Planckian metals

Workshop on Ultra-Quantum Matter
Institute for Advanced Study, Princeton
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INSTITUTE FOR ADVANCED STUDY

Talk online: sachdev.physics.harvard.edu

PHYSICS
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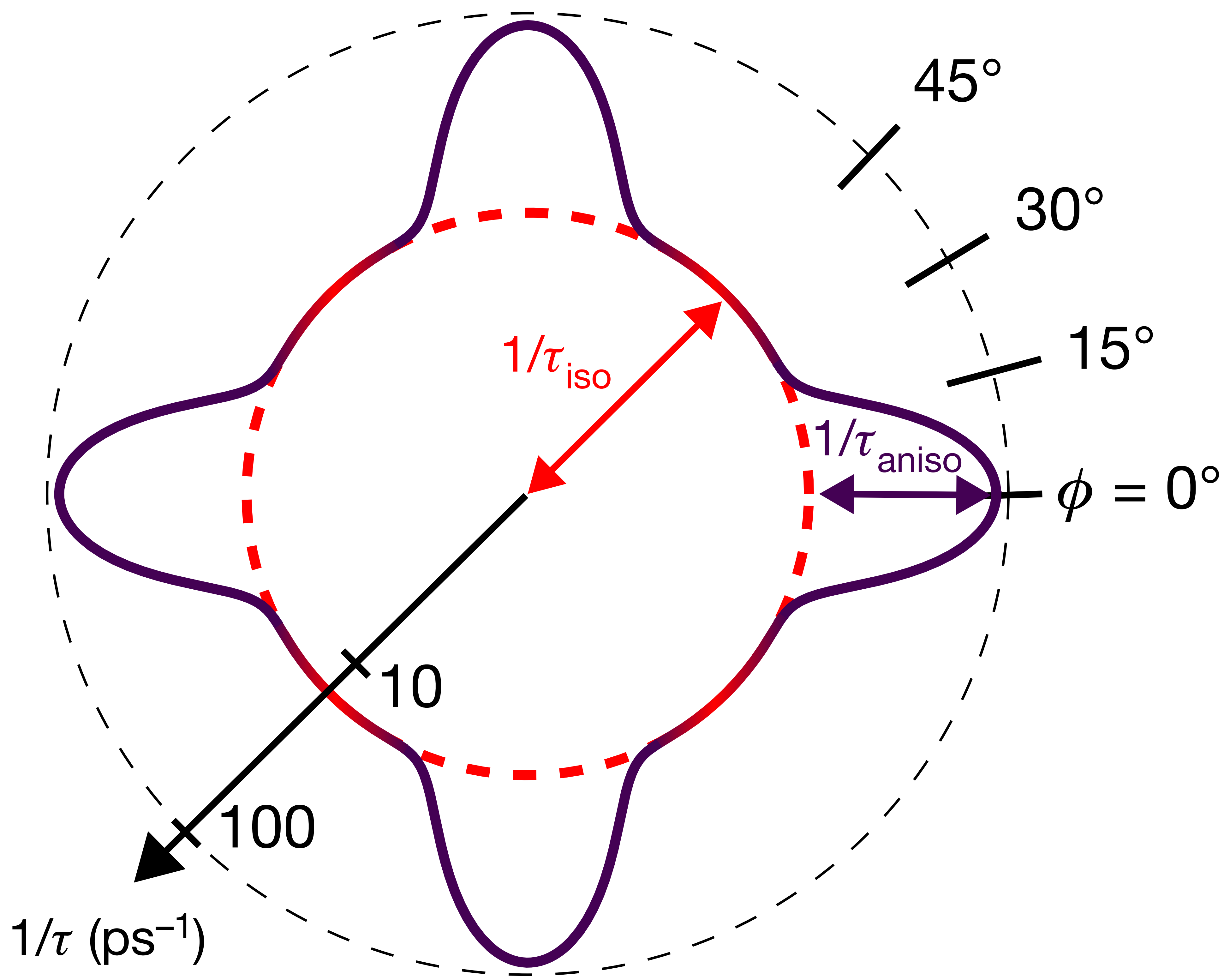
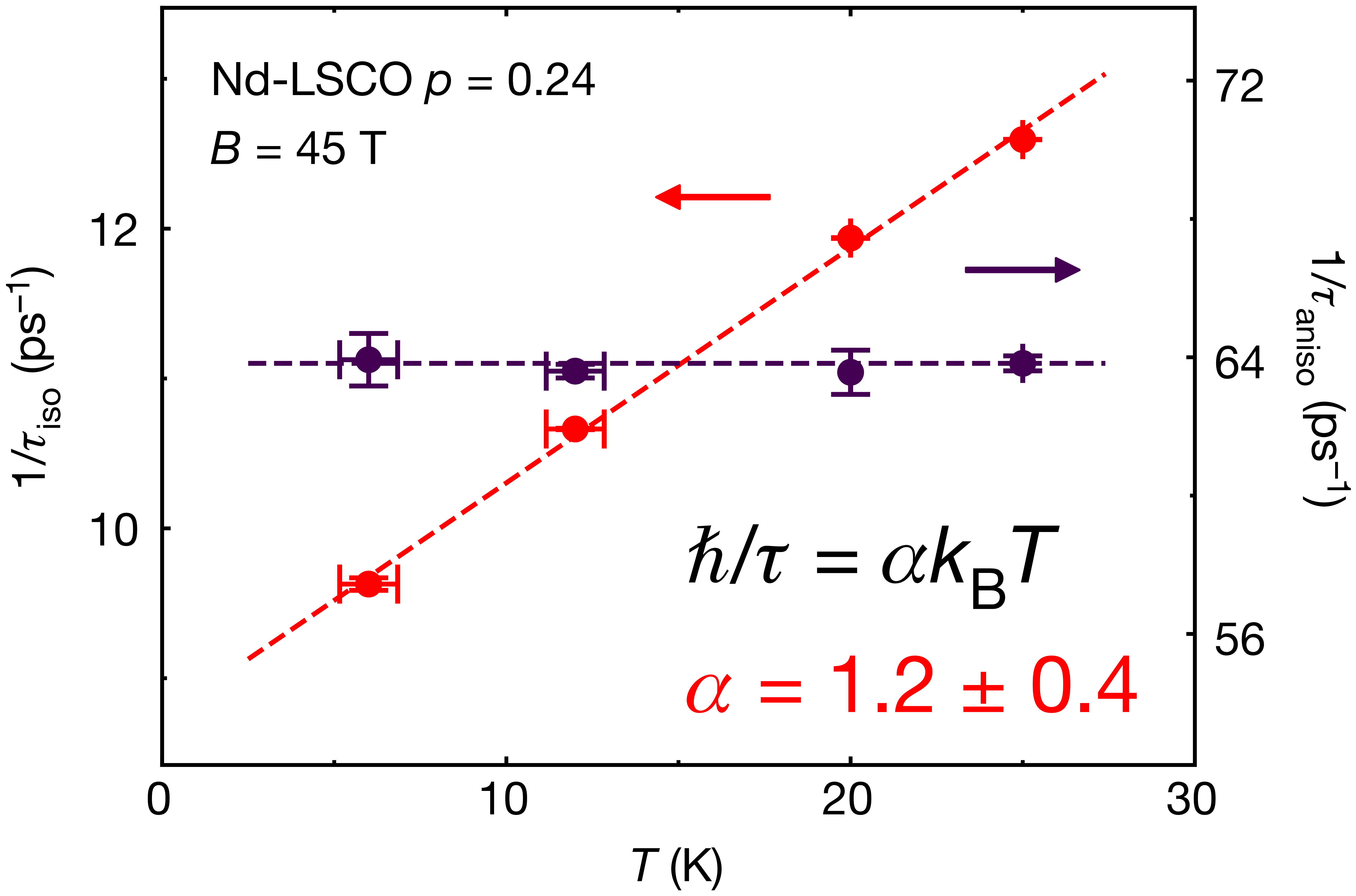
Linear-in temperature resistivity from an isotropic Planckian scattering rate

Nature **595**, 667-672 (2021)

G. Grissonnanche, Y. Fang, A. Legros, S. Verret, F. Laliberté, C. Collignon, J. Zhou, D. Graf, P. Goddard, L. Taillefer, B. J. Ramshaw

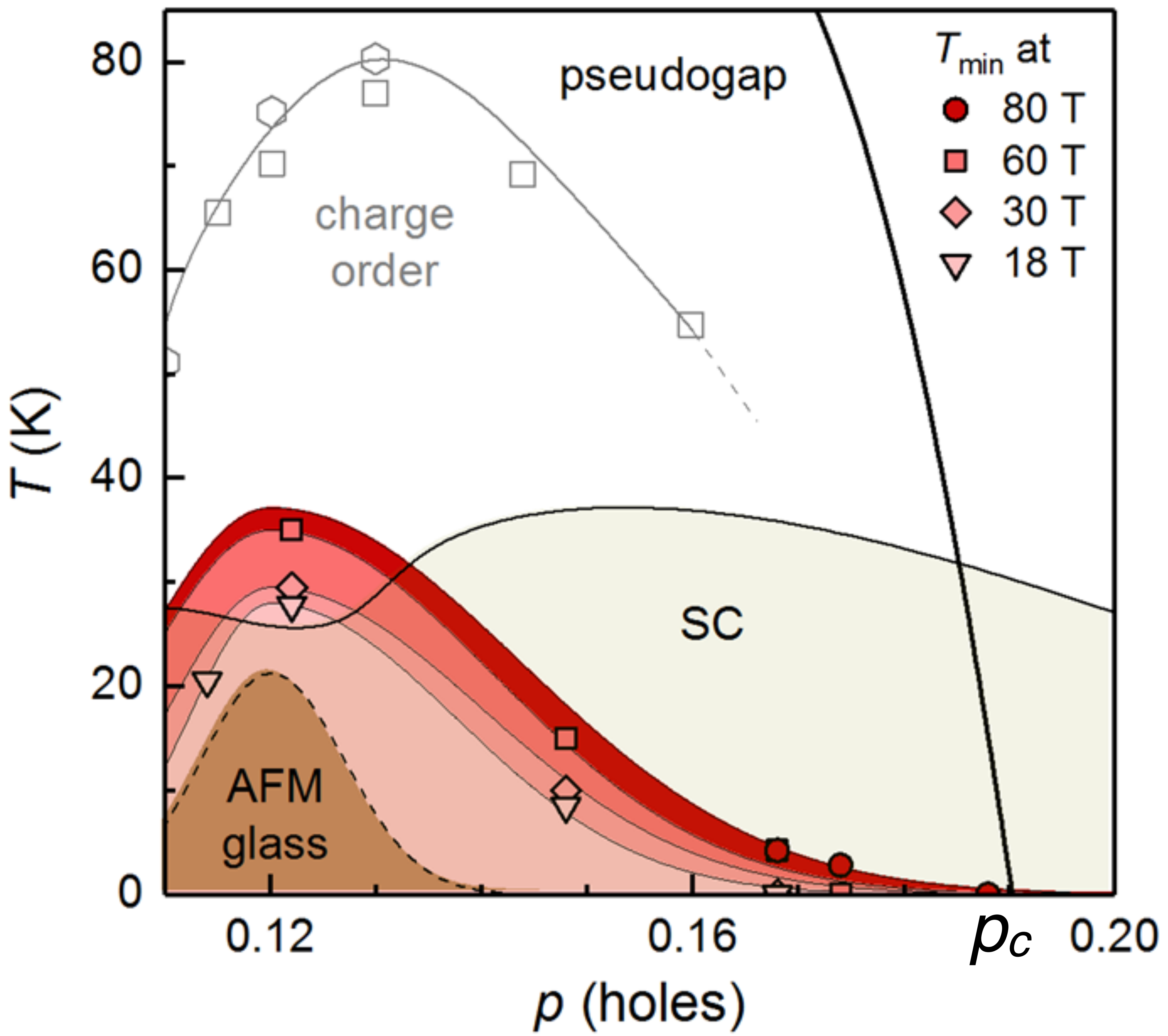




Hidden magnetism at the pseudogap critical point of a high temperature superconductor

Nature Physics **16**, 1064 (2020)

Mehdi Frachet[1]†, Igor Vinograd[1]†, Rui Zhou[1,2], Siham Benhabib[1], Shangfei Wu[1], Hadrien Mayaffre[1], Steffen Krämer[1], Sanath K. Ramakrishna[3], Arneil P. Reyes[3], Jérôme Debray[4], Tohru Kurosawa[5], Naoki Momono[6], Migaku Oda[5], Seiki Komiya[7], Shimpei Ono[7], Masafumi Horio[8], Johan Chang[8], Cyril Proust[1], David LeBoeuf[1*], Marc-Henri Julien[1*]



1. Random t-J model

2. Maximal chaos for a Fermi surface coupled to gauge fields in 2 dimensions

3. Unification?

1. Random t-J model

Microscopically unrealistic, describes observations

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describes observations

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

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

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

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

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

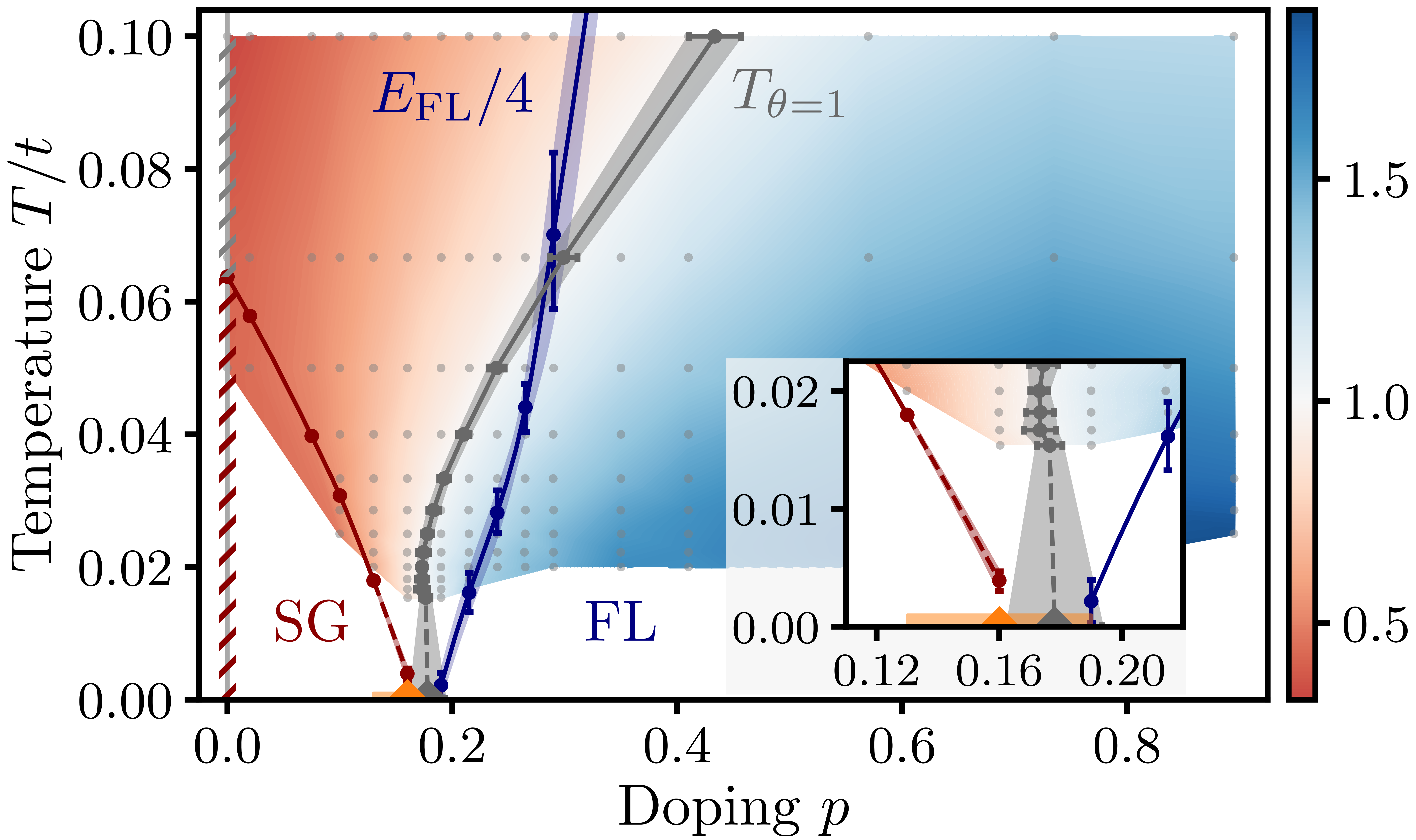
J_{ij} random, $\overline{J_{ij}} = 0$, $\overline{J_{ij}^2} = J^2$

t_{ij} random, $\overline{t_{ij}} = 0$, $\overline{t_{ij}^2} = t^2$

$J \quad \Rightarrow \quad$ two-particle interaction, as in SYK

$t \quad \Rightarrow \quad$ one-particle hopping, as in random matrices

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

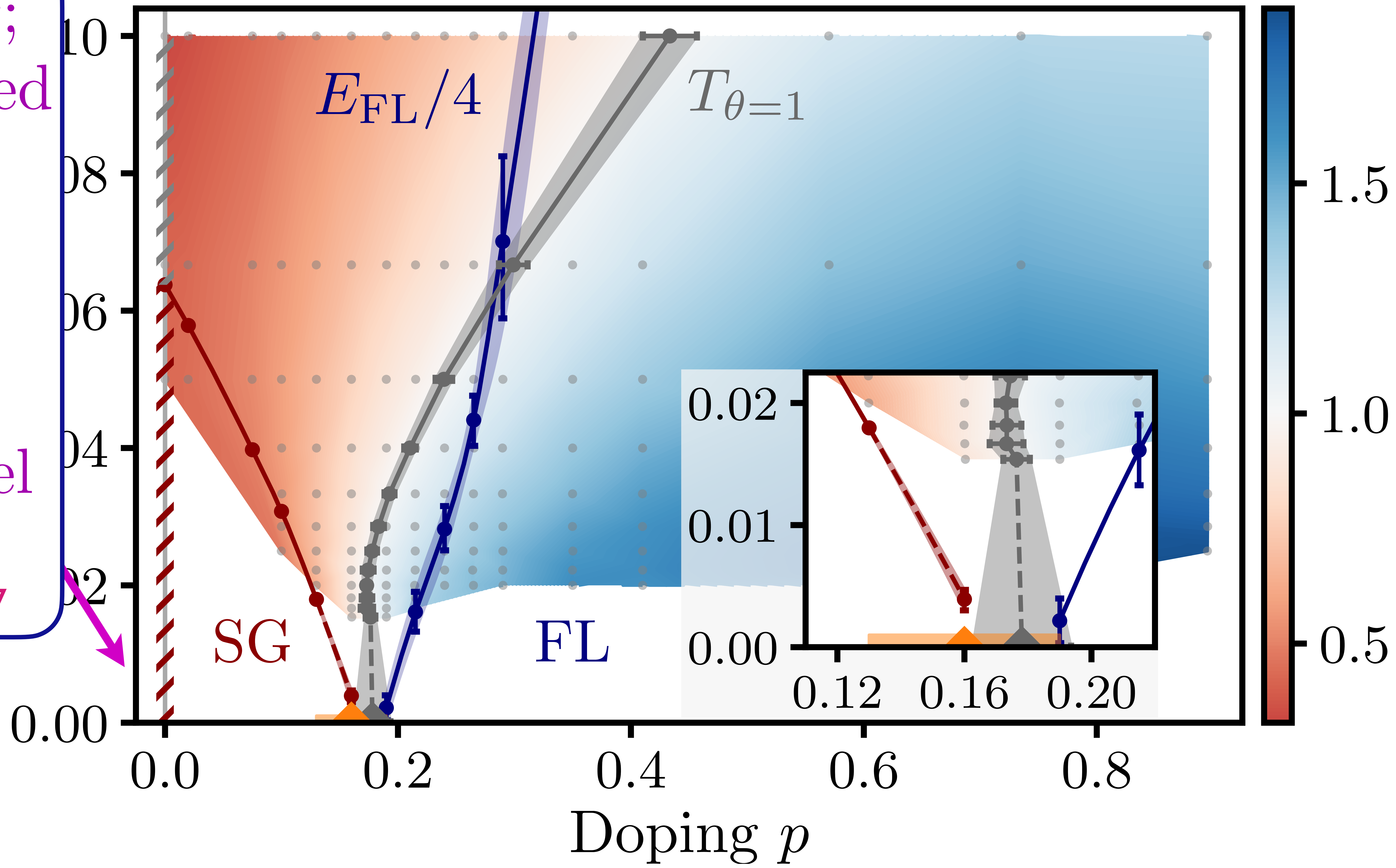
H. Shackleton, A. Wietek, A. Georges, and S. Sachdev, PRL **126**, 136602 (2021)

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

Spin glass order;
SYK fractionalized spin liquid
for $\omega > J q_{EA}$.

$T_c \sim J e^{-\sqrt{\pi M}}$
for SU(M) model

M. Christos, F. M. Haehl, and S. Sachdev, arXiv:2110.00007

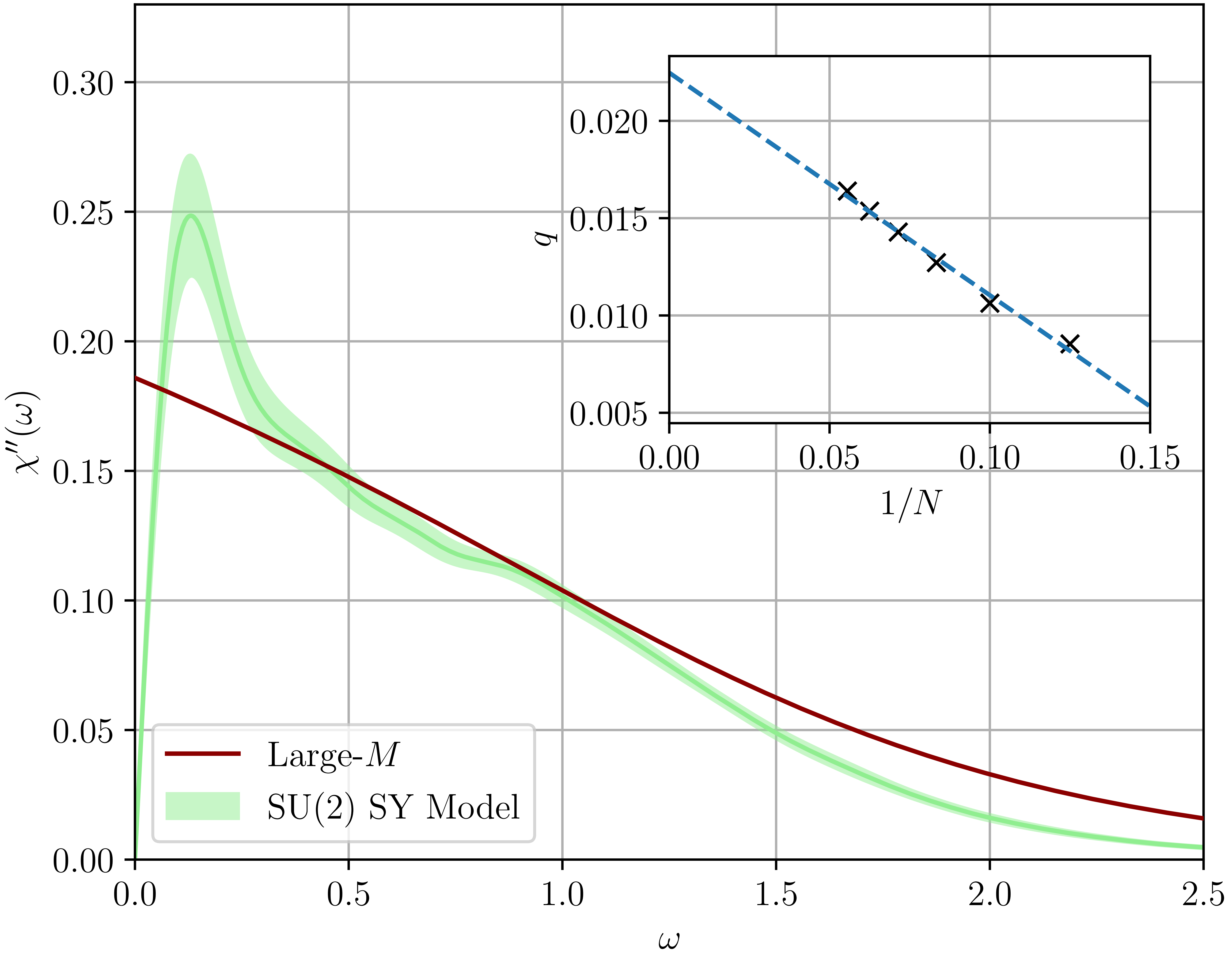


Maine Christos

Felix Haehl

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)

Exact diagonalization of clusters of SU(2) spins



H. Shackleton, A. Wietek, A. Georges, and S. Sachdev, PRL **126**, 136602 (2021)

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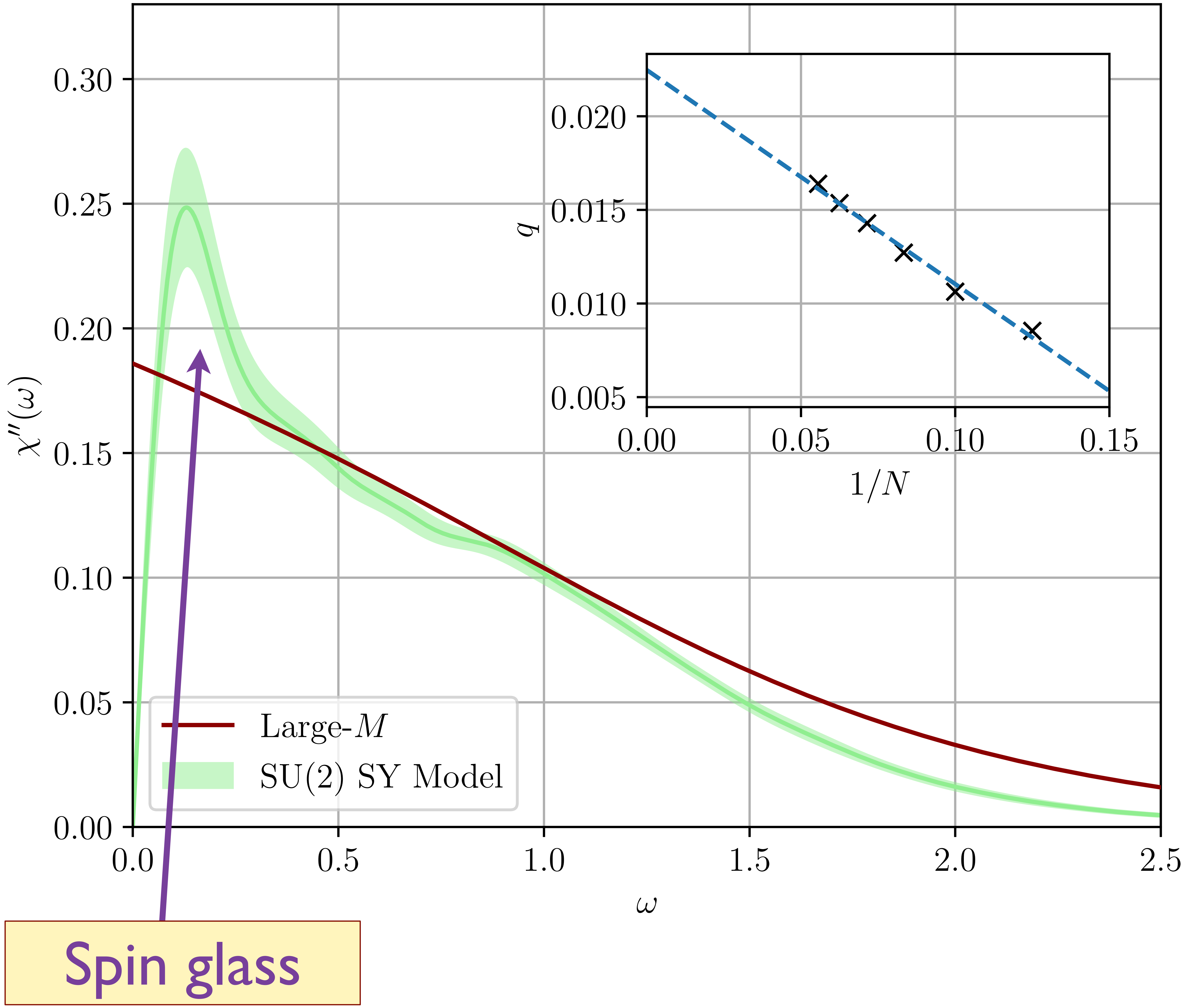

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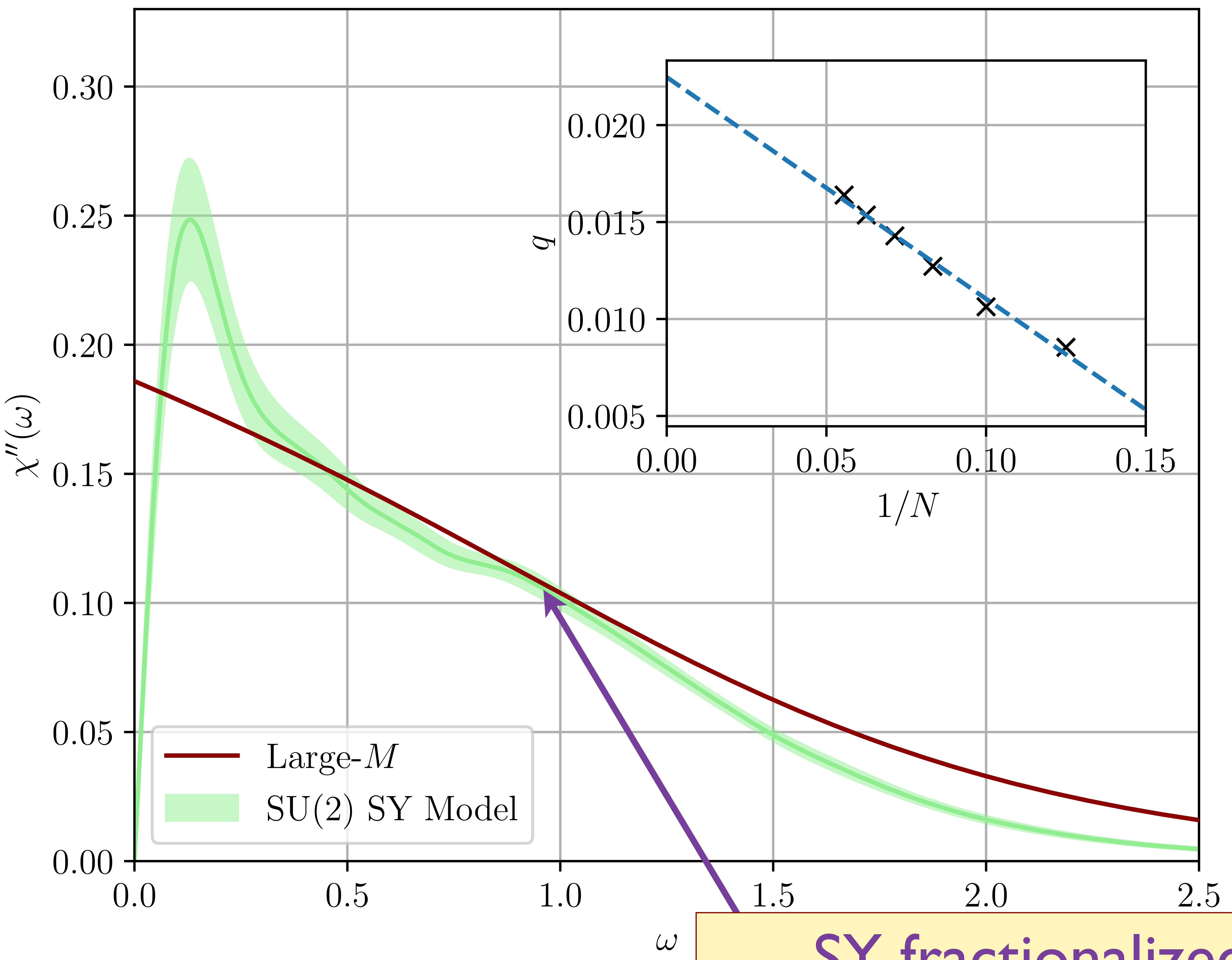

SY fractionalized spin liquid
(boundary graviton of Schwarzian theory)

H. Shackleton, A. Wietek, A. Georges, and S. Sachdev, PRL **126**, 136602 (2021)

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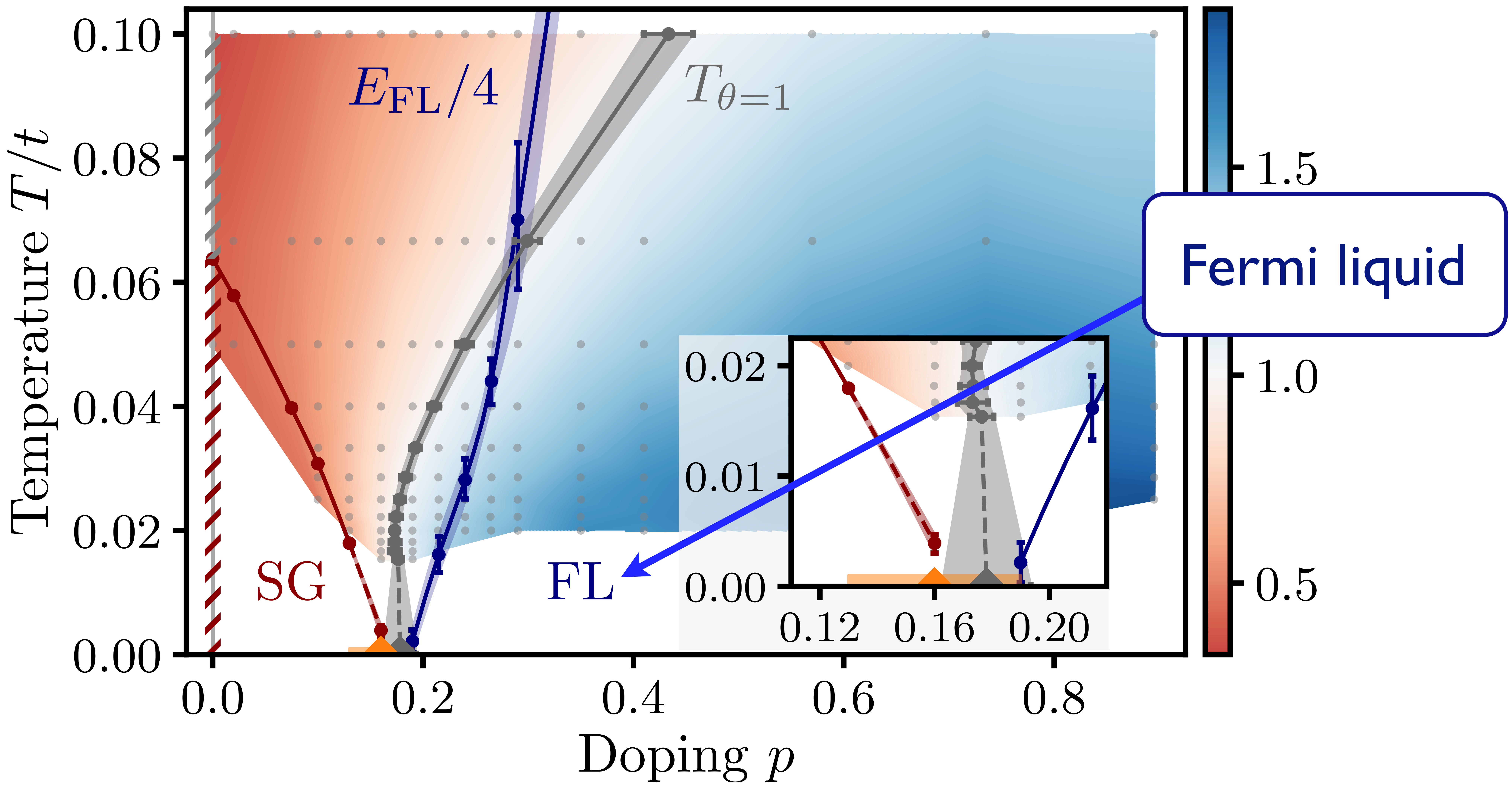

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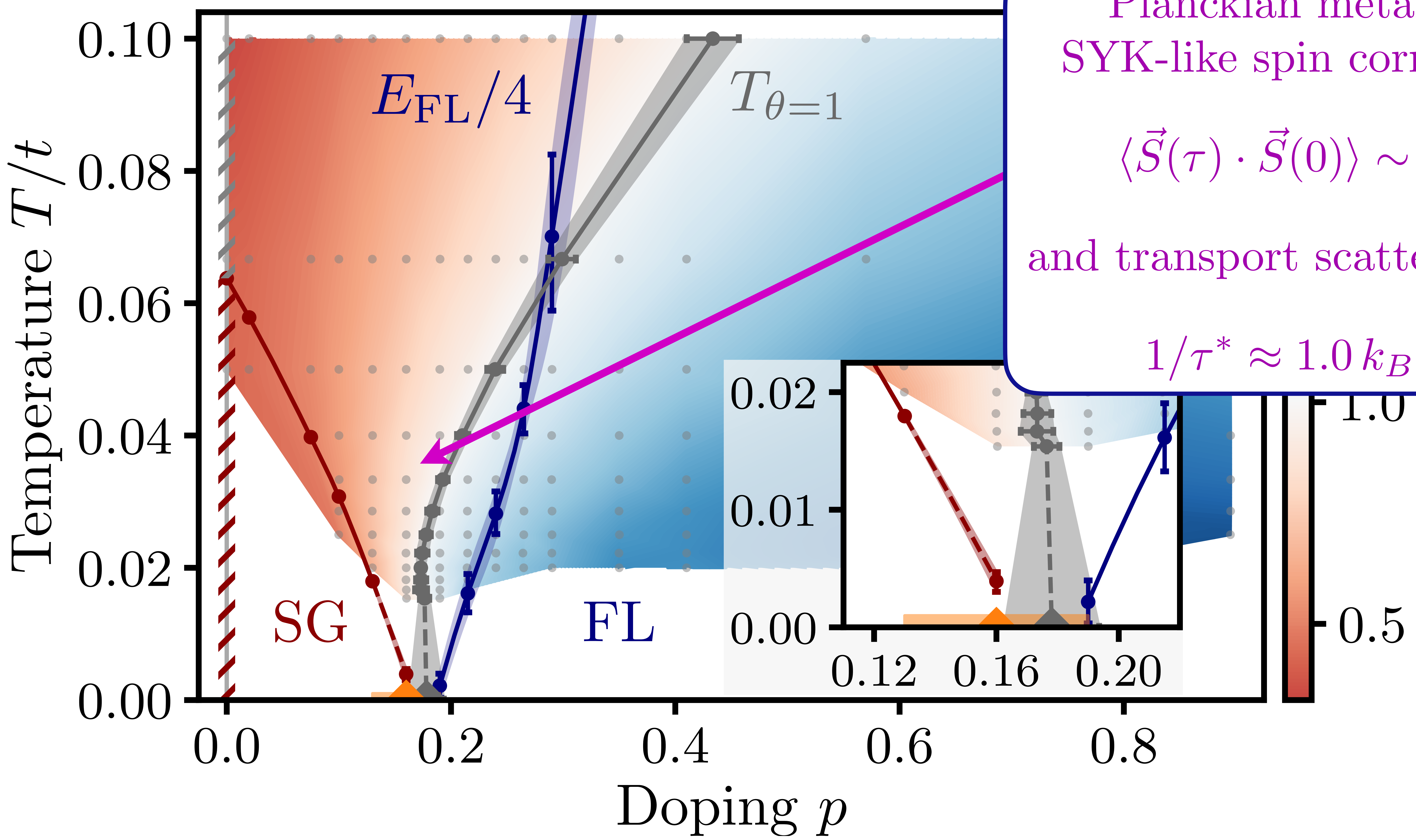


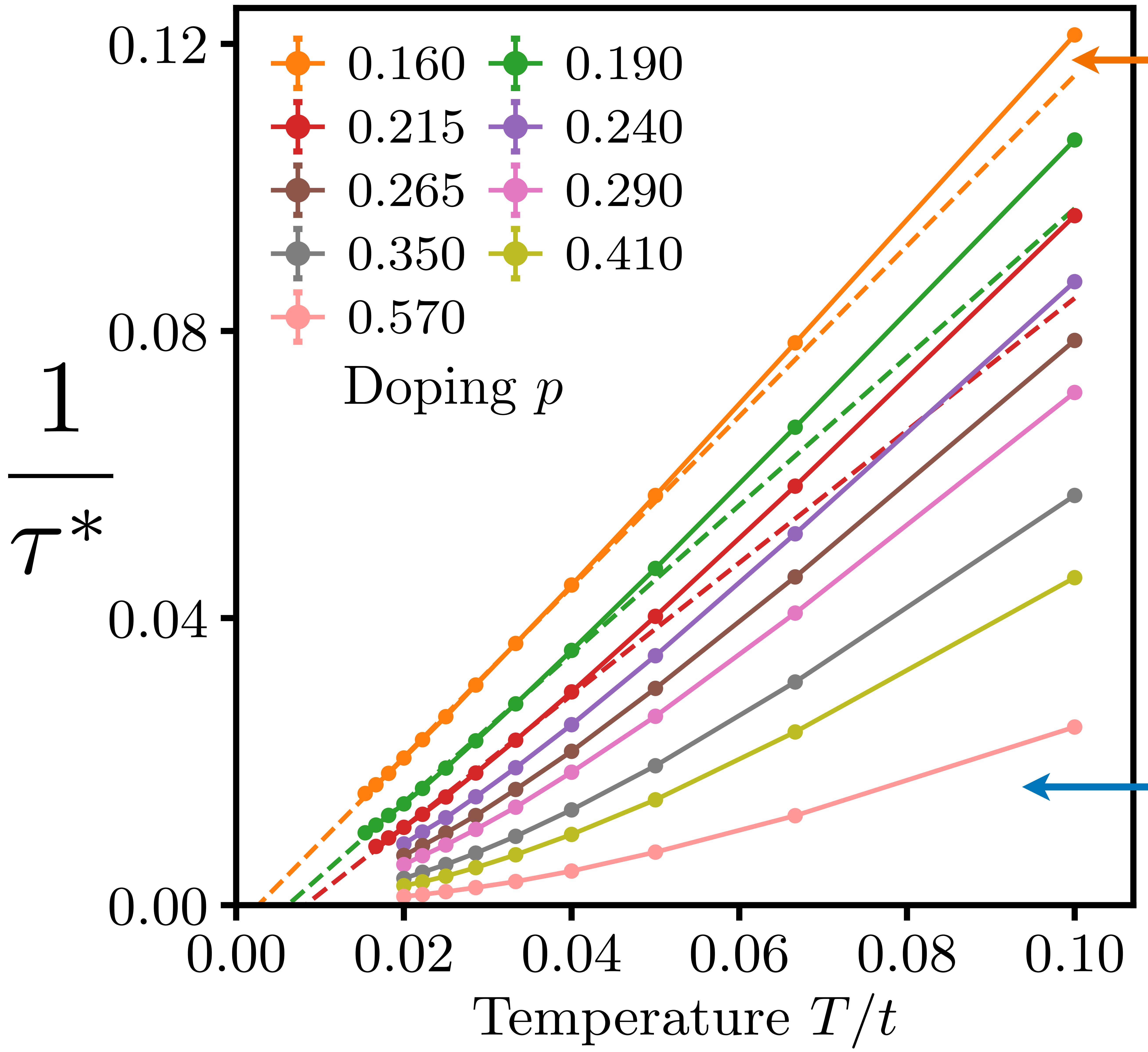
Planckian metal with SYK-like spin correlations

$$\langle \vec{S}(\tau) \cdot \vec{S}(0) \rangle \sim |\tau|^{-1}$$

and transport scattering time

$$1/\tau^* \approx 1.0\, k_B T/\hbar$$

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)



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

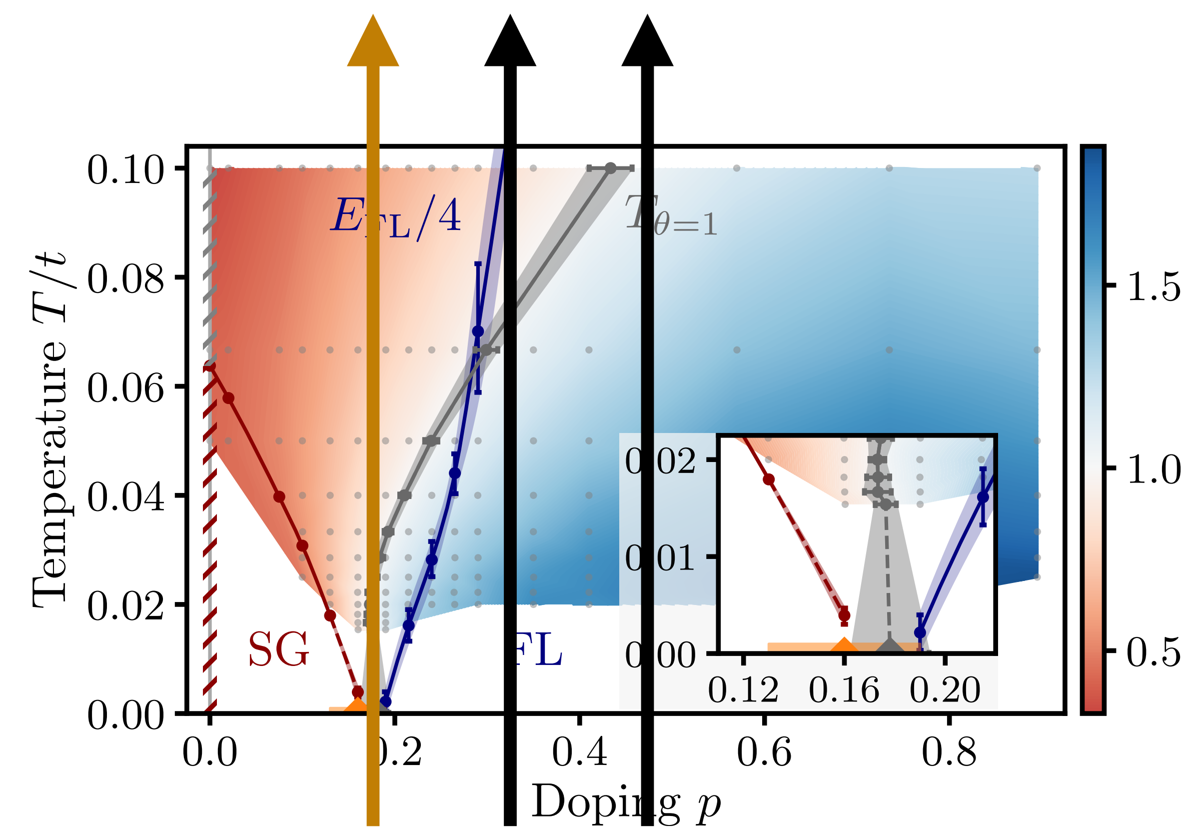
$$c \approx 1.0$$

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

Planckian metal
for $p \approx p_c$

Linear T resistivity
from Schwarzian mode
in large M theory

Haoyu Guo, Yingfei Gu, and S. Sachdev 2020



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

1. Random t-J model

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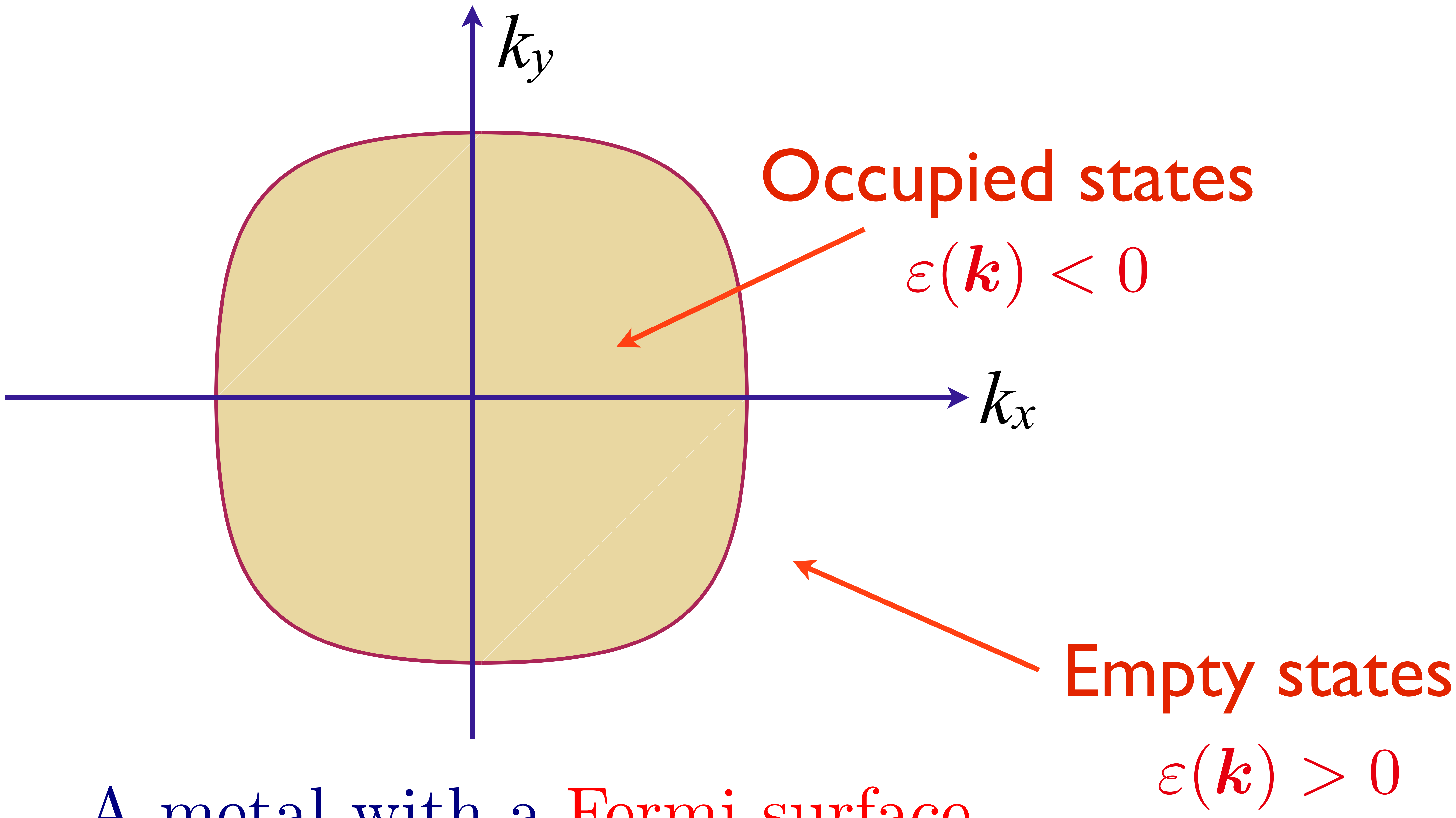
3. Unification?

Fermi surface coupled to a gauge field



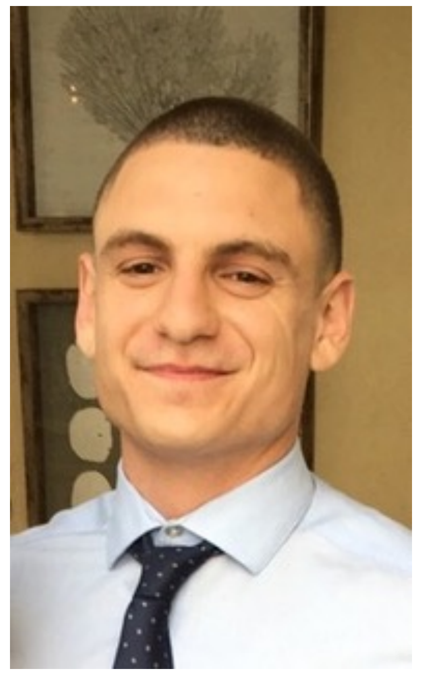
A metal with a Fermi surface
minimally coupled to a gauge field $\boldsymbol{A}$

$$\mathcal{L} = c^\dagger_{\boldsymbol{k}} \left(\frac{\partial}{\partial \tau} + \varepsilon(-i\boldsymbol{\nabla} - g\boldsymbol{A}) - \mu \right) c_{\boldsymbol{k}} + \frac{1}{2}(\boldsymbol{\nabla} \times \boldsymbol{A})^2$$

Large N theory of a critical Fermi surface

Main idea:

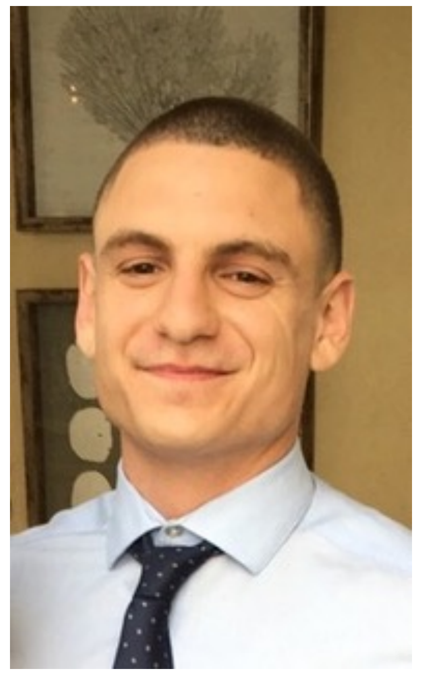
Introduce N flavors of fermions and bosons, and examine an *ensemble* of theories with different Yukawa couplings. In the large N limit, every member of the ensemble is expected to have the same critical properties, and so it is easier to study the average theory.



Ilya Esterlis, Haoyu Guo, Aavishkar Patel, S.S. arXiv: 2103.08615

Large N theory of a critical Fermi surface

N flavors of fermions $\psi_{\pm\alpha}$,
M flavors of a boson a_α, and
a "Yukawa coupling" $g_{\alpha\beta\gamma}$ which is a random function in flavor space. Note: there is *no spatial randomness*. Take the large N limit with M/N fixed.



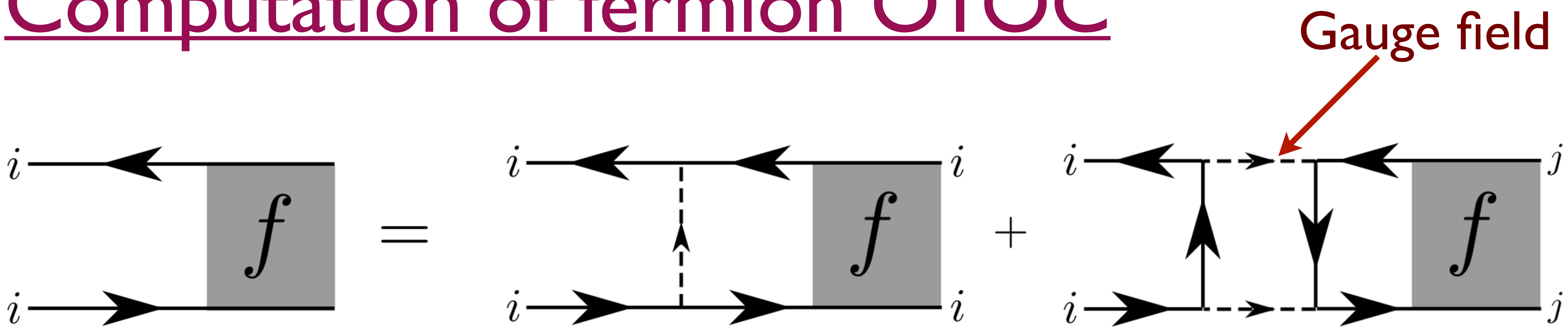
$$\mathcal{L} = \psi^\dagger_{+\alpha}\left(\partial_\tau - i\partial_x - \partial_y^2\right)\psi_{+\alpha} + \psi^\dagger_{-\alpha}\left(\partial_\tau + i\partial_x - \partial_y^2\right)\psi_{-\alpha} - \frac{g_{\alpha\beta\gamma}}{N} a_\alpha\left(\eta_{+\alpha}\psi^\dagger_{+\beta}\psi_{+\gamma} + \eta_{-\alpha}\psi^\dagger_{-\beta}\psi_{-\gamma}\right) + \frac{1}{2}\left(\partial_y a_\alpha\right)^2$$

$\eta_{\pm\alpha} = \pm 1$ depending upon nature of a_α: gauge field, Higgs field, order parameter ....

$$\overline{g_{\alpha\beta\gamma}} = 0 \quad , \quad \overline{|g_{\alpha\beta\gamma}|^2} = g^2$$

Ilya Esterlis, Haoyu Guo, Aavishkar Patel, S.S. arXiv: 2103.08615

Computation of fermion OTOC

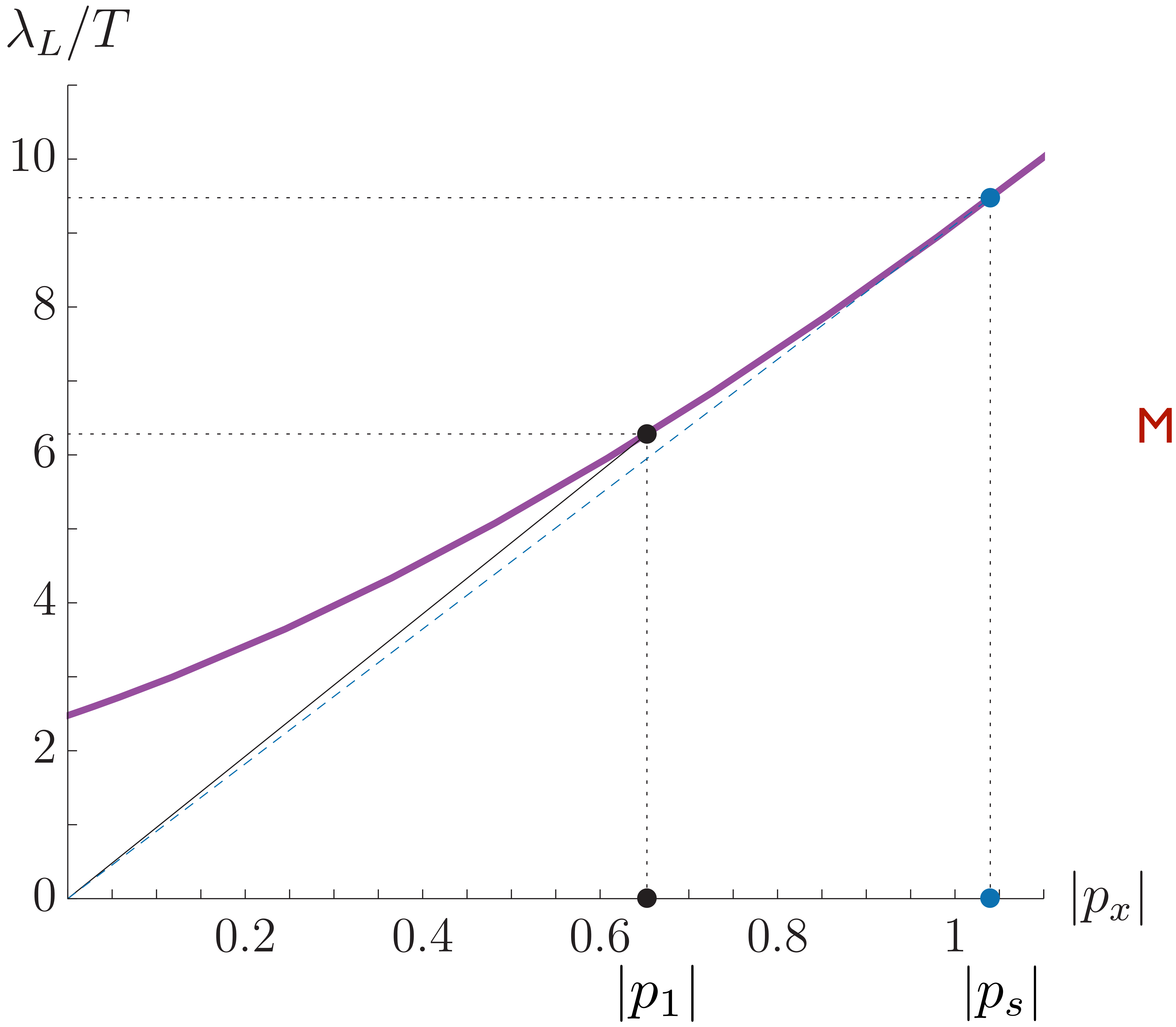


Invariance under adding a ladder

$$f(t)=\frac{1}{N^2}\theta(t)\sum_{i,j=1}^{N}\int d^2x\ \mathrm{Tr}\left[e^{-\beta H/2}\{\psi_i(x,t),\psi_j^\dagger(0)\}e^{-\beta H/2}\{\psi_i(x,t),\psi_j^\dagger(0)\}^\dagger\right]=\int d^2x\ f(t,x)$$

$$\left[T^{2/z}c_{f,z}\left(H_{1-2/z}\left(\frac{-ik_0-\pi T}{2\pi T}\right)+H_{1-2/z}\left(\frac{-i(\omega-k_0)-\pi T}{2\pi T}\right)\right)+2\mu(T)-p_x\right]\tilde{f}(k_0,\omega)$$
$$=g^2\int\frac{dk_0'dk_y'}{(2\pi)^2}\frac{c_b(k_0-k_0')|k_y'|}{(|k_y'|^z+m^2)^2+c_b^2(k_0-k_0')^2}\frac{\tilde{f}(k_0',\omega)}{\sinh\frac{k_0-k_0'}{2T}}$$
$$-\frac{ig^4}{8z\sin(\frac{2\pi}{z})c_b^{2-\frac{2}{z}}}\int\frac{dk_0'dk_{01}}{(2\pi)^2}\frac{(-ik_{01})^{\frac{2}{z}-1}-(i(k_{01}-\omega))^{\frac{2}{z}-1}}{2k_{01}-\omega}\frac{\tilde{f}(k_0',\omega)}{\cosh\frac{k_0-k_{01}}{2T}\cosh\frac{k_0'-k_{01}}{2T}}$$

As in [Patel, Sachdev 2016]



Maria Tikhanovskaya
Harvard

Aavishkar Patel
Berkeley

Gu and Kitaev (2019): Compute λ_L for *imaginary* momentum: *i.e.* $p_x = i|p_x|$ and include contribution of pole

We find maximal chaos with $\lambda_L = 2\pi T$,
and butterfly velocity $v_1 = 2\pi/|p_1| \approx 9.67 g^{-4/3} T^{1/3}$

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- Why should the 2+1 dimensions t-J model be described by a 0+1 dimensional SYK-like theory over a significant temperature range ?

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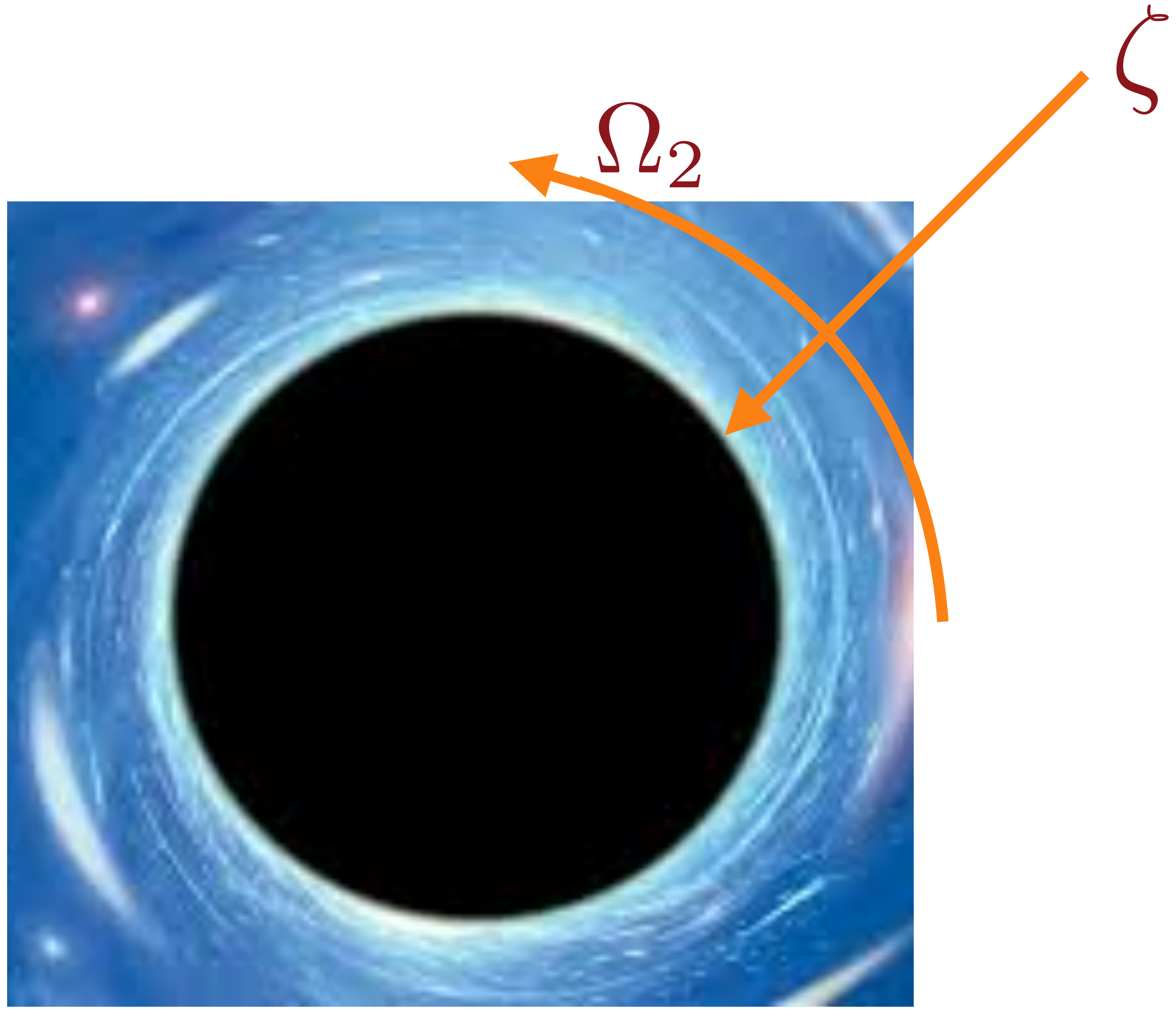
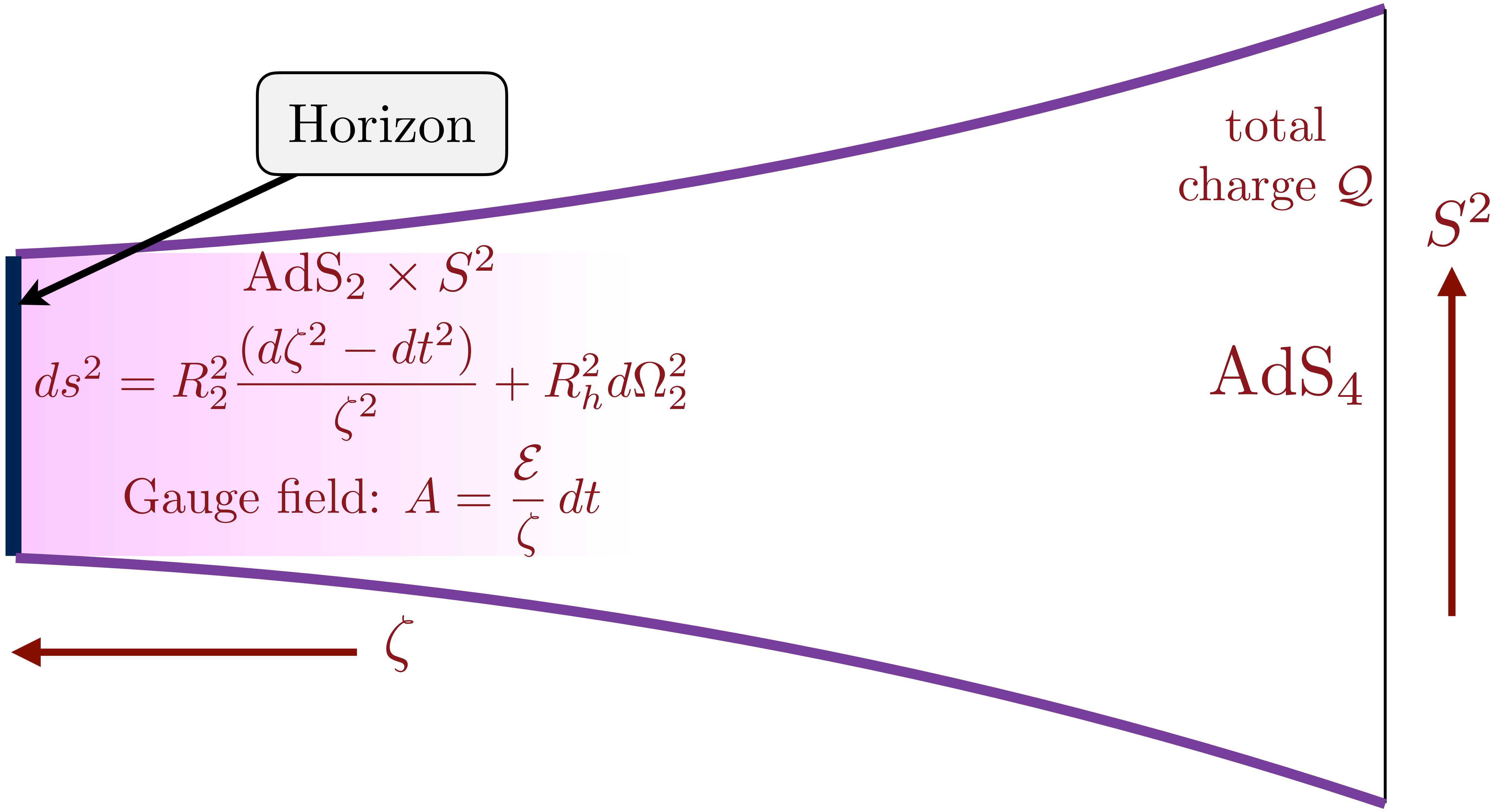
- Recall the dimensional reduction of 3+1 dimensional gravity of a charged black hole to a 1+1 dimensional theory on AdS_2 (which, in turn, displays SYK phases).





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- Recall the dimensional reduction of 3+1 dimensional gravity of a charged black hole to a 1+1 dimensional theory on AdS_2 (which, in turn, displays SYK phases).

- By the holographic mapping, this implies that certain models of Fermi surfaces coupled to large N gauge fields in 2+1 dimensions display a dimensional reduction to a 0+1 dimensional theory.

Tom Faulkner, Nabil Iqbal, Hong Liu, John McGreevy, Mark Mezei, David Vegh, 2011
D. Chowdhury, A. Georges, O. Parcollet, S. Sachdev, arXiv: 2109.05037

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- By the holographic mapping, this implies that certain models of Fermi surfaces coupled to large N gauge fields in 2+1 dimensions display a dimensional reduction to a 0+1 dimensional theory.

- The transition between the pseudogap and the Fermi liquid in the t-J model can be written as $SU(2) \times U(1)$ guage theory.

Ya-Hui Zhang, S. Sachdev, A Nikolaenko, M. Tikhanovskaya 2020, 2021
D. Chowdhury, Liujun Zou 2020