The pseudogap metal and its confinement transitions

Correlated Gapless Quantum Matter
KITP, Santa Barbara
May 21, 2024
Subir Sachdev

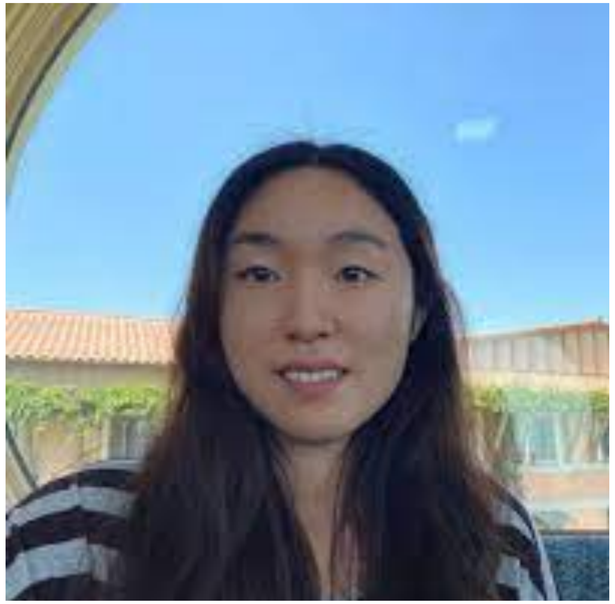
Maine Christos, Zhu-Xi Luo, Henry Shackleton, Ya-Hui Zhang, Mathias Scheurer, and S. Sachdev, *Proc. Nat. Acad. Sci.* **120**, e2302701120 (2023)

Maine Christos and S.Sachdev, *npj Quantum Materials* **9**, 4 (2024)

M. Christos, H. Shackleton, S. Sachdev, and Zhu-Xi Luo, arXiv:2402.09502

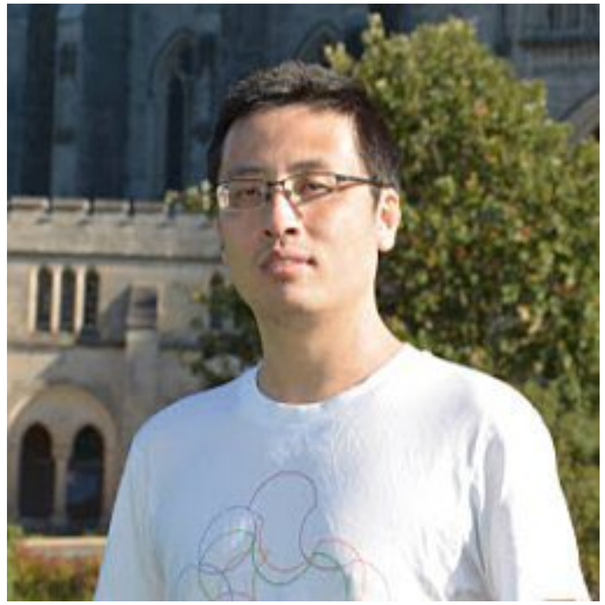
Pietro M. **B**onetti, Maine **C**hristos, S. **S**achdev (BCS), arXiv: 2405.08817

Maine Christos

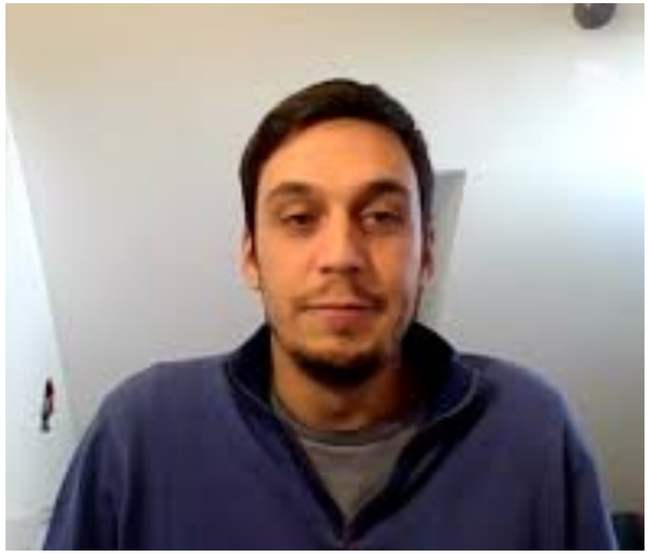


Zhu-Xi Luo

Mathias Scheurer



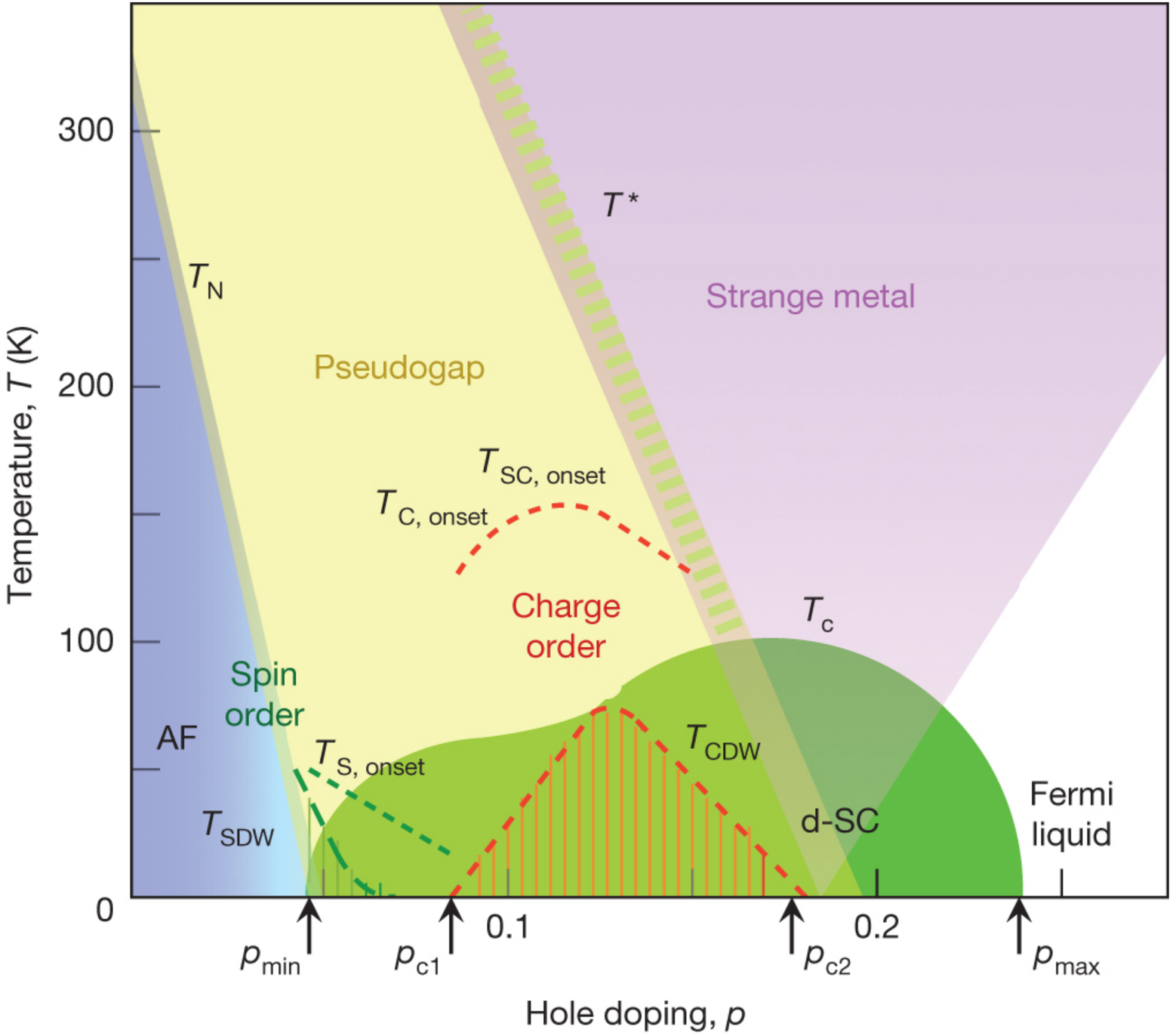
Ya-Hui Zhang

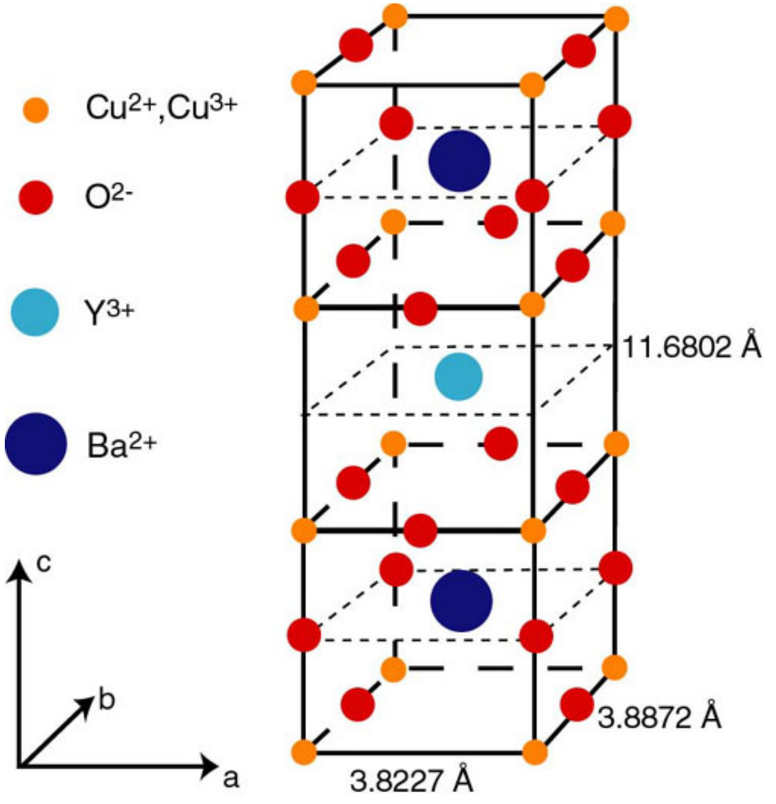


Pietro Bonetti

Henry Shackleton

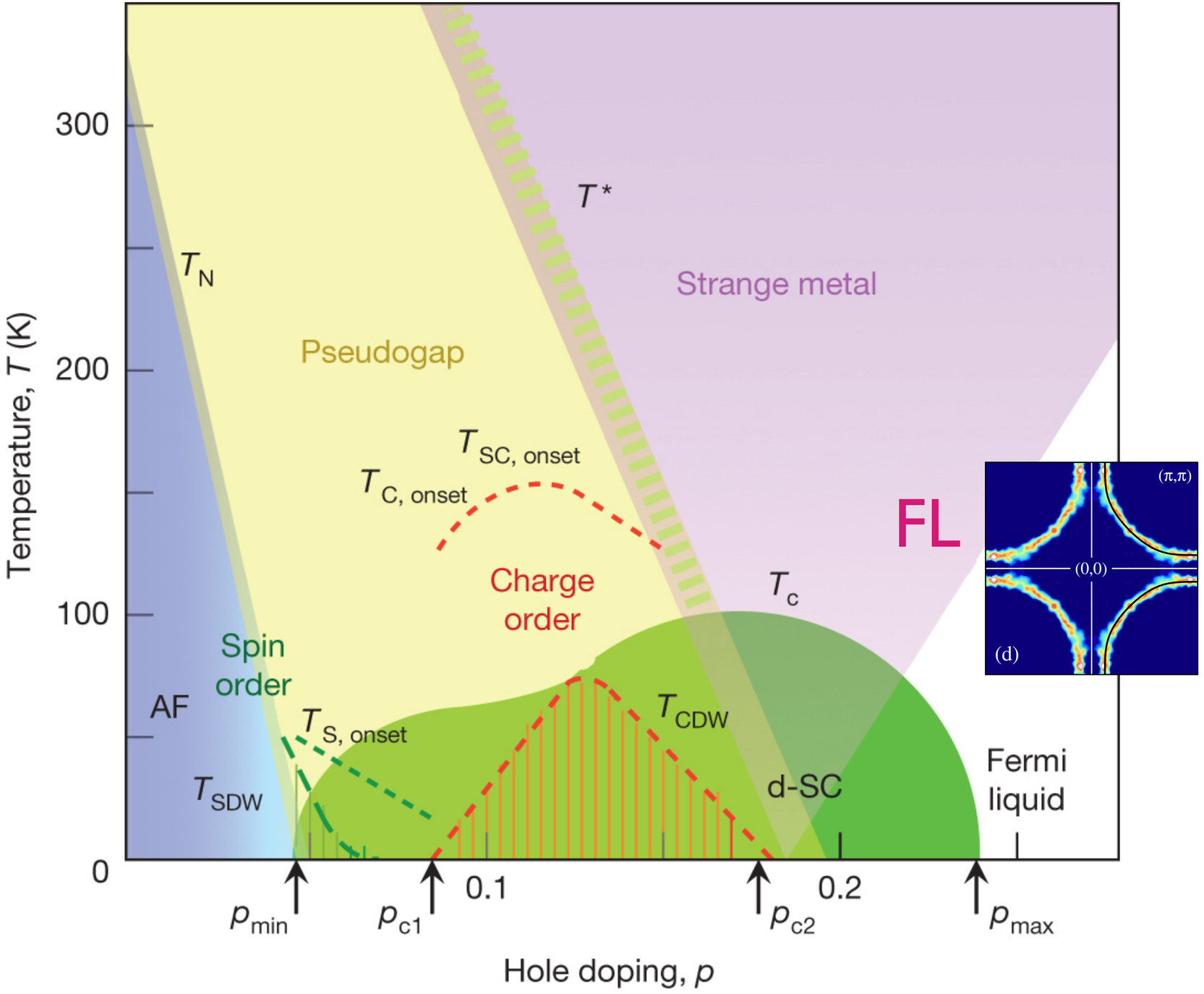
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)





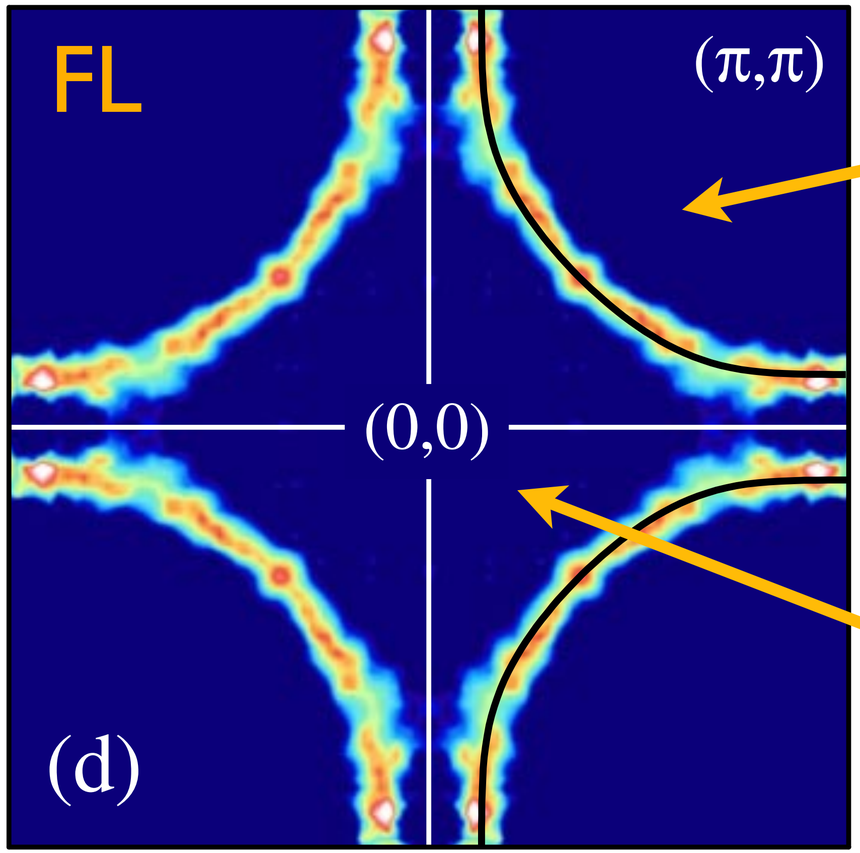
$YBa_2Cu_3O_{6+x}$

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



Fermi liquid
in the
overdoped metal

Photoemission at large p



$1+p$ holes

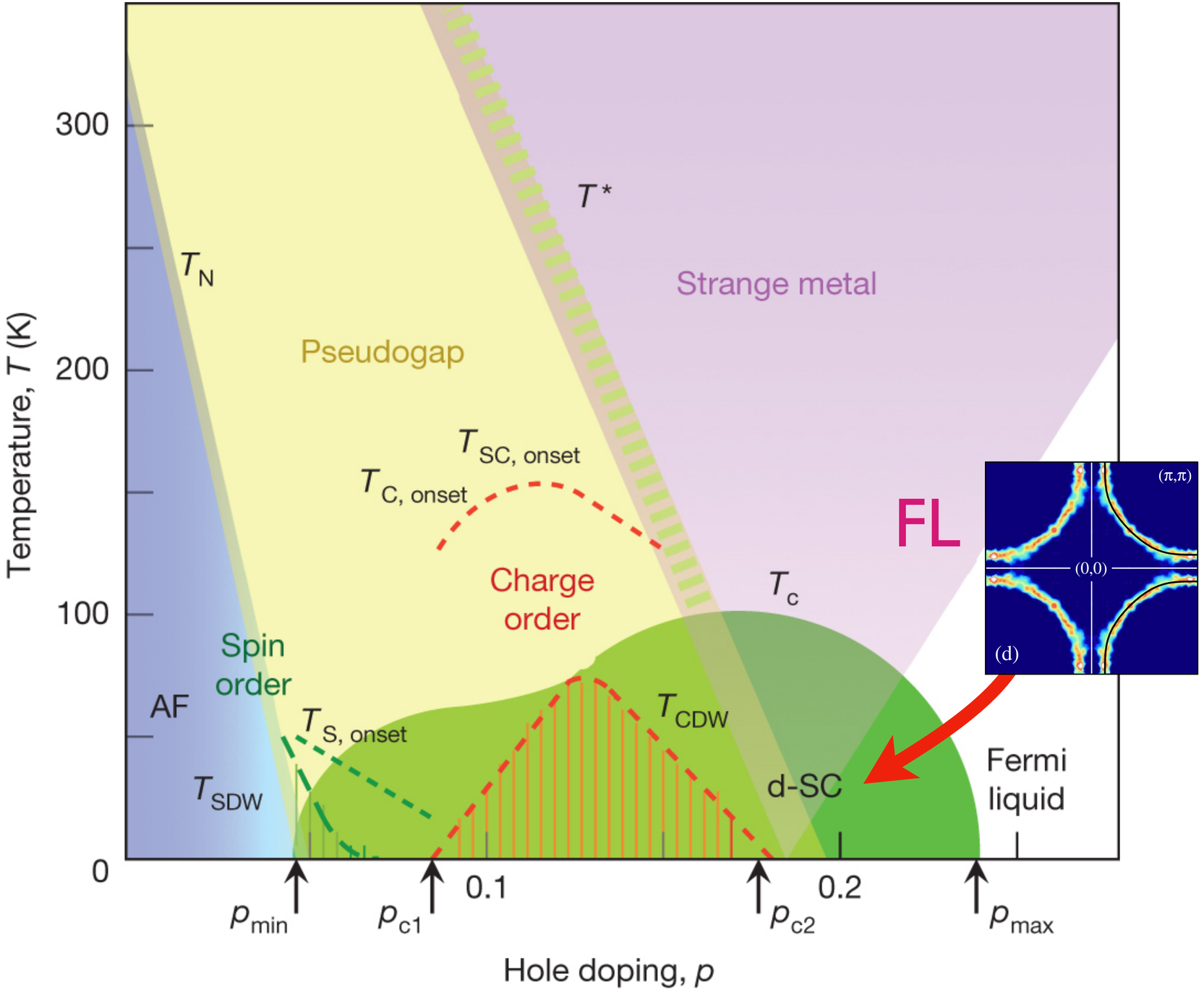
$1-p$ electrons

Overdoped $Tl_2Ba_2CuO_{6+\delta}$
$T_c = 30\text{K}$

$1+p$ mobile holes in a filled band of 2 electrons per site

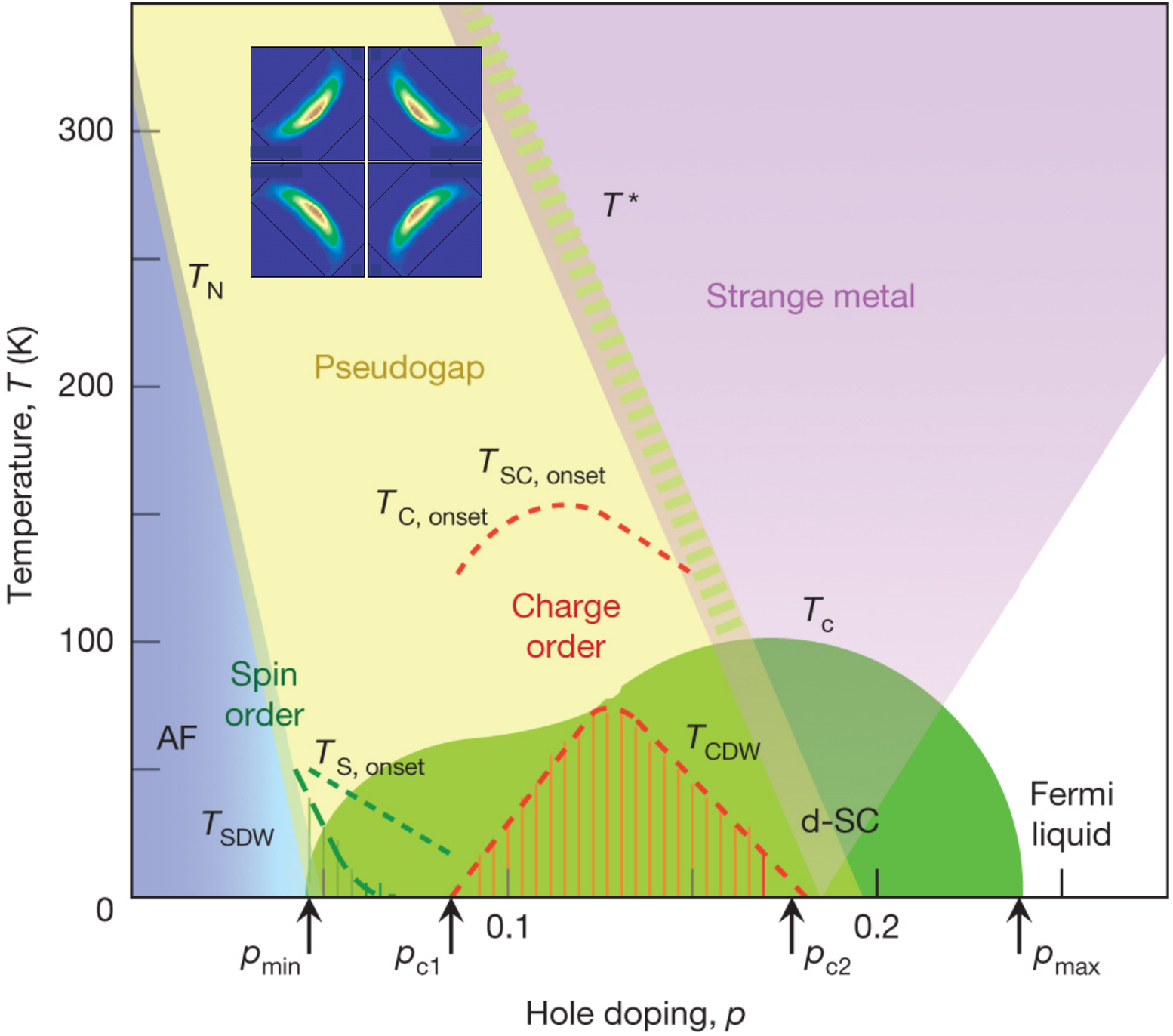
M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)

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



BCS-type theory of d-wave superconductivity (and charge order) induced by antiferromagnetic spin fluctuations.

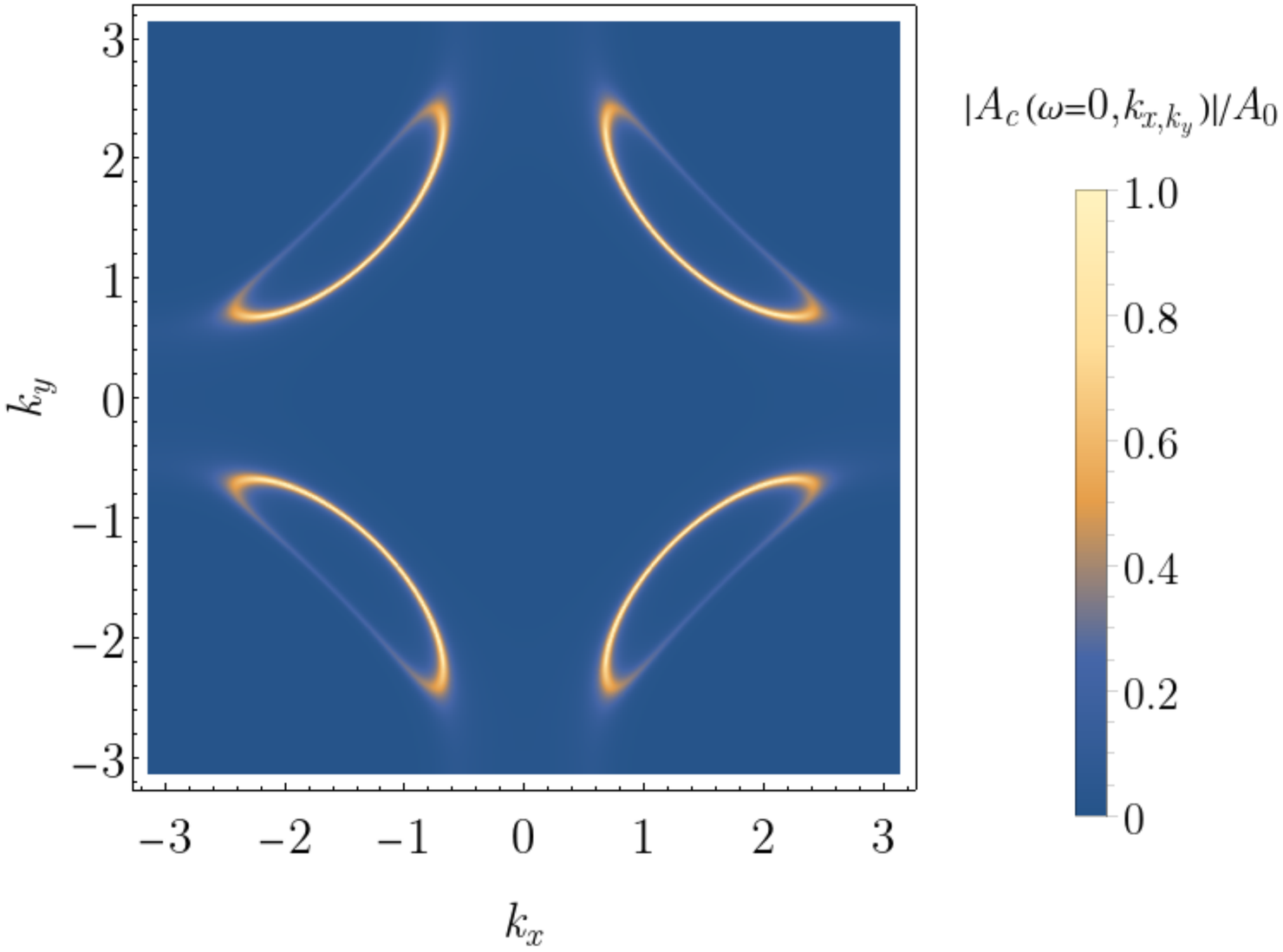
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



Pseudogap metal with "Fermi arcs"

"Backside problem 1"

Hole pocket Fermi surfaces of size p with charge e, spin-1/2 quasiparticles



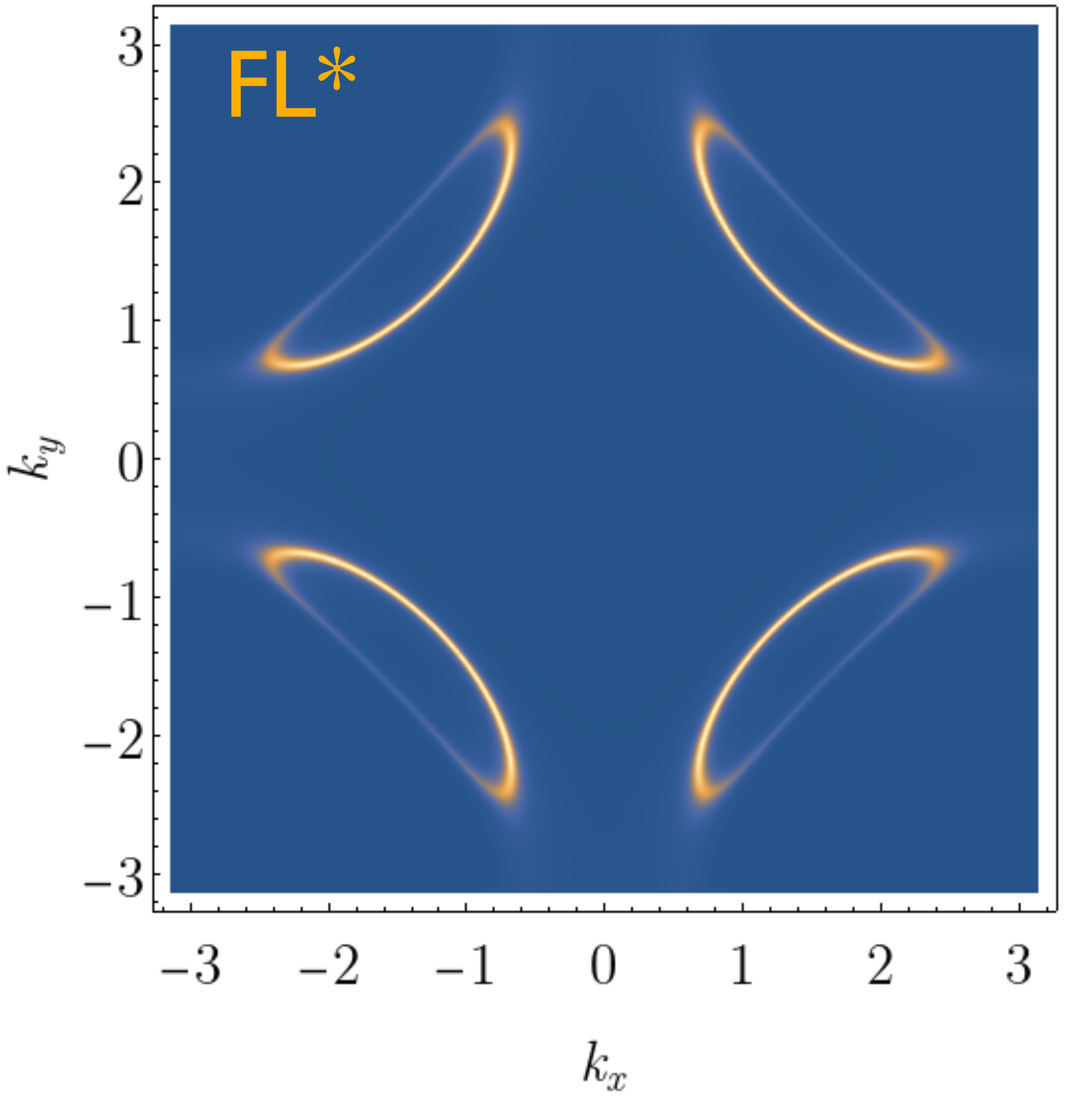
Kai-Yu Yang, T. M. Rice, Fu-Chun Zhang,
Phys. Rev. B **73**, 174501 (2006).
T. D. Stanescu and G. Kotliar,
Phys. Rev. B **74**, 125110 (2006).
C. Berthod, T. Giamarchi, S. Biermann, and A. Georges,
Phys. Rev. Lett. **97**, 136401 (2006).
S. Sakai, Y. Motome, M. Imada,
Phys. Rev. Lett. **102**, 056404 (2009).
J. Skolimowski and M. Fabrizio,
Phys. Rev. B **106**, 045109 (2022).

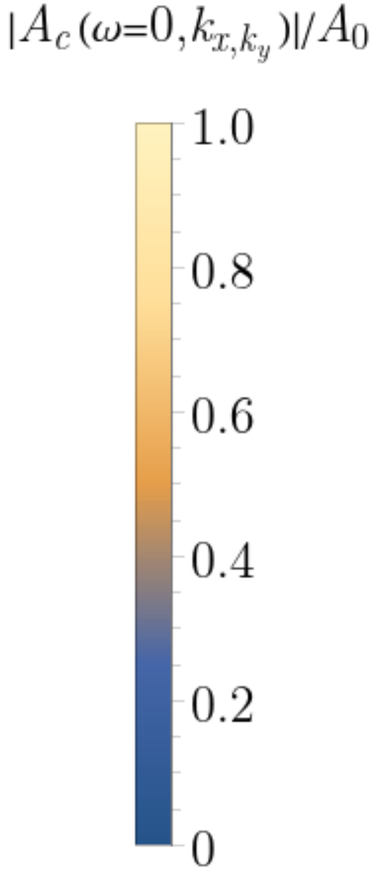
The Fermi surface does not enclose the Luttinger volume $(1+p)$.

Y. Qi and S. Sachdev *Phys. Rev. B* **81**, 115129 (2010)

E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. Sachdev, *Phys. Rev. B* **105**, 075146 (2022)

"Backside problem 1"





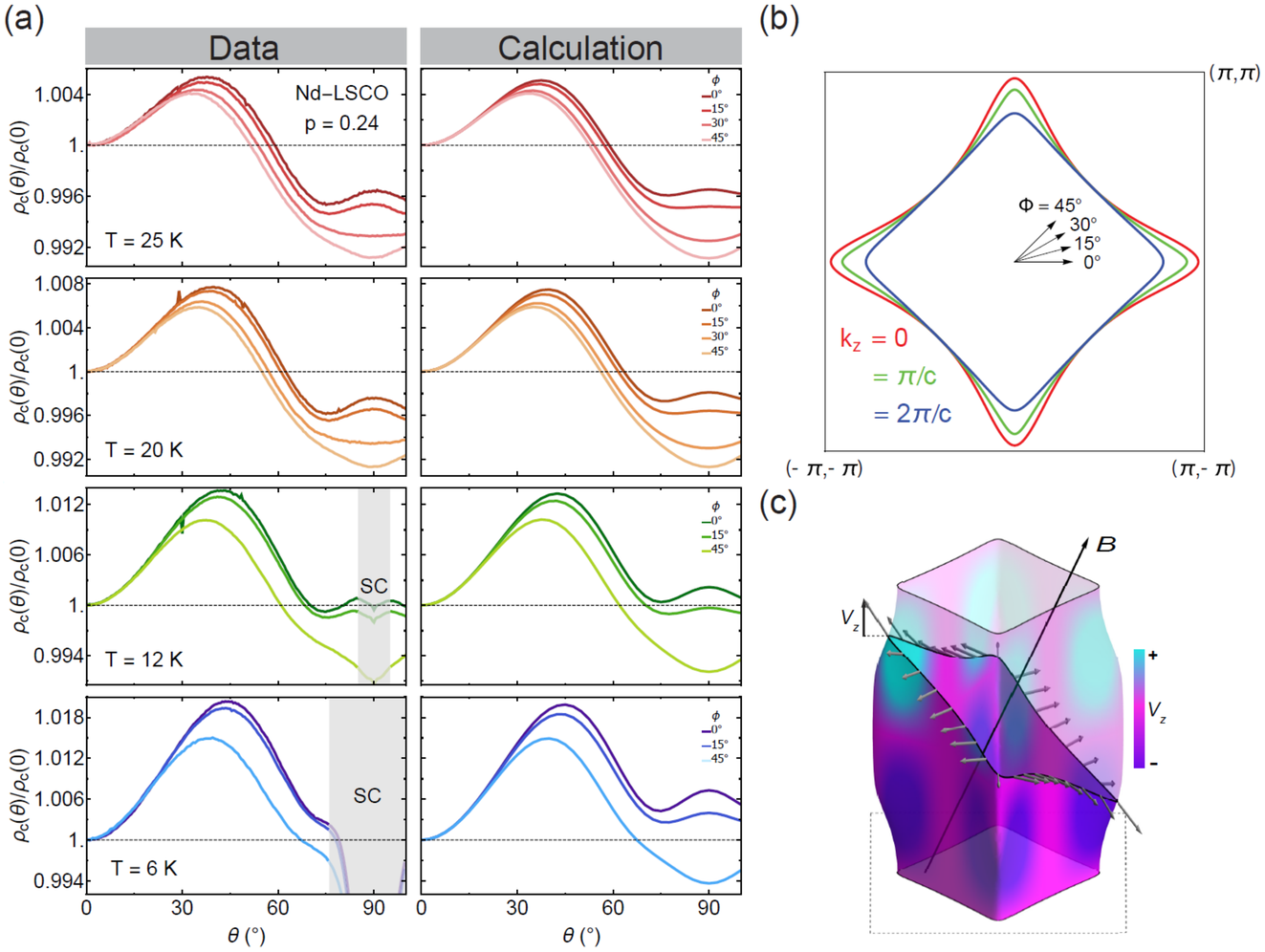
Hole pocket Fermi surfaces
of size p with
charge e, spin-1/2 quasiparticles
+
'spectator'
square lattice spin liquid
at half-filling.

FL*: Spin liquid is *required* because the Fermi surface does not enclose the Luttinger volume $(1+p)$.

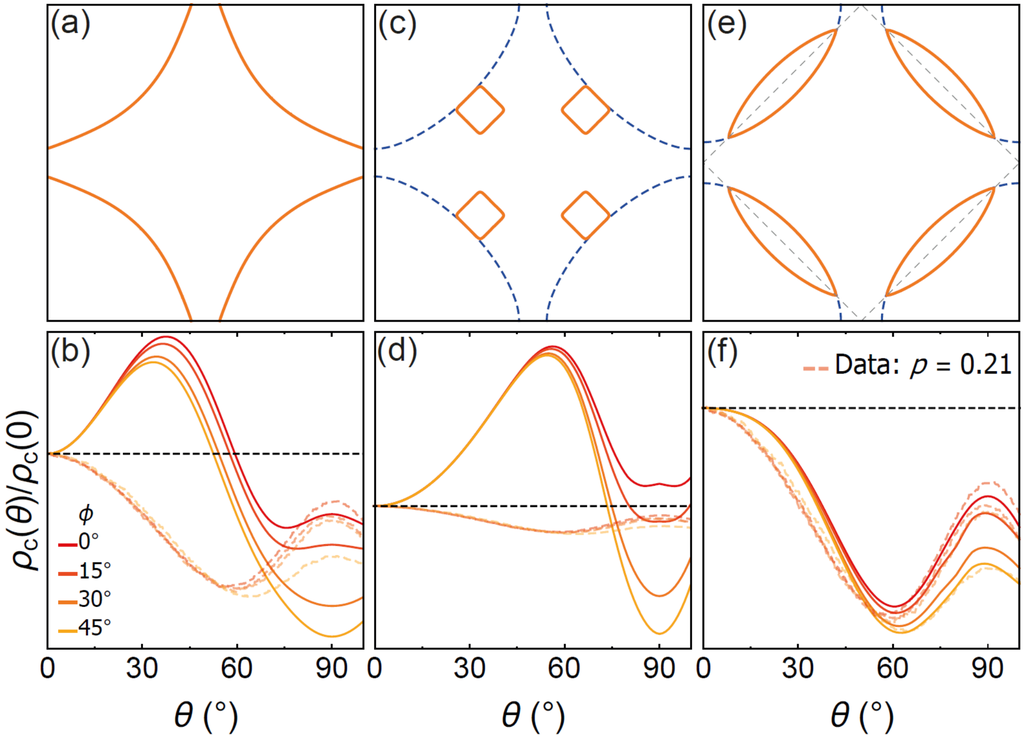
M. Oshikawa, *Phys. Rev. Lett.* **84**, 3370 (2000)
T. Senthil, S. Sachdev, and M. Vojta, *Phys. Rev. Lett.* **90**, 216403 (2003)
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)
A. Paramekanti and A. Vishwanath, *Phys. Rev. B* **70**, 245118 (2004)

Fermi surface transformation at the pseudogap critical point of a cuprate superconductor

Yawen Fang, Gaël Grissonnanche, Anaëlle Legros, Simon Verret, Francis Laliberté, Clément Collignon, Amirreza Ataei, Maxime Dion, Jianshi Zhou, David Graf, M. J. Lawler, Paul Goddard, Louis Taillefer, and B. J. Ramshaw, *Nature Physics* **18**, 558 (2022)

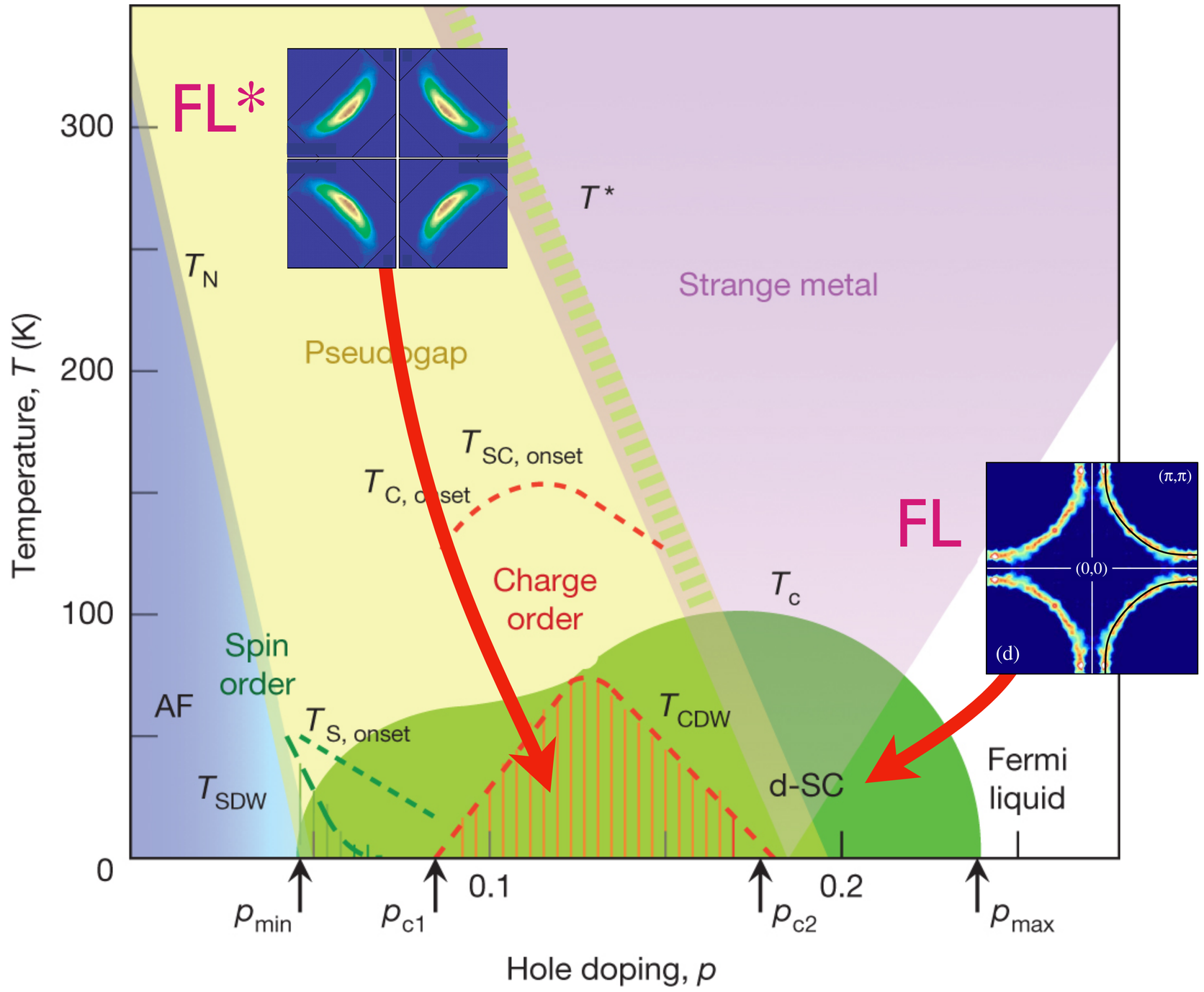


$p > p_c$ Large Fermi surface



$p < p_c$ Reconstructed Fermi surface

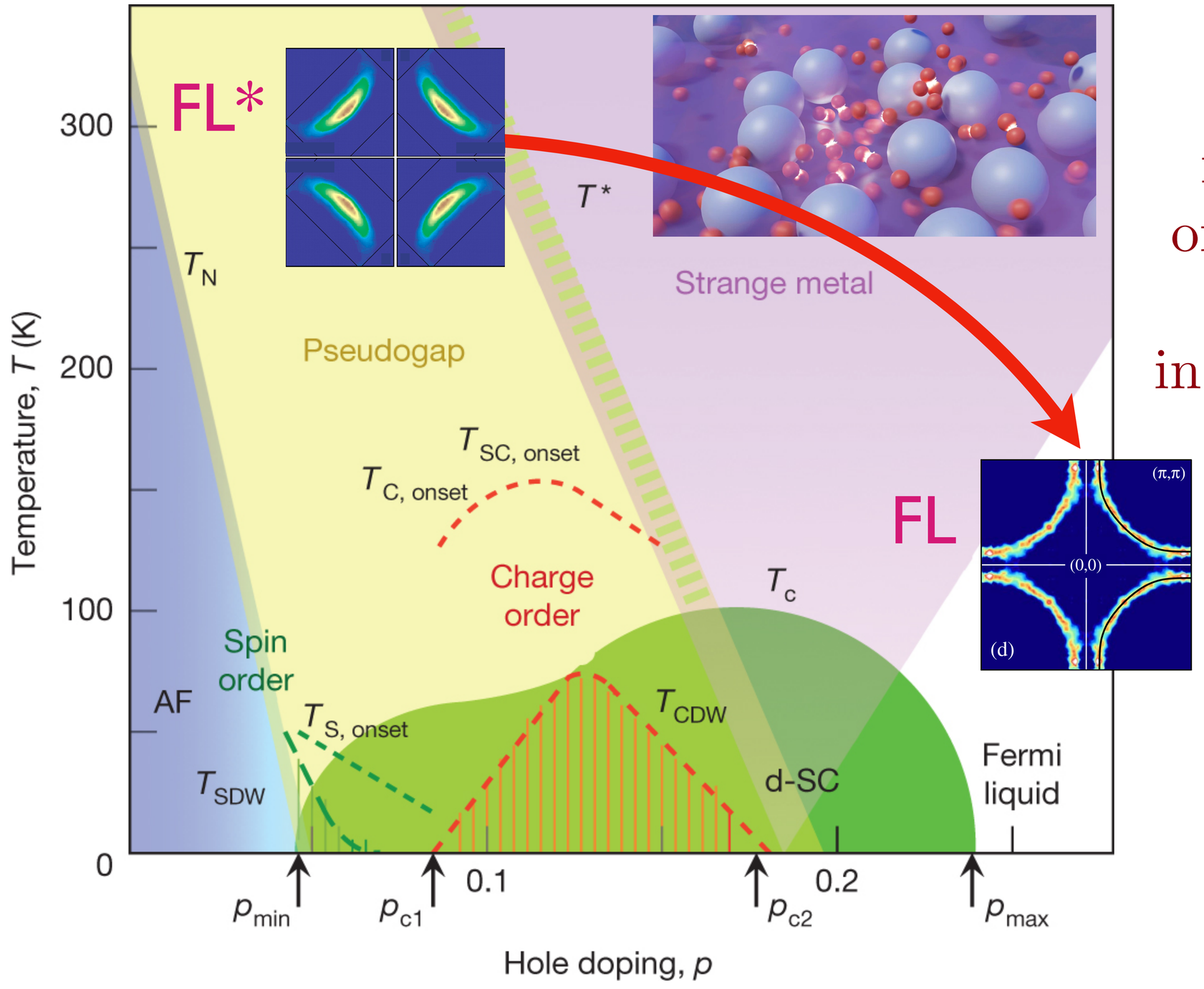
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



Obtain d-wave superconductor and charge order from a theory of *confinement* instabilities of FL*.

The resulting low T ordered states should be adiabatically connected to the corresponding states obtained from instabilities of FL.

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



Universal Yukawa-SYK theory for quantum-criticality of confinement transition from FL* to FL in the presence of disorder

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

1. Confinement transitions of the Kondo lattice

2. Ancilla theory of FL* in a single band model

3. Confinement of FL* with Neel-VBS DQCP

4. Backside problem 2:
   Nodal fermionic quasiparticles in d-wave SC
5. Backside problem 3:
   Quantum oscillations in CDW state

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$$\mathcal{H}_{KL} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^{\dagger}_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + \sum_{i} J_K \, c^{\dagger}_{i\sigma} \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \cdot \boldsymbol{S}_i + \sum_{\langle ij \rangle} J_H \, \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

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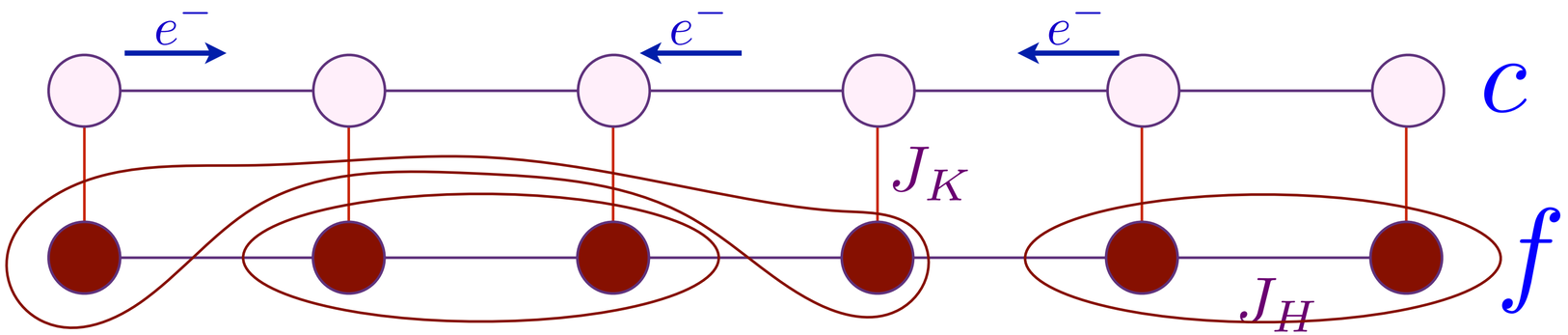


FL*

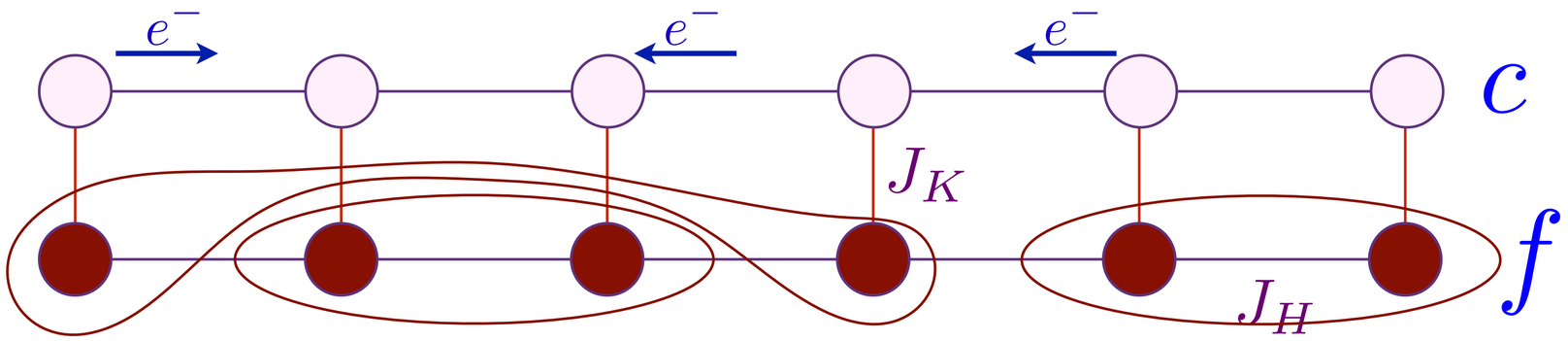
FL

J_K

Small Fermi surface of size p

$|\mathrm{FL}*\rangle = [\text{Projection onto one } f \text{ per site}]$
$\bowtie |\text{Slater determinant of } f\rangle$
$\otimes |\text{Slater determinant of } c\rangle$

$$\mathcal{H}_{KL} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + \sum_i J_K \, c^\dagger_{i\sigma} \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \cdot \boldsymbol{S}_i + \sum_{\langle ij \rangle} J_H \, \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$



FL*

$\} \langle B \rangle \neq 0$

FL

Fractionalized excitations of spin liquid are confined by the condensation of a Higgs boson $B \sim f^\dagger_\alpha c_\alpha$.

J_K

Small Fermi surface of size p

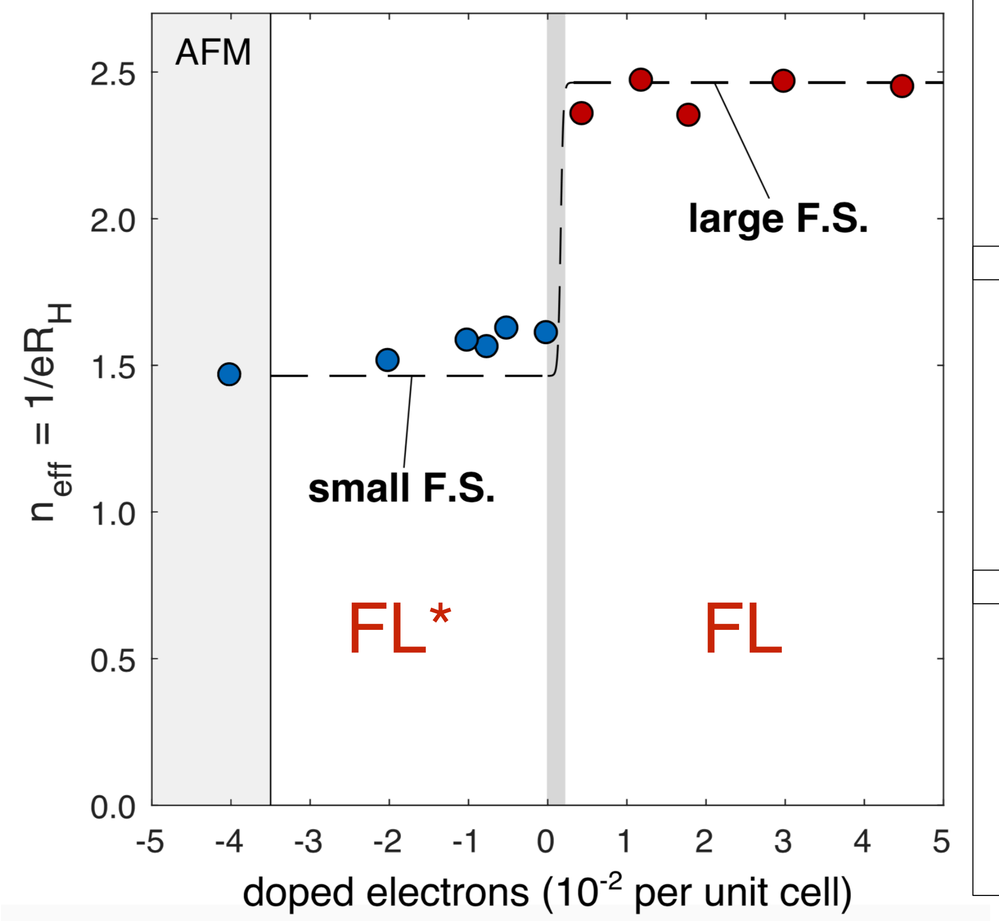
$|\mathrm{FL}*\rangle = [\text{Projection onto one } f \text{ per site}]$
$\bowtie |\text{Slater determinant of } f\rangle$
$\otimes |\text{Slater determinant of } c\rangle$

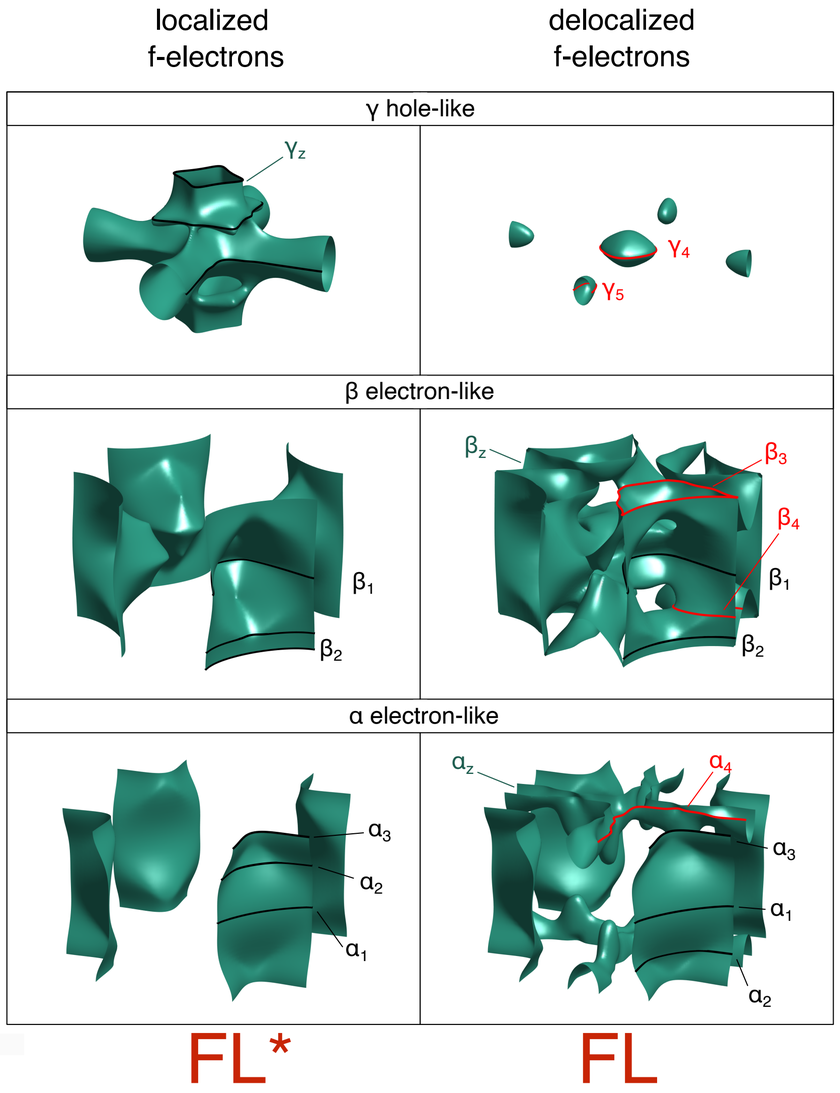
Large Fermi surface of size $1 + p$

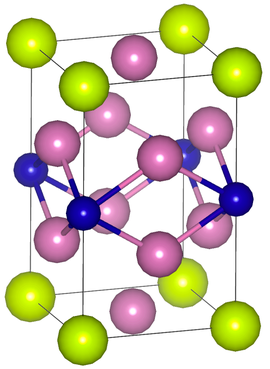
$|\mathrm{HFL}\rangle = [\text{Projection onto one } f \text{ per site}]$
$\bowtie |\text{Slater determinant of } (c, f)\rangle$

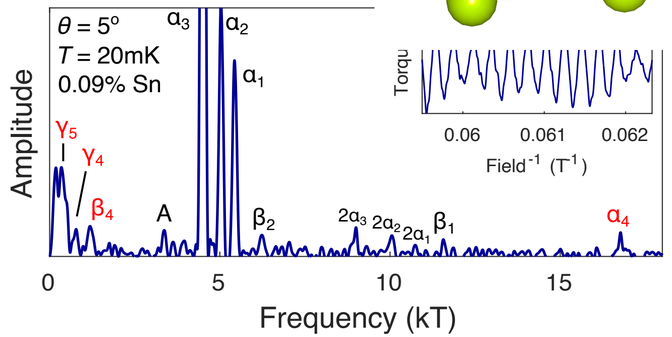
Evidence for a delocalization quantum phase transition without symmetry breaking in $CeCoIn_5$

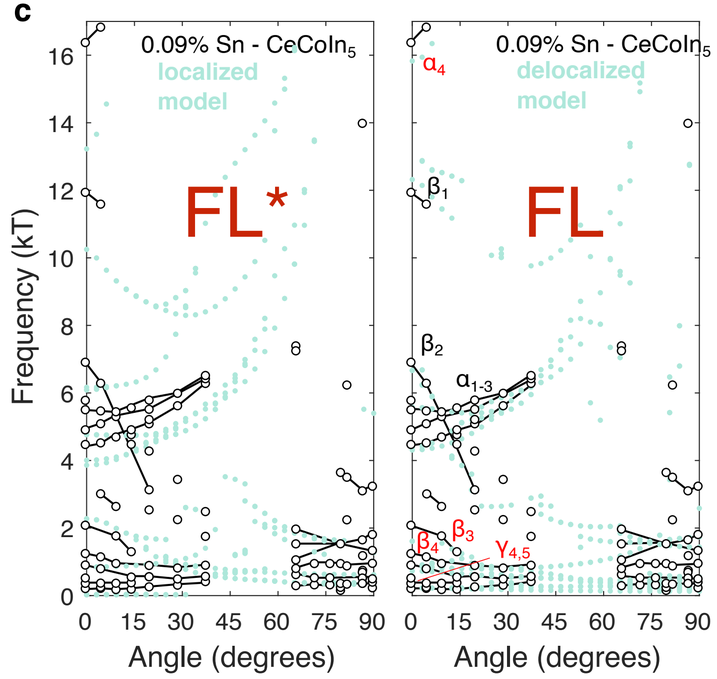
Nikola Maksimovic, Daniel H. Eilbott, Tessa Cookmeyer…….Ehud Altman, Alessandra Lanzara,James G. Analytis,
Science **375**, 76 (2021)











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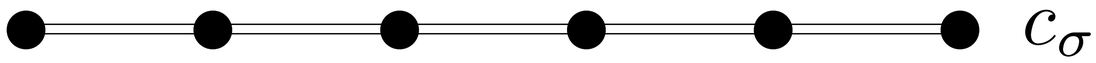
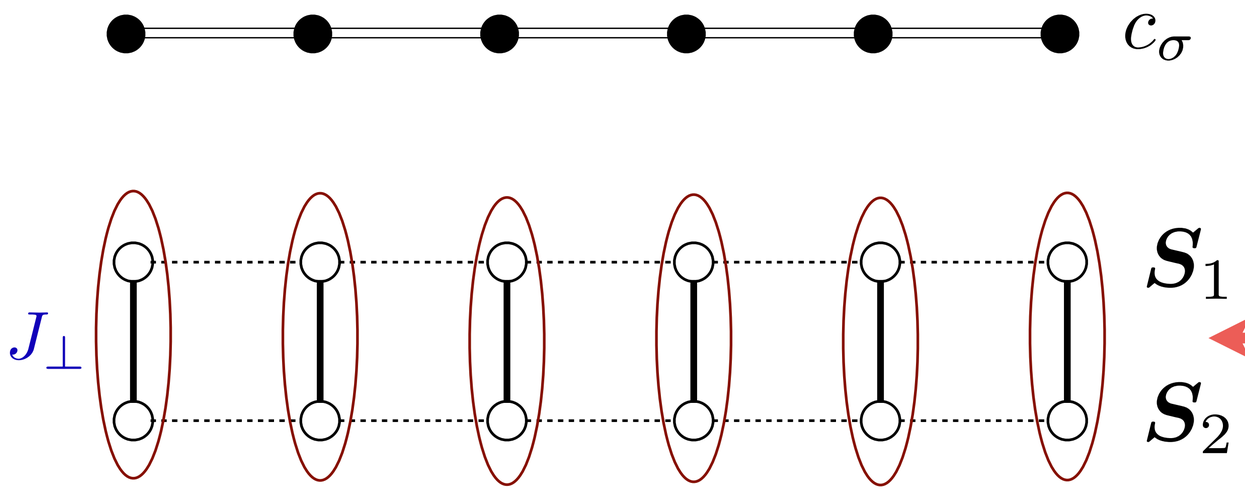
Ancilla theory of the Hubbard model



Hubbard model of hole density 1+p

Ancilla theory of the Hubbard model

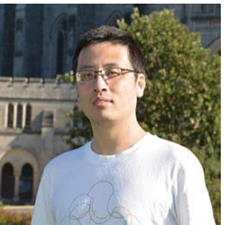


Hubbard model of hole density 1+p

Ancilla qubits in a "trivial" gapped insulator

$$\mathcal{H}_{\text{Hubbard}} + \mathcal{H}_{\text{trivial insulator}}$$

Ya-Hui Zhang



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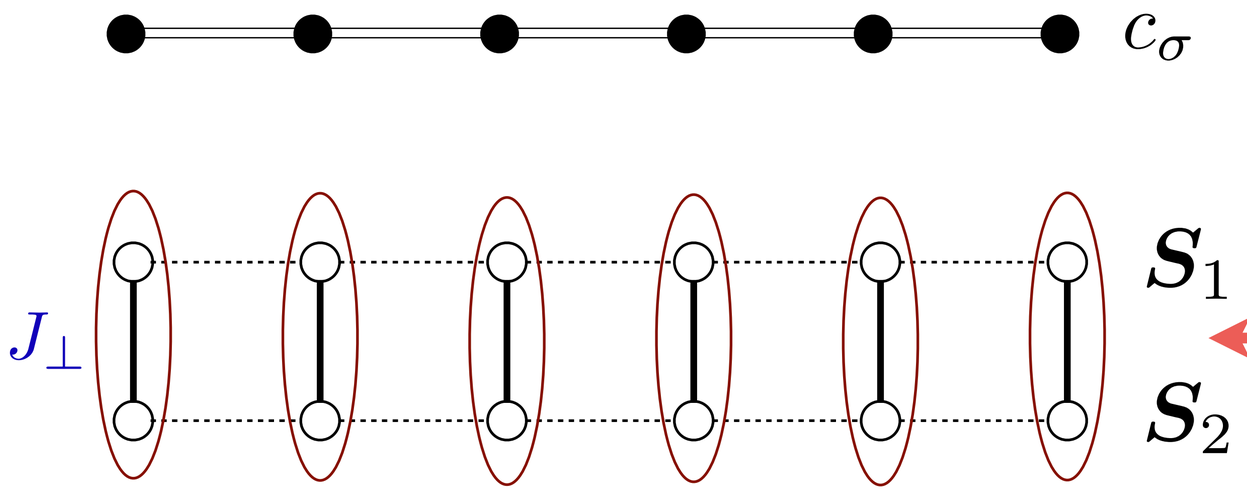
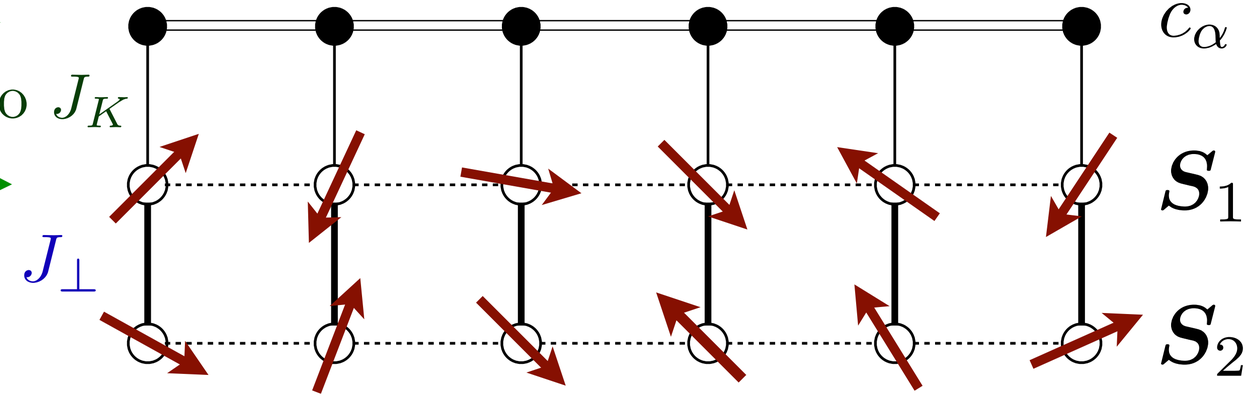


Hubbard model of hole density 1+p

Ancilla qubits in a "trivial" gapped insulator

$$U\left(\mathcal{H}_{\text{Hubbard}}+\mathcal{H}_{\text{trivial insulator}}\right)U^{-1}=\mathcal{H}_{\text{ancilla}}$$

Antiferromagnetic Kondo J_K



Free holes of density 1+p

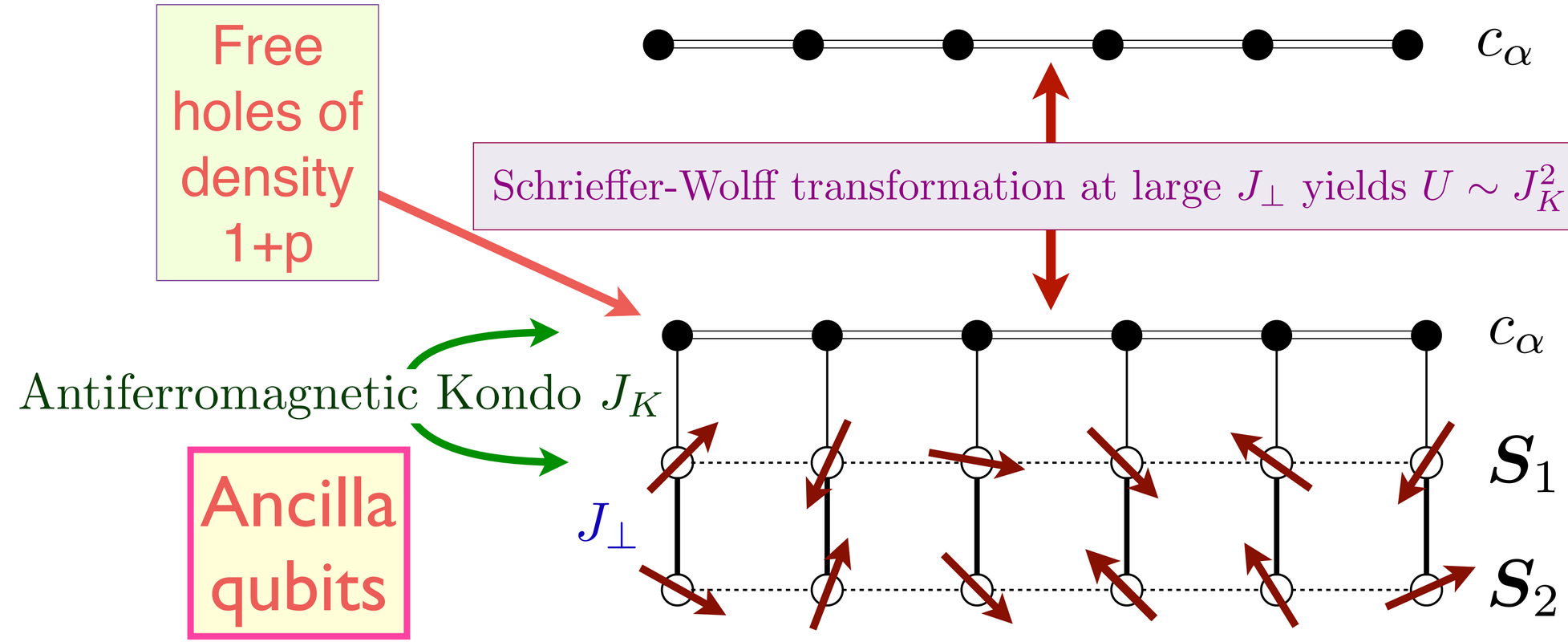
Ya-Hui Zhang

Ancilla theory of the Hubbard model

Ya-Hui Zhang and S. Sachdev,
Phys. Rev. Res. **2**, 023172 (2020)

Free holes of density 1+p

Hubbard model of hole density 1+p



Ancilla qubits

Ya-Hui Zhang

$$\mathcal{H}_{\text{ancilla}} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\alpha} c_{\mathbf{p}\alpha} + J_K \sum_i c^\dagger_{i\alpha} \frac{\boldsymbol{\sigma}_{\alpha\alpha'}}{2} c_{i\alpha'} \cdot \boldsymbol{S}_{1i} + J_\perp \sum_i \boldsymbol{S}_{1i} \cdot \boldsymbol{S}_{2i}$$

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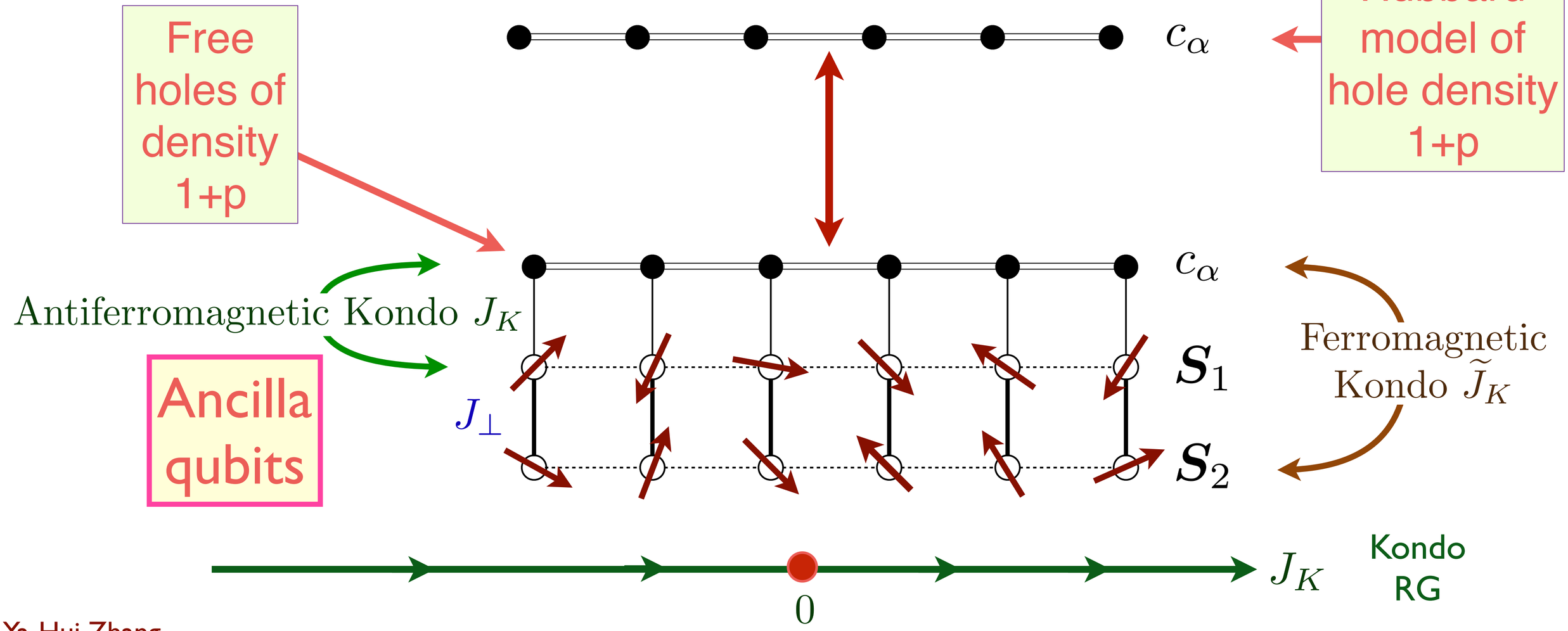

Ya-Hui Zhang

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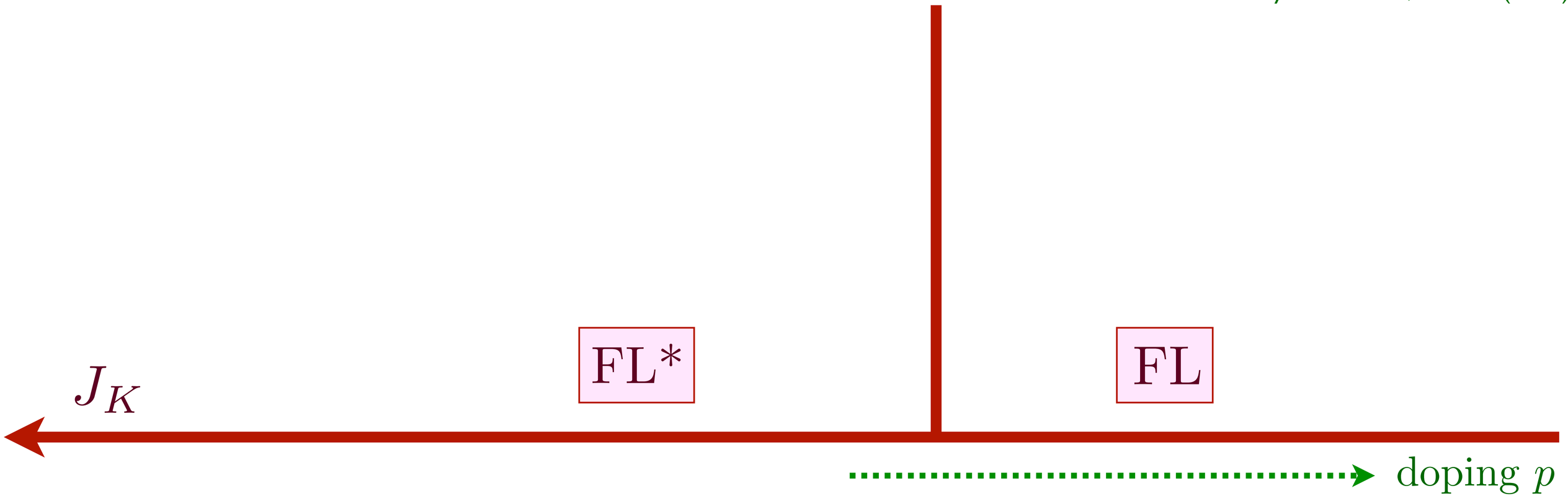

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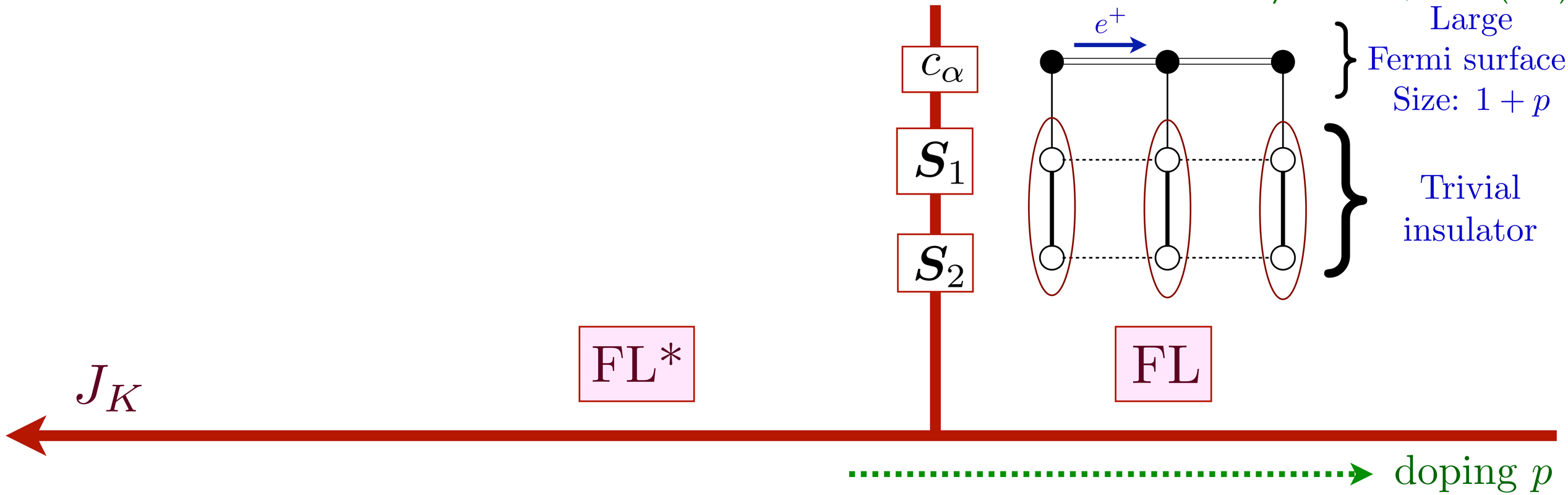

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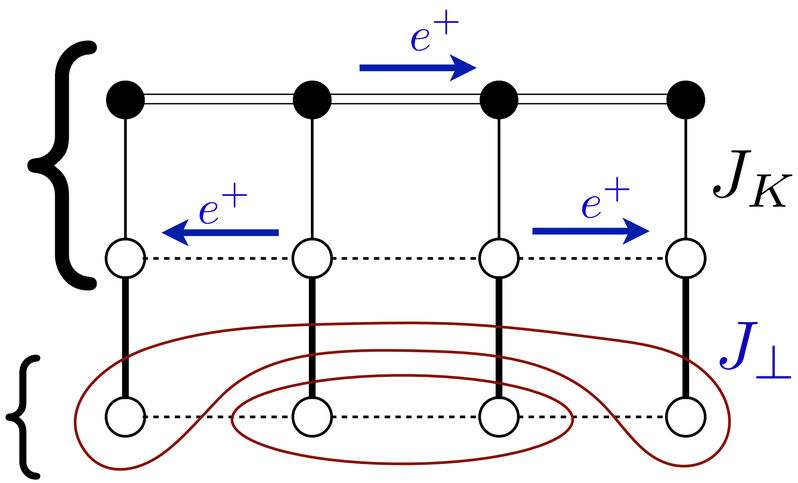
Ancilla theory of the Hubbard model

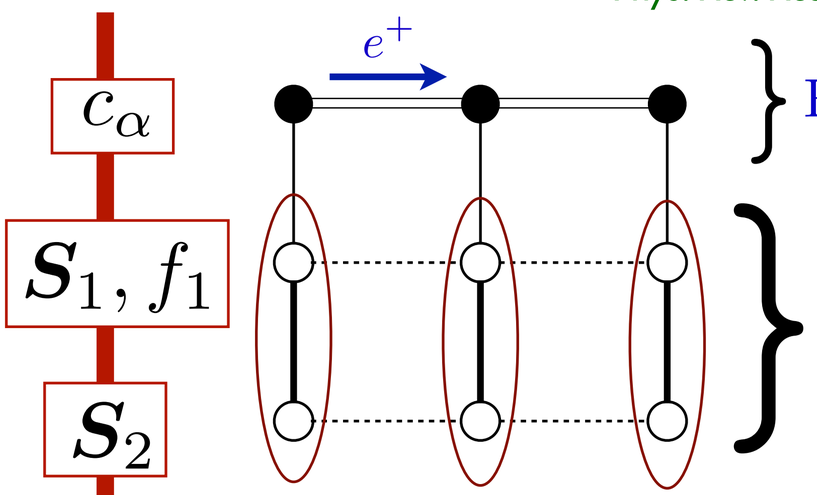
Ya-Hui Zhang and S. Sachdev,
Phys. Rev. Res. **2**, 023172 (2020)

Kondo lattice heavy Fermi liquid.
Size $1+p+1$ $= p \pmod 2$.
Small Fermi surface!

$\langle \Phi \rangle \neq 0$



Spin liquid



Large Fermi surface.
Size: $1+p$

Trivial insulator

FL*

FL

J_K

doping p

Pseudogap metal =
Kondo Lattice Heavy Fermi Liquid
$\oplus$
Spin Liquid

Fractionalized excitations of layer $\boldsymbol{S}_1$ confined by condensation of Higgs boson $\Phi \sim f^\dagger_{1\alpha} c_\alpha$.

Fratcionalized excitations of layer $\boldsymbol{S}_2$ remain deconfined

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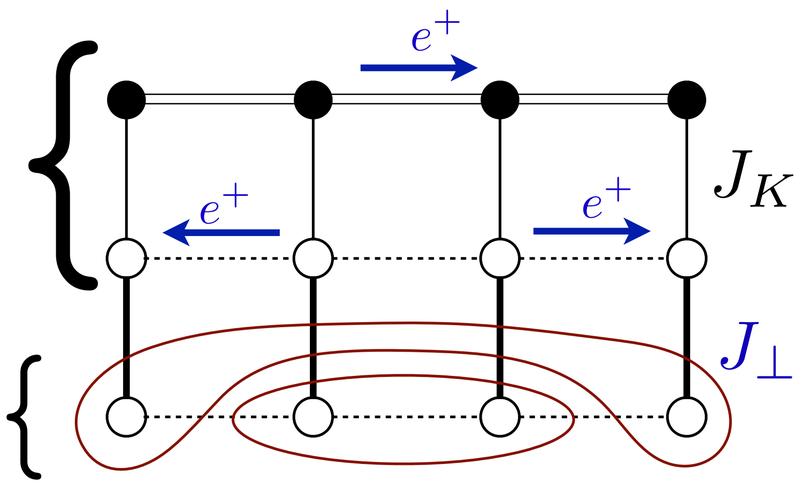
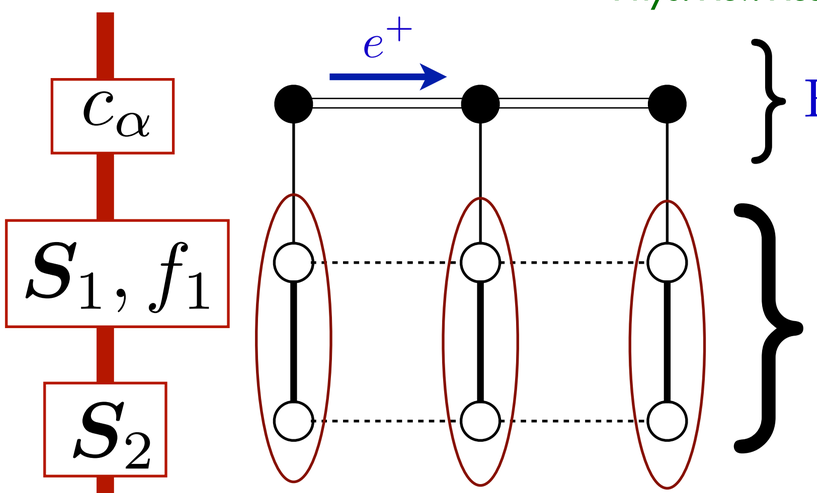


Spin liquid



Large Fermi surface.
Size: $1 + p$

Trivial insulator

FL*

FL

J_K

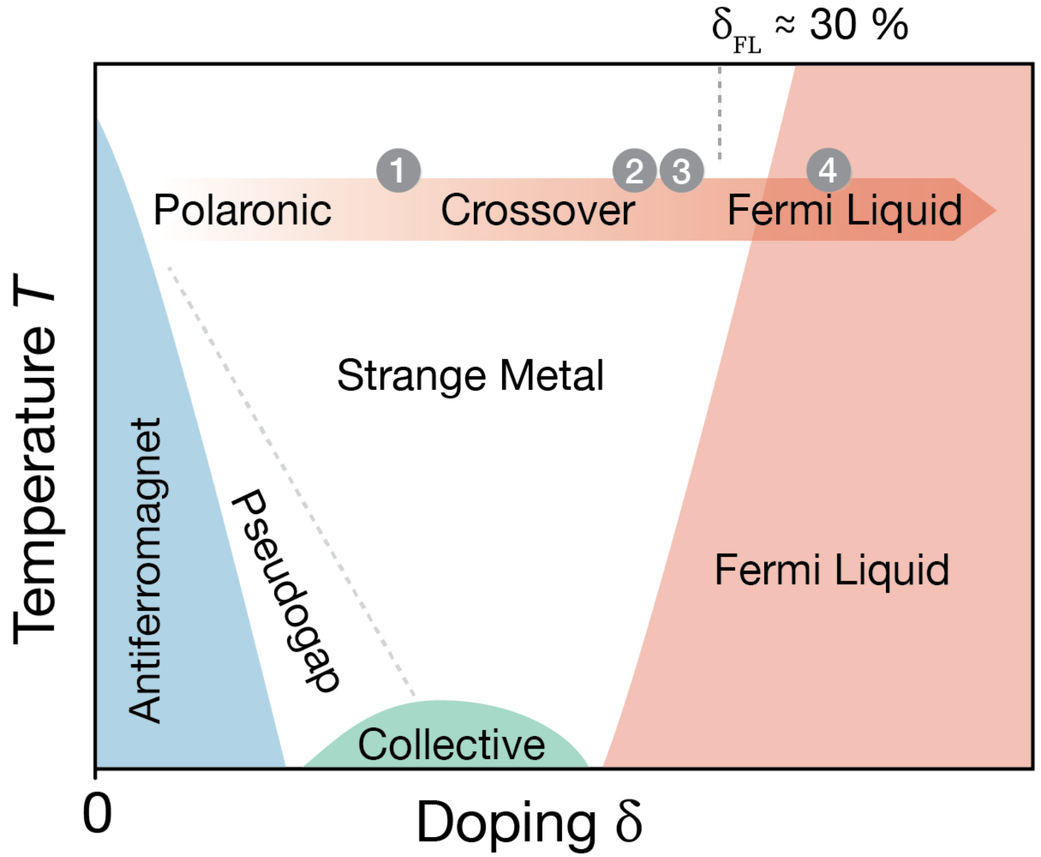
doping p

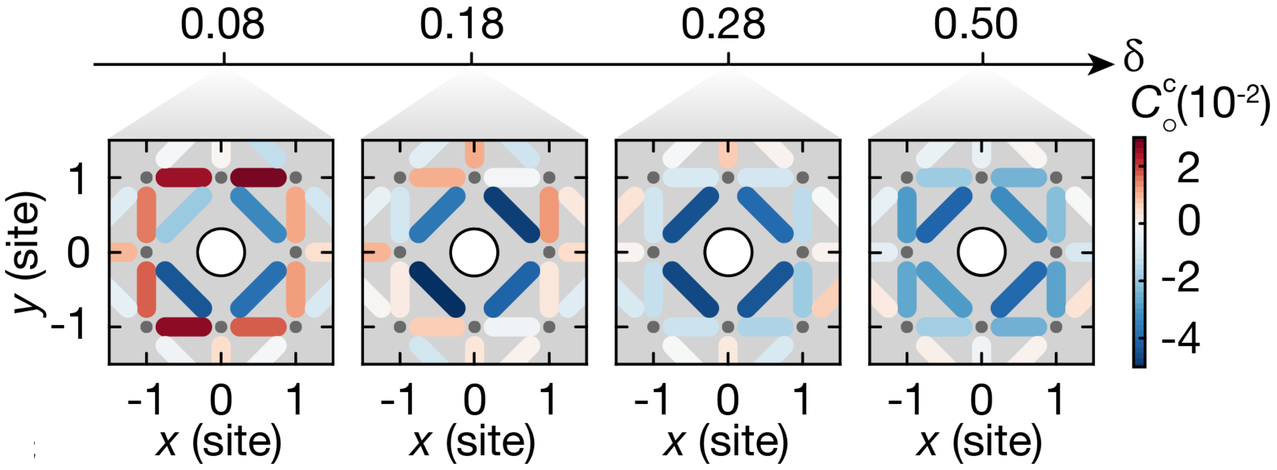
Pseudogap metal =
Kondo Lattice Heavy
Fermi Liquid
$\oplus$
Spin Liquid

$$|\mathrm{FL}*\rangle = [\text{Projection onto rung singlets of } \boldsymbol{S}_1, \boldsymbol{S}_2] \bowtie |\text{Slater determinant of } (c, f_1)\rangle \otimes |\text{Spin liquid of } \boldsymbol{S}_2\rangle$$

Ya-Hui Zhang

Replacement for "vanilla" Gutzwiller-projected Fermi liquid in the underdoped regime





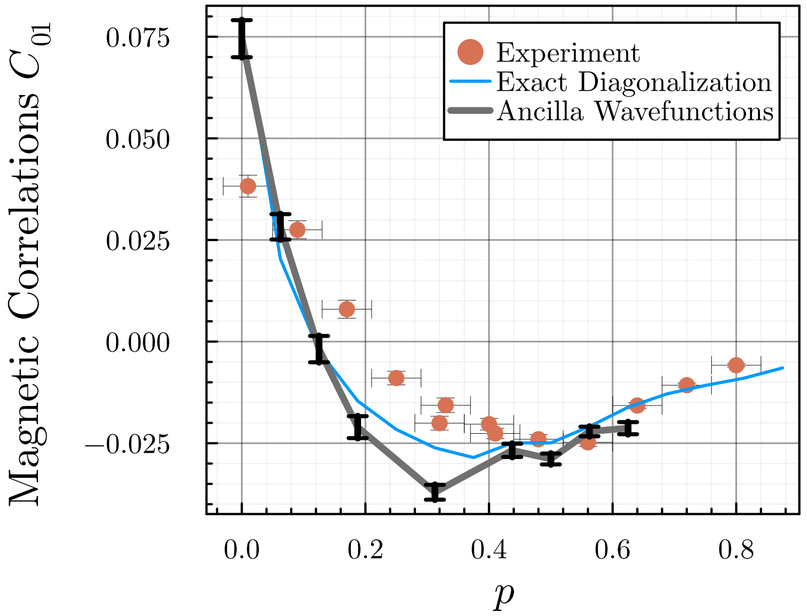
Ultracold fermionic atoms in optical lattices

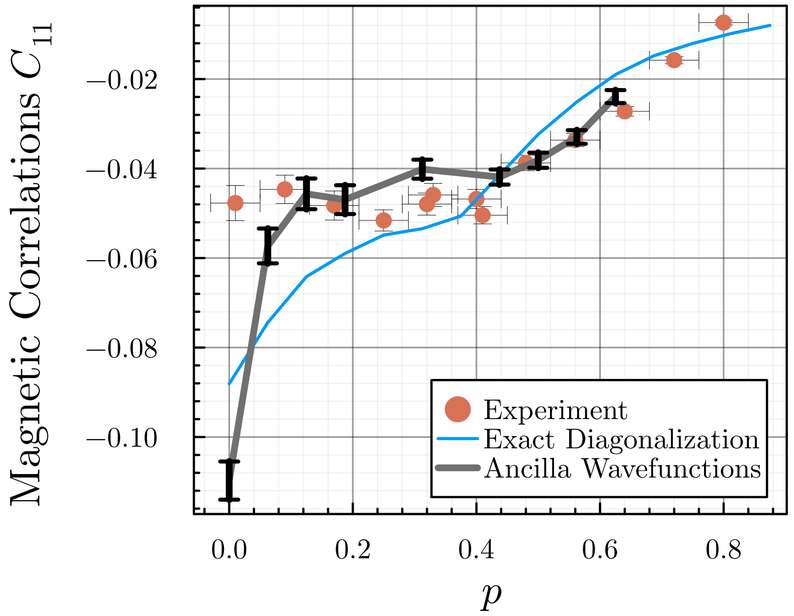
Microscopic evolution of doped Mott insulators from polaronic metal to Fermi liquid

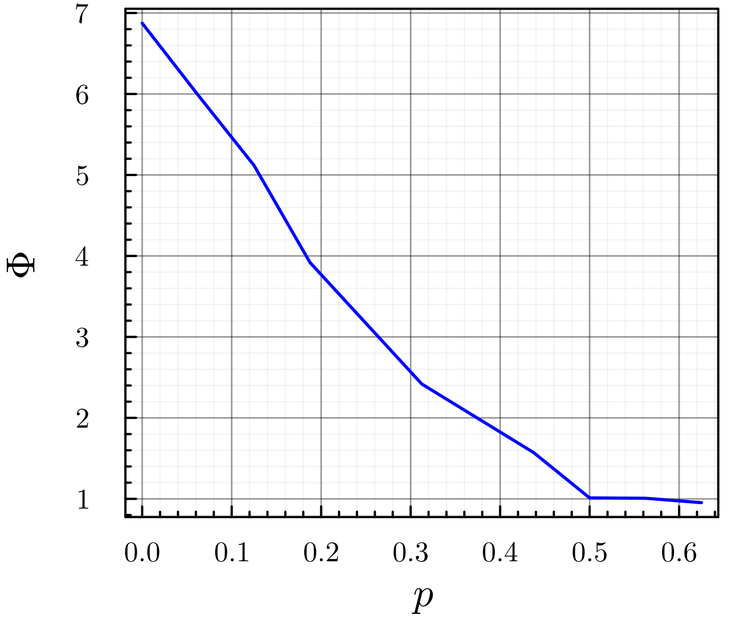
Joannis Koepsell, Dominik Bourgund, Pimonpan Sompet, Sarah Hirthe, Annabelle Bohrdt, Yao Wang, Fabian Grusdt, Eugene Demler, Guillaume Salomon, Christian Gross, Immanuel Bloch

Science **374** (2021) 82

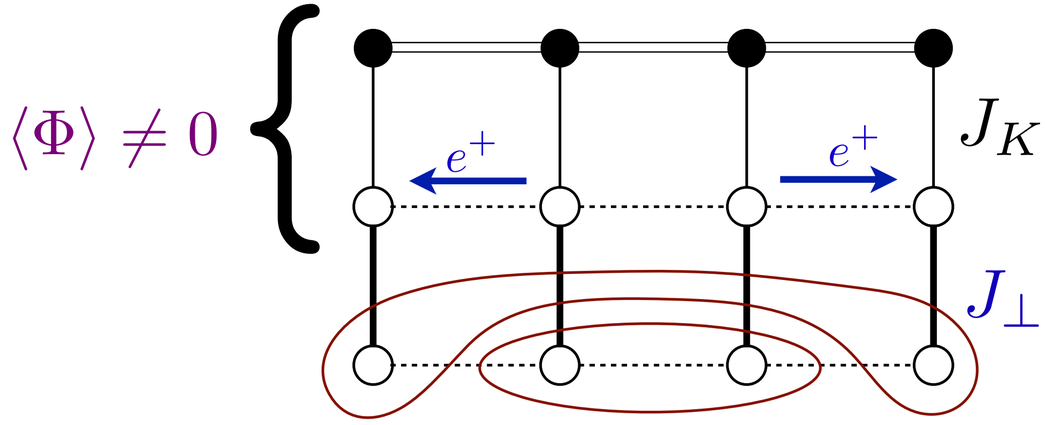
Max Planck Institute of Quantum Optics, Garching







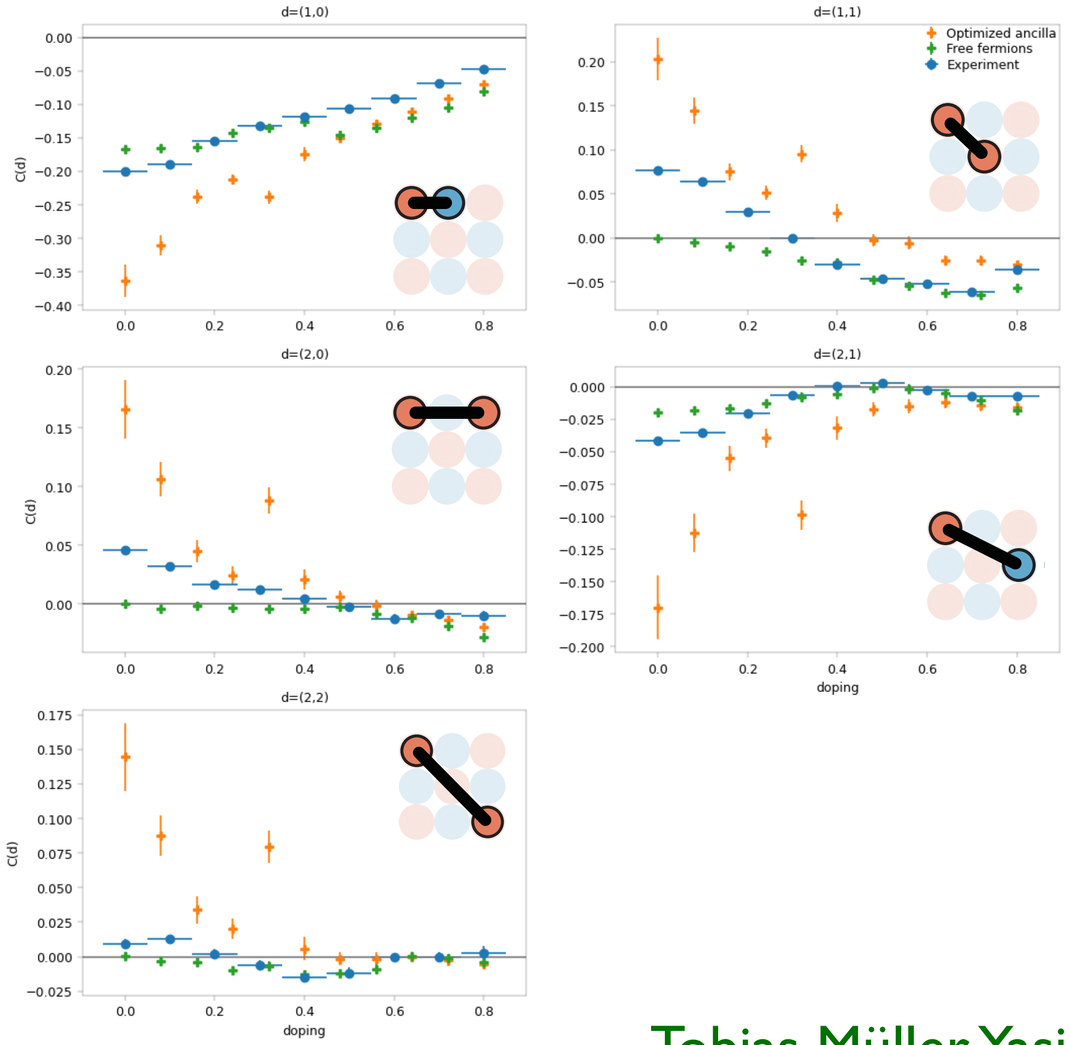
Higgs boson $\Phi \sim f^\dagger_{1\alpha} c_\alpha$.



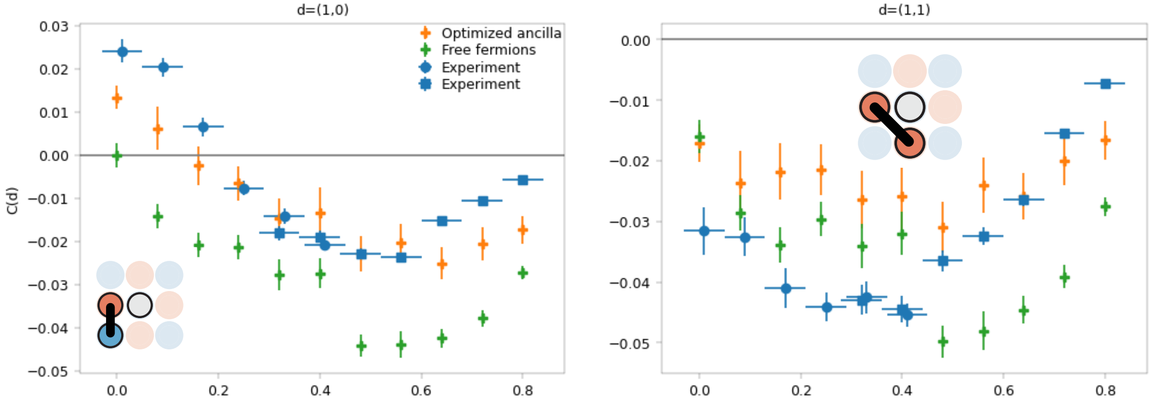
H. Shackleton and Shiwei Zhang, to appear

Results for Connected Correlators: Comparison with experiment

Bare Spin-Spin Correlators



Hole-induced Spin-Spin Correlators



Preliminary data

*Test different spin-liquid ansätze for second ancilla layer

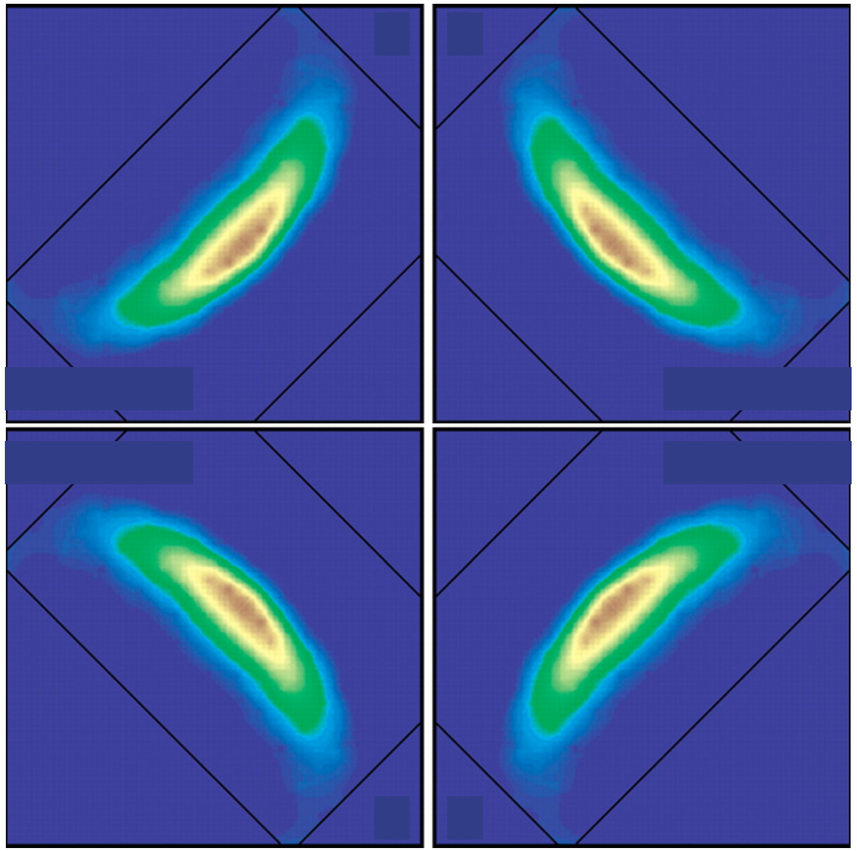
*Improve sampling of wave-functions

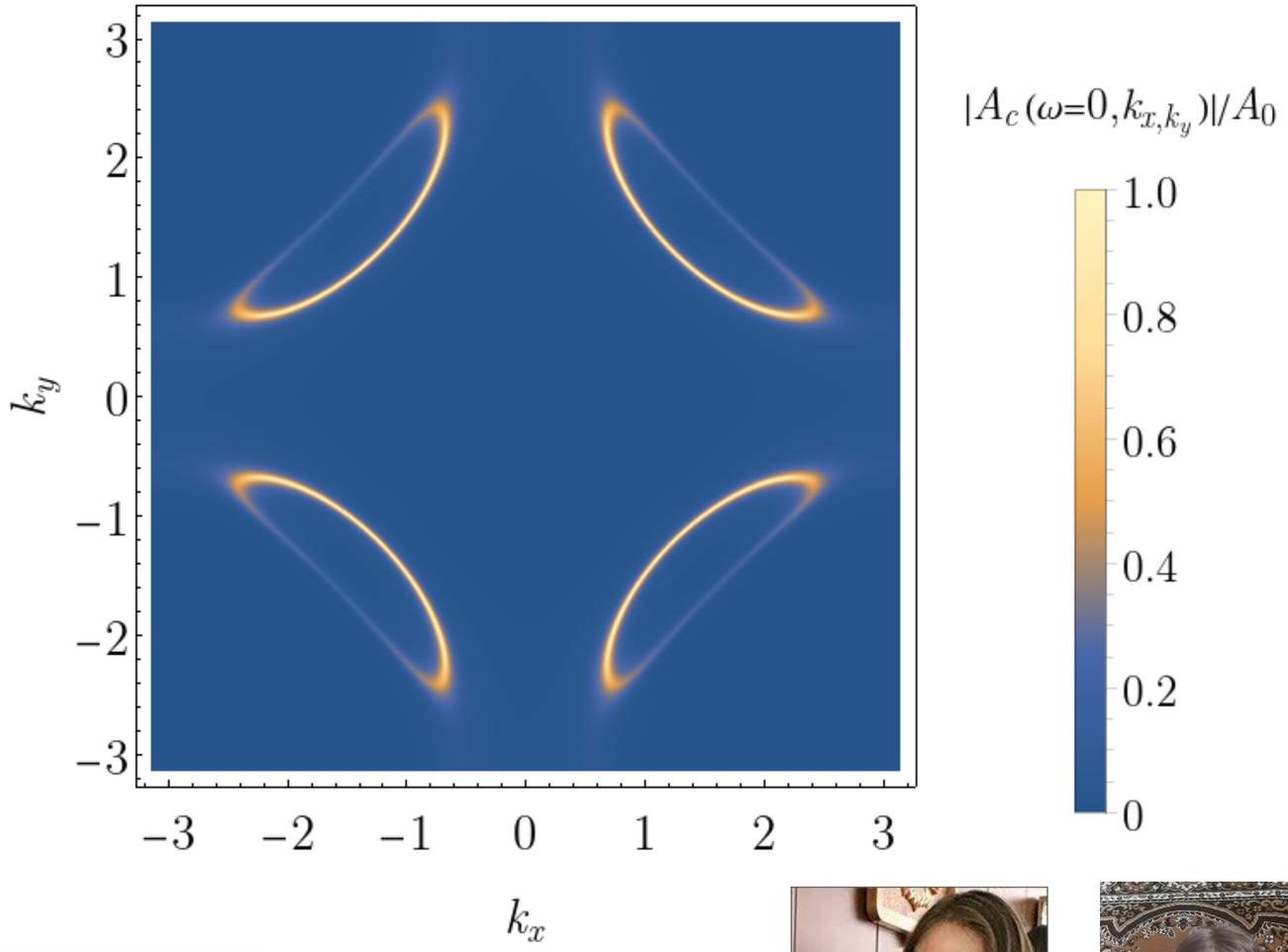
*Better statistics to obtain more reliable error-bars

Tobias Müller, Yasir Iqbal, S.S., Ronny Thomale to appear

Photoemission at small p

E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. S., PRB **105**, 075146 (2022)





$Ca_{2-x}Na_xCuO_2Cl_2$
at $x = 0.10$

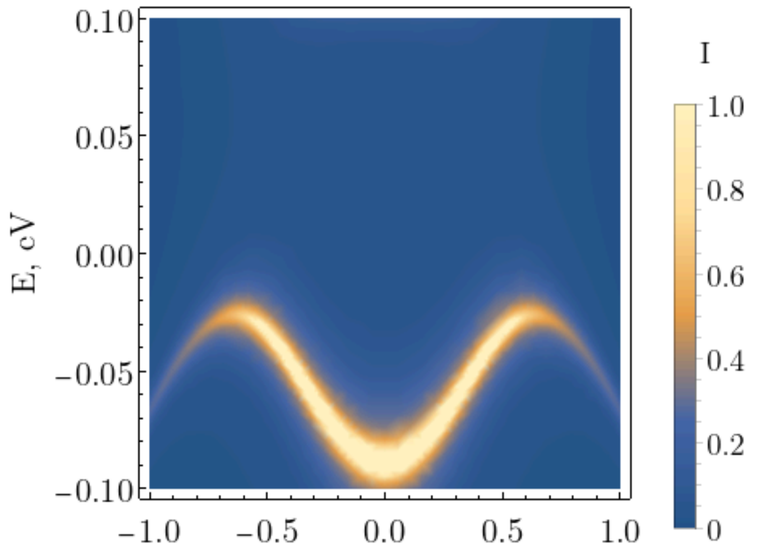
"Fermi arcs"

Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

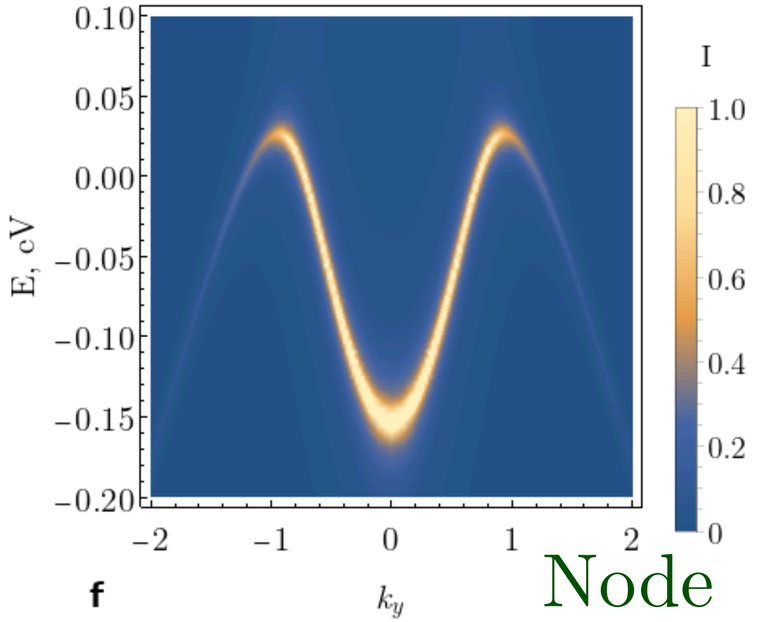
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. S., PRB **105**, 075146 (2022)

FL* in a ***one-band*** model

Second ancilla layer is needed to describe MDC and EDC

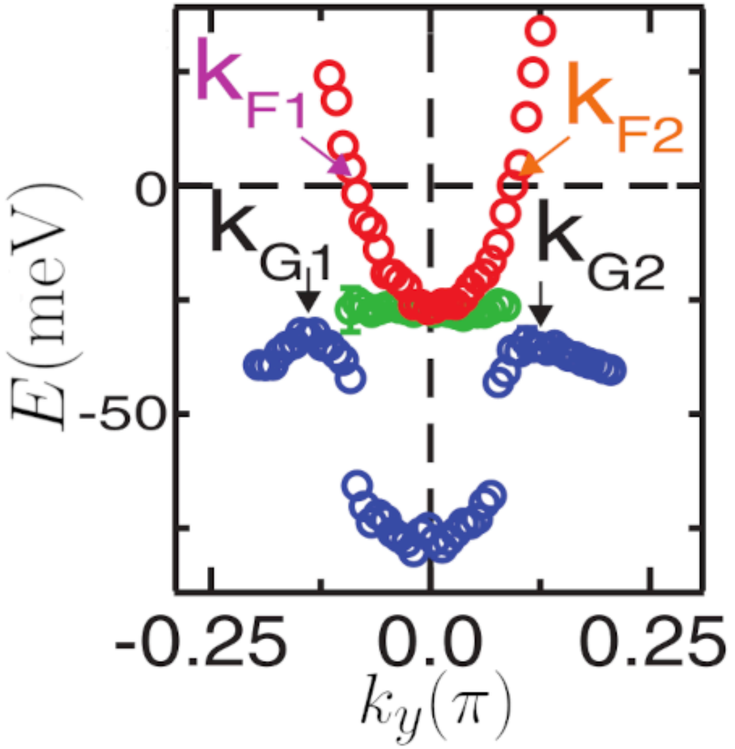


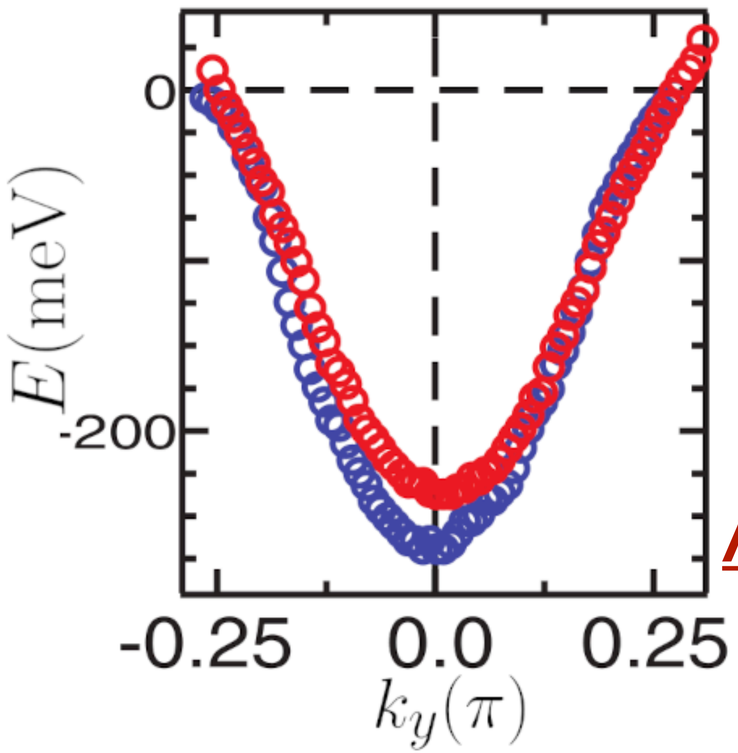
Anti-node



f

Node





R.-H. He, M. Hashimoto, H. Karapetyan, J. D. Koralek, J. P. Hinton, J. P. Testaud, V. Nathan, Y. Yoshida, H. Yao, K. Tanaka, W. Meevasana, R. G. Moore, D. H. Lu, S. K. Mo, M. Ishikado, H. Eisaki, Z. Hussain, T. P. Devereaux, S. A. Kivelson, J. Orenstein, A. Kapitulnik, and Z.-X. Shen, *Science* **331**, 1579 (2011)

ARPES on Bi2201

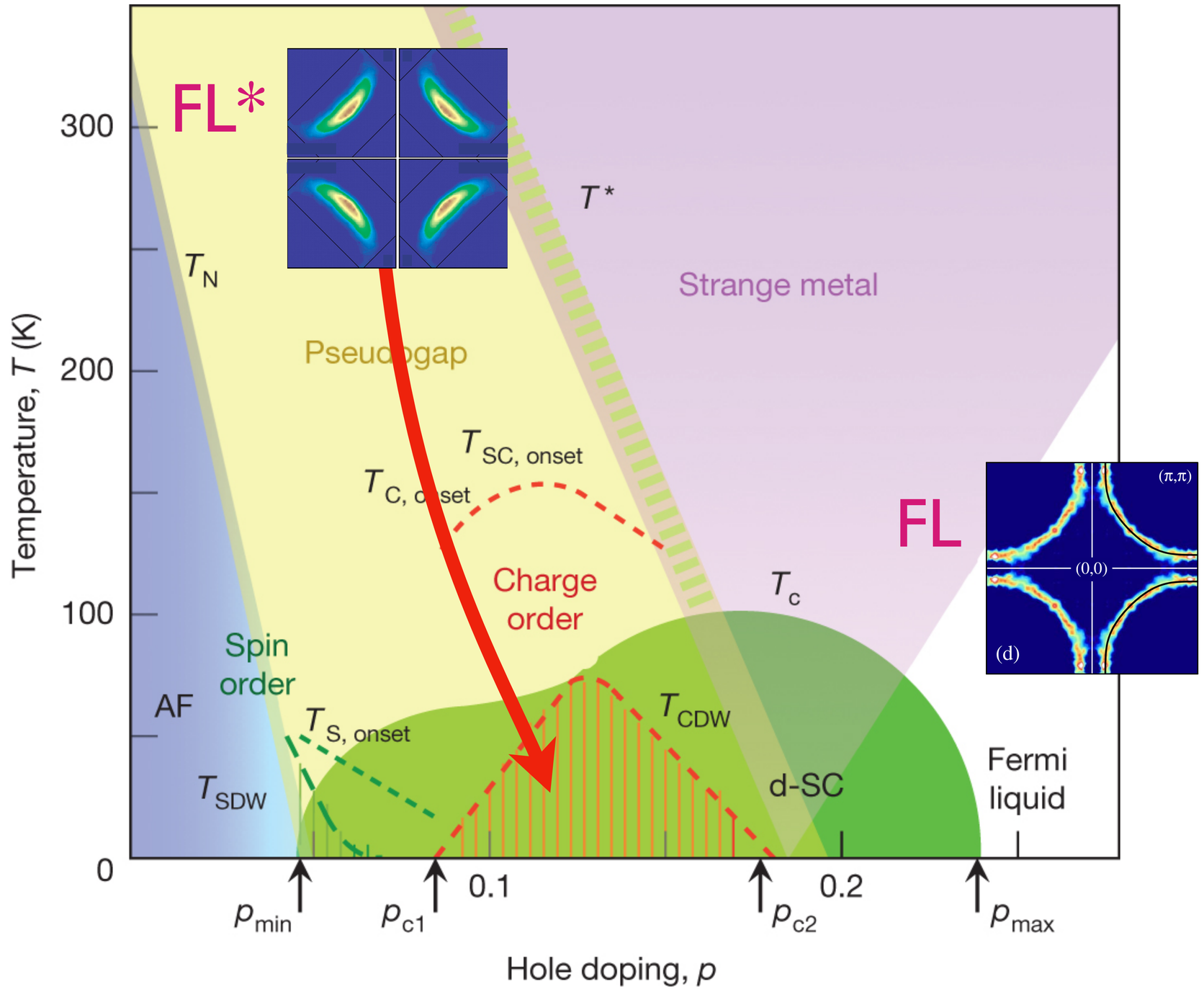
1. Confinement transitions of the Kondo lattice

2. Ancilla theory of FL* in a single band model

3. Confinement of FL* with Neel-VBS DQCP

4. Backside problem 2:
   Nodal fermionic quasiparticles in d-wave SC
5. Backside problem 3:
   Quantum oscillations in CDW state

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



Obtain d-wave superconductor and charge order from a theory of *confinement* instabilities of FL*.

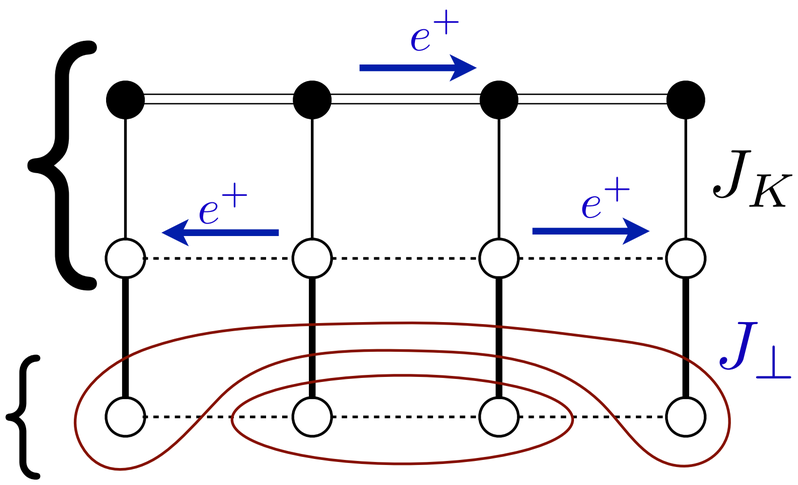
The resulting low T ordered states should be adiabatically connected to the corresponding states obtained from instabilities of FL.

Ancilla theory of the Hubbard model

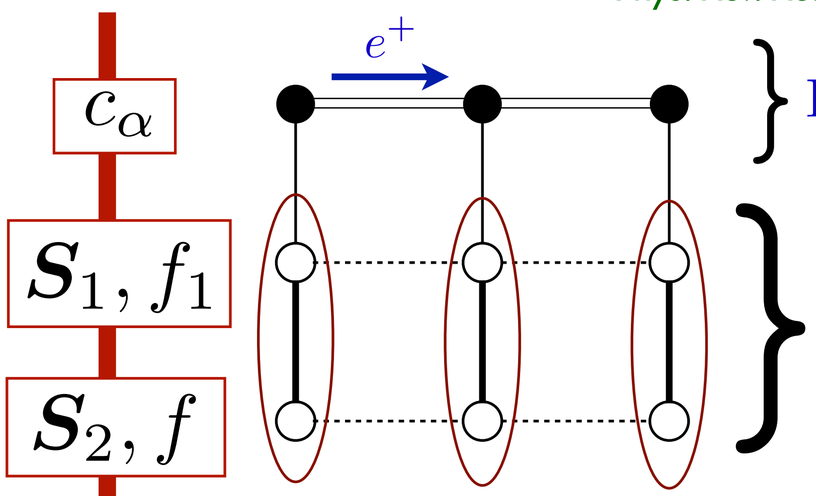
Ya-Hui Zhang and S. Sachdev,
Phys. Rev. Res. **2**, 023172 (2020)

Kondo lattice heavy Fermi liquid.
Size $1+p+1$ $= p \pmod 2$.
Small Fermi surface!

$\langle \Phi \rangle \neq 0$



Spin liquid



Large Fermi surface.
Size: $1+p$

Trivial insulator

FL*

FL

J_K

doping p

1. Choose Néel-VBS DQCP spin liquid: f_α spinons moving in π-flux coupled to $\mathrm{SU}(2)_N$ gauge field. Note $\Phi \sim f_{1\alpha}^\dagger c_\alpha$ is condensed.

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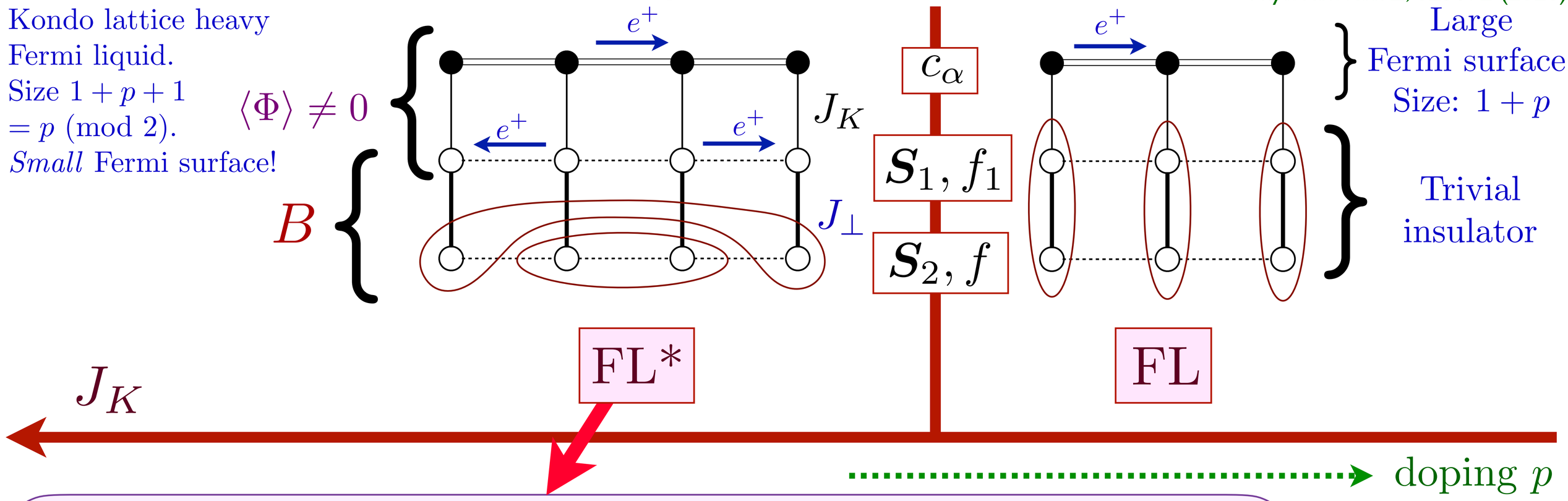


1. Choose Néel-VBS DQCP spin liquid: f_α spinons moving in π-flux coupled to $\mathrm{SU}(2)_N$ gauge field. Note $\Phi \sim f^\dagger_{1\alpha} c_\alpha$ is condensed.

2. Confine spin liquid by condensing charge e, $\mathrm{SU}(2)_N$ fundamental, Higgs boson

$$B \sim \begin{pmatrix} f^\dagger_{1\alpha} f_\alpha \\ \varepsilon_{\alpha\beta} f^\dagger_{1\alpha} f^\dagger_\beta \end{pmatrix}$$

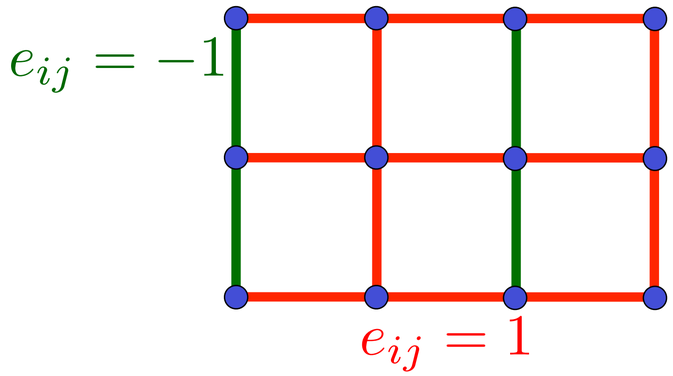
Boson with same quantum numbers in X.-G. Wen and P.A. Lee, PRL **76**, 503 (1996)

Confinement of SU(2)$_N$ gauge theory by charge fluctuations

- Begin with the π-flux spin liquid in the fermionic spinon description.

$$H_f = iJ \sum_{\langle ij \rangle} e_{ij} \left(f^\dagger_{i\alpha} f_{j\alpha} - f^\dagger_{j\alpha} f_{i\alpha} \right) = iJ \sum_{\langle ij \rangle} e_{ij} \left(\Psi^\dagger_i U_{ij} \Psi_j - \Psi^\dagger_j U_{ji} \Psi_i \right); \quad \Psi_i = \begin{pmatrix} f_{i\uparrow} \\ f^\dagger_{i\downarrow} \end{pmatrix}$$

H_f is invariant under SU(2) rotations in spin and SU(2)$_N$ rotations in Nambu space; U_{ij} is the SU(2)$_N$ gauge field.



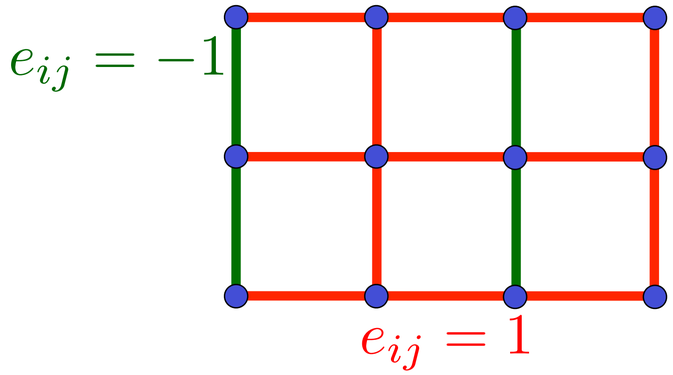
M. Christos, Zhu-Xi Luo, H. Shackleton, Ya-Hui Zhang, M. Scheurer, and S. S., *PNAS* **120**, e2302701120 (2023)

Confinement of $SU(2)_N$ gauge theory by charge fluctuations

- Begin with the π-flux spin liquid in the fermionic spinon description.

$$H_f = iJ \sum_{\langle ij \rangle} e_{ij} \left(f^\dagger_{i\alpha} f_{j\alpha} - f^\dagger_{j\alpha} f_{i\alpha} \right) = iJ \sum_{\langle ij \rangle} e_{ij} \left(\Psi^\dagger_i U_{ij} \Psi_j - \Psi^\dagger_j U_{ji} \Psi_i \right); \quad \Psi_i = \begin{pmatrix} f_{i\uparrow} \\ f^\dagger_{i\downarrow} \end{pmatrix}$$

H_f is invariant under SU(2) rotations in spin and $SU(2)_N$ rotations in Nambu space; U_{ij} is the $SU(2)_N$ gauge field.



- Introduce a charge e, $SU(2)_N$ fundamental boson B_i such that the composite of B_i and Ψ_i is an electron. The projective symmetries require

$$H_B = r \sum_i B^\dagger_i B_i + iw \sum_{\langle ij \rangle} e_{ij} \left(B^\dagger_i U_{ij} B_j - B^\dagger_j U_{ji} B_i \right) + \ldots$$

M. Christos, Zhu-Xi Luo, H. Shackleton, Ya-Hui Zhang, M. Scheurer, and S. S., *PNAS* **120**, e2302701120 (2023)

Confinement of SU(2)$_N$ gauge theory by charge fluctuations

$$\mathcal{L}(B) = H_B + \frac{u}{2}\sum_{\boldsymbol{i}} \rho_{\boldsymbol{i}}^2 + V_1 \sum_{\boldsymbol{i}} \rho_{\boldsymbol{i}} \left(\rho_{\boldsymbol{i}+\hat{\boldsymbol{x}}} + \rho_{\boldsymbol{i}+\hat{\boldsymbol{y}}}\right) + g \sum_{\langle \boldsymbol{ij}\rangle} |\Delta_{\boldsymbol{ij}}|^2 + J_1 \sum_{\langle \boldsymbol{ij}\rangle} Q_{\boldsymbol{ij}}^2 + K_1 \sum_{\langle \boldsymbol{ij}\rangle} J_{\boldsymbol{ij}}^2 .$$

site charge density: $\left\langle c_{\boldsymbol{i}\alpha}^\dagger c_{\boldsymbol{i}\alpha} \right\rangle \sim \rho_{\boldsymbol{i}} = B_{\boldsymbol{i}}^\dagger B_{\boldsymbol{i}}$

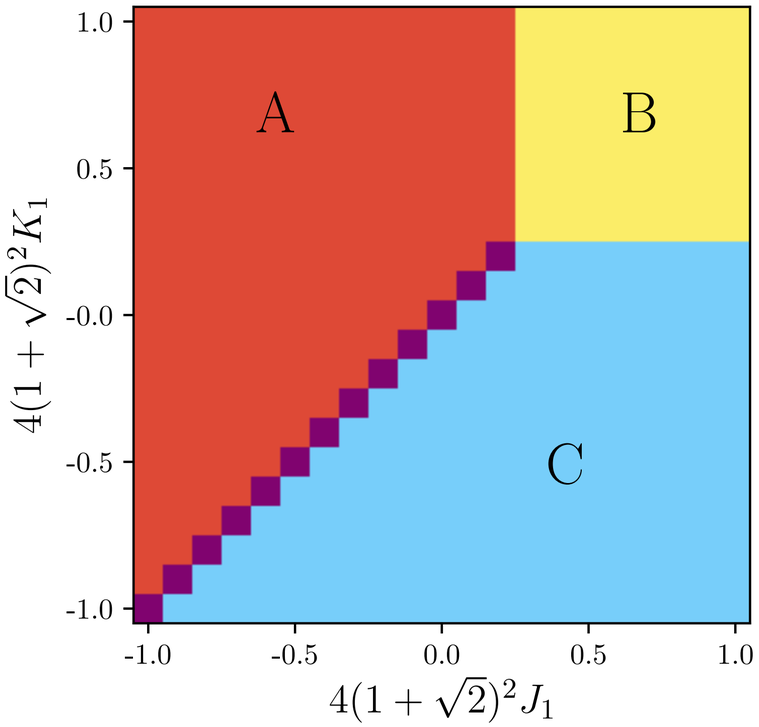
bond density: $\left\langle c_{\boldsymbol{i}\alpha}^\dagger c_{\boldsymbol{j}\alpha} + c_{\boldsymbol{j}\alpha}^\dagger c_{\boldsymbol{i}\alpha} \right\rangle \sim Q_{\boldsymbol{ij}} = Q_{\boldsymbol{ji}} = \mathrm{Im}\left(B_{\boldsymbol{i}}^\dagger e_{\boldsymbol{ij}} U_{\boldsymbol{ij}} B_{\boldsymbol{j}}\right)$

bond current: $i\left\langle c_{\boldsymbol{i}\alpha}^\dagger c_{\boldsymbol{j}\alpha} - c_{\boldsymbol{j}\alpha}^\dagger c_{\boldsymbol{i}\alpha} \right\rangle \sim J_{\boldsymbol{ij}} = -J_{\boldsymbol{ji}} = \mathrm{Re}\left(B_{\boldsymbol{i}}^\dagger e_{\boldsymbol{ij}} U_{\boldsymbol{ij}} B_{\boldsymbol{j}}\right)$

Pairing: $\langle \varepsilon_{\alpha\beta} c_{i\alpha} c_{j\beta} \rangle \sim \Delta_{\boldsymbol{ij}} = \Delta_{\boldsymbol{ji}} = \varepsilon_{ab} B_{a\boldsymbol{i}} e_{\boldsymbol{ij}} U_{\boldsymbol{ij}} B_{b\boldsymbol{j}}$.

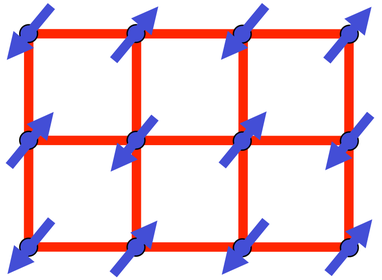
M. Christos, Zhu-Xi Luo, H. Shackleton, Ya-Hui Zhang, M. Scheurer, and S. S., *PNAS* **120**, e2302701120 (2023)

Global phase diagram of $SU(2)_N$ gauge theory

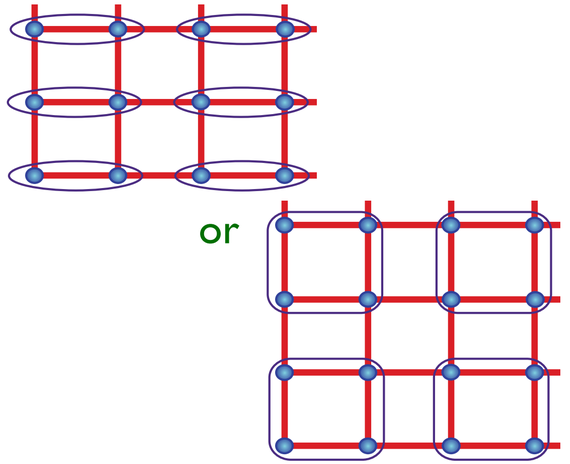


$\langle B \rangle \neq 0$

$\langle B \rangle = 0$



Confining phase:
Néel order

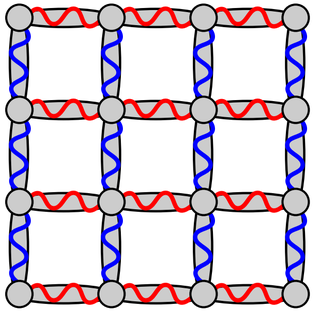


Confining phase:
VBS order

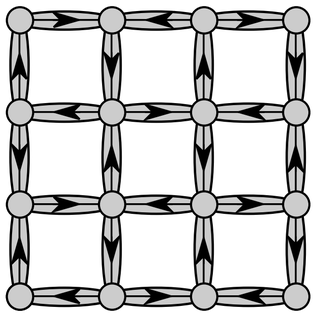
s

r

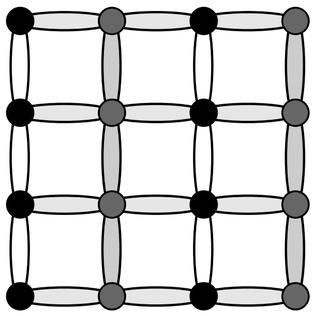
Phase B
d-wave SC



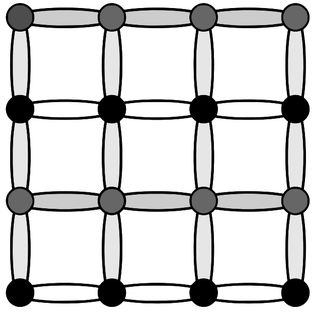
Phase C
d-density



Phase A
(π,0) stripe

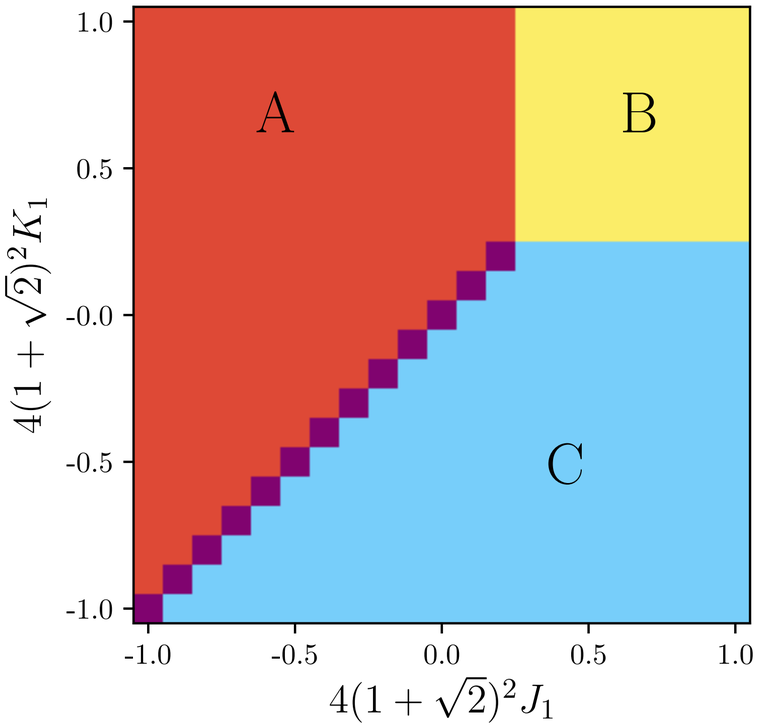


Phase A
(0,π) stripe



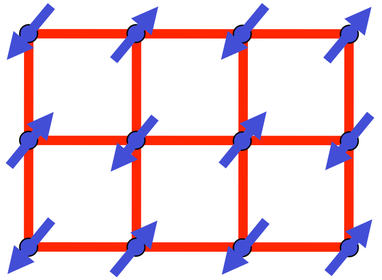
M. Christos, Zhu-Xi Luo, H. Shackleton, Ya-Hui Zhang, M. Scheurer, and S. S., *PNAS* **120**, e2302701120 (2023)

Global phase diagram of $SU(2)_N$ gauge theory

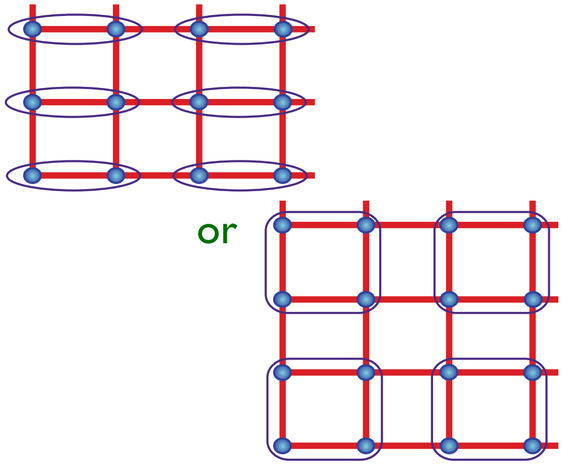


$\langle B \rangle \neq 0$

$\langle B \rangle = 0$



Confining phase:
Néel order

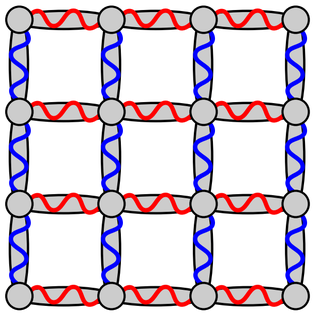


Confining phase:
VBS order

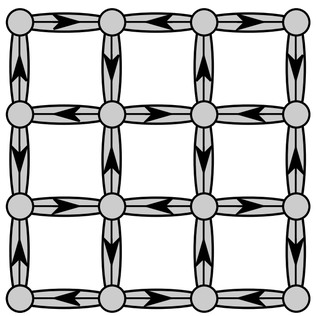
s

r

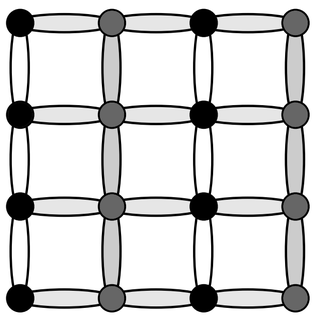
Phase B
d-wave SC



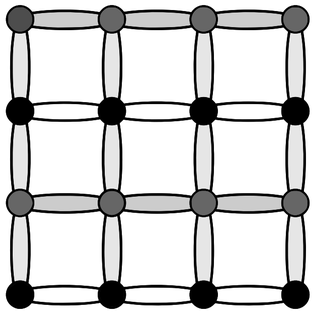
Phase C
d-density



Phase A
(π,0) stripe

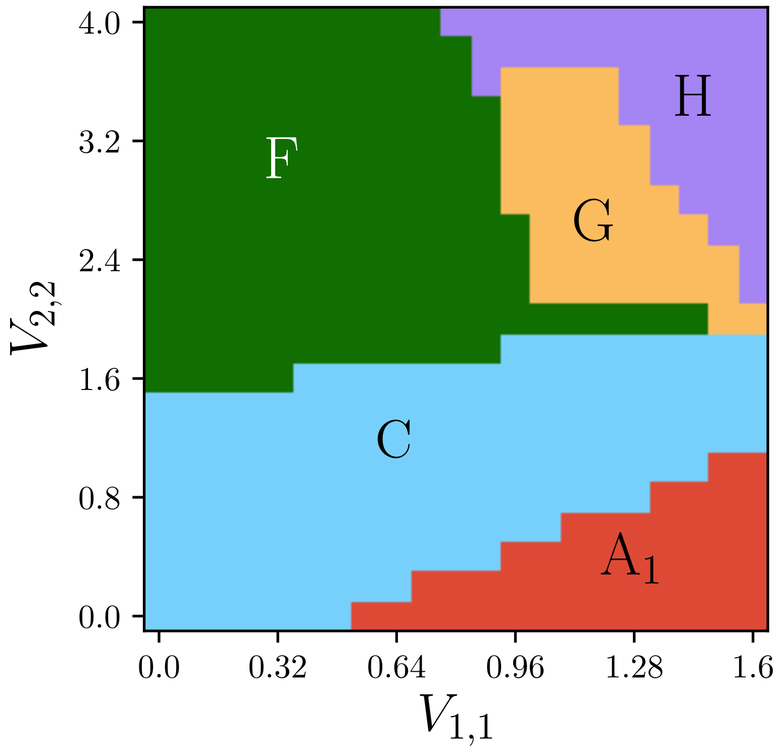


Phase A
(0,π) stripe



At half filling:
possible CFT/DQCP
with $N_f = 2$ Dirac fermions
and $N_b = 2$ complex scalars
coupled to $SU(2)_N$ gauge field.
M. Christos, H. Shackleton, S. S.,
and Zhu-Xi Luo, arXiv:2402.09502

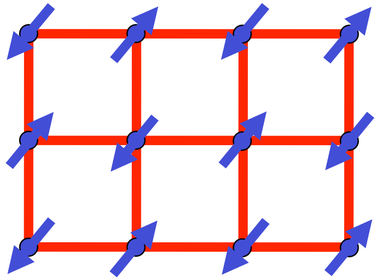
Global phase diagram of SU(2)$_N$ gauge theory



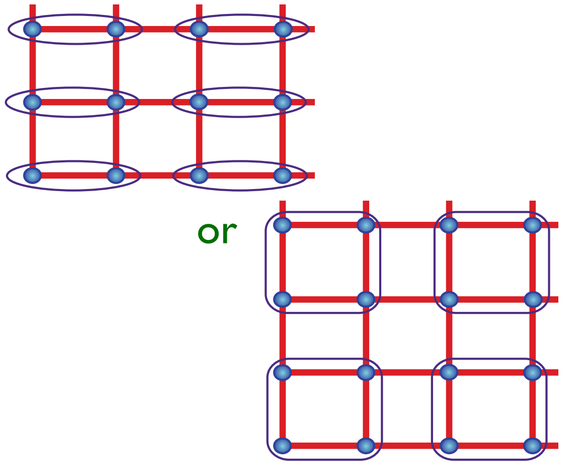
$\langle B \rangle \neq 0$

Including further-neighbor couplings in B

$\langle B \rangle = 0$



Confining phase: Néel order

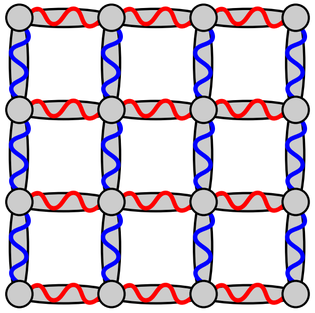


Confining phase: VBS order

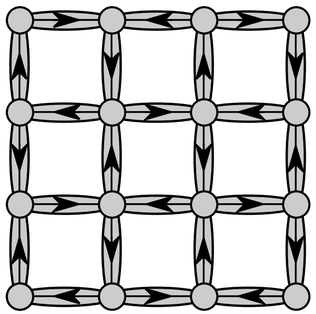
s

r

Phase B
d-wave SC



Phase C
d-density



Phase A
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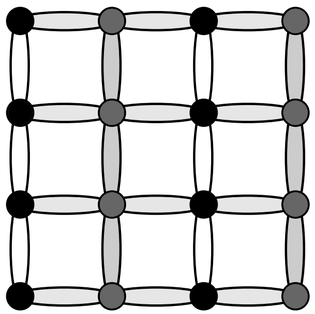
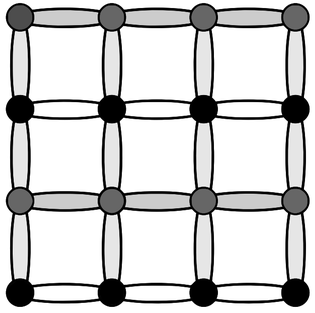
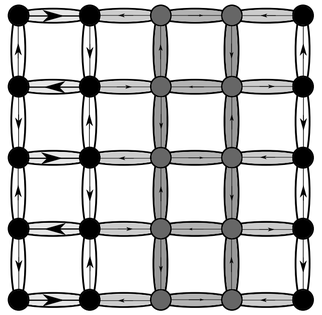


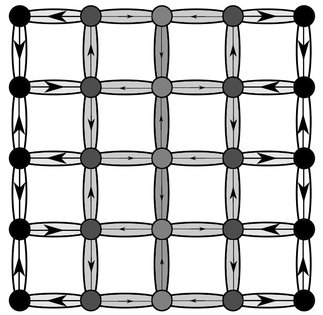
Phase A
(0,π) stripe



Phase F
Period 4 bond centered stripe + d-density



Phase G
Period 4 site centered stripe + d-density



M. Christos, Zhu-Xi Luo, H. Shackleton, Ya-Hui Zhang, M. Scheurer, and S. S., *PNAS* **120**, e2302701120 (2023)

1. Confinement transitions of the Kondo lattice

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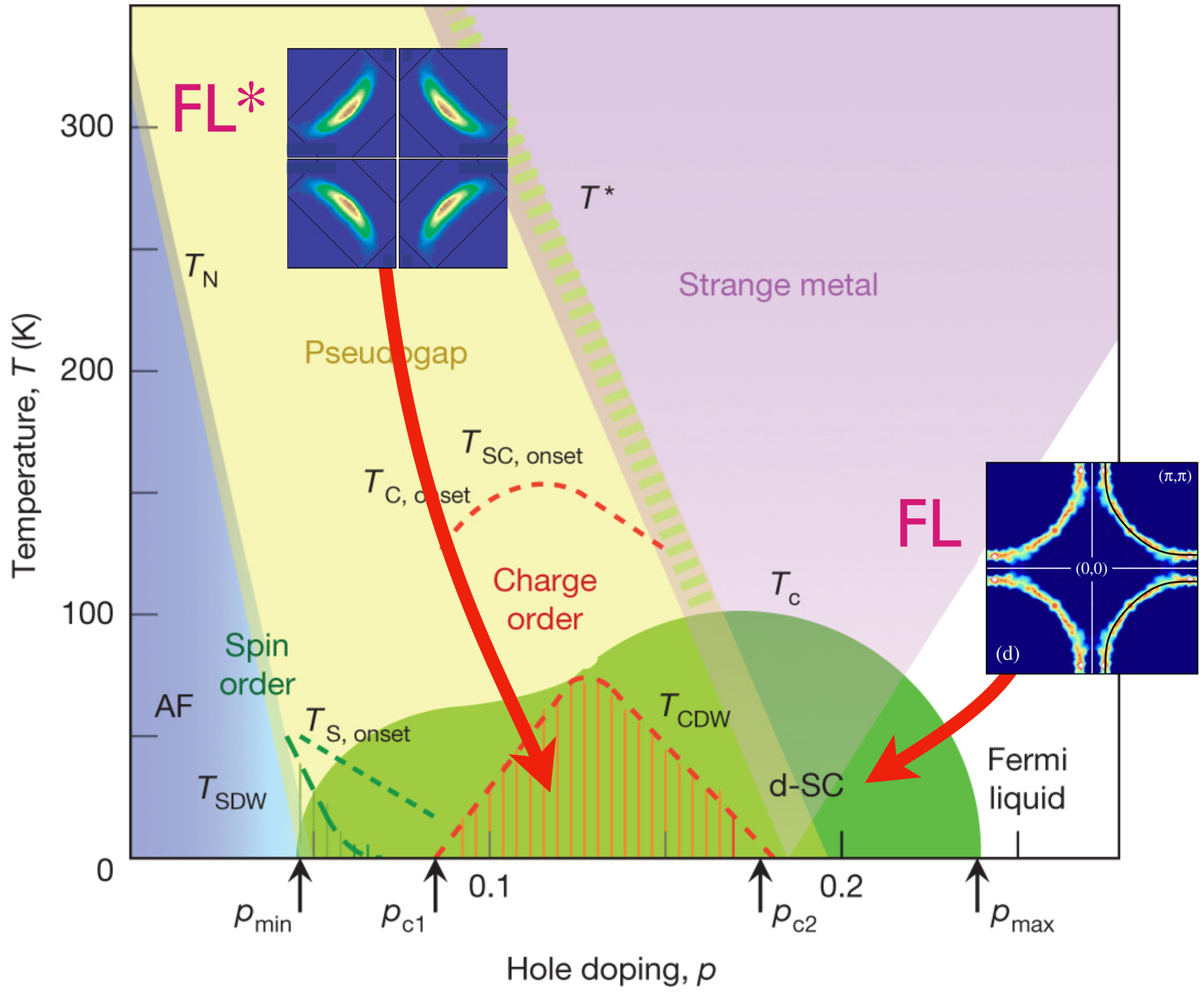
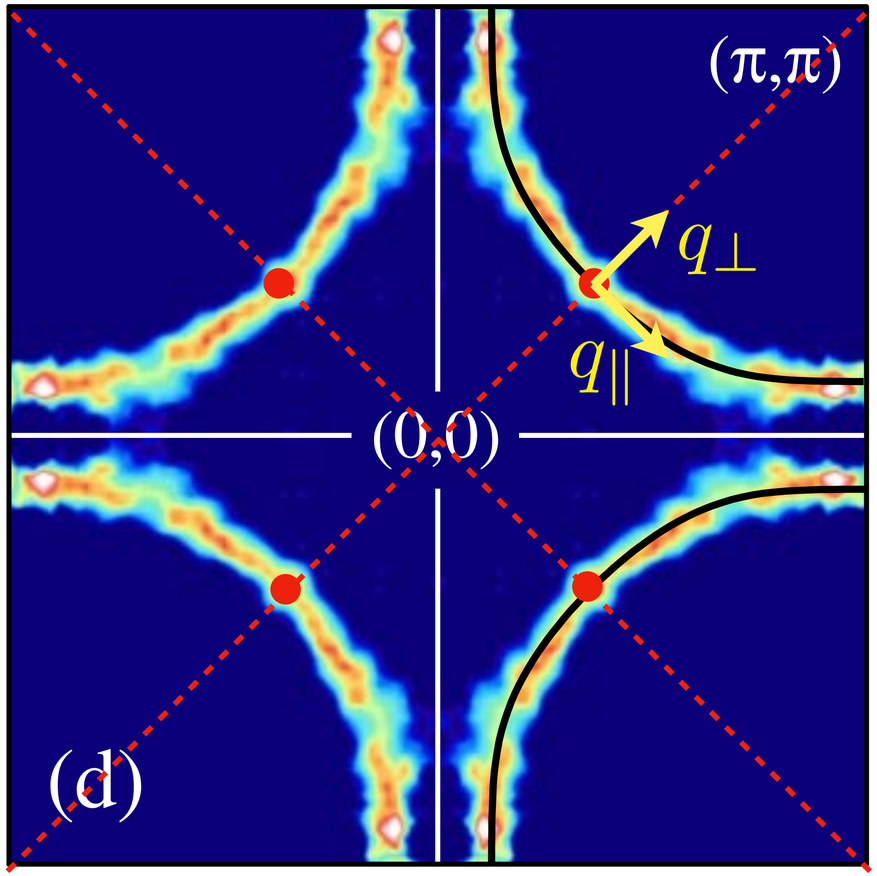
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



Obtain d-wave superconductor and charge order from a theory of *confinement* instabilities of FL*.

The resulting low T ordered states should be adiabatically connected to the corresponding states obtained from instabilities of FL.

FL→dSC



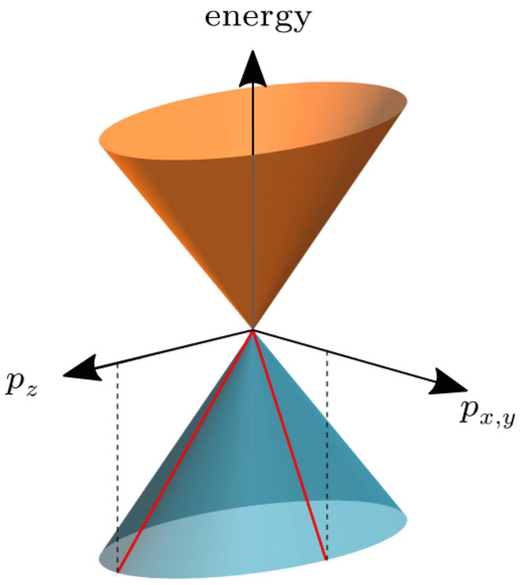
BCS/Bogoliubov quasiparticles
in a d-wave superconductor

$$E_{\boldsymbol{k}} = \left(\varepsilon_{\boldsymbol{k}}^2 + \Delta_{\boldsymbol{k}}^2\right)^{1/2}$$
$$\Delta_{\boldsymbol{k}} = \Delta_0 \left(\cos k_x - \cos k_y\right)$$

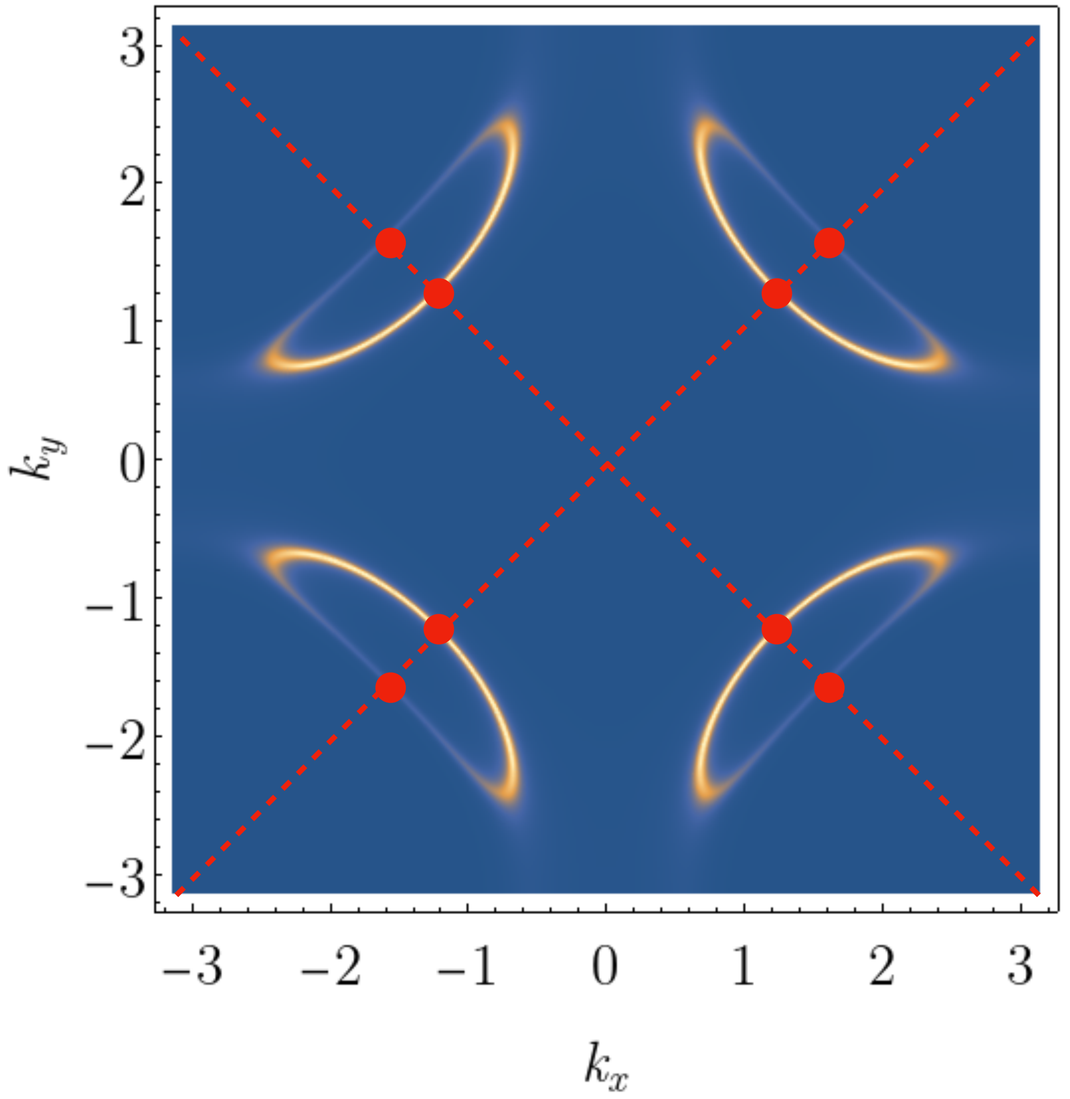
4 nodal points where

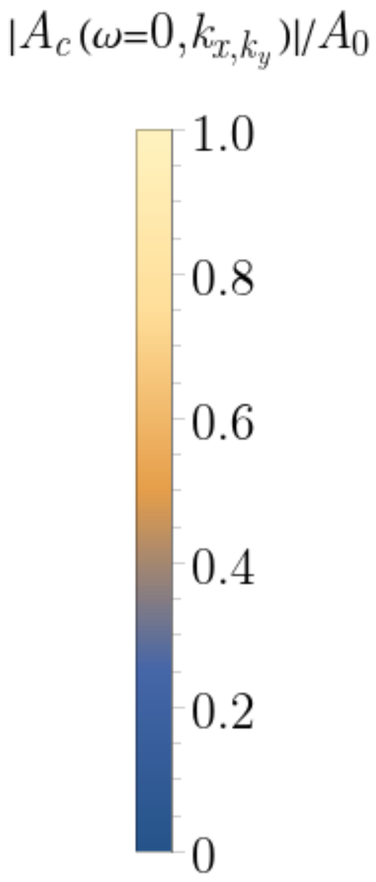
$$E_{\boldsymbol{k}_0+\boldsymbol{q}} = \left(v_F^2 q_\perp^2 + v_\Delta^2 q_\parallel^2\right)^{1/2}$$

with $v_F \gg v_\Delta$.



FL*→dSC*

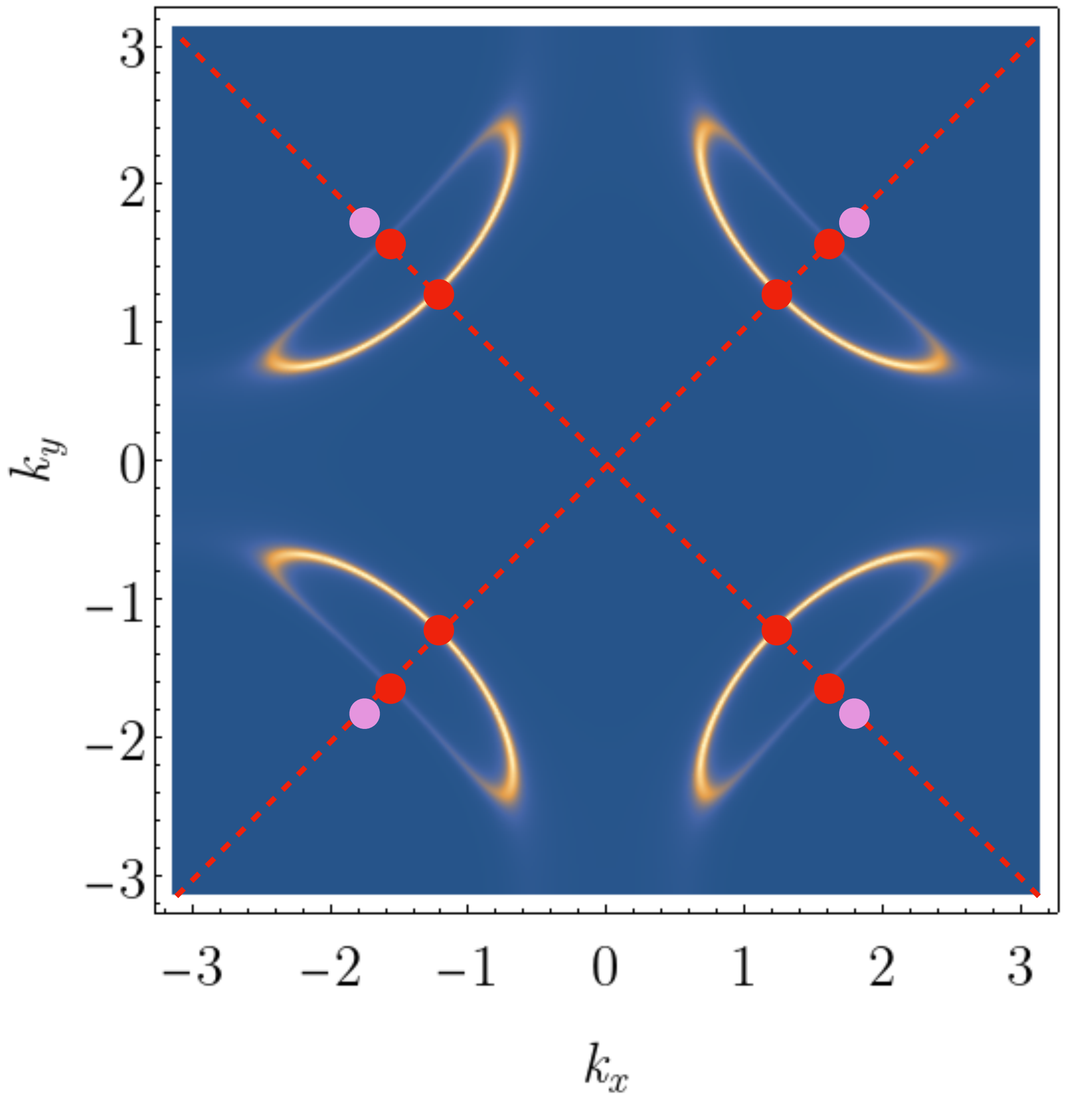


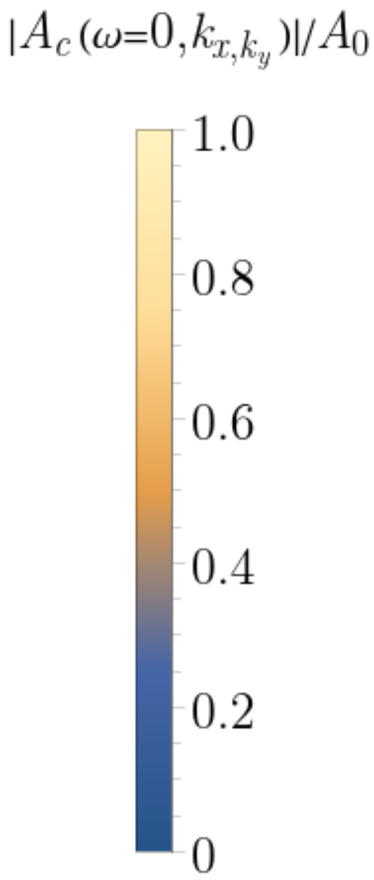


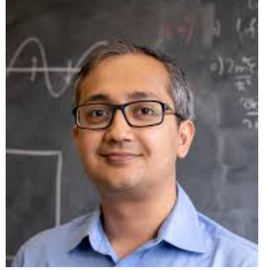
$$E_{\boldsymbol{k}} = \left(\varepsilon_{\boldsymbol{k}}^2 + \Delta_{\boldsymbol{k}}^2\right)^{1/2}$$
$$\Delta_{\boldsymbol{k}} = \Delta_0 \left(\cos k_x - \cos k_y\right)$$

Adding d-wave pairing
to the hole pockets
leads to 8 nodal points???

FL*→dSC*



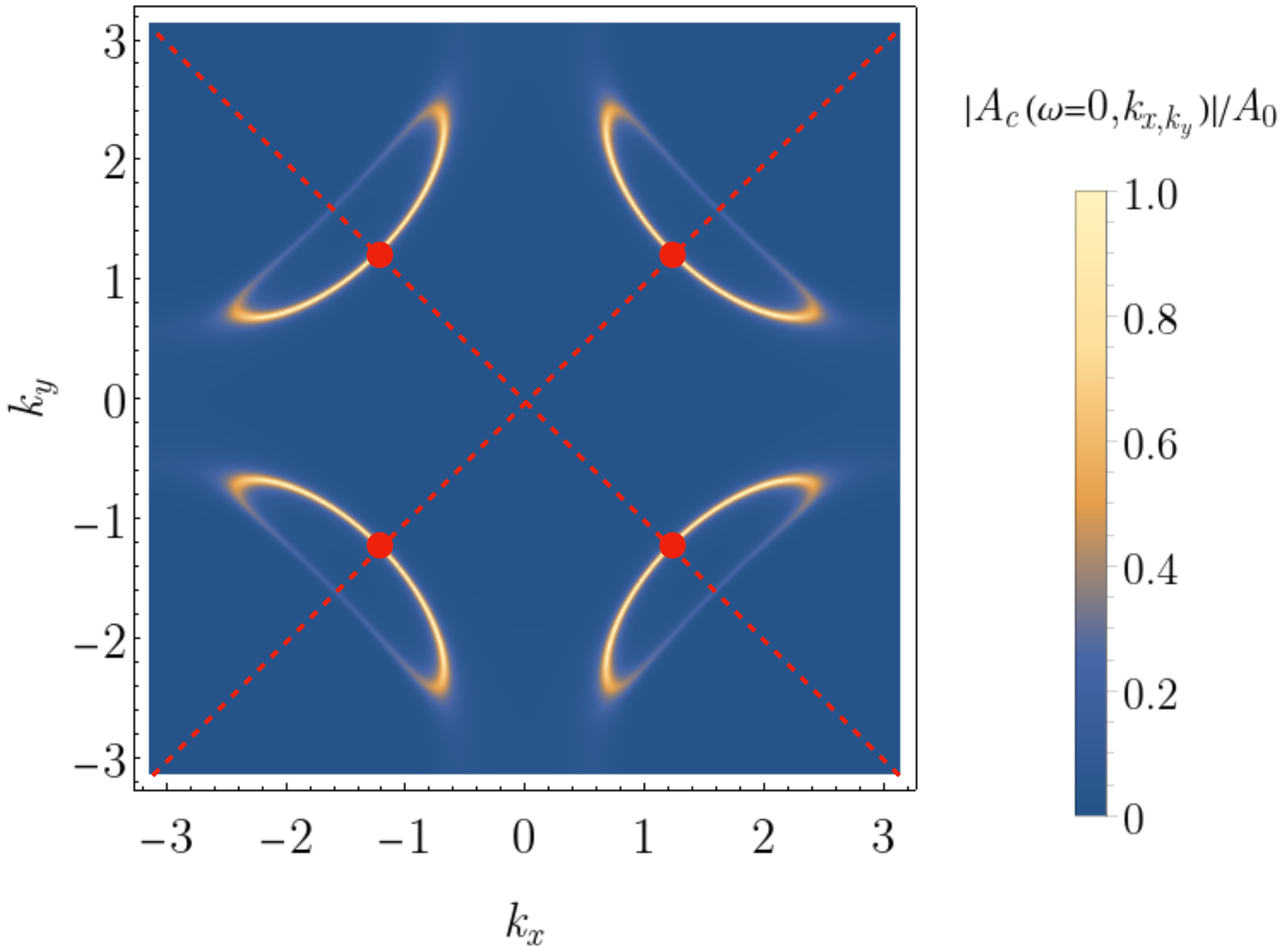


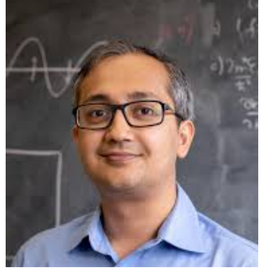


8 nodal points from
the Fermi pockets
and
4 nodal points from
the π-flux spin liquid

Shubhayu Chatterjee and S. Sachdev,
PRB **94**, 205117 (2016)
Maine Christos and S.Sachdev,
npj Quantum Materials **9**, 4 (2024)

FL*→dSC



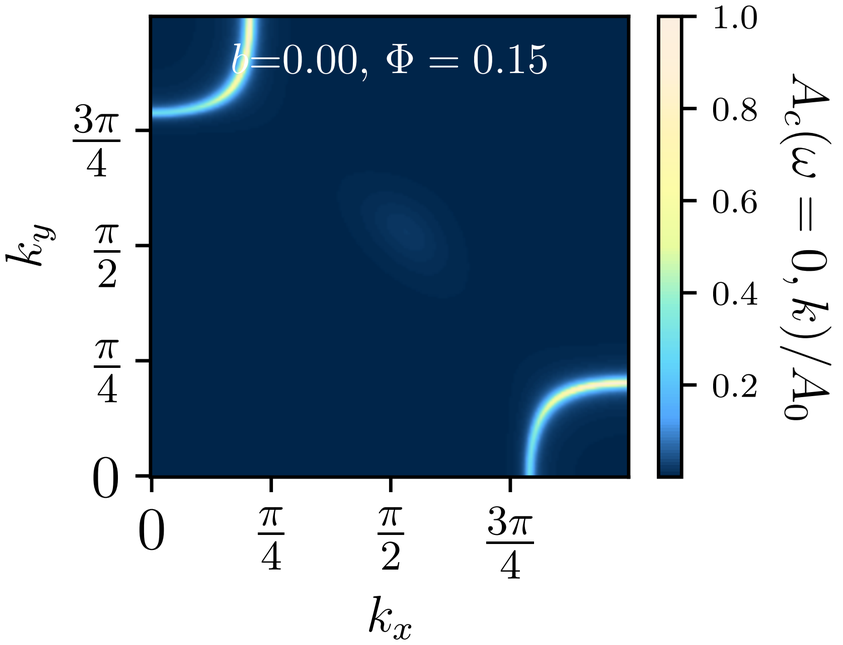


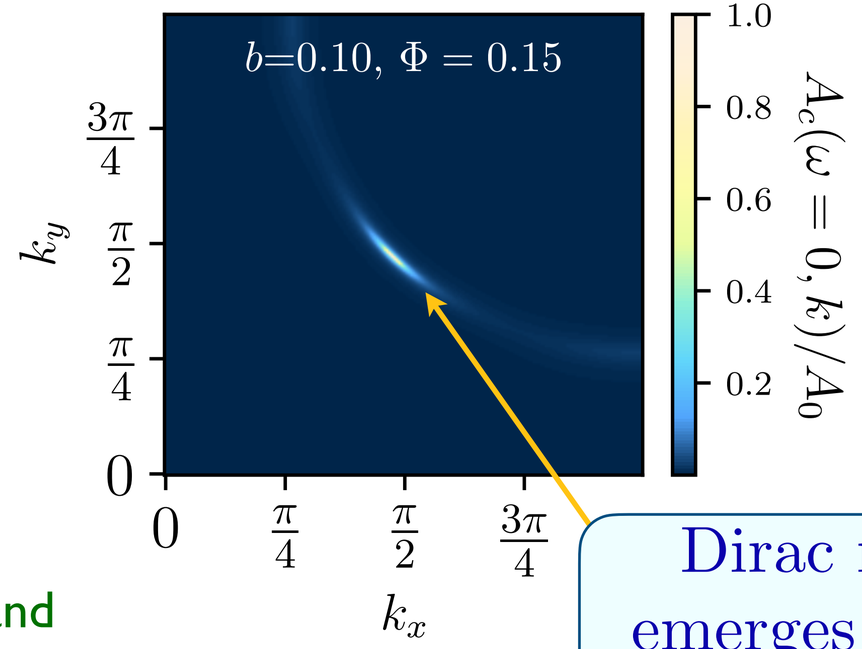
The B Higgs condensate
allows spinons and
Bogoliubov quasiparticles
to hybridize:

8 nodal points annihilate
each other, leaving
4 nodal points
with anisotropic velocities,
just as in a BCS d-wave state.

Shubhayu Chatterjee and S. Sachdev,
PRB **94**, 205117 (2016)
Maine Christos and S.Sachdev,
npj Quantum Materials **9**, 4 (2024)

Electron spectral density in electron-doped cuprates





FL*

d-wave superconductor obtained by condensing charge-e, SU(2) fundamental boson.

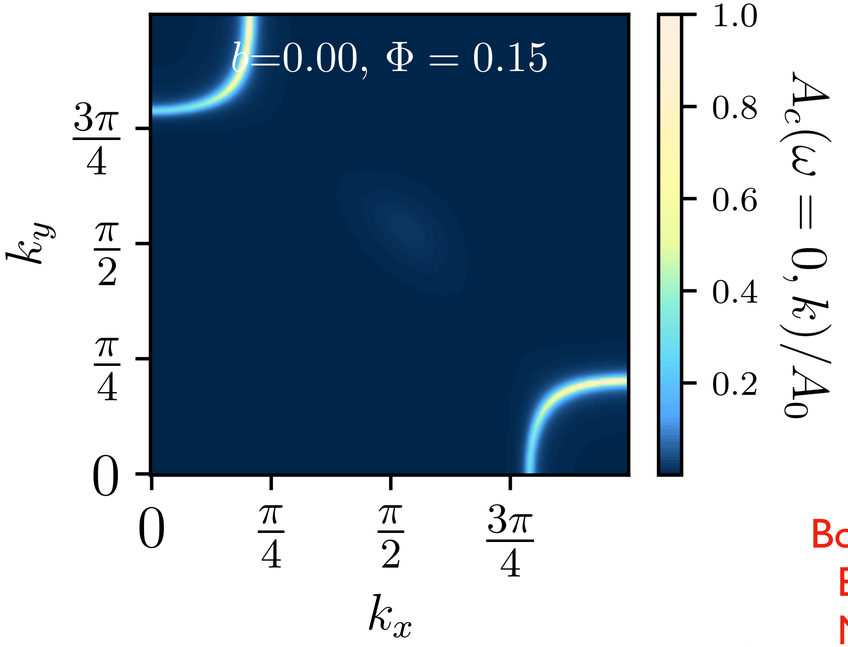
Nodes of the d-wave superconductor are remnants of the spinons of the π-flux state.

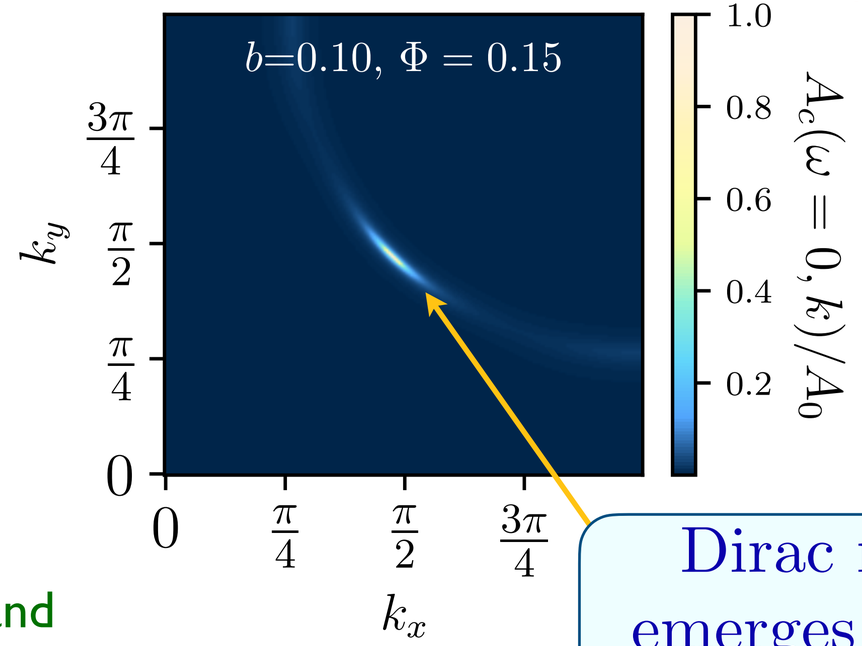
dSC

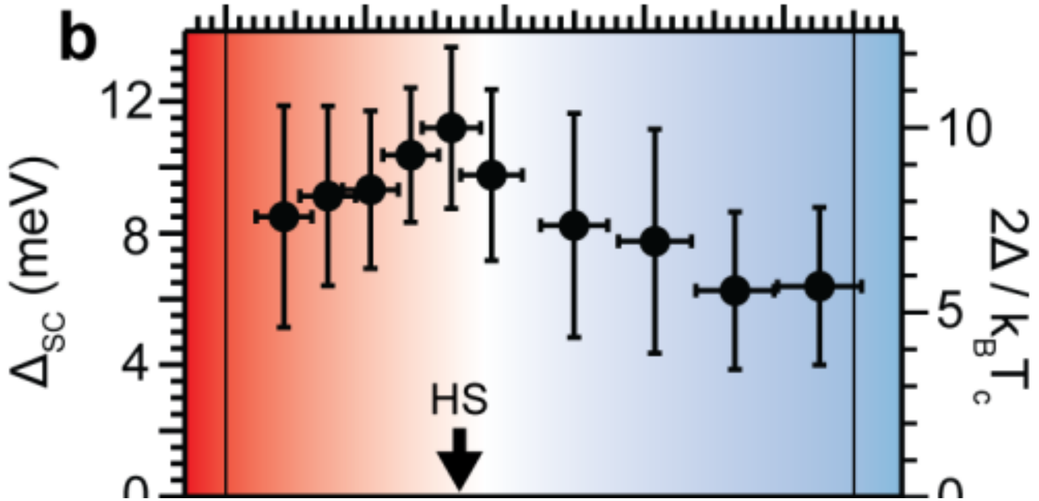
Dirac node emerges inside normal state gap

Maine Christos and S.Sachdev, npj Quantum Materials **9**, 4 (2024)

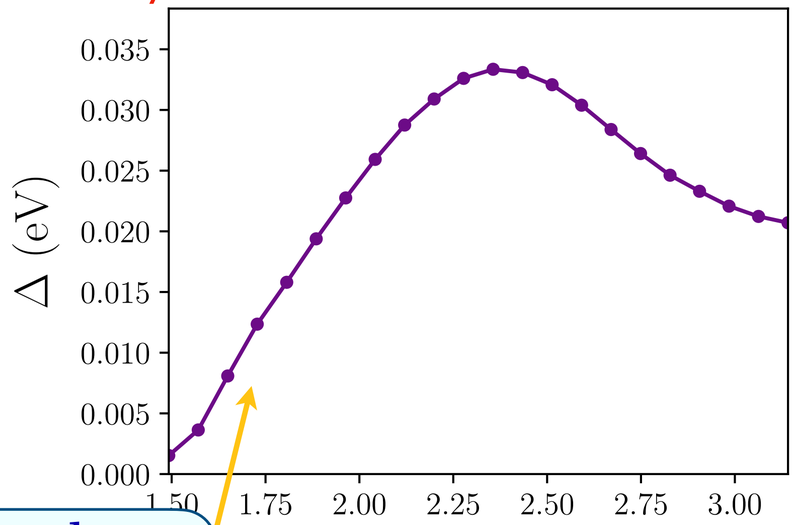
Electron spectral density in electron-doped cuprates







Bogoliubov Quasiparticle on the Gossamer Fermi Surface in Electron-Doped Cuprates, Ke-Jun Xu……Z.-X. Shen, arXiv:2308.05313; Nature Physics



Maine Christos and S.Sachdev, npj Quantum Materials **9**, 4 (2024)

Dirac node emerges inside normal state gap

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C. Proust and L. Taillefer, *The Remarkable Underlying Ground States of Cuprate Superconductors*, Annual Review of Condensed Matter Physics **10**, 409 (2019),

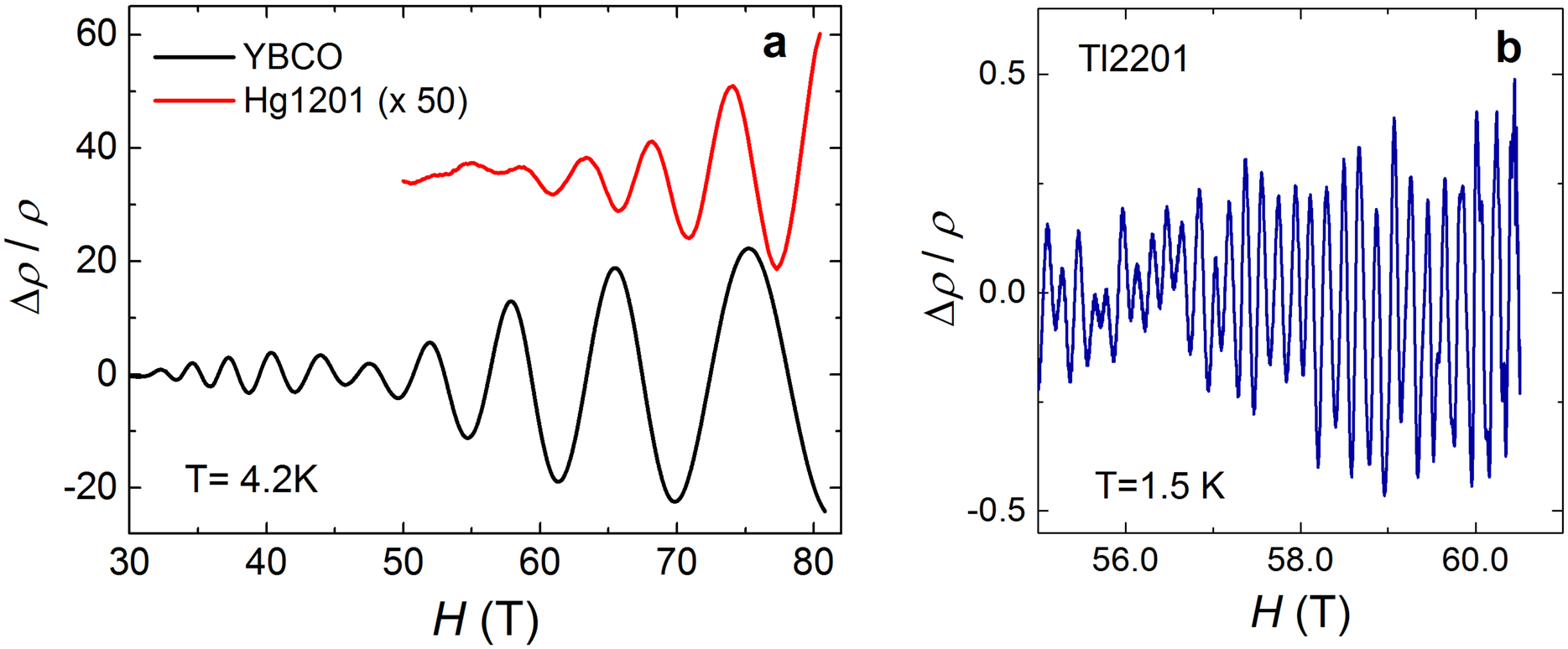
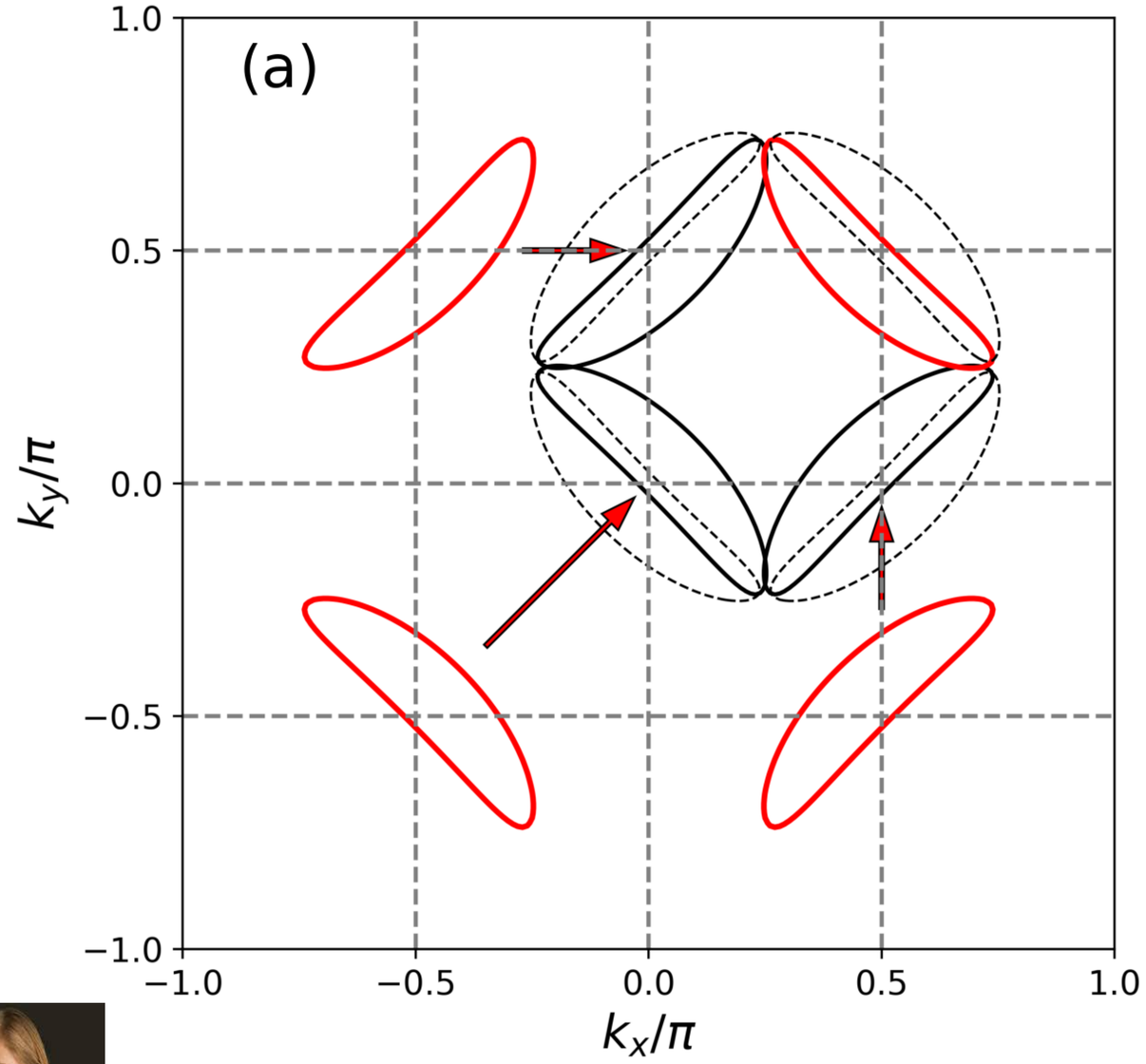


Figure 4

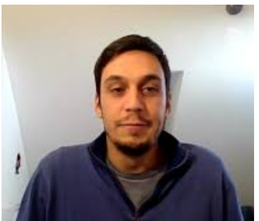
Quantum oscillations in cuprates. a) Underdoped YBCO ($p = 0.11$, $T_c = 62$ K) (black (22)) and Hg1201 ($p \simeq 0.1$, $T_c = 72$ K) (red (33), $\times 50$). **b)** Overdoped Tl2201 ($p \simeq 0.3$, $T_c \approx 10$ K) (28).

22. Vignolle B, et al. 2013. *C. R. Physique* 14:39–52
28. Vignolle B, et al. 2008. *Nature* 455:952–955
33. Barisic N, et al. 2013. *Nat. Phys.* 9:761–764

FL*



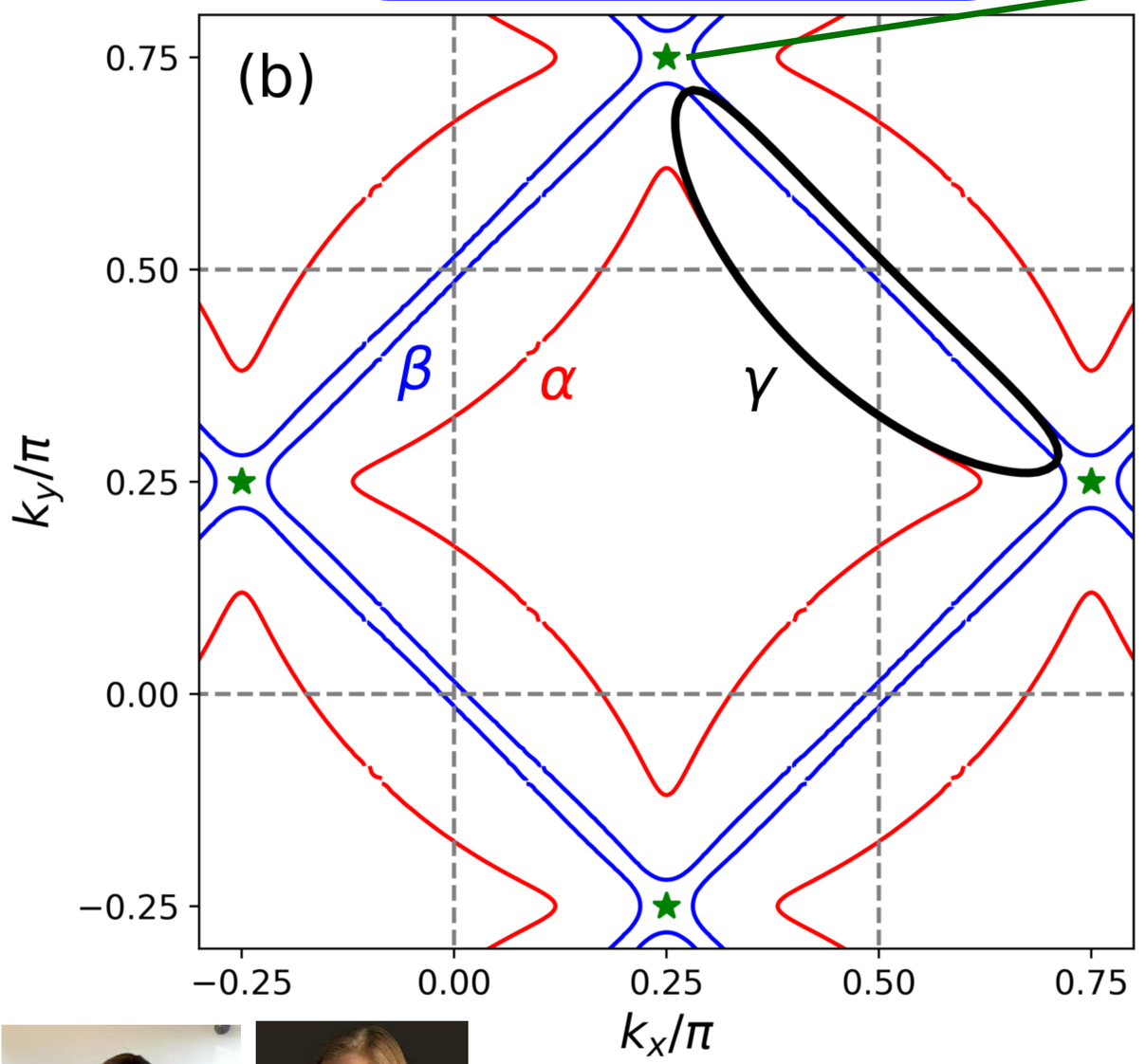
N. Harrison and S. Sebastian
electron pocket
(PRL **106**, 226402 (2011))

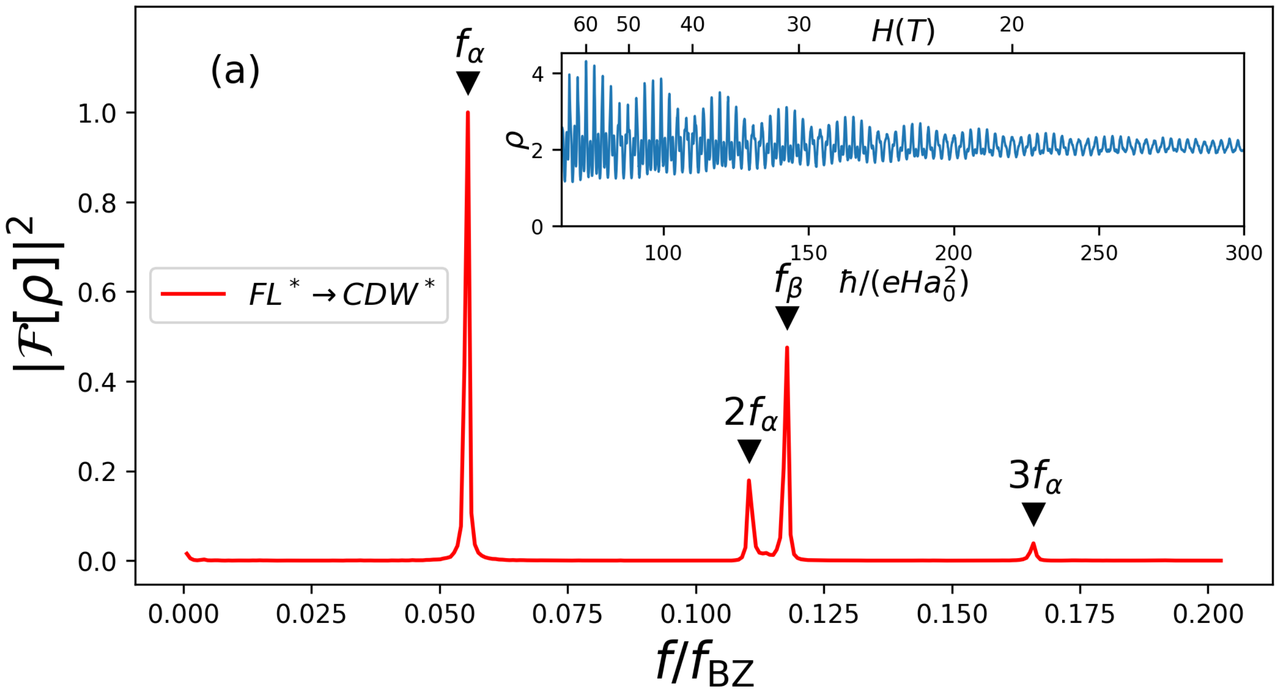


Pietro Bonetti, Maine Christos and S.S. (**BCS**), arXiv:2405.08817

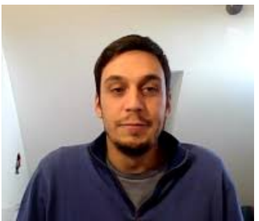
FL*→CDW*

Spinon



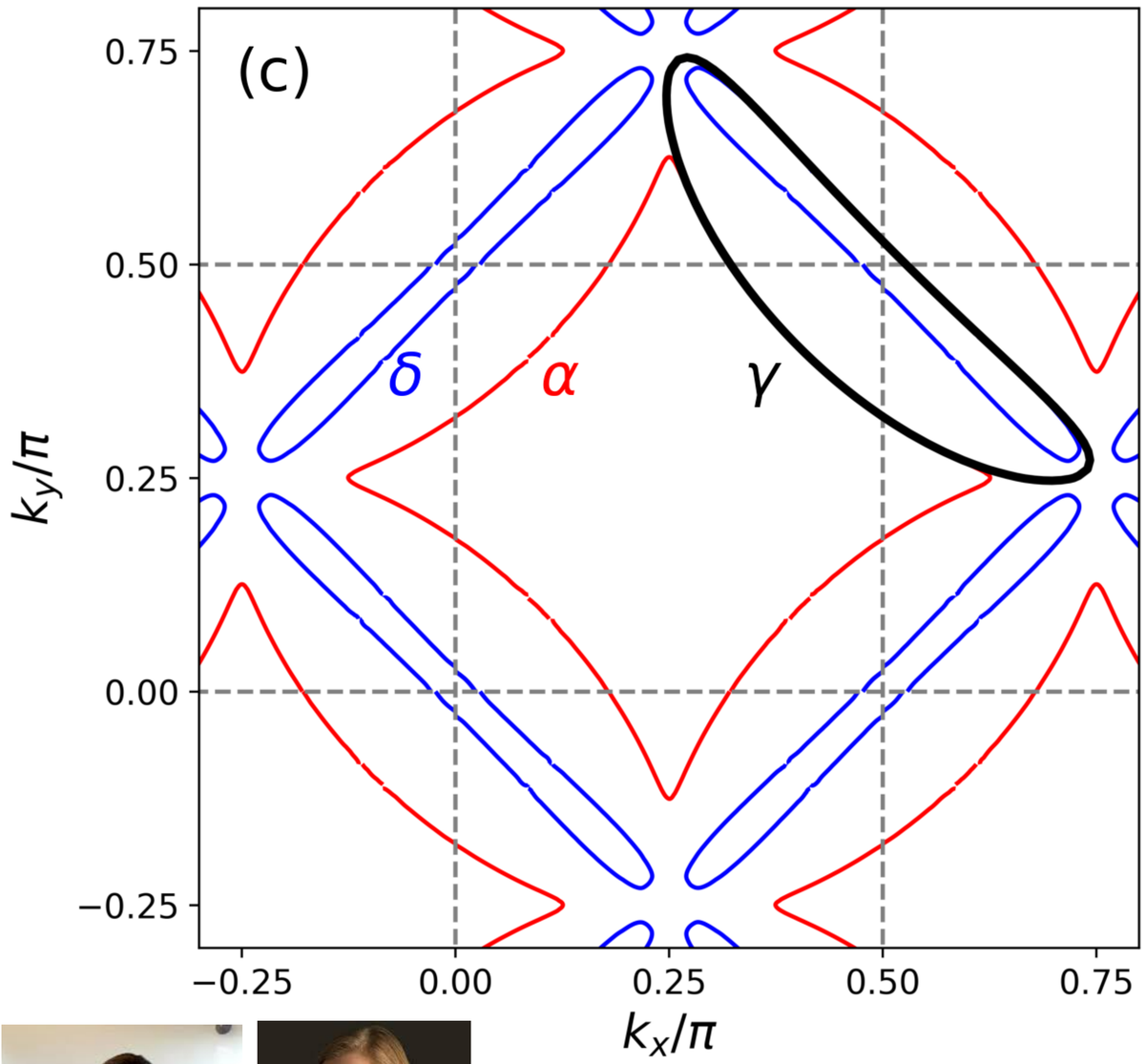


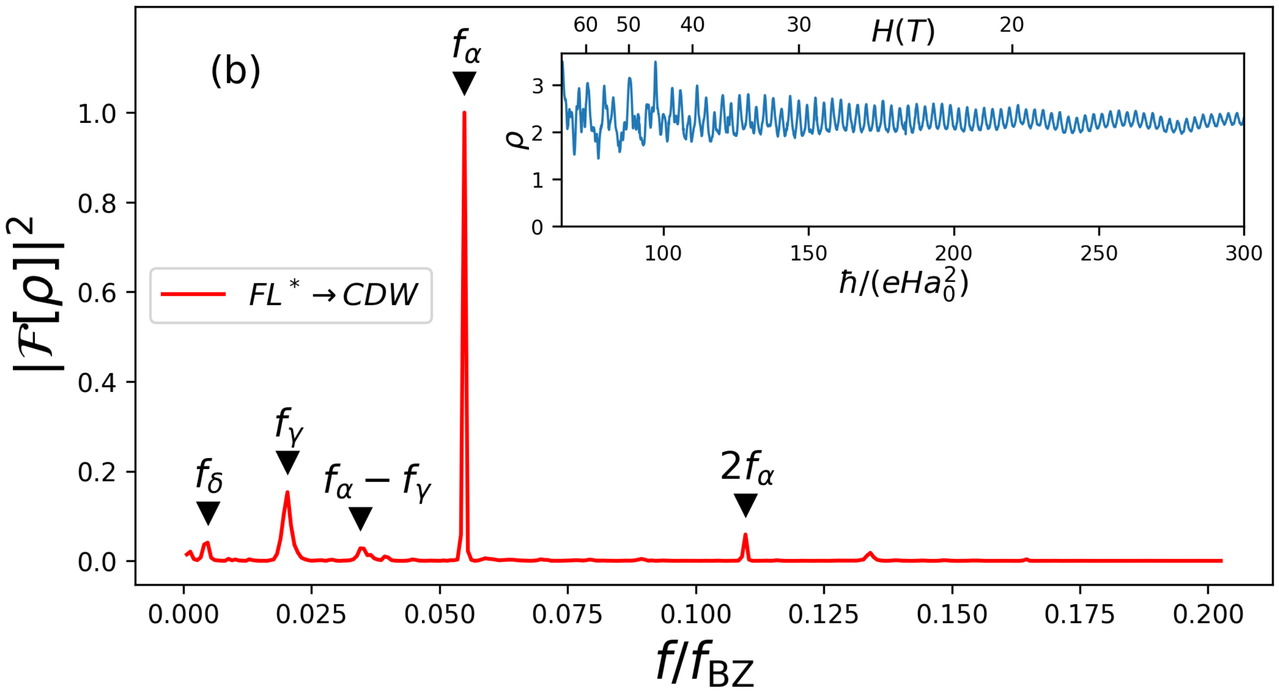
Computation does not account for spinons.
α and β pockets
show clear quantum oscillations.
Long Zhang and Jia-Wei Mei,
EPL **114**, 47008 (2016)



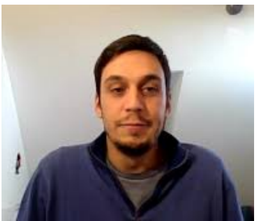
Pietro Bonetti, Maine Christos and S.S. (**BCS**), arXiv:2405.08817

FL*→CDW





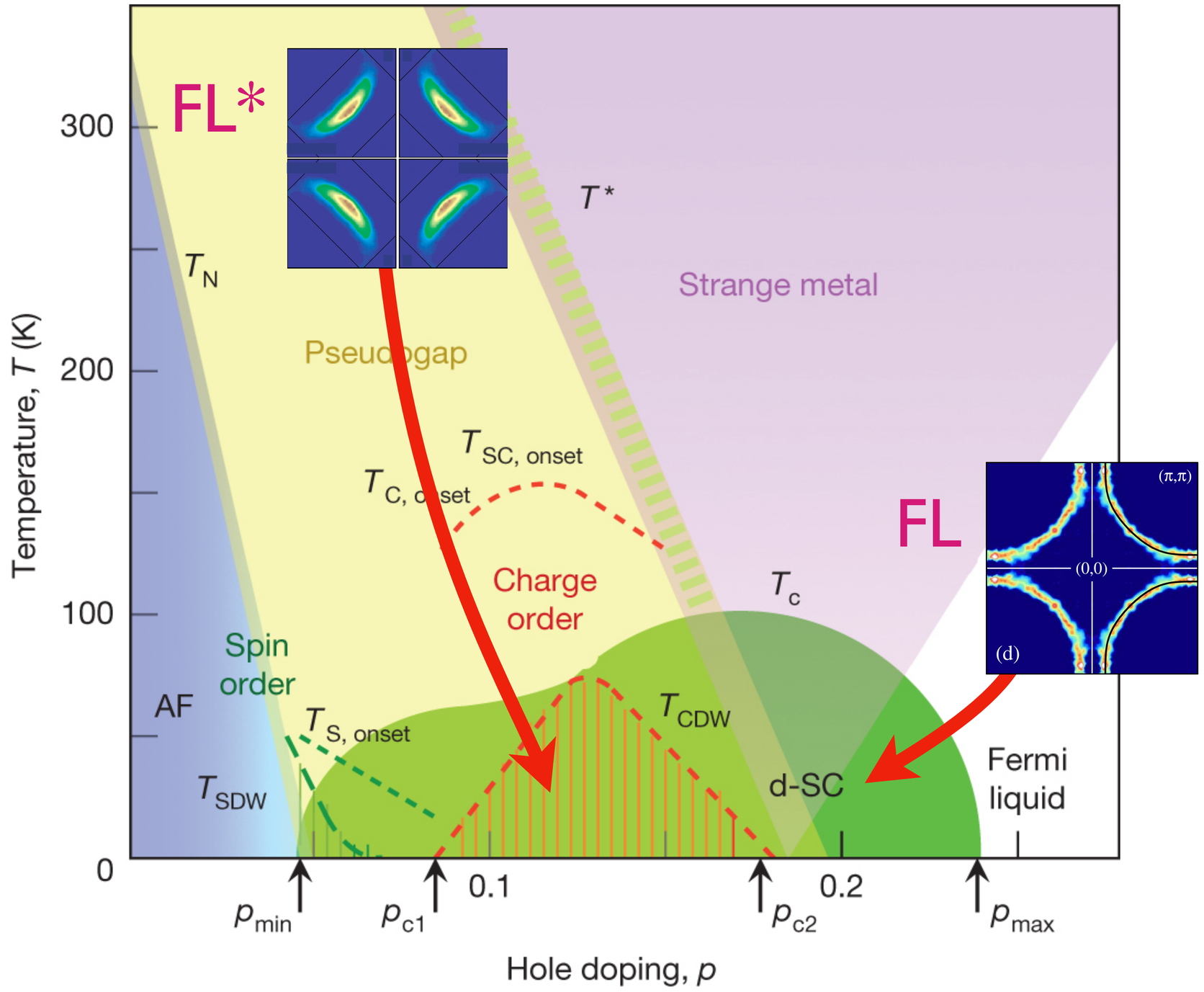
Period 4 CDW obtained by condensing B.
SU(2) gauge theory allows CDW with vanishing Δ_{ij} and J_{ij}.
Mixing between electrons and spinons removes β pocket.



Pietro Bonetti, Maine Christos and S.S. (**BCS**), arXiv:2405.08817

Summary

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



Obtain d-wave superconductor and charge order from a theory of *confinement* instabilities of FL*.

The resulting low T ordered states should be adiabatically connected to the corresponding states obtained from instabilities of FL.

Ancilla theory of pseudogap metal with hole pockets and underlying SU(2) gauge theory of π-flux spin liquid yields:

- Theory for Fermi arcs in hole-doped pseudogap metal.
- ADMR in pseudogap.
- Anti-nodal and nodal electronic dispersion.
- d-wave superconductor with 4 nodal points in both electron- and hole-doped cuprates.
- Near-equality of dSC and charge order onset temperatures
- Multipoint correlators measured by cold atom experiments
- Theory for strange metal in the crossover from FL* to FL
- Theory for quantum oscillations in high magnetic field