Recent new progress on variational approach for strongly correlated t-J model

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The minimal model
-- extended $t$-$J$ Hamiltonian

$$-\sum_{i,j,\sigma} t_{ij} \left( \tilde{c}_{i,\sigma}^{\dagger} \tilde{c}_{j,\sigma} + h.c. \right) + J \sum_{\langle i,j \rangle} \tilde{S}_i \cdot \tilde{S}_j$$

$t_{ij} = \text{n.n.}(t), \text{2nd n.n.}(t'), \text{3rd n.n.}(t'')$ hopping

$J = \text{n.n.} \text{AF spin-spin interaction}$

Strong constraint -- no two electrons on the same site

Use a variational Monte Carlo approach to satisfy the constraint

$$\left| \Psi \right> = \hat{P}_J \prod_{R_i} \left( 1 - n_{R_i \uparrow} n_{R_i \downarrow} \right) \left| \Psi_0 \right>$$

$$P_d = \prod_i (1 - n_{i \uparrow} n_{i \downarrow})$$

$\hat{P}_J$ -- hole-hole repulsive Jastrow factor!
Outline

Use variational approach

Part I:
To study strongly correlated superconducting state with spatial inhomogeneity: a theory for stripes in high temperature superconductors

Part II:
To study phase fluctuation of the strongly correlated superconducting state
**Neutron scattering** – probing spin ordering

**Magnetic period vs Doping → Half-doped Stripe!**

Yamada’s plot →

- **Bond-centered**
- **Site-centered**

Example of $x=1/8$ doping,
- Magnetic modulation period is $1/x$
- Charge modulation is $1/2x$

For vertical stripes

$$x = \varepsilon_S = 1/a_s$$

Yamada, Fujita, Tranquada, …

Vojta, Adv. in Phys. ‘09
Soft X-ray scattering – probing charge ordering

La$_{1.875}$Ba$_{0.125}$CuO$_4$

a$_S$ = 2a$_C$

Charge correlation in (H,0,L) plane

Stripe orbital pattern

Modulation period: 4a$_0$

Abbamonte, et al., Nature Physics ’05
Evidence for bond-centered electronic cluster glass state with unidirectional $4a_0$ domains!

V-shape LDOS!

Kohsaka, et al., Science ’07
Three main views about the formation mechanism of stripes:

1. Usual CDW or SDW needs a nesting wave vector and strong lattice coupling → a competing interaction? nesting vector?
   – Moskiewicz, ’99

2. Hubbard or t-J model favors phase separation and long-range Coulomb interaction frustrates the phase separation and leads to stripes → stability? why half-doped?

3. Competition between kinetic and exchange energies in Hubbard or t-J model
   – HF --- Zaanan, Poilblanc and Rice....
   – DMRG --- White and Scalapino (t’ or 2nd n.n. hopping suppresses stripes)
   – VMC --- Kobayashi and Yamada; Miyazaki et al.; Himeda, Kato and Ogata (t’ stabilizes stripes)...

To treat these competing states quantitatively and reliably ---- variational approach!
For a translational invariant state, it is straightforward to construct a variational wave function for a projected d-wave state or resonating valence bond state (by P. W. Anderson)

\[ |RVB\rangle = P_d \left[ \prod_k (u_k + v_k C_{k,\uparrow} C_{-k,\downarrow}^+) \right] |0\rangle = P_d |BCS\rangle \]

The Gutzwiller operator \( P_d \) enforces no doubly occupied sites for hole-doped systems:

\[ P_d = \prod_i (1 - n_{i,\uparrow} n_{i,\downarrow}) \]

\[ P_{N_e} |RVB\rangle = P_d \left( \sum_k \frac{v_k}{u_k} C_{k,\uparrow} C_{-k,\downarrow}^+ \right)^{N_e/2} |0\rangle = P_d \left( \sum_{i,j} a_{i,j} C_{i,\uparrow} C_{j,\downarrow}^+ \right)^{N_e/2} |0\rangle \]

\[ v_k / u_k = \frac{E_k - \xi_k}{\Delta_k}, \Delta_k = \Delta(\cos k_x - \cos k_y) \]

\[ \xi_k = -2(\cos k_x + \cos k_y) - 4t_v \cos k_x \cos k_y - 2t''(\cos 2k_x + \cos 2k_y) - \mu_v, \]

\[ E_k = \sqrt{\xi_k^2 + \Delta_k^2} \]
How to include the inhomogeneity into the wave function?

1. Solve the BdG equations and obtain the eigenvectors,

\[ \sum_j \begin{pmatrix} H_{ij} & F_{ij} \\ F_{ji}^* & -H_{ji} \end{pmatrix} \begin{pmatrix} u^n_j \\ v^n_j \end{pmatrix} = E_n \begin{pmatrix} u^n_i \\ v^n_i \end{pmatrix} \]

2. Make Bogoliubov transformation,

\[ \begin{pmatrix} \gamma_n \\ \bar{\gamma}_n \end{pmatrix} = \begin{pmatrix} u^n_i & v^n_i \\ \bar{u}^n_i & \bar{v}^n_i \end{pmatrix} \begin{pmatrix} c_{i\uparrow} \\ c_{i\downarrow}^\dagger \end{pmatrix}, \quad E_n > 0 \quad \bar{E}_n < 0 \]

3. Construct the trial wave function,

\[ \hat{P}_h \hat{P}_{Ne} |\Phi_0\rangle = \hat{P}_h \hat{P}_{Ne} \prod_n \gamma_n \bar{\gamma}_n^\dagger |0\rangle \propto \hat{P}_h \left( \sum_{i,j} (\hat{U}^{-1} \hat{V})_{ij} c_{i\uparrow}^\dagger c_{j\downarrow}^\dagger \right)^{N_e/2} |0\rangle \]

**Himeda et al., PRL ‘02**

Matrix size: 2N x 2N reduced to N x N

4. To optimize energy, change to a new set of parameters, back to steps 1,2,3..
There is a problem with this construction as d-wave pairing has a node, hence there is a possibility to hit a singular value.

A new way to express the wave function...

Yokoyama and Shiba, JPSJ 1988

Particle-hole (P-H) transformation

\[ c_{i\uparrow} \Rightarrow f_i \]

\[ c_{i\downarrow} \Rightarrow d_i^\dagger \]
Construct stripe $|\Psi_0> \text{ for hole-doped states}$

**Mean-field Hamiltonian**

\[
H_{MF} = \begin{pmatrix}
    H_{ij} & \Delta_j \\
    \Delta_i & -H_{ji}
\end{pmatrix}
\begin{pmatrix}
    c_{i\uparrow}^\dagger & c_{i\downarrow}^\dagger \\
    c_{j\uparrow} & c_{j\downarrow}
\end{pmatrix}
\]

\[
H_{ij\sigma} = - \sum_{\alpha=n,nn,nnn} \delta_{i+\alpha,j} + \left( \rho_i + \sigma m_i (-1)^{R_i^x + R_i^y} - \mu \right) \delta_{ij}
\]

3 new parameters,
- **Pair period**
- **Charge period**
- **Spin period**

**AF-RVB stripe** [In-Phase-$\Delta$ and Anti-Phase-$\mu$]

**Bond-centered**

\[
\tilde{Q}_\alpha = (Q_x, Q_y) = \left(0, \frac{2\pi}{a_\alpha}\right), \quad \alpha = C, P, S
\]

\[
\tilde{R}_i = \left(0, \frac{1}{2}\right), \quad \tilde{R}_0 = (R_i^x, R_i^y)
\]

**Charge:** \[\rho_i = \rho_v \cos\left[\tilde{Q}_C (\tilde{R}_i - \tilde{R}_0)\right]\]

**Spin:** \[m_i = m_v \sin\left[\tilde{Q}_S (\tilde{R}_i - \tilde{R}_0)\right]\]

**Pair:** \[\Delta_{i,i+x} = \Delta_v^M \cos\left[\tilde{Q}_P (\tilde{R}_i - \tilde{R}_0)\right] - \Delta_v^C\]

\[\Delta_{i,i+y} = -\Delta_v^M \cos\left[\tilde{Q}_P (\tilde{R}_i - \tilde{R}_0) + Q_y\right] + \Delta_v^C\]
The stripe states will involve charge density and spin density modulation, it will also involve pair field. What is the relation between these three quantities? Their relative periods?
Gutzwiller’s approximation in t-J model

\[
H_{t-J} = -t \sum_{\langle i, j \rangle, \sigma} \left( c_{i\sigma}^\dagger c_{j\sigma} + \text{h.c.} \right) + J \sum_{\langle i, j \rangle} S_i \cdot S_j
\]

\[
\langle S_i \cdot S_j \rangle = g_s (i) g_s (j) \langle S_i \cdot S_j \rangle_0
\]

\[
\langle c_{i\sigma}^\dagger c_{j\sigma} \rangle = g_{t\sigma} (i) g_{t\sigma} (j) \langle c_{i\sigma}^\dagger c_{j\sigma} \rangle_0
\]

Mean-field decoupling...

\[
\langle H_{t-J} \rangle = -t \sum_{\langle i, j \rangle, \sigma} g_{t\sigma} (i) g_{t\sigma} (j) \left( \chi_{ij\sigma} + \text{c.c.} \right) - J \sum_{\langle i, j \rangle} g_s (i) g_s (j) \left( \frac{3}{8} \left( \chi_{ij} \chi_{ij}^* + \Delta_{ij} \Delta_{ij}^* \right) - m_i m_j \right)
\]

\[
g_{t\sigma} (i) = (1 - n_{i\sigma}) \frac{n_i (1 - n_i)}{\sqrt{(1 - n_{i\uparrow})(1 - n_{i\downarrow})(n_i - 2n_{i\uparrow}n_{i\downarrow})}}
\]

\[
\chi_{ij\sigma} = \langle c_{i\sigma}^\dagger c_{j\sigma} \rangle_0 \quad \Delta_{ij} = \langle c_{i\downarrow} c_{j\uparrow} - c_{i\uparrow} c_{j\downarrow} \rangle_0
\]

\[
g_s (i) = \frac{n_i}{n_i - 2n_{i\uparrow}n_{i\downarrow}}
\]

\[
\chi_{ij} = \sum_{\sigma} \chi_{ij\sigma} \quad m_i = \langle S_i^z \rangle_0
\]

\[
n_i = 1 - x_i \quad n_{i\sigma} = \frac{1 - x_i}{2} + \sigma m_i
\]
What are the periods of these collective excitations?

Fluctuating charge, spin, and pair modes:

\[ x_i \rightarrow \bar{x} + \delta x_i \quad m_i \rightarrow \bar{m} + \delta m_i \quad \Delta_{ij} \rightarrow \bar{\Delta} + \delta \Delta_{ij} \]

In the case of \( \bar{m} = 0 \) and \( \bar{\Delta} \neq 0 \) (for h-doped cases),

The excitation will have c, s,p coupled modes due to

\[ \sim \delta x_i \delta m_{q}^{2} \rightarrow \delta x_{q} \delta m_{-q/2}^{2} \quad \sim \bar{\Delta} \delta x_{i} \delta \Delta_{ij} \rightarrow \bar{\Delta} \delta x_{q} \delta \Delta_{-q} \]

Collective mode pattern:

\[ \Rightarrow \text{Period: spin} = 2 \times \text{charge} \quad \text{pair} = \text{charge} \]

\[ \Rightarrow \text{Most favorable stripe pattern?} \]
two different stripe patterns

AF-RVB Stripe
(Anti-Phase-m, In-Phase-$\Delta$)

“AntiPhase” Stripe
(Anti-Phase-m, Anti-Phase-$\Delta$)

hole density

spin density

pairing amplitude

Pair field:
1. $2 \times$ period
2. $\Delta^c = 0$

Himeda, et al., PRL ’02

Optimized energy for $8a_0$ AR-RVB stripe

$J/t = 0.3$

Random Pattern

iPEPS also --- same type Stripe

iPEPS = infinite Projected Entanglement Pair State

The stripe they found in the pure t-J model:
same pattern as the AF-RVB stripe $\Rightarrow$

Period:
spin = 2 × charge ; pair = charge

The amplitude of modulation is a bit larger than our results.
These are their ground states.
For us, energies are too close to tell!

Red number: hole density
Black number: magnetization
Bond size: pairing strength
(J/t=0.4)

Corboz, et al., PRB 84, 041108 (2011)
For extended t-J models, stripe states have very low energies, but may be not enough to replace the uniform ground states!

What extra microscopic ingredient is required to obtain stripes or half-doped stripes?
Electron-Phonon Interaction

Strong coupling of charge order to the lattice!

Isotope Effect

Zhou, et al., a chapter in "Treatise of High Temperature Superconductivity", ed. by J.R. Schrieffer ’07
Mass-renormalization due to electron–phonon interaction

Mishchenko, et al., PRL 08

Effective mass:

\[
\begin{align*}
\lambda(\delta) / \lambda(0) & = f(\delta) = 1 - 3\delta \\
\Lambda &= \lambda(0) / \pi
\end{align*}
\]

Self-Consistent VMC

New \(<n_h>\)

Bare \(t^*/t\)

Optimize \(H_{t^*-J}\)
Half-doped Stripe has been stabilized!

$\Delta E = E(\text{Stripe}) - E(\text{RVB})$

Mass renormalization by electron-phonon coupling

$t_{ij}^* = t_{ij} \left(1 - \Lambda \left[ \frac{f(n_i^h) + f(n_j^h)}{2} \right] \right)$

$\lambda(\delta)/\lambda(0) \equiv f(\delta) = 1 - 3\delta$

$\Lambda = \lambda(0) / \pi$

$a_c \times \delta = 0.5$

$a_s \times \delta = 1.0$

$(t',t'',J)/t = (-0.2,0.1,0.3)$

$\epsilon_s = 1/a_s = \delta = \epsilon_c/2 = 1/2a_c$

C.P. Chou and T.K. Lee, PRB 81, 060503(R) (2010)
Long range Coulomb – favors 8a stripe!

\[- \sum_{i,j,\sigma} t_{ij} \left( \tilde{c}_{i,\sigma}^{\dagger} \tilde{c}_{j,\sigma} + \text{h.c.} \right) + J \sum_{\langle i,j \rangle} \tilde{S}_i \cdot \tilde{S}_j + V_C \sum_{i \neq j} \frac{\hat{n}_i^{h} \hat{n}_j^{h}}{|\vec{R}_i - \vec{R}_j|} \]

\[\Delta E = E(\text{Stripe}) - E(\text{RVB})\]

C.P. Chou and T.K. Lee, PRB 81, 060503(R) (2010)
Electron-doped Cuprates

Particle-hole Asymmetric!

Armitage, Fournier, and Greene, RMP ‘10
Inhomogeneous charge distribution?

1. Many indirect experiments on the spatial inhomogeneity
   Bakharev, et al., PRL ’04; Kang, et al., Nat. Mater. ’07; Dai, et al., PRB ’05; Zamborszky, et al., ’04; Sun, et al., PRL ’04; Kang, et al., PRB ’05 ...

2. A number of theoretical predictions (extended Hubbard model) on the filled or in-phase stripes
   Aichhorn, et al., EPL ’05; Sadori, et al., PRL ’00; Valenzuela, ’06 ...

3. There are also experimental evidences (chemical potential shift) against phase separation
   Niestemski, et al. Nature’07; Harima, et al., PRB ‘03; Yagi, et al., PRB ’06 ...

Up to now, no consensus yet!
What kind of period for stripe states?

Fluctuating charge, spin, and pair modes:

\[ x_i \rightarrow \bar{x} + \delta x_i \quad m_i \rightarrow \bar{m} + \delta m_i \quad \Delta_{ij} \rightarrow \bar{\Delta} + \delta \Delta_{ij} \]

In the case of \( \bar{m} \neq 0 \) and \( \bar{\Delta} \neq 0 \) (for e-doped cases), the significant contributions to the total energy are

\[ \sim \bar{m} \delta x_i \delta m_i \quad \sim \bar{\Delta} \delta x_i \delta \Delta_{ij} \]

Period: spin = charge = pair

“In-Phase-m” stripe in electron-doped cases?
Phase Diagram ($|t'/t|=0.1$)

No half-doped stripe in electron-doped cases!
“phase separation” !?

$24 \times 24$
$\delta$ = $\Lambda = 0.25$

Electron doping
Hole doping

24 × 24
$(t'',J)/t=(-t'/2,0.3)$

Glassy Stripe
Charge Pattern
Phase Diagram ($|t'/t| = 0.3$)

Stronger Particle-hole asymmetry!
Half-doped stripe for h-doped but not for e-doped!

Glassy Stripe Charge Pattern

Electron doping  Hole doping

$\Lambda = 0.25$
“Phase Separation” (t’/t=0.1)

Electron-rich phase v.s. Electron-poor phase
(AF+SC state: |<\textit{M}>| = 0.269)

AF-RVB Stripe

In-Phase-m Stripe:

In-Phase-m Stripe: |<\textit{M}>| = 0.265
Summaries

1. **Collective excitations** with spin, charge, and pair coupled naturally leads to appropriate lowest energy stripe patterns (AF-RVB) in the t-J-type model based on variational approach.

2. Long-range Coulomb interaction does not produce half-dopes stripes but it favors 8a at 1/8.

3. A model to renormalize the mass due to electron-phonon interaction is proposed:
   - In the hole-doped regime, a weak electron-phonon interaction is enough to stabilize the half-doped vertical stripes for doping \( \leq 1/8 \).
   - In the electron-doped regime, no stable half-doped stripe is found, phase separation seems more favorable.

Thank you for your attention!
Outline

Use variational approach

Part I:
To study strongly correlated superconducting state with spatial inhomogeneity: a theory for stripes in high temperature superconductors

Part II:
To study phase fluctuation of the strongly correlated superconducting state
Giant Nernst effect and quantum diamagnetism

what caused this strong phase fluctuation? competing interaction?

Strong phase fluctuation for cuprates, specially in the underdoped regime due to small number of holes, is that enough?

Wang et al, PRB, 2006
Until now, almost all of the variational calculations for the t-J model, except Yokoyama and Shiba (1988), have been using the canonical ensemble, a wave function with a fixed number of particles:

For $N_e$ electrons  

$$|RVB\rangle = P_d \left[ \prod_k (u_k + v_k C_{k,\uparrow}^+ C_{-k,\downarrow}^+) \right] |0\rangle = P_d |BCS\rangle$$

$$P_{N_e} |RVB\rangle = P_d \left( \sum_k \frac{v_k}{u_k} C_{k,\uparrow}^+ C_{-k,\downarrow}^+ \right)^{N_e/2} |0\rangle = P_d \left( \sum_{i,j} a_{i,j} C_{i,\uparrow}^+ C_{j,\downarrow}^+ \right)^{N_e/2} |0\rangle$$

What about the phase, the order parameter in SC? Are the results same as using the wave function with varying particle numbers? Difference with BCS as there is this projection operator?
number of particles fluctuates

\[
\left| \Psi_{dRVB} \right> = \hat{P}_d \prod_k \left( u_k + v_k c_k^{\uparrow} c_{-k}^{\uparrow} \right) \left| 0 \right>
\]

Yokoyama and Shiba, JPSJ 1988

Particle-hole (P-H) transformation

\[ c_i^{\uparrow} \Rightarrow f_i \]
\[ c_i^{\downarrow} \Rightarrow d_i^{\dagger} \]

In df space,

\[ \left| \text{vac} \right>_{(df)} , d^{\dagger} \left| \text{vac} \right>_{(df)} , f^{\dagger} \left| \text{vac} \right>_{(df)} , f^{\dagger} d^{\dagger} \left| \text{vac} \right>_{(df)} \]

\[ \left| h \right> \Rightarrow \left| d \right>_{(df)} \]

Mapping Table:

\[ \left| \downarrow \right> \Rightarrow \left| 0 \right>_{(df)} \]
\[ \left| \uparrow \right> \Rightarrow \left| df \right>_{(df)} \]

\[ \left| \uparrow \downarrow \right> \Rightarrow \left| f \right>_{(df)} \]

\( (N_d + N_f = N, \text{ if no magnetization}) \)

Conserve “particles” \( (N_d - N_f = N_h) \)
In the “df” representation

$$\left| \Psi_{dRVB} \right\rangle_{(df)} = \hat{P}_d \prod_k (u_k d_k^\dagger + v_k f_k^\dagger) \left| 0 \right\rangle_{(df)}$$

**New process in the Monte-Carlo simulation**

**HOPPING:**

$$\downarrow + h \Leftrightarrow h + \downarrow$$
$$0 + d \Leftrightarrow d + 0$$
$$\text{df} + d \Leftrightarrow d + \text{df}$$

**EXCHANGE:**

$$\uparrow + \downarrow \Leftrightarrow \downarrow + \uparrow$$
$$\text{df} + 0 \Leftrightarrow 0 + \text{df}$$

$$\uparrow + \downarrow \Leftrightarrow h + h$$
$$\text{df} + 0 \Leftrightarrow d + d$$
Examine this wave function

\[
\Psi_{dRVB}^{(df)} = \hat{P}_G \prod_k \left( u_k d_k^\dagger + v_k f_k^\dagger \right) |0\rangle^{(df)}
\]

it has a problem:

All variational parameters are fixed (to the half-filling case) except \( \Delta_v \).

Average doping density \( \langle \delta \rangle \) becomes a function of the variational parameter \( \Delta_v \)! The projection operator changes the particle distribution function.

We must introduce a fugacity factor: \( g \)

\[
\Psi_{dRVB}^g \Psi_{dRVB}^{(df)} = \hat{P}_d \prod_k \left( g u_k d_k^\dagger + v_k f_k^\dagger \right) |0\rangle^{(df)}
\]
free-energy optimization

\[ F(\mu_g) = E(N_e) - \mu_g N_e \quad dF = 0 \Rightarrow \mu_g = \frac{\partial E}{\partial N_e} \]

Chemical potential \( \mu_g \) is different from the variational parameter \( \mu_v \) in BCS coherent factors!

To optimize the variational energy, a hole-hole repulsive Jastrow factor is included!

\[ \hat{P}_j = \prod_{i<j} \left\{ 1 - \left[ 1 - \left| \vec{r}_{ij} \right| \right]^{\alpha} \cdot \left( \nu_{\vec{\beta}} \right)^{\delta_{\vec{R}_j, \vec{R}_i + \vec{\beta}}} \right\} \hat{n}_i^h \hat{n}_j^h \]

\[ \vec{r}_{ij} = \vec{R}_i - \vec{R}_j \text{ with PBC} \quad \vec{\beta} = \text{1st, 2nd, 3rd neighbors} \]
Free Energy Minimization

consistency between the two ensembles

\[ g(R) \]

\[ V_B g = \hat{P}_d \hat{P}_d \Psi_{dB}^g \]

\[ N = 144 \]

\[ (t', t'', J)/t = (-0.3, 0.15, 0.3) \]
The phase fluctuation of d-RVB

\[ \Delta \Theta = \sqrt{\frac{1}{2} \Delta^2 \left( \left\langle \left| \hat{\Delta}_+ \hat{\Delta} - \hat{\Delta}_+^\dagger \hat{\Delta}_-^\dagger \right| \Psi_{dRVB}^g \right\rangle \right) } \]

- Three parts need to be calculated…

\[ \Delta_0 = \left| \sum_R \varphi_R \sum_i \left\langle c_{i \uparrow}^\dagger c_{i+R \downarrow}^\dagger \right\rangle \right| \quad \varphi_{R=R_j-R_i} = \frac{1}{N} \sum_k \varphi(k) e^{ik(R_j-R_i)} \]

\[ \left\langle \hat{\Delta}_+^\dagger \hat{\Delta}_-^\dagger \right\rangle = \sum_{R_1, R_2 \neq 0} \varphi_{R_1} \varphi_{R_2}^* \sum_{i,j} \left\langle c_{i \uparrow}^\dagger c_{i+R_1 \downarrow}^\dagger c_{j \downarrow} c_{j+R_2 \uparrow} \right\rangle \]

\[ \rightarrow \text{Pair-pair correlation!} \]

\[ \left\langle \hat{\Delta}_+^\dagger \hat{\Delta}_-^\dagger \right\rangle = - \sum_{R_1, R_2 \neq 0} \varphi_{R_1} \varphi_{R_2} \sum_{i \neq j} \left\langle c_{i \uparrow}^\dagger c_{i+R_1 \downarrow}^\dagger c_{j \downarrow} c_{j+R_2 \uparrow}^\dagger \right\rangle \rightarrow \left\langle f_i^\dagger d_{i+R_1}^\dagger f_{j+R_2}^\dagger d_j \right\rangle \]

\[ \rightarrow \text{Two hopping process!} \]
The doping dependence of fluctuations

Strong phase fluctuation near underdoped regions

→ Away from the minimum uncertainty principle!

With Jastrow: $\Delta N_e$, $\Delta \Theta$, $\Delta N_e \Delta \Theta$

Without Jastrow: $\Delta N_e$, $\Delta \Theta$, $\Delta N_e \Delta \Theta$

BCS value is 1

PRB 85, 054510 (2012).
Summaries

• An algorithm for the grand-canonical wave function is re-introduced.

• Projected BCS wave function is modified by a fugacity factor.

• Mott physics has produced a very large phase fluctuation, (Tesanovic) especially at UD for two main reasons
  1. very low charge carrier density
  2. the particle number distribution function is no longer a Gaussian. $\Delta \Theta \Delta N_e \gg 1$ --- instability of SC
  -- AFM, CPCDW (Cooper pair CDW), stripe, ..

• Chemical potential (and probably tunneling conductance) as a function of hole density agrees with experiments on cuprates fairly well.

Thank you for your attention!