Superconductivity in the doped Hubbard and t-J models on the square lattice

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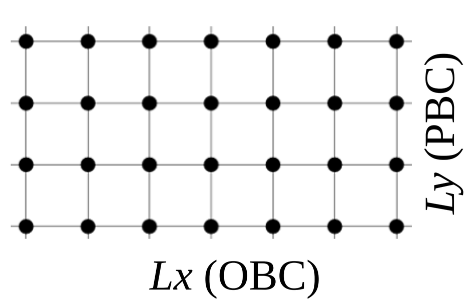
❖ Introduction and Motivation

- The Hubbard and t-J models are widely regarded as the starting point to understand high-Tc superconductivity, such as cuprates.[1-2]
- Enormous effort has been devoted to studying the properties of the models at intermediate couplings, however, no general theoretically controlled methods or consensus.[1-2]
- Previous studies suggest striped ground state with unidirectional charge-density-wave order, many low-lying states close in energy. However, no direct evidence for the presence of superconductivity.[3]
- ***Question:*** *Can we have long-range superconductivity in doped Hubbard and t-J models on square lattice wider than 2-leg ladder?*

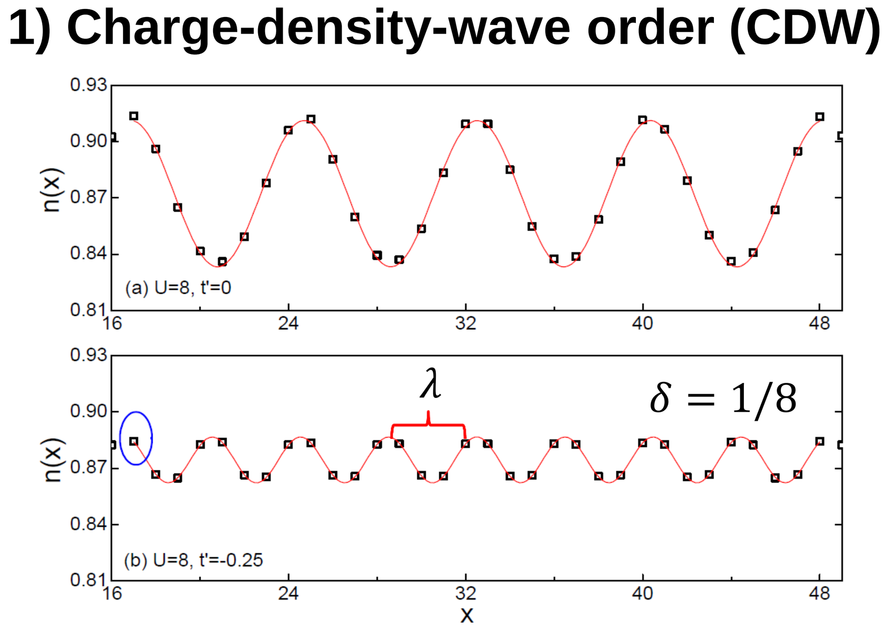
❖ Hubbard Model and DMRG study [4-5]

$$H = -\sum_{ij,\sigma} t_{ij}\left(c^+_{i\sigma}c_{j\sigma} + h.c.\right) + U\sum_i n_{i\uparrow}n_{i\downarrow}$$



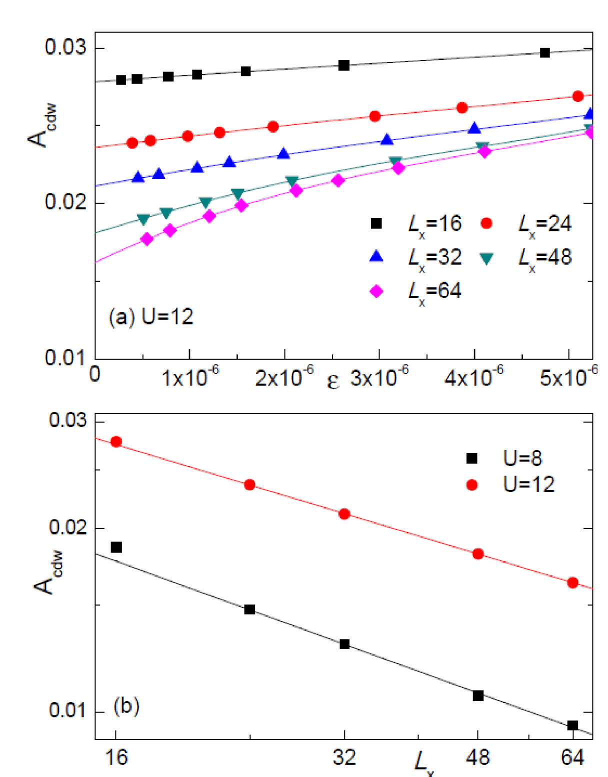
- ✓ $N=L_x*L_y$, $L_y=4$, $L_x=16\sim64$, hole doping δ=1/8
- ✓ Isotropic hopping t=1, t'=-0.25, and U=8~12
- ✓ Keep m=4096~20000 states with ~100 sweeps

1) Charge-density-wave order (CDW)



$n(x) = \delta_0 + A_{cdw}(L_x)\cos(\frac{2\pi}{\lambda}x + \phi)$

$A_{cdw}(L_x) \sim L_x^{-K_c/2}$ *Quasi-long-range CDW order*

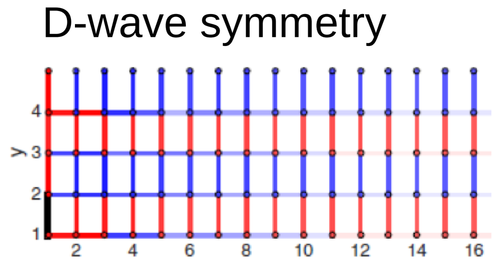


2) Superconductivity (SC) $\alpha = \hat{x}, \hat{y}$

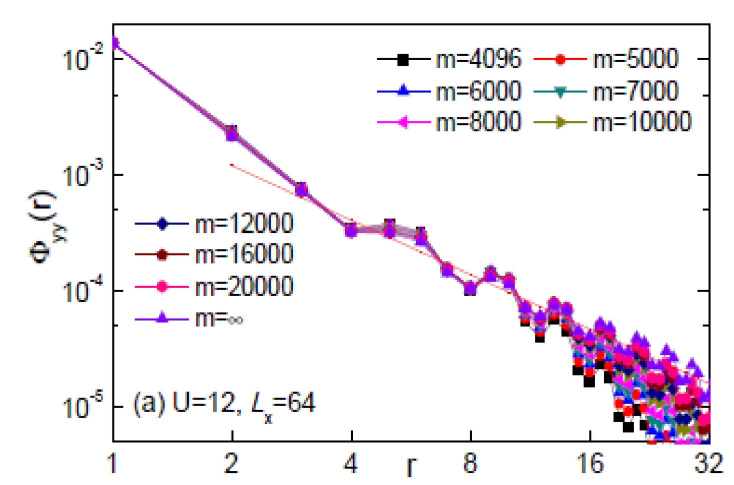
$$\Phi_{\alpha\beta}(x) = \frac{1}{L_y}\sum_{y=1}^{L_y}\langle\Delta^\dagger_\alpha(x_0,y)\Delta_\beta(x_0+x,y)\rangle$$

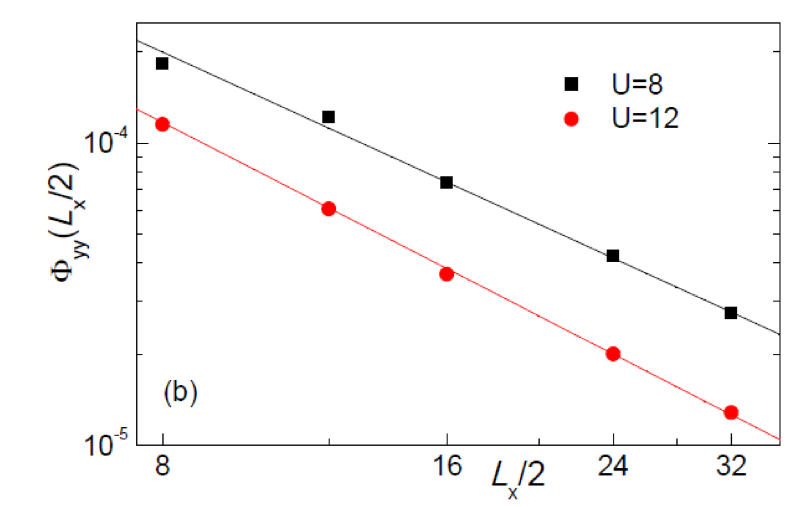
$$\Delta^\dagger_\alpha(x,y) = \frac{1}{\sqrt{2}}\left[c^\dagger_{(x,y),\uparrow}c^\dagger_{(x,y)+\alpha,\downarrow} - c^\dagger_{(x,y),\downarrow}c^\dagger_{(x,y)+\alpha,\uparrow}\right]$$

D-wave symmetry

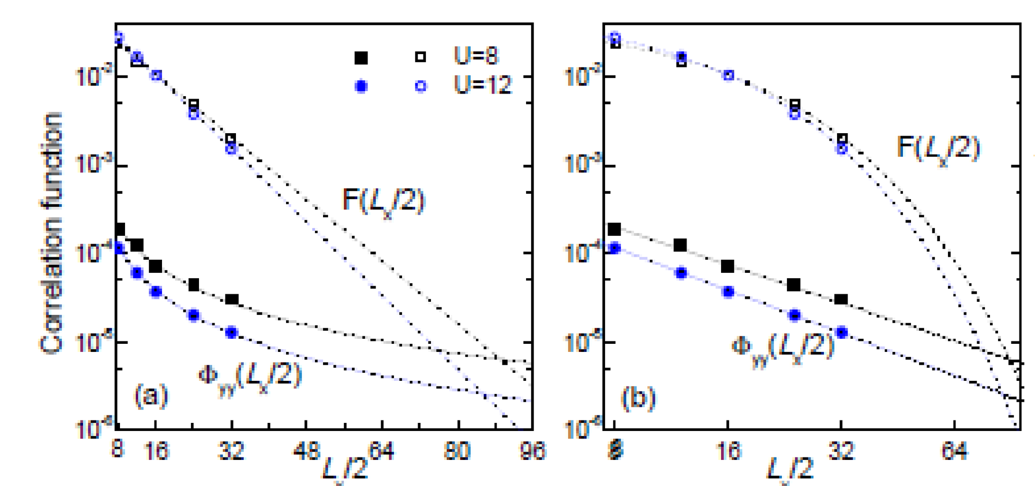


Quasi-long-range SC: $\Phi_{yy}(r) \sim r^{-K_{sc}}$ $\qquad \Phi_{yy}(L_x/2) \sim (L_x/2)^{-K_{sc}}$





3) Spin-spin correlation



$$F(x) = \frac{1}{L_y}\sum_{y=1}^{L_y}|\langle\vec{S}_{x_0,y}\cdot\vec{S}_{x_0+x,y}\rangle|$$

Short-range spin correlation $F(L_x/2) \sim e^{-L_x/2\xi_s}$

4) Luther-Emery liquid [6]

$A_{cdw}(L_x) \sim L_x^{-K_c/2}$

$\Phi\left(\frac{L_x}{2}\right) \sim \left(\frac{L_x}{2}\right)^{-1/K_{sc}}$

$K_c \times K_{sc} = 1$

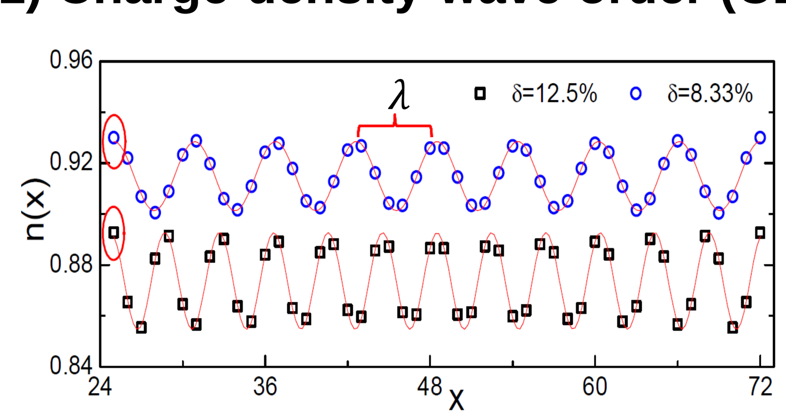
U	K_c	K_{sc}	K_cK_{sc}	ξ_s
8	0.90(6)	1.43(8)	1.3 (2)	9.8(6)
12	0.75(6)	1.60(7)	1.2(2)	8.3(4)

❖ t-J Model and DMRG study [7]

$$H = -t\sum_{\langle ij\rangle}\left(c^+_{i\sigma}c_{j\sigma} + h.c.\right) + J\sum_{\langle ij\rangle}\left(S_i\cdot S_j - \frac{n_in_j}{4}\right)$$

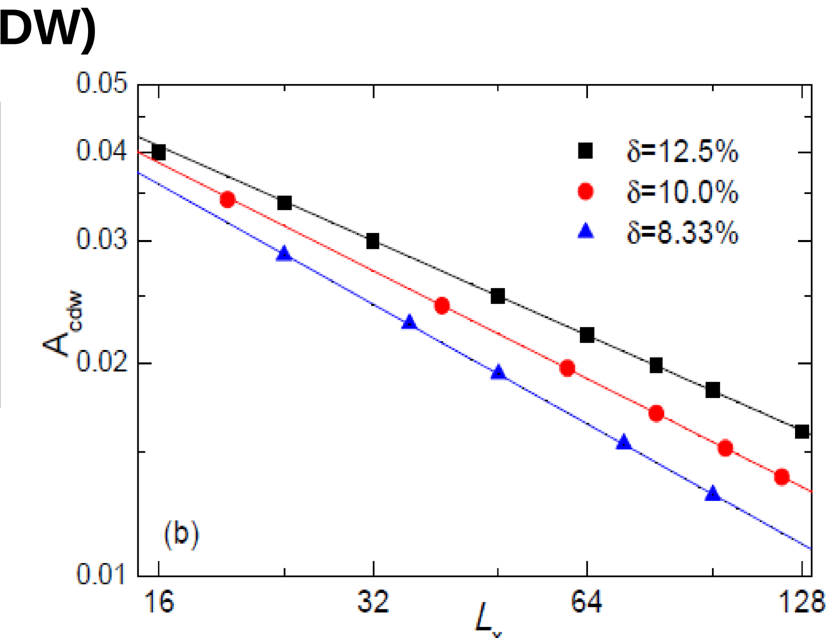
- ✓ $N=L_x*L_y$, $L_y=4$, $L_x=16\sim128$, hole doping δ=5%~12.5%
- ✓ Isotropic hopping and spin interaction t=3, J=1
- ✓ Keep m=2187~15000 states with ~100 sweeps

1) Charge-density-wave order (CDW)



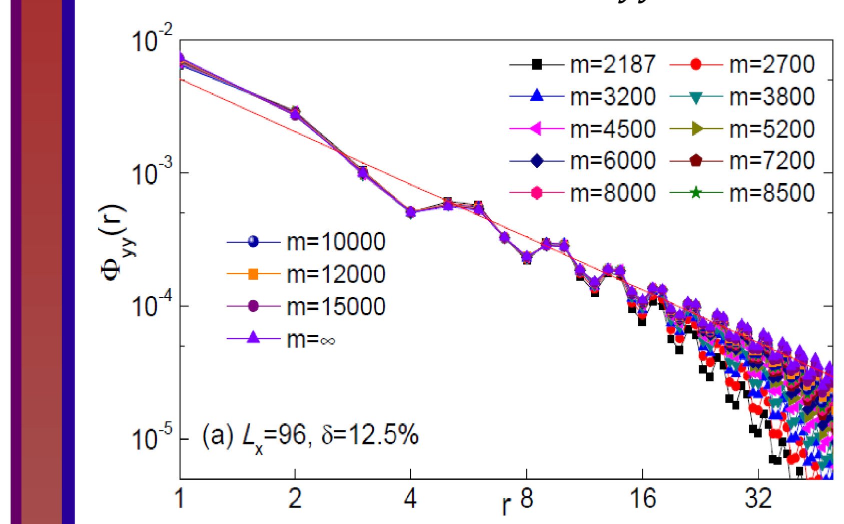
$n(x) = \delta_0 + A_{cdw}(L_x)\cos(\frac{2\pi}{\lambda}x + \phi)$

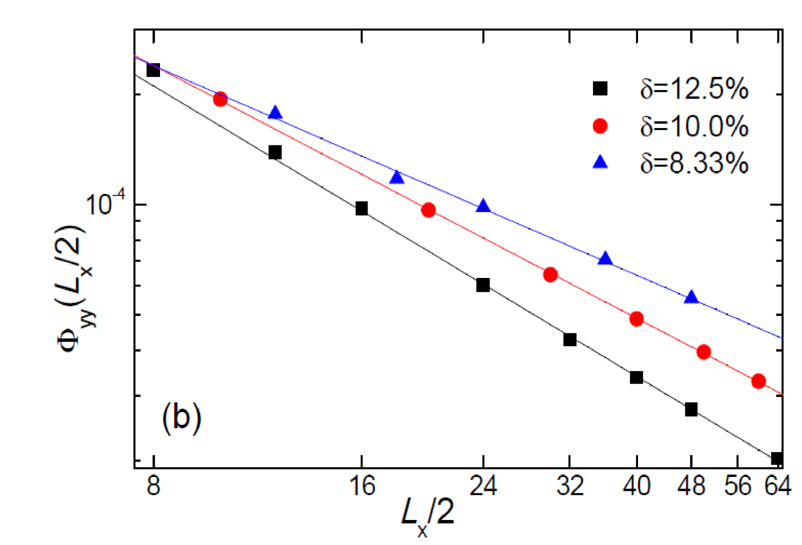
$A_{cdw}(L_x) \sim L_x^{-K_c/2}$ *Quasi-long-range CDW order*



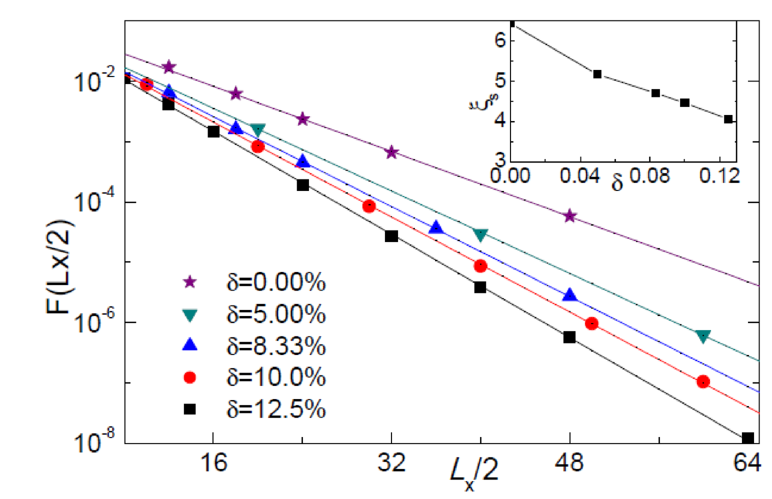
2) Superconductivity (SC)

Quasi-long-range SC: $\Phi_{yy}(r) \sim r^{-K_{sc}}$ $\qquad \Phi_{yy}(L_x/2) \sim (L_x/2)^{-K_{sc}}$





3) Spin-spin correlation



$$F(x) = \frac{1}{L_y}\sum_{y=1}^{L_y}|\langle\vec{S}_{x_0,y}\cdot\vec{S}_{x_0+x,y}\rangle|$$

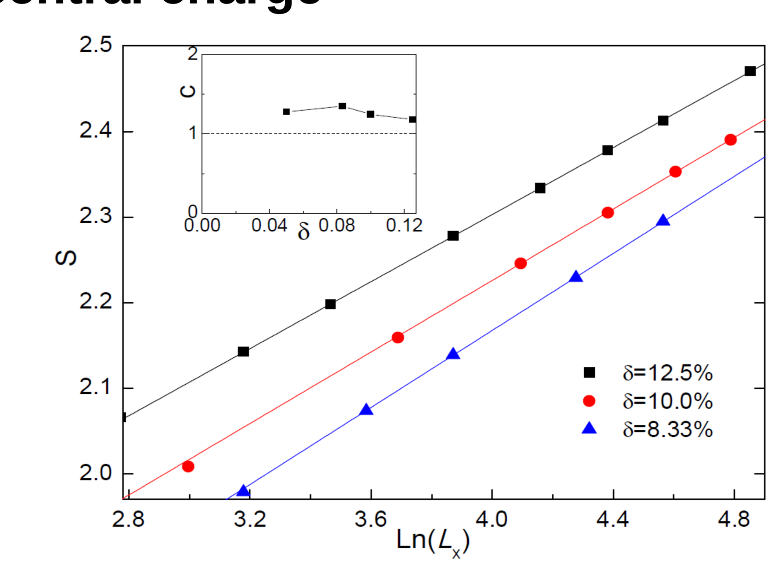
Short-range spin correlation $F(L_x/2) \sim e^{-L_x/2\xi_s}$

4) Entanglement entropy and central charge

$S = -\mathrm{Tr}\rho\ln\rho$

$S\left(\frac{L_x}{2}\right) = \frac{c}{6}\ln(L_x) + \tilde{c}$

c=central charge

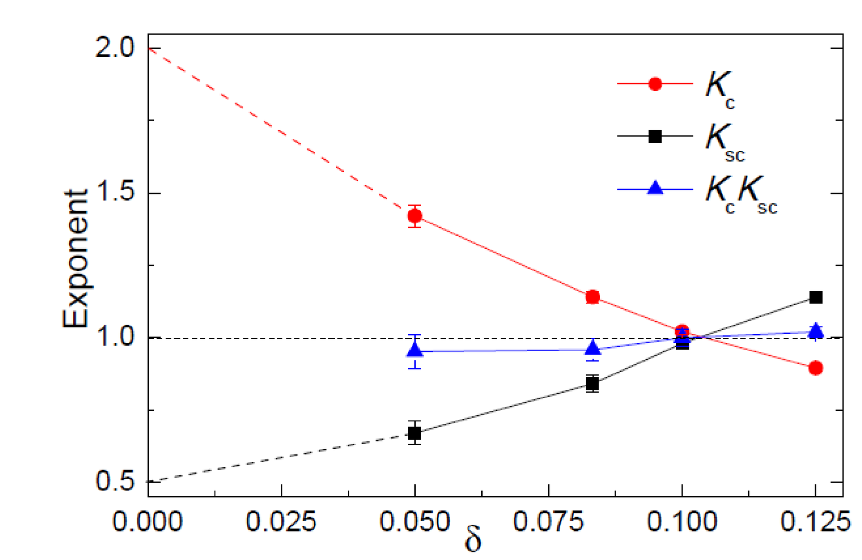


5) Luther-Emery liquid

$A_{cdw}(L_x) \sim L_x^{-K_c/2}$

$\Phi\left(\frac{L_x}{2}\right) \sim \left(\frac{L_x}{2}\right)^{-1/K_{sc}}$

$K_c \times K_{sc} = 1$



❖ Conclusion

- ✓ The ground state of the lightly hole-doped Hubbard and t-J models is a Luther-Emery liquid with a gap in the spin sector.
- ✓ Both superconducting order and charge-density-wave order are quasi-long-ranged.

References

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The authors acknowledge support from the U.S. Department of Energy, Office of Basic Energy Sciences, Materials Science and Engineering Division, under Contract No. DE-AC02-76SF00515, Office of Advanced Scientific Computing Research, Scientific Discovery through Advanced Computing (SciDAC) program. SAK was supported in part by Department of Energy under grant number DE-AC02- 76SF00515 at Stanford.