Title: Modeling the pseudogap state in cuprates: quantum disordered pair density wave

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Series: Condensed Matter

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Abstract: I will briefly review the pseudogap phenomenology in high Tc cuprate superconductor, especially the recent experiments, and propose a unified picture of the phenomenology under only one assumption: the fluctuating pair density wave. By quantum disordering a pair density wave, we found a state composed of insulating antinodal pairs and nodal electron pocket. We compare the theoretical predictions with ARPES results, optical conductivity, quantum oscillation and other experiments.

Modeling the pseudogap state in cuprates: quantum disordered pair density wave

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Z. Dai, T. Senthil, P. A. Lee, arXiv: 1906.01656

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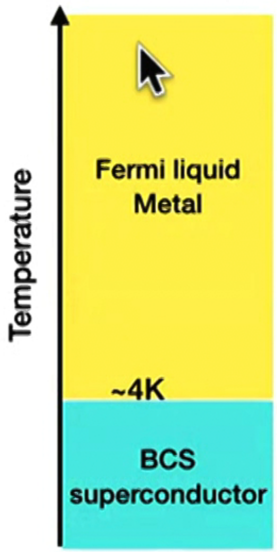
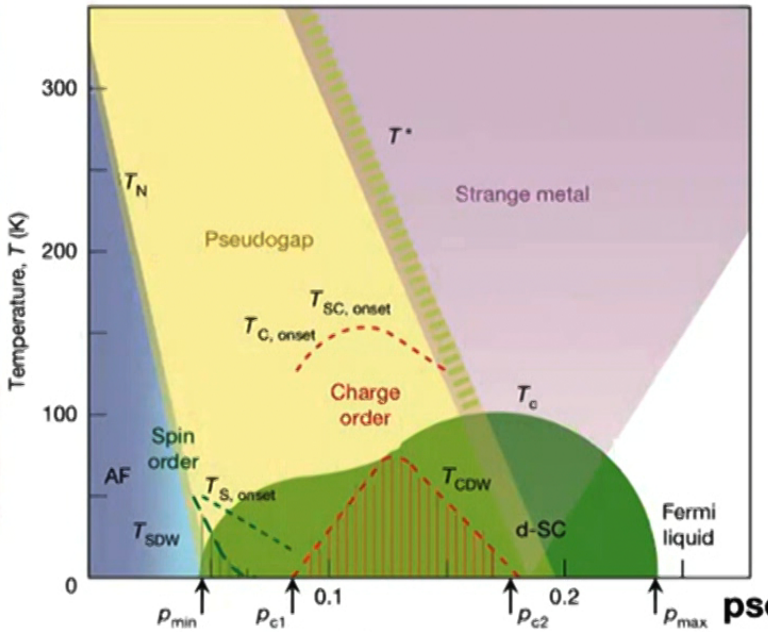
BCS superconductor **Cuprate high Tc superconductor**





Keimer, Bernhard, et al. *Nature* 518.7538 (2015): 179-186.

- **Superconductor:** Tc ~ 100K
- **Strange metal:** large Fermi surface, linear T resistivity??
- **Pseudogap:** electron gap on part of the Fermi surface, Fermi arc??

Doping dependence: **pseudogap** is an intermediate phase between the Mott insulator at half filling, and the Fermi liquid at larger doping

Goal： use a single assumption to explain the pseudogap phenomenology at low temperature

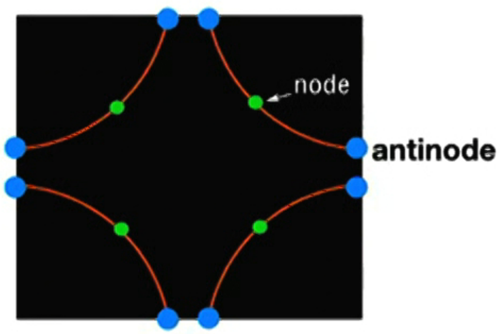
Outline

- **Brief review of the pseudogap**
- Review of pair density wave (PDW) order
- Quantum disordered PDW: effective theory of pseudogap

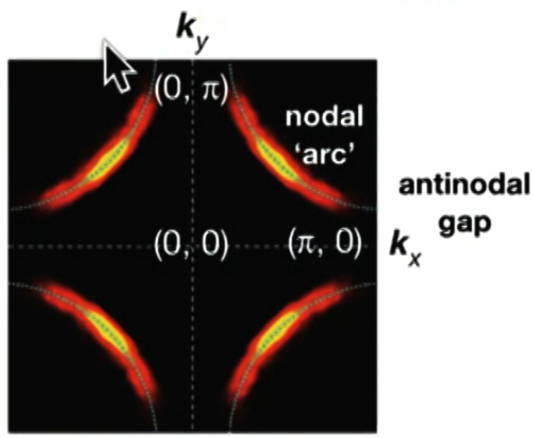
  Claim: small electron pocket + insulator of electron pairs
- Electron spectrum of fluctuating superconductor
- Comparison with experimental results

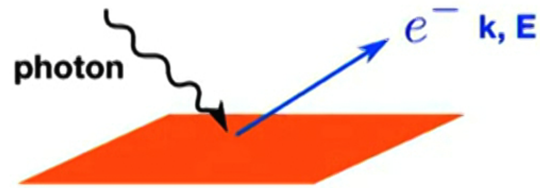
Pseudogap: antinodal Gap seen in ARPES

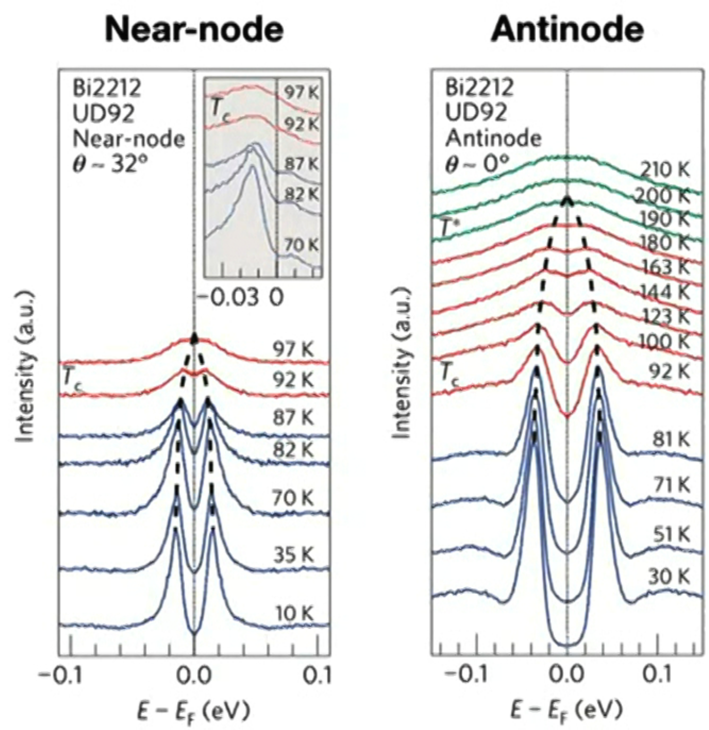
high temperature: large Fermi surface
d wave superconductor: gapless node



T < T* : antinodal electron gap

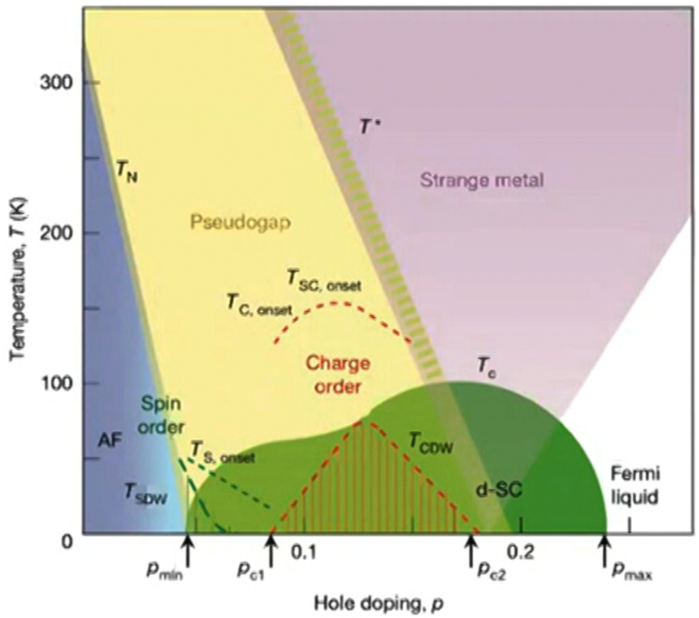


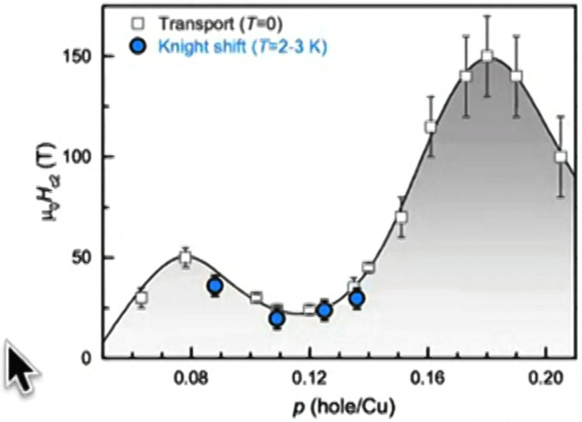




5 Hashimoto, Makoto, et al. *Nature Physics* 10.7 (2014): 483-495.

High-field metallic pseudogap ground state





Zhou, Rui, et al. PNAS 114.50 (2017): 13148-13153.

At high field and the lowest temperature, quantum oscillation from a small electron Fermi surface, 2% of the original BZ

↓

Fermi Liquid with small Fermi surface?

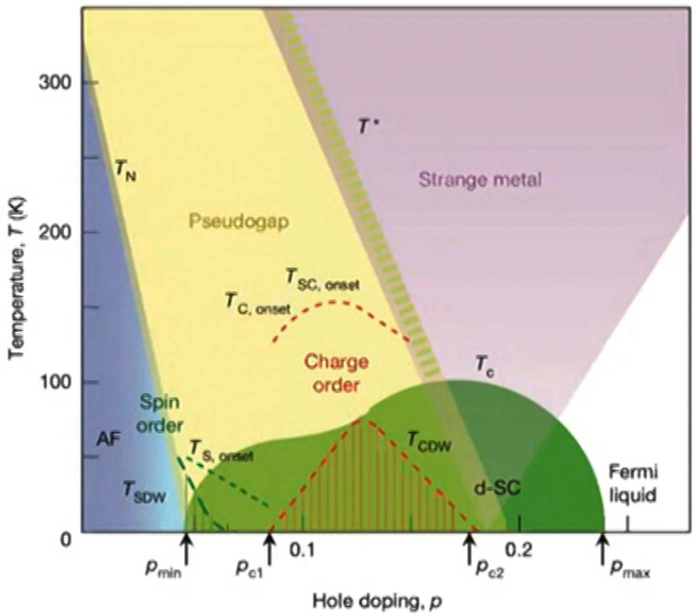
Our goal: to understand pseudogap at the lowest temperature, H > Hc2, or Tc <<T << T*

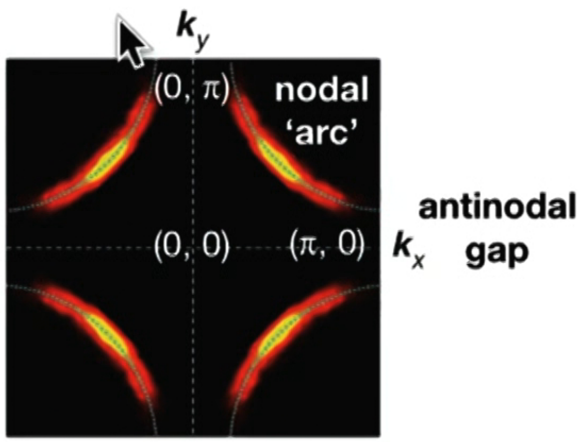
Assumption: quantum fluctuating PDW

Z. Dai, T. Senthil, P. A. Lee, arXiv: 1906.01656

Previous theoretical approach

- Charge density wave (CDW) alone cannot explain the pseudogap
- Pseudogap was traditionally explained by fluctuating d wave SC





Fluctuating SC can explain the decrease of density of states, but is difficult to explain the nodal arcs

Fluctuating pair density wave as a mother state

- **Use the idea of fluctuating superconductivity to get a metal with pseudogap, but consider a different pairing**
- **PDW: electron pair condense at nonzero momentum**

$$\Delta_{\vec{P}} = \langle c_{\vec{k},\uparrow} c_{-\vec{k}+\vec{P},\downarrow} \rangle \neq 0$$

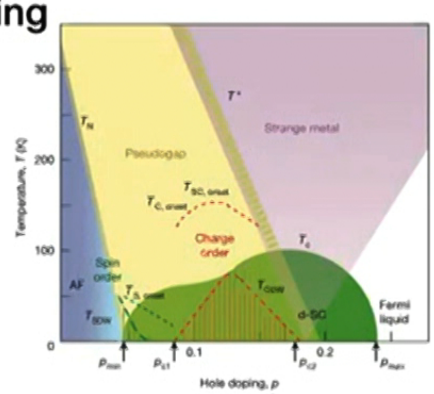
- **Bidirectional PDW, wave vector half of the CDW**

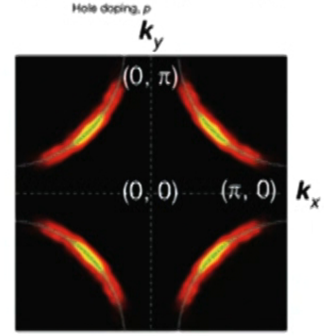
$$\vec{P} = P\hat{x}, -P\hat{x}, P\hat{y}, -P\hat{y}$$

Generate CDW at momentum $Q_{\mathrm{CDW}} = 2P$

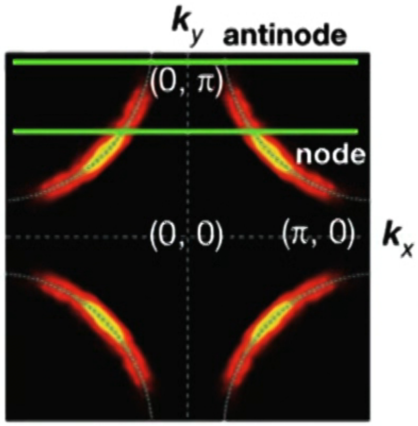
- **Pair density wave (PDW) has a number of advantages**

1. Gap out only antinodal electrons, leaves gapless ‘Fermi arc’
2. Explains ARPES in detail
3. Generate secondary CDW at wave vector Q = 2P
4. Explain the quantum oscillation at high field



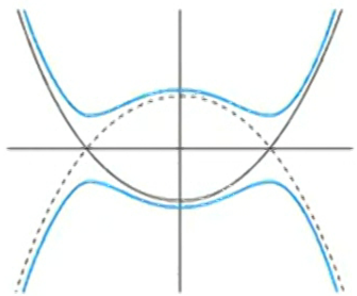


P. A. Lee, PRX 4, 031017
Z. Dai, T. Senthil, P. A. Lee, arXiv: 1906.01656



PDW spectrum along two cuts

Mix electron and hole
at different momentum



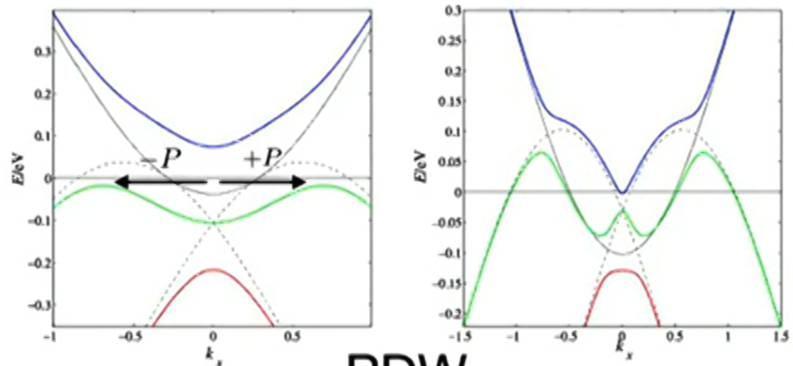
BCS (for comparison)

$$\langle c_{k\uparrow} c_{-k\downarrow} \rangle \neq 0$$

$$c_{k\uparrow} \rightarrow c^{\dagger}_{-k\downarrow}$$

gapped antinode

gapless node



PDW

$$\langle c_{k\uparrow} c_{-k\pm P\downarrow} \rangle \neq 0$$

$$c_{k\uparrow} \rightarrow c^{\dagger}_{-k+P\downarrow}$$

P. A. Lee, PRX 4, 031017

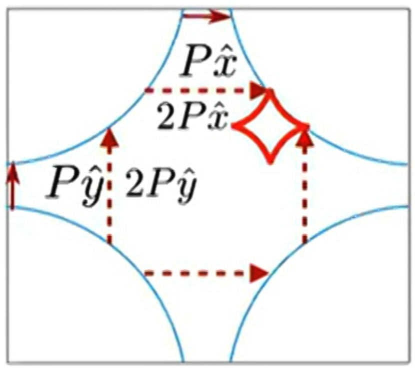
Secondary CDW and MDW fold the B.Z.

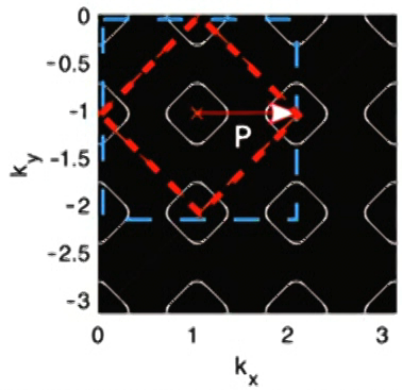
Period-6 PDW

$$c_k \xrightarrow{\Delta_{\mathbf{P}_1}} c^{\dagger}_{-k+\mathbf{P}_1} \xrightarrow{\Delta_{\mathbf{P}_2}} c_{k-\mathbf{P}_1+\mathbf{P}_2}$$

PDWs at $\pm P\hat{x}$ generate CDW at $2P\hat{x}$

CDW connects nodal arcs into the Harrison-Sebastian pocket





Magnetization Density Wave from orbital current

PDWs at $P\hat{x}$ and $P\hat{y}$ generate MDW at $P\hat{x} + P\hat{y}$

MDW sets the unit cell for the fluctuating PDW state

D. Agterberg and H. Tsunetsugu, Nature Physics 4, 639 (2008)

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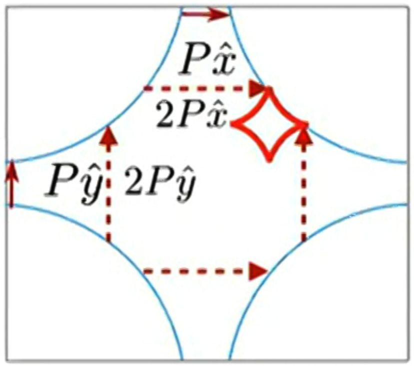

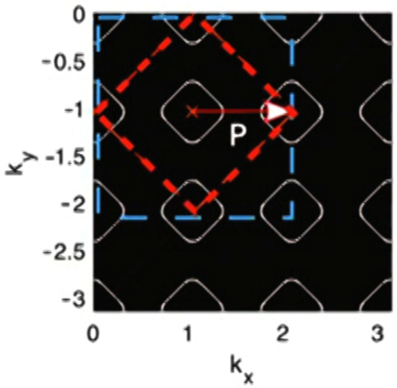

Magnetization Density Wave from orbital current

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MDW sets the unit cell for the fluctuating PDW state

D. Agterberg and H. Tsunetsugu, Nature Physics 4, 639 (2008)

Outline

- Brief review of pseudogap phenomenology
- Review of pair density wave (PDW)
- **Quantum disordered PDW: high field pseudogap ground state**

  Claim: small electron pocket + insulator of antinodal pairs
- Electron spectrum of quantum disordered superconductor
- Comparison with experimental results

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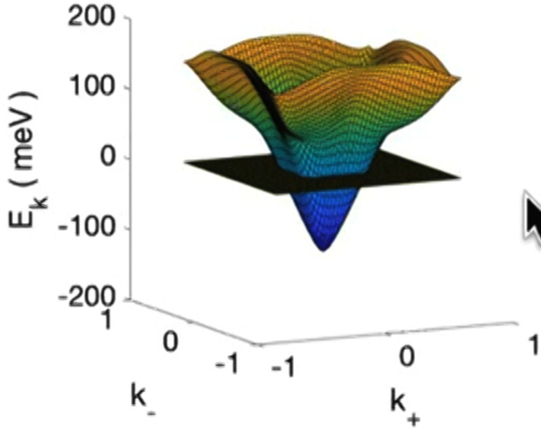
Definition of *quantum disordered (fluctuating) order*

For an order parameter O. A *quantum disordered phase of O* refers to any phase where O does not have long range order (namely <O>=0), but the phase is close to a transition into the ordered phase, thus <O(r)O(0)> has a long correlation length relative to lattice scale.

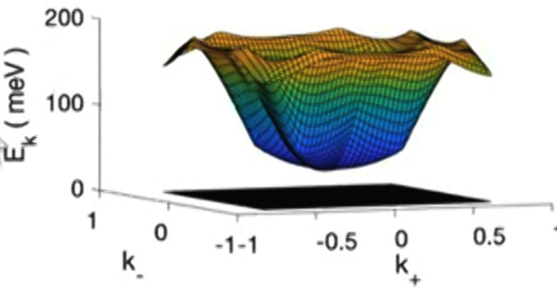
Here O = PDW

To construct quantum disordered PDW, we want to drive the PDW state to a non-superconducting state

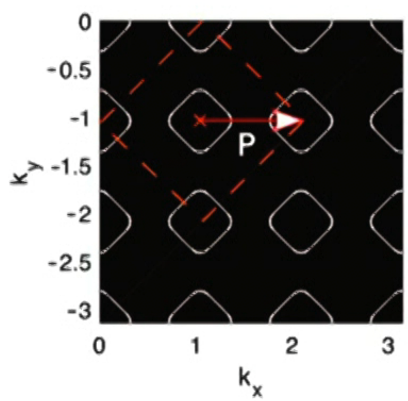
Band structure of ordered PDW



The gapless band



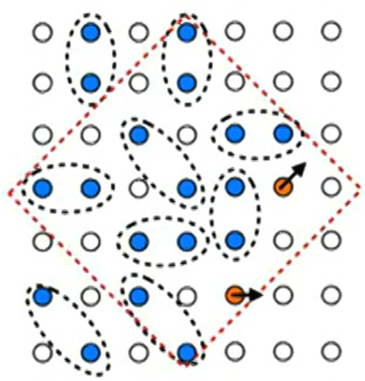
The lowest gapped band

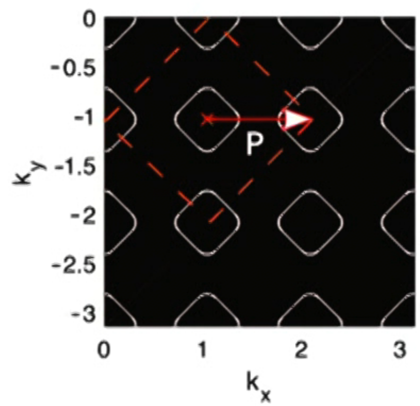


- **1 gapless band weakly coupled to PDW**
- **All other bands are gapped by PDW**
- **Treat them them separately when considering the fluctuation of PDW**

The fluctuating PDW state

- Keep the secondary MDW and CDW, disorder PDW
- Treat the gapless band and gapped bands separately
- Small electron pocket + Bosonic Mott insulator





Z.Dai, T. Senthil, P. A. Lee, arXiv: 1906.01656

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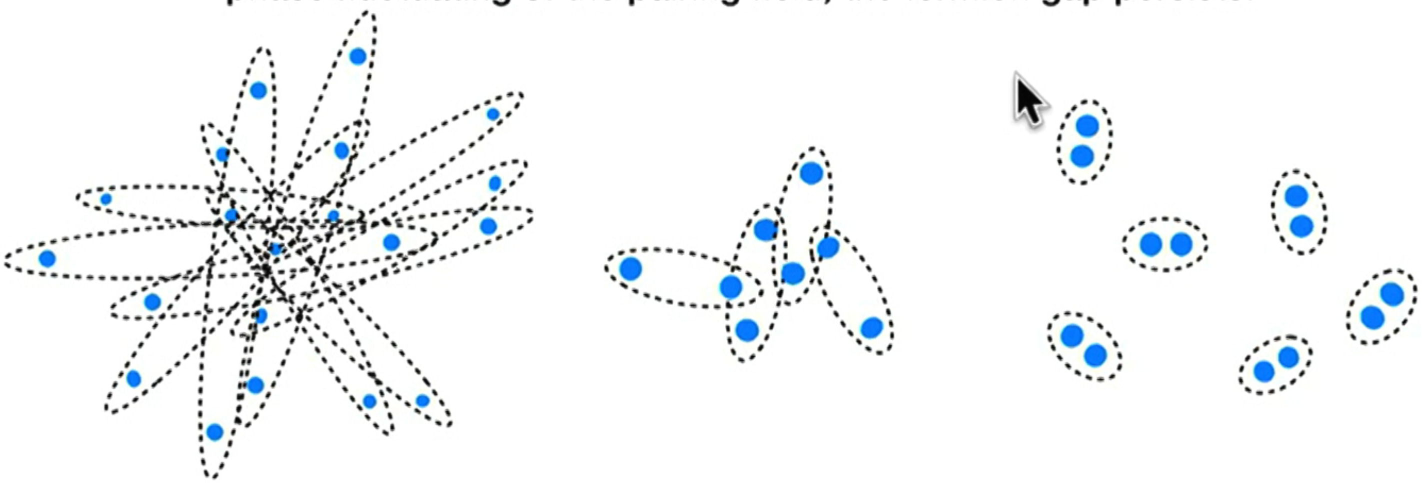
Gapped antinodal electrons and fluctuating SC

Two possibilities when superconductivity is quantum disordered:

1. **If the pairing is weak, the fermion gap may disappear.**
2. **If the pairing is strong, and the long range order is destroyed by the phase fluctuating of the pairing field, the fermion gap persists.**



BCS limit
pairs overlap

Cuprate is in between
coherence length ~ 4a

BEC limit
pairing gap is just the binding energy

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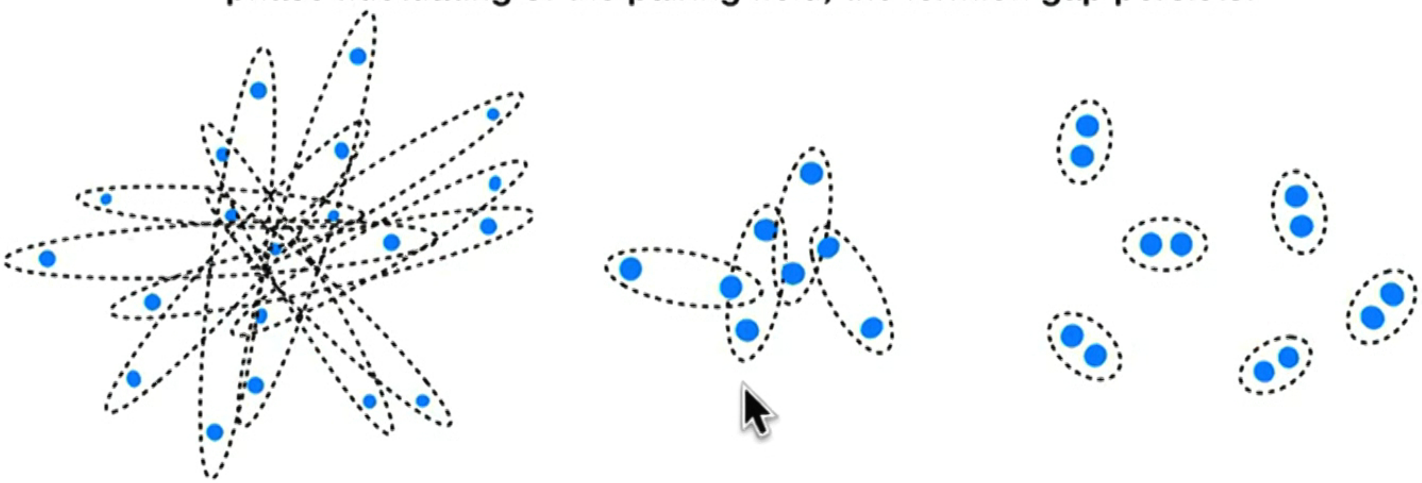

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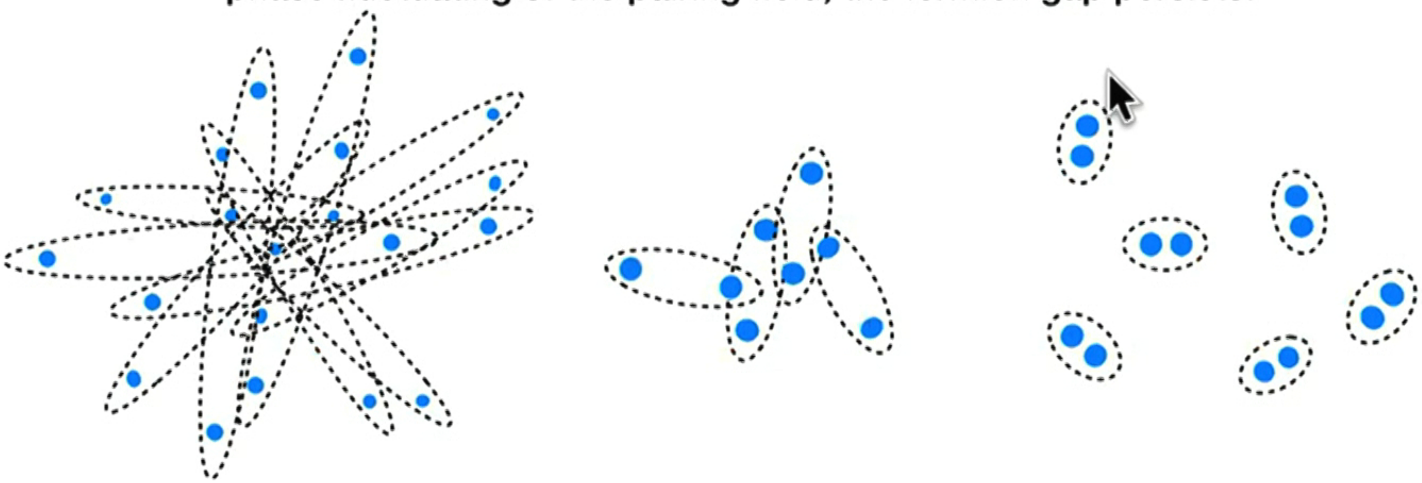

BCS limit
pairs overlap

Cuprate is in between
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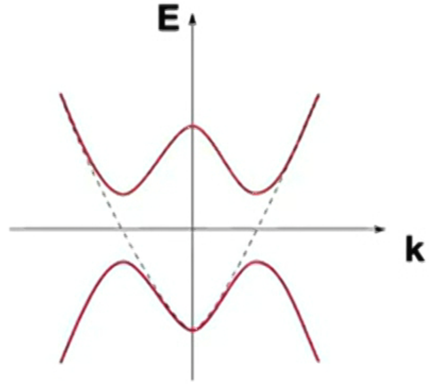
BEC limit
pairing gap is just the binding energy

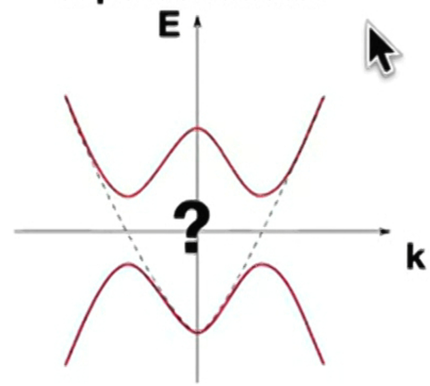
Bogoliubov paradox?
fluctuating s wave superconductor

superconductor



Fermion spectrum in a superconductor is described by Bogoliubov band: superposition of electron and hole

quantum-disordered superconductor



How can an insulator with charge conservation have a similar band?

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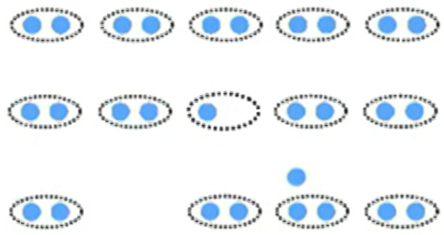
Z.Dai, T. Senthil, P. A. Lee, arXiv: 1906.01656

Antinodal electron spectrum

Mott insulator GS:

1-particle state: single hole

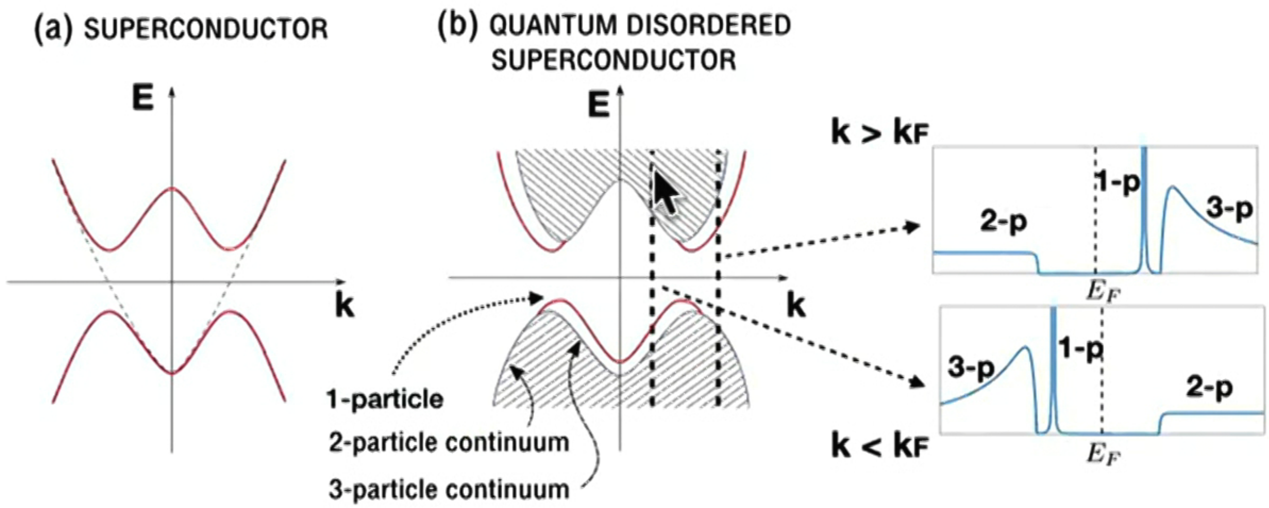
2-particle state: electron + pair



3-particle state: hole + charge 2e pair + charge -2e pair

$$H = (c_{k\uparrow}^\dagger, c_{-k\downarrow}) \begin{pmatrix} \epsilon_k & |\Delta| e^{i\phi} \\ |\Delta| e^{-i\phi} & -\epsilon_k \end{pmatrix} \begin{pmatrix} c_{k\uparrow} \\ c_{-k\downarrow}^\dagger \end{pmatrix}$$

$$\psi_k = u c_{k\uparrow} + v c_{-k\downarrow}^\dagger$$
$$= |u| c_{k\uparrow} + |v| e^{i\phi} c_{-k\downarrow}^\dagger$$



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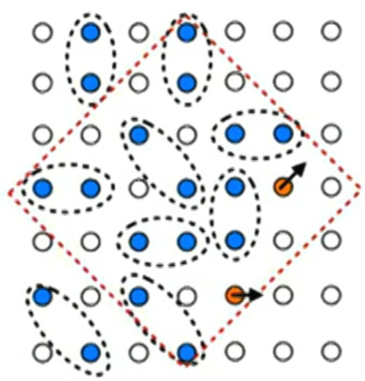
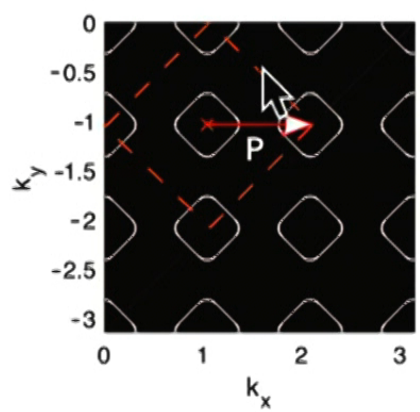
The fluctuating PDW state

- Keep the secondary MDW and CDW, disorder PDW
- Treat the gapless band and gapped bands separately
- Small electron pocket + Bosonic Mott insulator





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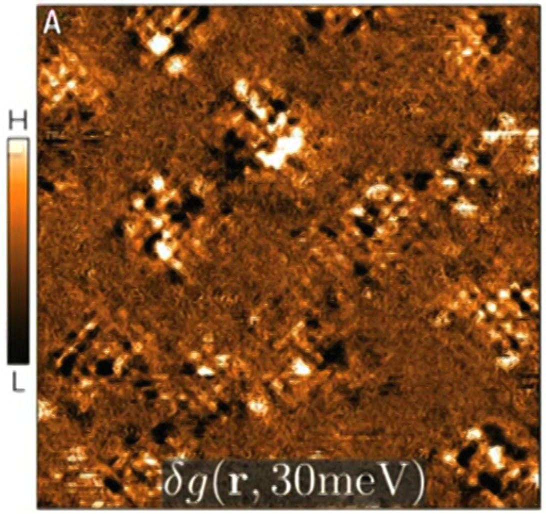
Experimental observation of short range PDW



S. D. Edkins et al., Science 364, 976 (2019)

Y. Wang et al., PRB 97, 174510

Z. Dai et al., PRB 97, 174511

STM experiment in 2018, Seamus Davis group

- static density wave in the vortex halo of the d wave SC
- wave vector half of the previous CDW

Our interpretation:

- short range PDW pinned by the vortex
- generate CDW at the same wave vector
- vortex halo determined by the correlation length of PDW
- small Hc2 explained by the overlap of vortex halo

When d wave SC is killed, PDW becomes fluctuating again

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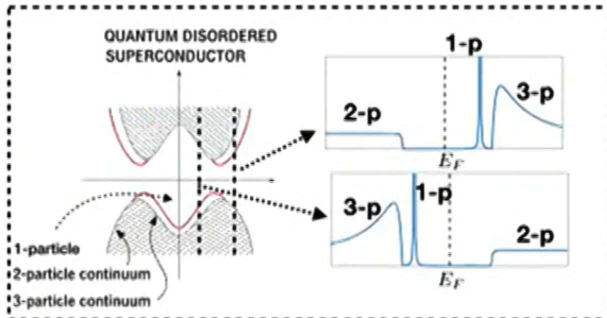
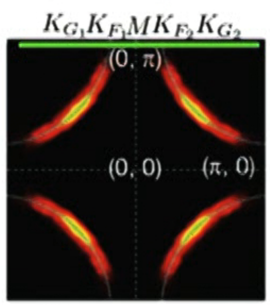
Antinodal electron spectrum in fluctuating PDW

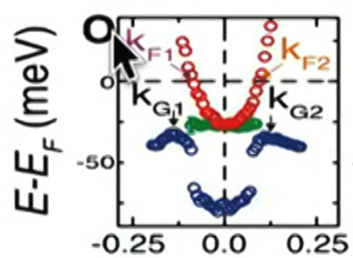
Theory

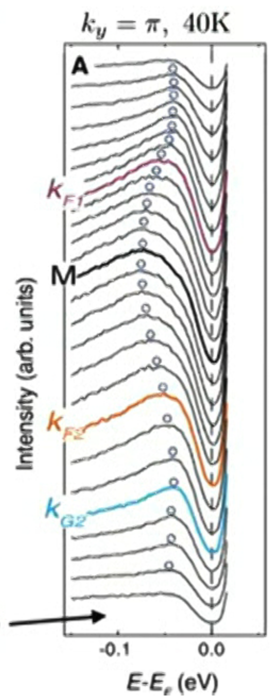


ARPES results for Bi2201

momentum along a cut ky ~ pi



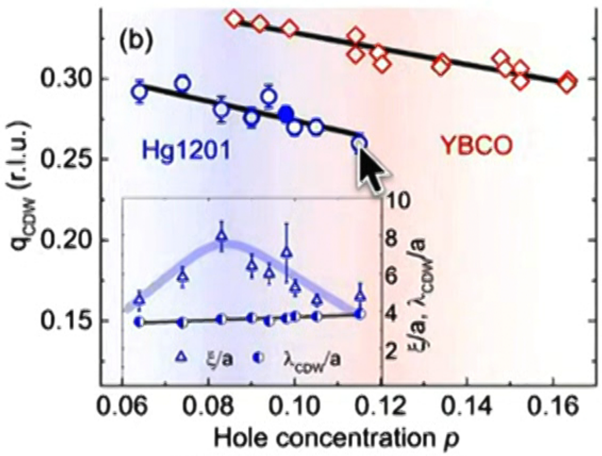


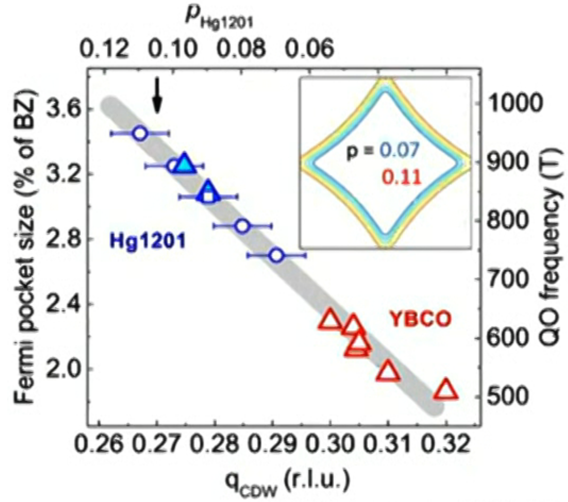


He, Rui-Hua, et al. *Science* 331.6024 (2011): 1579-1583.

Step function shows up only below T* near antinode

Luttinger's theorem



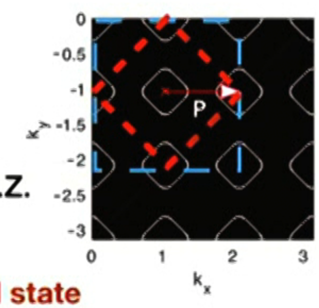


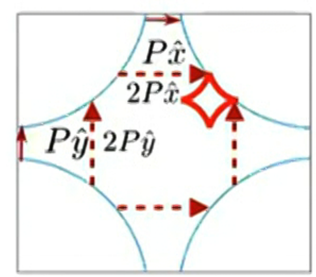
Commensurate point:
YBCO at 8% doping,Hg1201 at 12% doping

W. Tabis et al., PRB 96, 134510

- **Lutting's theorem makes sense only in the commensurate case**
- **Need to pick a B.Z.**
- **Luttinger's theorem satisfied if we pick the MDW B.Z.**
- **Fluctuating PDW picture suggests the MDW B.Z.**

→ **Possibility of a non-exotic ground state**





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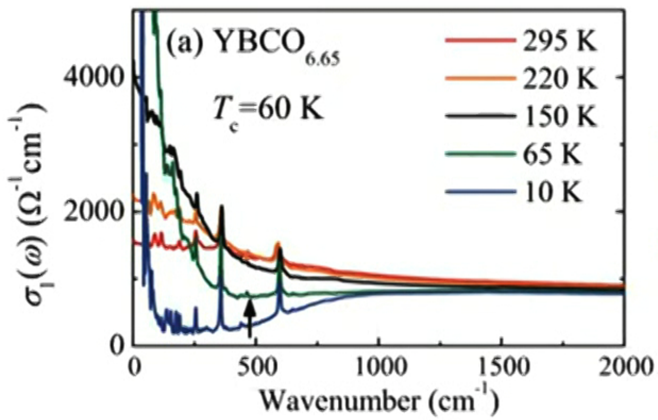
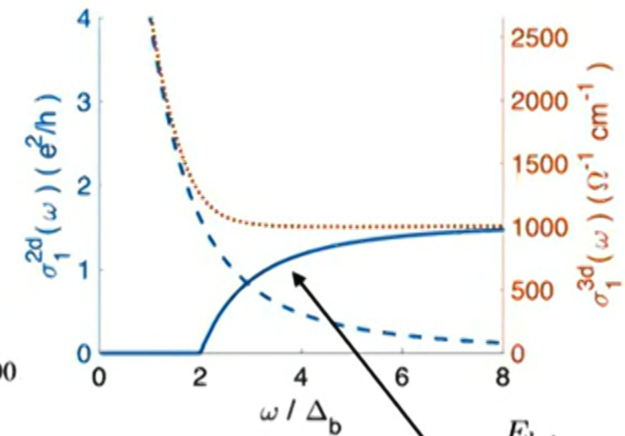
Infrared conductivity

Experiment



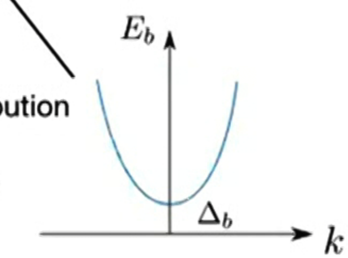
Theory



Drude peak $\sigma = \dfrac{ne^2/m}{1/\tau - i\omega}$

$$\mathrm{Re}\sigma = \frac{ne^2\tau/m}{1+\omega^2\tau^2}$$

boson contribution



$$\frac{1}{16}\frac{e^{*2}}{\hbar} = \frac{\pi}{2}e^2/h$$

Mid-infrared plateau almost exactly $\frac{\pi}{2}e^2/h$ **per layer!**

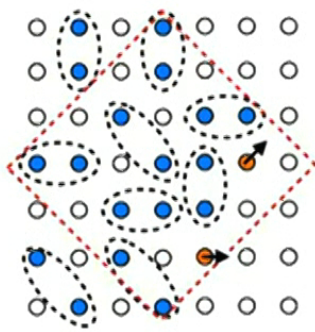
D. N. Basov and T. Timusk, Rev. Mod. Phys. **77**, 721 (2005)

Z.Dai, T. Senthil, P. A. Lee, arXiv: 1906.01656

Conclusion

Goal: use a single assumption to explain the pseudogap phenomenology at low temperature

- Quantum-disordered PDW state captures the pseudogap phenomenology at low T
- Simple construction: a small-pocket Fermi liquid + bosonic Mott insulator
- Successfully explain the ARPES data in Bi2201, and the infrared conductivity plateau
- Explain CDW, small H_{c2}, quantum oscillation of a small pocket, consistent with the Luttinger's theorem
- MDW and the low-energy boson may be measured directly in the future



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Z. Dai, T. Senthil, P. A. Lee, arXiv: 1906.01656