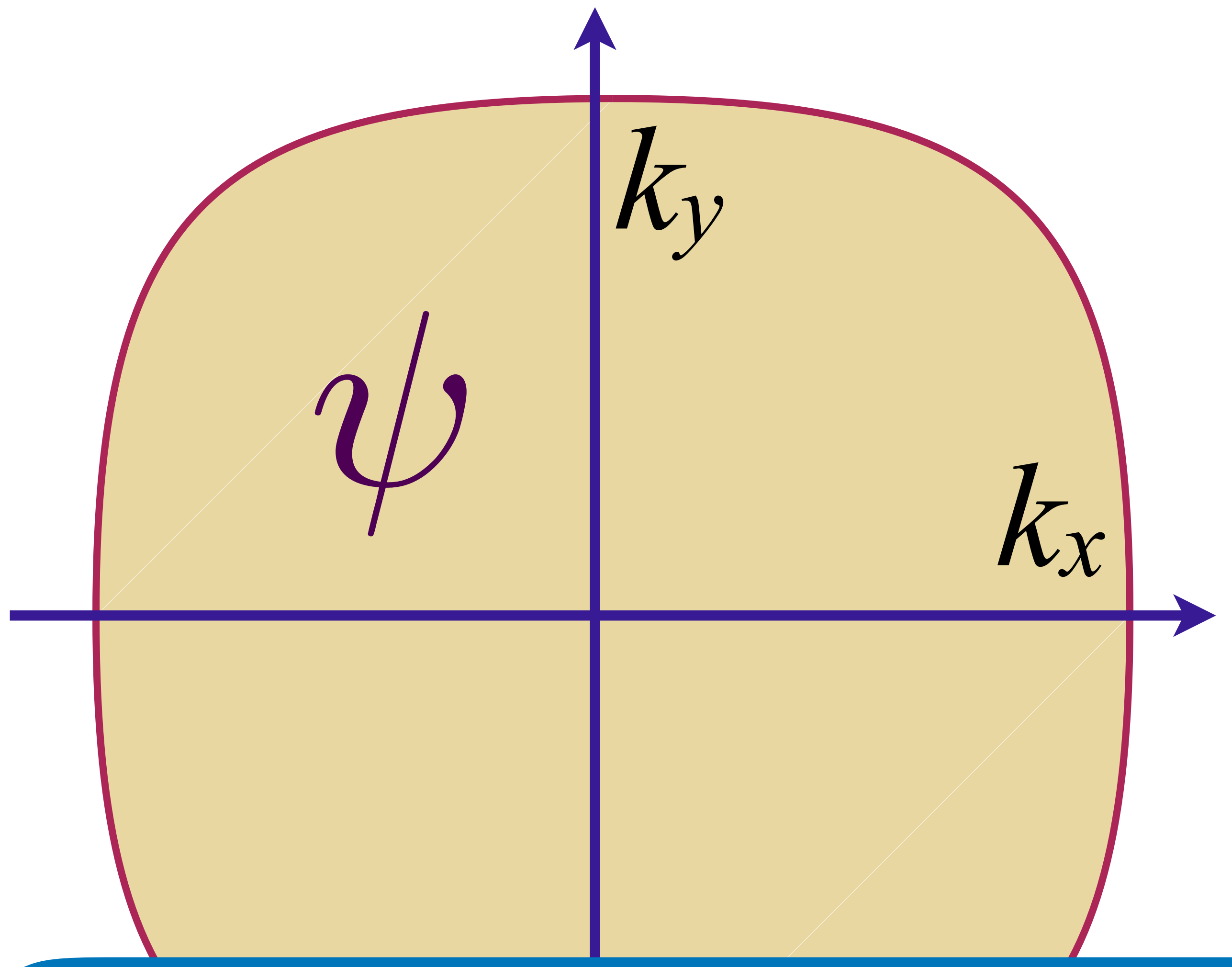

$$\phi^2 + \ [g + g'(\boldsymbol{r})]\psi^\dagger \psi \, \phi$$

$$+v(\boldsymbol{r})\psi^\dagger \psi$$

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; Transport insensitive to g; Marginal Fermi liquid self energy and $T\ln(1/T)$ specific heat.

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No spatial disorder

A non-Fermi liquid but NOT a strange metal

Fermi surface coupled to a critical boson:

Potential disorder *v*

A marginal Fermi liquid but NOT a strange metal

Fermi surface coupled to a critical boson:

Interaction disorder *g'*

A marginal Fermi liquid AND a strange metal

The future

- Quantitative fitting of different experiments

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- More observables: magnetoresistance, cyclotron resonance, shot noise . . .

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- More observables: magnetoresistance, cyclotron resonance, shot noise . . .
- $1/N$ corrections

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- Quantitative fitting of different experiments
- More observables: magnetoresistance, cyclotron resonance, shot noise ...
- $1/N$ corrections
- Compute T_c to superconductivity