Giovanni Sordi

Patrick Sémon

Kristjan Haule

Strongly correlated superconductivity and Mott transition

André-Marie Tremblay

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Abstract: B23.00004 :

arXiv:1201.1283

11:51 AM–12:03 PM

Room: 255

VERITATEM IN CHARITATE

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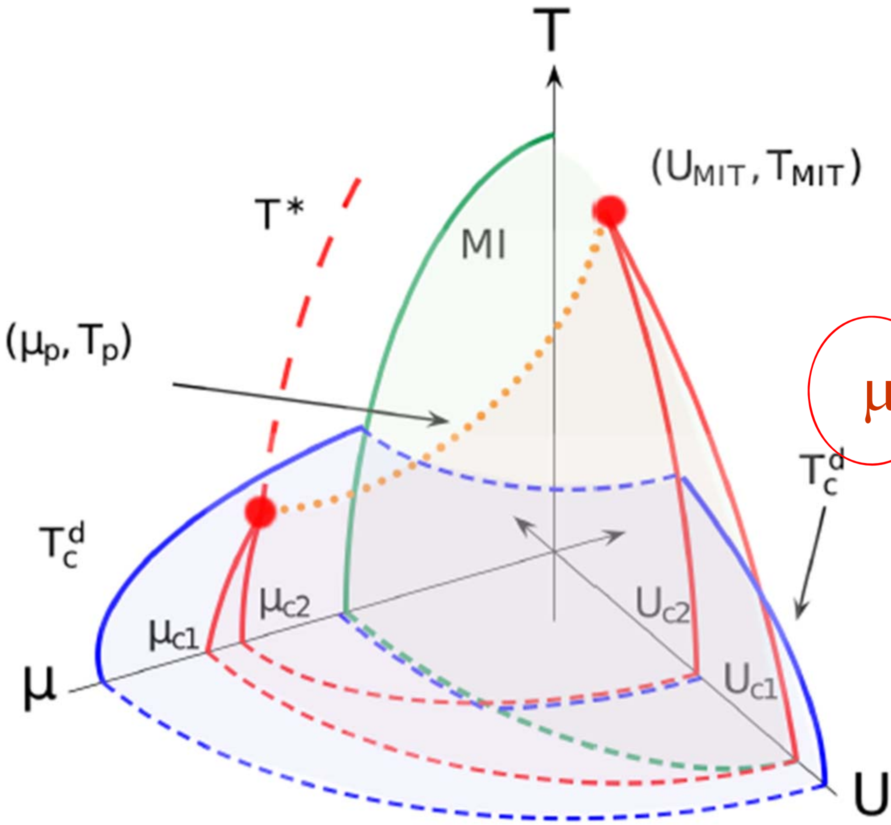
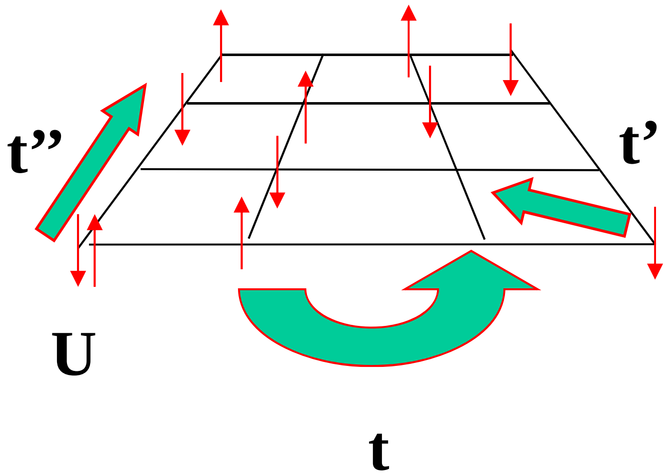
CIFAR

CANADIAN INSTITUTE for ADVANCED RESEARCH

D-wave superconductivity in the one-band Hubbard model





μ

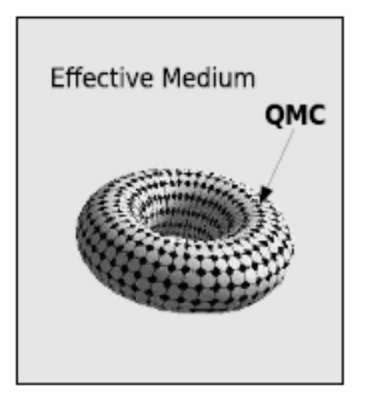
$$H = -\sum_{<ij>\sigma} t_{i,j}\left(c_{i\sigma}^{\dagger}c_{j\sigma} + c_{j\sigma}^{\dagger}c_{i\sigma}\right) + U\sum_{i} n_{i\uparrow}n_{i\downarrow}$$

d-wave superconductivity

- Weak coupling
  - C. J. Halboth and W. Metzner, Phys. Rev. Lett. 85, 5162 (2000).
  - B. Kyung, J.-S. Landry, and A. M. S. Tremblay, Phys. Rev. B 68, 174502 (2003).
  - C. Bourbonnais and A. Sedeki, Physical Review B 80, 085105 (2009).
  - D. J. Scalapino, Physica C: Superconductivity 470, Supplement 1, S1 (2010), ISSN 0921-4534, proceedings of the 9th International Conference on Materials and Mech anisms of Superconductivity.
- Renormalized Mean-Field Theory
  - P. W. Anderson, P. A. Lee, M. Randeria, T. M. Rice, N. Trivedi, and F. C. Zhang, Journal of Physics: Condensed Matter 16, R755 (2004).
  - K.-Y. Yang, T. M. Rice, and F.-C. Zhang, Phys. Rev. B 73, 174501 (2006).
- Slave particles
  - P. A. Lee, N. Nagaosa, and X.-G. Wen, Rev. Mod. Phys. 78, 17 (2006).
  - M. Imada, Y. Yamaji, S. Sakai, and Y. Motome, Annalen der Physik 523, 629 (2011)
- Variational approaches
  - T. Giamarchi and C. Lhuillier, Phys. Rev. B 43, 12943 (1991).
  - A. Paramekanti, M. Randeria, and N. Trivedi, Phys. Rev. B 70, 054504 (2004).

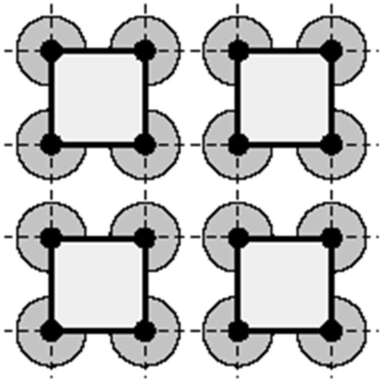
Method

2d Hubbard: Cluster gen. of DMFT

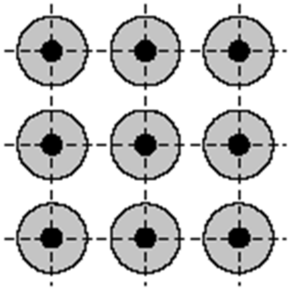


DCA

C-DMFT



DMFT



Hettler …Jarrell…Krishnamurty PRB **58** (1998)
Kotliar et al. PRL **87** (2001)
M. Potthoff *et al.* PRL **91,** 206402 (2003).
Maier, Jarrell et al., Rev. Mod. Phys. **77**, 1027 (2005)

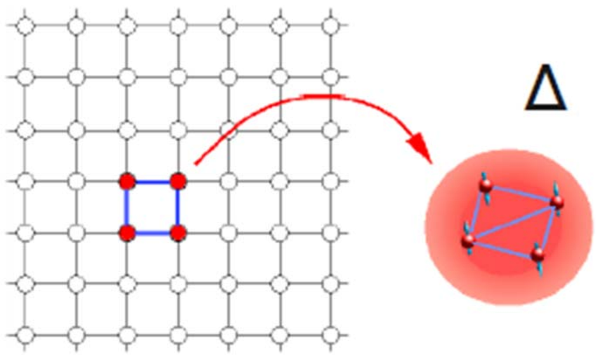
$T = 0$ results

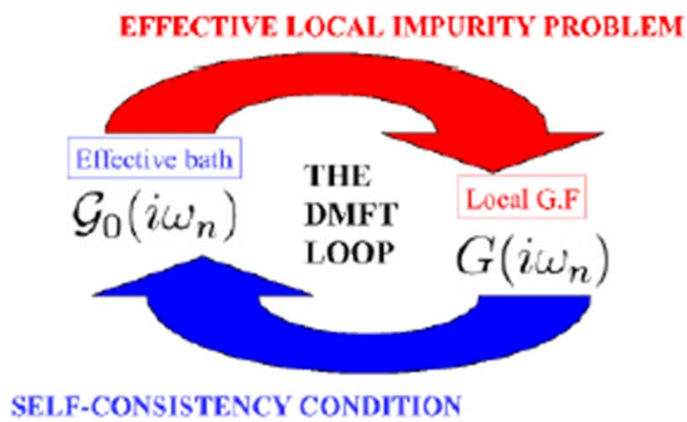
- D. Sénéchal, P.-L. Lavertu, M.-A. Marois, and A.-M. S. Tremblay, Phys. Rev. Lett. **94**, 156404 (2005).
- B. Kyung and A.-M. S. Tremblay, Physical Review Letters **97**, 046402 (pages 4) (2006).
- M. Aichhorn, E. Arrigoni, M. Potthoff, and W. Hanke, Phys. Rev. B **74**, 024508 (2006).
- M. Capone and G. Kotliar, Phys. Rev. B **74**, 054513 (2006).
- M. Aichhorn, E. Arrigoni, M. Potthoff, and W. Hanke, Phys. Rev. B **76**, 224509 (2007).
- S. S. Kancharla, B. Kyung, D. Sénéchal, M. Civelli, M. Capone, G. Kotliar, and A.-M. S. Tremblay, Phys. Rev. B **77**, 184516 (2008).
- M. Civelli, Phys. Rev. Lett. **103**, 136402 (2009).
- M. Balzer, W. Hanke, and M. Potthoff, Phys. Rev. B **81**, 144516 (2010).
- W. Hanke, M. Kiesel, M. Aichhorn, S. Brehm, and E. Arrigoni, The European Physical Journal - Special Topics **188**, 15 (2010), ISSN 1951-6355, 10.1140/epjst/e2010-01294-y.
- C. Weber, C.-H. Yee, K. Haule, and G. Kotliar, ArXiv e-prints (2011), 1108.3028.

Will comment on finite *T* results later

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

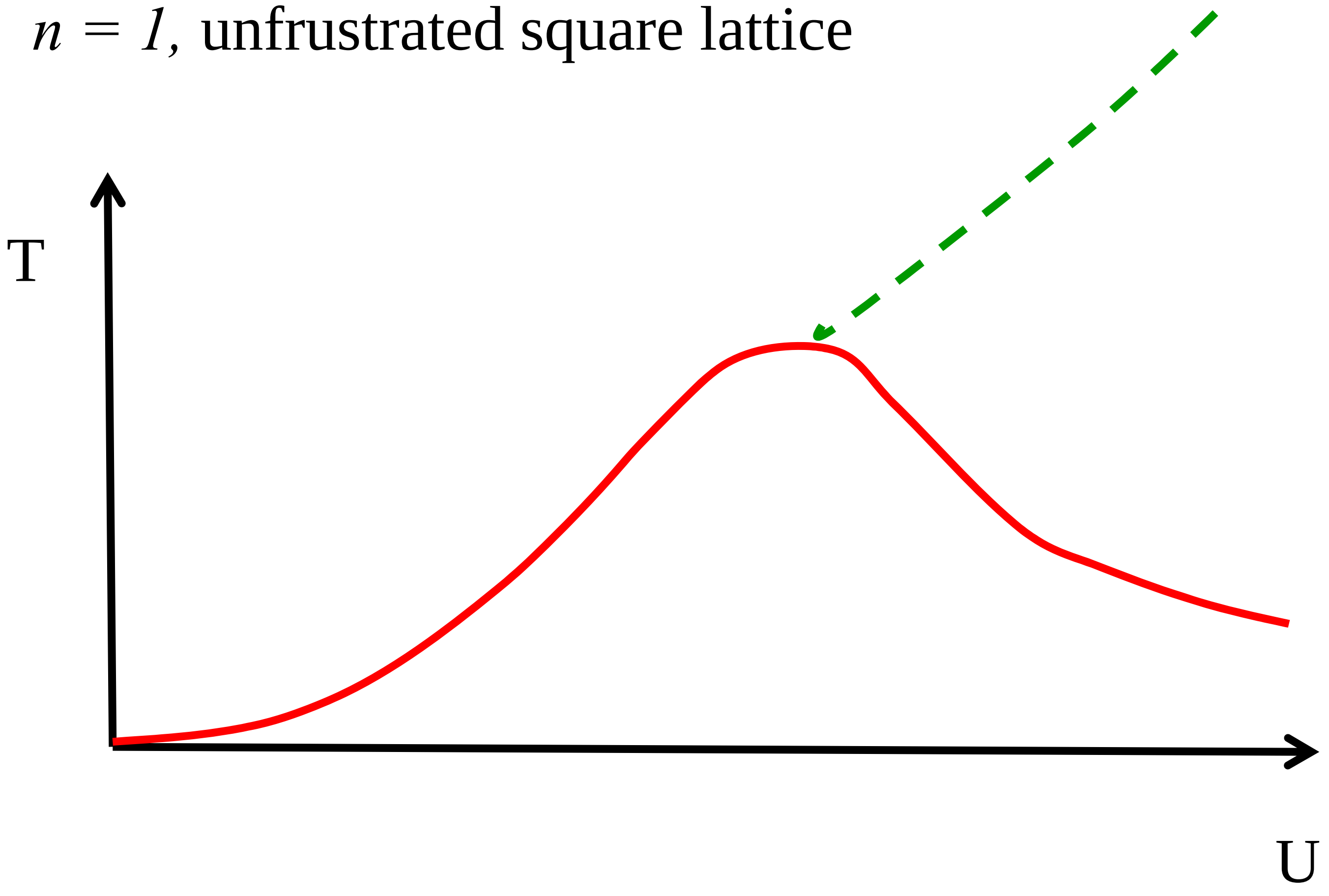
P. Werner, PRL 2006
P. Werner, PRB 2007
K. Haule, PRB 2007

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

What does the method tell us: example at half-filling

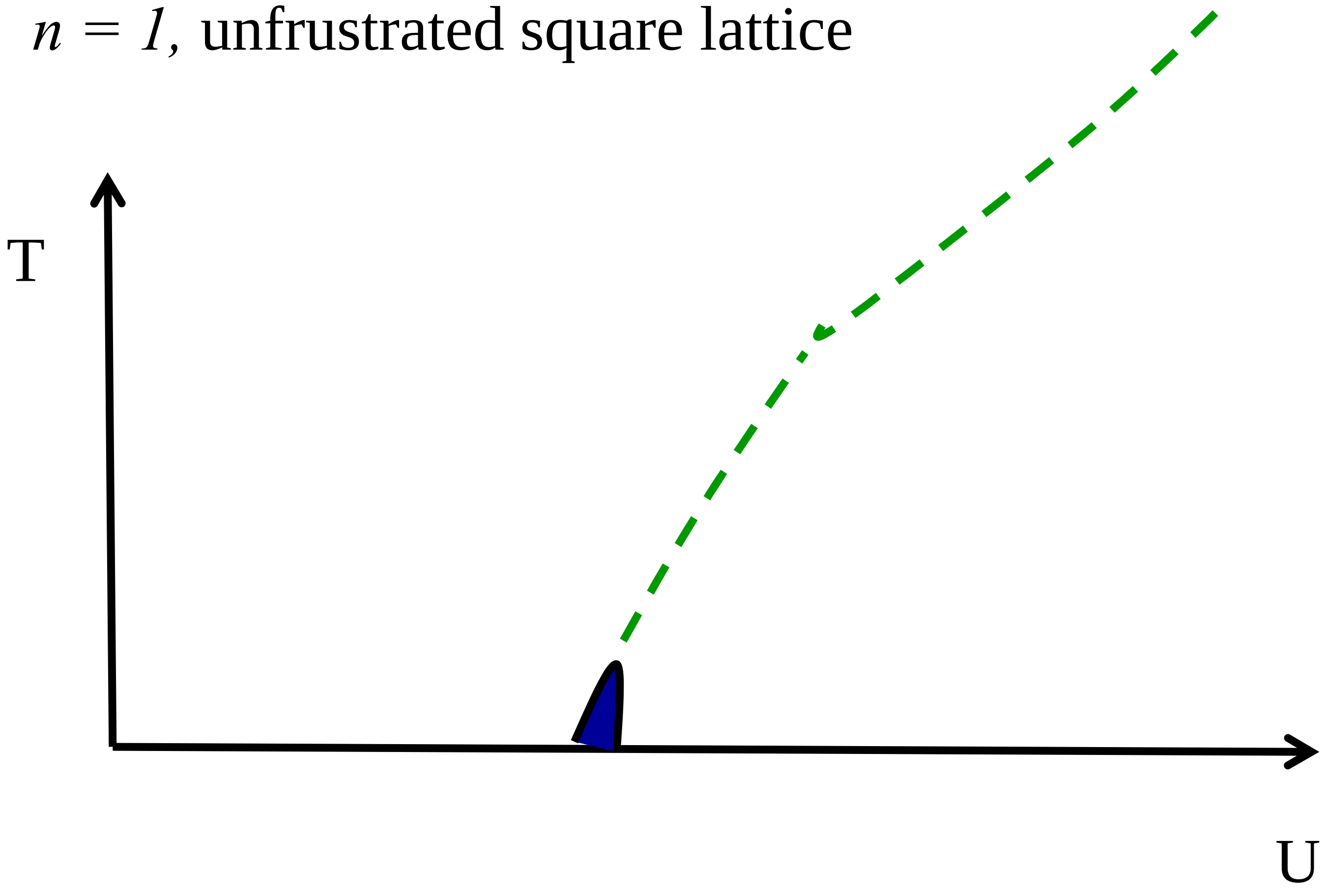
Local moment and Mott transition

n = 1, unfrustrated square lattice

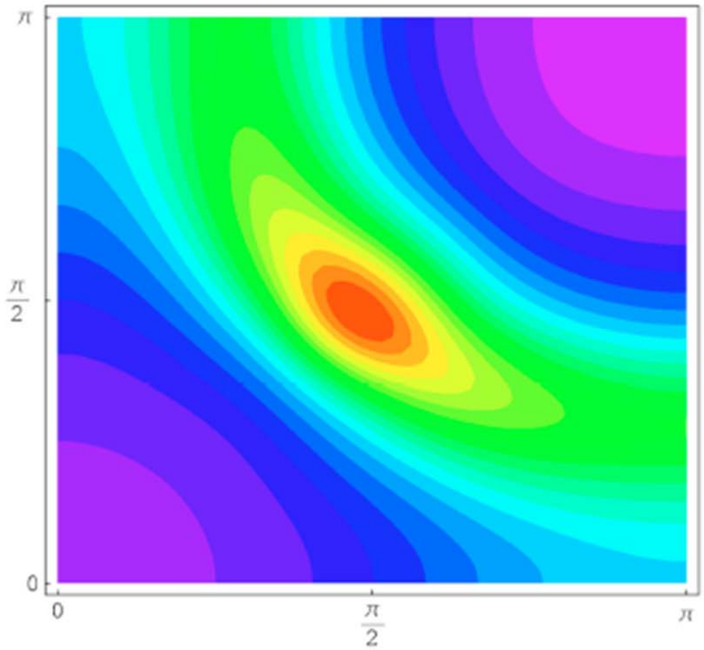


Local moment and Mott transition

n = 1, unfrustrated square lattice



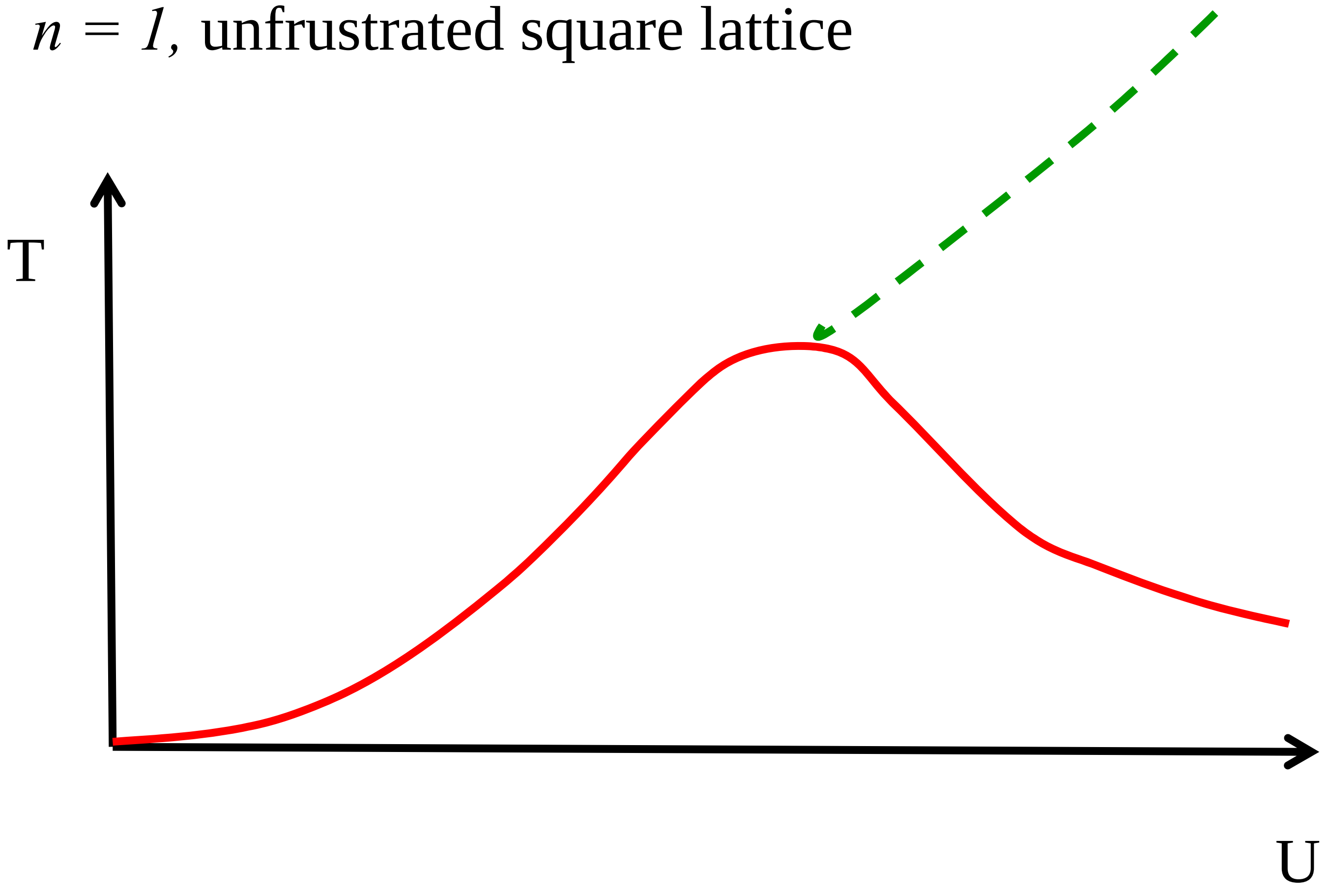
Momentum resolution with 4 sites



B. Kyung, S. Kancharla, D. Sénéchal, A.-M.S. Tremblay, M. Civelli, G. Kotliar, Phys. Rev. B **73**, 165114 (2006).

Local moment and Mott transition

$n = 1$, unfrustrated square lattice



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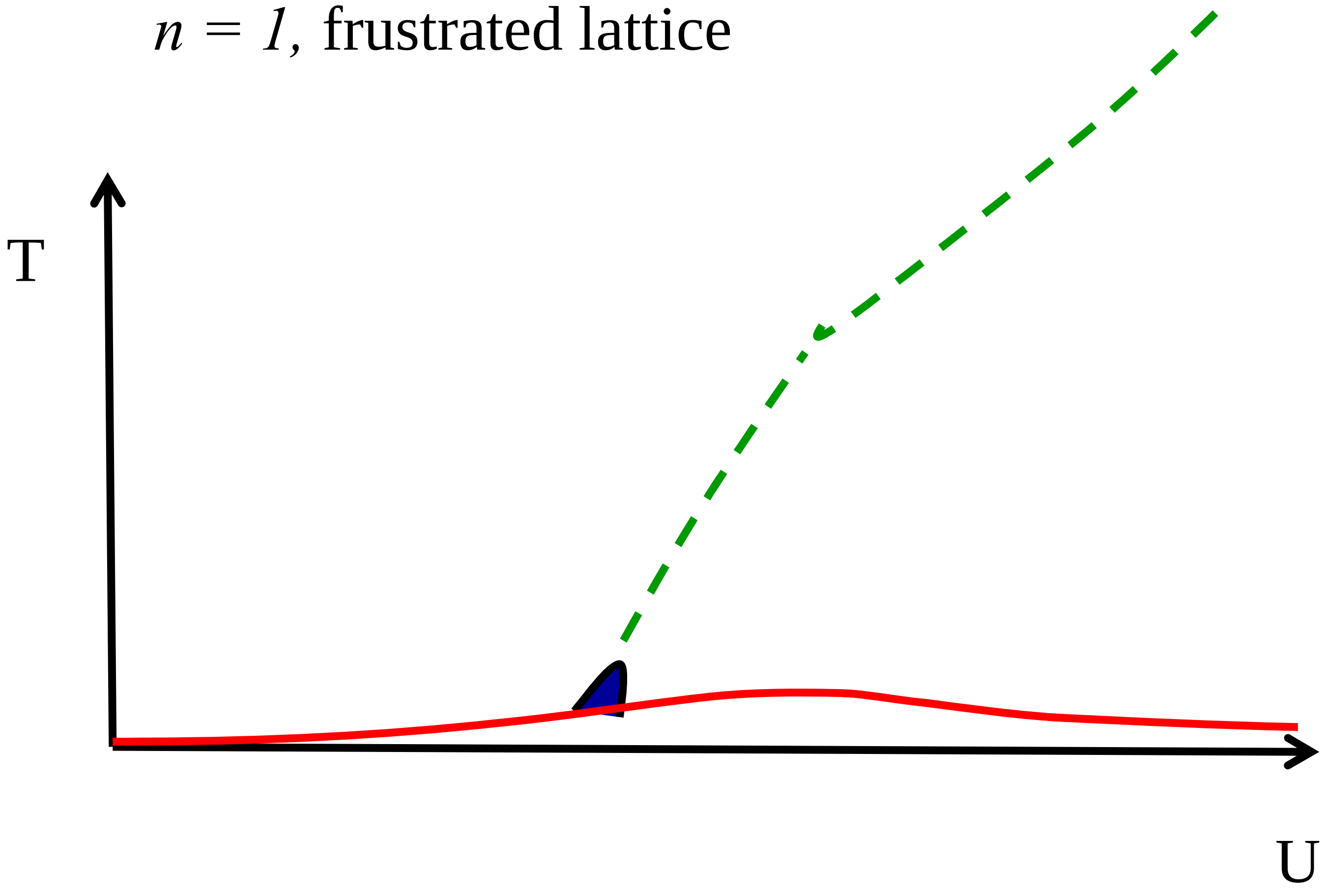
Mott transition

$n = 1$, frustrated lattice



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Giovanni Sordi

Normal state finite *T* phase diagram

Giovanni Sordi: *Wednesday* *9:36 AM* *P54.00009*

G. Sordi, P. Sémon, K. Haule, and A.-M. S. Tremblay,
arXiv:1110.1392 (2011)

G. Sordi, K. Haule, and A.-M. S. Tremblay,
Phys. Rev. B 84 075161 (2011)

G. Sordi, K. Haule, and A.-M. S. Tremblay,
Phys. Rev. Lett. 104, 226402 (2010)

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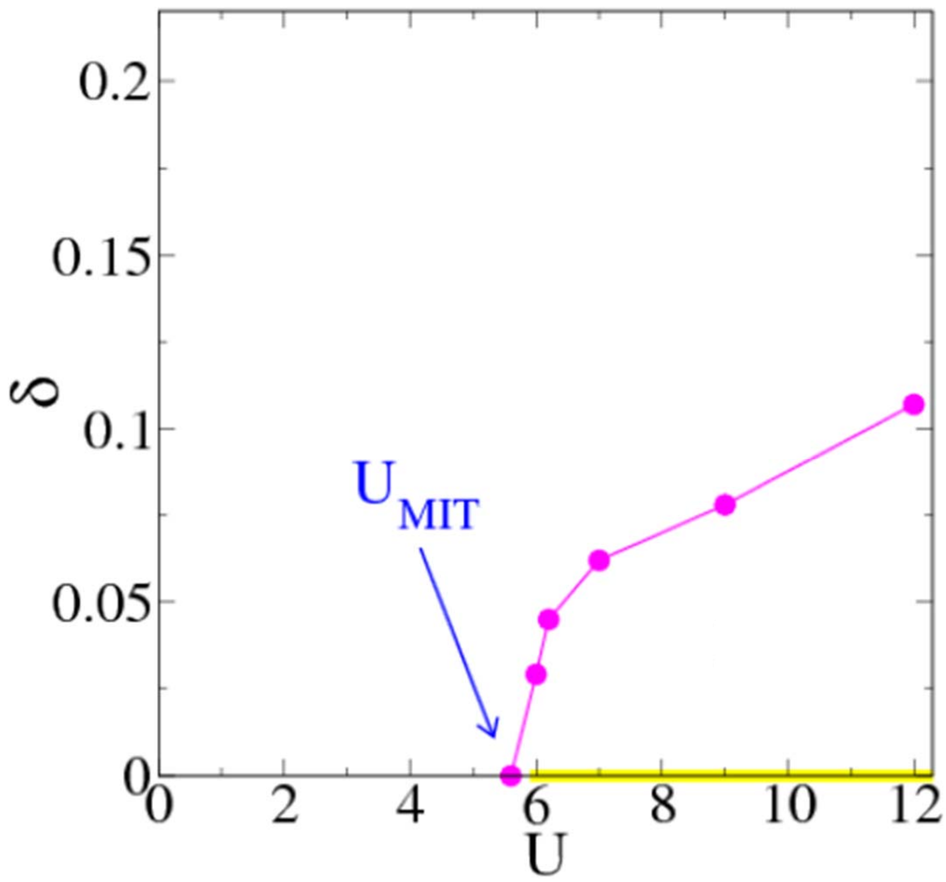
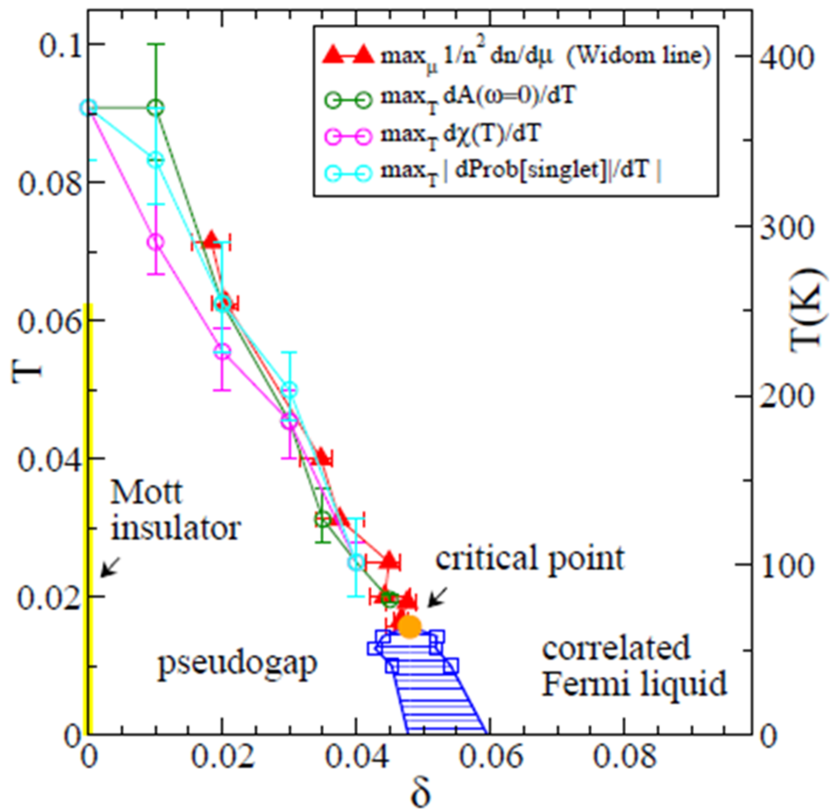
Link to Mott transition up to optimal doping

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



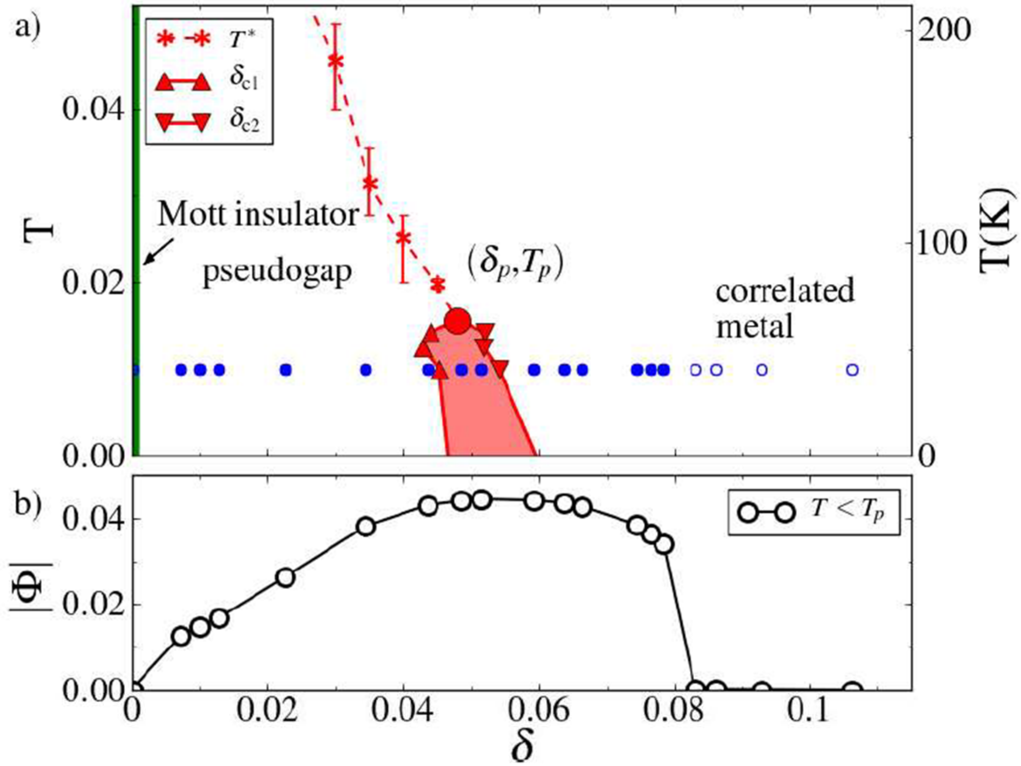
Normal state *U=6.2t*



Superconductivity
(when AFM not permitted)

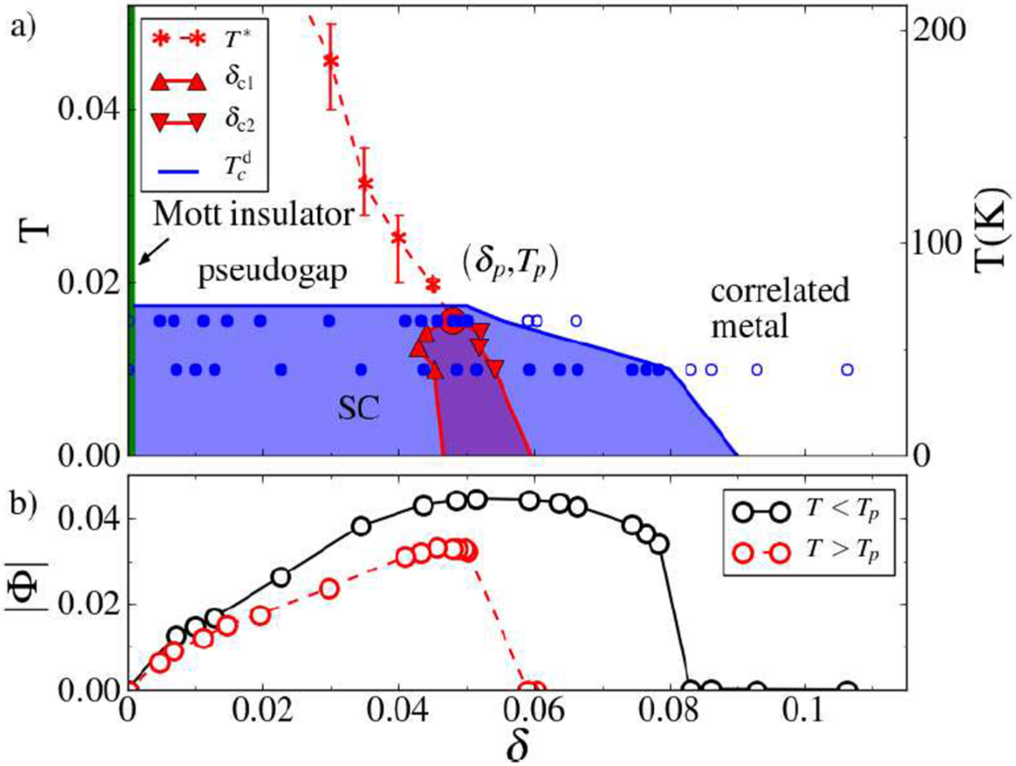
arXiv:1201.1283v1

Order parameter as a function of doping, T fixed



similar to $\Phi(\delta)$ at $T = 0$: Capone&Kotliar 2006; Kancharla et al 2008; Civelli 2009, Balzer et al 2010, etc $\rightarrow$ T_c^d could only be surmized

Order parameter as a function of doping, T fixed



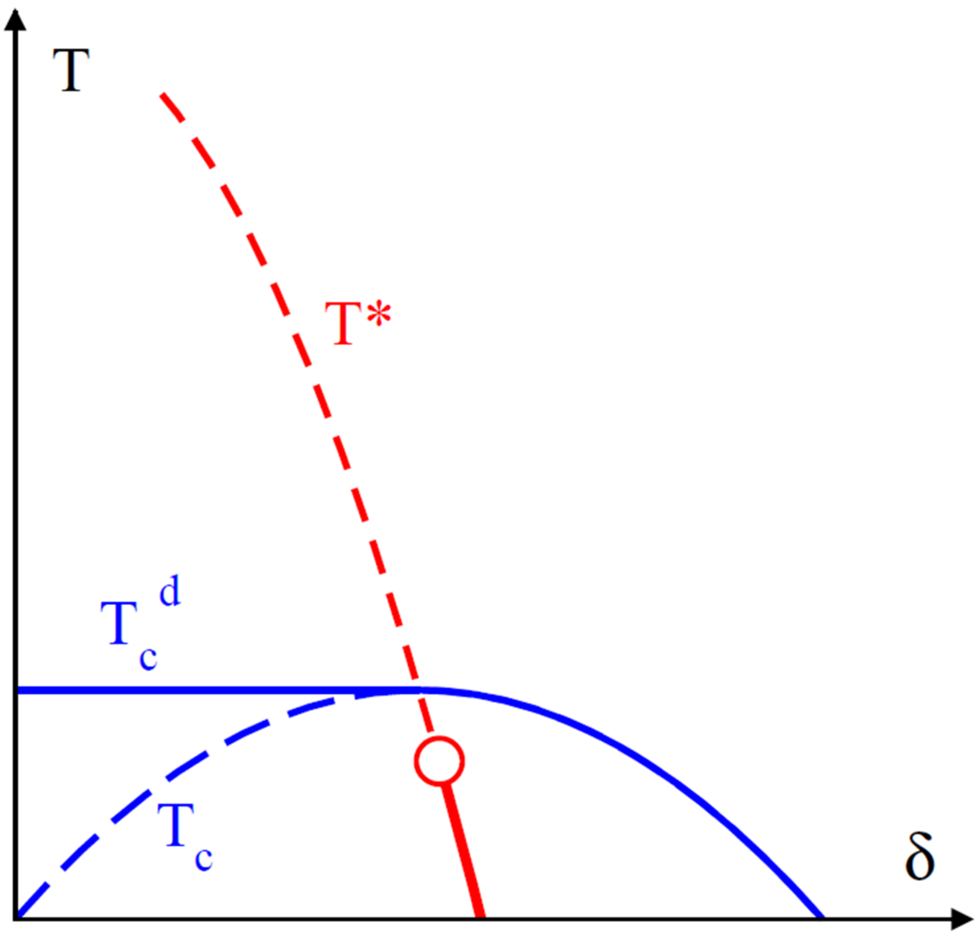
similar to $\Phi(\delta)$ at $T = 0$: Capone&Kotliar 2006; Kancharla et al 2008; Civelli 2009, Balzer et al 2010, etc $\rightarrow$ T_c^d could only be surmized

- SC region: region where $\Phi \neq 0$
- SC hides the 1st order transition of the underlying NS
- T_c^d distinct from T^*
- T_c^d does not scale with Φ
- Mott physics causes Φ to drop, but does NOT produce a fall in T_c^d

T. Maier, M. Jarrell, T. Pruschke, and J. Keller, Phys. Rev. Lett. **85**, 1524 (2000).
T. A. Maier, M. Jarrell, T. C. Schulthess, P. R. C. Kent, and J. B. White, Phys. Rev. Lett. **95**, 237001 (2005).
K. Haule and G. Kotliar, Phys. Rev. B **76**, 104509 (2007).

What makes T_c fall ?

The experimentally observed drop of T_c at low doping must come from mechanisms not included here:



1. quantum and classical fluctuations in the magnitude and phase of the order parameter

   Emery&Kivelson, Nat 1995; Emery&Kivelson, PRL 1995; Podolsky et al, PRL 2007; Tesanovic, Nat Phys 2008; Ussishkin et al, PRL 2002

2. competing order

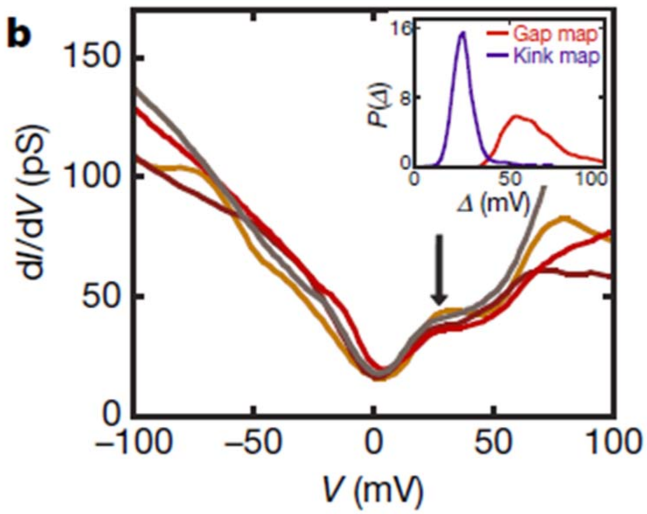
   Fradikin et al, Annual Rev Cond Mat 2010

3. disorder

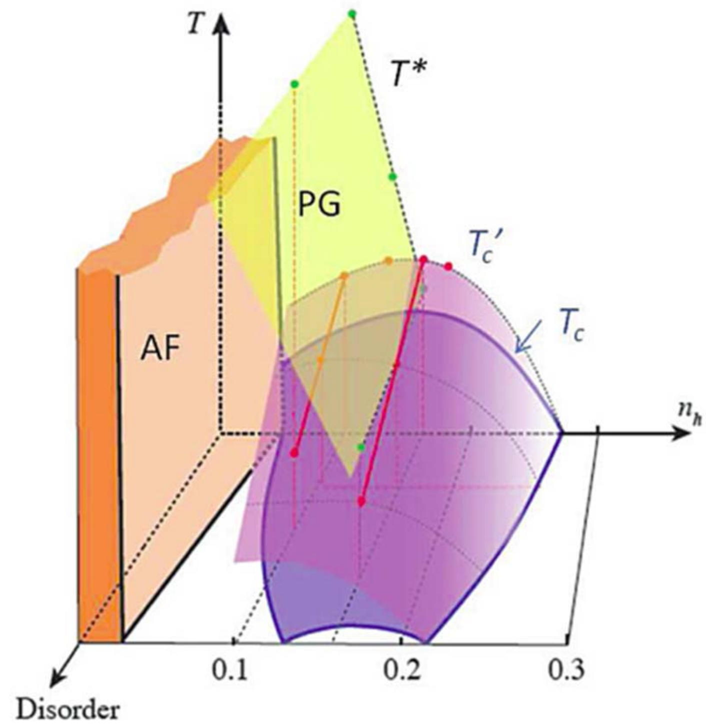
   Rullier-Albenque et al, EPL 2008; Alloul et al, RMP 2009

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)

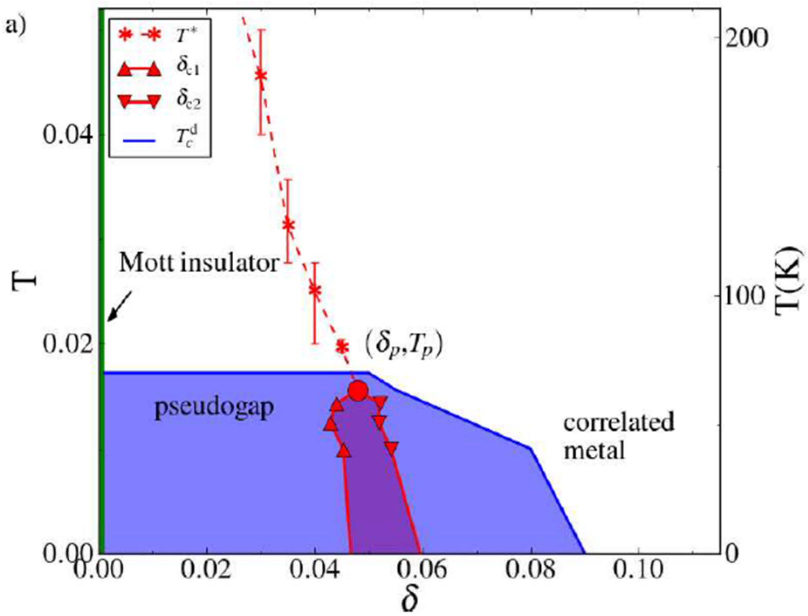


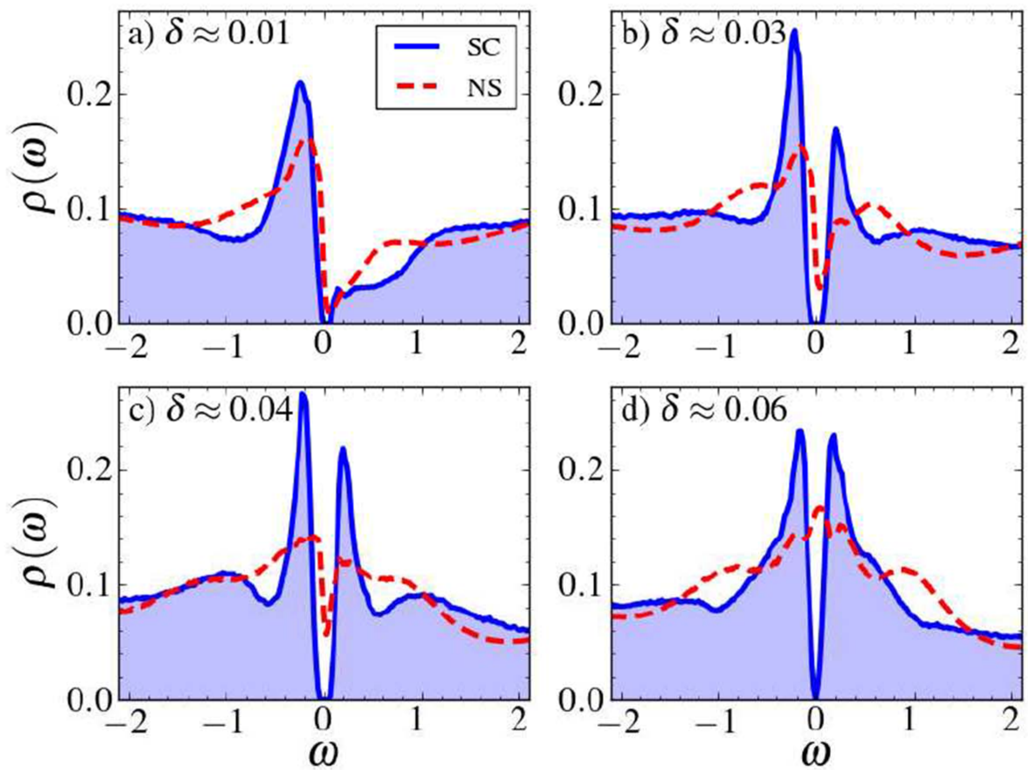
F. Rullier-Albenque, H. Alloul, and G.Rikken, Phys. Rev. B **84**, 014522 (2011).

Avoided first-order transition leaves its mark

density of states:

superconducting state VS normal state



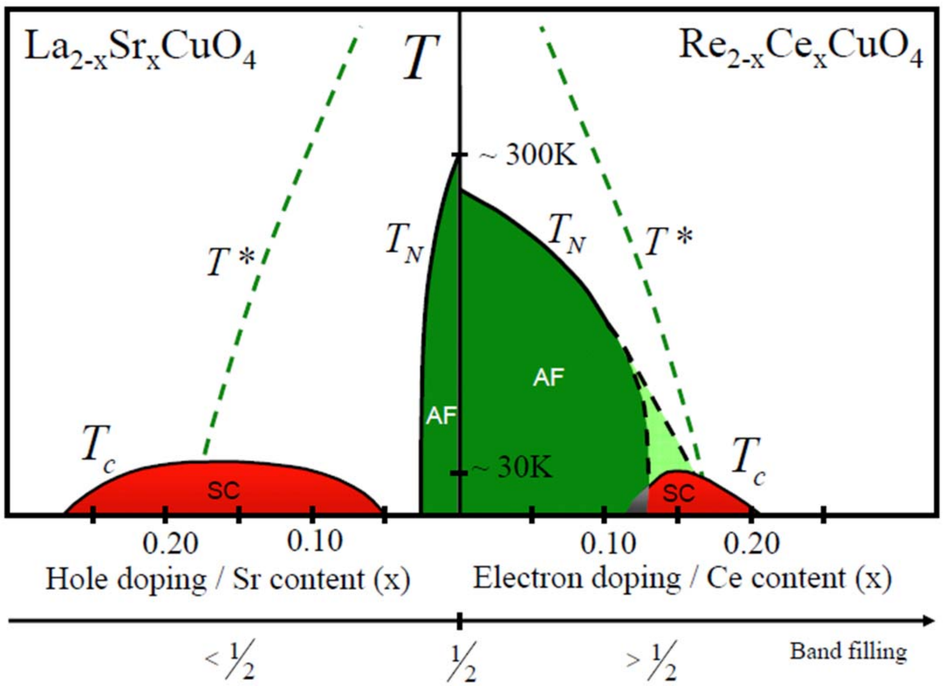


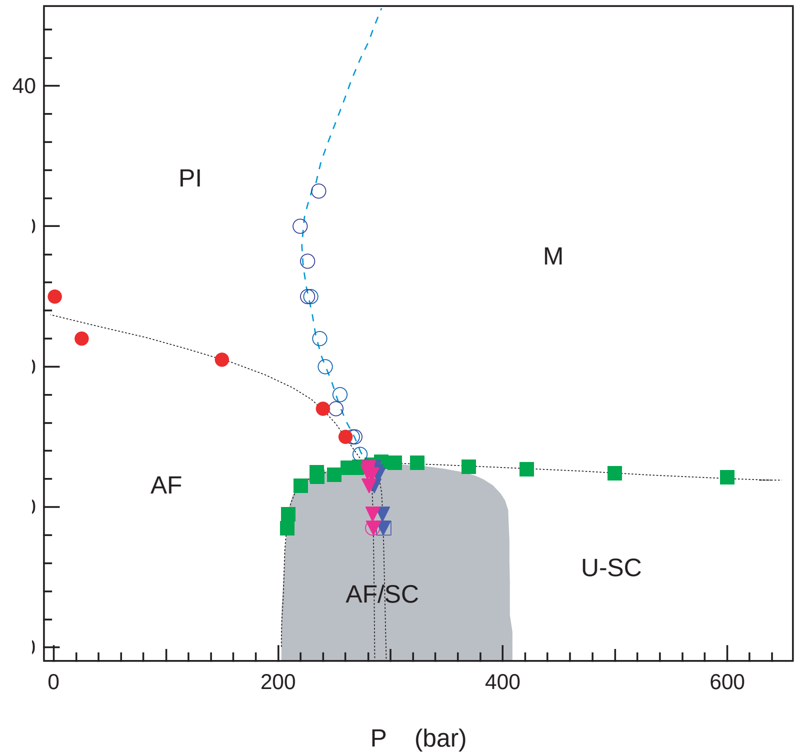
Low doping: large particle-hole asymmetry

Bandwidth vs doping driven transition

Cuprates vs organics

Armitage, Fournier, Greene, RMP (2009)





Phase diagram (X=Cu[N(CN)$_2$]Cl)
S. Lefebvre et al. PRL **85**, 5420 (2000),
P. Limelette, et al. PRL **91** (2003)
F. Kagawa, K. Miyagawa, + K. Kanoda
PRB **69** (2004) +Nature **436** (2005)

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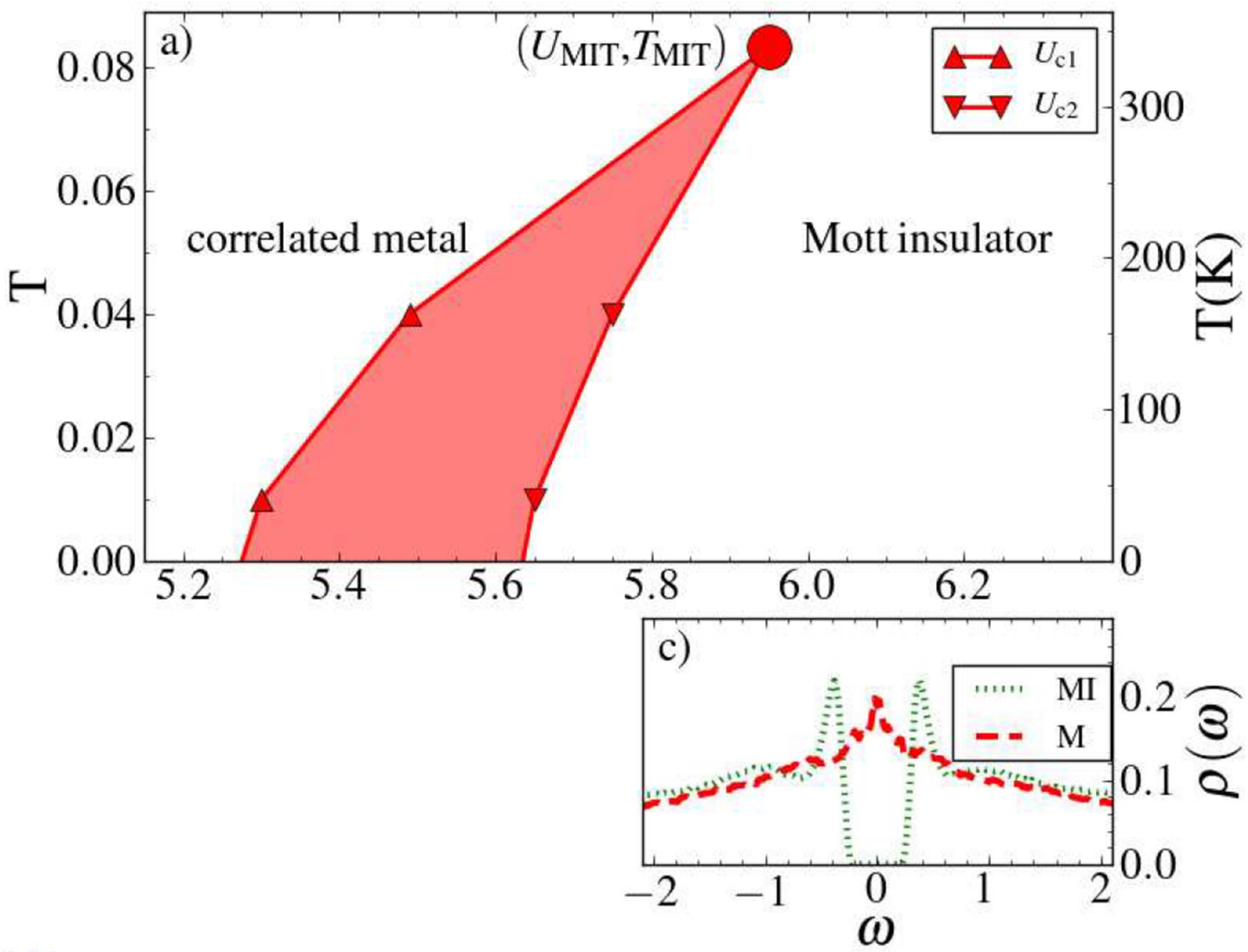
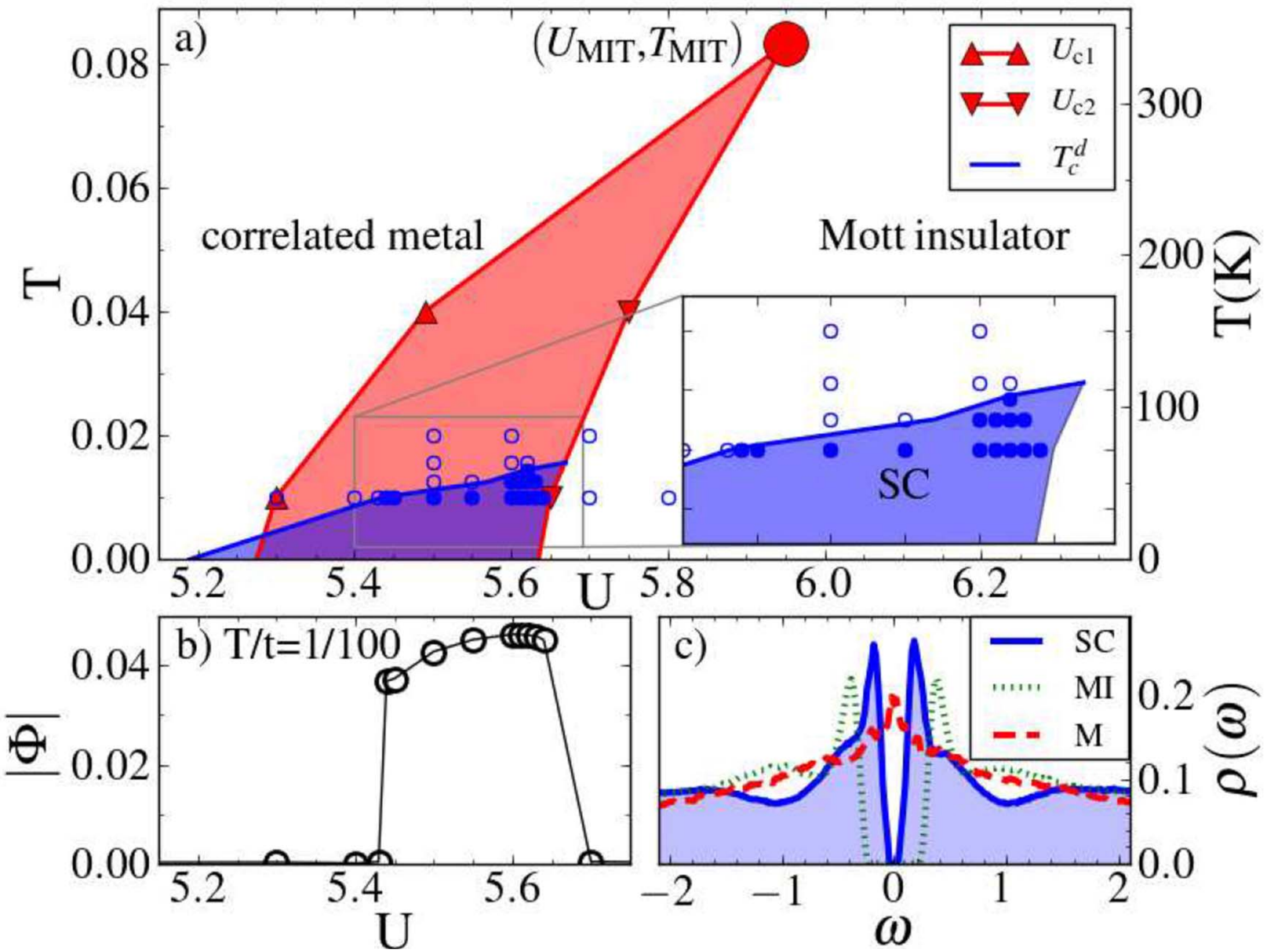
Normal state Mott transition, *n = 1*

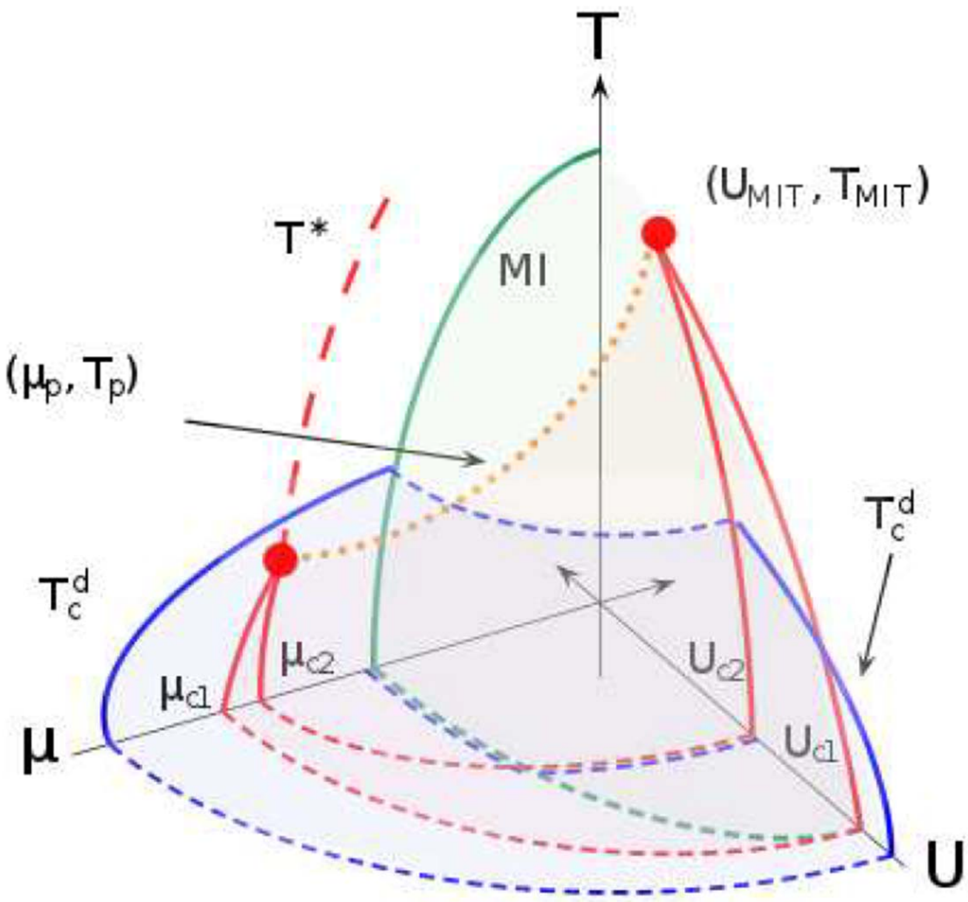


Normal state Mott transition



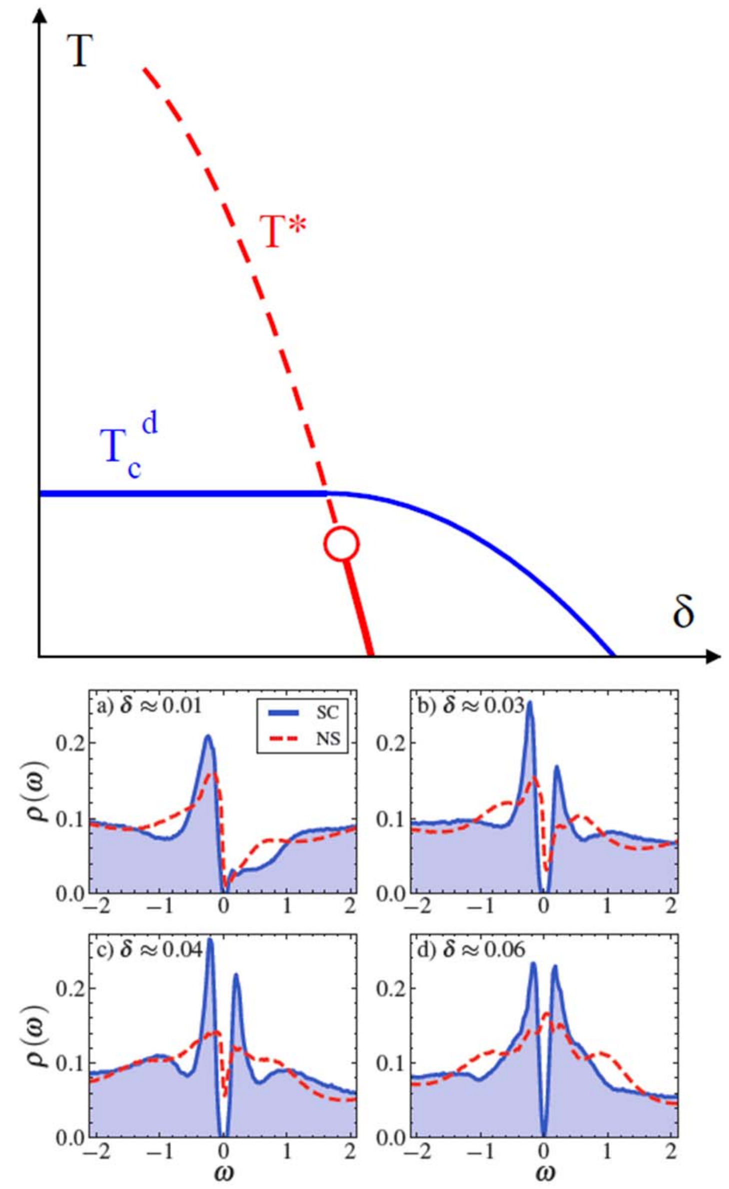
OOKE

Unified phase diagram



- Normal-state metal close to Mott insulator is unstable to SC at any filling
- The SC phase is continuously connected across dopings.

Our contributions for the doped case



- $T_c^d \neq T^*$
- T_c^d does not vanish as δ –> 0
  - Mott physics alone does not suppress T_c
  - SC fluctuations left
- First-order transition in normal state is removed by SC but leaves its mark on the dynamics.

Merci

Thank you

G. Sordi, P. Sémon, K. Haule, and A.-M. S. Tremblay, arXiv:1201.1283 (2012)

G. Sordi, P. Sémon, K. Haule, and A.-M. S. Tremblay, arXiv:1110.1392 (2011)

G. Sordi, K. Haule, and A.-M. S. Tremblay, Phys. Rev. B 84 075161 (2011)

G. Sordi, K. Haule, and A.-M. S. Tremblay, Phys. Rev. Lett. 104, 226402 (2010)