Paramagnon fractionalization theory of the cuprate pseudogap

Quantum Simulation of Doped Hubbard Systems
ITAMP, Harvard, Nov 15, 2022

Subir Sachdev

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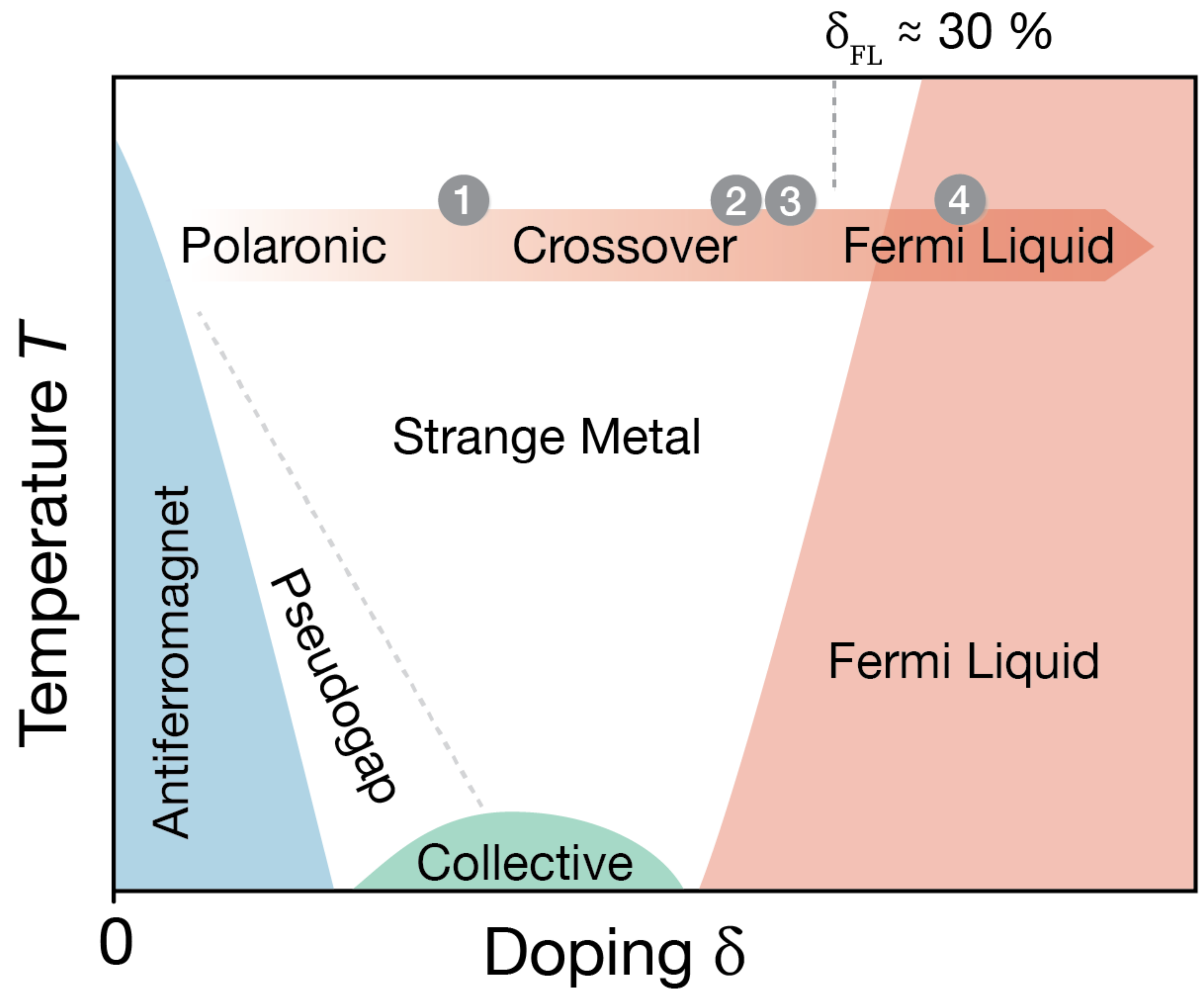
Talk online: sachdev.physics.harvard.edu

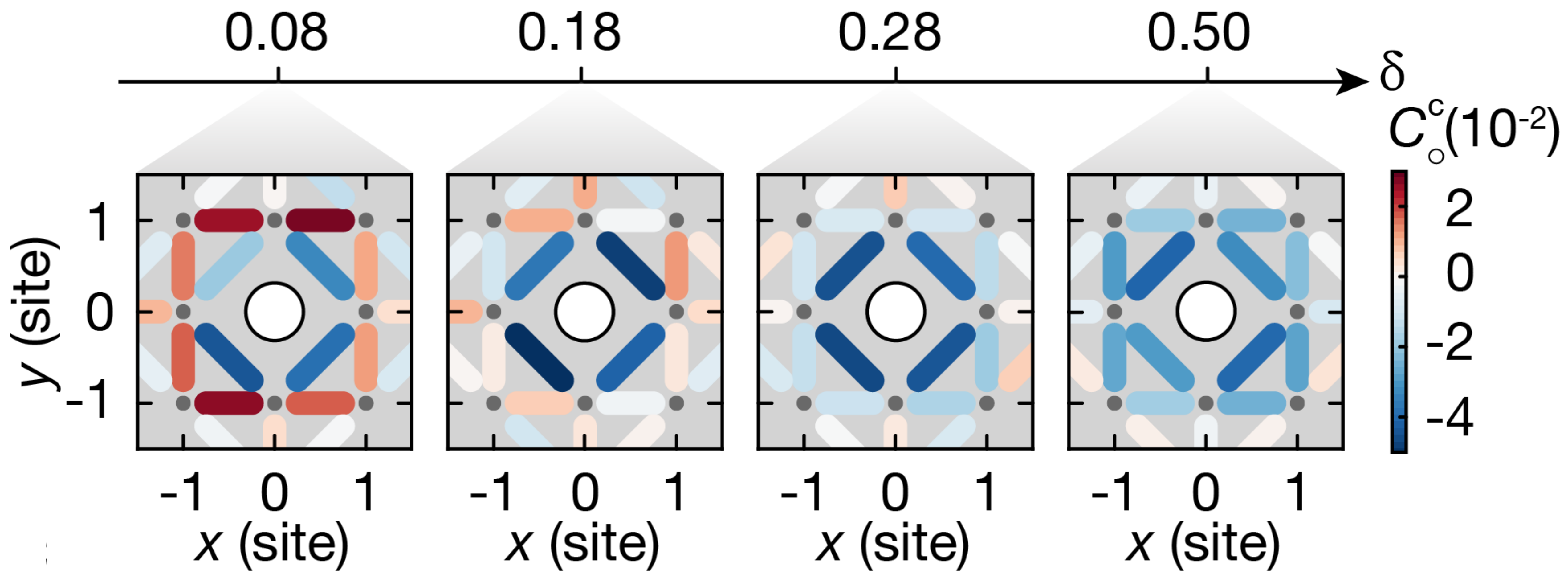


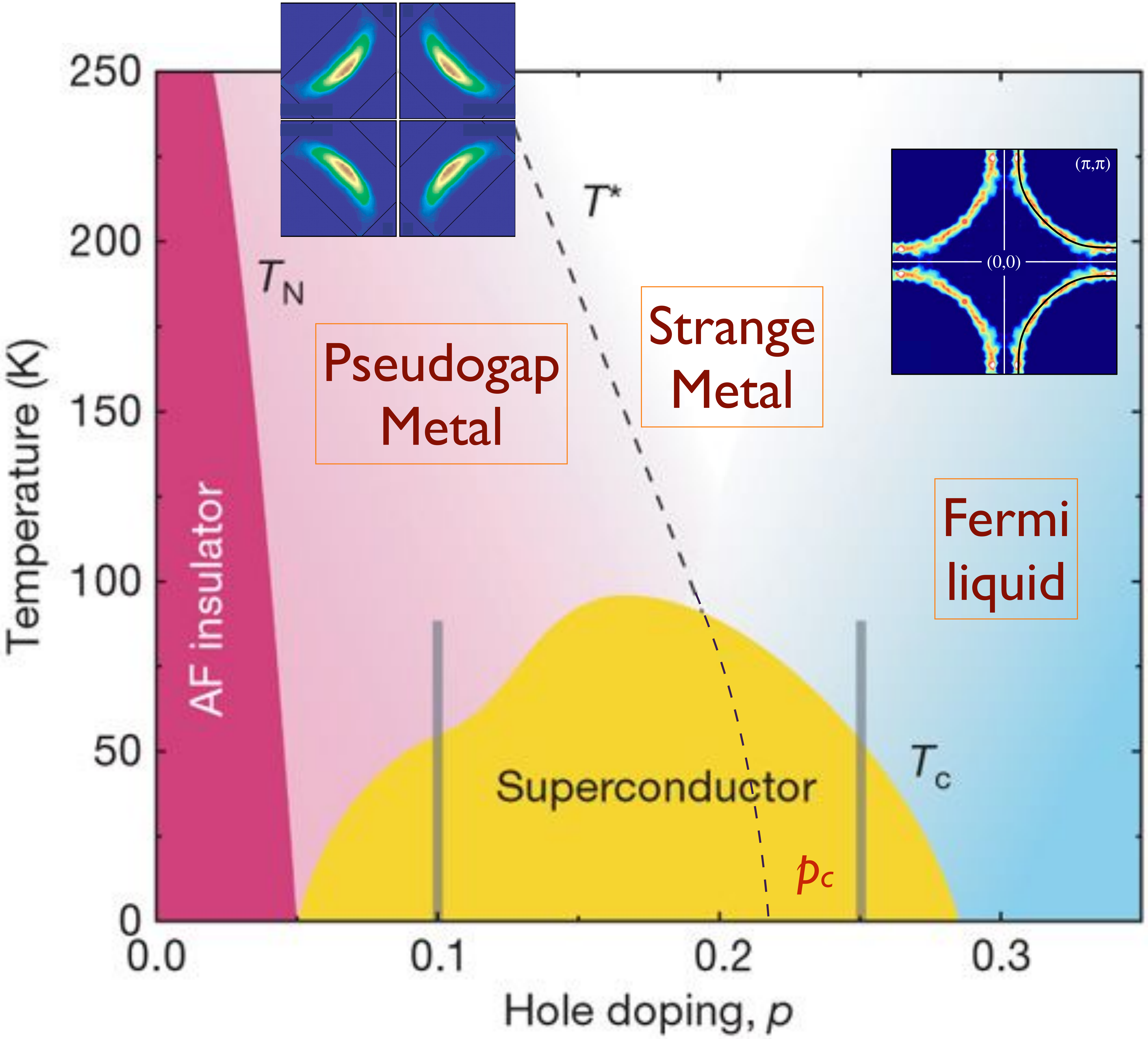
Ultracold fermionic atoms in optical lattices

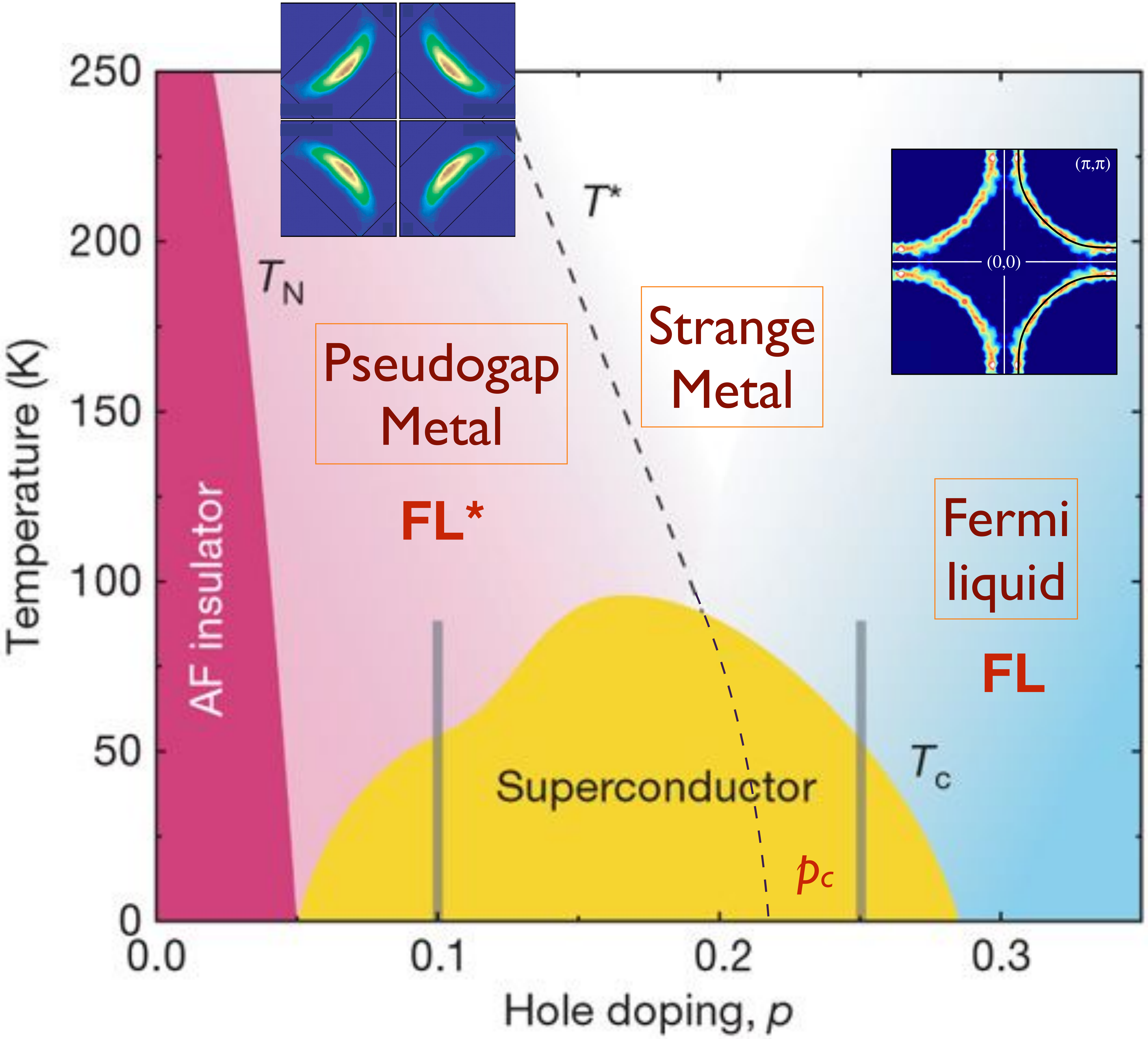
Microscopic evolution of doped Mott insulators from polaronic metal to Fermi liquid

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

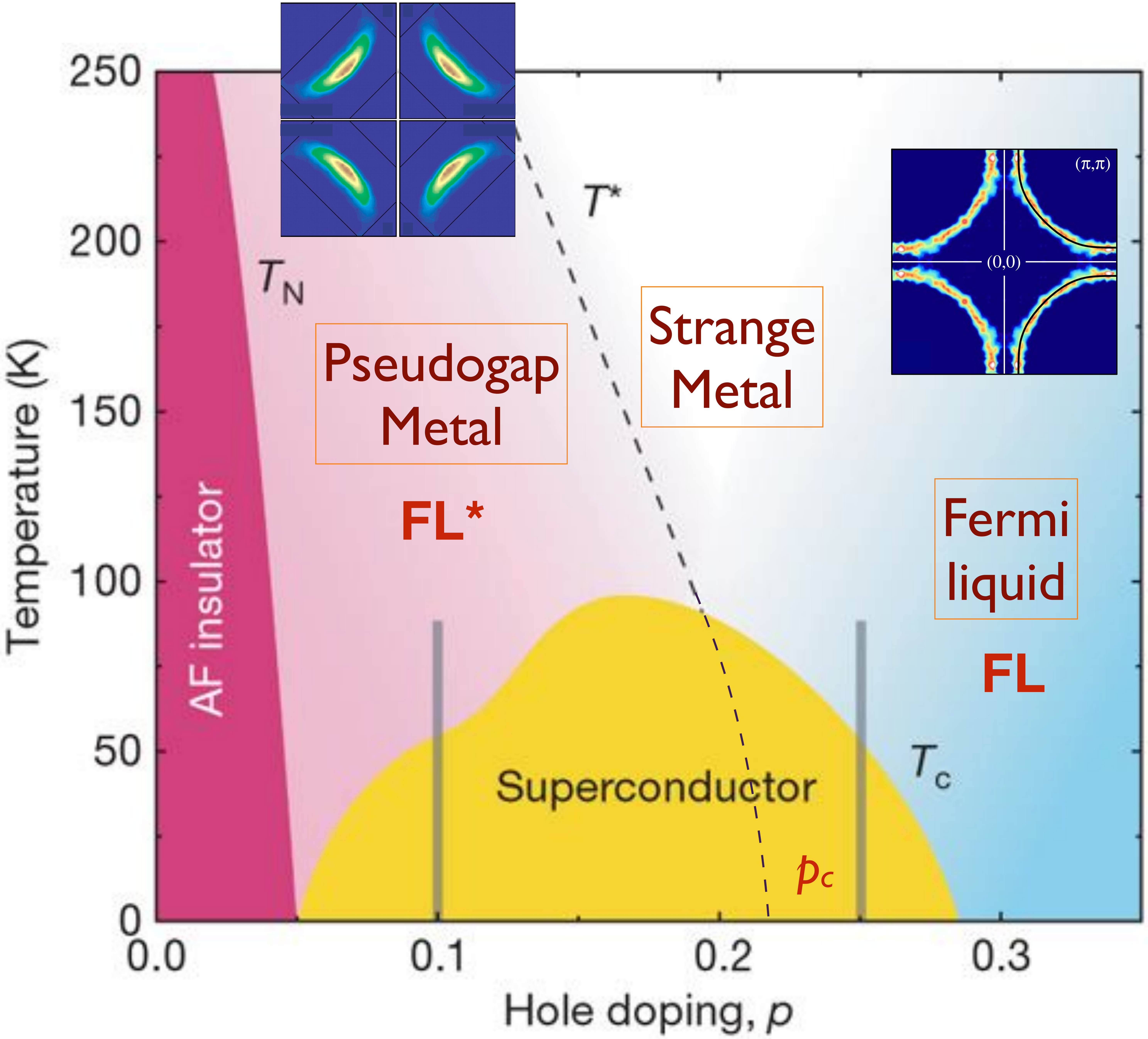
Science **374** (2021) 82




250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
T*
(π,π)
(0,0)
T_N
Pseudogap Metal
Strange Metal
Fermi liquid
AF insulator
Superconductor
T_c
p_c



- View the pseudogap metal as quantum state (FL*), which could be stable at $T = 0$ under suitable conditions.



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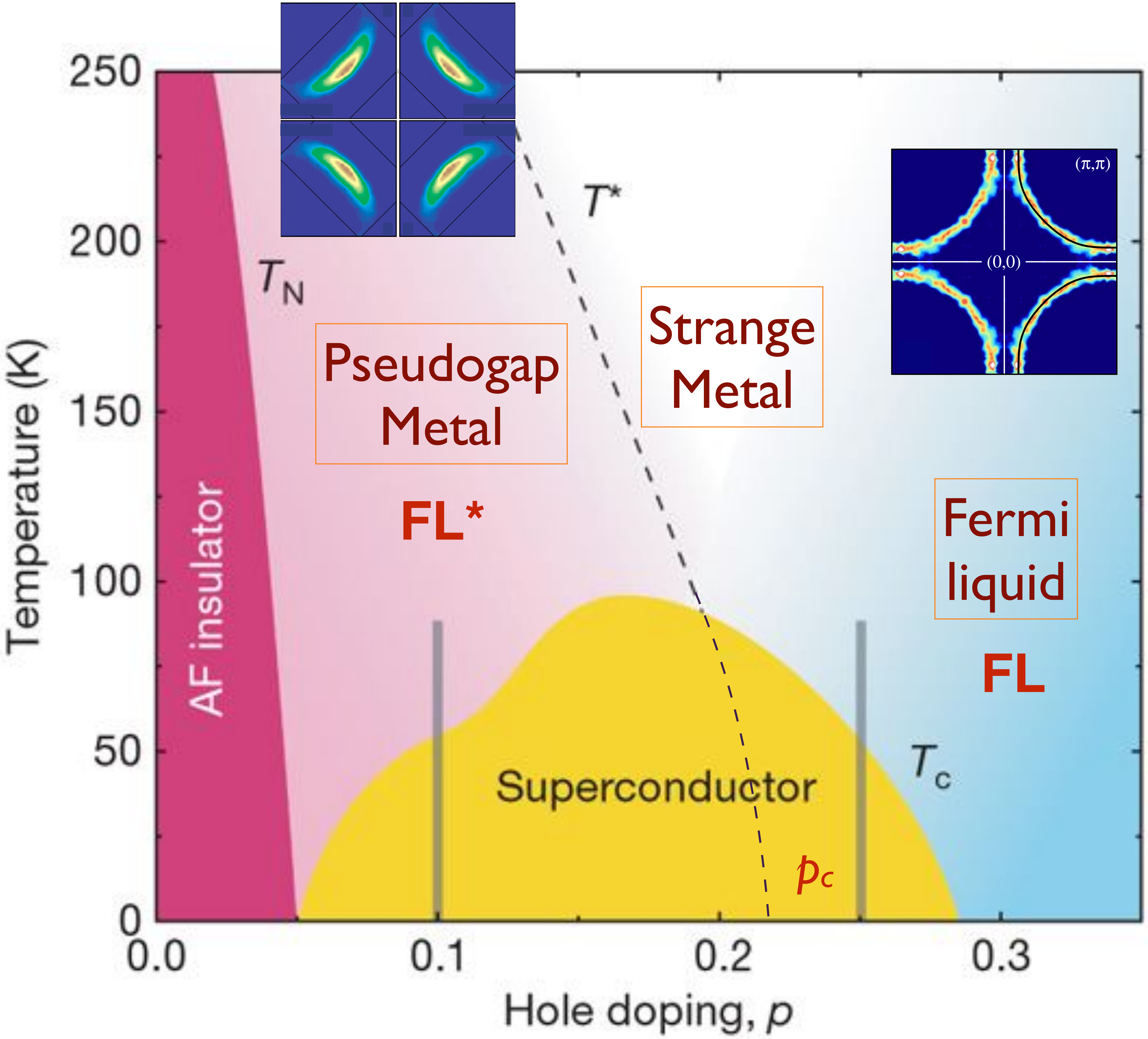


- View the pseudogap metal as quantum state (FL*), which could be stable at $T = 0$ under suitable conditions.
- Start with a mean-field theory of FL*, which yields a variational wavefunction.
- FL* will serve as the ‘parent’ for the other regions in the phase diagram.

1. Paramagnon fractionalization theory of the Hubbard model

2. Photoemission in the cuprates

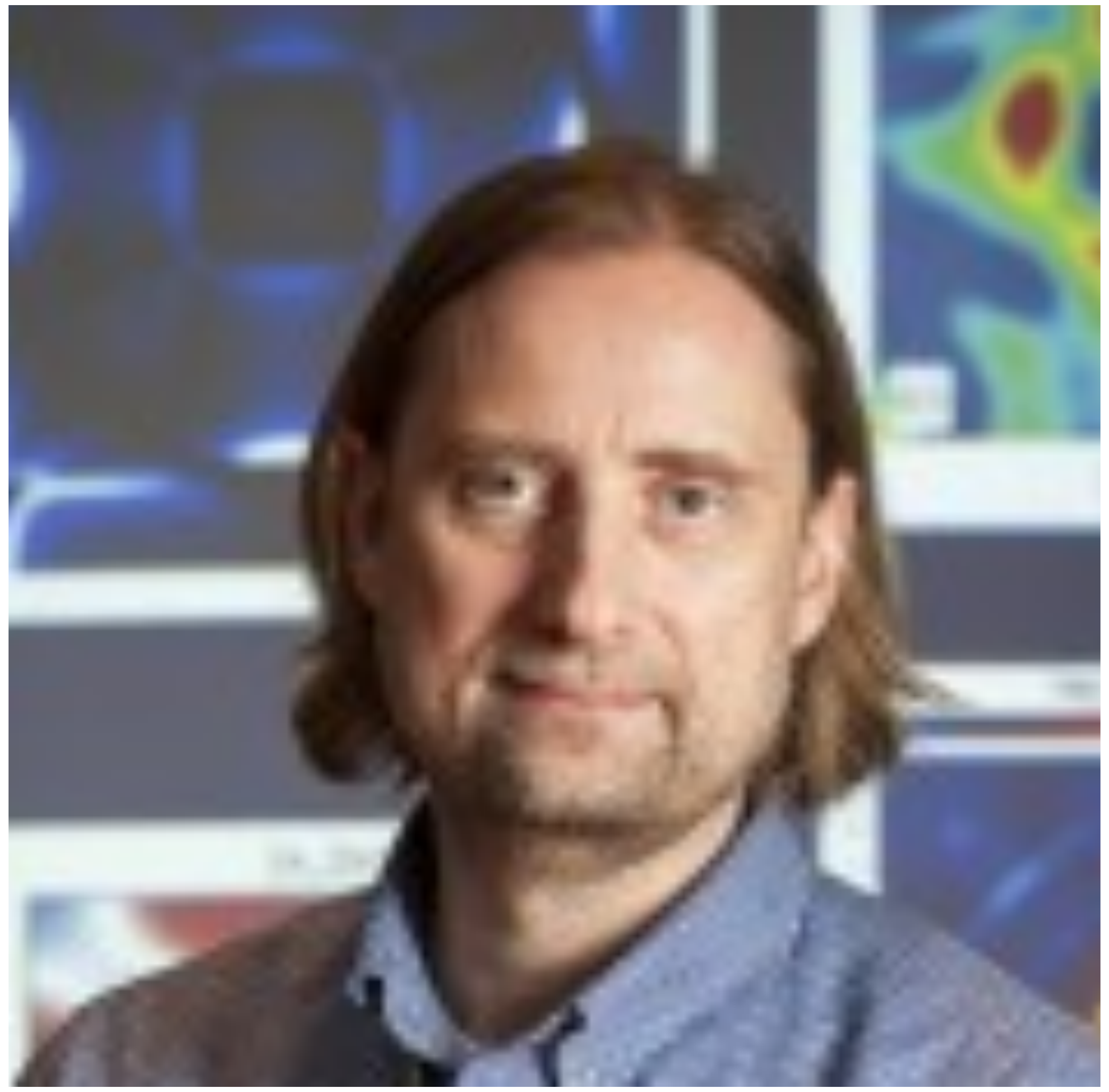
3. Confinement transitions from the pseudogap metal

Yahui Zhang

Alexander Nikolaenko

Maria Tikhanovskaya

Eric Mascot



Dirk Morr

arXiv: 2001.09159
arXiv: 2103.05009

arXiv: 2006.01140
arXiv: 2111.13703

Paramagnon theory of the Hubbard model

$$H = -\sum_{i<j} t_{ij} c_{i\sigma}^\dagger c_{j\sigma} + U \sum_i \left(n_{i\uparrow} - \frac{1}{2}\right)\left(n_{i\downarrow} - \frac{1}{2}\right) - \mu \sum_i c_{i\sigma}^\dagger c_{i\sigma}$$

We use the operator equation (valid on each site i):

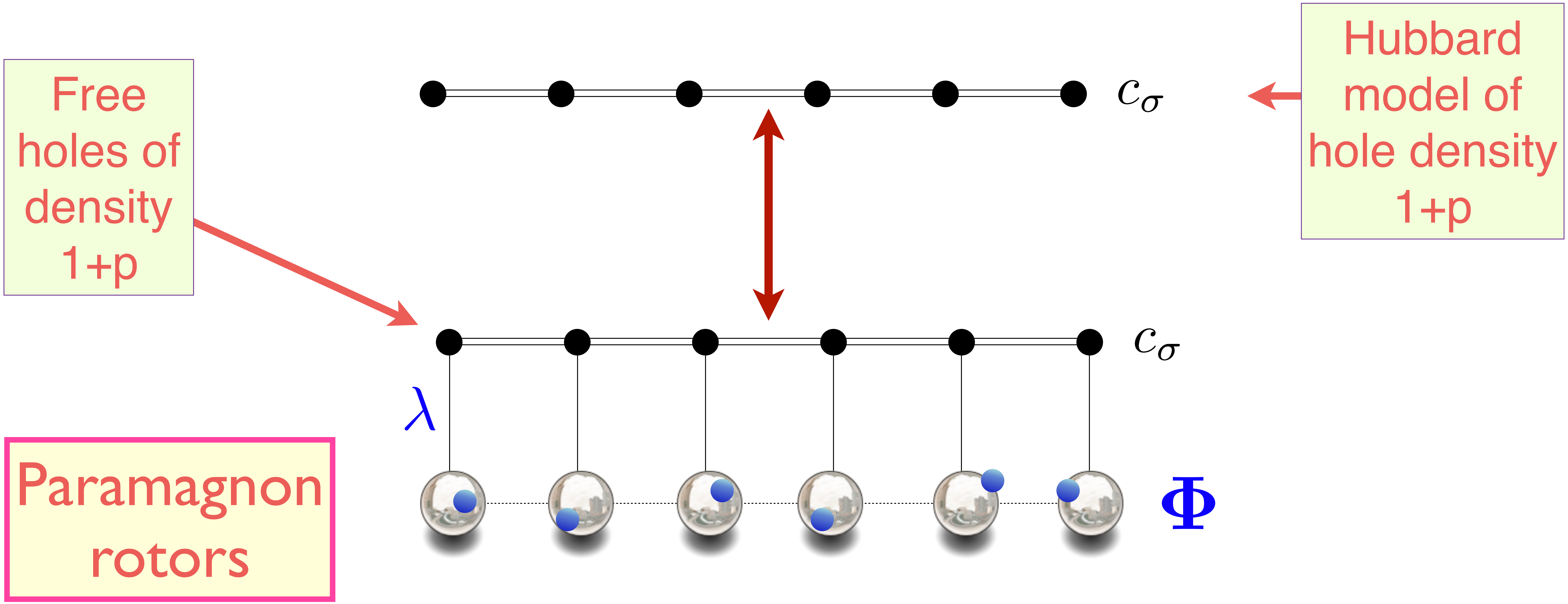
$$U\left(n_\uparrow - \frac{1}{2}\right)\left(n_\downarrow - \frac{1}{2}\right) = -\frac{2U}{3}\boldsymbol{S}^2 + \frac{U}{4}$$

Then we decouple the interaction via

$$\exp\left(\frac{2U}{3}\sum_i \int d\tau \boldsymbol{S}_i^2\right) = \int \mathcal{D}\boldsymbol{\Phi}_i(\tau) \exp\left(-\sum_i \int d\tau \left[\frac{3}{8U}\boldsymbol{\Phi}_i^2 - \boldsymbol{\Phi}_i \cdot c_{i\sigma}^\dagger \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'}\right]\right)$$

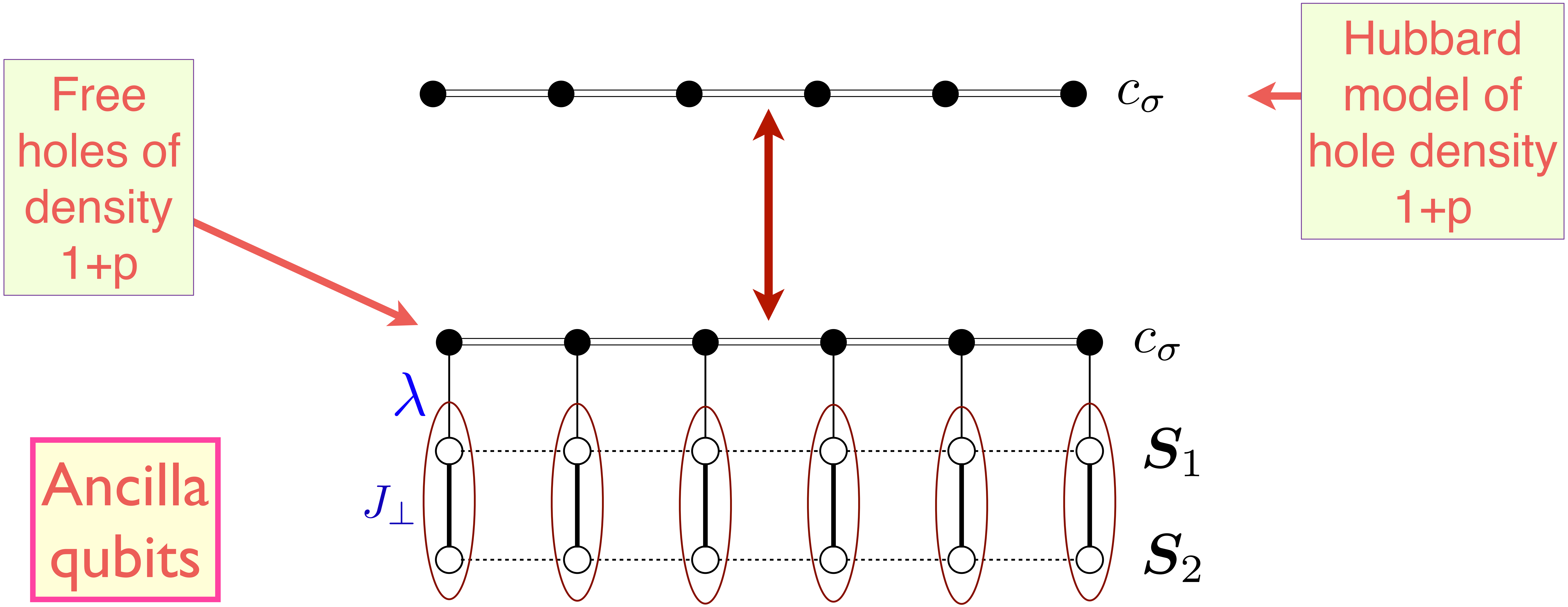
This yields the 'Scalapino-Pines-Chubukov-Schmalian...' theory for a 'paramagnon quantum rotor' $\boldsymbol{\Phi}_i$ coupled to otherwise free fermions $c_{i\sigma}$.

Paramagnon theory of the Hubbard model



$$\mathcal{H}_{\rm paramagnon} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} - \lambda \sum_i c^\dagger_{i\sigma} \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \cdot \mathbf{\Phi}_i + \frac{J_\perp}{2} \sum_i \boldsymbol{P}^2_{\mathbf{\Phi}i} + \sum_i V(\mathbf{\Phi}_i) + \ldots$$

Paramagnon theory of the Hubbard model



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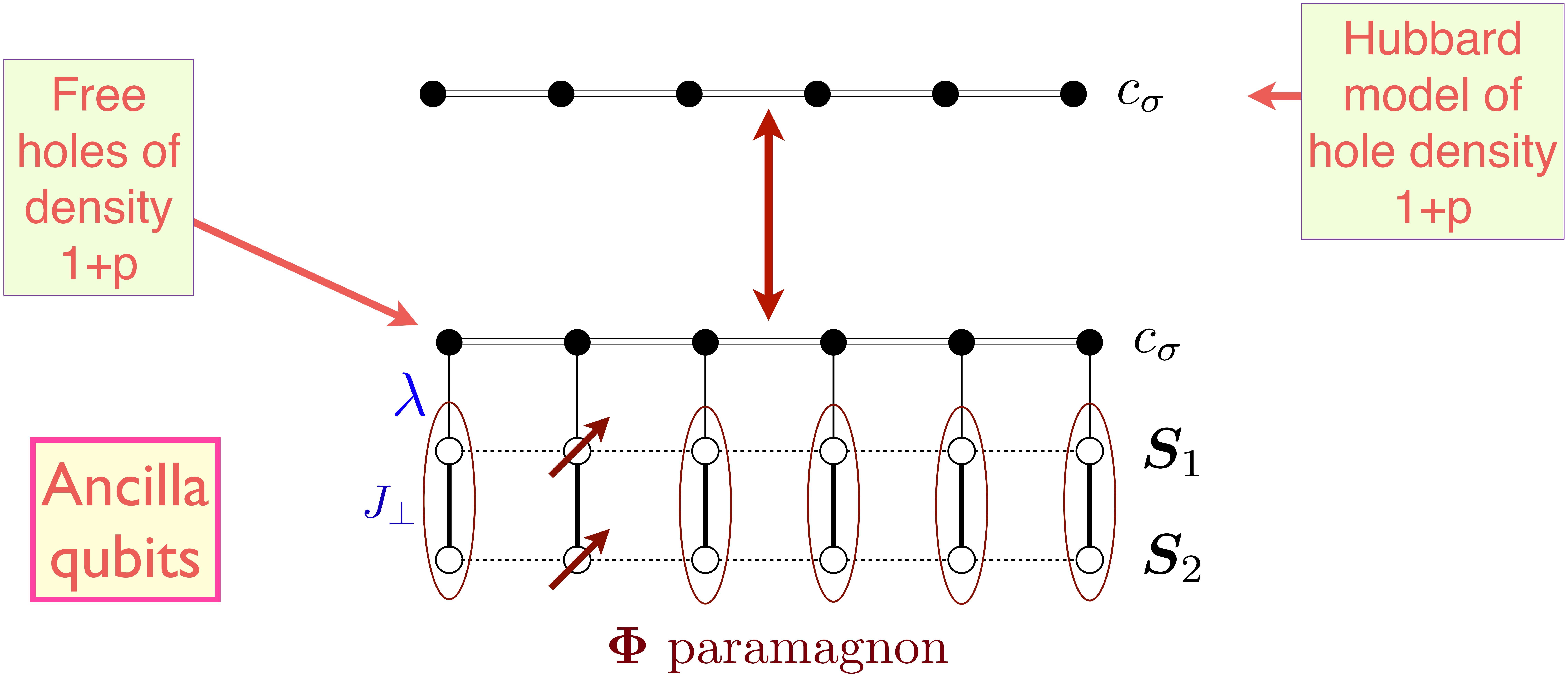

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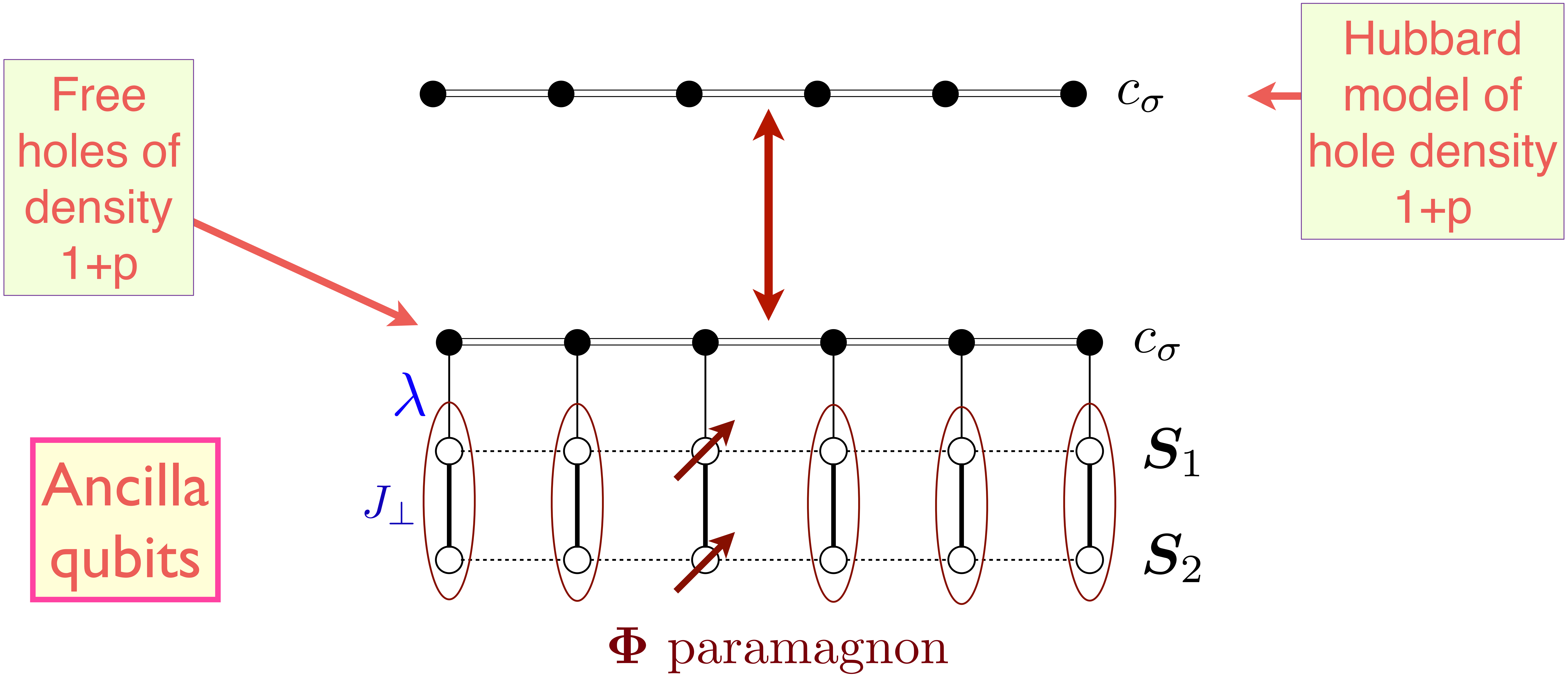

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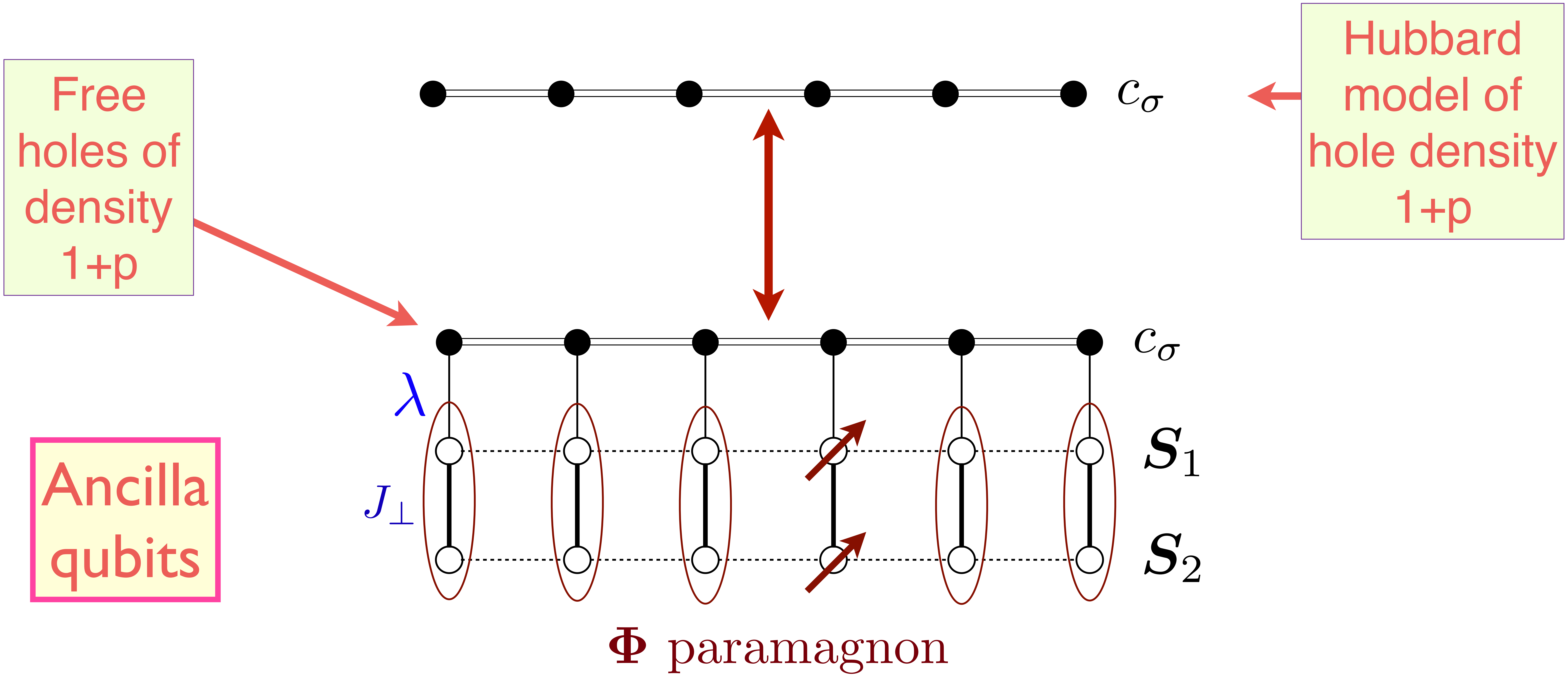

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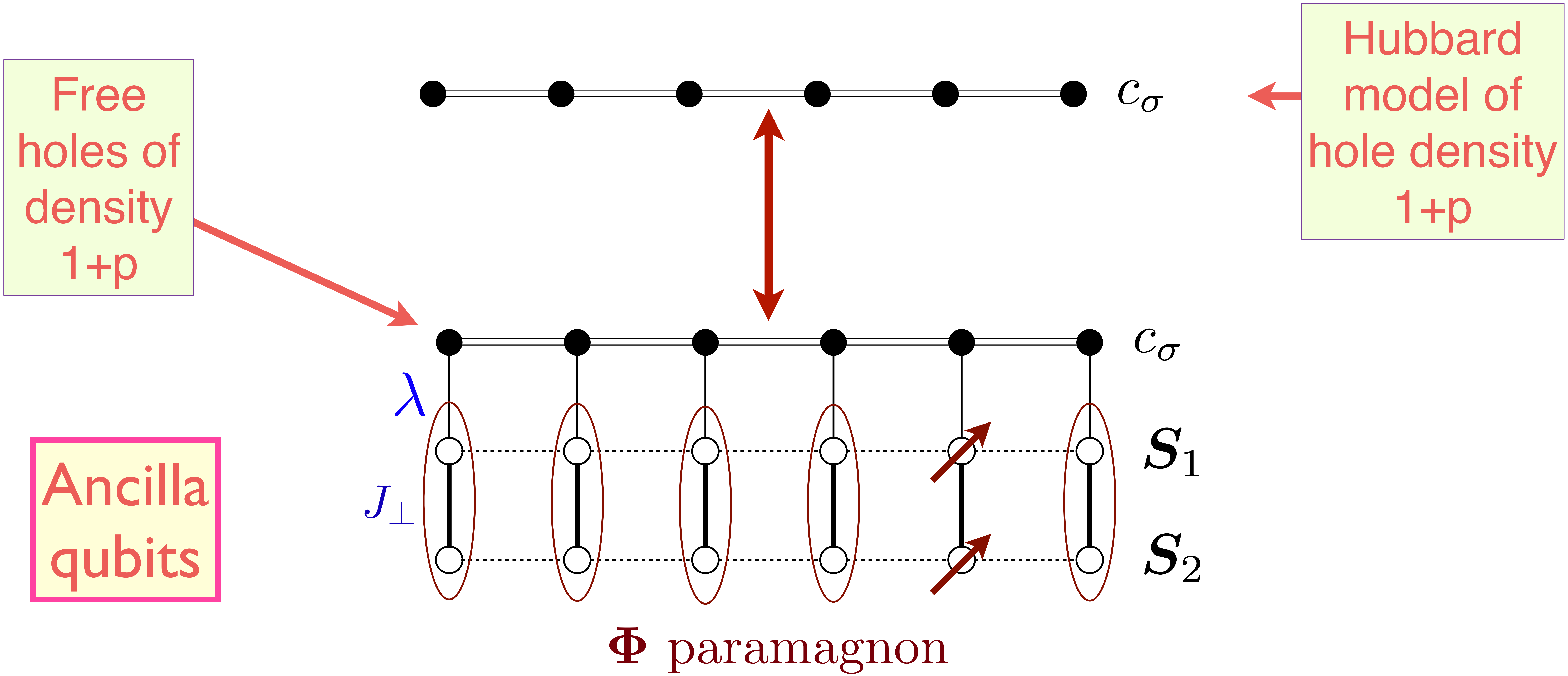

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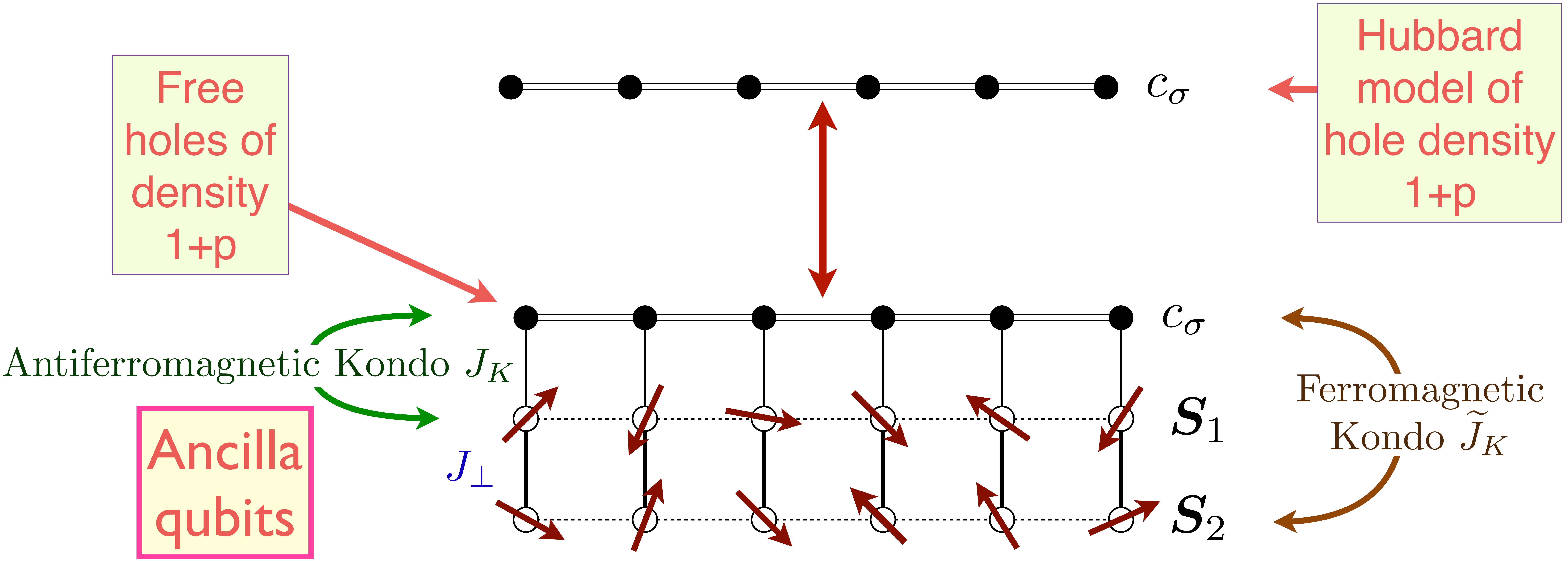
Paramagnon fractionalization theory of the Hubbard model



$$\boldsymbol{\Phi}_i = \frac{1}{\sqrt{3}}\left(\boldsymbol{S}_{2i} - \boldsymbol{S}_{1i}\right)$$

$$\mathcal{H}_{\rm paramagnon} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + J_K \sum_i c^\dagger_{i\sigma} \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \cdot \boldsymbol{S}_{1i} - \widetilde{J}_K \sum_i c^\dagger_{i\sigma} \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \cdot \boldsymbol{S}_{2i} + \ldots$$

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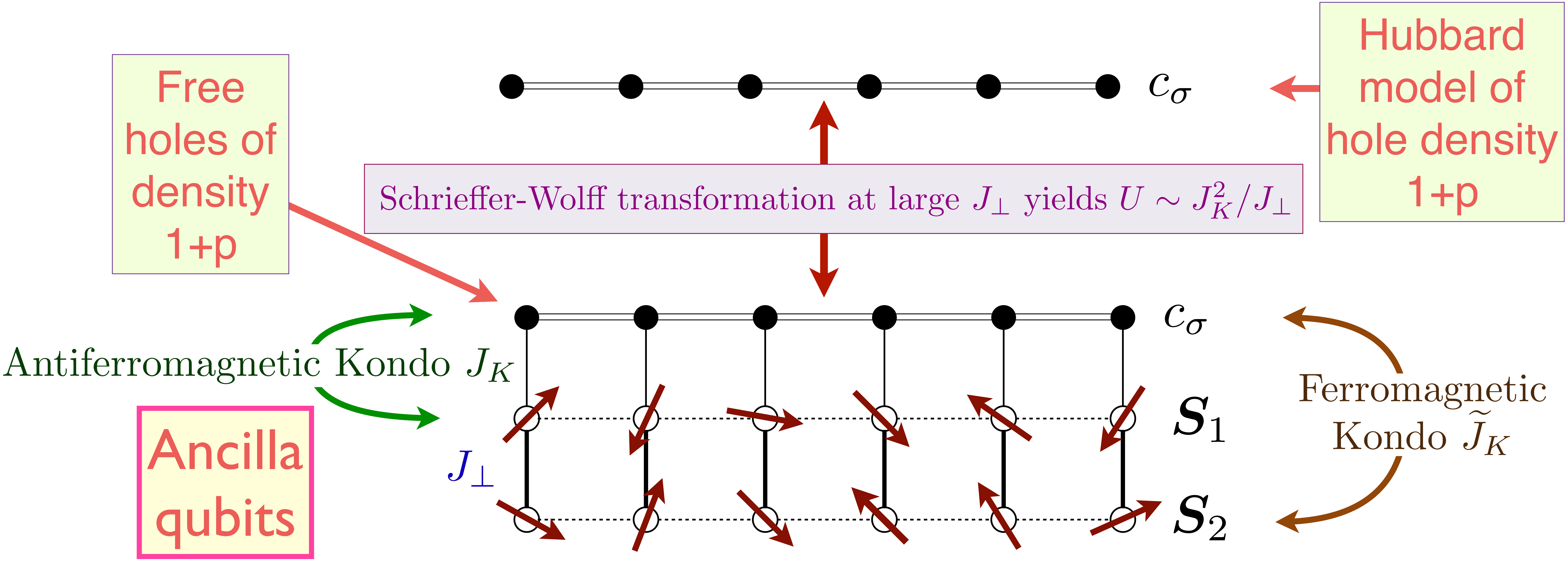

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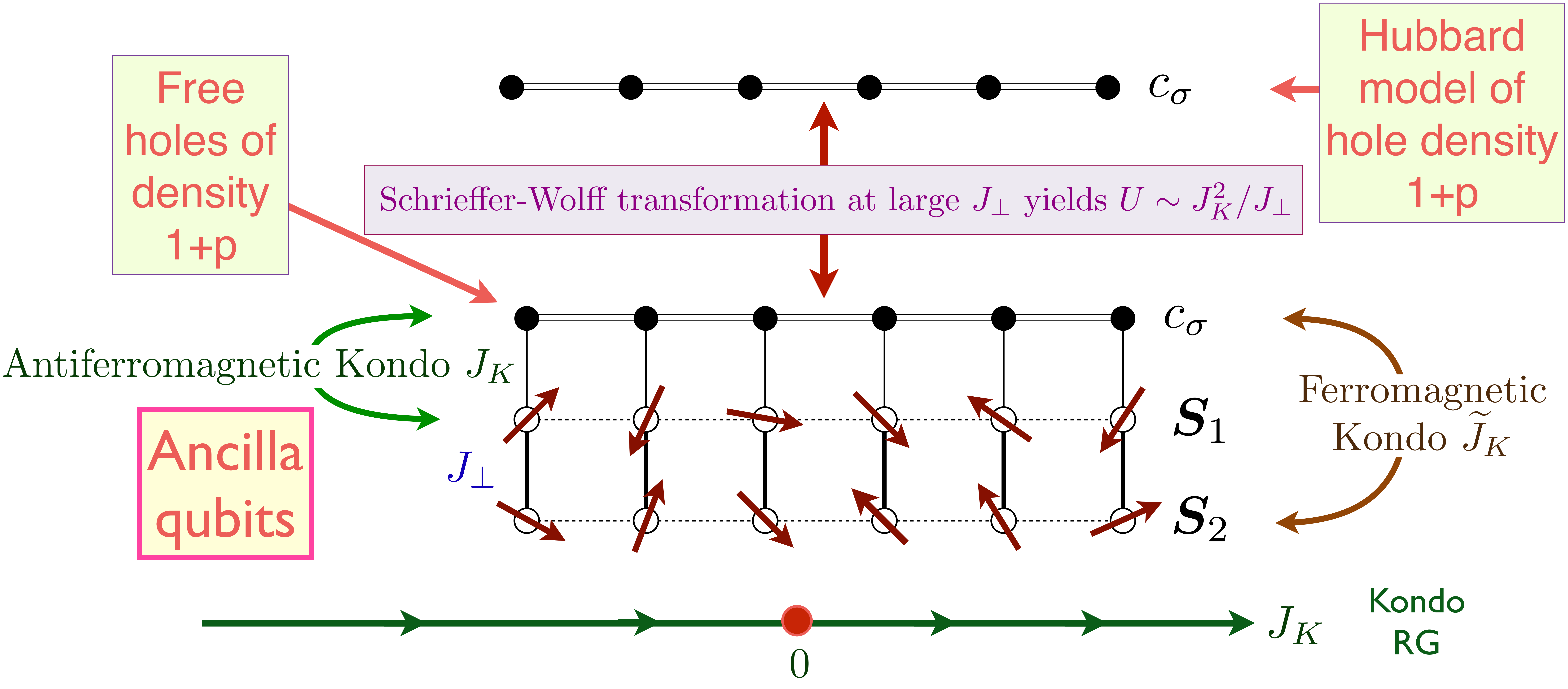

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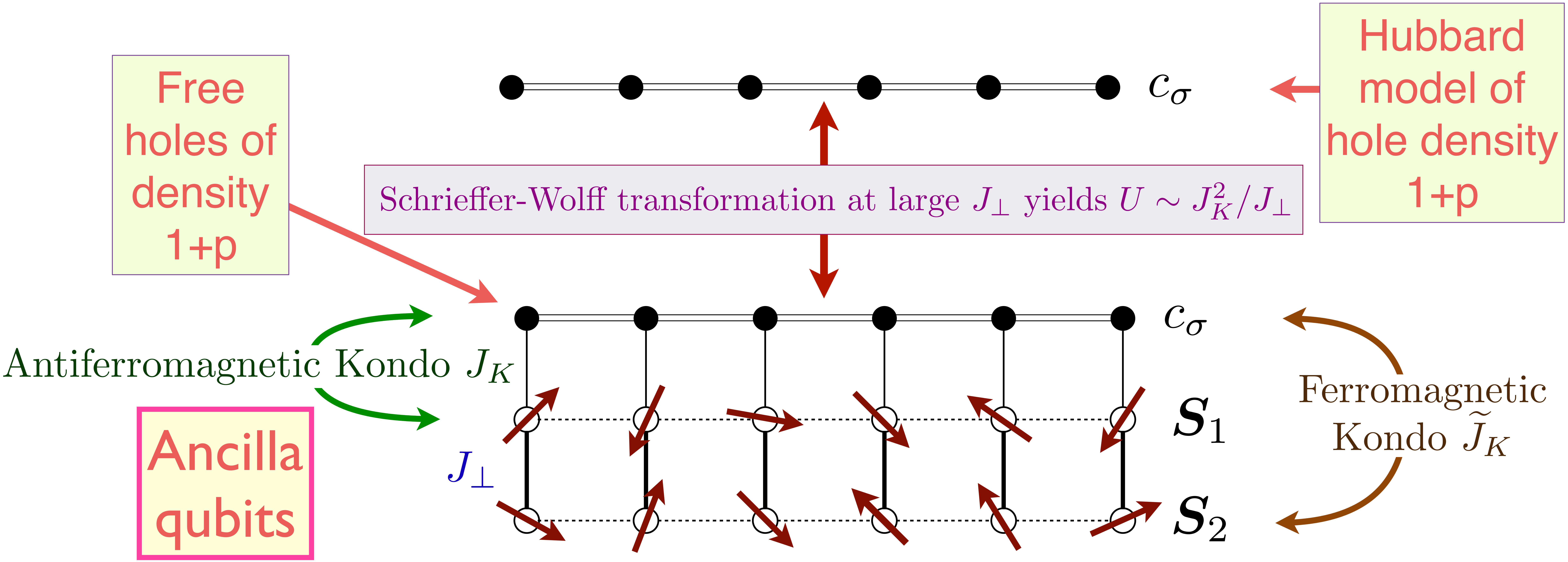
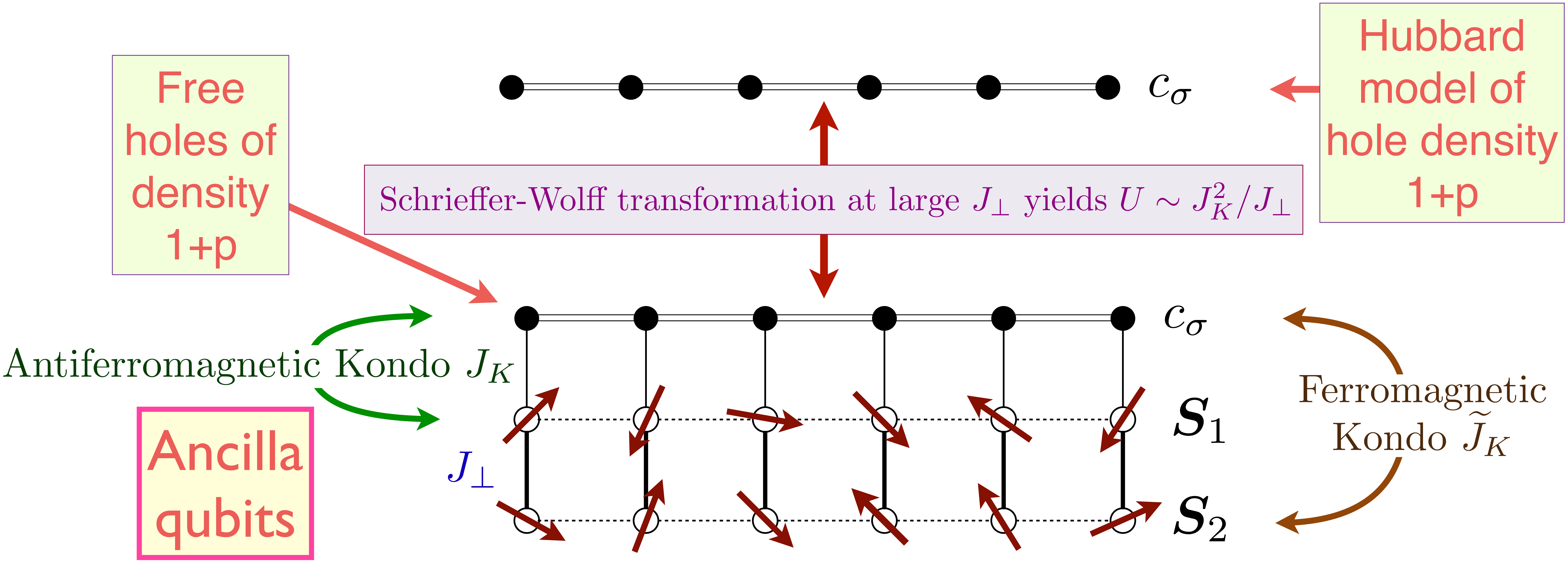


A FL* state is realized when the antiferromagnetic Kondo coupling dominates over $J_\perp$, and the c_σ and $\boldsymbol{S}_1$ form a heavy Fermi liquid state (as found in the heavy fermion compounds) of hole density $(1+p)+1 = 2+p = p \bmod 2$!

Paramagnon fractionalization theory of the Hubbard model



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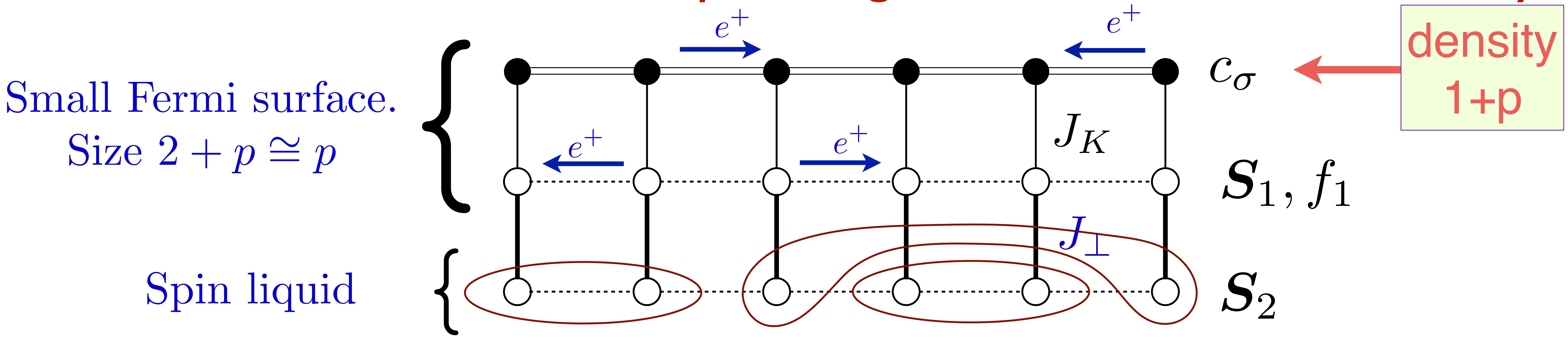
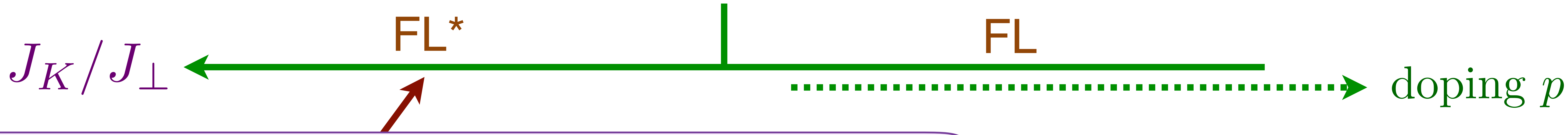
The $\boldsymbol{S}_2$ must form an 'odd' spin liquid which does not break translational symmetry, to obtain a metal with a non-Luttinger volume Fermi surface.

Trial wavefunctions in the paramagnon fractionalization theory





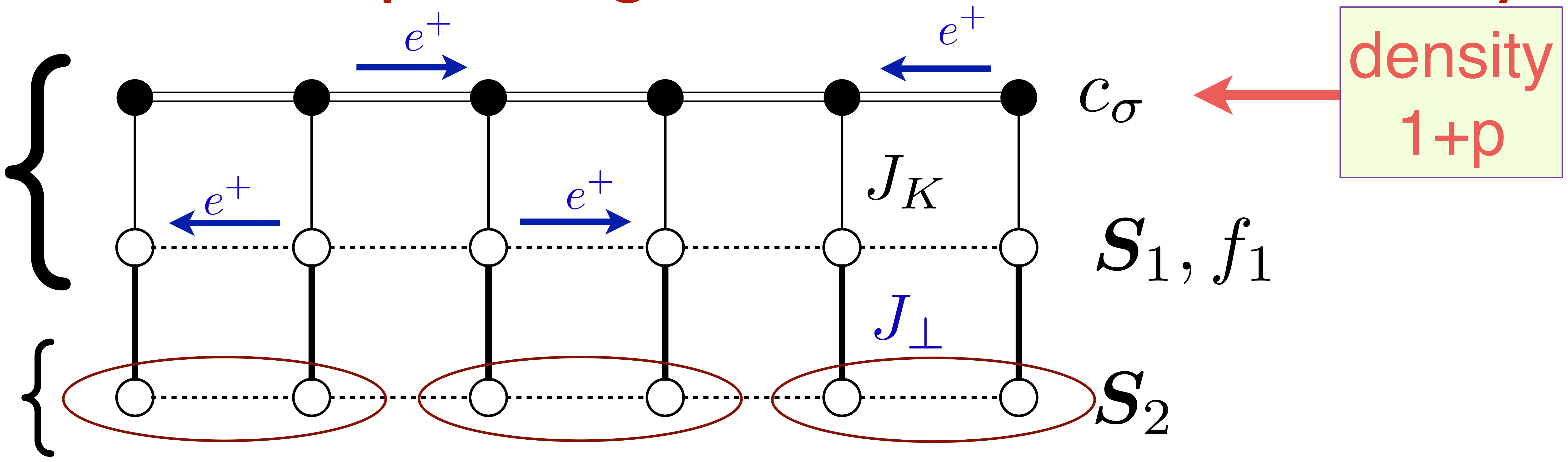
Small Fermi surface of size p

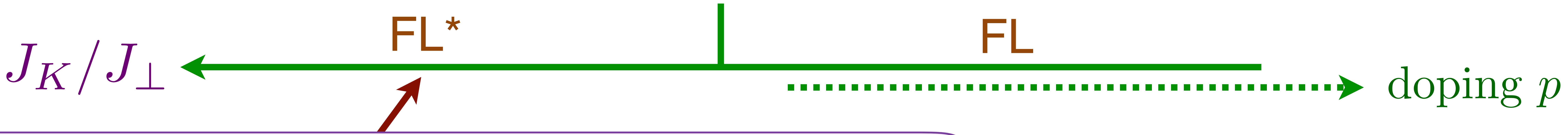
$$|\mathrm{FL}*\rangle = [\text{Projection onto rung singlets of } \boldsymbol{S}_1, \boldsymbol{S}_2] \bowtie |\text{Slater determinant of } (c, f_1)\rangle \otimes |\text{Spin liquid of } \boldsymbol{S}_2\rangle$$

Trial wavefunctions in the paramagnon fractionalization theory

Small Fermi surface.
Size $2 + p \cong p$

Spin liquid





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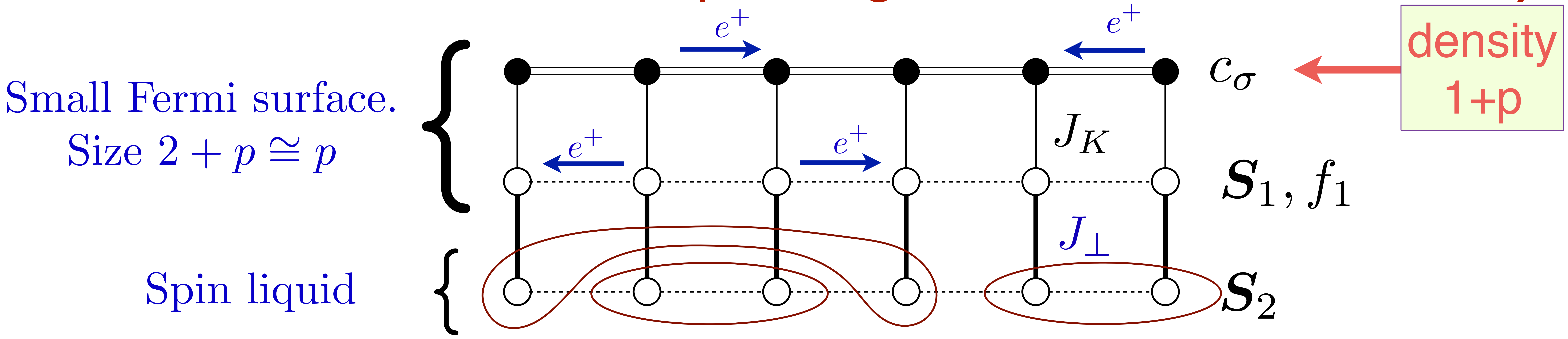
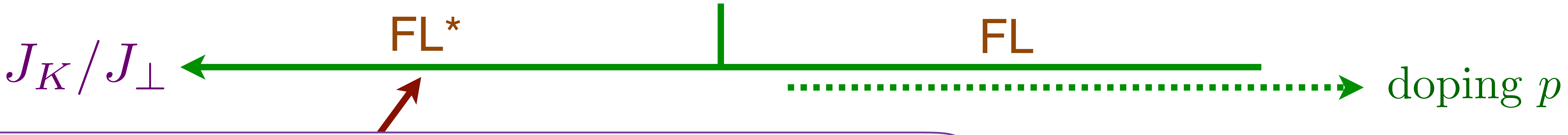
Trial wavefunctions in the paramagnon fractionalization theory





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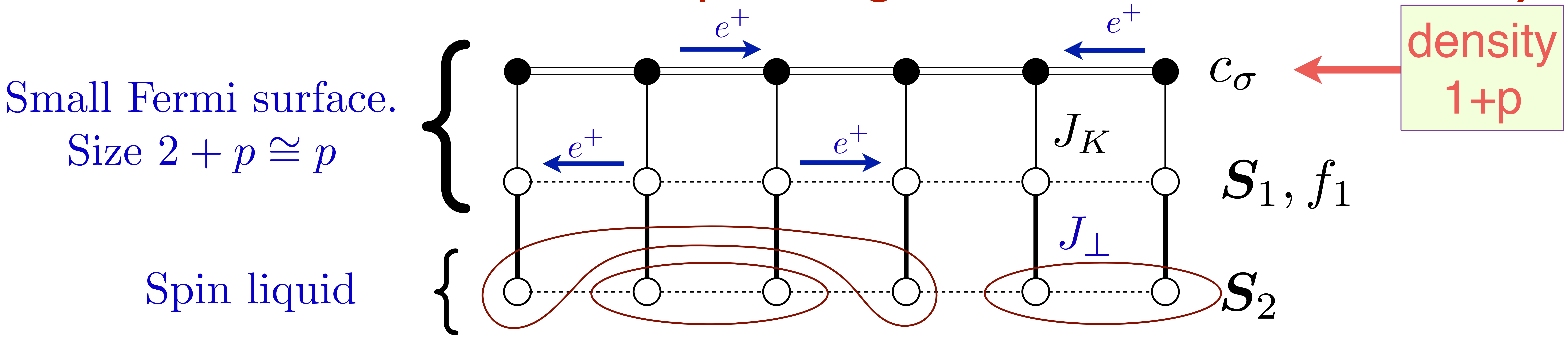

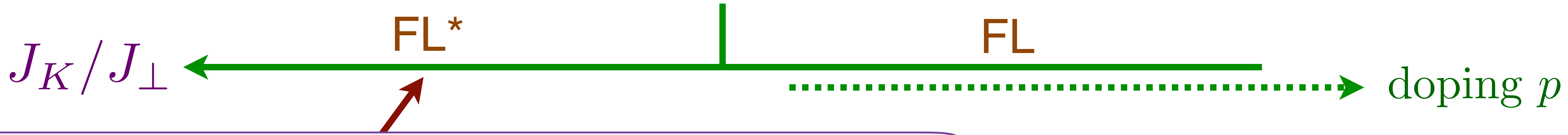

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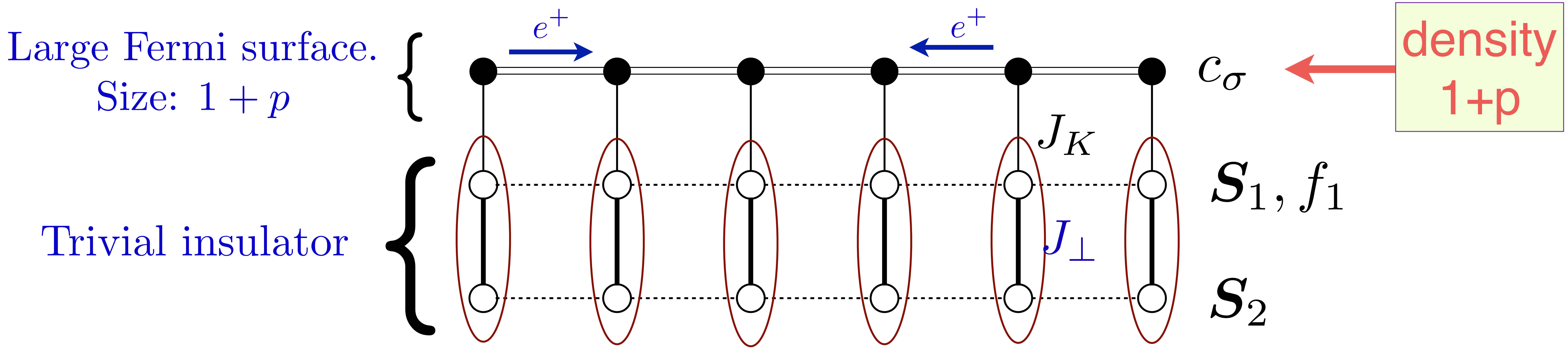
$\bowtie |\text{Slater determinant of } (c, f_1)\rangle$
$\otimes |\text{Spin liquid of } \boldsymbol{S}_2\rangle$

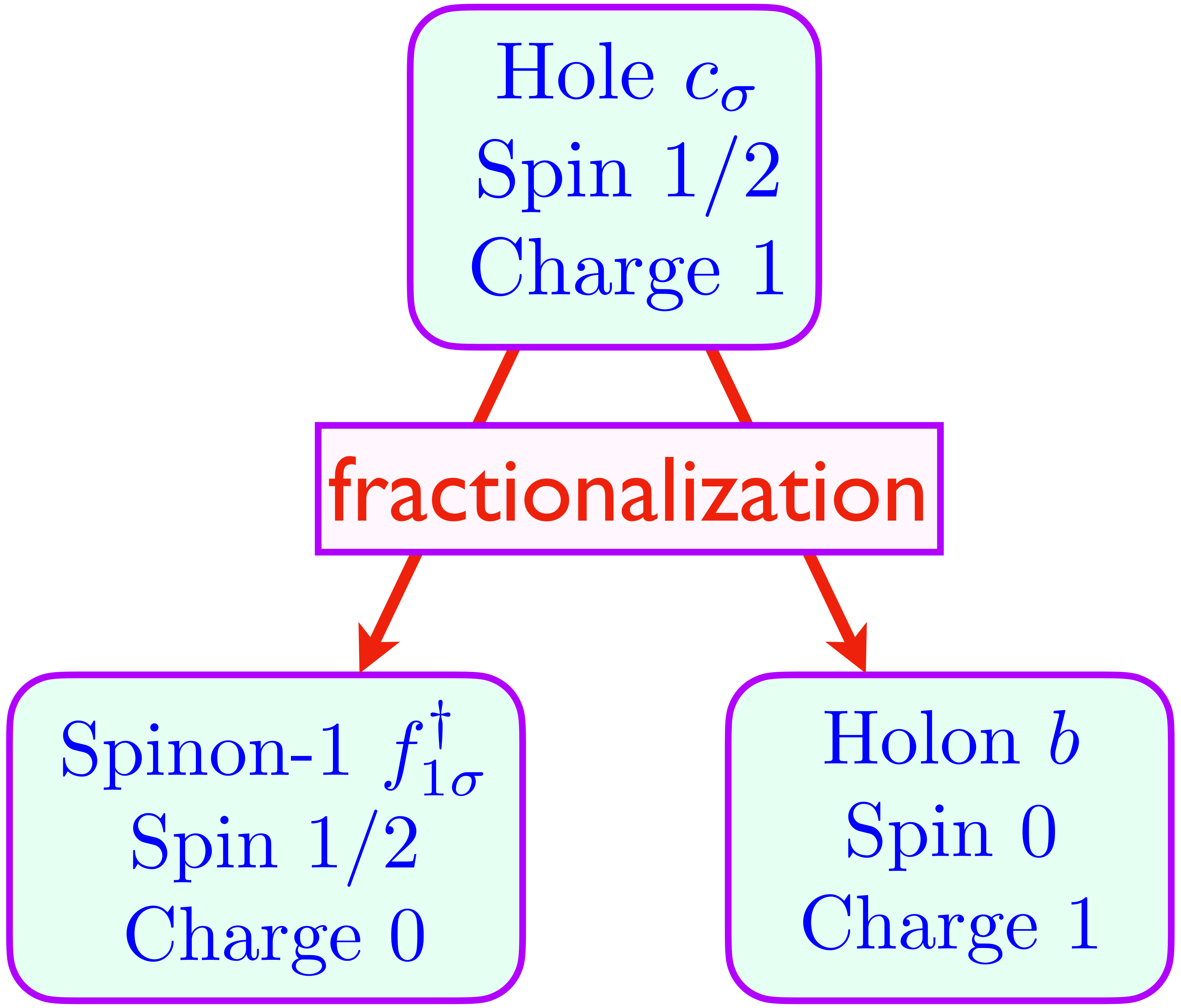
Pseudogap metal =
Kondo Lattice Heavy
Fermi Liquid
$\oplus$
Spin Liquid

Trial wavefunctions in the paramagnon fractionalization theory

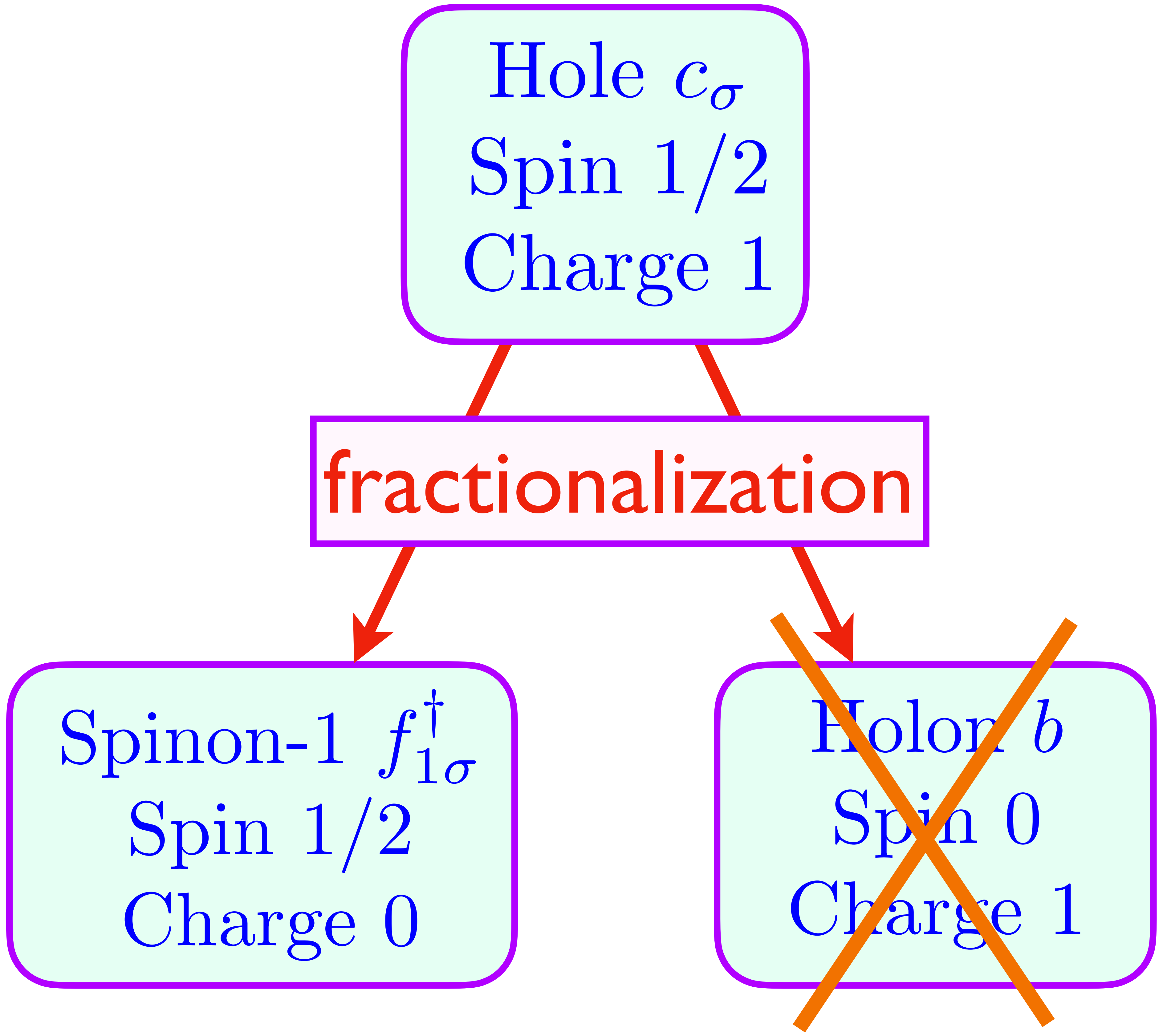


Large Fermi surface of size $1+p$

$$|\text{FL}\rangle = |\text{Rung singlets of } \boldsymbol{S}_1, \boldsymbol{S}_2\rangle \otimes |\text{Slater determinant of } c\rangle$$



Electron fractionalization



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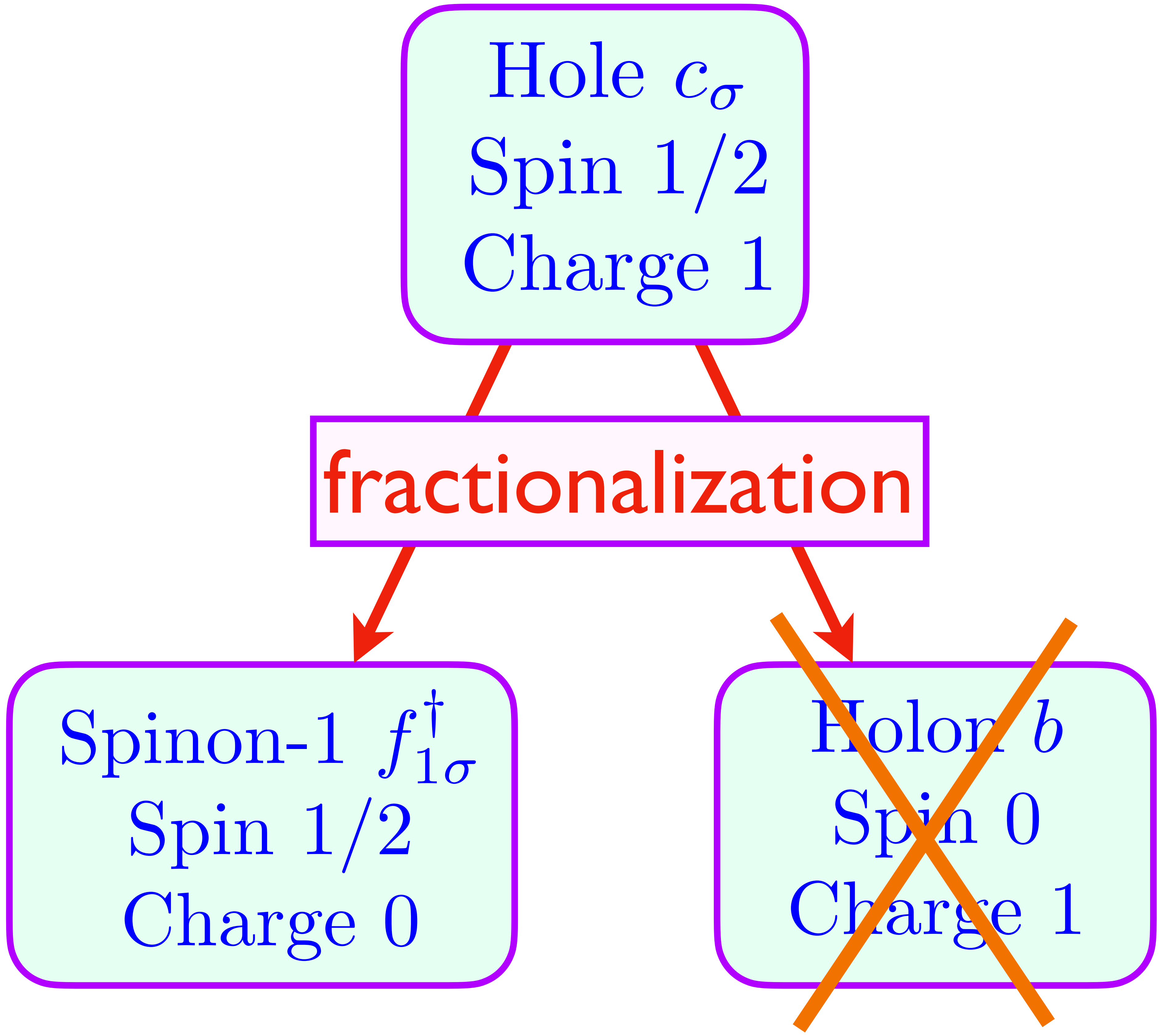

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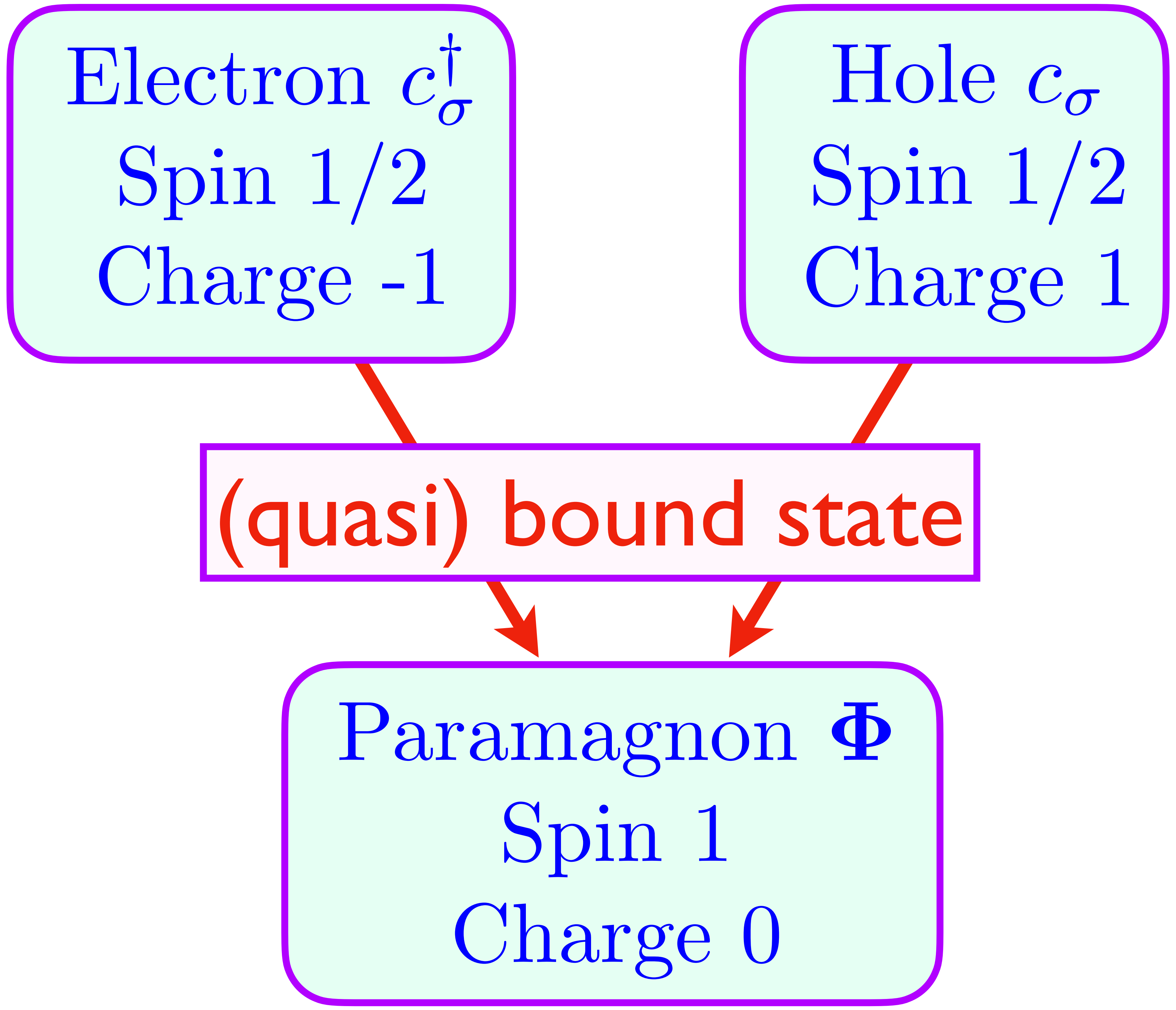
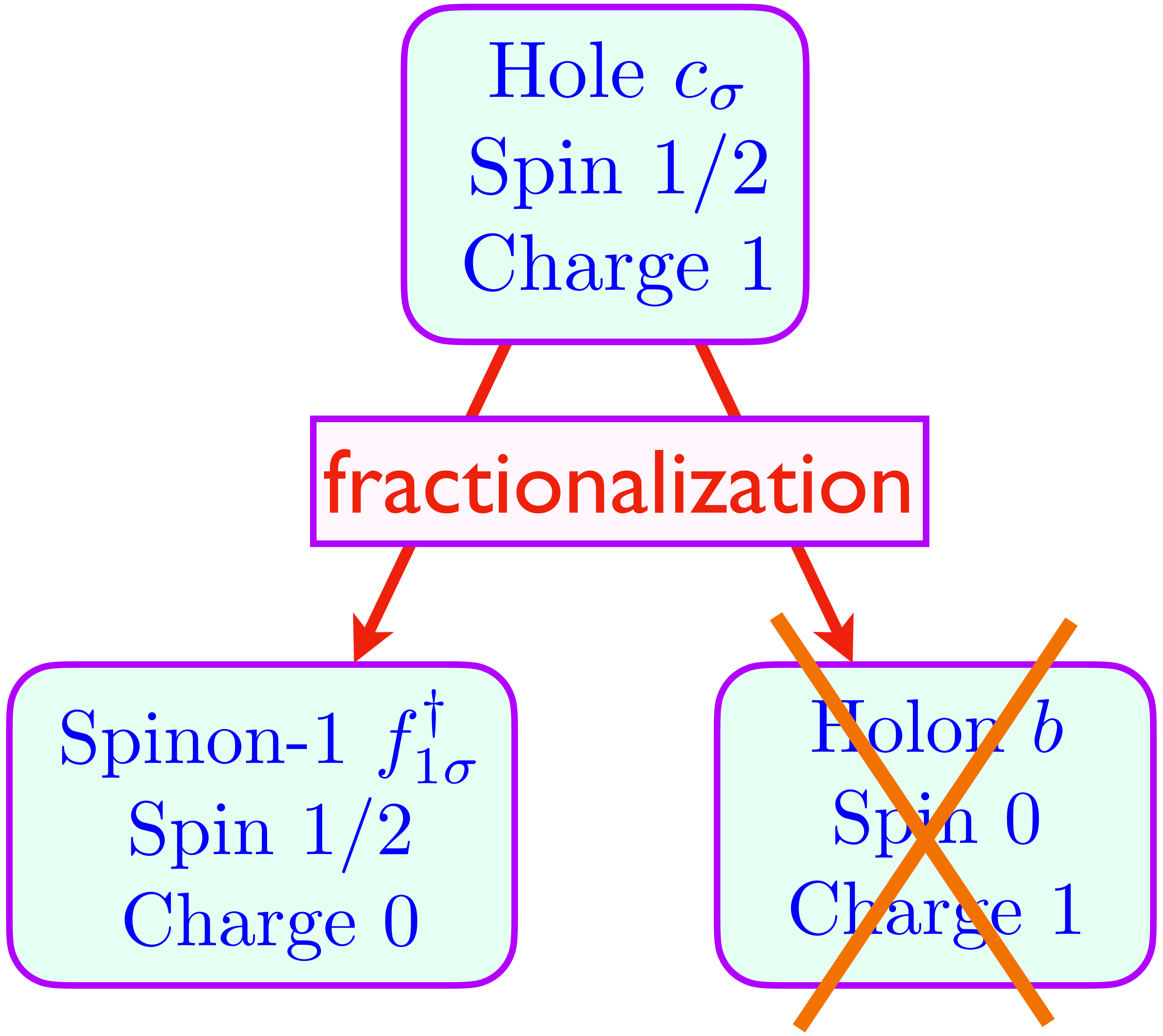
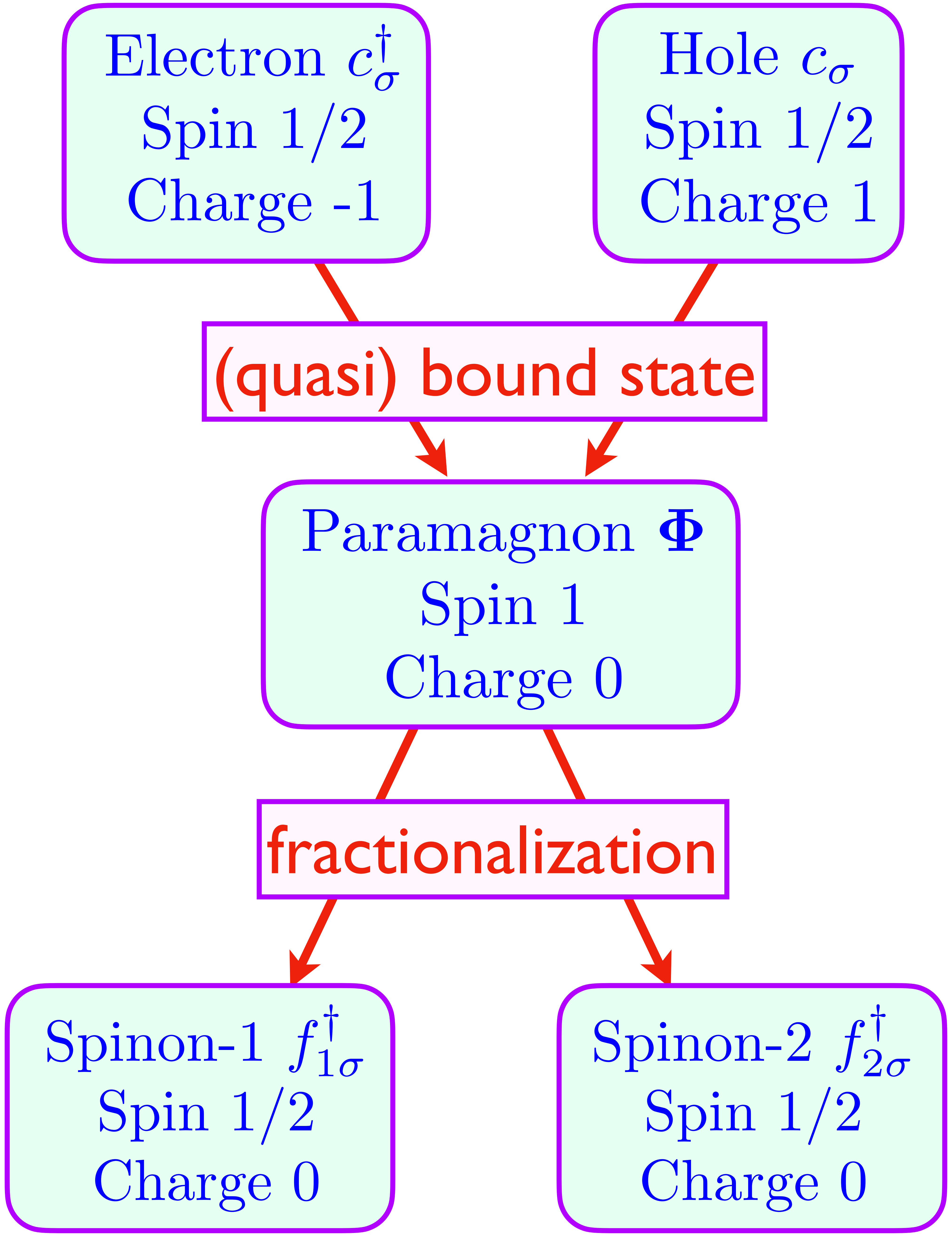


Don't fractionalize the electron;
fractionalize the paramagnon!



Electron fractionalization



Paramagnon fractionalization

Don't fractionalize the electron; fractionalize the paramagnon!

1. Paramagnon fractionalization theory of the Hubbard model

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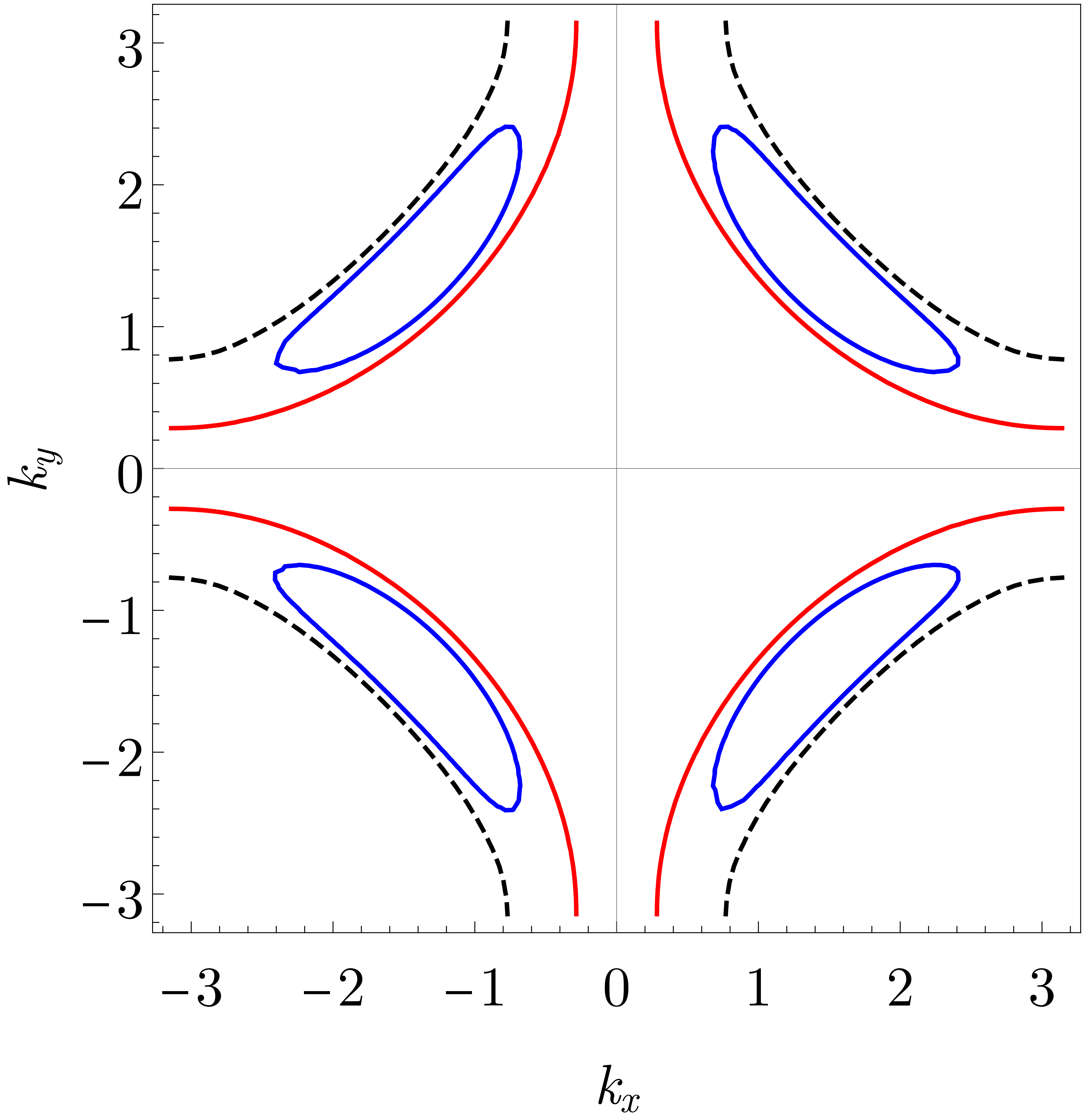
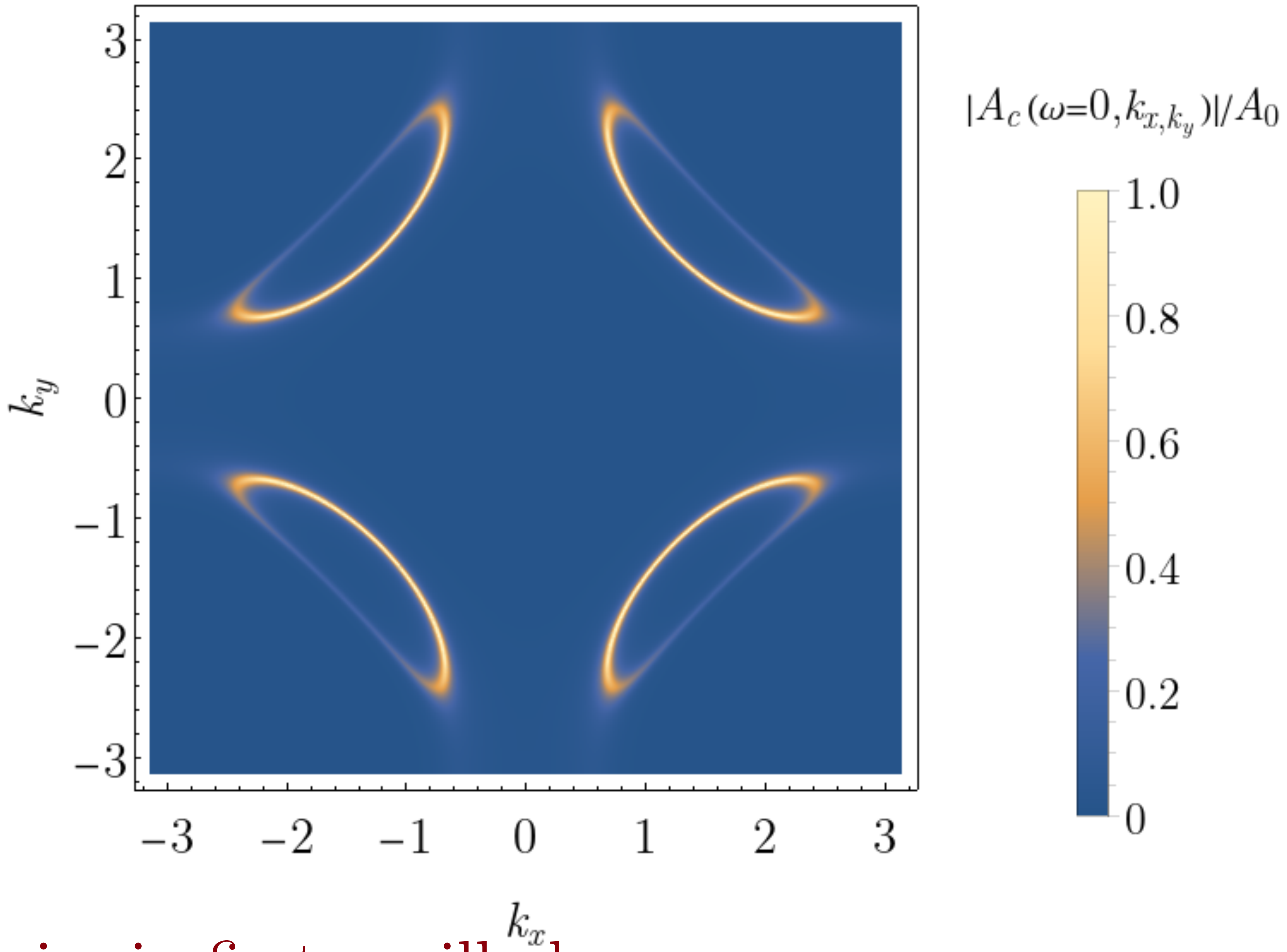
3. Confinement transitions from the pseudogap metal

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

"Fermi arc" spectral functions



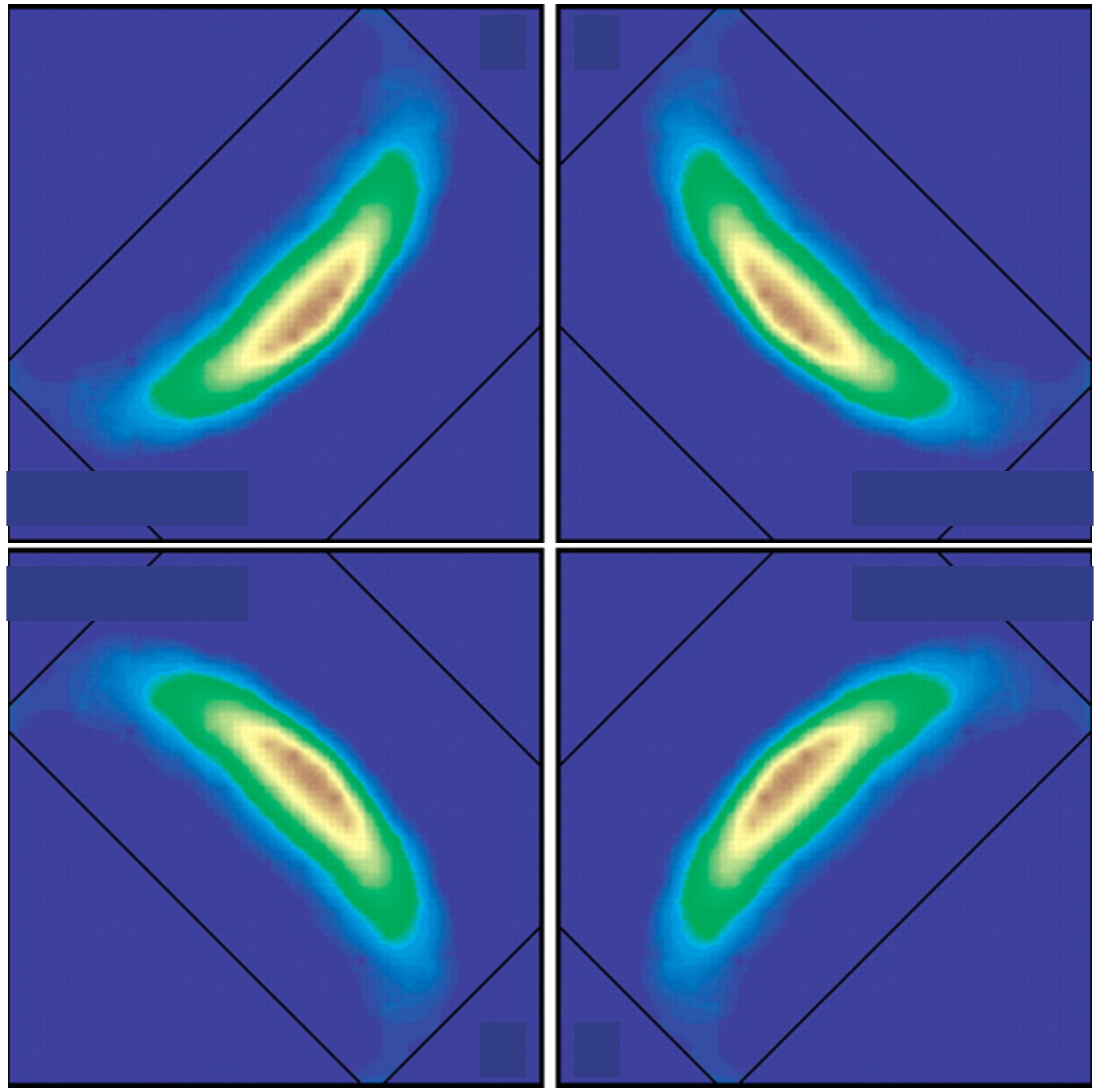


FL*: Condensate B breaks gauge symmetries in first ancilla layer.

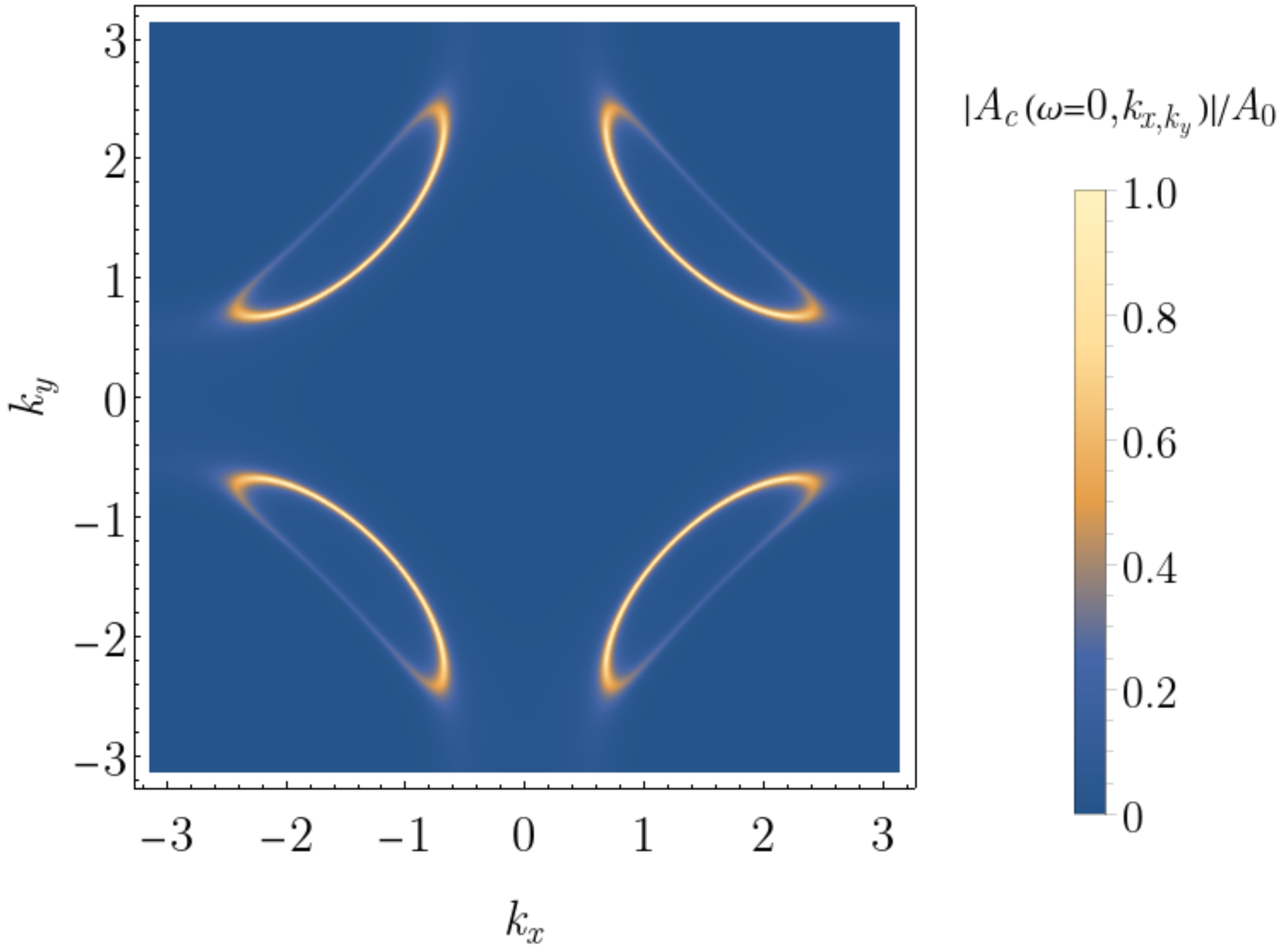
$$H = -\sum_{i,j} t_{ij} c_{i\sigma}^\dagger c_{j\sigma} + \sum_{i,j} t_{1,ij} f_{1i\sigma}^\dagger f_{1j\sigma} + \sum_i B\left(c_{i\sigma}^\dagger f_{1i\sigma} + f_{1i\sigma}^\dagger c_\sigma\right)$$

Precursors:
Kai-Yu Yang, T. M. Rice, Fu-Chun Zhang, PRB **73**, 174501 (2006)
Yang Qi, SS, PRB **81**, 115129 (2010)
Eun-Gook Moon, SS, PRB **83**, 224508 (2011)

Photoemission at small p



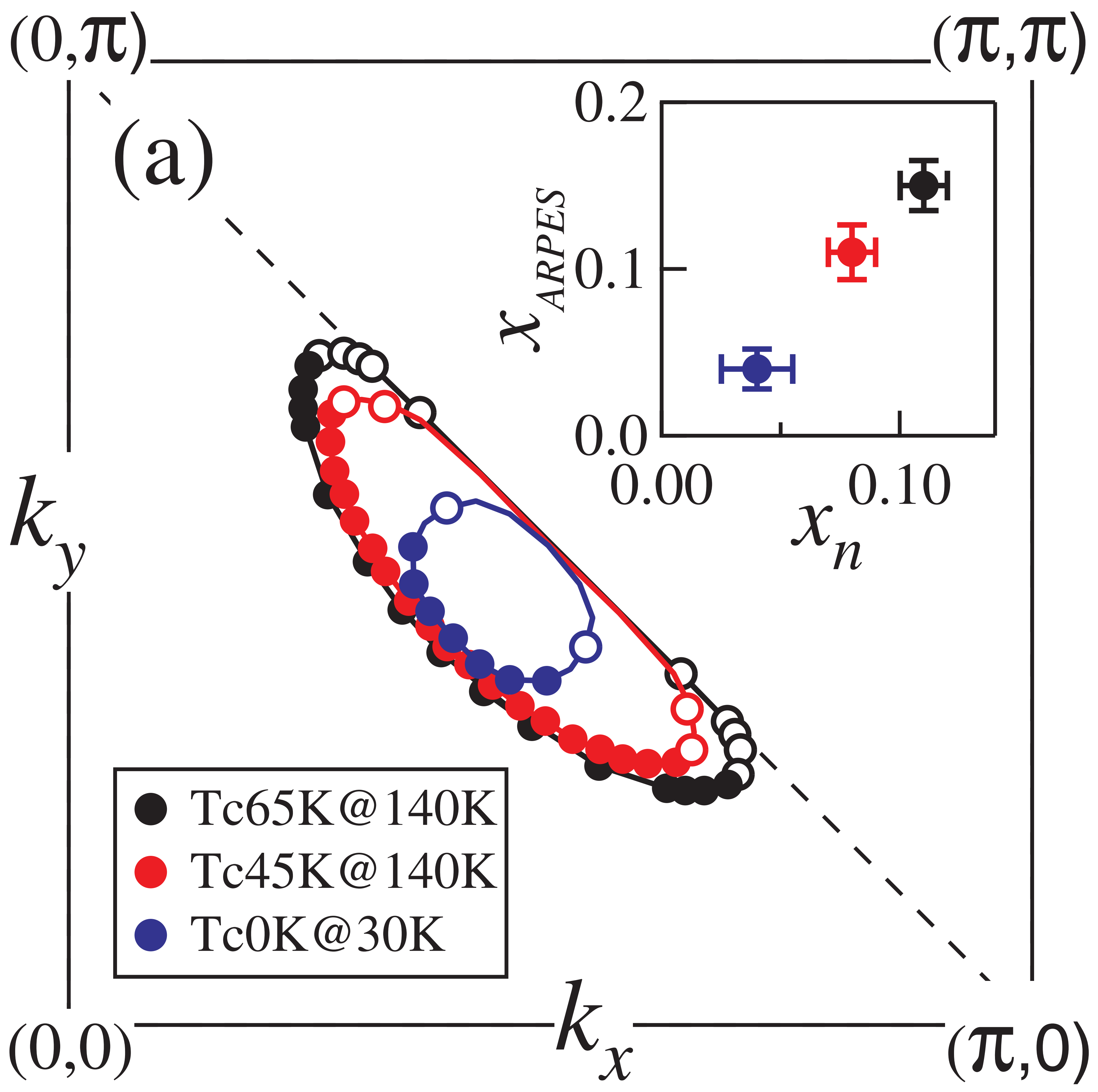
$Ca_{2-x}Na_xCuO_2Cl_2$
at $x = 0.10$



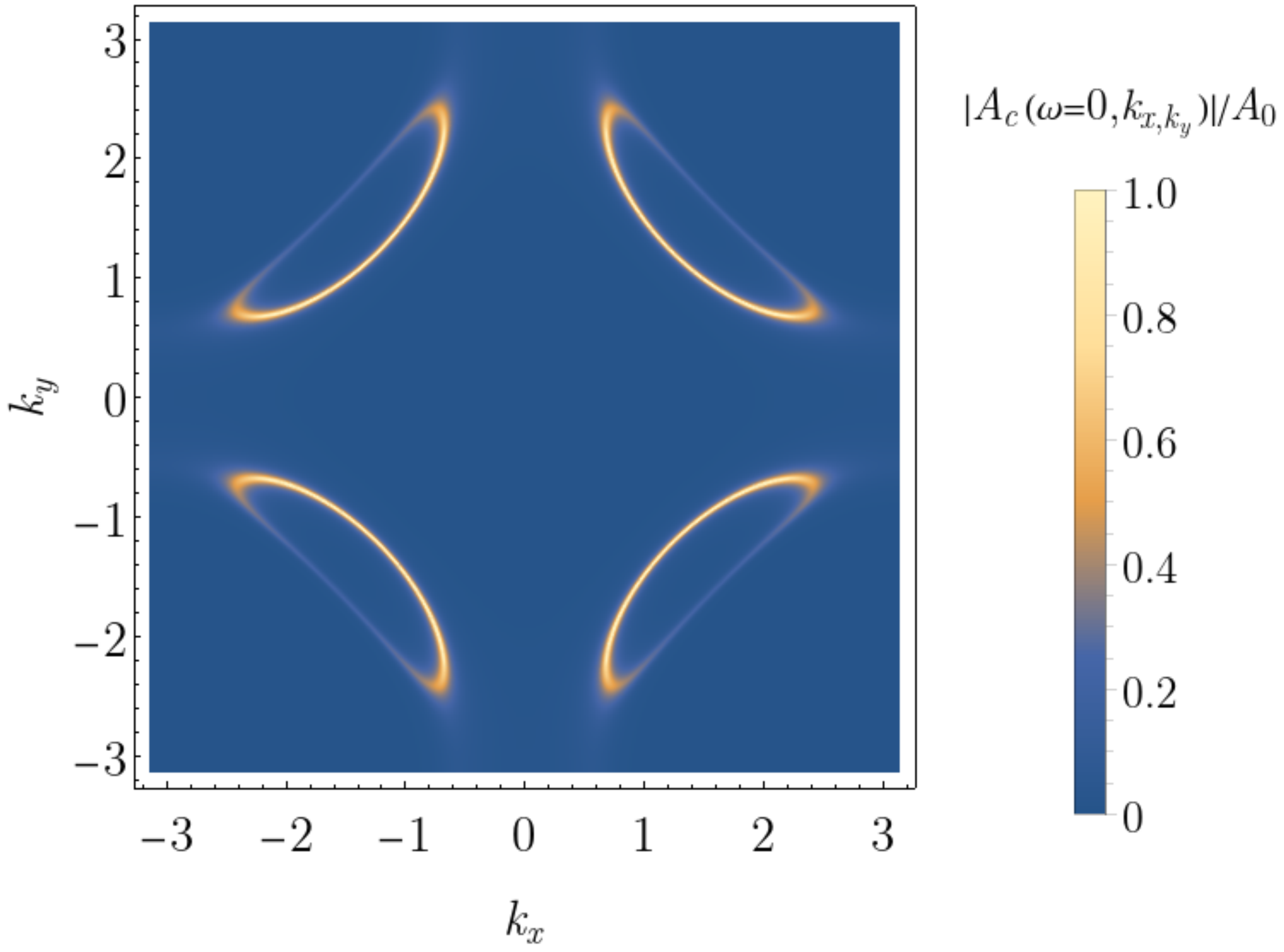
"Fermi arcs"

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)

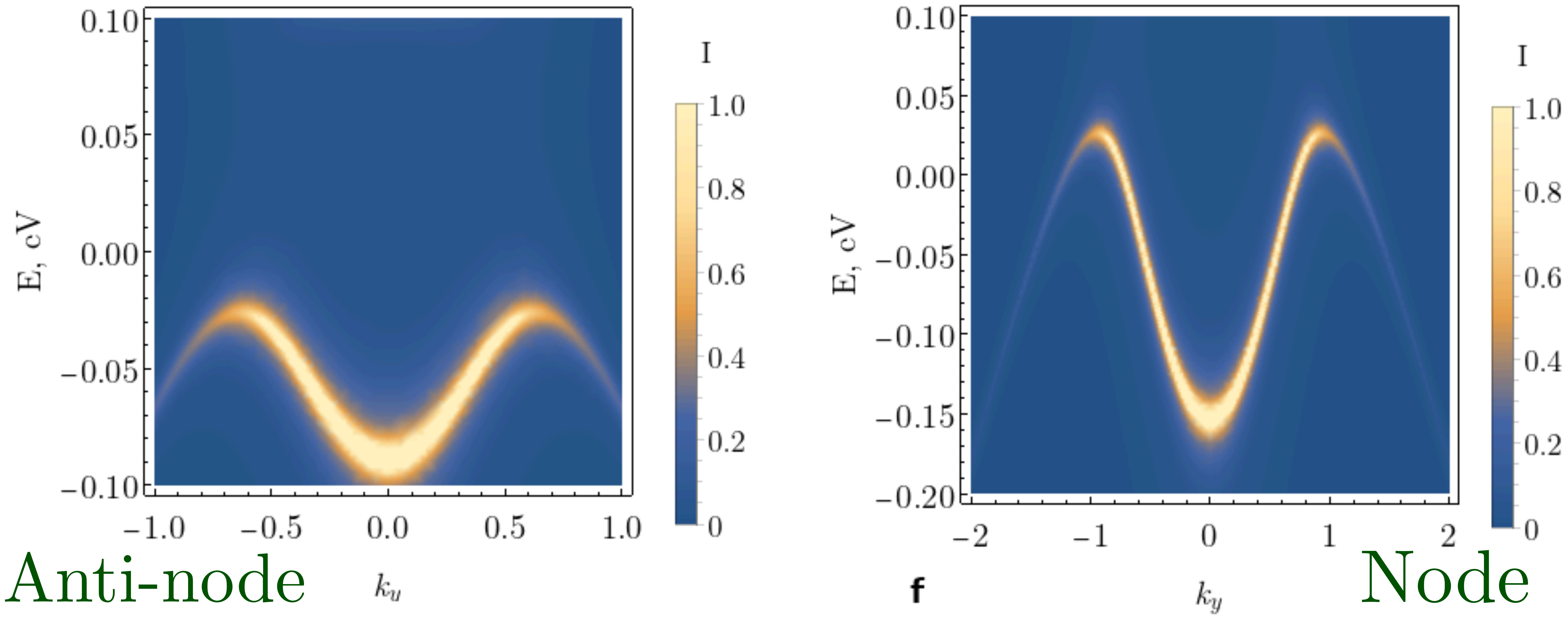
Photoemission at small p



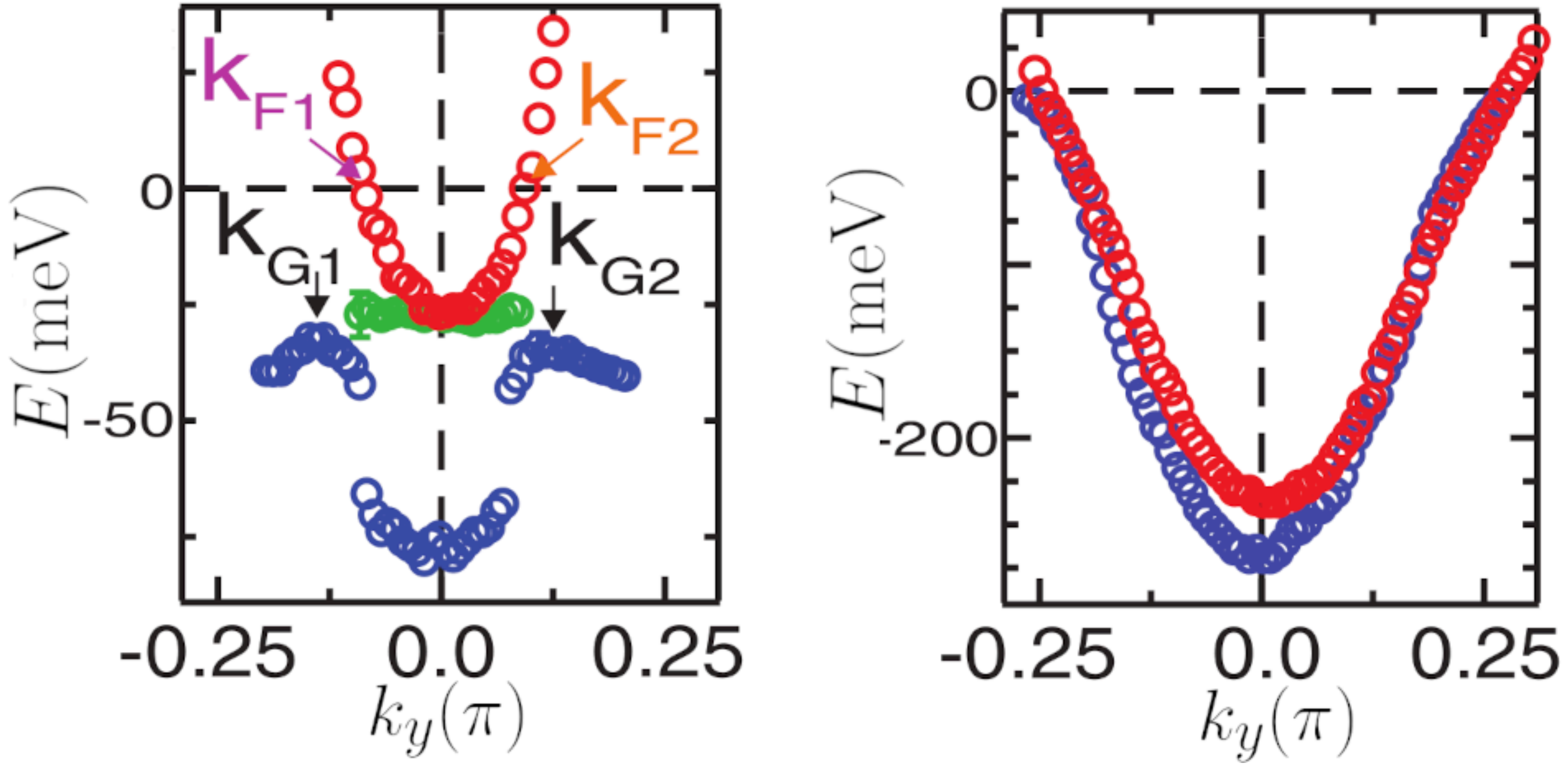
"Fermi pockets"



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).



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



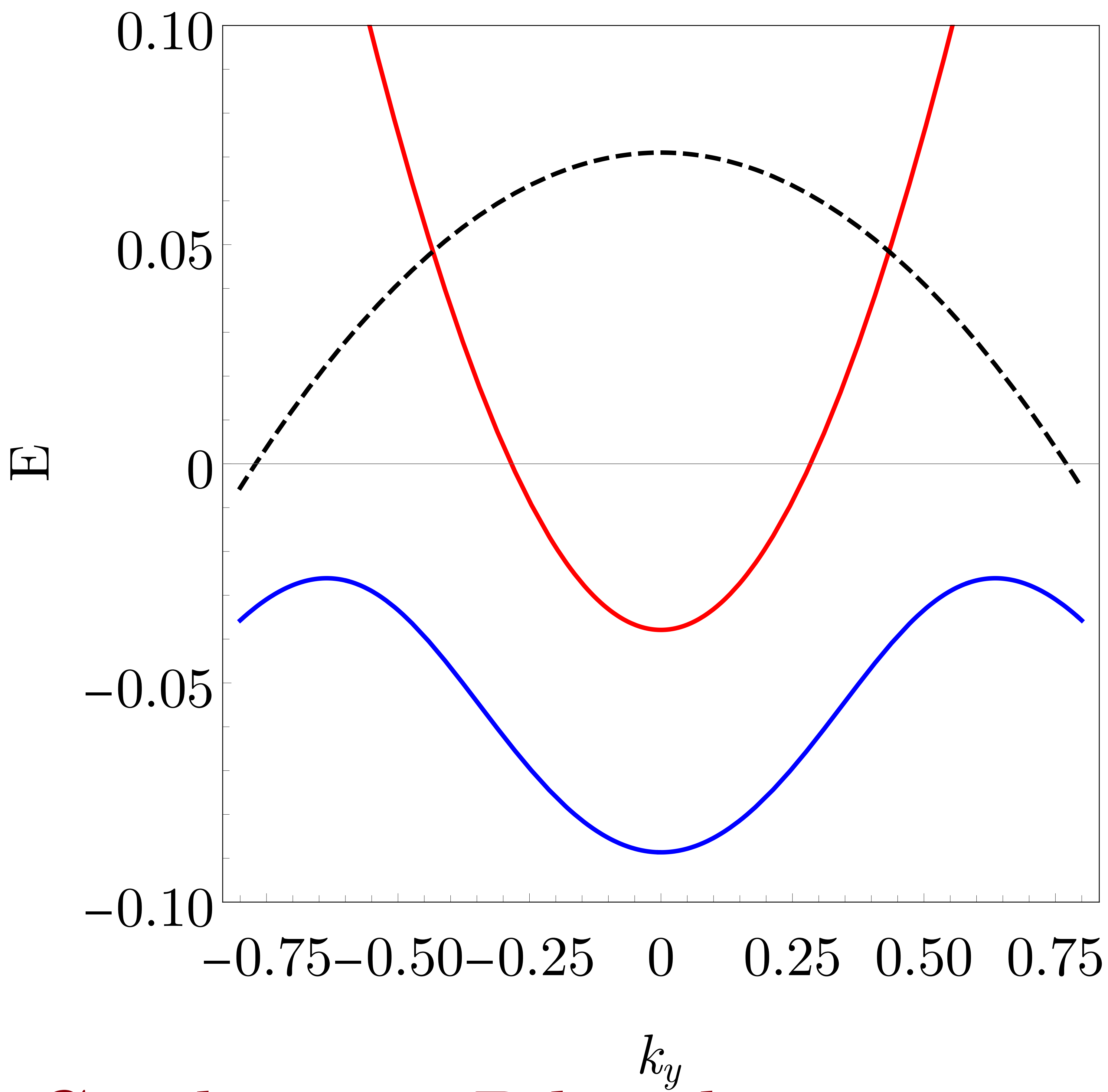
ARPES on Bi2201

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)

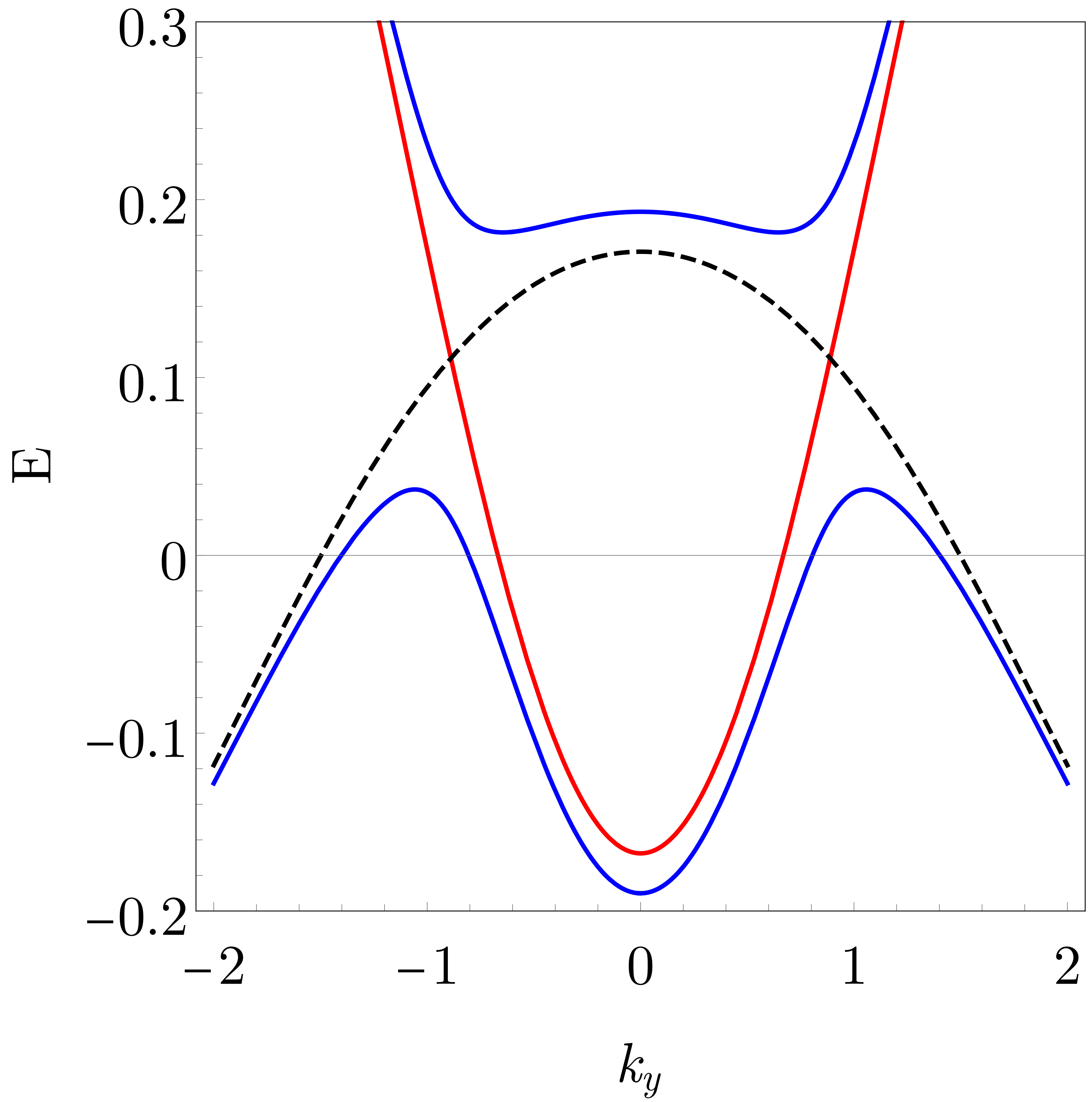
FL* in a ***one-band*** model

Electronic dispersion

Anti-node: $k_x = \pi$



Node: $k_x = 2$

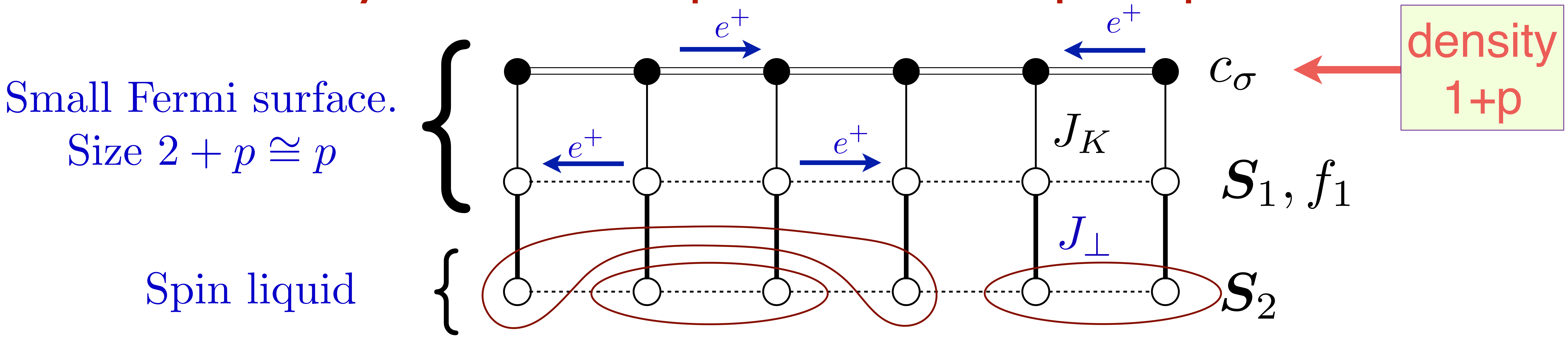


FL*: Condensate B breaks gauge symmetries in first ancilla layer.

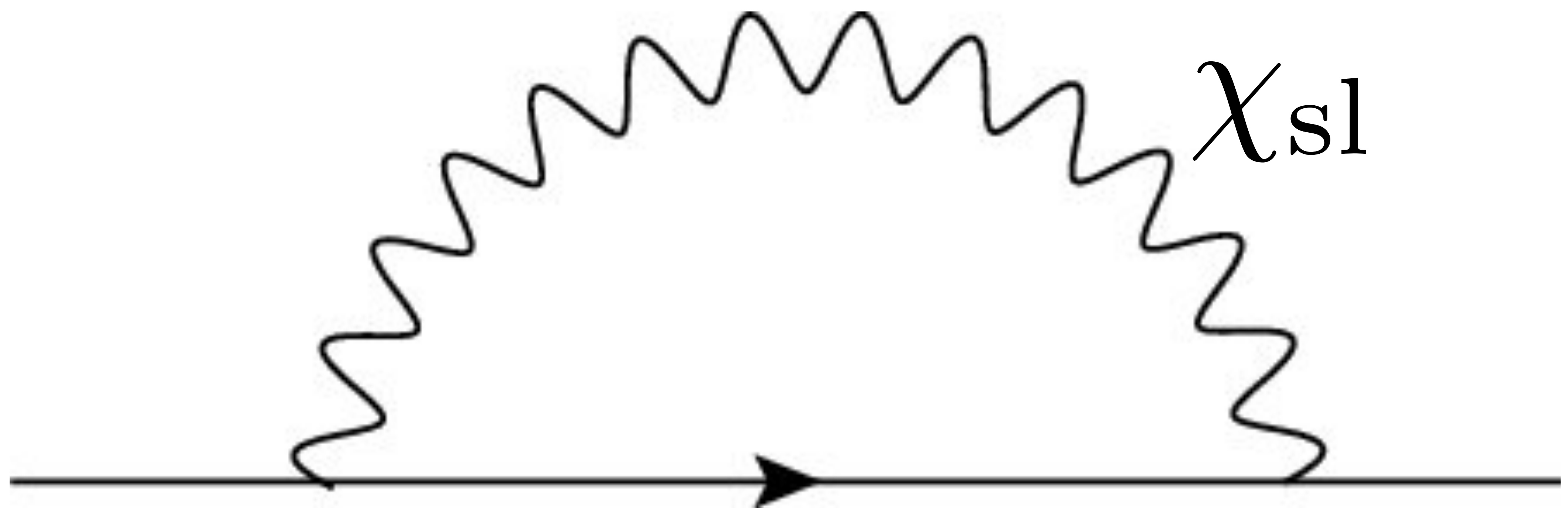
$$H = -\sum_{i,j} t_{ij} c_{i\sigma}^\dagger c_{j\sigma} + \sum_{i,j} t_{1,ij} f_{1i\sigma}^\dagger f_{1j\sigma} + \sum_i B\left(c_{i\sigma}^\dagger f_{1i\sigma} + f_{1i\sigma}^\dagger c_\sigma\right)$$

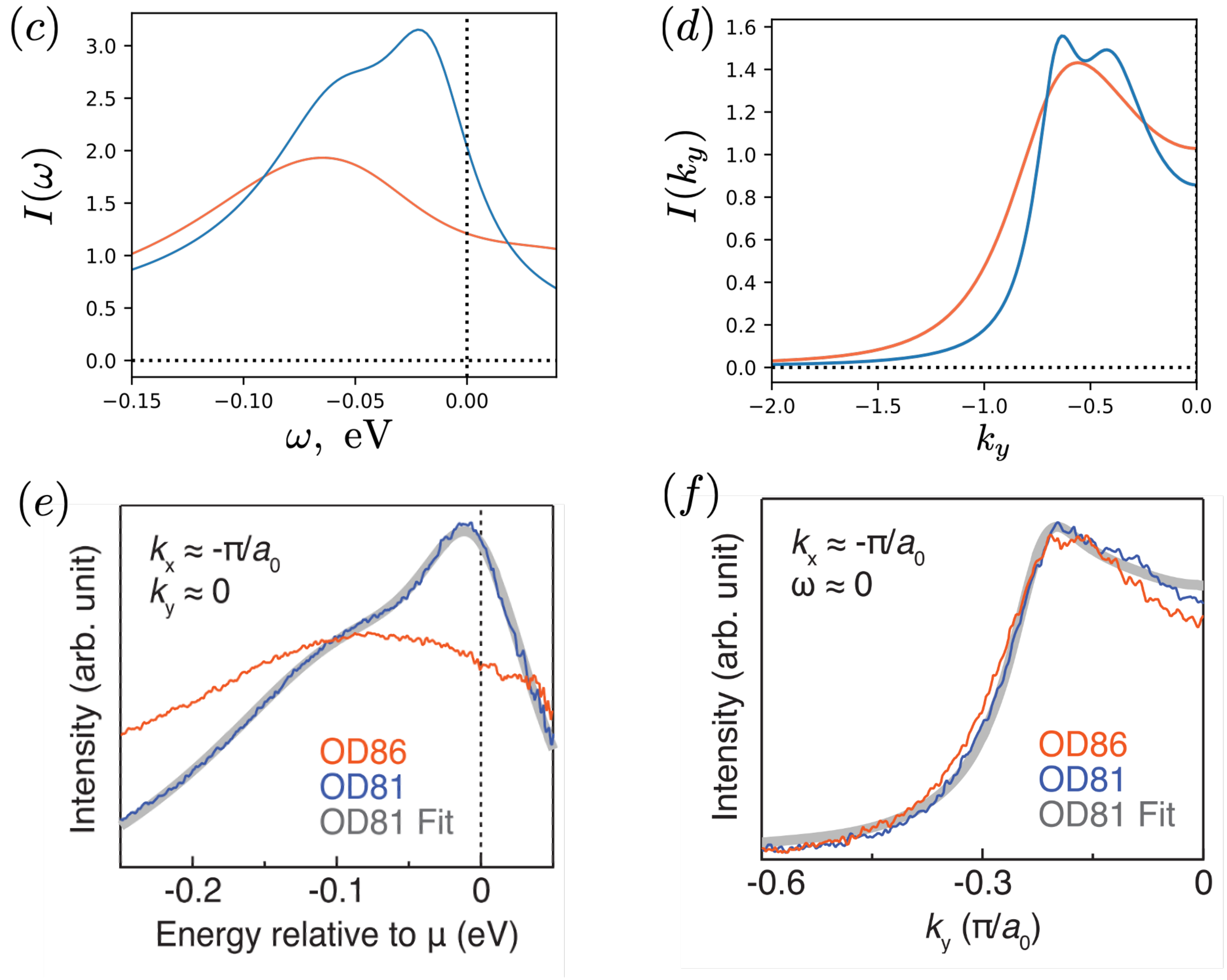
Precursors:
Kai-Yu Yang, T. M. Rice, Fu-Chun Zhang, PRB **73**, 174501 (2006)
Yang Qi, SS, PRB **81**, 115129 (2010)
Eun-Gook Moon, SS, PRB **83**, 224508 (2011)

Dynamic consequences of the spin liquid



The only singular gauge fluctuations are those in the spin liquid of the $\boldsymbol{S}_2$. We can compute their influence on the electronic spectrum perturbatively in the exchange couplings in terms of the dynamic spin susceptibility $\chi_{\rm sl}$.





Antinodal EDC and MDC

(c,d) Theory with SYK spin liquid in Ψ_2 layer. Similar EDC obtained by gapless $\mathbb{Z}_2$ spin liquid

(e,f) Experiments on Bi2212 by S.-D. Chen, M. Hashimoto, Y. He, D. Song, K.-J. Xu, J.-F. He, T. P. Devereaux, H. Eisaki, D.-H. Lu, J. Zaanen, and Z.-X. Shen, Science **366**, 1099 (2019).

1. Paramagnon fractionalization theory of the Hubbard model

2. Photoemission in the cuprates

3. Confinement transitions from the pseudogap metal

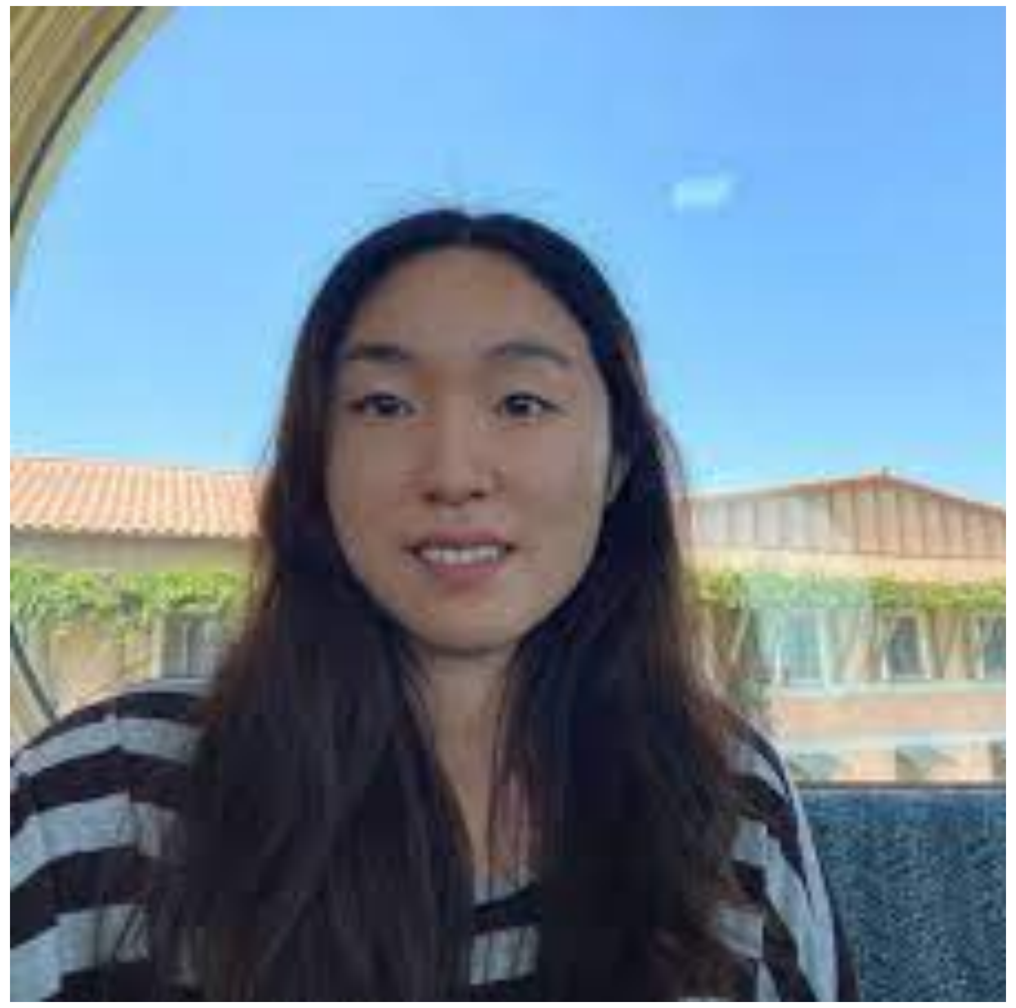
Alexander Nikolaenko

Darshan Joshi

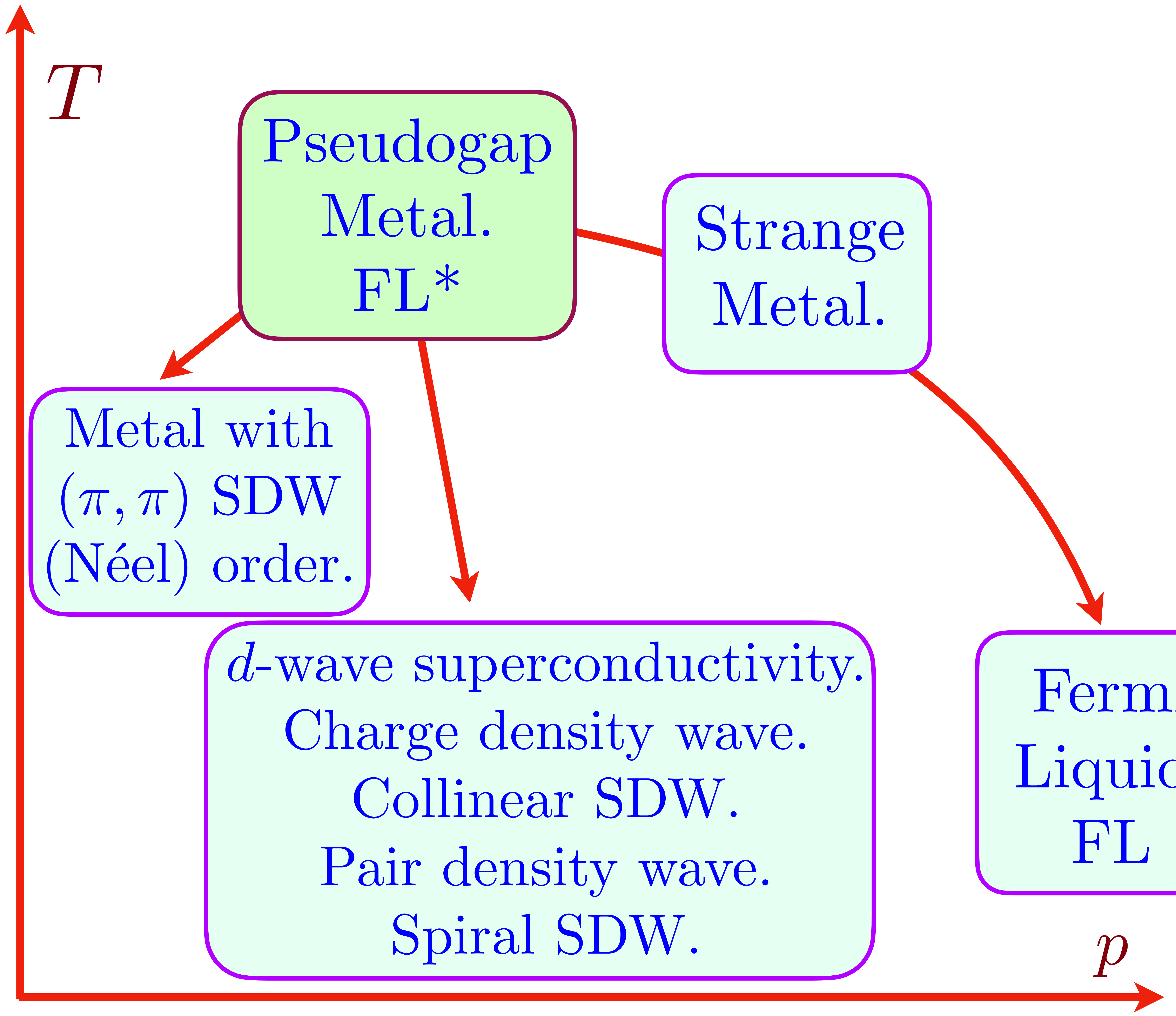
Jonas von Milczewski

Henry Shackleton

Maine Christos



Zhu-Xi Luo



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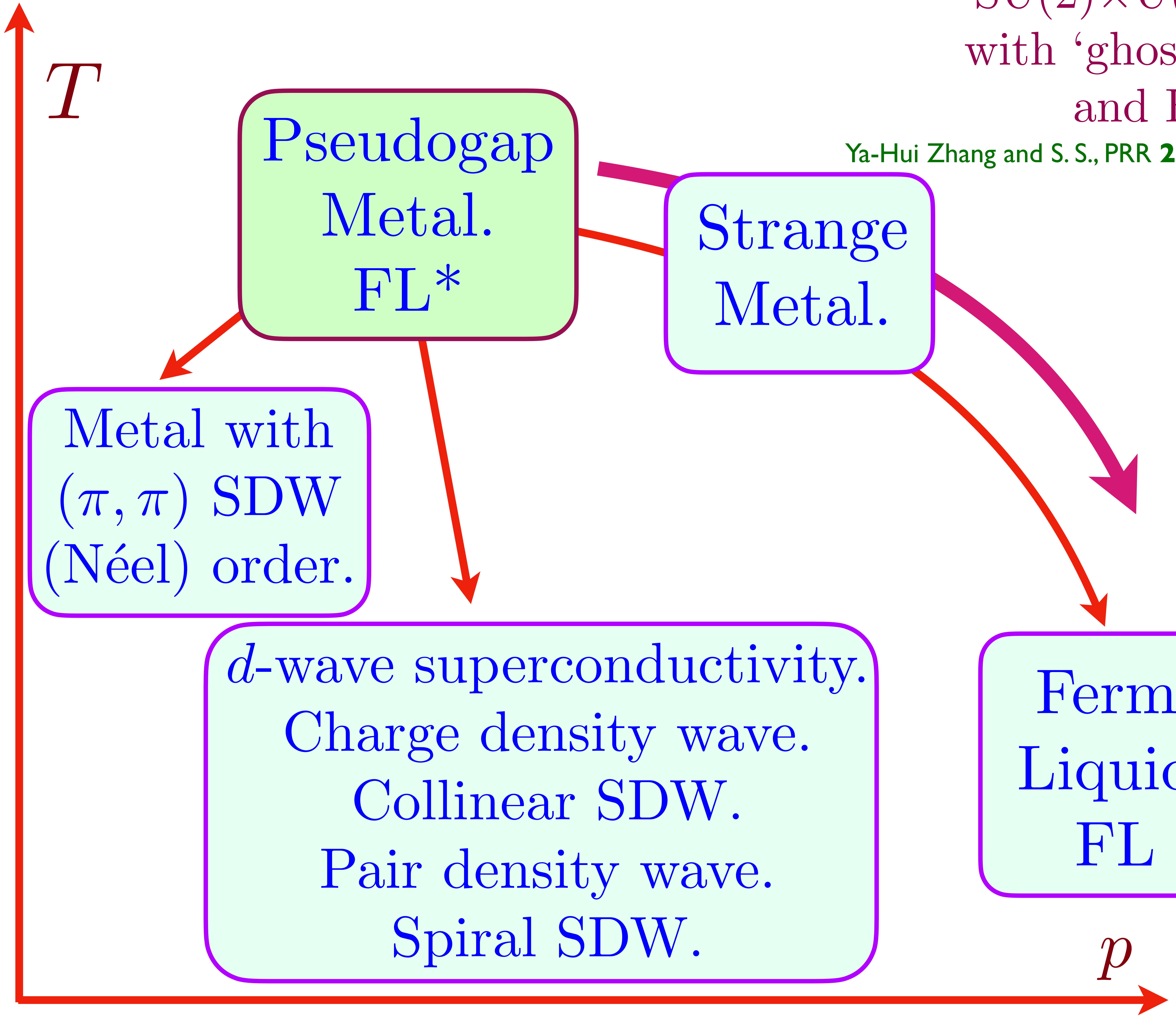
Metal with (π, π) SDW (Néel) order.
d-wave superconductivity.
Charge density wave.
Collinear SDW.
Pair density wave.
Spiral SDW.
Fermi Liquid. FL
p

Yahui Zhang

SU(2)×U(1) gauge theory with ‘ghost’ Fermi surfaces and Higgs fields.

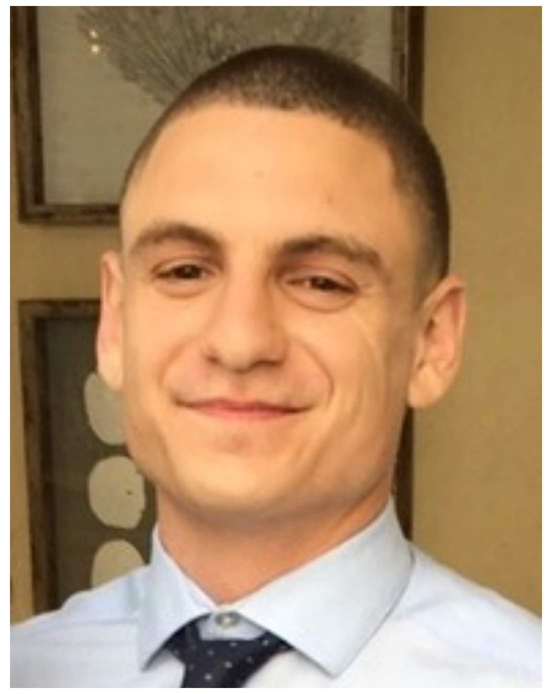
Ya-Hui Zhang and S. S., PRR **2**, 023172; PRB **102** , 155124 (2020)



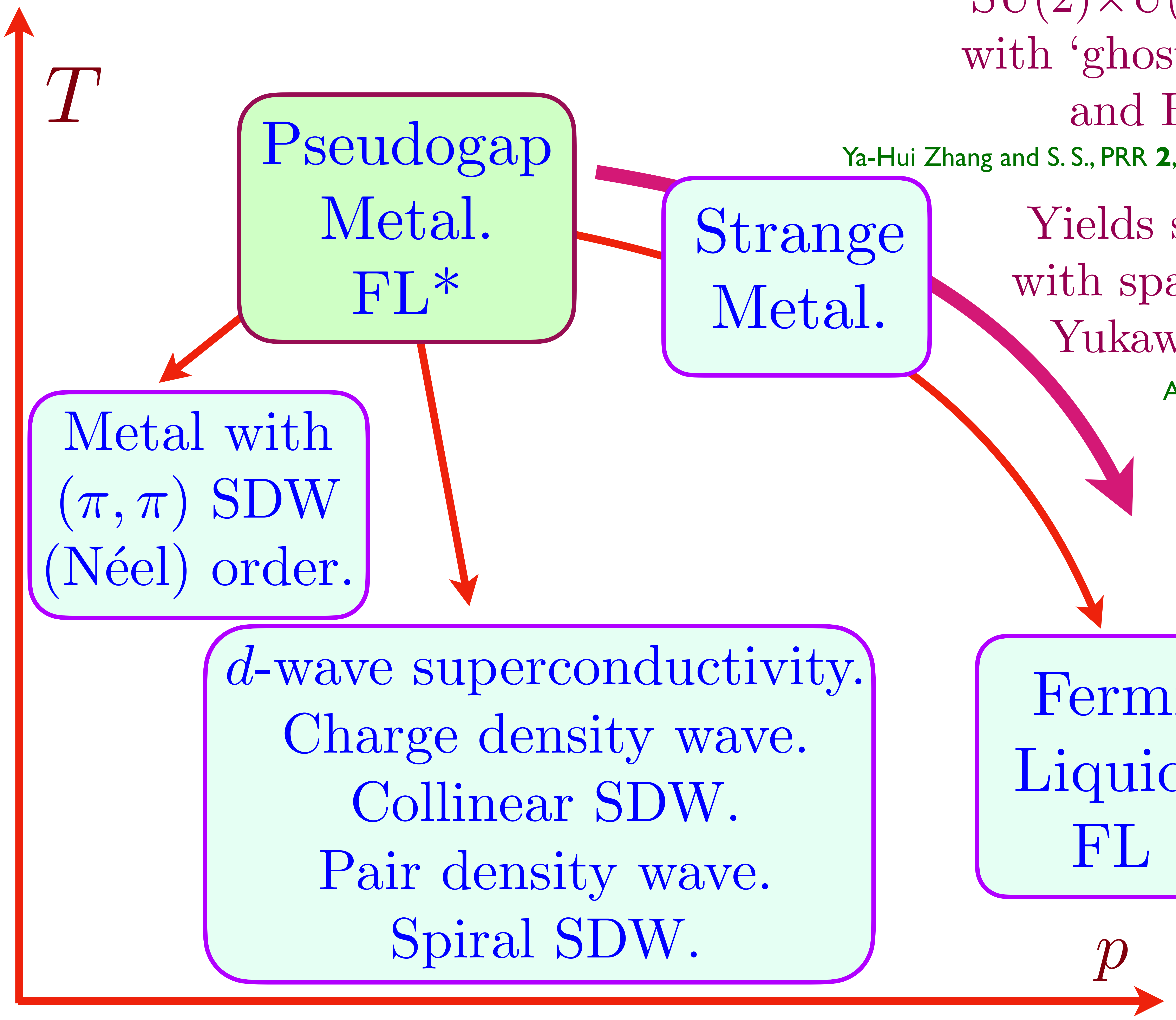
Yahui
Zhang

Aavishkar
Patel

Haoyu
Guo



Ilya
Esterlis



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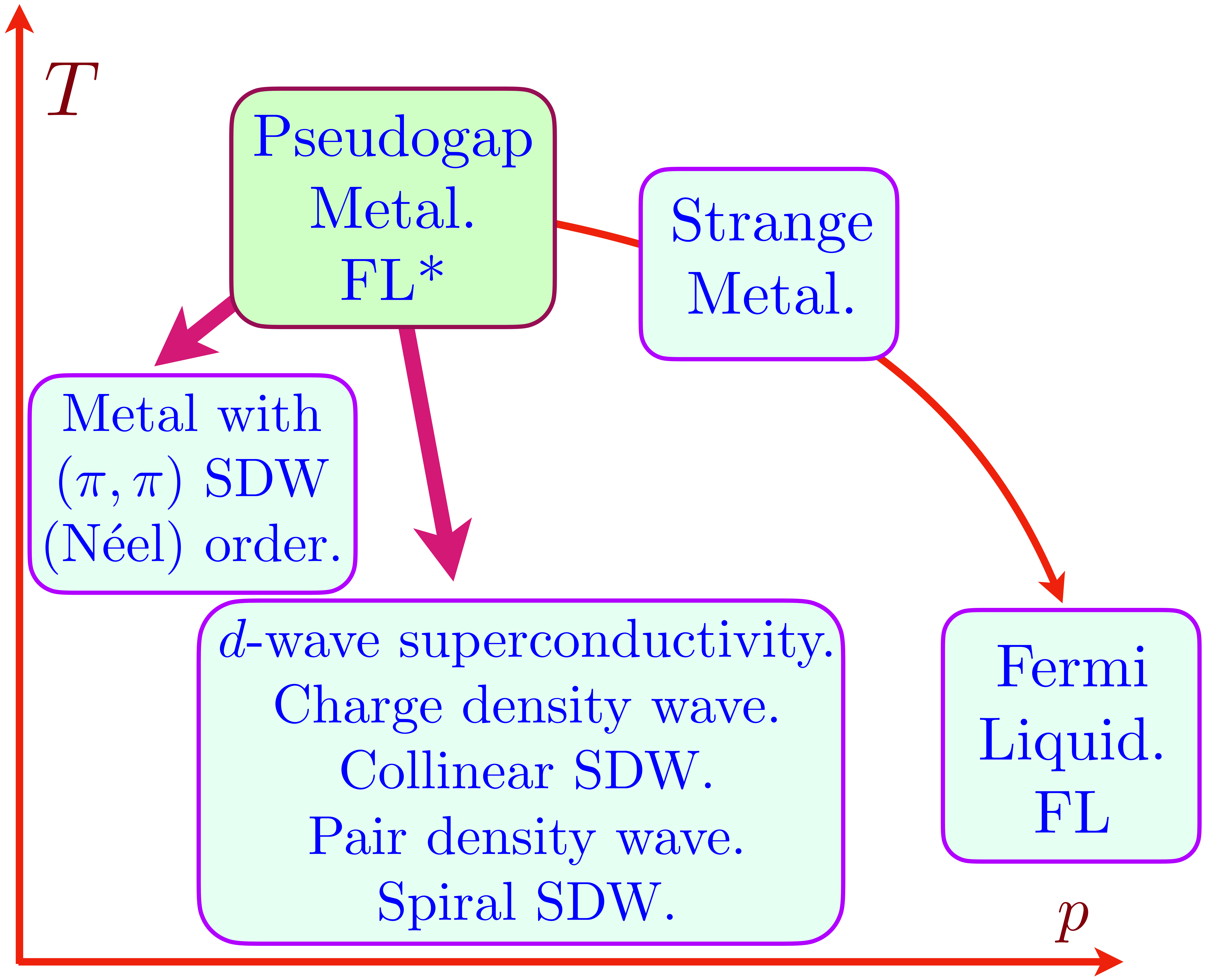
Ya-Hui Zhang and S. S., PRR **2**, 023172; PRB **102** , 155124 (2020)

Yields strange metal with spatially random Yukawa couplings.

A. A. Patel, Haoyu Guo, I. Esterlis, and S. S., arXiv:2203.04990



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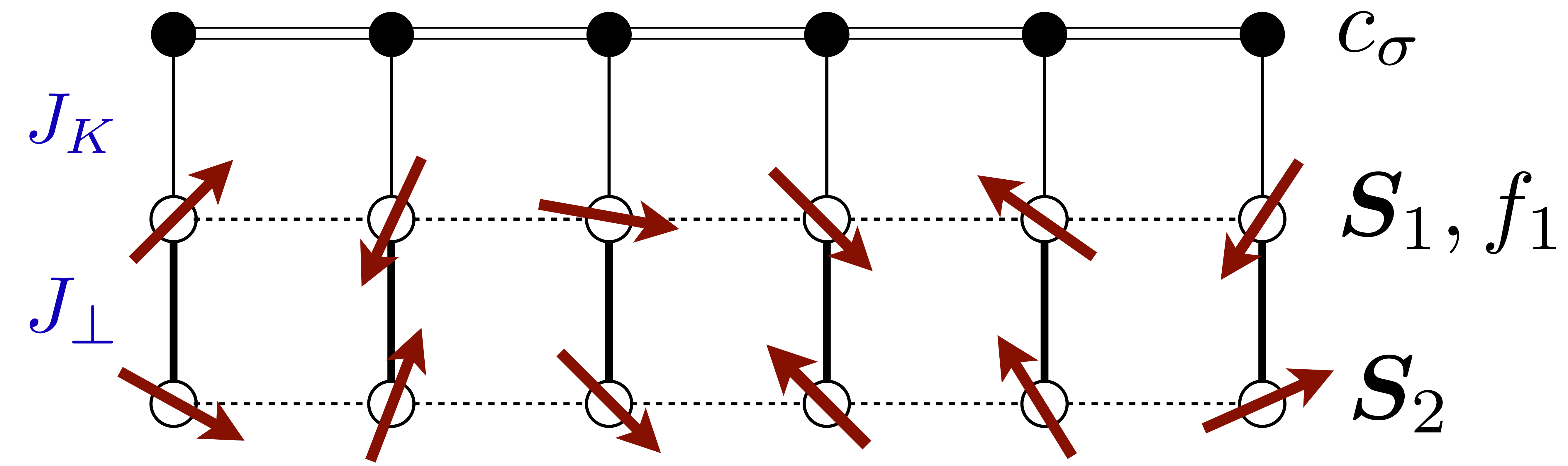
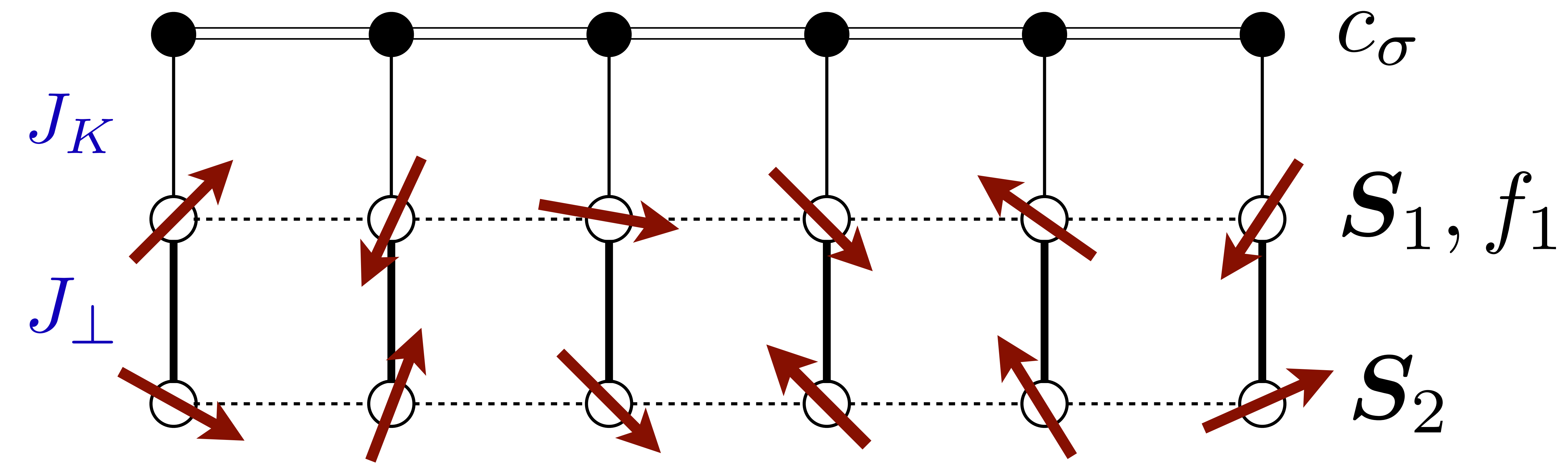


Spin liquid of $\boldsymbol{S}_2$:

(A) Schwinger boson representation ($\boldsymbol{S}_{2i} = b^\dagger_{i\alpha}\boldsymbol{\sigma}_{\alpha\beta}b_{i\beta}$) leads to spin liquid described by $\mathbb{CP}^1$ field theory: $N_f = 2$ relativistic complex scalars, Z, coupled to a U(1) gauge field.



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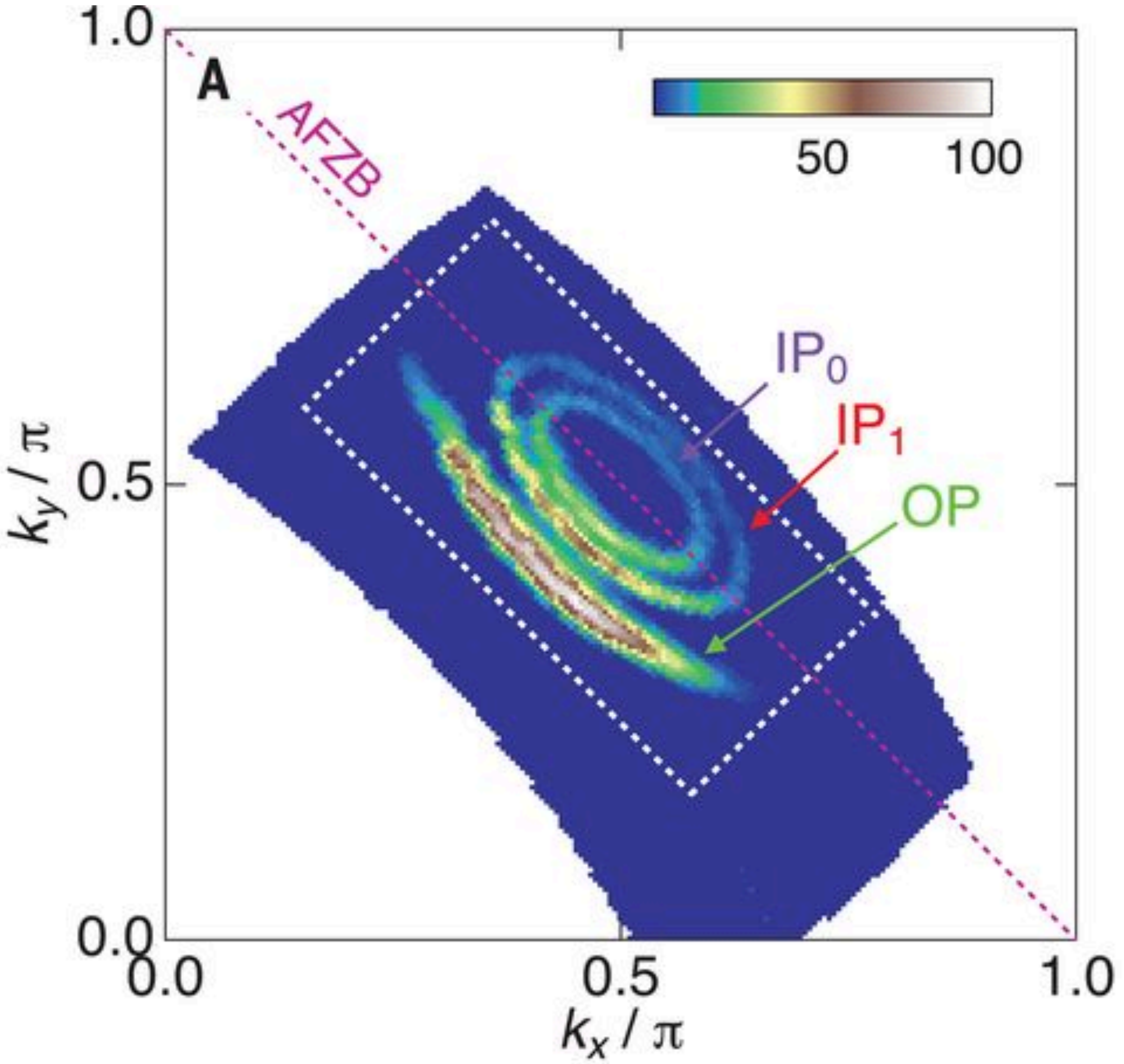
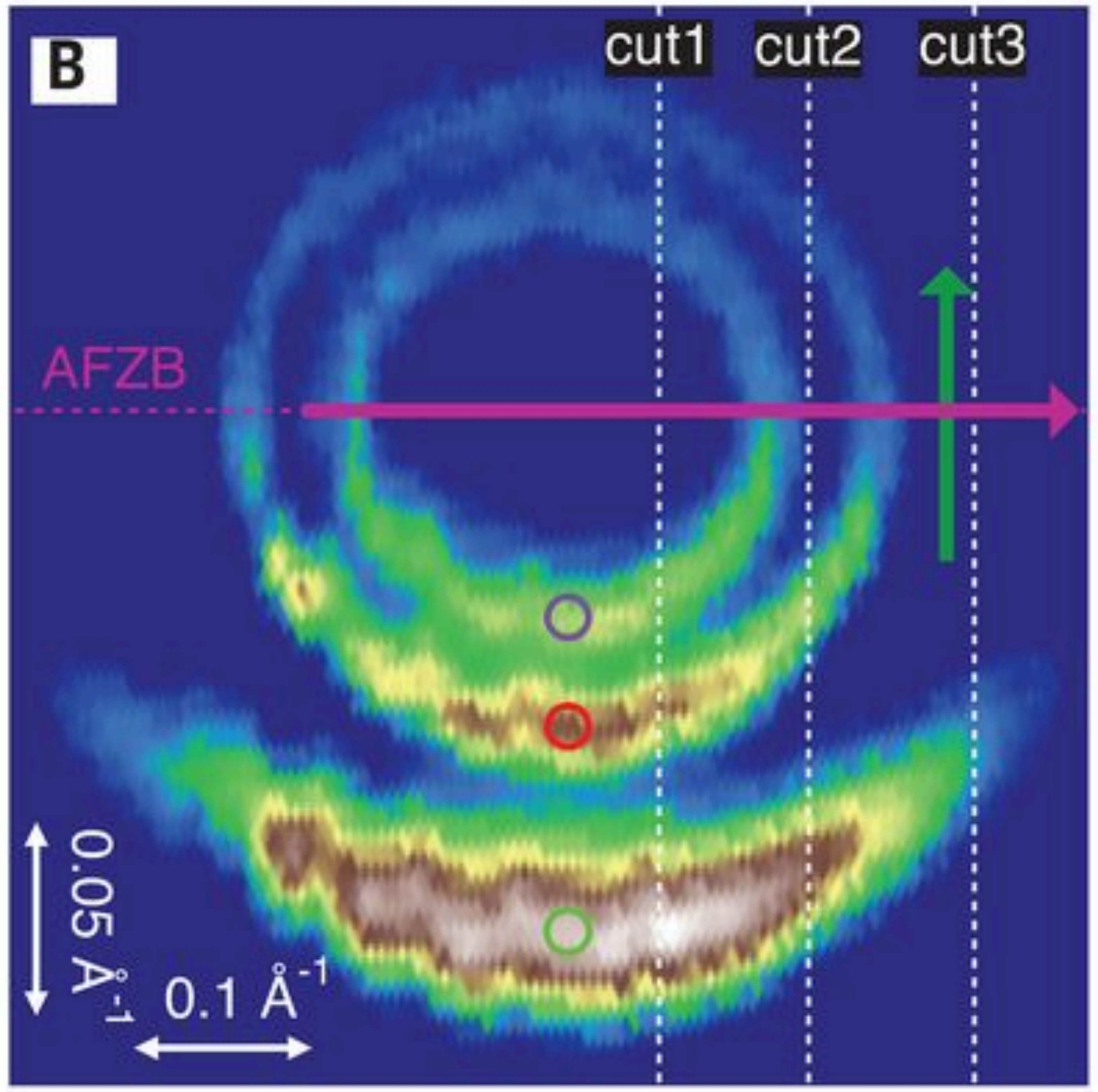
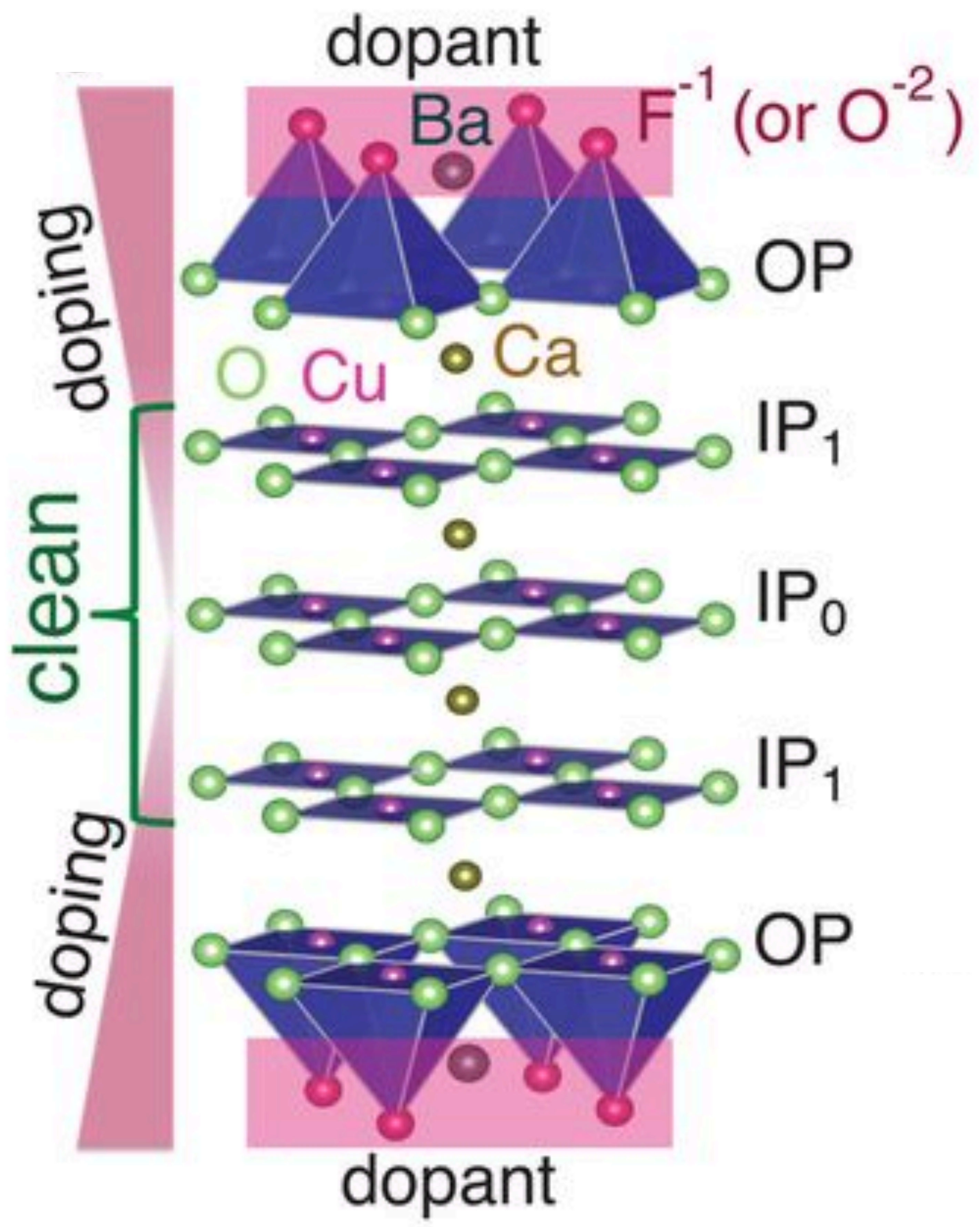
Confinement transition: Condensation of Z leads to (π, π) Néel order, or incommensurate spiral spin density waves.

Observation of small Fermi pockets protected by clean CuO_2 sheets of a high-T_c superconductor

So Kunisada[1], Shunsuke Isono[2], Yoshimitsu Kohama[1,3], Shiro Sakai[4], Cédric Bareille[1], Shunsuke Sakuragi[1], Ryo Noguchi[1], Kifu Kurokawa[1], Kenta Kuroda[1], Yukiaki Ishida[1], Shintaro Adachi[5], Ryotaro Sekine[2], Timur K. Kim[6], Cephise Cacho[6], Shik Shin[1,7], Takami Tohyama[8], Kazuyasu Tokiwa[2*], Takeshi Kondo[1,3*]

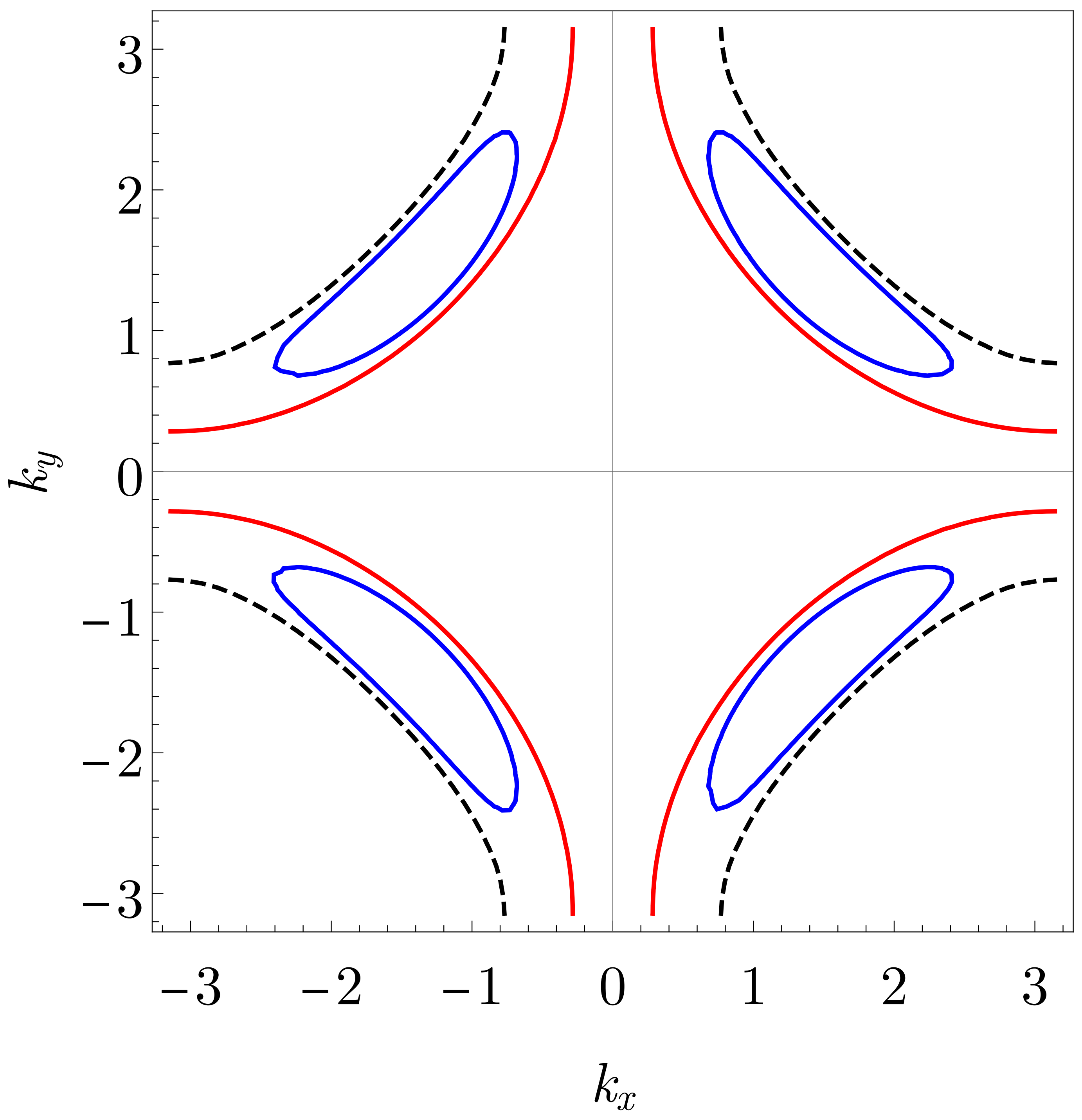




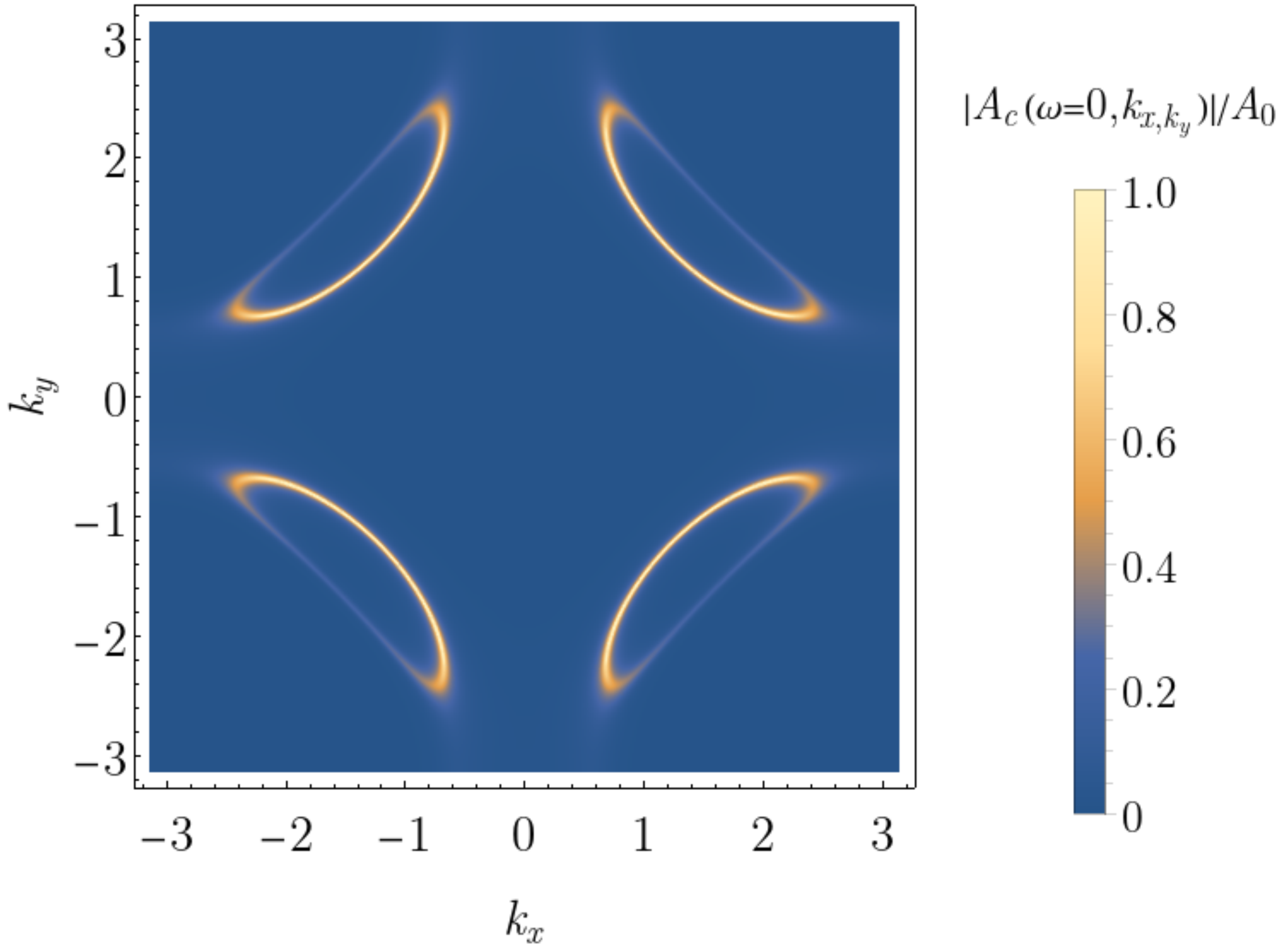


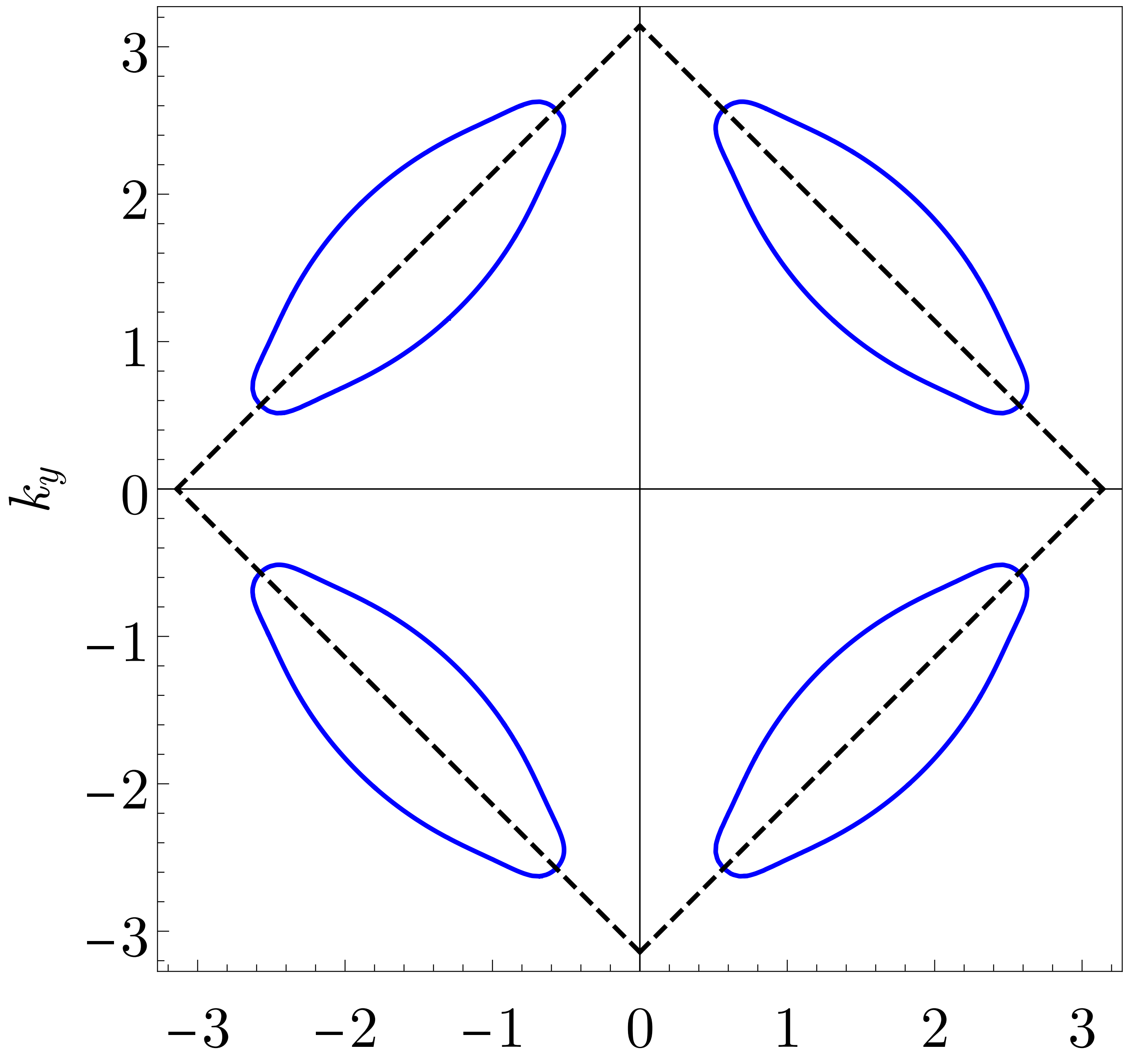
Hole pockets in a metallic SDW state with Néel order at (π, π).

Science **369**, 833 (2020).

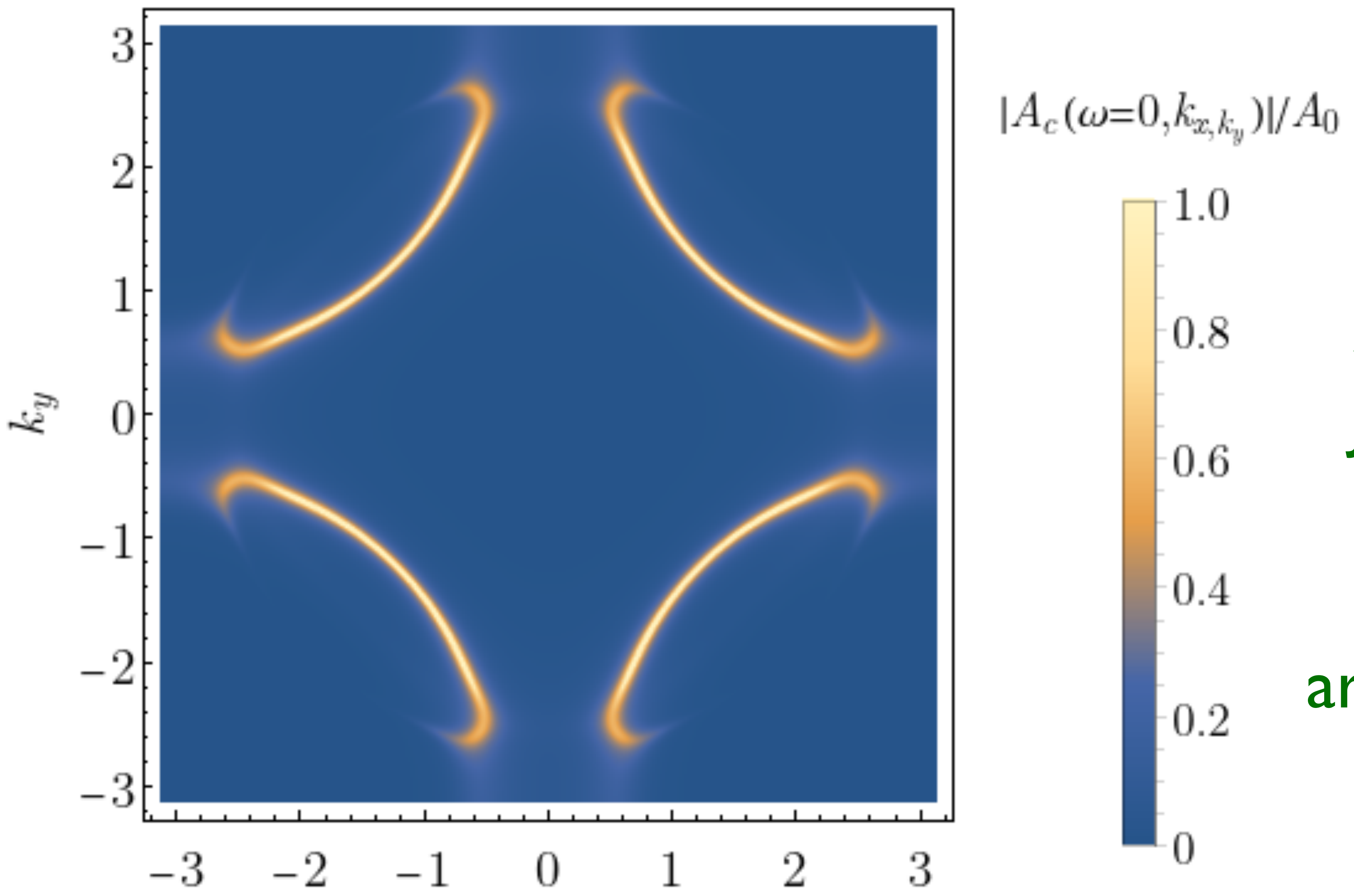


FL*
$\langle Z \rangle = 0$

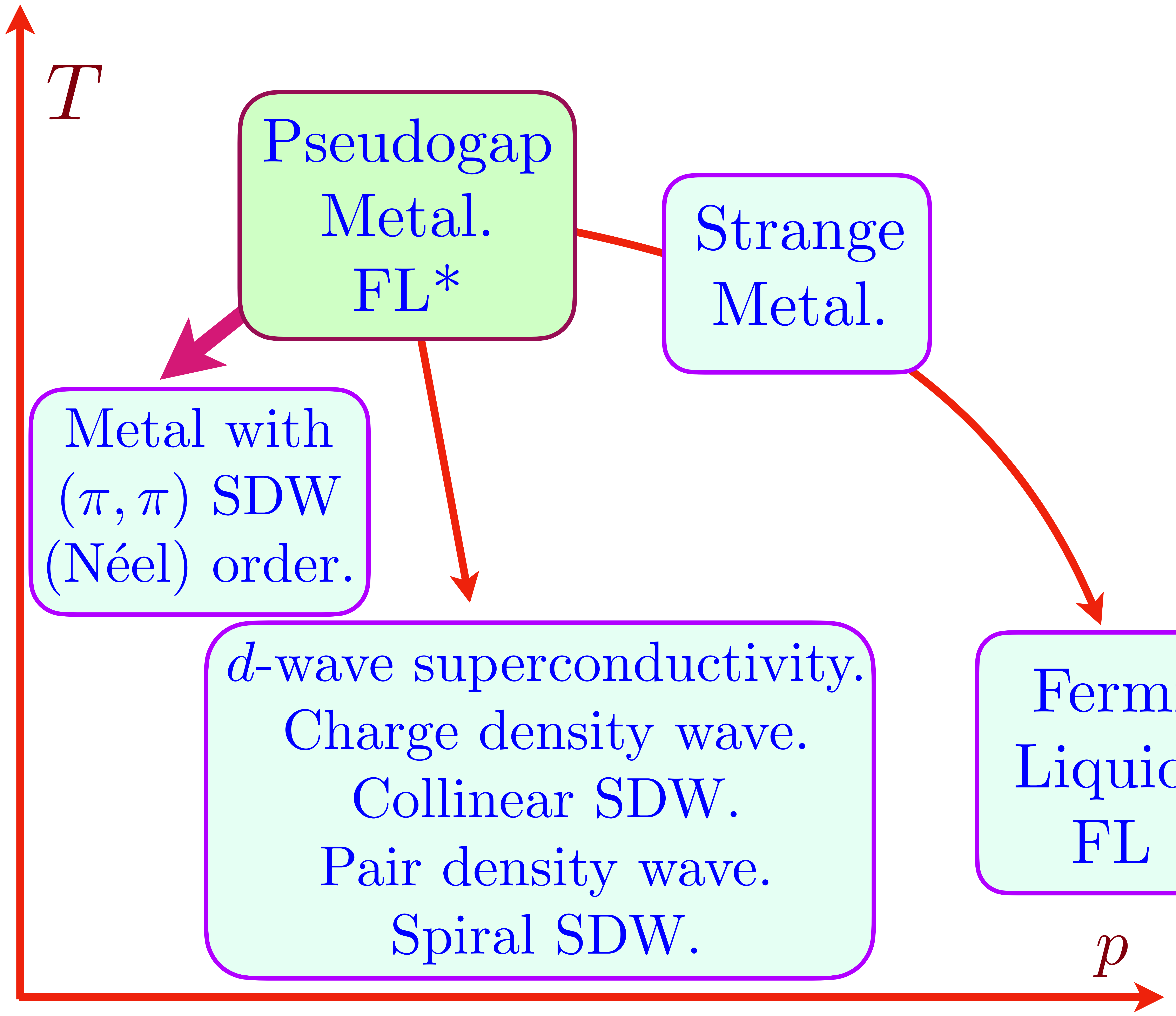




Néel
(π, π) SDW
$\langle Z \rangle \neq 0$



A. Nikolaenko,
J. v. Milczewski,
D. G. Joshi,
S.S.,
arXiv:2211.xxxxx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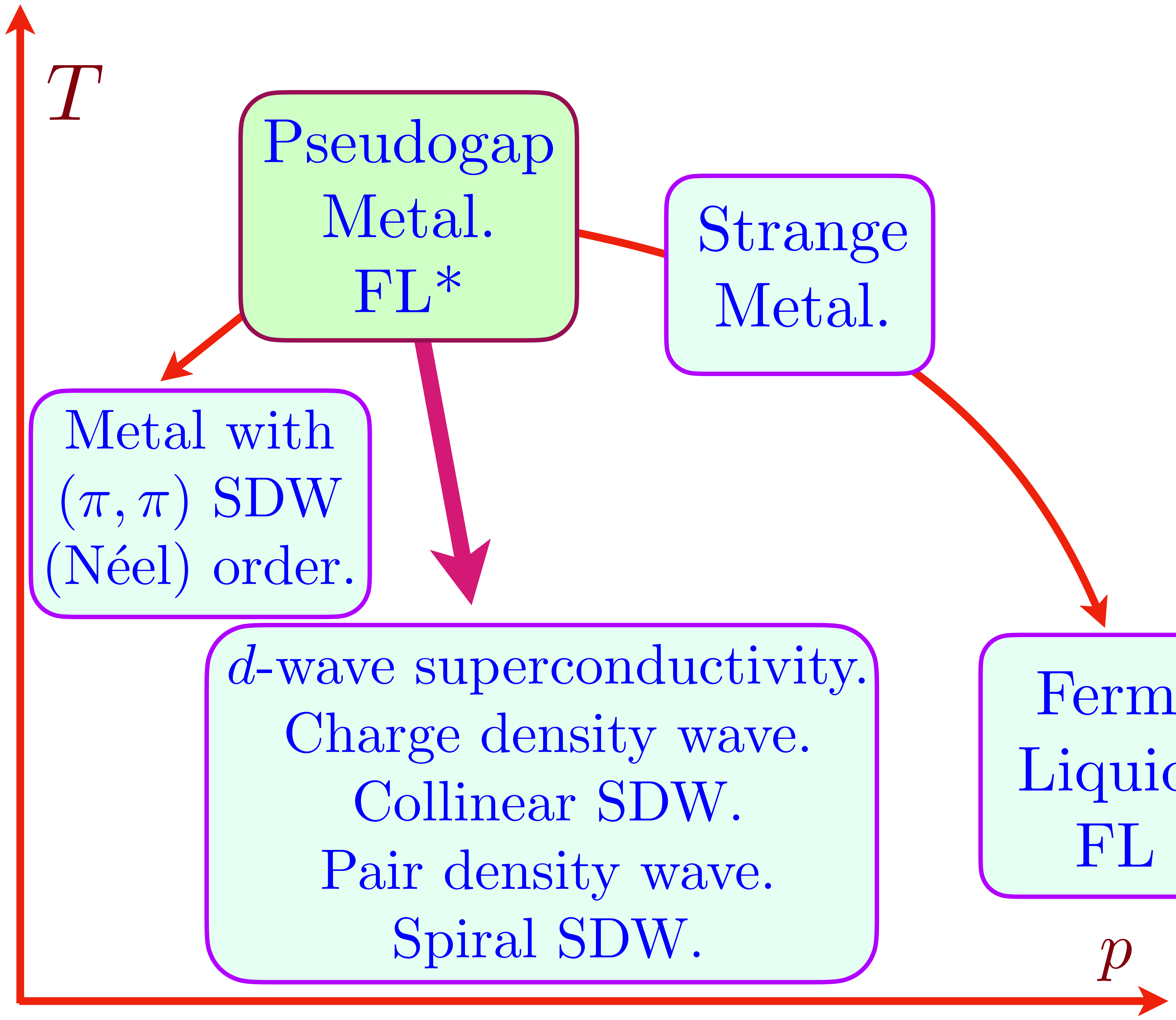

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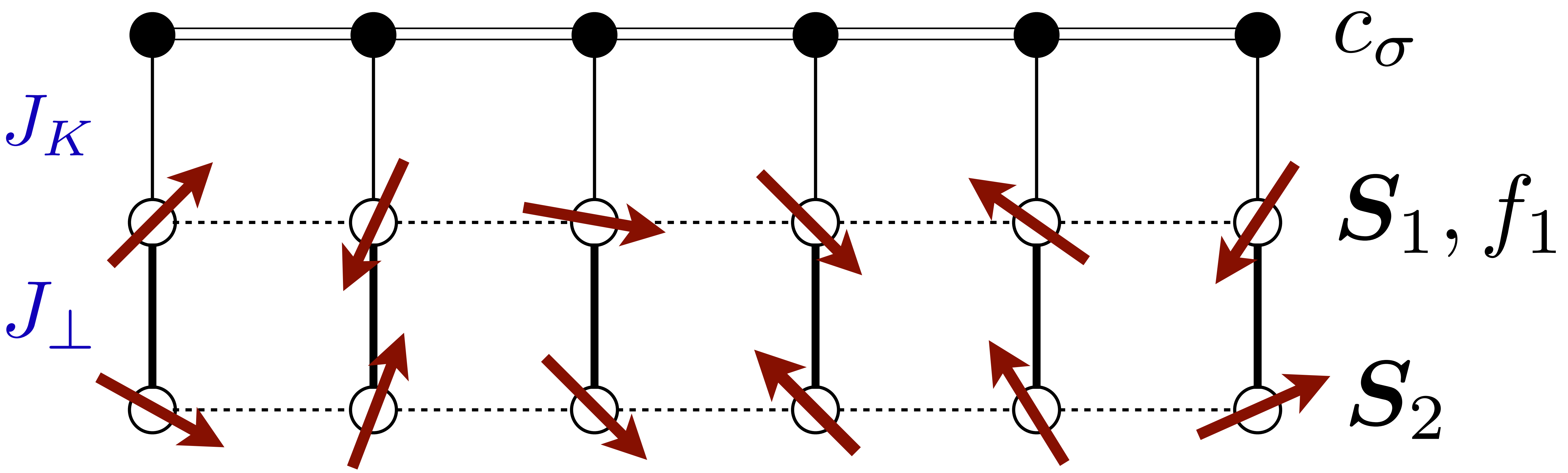

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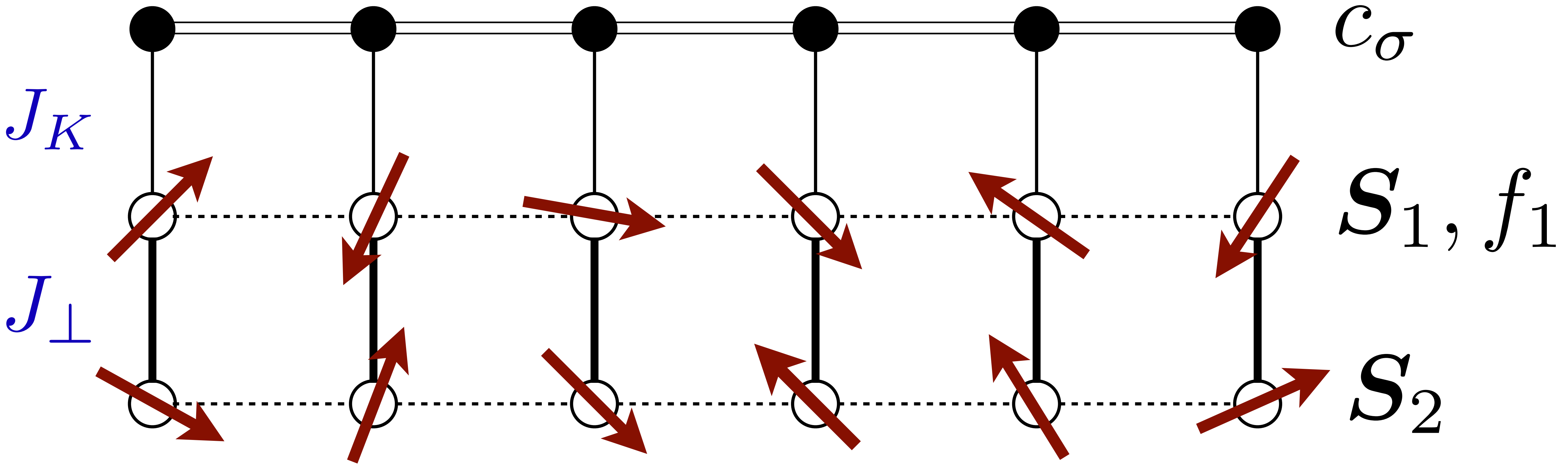

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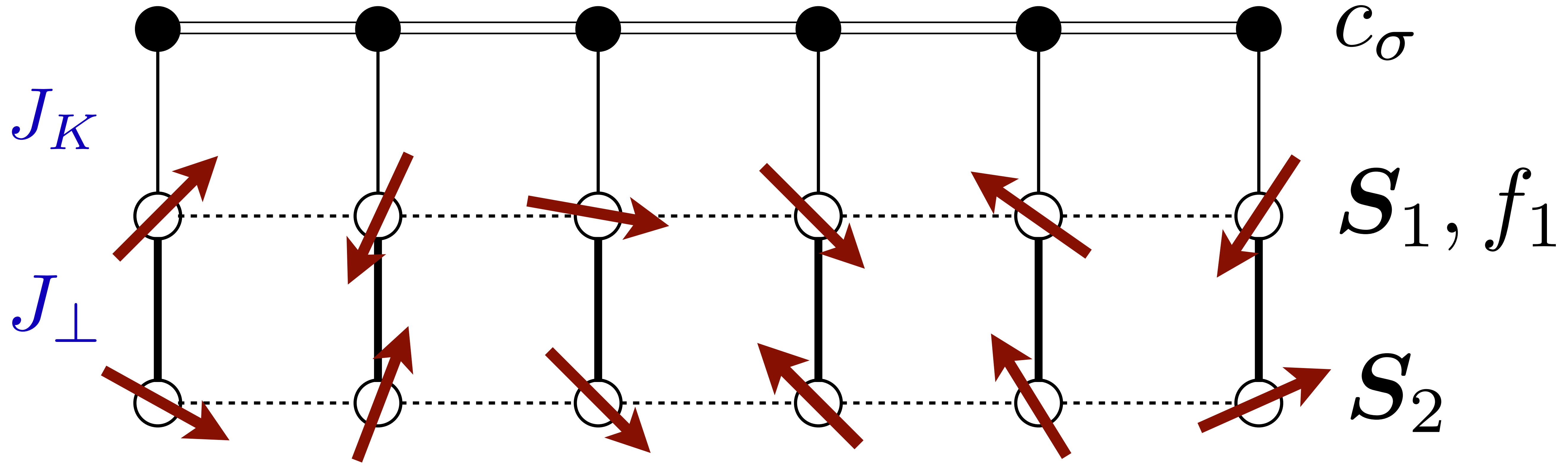

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Boson-fermion duality

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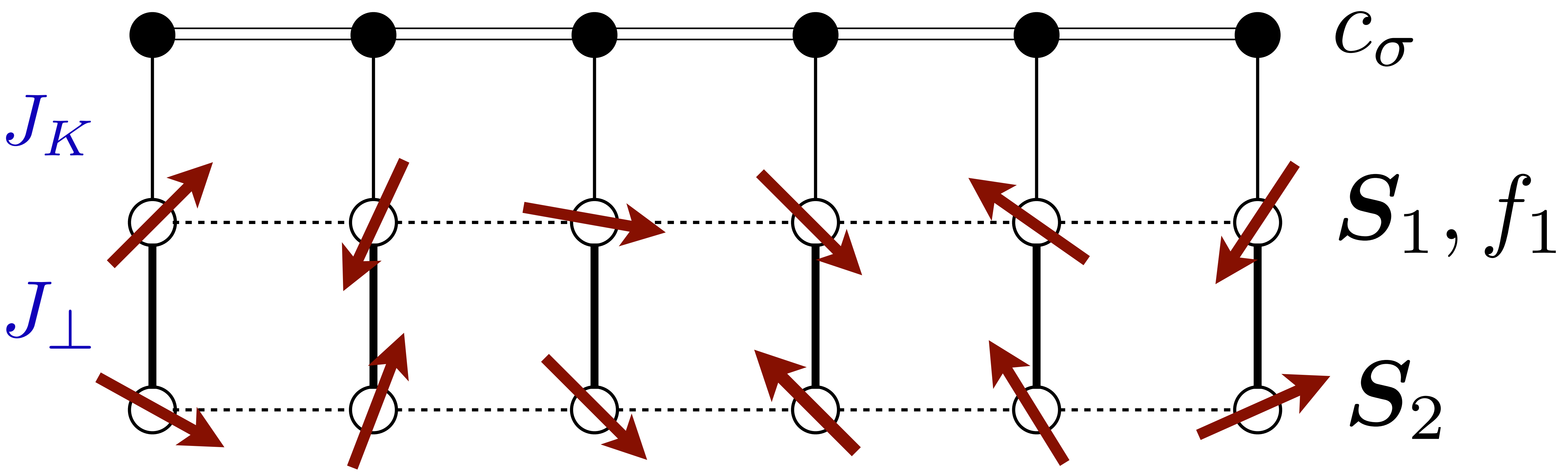
Chong Wang, A. Nahum, M.A. Metlitski, Cenke Xu, and T. Senthil, PRX **7**, 031051 (2017)



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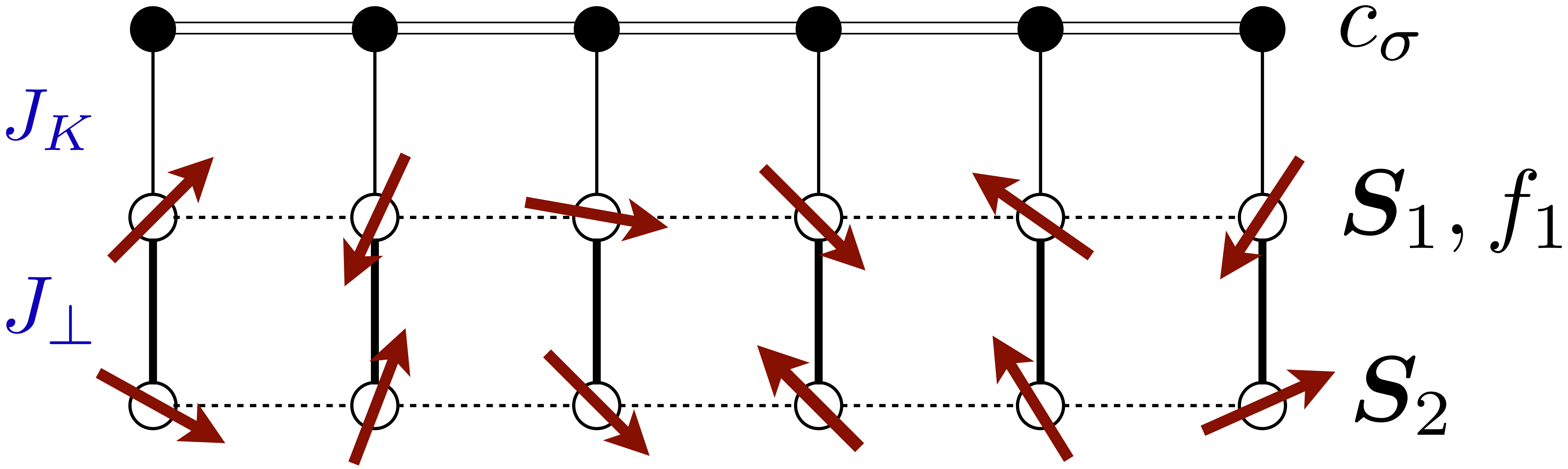
There is now good evidence that the $N_f = 2$ SU(2)-QCD CFT is not stable.



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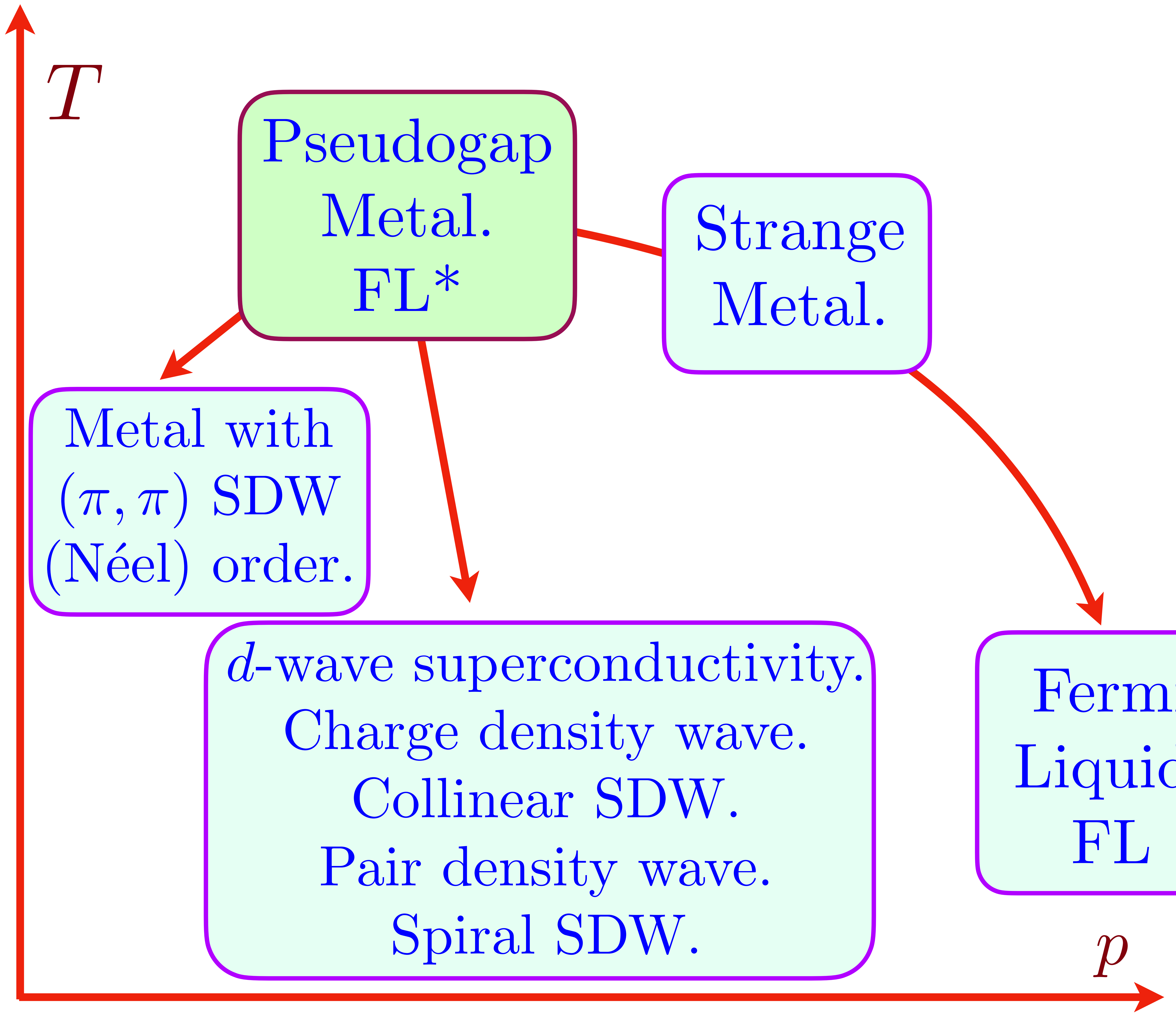
Chong Wang, A. Nahum, M.A. Metlitski, Cenke Xu, and T. Senthil, PRX **7**, 031051 (2017)



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Summary

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  Don't fractionalize the mobile electron, but fractionalize the paramagnon into 'ancilla qubits'.
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- Outlook:

  - 'Back side' of hole pockets in FL* phase may be observable in cleaner samples.
  - Theory for multi-point correlators in cold atom experiments.
  - Theory for FL*-FL transition leads to strange metal with spatially random couplings.
  - Theory of quantum oscillations in underdoped cuprates at high fields.