Title: Universal theory of strange metals

Speakers: Subir Sachdev

Series: Quantum Matter

Date: March 14, 2024 - 2:00 PM

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Abstract: Abstract TBA

Zoom link

Universal theory of strange metals

Subir Sachdev

Perimeter Institute, Waterloo
March 14, 2024

PHYSICS
HARVARD

Ilya Esterlis
Wisconsin

Haoyu Guo
Cornell

Aavishkar Patel
Flatiron

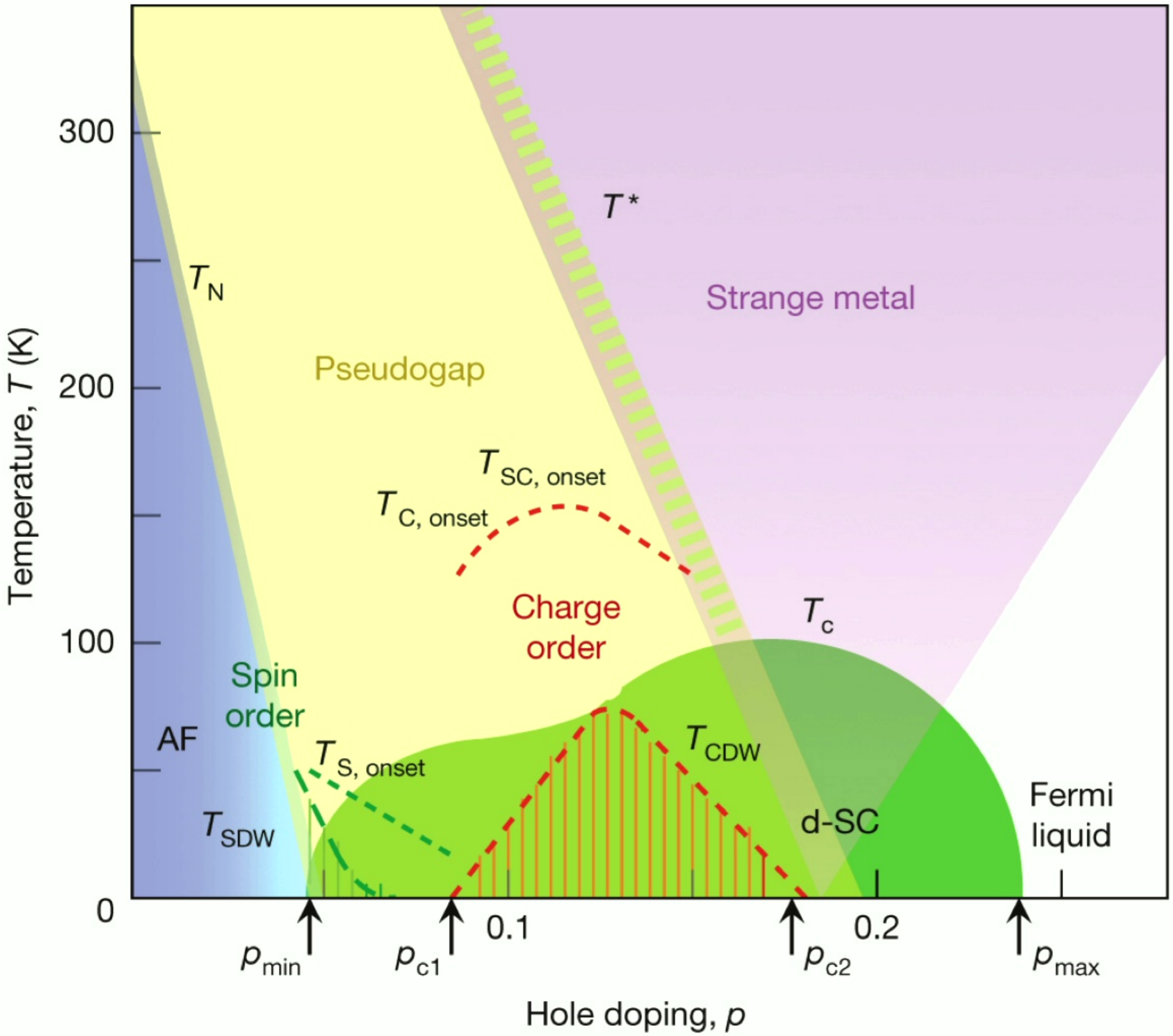
Chenyuan Li
Harvard

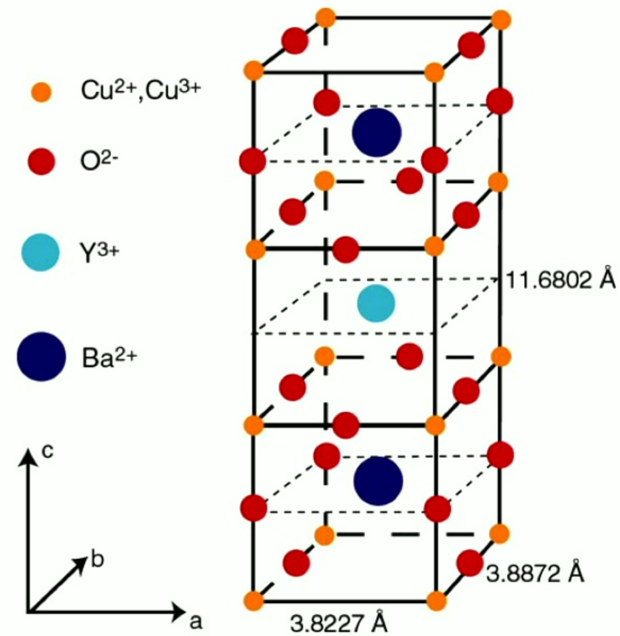
Davide Valentinis
KIT

Joerg Schmalian
KIT

Peter Lunts
Harvard

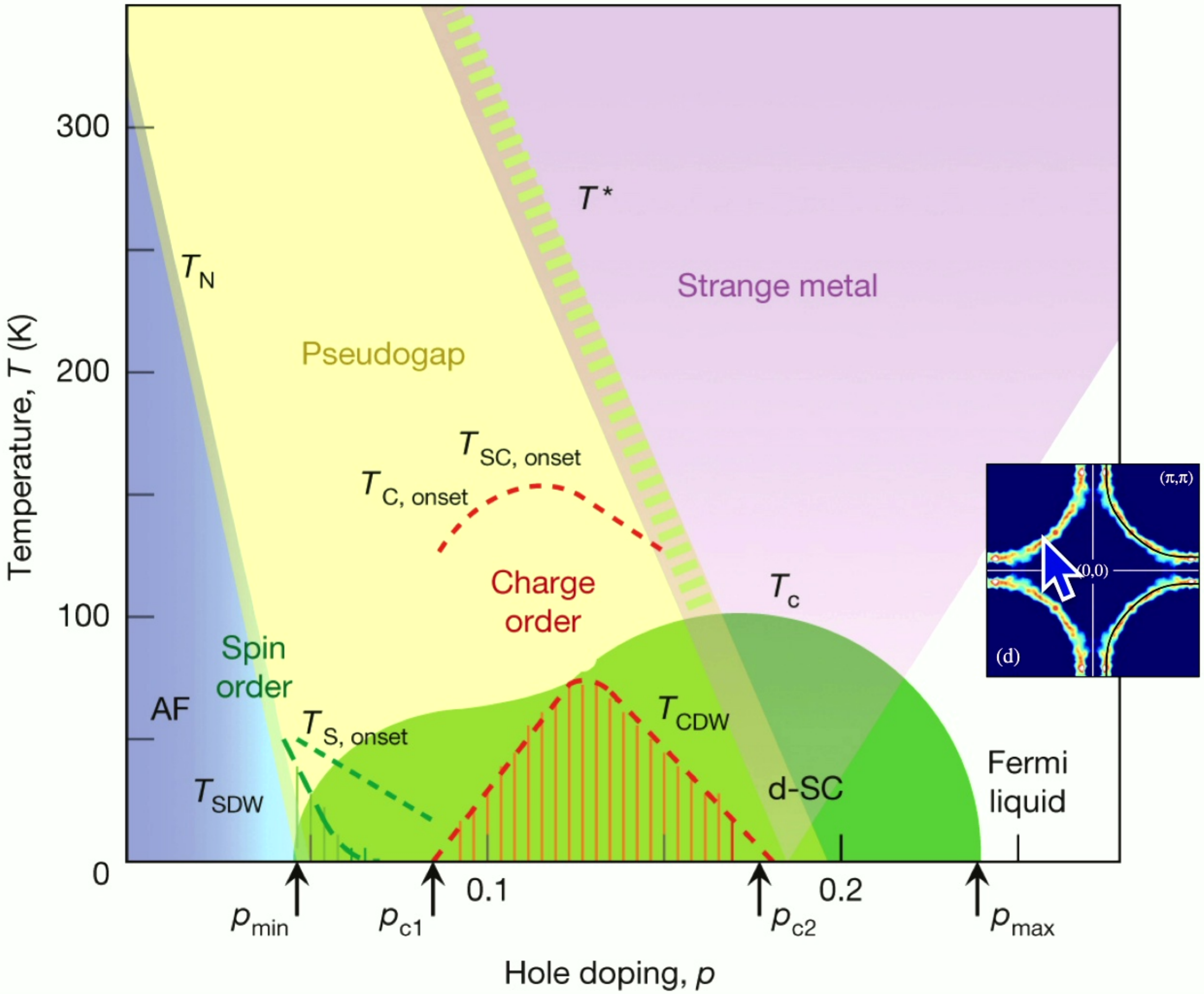
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)





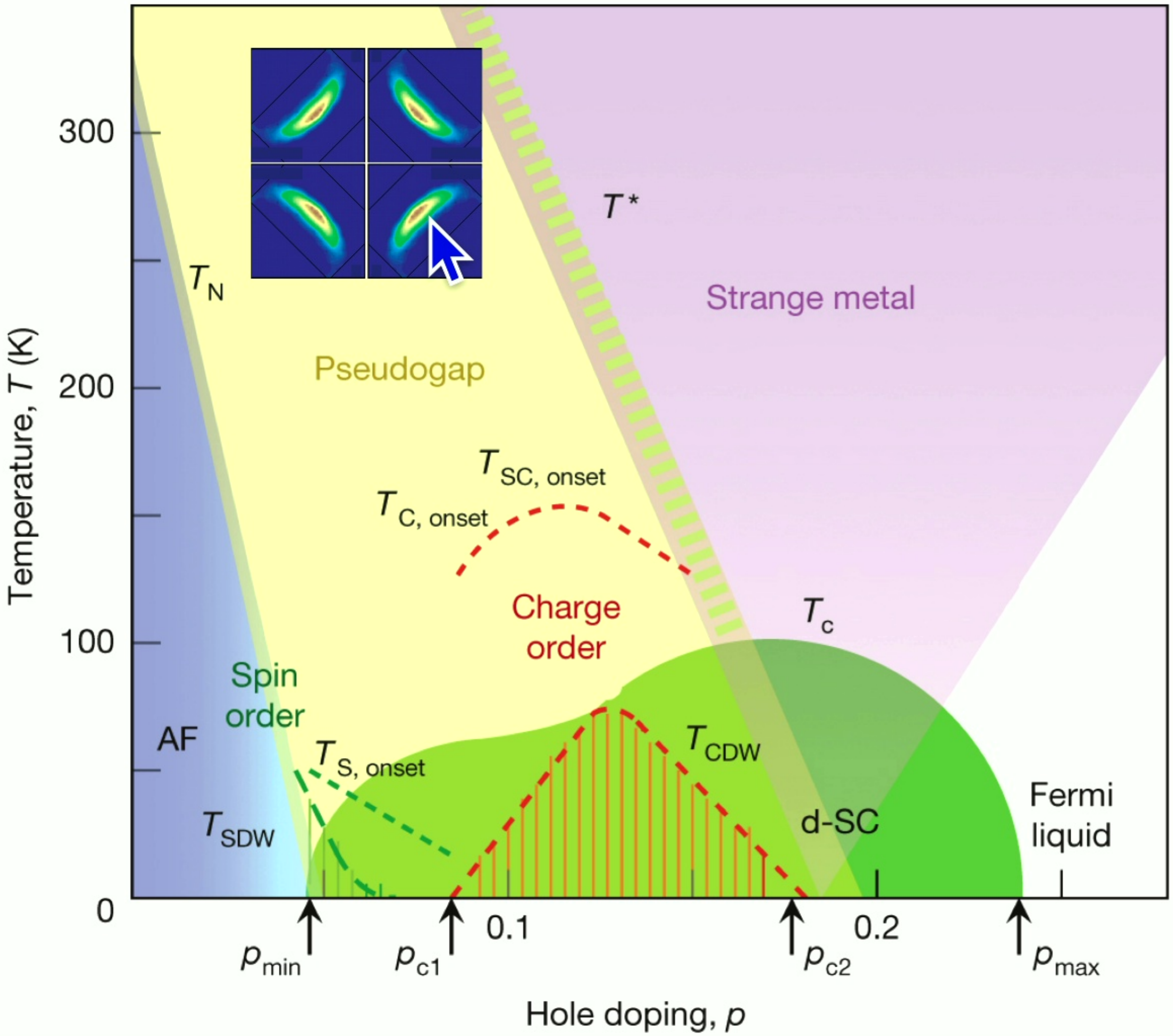
$YBa_2Cu_3O_{6+x}$

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



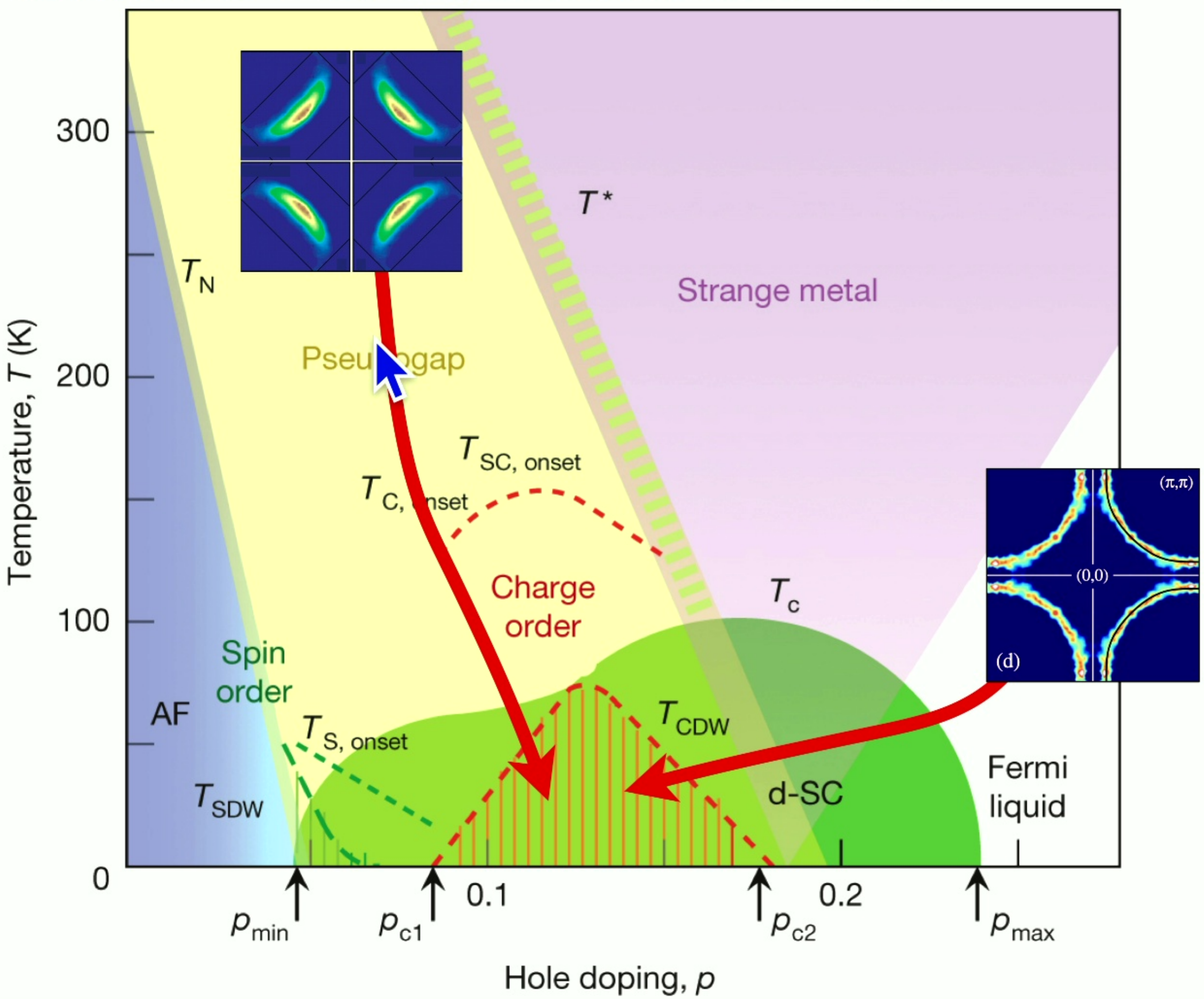
Fermi liquid in the overdoped metal

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



Pseudogap metal with "Fermi arcs"

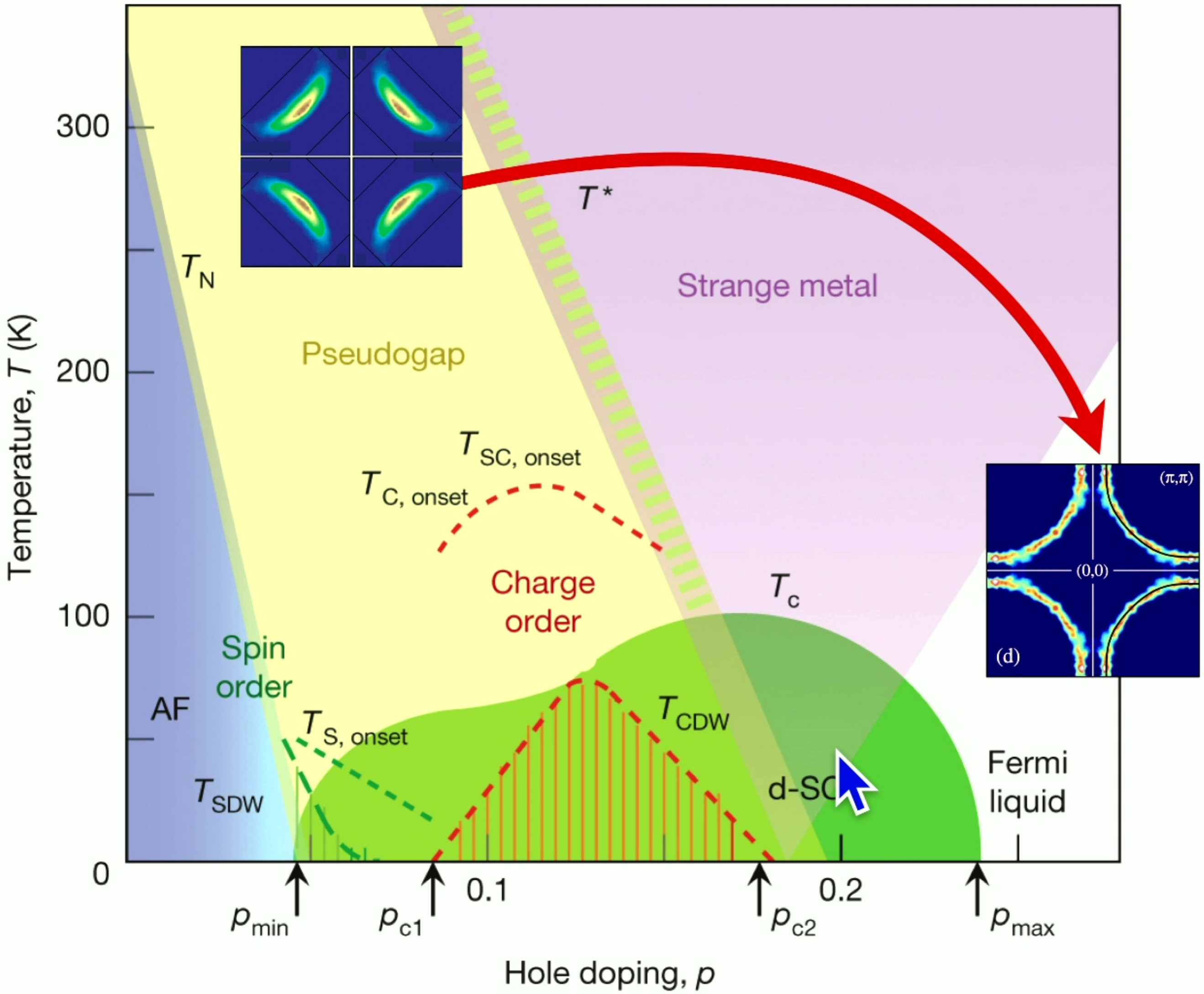
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



Build a theory for the phase diagram from a theory of the pseudogap metal as a 'metastable' $T = 0$ quantum phase.

Lowest T phases obtained from pseudogap metal should connect smoothly to conventionally order phases obtained from the Fermi liquid.

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



Build a theory for the phase diagram from a theory of the pseudogap metal as a 'metastable' $T = 0$ quantum phase.

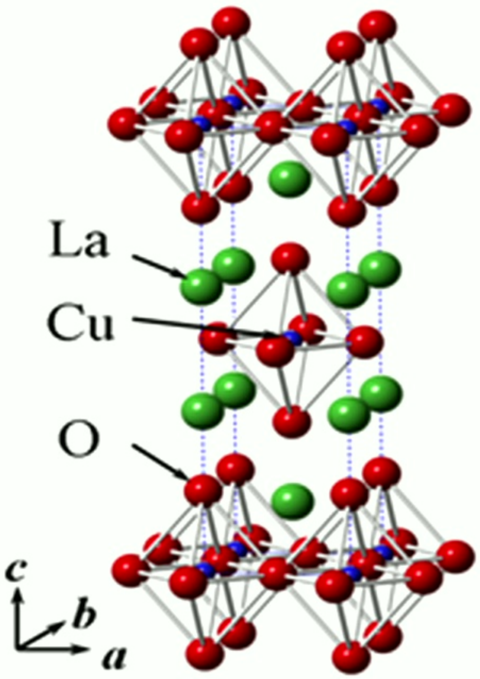
Strange metal described by quantum critical region of a $T = 0$ quantum transition between the pseudogap metal (FL*) and the Fermi liquid (FL).

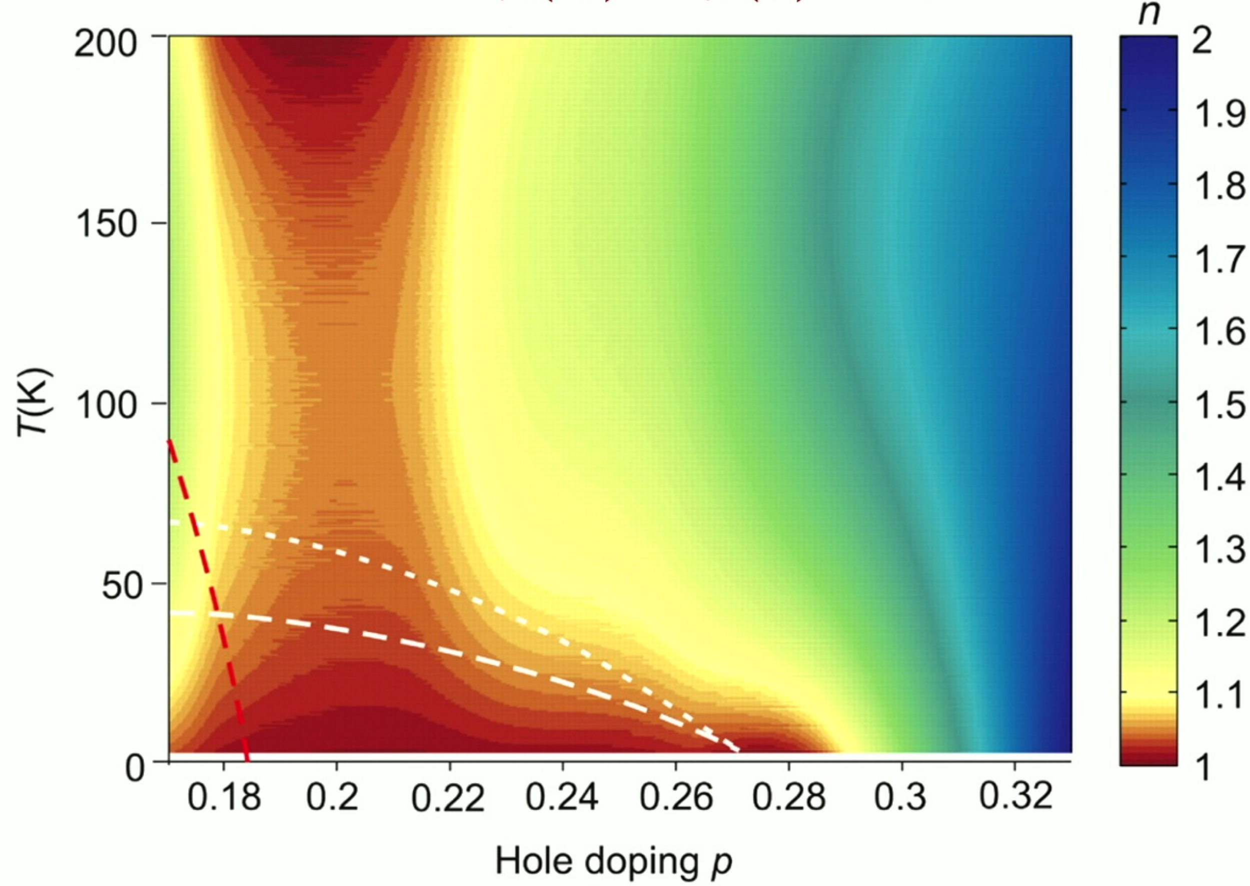
Anomalous Criticality in the Electrical Resistivity of $La_{2-x}Sr_xCuO_4$

R. A. Cooper,[1] Y. Wang,[1] B. Vignolle,[2] O. J. Lipscombe,[1] S. M. Hayden,[1] Y. Tanabe,[3] T. Adachi,[3] Y. Koike,[3] M. Nohara,[4*] H. Takagi,[4] Cyril Proust,[2] N. E. Hussey[1]†

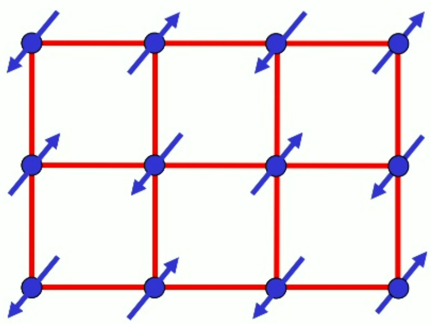
SCIENCE VOL 323 603 2009

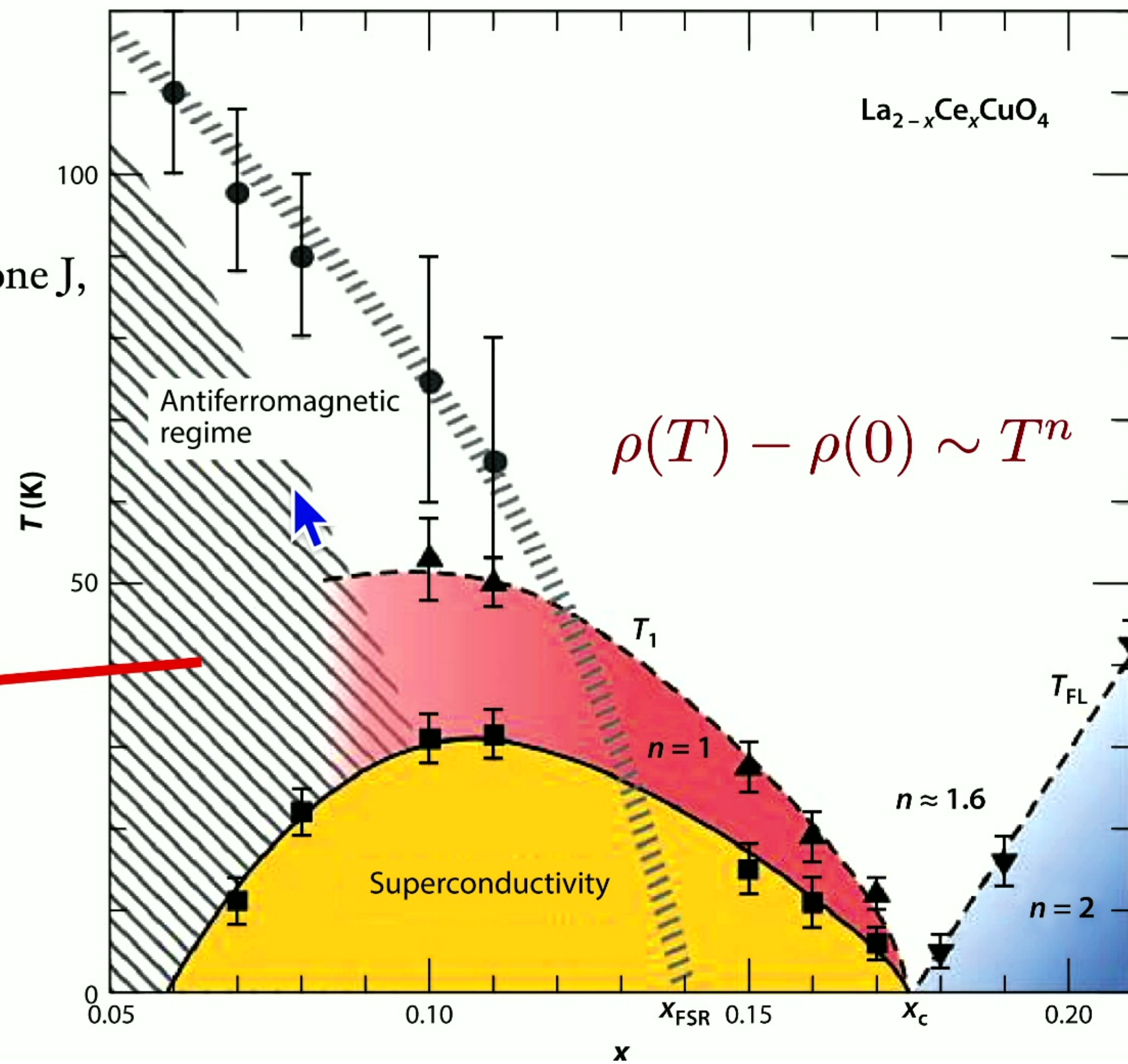
$$\rho(T) - \rho(0) \sim T^n$$



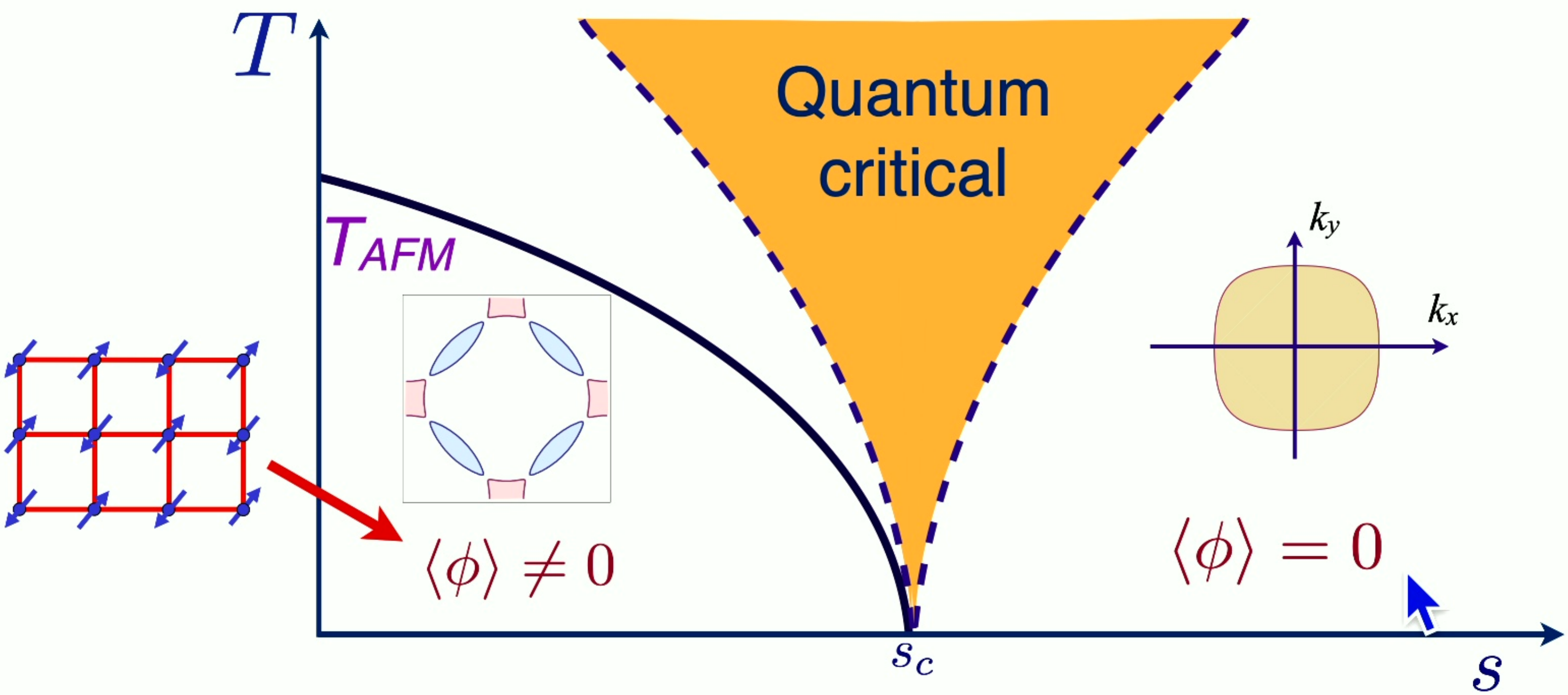


Jin K, Butch NP, Kirshenbaum K, Paglione J, Greene RL. 2011. *Nature* 476:73–75





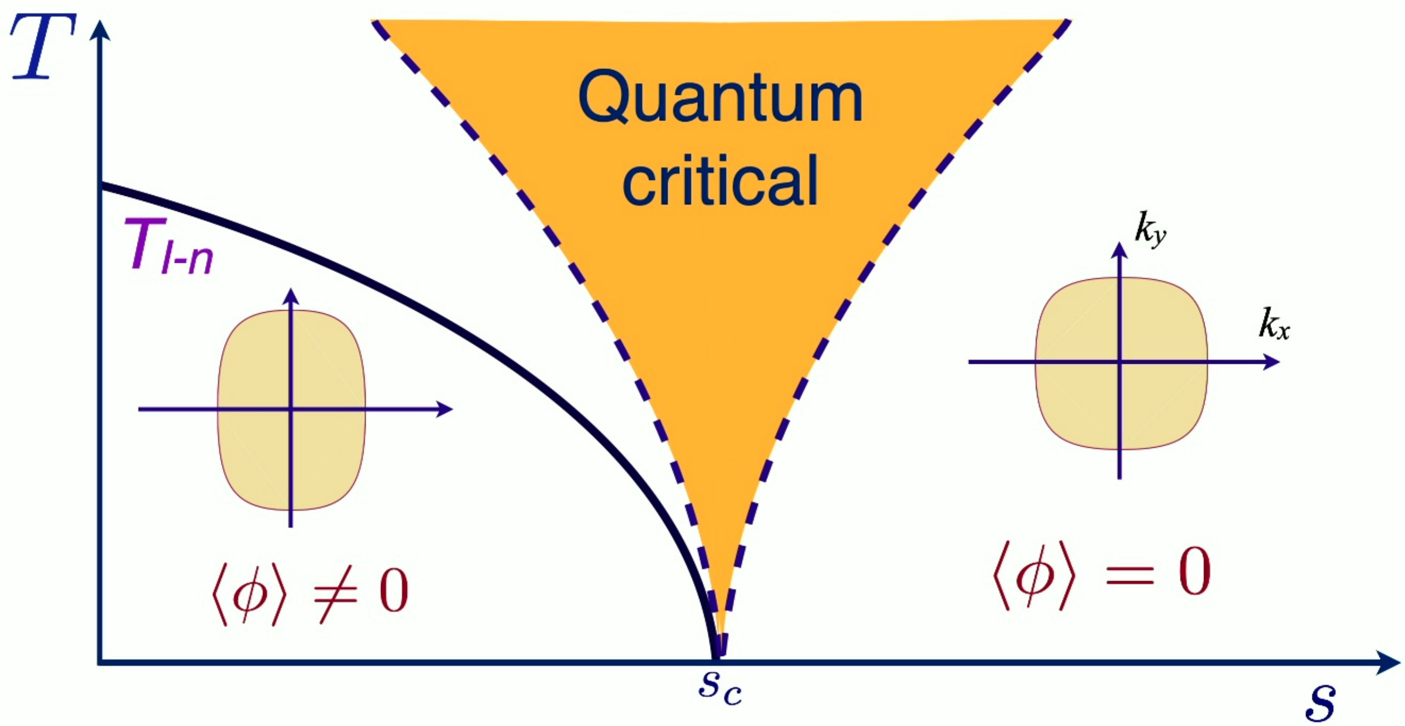
Quantum criticality of AF ordering in a metal



Francisco Borges, Anton Borissov, Ashutosh Singh, Andres Schlief, Sung-Sik Lee

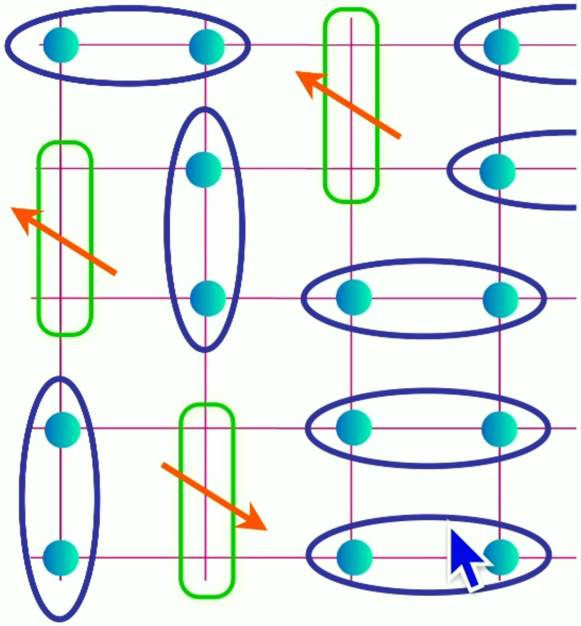
Annals of Physics 450, 169221 (2023)

Quantum criticality of Ising-nematic ordering in a metal

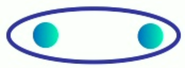


Francisco Borges, Anton Borissov, Ashutosh Singh, Andres Schlief, Sung-Sik Lee
Annals of Physics 450, 169221 (2023)

Pseudogap metal to Fermi liquid in single band model



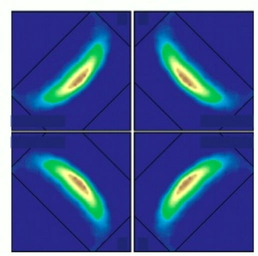
Φ Higgs boson with the fundamental gauge charge of an emergent SU(2) gauge field.

 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

 $= (|\uparrow\circ\rangle + |\circ\uparrow\rangle)/\sqrt{2}$

Small Fermi surface of size p + spin liquid.

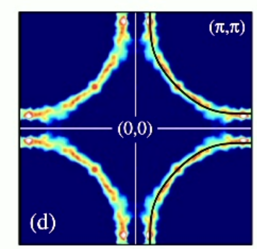
FL*



$\langle \Phi \rangle \neq 0$

Large Fermi surface of size $1 + p$

FL

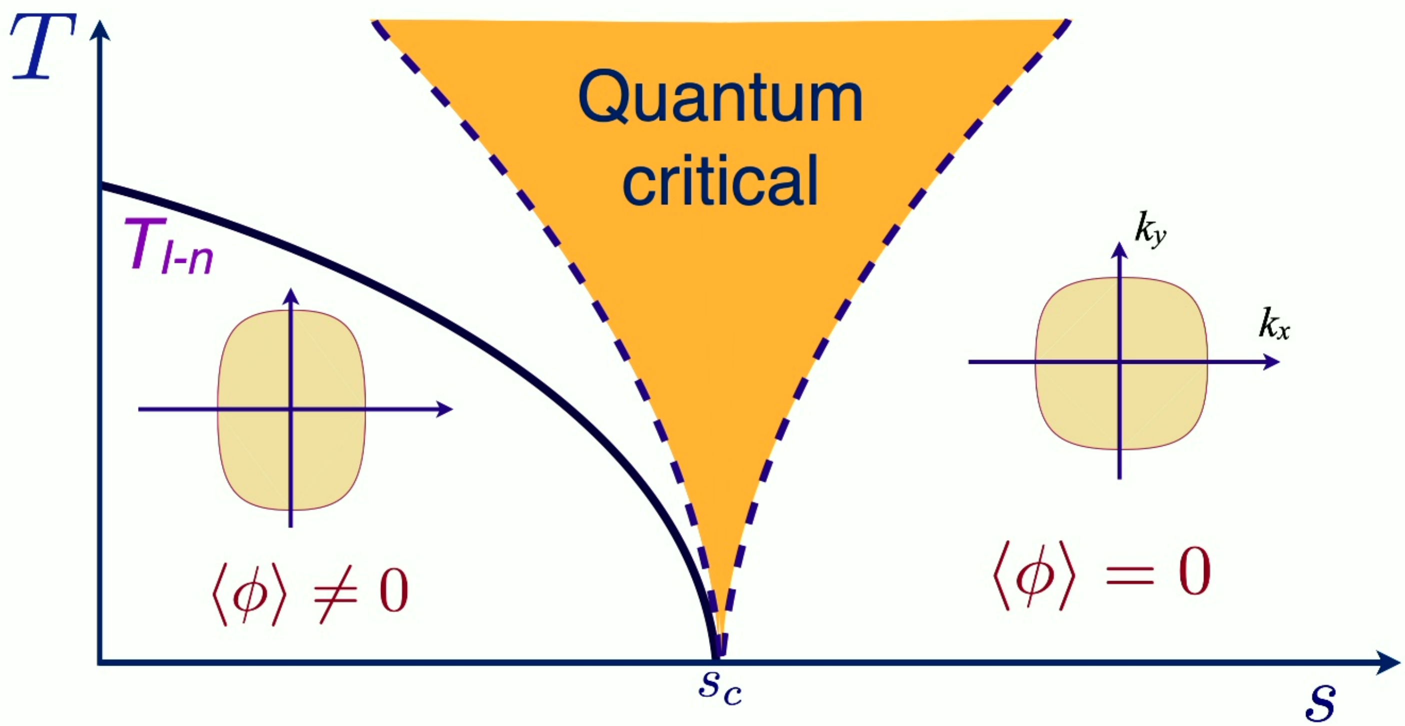


$\langle \Phi \rangle = 0$

doping p

Ya-Hui Zhang and S.S. *Phys. Rev. Research* **2**, 023172 (2020); *Phys. Rev. B* **102**, 155124 (2020)

Quantum criticality of Ising-nematic ordering in a metal

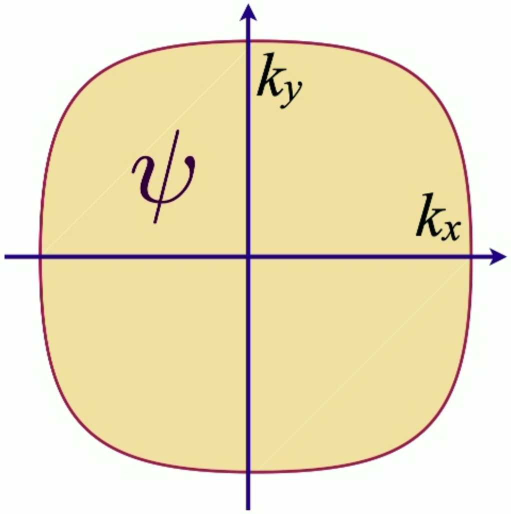


Francisco Borges, Anton Borissov, Ashutosh Singh, Andres Schlief, Sung-Sik Lee
Annals of Physics 450, 169221 (2023)

Fermi surface + critical boson with no spatial 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,
spin-density wave order,
Higgs boson for Fermi-volume changing transition



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

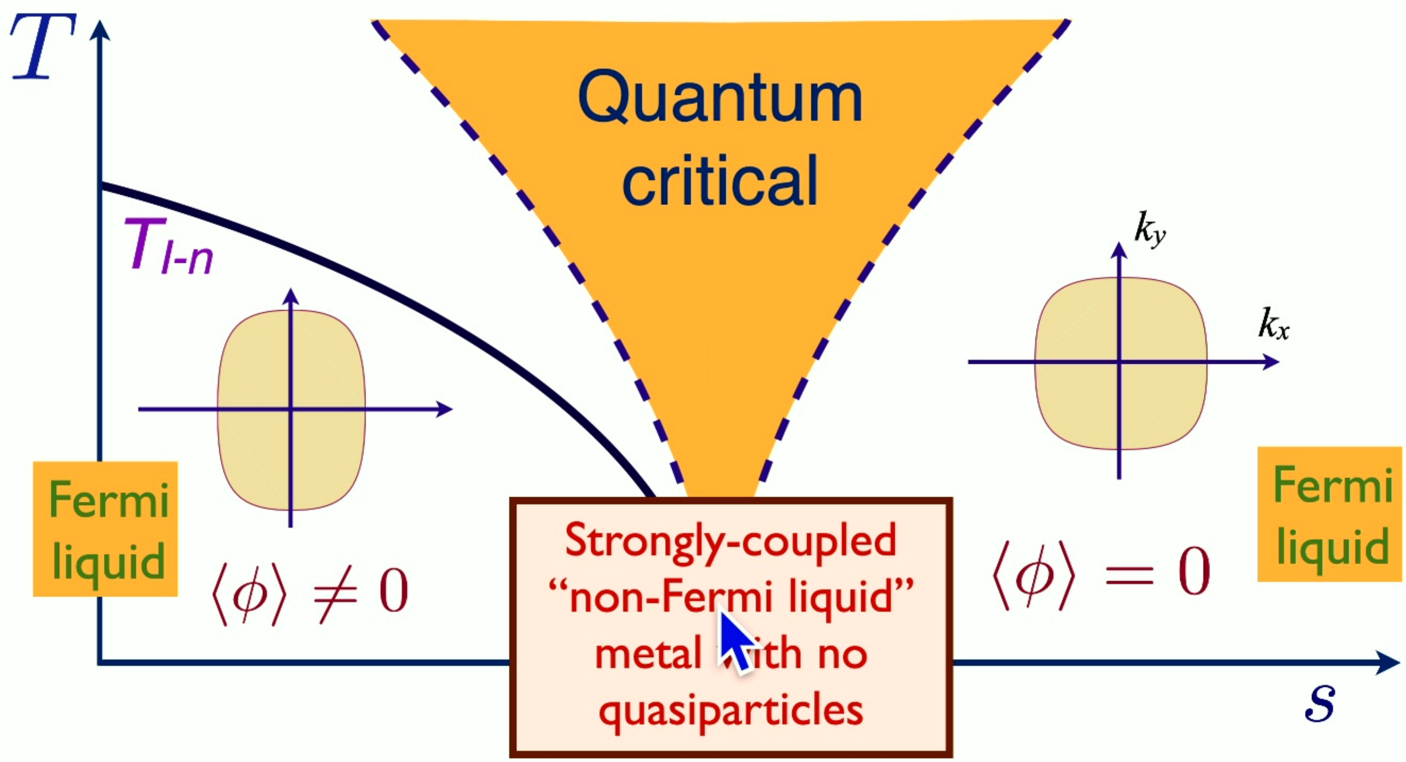
$$+K\,[\nabla_{\boldsymbol{r}}\phi(\boldsymbol{r})]^2 + u\,[\phi(\boldsymbol{r})]^4$$

A non-Fermi liquid in the electron spectral function but a perfect metal in transport!

$$\Sigma(\omega) \sim \omega^{2/3}$$
$$\sigma(\omega) = iD/(\omega - \omega_c) + \omega^0 + \ldots$$

Haoyu Guo, Aavishkar Patel, Ilya Esterlis, S.S., PRB **106**, 115151 (2022)
Haoyu Guo, Davide Valentinis, J. Schmalian, S.S., Aavishkar Patel, PRB **109**, 075162 (2024)
D.L. Maslov and A.V. Chubukov, Rep. Prog. Phys. **80**, 026503 (2017)
Zhengyan Darius Shi, Dominic V. Else, Hart Goldman, T. Senthil, SciPost Phys. **14**, 113 (2023)

Quantum criticality of Ising-nematic ordering in a metal



Francisco Borges, Anton Borissov, Ashutosh Singh, Andres Schlief, Sung-Sik Lee
Annals of Physics 450, 169221 (2023)

I. Yukawa-SYK model

II. Universal Yukawa-SYK theory in d=2 spatial dimensions

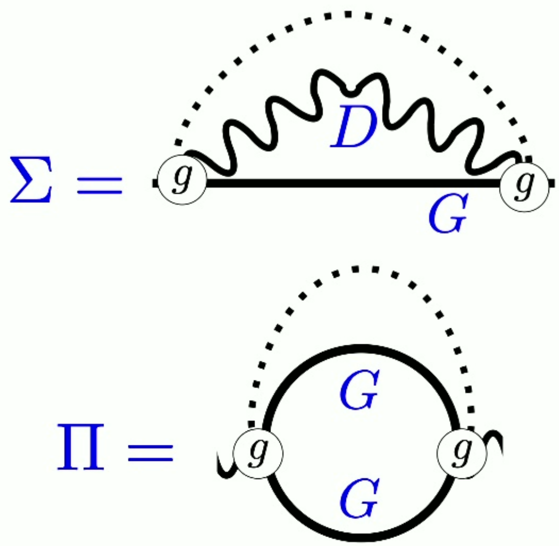
III. Random "mass" Hertz theory at low T

Yukawa-SYK models

$$\mathcal{H} = -\mu \sum_i \psi_i^\dagger \psi_i + \sum_\ell \frac{1}{2}\left(\pi_\ell^2 + \omega_0^2 \phi_\ell^2\right) + \frac{1}{N} \sum_{ij\ell} g_{ij\ell} \psi_i^\dagger \psi_j \phi_\ell$$

with $g_{ij\ell}$ independent random numbers with $\overline{g_{ij\ell}} = 0$, $\overline{g_{ij\ell}^2} = g^2$.

Leads to fully self-consistent Migdal-Eliashberg equations $\Sigma_\psi \sim g^2 G_\psi G_\phi$, $\Sigma_\phi \sim g^2 G_\psi G_\psi$ in a SYK-like large N limit.



W. Fu, D. Gaiotto, J. Maldacena, and S. Sachdev, PRD **95**, 026009 (2017)
J. Murugan, D. Stanford, and E. Witten, JHEP 08, 146 (2017)
A. A. Patel and S. Sachdev, PRB **98**, 125134 (2018)
E. Marcus and S. Vandoren, JHEP 01, 166 (2018)
Yuxuan Wang, PRL **124**, 017002 (2020)
I. Esterlis and 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
Jaewon Kim, E. Altman, and Xiangyu Cao, PRB **103**, 081113 (2021)
W. Wang, A. Davis, G. Pan, Yuxuan Wang, and Zi Yang Meng, PRB **103**, 195108 (2021)
I. Esterlis, H. Guo, A. A. Patel, and S. Sachdev, PRB **103**, 235129 (2021).

Yukawa-SYK models

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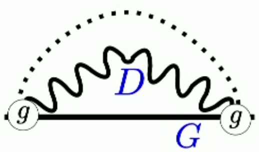
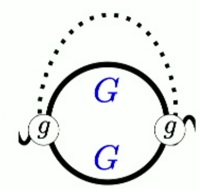
with $g_{ij\ell}$ independent random numbers with $\overline{g_{ij\ell}} = 0$, $\overline{g_{ij\ell}^2} = g^2$. Large N saddle-point equations:

$\Sigma =$ 

$$G(i\omega_n) = \frac{1}{i\omega_n + \mu - \Sigma(i\omega_n)} \quad , \quad D(i\omega_n) = \frac{1}{\omega_n^2 + \omega_0^2 - \Pi(i\omega_n)}$$
$$\Sigma(\tau) = g^2 G(\tau) D(\tau) \quad , \quad \Pi(\tau) = -g^2 G(\tau) G(-\tau)$$

$\Pi =$ 

Make the low frequency ansatz

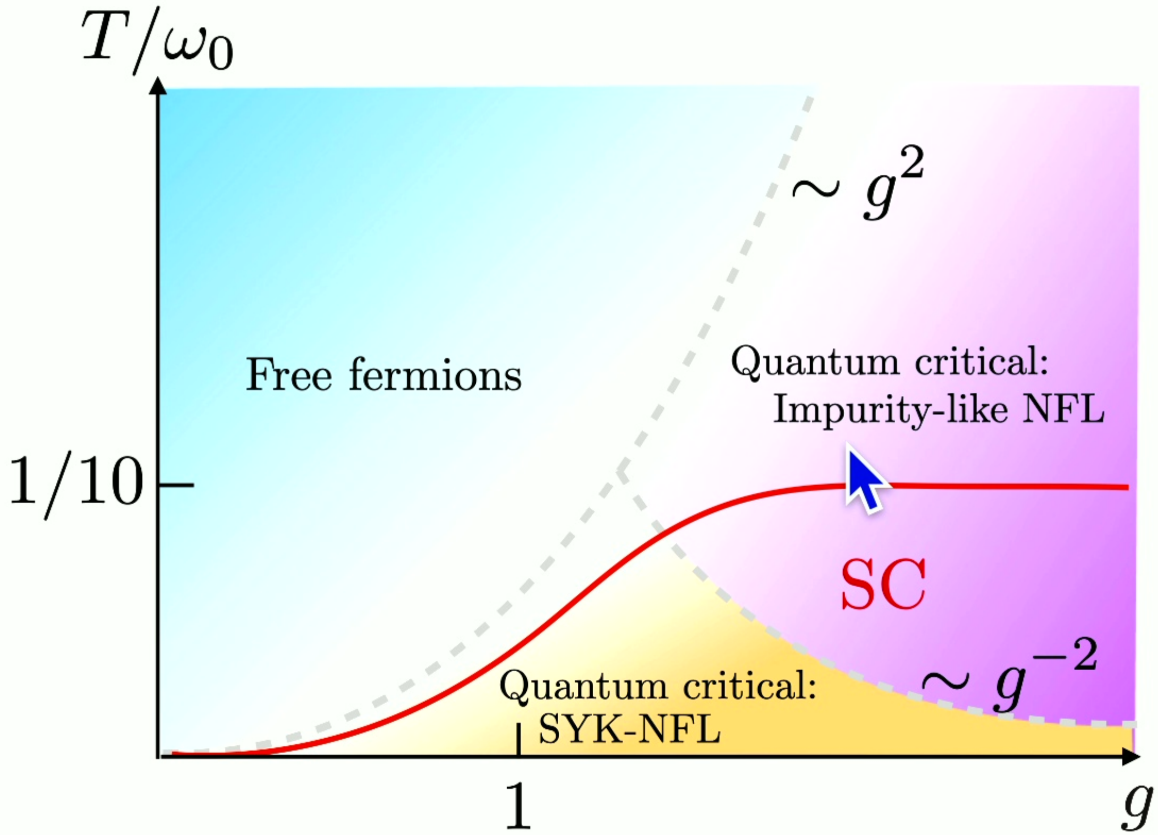
$$G(i\omega) \sim -i\,\mathrm{sgn}(\omega)|\omega|^{-(1-2\Delta)} \quad , \quad D(i\omega) \sim |\omega|^{1-4\Delta} \quad , \quad \frac{1}{4} < \Delta < \frac{1}{2}$$

A consistent solution exists for

$$\frac{4\Delta - 1}{2(2\Delta - 1)[\sec(2\pi\Delta) - 1]} = 1 \quad , \quad \Delta = 0.42037\ldots$$

I. Esterlis and J. Schmalian, PRB **100**, 115132 (2019)
See also Yuxuan Wang, PRL **124**, 017002 (2020)

Yukawa-SYK models



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with $g_{ij\ell}$ independent random numbers with $\overline{g_{ij\ell}} = 0$, $\overline{g_{ij\ell}^2} = g^2$. Large N saddle-point equations:

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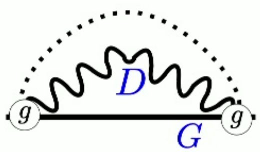

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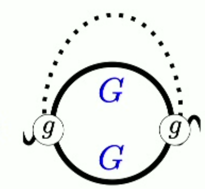
$\Pi =$



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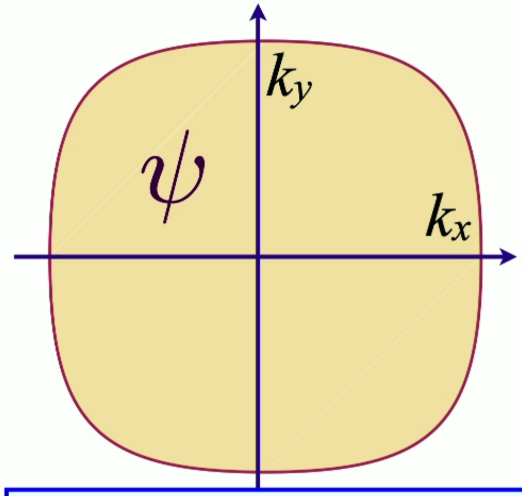
II. Universal Yukawa-SYK theory in d=2 spatial dimensions

III. Random "mass" Hertz theory at low T

Fermi surface + critical boson with potential 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,
spin-density wave order,
Higgs boson for Fermi-volume changing transition

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

$$+K\,[\nabla_{\boldsymbol{r}}\phi(\boldsymbol{r})]^2 + u\,[\phi(\boldsymbol{r})]^4 \; + v(\boldsymbol{r})\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})$$

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

Fermi surface + critical boson with potential and interaction disorder

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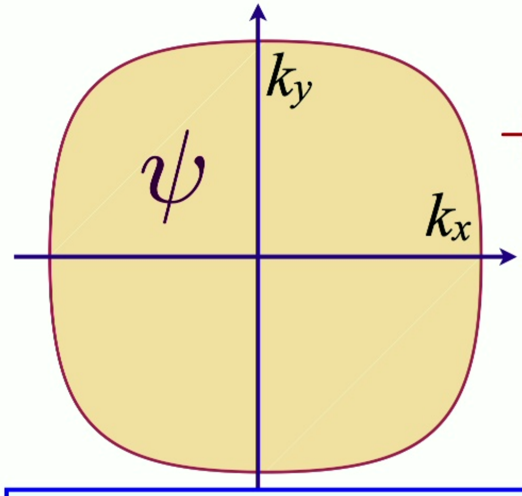

$$+[s + \delta s(\boldsymbol{r})]\,[\phi(\boldsymbol{r})]^2 + \qquad + g\,\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})\,\phi(\boldsymbol{r})$$

$$+K\,[\nabla_{\boldsymbol{r}}\phi(\boldsymbol{r})]^2 + u\,[\phi(\boldsymbol{r})]^4 \; + v(\boldsymbol{r})\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})$$

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

Spatially random mass $\delta s(\boldsymbol{r})$ with $\overline{\delta s(\boldsymbol{r})} = 0$, $\overline{\delta s(\boldsymbol{r})\delta s(\boldsymbol{r}')} = \delta s^2\delta(\boldsymbol{r} - \boldsymbol{r}')$

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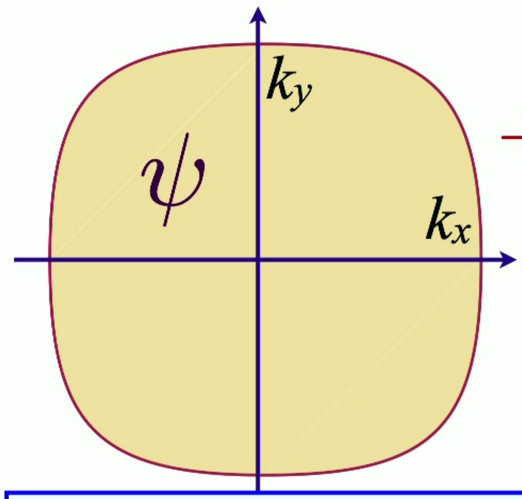

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RG analysis (Harris criterion) shows that $\delta s(\boldsymbol{r})$ is most relevant disorder.

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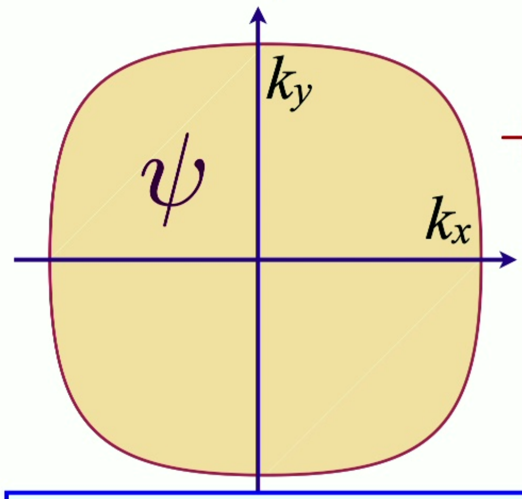

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$$+K\,[\nabla_{\boldsymbol{r}}\phi(\boldsymbol{r})]^2 + u\,[\phi(\boldsymbol{r})]^4 \; + v(\boldsymbol{r})\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})$$

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. Sachdev, *Science* **381**, 790 (2023)

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

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Rescale $\phi(\boldsymbol{r})$ to obtain a theory with $\delta s(\boldsymbol{r}) = 0$.

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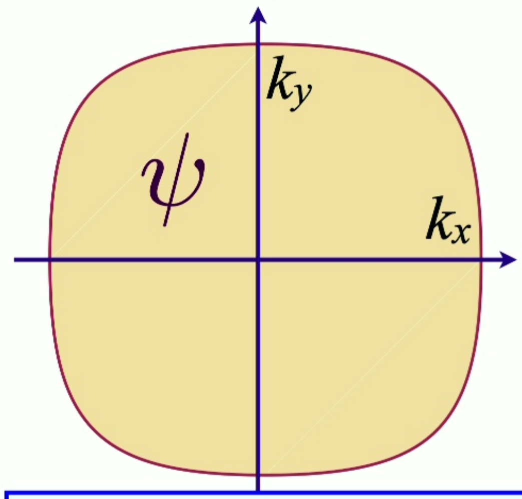

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$$+K\,[\nabla_{\boldsymbol{r}}\phi(\boldsymbol{r})]^2 + u\,[\phi(\boldsymbol{r})]^4 + v(\boldsymbol{r})\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})$$

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. Sachdev, *Science* **381**, 790 (2023)

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

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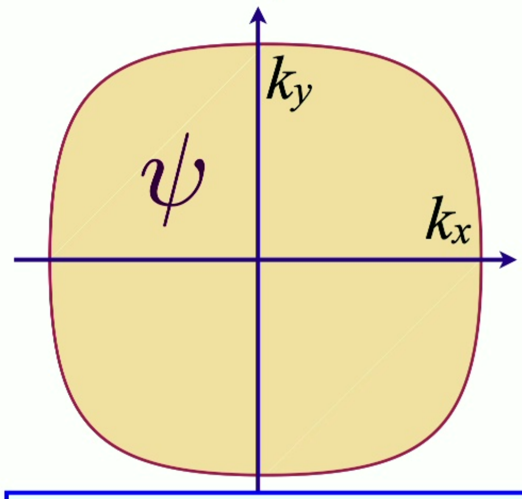

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$$+s\,[\phi(\boldsymbol{r})]^2 + [g + g'(\boldsymbol{r})]\,\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})\,\phi(\boldsymbol{r})$$

$$+K\,[\nabla_{\boldsymbol{r}}\phi(\boldsymbol{r})]^2 + u\,[\phi(\boldsymbol{r})]^4 \; + v(\boldsymbol{r})\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})$$

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. Sachdev, *Science* **381**, 790 (2023)

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

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

Analyze such a theory in a self-averaging manner as in the Yukawa-SYK model.
Should be applicable as long as eigenmodes of $\phi(\boldsymbol{r})$ are extended.

Fermi surface + critical boson with potential and interaction disorder

SYK-type self-consistent equations

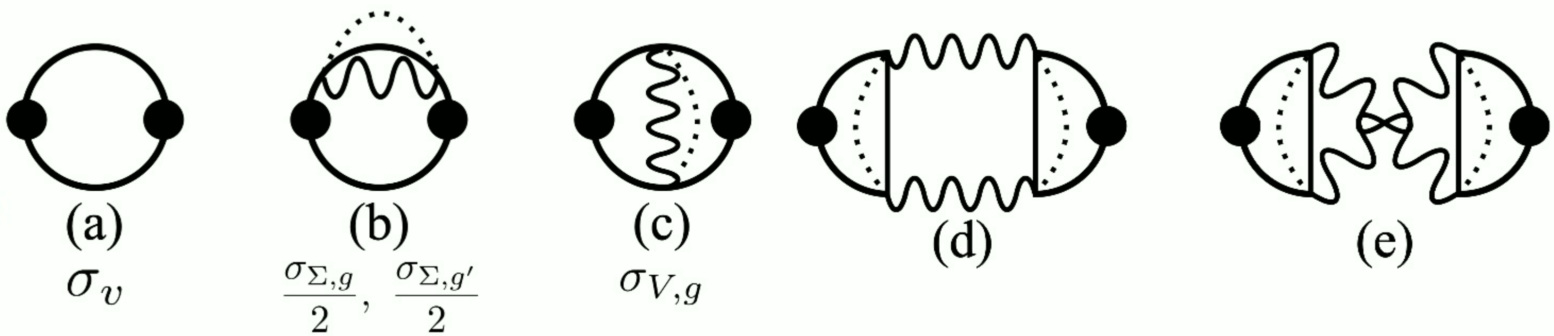
$$\Sigma(\tau,\mathbf{r}) = g^2 D(\tau,\mathbf{r})G(\tau,\mathbf{r}) + v^2 G(\tau,\mathbf{r})\delta^2(\mathbf{r}) + g'^2 G(\tau,\mathbf{r})D(\tau,\mathbf{r})\delta^2(\mathbf{r}),$$

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

$$G(i\omega,\mathbf{k}) = \frac{1}{i\omega - \varepsilon(\mathbf{k}) + \mu - \Sigma(i\omega,\mathbf{k})},$$

$$D(i\Omega,\mathbf{q}) = \frac{1}{\Omega^2 + \mathbf{q}^2 + m_b^2 - \Pi(i\Omega,\mathbf{q})}.$$

Conductivity:



+ all ladders and bubbles…..

Fermi surface + critical boson with potential and interaction disorder

Electron Green's function: $G(\omega) \sim \dfrac{1}{\omega \dfrac{m^*(\omega)}{m} - \varepsilon(\boldsymbol{k}) + i \left(\dfrac{1}{\tau_e} + \dfrac{1}{\tau_{\rm in}(\omega)} \right) \mathrm{sgn}(\omega)}$

$$\frac{1}{\tau_e} \sim v^2 \quad ; \quad \frac{1}{\tau_{\rm in}(\omega)} \sim \left(\frac{g^2}{v^2} + g'^2 \right) |\omega| \quad ; \quad \frac{m^*(\omega)}{m} \sim \frac{2}{\pi} \left(\frac{g^2}{v^2} + g'^2 \right) \ln(\Lambda/\omega)$$

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

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

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S.S., *Science* **381**, 790 (2023)

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Conductivity: $\sigma(\omega) \sim \dfrac{1}{\dfrac{1}{\tau_{\rm trans}(\omega)} - i\omega \dfrac{m^*_{\rm trans}(\omega)}{m}}$

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

B. Michon……A. Georges, Nat. Commun. **14**, 3033 (2023)

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Residual resistivity is determined by v^2; Linear-in-T resistivity determined by g'^2;
Transport insensitive to g;

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S.S., *Science* **381**, 790 (2023)

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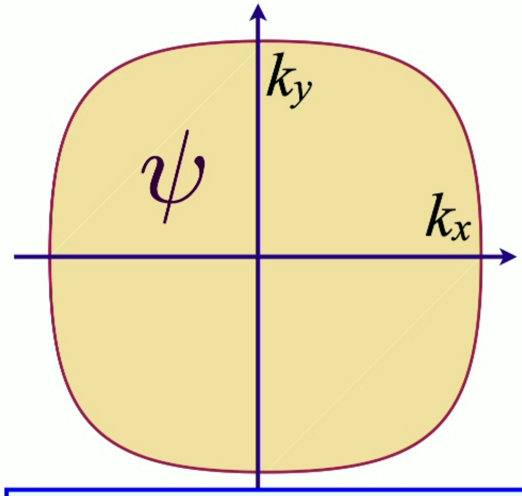

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e.g. Ising-nematic order,
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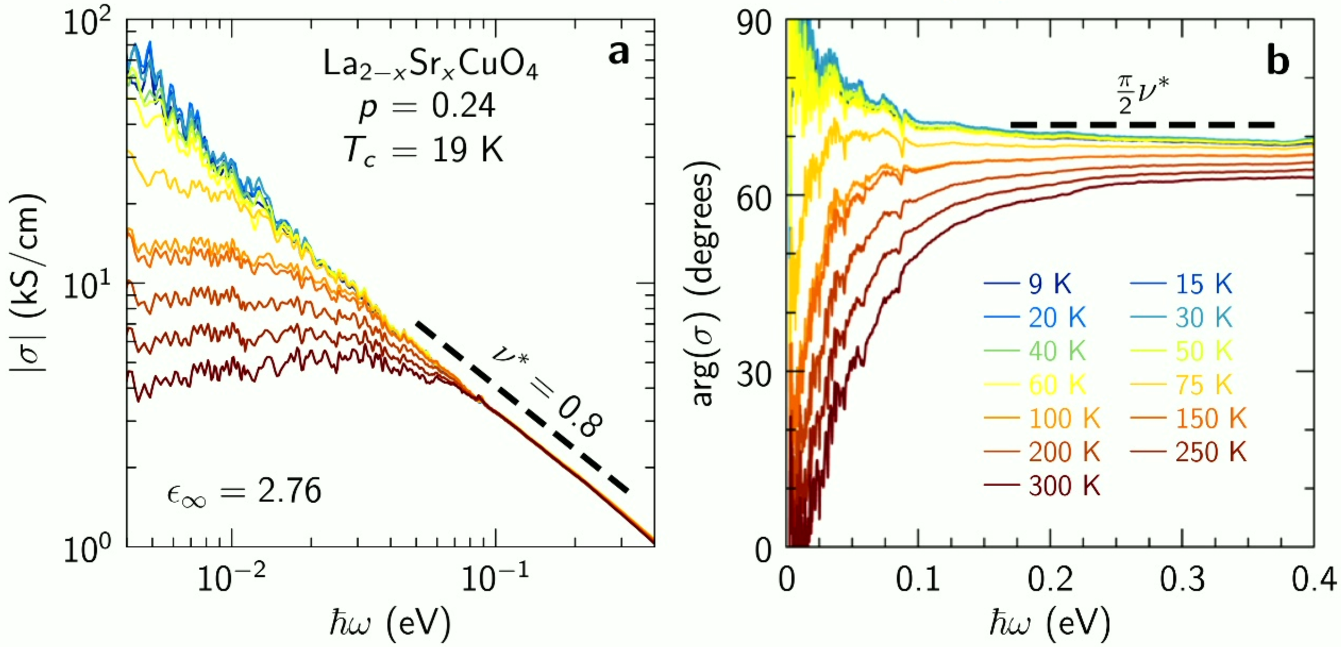
Reconciling scaling of the optical conductivity of cuprate superconductors with Planckian resistivity and specific heat

B. Michon, C. Berthod, C. W. Rischau, A. Ataei, L. Chen, S. Komiya, S. Ono, L. Taillefer, D. van der Marel, A. Georges

Nature Communications **14**, Article number: 3033 (2023)

$$\sigma(\omega) = i\frac{e^2K/(\hbar d_c)}{\hbar\omega\frac{m^*(\omega)}{m} + i\frac{\hbar}{\tau(\omega)}}$$



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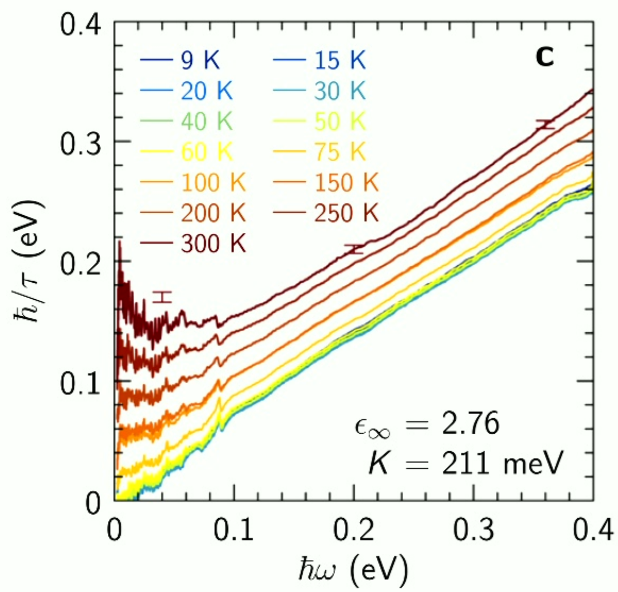

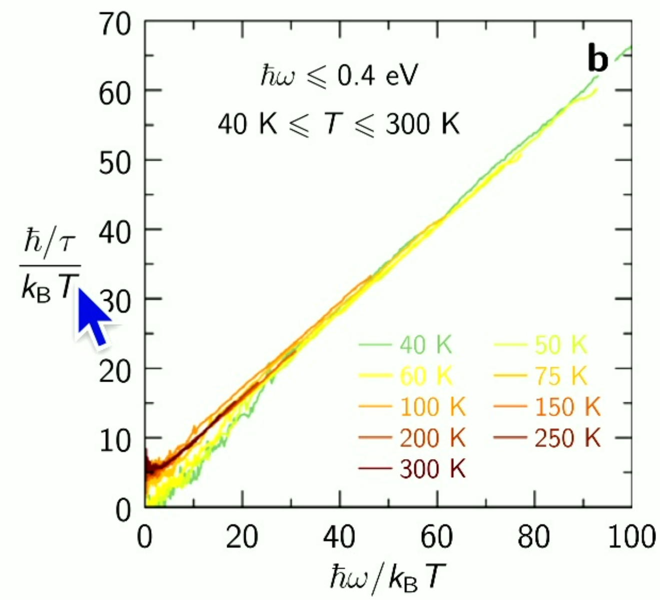

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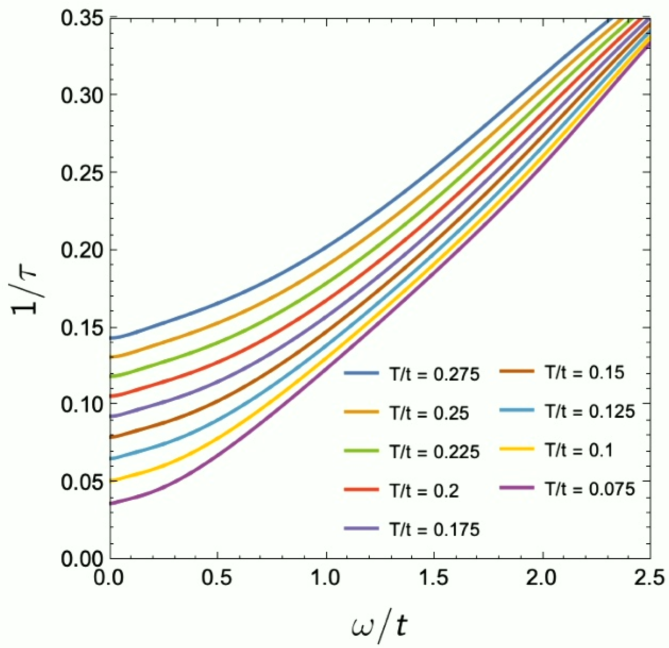
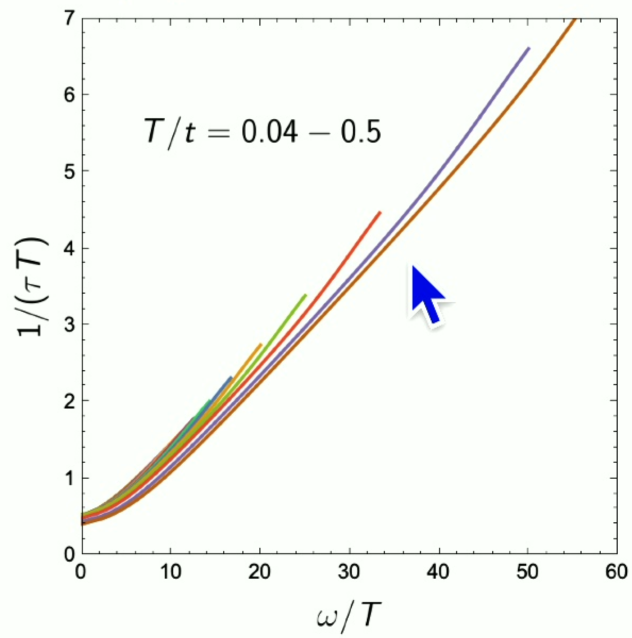
Strange metal and superconductor in the two-dimensional Yukawa-SYK model

$g = 0$

Chenyuan Li, Aavishkar A. Patel, Haoyu Guo, Davide Valentinis, Jorg Schmalian, S.S., Ilya Esters, to appear

$$\sigma(\omega) = i\frac{e^2 K/(\hbar d_c)}{\hbar\omega\frac{m^*(\omega)}{m} + i\frac{\hbar}{\tau(\omega)}}$$





I. Yukawa-SYK model

II. Universal Yukawa-SYK theory in d=2 spatial dimensions

III. Random "mass" Hertz theory at low T

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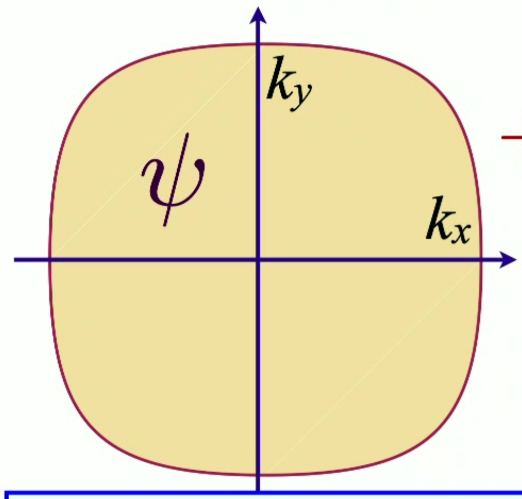

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e.g. Ising-nematic order,
spin-density wave order,
Higgs boson for Fermi-volume changing transition

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Spatially random mass $\delta s(\boldsymbol{r})$ with $\overline{\delta s(\boldsymbol{r})} = 0$, $\overline{\delta s(\boldsymbol{r})\delta s(\boldsymbol{r}')} = \delta s^2\delta(\boldsymbol{r} - \boldsymbol{r}')$

RG analysis (Harris criterion) shows that $\delta s(\boldsymbol{r})$ is most relevant disorder.
Mapping of $\delta s(\boldsymbol{r})$ to $g'(\boldsymbol{r})$ only works if eigenmodes of $\phi(\boldsymbol{r})$ are extended.

Bosonic eigenmodes in random mass Hertz theory

Integrate out the fermions (assuming fermionic eigenmodes remain extended), and considering the Landau-damped Hertz theory for the boson alone, in the presence of a random mass.

$$\mathcal{S}_\phi = \int d\tau \Big[\frac{J}{2} \sum_{\langle ij \rangle} (\phi_{ia} - \phi_{ja})^2 + \sum_j \Big(\frac{s + s'_j}{2} \phi_{ja}^2 + \frac{u}{4M} \left(\phi_{ja}^2 \right)^2 \Big) \Big]$$

$$\mathcal{S}_{\phi d} = \frac{T}{2} \sum_\Omega \sum_j \left(\gamma |\Omega| + \Omega^2/c^2 \right) |\phi_{ja}(i\Omega)|^2 \,,$$

where $a = 1 \ldots M$ is a flavor index for an order parameter with $\mathrm{O}(M)$ symmetry. Analyze in a self-consistent quadratic theory, treating disorder numerically exactly

$$\overline{\mathcal{S}}_\phi = \int d\tau \Big[\frac{J}{2} \sum_{\langle ij \rangle} (\phi_{ia} - \phi_{ja})^2 + \sum_j \frac{\overline{s}'_j}{2} \phi_{ja}^2 \Big]$$

Similar analysis in $d = 1$ works very well
A. Del Maestro, B. Rosenow, M. Müller and S. Sachdev, Phys. Rev. Lett. **101**, 035701 (2008).

$$\overline{s}'_j = s + s'_j + \frac{u}{M} \sum_a \langle \phi_{ja}^2 \rangle_{\overline{\mathcal{S}}_\phi + \mathcal{S}_{\phi d}} = s + s'_j + uT \sum_\Omega \sum_\alpha \frac{\psi_{\alpha i} \psi_{\alpha j}}{\gamma |\Omega| + \Omega^2/c^2 + e_\alpha}$$

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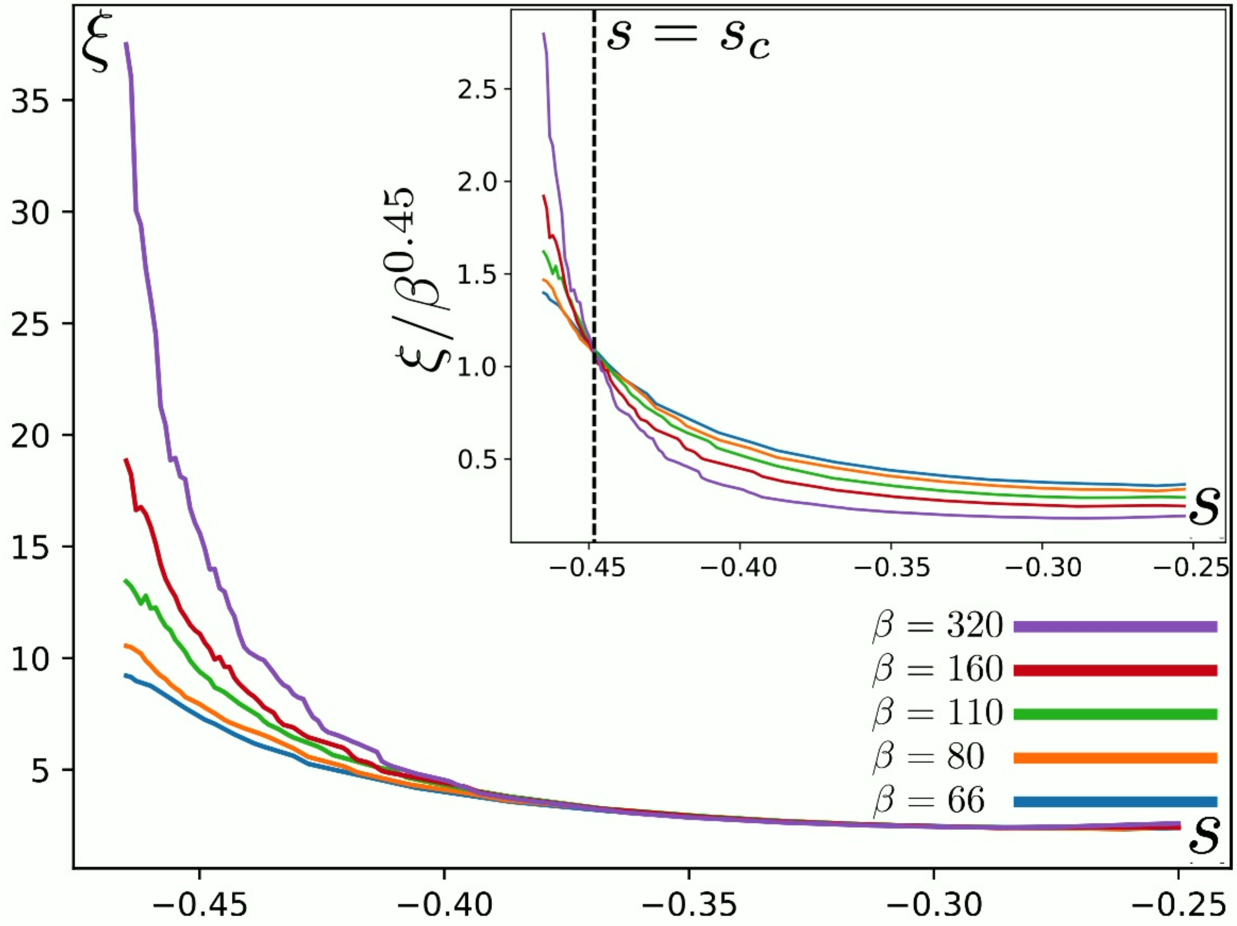
Aavishkar A. Patel, Peter Lunts, S.S., PNAS to appear, *arXiv:2312.06751*

Bosonic eigenmodes in random mass Hertz theory

ϕ correlation length ξ



Aavishkar A. Patel, Peter Lunts, S.S., *PNAS to appear, arXiv:2312.06751*

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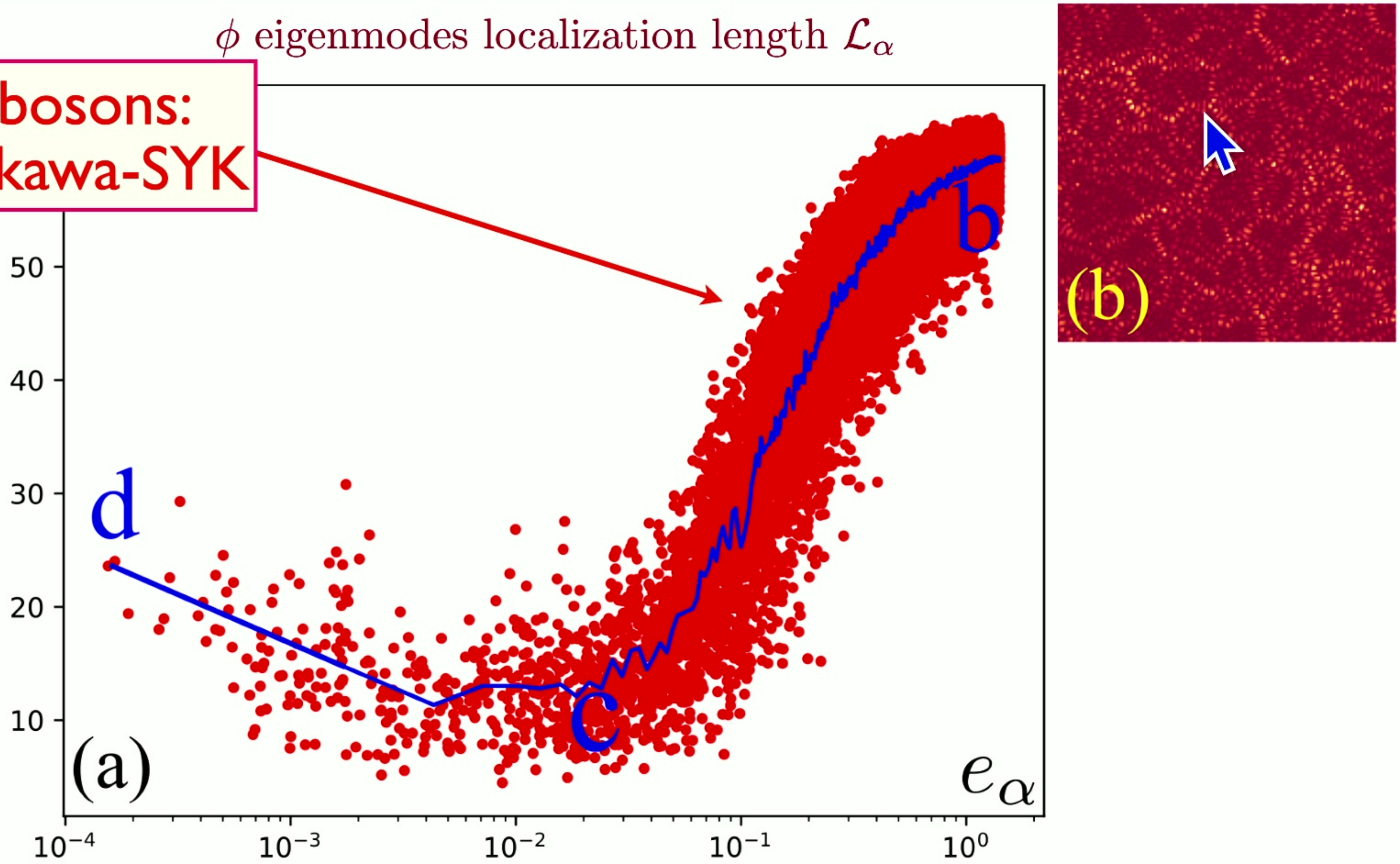
Bosonic eigenmodes in random mass Hertz theory

Extended bosons: physics of Yukawa-SYK

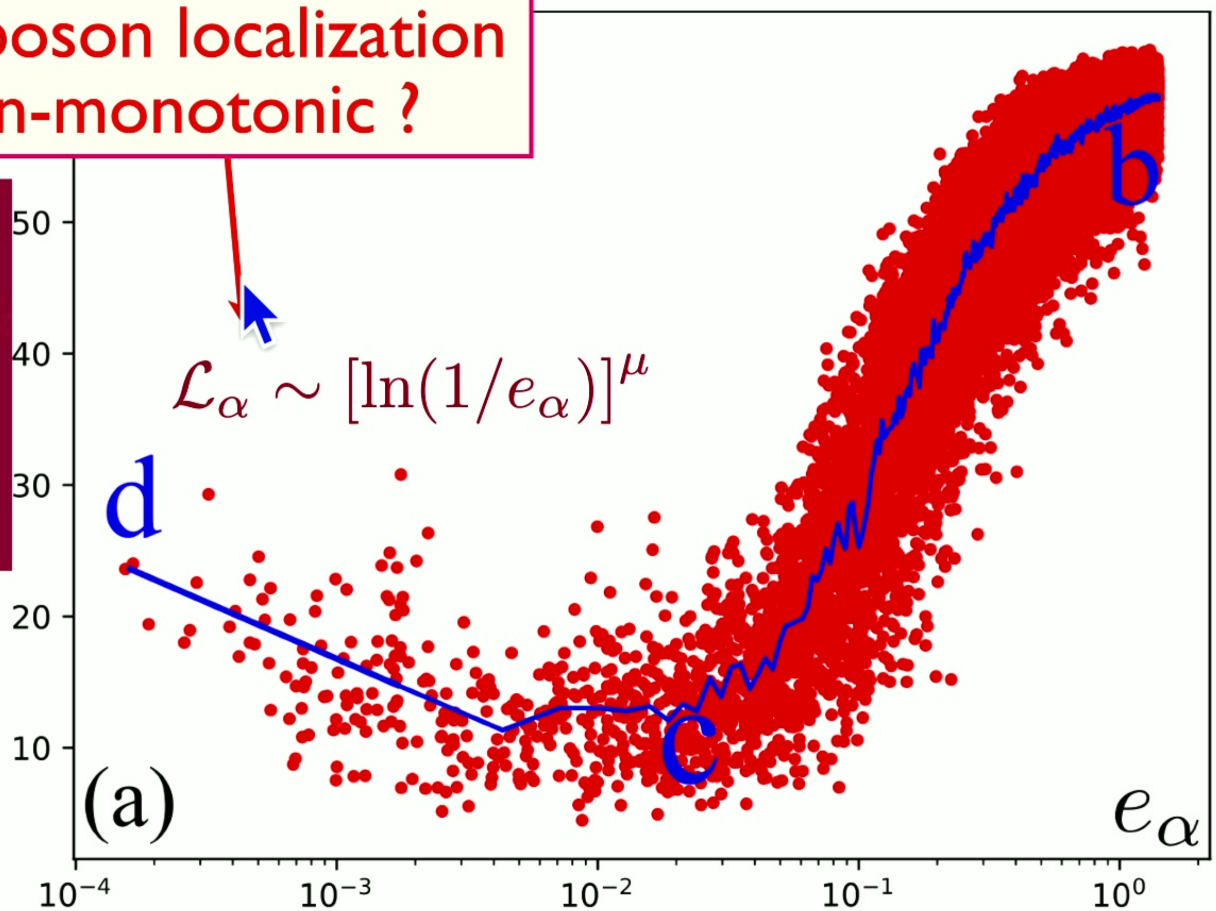


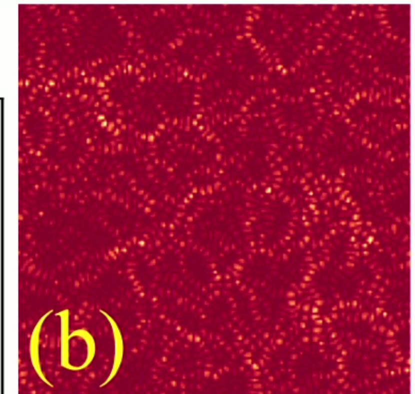
Aavishkar A. Patel,
Peter Lunts, S.S.,
PNAS to appear,
arXiv:2312.06751

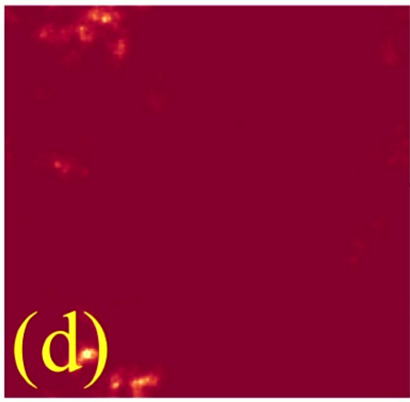
Landau-damped bosonic eigenmodes with random mass

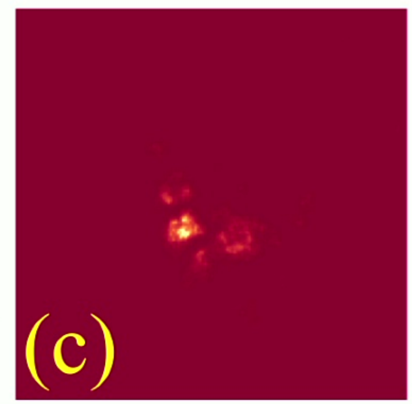
ϕ eigenmodes localization length $\mathcal{L}_\alpha$

Why is the boson localization length non-monotonic ?









Aavishkar A. Patel,
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PNAS to appear,
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T. Vojta and J. Schmalian, PRB **72**, 045438 (2005)

PRL **99,** 230601 (2007) PHYSICAL REVIEW LETTERS

Effects of Dissipation on a Quantum Critical Point with Disorder

José A. Hoyos, Chetan Kotabage, and Thomas Vojta
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$$\mathcal{S}_b = \int d\tau \left(-\sum_{\langle ij \rangle} J_{ij}\phi_{ia}\phi_{ja} + \sum_j \left[\frac{s_j}{2}\phi_{ja}^2 + \frac{u}{4}\left(\phi_{ja}^2\right)^2 \right] \right) + \frac{T\gamma}{2}\sum_{\omega_n}\sum_j |\omega_n||\phi_{ja}(\omega_n)|^2$$

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$$\widetilde{J}_{ij} = J_{ij} + \frac{J_{i2}J_{2j}}{s_2}$$

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$$H_{\mathrm{RTFIM}} = -\sum_{\langle ij \rangle} J_{ij} Z_i Z_j - \sum_j s_j X_j$$

Numerically studied in *d*=2 by
O. Motrunich, S.-C. Mau, D.A. Huse and D.S. Fisher,
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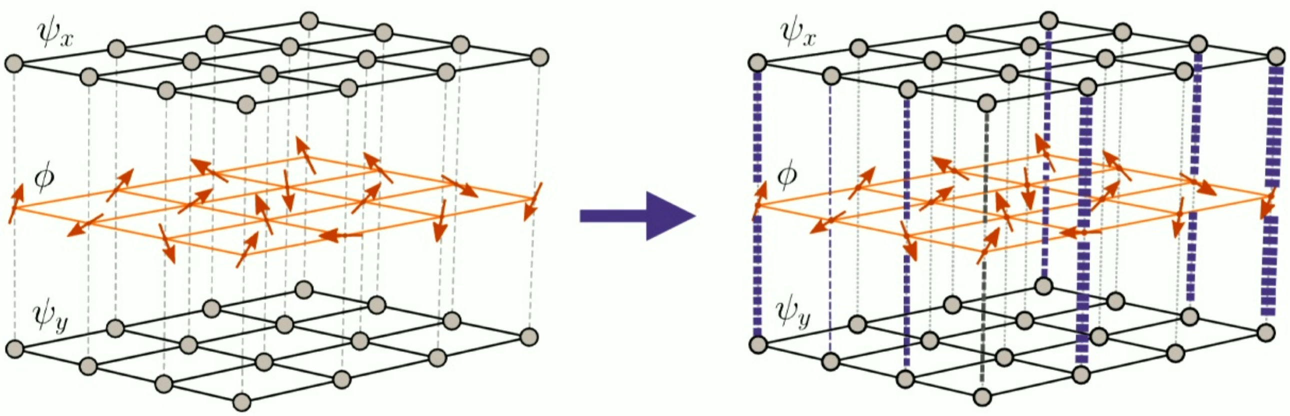
Model for sign-free QMC

$$\mathcal{S} = \int d\tau \sum_{\sigma=\uparrow,\downarrow} \sum_{\alpha=0,1} \sum_{j=1}^{2} \sum_{\vec{r},\vec{r}'} \psi^\dagger_{\alpha,\sigma,j,\vec{r}} \left[\partial_\tau - (-1)^\alpha \mu - \delta_{\vec{r},\vec{r}'} - t_{\alpha,\vec{r},\vec{r}'}\right] \psi_{\alpha,\sigma,j,\vec{r}'}$$

$$+ \int d\tau \sum_{\vec{r}} \left[\frac{1}{c^2}(\partial_\tau \vec{\phi}_{\vec{r}})^2 + \frac{1}{2}(\nabla \vec{\phi}_{\vec{r}})^2 + \frac{r}{2}(\vec{\phi}_{\vec{r}})^2 + \frac{u}{4}(\vec{\phi}_{\vec{r}})^4\right] + \sum_{\sigma,\sigma'=\uparrow,\downarrow} \sum_{j=1}^{2} \int d\tau \sum_{\vec{r}} \boxed{g'(\vec{r}) e^{i\vec{Q}_{\mathrm{AF}}\cdot\vec{r}}} \vec{\phi}_{\vec{r}} \cdot \left[\psi^\dagger_{0,\sigma,\vec{r}}\, \vec{\tau}_{\sigma,\sigma'}\, \psi_{1,\sigma',\vec{r}} + \mathrm{H.c.}\right].$$

$g = 0$



coupling g = const   coupling g = spatially random

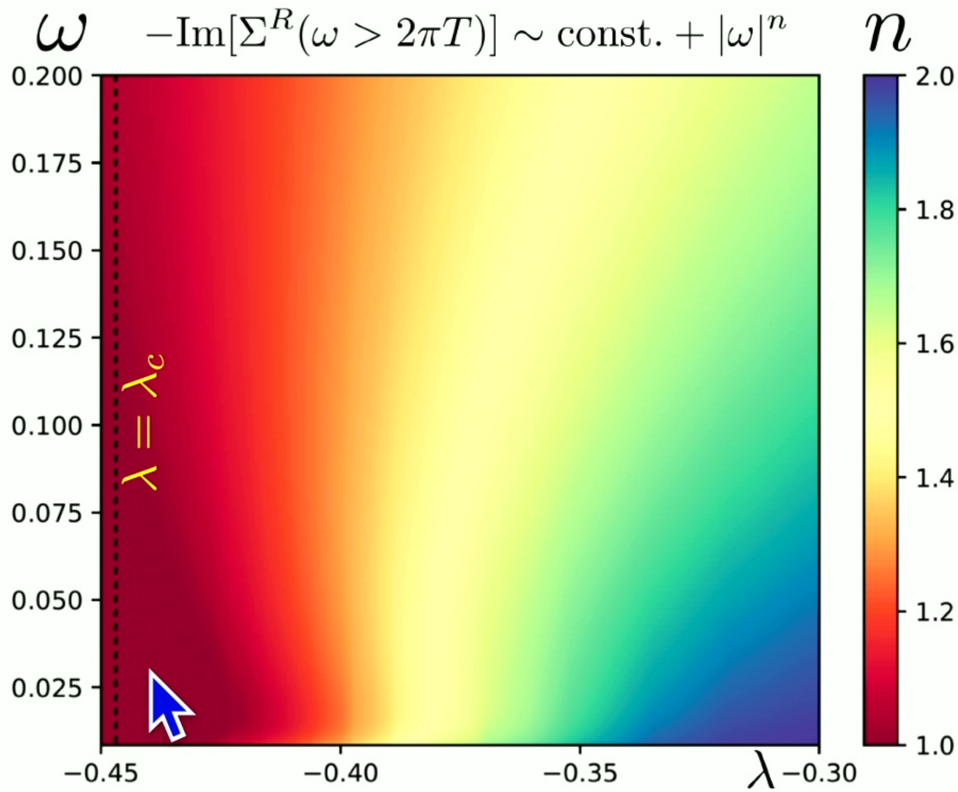
Two-band structure: Berg, Metlitsl Sachdev, Science **338** 1606-1609 (2012).

Aavishkar A. Patel, Peter Lunts, M. Albergo **(to appear)**

Bosonic eigenmodes in random mass Hertz theory

Transport scattering rate

$$\Sigma(i\omega) = -i\pi g'^2 \mathcal{N}_0 \frac{T}{L^2} \sum_{\alpha,\Omega} \frac{\text{sgn}(\omega+\Omega)}{\gamma|\Omega| + \Omega^2/c^2 + e_\alpha} .$$



$L = 160, \beta = 800$, 10 disorder samples

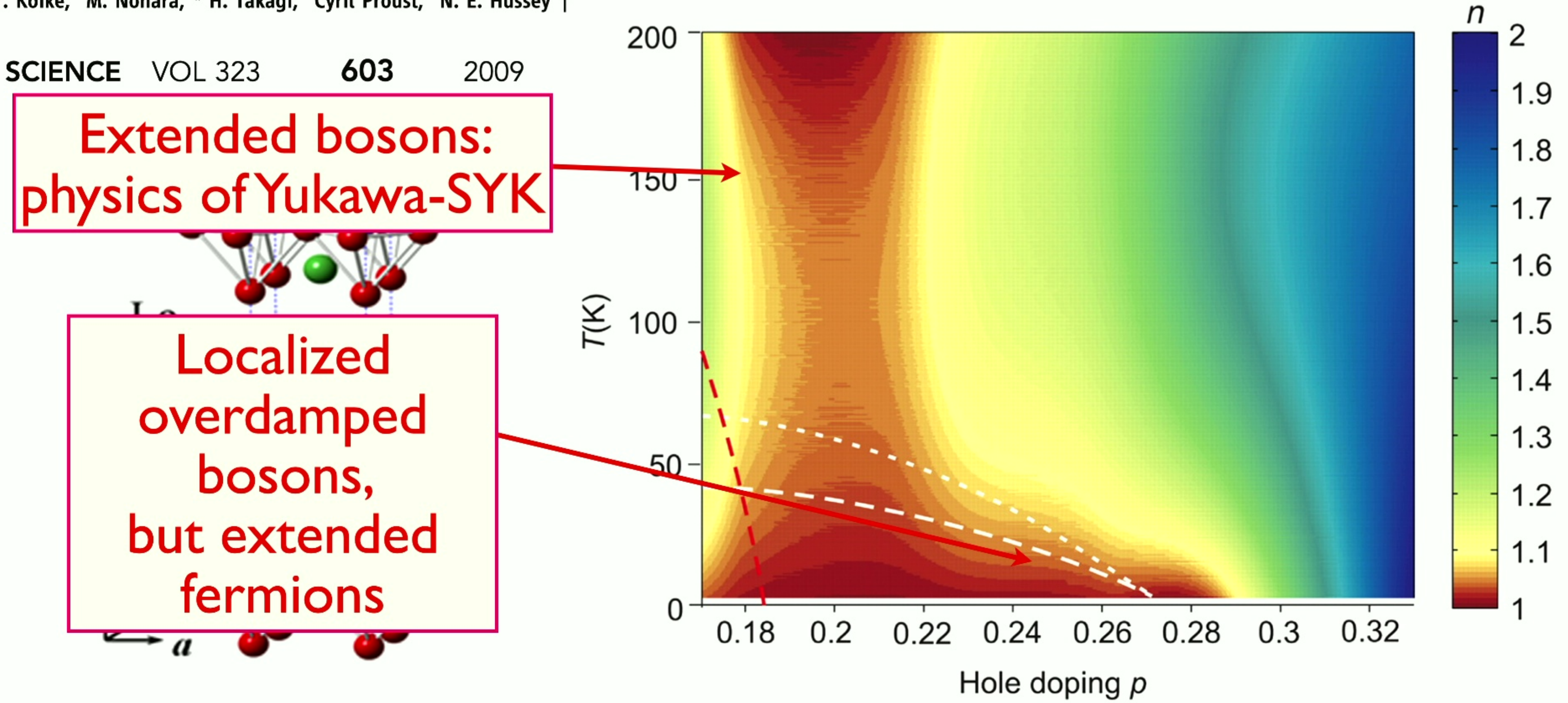
Extended region in λ with $n \approx 1$ - a strange metal *phase*

Aavishkar A. Patel,
Peter Lunts, S.S.,
PNAS to appear,
arXiv:2312.06751

Anomalous Criticality in the Electrical Resistivity of $La_{2-x}Sr_xCuO_4$

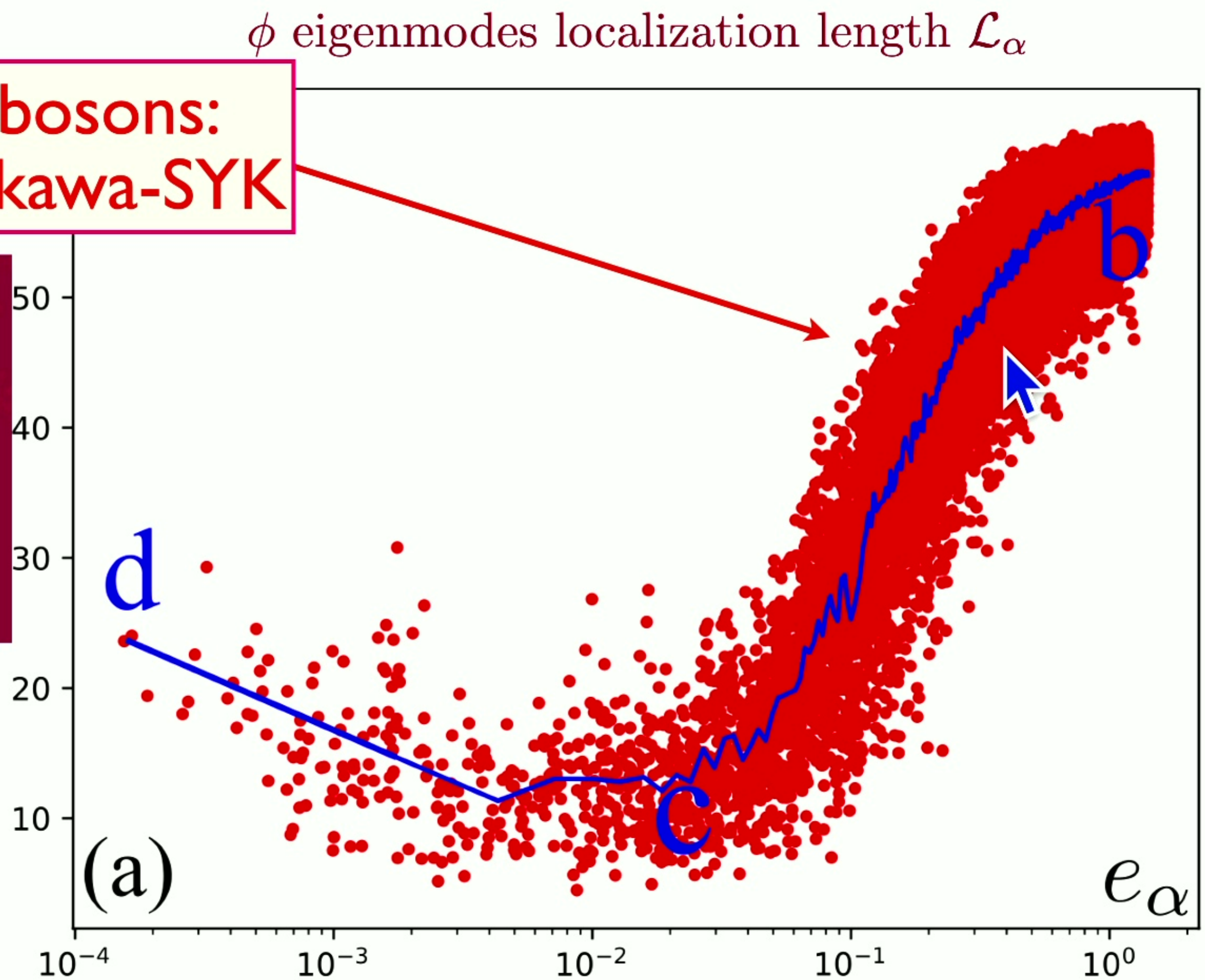
R. A. Cooper,[1] Y. Wang,[1] B. Vignolle,[2] O. J. Lipscombe,[1] S. M. Hayden,[1] Y. Tanabe,[3] T. Adachi,[3] Y. Koike,[3] M. Nohara,[4*] H. Takagi,[4] Cyril Proust,[2] N. E. Hussey[1]†

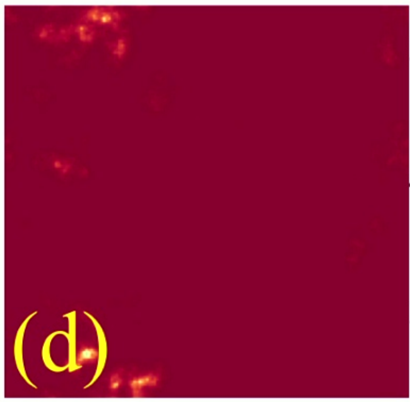
SCIENCE VOL 323 603 2009

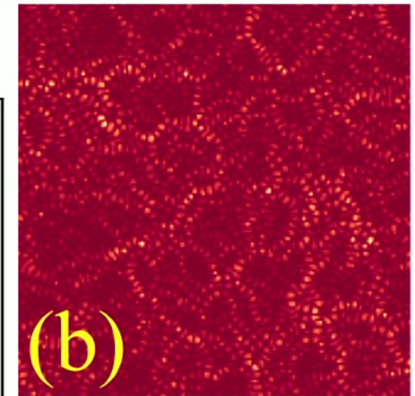


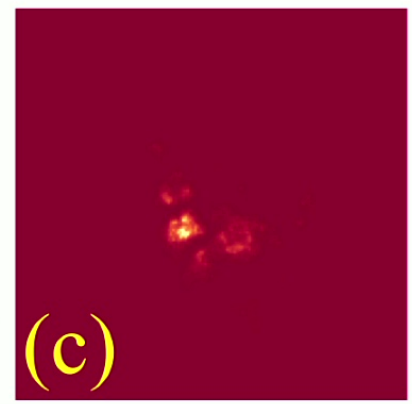
Bosonic eigenmodes in random mass Hertz theory

Extended bosons: physics of Yukawa-SYK



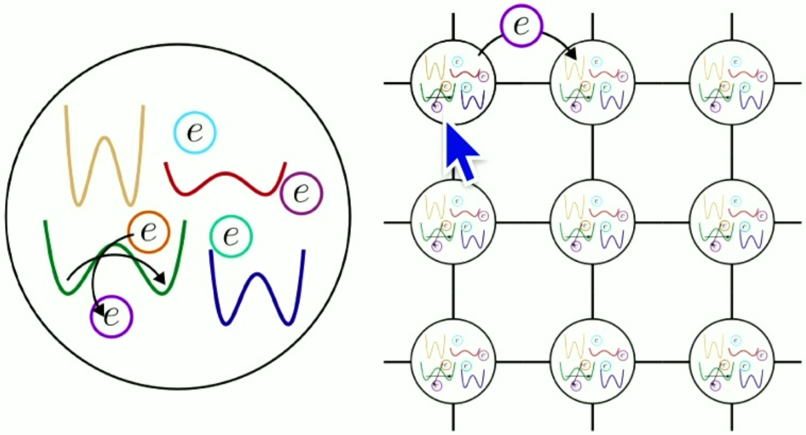






Aavishkar A. Patel,
Peter Lunts, S.S.,
PNAS to appear,
arXiv:2312.06751

Tuneable non-Fermi liquid phase in electronic glasses

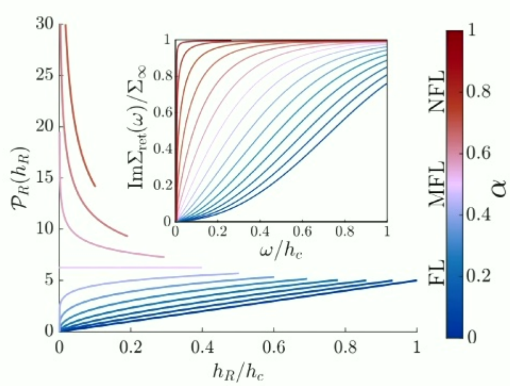


generalization of the Sachdev-Ye-Kitaev approach to two-level systems in glasses

⇓

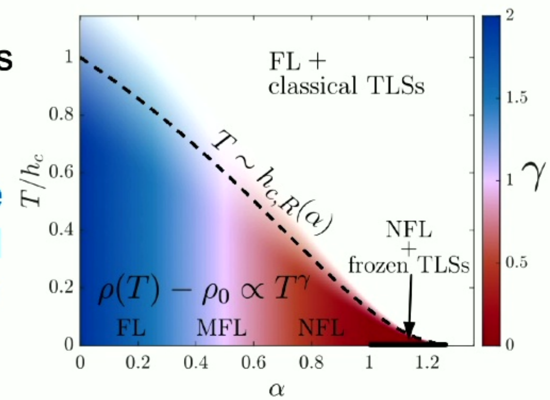
controlled approach to obtain a tunable Non-Fermi liquid state

strong renormalizations of the TLS distribution function



non-Fermi liquid physics in electronic glasses

Is this relevant to the physics of correlated quantum materials?



Noga Bashan, Evyatar Tulipman, Jörg Schmalian, Erez Berg, arXiv:2310.07768

Anomalous Criticality in the Electrical Resistivity of $La_{2-x}Sr_xCuO_4$

R. A. Cooper,[1] Y. Wang,[1] B. Vignolle,[2] O. J. Lipscombe,[1] S. M. Hayden,[1] Y. Tanabe,[3] T. Adachi,[3] Y. Koike,[3] M. Nohara,[4*] H. Takagi,[4] Cyril Proust,[2] N. E. Hussey[1]†

SCIENCE VOL 323 603 2009

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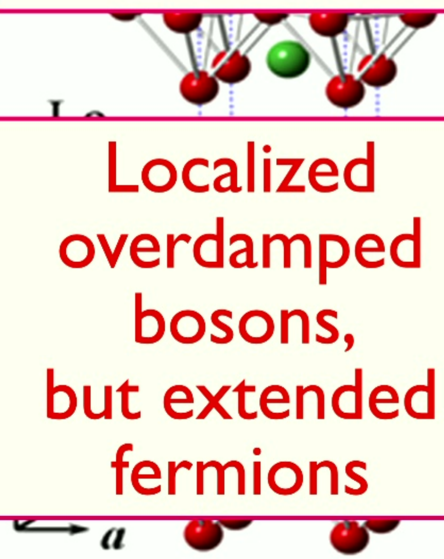
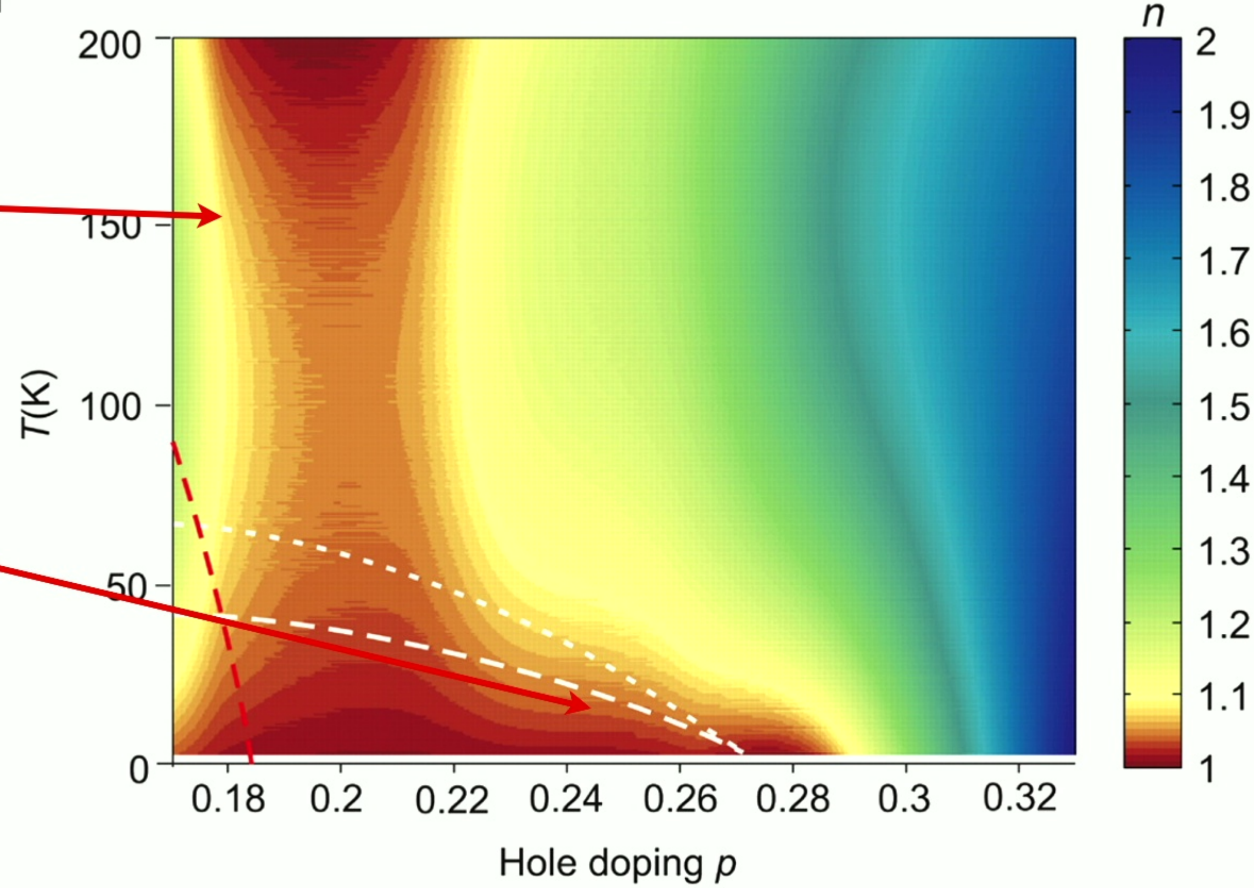
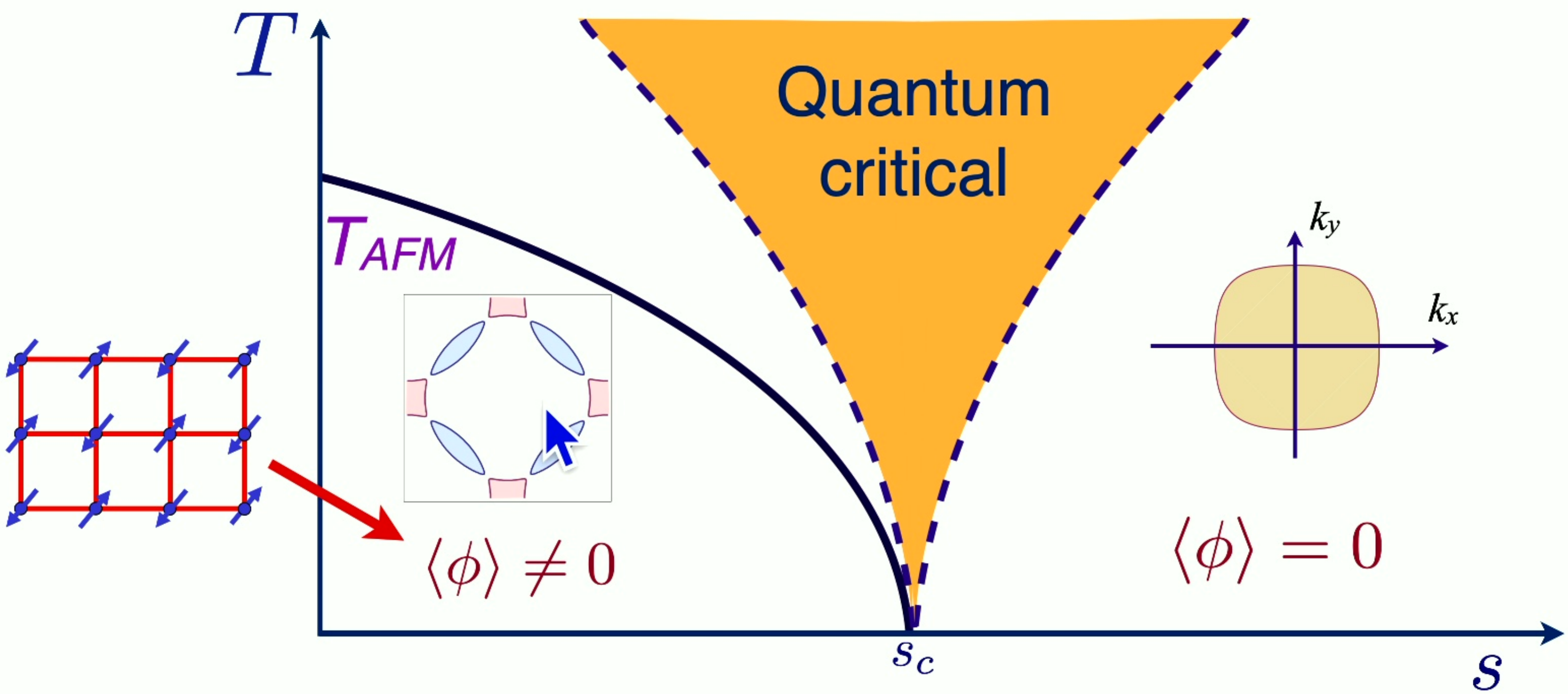


Localized overdamped bosons, but extended fermions

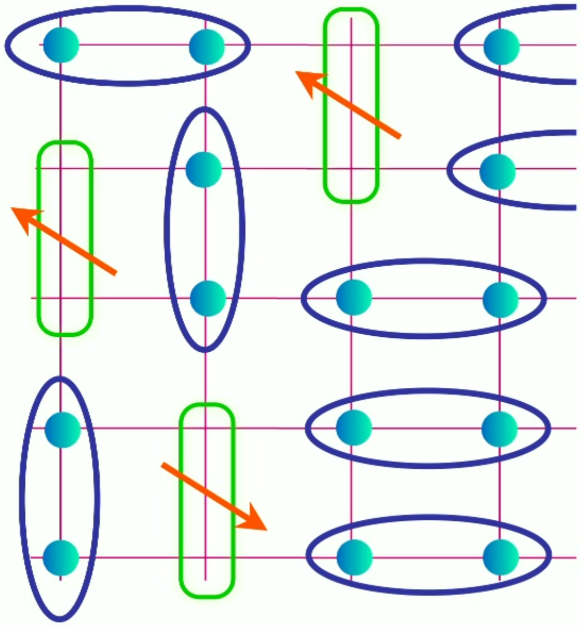


Quantum criticality of AF ordering in a metal

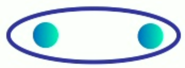


Francisco Borges, Anton Borissov, Ashutosh Singh, Andres Schlief, Sung-Sik Lee
Annals of Physics 450, 169221 (2023)

Pseudogap metal to Fermi liquid in single band model



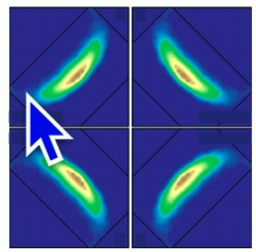
Φ Higgs boson with the fundamental gauge charge of an emergent SU(2) gauge field.

 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

 $= (|\uparrow\circ\rangle + |\circ\uparrow\rangle)/\sqrt{2}$

Small Fermi surface of size p + spin liquid.

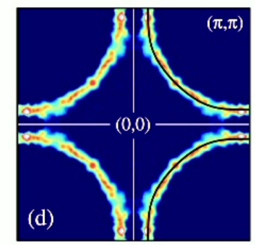
FL*



$\langle \Phi \rangle \neq 0$

Large Fermi surface of size $1 + p$

FL



$\langle \Phi \rangle = 0$

doping p

Ya-Hui Zhang and S.S. *Phys. Rev. Research* **2**, 023172 (2020); *Phys. Rev. B* **102**, 155124 (2020)

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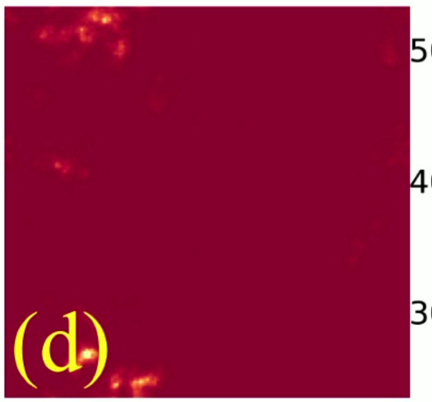

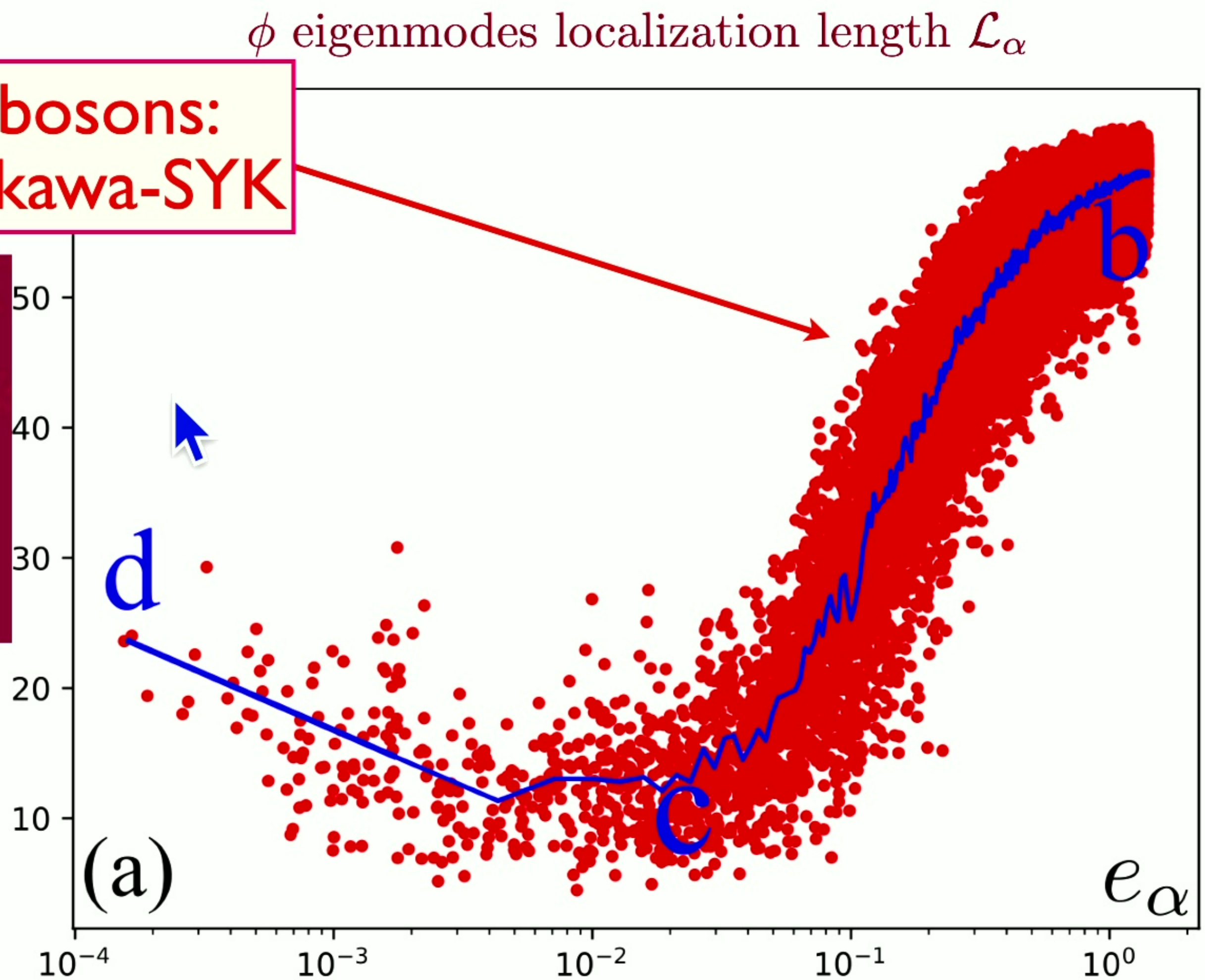

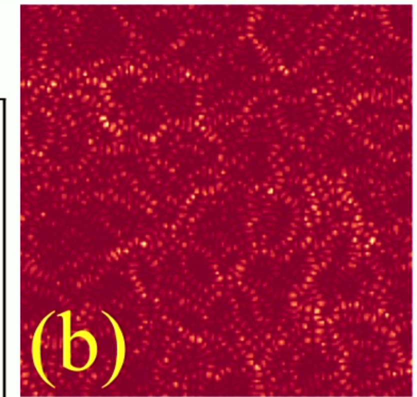

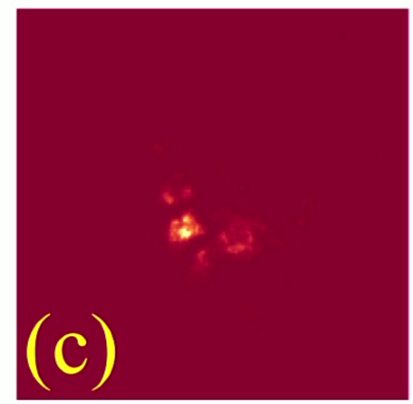

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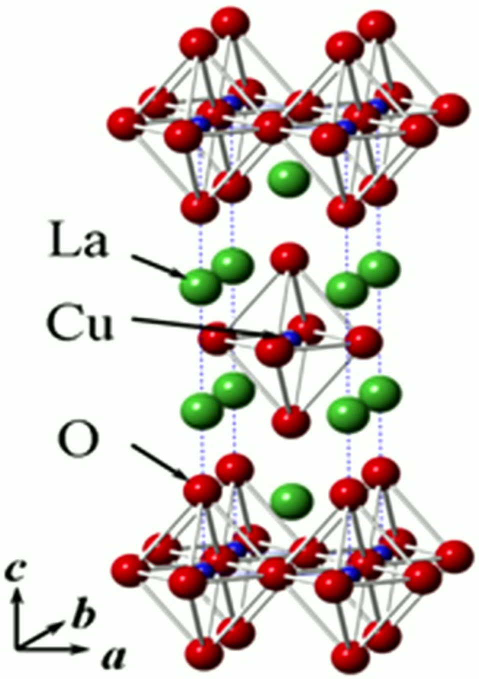
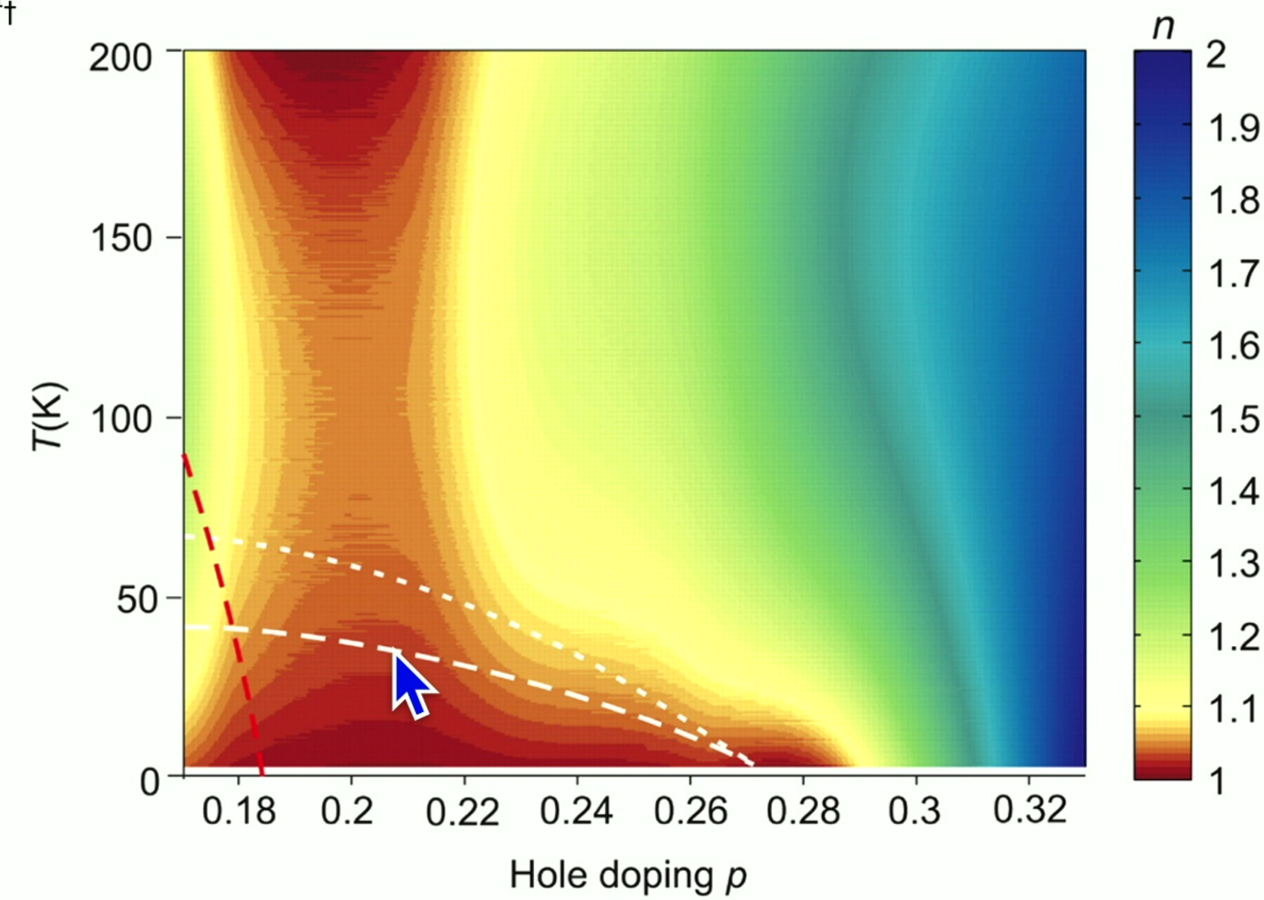


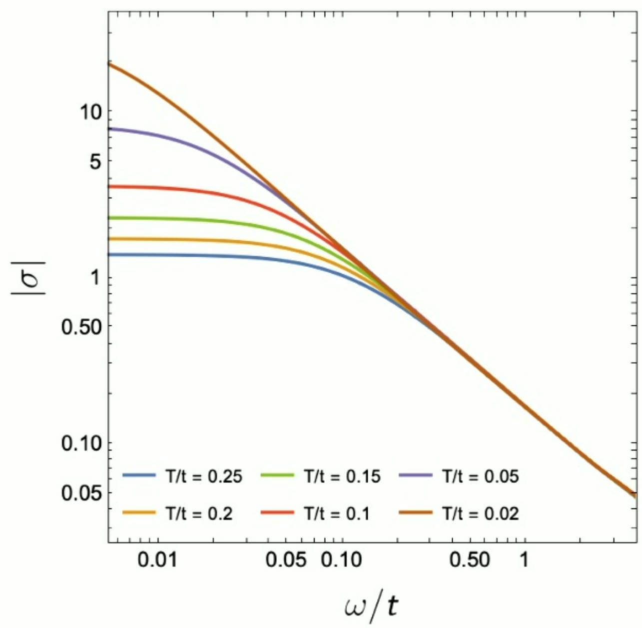


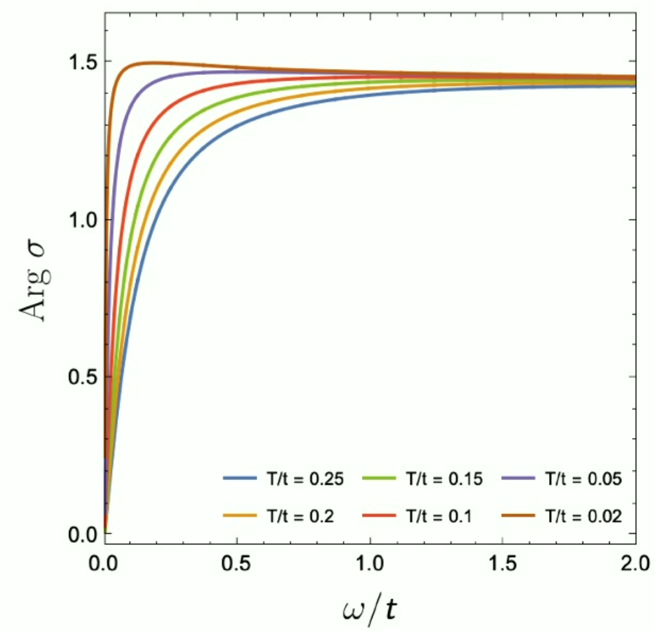
Strange metal and superconductor in the two-dimensional Yukawa-SYK model

$g = 0$

Chenyuan Li, Aavishkar A. Patel, Haoyu Guo, Davide Valentinis, Jorg Schmalian, S.S., Ilya Esters, to appear

$$\sigma(\omega) = i \frac{e^2 K/(\hbar d_c)}{\hbar\omega \frac{m^*(\omega)}{m} + i \frac{\hbar}{\tau(\omega)}}$$





Fermi surface + critical boson with potential and interaction disorder

SYK-type self-consistent equations

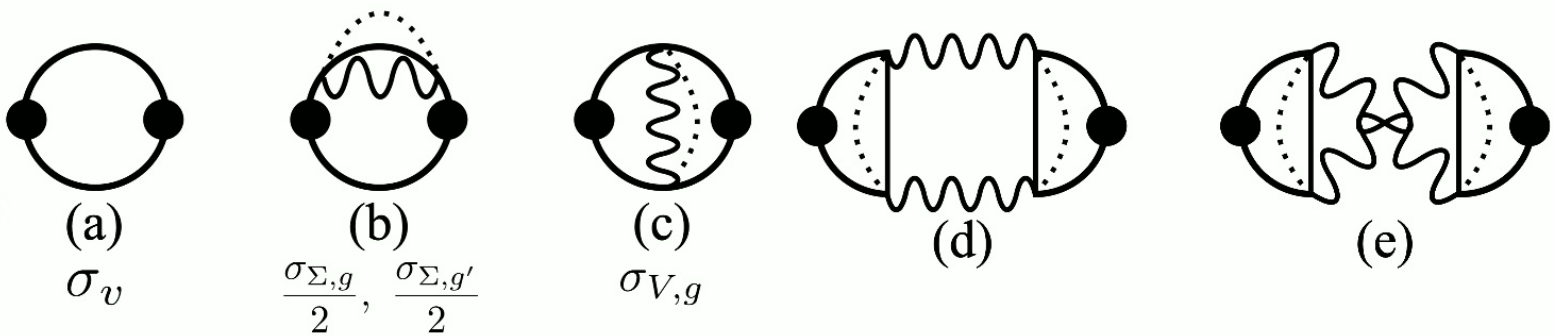
$$\Sigma(\tau,\mathbf{r}) = g^2 D(\tau,\mathbf{r})G(\tau,\mathbf{r}) + v^2 G(\tau,\mathbf{r})\delta^2(\mathbf{r}) + g'^2 G(\tau,\mathbf{r})D(\tau,\mathbf{r})\delta^2(\mathbf{r}),$$

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

$$G(i\omega,\mathbf{k}) = \frac{1}{i\omega - \varepsilon(\mathbf{k}) + \mu - \Sigma(i\omega,\mathbf{k})},$$

$$D(i\Omega,\mathbf{q}) = \frac{1}{\Omega^2 + \mathbf{q}^2 + m_b^2 - \Pi(i\Omega,\mathbf{q})}.$$

Conductivity:



+ all ladders and bubbles…..

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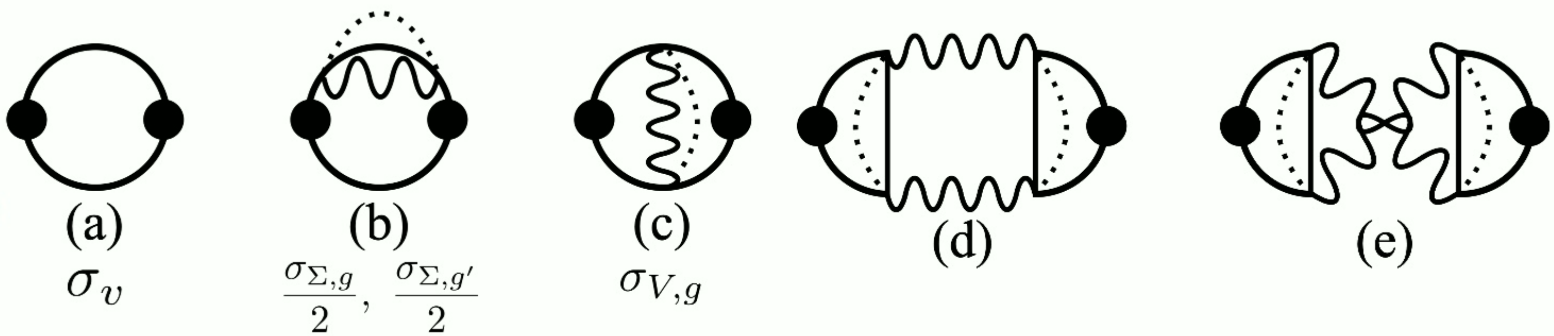

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