The role of disorder in the theory of strange metals

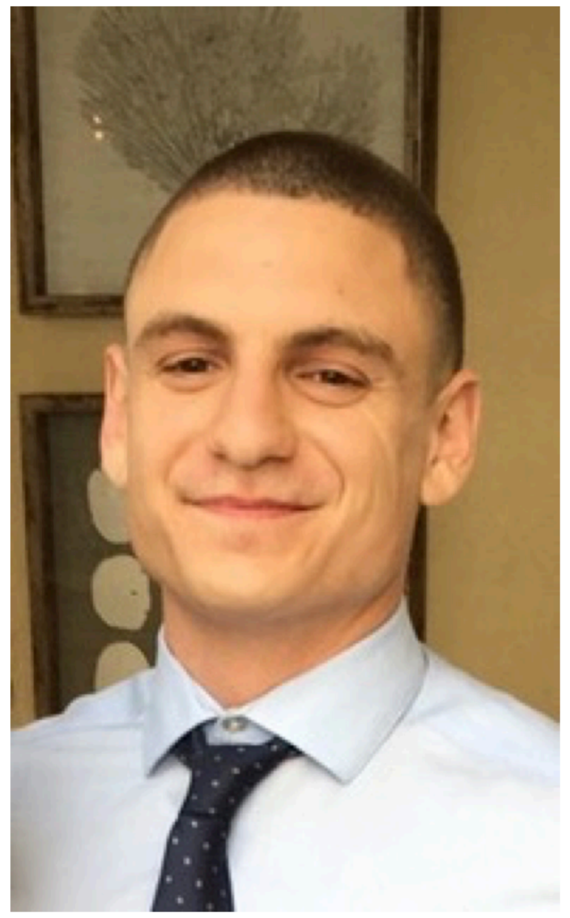
Subir Sachdev

FTPI March Meeting
University of Minnesota
March 1, 2024

PHYSICS

Aavishkar A. Patel, Peter Lunts, and S. S., arXiv:2312.06751
Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, and S. S., Science **381**, 790 (2023)

HARVARD



Ilya Esterlis
Wisconsin

Haoyu Guo
Cornell

Aavishkar Patel
Flatiron

Peter Lunts
Harvard

Alex Nikolaenko
Harvard

Davide Valentinis
KIT

Joerg Schmalian
KIT

Chenyuan Li
Harvard

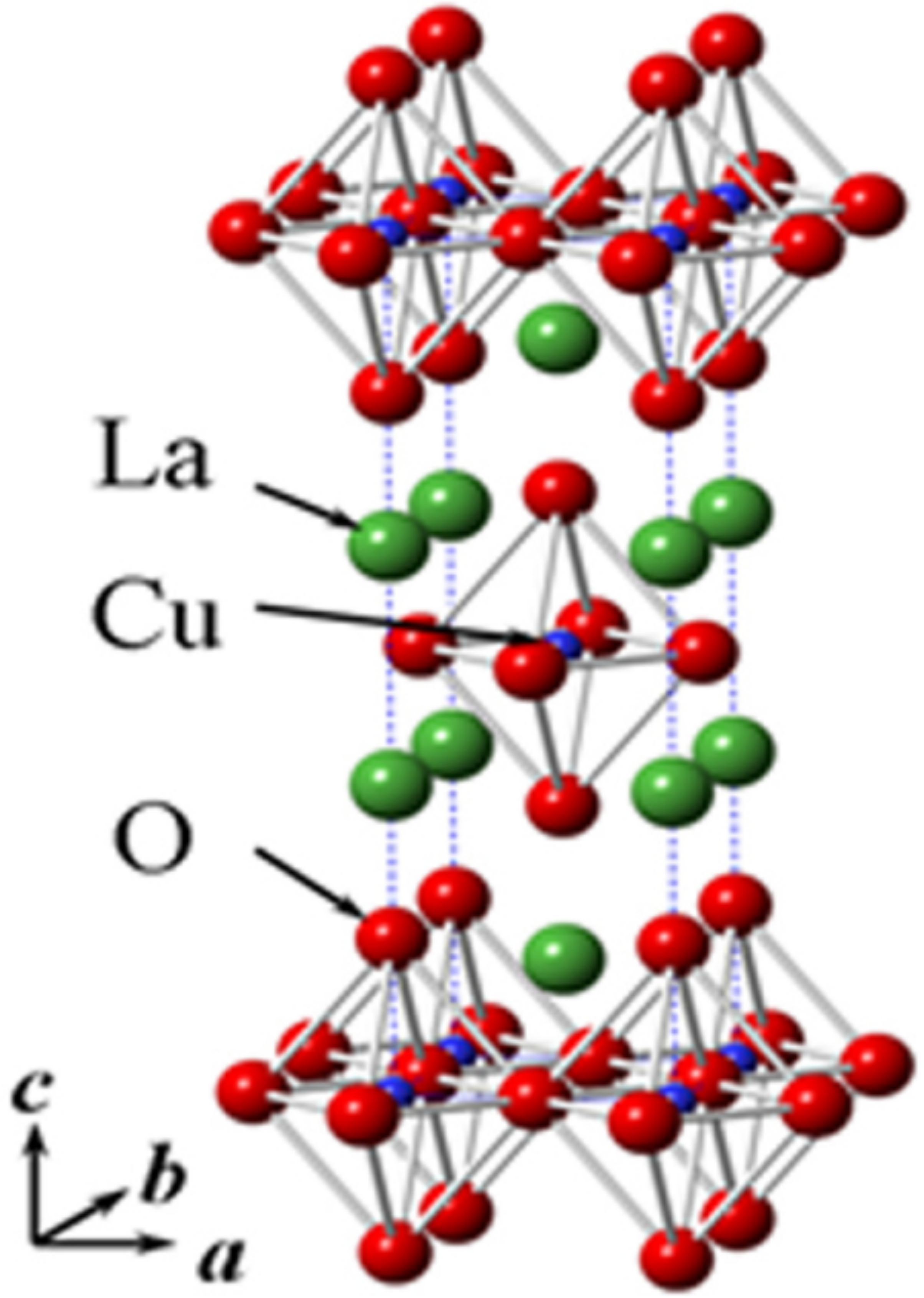
Serhii Kryhin
Harvard

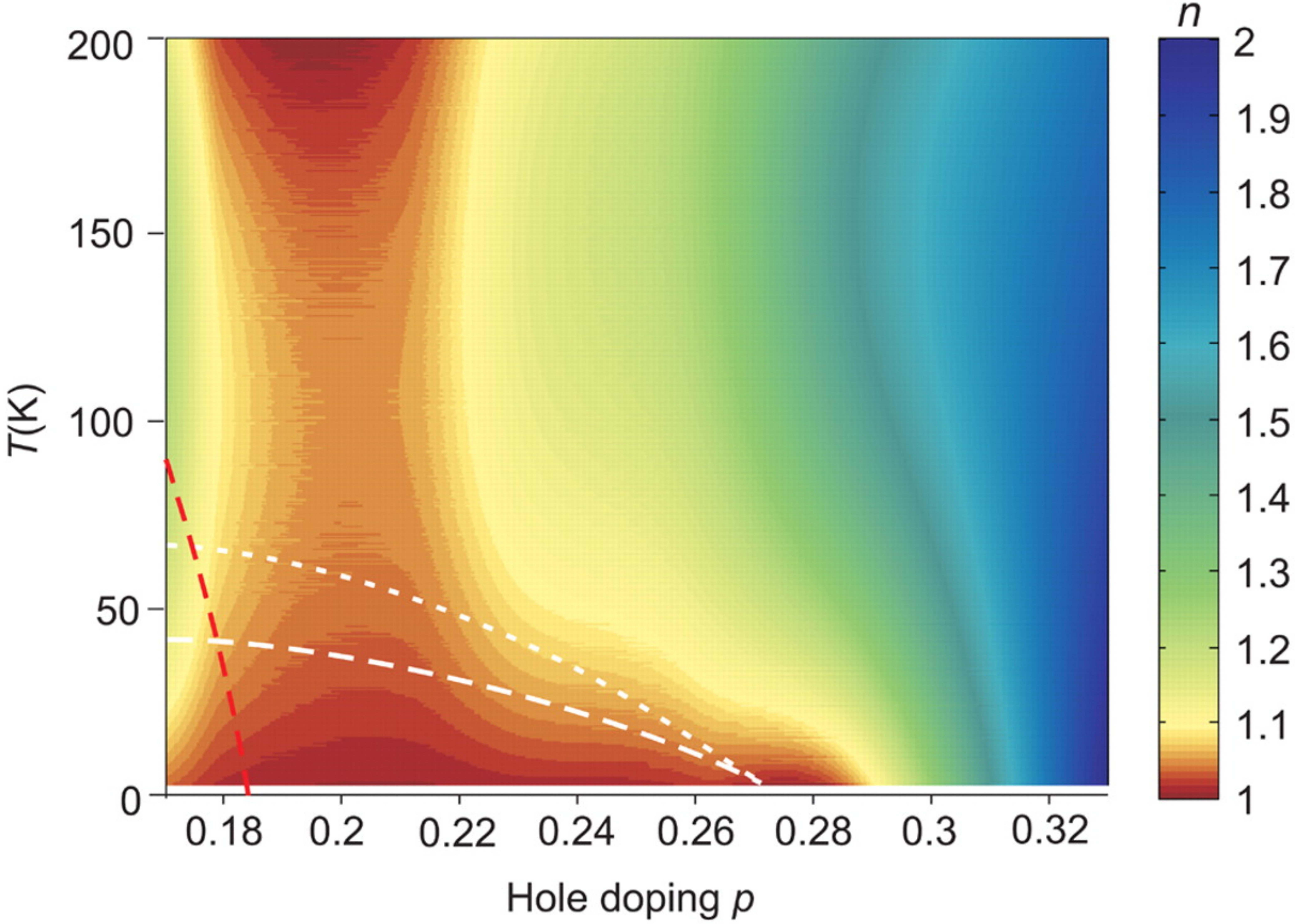
Pavel Volkov
UConn

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

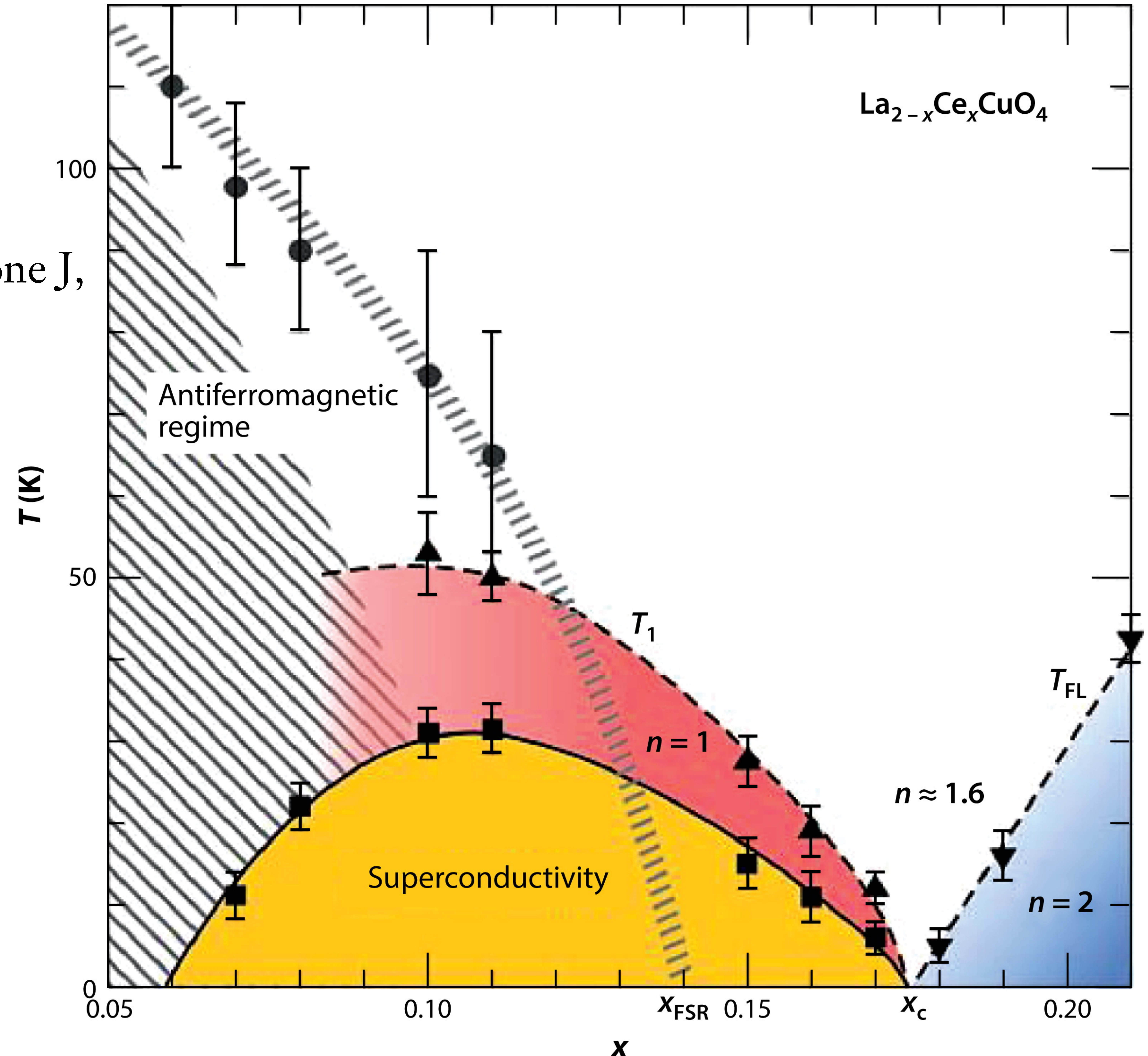
R. A. Cooper,[1] Y. Wang,[1] B. Vignolle,[2] O. J. Lipscombe,[1] S. M. Hayden,[1] Y. Tanabe,[3] T. Adachi,[3] Y. Koike,[3] M. Nohara,[4]* H. Takagi,[4] Cyril Proust,[2] N. E. Hussey[1]†

SCIENCE VOL 323 **603** 2009

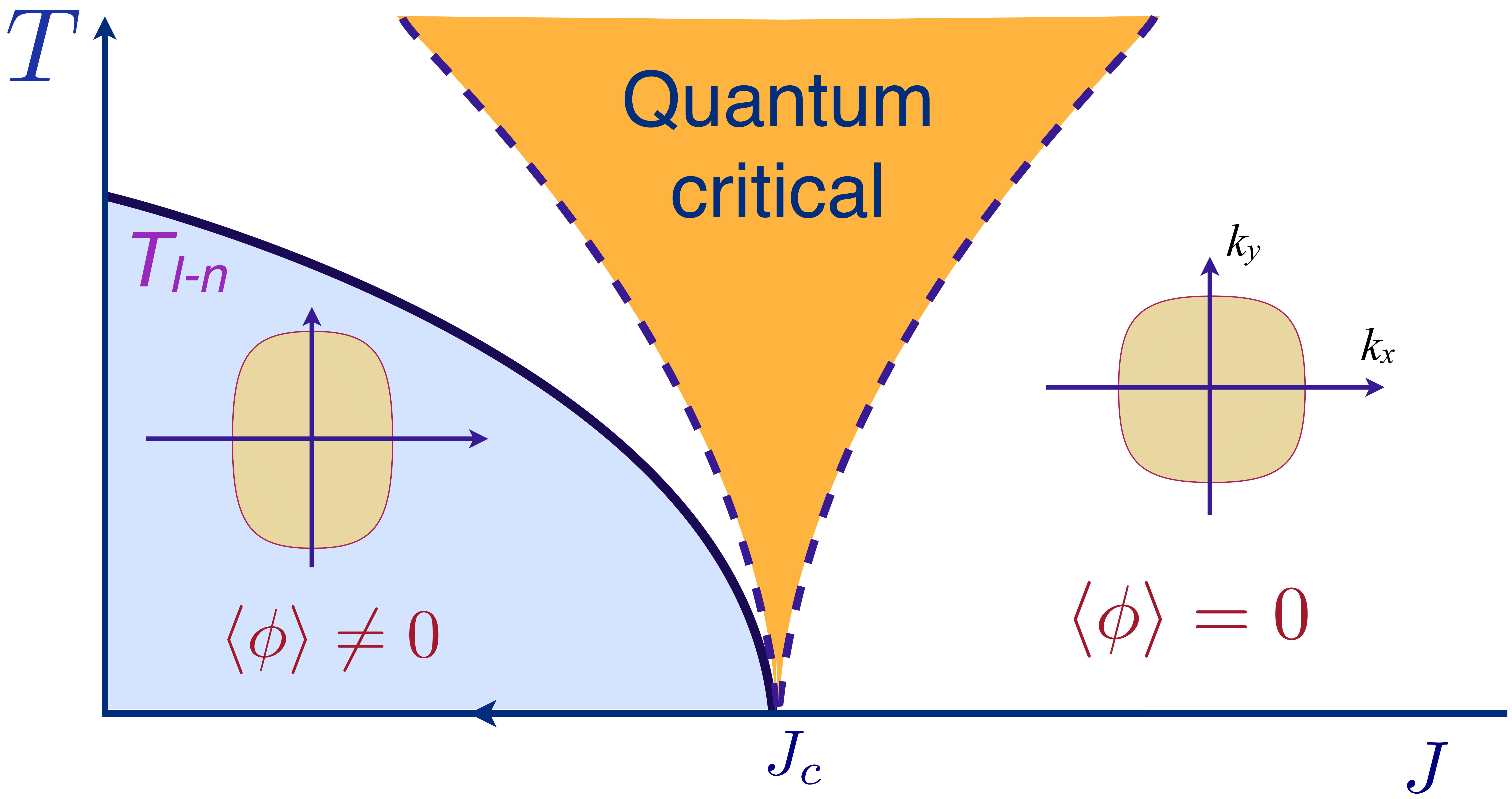




Jin K, Butch NP, Kirshenbaum K, Paglione J, Greene RL. 2011. *Nature* 476:73–75

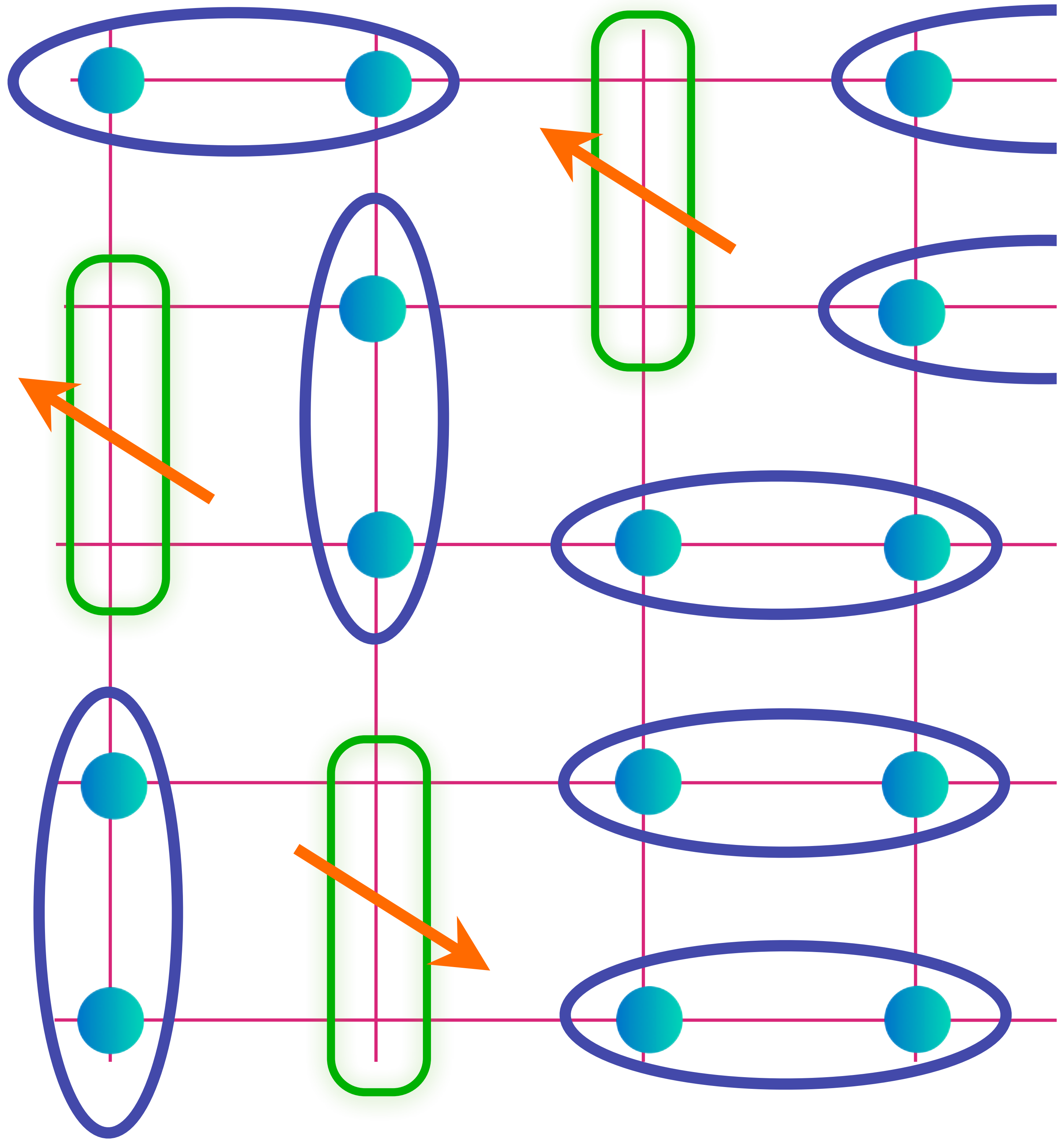


Quantum criticality of Ising-nematic ordering in a metal

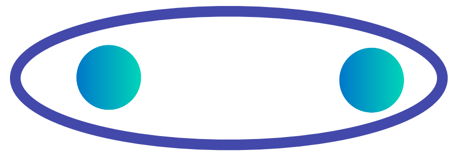


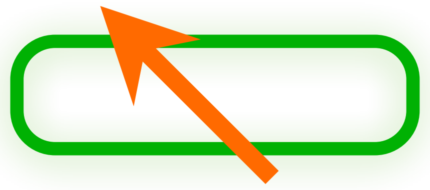
Phase diagram as a function of T and J

Pseudogap metal to Fermi liquid in single band model



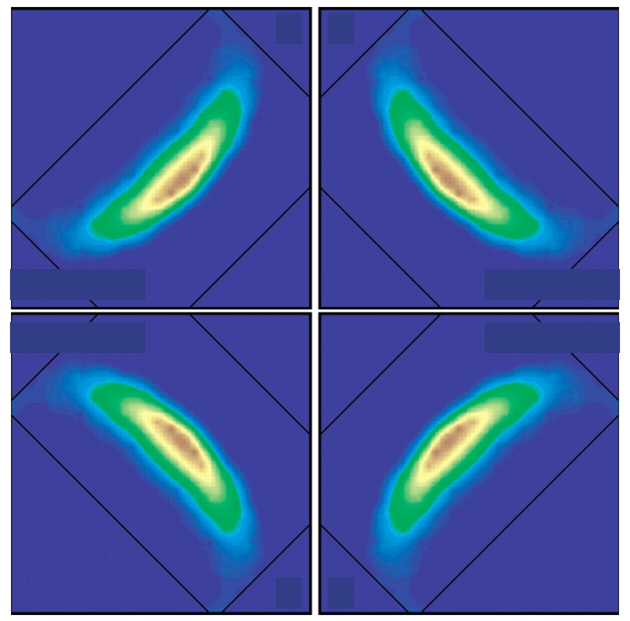
Φ Higgs boson with the fundamental gauge charge of an emergent SU(2) gauge field.

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

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

Small Fermi surface of size p + spin liquid.

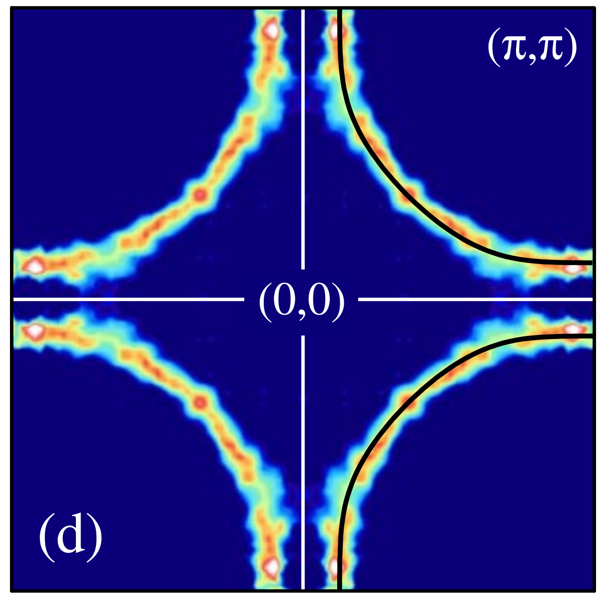
FL*



$\langle \Phi \rangle \neq 0$

Large Fermi surface of size $1 + p$

FL

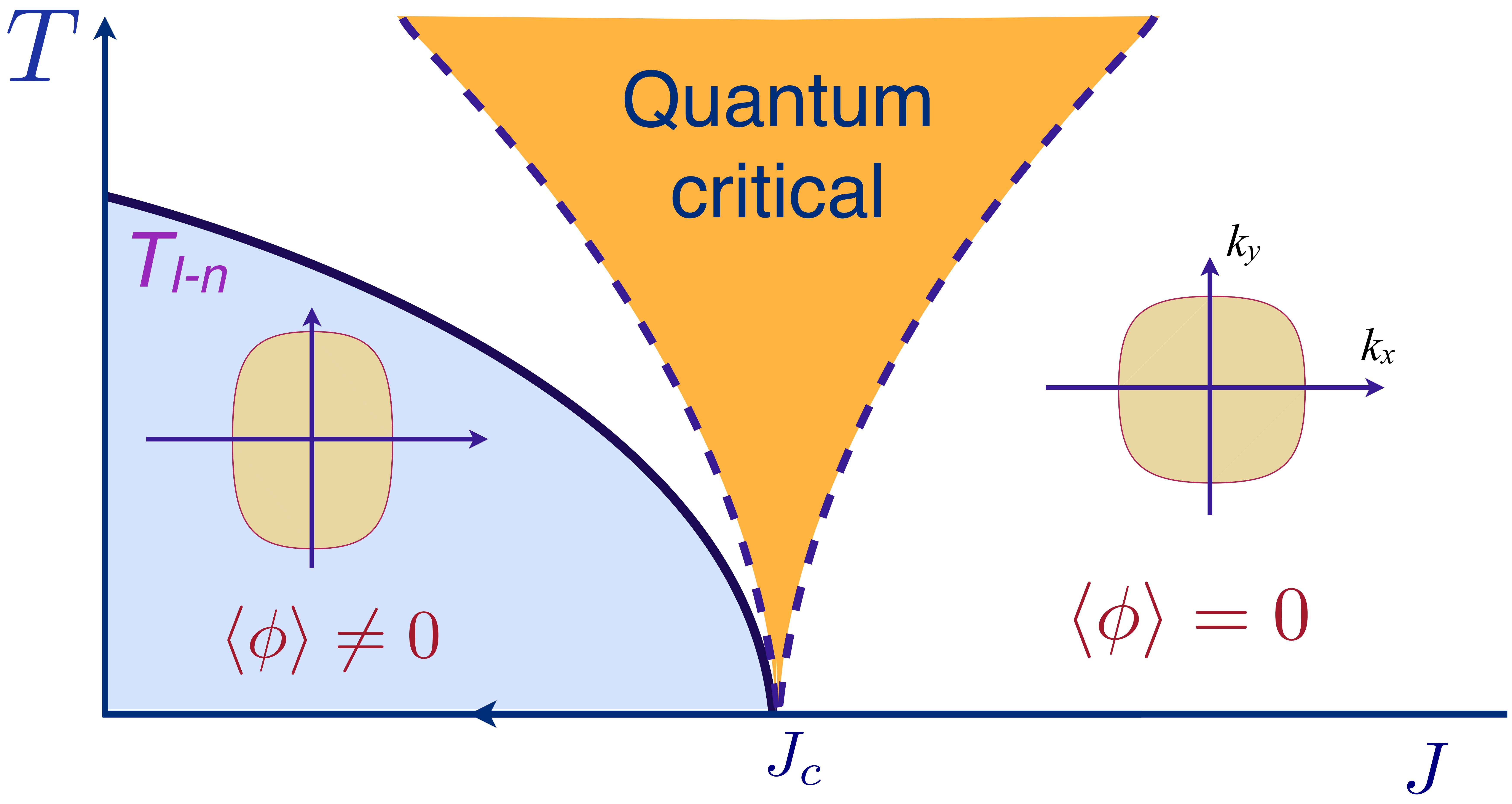


$\langle \Phi \rangle = 0$

doping p

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

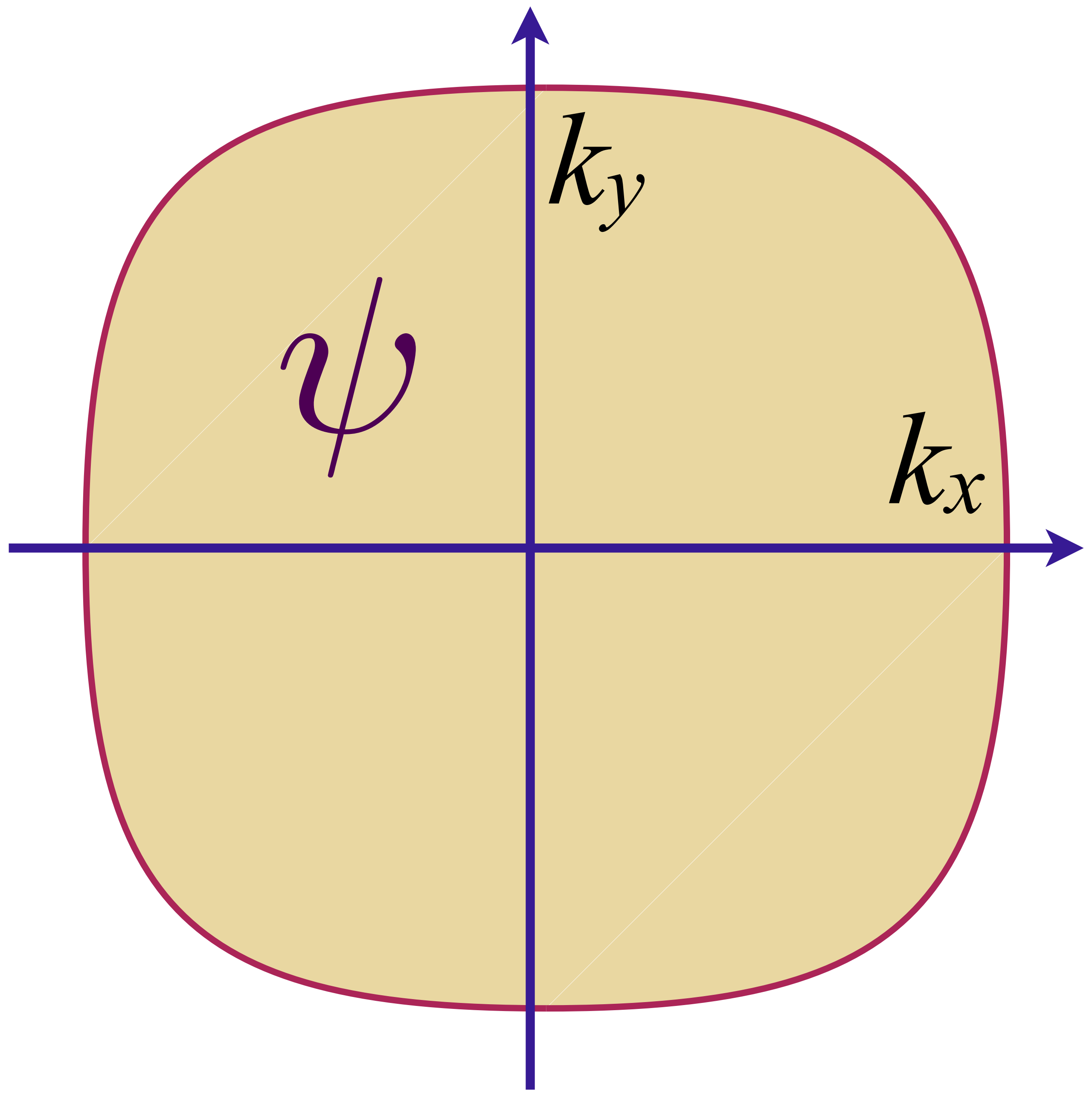
Quantum criticality of Ising-nematic ordering in a metal



Phase diagram as a function of T and J

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

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

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

Fermi surface + critical boson with potential and interaction disorder

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

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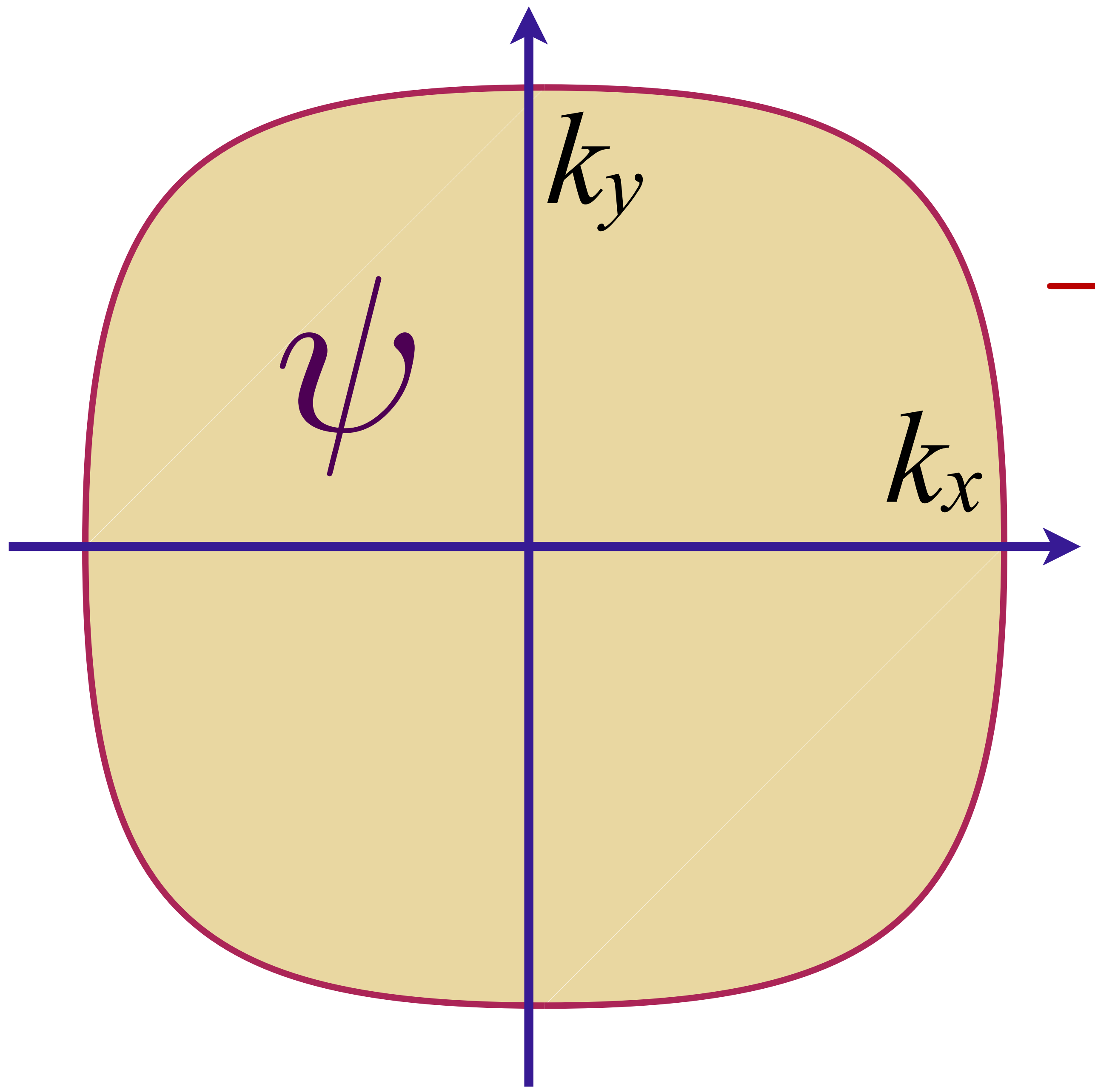

$$+[s + \delta s(\boldsymbol{r})]\,[\phi(\boldsymbol{r})]^2 + [g + g'(\boldsymbol{r})]\,\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})\,\phi(\boldsymbol{r})$$

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

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

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

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

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

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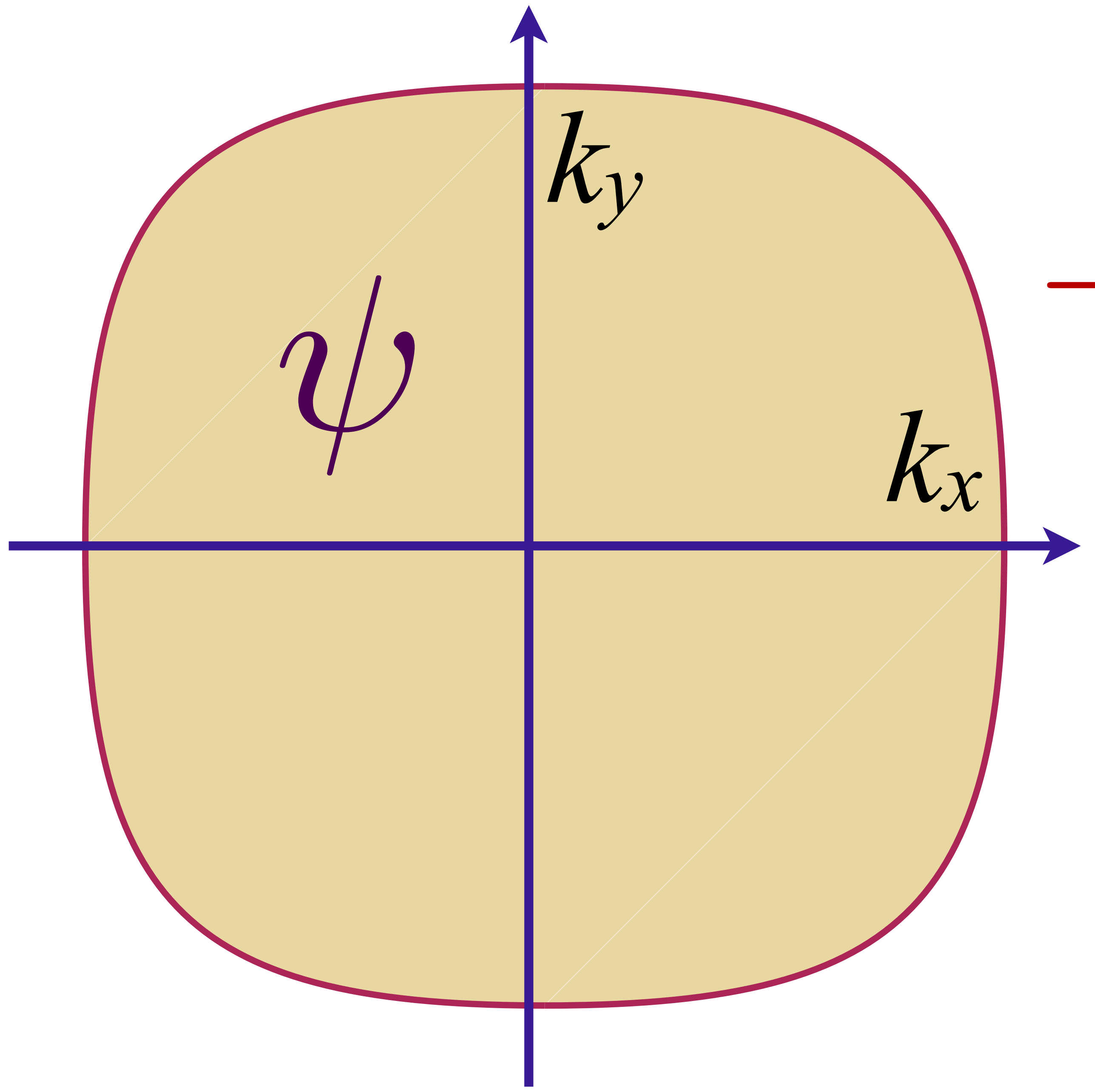

$$+[s + \delta s(\boldsymbol{r})] \, [\phi(\boldsymbol{r})]^2 + [g + g'(\boldsymbol{r})] \, \psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r}) \, \phi(\boldsymbol{r})$$

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

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

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

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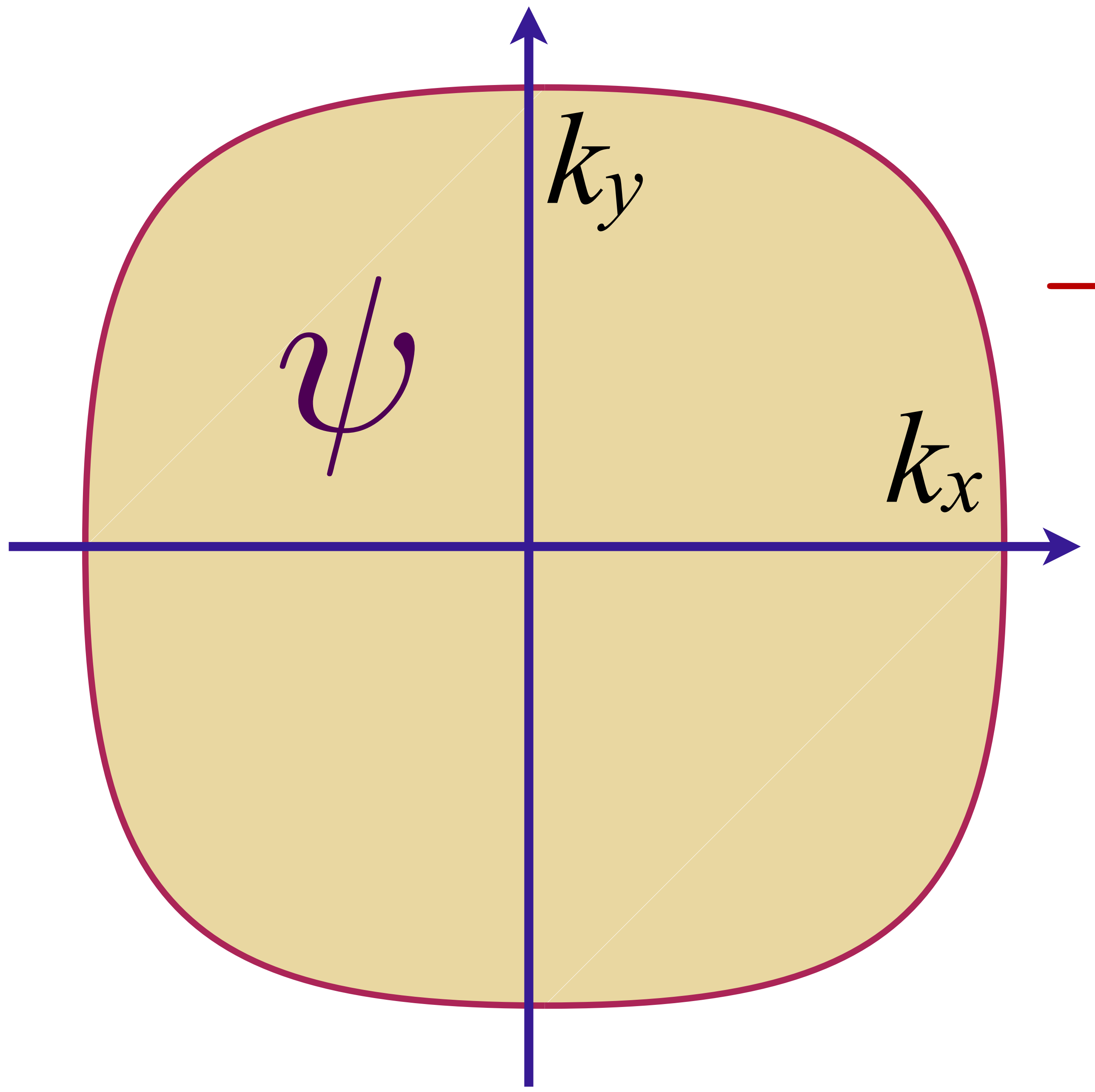

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Rescale $\phi(\boldsymbol{r})$ to obtain a theory with $\delta s = 0$, while inducing larger g' and other less relevant couplings; analyze such a theory in a self-averaging manner as in the Yukawa-SYK model.

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

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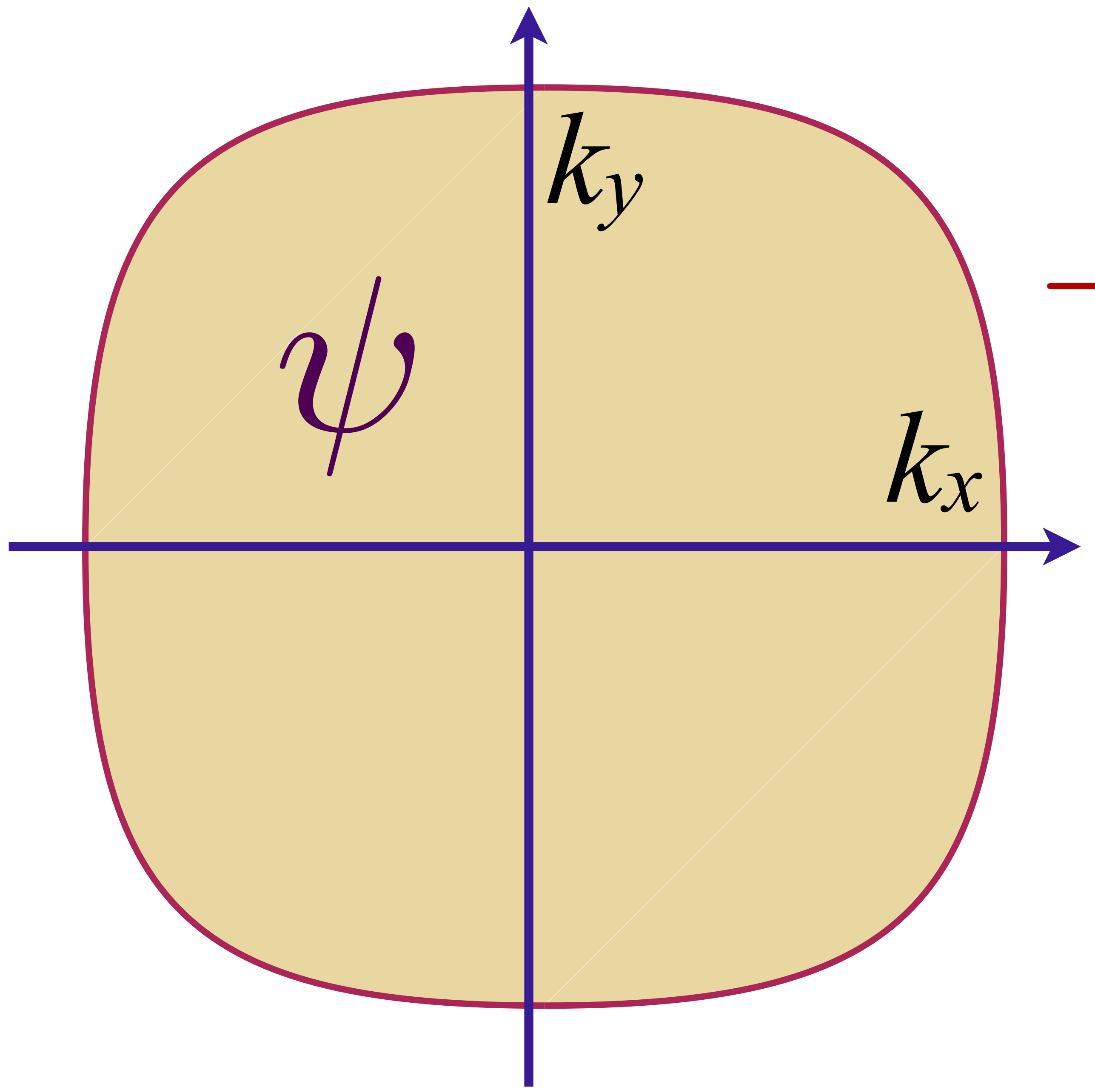

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Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. Sachdev, *Science* **381**, 790 (2023)

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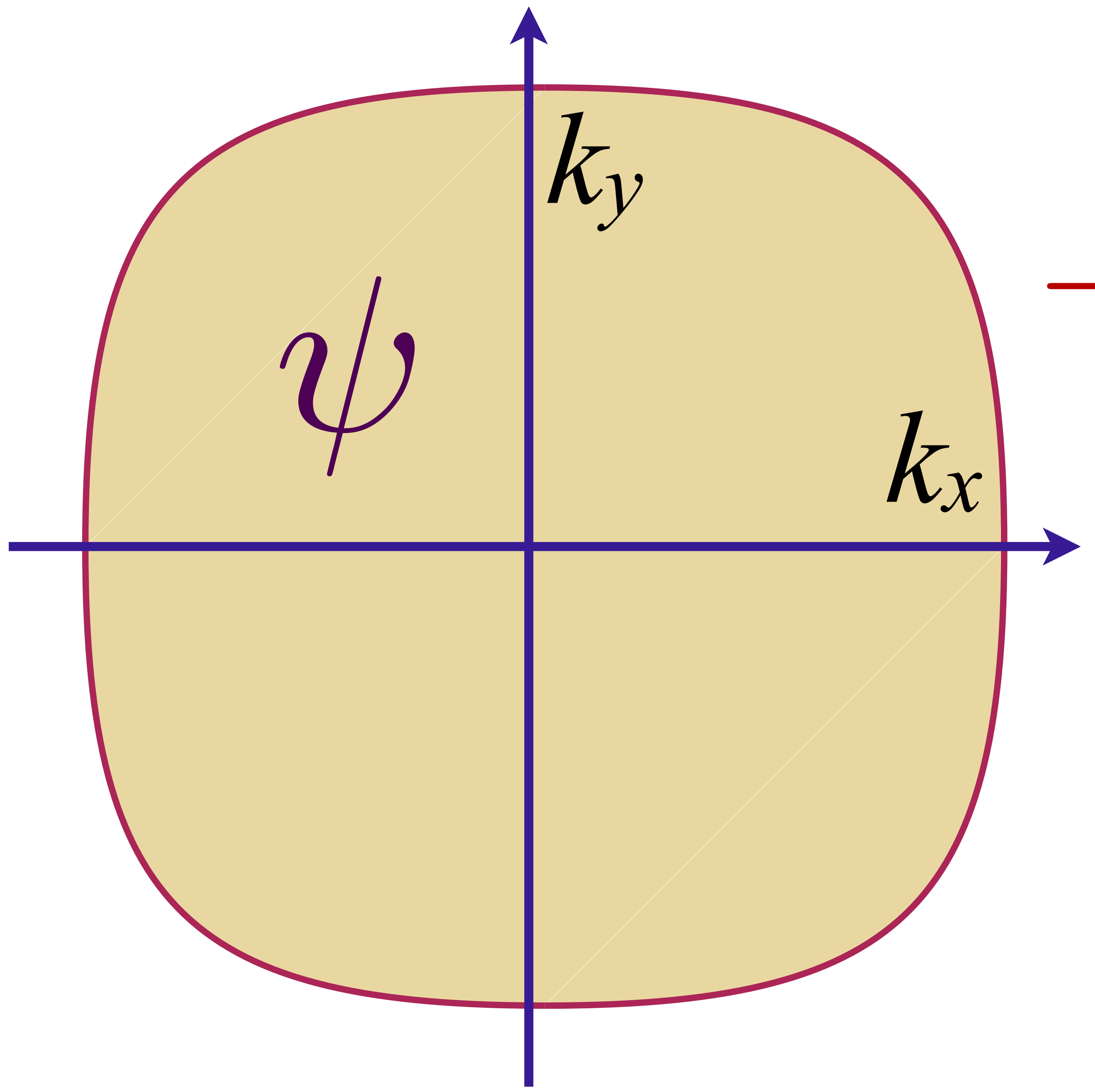

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RG analysis (Harris criterion) shows that $\delta s(\boldsymbol{r})$ is most relevant disorder.
Rescale $\phi(\boldsymbol{r})$ to obtain a theory with $\delta s = 0$, while inducing larger g' and other less relevant couplings; analyze such a theory 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

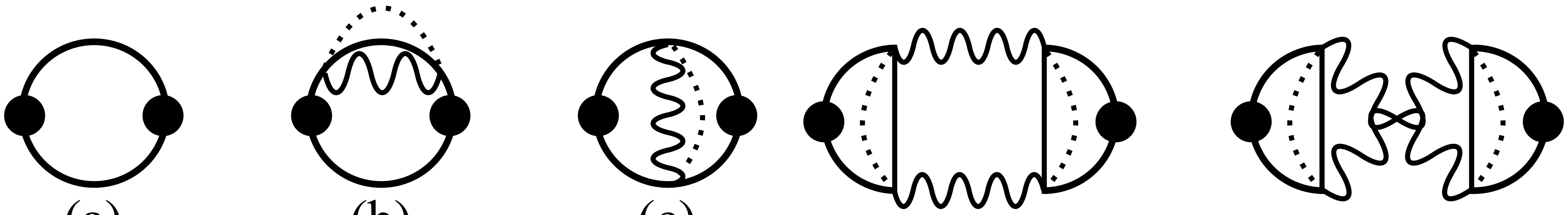
$$\Sigma(\tau,\mathbf{r}) = g^2 D(\tau,\mathbf{r})G(\tau,\mathbf{r}) + v^2 G(\tau,\mathbf{r})\delta^2(\mathbf{r}) + {g'}^2 G(\tau,\mathbf{r})D(\tau,\mathbf{r})\delta^2(\mathbf{r}),$$

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

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

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

Conductivity:



(a) σ_v

(b) $\frac{\sigma_{\Sigma,g}}{2}$, $\frac{\sigma_{\Sigma,g'}}{2}$

(c) $\sigma_{V,g}$

(d)

(e)

+ all ladders and bubbles…..

Fermi surface + critical boson with potential and interaction disorder

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

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

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

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

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.

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

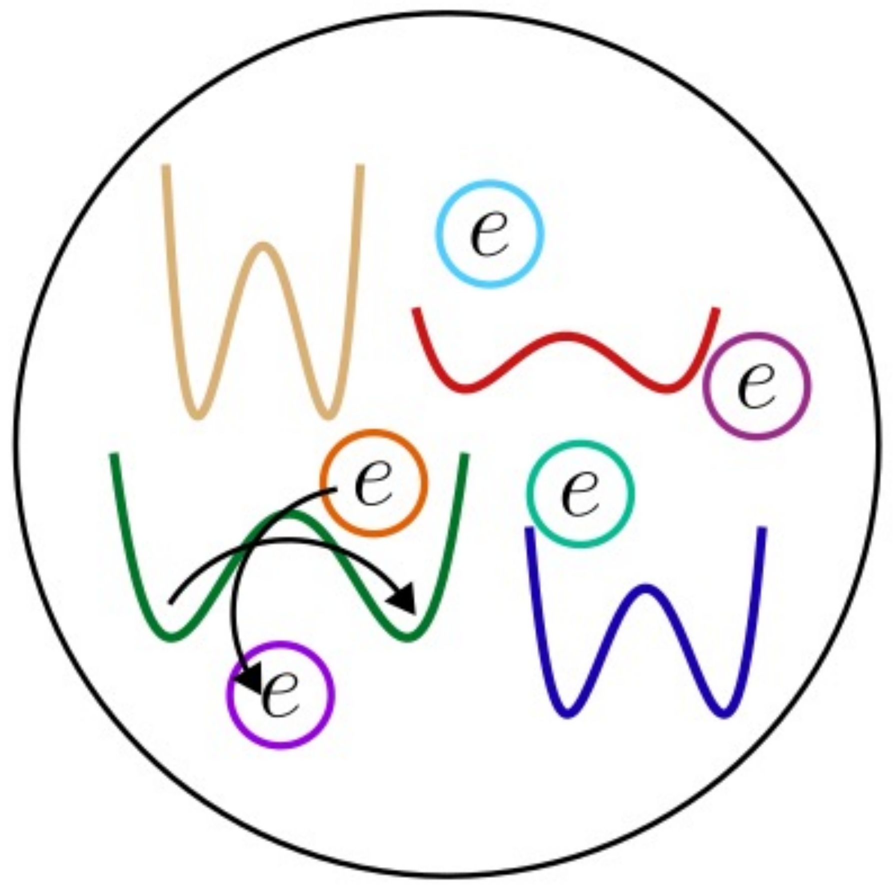
Quantum Interference of Hydrodynamic Modes in a Dirty Marginal Fermi Liquid

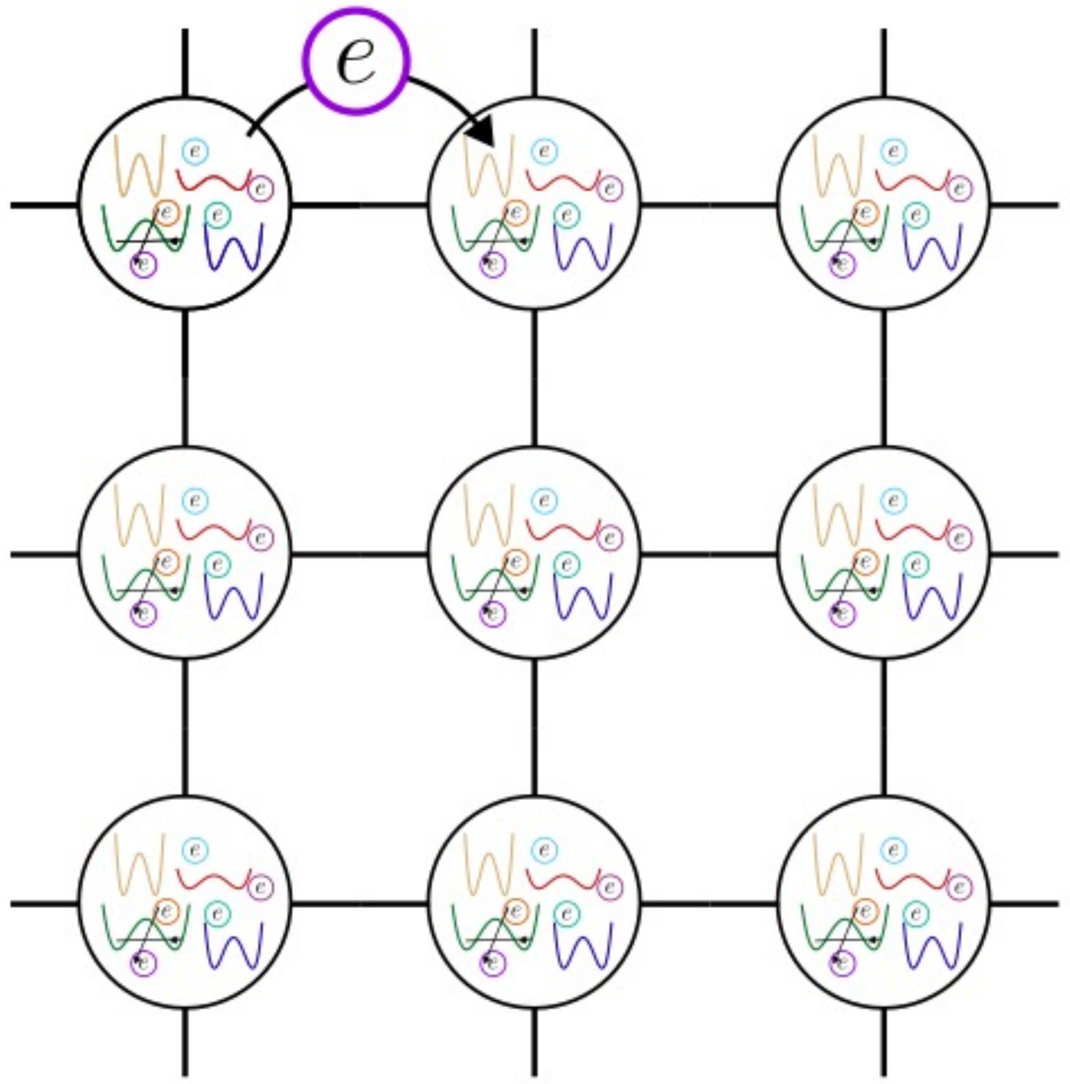
Tsz Chun Wu, Yunxiang Liao, Matthew S. Foster
Phys. Rev. B **106**, 155108 (2022)

Diffusion (Altshuler-Aronov) corrections to conductivity are singular $\sim 1/T$.

Our interpretation: need to consider strong-disorder effects, where the dominant effect is the localization of overdamped bosonic modes ...

Tuneable non-Fermi liquid phase in electronic glasses



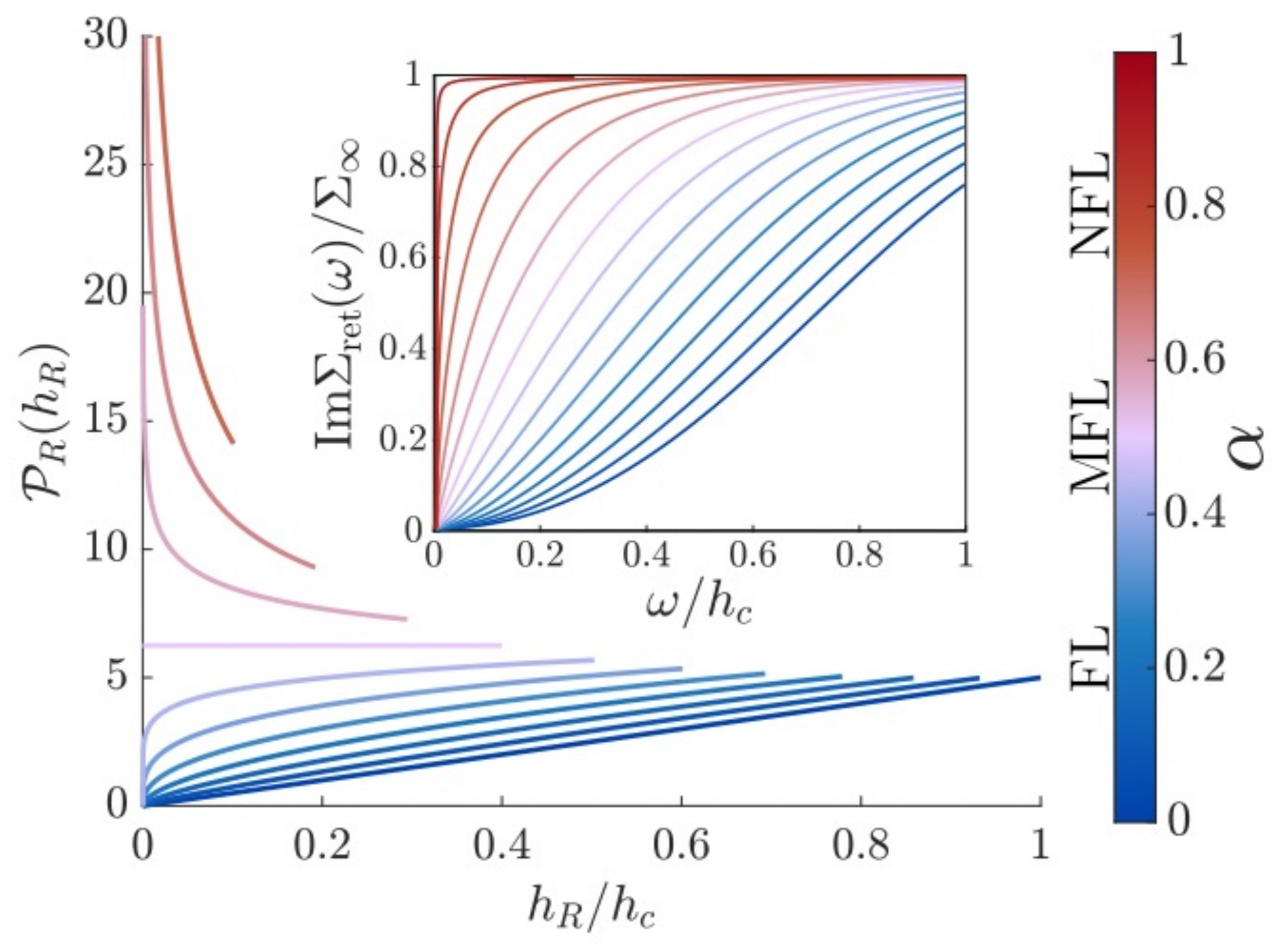


generalization of the Sachdev-Ye-Kitaev approach
to two-level systems in glasses

$\Downarrow$

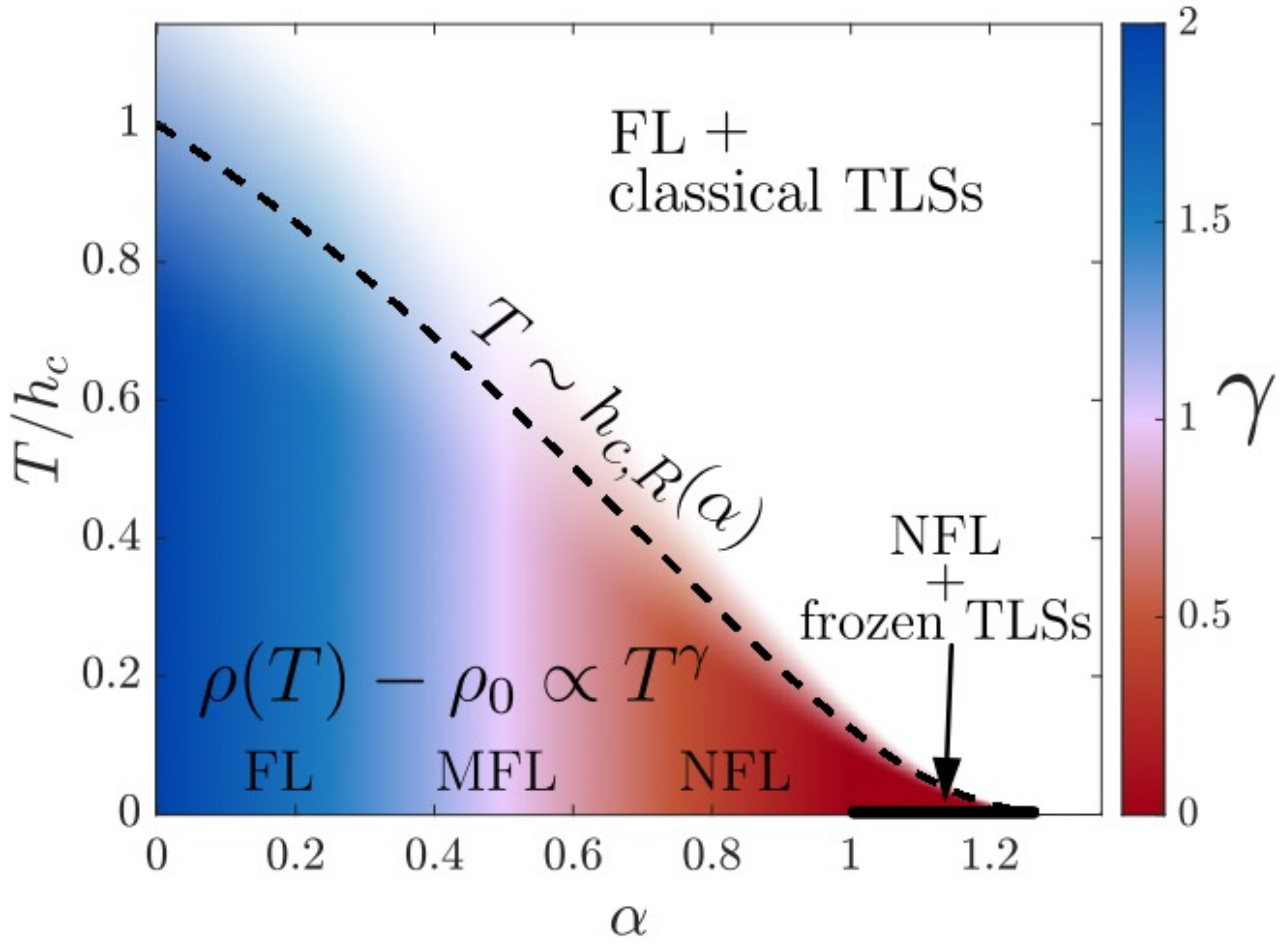
controlled approach to obtain a tunable
Non-Fermi liquid state

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

Analysis of Landau-damped bosonic eigenmodes

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.

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

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

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

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

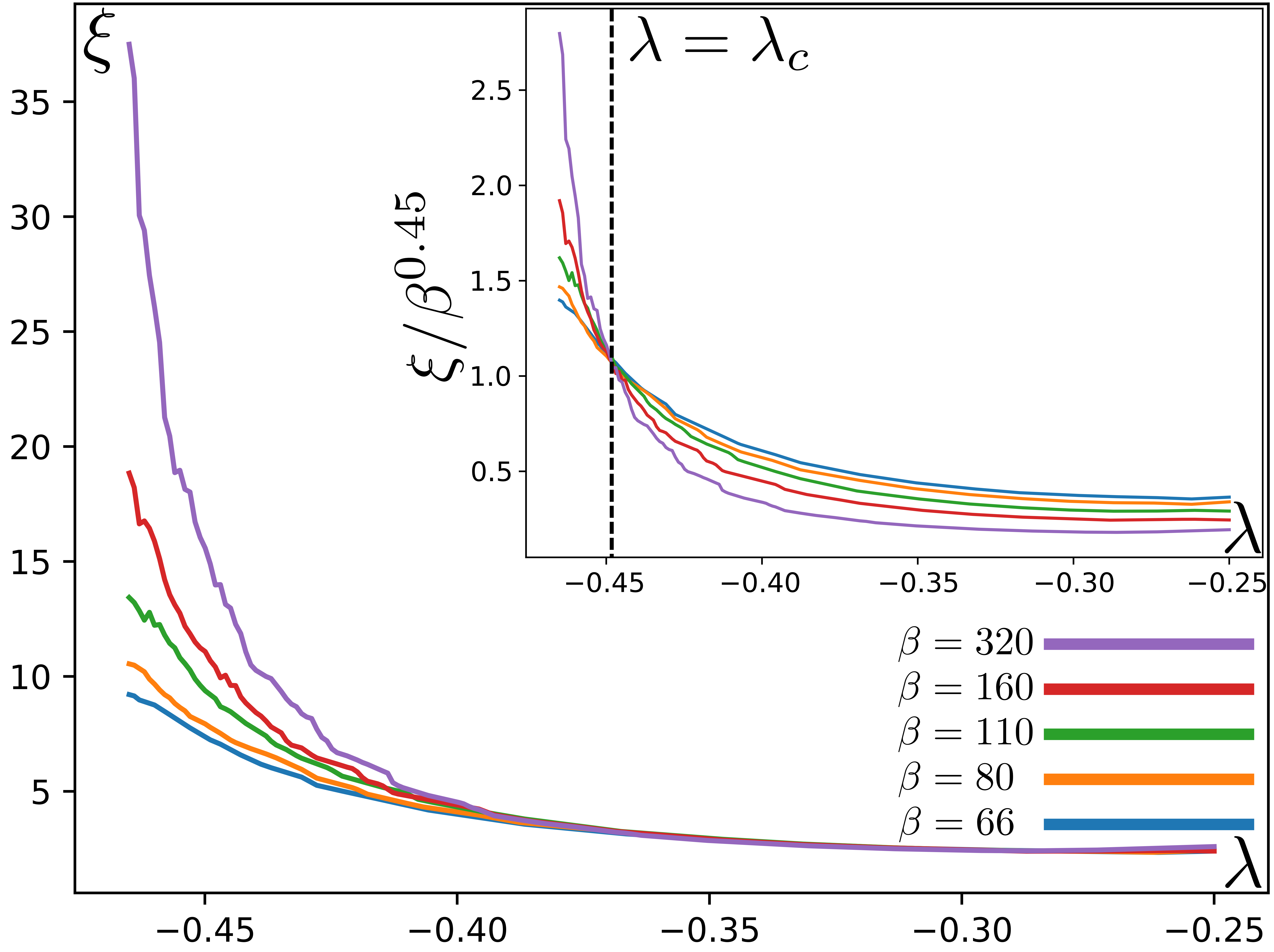
$$\overline{\lambda}'_j = \lambda + \lambda'_j + \frac{u}{M} \sum_a \langle \phi_{ja}^2 \rangle_{\overline{\mathcal{S}}_\phi + \mathcal{S}_{\phi d}} = \lambda + \lambda'_j + uT \sum_\Omega \sum_\alpha \frac{\psi_{\alpha i} \psi_{\alpha j}}{\gamma |\Omega| + \Omega^2/c^2 + e_\alpha}$$

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

where e_α and $\psi_{\alpha j}$ are eigenvalues and eigenfunctions of the ϕ quadratic form in $\overline{\mathcal{S}}_\phi$, labeled by the index $\alpha = 1 \ldots L^2$ for a $L \times L$ sample.

Analysis of Landau-damped bosonic eigenmodes

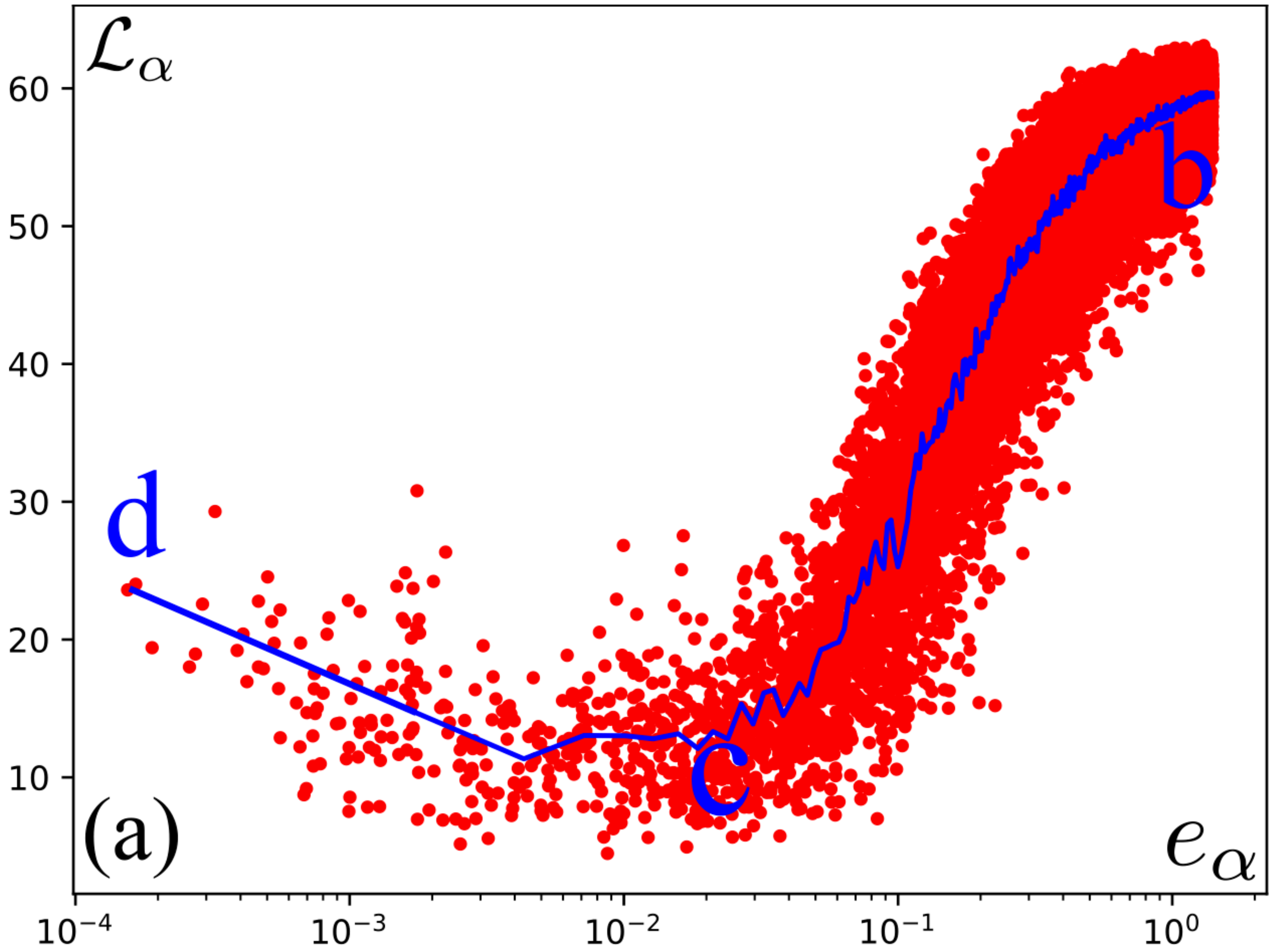
ϕ correlation length ξ



Aavishkar A. Patel,
Peter Lunts, S.S.,
arXiv:2312.06751

Analysis of Landau-damped bosonic eigenmodes

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



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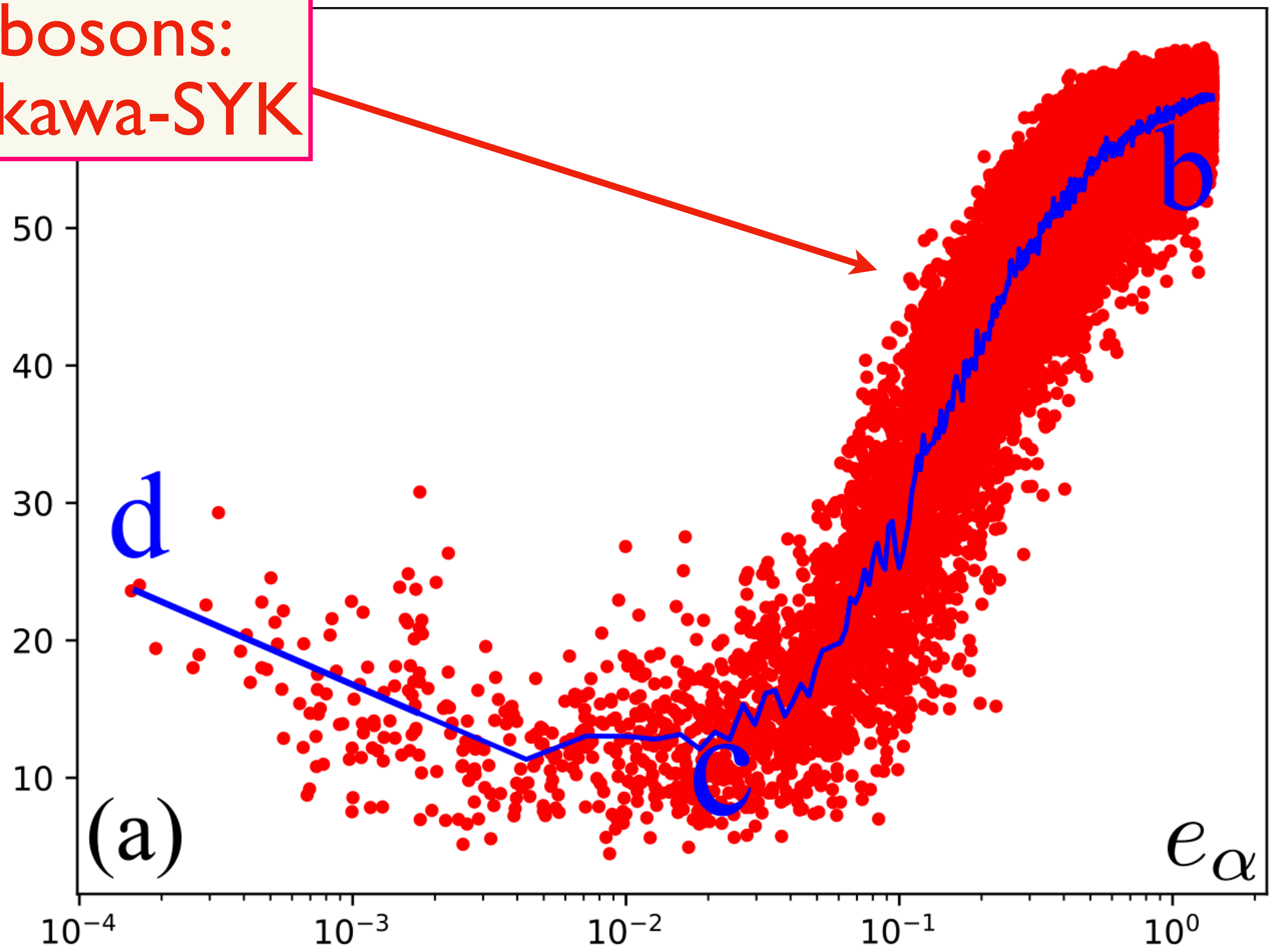
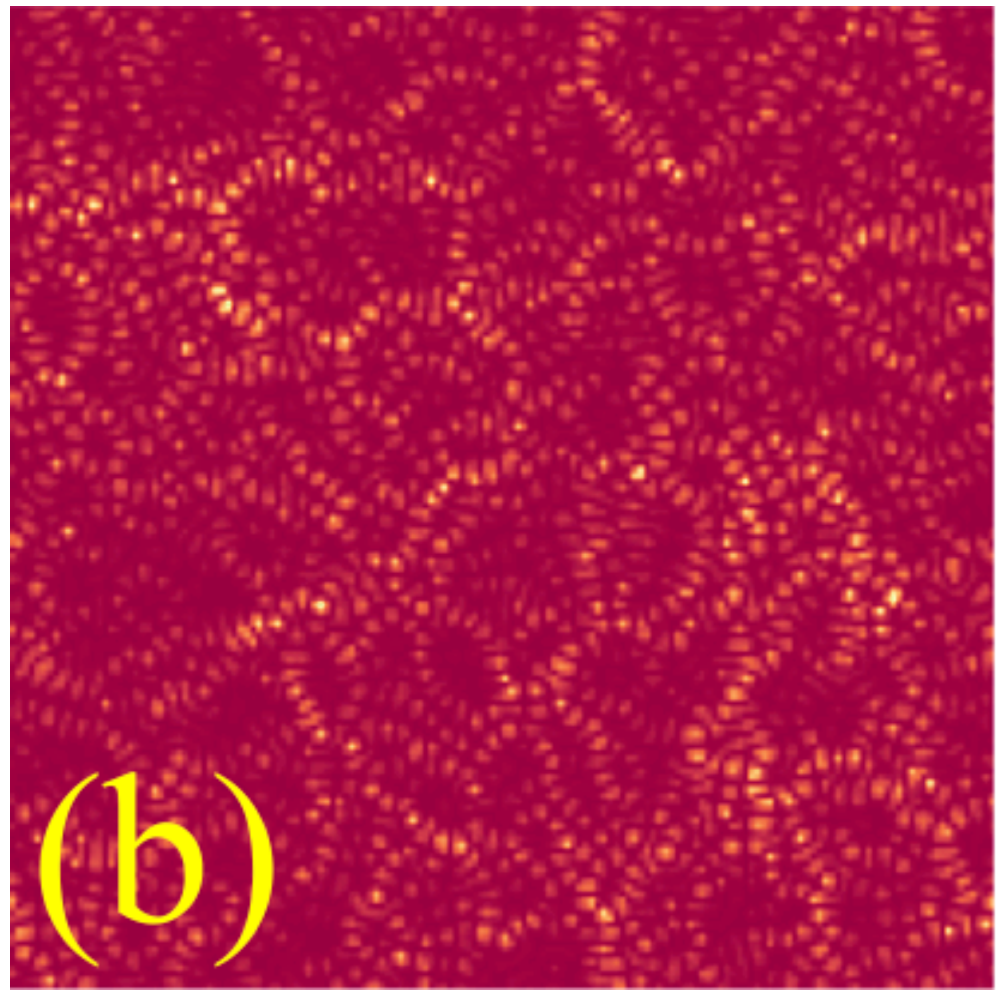
Extended bosons: physics of Yukawa-SYK





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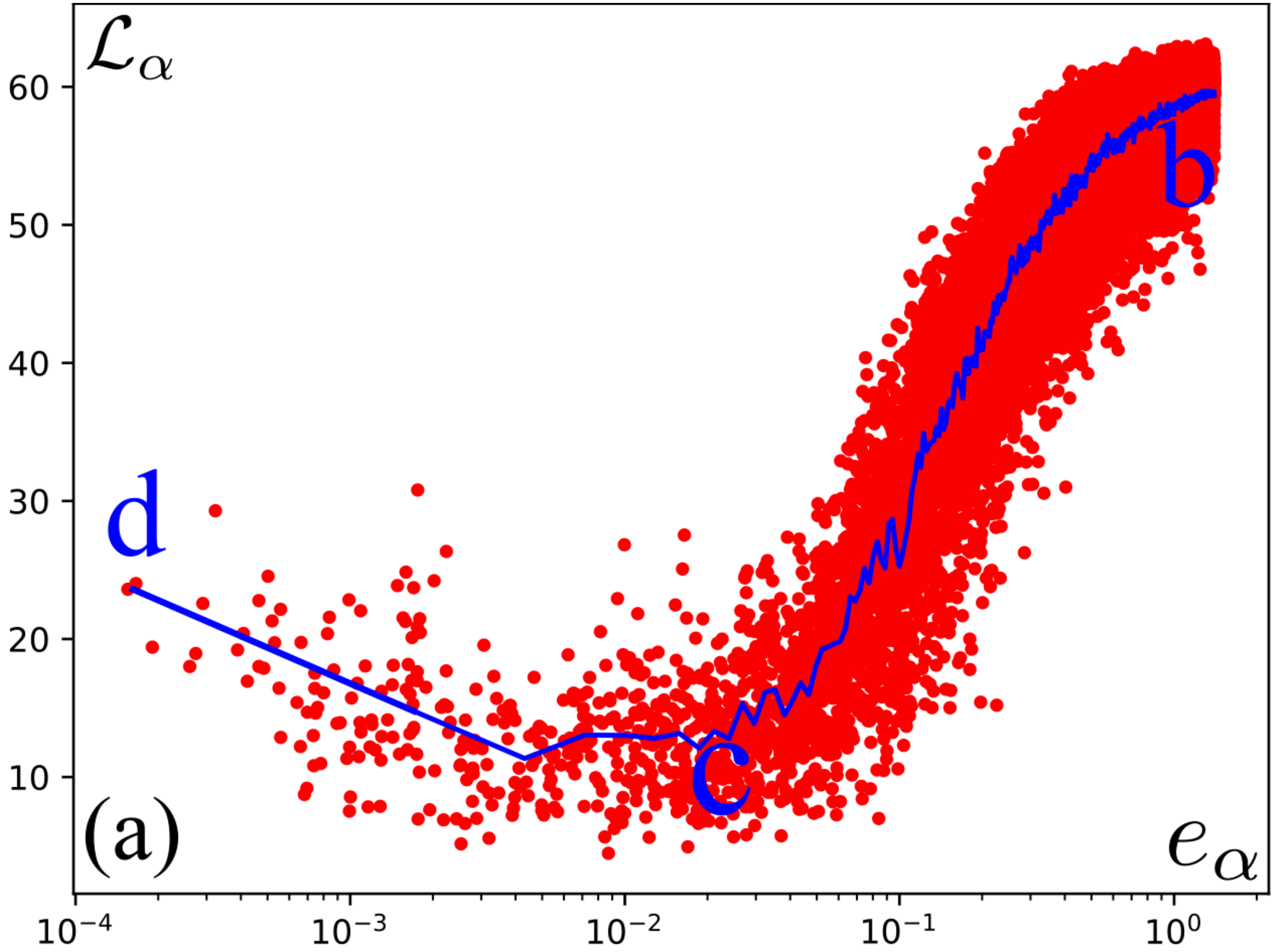

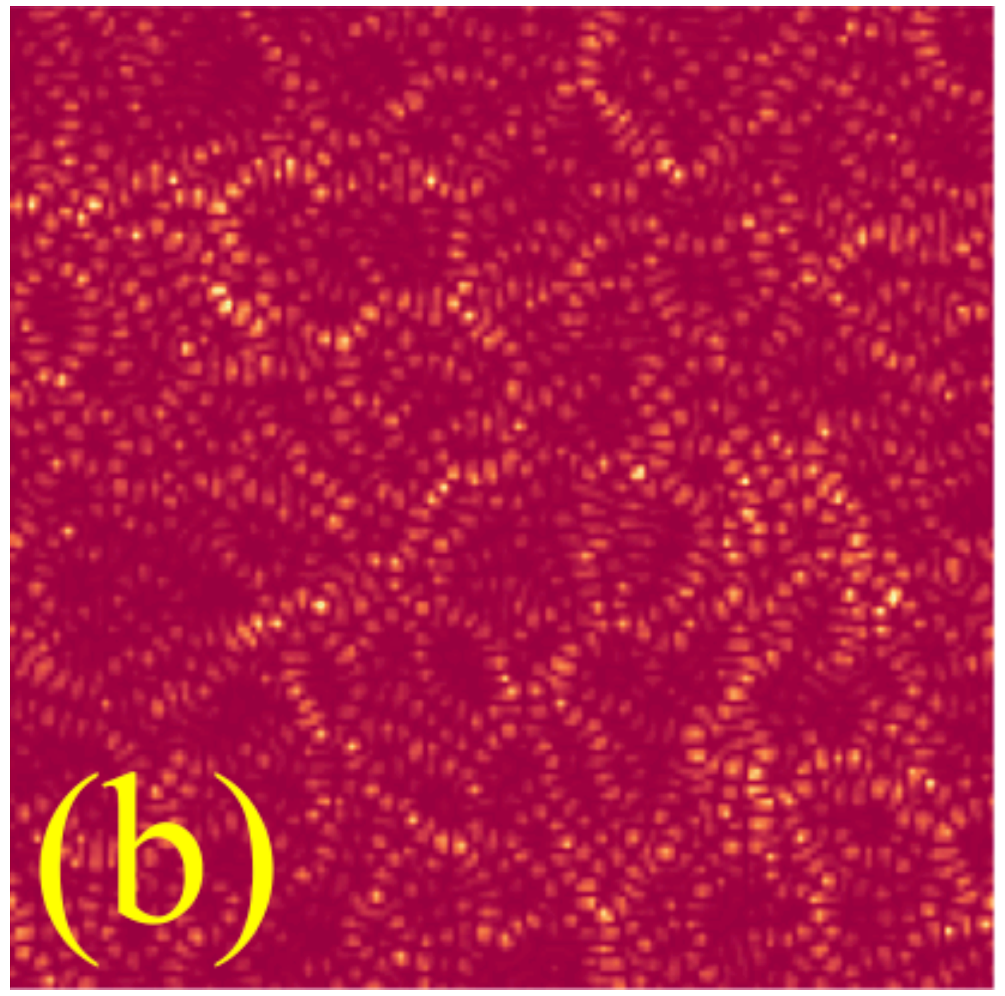

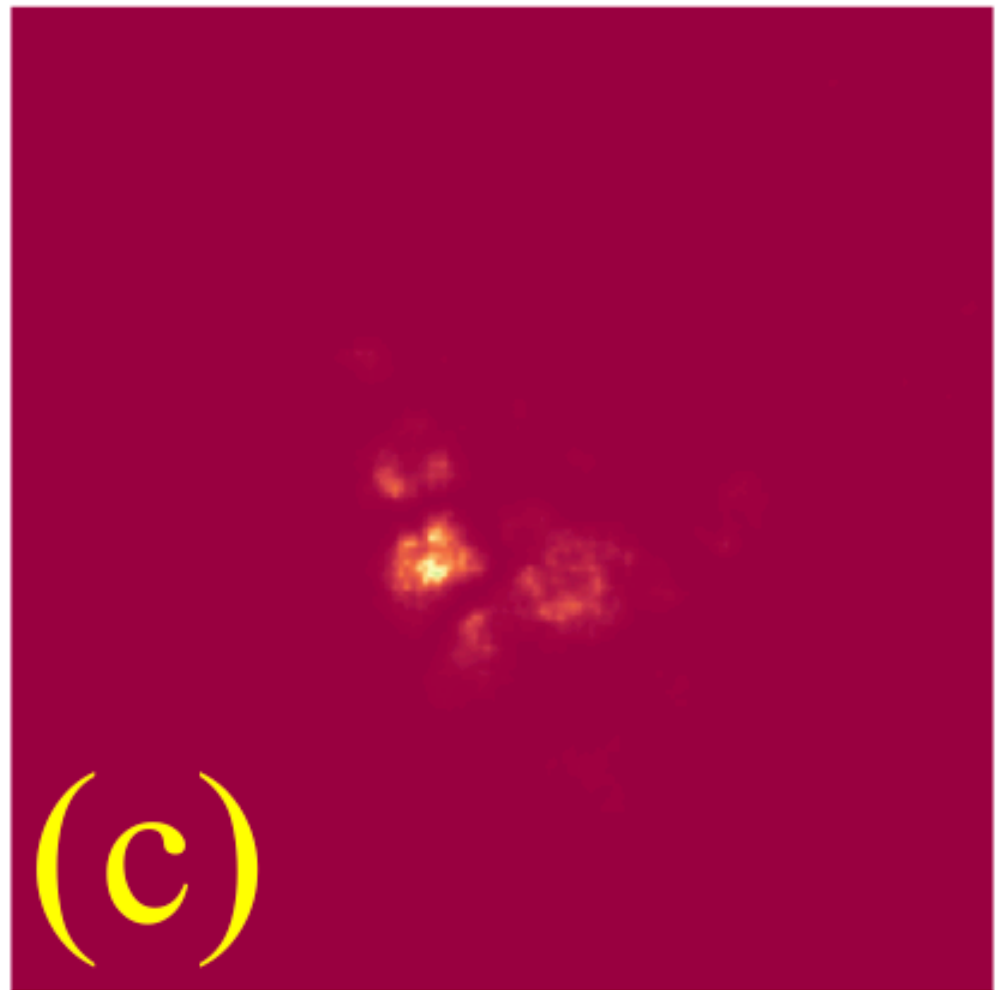

Aavishkar A. Patel, Peter Lunts, S.S., *arXiv:2312.06751*

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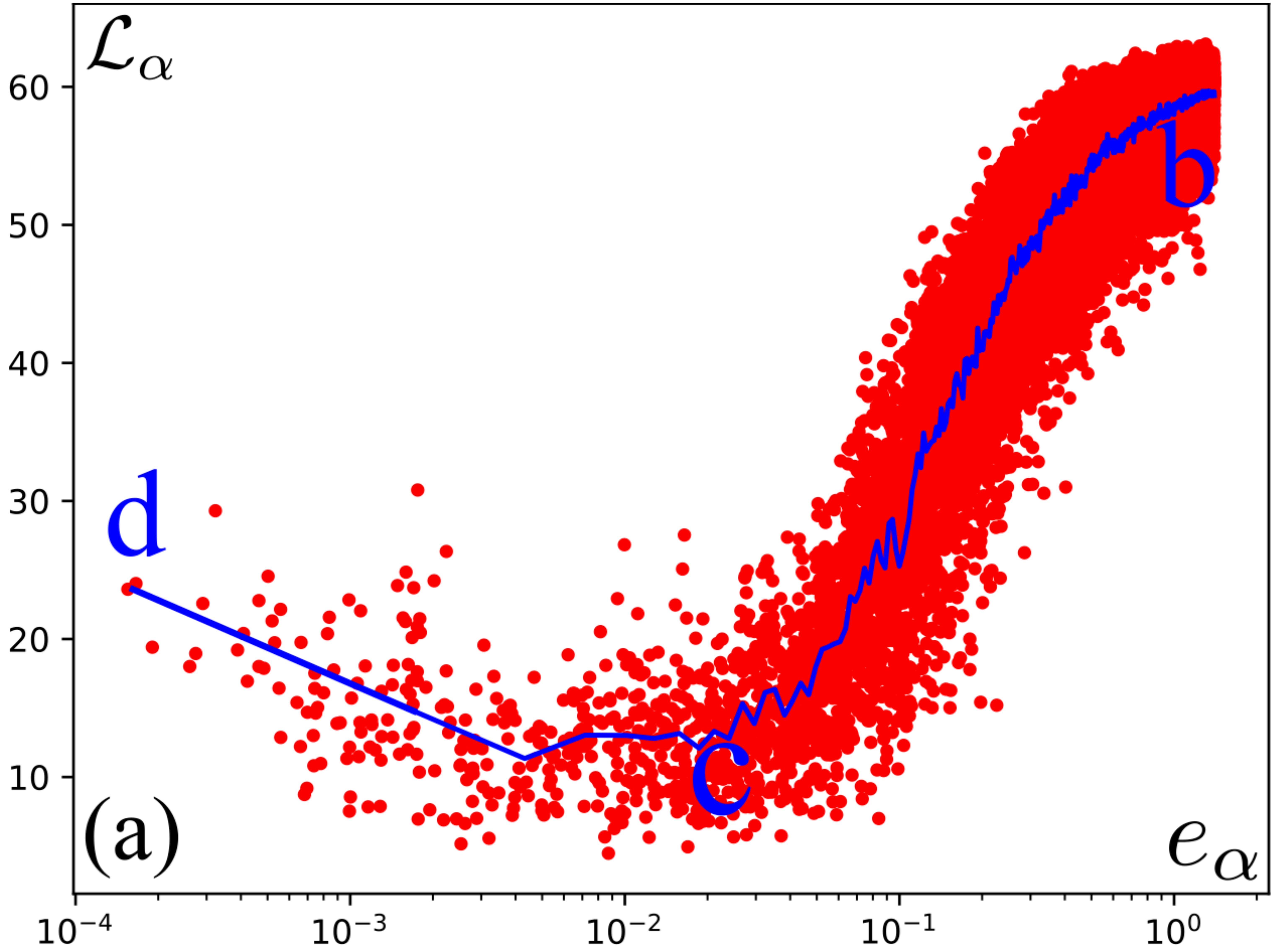

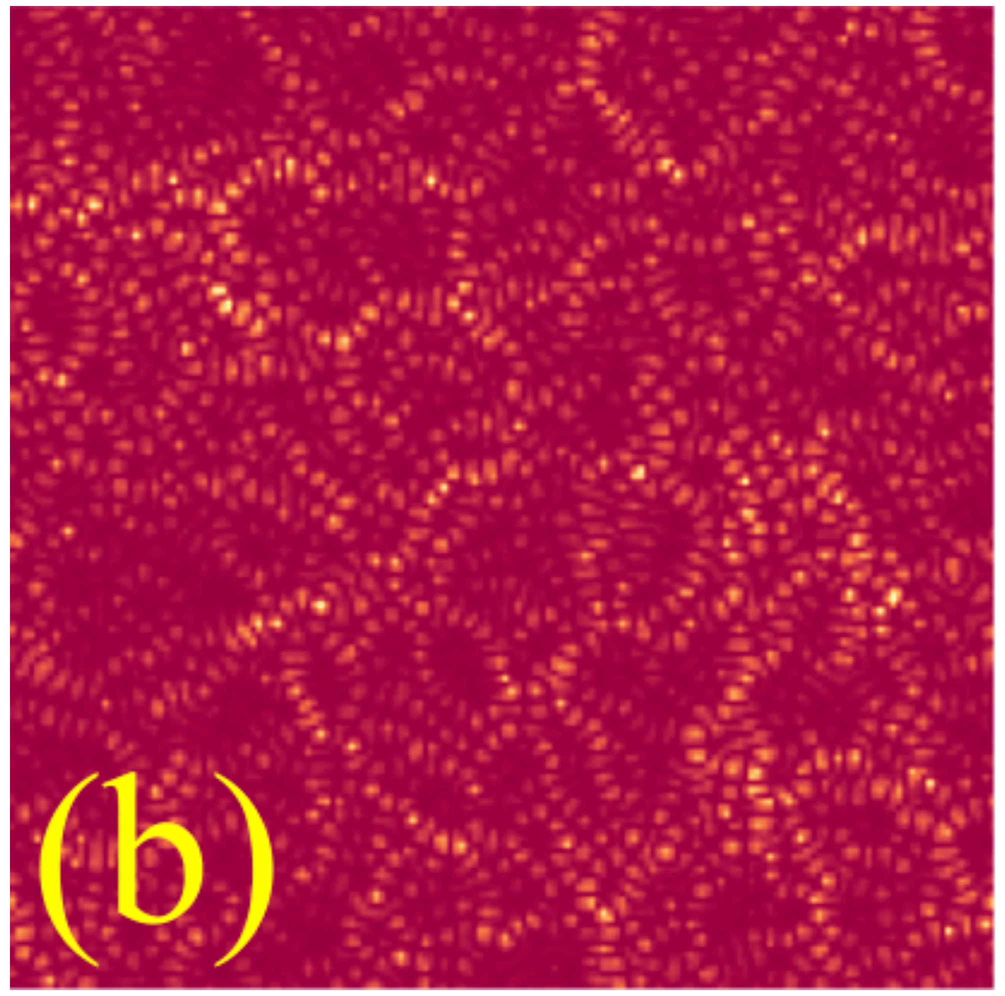

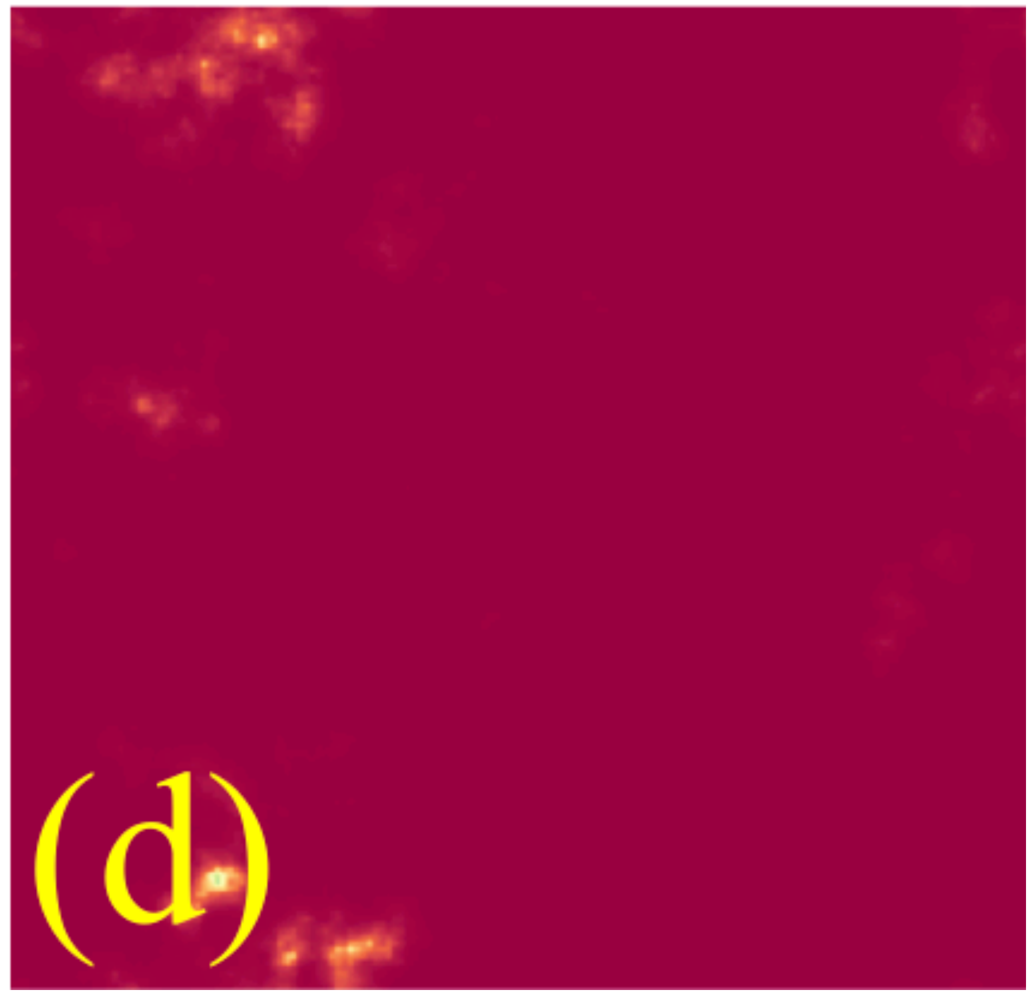

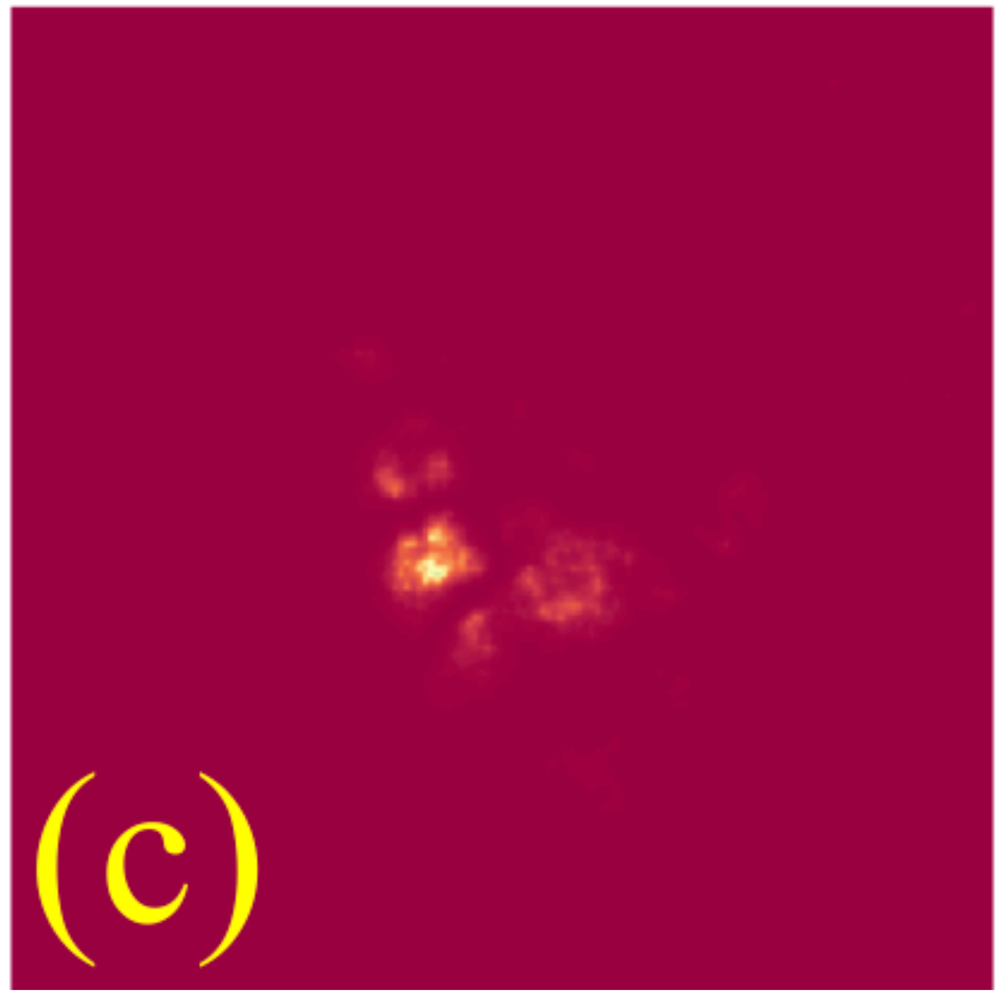

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Analysis of Landau-damped bosonic eigenmodes

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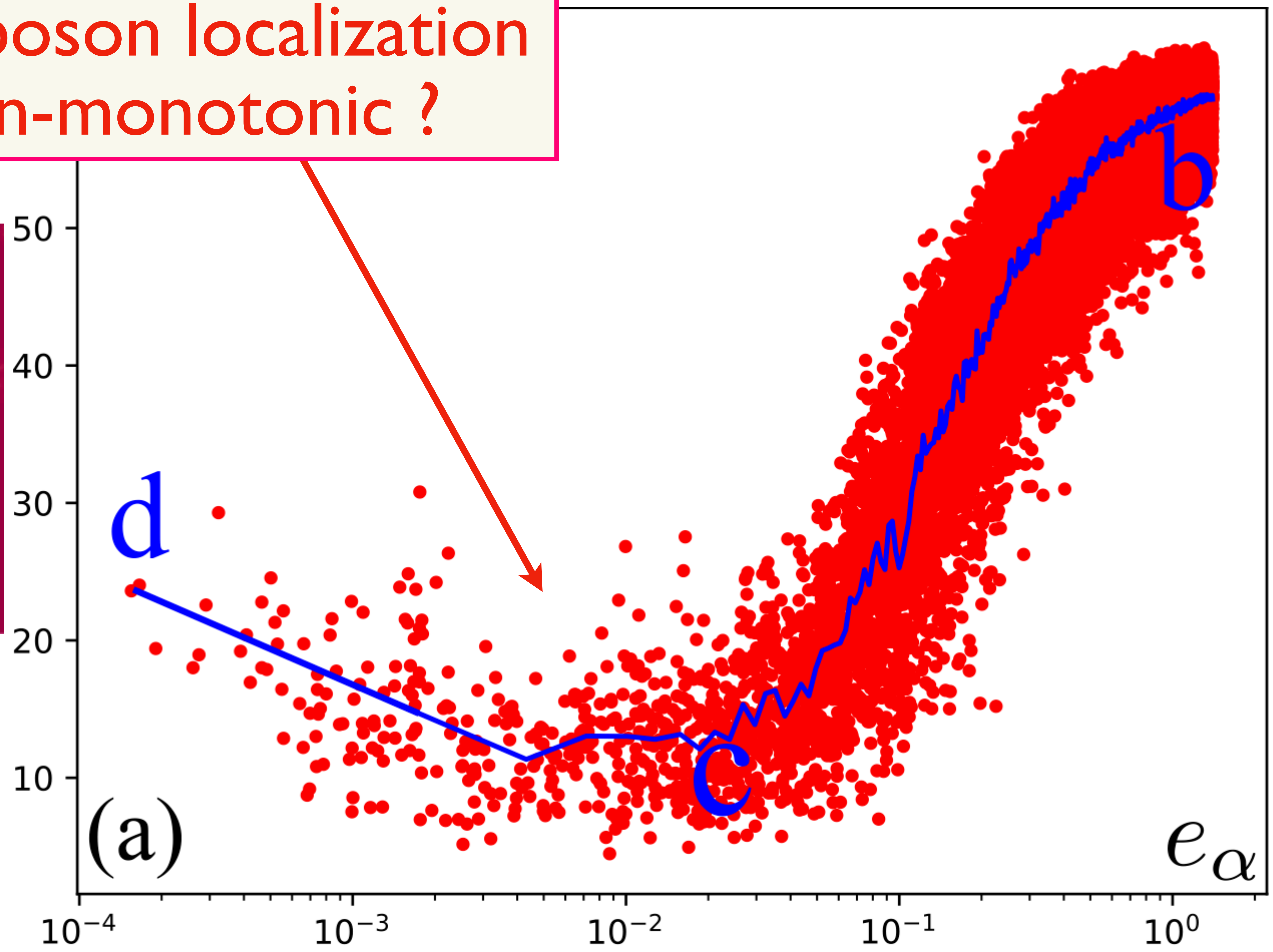
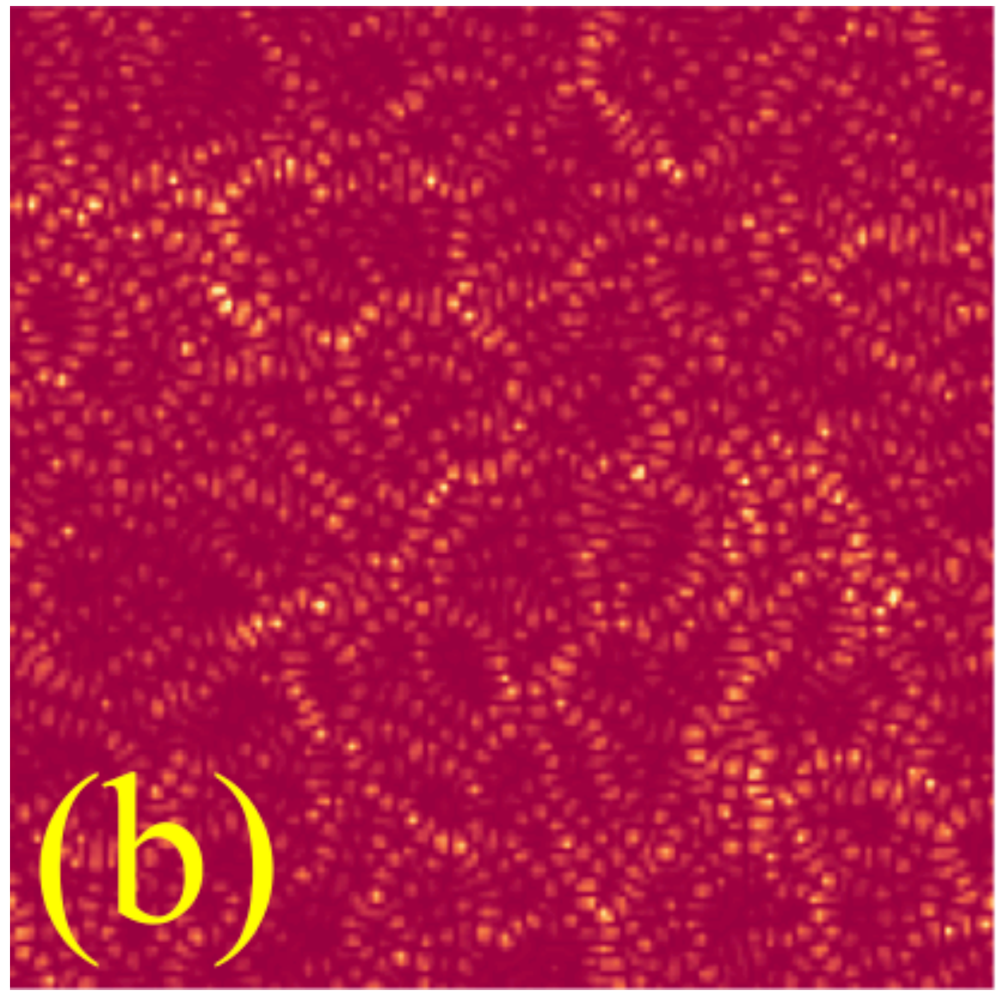
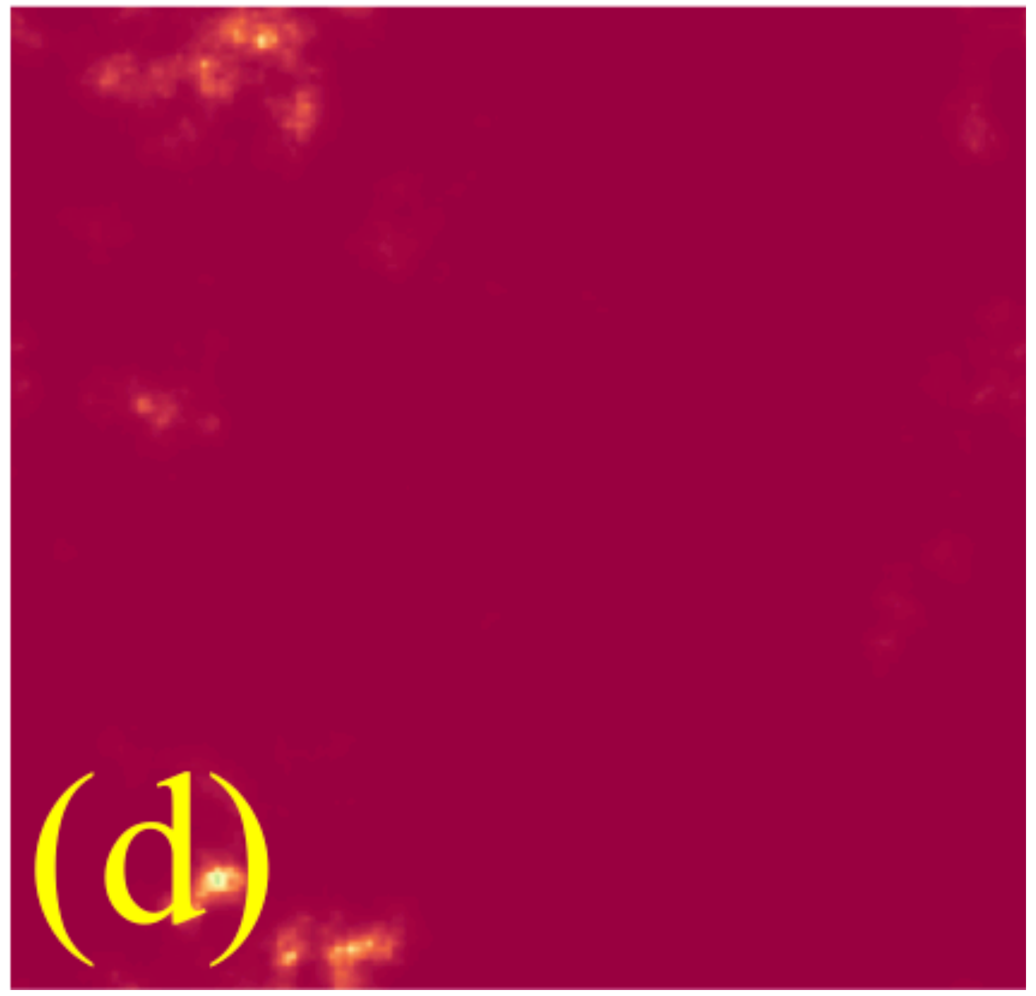
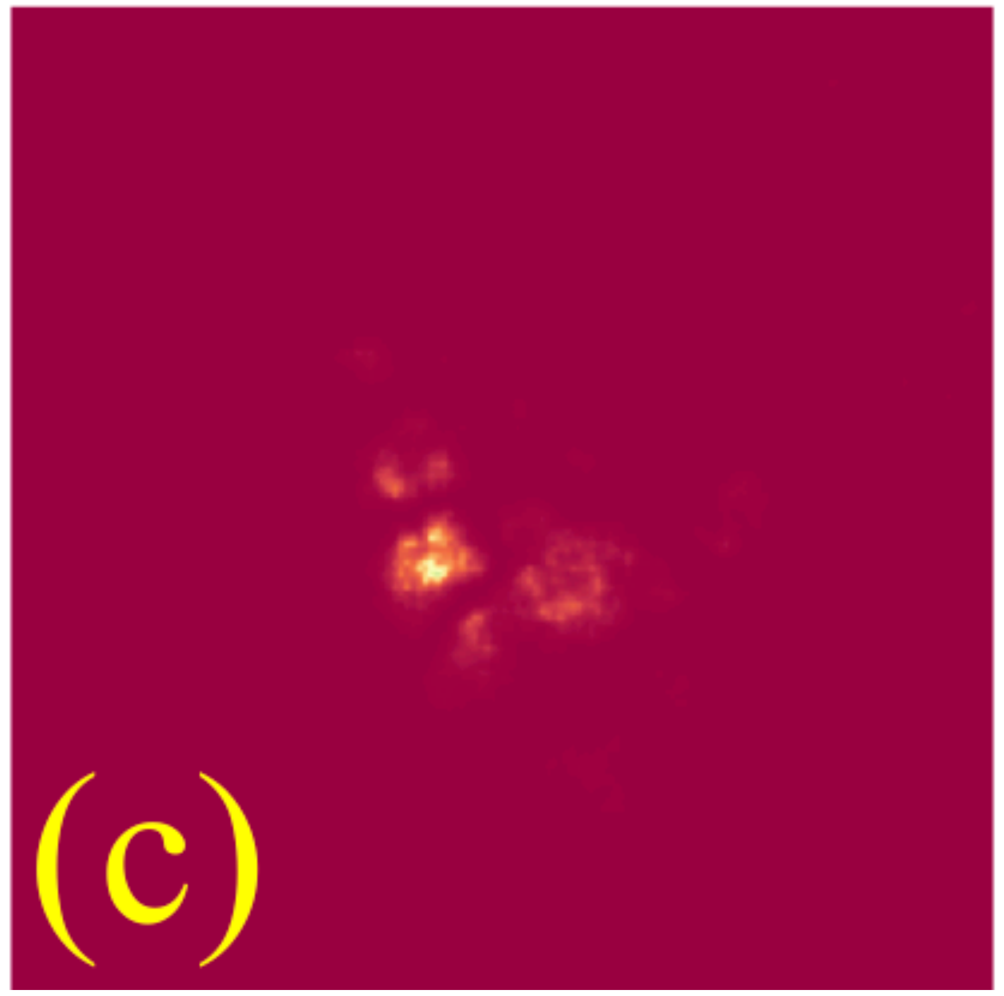
Why is the boson localization length non-monotonic ?









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

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

Department of Physics, University of Missouri-Rolla, Rolla, Missouri 65409, USA

(Received 19 May 2007; published 4 December 2007)

We study the effects of dissipation on a disordered quantum phase transition with $O(N)$ order-parameter symmetry by applying a strong-disorder renormalization group to the Landau-Ginzburg-Wilson field theory of the problem. We find that Ohmic dissipation results in a nonperturbative infinite-randomness critical point

$$\mathcal{S}_b = \int d\tau \left(-\sum_{\langle ij \rangle} J_{ij}\phi_{ia}\phi_{ja} + \sum_j \left[\frac{s_j}{2}\phi_{ja}^2 + \frac{u}{4}\left(\phi_{ja}^2\right)^2 \right] \right) + \frac{T\gamma}{2}\sum_{\omega_n}\sum_j |\omega_n||\phi_{ja}(\omega_n)|^2$$

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Strong disorder RG identical to that for the RTFIM (D.S. Fisher)

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

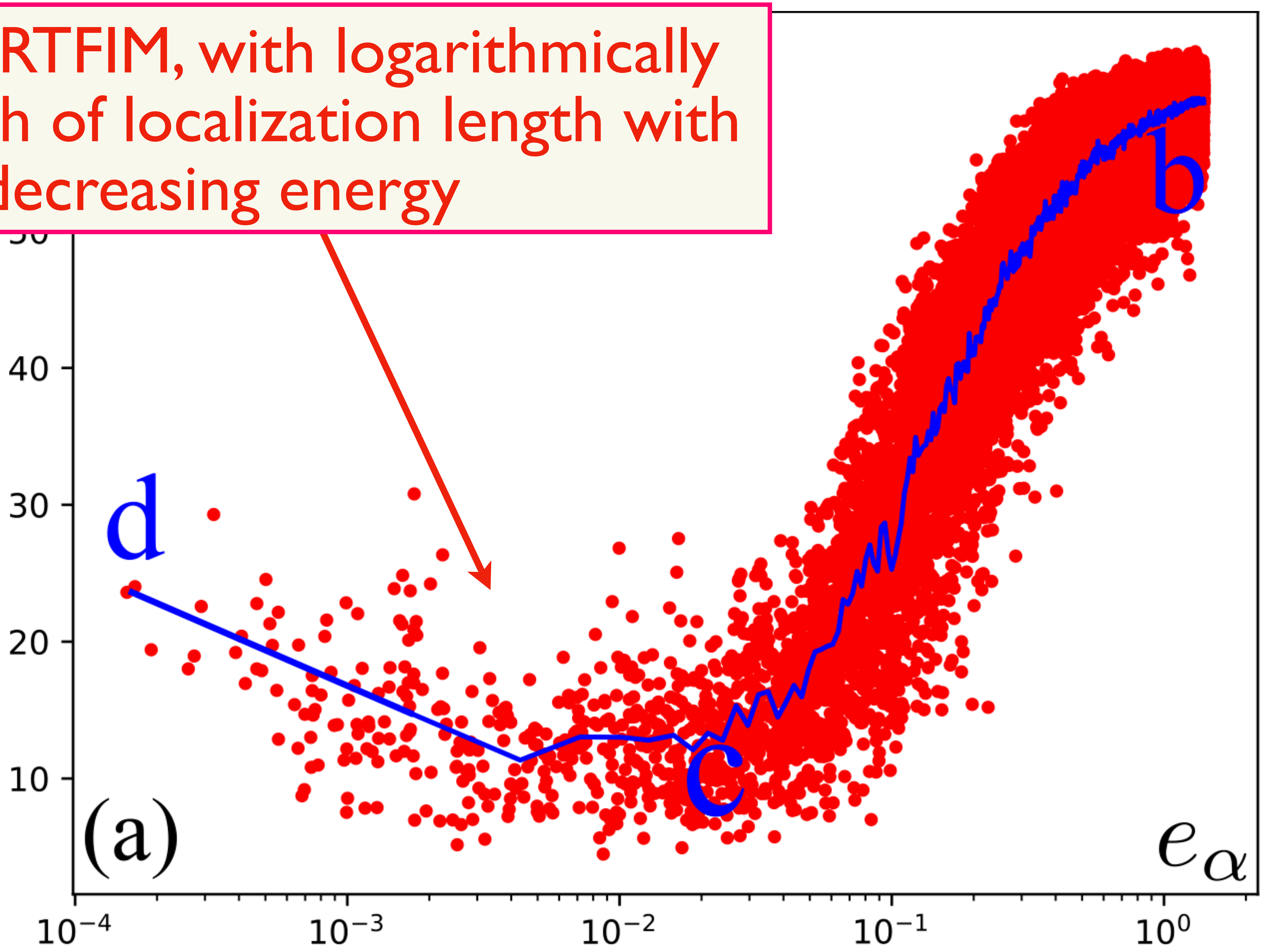
$$\widetilde{s}_2 = 2\frac{s_2 s_3}{J_{23}}$$

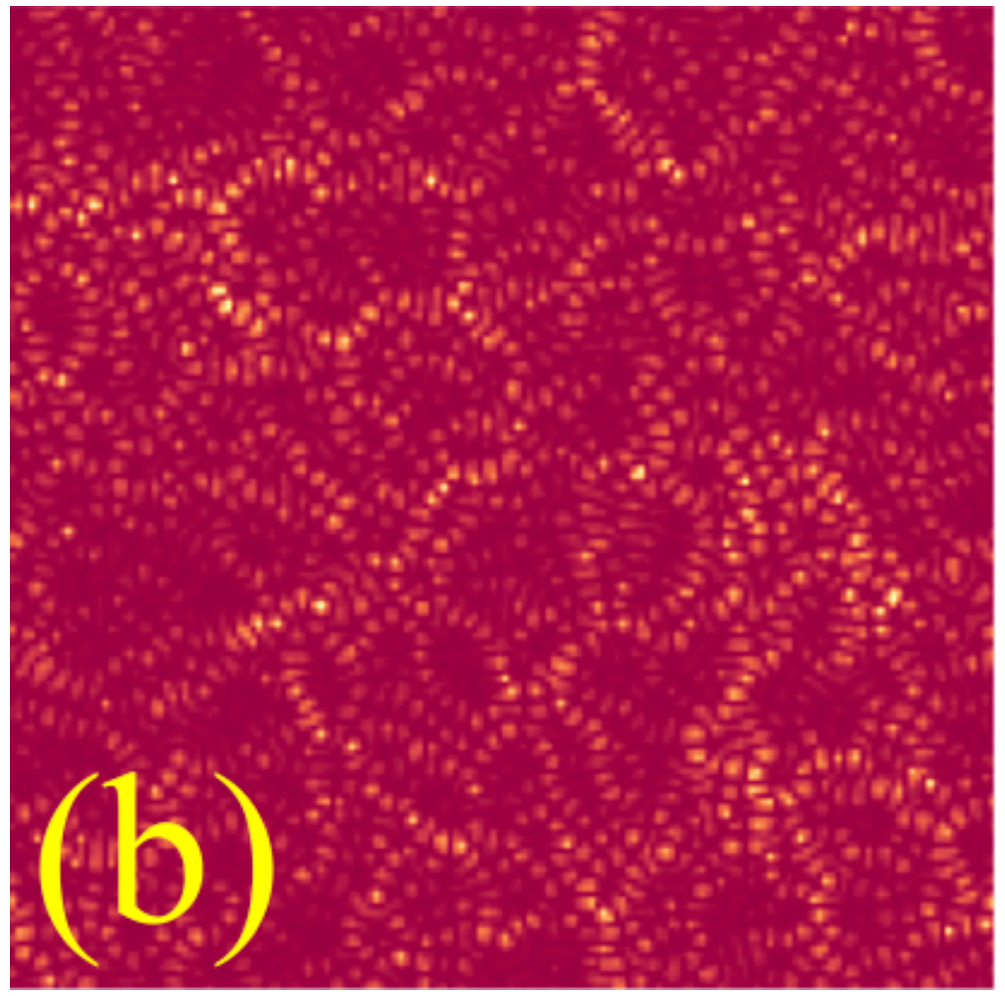
$$H_{\mathrm{RTFIM}} = -\sum_{\langle ij\rangle} J_{ij} Z_i Z_j - \sum_j s_j X_j$$

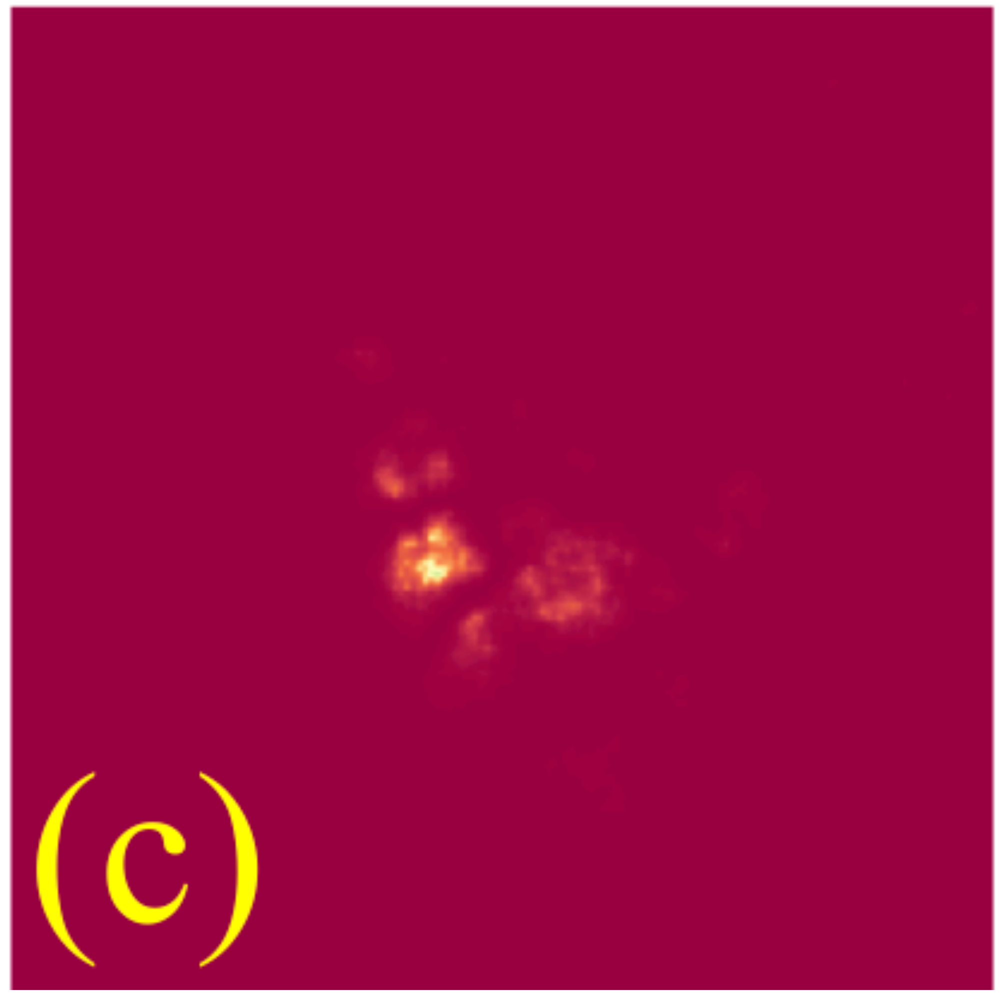
Analysis of Landau-damped bosonic eigenmodes

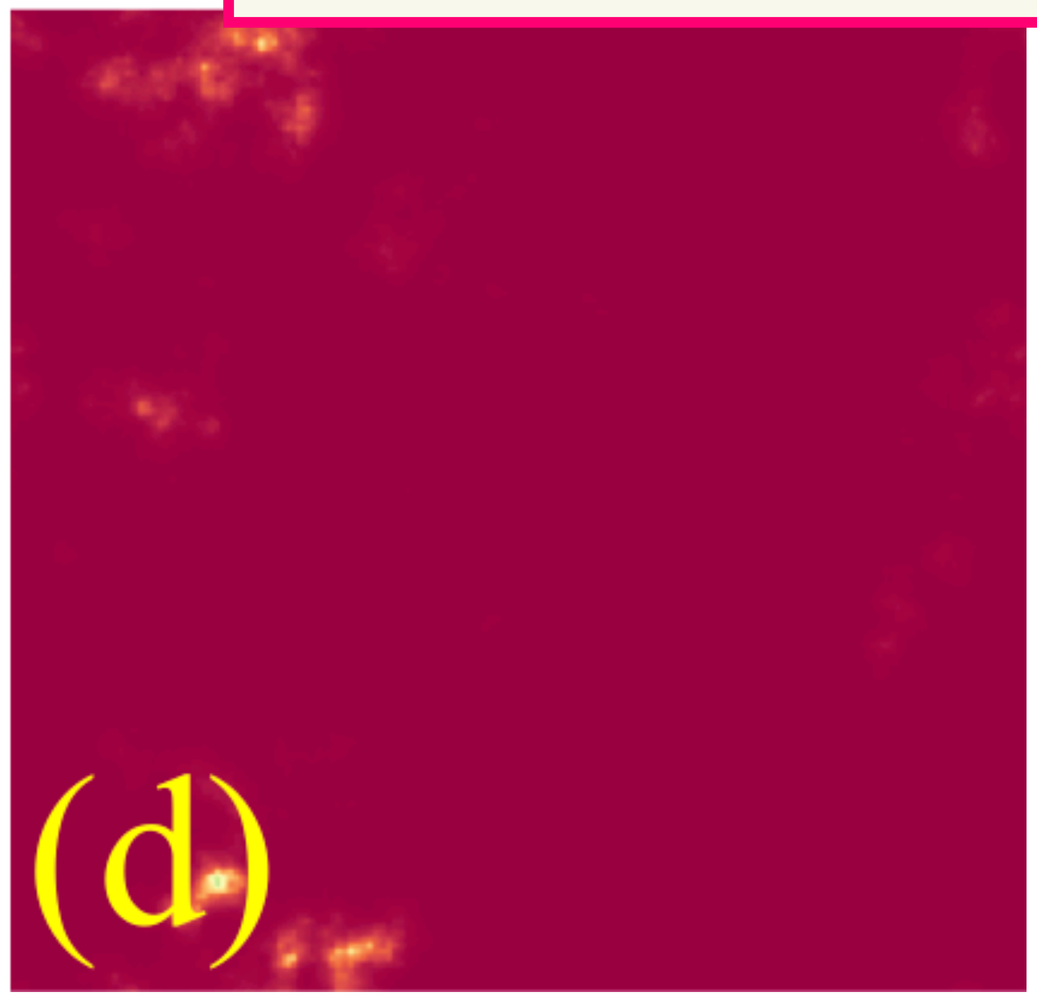
ϕ eigenmodes localization length $\mathcal{L}_\alpha$

Physics of RTFIM, with logarithmically slow growth of localization length with decreasing energy









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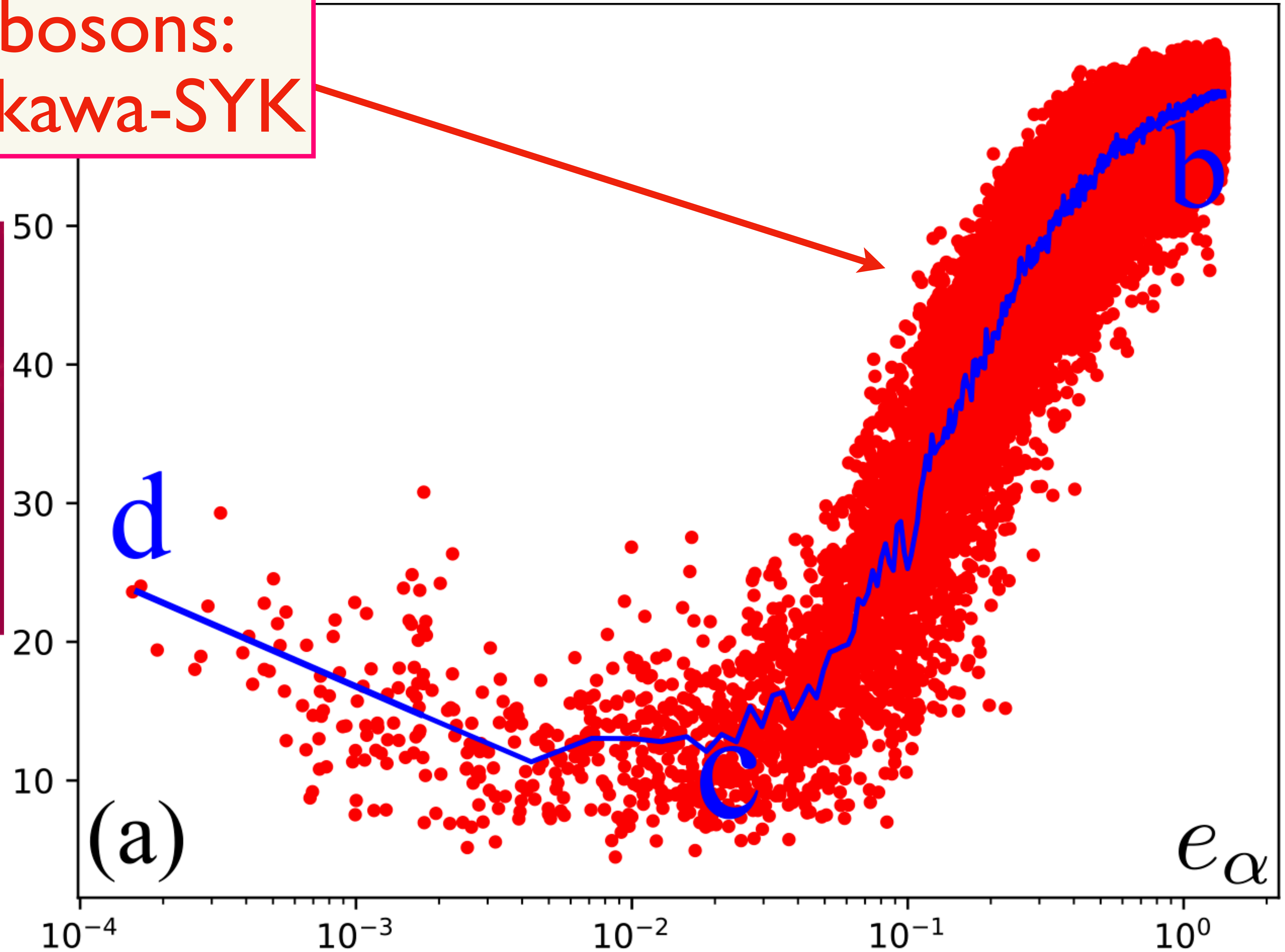
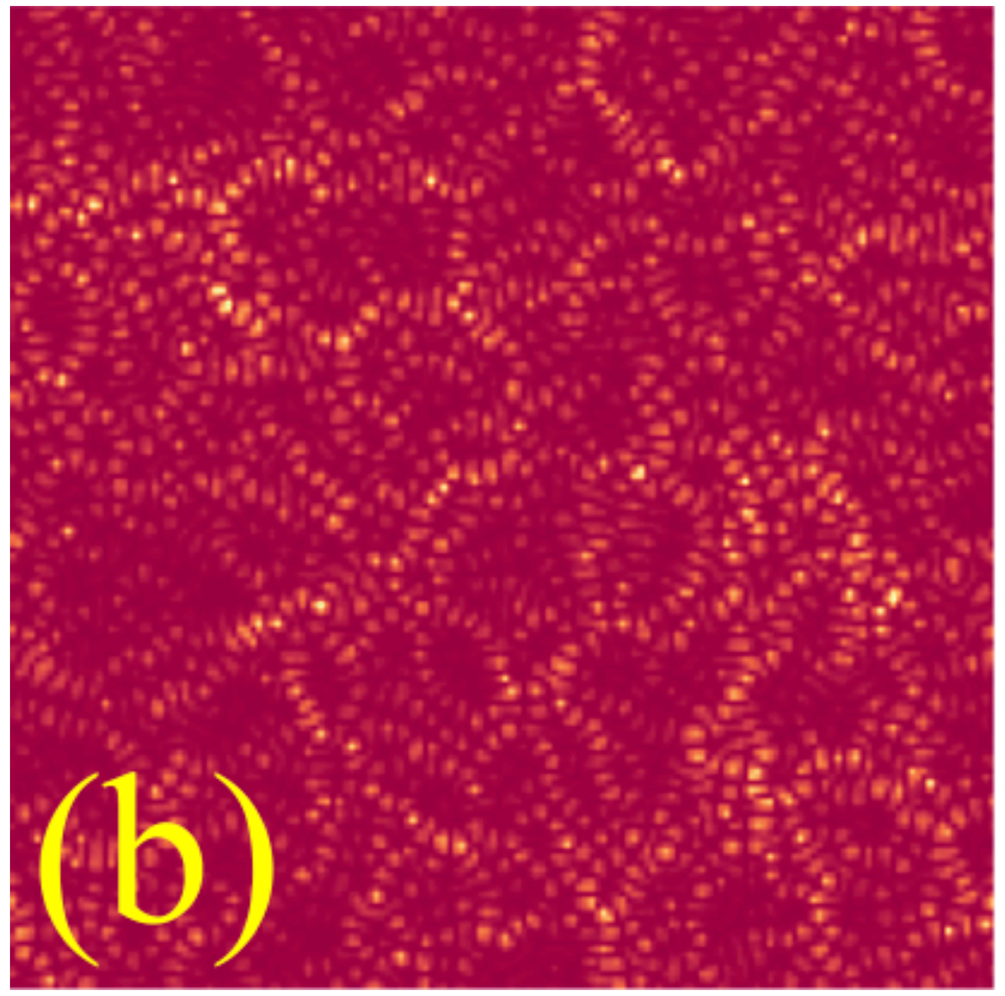
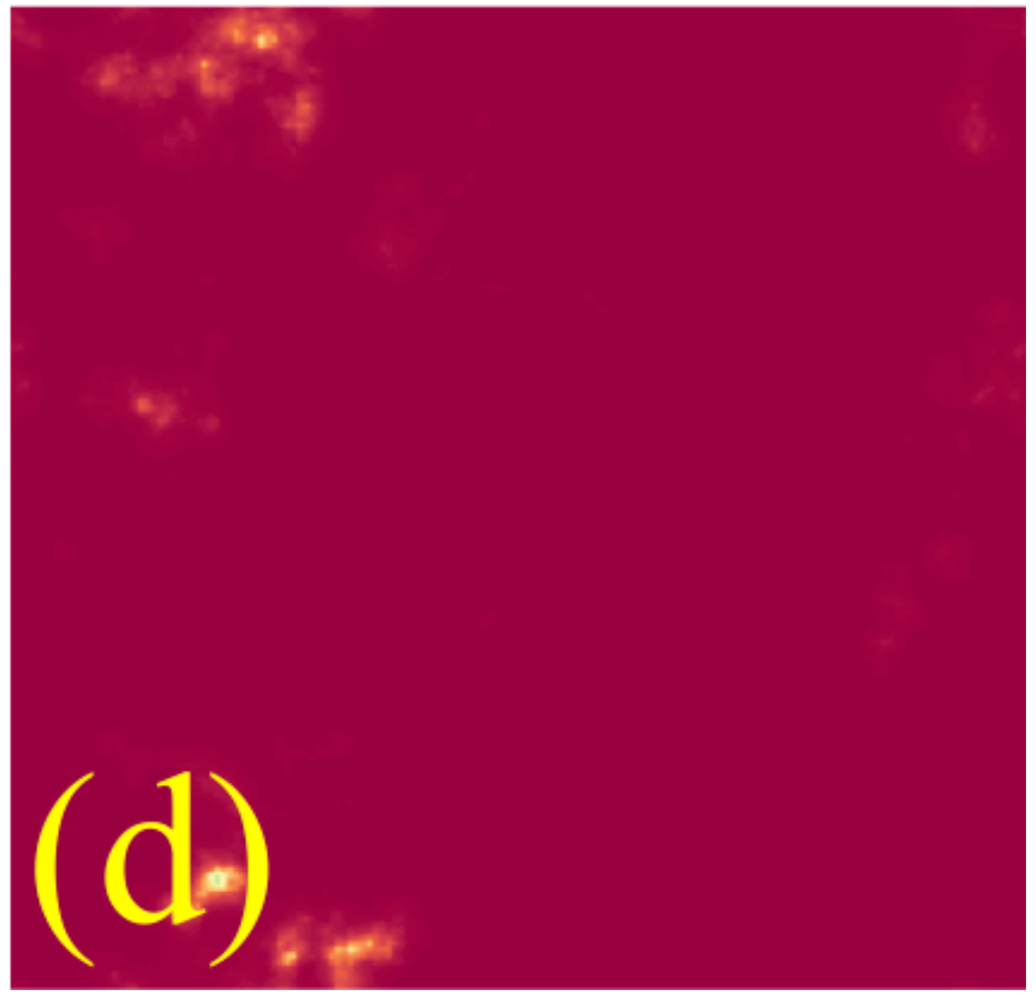
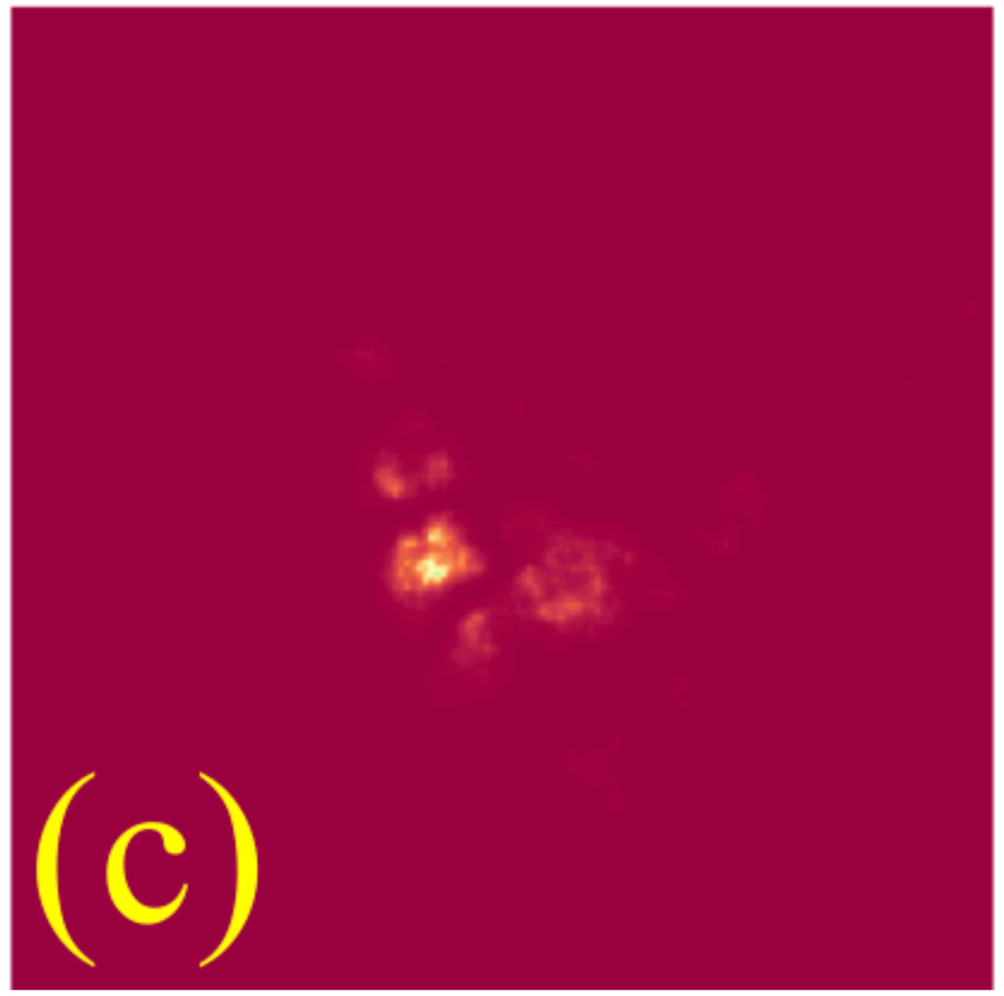
Extended bosons: physics of Yukawa-SYK





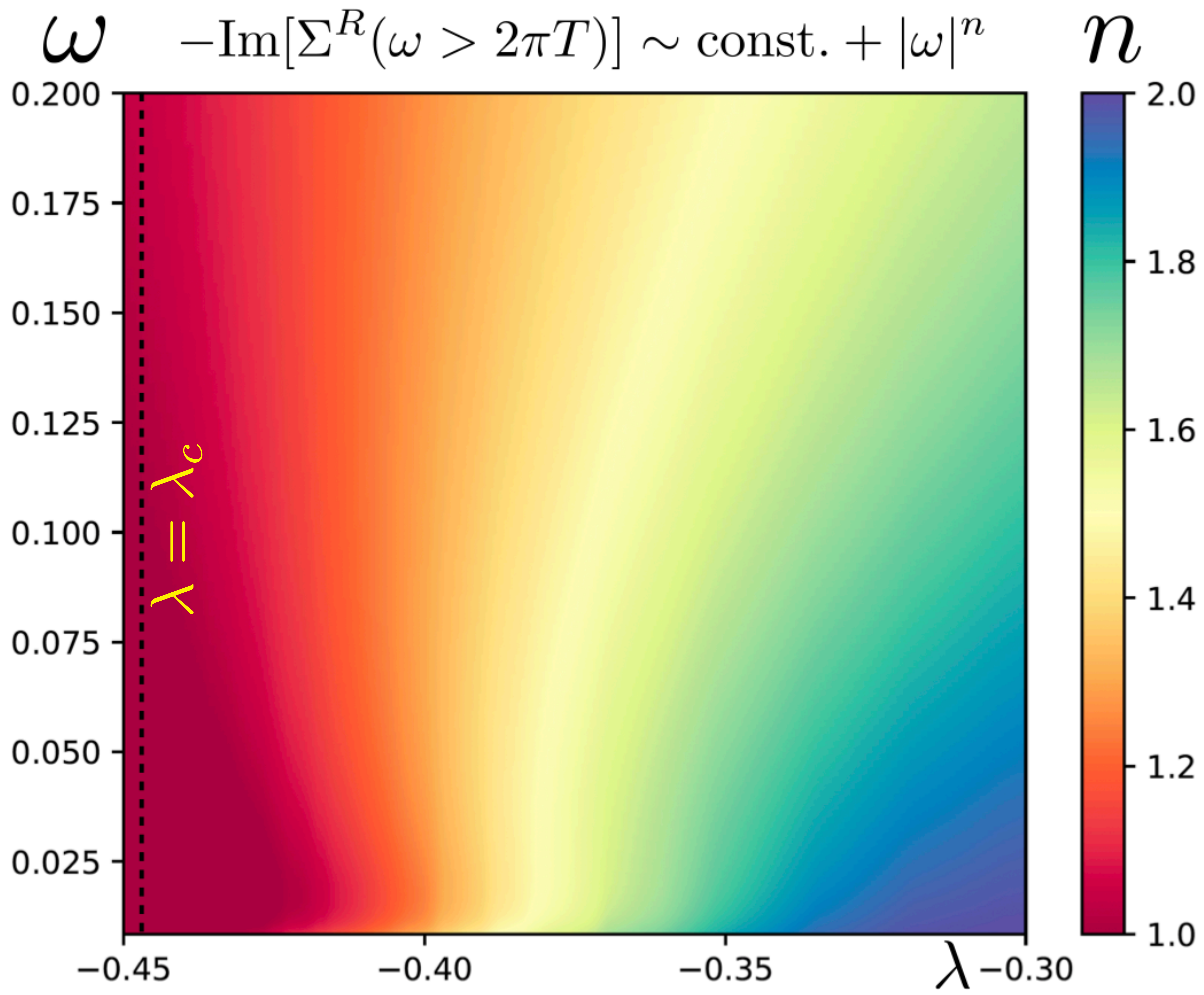




Aavishkar A. Patel,
Peter Lunts, S.S.,
arXiv:2312.06751

Transport scattering rate

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

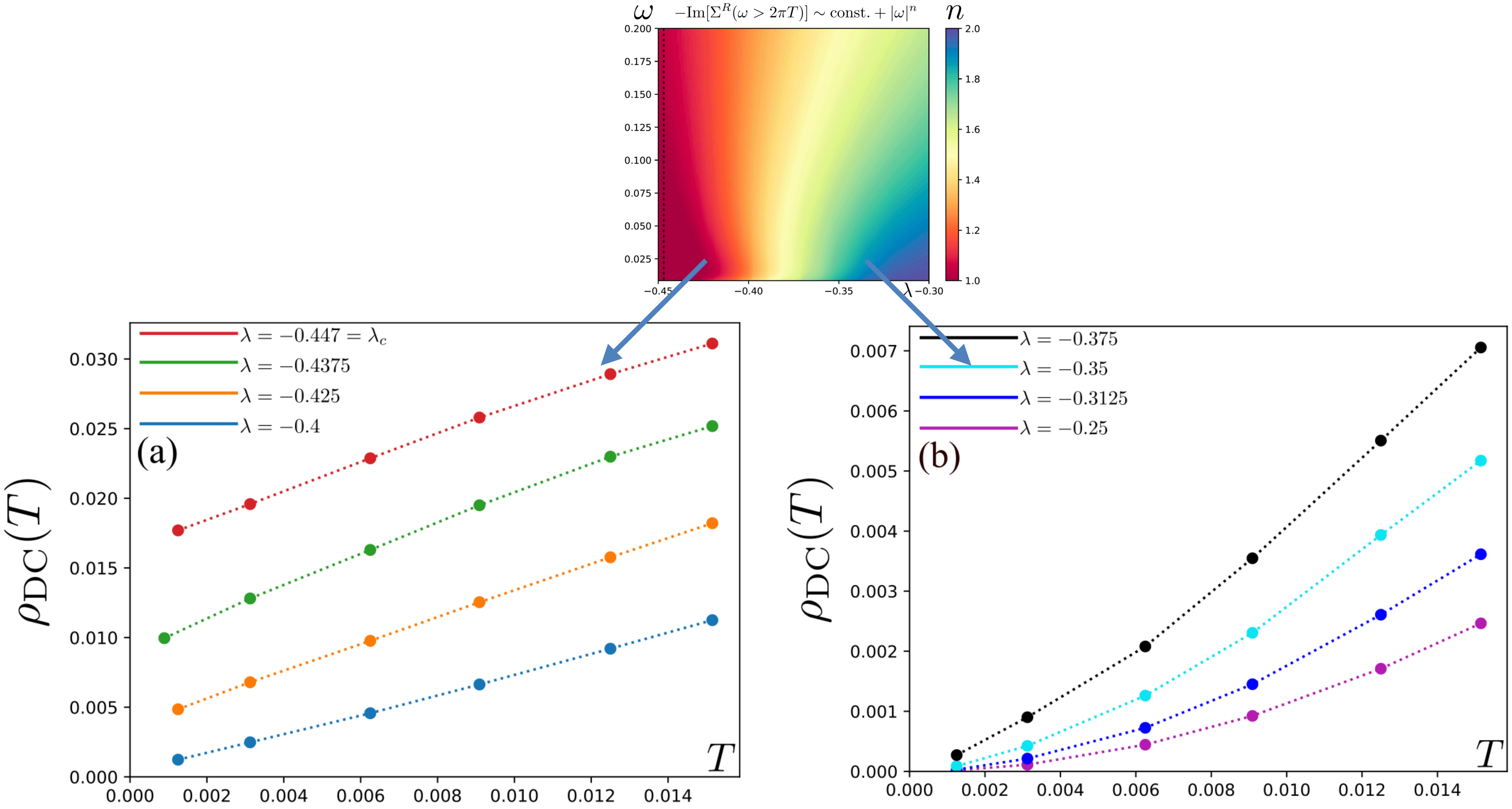


$L = 160, \beta = 800$, 10 disorder samples

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

Aavishkar A. Patel,
Peter Lunts, S.S.,
arXiv:2312.06751

DC resistivity



Extended region in λ with T-linear resistivity - a strange metal *phase*

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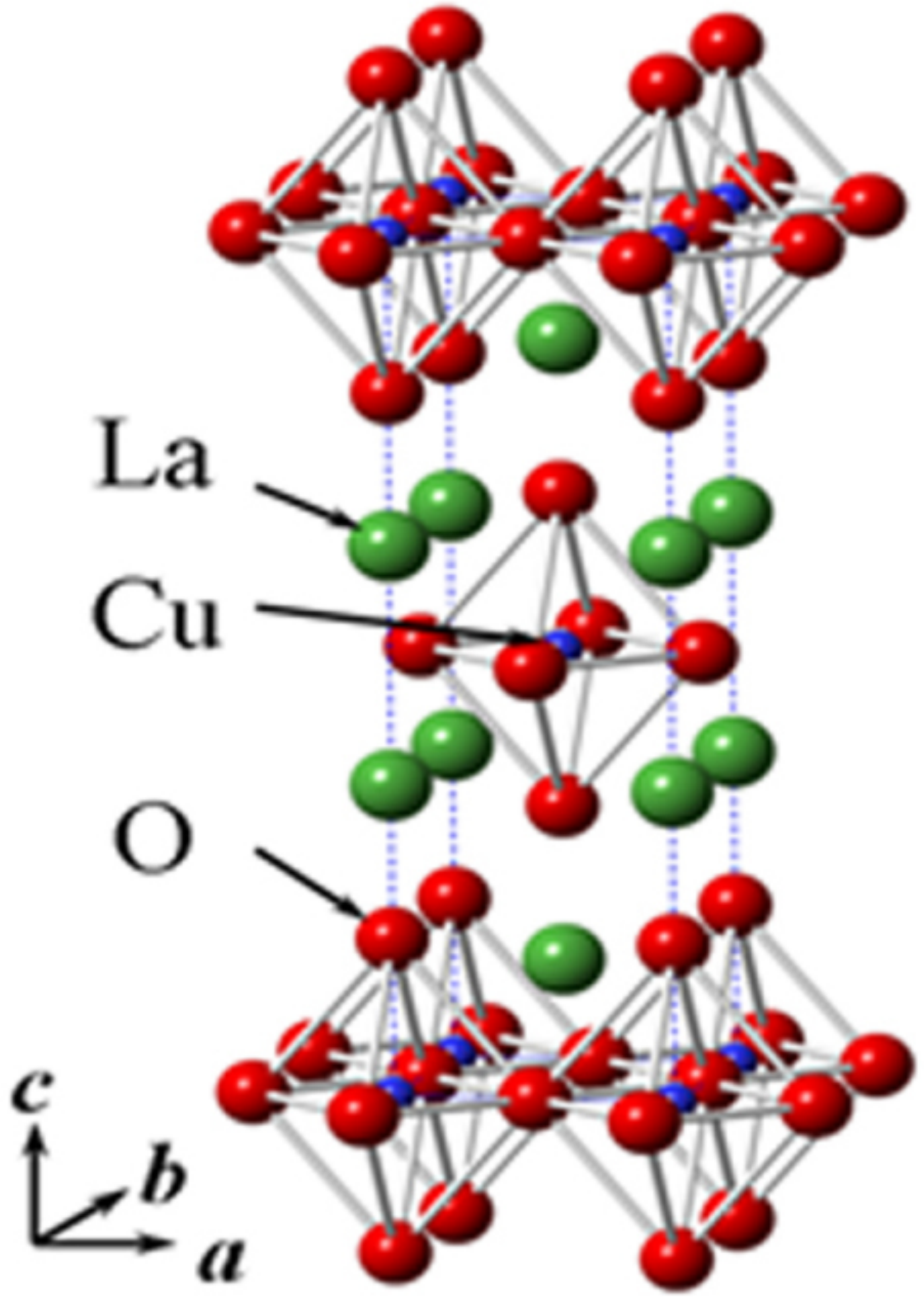
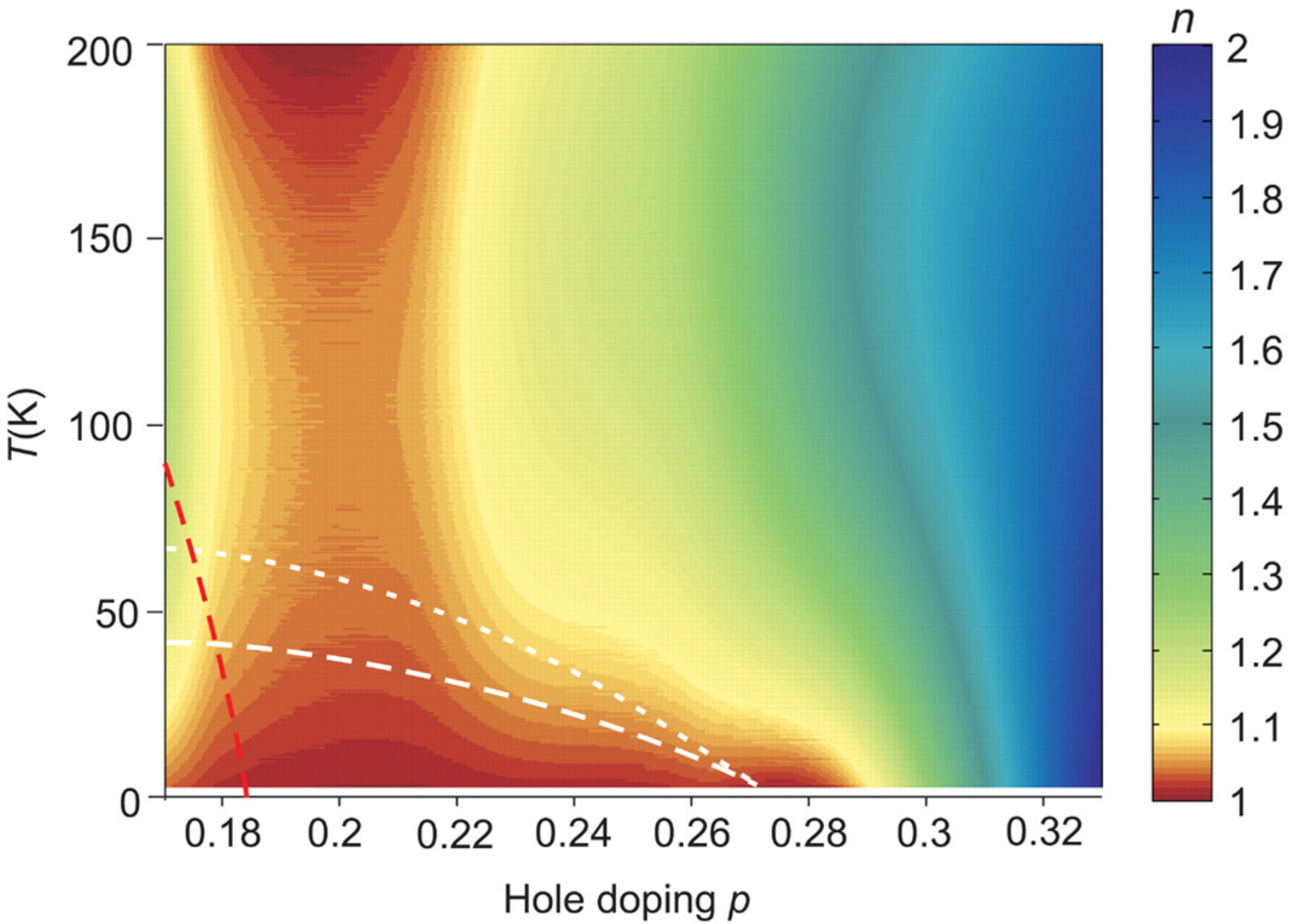
Anomalous Criticality in the Electrical Resistivity of $La_{2-x}Sr_xCuO_4$

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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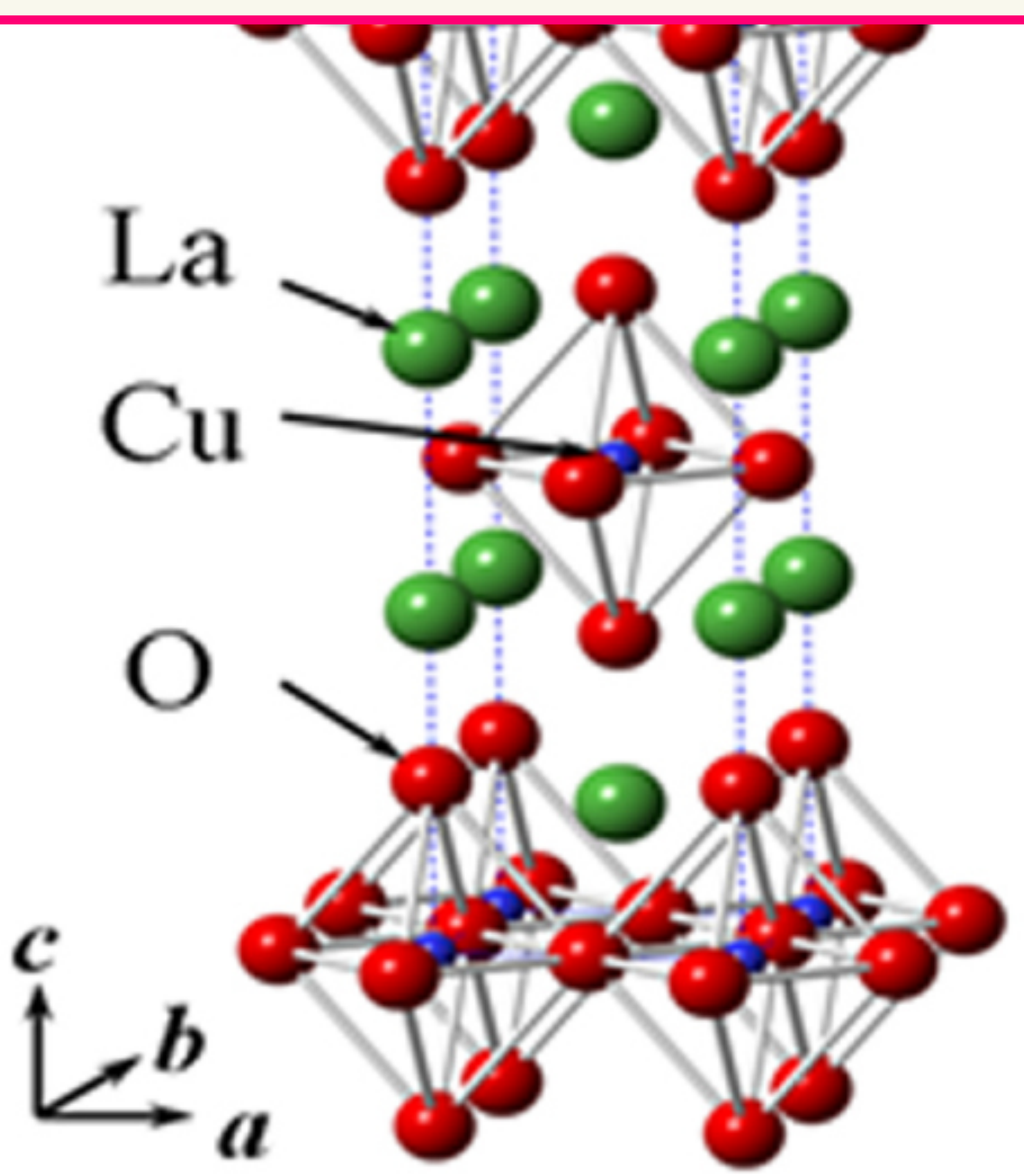
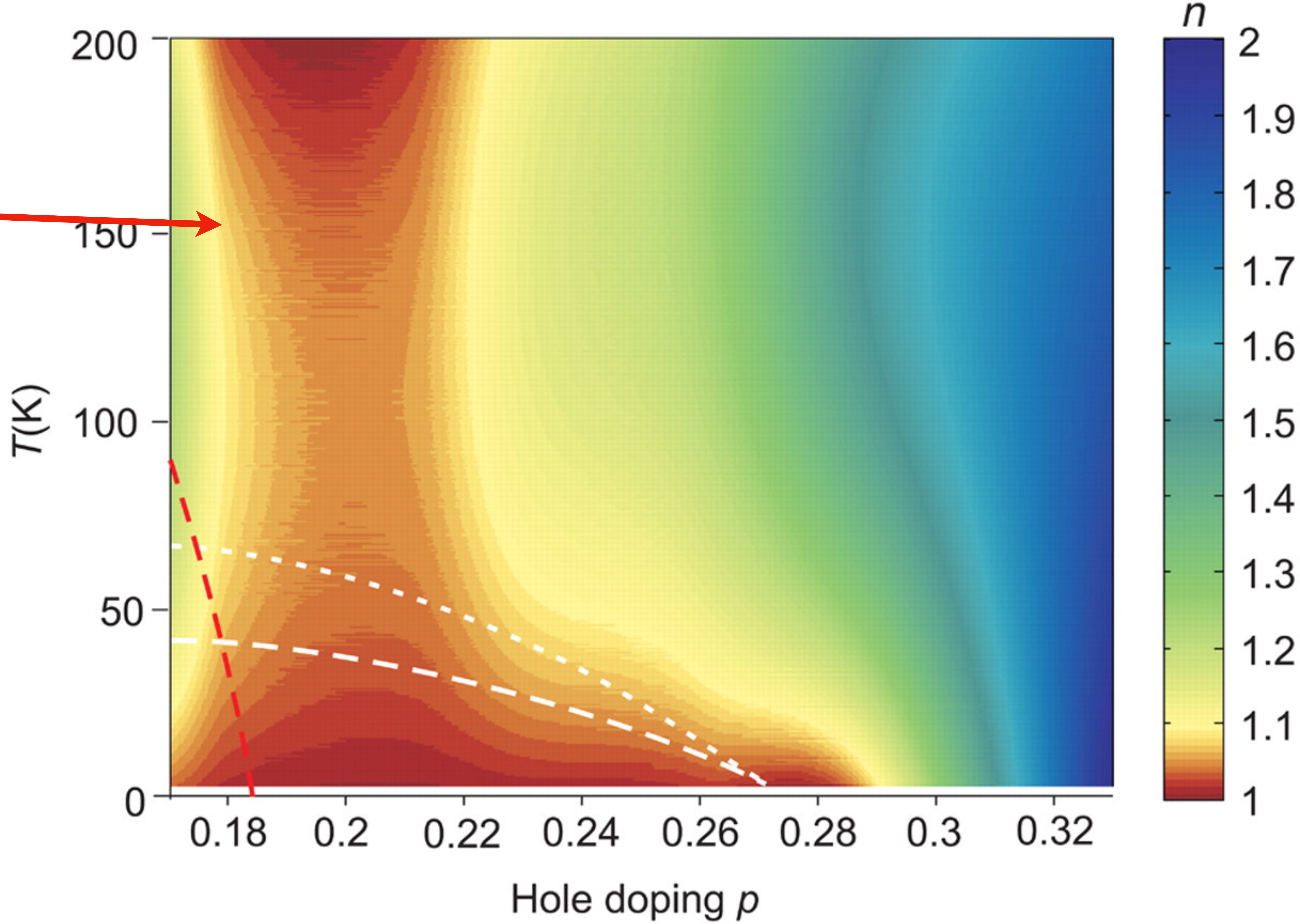
Extended bosons: physics of Yukawa-SYK





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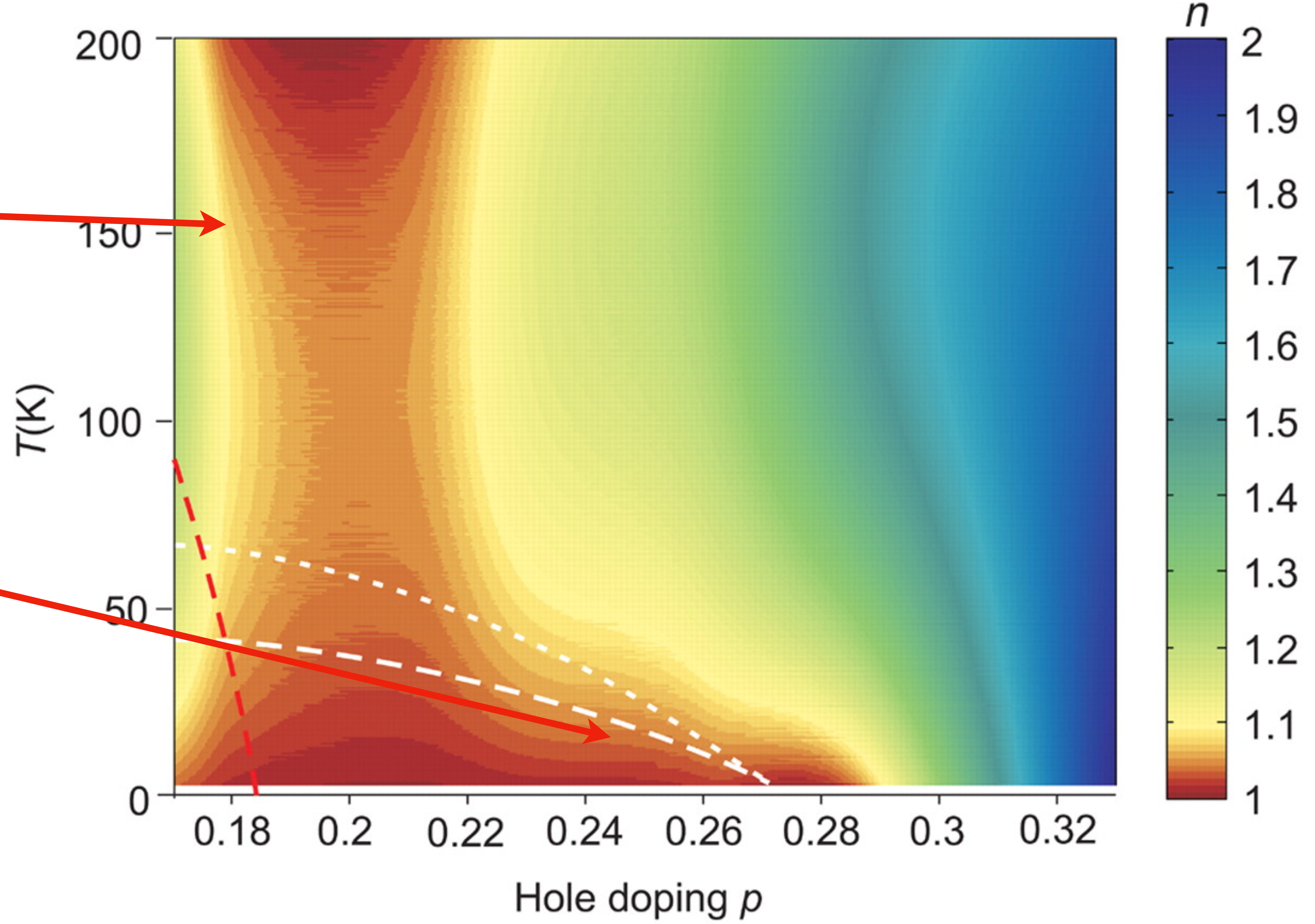
Extended bosons:
physics of Yukawa-SYK

Localized
overdamped
bosons,
but extended
fermions



Outlook

- Quantum Monte Carlo
- Shot noise
- Strong non-linear response
- Cyclotron resonance and quantum oscillations
- Magnetotransport
- Superconductivity

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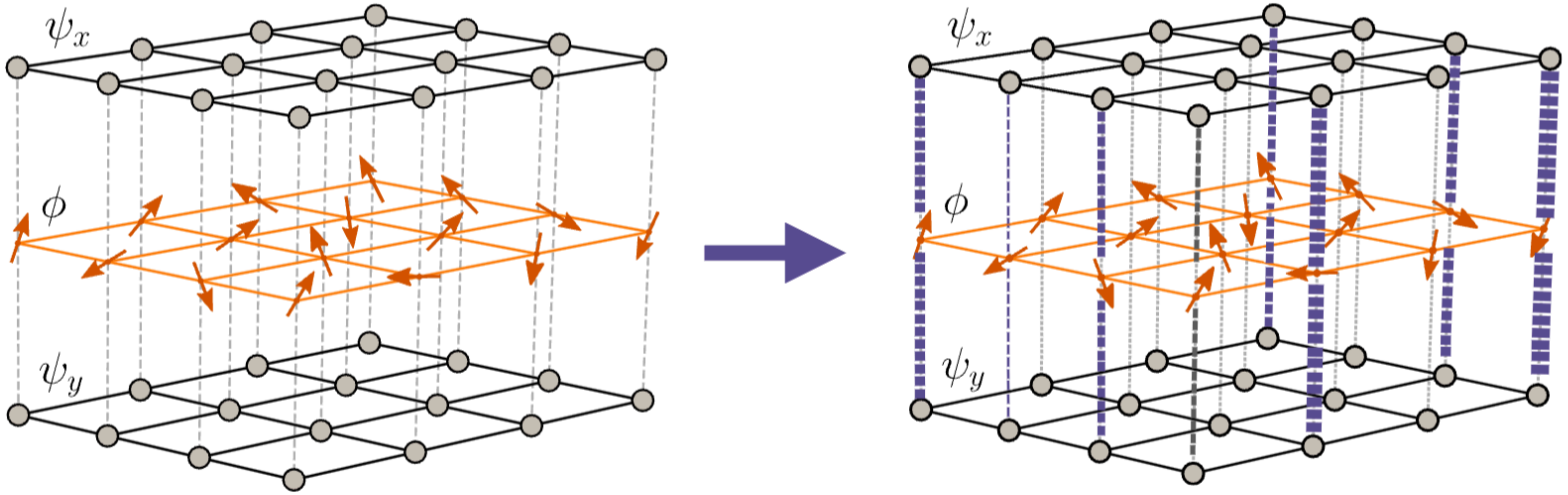
Model for sign-free QMC

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

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

$\boxed{g = 0}$



coupling g = const

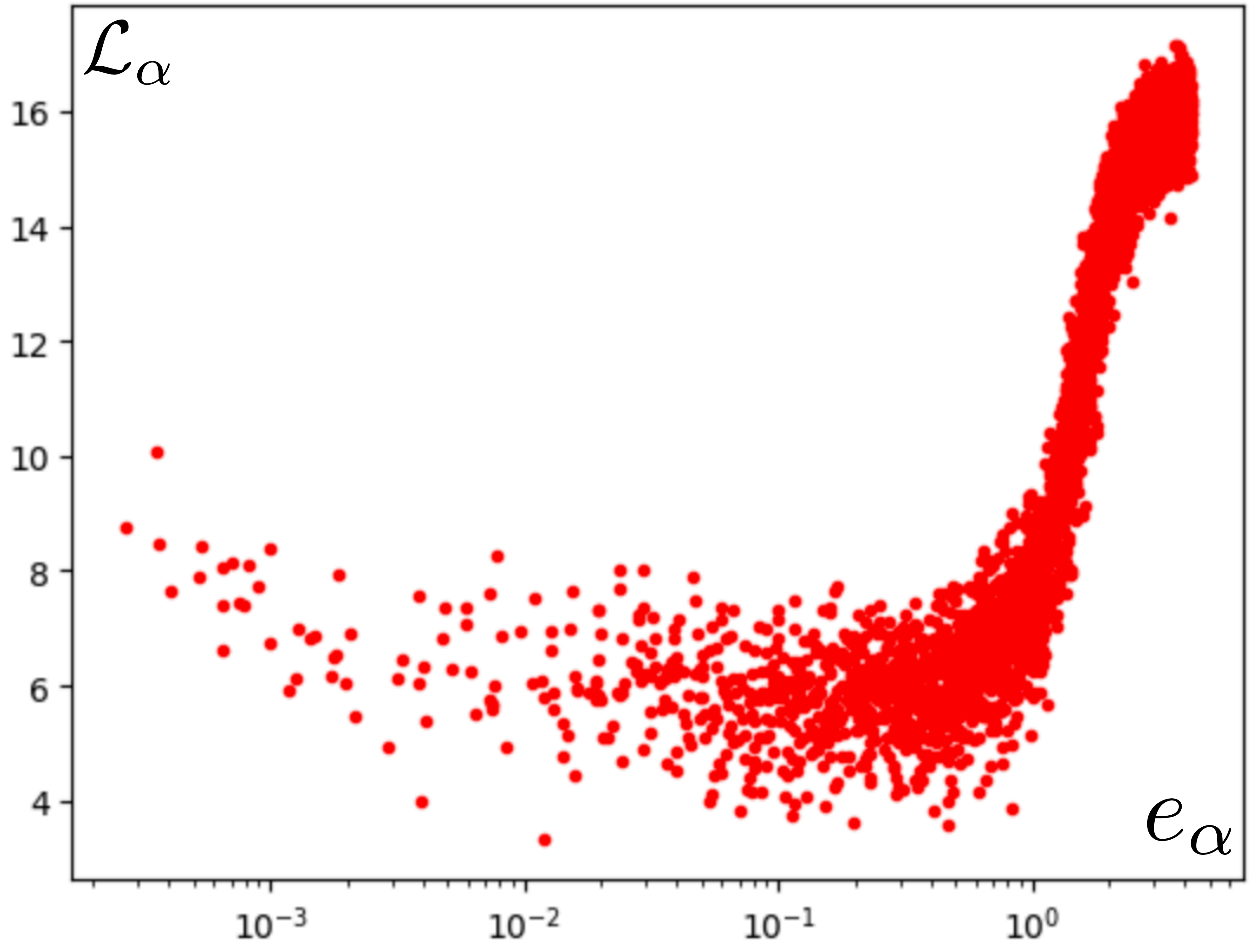
coupling g = spatially random

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

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

Boson eigenmodes at $\Omega = 0$ from QMC

- Localization length vs eigenvalue



10 disorder samples, $L = 40,\ \beta t = 66,\ g'^2 = t/2,\ \lambda \approx \lambda_c$

- Same qualitative features as large-M: localization followed by slow delocalization as energy is reduced.

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

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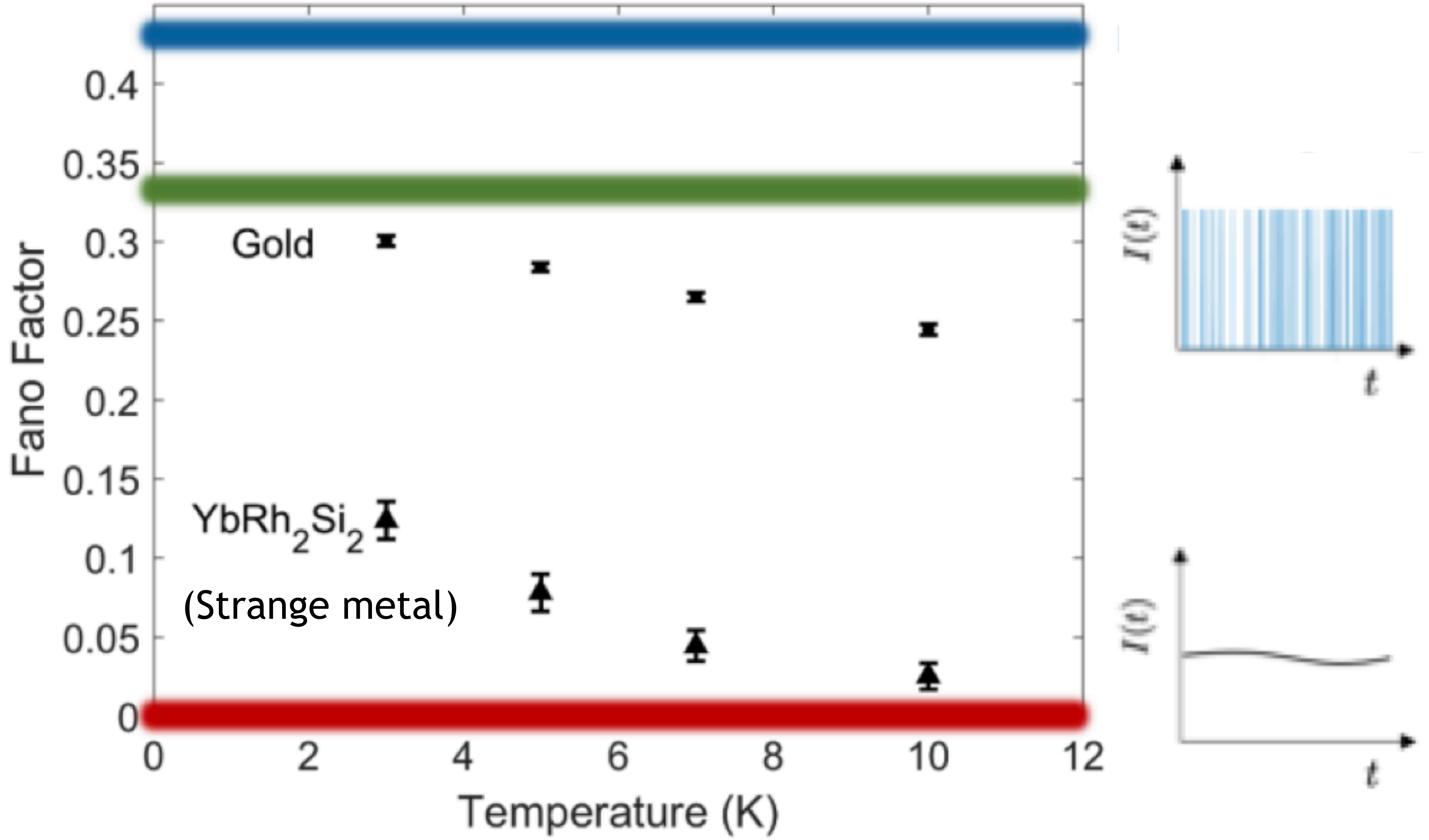
Strange metals: Experimental signatures

Inelastic scattering from shot noise



Chen et al, Science **382**, 907-911 (2023)

- Shot noise reflects granularity of current.
- Inelastic scattering into a boson bath degrades momentum and energy and reduces granularity, suppressing shot noise.

Theory: A. Nikolaenko, Aaavishkar A. Patel, S. Sachdev, **Phys. Rev. Research 5, 043143 (2023)** and **to appear**

$$\boxed{g = 0,\ g' \neq 0,\ v \neq 0}$$

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Strong non-linear response of strange metals

Serhii Kryhin, Subir Sachdev, and Pavel A. Volkov

arXiv:2403.xxxxx

...Uniting the large-N and Keldysh field theory formalisms, we derive a set of kinetic equations for the strange metal and use it to compute nonlinear conductivity. We find that the third-order conductivity is enhanced by a factor of T_F/T in comparison to a Fermi liquid, resulting in a strong temperature dependence. This behavior is shown to arise from the strong, non-analytic energy dependence of scattering rate and self-energies for electrons. We discuss the potential for nonanalytic nonlinear electric field response arising at low temperatures.

$\boxed{g = 0,\ g' \neq 0,\ v \neq 0}$

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Cyclotron resonance and quantum oscillations of critical Fermi surfaces

Haoyu Guo, Davide Valentinis, Jörg Schmalian, Subir Sachdev, and Aavishkar A. Patel
Physical Review B **109**, 075162 (2024)

…We show that a version of Kohn's theorem continues to apply to disorder-free non-Fermi-liquids with a critical boson near zero momentum. However, marginal Fermi liquids arising from a spatially random Yukawa coupling between the electrons and bosons do give rise to significant corrections to the cyclotron mass that we compute.

Outlook

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- Superconductivity

Davide Valentinis, Aavishkar A. Patel, …

Magnetoresistance, Hall conductivity, Hall angle, in self-consistent theory

$\boxed{g = 0,\, g' \neq 0,\, v \neq 0}$

Outlook

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Chenyuan Li, Ilya Esterlis . . .

Correlation between T_c and linear-T slope
Spectral functions in superconductor
Superfluid density

$\boxed{g = 0,\ g' \neq 0,\ v \neq 0}$

Outlook

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