Happy Birthday Louis!

Happy Birthday Louis!

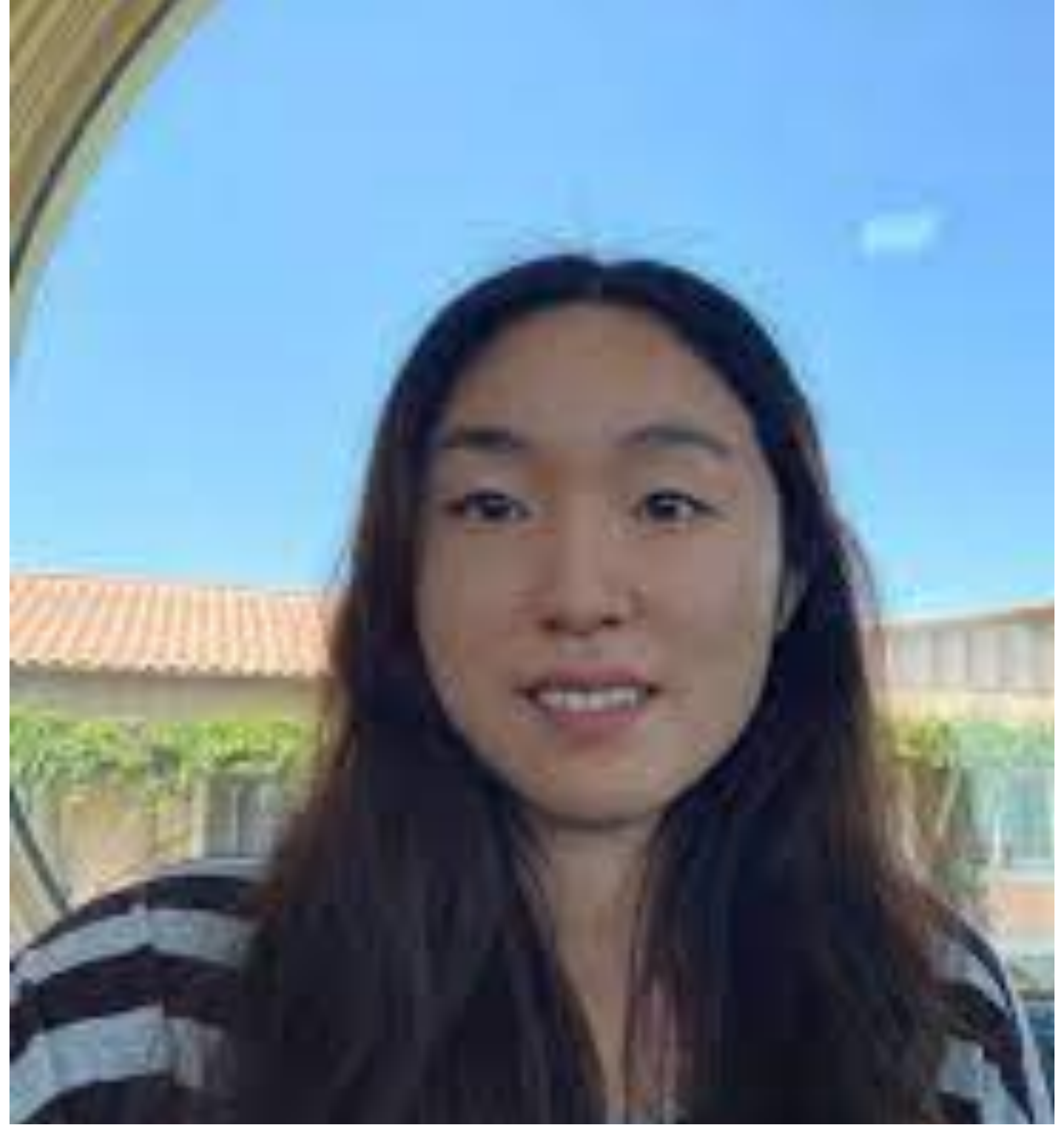
Decoding the phases of the cuprates using fractionalization and spinons

Key Advances in Quantum Materials
Jouvence, Canada
October 15, 2024
Subir Sachdev

Maine Christos, Zhu-Xi Luo, Henry Shackleton, Ya-Hui Zhang, Mathias Scheurer, S. S., *PNAS* **120**, e2302701120 (2023)
A. Nikolaenko, J. v. Milczewski, D. G. Joshi, S.S., PRB **108**, 045123 (2023)
Maine Christos and S.S., *npj Quantum Materials* **9**, 4 (2024)
M. Christos, H. Shackleton, S. S., and Zhu-Xi Luo, PRR **6**, 033018 (2024)
Pietro M. Bonetti, Maine Christos, S.S. (BCS), arXiv: 2405.08817
Jia-Xin Zhang, S. Sachdev, arXiv:2406.12964

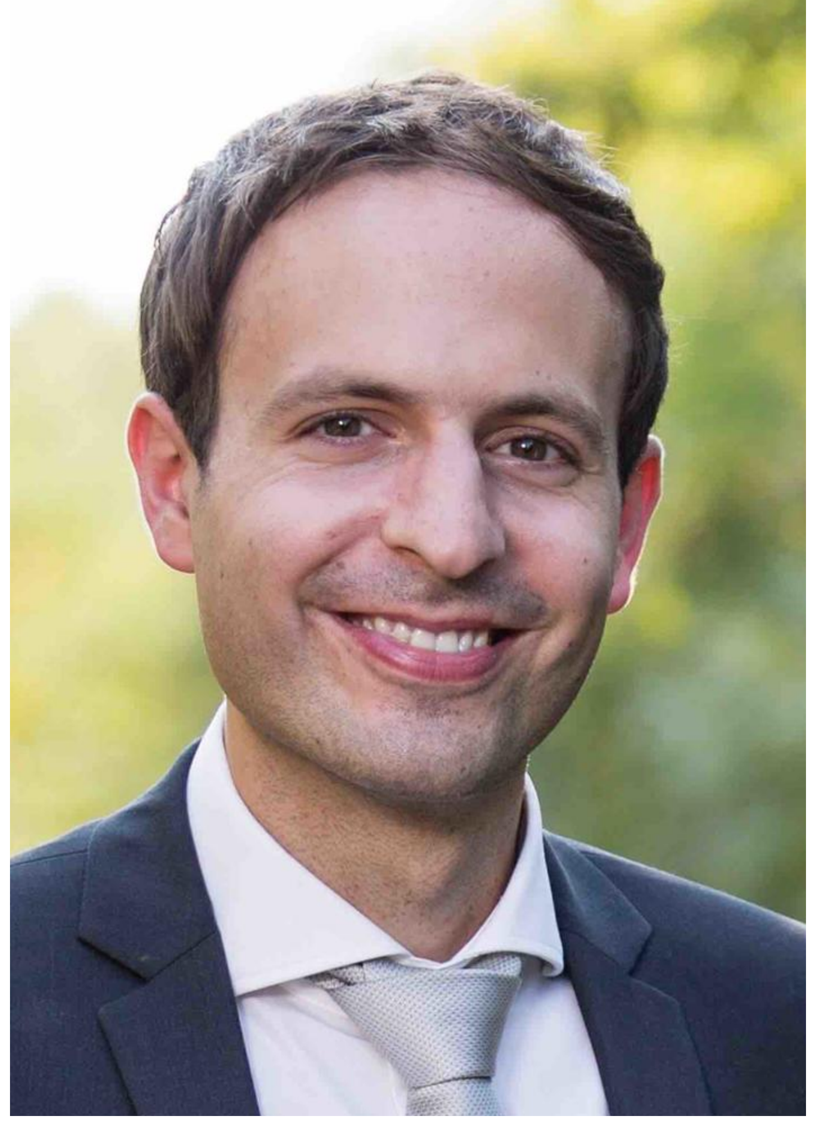
PHYSICS
VE RI TAS
HARVARD

Maine Christos



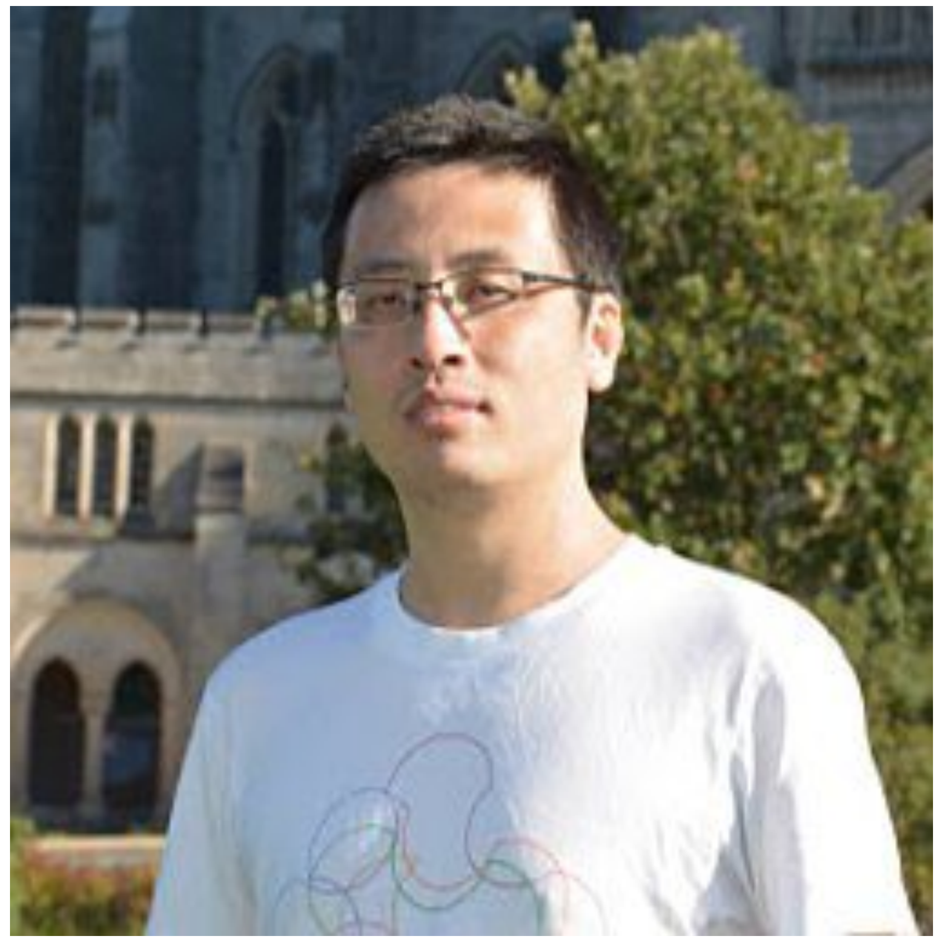
Zhu-Xi Luo

Maria Tikhanovskaya



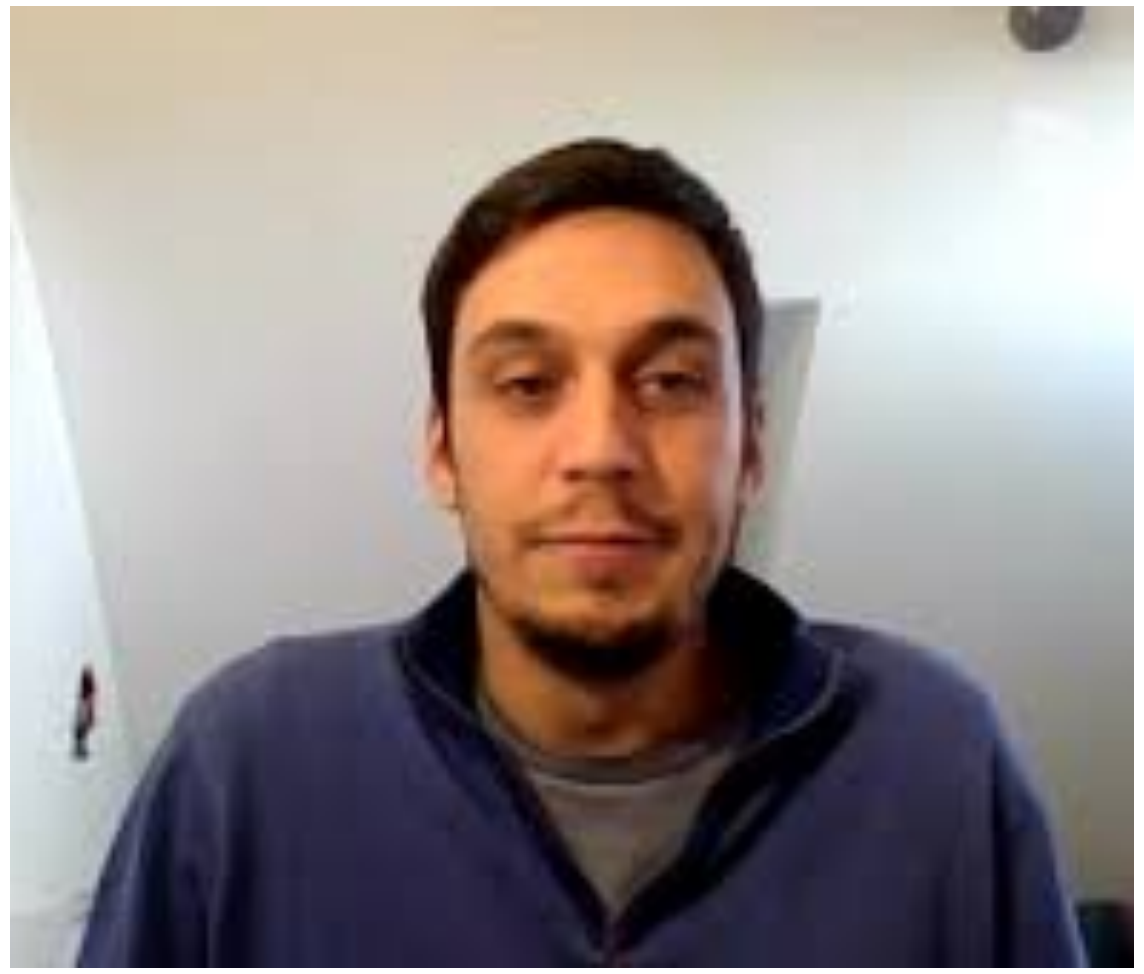
Mathias Scheurer

Jia-Xin Zhang



Ya-Hui Zhang

Alexander Nikolaenko

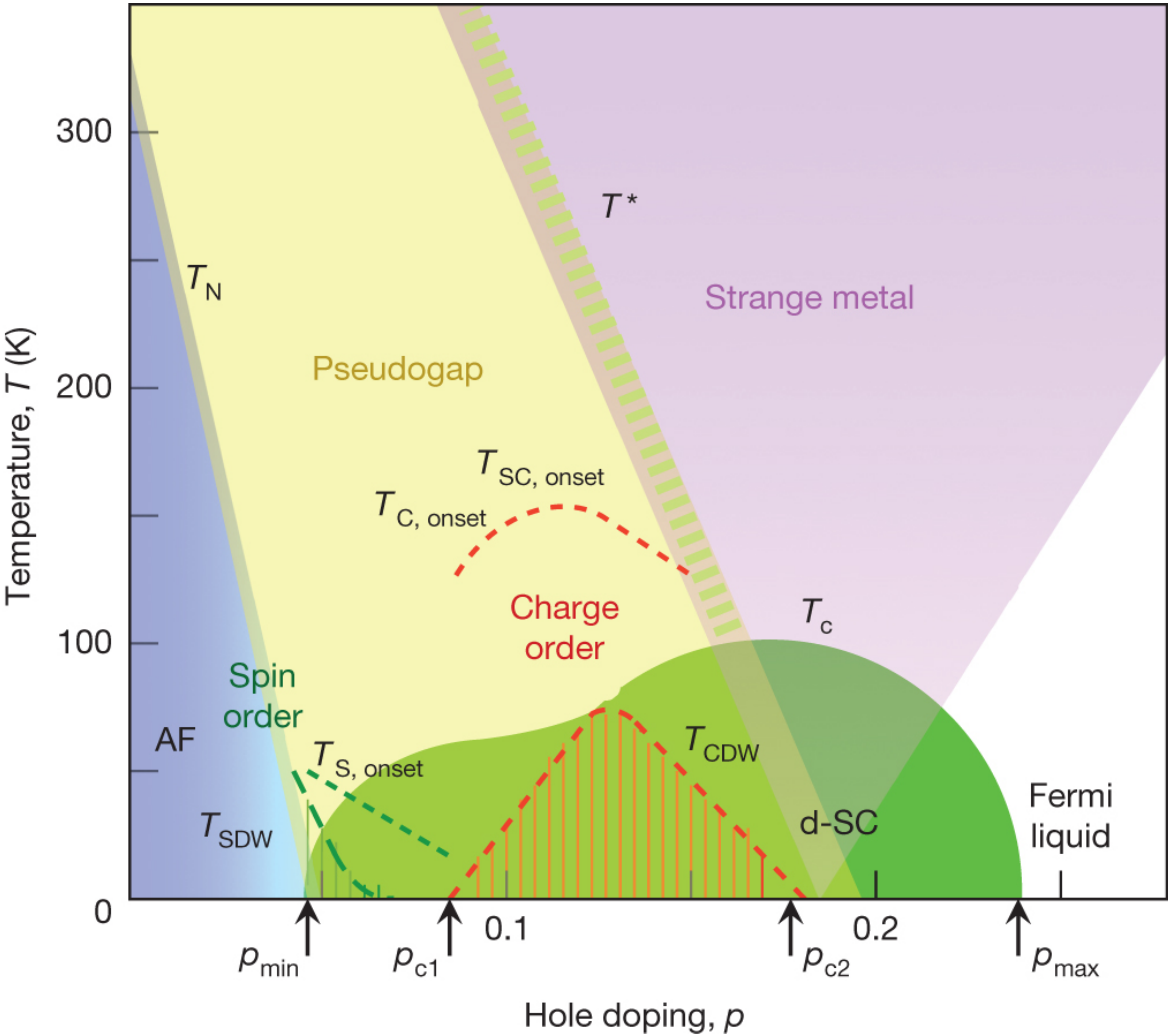


Pietro Bonetti

Henry Shackleton

Darshan Joshi

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



Pseudogap puzzles:

A. Photoemission: Fermi arcs
B. RIXS: Intense paramagnons
C. Quantum oscillations
D. Velocities of Bogoliubov quasiparticles in the d-wave superconductor

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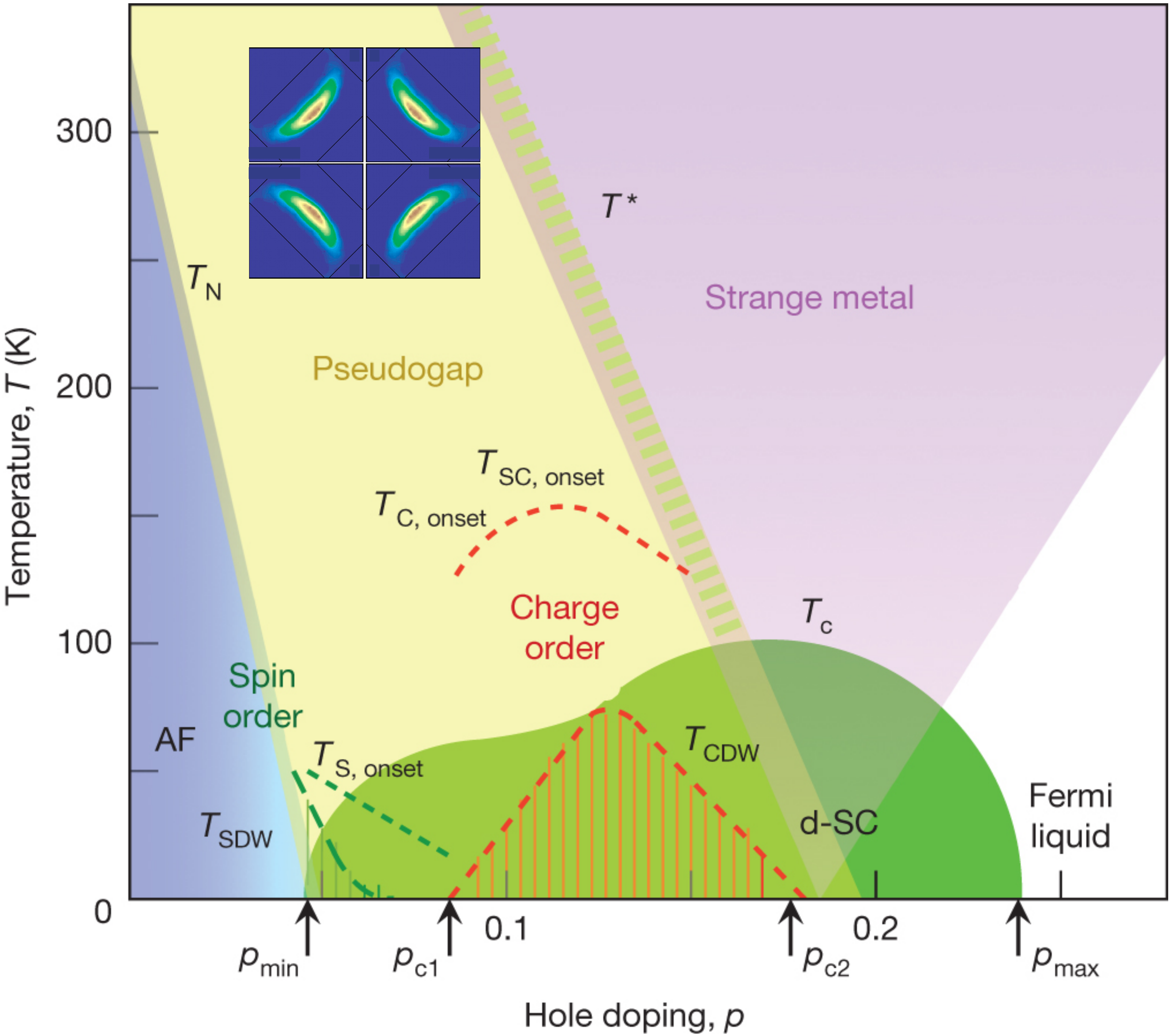
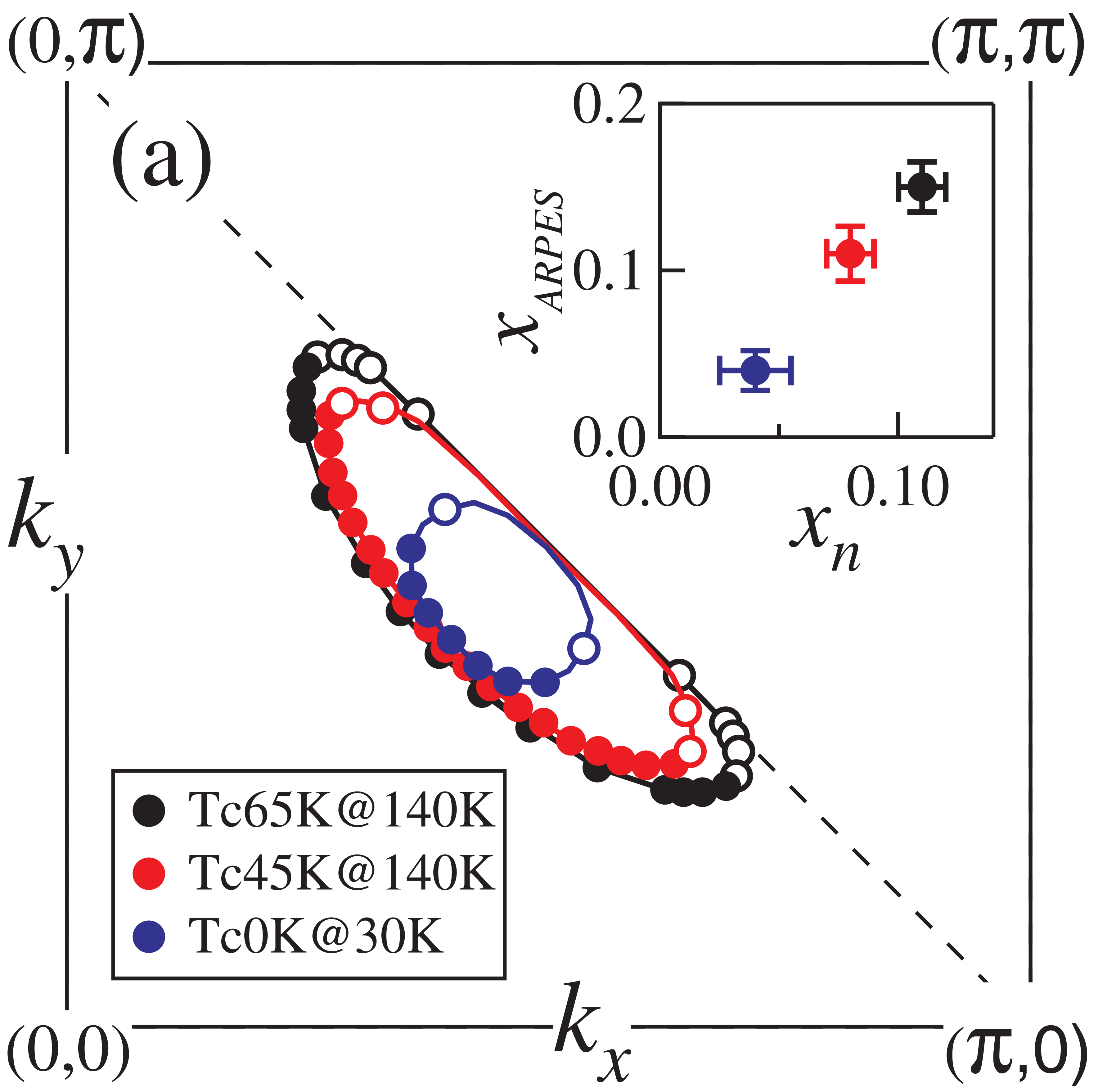
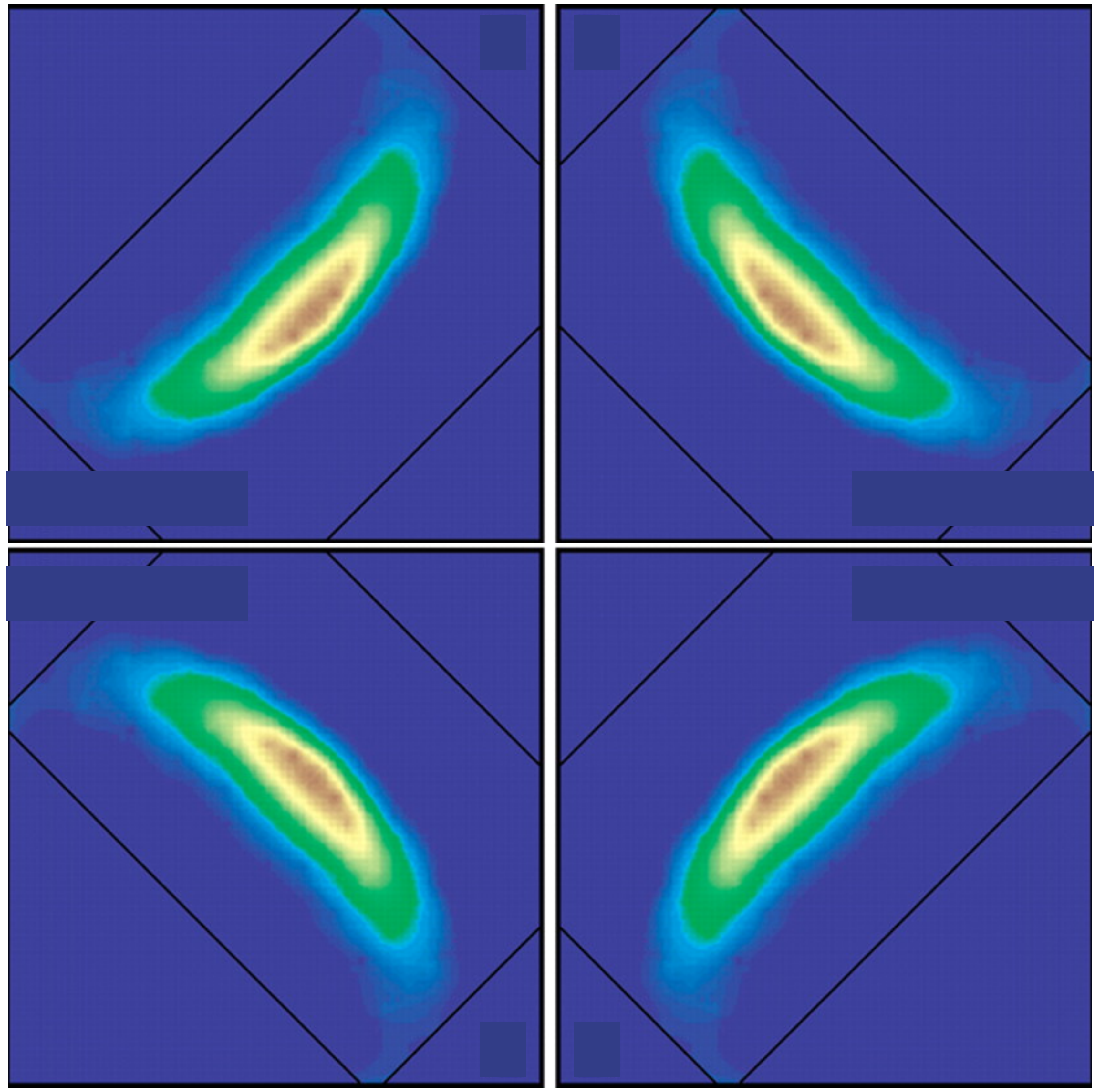


Pseudogap metal with "Fermi arcs"

Photoemission expts at small p



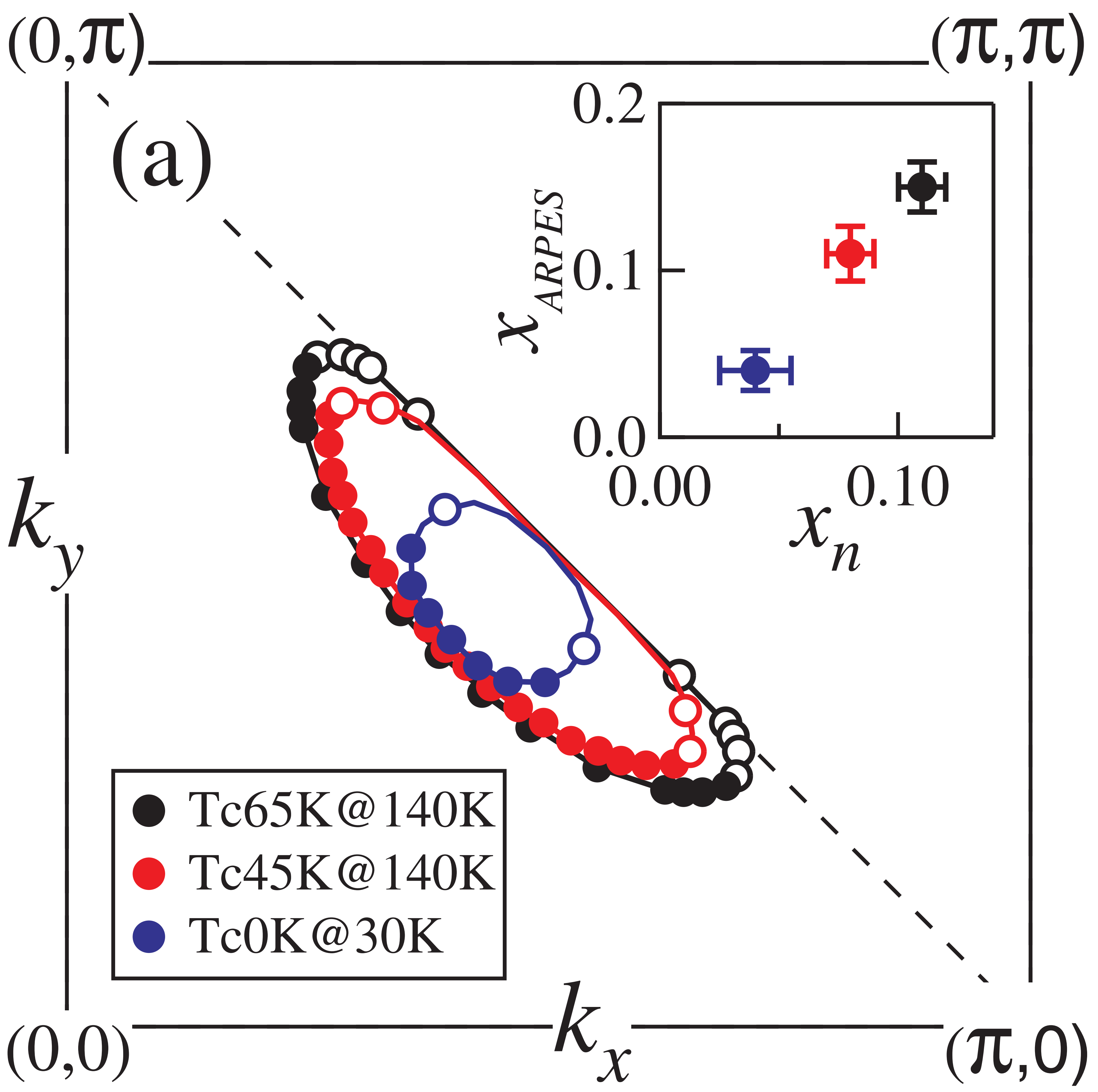
Reconstructed Fermi Surface of Underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ Cuprate Superconductors, H.-B. Yang, J. D. Rameau, Z.-H. Pan, G. D. Gu, P. D. Johnson, H. Claus, D. G. Hinks, and T. E. Kidd, PRL **107**, 047003 (2011).



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

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)

Photoemission expts at small p



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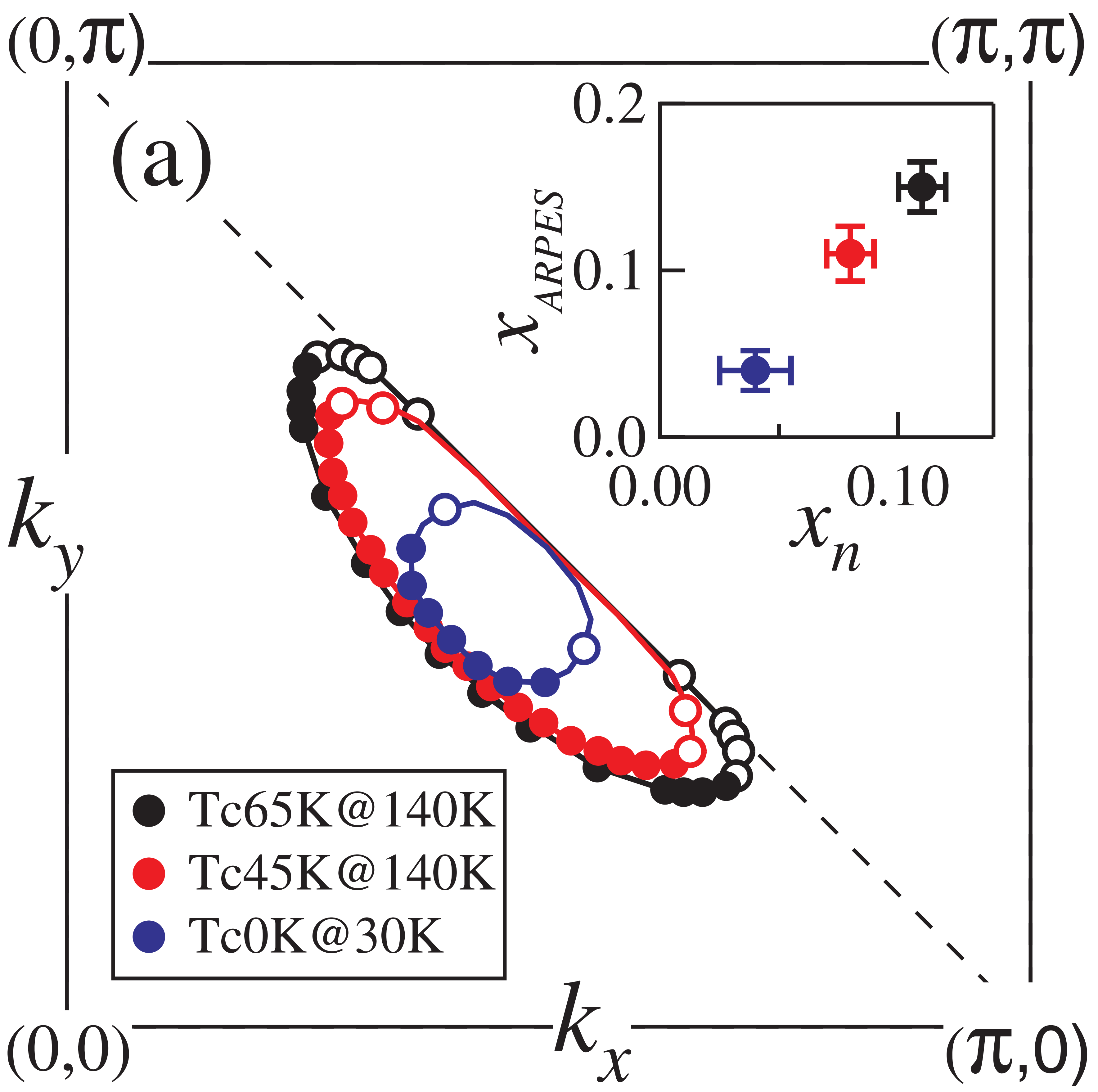
Non-Luttinger volume Fermi surfaces from various self-consistent Green's function approaches.

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).
N. Wagner….A. Georges, G. Sangiovanni, *Nature Communication* **14**, 7531 (2023)
Jinchao Zhao, Gabriele La Nave, Philip Phillips, *Phys. Rev. B* **108**, 165135
Jing-Yu Zhao, Zheng-Yu Weng, arXiv:2309.11556

Photoemission expts at small p



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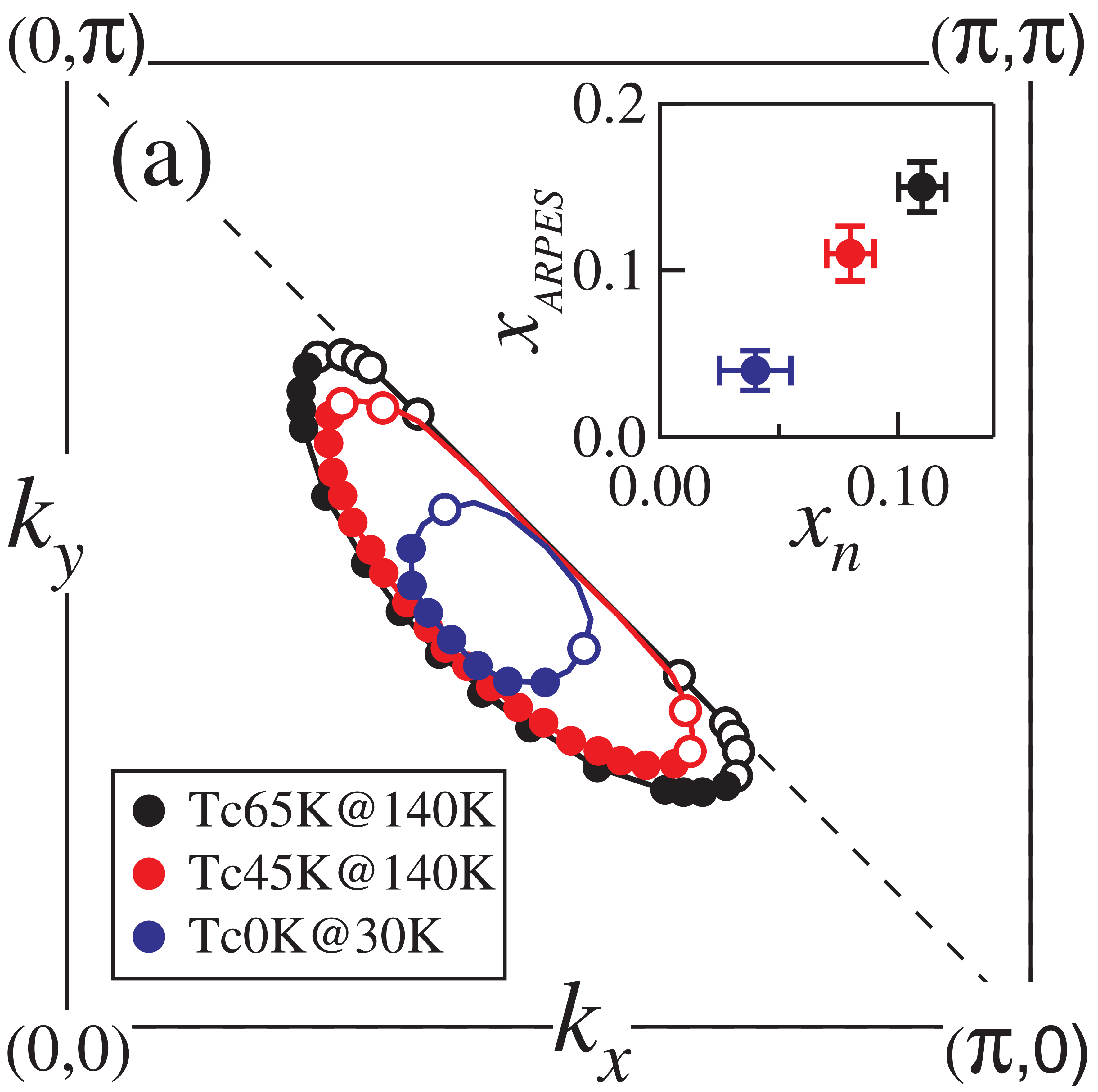
Non-Luttinger volume Fermi surfaces from various self-consistent Green's function approaches.

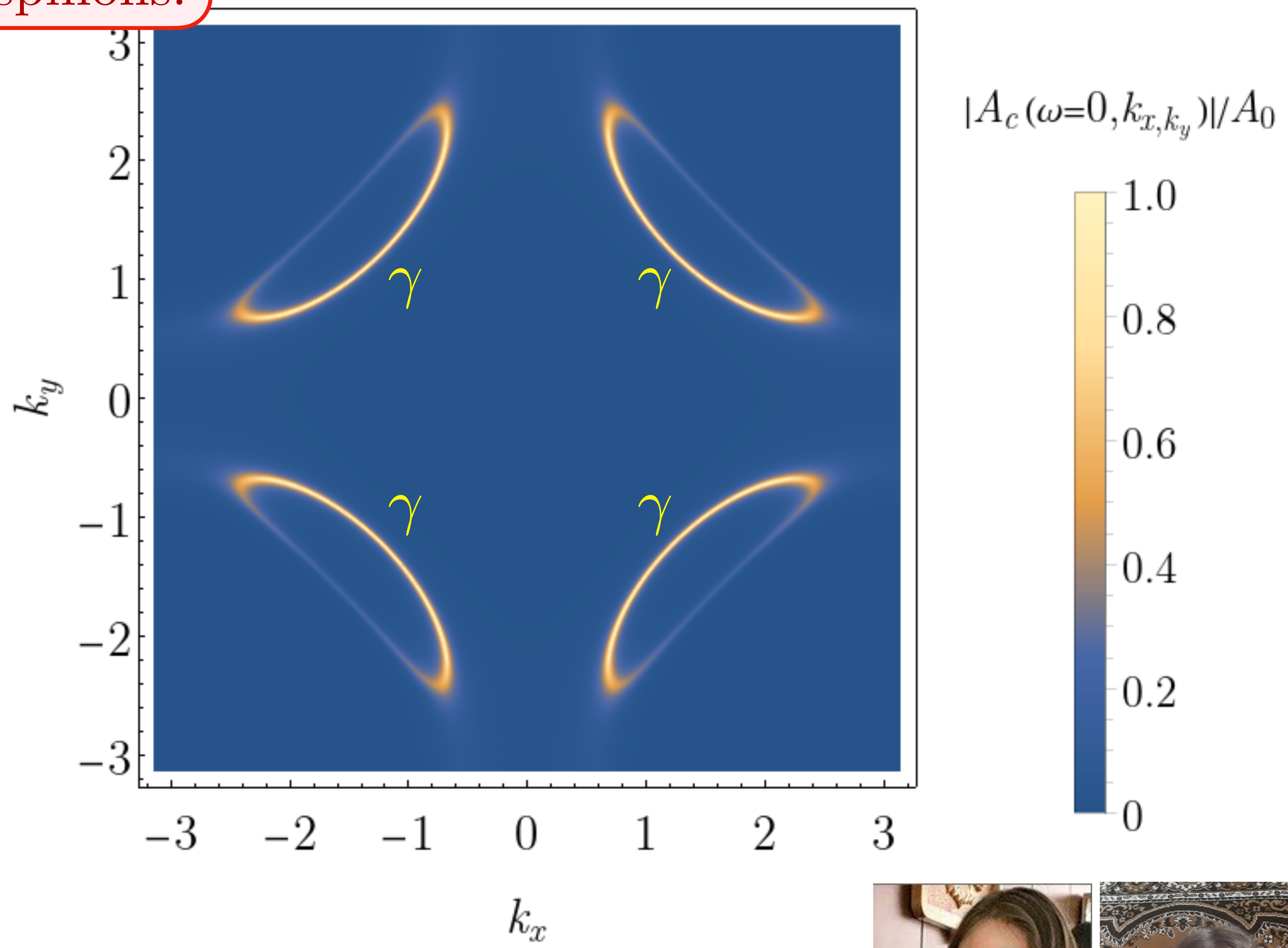
Oshikawa's topological Luttinger argument implies that non-Luttinger Fermi surfaces must be accompanied by fractionalized spinon excitations

T. Senthil, M. Vojta, S.S., PRB **69**, 035111 (2004)
R. K. Kaul, A. Kolezhuk, M. Levin, S. S., T. Senthil, PRB **75** , 235122 (2007)
Y. Qi, S. S., PRB **81**, 115129 (2010)

Ancilla theory of pseudogap metal: FL*— electrons hybridized by a half-filled band of fermions (f_1), and exchange coupled to a spin liquid layer with spinons.

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





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$$H_{\rm mf} = -\sum_{i,j} t_{ij} c^\dagger_{i\sigma} c_{j\sigma} - \sum_{i,j} t_{1,ij} f^\dagger_{1i\sigma} f_{1j\sigma} - \sum_i \Phi \left(c^\dagger_{i\sigma} f_{1i\sigma} + f^\dagger_{1i\sigma} c_{i\sigma} \right)$$

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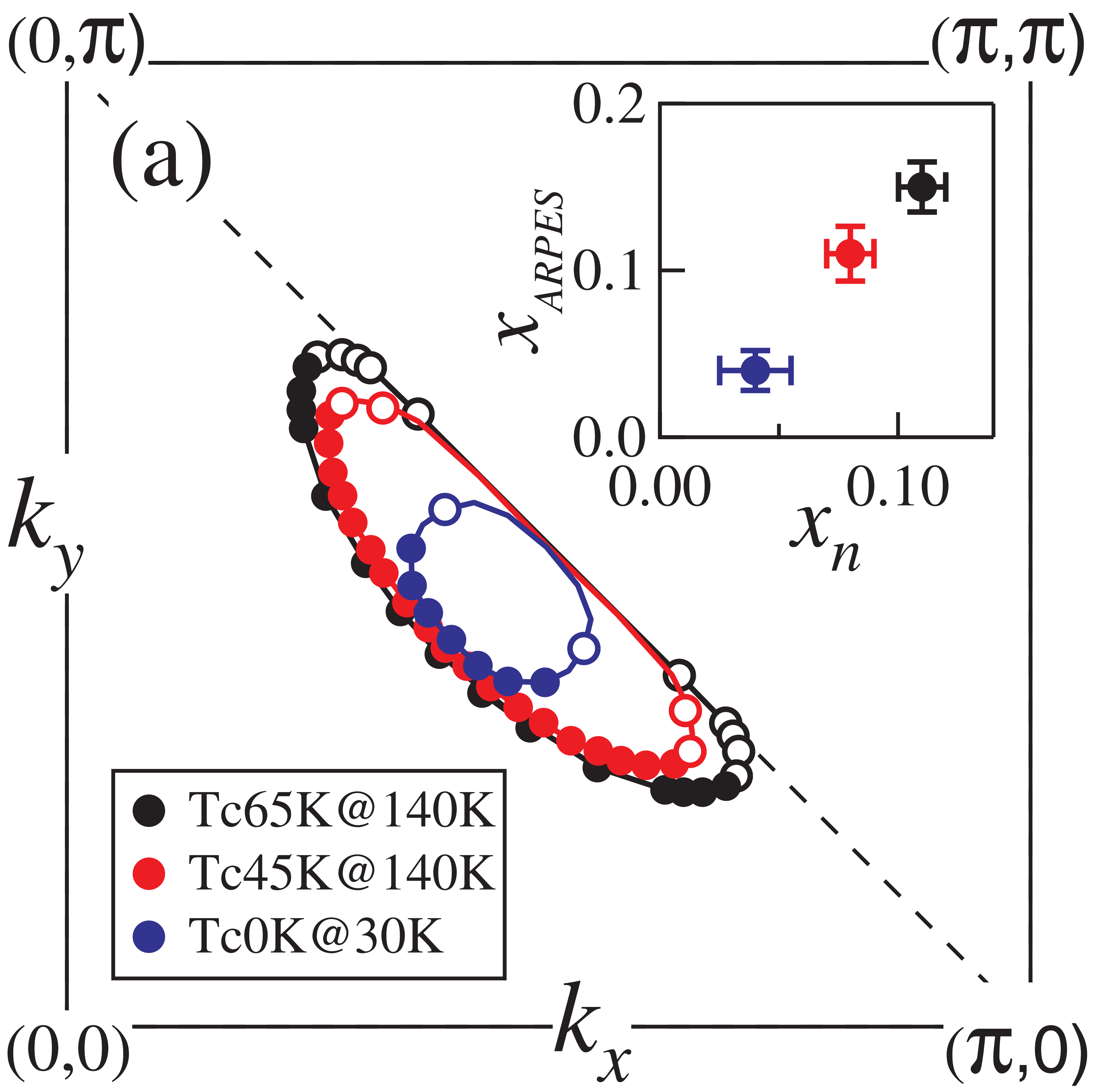

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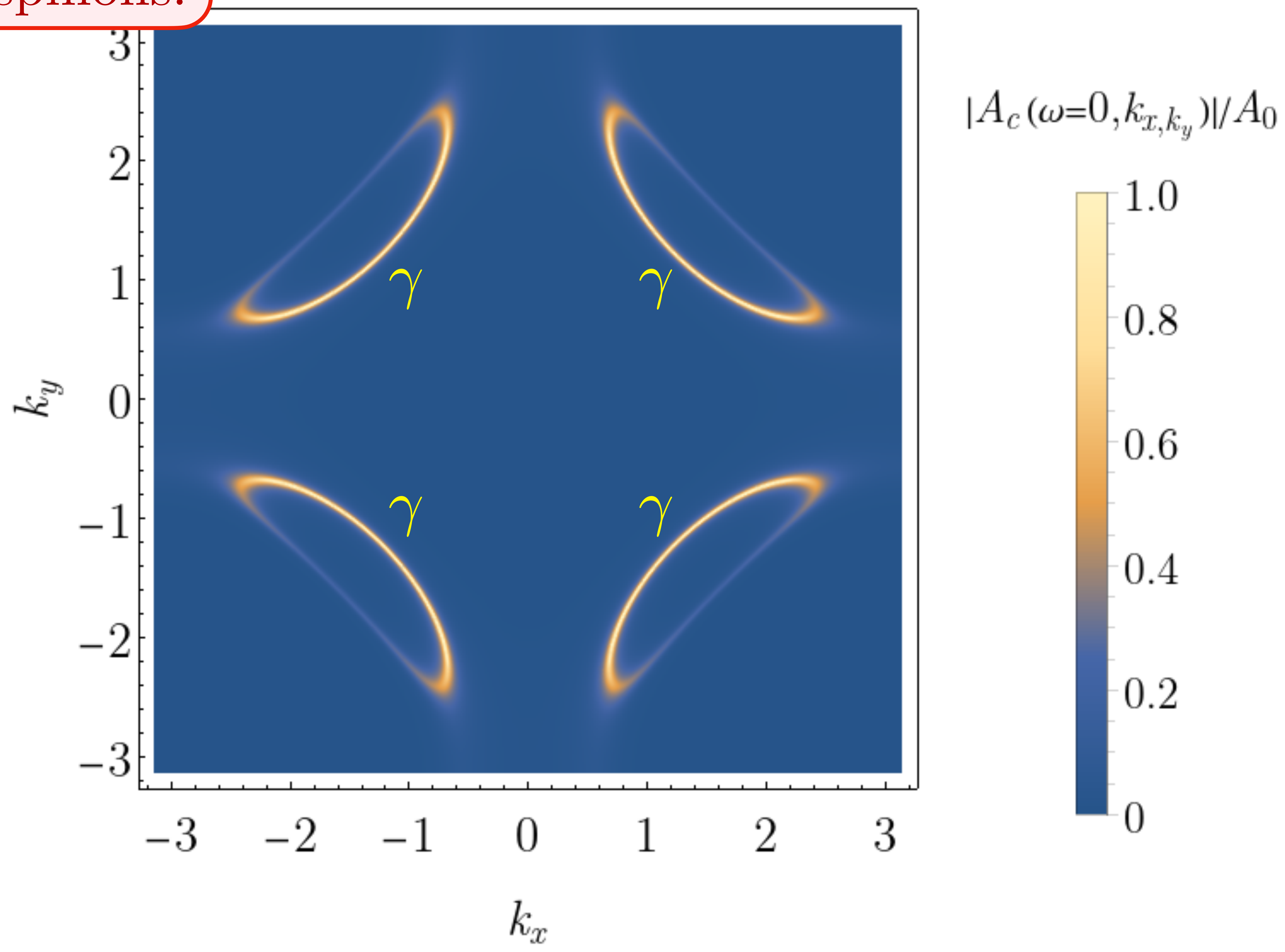


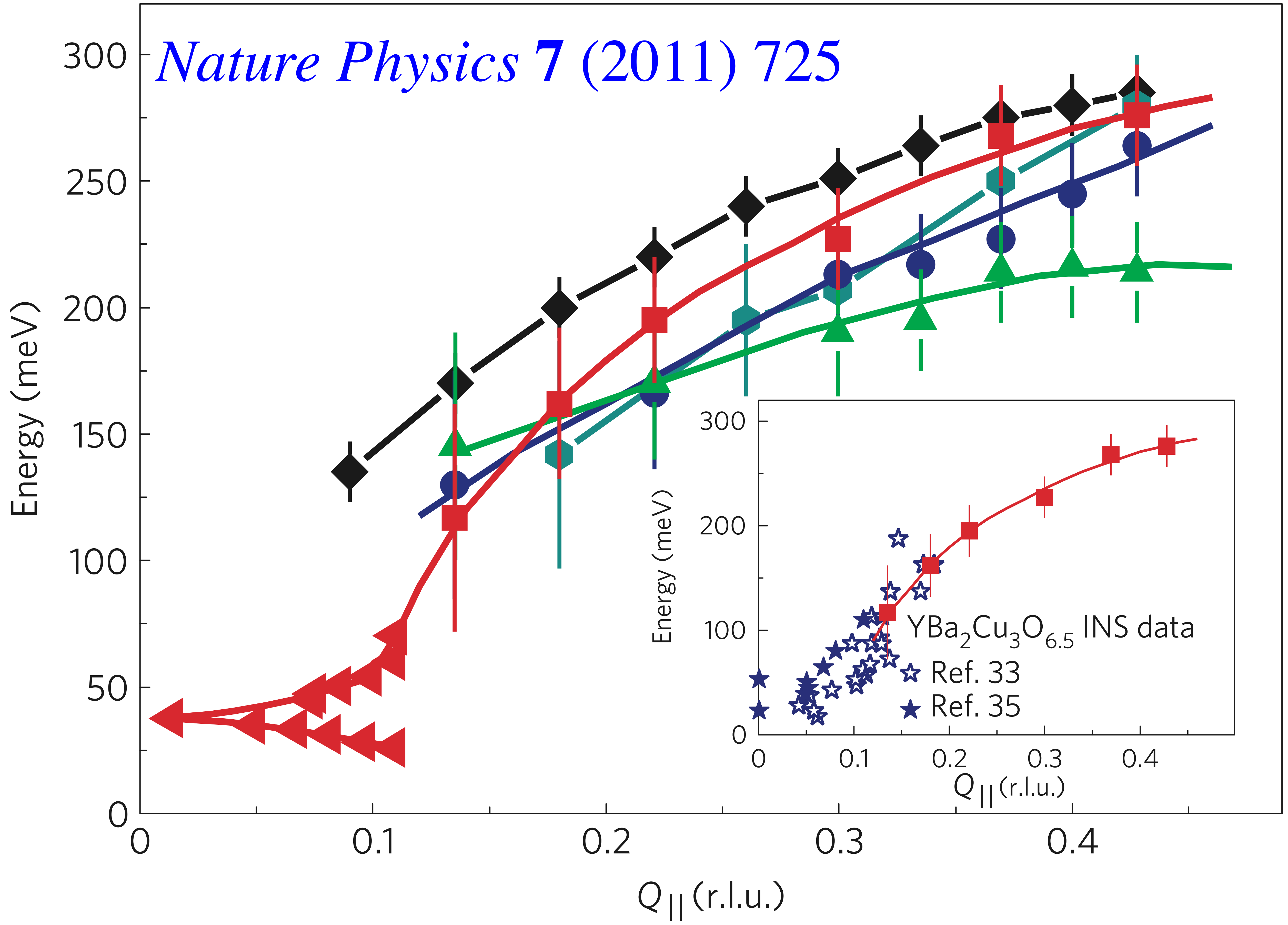
Puzzle:
why is the photoemission intensity on the "backsides" of the hole pockets so low?

Pseudogap puzzles:

A. Photoemission: Fermi arcs
B. RIXS: Intense paramagnons
C. Quantum oscillations
D. Velocities of Bogoliubov quasiparticles in the d-wave superconductor

Intense paramagnon excitations in a large family of high-temperature superconductors

M. Le Tacon[1★], G. Ghiringhelli[2], J. Chaloupka[1], M. Moretti Sala[2], V. Hinkov[1,3], M. W. Haverkort[1], M. Minola[2], M. Bakr[1], K. J. Zhou[4], S. Blanco-Canosa[1], C. Monney[4], Y. T. Song[1], G. L. Sun[1], C. T. Lin[1], G. M. De Luca[5], M. Salluzzo[5], G. Khaliullin[1], T. Schmitt[4], L. Braicovich[2] and B. Keimer[1★]



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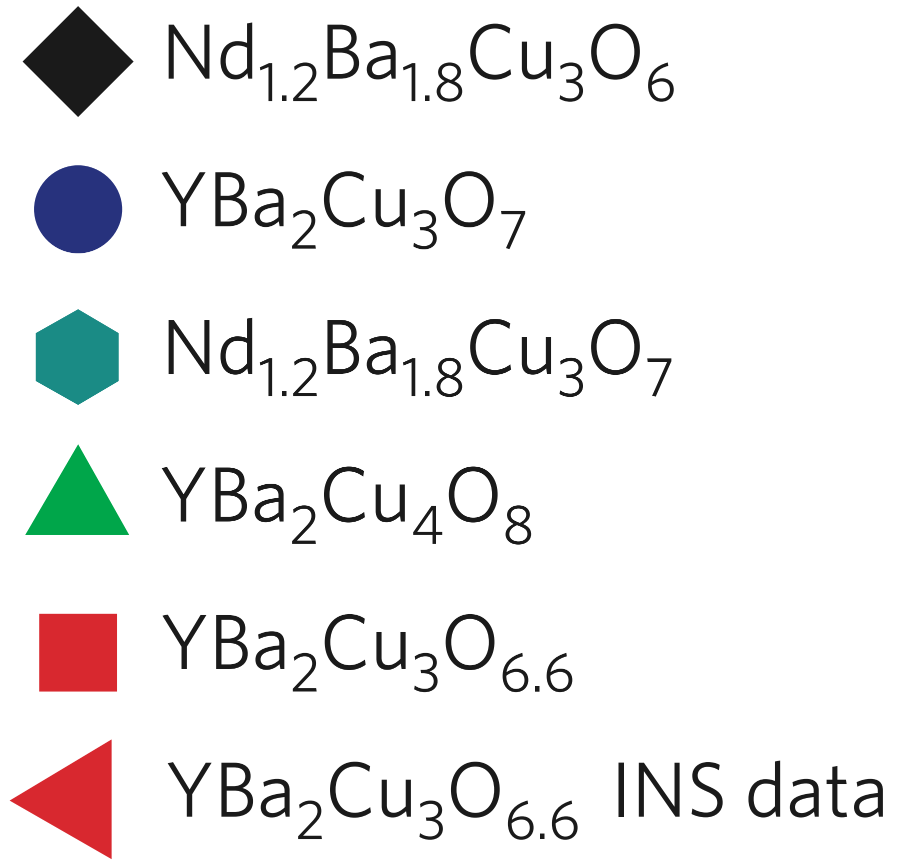
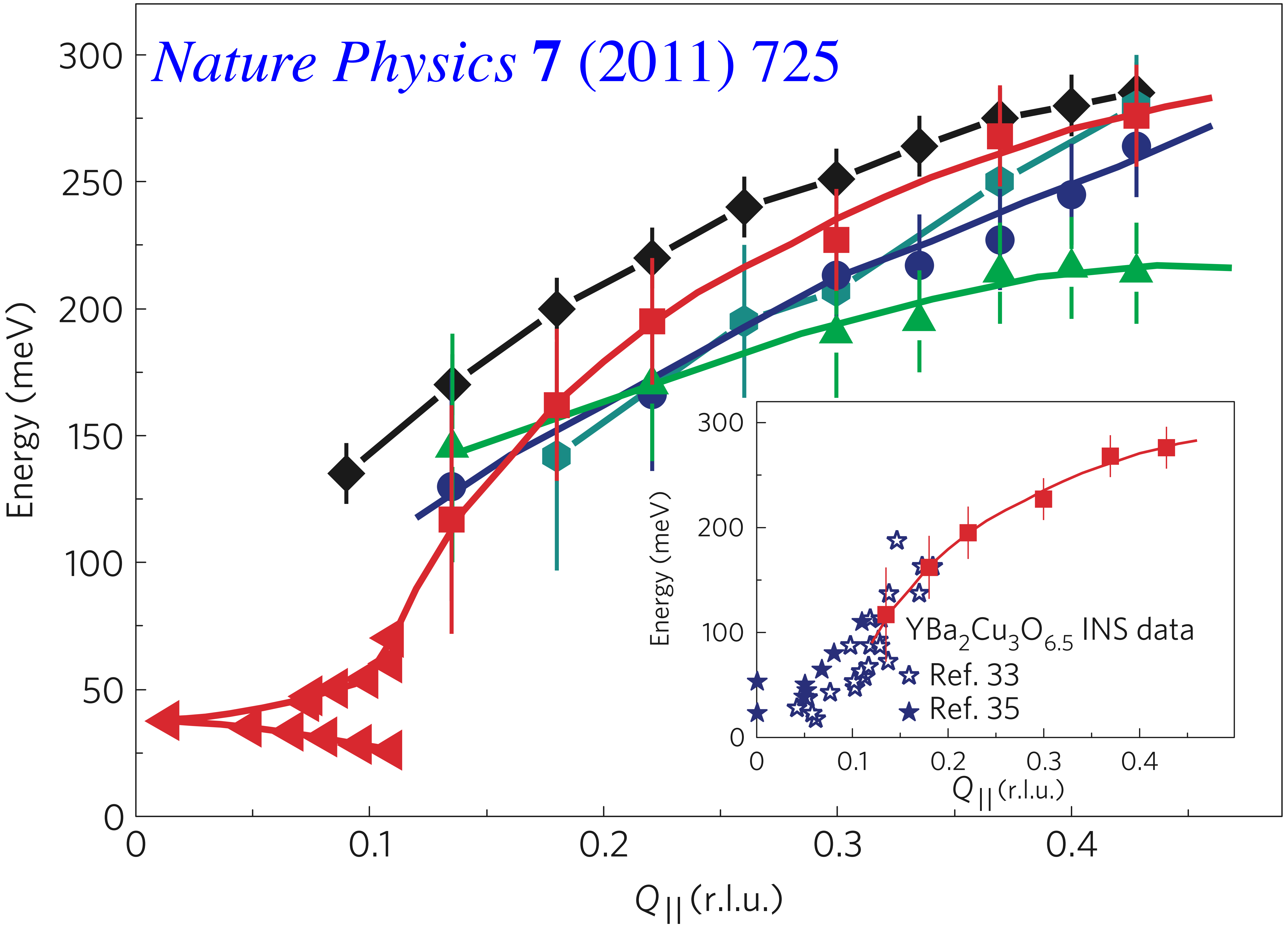


- Difficult to have intense paramagnons from a small Fermi surface.



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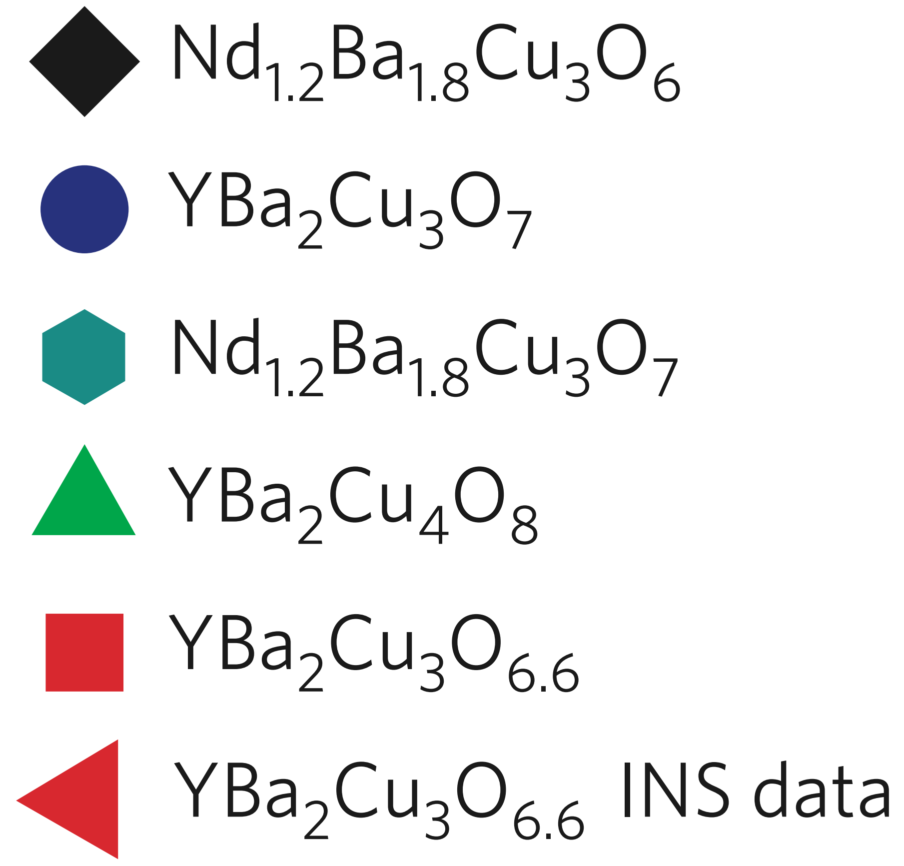
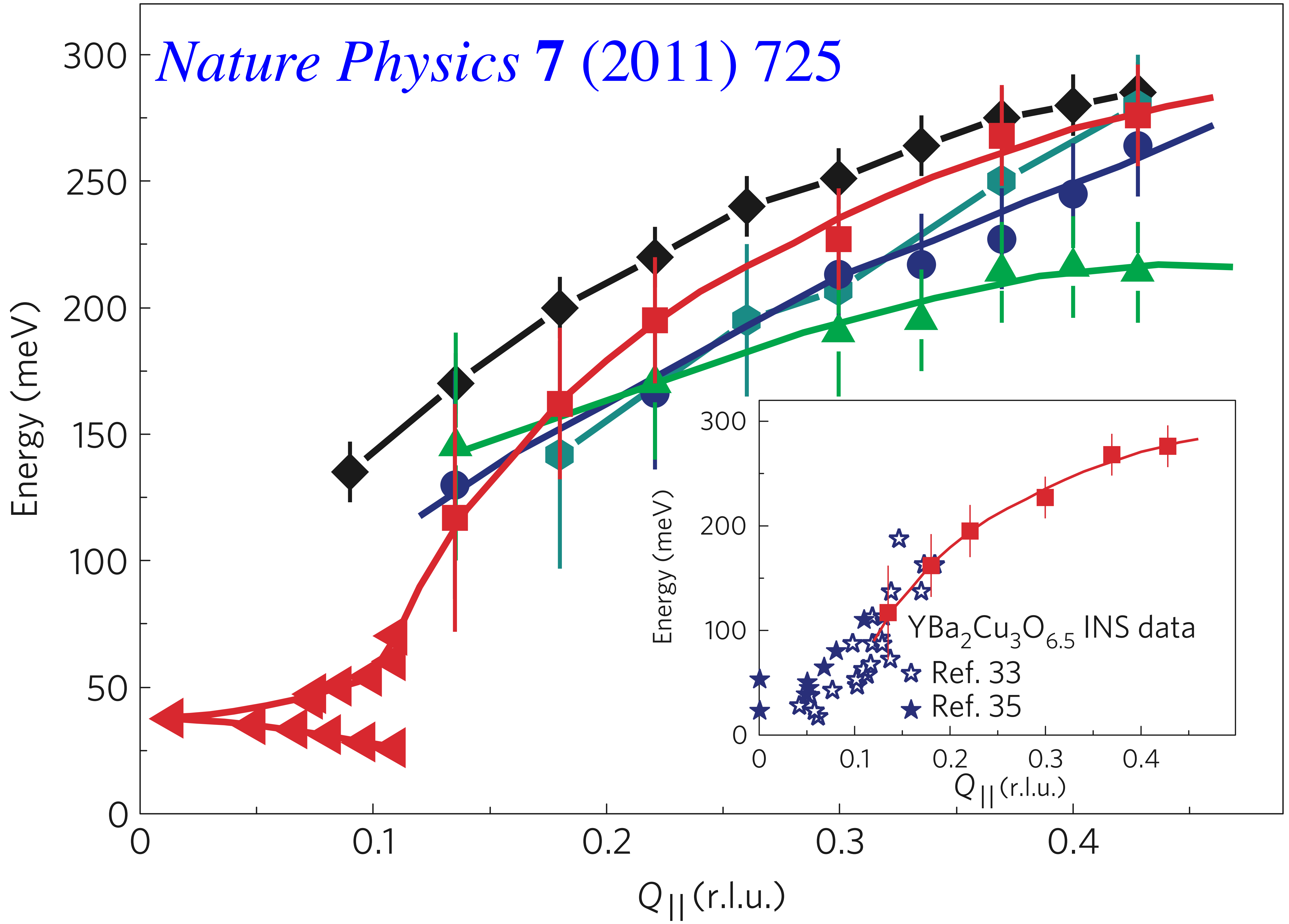


- Difficult to have intense paramagnons from a small Fermi surface.
- Spin waves only present at low energies in the presence of antiferromagnetic order



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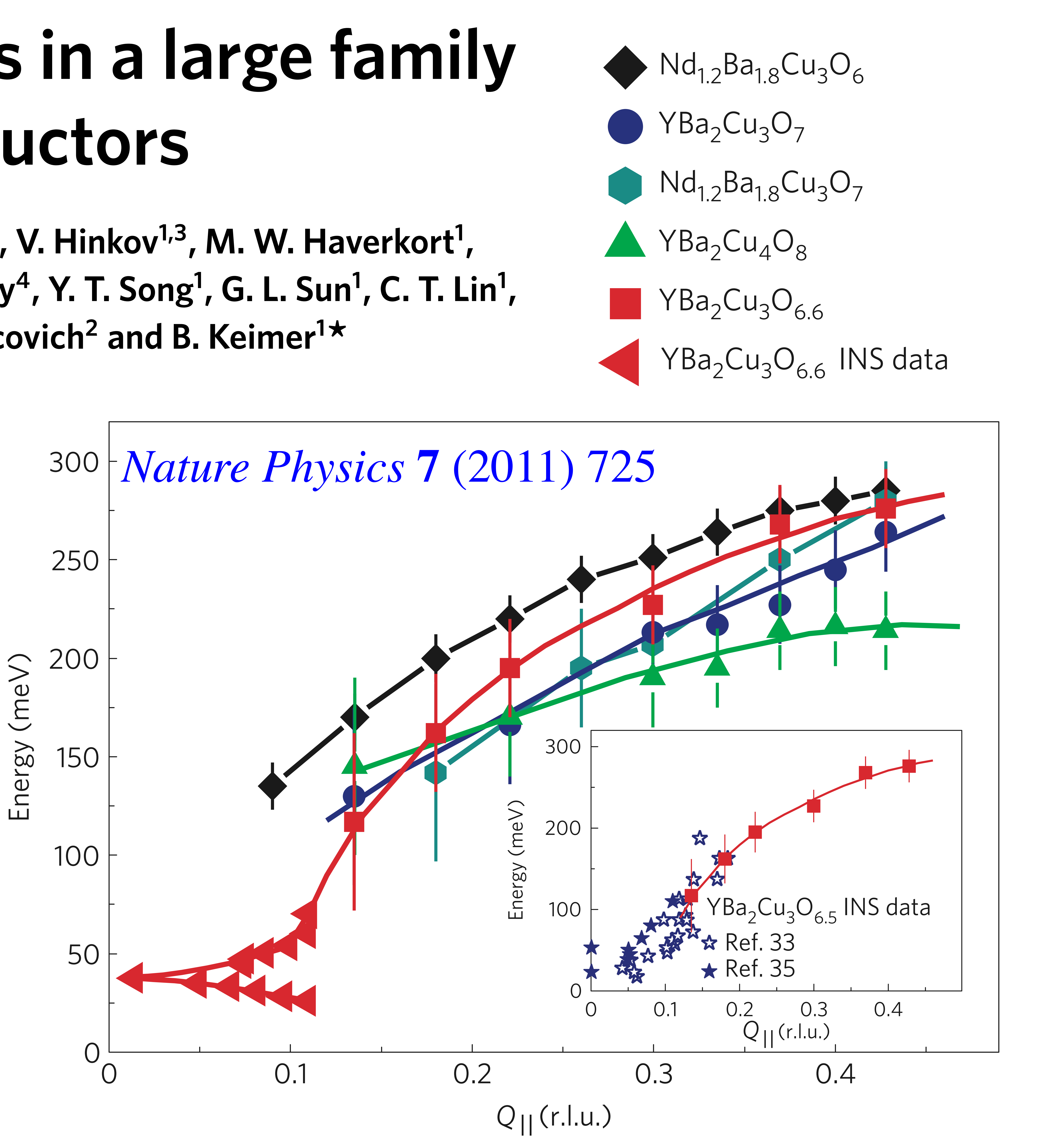
- Difficult to have intense paramagnons from a small Fermi surface.
- Spin waves only present at low energies in the presence of antiferromagnetic order
- Most natural interpretation is a spinon continuum (I claim)…



Pseudogap puzzles:

A. Photoemission: Fermi arcs

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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),

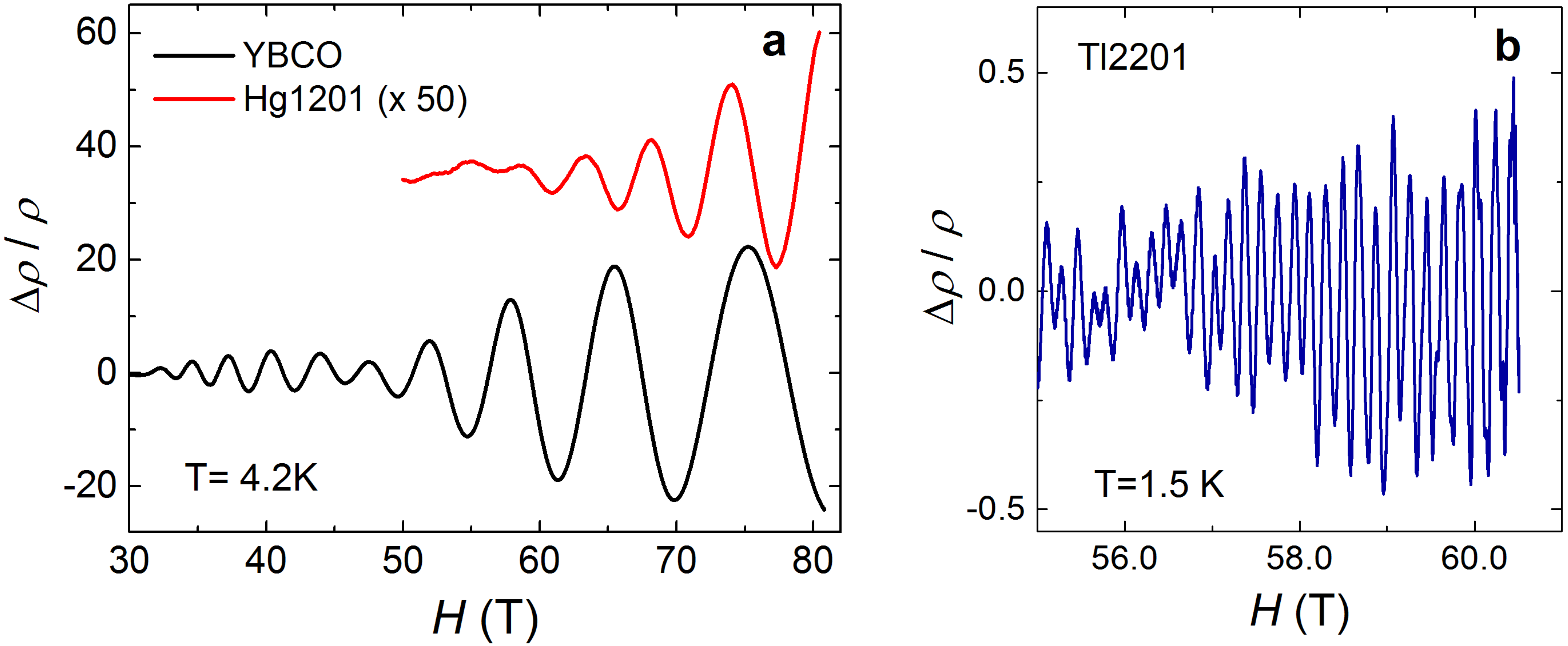
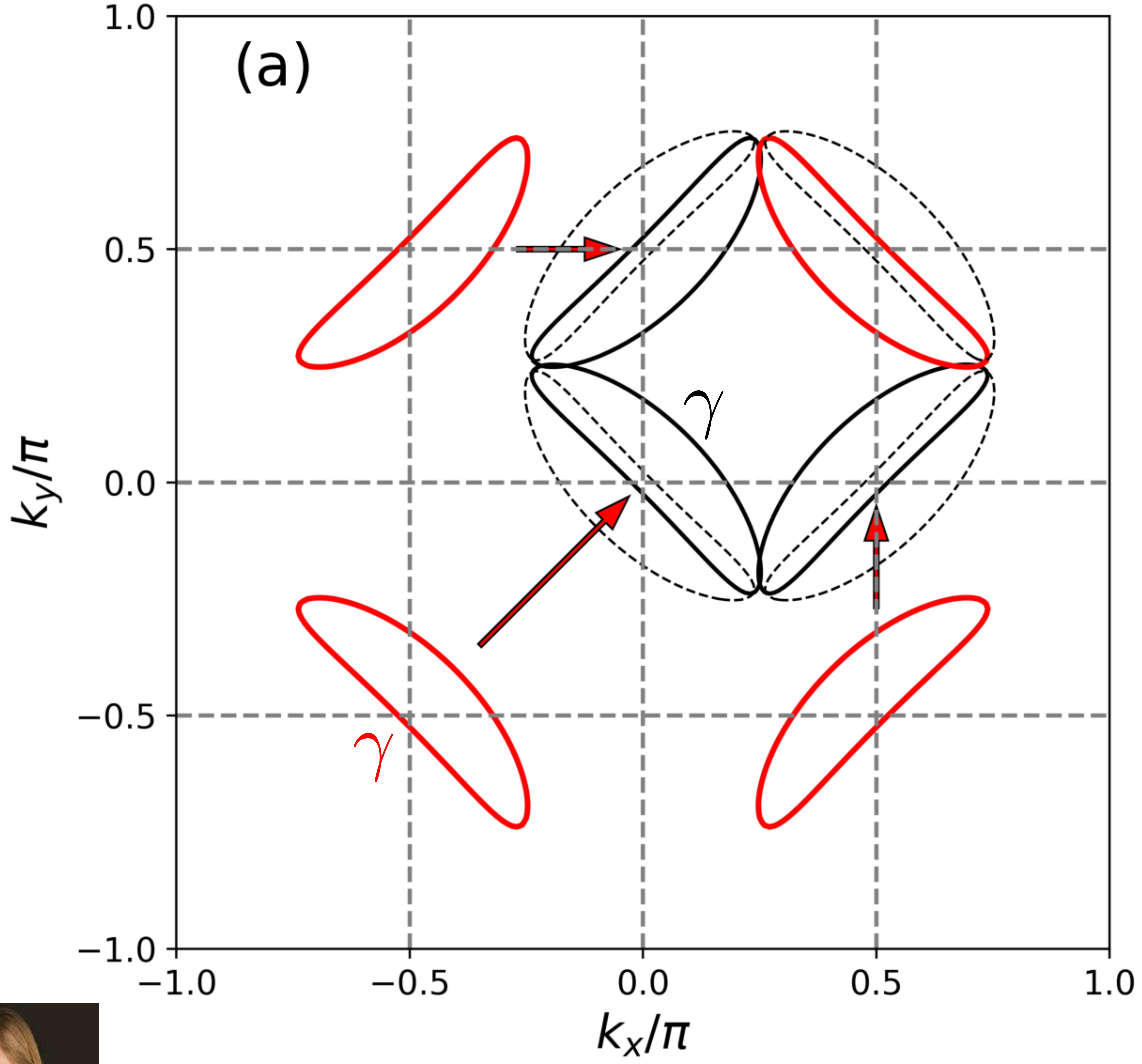


Figure 4

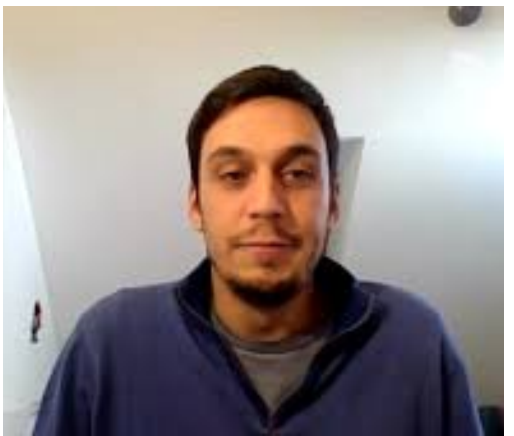
Quantum oscillations in cuprates. a) Underdoped YBCO ($p = 0.11$, $T_c = 62$ K) (black (22)) and Hg1201 ($p \simeq 0.1$, $T_c = 72$ K) (red (33), ×50). **b)** Overdoped Tl2201 ($p \simeq 0.3$, $T_c \approx 10$ K) (28).

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*

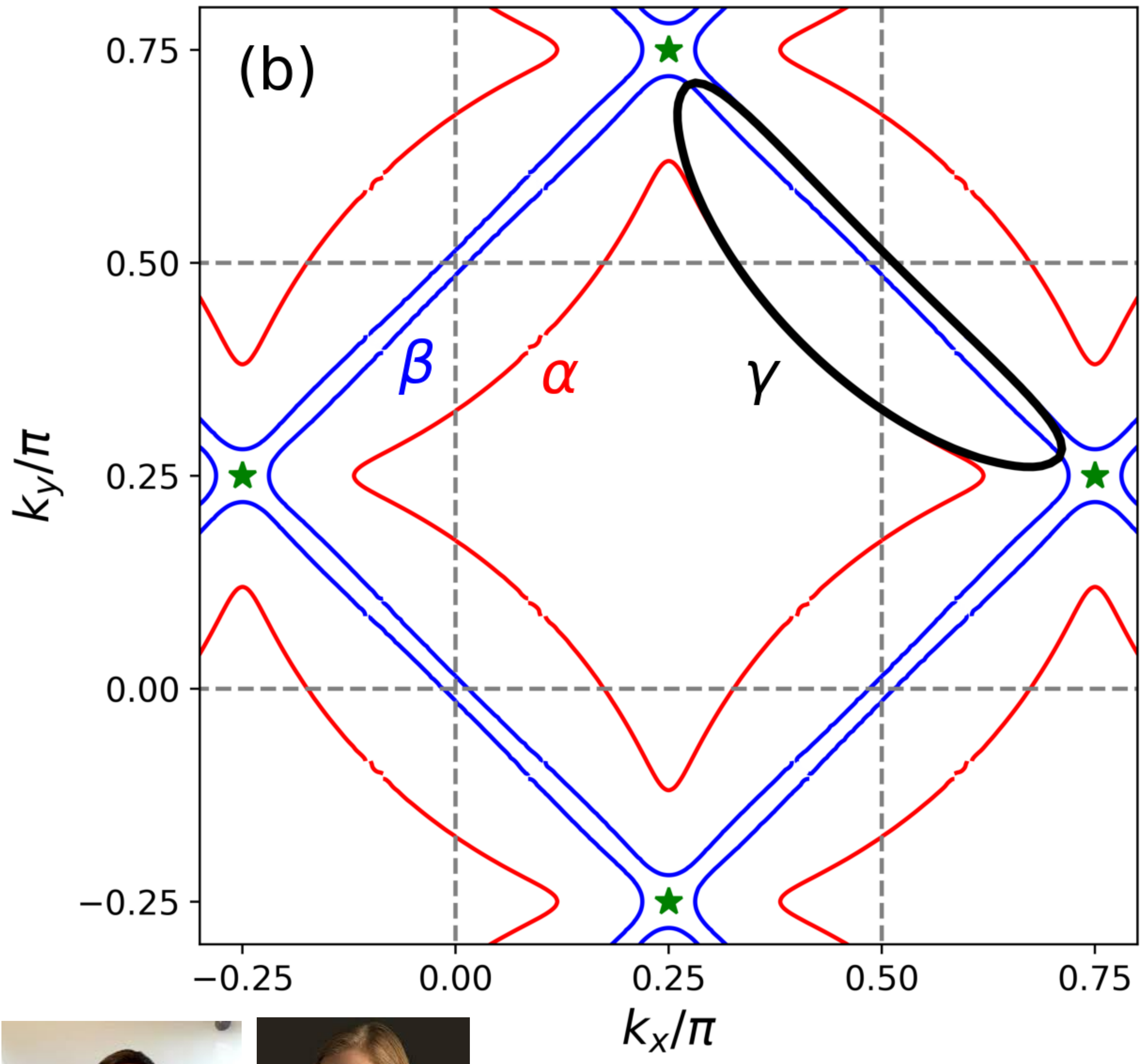


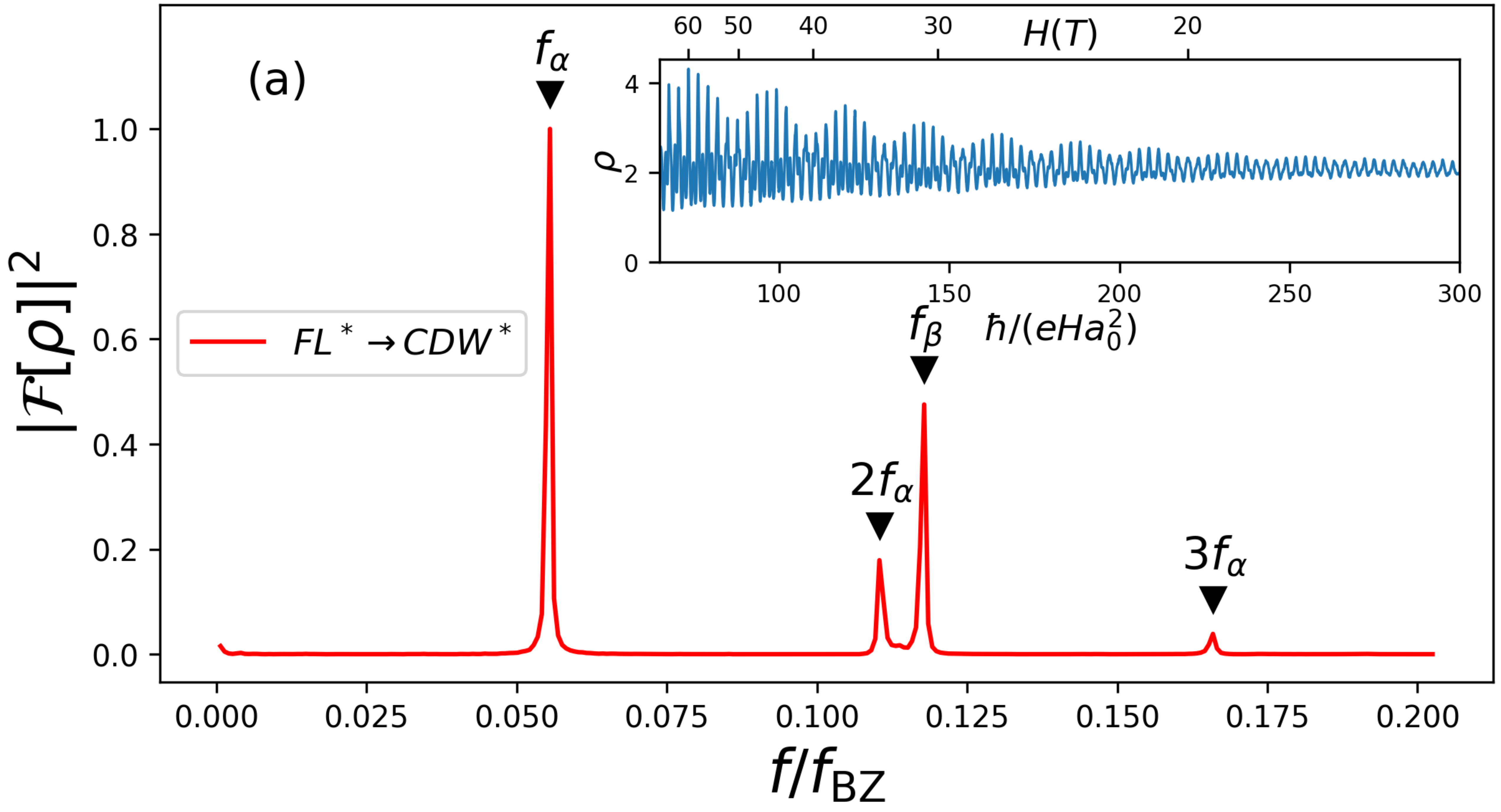
N. Harrison and S. Sebastian
electron pocket
(PRL **106**, 226402 (2011))



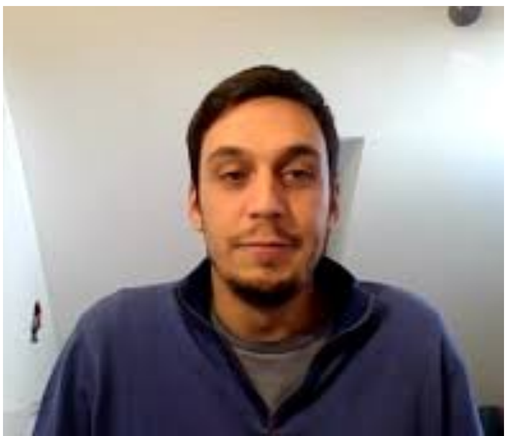
Pietro Bonetti, Maine Christos and S.S. (BCS), arXiv:2405.08817

FL*→CDW*





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

Pseudogap puzzles:

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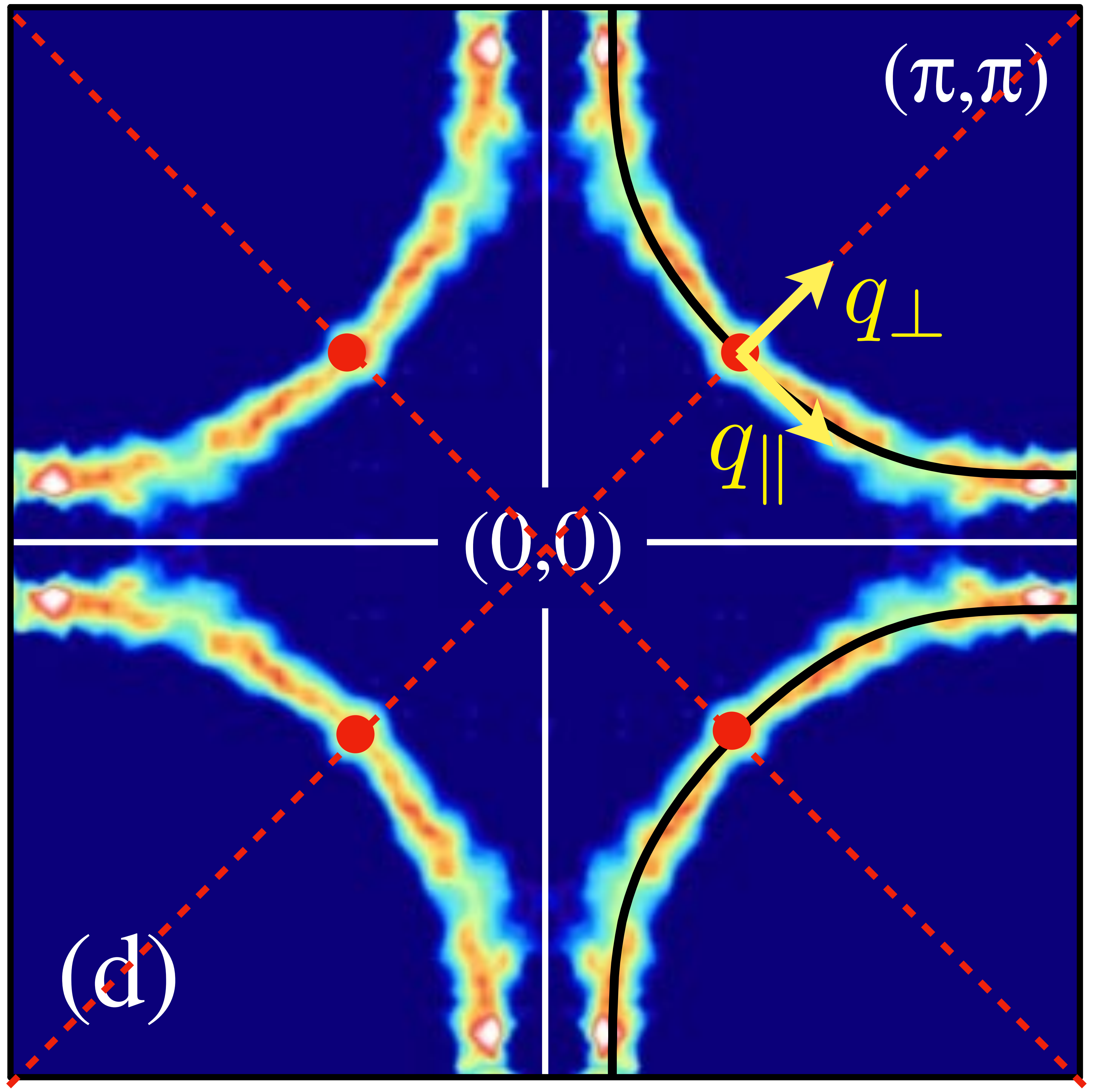
FL→dSC



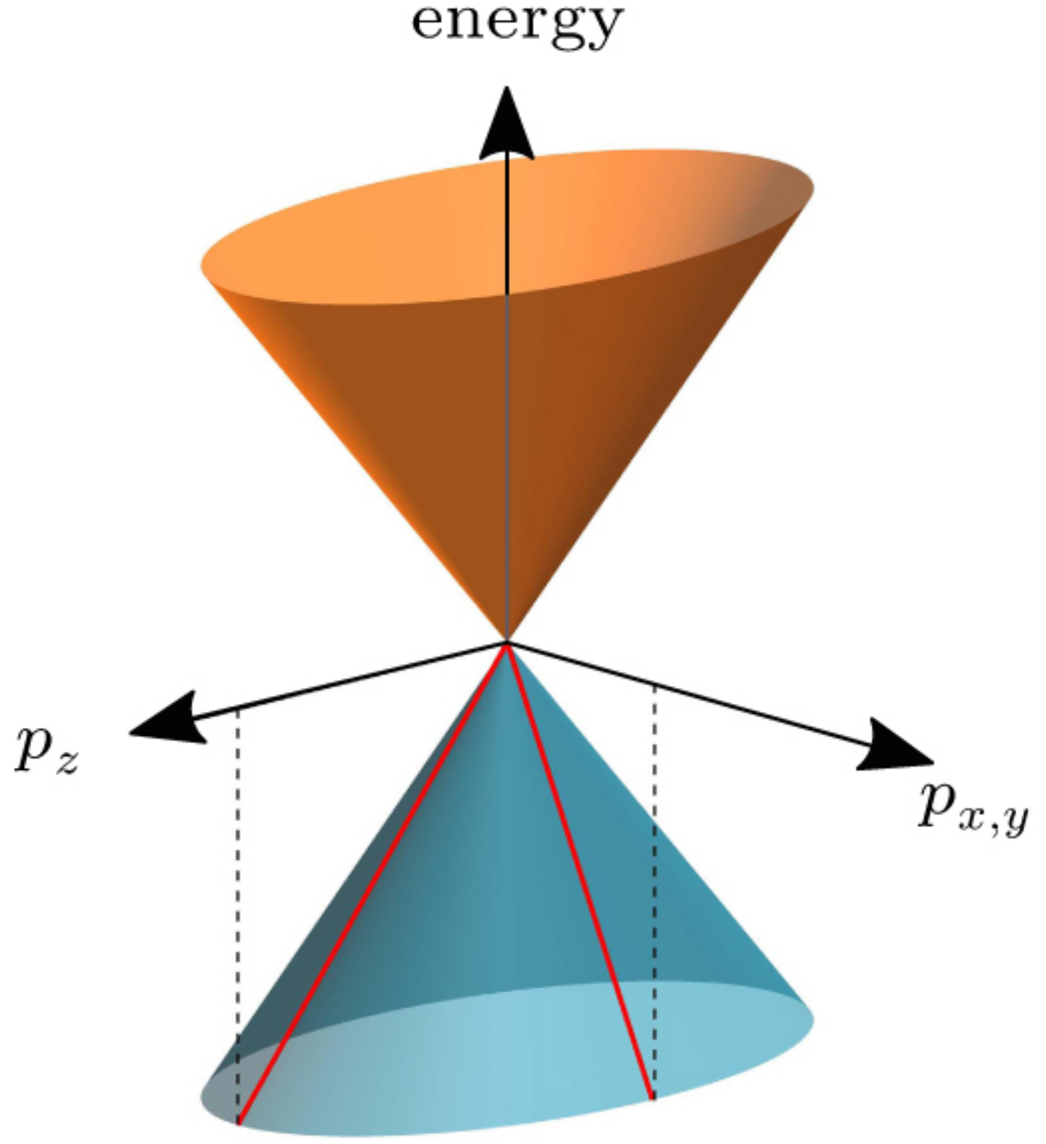
BCS/Bogoliubov quasiparticles in a d-wave superconductor

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

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 $v_F \gg v_\Delta$.



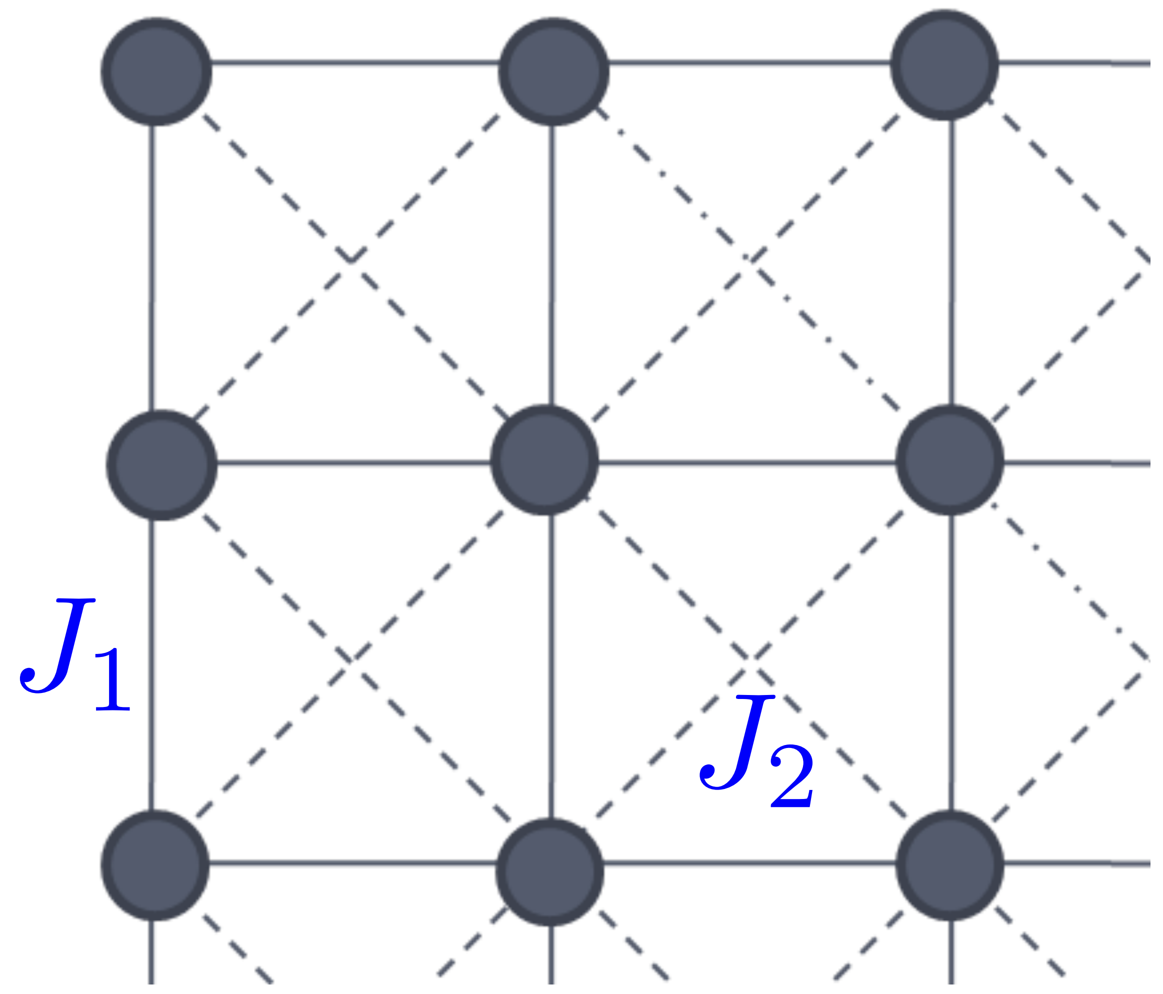
Early work described the emergence of nodal d-wave superconductivity from a spin liquid with spinons with a Dirac dispersion: in this approach, the spinons of the spin liquid are directly transformed into the nodal Bogoliubov quasiparticles of the d-wave superconductor.

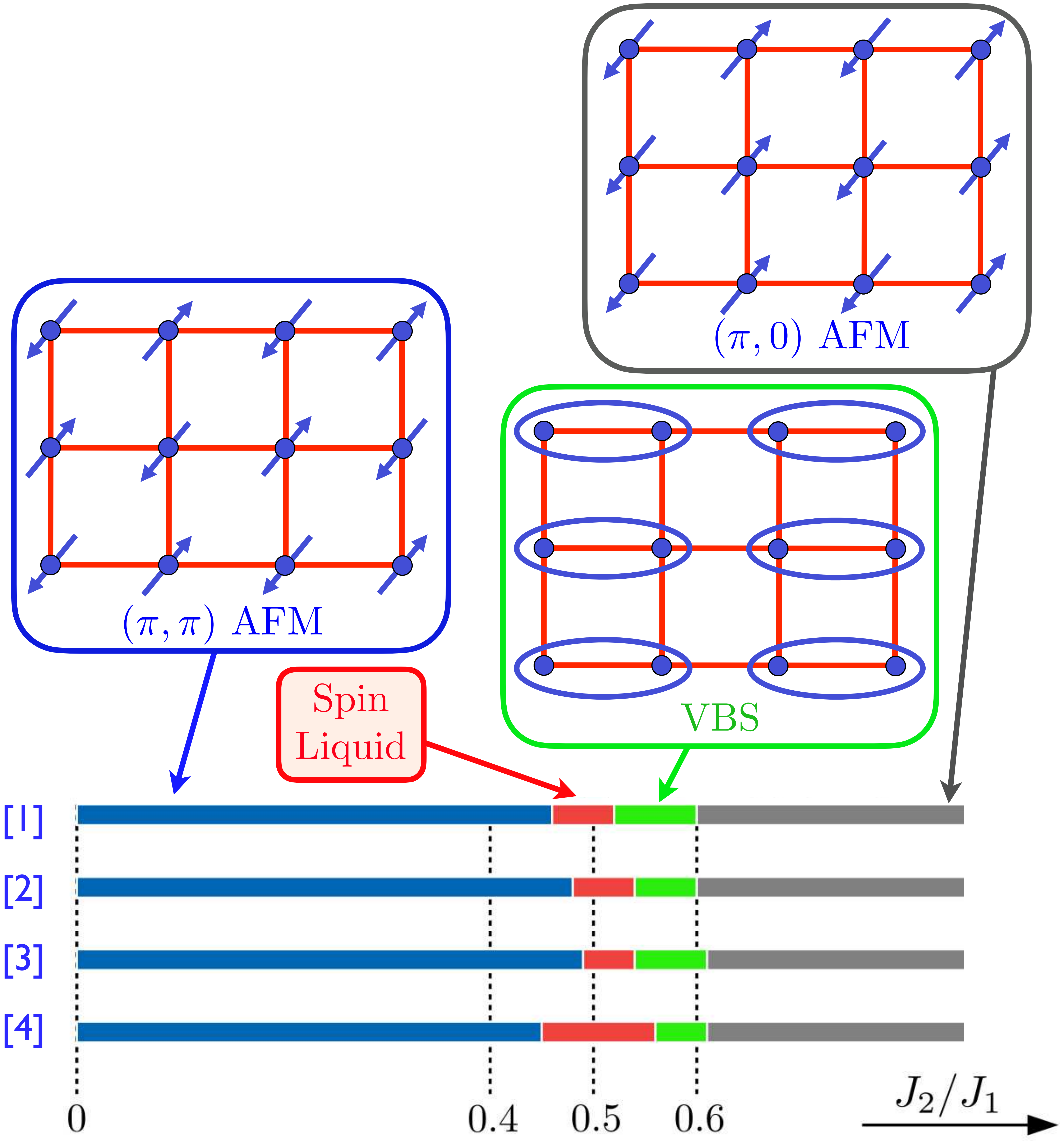
F.C. Zhang, C. Gros, T.M. Rice, H. Shiba, Superconductor Sci. Tech. **1** (1988) 36
D. A. Ivanov, T. Senthil, PRB **66**, 115111 (2002).
P. A. Lee, N. Nagaosa, X.-G. Wen, RMP **78**, 17 (2006)

This leads to a d-wave superconductor with $v_F \approx v_\Delta$ at low doping, in contrast to observations.

Recent insights on square lattice spin liquids

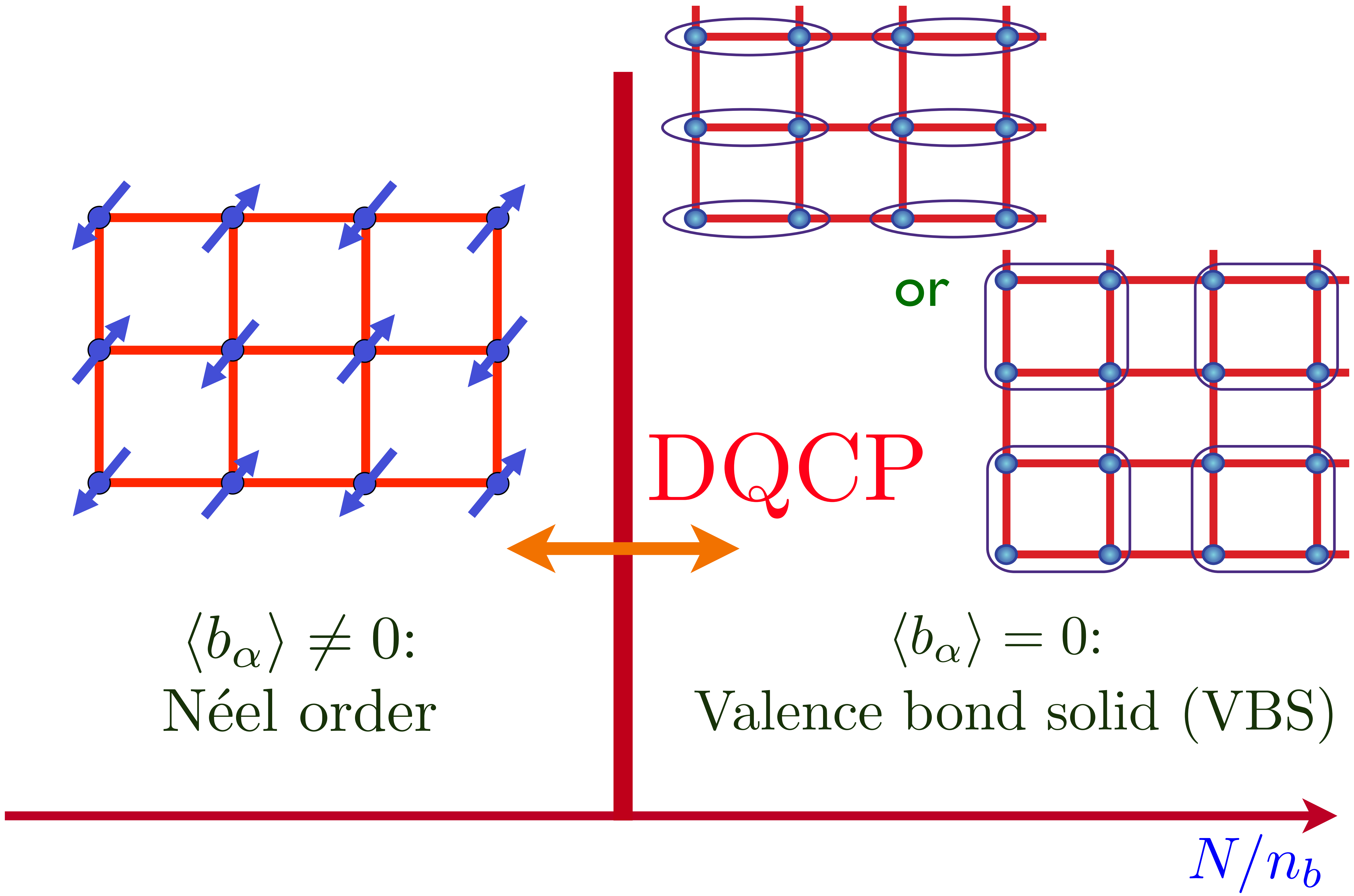
$$H = J_1 \sum_{\langle i,j\rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + J_2 \sum_{\langle\langle i,j\rangle\rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$





1. L. Wang and A. W. Sandvik, *Phys. Rev. Lett.* **121**, 107202 (2018)
2. F. Ferrari and F. Becca, *Phys. Rev. B* **102**, 014417 (2020)
3. Y. Nomura and M. Imada, *Phys. Rev. X* **11**, 031034 (2021)
4. W.-Y. Liu, S.-S. Gong, Y.-B. Li, D. Poilblanc, W.-Q. Chen, and Z.-C. Gu, *Science Bulletin* **67,** 1034 (2022)

Insulating S=1/2 antiferromagnet



$$H = \sum_{i<j} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

Schwinger bosons

$$\boldsymbol{S}_i = \frac{1}{2} b^\dagger_{i\alpha} \boldsymbol{\sigma}_{\alpha\beta} b_{i\beta}\,, \qquad \sum_{\alpha=1}^{N=2} b^\dagger_{i\alpha} b_{i\alpha} = n_b = 2S$$

Mean-field spin liquid
with gapped bosonic spinons.

Low energy $\mathbb{CP}^1$ U(1) gauge theory

$$z_\alpha \sim b_{A\alpha} + \varepsilon_{\alpha\beta} b^\dagger_{B\beta}$$

$$\mathcal{L} = |(\partial_\mu - i a_\mu) z_\alpha|^2 + s|z_\alpha|^2 + u|z_\alpha|^4 + \mathcal{L}_{\text{monopole}}$$

N. Read and S. Sachdev, Phys. Rev. Lett. **62**, 1694 (1989)
N. Read and S. Sachdev, Phys. Rev. B **42**, 4568 (1990)

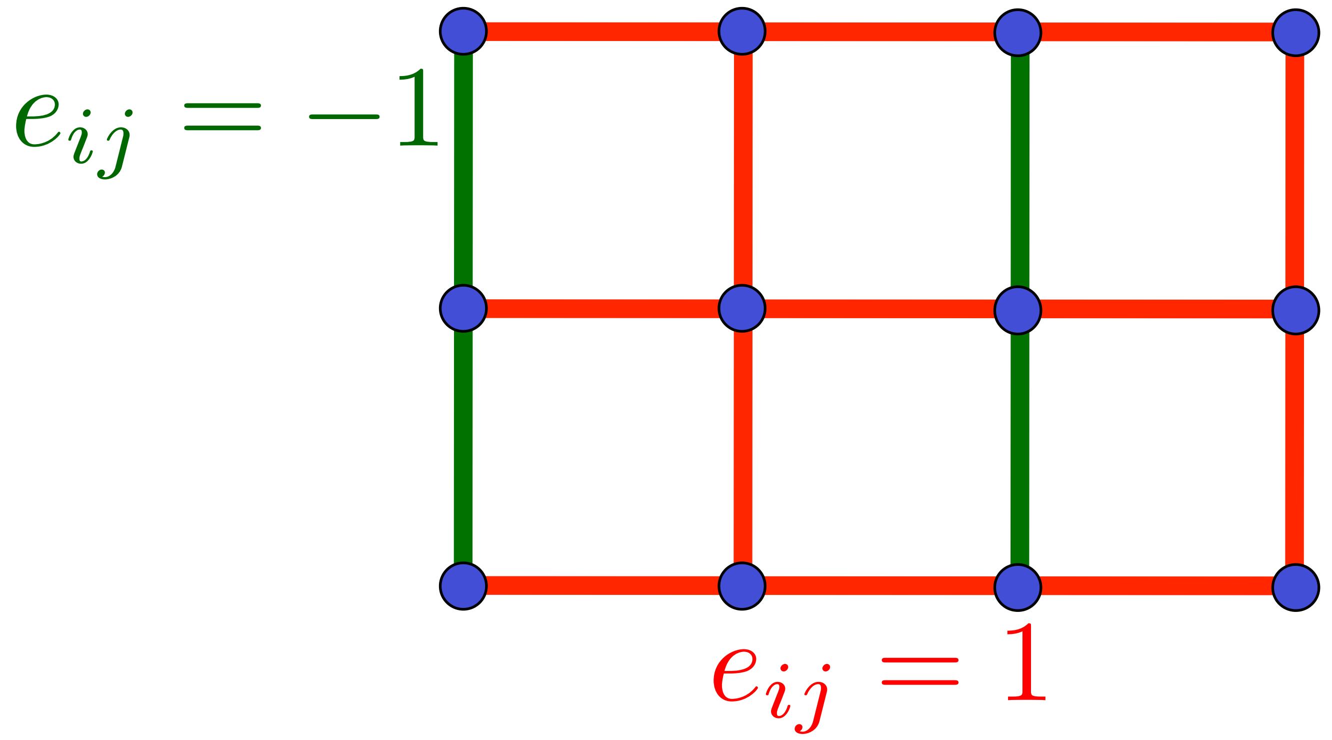
Insulating S=1/2 antiferromagnet

π-flux Spin liquid

$$H = \sum_{i<j} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

Schwinger fermions

$$\boldsymbol{S}_i = \frac{1}{2} f_{i\alpha}^\dagger \boldsymbol{\sigma}_{\alpha\beta} f_{i\beta} \,, \quad \sum_{\alpha=\uparrow,\downarrow} f_{i\alpha}^\dagger f_{i\alpha} = 1$$



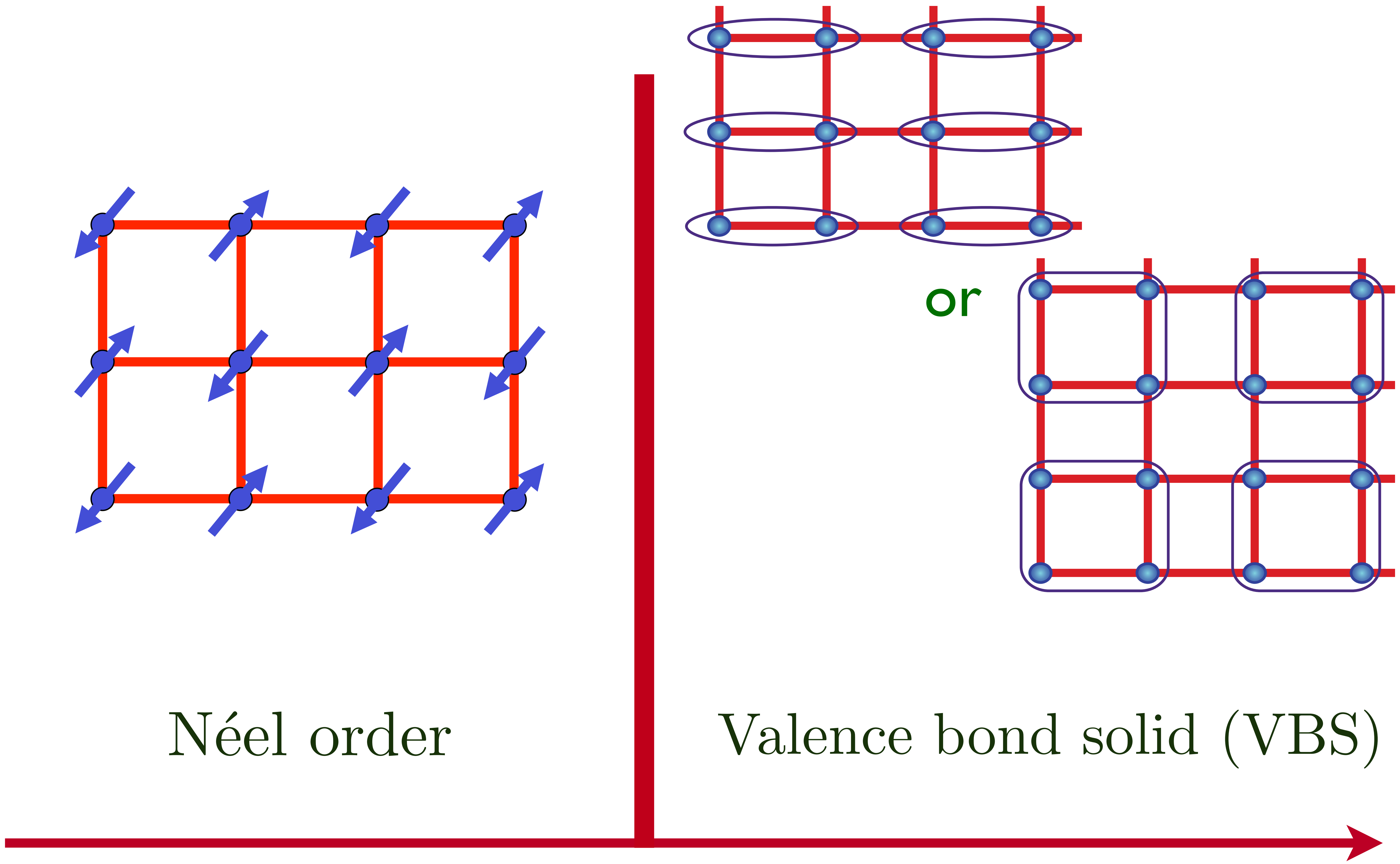
π-flux mean-field theory
with gapless spinons at 2 Dirac points.

I. Affleck and J.B. Marston, PRB **37**, 3774 (1988)

$$H_f = iJ \sum_{\langle ij \rangle} e_{ij} \left(f_{i\alpha}^\dagger f_{j\alpha} - f_{j\alpha}^\dagger f_{i\alpha} \right) \quad , \quad \varepsilon_{\mathbf{k}} = 2J\sqrt{\sin^2(k_x) + \sin^2(k_y)}$$

SU(2) QCD with $N_f = 2$ massless fermions; $\mathcal{L} = i\overline{\Psi}_s \gamma_\mu D_\mu \Psi_s$.

Insulating S=1/2 antiferromagnet



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SU(2) QCD with $N_f = 2$ massless fermions; $\mathcal{L} = i\overline{\Psi}_s \gamma_\mu D_\mu \Psi_s$.
Confining instability to precisely the Néel and VBS orders of $\mathbb{CP}^1$ theory.

Bosonic spinons:
$\mathbb{CP}^1$ U(1) gauge theory

Nearly-critical S=1/2 square lattice anti-ferromagnet

$\mathrm{SU}(2)_N$ gauge theory of $N_f = 2$ fundamental, massless, Dirac fermions.

Obtained from a saddle-point of fermionic spinons moving in π-flux.

SO(5) non-linear σ-model of Néel/VBS orders with $k = 1$ WZW term

A. Tanaka and X. Hu, *Phys. Rev. Lett.* **95**, 036402 (2005); T. Senthil and M.P.A. Fisher *Phys. Rev. B* **74**, 064405 (2006);
Ying Ran and X.-G. Wen, cond-mat/0609620; C. Wang, A. Nahum, M. A. Metlitski, C. Xu, and T. Senthil, *Phys. Rev. X* **7**, 031051 (2017)

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SO(5) non-linear σ-model of Néel/VBS orders with $k = 1$ WZW term

Many numerical works show that deconfined critical theory applies over a substantial length scale, but ultimately confines at the longest distances.

Zheng Zhou, Liangdong Hu, Wei Zhu, and Yin-Chen He, PRX **14**, 021044 (2024); S. M. Chester and N. Su, PRL **132**, 111601 (2024).
B.-B. Chen, X. Zhang, Y. Wang, K. Sun, and Z. Y. Meng, arXiv:2307.05307;
J. Takahashi, H. Shao, B. Zhao, W. Guo, and A. W. Sandvik, arXiv:2405.06607.

Pseudogap answers:

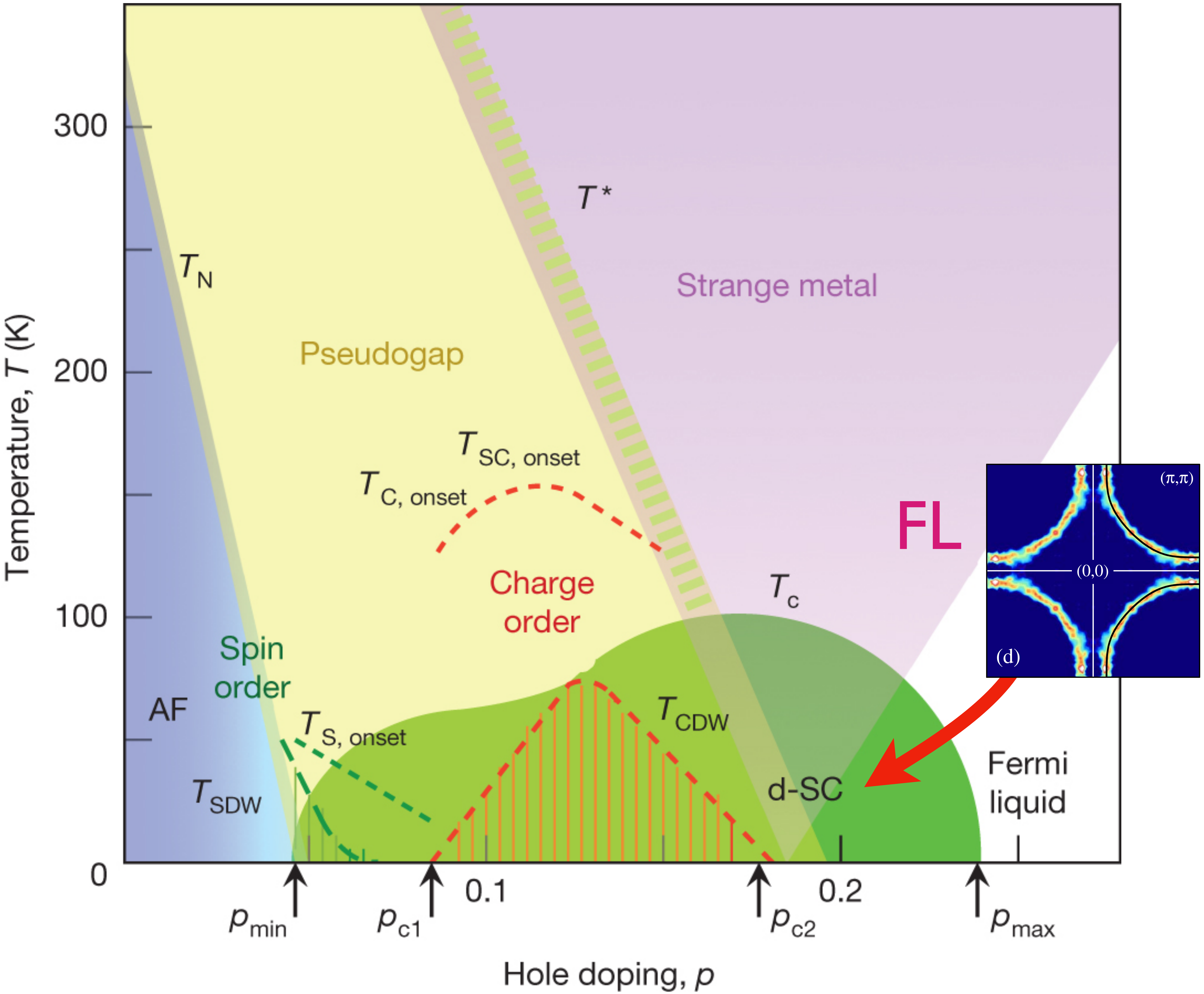
A. Photoemission: Fermi arcs

B. RIXS: Intense paramagnons

C. Quantum oscillations

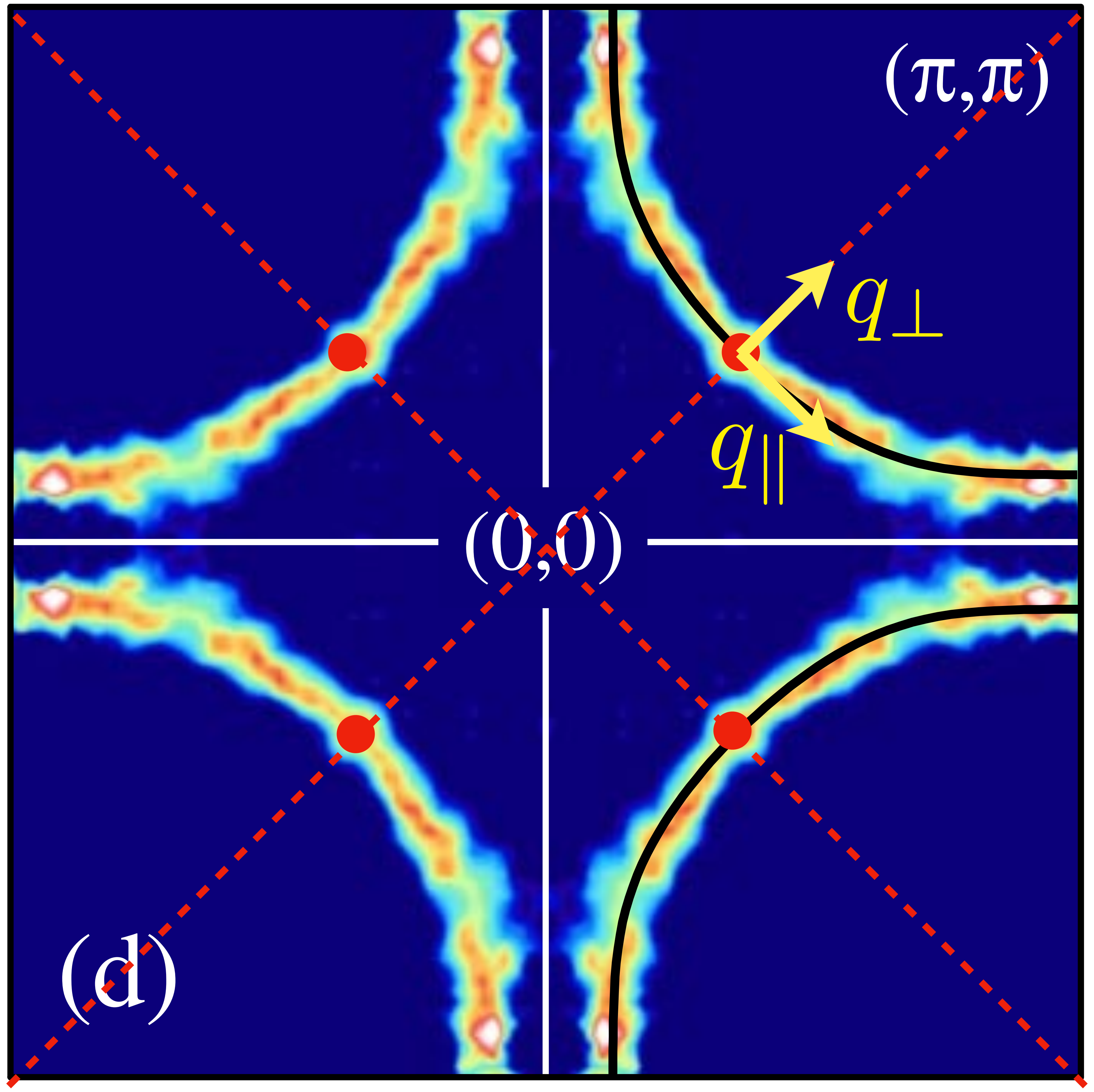
D. Velocities of Bogoliubov quasiparticles in the d-wave superconductor

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.

FL→dSC



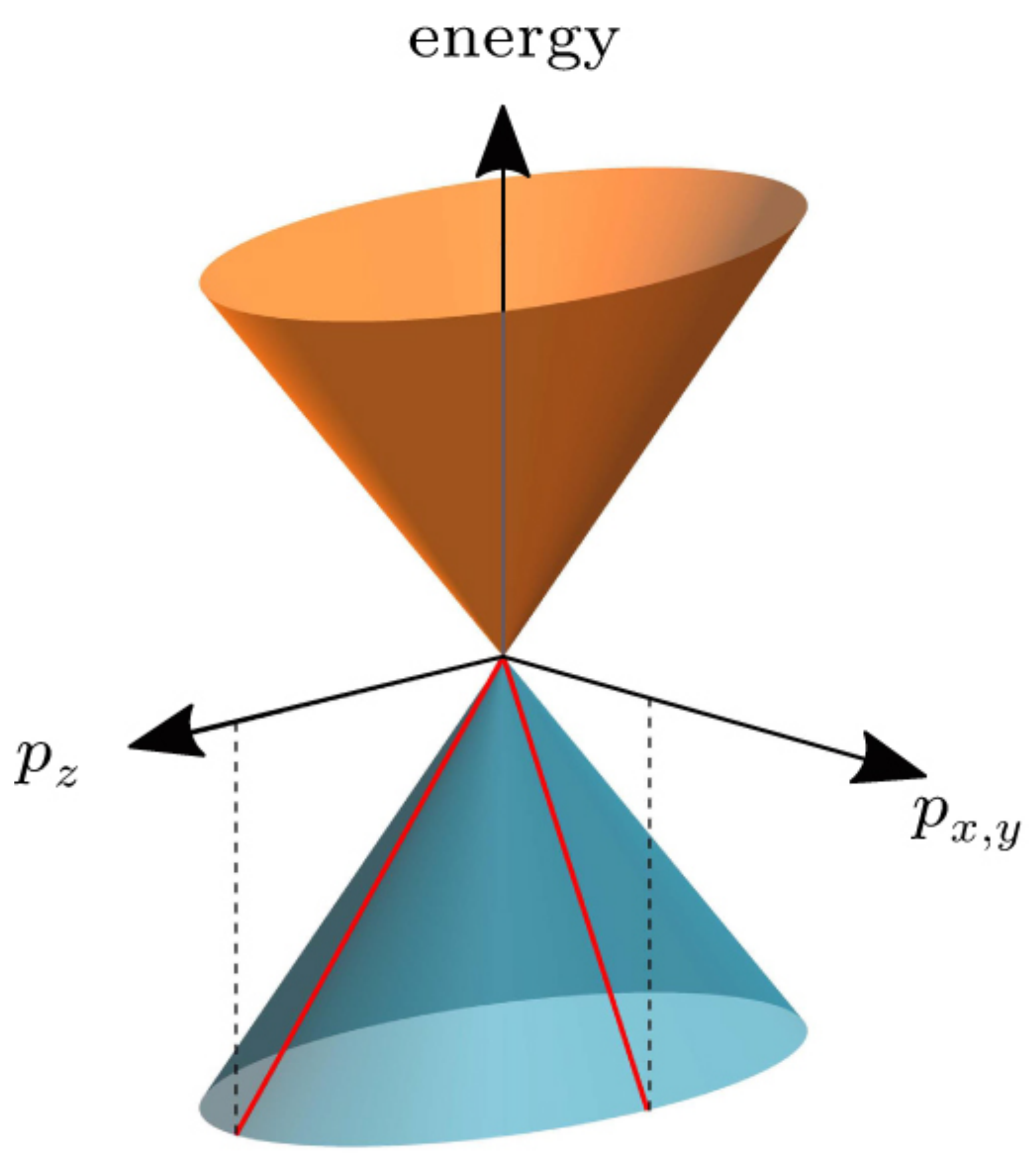
BCS/Bogoliubov quasiparticles in a d-wave superconductor

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

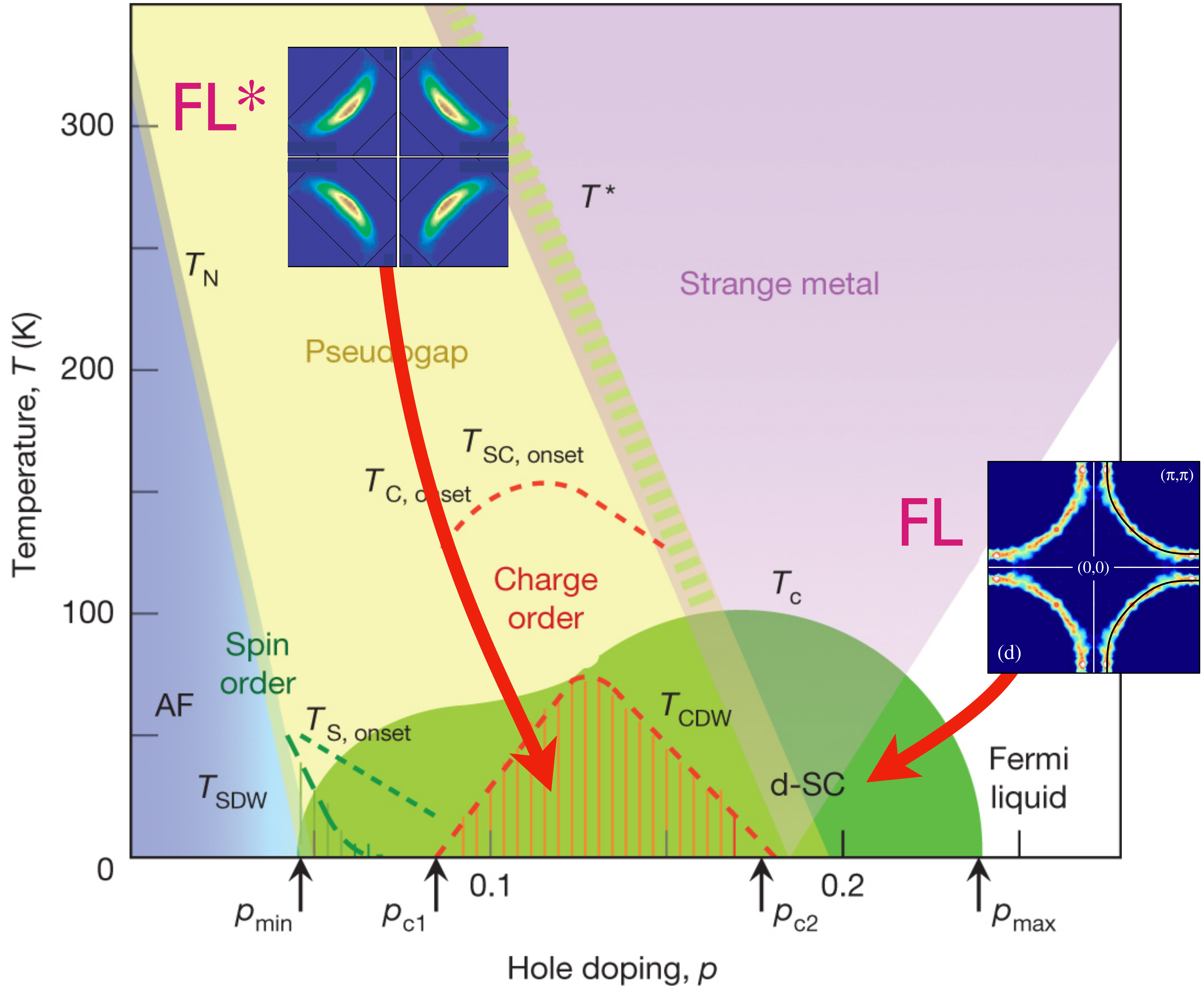
4 nodal points where

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

with $v_F \gg v_\Delta$.



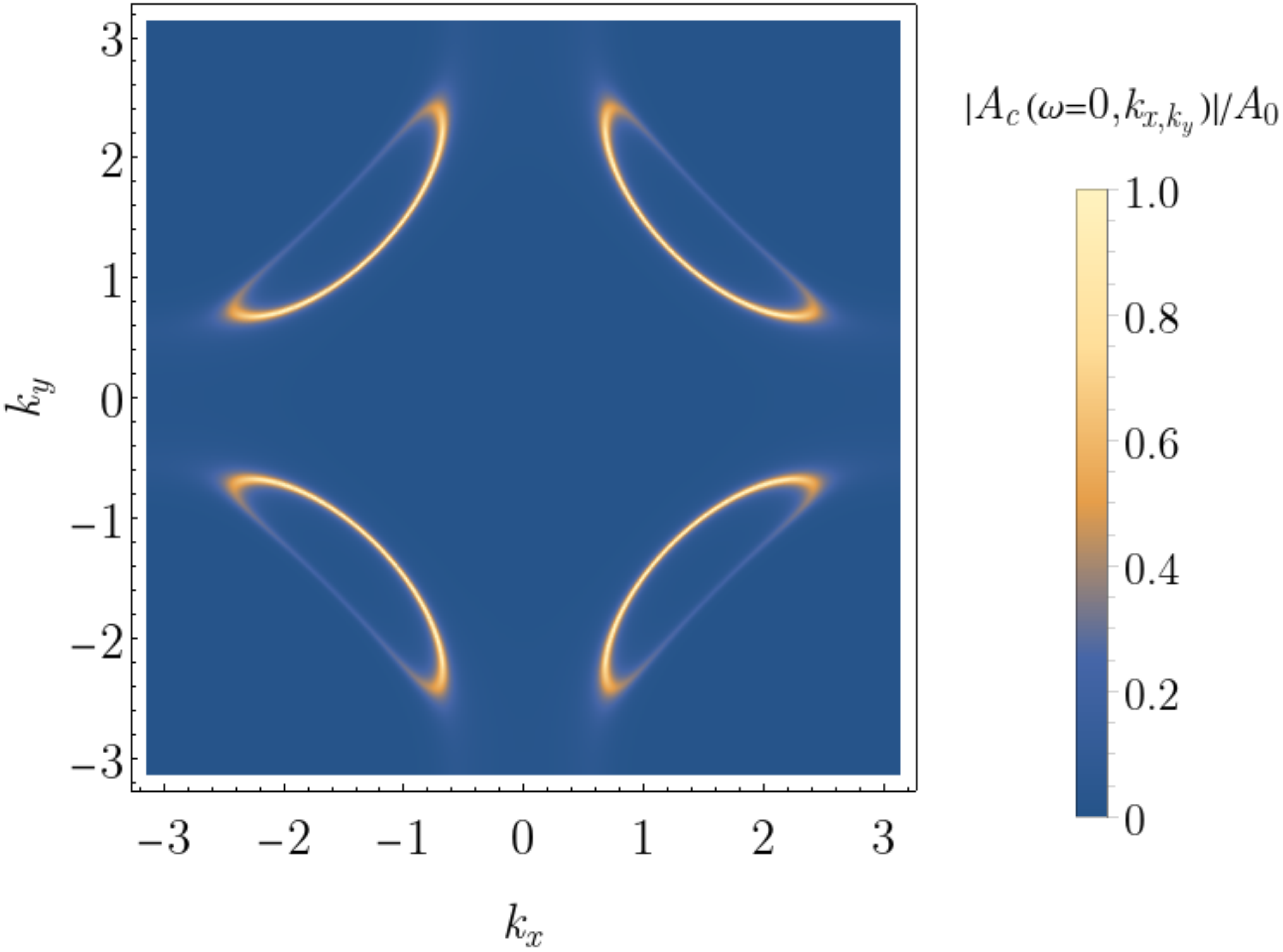
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



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

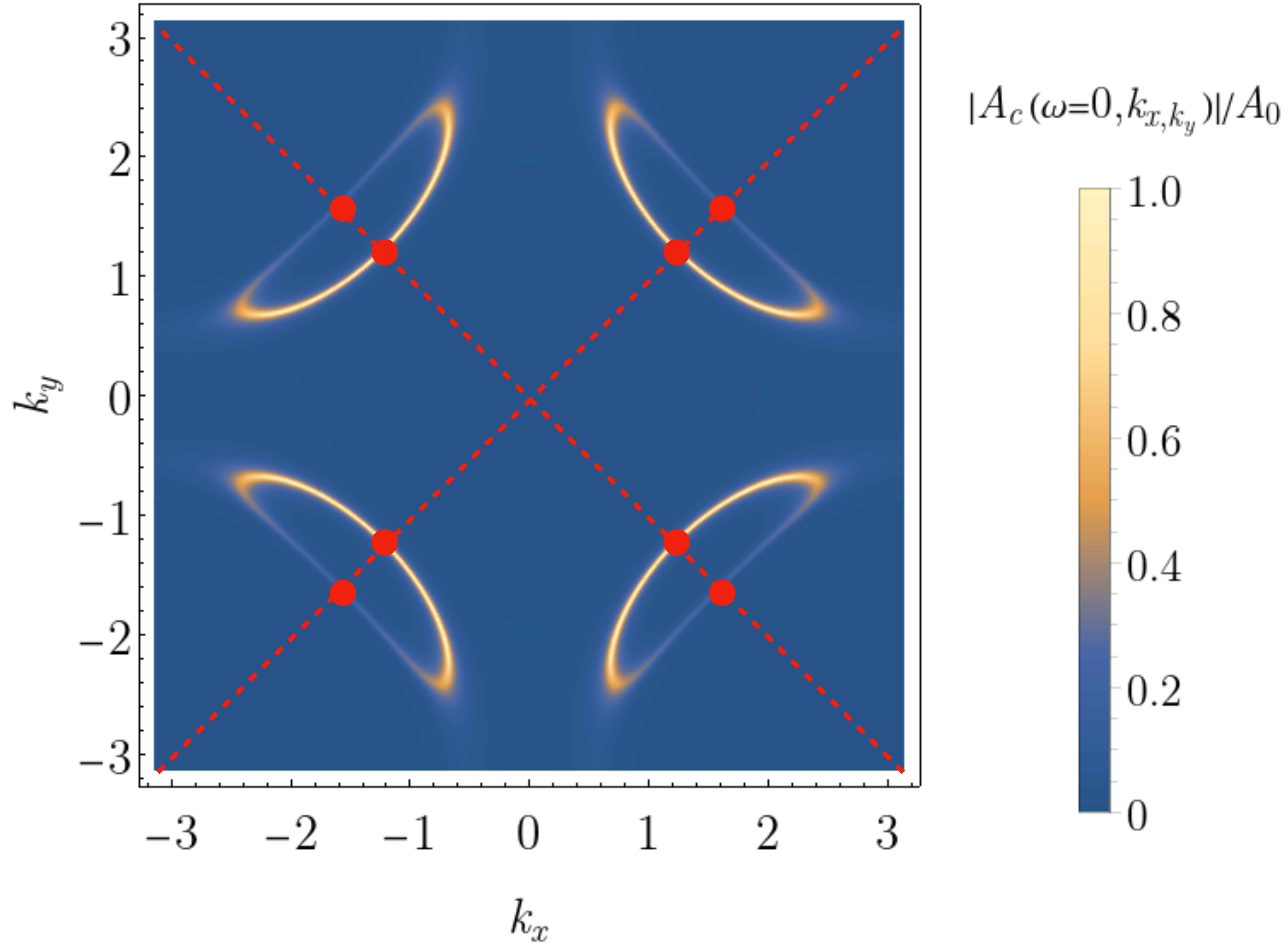
The resulting low T ordered states should be adiabatically connected to the corresponding states obtained from instabilities of FL.

FL*



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

FL*→dSC*

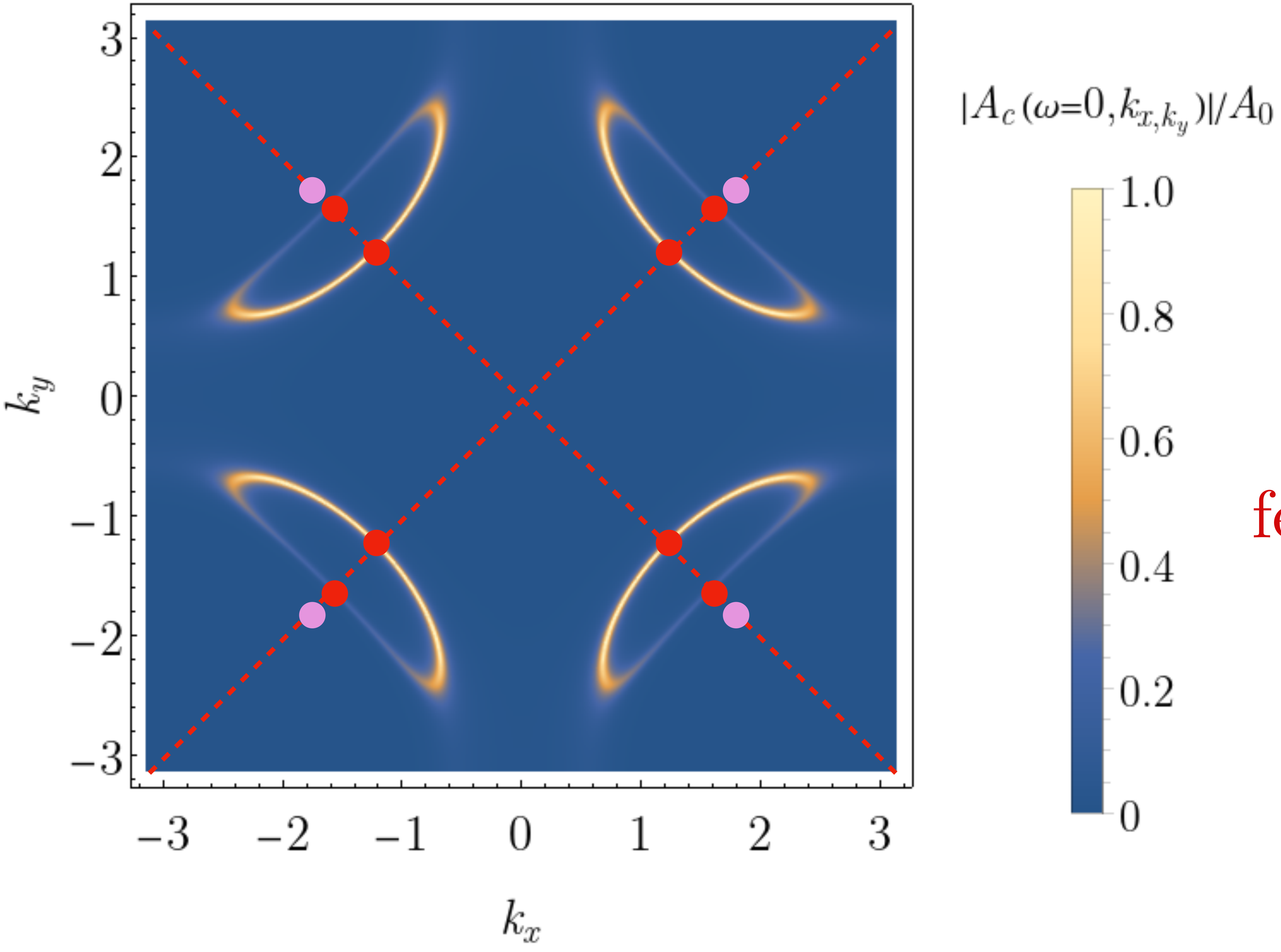


$$E_{\boldsymbol{k}} = \left(\varepsilon_{\boldsymbol{k}}^2 + \Delta_{\boldsymbol{k}}^2\right)^{1/2}$$

$$\Delta_{\boldsymbol{k}} = \Delta_0 \left(\cos k_x - \cos k_y\right)$$

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

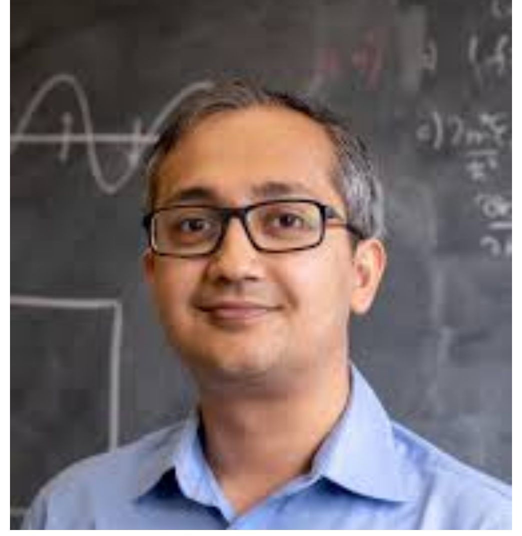
FL*→dSC*

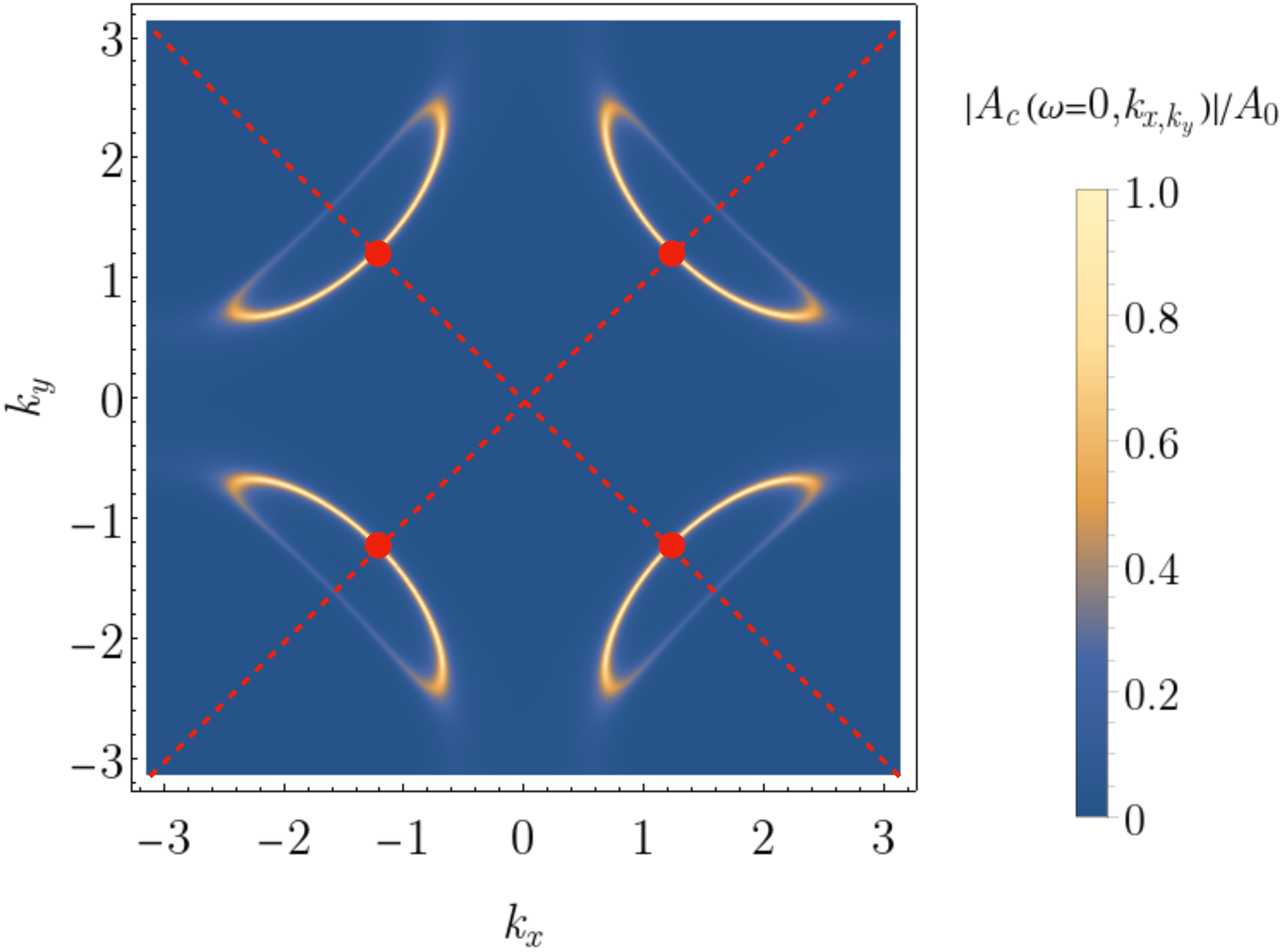


8 nodal points of
Bogoliubov quasiparticles
from the Fermi pockets
and
4 nodal points of
fermionic Dirac spinons from
the π-flux spin liquid

FL*→dSC

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





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

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.

FL*→dSC

Shubhayu Chatterjee and S. Sachdev,
PRB **94**, 205117 (2016)
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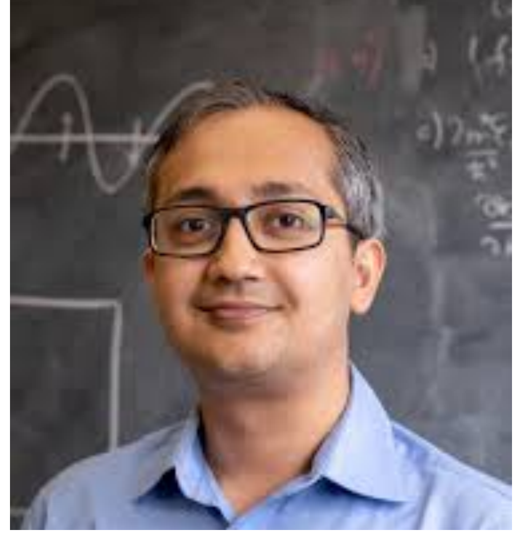
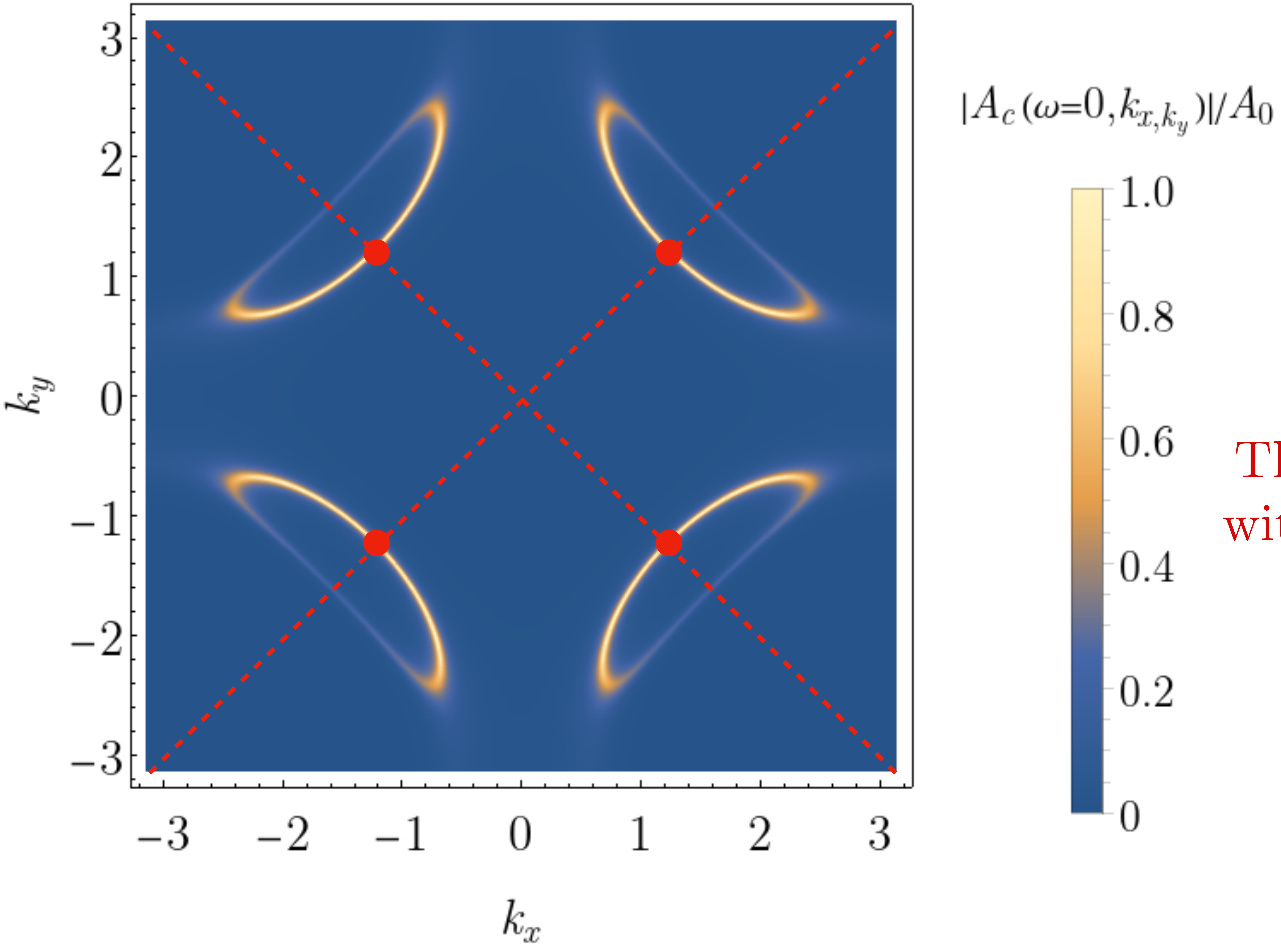
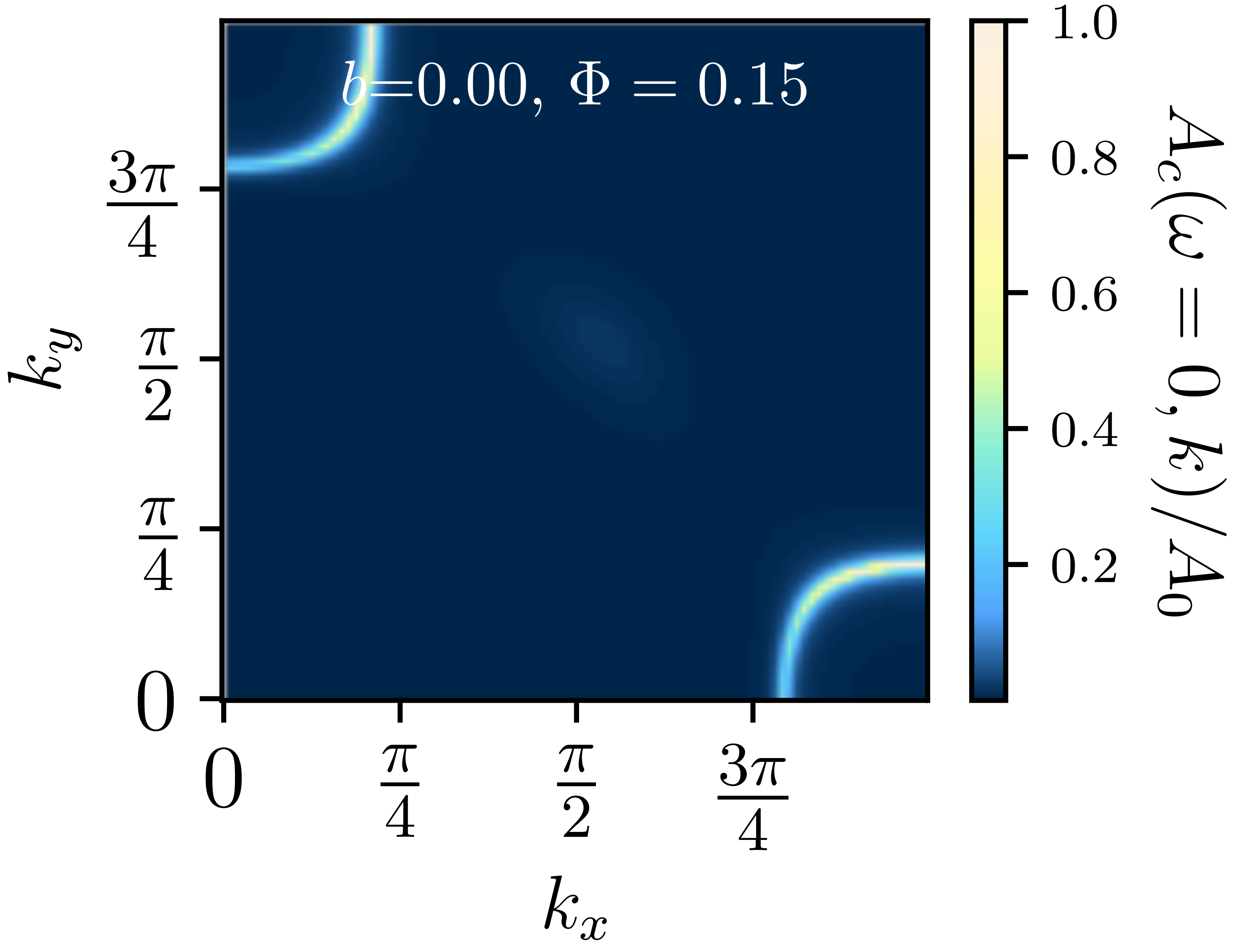




The spinons do *not* become the Bogoliubov quasiparticles, they *annihilate* the unwanted Bogoliubov quasiparticles.
This leads to a d-wave superconductor with 4 nodal Bogoliubov quasiparticles, with $v_F \gg v_\Delta$, consistent with observations.

Electron spectral density in electron-doped cuprates



FL*

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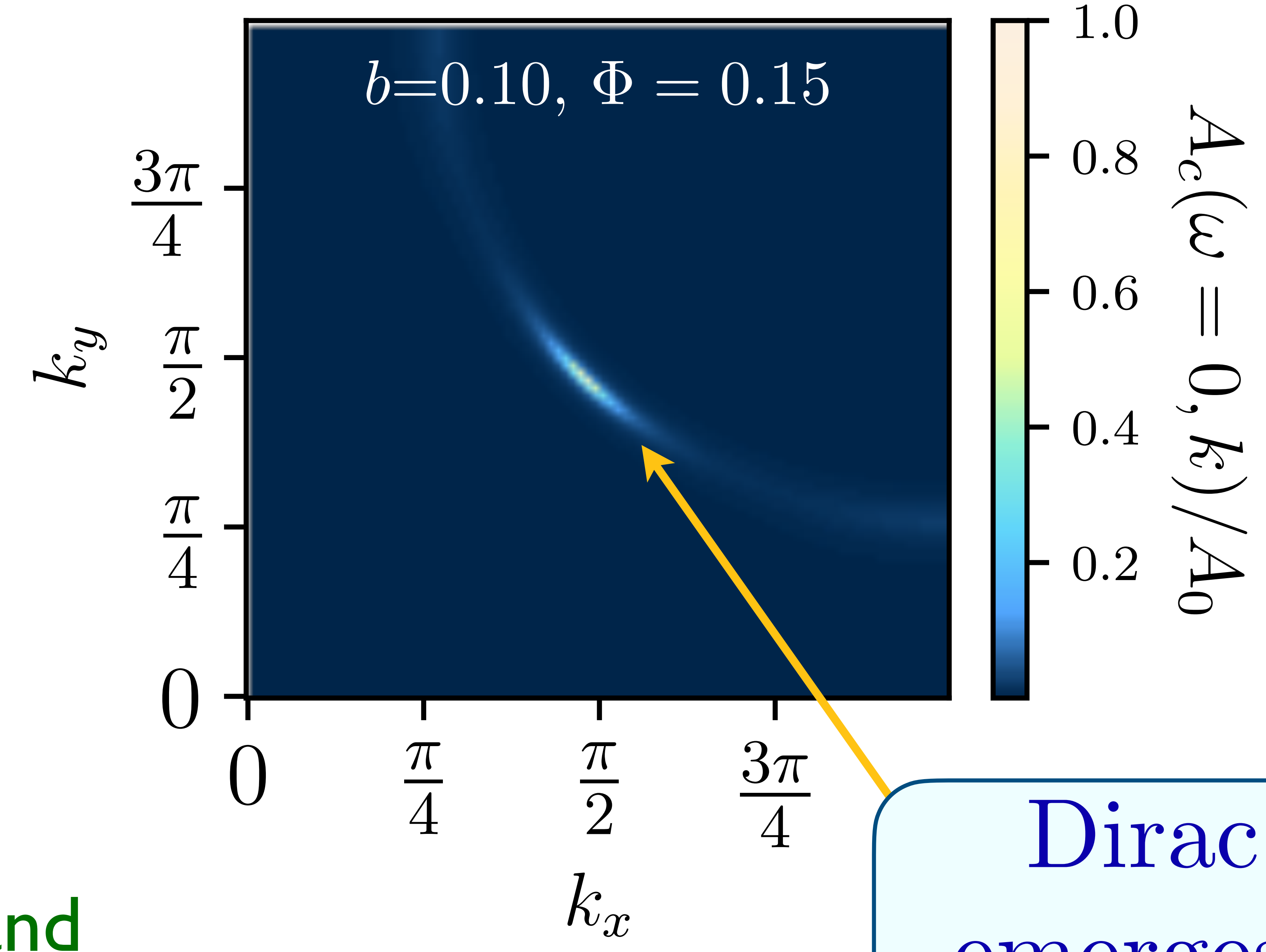

Dirac node emerges inside normal state gap

dSC

In the electron-doped case, nodes of the d-wave superconductor *are* remnants of the spinons of the π-flux state.

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

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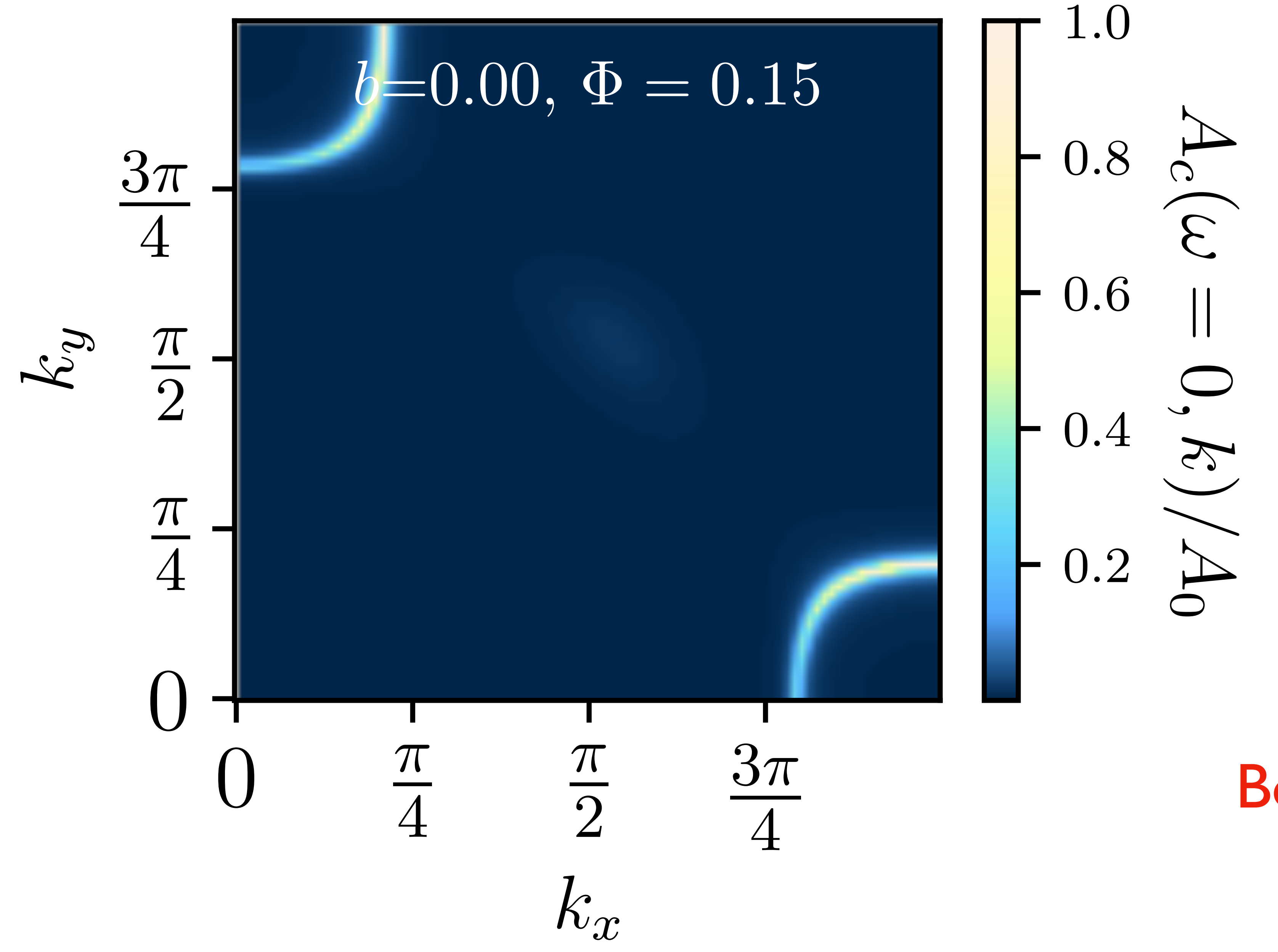
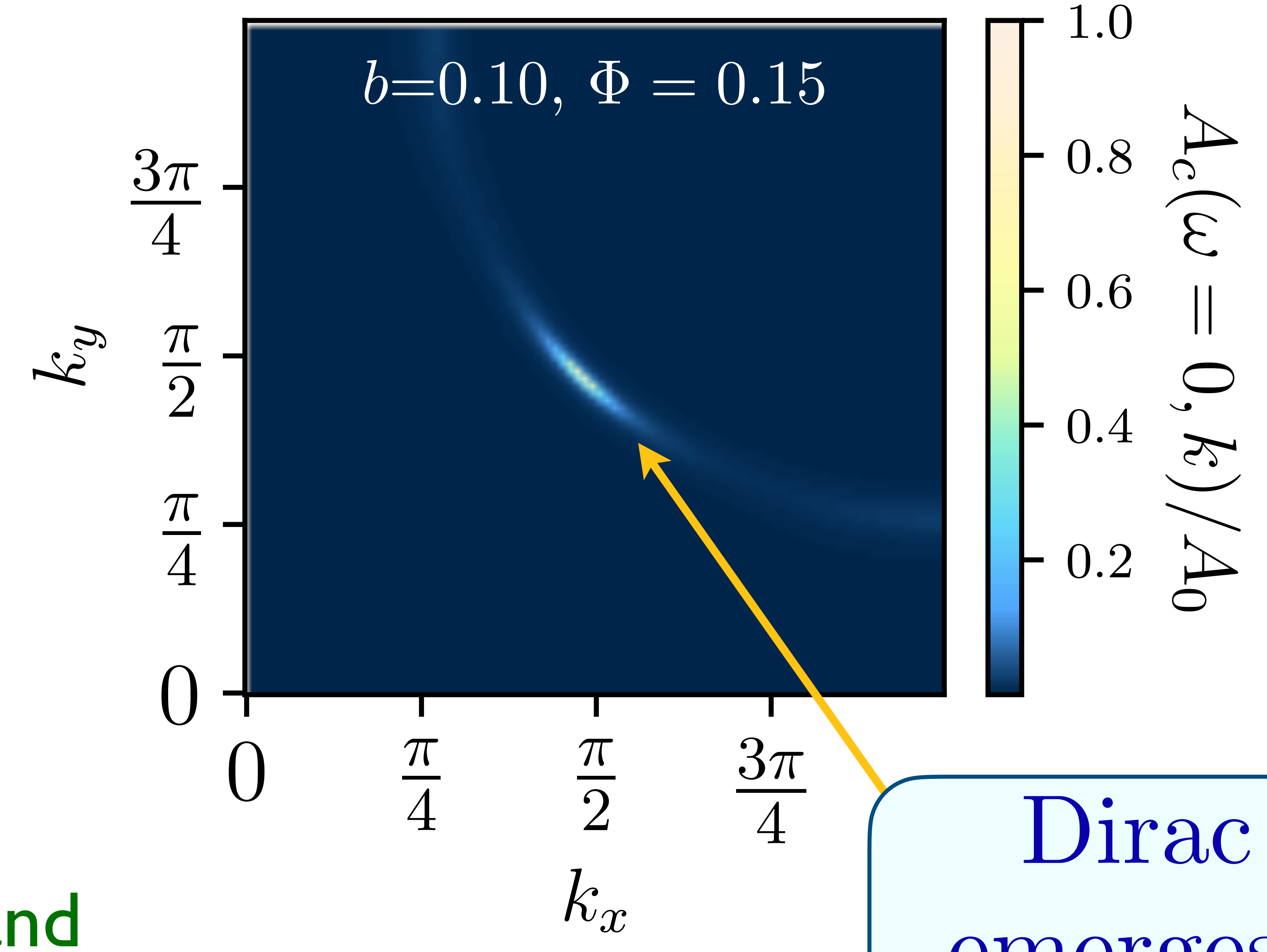
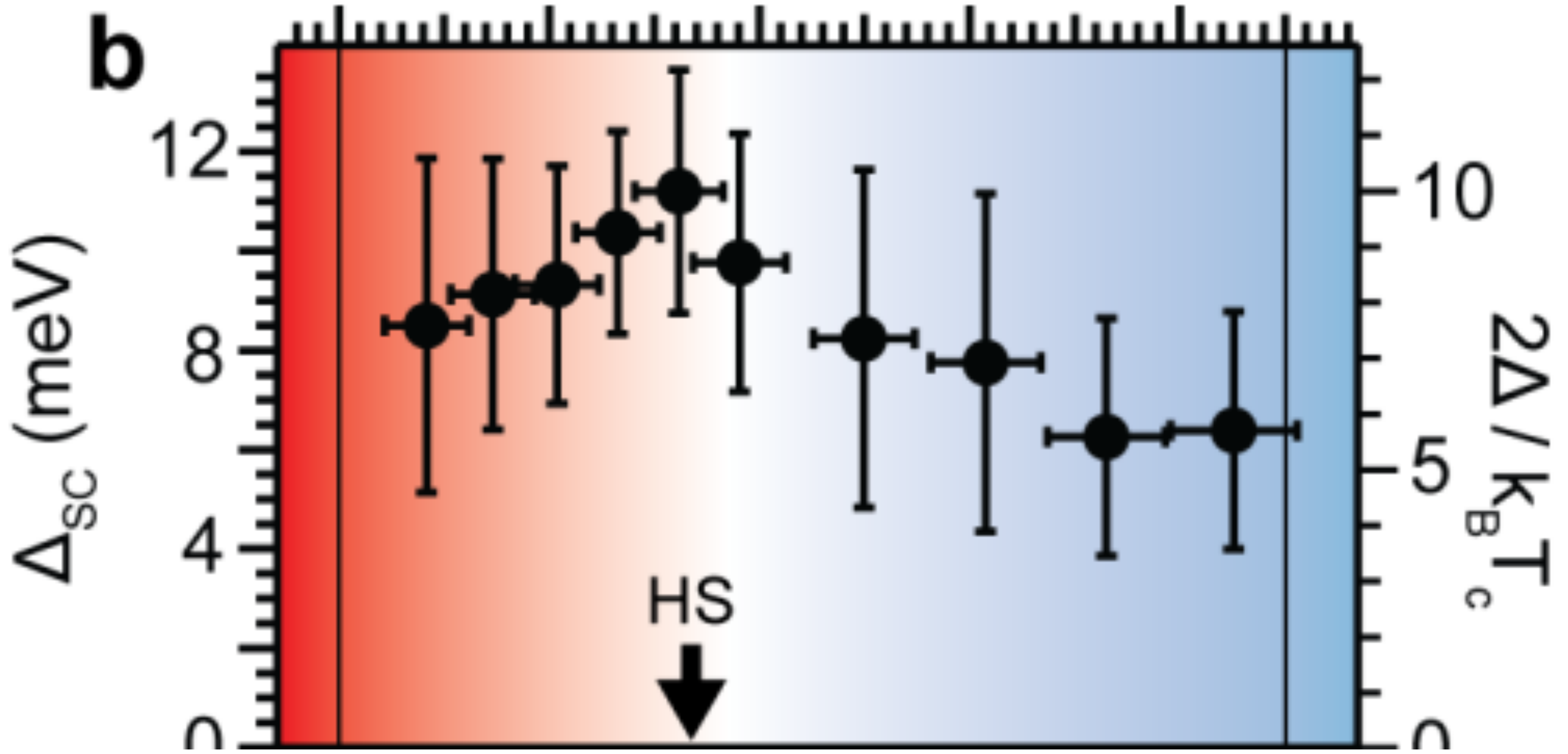
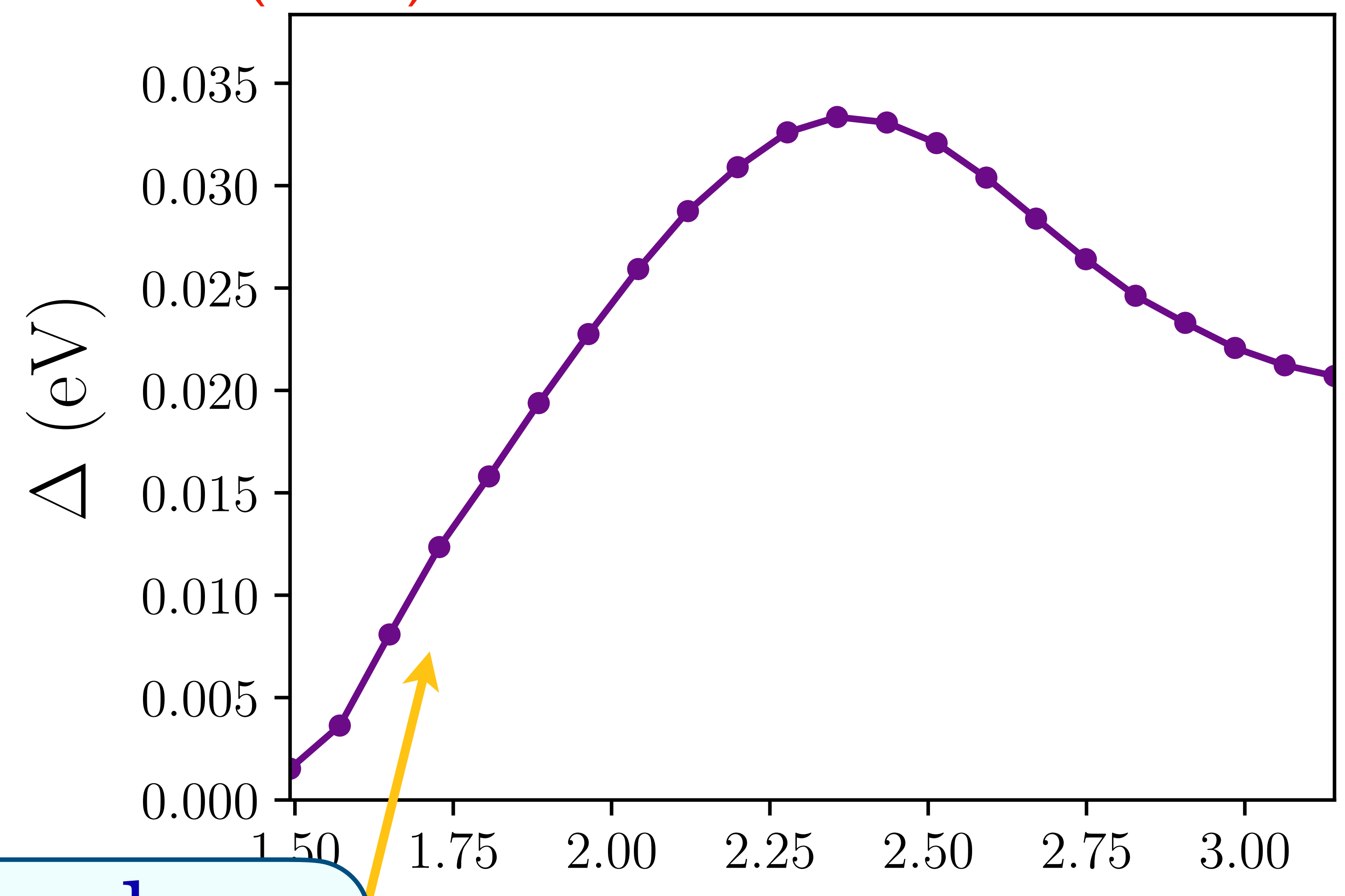




Maine Christos and S.Sachdev, npj Quantum Materials **9**, 4 (2024)



Bogoliubov Quasiparticle on the Gossamer Fermi Surface in Electron-Doped Cuprates, Ke-Jun Xu……Z.-X. Shen; Nature Physics **19**, 1834 (2023)



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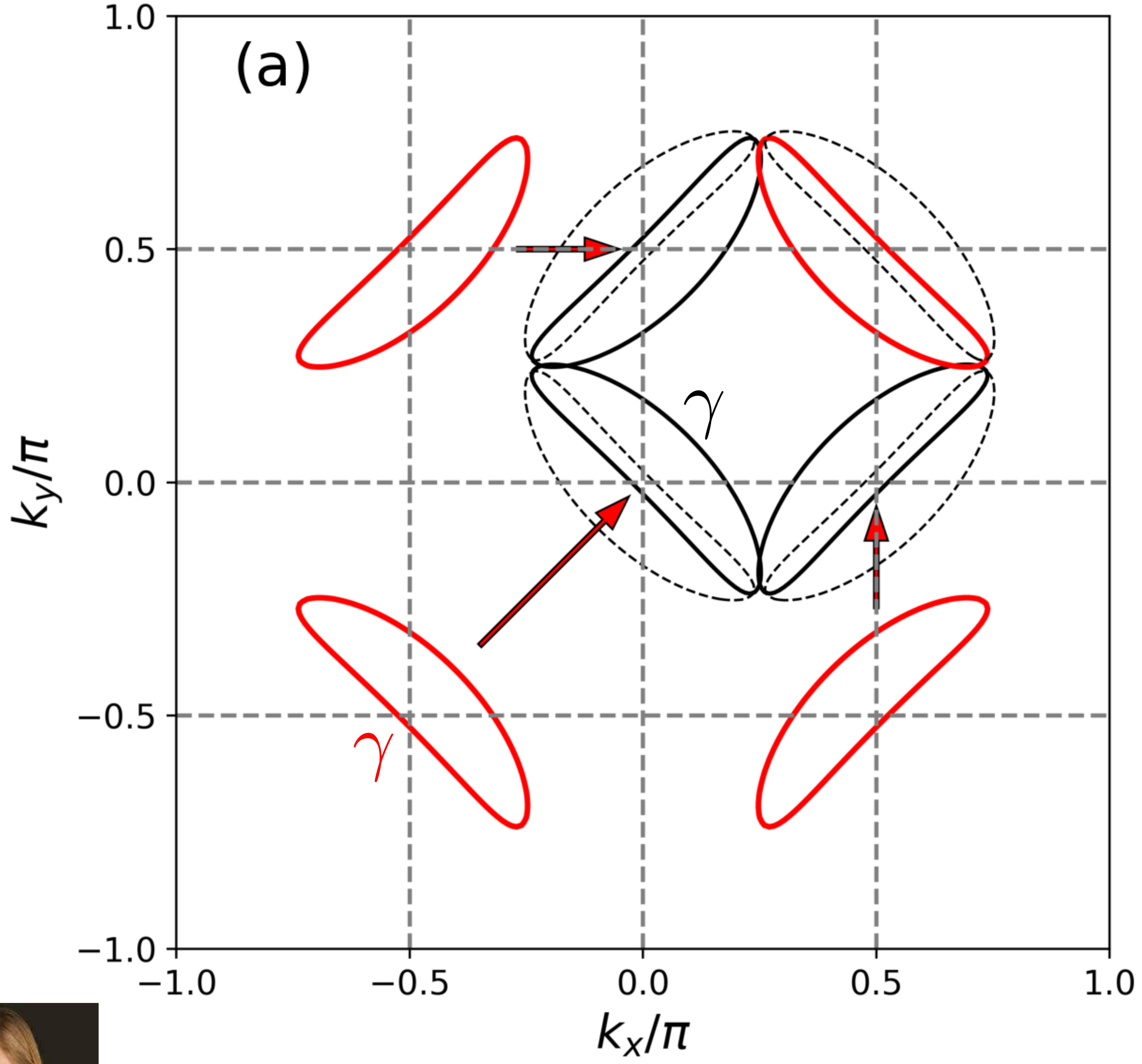
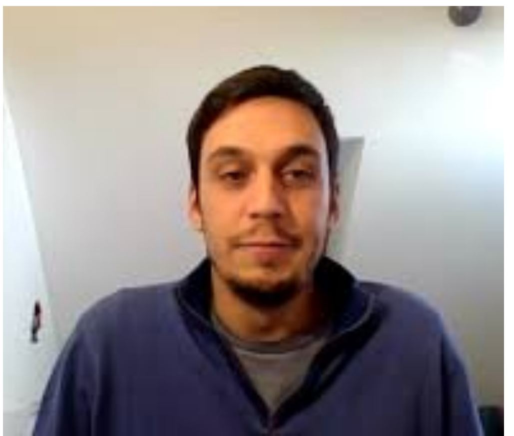
FL*

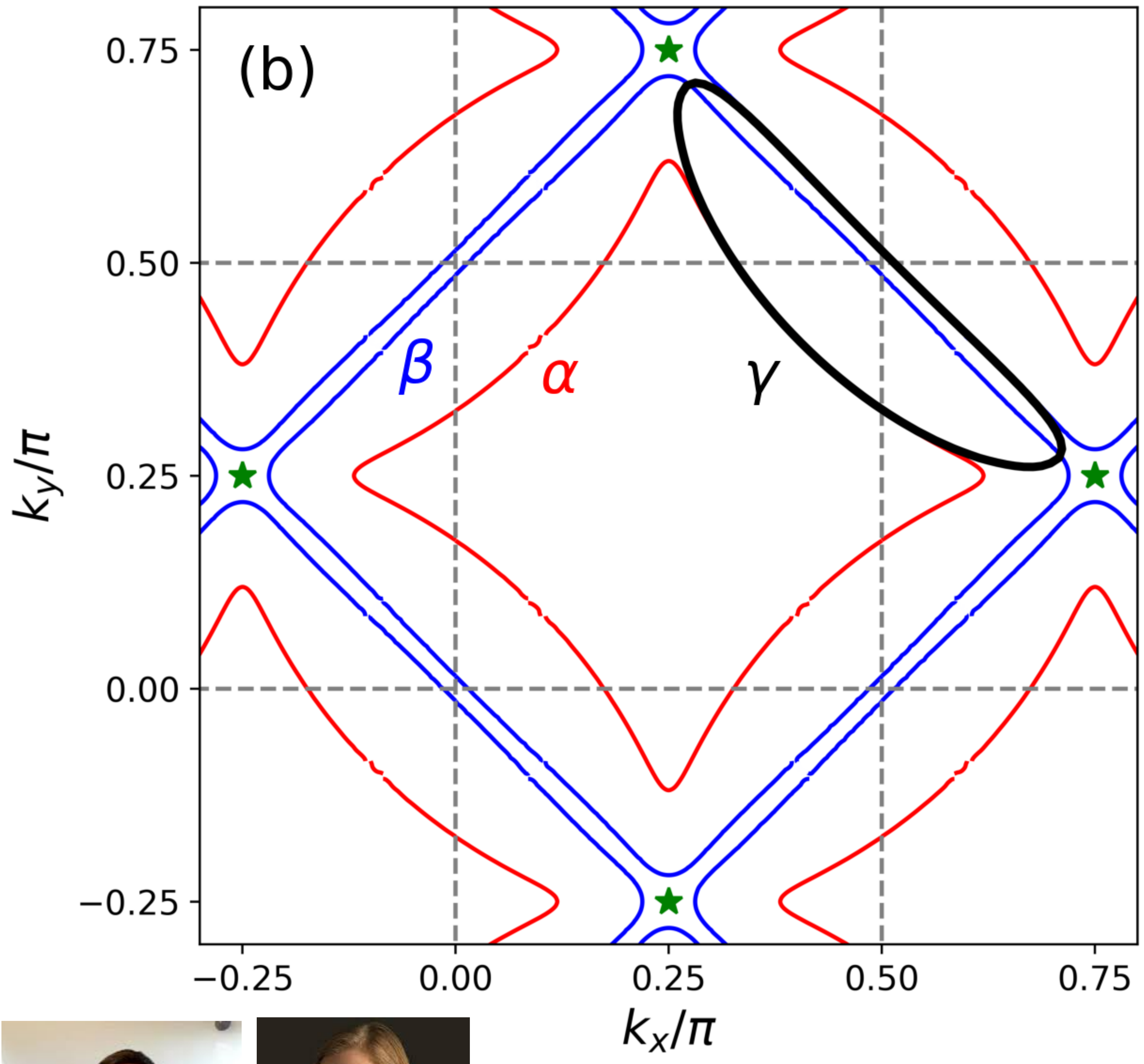


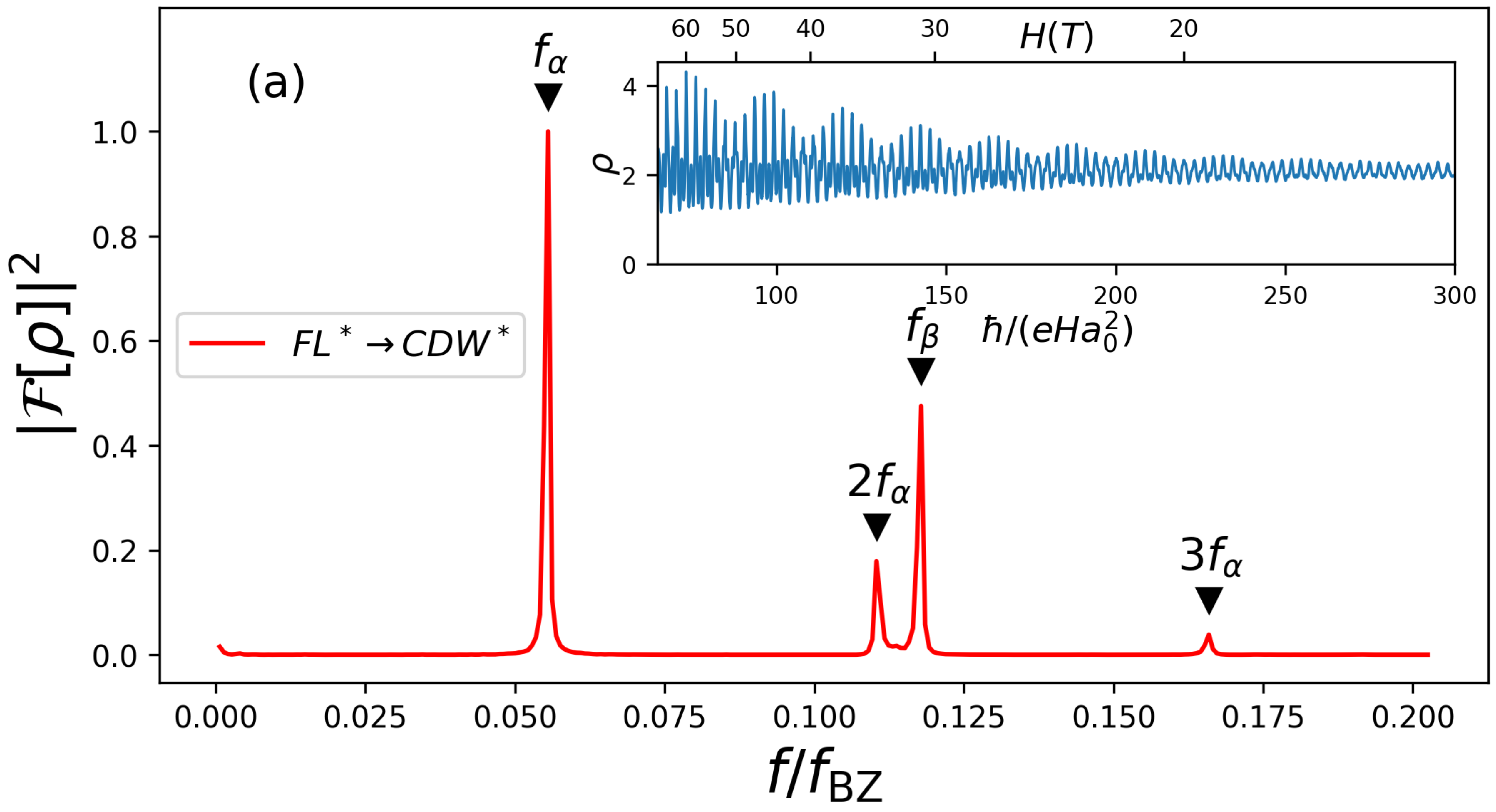
N. Harrison and S. Sebastian
electron pocket
(PRL **106**, 226402 (2011))



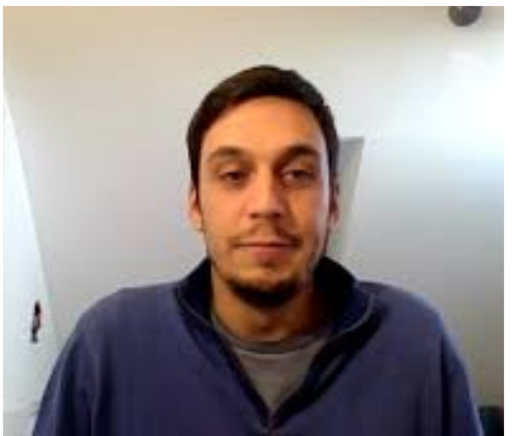
Pietro Bonetti, Maine Christos and S.S. (BCS), arXiv:2405.08817

FL*→CDW*





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



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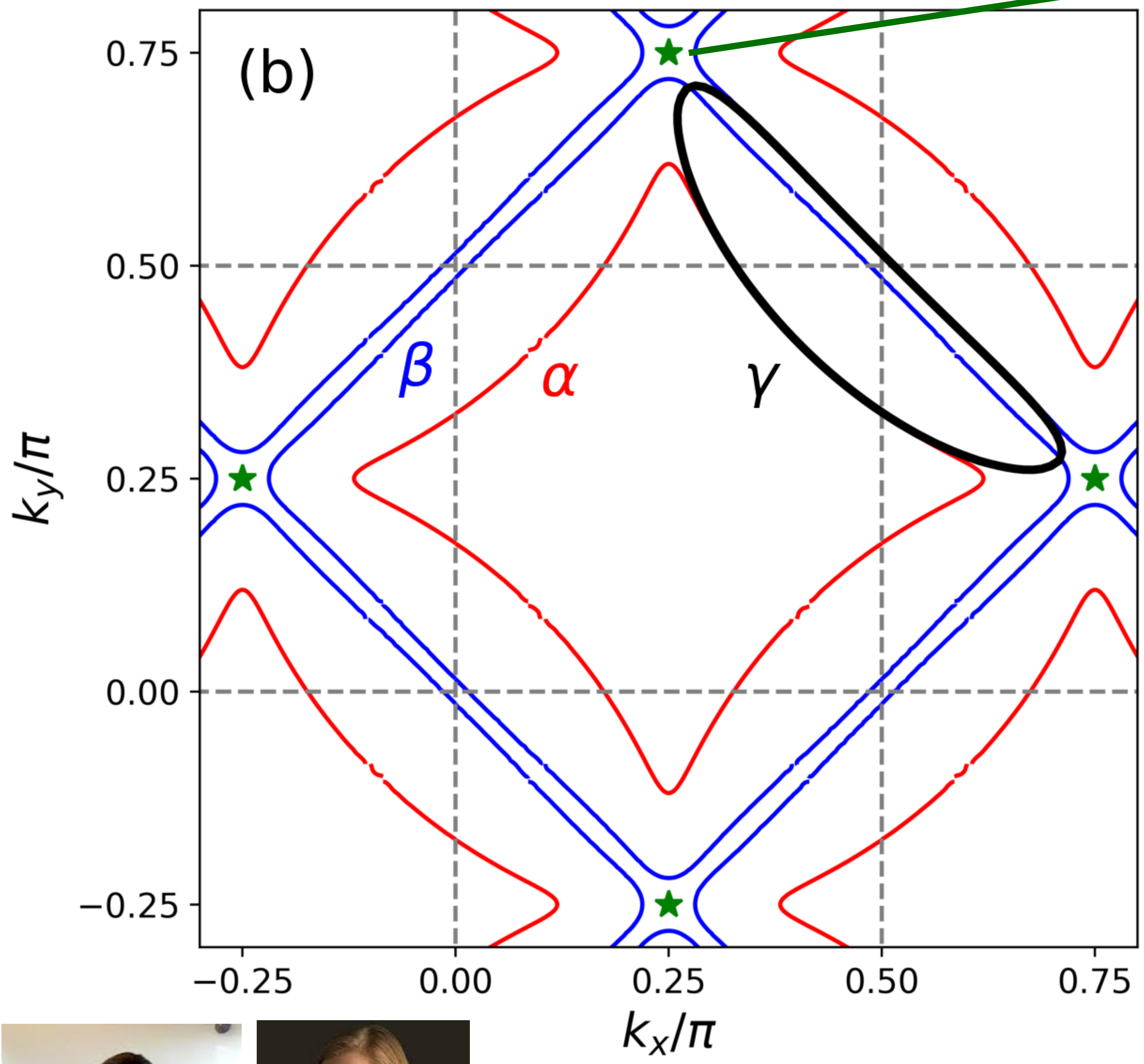
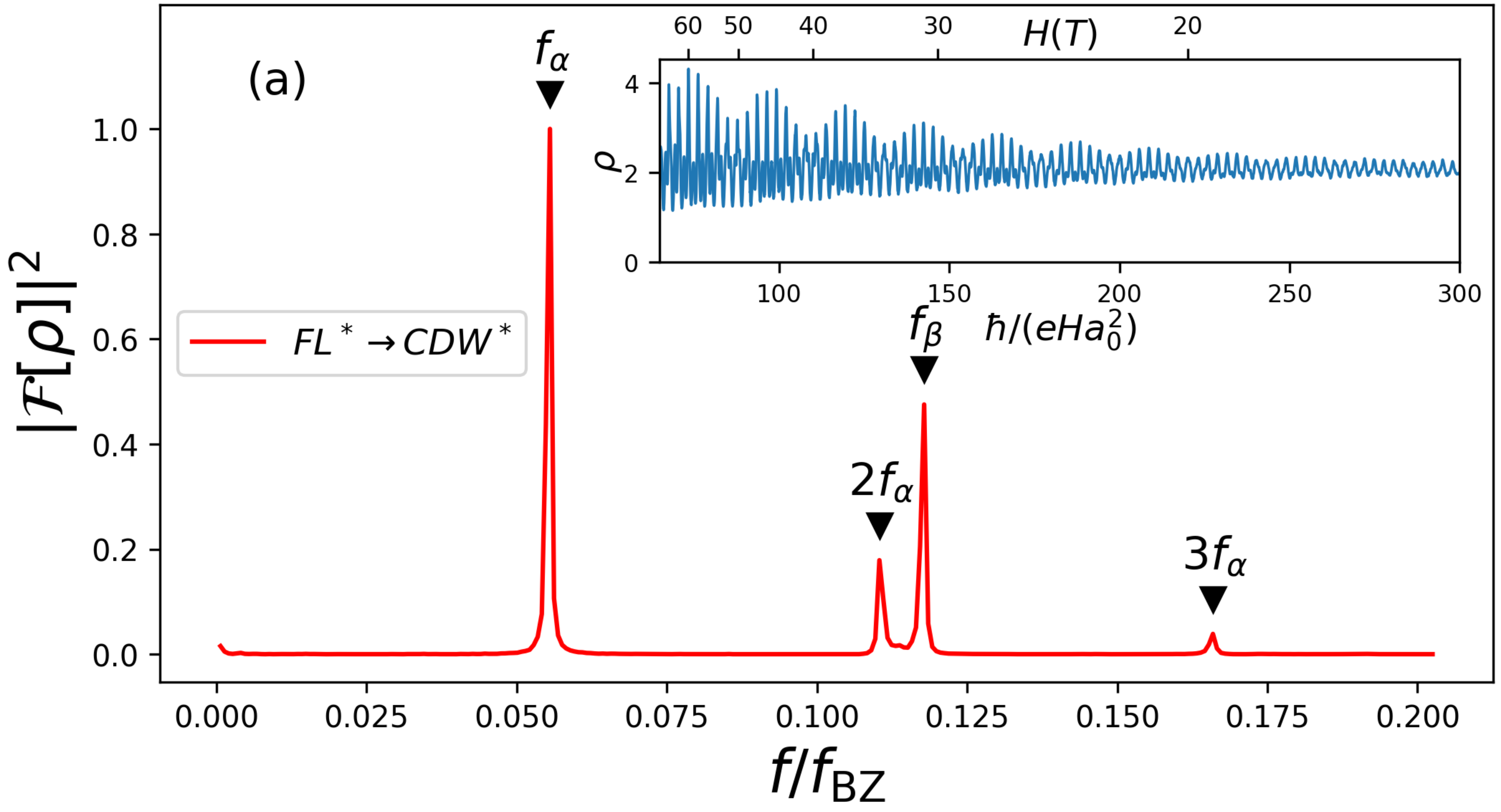
FL*→CDW*

Spinon





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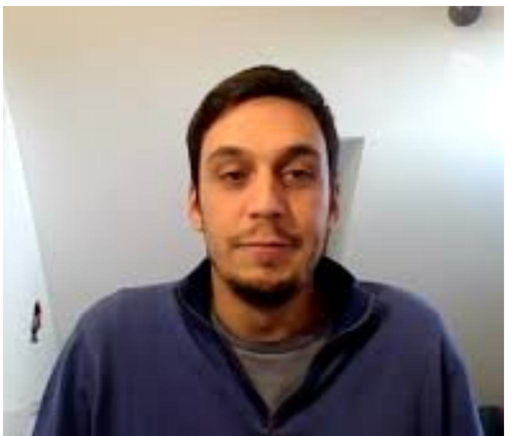

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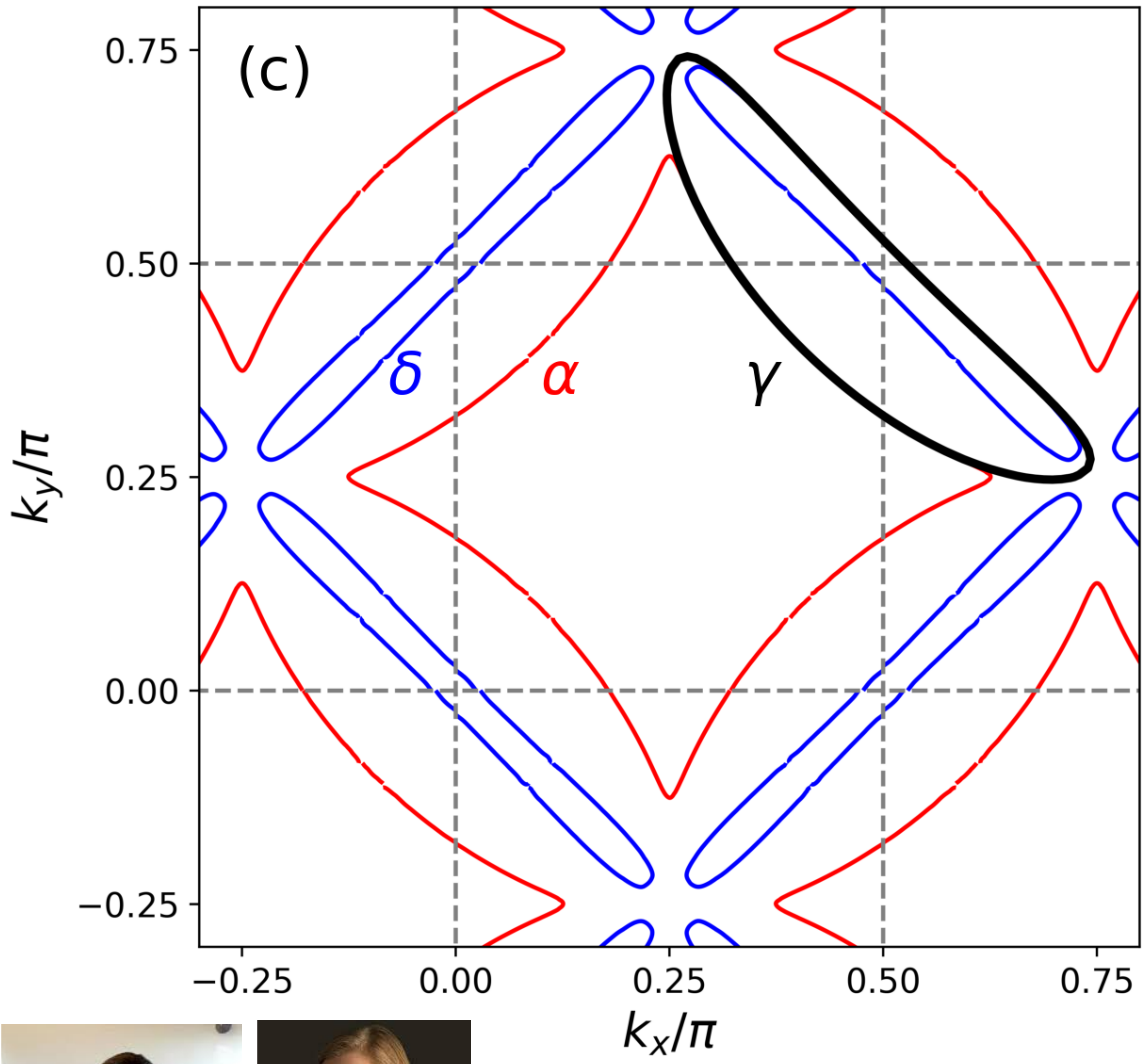
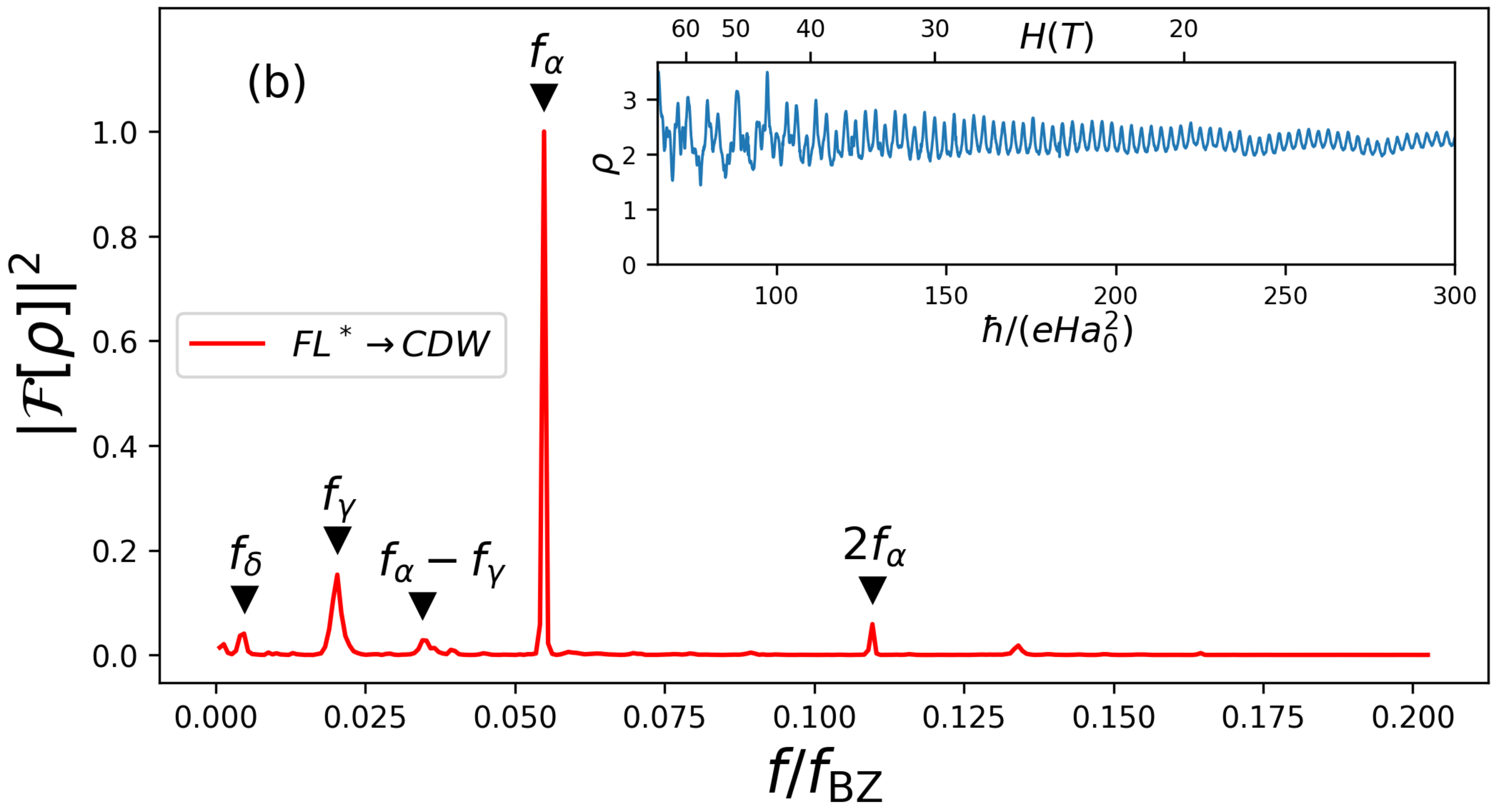
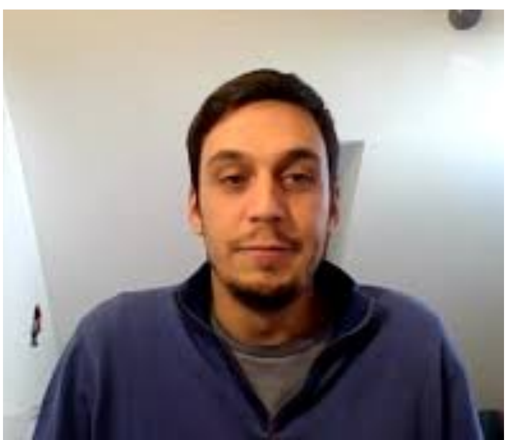




Period 4 CDW obtained by condensing B. Mixing between electrons and spinons removes β pocket.



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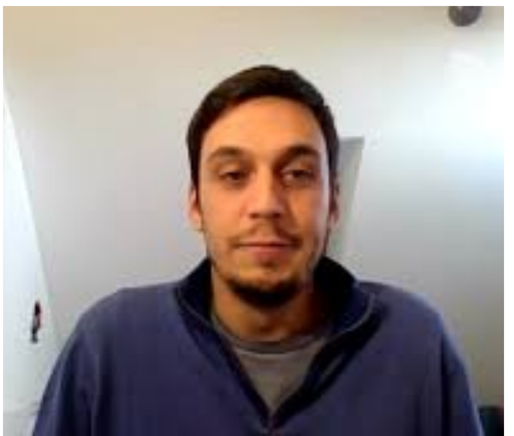
$$S(\boldsymbol{q}, \omega) \sim \omega^{2\Delta_{\boldsymbol{q}} - 3}$$

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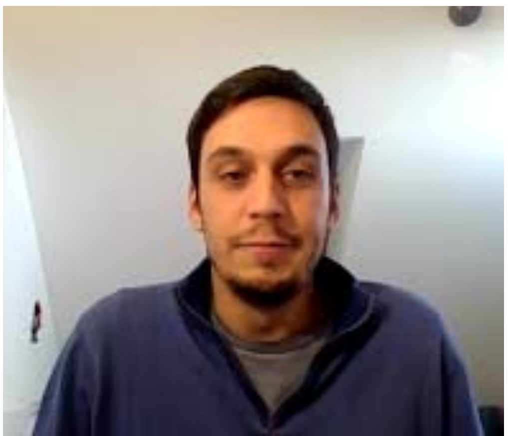

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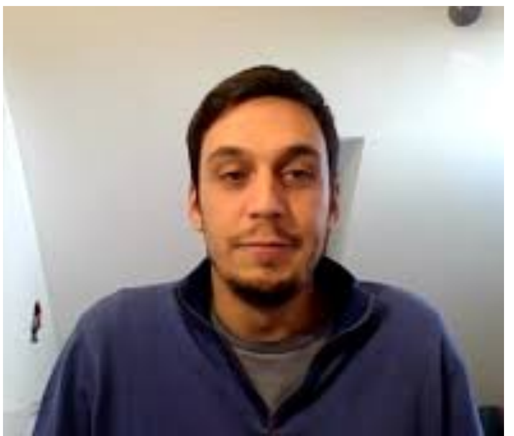


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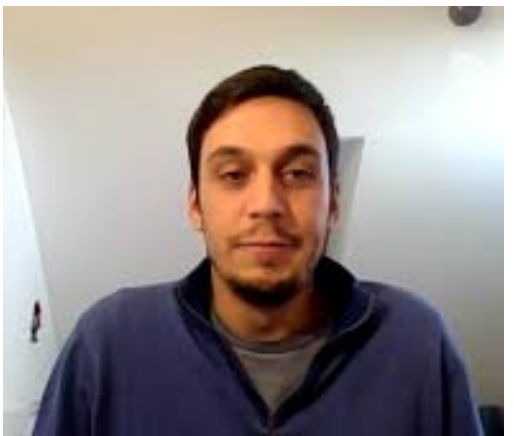
These results imply that the free Dirac fermion theory of the spin liquid is not accurate for $S(\boldsymbol{q}, \omega)$, but is useful for fermiology. The bosonic $\mathbb{CP}^1$ theory of the *same* spin liquid should be a better starting point for $S(\boldsymbol{q}, \omega)$.

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Pseudogap puzzles & answers:

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Spinons required by non-Luttinger Fermi surface in A solve puzzles B, C, D!