High-Temperature Superconductivity and Strong Correlations (II)

Zheng-Yu Weng

Institute for Advanced Study
Tsinghua University, Beijing

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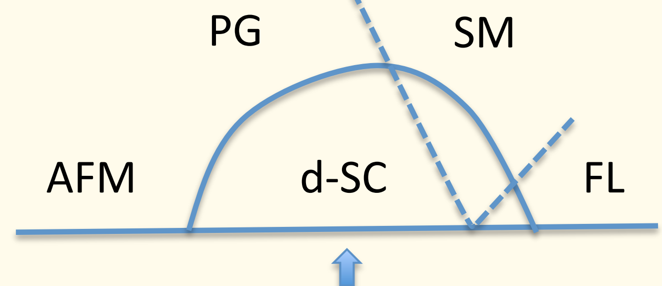
Outline

- High-T_c superconductivity: A general survey
- High-T_c cuprates as strongly correlated electron systems
- Mott physics: Basic organizing principles
- Examples
- Understanding of the phase diagram
- Summary and conclusion

Mechanism of superconductivity in high-T_c cuprates: What is the most essential issue?

Ground state wavefunction = Cooper pair condensation + additional structure



- Cooper pair condensation

  BCS like: d-wave pairing symmetry;

  Bogoliubov nodal quasiparticle; GL equation (low-energy, long distance)

- additional structure (short-range, high-energy)

  non-FL–like: pseudogap, AF, strange metal, ...

quantum order? long-range entanglement? fractionalization? competing order?

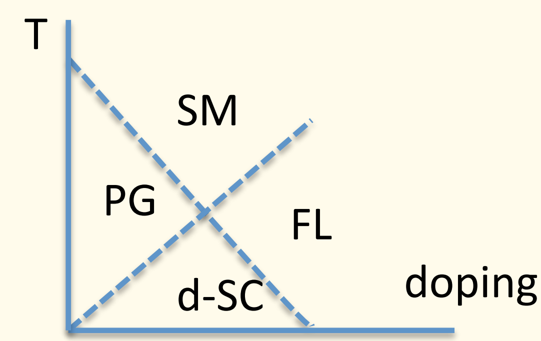
- Example: Anderson's RVB theory:

P_G : Gutzwiller projection

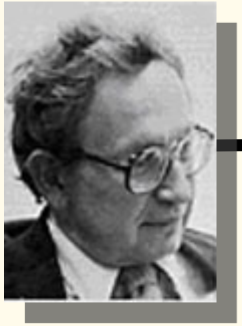
$$|\Psi_{RVB}\rangle = P_G|\mathrm{BCS}\rangle$$

doped Mott insulator picture: on-site Coulomb repulsion

no double occupancy



Baskaran, Zou, Anderson; ...



Cuprates = doped Mott Insulator

Anderson, Science 1987

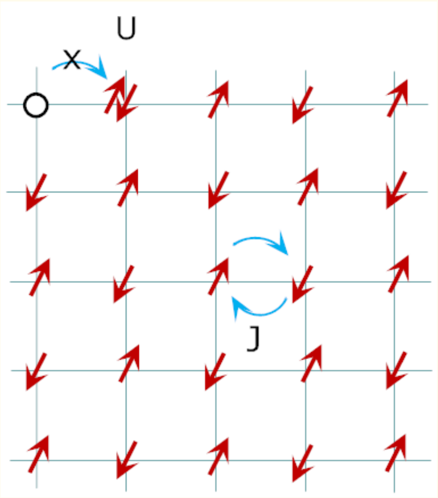
one-band large-U Hubbard/t-J model:

$$H_t = -t \sum_{<ij>\sigma} c_{i\sigma}^{\dagger} c_{j\sigma} + H.c.$$

$$H_J = \sum_{<ij>} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \frac{n_i n_j}{4} \right)$$

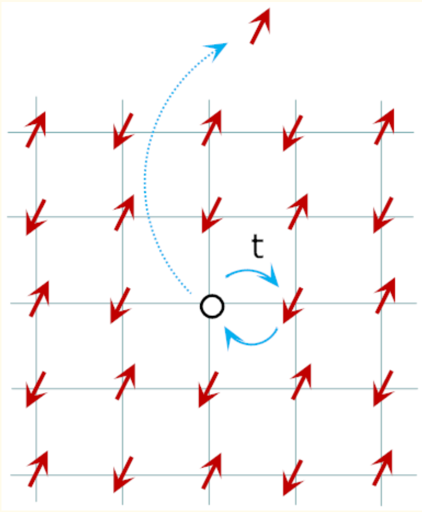
$$\sum_{\sigma} c_{i\sigma}^{\dagger} c_{i\sigma} \leq 1$$

Mott insulator



Heisenberg model

doped Mott insulator



t-J model

Half-filling

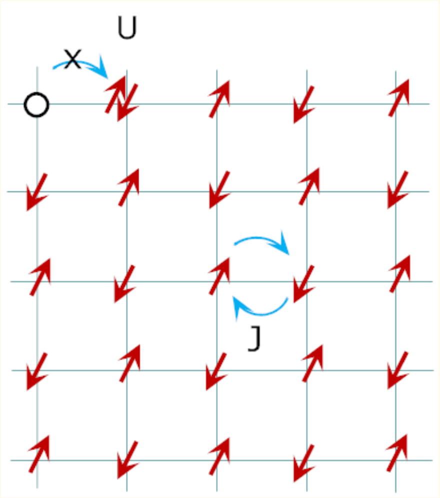
How to construct the ground state at finite doping?

Guiding principles:

- No double occupancy constraint

Anderson's RVB ansatz: $\left|\Psi_{RVB}\right\rangle = P_G \left|\mathrm{BCS}\right\rangle$ P_G : Gutzwiller projection

- Accurate AFM ground state at half-filling limit



Heisenberg model:

well describes antiferromagnetism in the cuprate

《Quantum Phase Transitions》 S. Sachdev

Ground state at Half-filling:

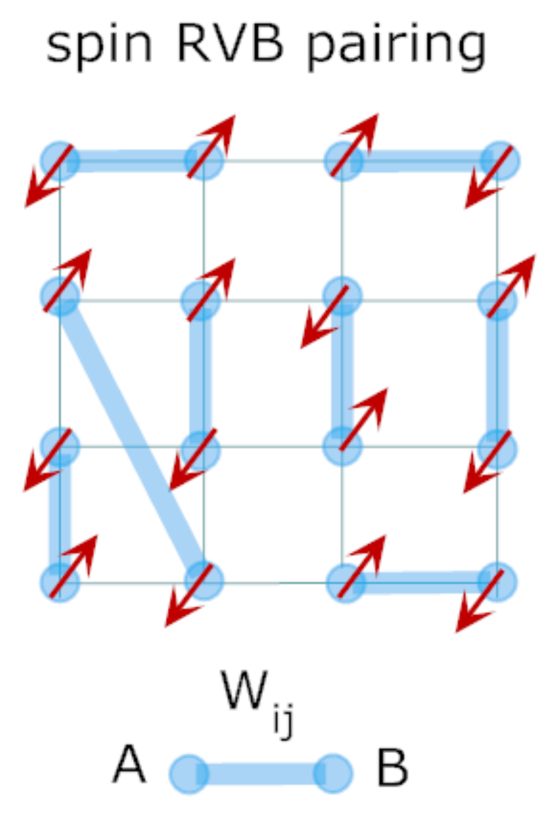
Liang –Docout-Anderson wave function

$$|\mathrm{b-RVB}\rangle = \sum_{\{\sigma_s\}} \Phi_{\mathrm{RVB}}(\sigma_1, \sigma_1, \cdots, \sigma_N)\, c^\dagger_{1\sigma_1} c^\dagger_{2\sigma_2} \cdots c^\dagger_{N\sigma_N} |0\rangle$$

$$\Phi_{\mathrm{RVB}}(\{\sigma_s\}) \equiv \sum_{\text{partition}} \prod_{(ij)} (-1)^i W_{ij} \qquad i:\uparrow \quad j:\downarrow$$

$$W_{ij} \propto \frac{1}{|\mathbf{r}_{ij}|^3} \qquad ij \in A, B$$

bosonic resonating valence bond (b-RVB) state!



variational energy	E_G = -0.3344	$m = 0.30$
exact numerics	E_G = -0.3346	$m = 0.31$

Liang, Docout, Anderson (1988)

How to construct the ground state at finite doping?

Guiding principles:

- No double occupancy constraint

- Accurate AFM ground state at half-filling limit

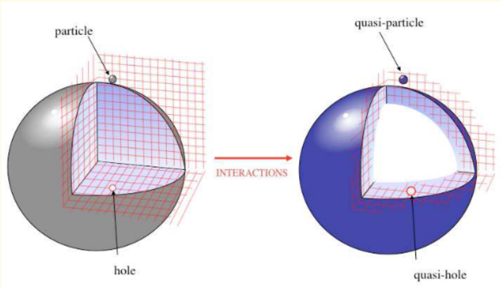
$$\left|\text{b-RVB}\right\rangle$$

- Emergent sign structure for the t-J/Hubbard model

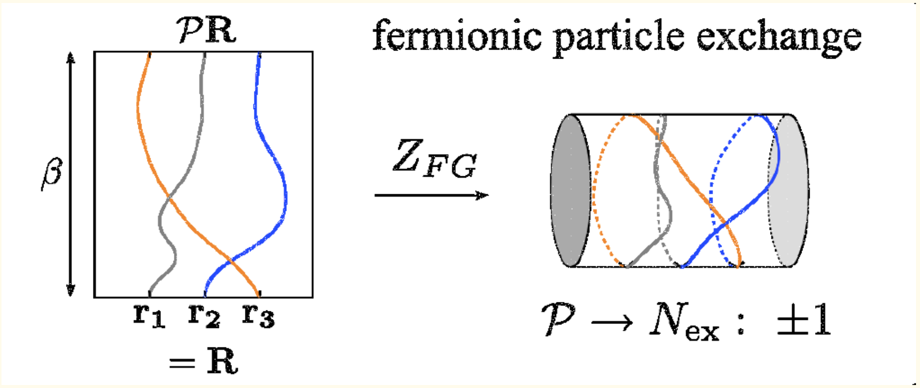
Statistical sign structure for Fermion systems

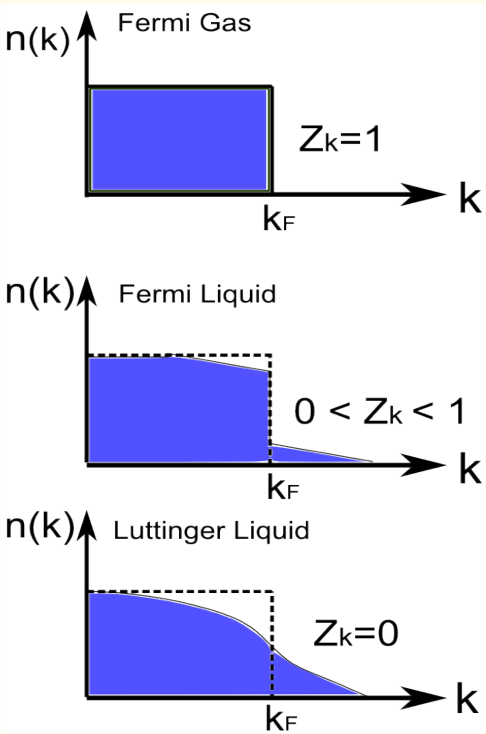
Fermion signs

$$\psi(x_1, x_2, \ldots) = -\psi(x_2, x_1, \ldots)$$



Landau Fermi Liquid





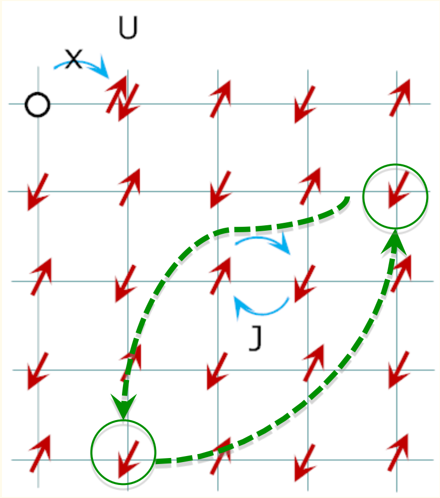
$$Z_{FG} \equiv Tr\left(e^{-\beta H}\right) = \sum_{loop\ c} (-1)^{N_{ex}(c)} W(c) \ , \quad W(c) \geq 0$$

(1) Fermi liquid: Fermion signs

$$Z_{FG} = \sum_{loop\ c} (-1)^{N_{ex}(c)} W(c) \quad W(c) \geq 0$$

(2) Off Diagonal Long Rang Order (ODLRO):
compensating the Fermion signs

Bose condensation
Cooper pairing in SC state
CDW ("exciton" condensation)
SDW (weak coupling)

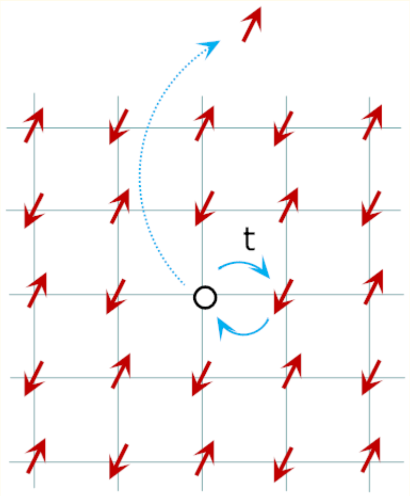


(3) Antiferromagnetic order (strong coupling)

$$Z_{Heisenberg} = \sum_{loop\ c} W(c) \qquad W(c) = \sum_{n} \frac{(\beta J/2)^n}{n!} \delta_{M_{\uparrow\downarrow}+M_Q,n} \geq 0$$

Complete disappearance of Fermion signs!

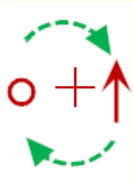
Single-hole-doped Heiserberg model:

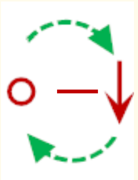


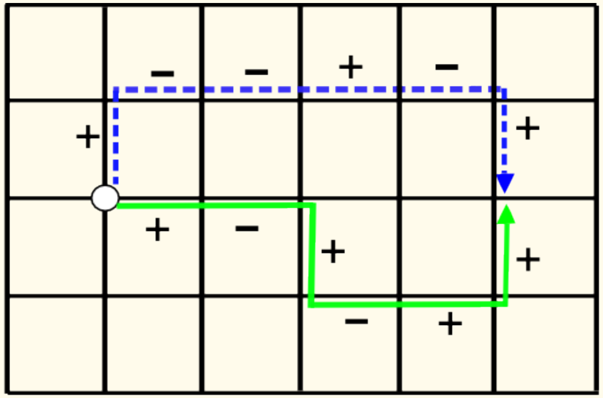
$$Z_{1-hole} = \mathrm{Tr}(e^{-\beta H}) = \sum_{loop\ c} \tau_c W(c)$$

$$\tau_c \equiv (+1)\times(-1)\times(-1)\times\ldots\ldots$$
$$= (-1)^{N_h^{\downarrow}(c)}$$

$$W(c) = \underbrace{\frac{2t}{J}\cdot\frac{2t}{J}\cdots\frac{2t}{J}}_{M_h(C)} \sum_n \frac{(\beta J/2)^n}{n!}\delta_{M_h+M_{\uparrow\downarrow},n} \geq 0$$







Phase string effect

D.N. Sheng, Y.C. Chen, ZYW, PRL (1996); ZYW et al., PRB (1997)

General sign structure at arbitrary doping, dimensions, temperature for the t-J model

$$Z = \sum_c \tau_c \mathcal{Z}(c)$$

$$\mathcal{Z}(c) \geq 0$$

$$\tau_c = (-1)^{N_h^{\downarrow}(c)} \times (-1)^{N_h^{h}(c)}$$

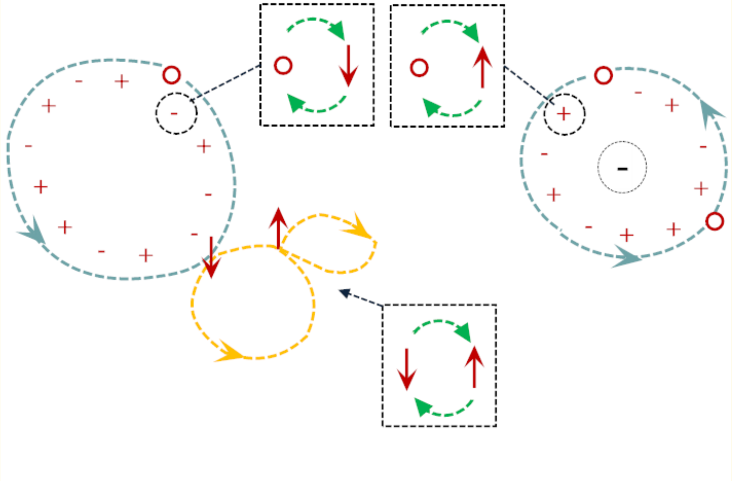
fermion signs

$$\mathcal{Z}[c] = \left(\frac{2t}{J}\right)^{M_h[c]} \sum_n \frac{(\beta J/2)^n}{n!} \delta_{n, M_h + M_{\uparrow\downarrow} + M_Q}$$

$M_h(C)$ = total steps of hole hoppings

$M_{\uparrow\downarrow}(C)$ = total number of spin exchange processes

$M_Q(C)$ = total number of opposite spin encounters



Wu, Weng, Zaanen, PRB (2008)

How to construct the ground state at finite doping?

Guiding principles:

- No double occupancy constraint
- Accurate AFM ground state at half-filling limit
- Emergent sign structure for the t-J/Hubbard model

Organizing principles for emergent physics of strongly correlated electrons!

New class of ground state wave function

$$|\Psi_G\rangle = e^{\hat{D}}|\text{b-RVB}\rangle$$

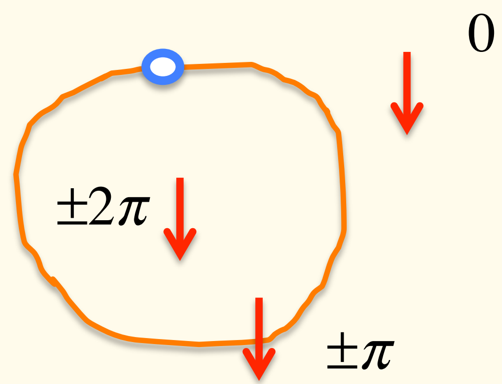
protected by Mott gap!

$$\Phi_{\text{RVB}}(\{\sigma_s\}) \equiv \sum_{\text{partition}} \prod_{(ij)} (-1)^i W_{ij} \qquad \hat{D} = \sum_{ij} g_{ij} \tilde{c}_{i\uparrow} \tilde{c}_{j\downarrow}$$

two-component RVB state

$$\tilde{c}_{i\sigma} = c_{i\sigma} e^{-i\hat{\Omega}_i}$$

$$\hat{\Omega}_i = -\sum_l \theta_i(l) n^b_{l\downarrow}, \quad \theta_i(l) = \theta_l(i) \pm \pi$$



sign structure of the t-J model

Anderson's one-component RVB ansatz:

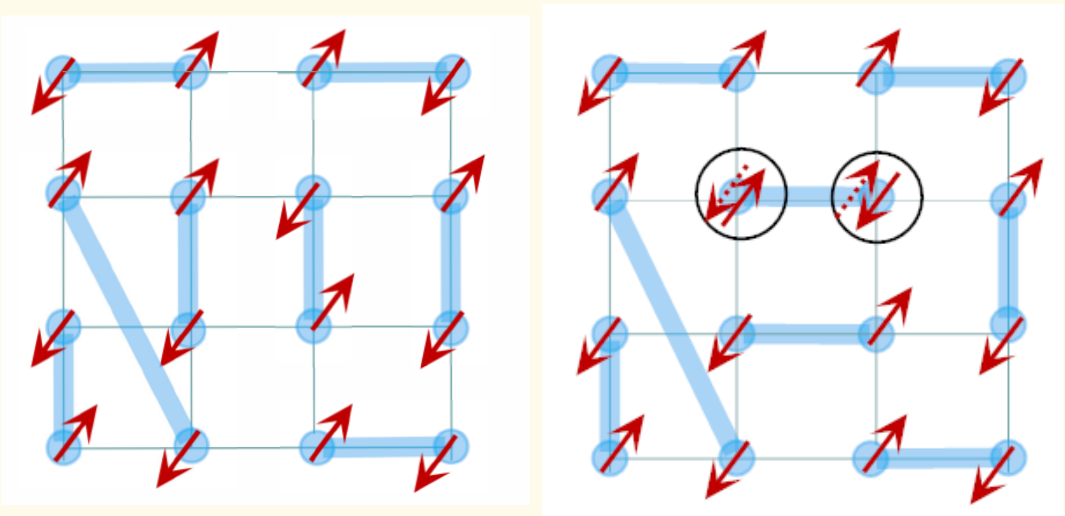
$$|\Psi_{RVB}\rangle = P_G|\text{BCS}\rangle$$

P_G : Gutzwiller projection

Z.Y. Weng, NJP (2011)

Wave function expression:

$$\left|\Psi_G\right\rangle = e^{\hat{D}}\left|\text{b-RVB}\right\rangle \quad \Longrightarrow \quad \left|\Psi_G\right\rangle = \hat{\Lambda}_h\left(\exp\sum_{ij} g_{ij} c_{i\uparrow} c_{j\downarrow}\right)\left|\text{b-RVB}\right\rangle$$



$$\hat{\Lambda}_h = \left[\prod_l e^{-i\hat{\Omega}_l}\right]\phi_h(l_1, l_2, \ldots, l_{N_h})$$

$$\Phi_{\text{RVB}}\left(\{\sigma_s\}\right) \equiv \sum_{\text{partition}} \prod_{(ij)} (-1)^i W_{ij}$$

$$\Psi_G = K\Phi_a(l_1, l_2, \ldots, l_{N_h})\Phi_{\text{RVB}}(i_1\ldots; j_1\ldots)$$

$$K \equiv \prod_{hd} \frac{\left(z_{l_h}^* - z_{j_d}^*\right)}{|z_{l_h} - z_{j_d}|}\phi_h(l_1, l_2, \ldots, l_{N_h}) = \prod_{hu}\left(z_{l_h} - z_{i_u}\right)^{1/2} \prod_{hd}\left(z_{l_h}^* - z_{j_d}^*\right)^{1/2} \prod_{i \neq j} \frac{\left(z_i^* - z_j^*\right)^{1/2}}{|z_i - z_j|^{1/2}}\phi_h(l_1, l_2, \ldots, l_{N_h})$$

mutual statistics!

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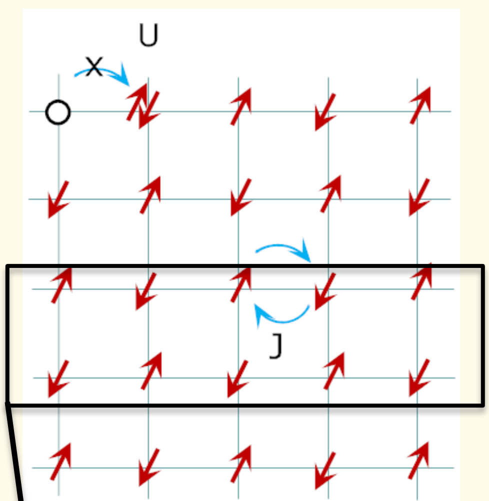
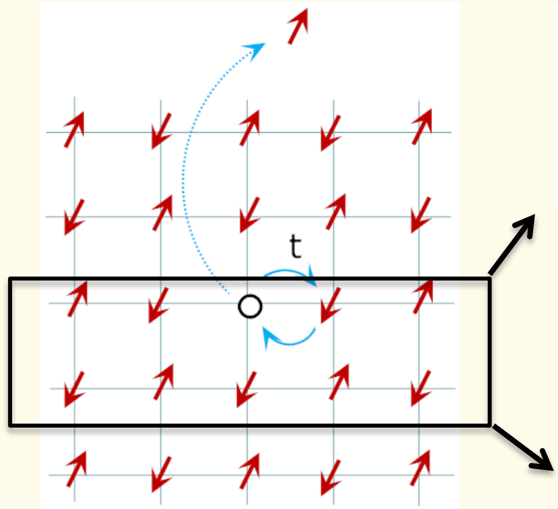
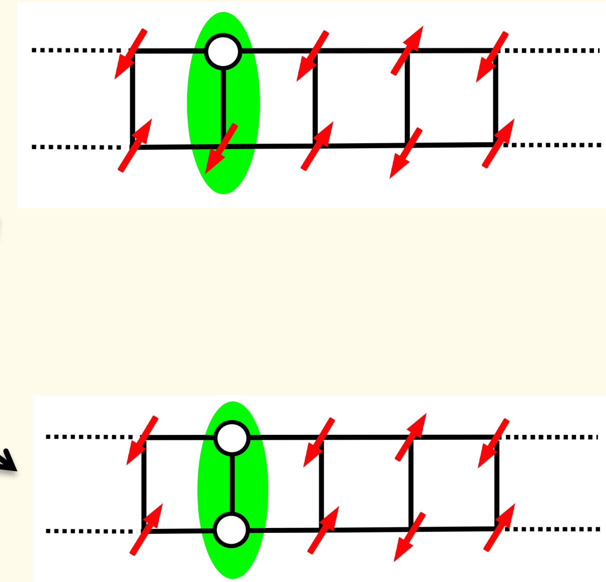
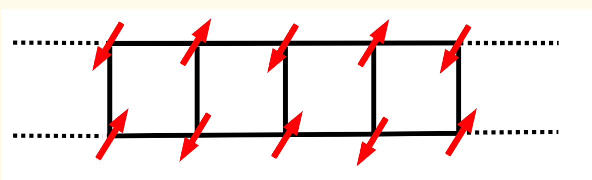
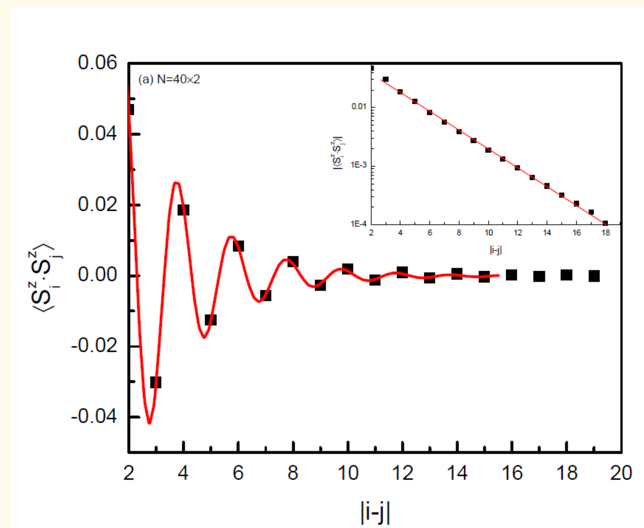
Example: Two-leg t-J ladder doped by one or two holes





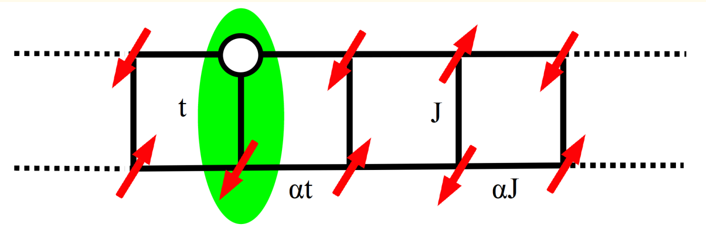


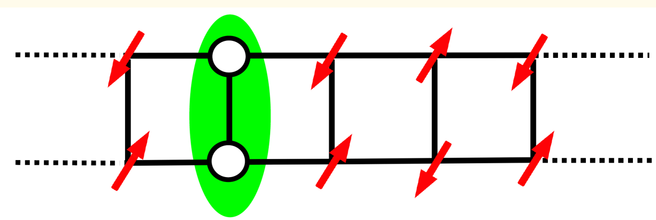




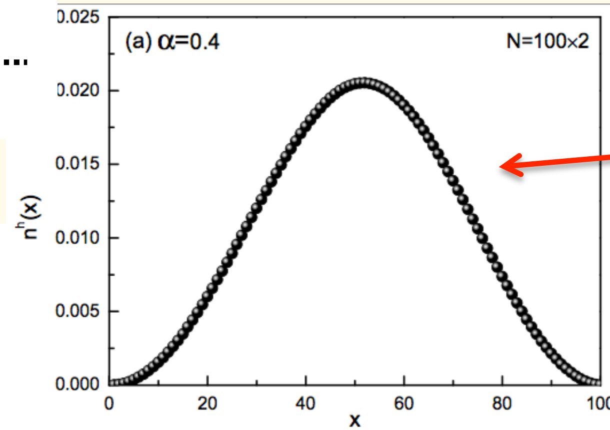
Half-filled 2-leg ladder is a Mott insulator with a spin gap

DMRG simulation

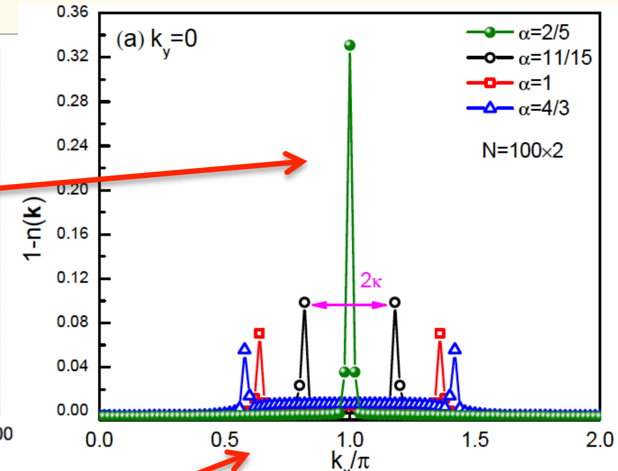




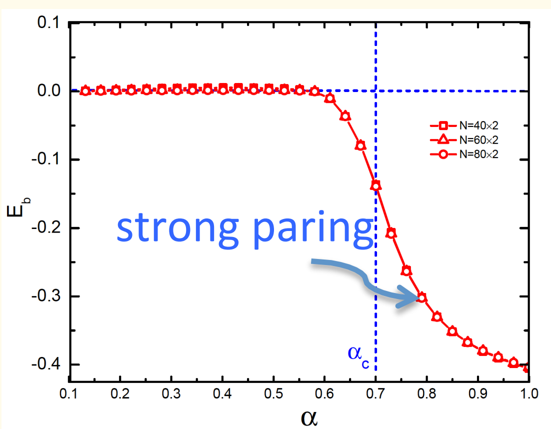
hole distribution

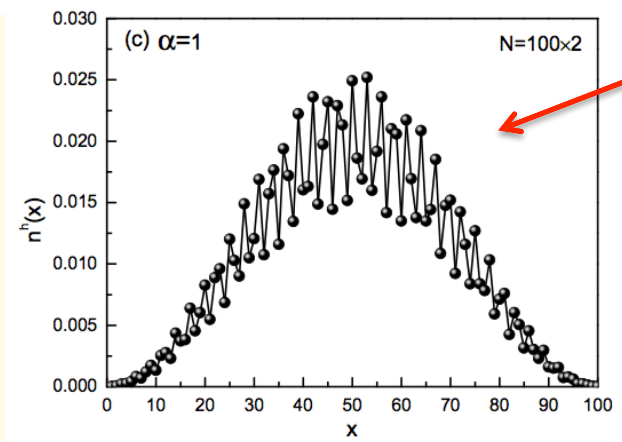


Fermi point reconstruction



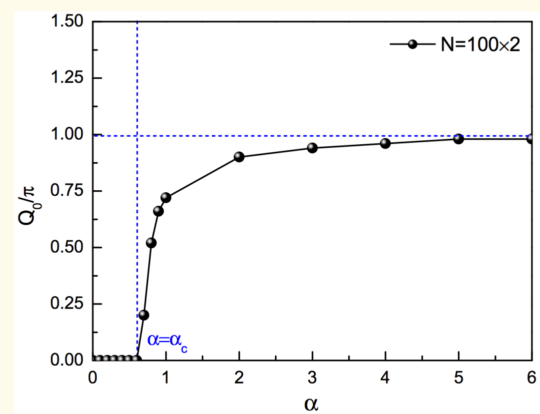
two hole binding energy (t/J=3)





charge modulation

wavevector $Q_0 = 2\kappa$



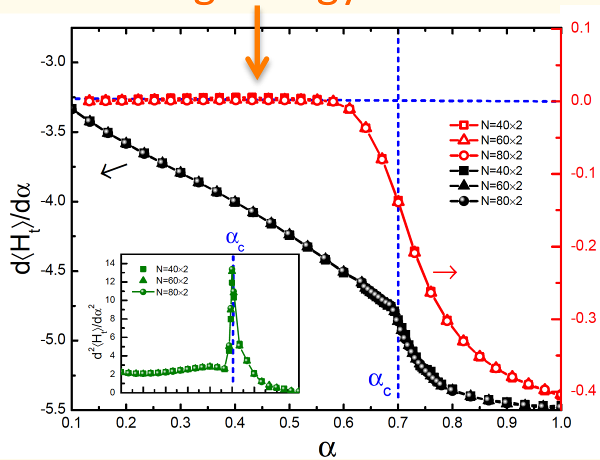
Z. Zhu, et al. arXiv: 1409. 3241; 1412.3462 t-J model

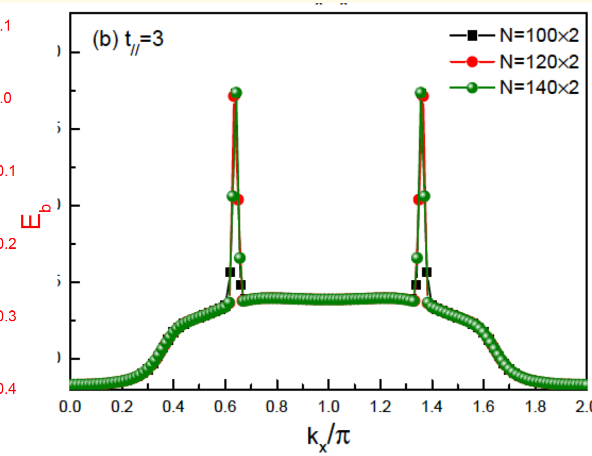
$$Z = \sum_{loop\ c} \tau_c W(c)$$

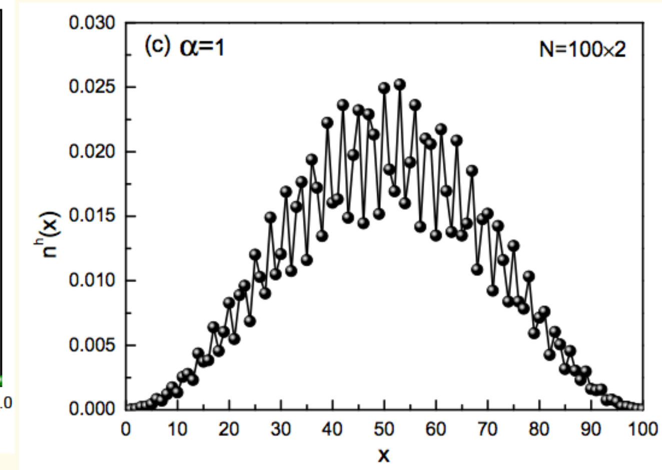
$$H_t = -t \sum_{\langle ij \rangle \sigma} \left(c_{i\sigma}^{\dagger} c_{j\sigma} + h.c. \right) \quad H_J = J \sum_{\langle ij \rangle} \left(\mathbf{S}_i \mathbf{S}_j - \frac{1}{4} n_i n_j \right)$$

$$\tau_c \equiv (+1) \times (-1) \times (-1) \times \ldots\ldots$$

binding energy





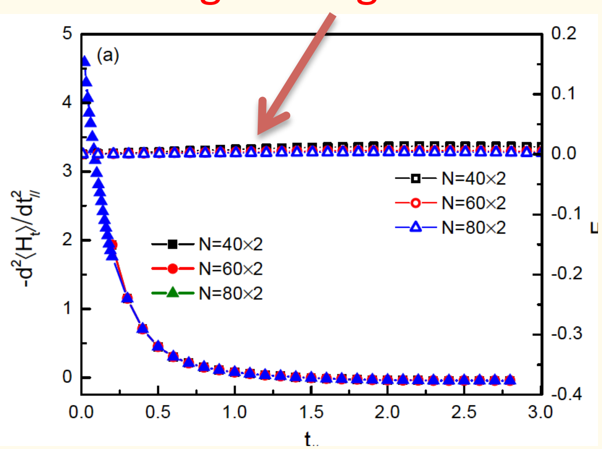


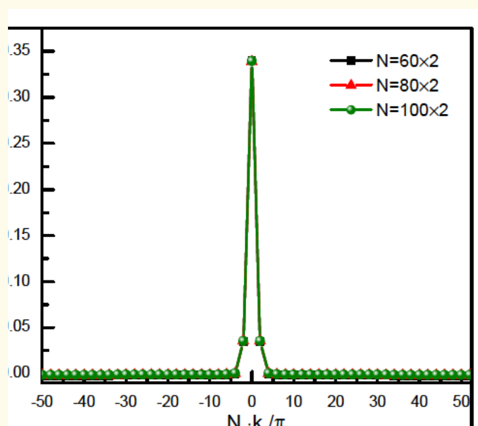
sigma t-J model

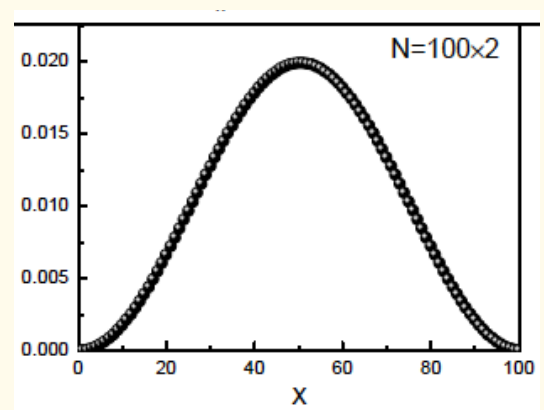
$$Z = \sum_{loop\ c} W(c)$$

$$H_{\sigma \cdot t} = -t \sum_{\langle ij \rangle \sigma} \sigma (c_{i\sigma}^{\dagger} c_{j\sigma} + h.c.)$$

vanishing binding

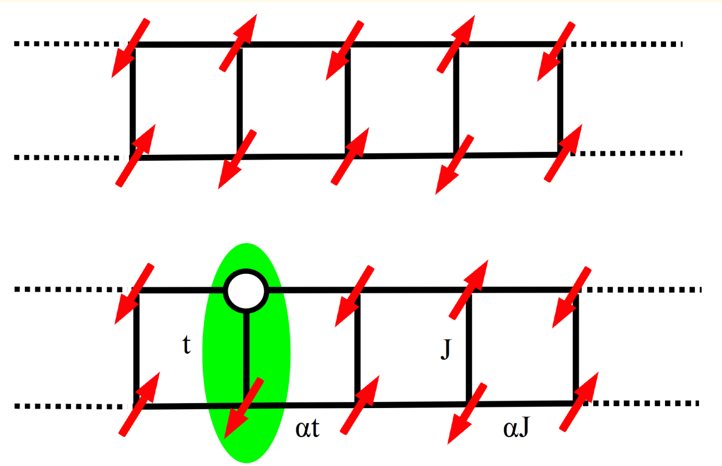




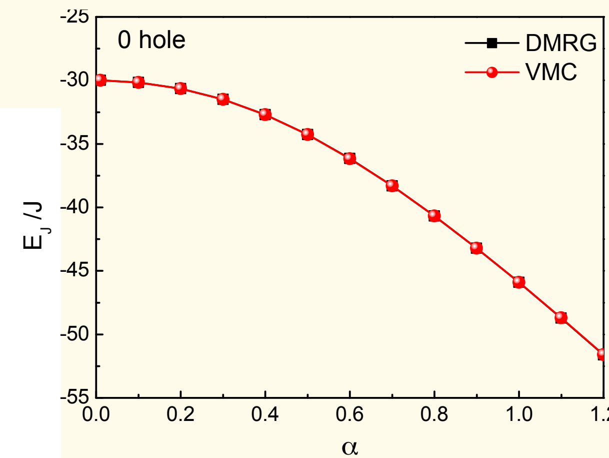


Variational Monte Carlo study

Q-R.Wang, Y. Qi, ZYW



$|\text{b-RVB}\rangle$

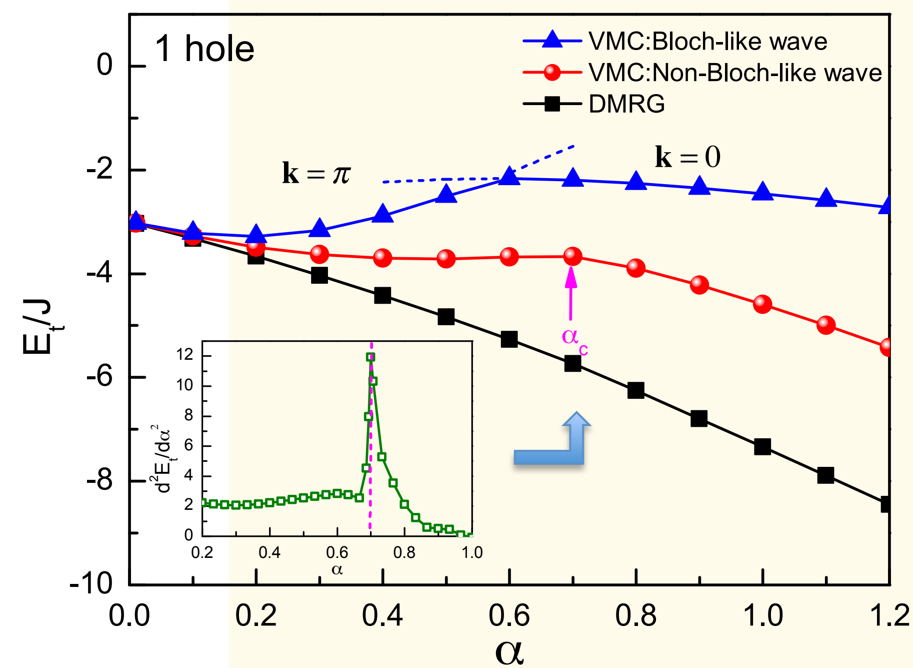


$$|\Psi_G\rangle_{1h} = \left(\sum_{ij}\phi_h(i)\tilde{c}_{i\uparrow}\right)|\text{b-RVB}\rangle$$

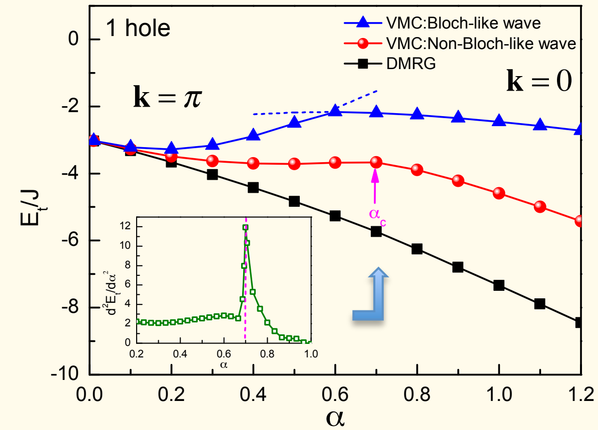
$$\tilde{c}_{i\sigma} = e^{-i\hat{\Omega}_i} c_{i\sigma}$$

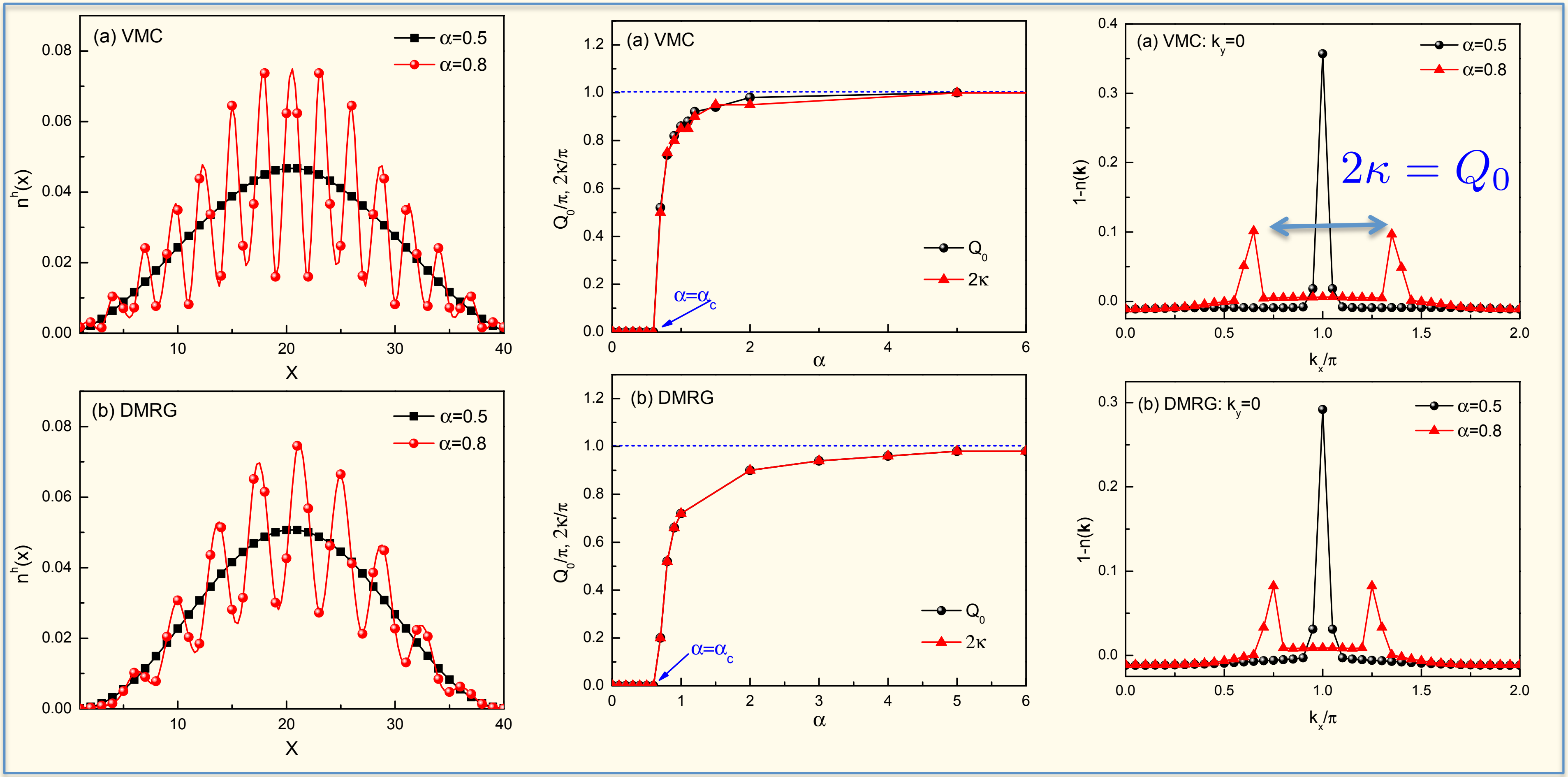
compare to $\quad \phi_h(i)e^{-i\hat{\Omega}_i} \to \frac{1}{\sqrt{N}} e^{i\mathbf{k}\cdot\mathbf{r}_i}$

$$|\mathbf{k}\rangle_{\text{BL}} = \left(\frac{1}{\sqrt{N}}\sum_{ij} e^{i\mathbf{k}\cdot\mathbf{r}_i} c_{i\uparrow}\right)|\text{b-RVB}\rangle$$



$$\left|\Psi_G\right\rangle = \left(\sum_{ij} \phi_h(i) e^{-i\hat{\Omega}_i} c_{i\uparrow} \right) \left| \text{b-RVB} \right\rangle$$





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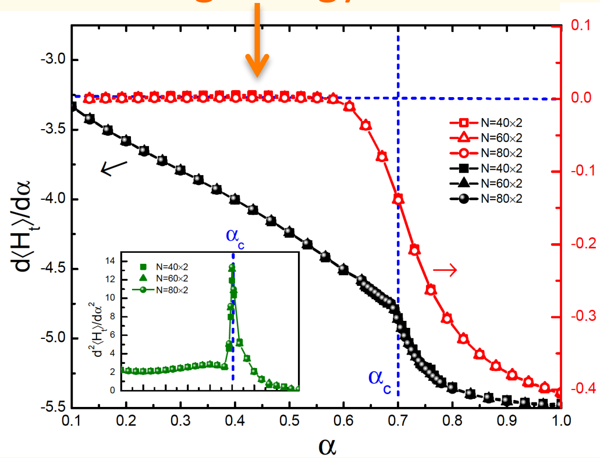
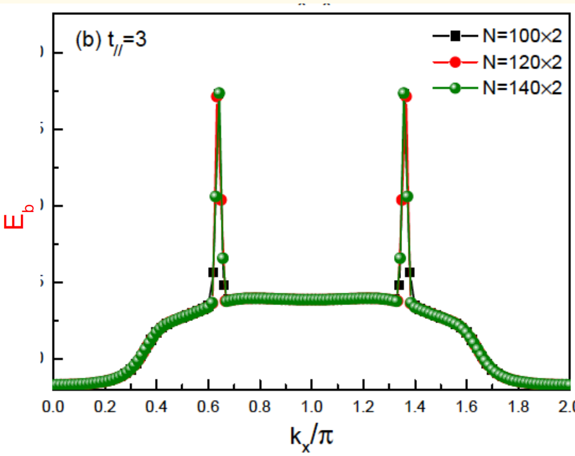
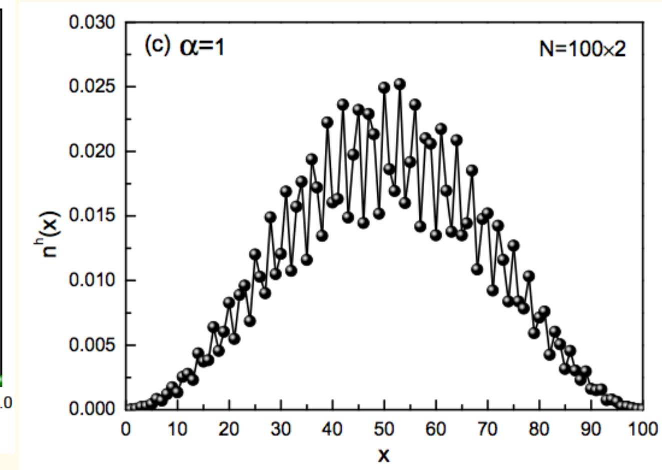
$$\tau_c \equiv (+1) \times (-1) \times (-1) \times \ldots\ldots$$

binding energy







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$$H_{\sigma \cdot t} = -t \sum_{\langle ij \rangle \sigma} \sigma (c_{i\sigma}^{\dagger} c_{j\sigma} + h.c.)$$

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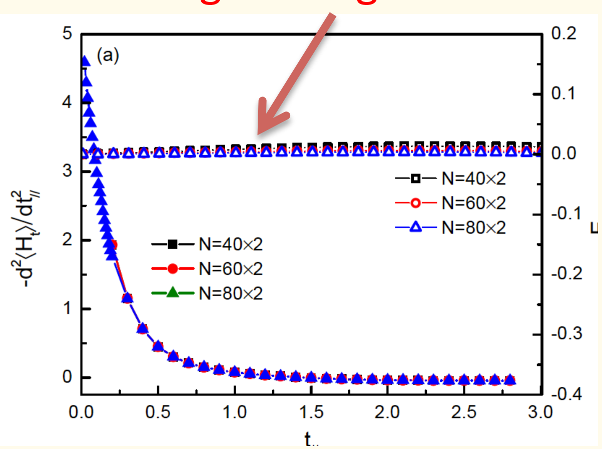
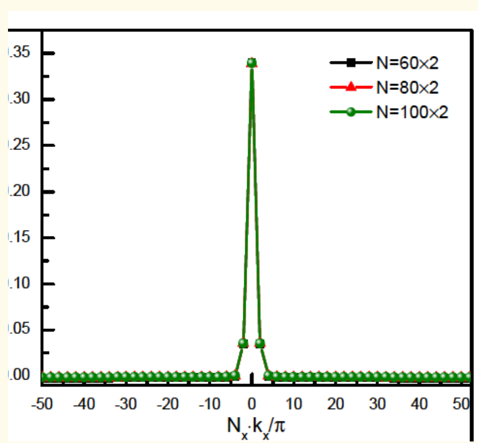
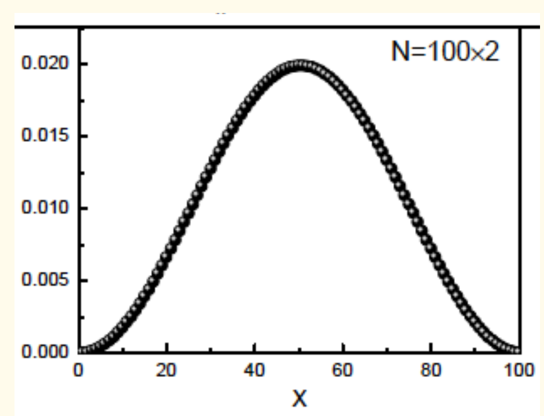






Moral of the story of the doped two-leg t-J/Hubbard ladder

"pseudogap phenomenon":

- spin gapped background
- charge modulation
- Fermi point reconstruction
- charge modulation ⟷ strong pairing

  two sides of one coin!

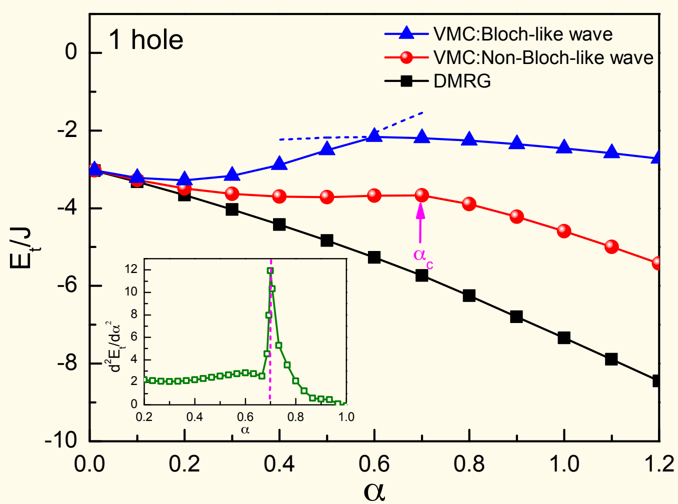
- phase string effect is responsible

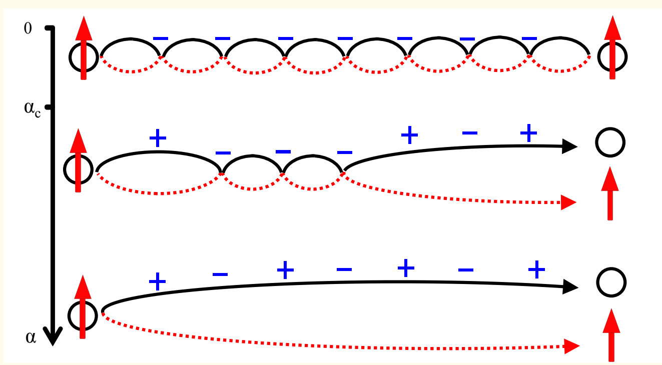
$$|\Psi_G\rangle = \left(\sum_{ij}\varphi_h(i)e^{-i\hat{\Omega}_i}c_{i\uparrow}\right)|\phi_0\rangle, \qquad |\phi_0\rangle \equiv |\text{b-RVB}\rangle$$

$$\langle H_t\rangle = \langle\phi_0|\hat{H}_h|\phi_0\rangle \qquad \hat{t}_{ji} \equiv t^0_{ji}\hat{H}_{ji}$$

$$\hat{H}_h = -\sum_{\langle ij\rangle}\hat{t}_{ji}\varphi_h^\dagger(j)\varphi_h(i) + \text{h.c.} \qquad t^0_{ji} \equiv t_{ji}\left(\frac{1}{4} - \frac{1}{3}\langle\phi_0|\mathbf{S}_i\cdot\mathbf{S}_j|\phi_0\rangle\right)$$

$$\hat{H}_{ji} \equiv e^{i(A^s_{ji}-\phi^0_{ji})} \qquad A^s_{ji} - \phi^0_{ji} \equiv \sum_{l\neq j,i}(\theta_j(l) - \theta_i(l))n^b_{j\downarrow}$$



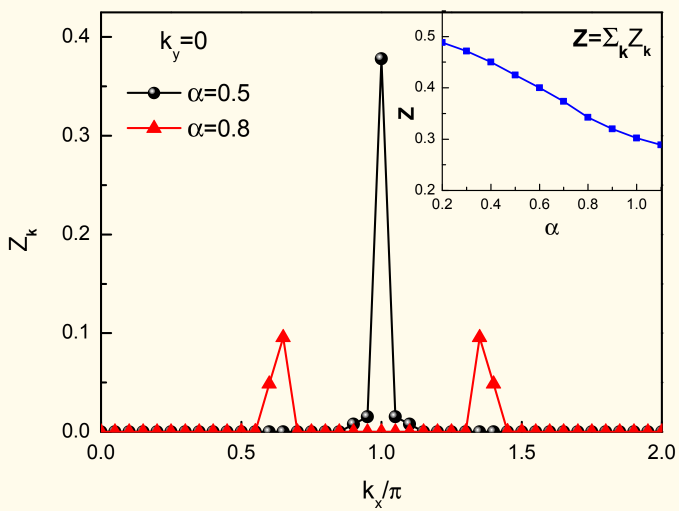


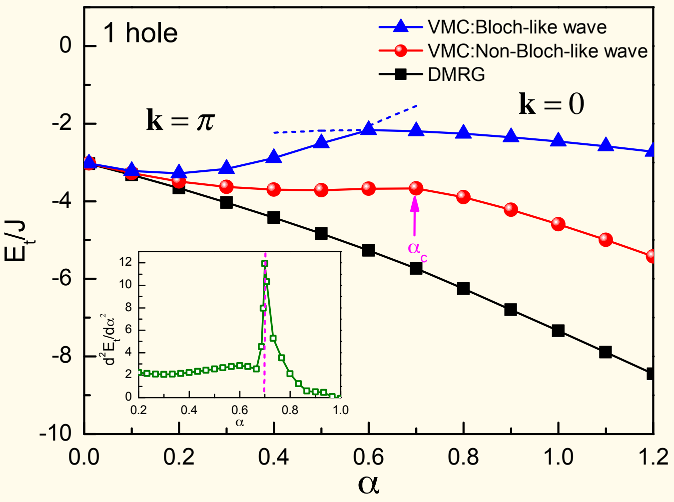
Issue of quasiparticle: S. White, D. Scalapino, S. Kivelson, arXiv. 1502.04403

$$|\Psi_G\rangle = \left(\sum_{ij} \phi_h(i) e^{-i\hat{\Omega}_i} c_{i\uparrow}\right)|\text{b-RVB}\rangle \quad \text{vs.} \quad |\mathbf{k}\rangle_{\text{BL}} \equiv \left(\frac{1}{\sqrt{N}} \sum_{ij} e^{i\mathbf{k}\cdot\mathbf{r}_i} c_{i\uparrow}\right)|\text{b-RVB}\rangle$$

$$|\Psi_G\rangle = a_{\mathbf{k}} |\mathbf{k}\rangle_{\text{BL}} + \ldots.$$

$$a_{\mathbf{k}} \equiv_{\text{BL}} \langle \mathbf{k}|\Psi_G\rangle \quad Z_{\mathbf{k}} \equiv |a_{\mathbf{k}}|^2$$





Breakdown of the Landau's one-to-one correspondence of qp picture

(Fermi surface reconstruction in violation of the Luttinger theorem)

2D case at finite doping:

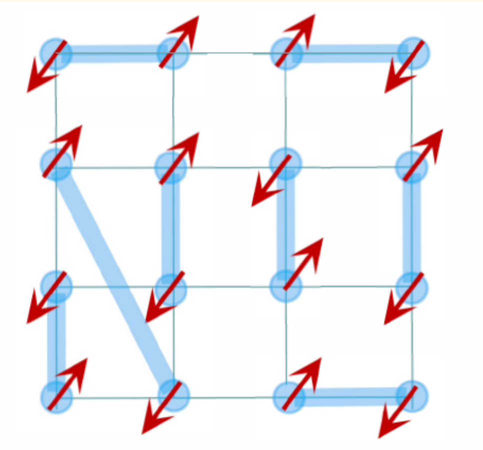
$$|\Psi_G\rangle = e^{\hat{D}}|\text{b-RVB}\rangle$$

$$\hat{D} = \sum_{ij} g_{ij}\tilde{c}_{i\uparrow}\tilde{c}_{j\downarrow}$$

$$\tilde{c}_{i\sigma} = c_{i\sigma}e^{-i\hat{\Omega}_i}$$

$$\Phi_{\text{RVB}}(\{\sigma_s\}) \equiv \sum_{\text{partition}} \prod_{(ij)} (-1)^i W_{ij}$$

two-component RVB state



$$|\text{b-RVB}\rangle$$

AFM | spin liquid | `Curie-Weiss' → **doping**

$$W_{ij} \propto \frac{1}{|\mathbf{r}_{ij}|^3} \qquad |W_{ij}| \propto \exp\left[-\frac{|\mathbf{r}_{ij}|^2}{2\xi^2}\right] \qquad W_{ij} \to W\delta_{ij}$$

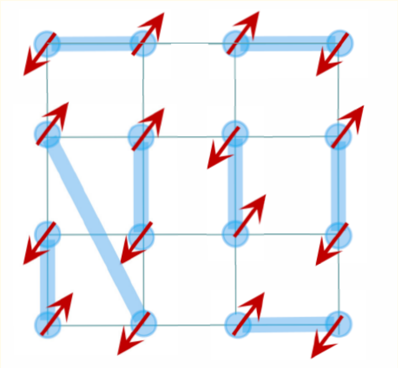
$$|\Psi_G\rangle = e^{\hat{D}}|\text{b-RVB}\rangle$$

$$\hat{D} = \sum_{ij} g_{ij}\tilde{c}_{i\uparrow}\tilde{c}_{j\downarrow}$$

$$\Phi_{\rm RVB}(\{\sigma_s\}) \equiv \sum_{\text{partition}} \prod_{(ij)} (-1)^i W_{ij}$$

$$\tilde{c}_{i\sigma} = c_{i\sigma} e^{-i\hat{\Omega}_i}$$

two-component RVB state

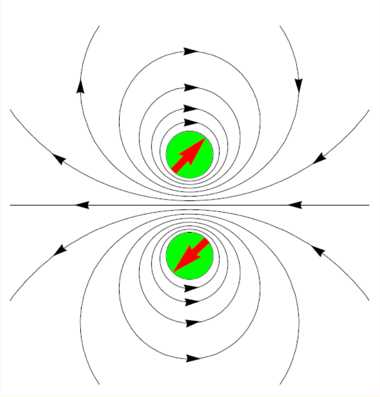


finite doping $\left\langle \hat{D} \right\rangle = \sum_{ij} g_{ij} \left\langle \tilde{c}_{i\uparrow}\tilde{c}_{j\downarrow} \right\rangle \neq 0 \Rightarrow \left\langle \tilde{c}_{i\uparrow}\tilde{c}_{j\downarrow} \right\rangle = \Delta^0_{ij} \neq 0$

superconducting order parameter

$$\left\langle c_{i\uparrow}c_{j\downarrow} \right\rangle = \Delta^0_{ij} \left\langle e^{i(\hat{\Omega}_i + \hat{\Omega}_j)} \right\rangle$$

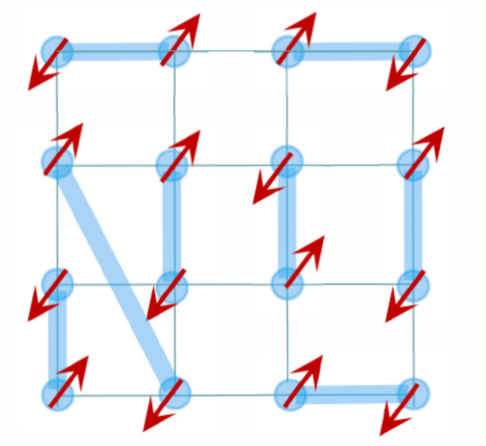
$$\hat{\Omega}_i = -\sum_{l\neq i} \arg(i-l)\left[n^b_{l\downarrow}\right] = \frac{1}{2}\sum_{l\neq i} \arg(i-l)\left[n^b_{l\uparrow} - n^b_{l\downarrow} - 1\right]$$



$$|\Psi_G\rangle = e^{\hat{D}}|\text{b-RVB}\rangle$$

$$\hat{D} = \sum_{ij} g_{ij}\tilde{c}_{i\uparrow}\tilde{c}_{j\downarrow} \qquad \tilde{c}_{i\sigma} = c_{i\sigma}e^{-i\hat{\Omega}_i}$$

$$|\text{b-RVB}\rangle =$$



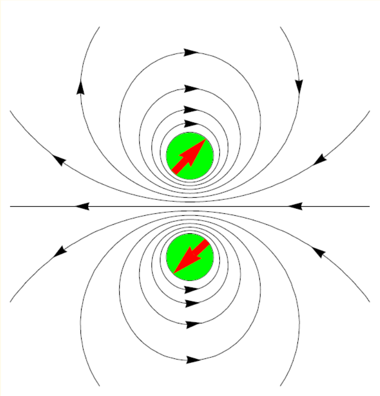
$$k_B T_c \simeq E_g/6$$

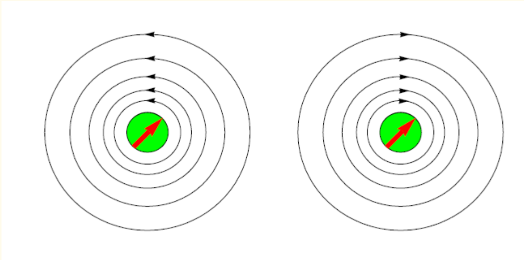
$e^{\hat{D}}$ — **localization** | SC | **FL** → **doping**

$|\text{b-RVB}\rangle$ — AFM | spin liquid | \`Kondo lattice'

superconducting transition

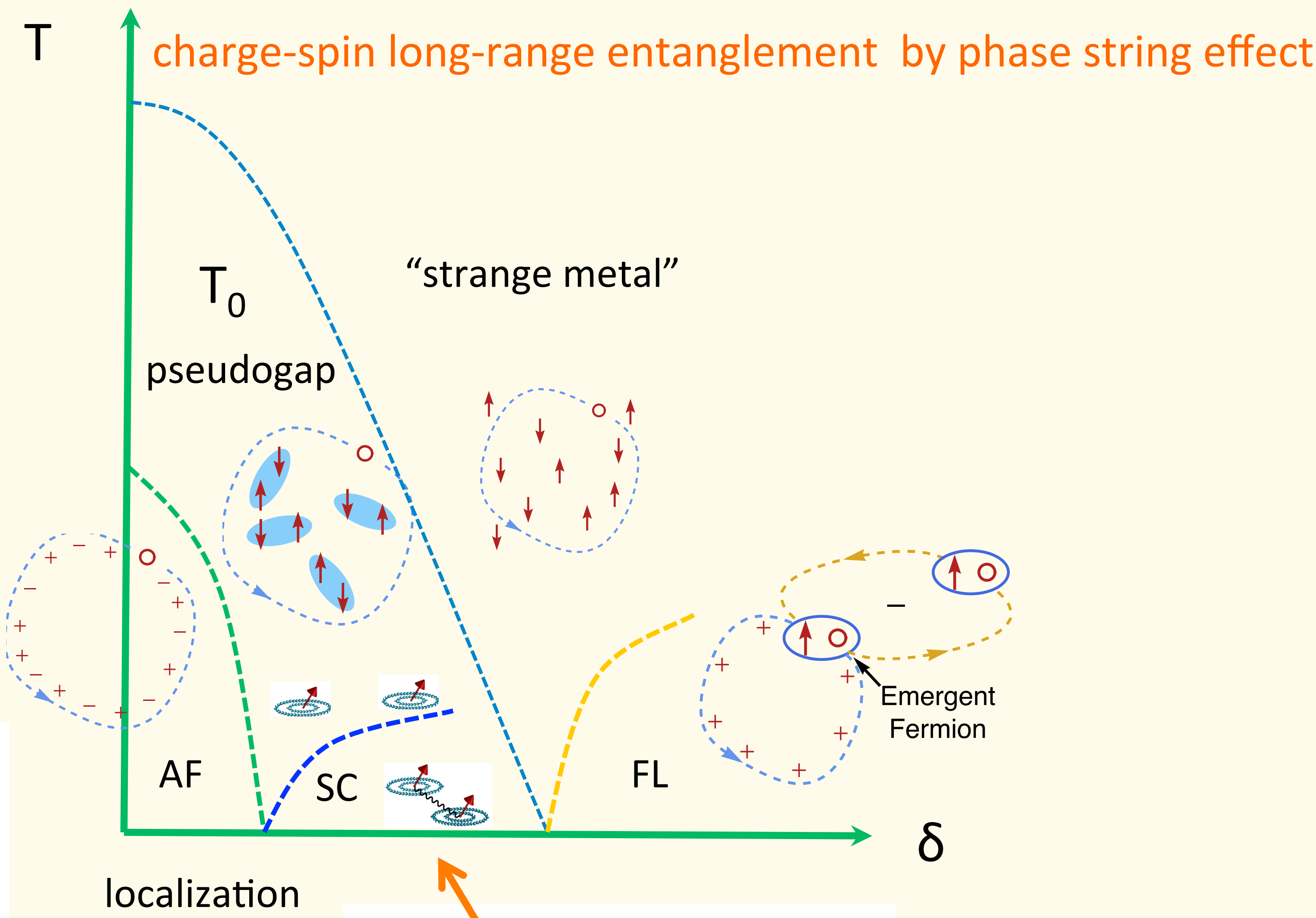
$$\langle c_{i\uparrow}c_{j\downarrow}\rangle = \Delta^0_{ij}\langle e^{i(\hat{\Omega}_i+\hat{\Omega}_j)}\rangle \to 0$$

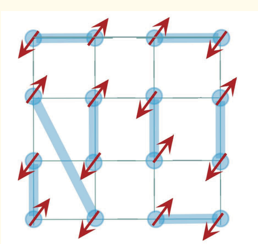




J.W. Mei & ZYW, PRB (2010)

Global phase diagram





AF = long-range RVB

$$|\Psi_G\rangle = \Lambda_h \left(\sum_{ij} g_{ij} c_{i\uparrow} c_{j\downarrow} \right)^{\frac{N_h}{2}} |\mathrm{RVB}\rangle$$

$$\Lambda_h = \left[\prod_{hd} \frac{\left(z^*_{l_h} - z^*_{j_d}\right)}{|z_{l_h} - z_{j_d}|} \right] \phi_h(l_1, l_2, \ldots, l_{N_h})$$

Fractionalization description of the ground state

$$|\Psi_G\rangle = \hat{\Lambda}_h \left(\exp \sum_{ij} g_{ij} c_{i\uparrow} c_{j\downarrow} \right) |\text{b-RVB}\rangle \qquad \hat{\Lambda}_h = \left[\prod_l e^{-i\hat{\Omega}_l} \right] \phi_h(l_1, l_2, \ldots, l_{N_h})$$

$$c_{i\sigma} = h_i^\dagger a_{i-\sigma}^\dagger e^{i\hat{\Omega}_i}$$

$$|\Psi_G\rangle = \mathcal{P}\left[|\Phi_h\rangle \times |\Phi_a\rangle \times |\Phi_b\rangle \right]$$

$$|\Phi_\text{h}\rangle \equiv \sum_{\{l_\text{h}\}} \varphi_\text{h}(l_1, l_2, \ldots) h_{l_1}^\dagger h_{l_2}^\dagger \cdots |0\rangle_h,$$

– holon condensation

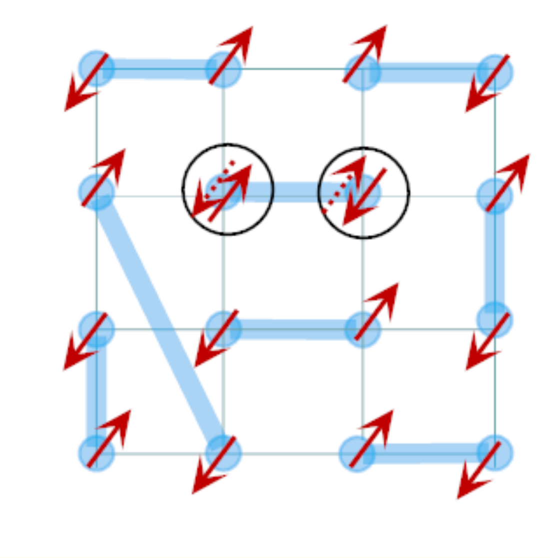
$$|\Phi_a\rangle \equiv \exp \left(\sum_{ij} \tilde{g}_{ij} a_{i\downarrow}^\dagger a_{j\uparrow}^\dagger \right) |0\rangle_a,$$

– backflow spinon: BCS-like

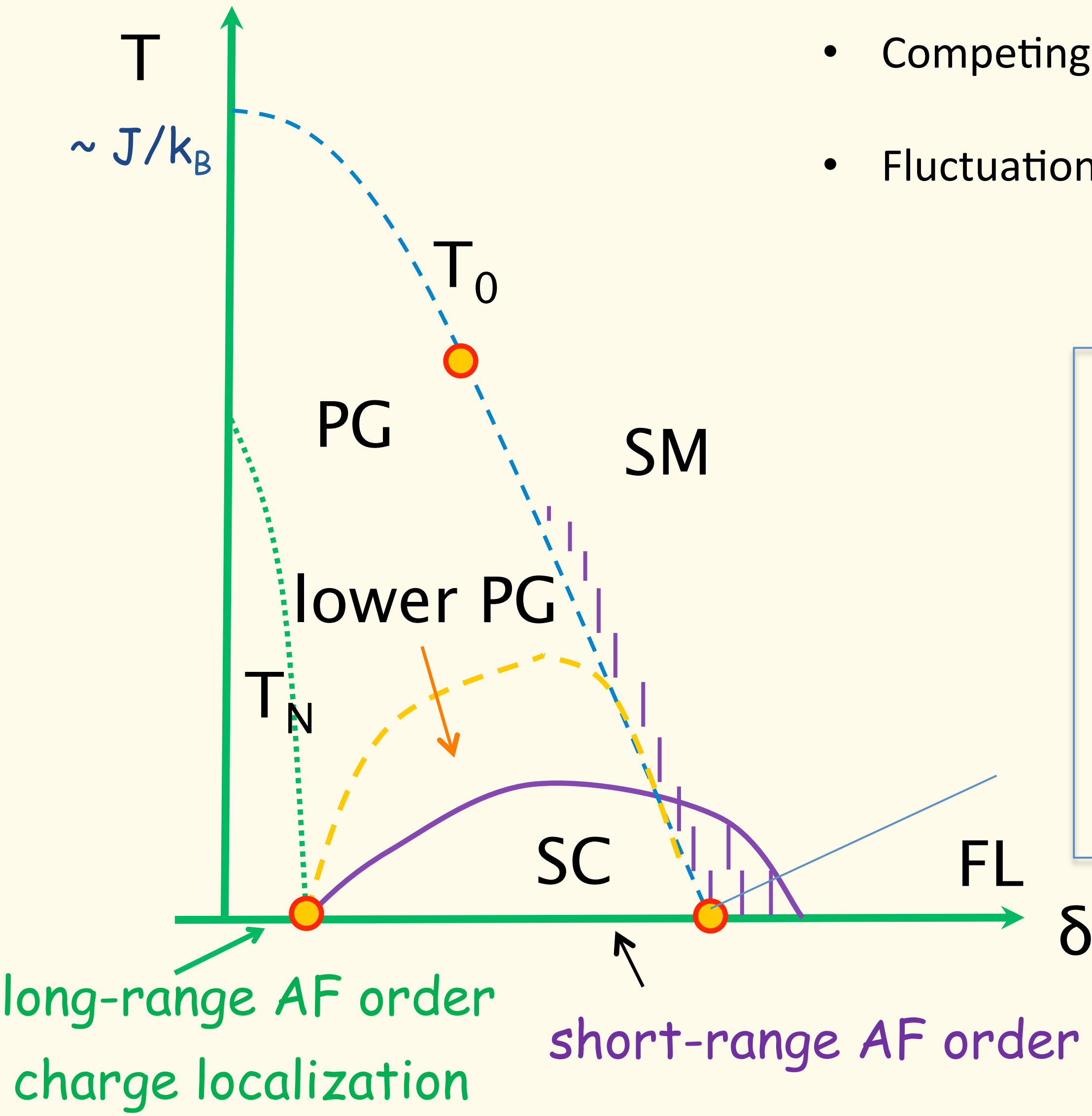
$$|\Phi_b\rangle \equiv \exp \left(\sum_{ij} W_{ij} b_{i\uparrow}^\dagger b_{j\downarrow}^\dagger \right) |0\rangle_b.$$

– bosonic spinon: b-RVB

three hidden orders



two-dimensional limit, T>0



Competing order or Fluctuating regime?

- Competing orders: generalized GL eq.
- Fluctuations: fractionalization of electron degrees of degree due to Mottness

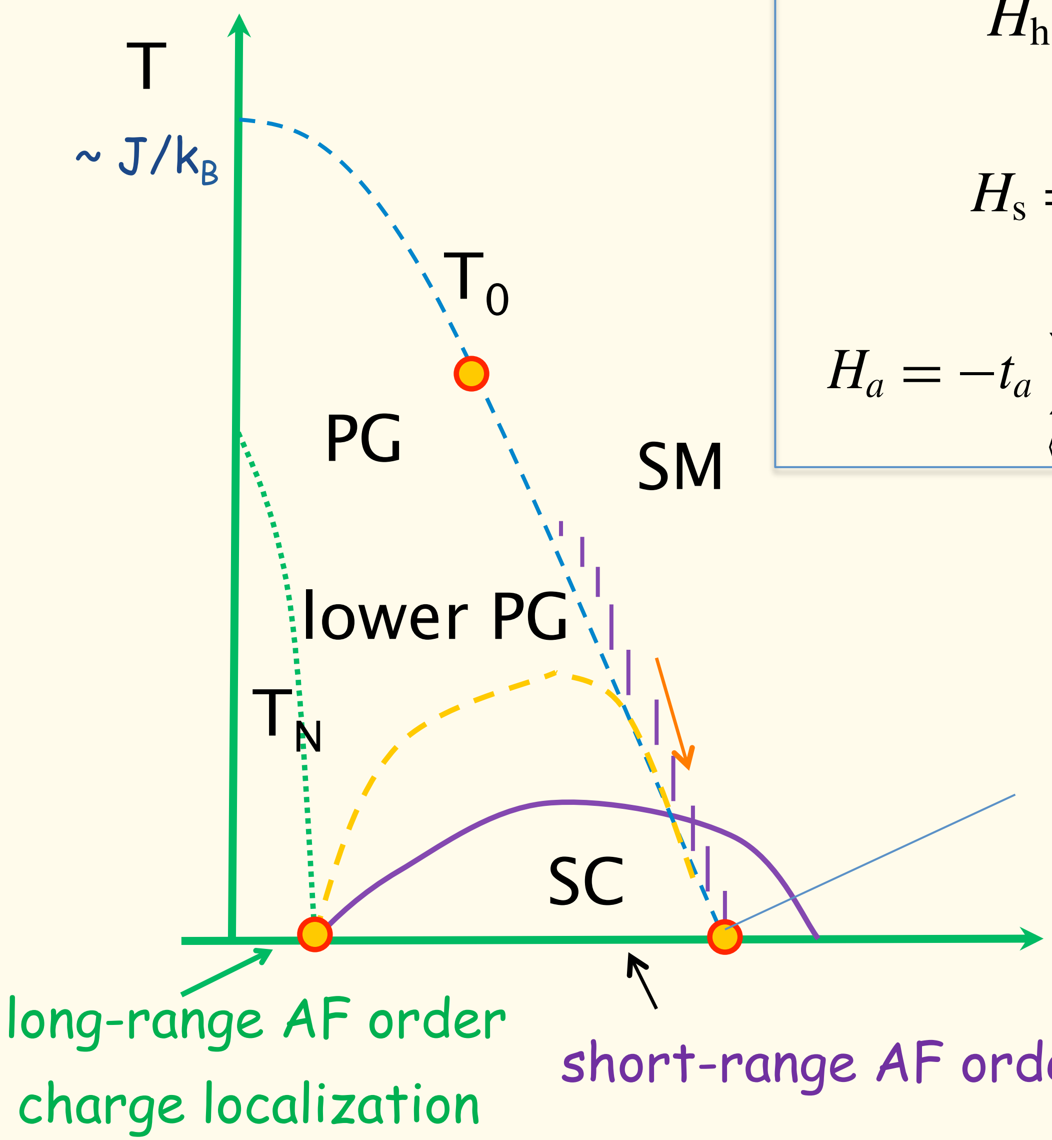
$$|\Psi_G\rangle = \hat{P}\left[|\Phi_h\rangle \otimes |\Phi_a\rangle \otimes |\Phi_b\rangle\right]$$

three hidden orders:

- holon condensation
- bosonic spinon RVB
- backflow spinon RVB

AF and SC instabilities at T=0

$$|\Psi_G\rangle = \mathcal{P}\left[|\Phi_h\rangle \times |\Phi_a\rangle \times |\Phi_b\rangle\right]$$



$$H_h = -t_h \sum_{\langle ij\rangle} (e^{iA^s_{ij}}) h_i^\dagger h_j + \text{h.c.},$$

$$H_s = -J_s \sum_{\langle ij\rangle\sigma} (e^{i\sigma A^h_{ij}}) b_{i\sigma}^\dagger b_{j-\sigma}^\dagger + \text{h.c.}$$

$$H_a = -t_a \sum_{\langle ij\rangle\sigma} e^{-i\phi^0_{ij}} a_{i\sigma}^\dagger a_{j\sigma} - J_a \sum_{\langle ij\rangle} \eta_{ij} \hat{\Delta}^a_{ij} + \text{h.c.}$$

mutual Chern-Simons theory

S.P. Kou, X.L. Qi, ZYW, PRB (2005)
P. Ye, C.S. Tian, X.L. Qi, ZYW, PRL (2011)

Mean-field theory

Y. Ma, P. Ye, ZYW, NJP (2014)

Strange metal behavior

Z.C. Gu, ZYW, PRB (2005)

Conclusion

- Constructed a ground state wavefunction based on three general principles:

$$\left|\Psi_G\right\rangle = e^{\hat{D}}\left|\text{b-RVB}\right\rangle$$

No double occupancy constraint;
Correct AFM state at half-filling;
Phase string sign structure at finite doping

- By VMC, the wavefunction reproduces the novel properties of one-hole-doped 2-leg t-J model by DMRG:

  QCP, charge modulation, Fermi surface reconstruction etc.

- In 2D, the wavefunction predicts AFM, d-wave SC, and FL phases as a function of doping

- Fractionalization and mutual Chern-Simons gauge theory description of elementary excitations and finite-temperature phase diagram

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Kai Wu (SLAC), Jan Zannen (Leiden): Sign structure

Supeng Kou (BNU), , Xiaoliang Qi (Stanford), P. Ye (PI), Chushun Tian (Tsinghua):

Mutual Chern-Simons theory

Jia-Wei Mei （PI) : SC transition and Tc formula

Peng Ye (PI), Yao Ma (Tsinghua), Zhengcheng Gu (PI): Pseudogap phase