d-wave superconducting phase diagram of the two dimensional Hubbard model

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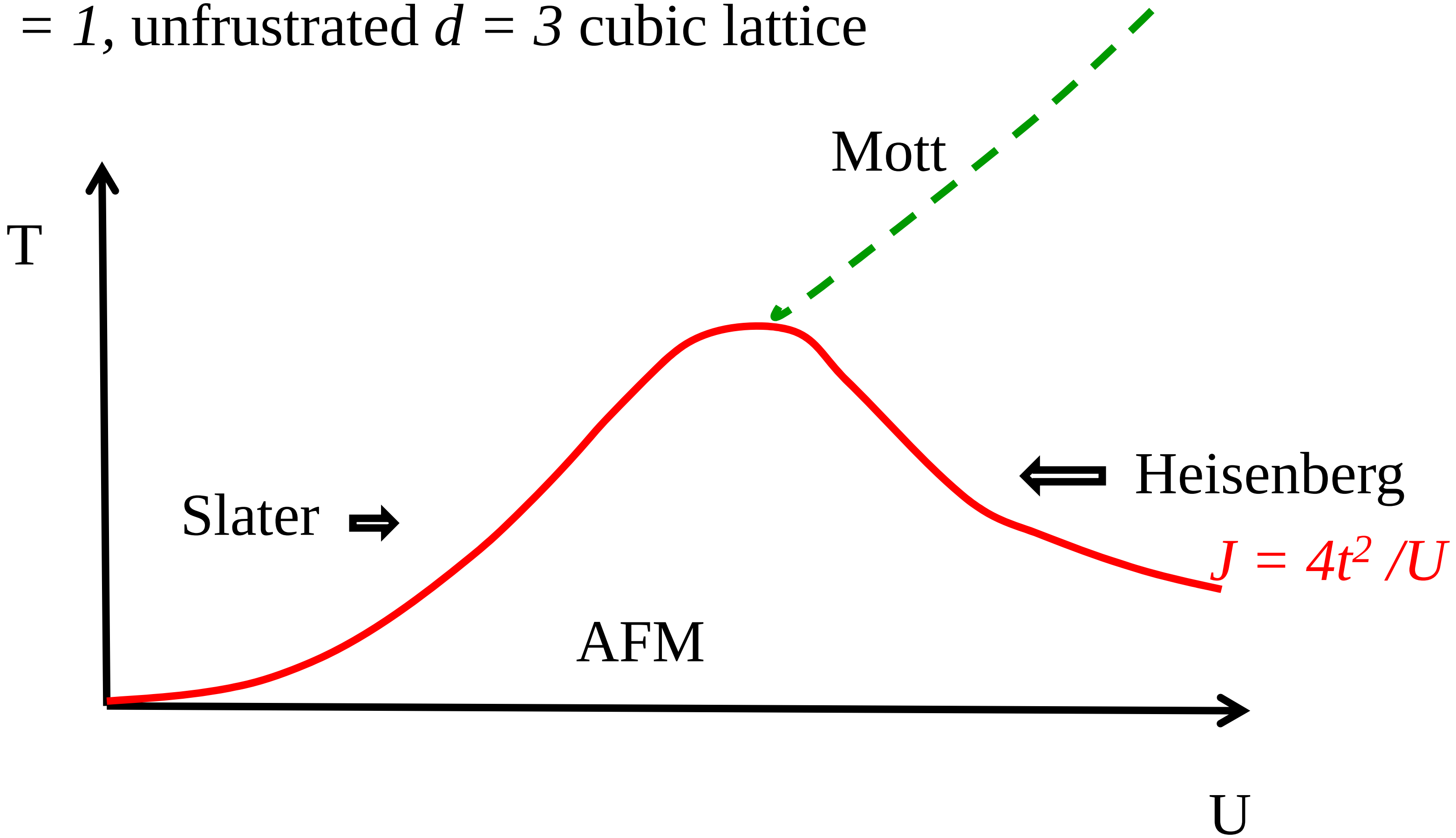
Y47.00001 8:00 AM–8:12 AM, Friday March 7, 2014

APS March meeting, Denver, Colorado

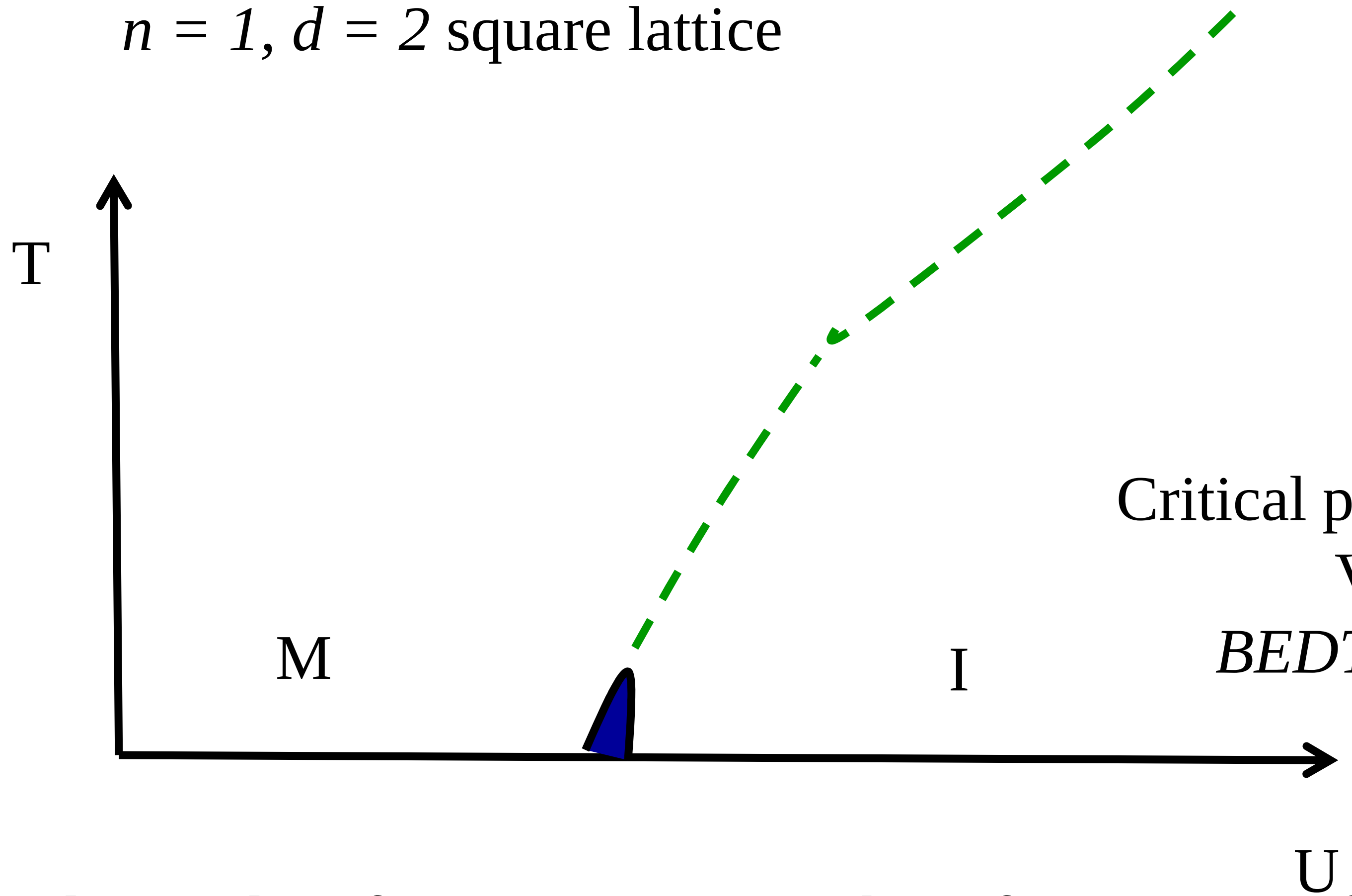
Strongly correlated vs weakly correlated: AFM as an example

$n = 1$, unfrustrated $d = 3$ cubic lattice



Strongly correlated vs weakly correlated: AFM as an example

$n = 1, d = 2$ square lattice

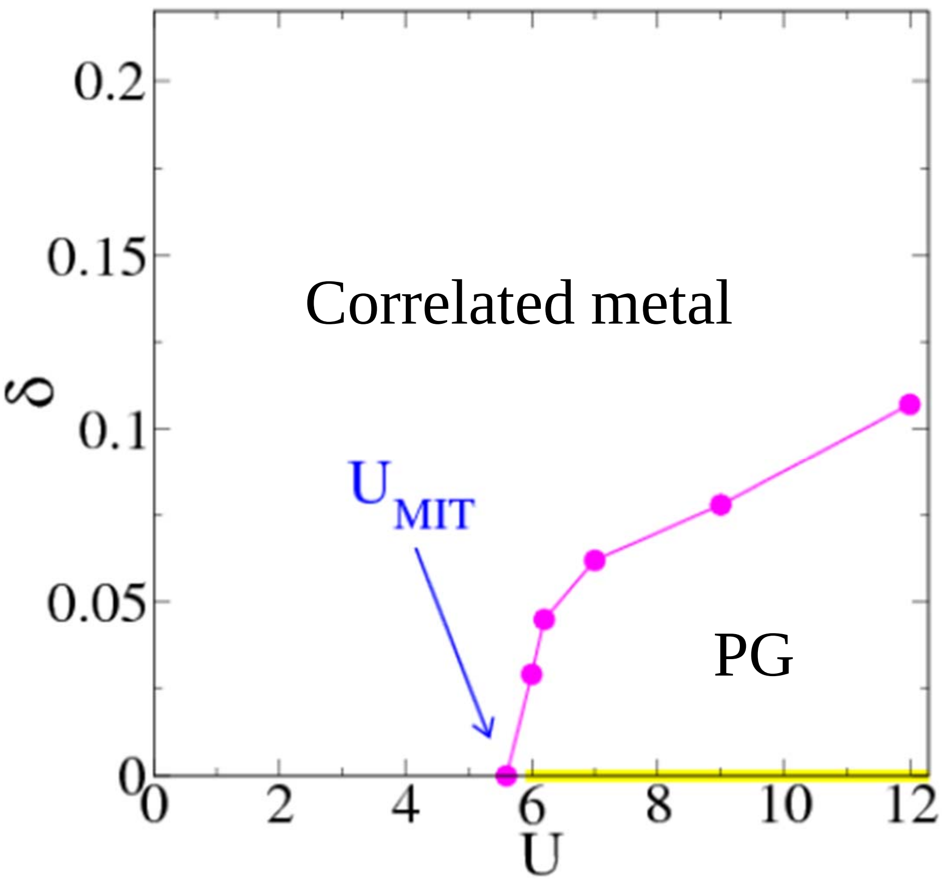


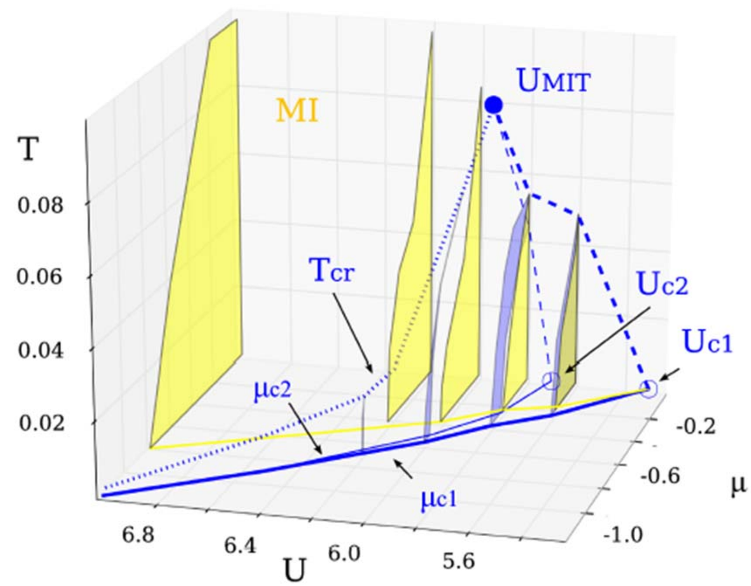
Critical point visible in V_2O_3, *BEDT* organics

Understanding finite temperature phase from a *mean-field theory* down to $T = 0$

A finite-doping first order transition, linked to Mott transition up to optimal doping

Doping dependence of critical point as a function of *U*





Sordi et al. PRL 2010, PRB 2011

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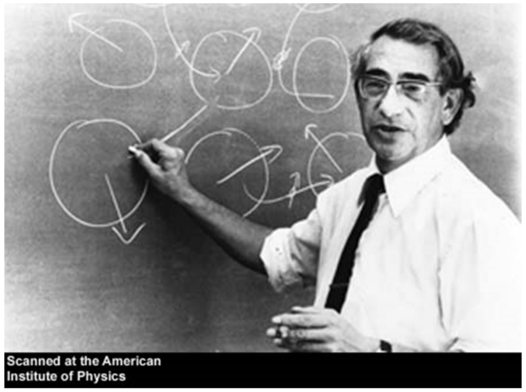
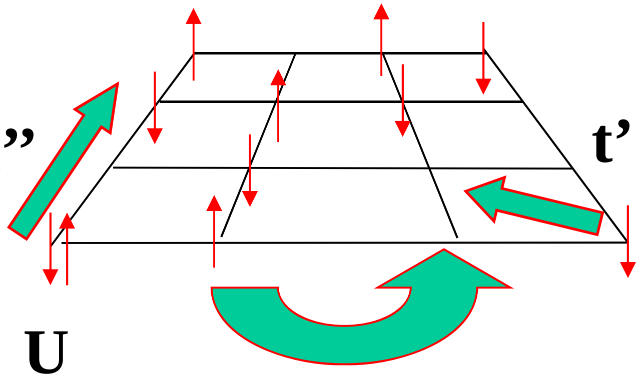
Model and Method

Hubbard model



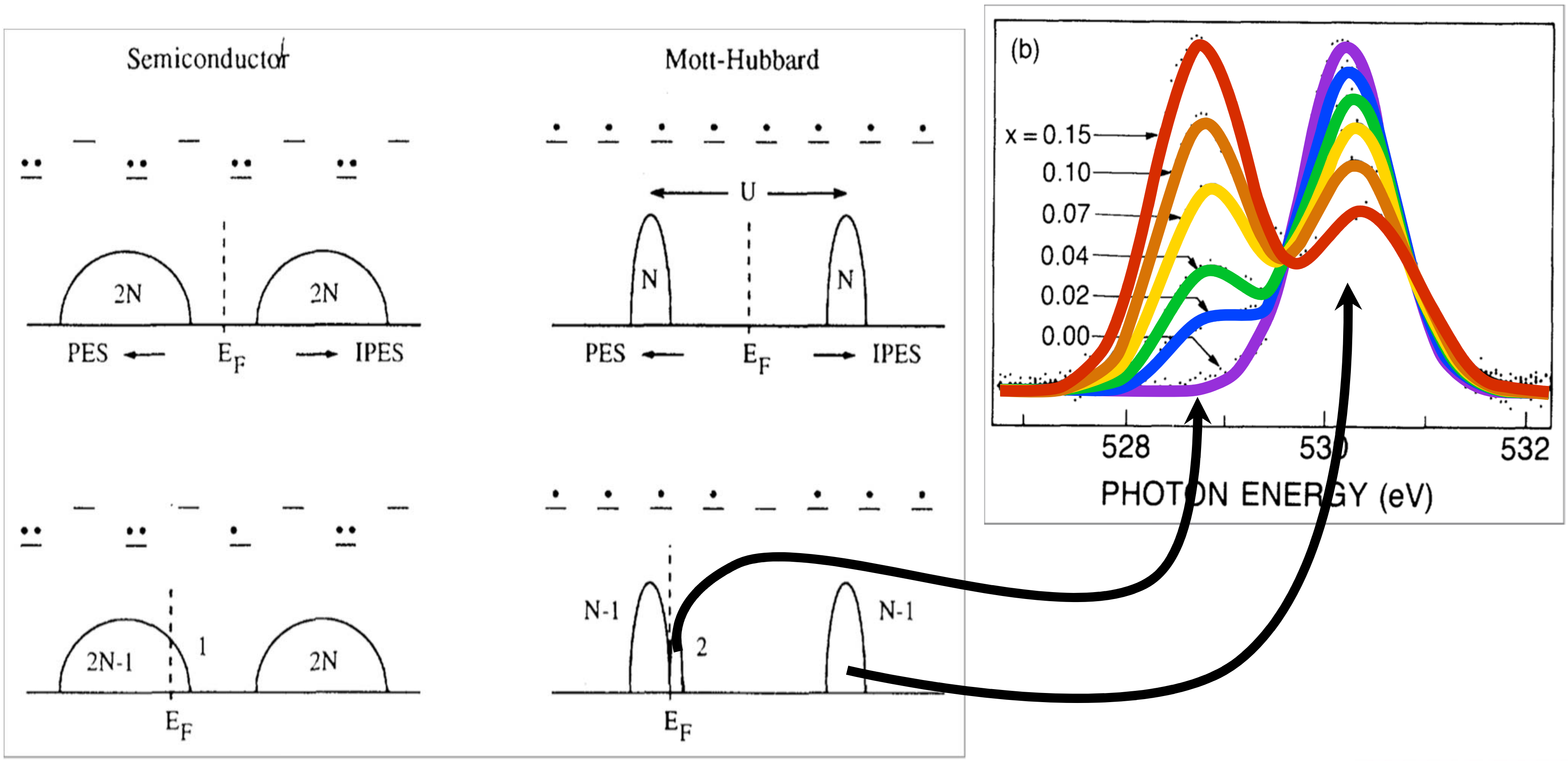
1931-1980

μ



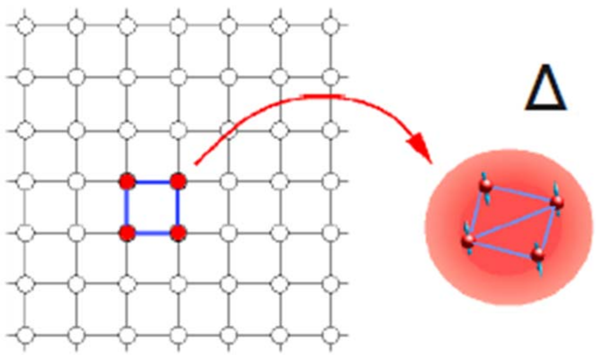
$$H = -\sum_{<ij>\sigma} t_{i,j}\left(c^{\dagger}_{i\sigma}c_{j\sigma} + c^{\dagger}_{j\sigma}c_{i\sigma}\right) + U\sum_{i} n_{i\uparrow}n_{i\downarrow}$$

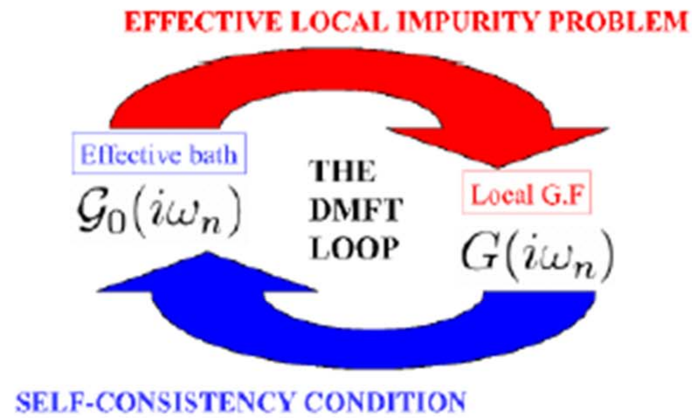
h-doped cuprates are strongly correlated



C-DMFT

$$Z = \int \mathcal{D}[\psi^\dagger, \psi]\, \mathrm{e}^{-S_c - \int_0^\beta d\tau \int_0^\beta d\tau' \sum_{\mathbf{K}} \psi^\dagger_{\mathbf{K}}(\tau)\Delta_{\mathbf{K}}(\tau,\tau')\psi_{\mathbf{K}}(\tau')}$$





Mean-field is not a trivial problem! Many impurity solvers.

Here: continuous time QMC

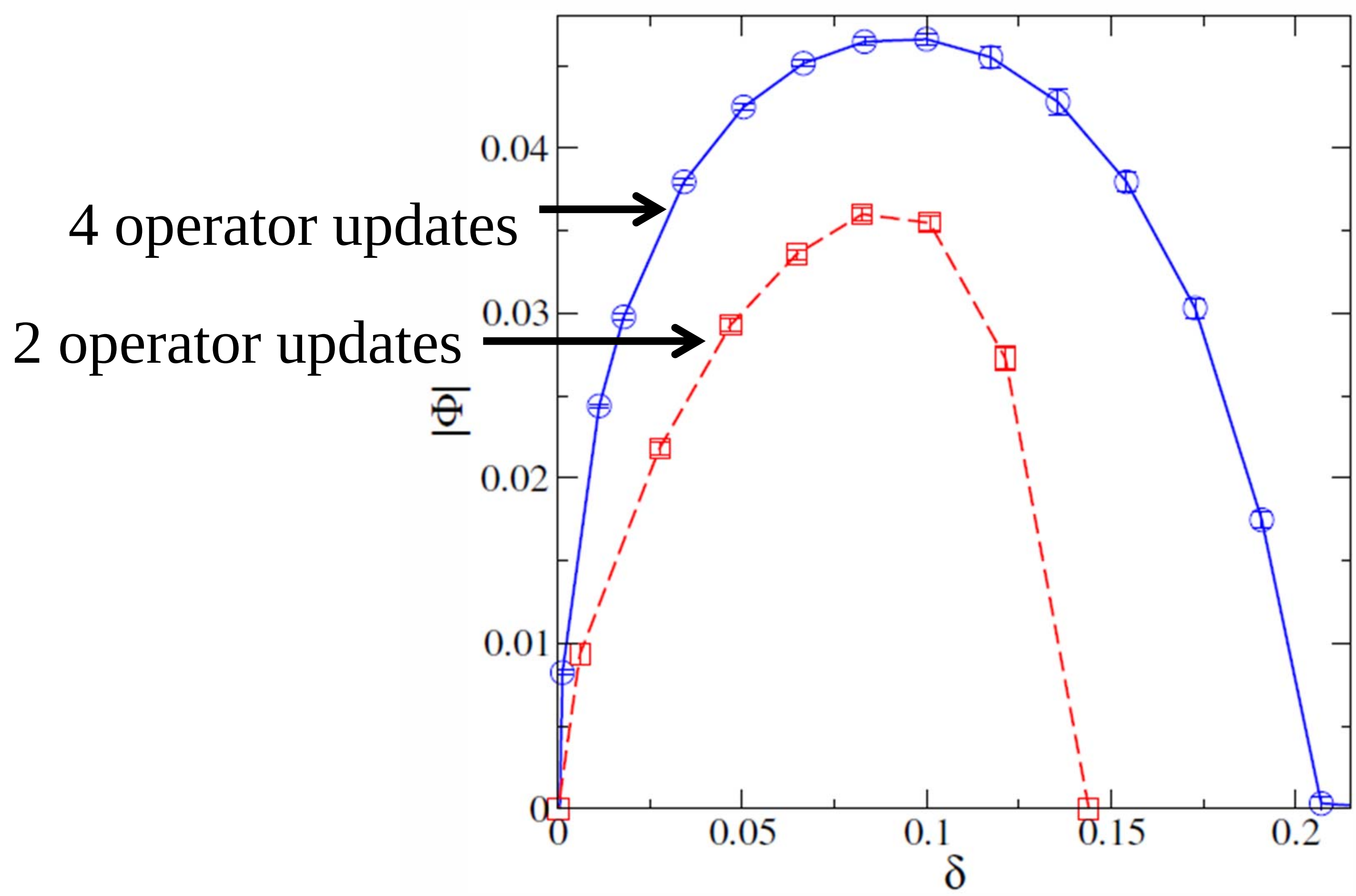
P. Werner, PRL 2006
P. Werner, PRB 2007
K. Haule, PRB 2007

$$\Delta(i\omega_n) = i\omega_n + \mu - \Sigma_c(i\omega_n) - \left[\sum_{\tilde{k}} \frac{1}{i\omega_n + \mu - t_c(\tilde{k}) - \Sigma_c(i\omega_n)}\right]^{-1}$$

Standard 2 operator updates in CTQMC are not ergodic in SC state (fixed here)

Please ask in question period…

4 vs 2 operator updates: d-wave order parameter



U/t =9

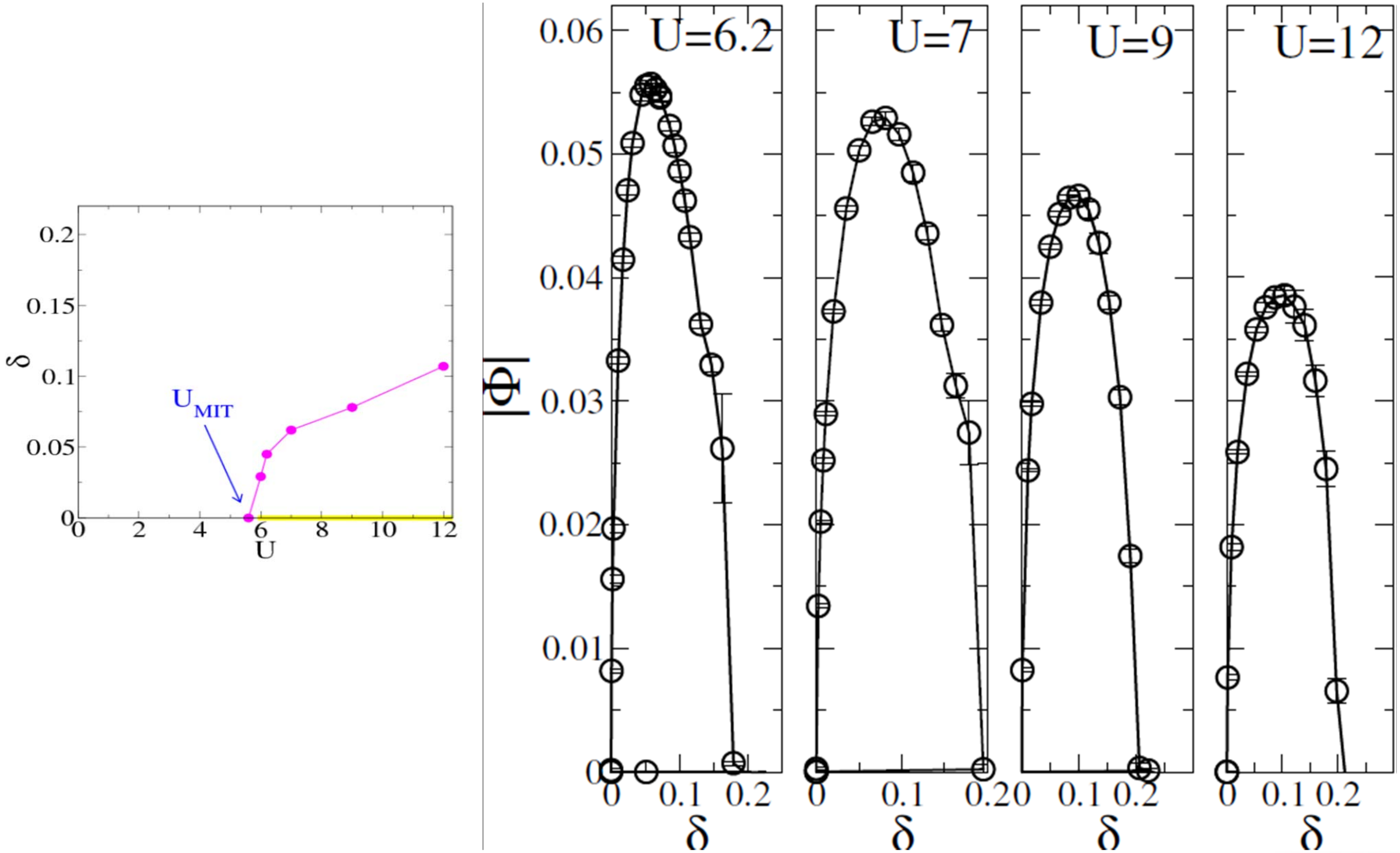
T/t = /100

P. Sémon, G. Sordi, A.-M.S. Tremblay, arxiv.org/1402.7087

Compare ED solver: Kancharla, Kyung, Civelli, Sénéchal, Kotliar AMST Phys. Rev. B (2008)

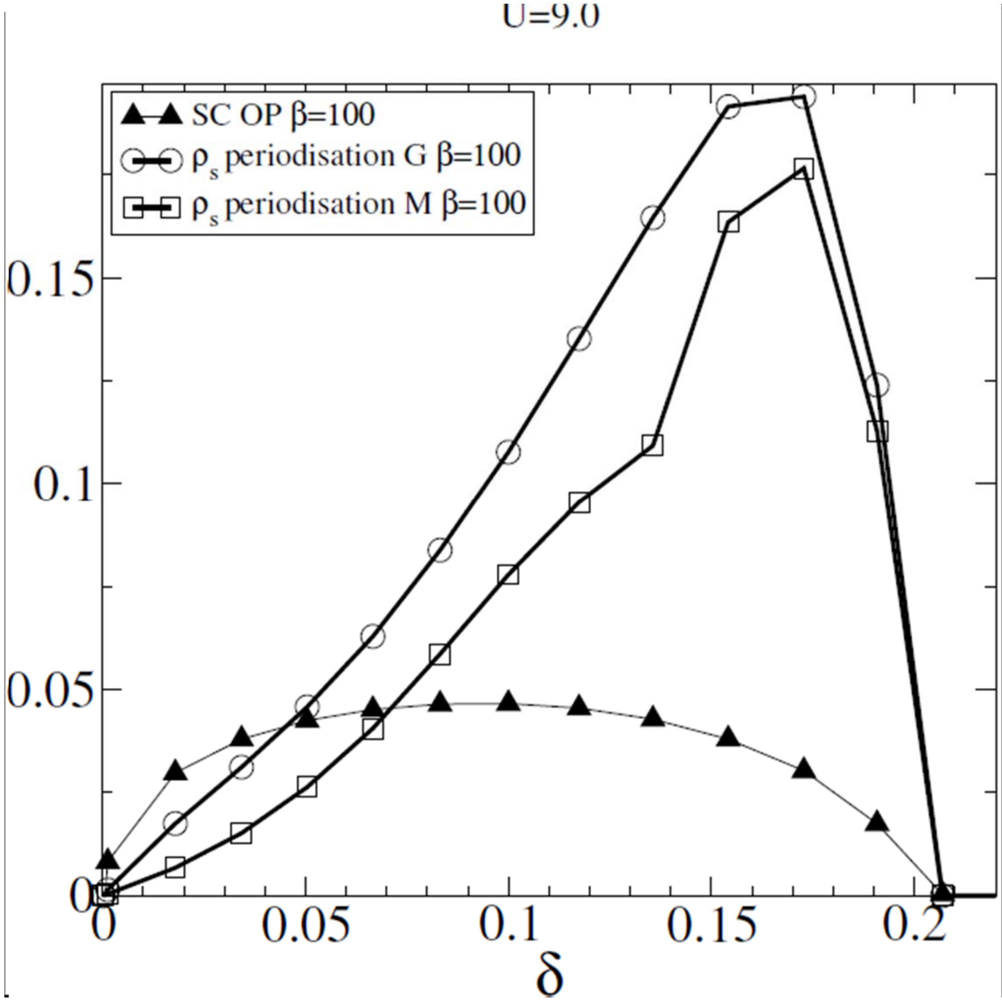
Superconductivity at $U > U_{MIT}$

Dome moves to larger dopings with U

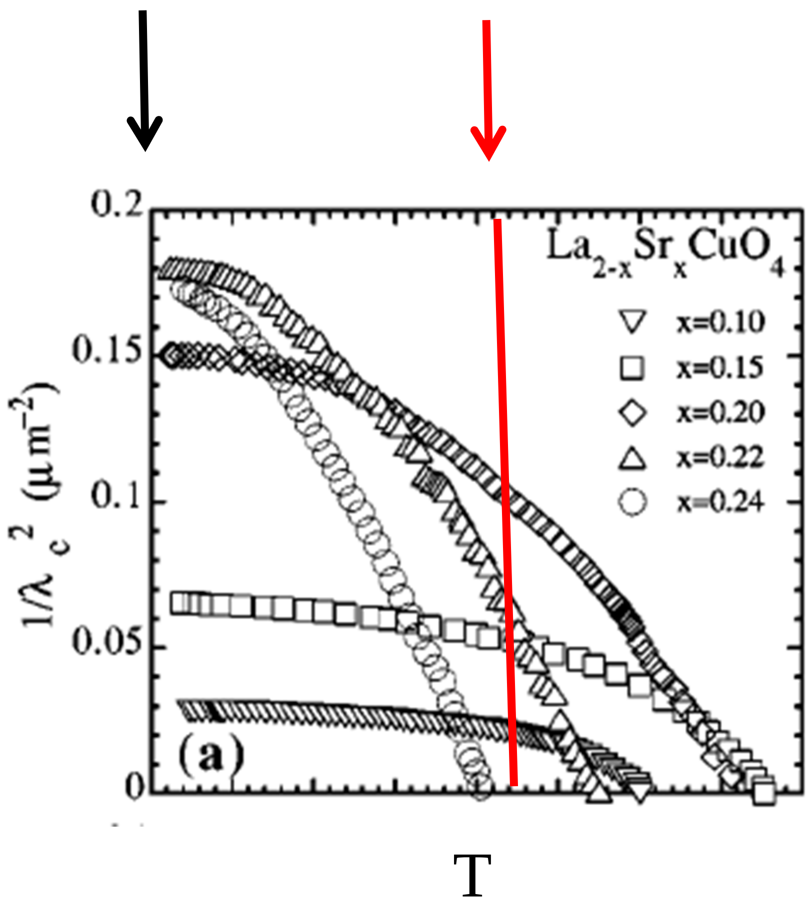


Max. at lowest T follows N.S. first order transition

c-axis Superfluid density *U = 9t*, *T=1/100*

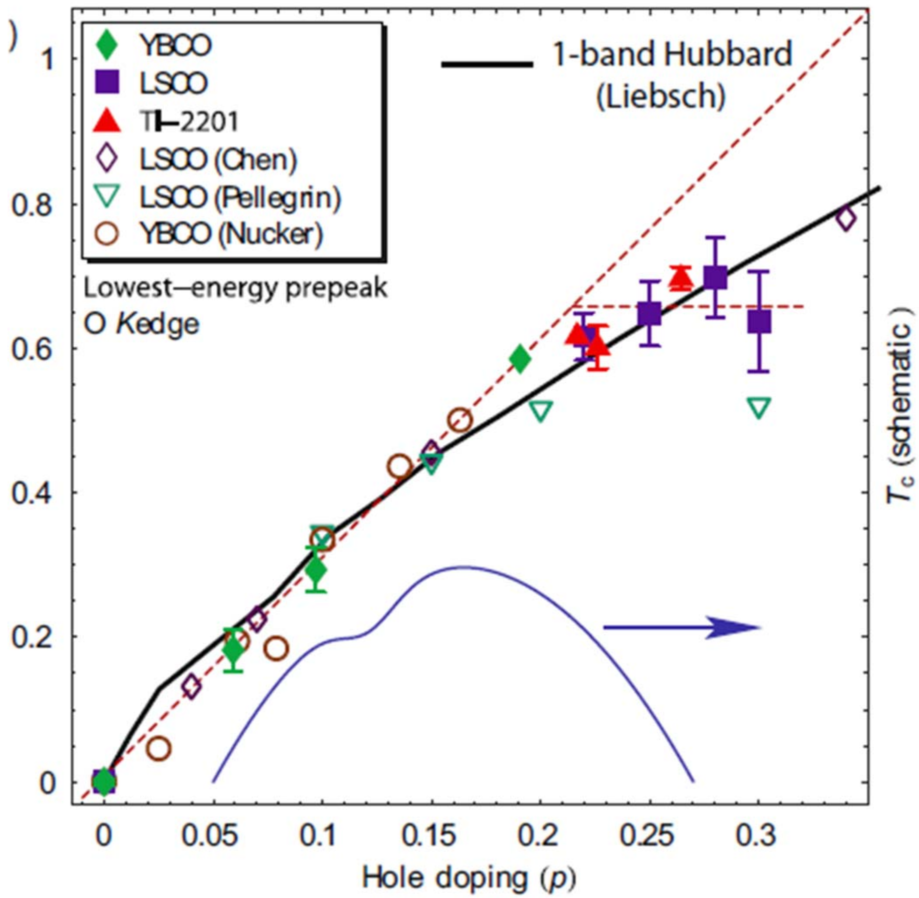


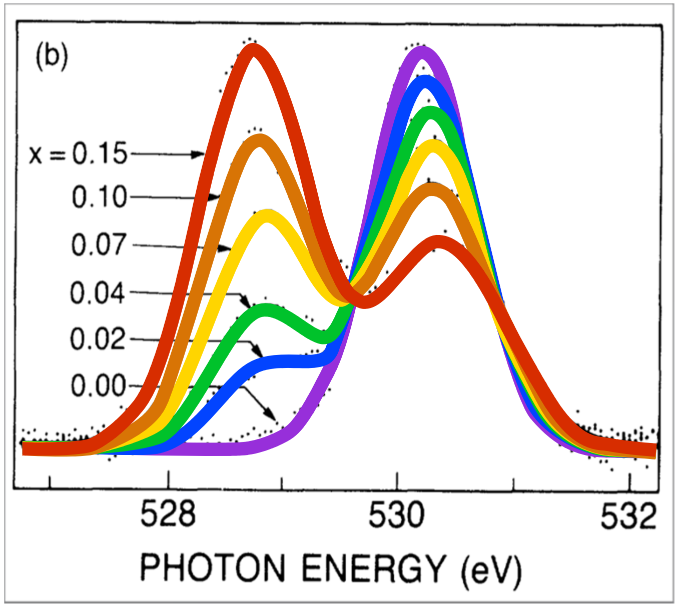
See also, Gull Millis, PRB, 2013



Panagopoulos et al. PRB 2000

Compare with number of cariers





Peets et al. PRL 2009, Phillips and Jarrell, PRL 2010

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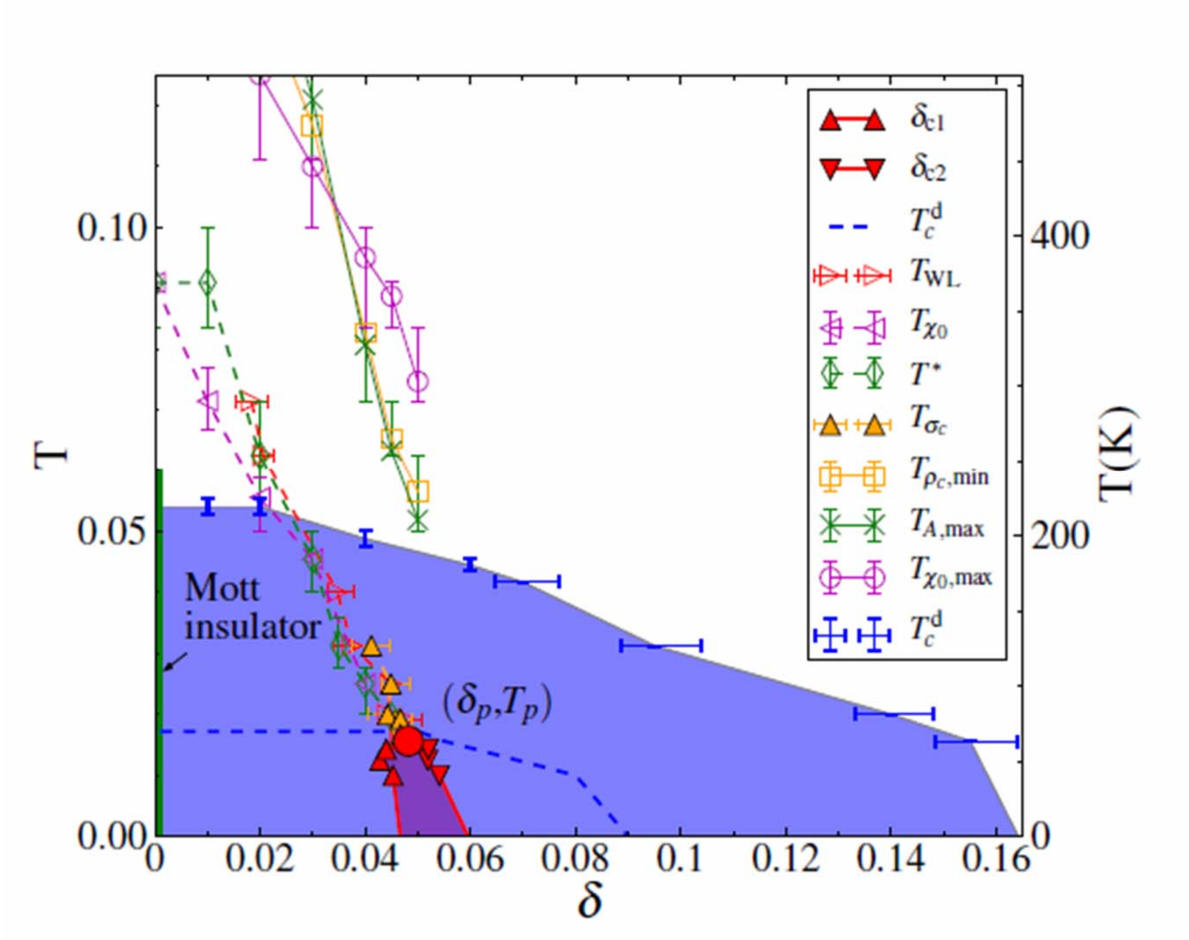
Phase diagram for $U = 6.2\ t$



P. Sémon, G. Sordi, A.-M.S. Tremblay, arxiv.org/1402.7087

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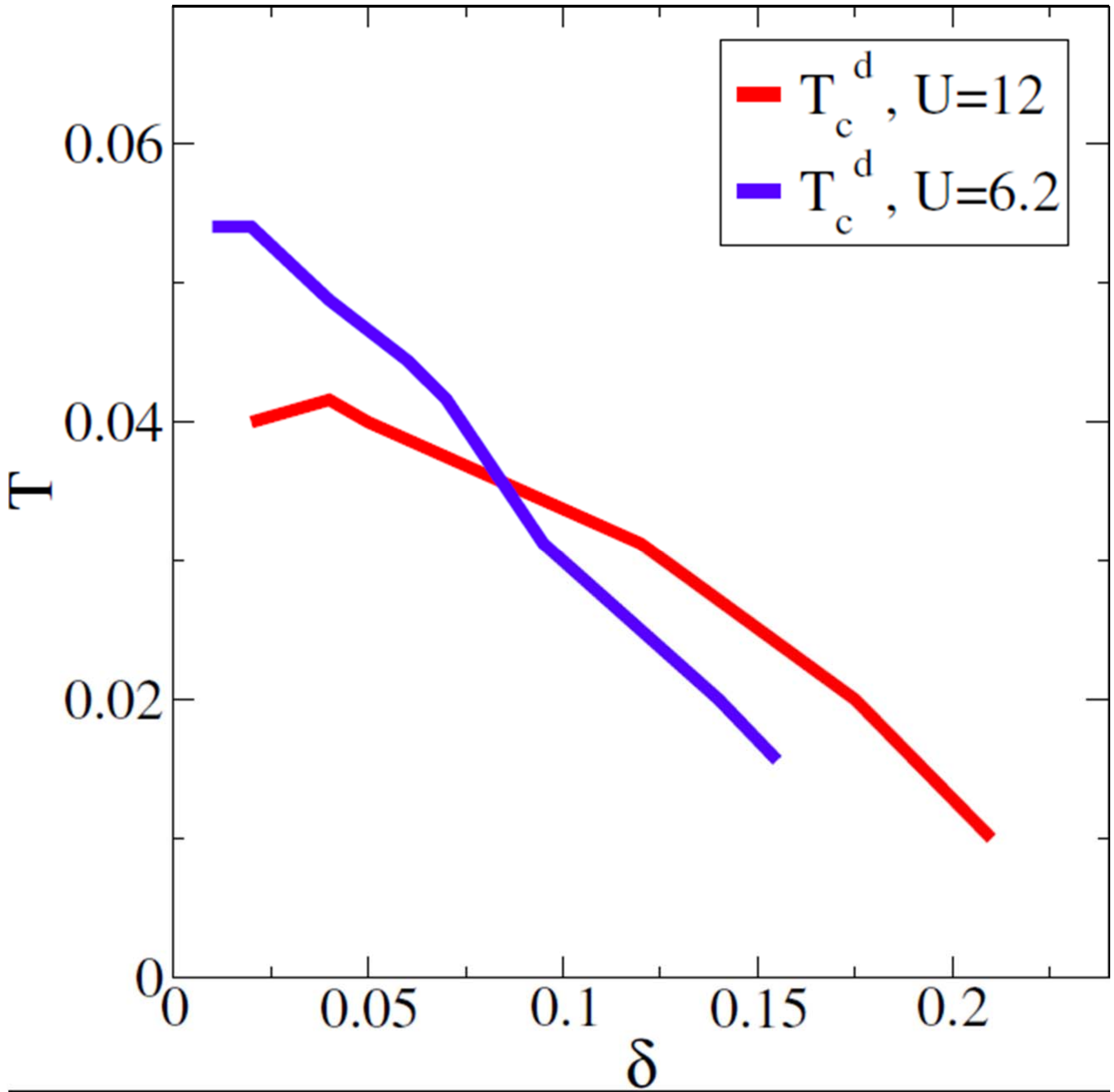
T_c^d



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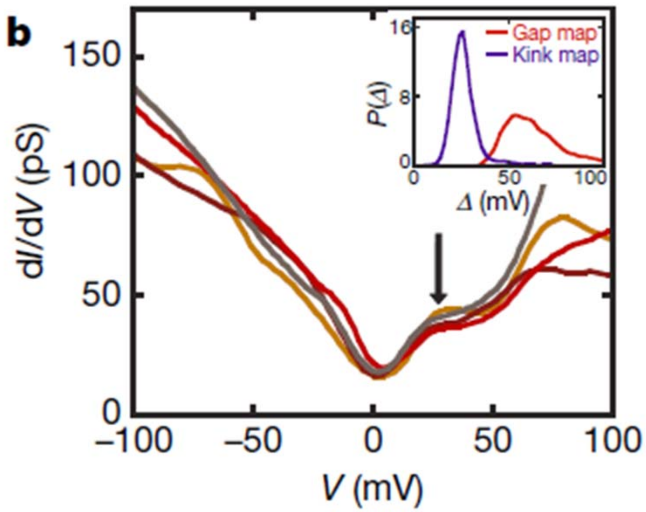
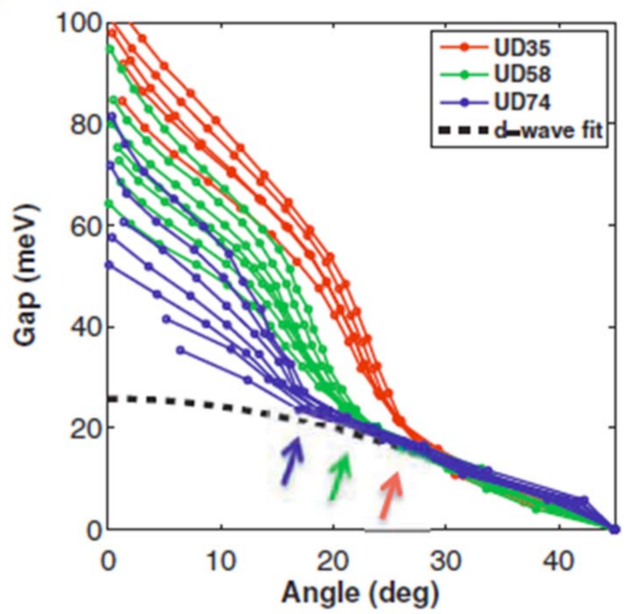
Meaning of T_c^d

- Local pair formation



K. K. Gomes, A. N. Pasupathy, A. Pushp, S. Ono, Y. Ando, and A. Yazdani, Nature **447**, 569 (2007)

Meaning of T_c^d : Local pair formation



A. Pushp, Parker, … A. Yazdani, Science **364**, 1689 (2009)

However, our measurements demonstrate that the nodal gap does not change with reduced doping. The pairing strength does not get weaker or stronger as the Mott insulator is approached; rather, it saturates.

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Summary

- CTQMC hybridization expansion needs 4 operator updates on plaquette with d-wave SC
- Strongly correlated superconductivity
  - $T=0$ max OP scales with 1st order transition
  - Superfluid density scales like doping beyond max. T_c^d and beyond max. OP.
  - T_c^d does not scale with $T=0$ d-wave order-parameter in underdoped regime.

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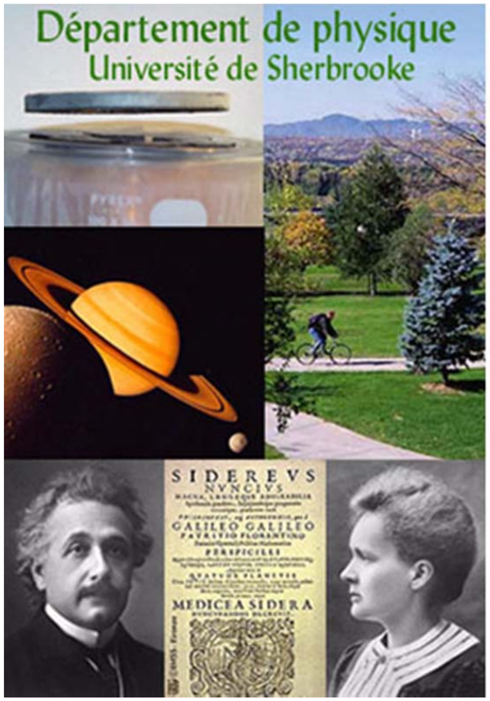

André-Marie Tremblay

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Merci

Thank you

Ergodicity of the hybridization expansion with two operator updates and broken symmetry

$$H_{\text{imp}} = H_{\text{loc}}(d_i^\dagger, d_i) + \sum_{i\mu}(V_{\mu i} a_\mu^\dagger d_i + V_{\mu i}^* d_i^\dagger a_\mu) + \sum_\mu \epsilon_\mu a_\mu^\dagger a_\mu,$$

$$Z = \mathrm{Tr} T_\tau e^{-\beta H_0} e^{-\int_0^\beta d\tau (H_{\text{hyb}}(\tau) + H_{\text{hyb}}^\dagger(\tau))}$$

$$= \sum_{k\geq 0} \frac{1}{k!^2} \int_0^\beta d\tau_1 \cdots d\tau_k \int_0^\beta d\tau_1' \cdots d\tau_k' \mathrm{Tr} T_\tau e^{-\beta H_0} \times H_{\text{hyb}}(\tau_1) H_{\text{hyb}}^\dagger(\tau_1') \cdots H_{\text{hyb}}(\tau_k) H_{\text{hyb}}^\dagger(\tau_k').$$

$$\boxed{\mathrm{Tr}[d_{\uparrow(0,\pi)} d_{\downarrow(0,\pi)} d^\dagger_{\downarrow(\pi,0)} d^\dagger_{\uparrow(\pi,0)}] \times F_{\uparrow(0,\pi),\downarrow(0,\pi)} \overline{F}_{\uparrow(\pi,0),\downarrow(\pi,0)}}$$

P. Sémon, G. Sordi, A.-M.S. Tremblay, arxiv.org/1402.7087

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