Gauge Fluctuations, Confinement, and the Pseudogap in Cuprates

45'

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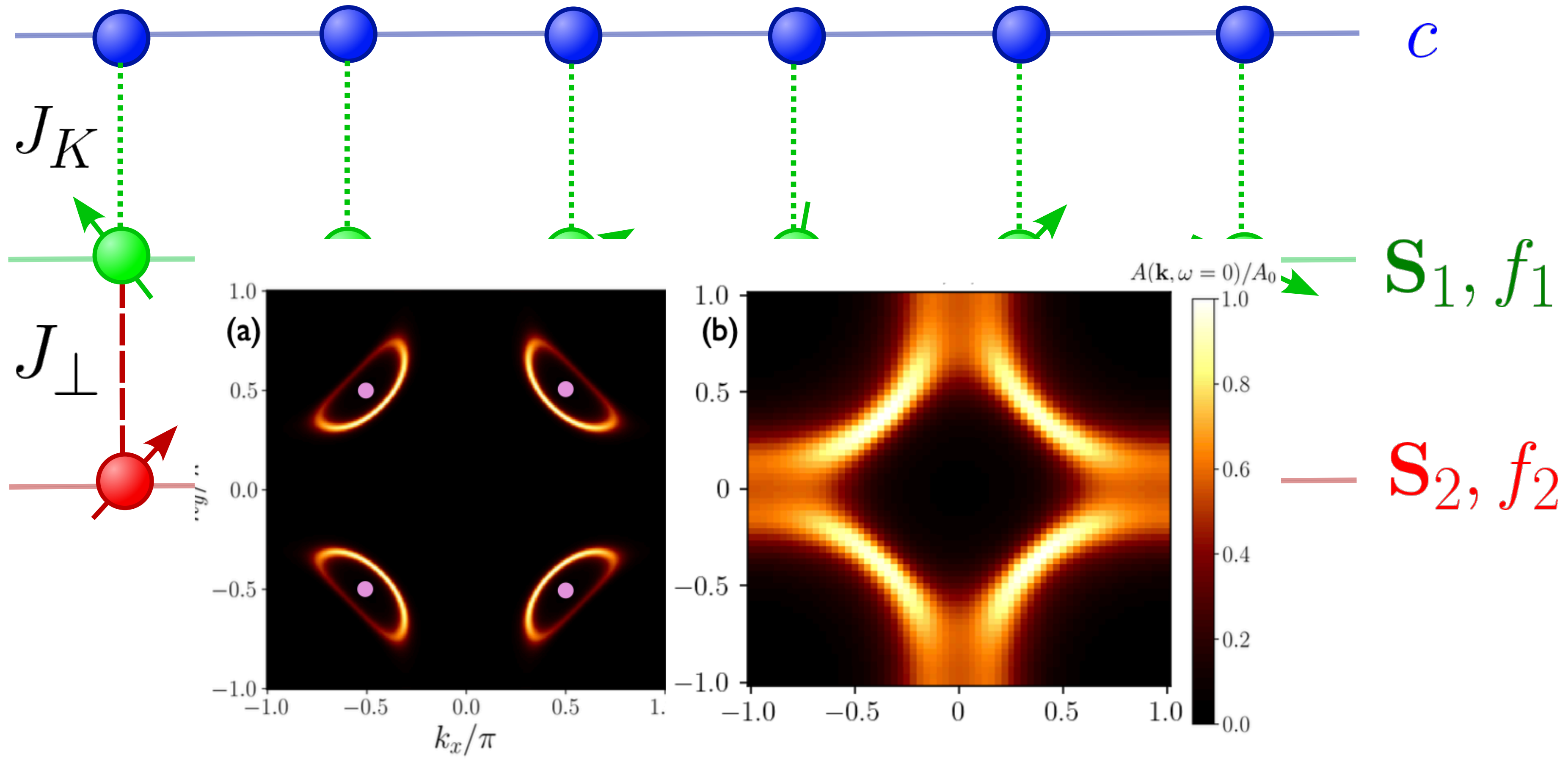

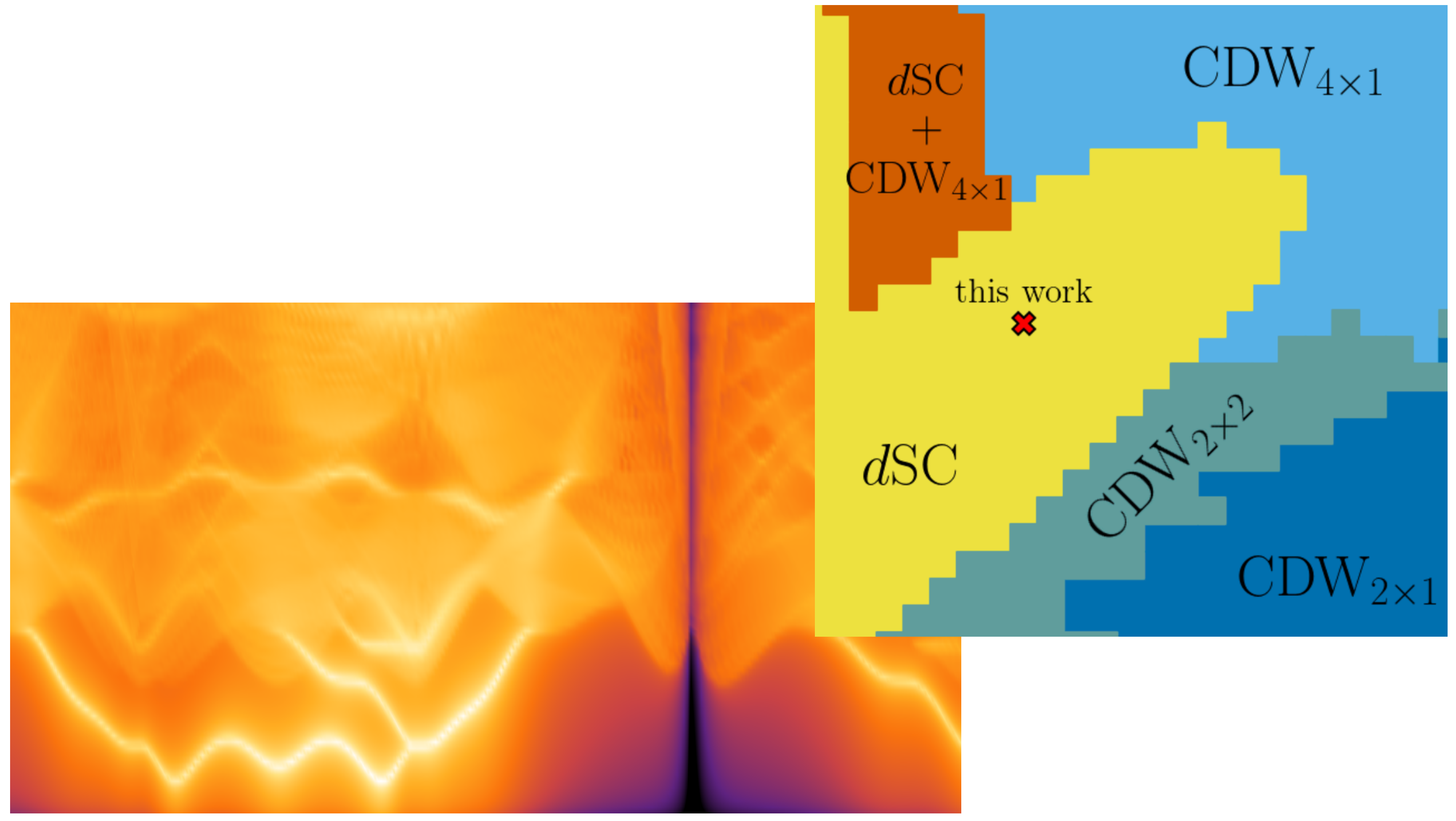

School & Conference on Quantum Matter, ICTP (Trieste), December 11, 2025

Collaborators

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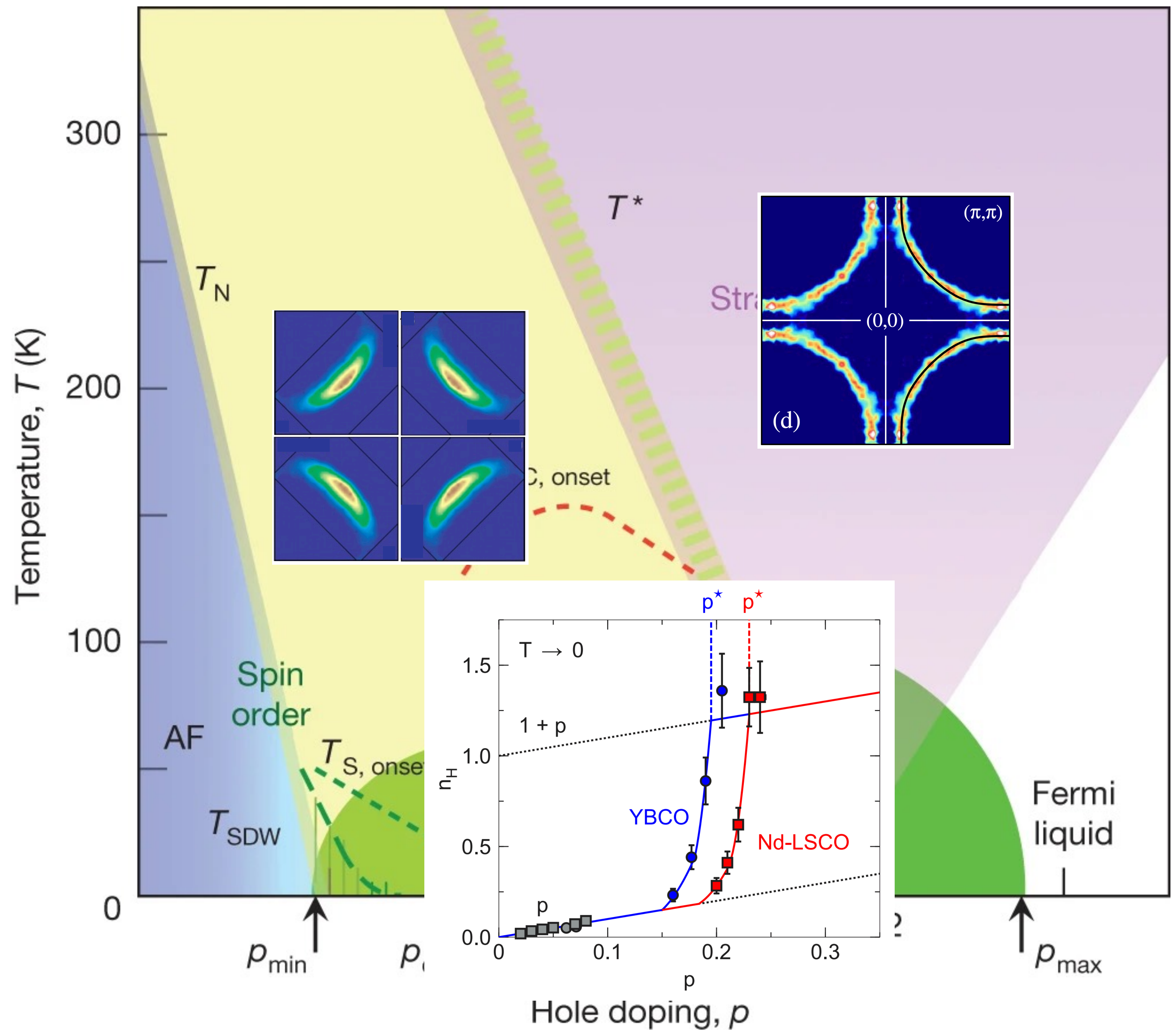
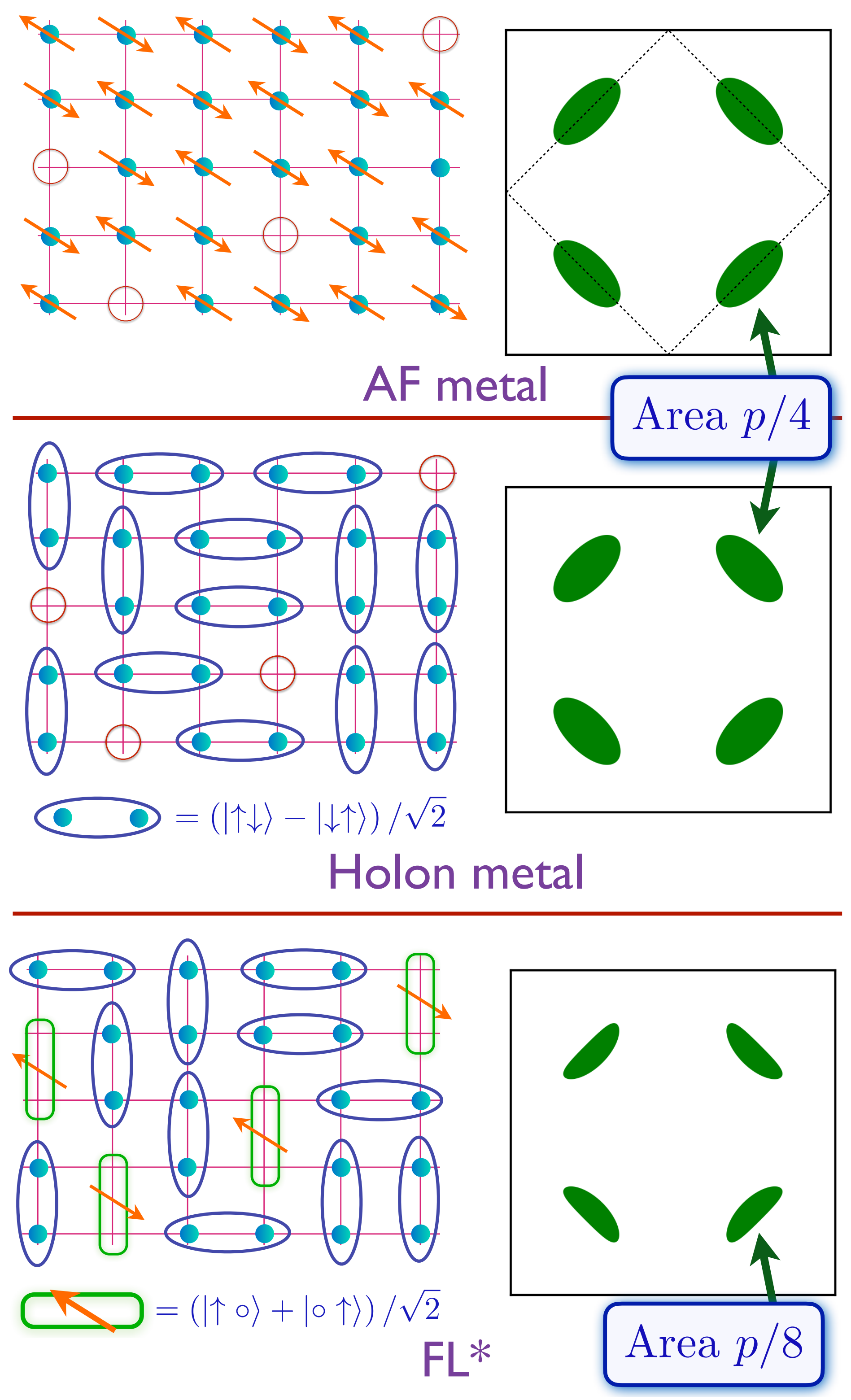
Harvard University

Pseudogap Phase in Cuprates



Keimer *et al.*, Nature **518**, 179 (2015)



- Eberlein *et al.*, PRL **117**, 187001 (2016)
- Storey, EPL **113**, 27003 (2016)
- PMB*, Mitscherling*, *et al.*, PRB **101**, 165142 (2020)

- Scheurer *et al.*, PNAS **115** (16) E3665 (2018)
- PMB & Metzner, PRB **106**, 205152 (2022)

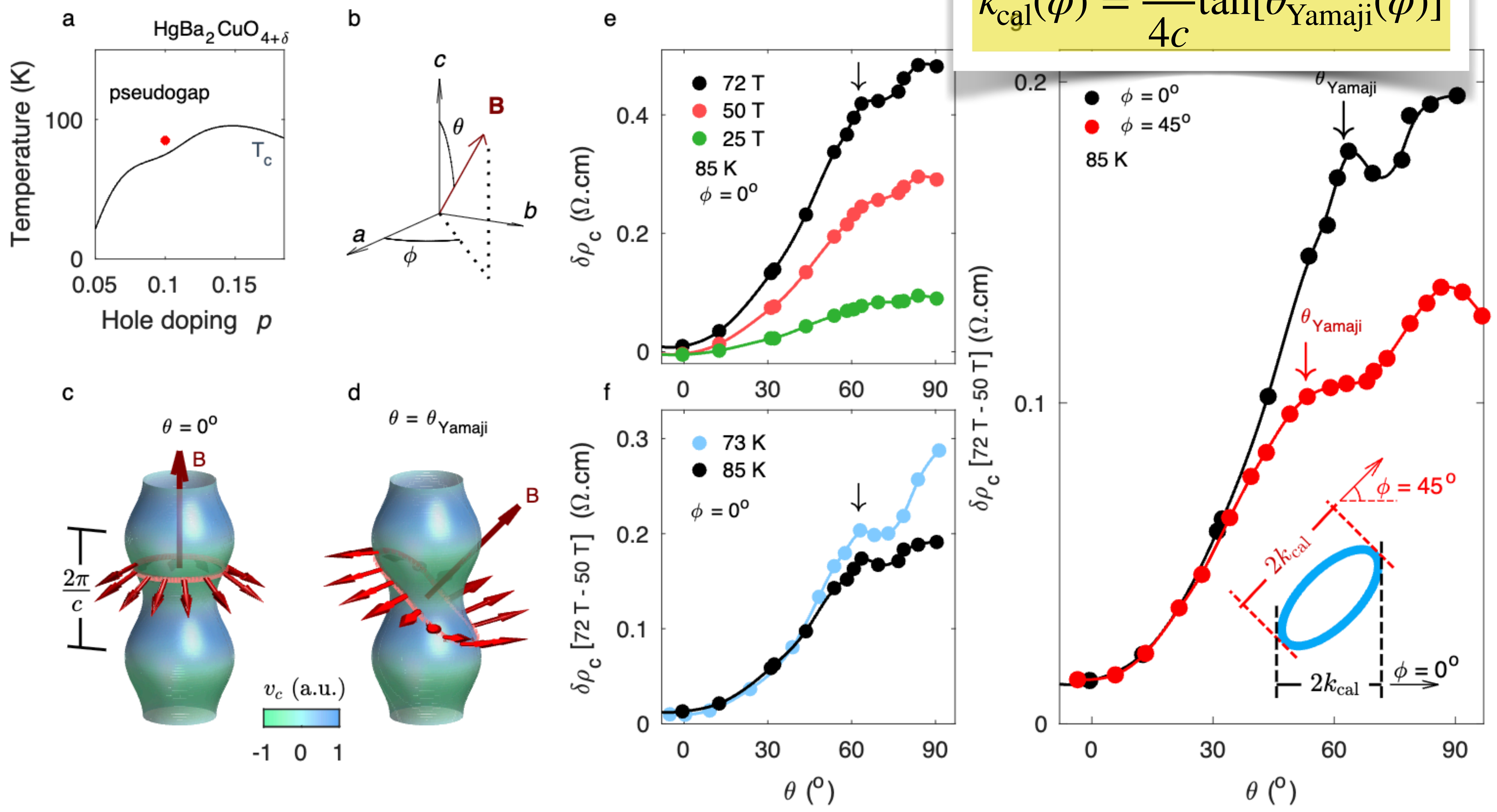
Zhang & Sachdev, PRR **2**, 023172 (2020)

Observation of the Yamaji Effect

Nat. Phys. (2025)

Observation of the Yamaji effect in a cuprate superconductor

Mun K. Chan,[1,*] Katherine A. Schreiber,[1] Oscar E. Ayala-Valenzuela,[1]
Eric D. Bauer,[2] Arkady Shekhter,[1] and Neil Harrison[1]



$$k_{cal}(\varphi) = \frac{3\pi}{4c}\tan[\theta_{Yamaji}(\varphi)]$$

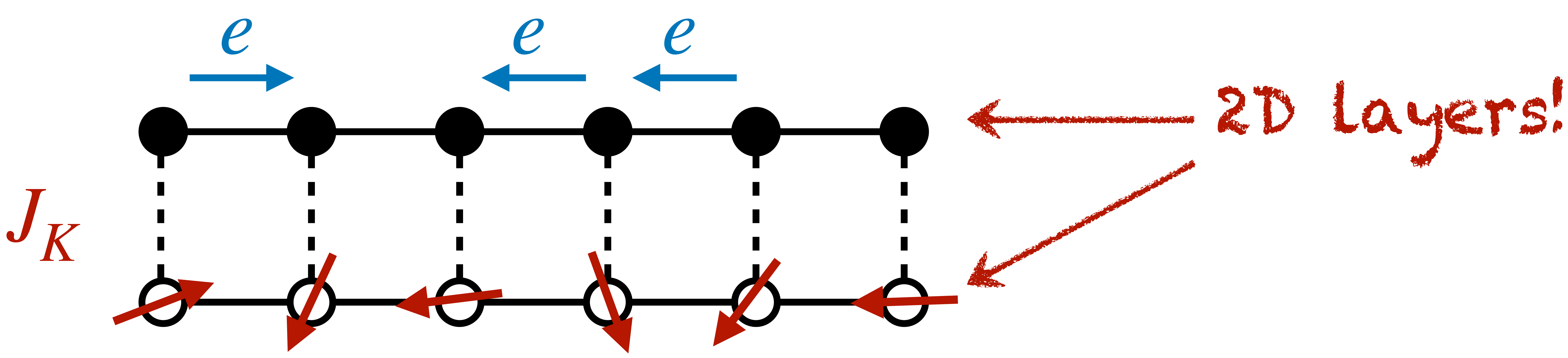
Hole pockets have sizes of 1.3% of the BZ

$$\frac{p}{8} = 1.25\,\%$$

Compatible with FL* scenario!

FL* Theory

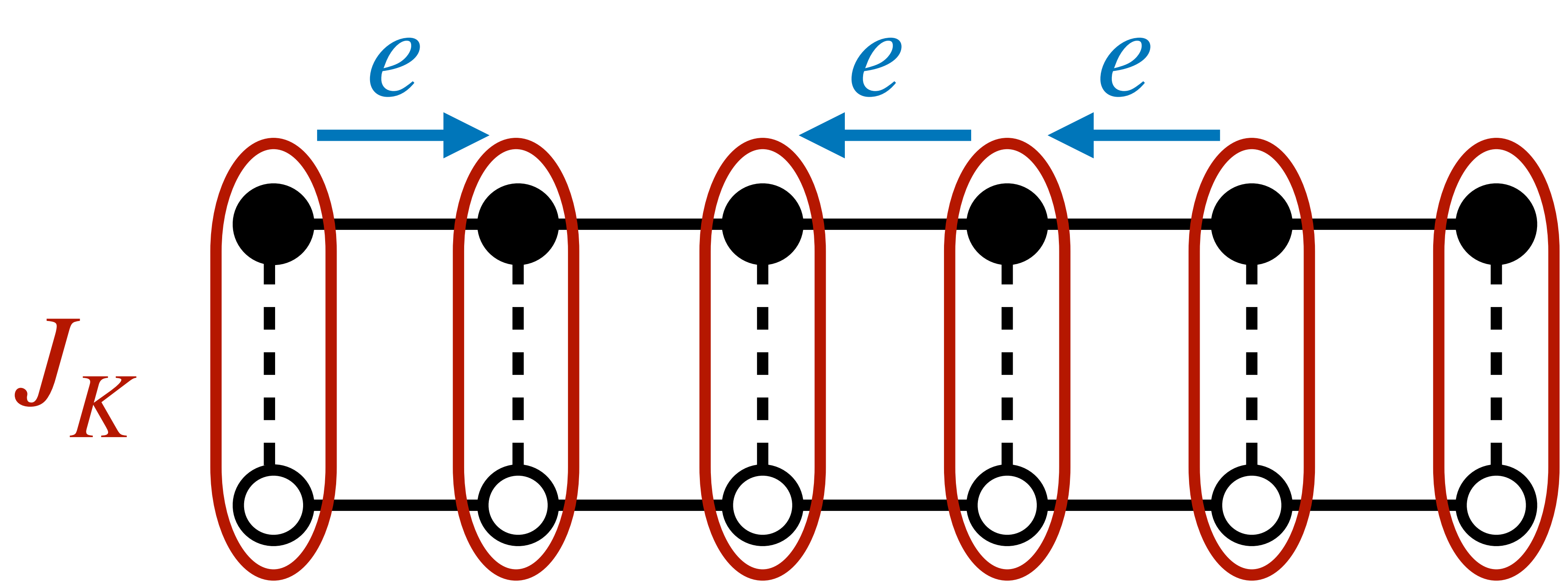
Kondo Lattice



Kondo Lattice

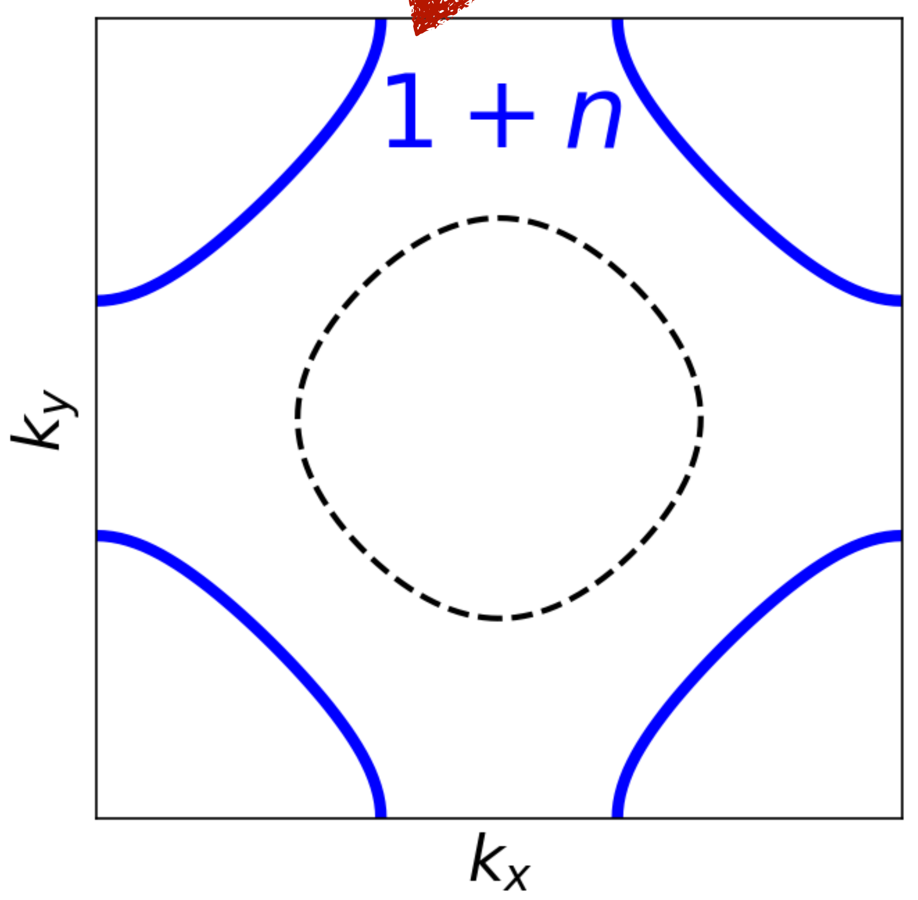
Heavy Fermi Liquid

composite electrons w FS volume $1+n$



$\boxed{\boldsymbol{S} = f^\dagger \boldsymbol{\sigma} f}$

f's are half-filled!



$\langle c^\dagger f \rangle \neq 0$

U(1) symmetry

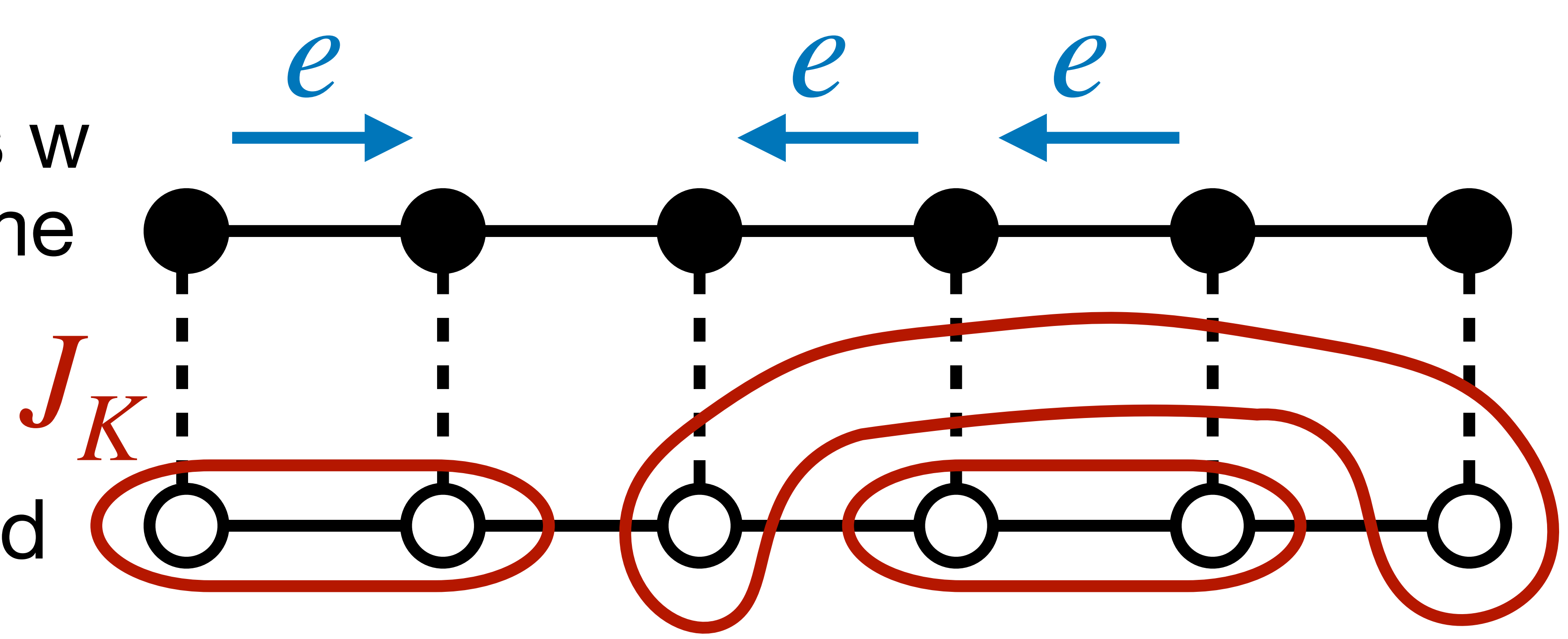
$c \rightarrow e^{i\alpha} c$

$f \rightarrow e^{i\alpha} f$

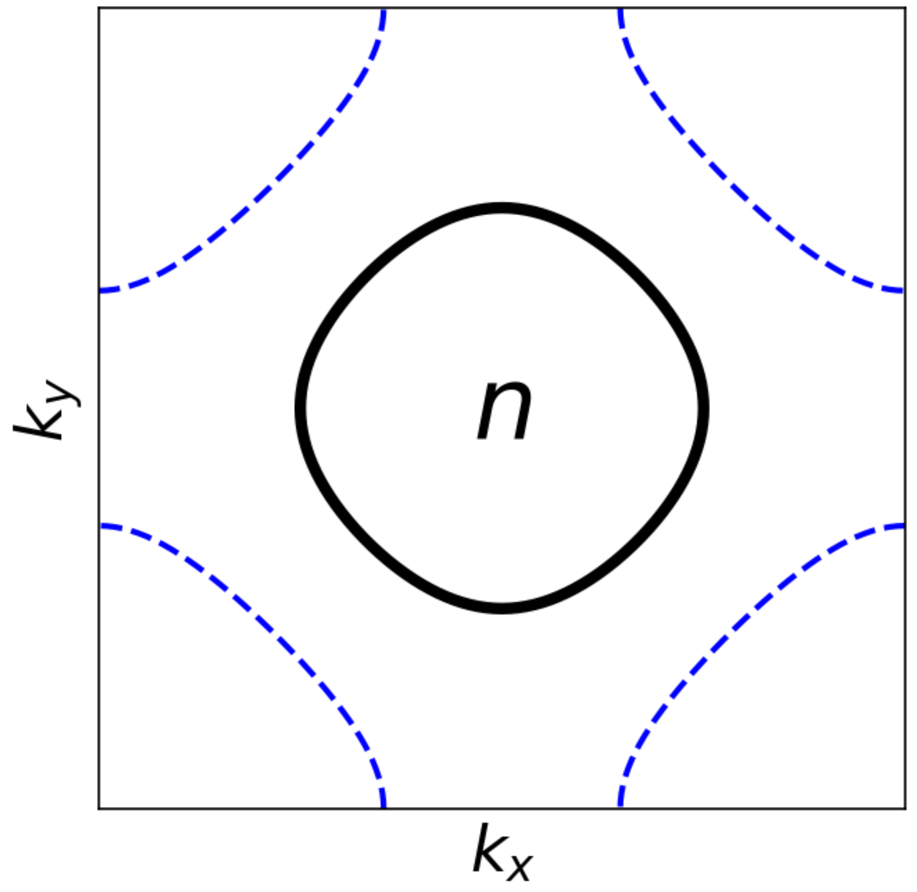
Fermi Liquid *

electrons w FS volume n

spin liquid



Senthil, Sachdev Vojta, PRL 2003
Senthil, Vojta, Sachdev, PRB 2004



$\langle c^\dagger f \rangle = 0$

U(1) symmetry

$c \rightarrow e^{i\alpha} c$

$f \rightarrow f$

The AKLT model: a recap

$$H = \sum_{\langle i,j \rangle} P_{ij}^{(2)}$$

$$= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$$= |+\rangle\langle\uparrow\uparrow| + |0\rangle\frac{\langle\uparrow\downarrow| + \langle\downarrow\uparrow|}{\sqrt{2}} + |-\rangle\langle\downarrow\downarrow|$$

from Wikipedia.org

- Enlarge Hilbert space: $|+\rangle, |0\rangle, |-\rangle$

  to $|\uparrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle, |\downarrow\downarrow\rangle,$

- Project out local singlets

  $$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

Ancilla Layer Model I

Zhang & Sachdev, PRR **2**, 023172 (2020)

consider a model of interacting spin-$\frac{1}{2}$ electrons

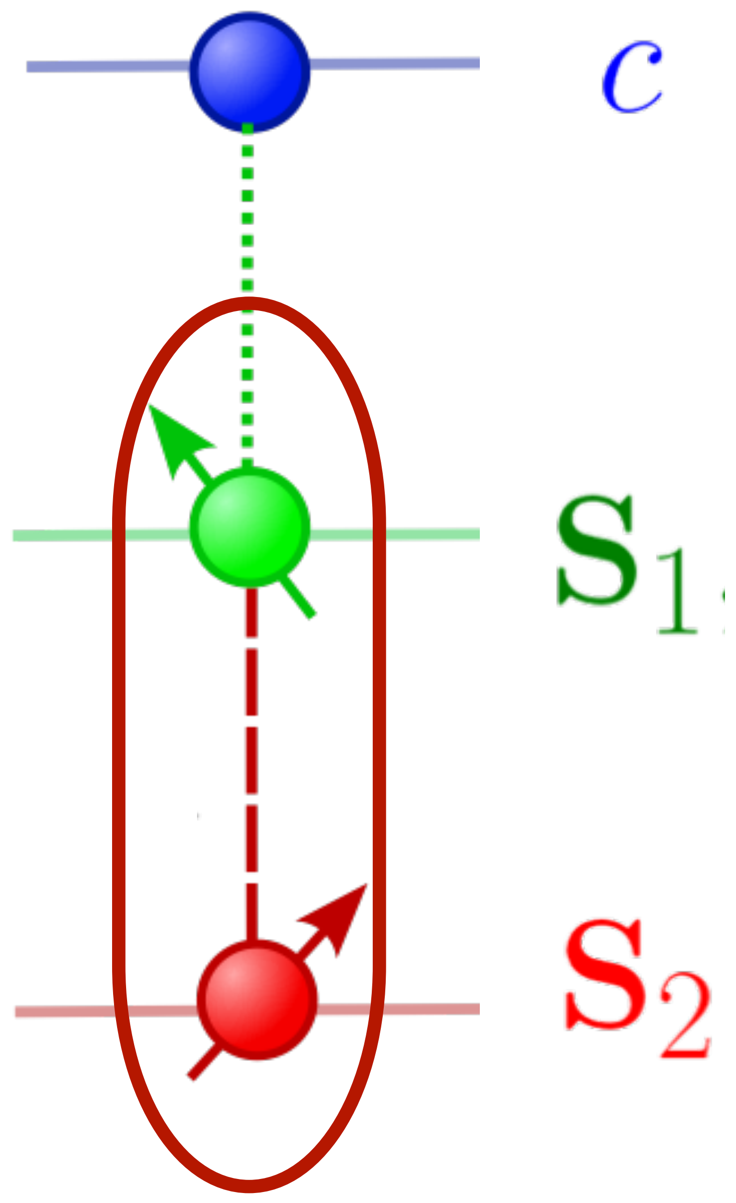
4 local states $|0\rangle, |\uparrow\rangle, |\downarrow\rangle, |\uparrow\downarrow\rangle$

c

Ancilla Layer Model I

Zhang & Sachdev, PRR **2**, 023172 (2020)

consider a model of interacting spin-$\frac{1}{2}$ electrons



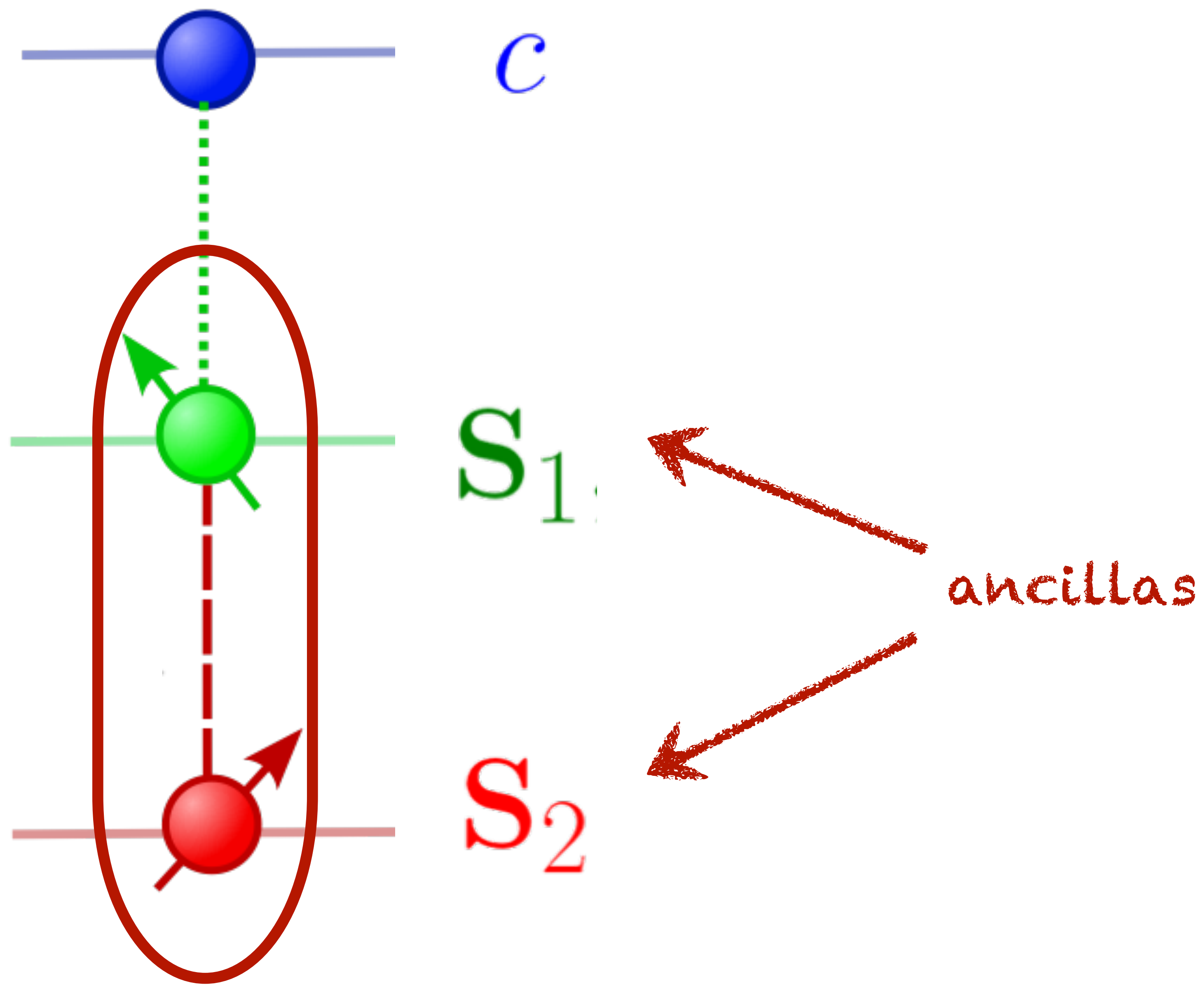
4 local states $|0\rangle, |\uparrow\rangle, |\downarrow\rangle, |\uparrow\downarrow\rangle$

$\rightarrow$ add a singlet $|0,s\rangle, |\uparrow, s\rangle, |\downarrow, s\rangle, |\uparrow\downarrow, s\rangle$

Ancilla Layer Model I

Zhang & Sachdev, PRR **2**, 023172 (2020)

consider a model of interacting spin-$\frac{1}{2}$ electrons



4 local states $|0\rangle, |\uparrow\rangle, |\downarrow\rangle, |\uparrow\downarrow\rangle$

→ add a singlet $|0,s\rangle, |\uparrow, s\rangle, |\downarrow, s\rangle, |\uparrow\downarrow, s\rangle$

→ enlarge to

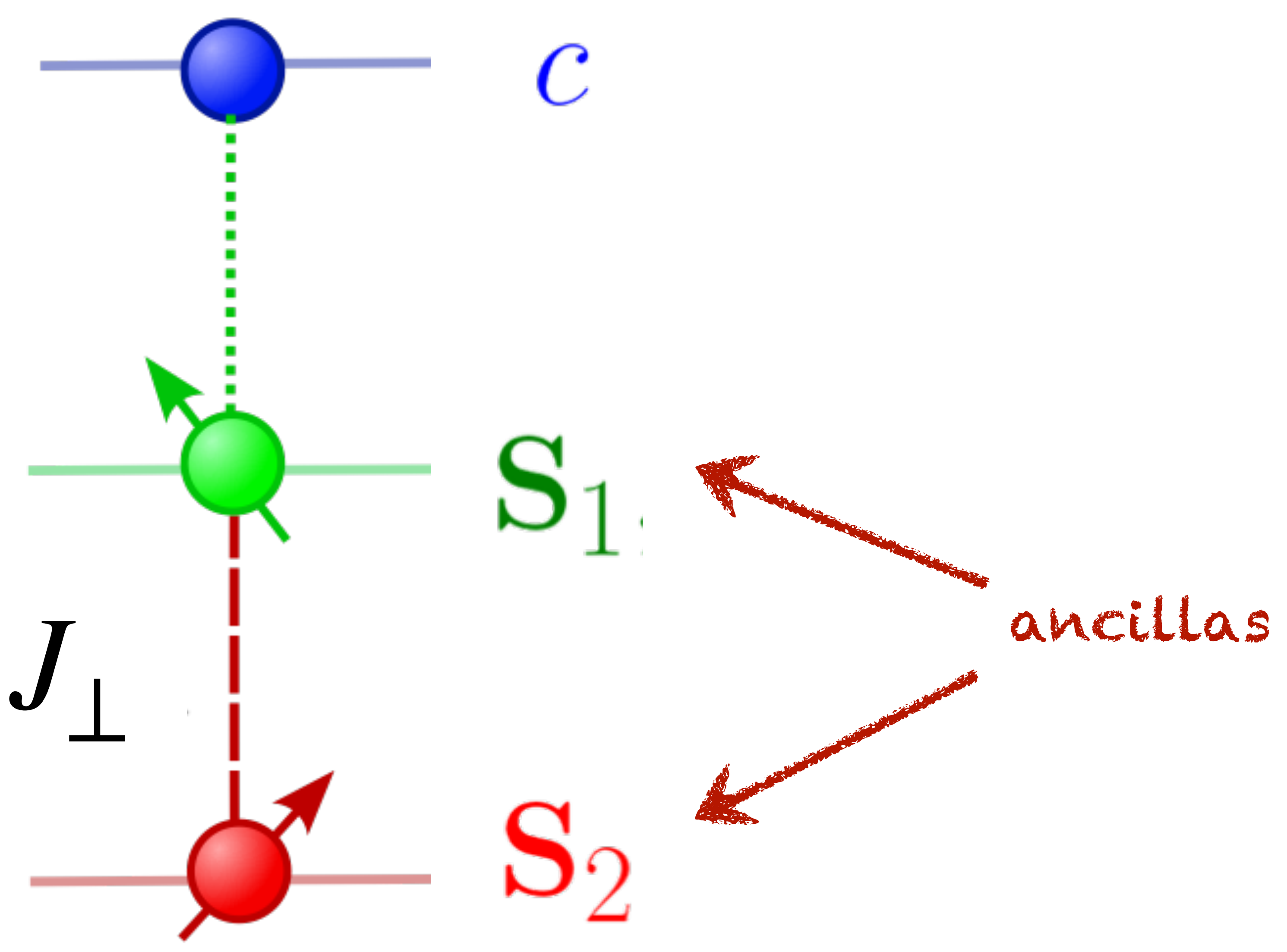
$$\begin{array}{l}
|0, \uparrow\uparrow\rangle, |\uparrow, \uparrow\uparrow\rangle, |\downarrow, \uparrow\uparrow\rangle, |\uparrow\downarrow, \uparrow\uparrow\rangle \\
|0, \uparrow\downarrow\rangle, |\uparrow, \uparrow\downarrow\rangle, |\downarrow, \uparrow\downarrow\rangle, |\uparrow\downarrow, \uparrow\downarrow\rangle \\
|0, \downarrow\uparrow\rangle, |\uparrow, \downarrow\uparrow\rangle, |\downarrow, \downarrow\uparrow\rangle, |\uparrow\downarrow, \downarrow\uparrow\rangle \\
|0, \downarrow\downarrow\rangle, |\uparrow, \downarrow\downarrow\rangle, |\downarrow, \downarrow\downarrow\rangle, |\uparrow\downarrow, \downarrow\downarrow\rangle
\end{array}$$

→ project onto $\frac{1}{\sqrt{2}}(|\Omega, \uparrow\downarrow\rangle - |\Omega, \downarrow\uparrow\rangle)$

Ancilla Layer Model I

Zhang & Sachdev, PRR **2**, 023172 (2020)

consider a model of interacting spin-$\frac{1}{2}$ electrons



4 local states $|0\rangle, |\uparrow\rangle, |\downarrow\rangle, |\uparrow\downarrow\rangle$

→ add a singlet $|0,s\rangle, |\uparrow, s\rangle, |\downarrow, s\rangle, |\uparrow\downarrow, s\rangle$

→ enlarge to
$$\begin{array}{llll} |0, \uparrow\uparrow\rangle, & |\uparrow, \uparrow\uparrow\rangle, & |\downarrow, \uparrow\uparrow\rangle, & |\uparrow\downarrow, \uparrow\uparrow\rangle \\ |0, \uparrow\downarrow\rangle, & |\uparrow, \uparrow\downarrow\rangle, & |\downarrow, \uparrow\downarrow\rangle, & |\uparrow\downarrow, \uparrow\downarrow\rangle \\ |0, \downarrow\uparrow\rangle, & |\uparrow, \downarrow\uparrow\rangle, & |\downarrow, \downarrow\uparrow\rangle, & |\uparrow\downarrow, \downarrow\uparrow\rangle \\ |0, \downarrow\downarrow\rangle, & |\uparrow, \downarrow\downarrow\rangle, & |\downarrow, \downarrow\downarrow\rangle, & |\uparrow\downarrow, \downarrow\downarrow\rangle \end{array}$$

→ project onto $\dfrac{1}{\sqrt{2}}(|\Omega, \uparrow\downarrow\rangle - |\Omega, \downarrow\uparrow\rangle)$

"soft projection" $-J_\perp \boldsymbol{S}_1 \cdot \boldsymbol{S}_2\,,\quad J_\perp \gg E_{\text{model}}$

Ancilla Layer Model II

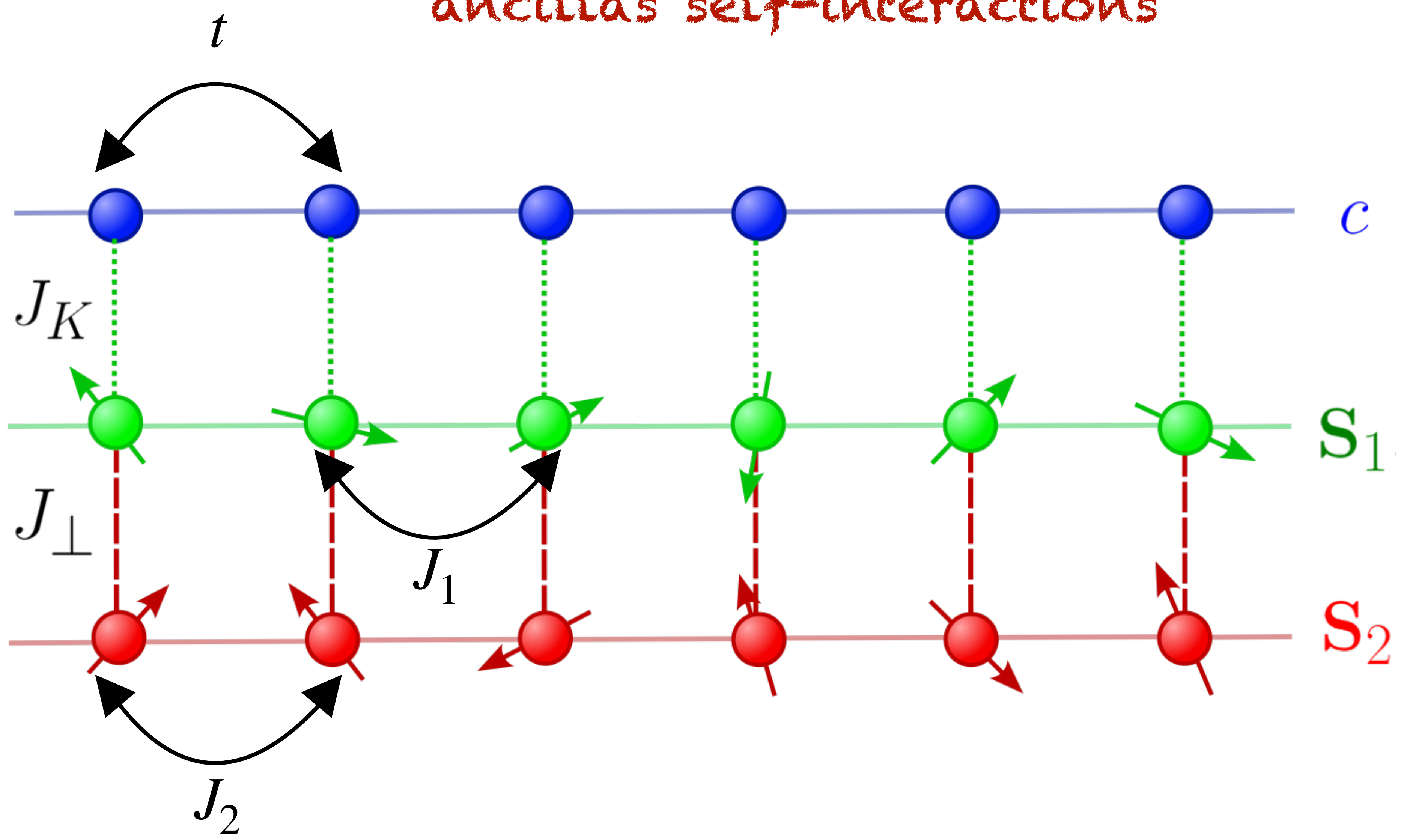
Zhang & Sachdev, PRR **2**, 023172 (2020)

$$H = -\sum_{i,j} t_{ij} c_i^\dagger c_j + J_\perp \sum_i \boldsymbol{S}_{1,i} \cdot \boldsymbol{S}_{2,i}$$ soft projector

$$+ J_K \sum_i c_i^\dagger \boldsymbol{\sigma} c_i \cdot \boldsymbol{S}_{1,i}$$ interaction

$$+ \sum_{ij} J_{1,ij} \boldsymbol{S}_{1,i} \cdot \boldsymbol{S}_{1,j} + \sum_{ij} J_{2,ij} \boldsymbol{S}_{2,i} \cdot \boldsymbol{S}_{2,j}$$

ancillas self-interactions



project out triplet states perturbatively in $1/J_\perp$

$$\rightarrow H_{\rm el} = -\sum_{ij} t_{ij} c_i^\dagger c_j + U \sum_i n_{i,\uparrow} n_{i,\downarrow} - \sum_{ij} J_{ij} (c_i^\dagger \boldsymbol{\sigma} c_i) \cdot (c_j^\dagger \boldsymbol{\sigma} c_j)$$

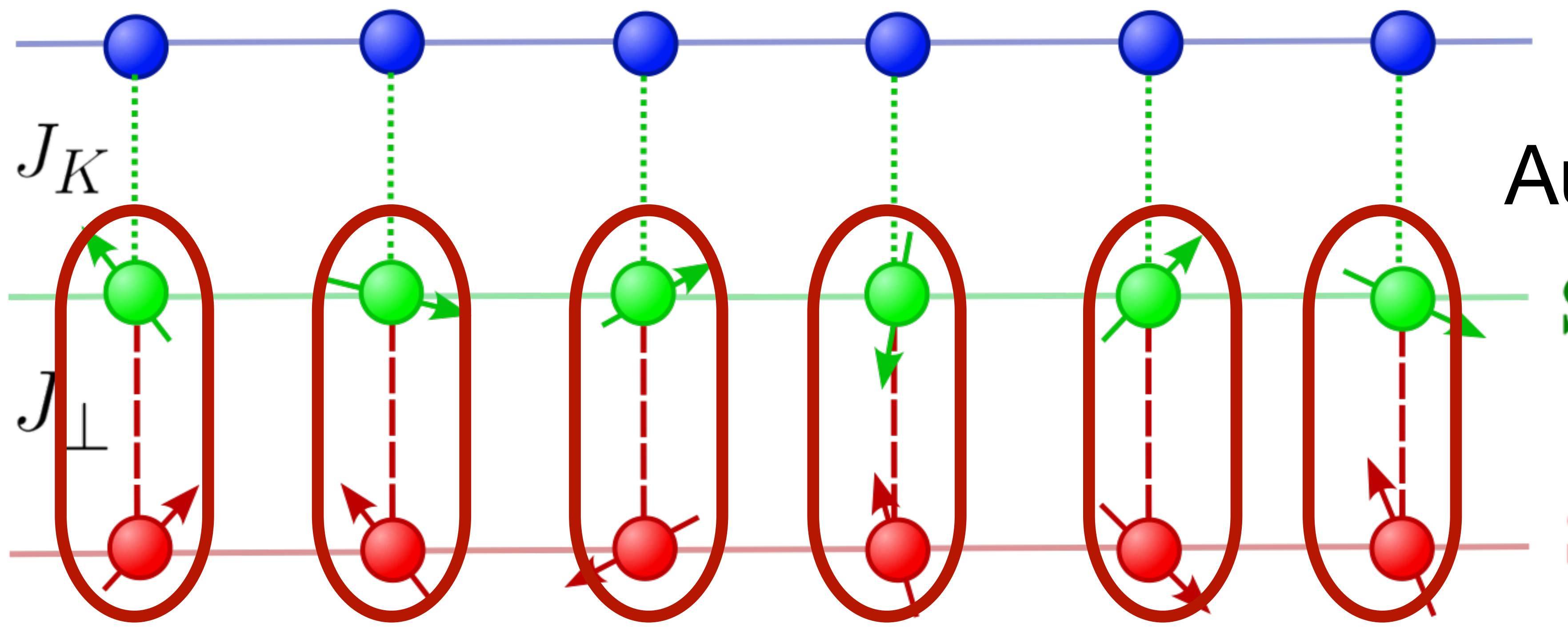
Nikolaenko *et al.*, PRB 103, 235138 (2021)

$$U = \frac{3J_K^2}{8J_\perp} + \frac{3J_K^3}{16J_\perp^2} + \mathcal{O}(1/J_\perp^3)$$

$$J = \frac{J_K^2 (J_1 + J_2)}{4J_\perp^2} + \mathcal{O}(1/J_\perp^3)$$

FL phase

Zhang & Sachdev, PRR **2**, 023172 (2020)



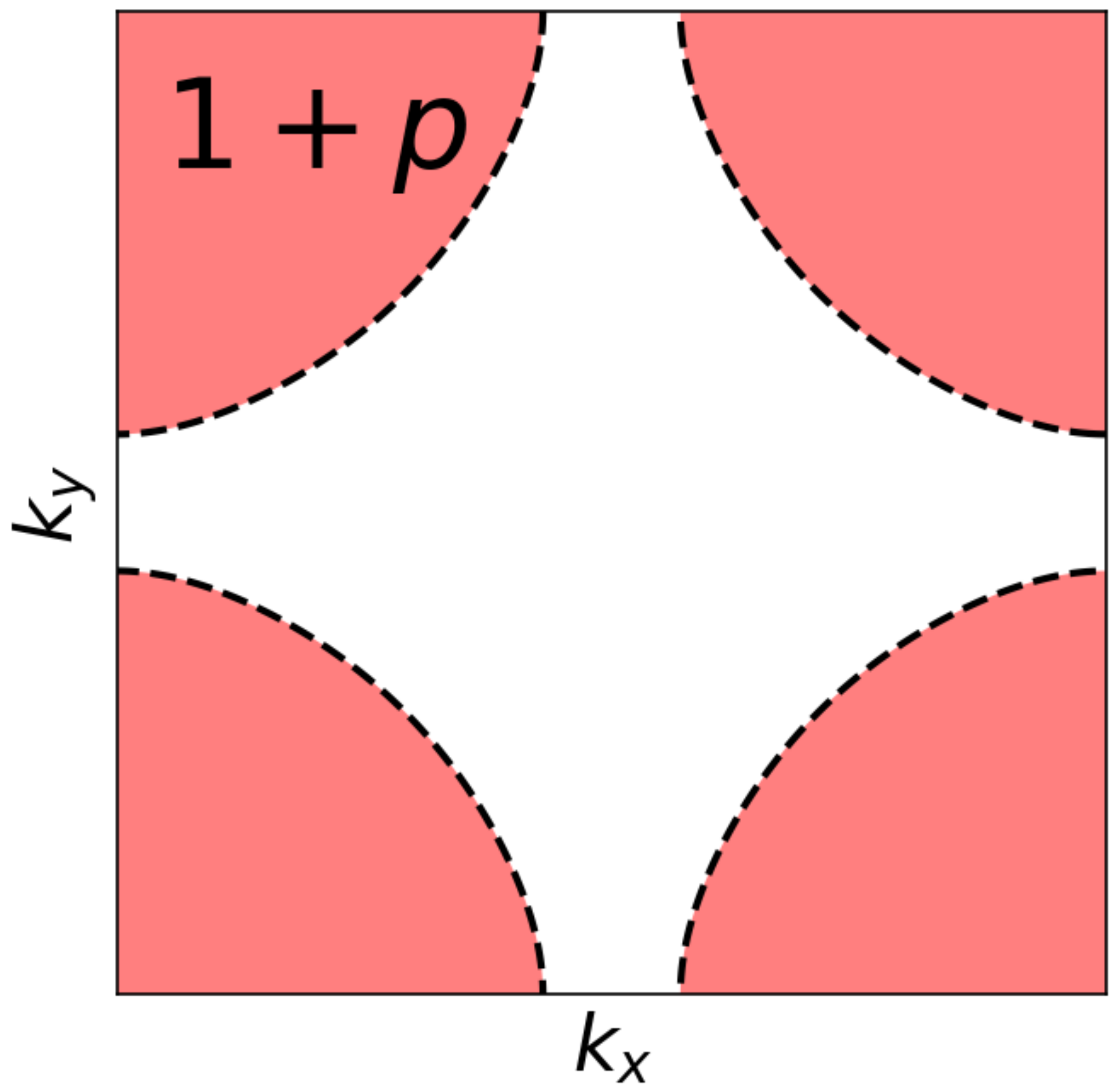
itinerant electrons

Auxiliary fermion representation

$\mathbf{S}_1, f_1$ $\quad \boldsymbol{S}_{1,i} = f^\dagger_{1,i}\boldsymbol{\sigma} f_{1,i} \qquad f^\dagger_{1,i} f_{1,i} = 1$

$\mathbf{S}_2, f_2$ $\quad \boldsymbol{S}_{2,i} = f^\dagger_{2,i}\boldsymbol{\sigma} f_{2,i} \qquad f^\dagger_{2,i} f_{2,i} = 1$

rung singlets



U(1) symmetry

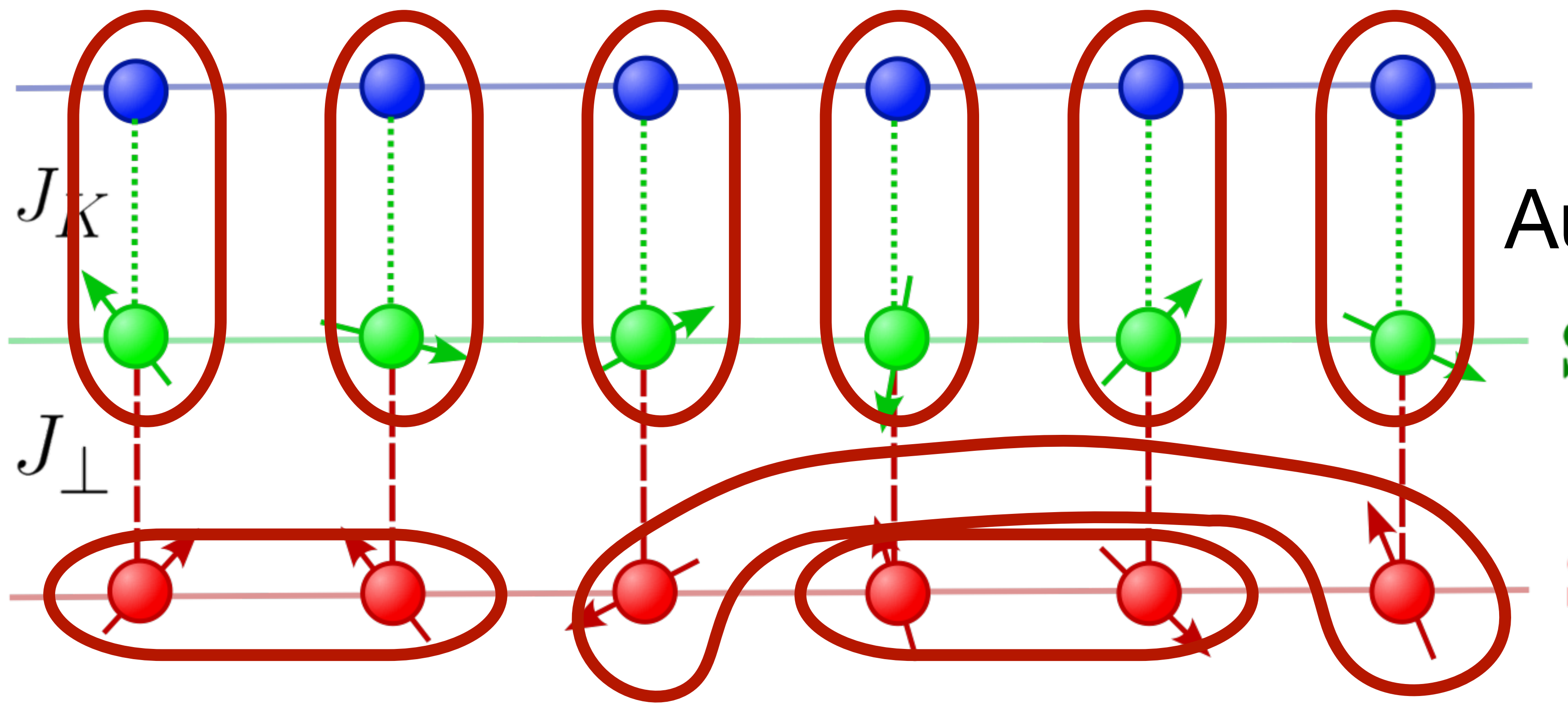
$c \to e^{i\alpha} c$

$f_{1,2} \to f_{1,2}$

$$V_{\mathrm{FS}} = 1 + p$$

FL* phase

Zhang & Sachdev, PRR **2**, 023172 (2020)



c

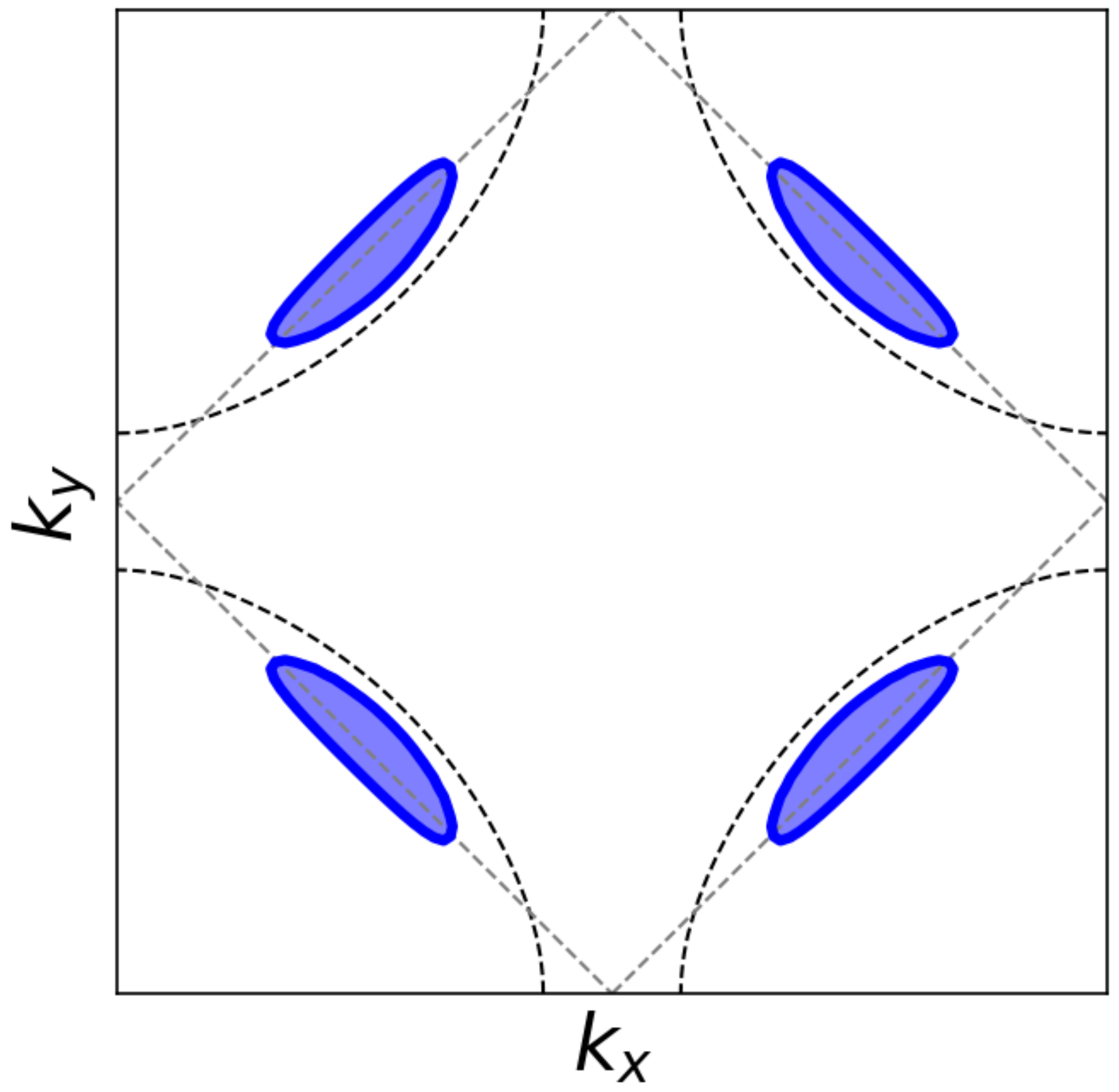
Auxiliary fermion representation

$\mathbf{S}_1, f_1$ $\quad \boldsymbol{S}_{1,i} = f^\dagger_{1,i}\boldsymbol{\sigma} f_{1,i} \qquad f^\dagger_{1,i} f_{1,i} = 1$

$\mathbf{S}_2, f_2$ $\quad \boldsymbol{S}_{2,i} = f^\dagger_{2,i}\boldsymbol{\sigma} f_{2,i} \qquad f^\dagger_{2,i} f_{2,i} = 1$

$\}$ **Hybridized** $\phi \sim c^\dagger_i f_i$

spin liquid



U(1) symmetry

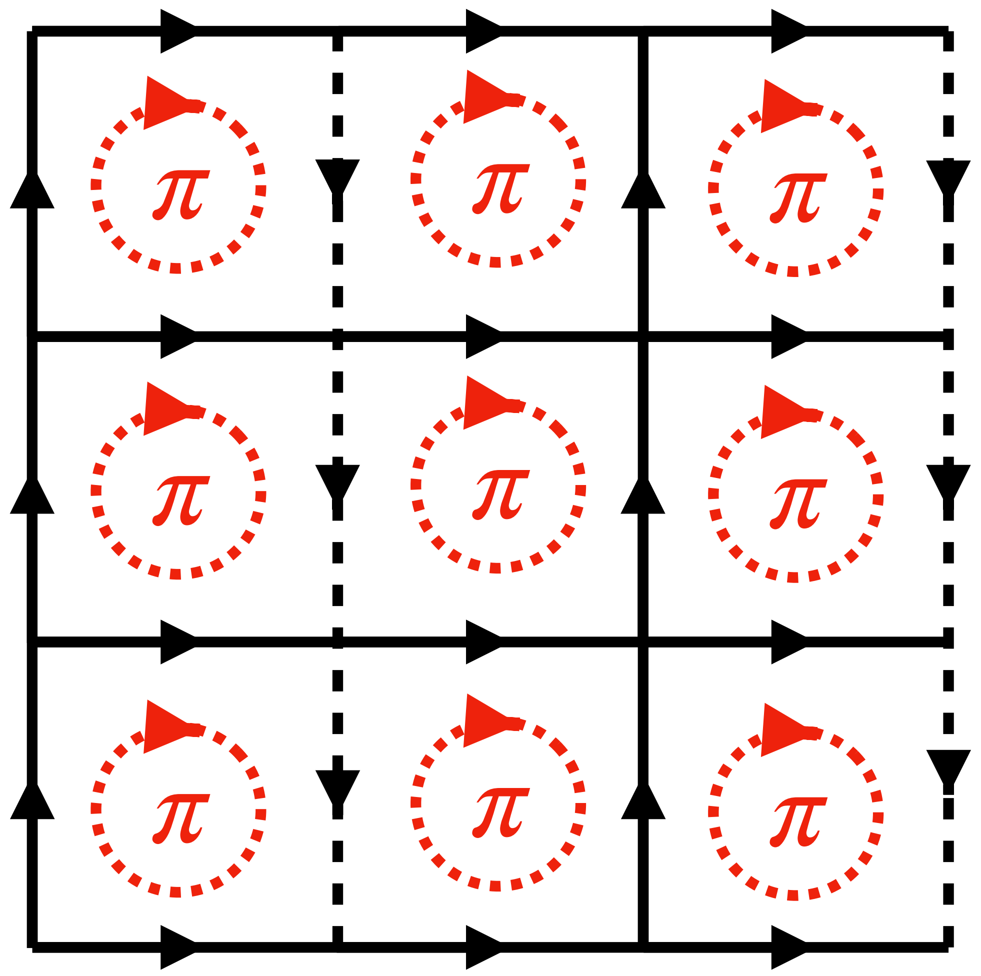
$\langle c^\dagger f_1 \rangle \neq 0$

$c \to e^{i\alpha} c$
$f_1 \to e^{i\alpha} f_1$
$f_2 \to \quad f_2$

$$V_{\text{FS}} = (1 + p + 1) \bmod 2 = p$$

π-Flux Spin Liquid

Affleck & Marston, PRB **37**, 3774(R) (1988)



$$\psi_i = \left(f_{2,i,\uparrow}, f^{\dagger}_{2,i,\downarrow}\right)^T$$

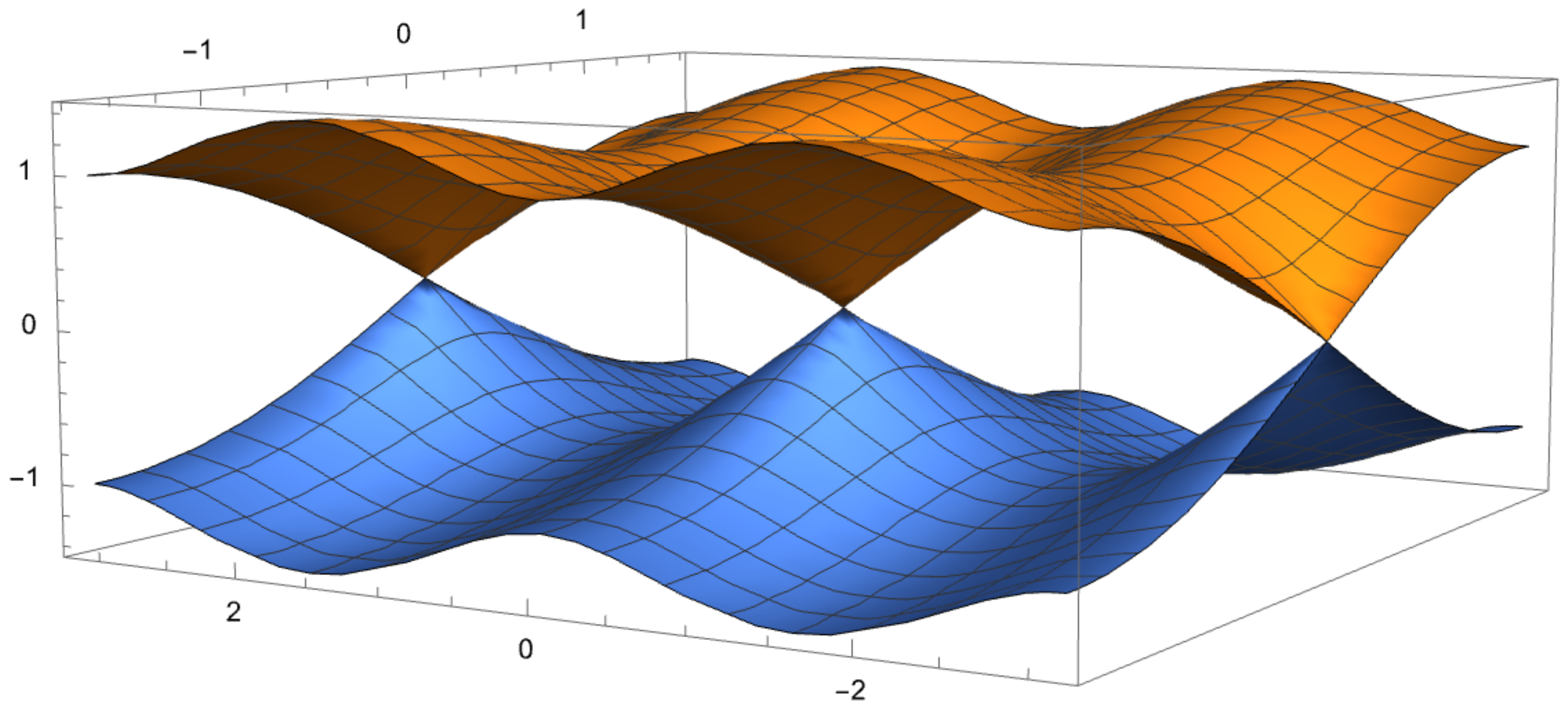
$$\boxed{\mathscr{H}^{\mathrm{QSL}}_{\pi-\mathrm{flux}} = J \sum_{\langle i,j \rangle} \psi_i^{\dagger}\, e_{ij}\, U_{ij}\, \psi_j}$$

$$e_{i,i\pm\hat{x}} = \pm\, i \qquad e_{i,i\pm\hat{y}} = \pm\, i(-1)^x$$

$$U_{ij} \sim e^{-i \sum_{a=1}^{3} (\boldsymbol{r}_i - \boldsymbol{r}_j)\cdot \boldsymbol{A}^a_{(i+j)/2} \frac{\sigma^a}{2}} \in \mathrm{SU}(2)$$ link field

SU(2) gauge invariance!

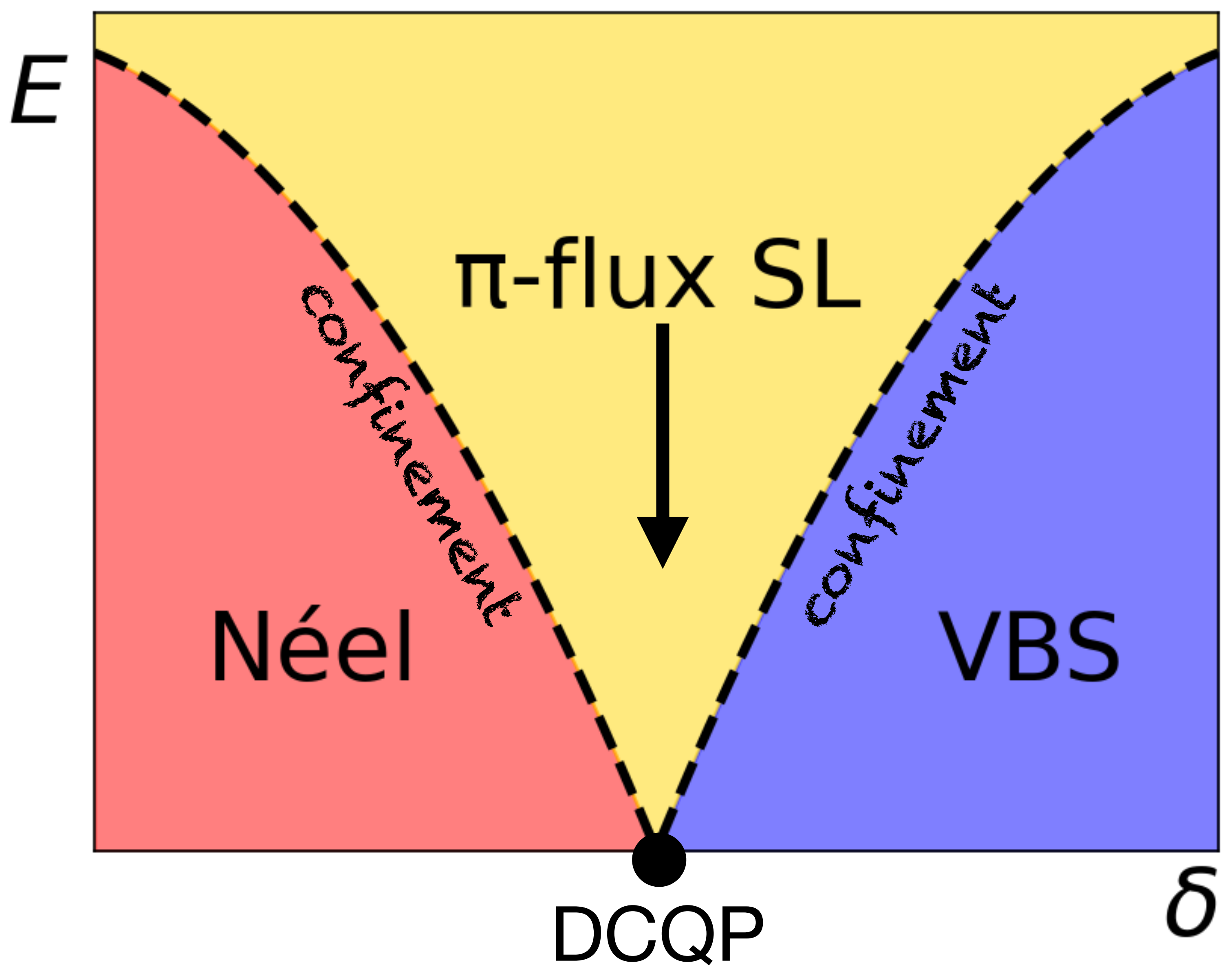
$$E^{\pm}_{\boldsymbol{k}} = \pm\, 2J\sqrt{(\sin k_x)^2 + (\sin k_y)^2}$$



2 Dirac cones

Stable at intermediate energy scales, eventually unstable to Néel or VBS order

C. Wang *et al.*, Phys. Rev. X **7**, 031051 (2017)



Bosonic Chargons Theory

Christos *et al.*, PNAS **120**, e2302701120 (2023)

Decouple $-J_\perp \sum_i \boldsymbol{S}_{1,i} \cdot \boldsymbol{S}_{2,i} \Rightarrow$ complex boson field $\left(B_{1,i}, B_{2,i}\right)^T$

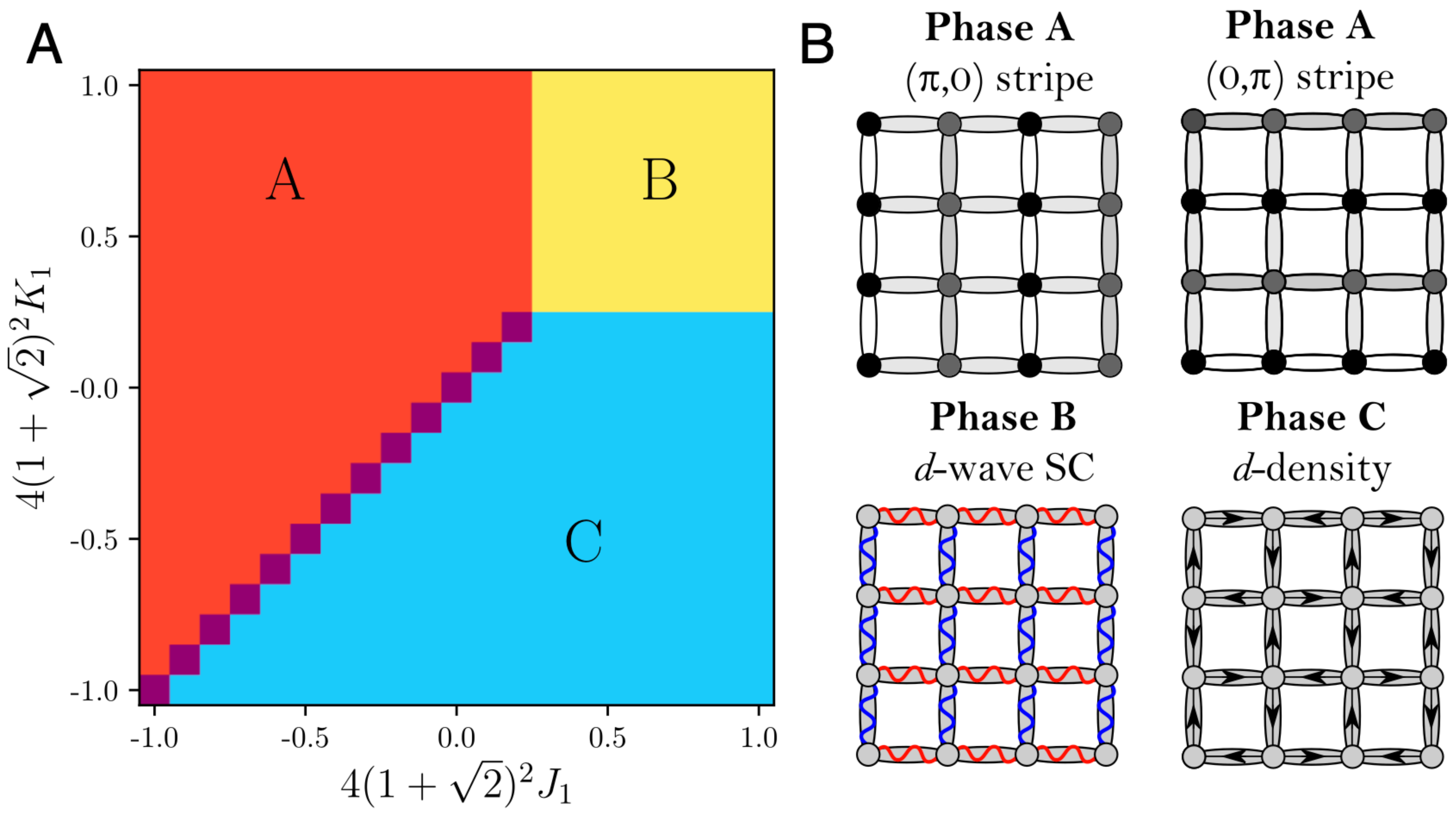
$$B_1 \sim f^\dagger_{1,\sigma} f_{2,\sigma},\ B_2 \sim f^\dagger_{1,\uparrow} f^\dagger_{2,\downarrow} - f^\dagger_{1,\downarrow} f^\dagger_{2,\uparrow}$$

- EM charge e (f_1 has charge e in FL* phase)
- no SU(2) spin
- $\in$ fundamental of SU(2) $\Rightarrow$ π-flux background

Gauge invariant bilinears

e_{ij} : π-flux hoppings

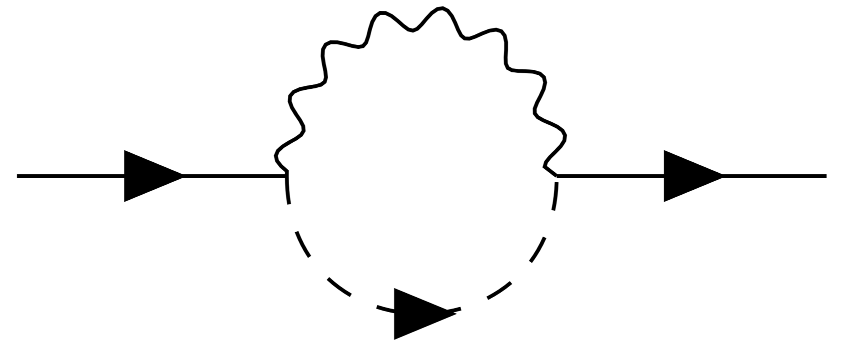
- $\rho_i = B_i^\dagger B_i \sim c_i^\dagger c_i \Rightarrow$ charge density OP
- $Q_{ij} = \mathrm{Re}\left\{B_i^\dagger e_{ij} U_{ij} B_j\right\} \sim c_i^\dagger c_j + c_j^\dagger c_i \Rightarrow$ bond density OP
- $J_{ij} = \mathrm{Im}\left\{B_i^\dagger e_{ij} U_{ij} B_j\right\} \sim i(c_i^\dagger c_j - c_j^\dagger c_i) \Rightarrow$ current density OP
- $\Delta_{ij} = B_i e_{ij} [i\sigma^2] U_{ij} B_j \sim c_i [i\sigma^2] c_j \Rightarrow$ superconducting OP

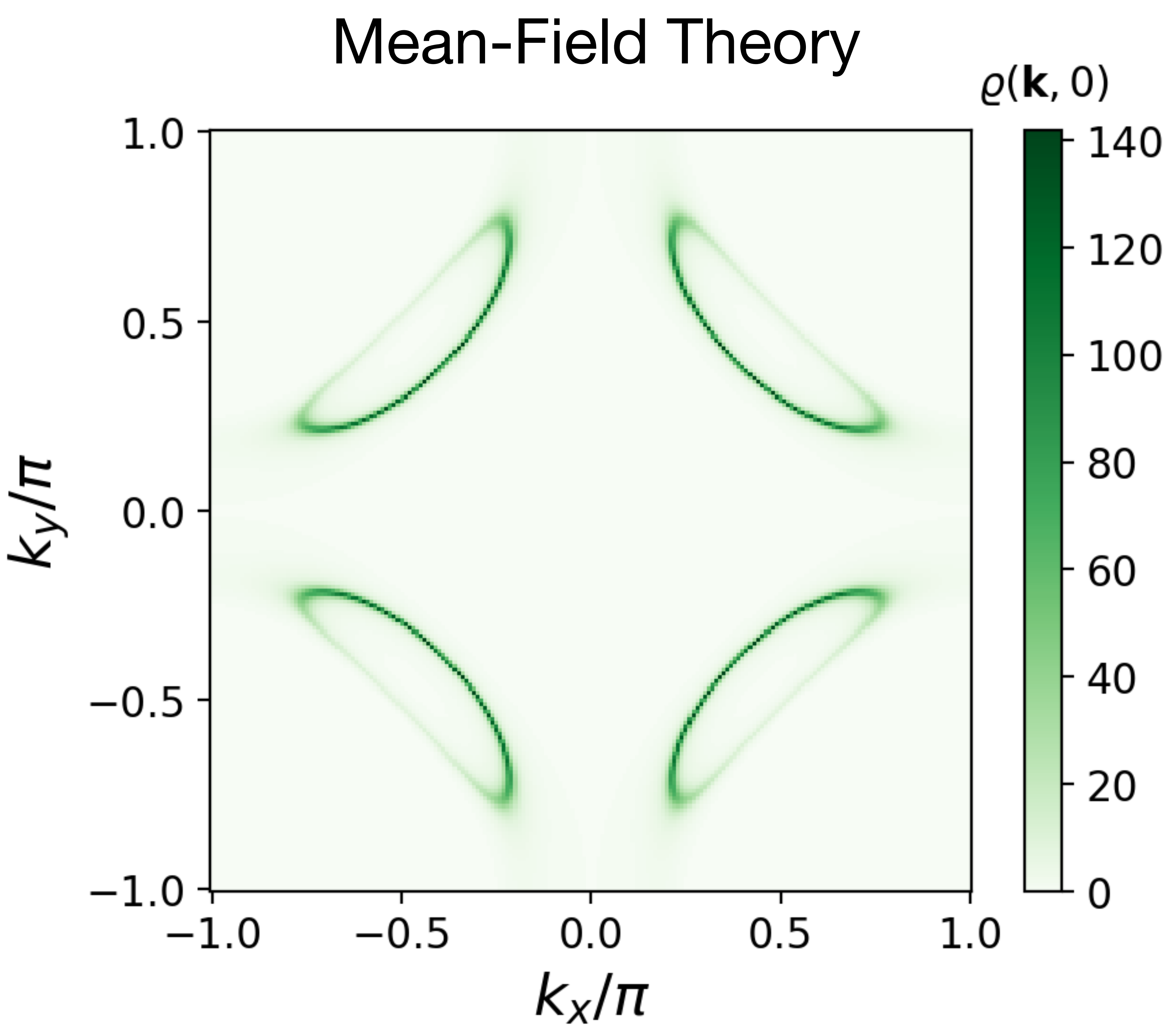


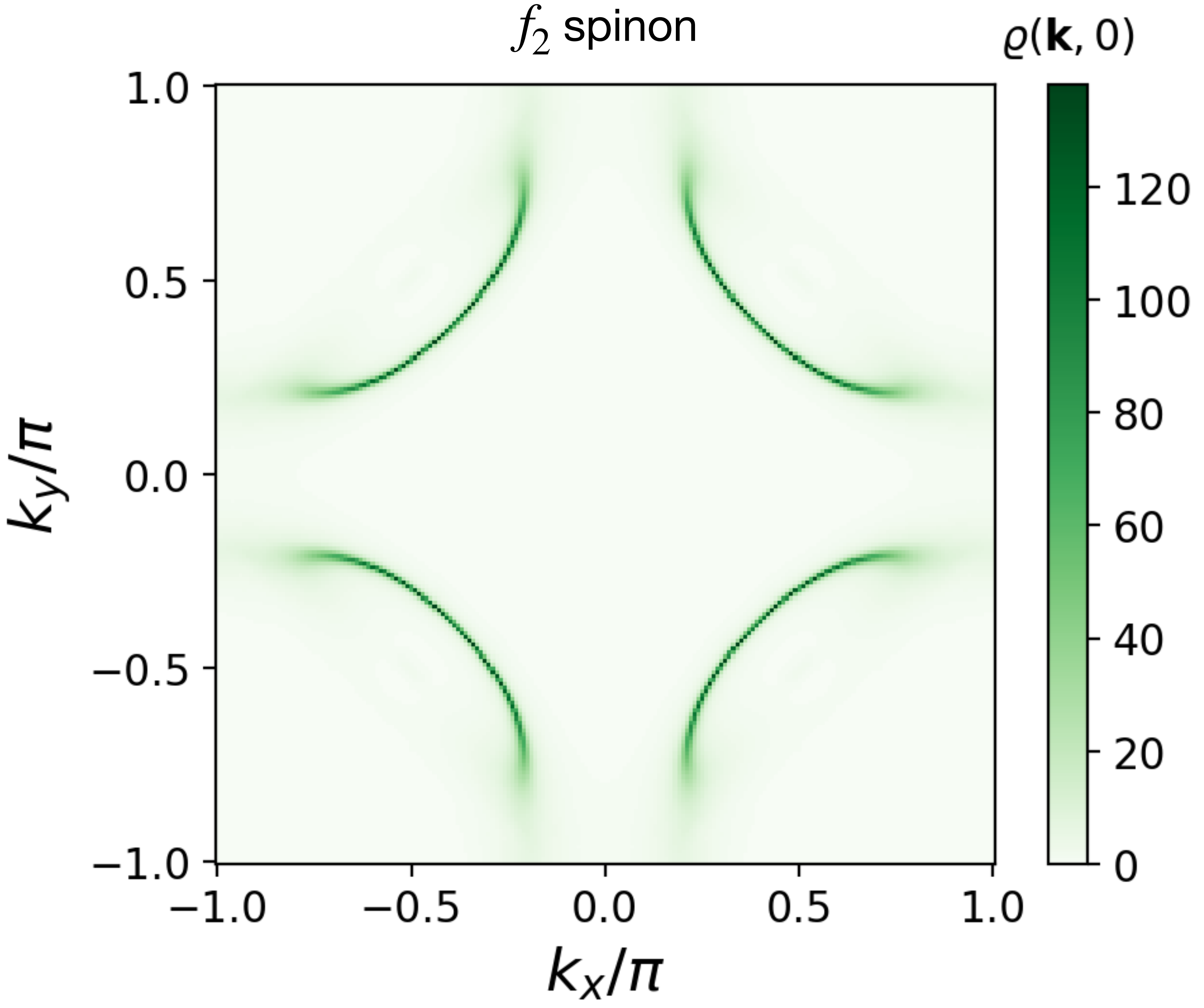
Christos *et al.*, PNAS (2023)

condensation of B_i $\Rightarrow$ confines the SU(2) gauge field + additional orders

Beyond Mean-Field Theory







Pandey, Christos, PMB, Shanker, Nikolaenko, Sharma, Sachdev, arXiv:2507.05336 (2025)

Thermal Bosonic Chargons

Pandey, Christos, PMB, Shanker, Nikolaenko, Sharma, Sachdev, arXiv:2507.05336 (2025)

Consider effective classical theory for the chargons at finite temperature T

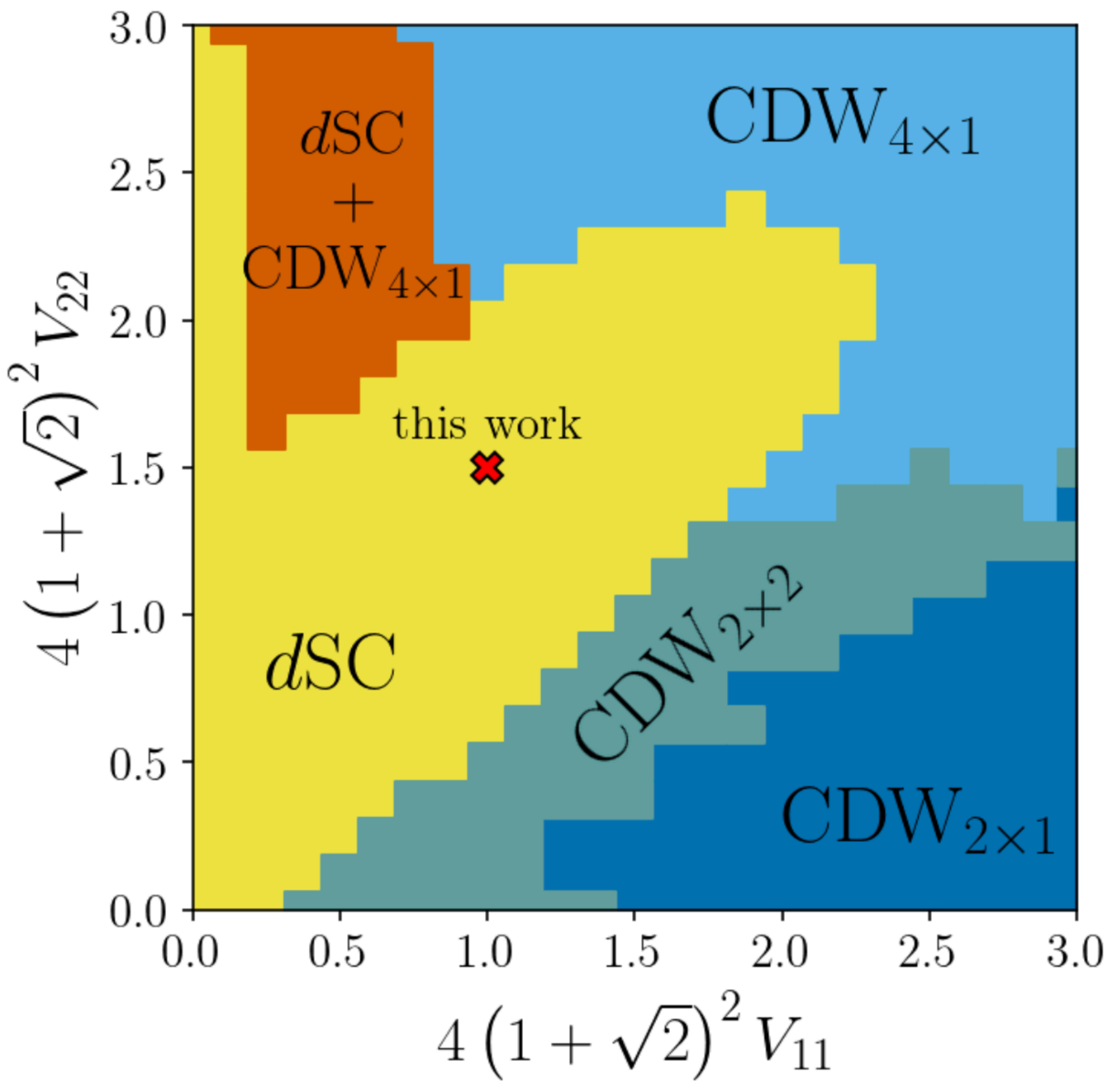
SU(2) gauge field

π-flux hoppings

$$\mathscr{E}_2[B,U] = \kappa \sum_{\square} \left[1 - \frac{1}{2}\mathrm{ReTr} \prod_{i,j\in\square} U_{ij}\right] + r\sum_i B_i^\dagger B_i - iw \sum_{\langle i,j\rangle} B_i^\dagger e_{ij} U_{ij} B_j$$

$$\mathscr{E}_4[B,U] = \frac{u}{2}\sum_i \rho_i^2 + V_1 \sum_i \rho_i(\rho_{i+\hat{x}} + \rho_{i+\hat{y}}) + g\sum_{\langle i,j\rangle} |\Delta_{ij}|^2 + J_1 \sum_{\langle i,j\rangle} Q_{ij}^2$$
$$+ K_1 \sum_{\langle ij\rangle} J_{ij}^2 + V_{11}\sum_i \rho_i(\rho_{i+\hat{x}+\hat{y}} + \rho_{i+\hat{x}-\hat{y}})$$
$$+ V_{22}\sum_i \rho_i(\rho_{i+2\hat{x}+2\hat{y}} + \rho_{i+2\hat{x}-2\hat{y}})$$

MF phase diagram



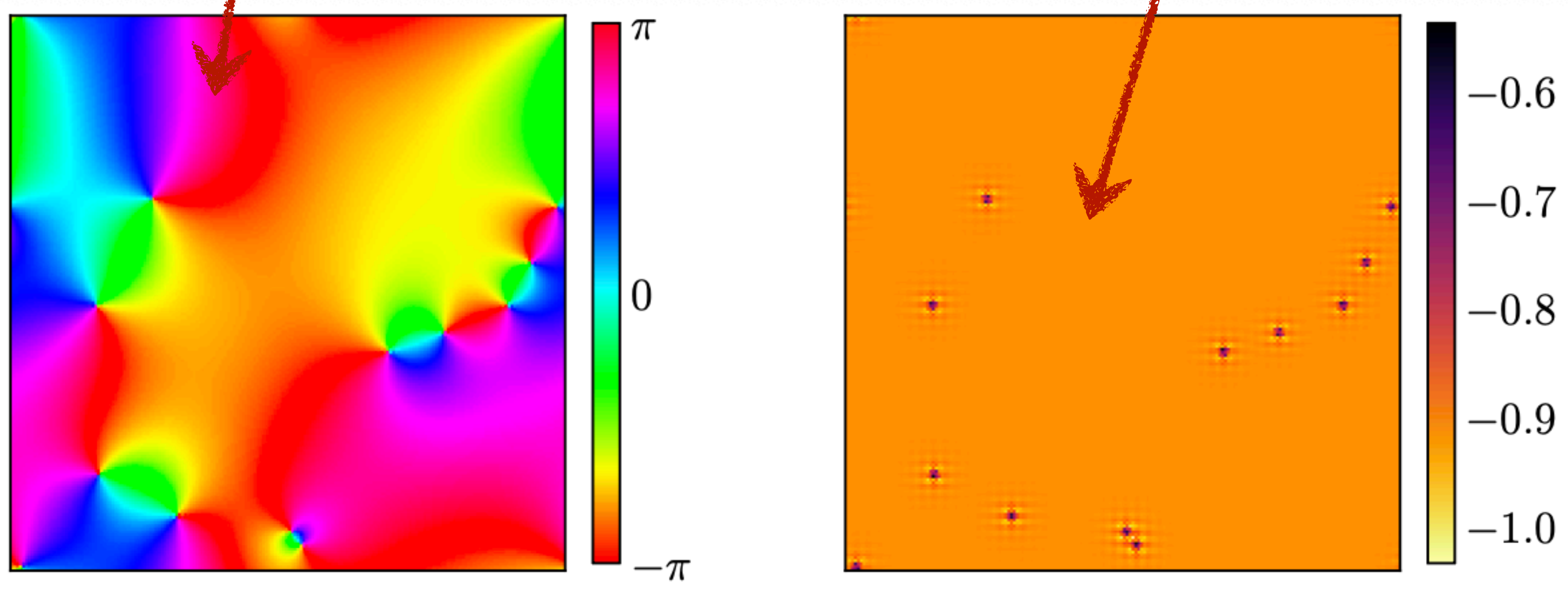
$r = -0.732, w = 0.40, u = 0, V_1 = 0, g = 0.02,$
$J_1 = K_1 = 2/(1+\sqrt{2})^2$

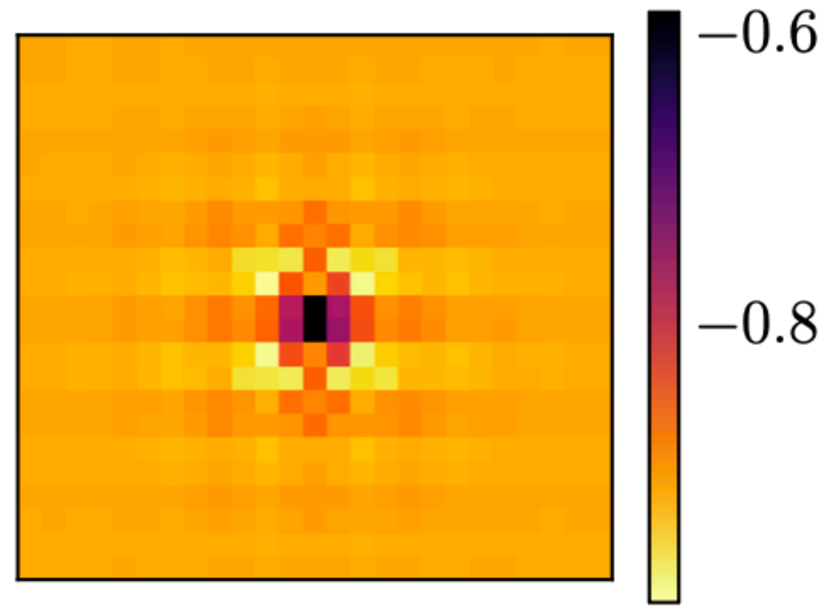
KT transition

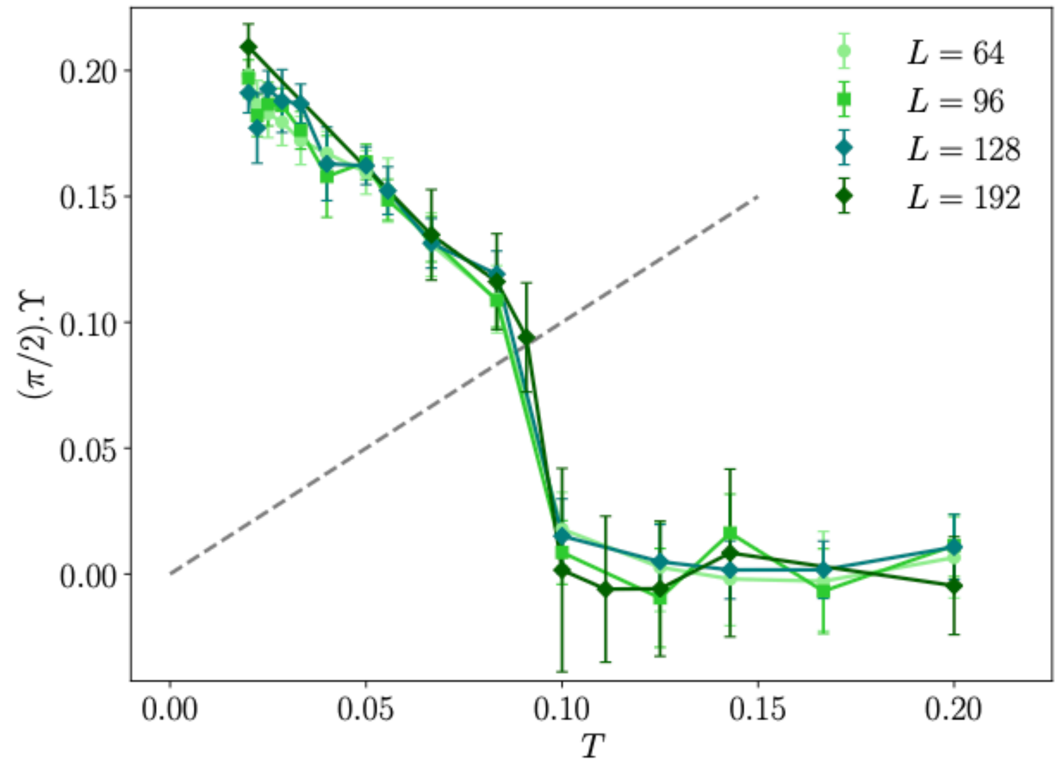
Pandey, Christos, PMB, Shanker, Nikolaenko, Sharma, Sachdev, arXiv:2507.05336 (2025)

$\arg\Delta_{ij} = \arg\left\{B_i \epsilon U_{ij} B_j\right\}$

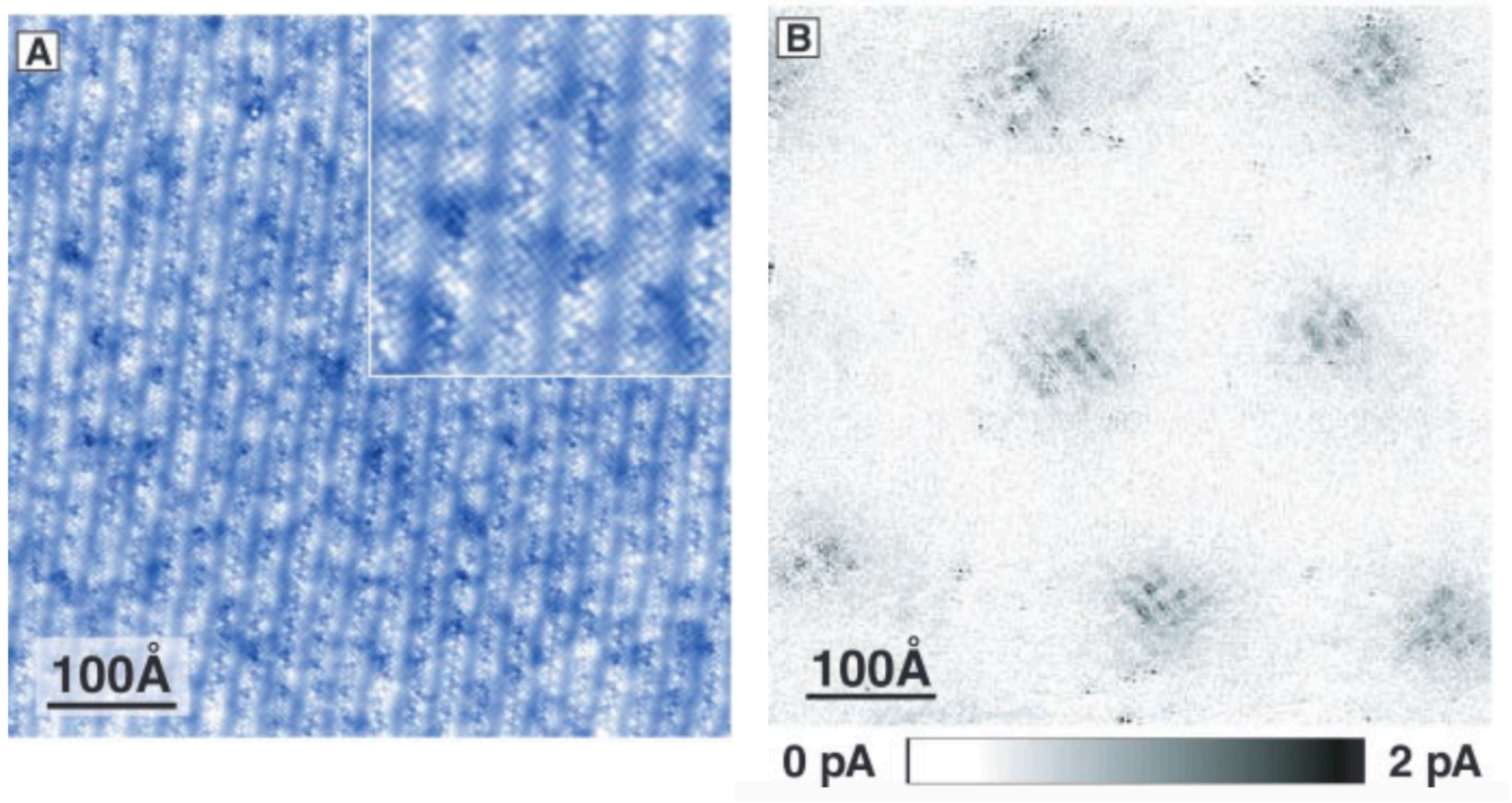
$Q_{ij} = \mathrm{Re}\left\{B_i^\dagger e_{ij} U_{ij} B_j\right\}$







- charge-e OP **but** $\dfrac{h}{2e}$ vortices
- period-4 CDW in the vortex cores



Hoffman *et al.*, Science **295**, 466 (2002)

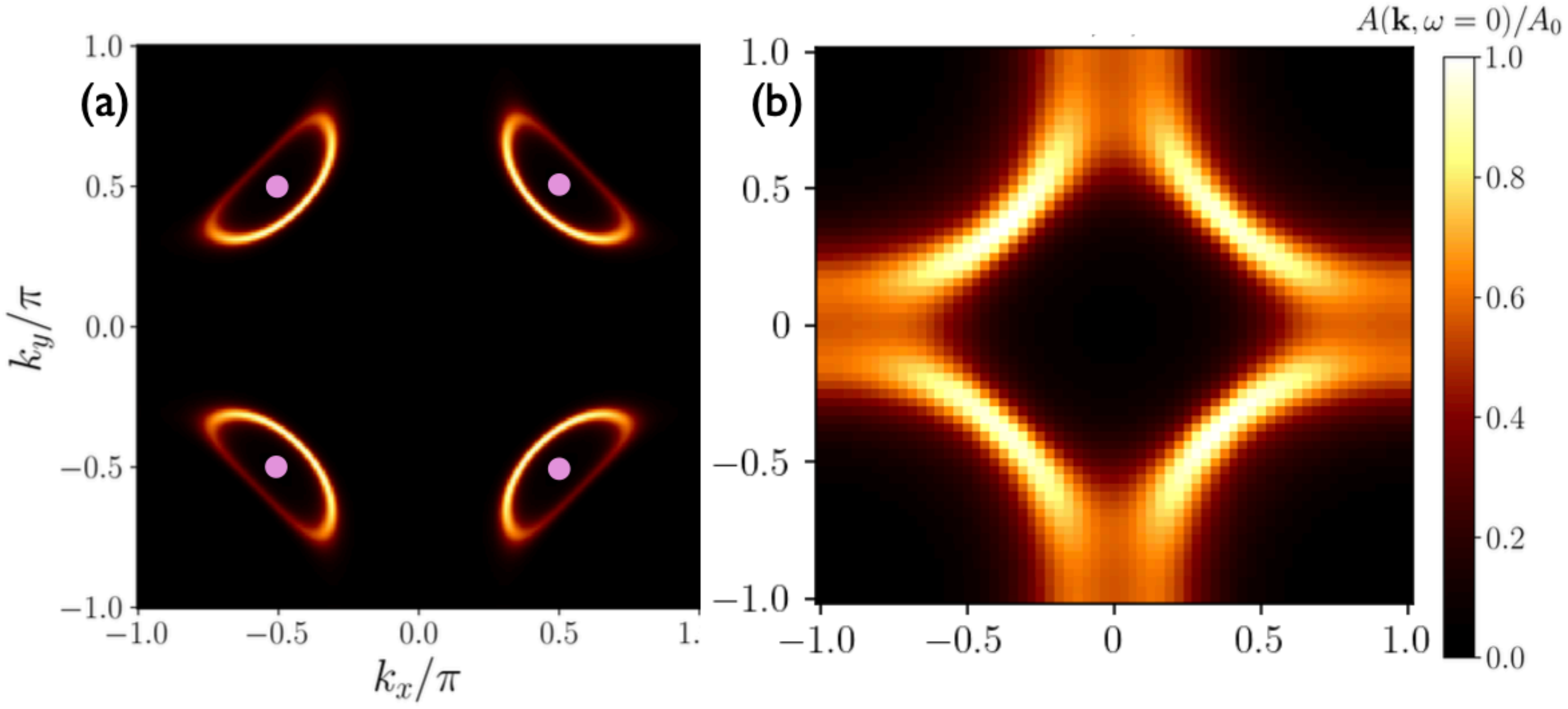
Fermi Surface topology

Pandey, Christos, PMB, Shanker, Nikolaenko, Sharma, Sachdev, arXiv:2507.05336 (2025)

$$\mathscr{H} = -\sum_{i,j} t^c_{ij} c^\dagger_i c_j - \sum_{i,j} t^f_{ij} f^\dagger_{1,i} f_{1,j} + iJ \sum_{\langle i,j\rangle} f^\dagger_{2,i} e_{ij} U_{ij} f_{2,j} + g\sum_i \left[B_{1,i} f^\dagger_{2,i} f_{1,i} - B_{2,i} f_{2,i} \begin{pmatrix}0 & -1\\ 1 & 0\end{pmatrix} f_{1,i} + \text{H.c.}\right]$$

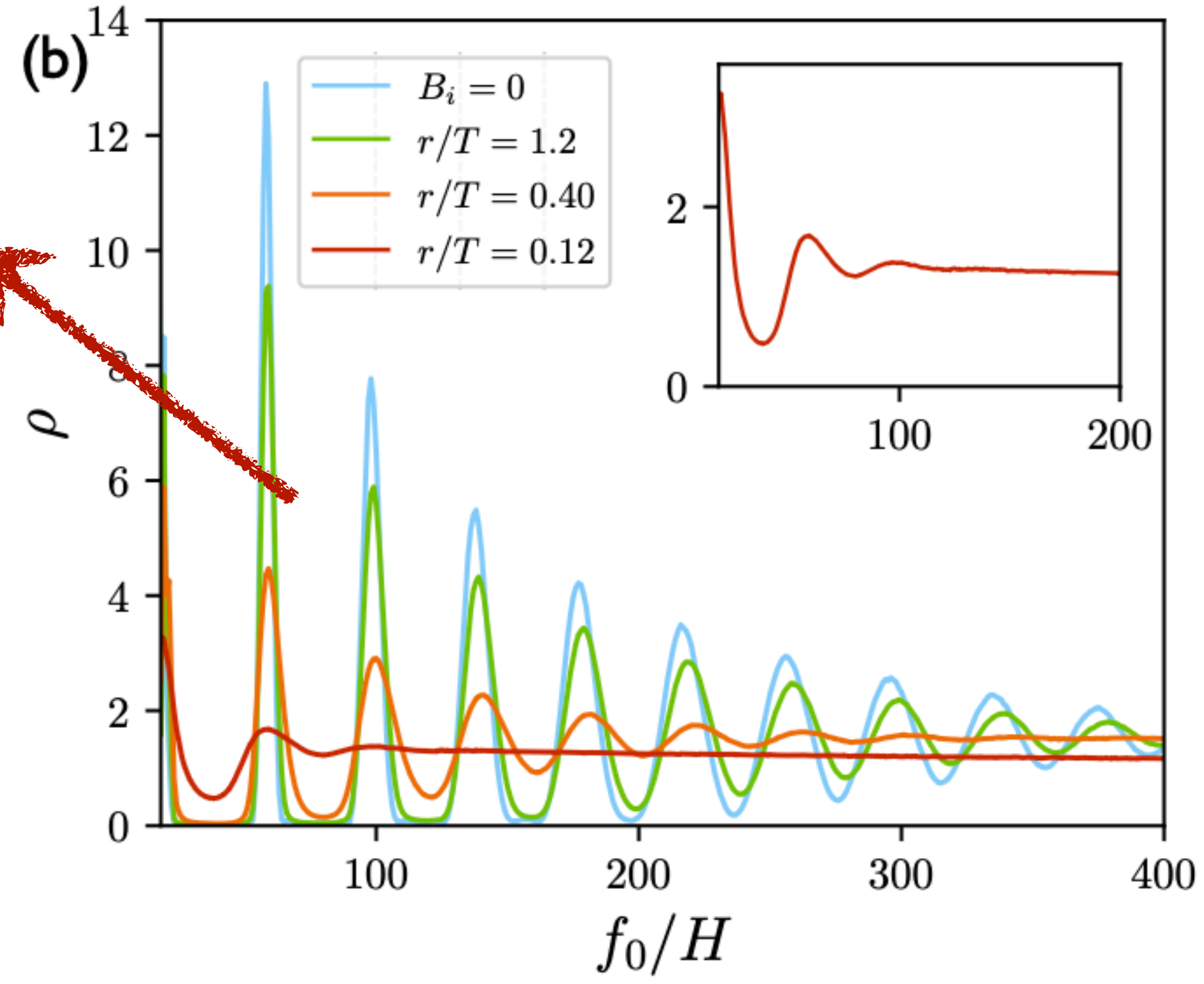
"Born-Oppenheimer" approx.→ sample U & B according to $e^{-\beta(\mathscr{E}_2[B,U]+\mathscr{E}_4[B,U])}$ then average

MF *vs* BO spectral function



Quantum oscillations

freq. $p/8$



Dynamical Spin Structure Factor

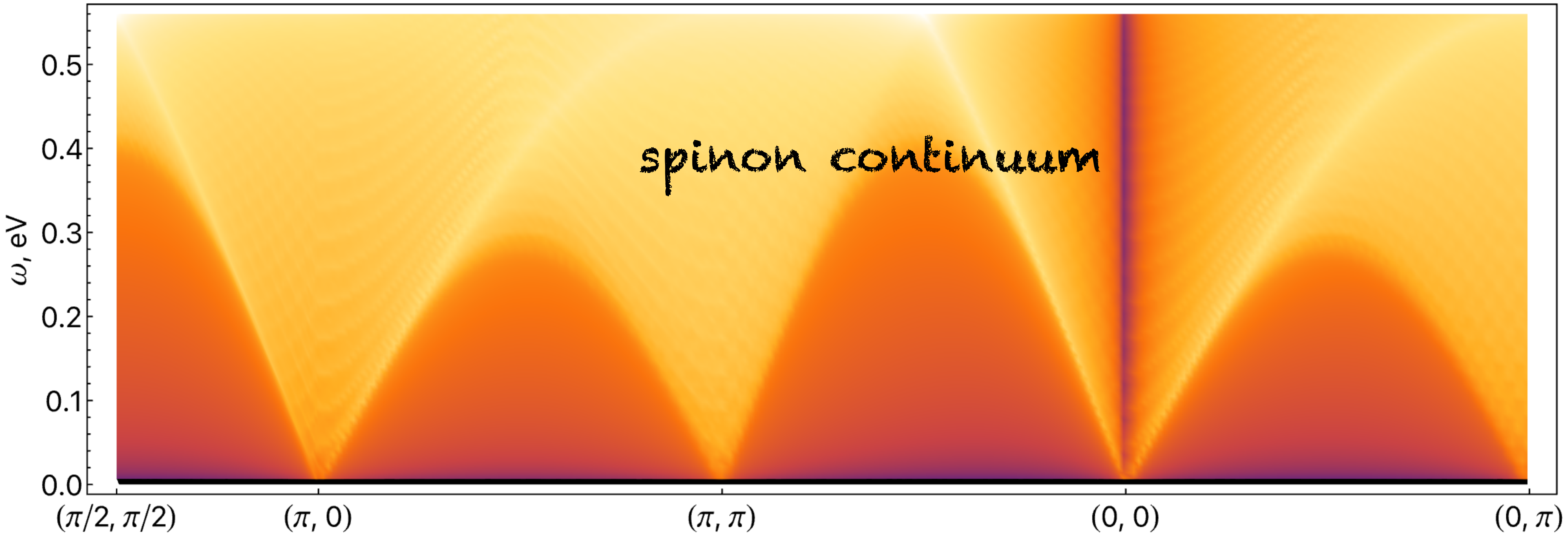
Nikolaenko, PMB, Sachdev, arXiv:2511.03792 (2025)

π-flux SL

$$\mathscr{H} = w \sum_{\langle i,j \rangle} (1+ \quad\quad) \, \psi_i^\dagger e_{ij} \psi_j$$

bare π-flux susc.

$$\chi_{\text{spin}}(q,\omega) = \chi_0(q,\omega)$$



Dynamical Spin Structure Factor

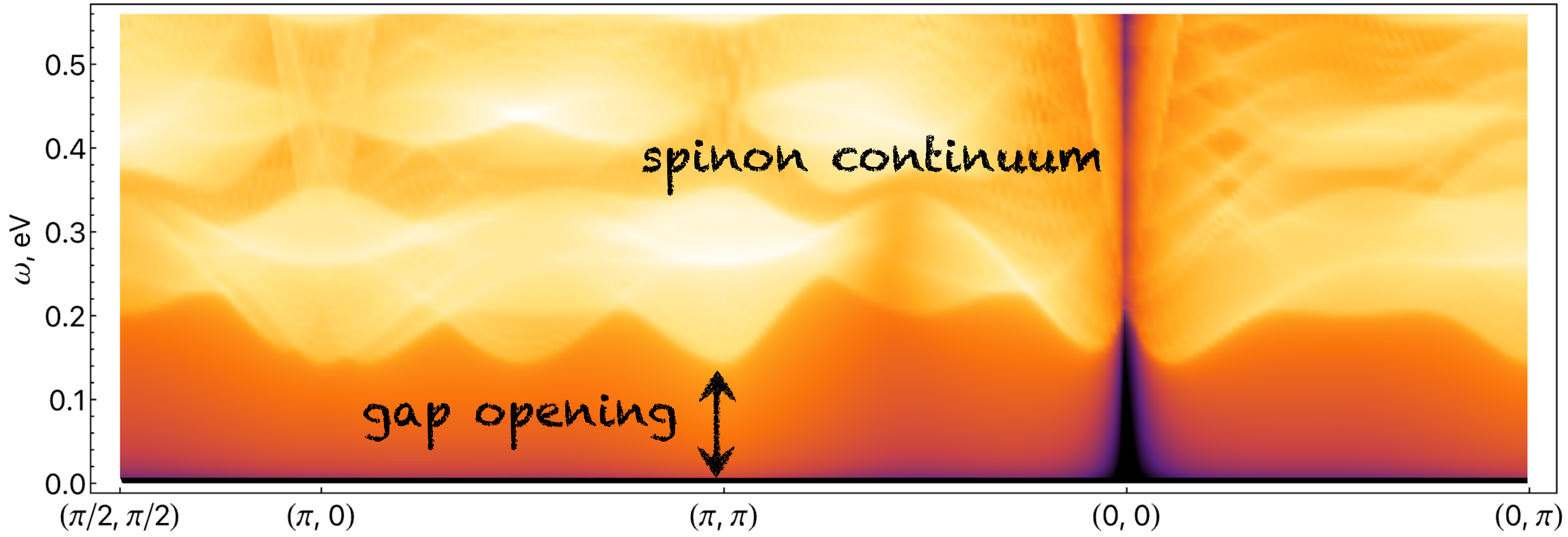
Nikolaenko, PMB, Sachdev, arXiv:2511.03792 (2025)

bare π-flux + CDW susc.

π-flux SL + period-4 CDW

$$\mathscr{H} = w \sum_{\langle i,j \rangle} (1+Q_{ij})\, \psi_i^\dagger e_{ij} \psi_j$$

$$\chi_{\text{spin}}(q,\omega) = \chi_0(q,\omega)$$



Dynamical Spin Structure Factor

Nikolaenko, PMB, Sachdev, arXiv:2511.03792 (2025)

π-flux SL + period-4 CDW

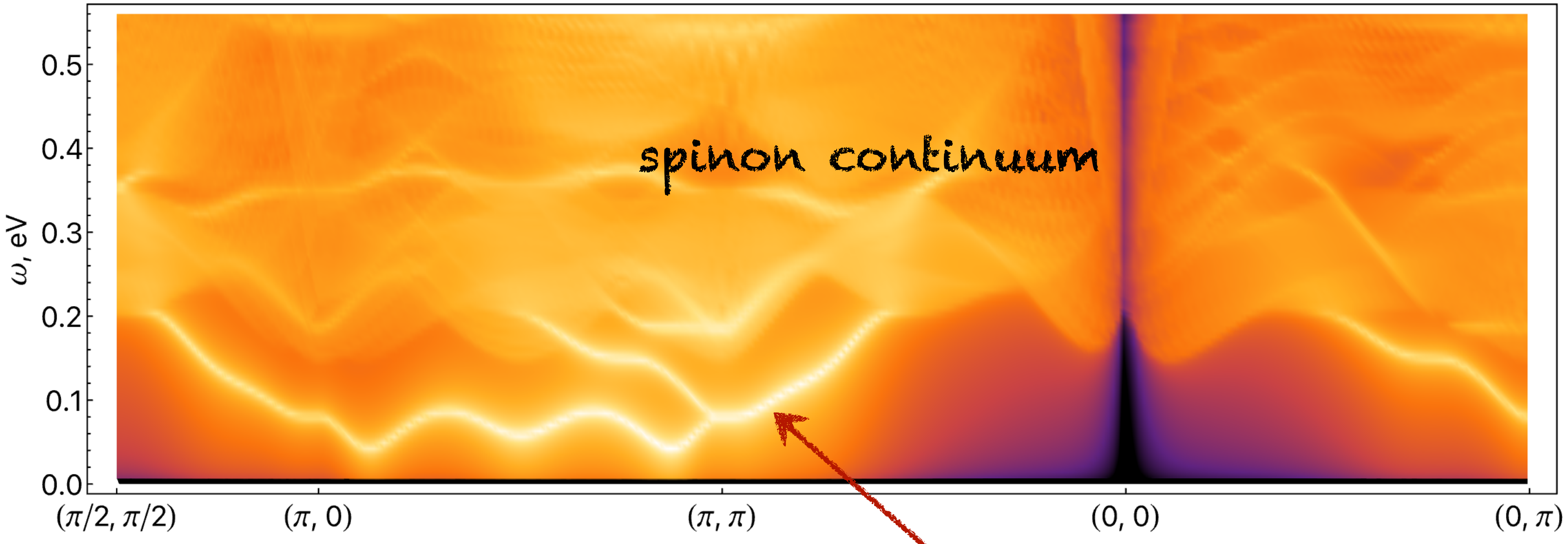
$$\mathscr{H} = w \sum_{\langle i,j \rangle} (1+Q_{ij})\, \psi_i^\dagger e_{ij} \psi_j + \sum_{ij} J_{ij}\, (1+Q_{ij})\, (f_i^\dagger \boldsymbol{\sigma} f_i) \cdot (f_j^\dagger \boldsymbol{\sigma} f_j)$$

bare π-flux + CDW susc.

$$\chi_{\rm spin}(q,\omega) = \frac{\chi_0(q,\omega)}{1 - J(q)\chi_0(q,\omega)}$$

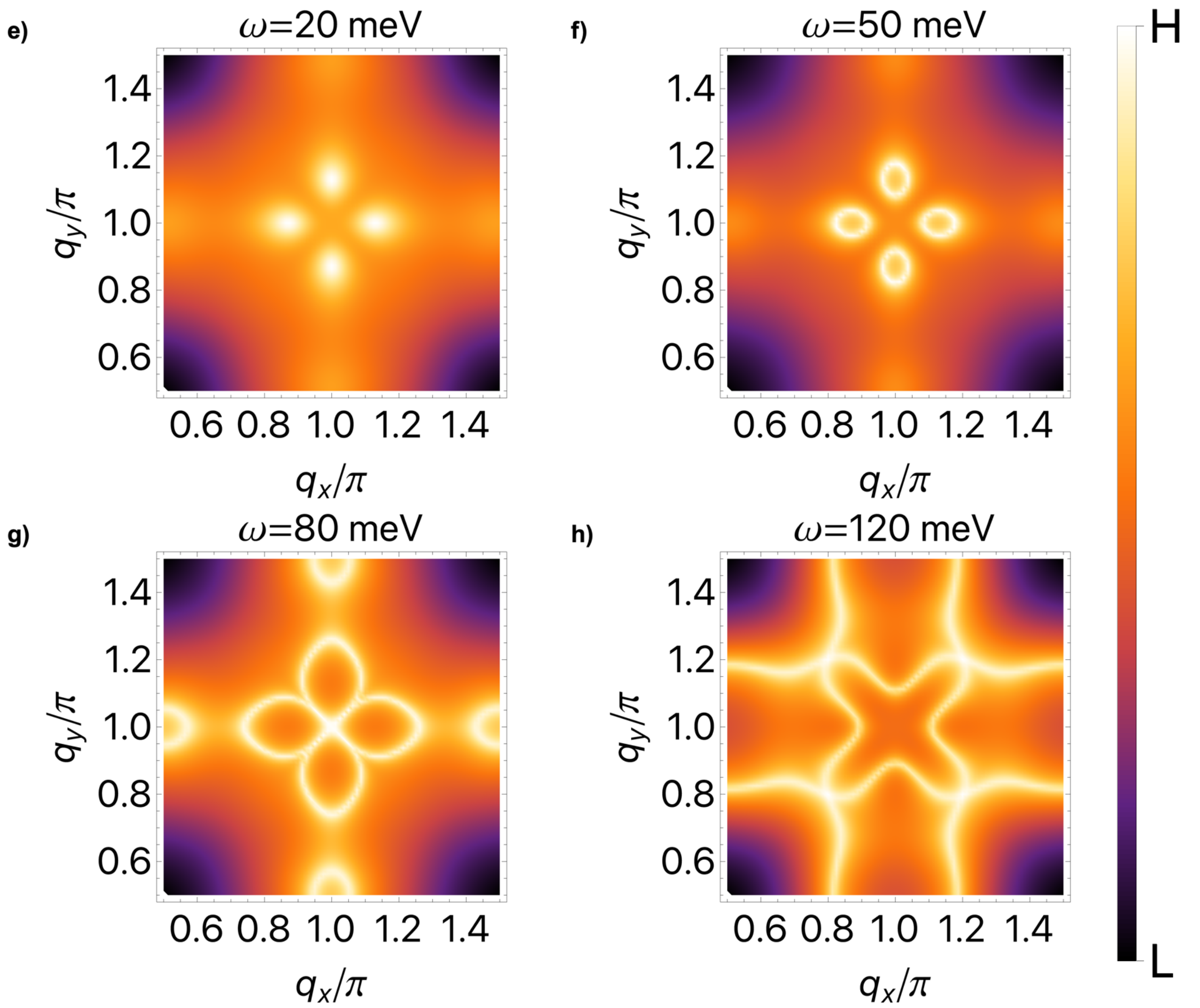
Willsher & Knolle, arXiv:2503.13831 (2025)

$$-{\rm Im}\chi_{\rm spin}(q,\omega)$$



S=1 2-spinon bound states

Hourglass spectrum



Dynamical Spin Structure Factor

Nikolaenko, PMB, Sachdev, arXiv:2511.03792 (2025)

π-flux SL + period-4 CDW

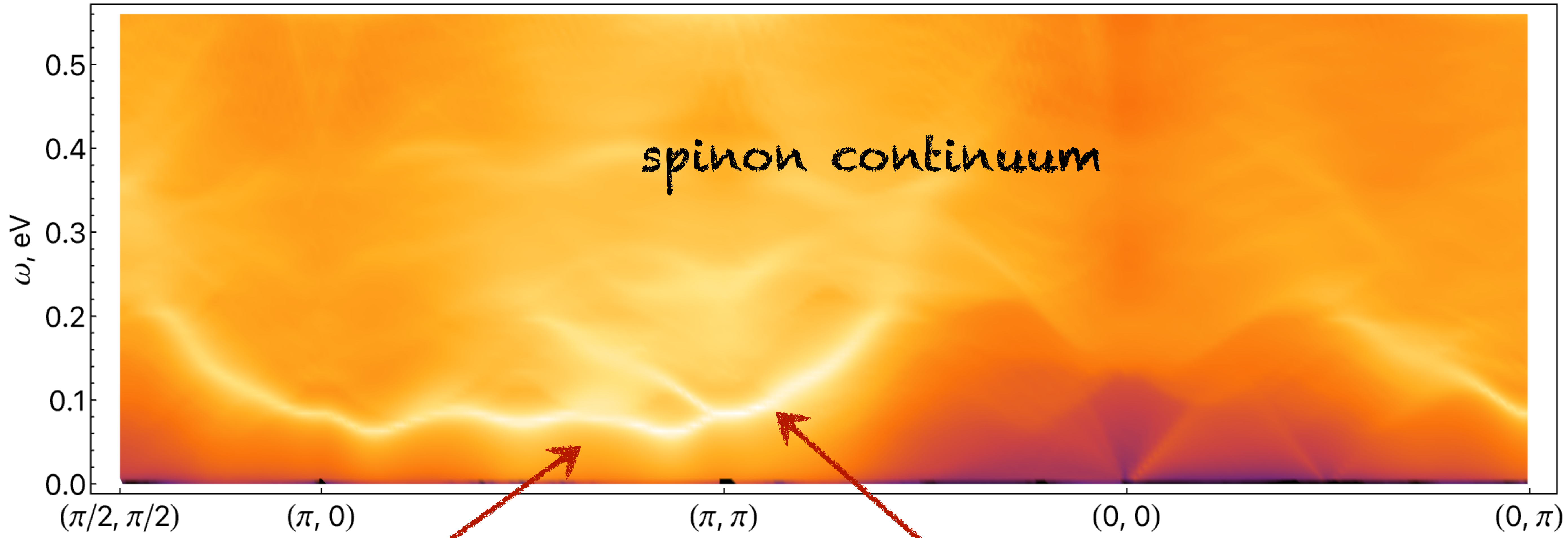
$$\mathscr{H} = w \sum_{\langle i,j \rangle} (1+Q_{ij})\, \psi_i^\dagger e_{ij} \psi_j + \sum_{ij} J_{ij} (1+Q_{ij})\, (f_i^\dagger \boldsymbol{\sigma} f_i) \cdot (f_j^\dagger \boldsymbol{\sigma} f_j) + \text{coupling to electrons}$$

bare π-flux + CDW + electrons susc.

$$\chi_{\rm spin}(q,\omega) = \frac{\chi_0(q,\omega)}{1 - J(q)\chi_0(q,\omega)}$$

Willsher & Knolle, arXiv:2503.13831 (2025)

$-\mathrm{Im}\chi_{\rm spin}(q,\omega)$

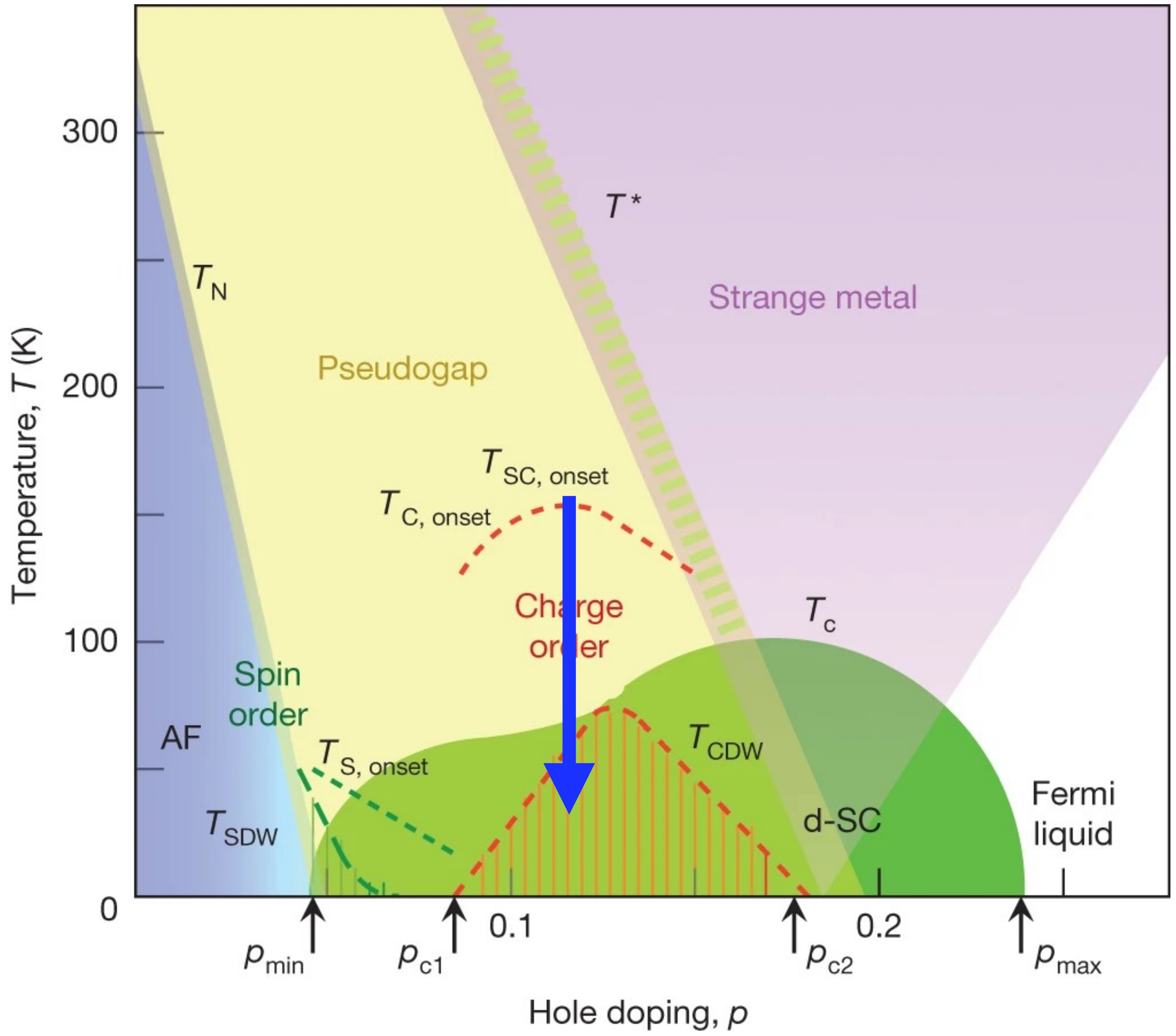


broadening of the bound state dispersions

S=1 2-spinon bound states

Low Temperature Measurements

Low Temperature Measurements



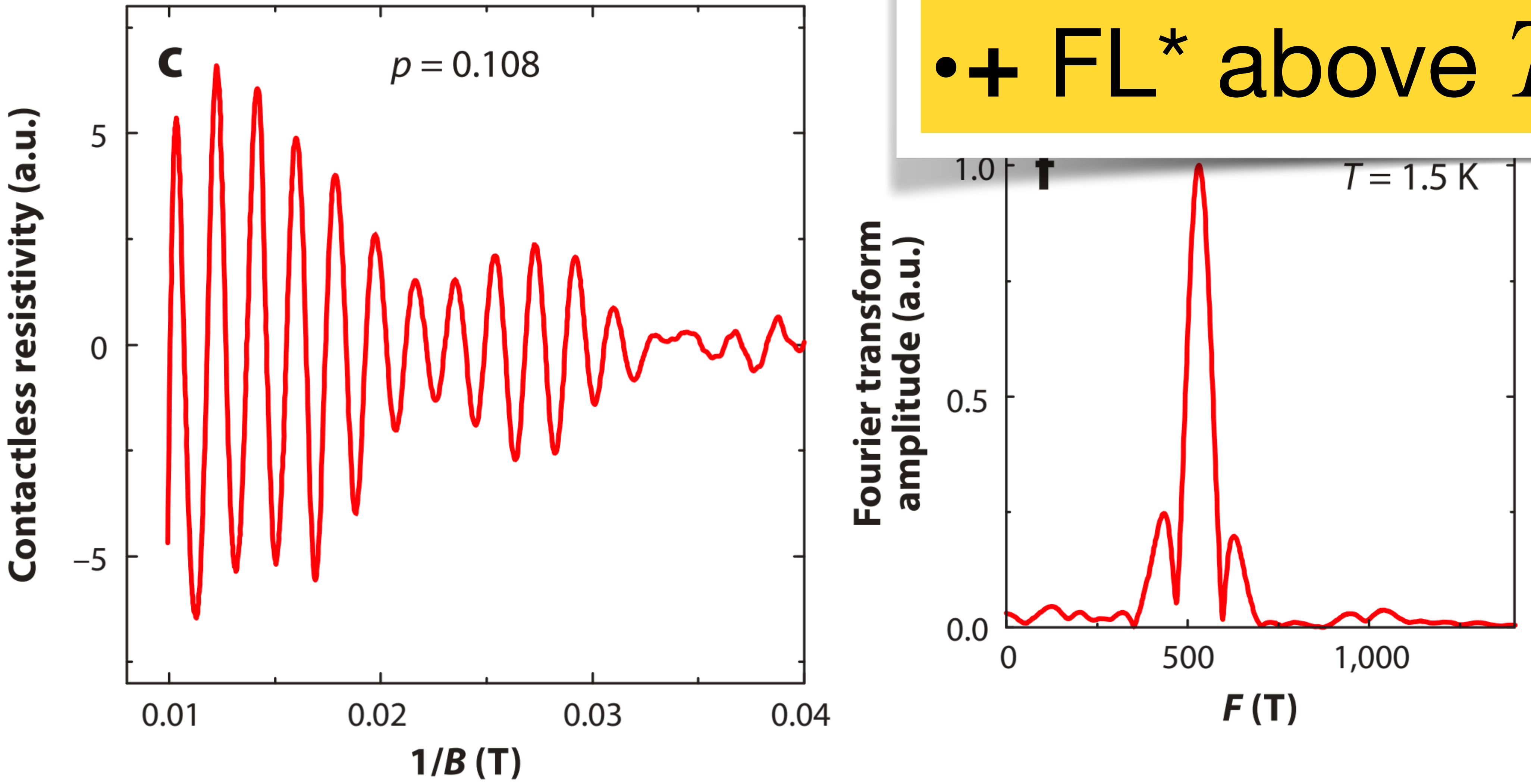
Keimer *et al.*, Nature **518**, 179 (2015)

Low Temperature Measurements

Quantum Oscillations

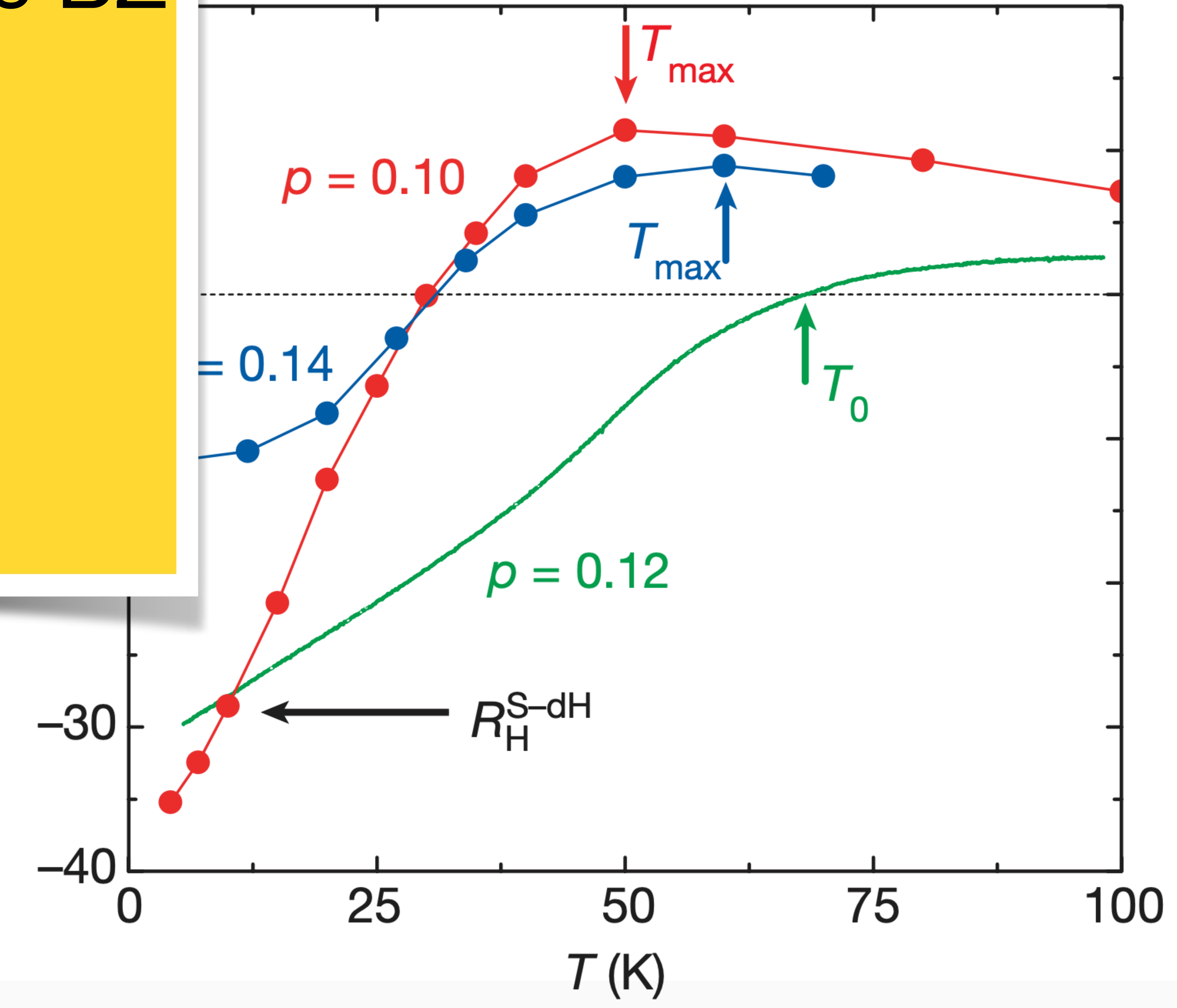
- oscillation frequency (in T
  section $f_H = \hbar A_\perp/(2\pi e)$
- underdoped regime: sing
  frequency corresponding
  area

- Fermi Surface ~2% of the BZ
- Electron Pockets
- CDW order
- + FL* above T_{CDW}



Sebastian & Proust, Ann. Rev. Cond. Matt. Phys. **6**, 411 (2015)

Hall Resistance



LeBoeuf, *et al.*, Nature **450**, 533 (2007)

CDW* *vs* CDW

CDW*

nonuniform density + deconfined SU(2) gauge field

- add modulated potential $V\sum_i \left[\cos(Qx)+\cos(Qy)\right] c_i^\dagger c_i$ to the physical electrons

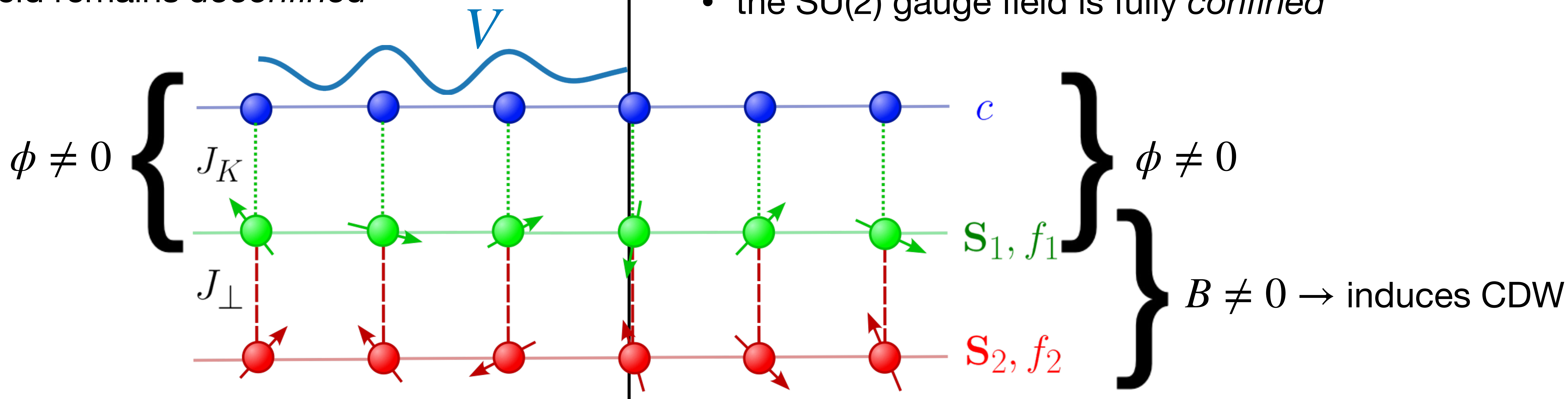
- the SU(2) gauge field remains *deconfined*

CDW

nonuniform density + confined SU(2) gauge field

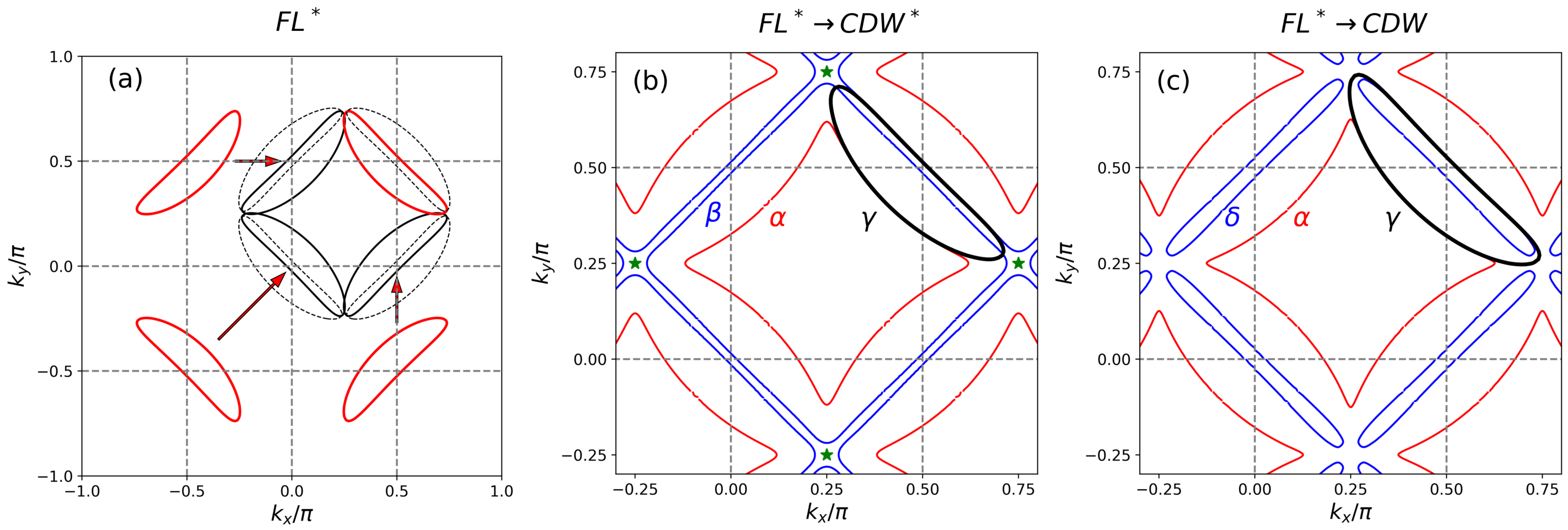
- condensation of B_i such that
  $\rho_i = B_i^\dagger B_i = |b|^2\left(1-[(-1)^x+(-1)^y]/2\right)\cos^2(qx)\cos^2(qy),$
  $J_{ij}=\Delta_{ij}=0$

- the SU(2) gauge field is fully *confined*



Fermi surfaces in the CDW phase

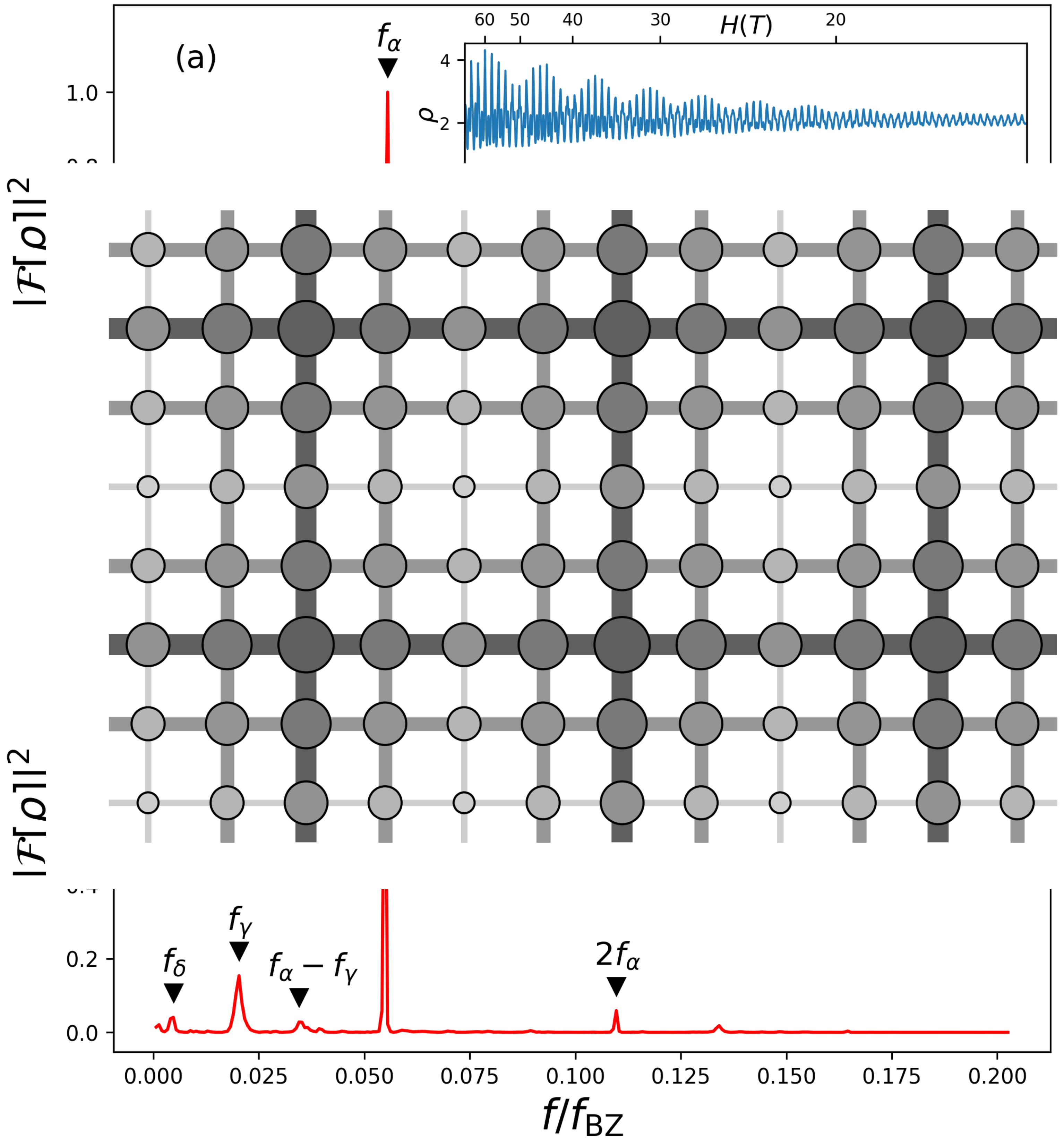
PMB, Christos, Sachdev, PNAS 121 (50), e2418633121 (2024)



- CDW* gives two electron pockets, one made by the physical electrons, one made by the f_1 -spinons
- the condensation of B_i hybridizes the larger eletron pocket with its shifted copies and gives 2 small, elongated hole pockets

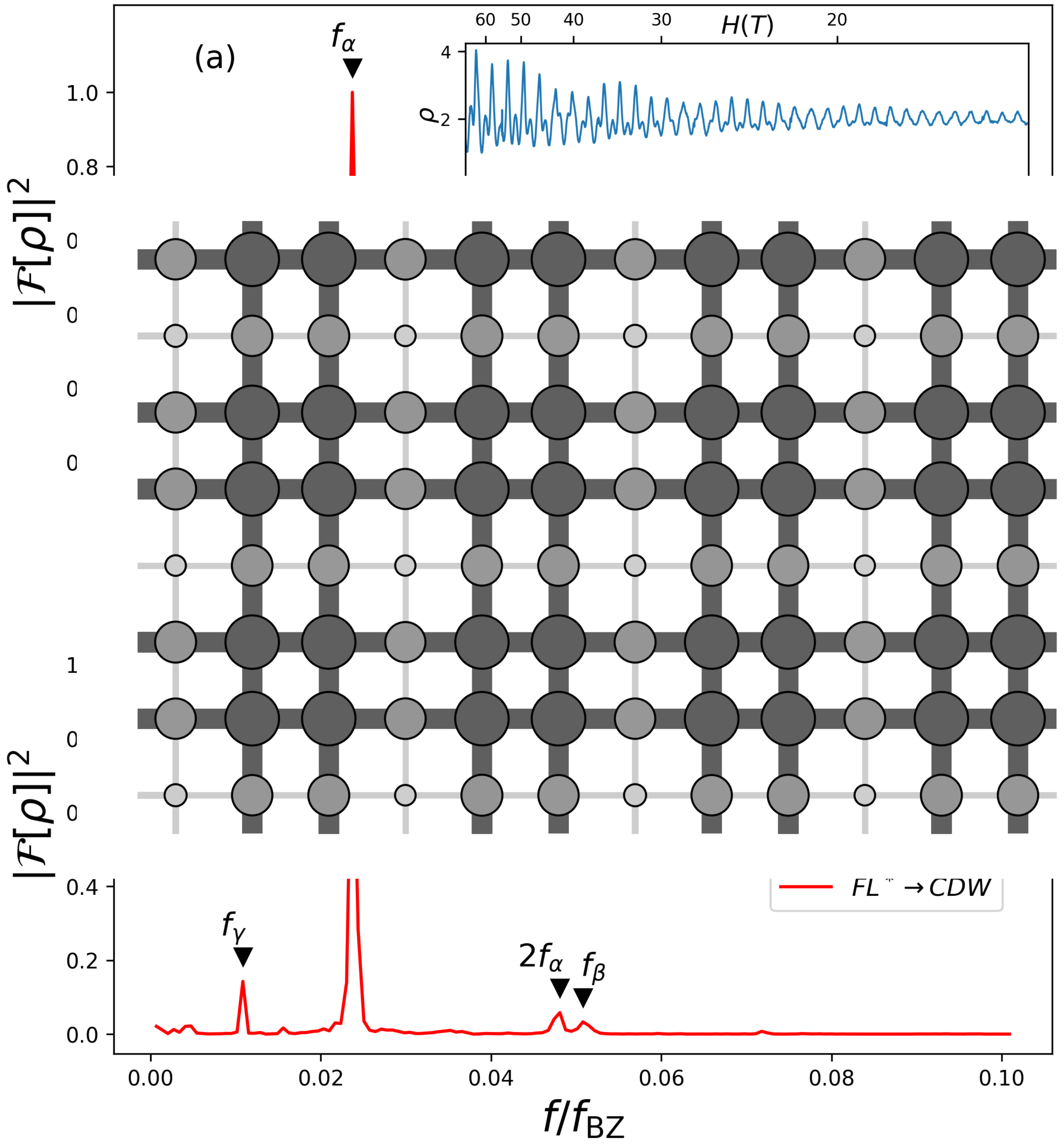
Quantum Oscillations in the DOS

Period-4 b-CDW*/CDW



$$f_\alpha \sim 1500\mathrm{T},\ \ f_\beta \sim 3300\mathrm{T}$$

Period-6 b-CDW*/CDW



$$f_\alpha \sim 650\mathrm{T},\ \ f_\beta \sim 1400\mathrm{T}$$

- the CDW* phase has a significant peak at the β-pocket frequency
- the CDW phase has a single significant contribution at the α-pocket frequency
- the period-6 CDW has oscillations frequencies close to the experimental values of 500 T to 800 T.

Excess Specific Heat

PHYSICAL REVIEW B **102**, 014506 (2020)

High density of states in the pseudogap phase of the cuprate superconductor $HgBa_2CuO_{4+\delta}$ from low-temperature normal-state specific heat

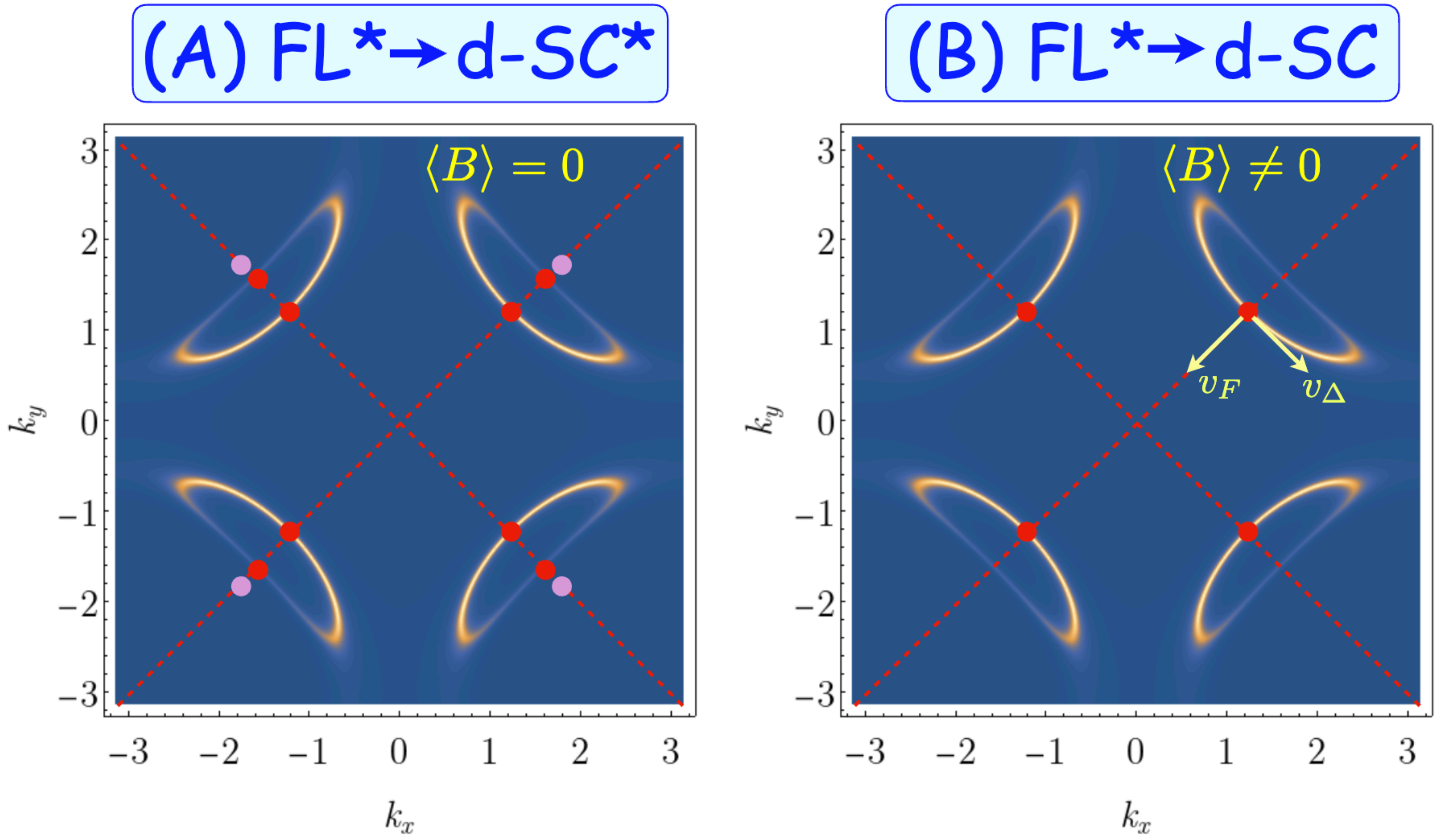
C. Girod,[1,2] A. Legros,[2,3] A. Forget,[3] D. Colson,[3] C. Marcenat,[4] A. Demuer,[5] D. LeBoeuf,[5] L. Taillefer,[2,6,*] and T. Klein[1,†]

Second, the high γ value implies that the Fermi surface must consist of more than the single electronlike pocket detected by quantum oscillations in $HgBa_2CuO_{4+\delta}$ at $p \simeq 0.09$, whose effective mass $m^\star = 2.7m_0$ yields only $\gamma = 4.0\ \mathrm{mJ/K^2\ mol}$. This missing mass imposes a revision of the current scenario for how pseudogap and charge order, respectively, transform and reconstruct the Fermi surface of cuprates.

The elongated hole pockets might account for the excess specific heat

d-SC phase

Christos, Sachdev, NPQ Quantum Materials 9, 4 (2024)



Spin liquid nodes hybridize with backsides for FL*→ *d*-SC

Summary

- FL* is a good candidate '**mother state**' for the low-temperature physics of **underdoped cuprates**
- Ancilla Layer Model has a mean-field **FL* phase**
- FL* can eventually **confine** and form **Néel/VBS** or can be Higgsed down to form a ***d*-wave superconductor/ CDW**
- FL* can explain the presence of **Fermi arcs** in photoemission experiments and of **small Fermi surfaces** in QO experiments
- Dynamical Spin structure factor displays spinon bound states forming an "**hourglass**" **spectrum**
- Spin liquid is crucial to obtain the **FS topology** seen in QO experiments in the **CDW phase** and 4 nodes in the **d-SC phase**

Review article

PMB, Christos, Nikolaenko, Patel, Sachdev, arXiv:2508.20164 (2025)

Critical quantum liquids and the cuprate high temperature superconductors

Thank you!