Strongly correlated superconductivity

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CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH

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VERITATEM IN CHARITATE

CMP in the City, London, 17th June 2013

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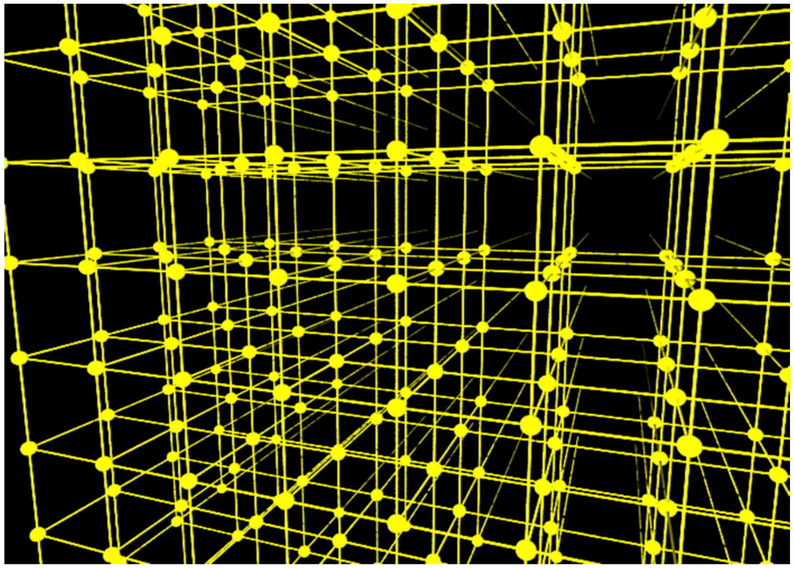
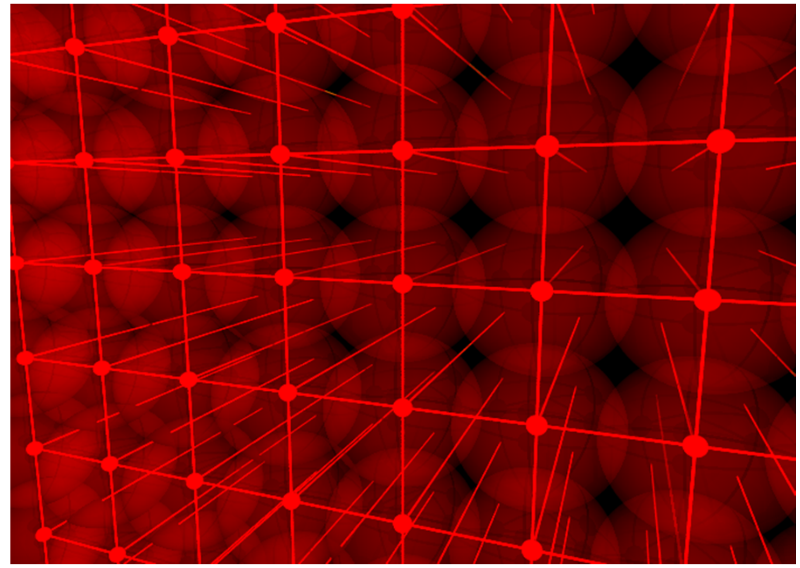
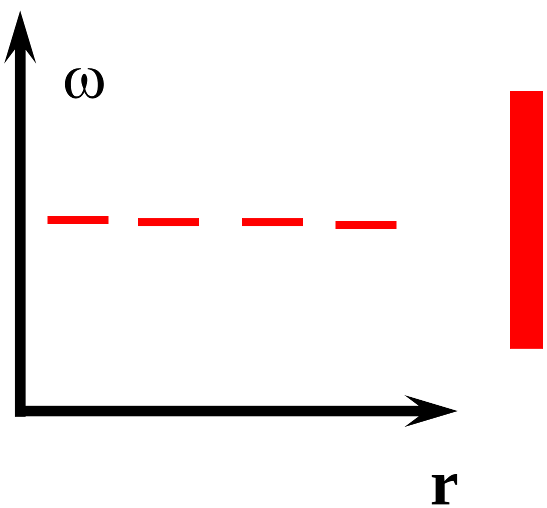
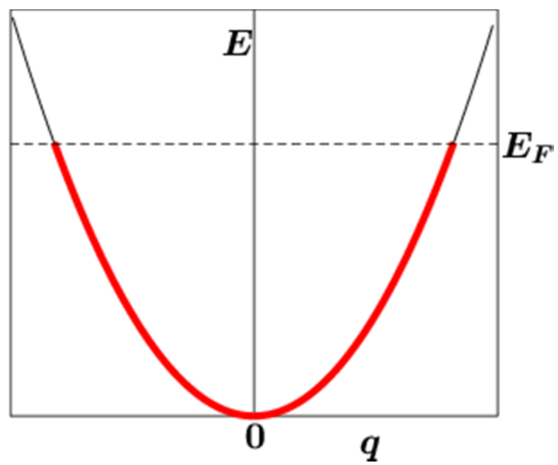
How to make a metal





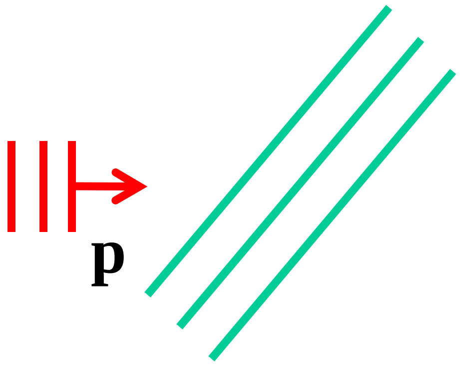




Courtesy, S. Julian

Superconductivity

Attraction mechanism in the metallic state



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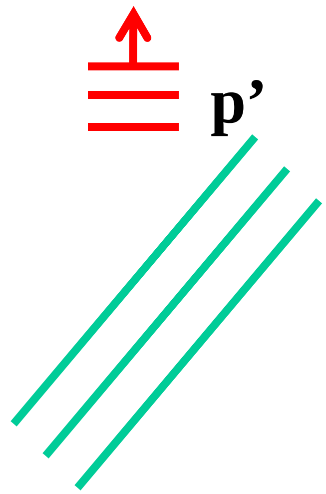
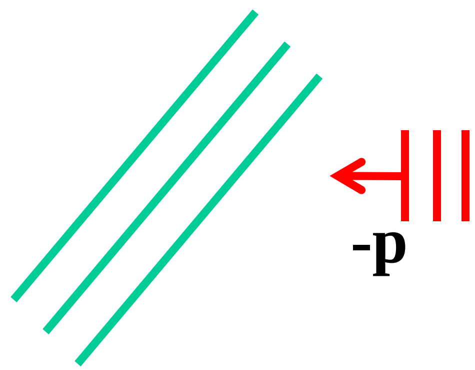
Attraction mechanism in the metallic state



Attraction mechanism in the metallic state



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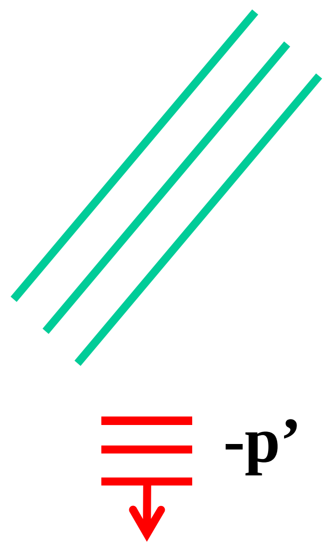
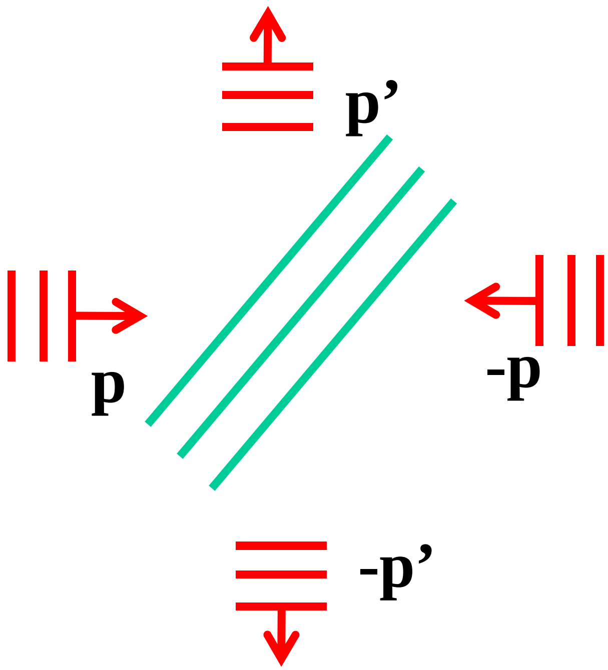
Attraction mechanism in the metallic state



Attraction mechanism in the metallic state



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#1 Cooper pair, #2 Phase coherence

$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow}$$

$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \left(\langle \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \rangle \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} + \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \left\langle \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} \right\rangle \right)$$

$$|\mathrm{BCS}(\theta)\rangle = \ldots + e^{iN\theta}|N\rangle + e^{i(N+2)\theta}|N+2\rangle + \ldots.$$

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Breakdown of band theory
Half-filled band is metallic?

Half-filled band: Not always a metal

NiO, Boer and Verway

Peierls, 1937

Mott, 1949

« Conventional » Mott transition

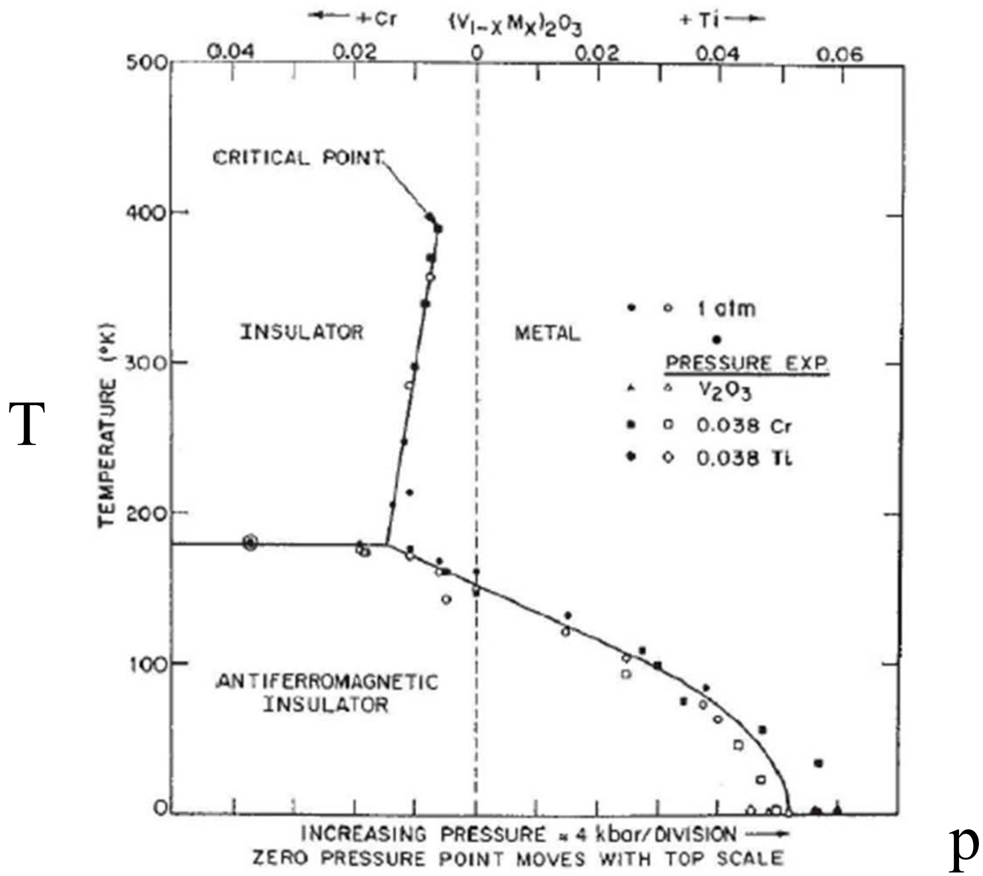
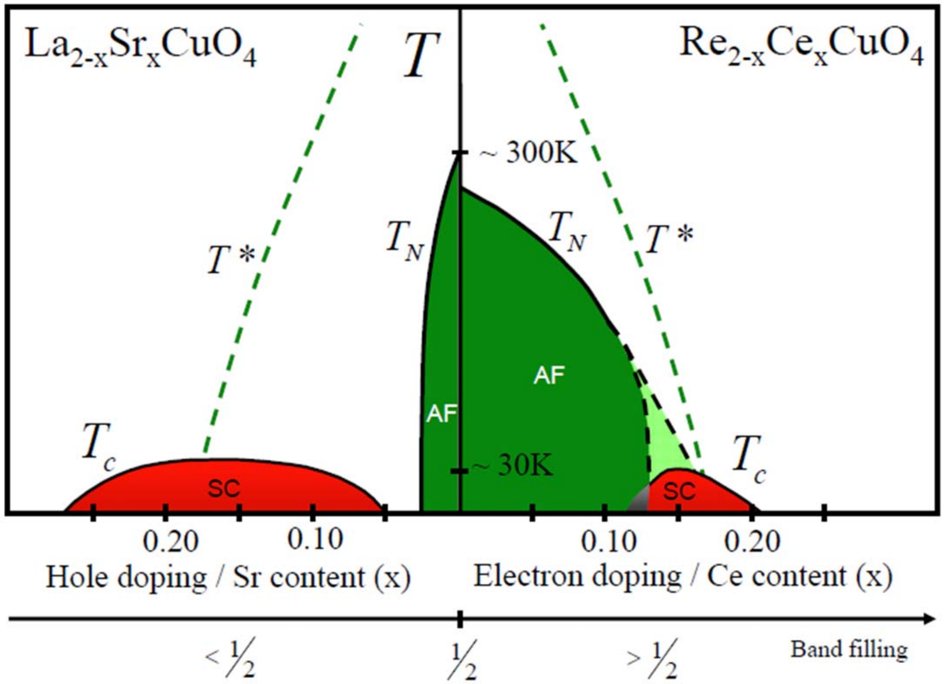


Figure: McWhan, PRB 1970; Limelette, Science 2003

Superconductivity, in the presence of strong repulsion?

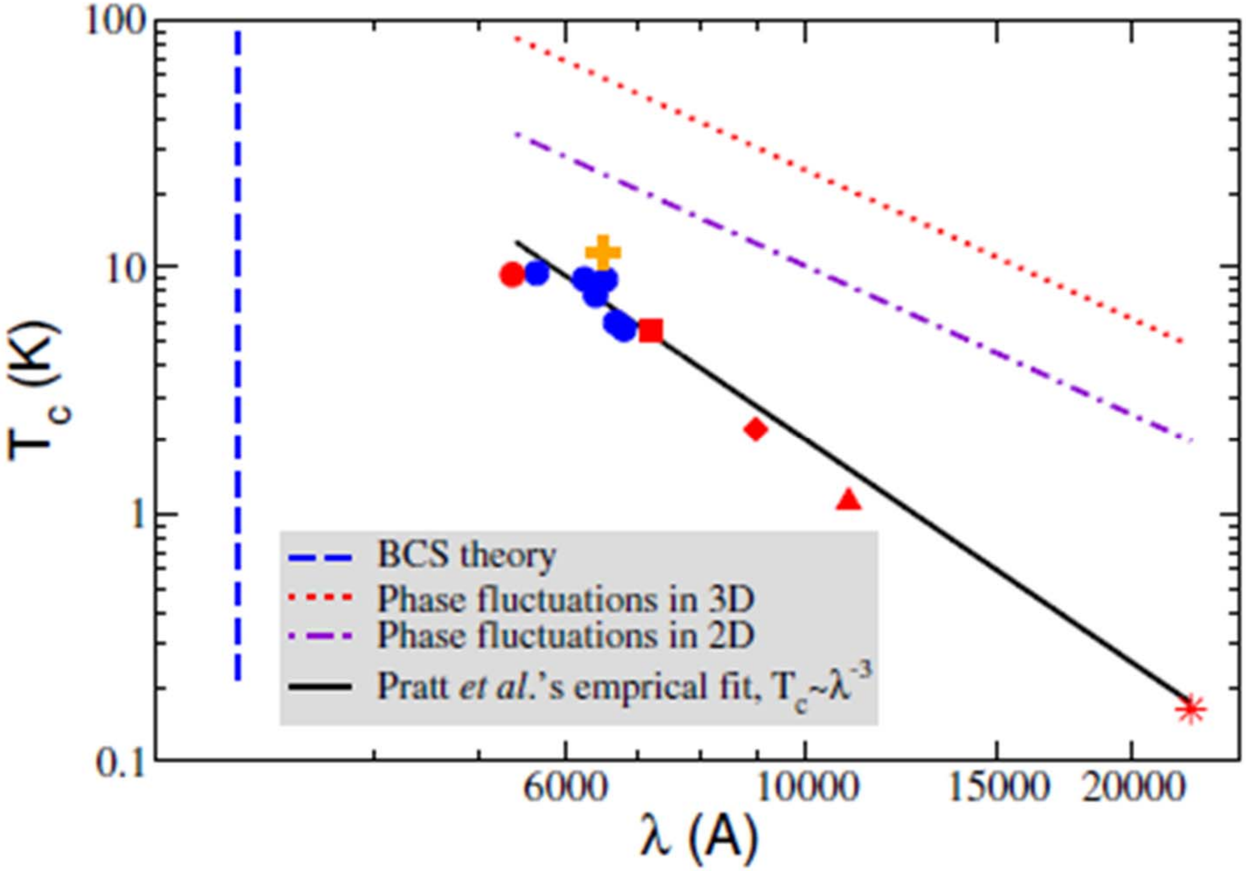
High-temperature superconductors

Armitage, Fournier, Greene, RMP (2009)



Mott Physics away from $n = 1$

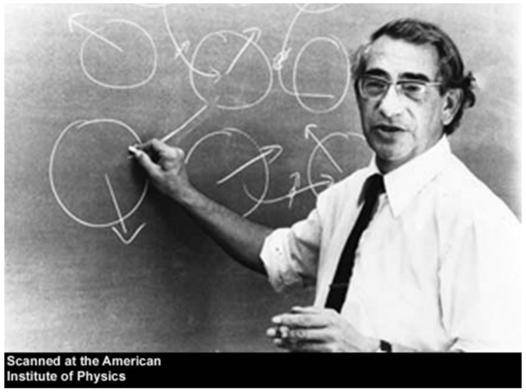
Strongly correlated SC: Layered *d=2* organics



Powell, McKenzie J. Phys.: Condens. Matter **18** (2006) R827–R866

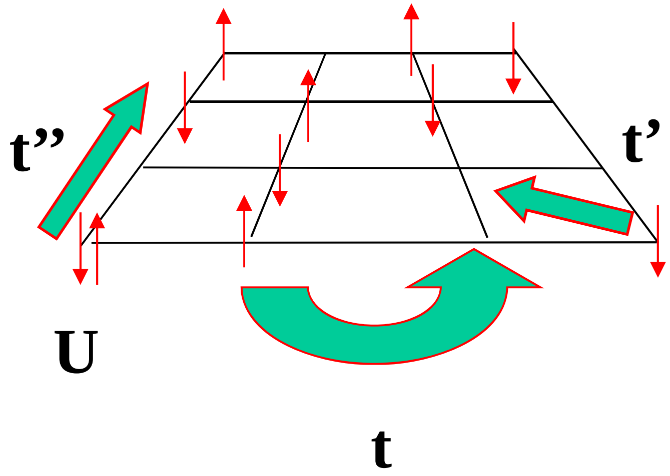
Model

Hubbard model

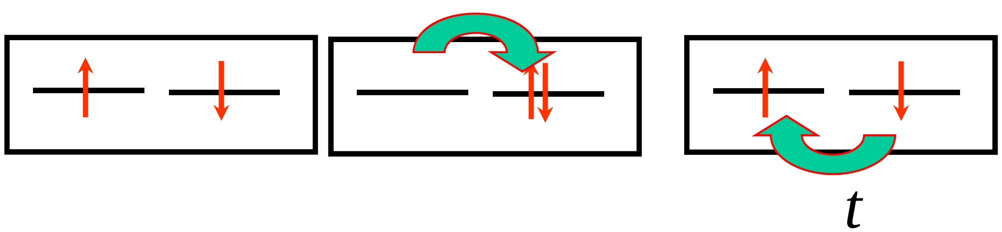


1931-1980

μ



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



$t = 1$

Effective model, Heisenberg: $J = 4t^2/U$

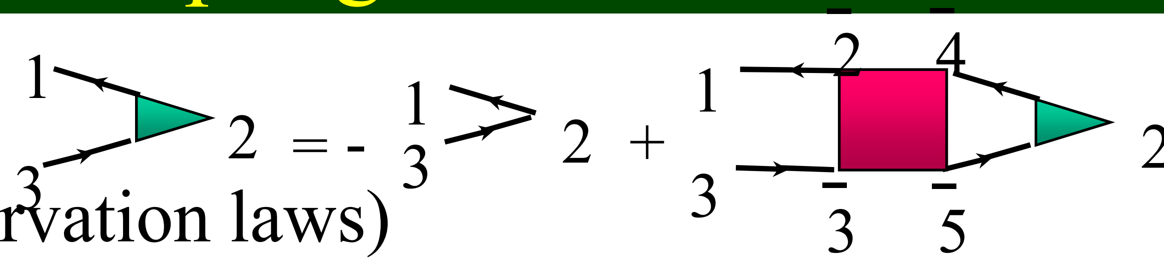
Outline

- **Weak to intermediate coupling**
  - **TPSC**
  - **e-doped cuprates**
- A phase at weak and at strong coupling
- h-doped cuprates as doped Mott insulators
- Cluster Dynamical Mean-Field Theory
- Strong coupling superconductivity
  - Organics
  - High Tc

Methodology

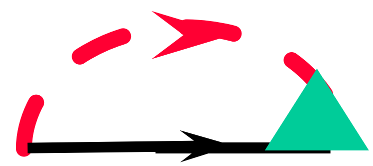
Weak-coupling approaches

Theory difficult even at weak to intermediate coupling!



- RPA (OK with conservation laws)
  - Mermin-Wagner
  - Pauli X
- Moryia (Conjugate variables HS $\phi^4 = <\phi^2> \phi^2$)
  - Adjustable parameters: *c* and U_{eff} X
  - Pauli
- FLEX X
  - No pseudogap
  - Pauli
- Renormalization Group X
  - 2 loops

Σ =



Rohe and Metzner (2004)
Katanin and Kampf (2004)

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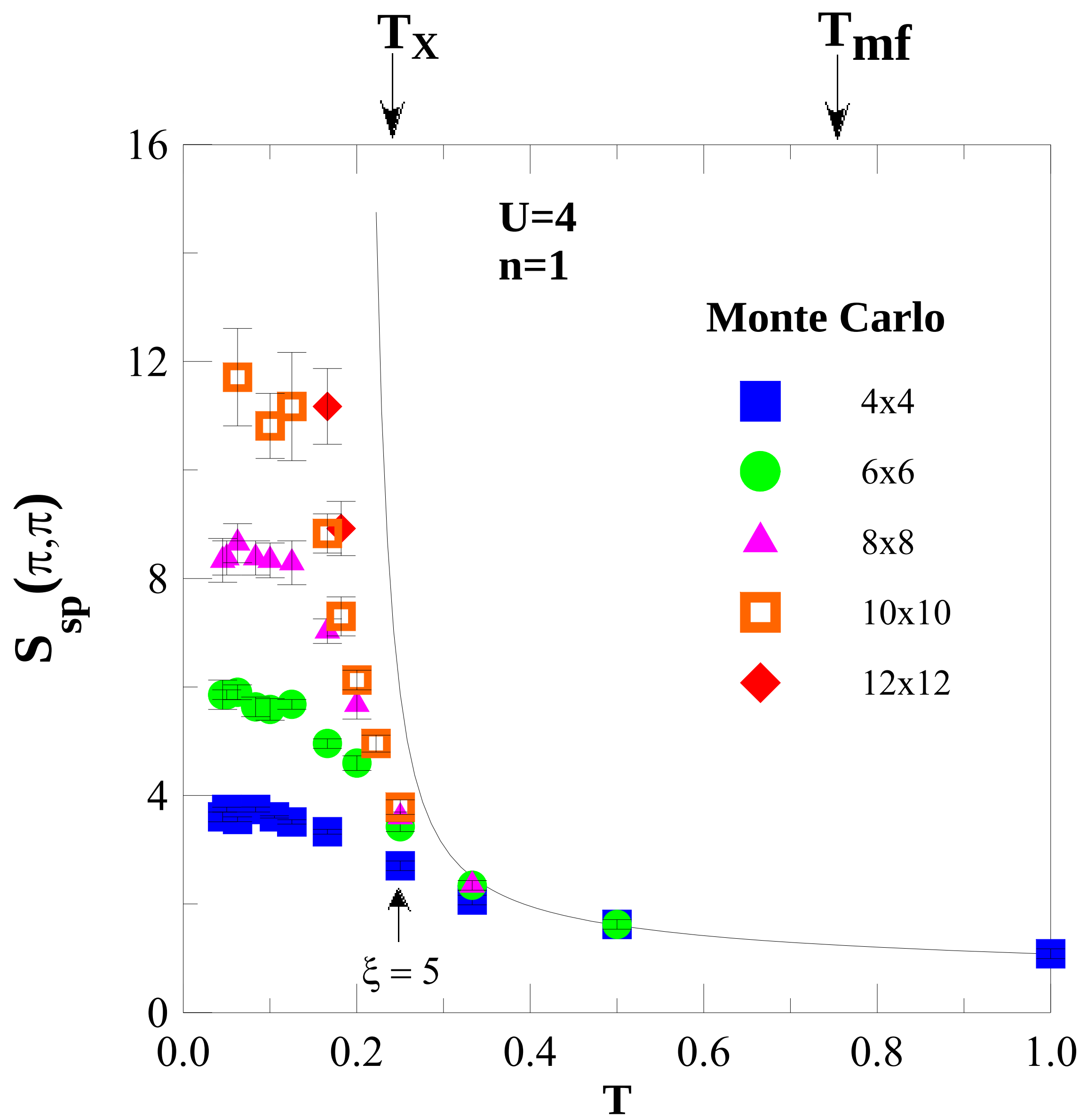
Two-Particle-Self-Consistent Approach

Benchmarks for TPSC

n=1

$$\xi \sim \exp\left(C(T)/T\right)$$



Calc.: Vilk et al. P.R. B **49,** 13267 (1994)

QMC: S. R. White, et al. Phys. Rev. **40**, 506 (1989).

$O(N=\infty)$ A.-M. Daré, Y.M. Vilk and A.-M.S.T Phys. Rev. B **53**, 14236 (1996)

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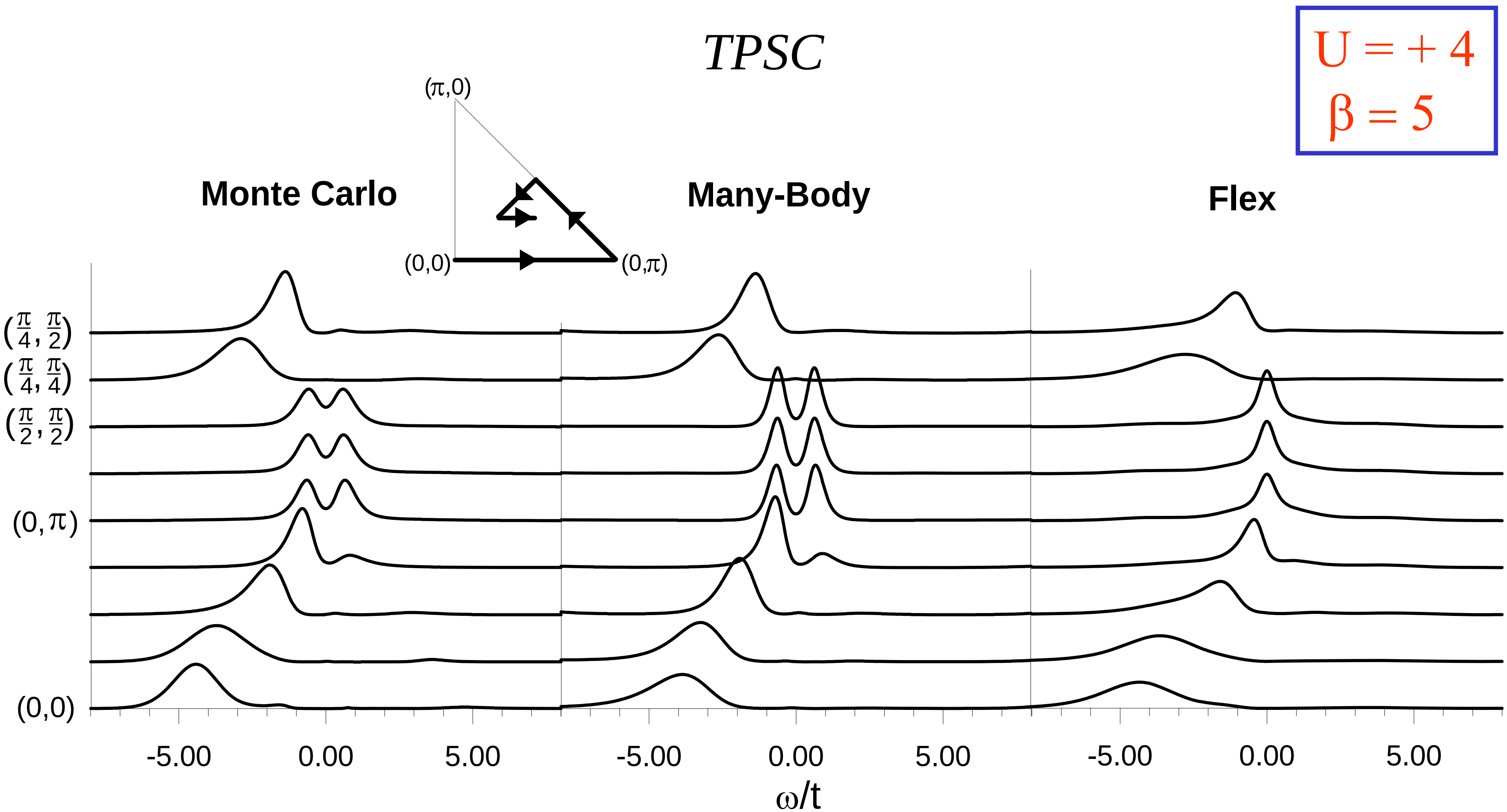
QMC benchmark for TPSC



Calc. + QMC: Moukouri et al. P.R. B 61, 7887 (2000).

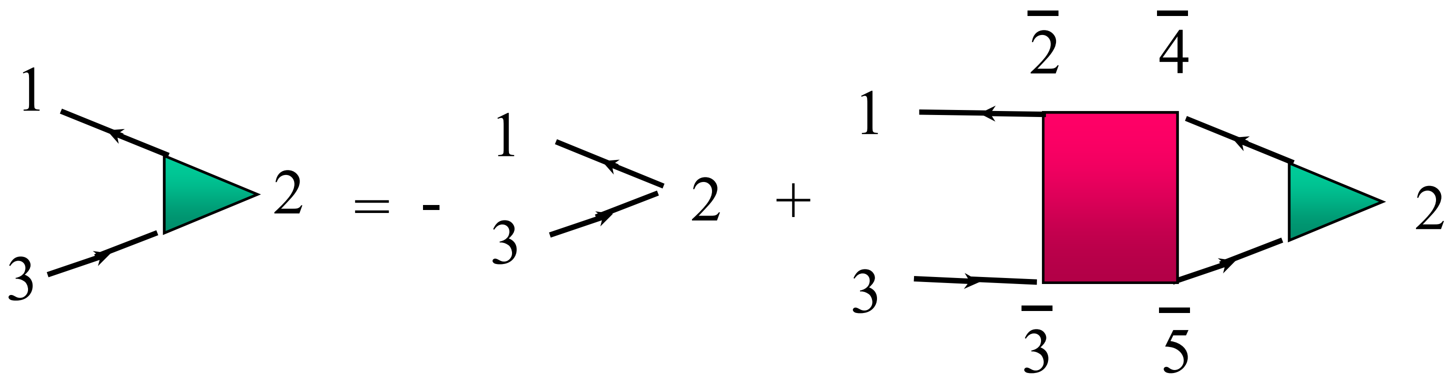
Two-Particle Self-Consistent Approach

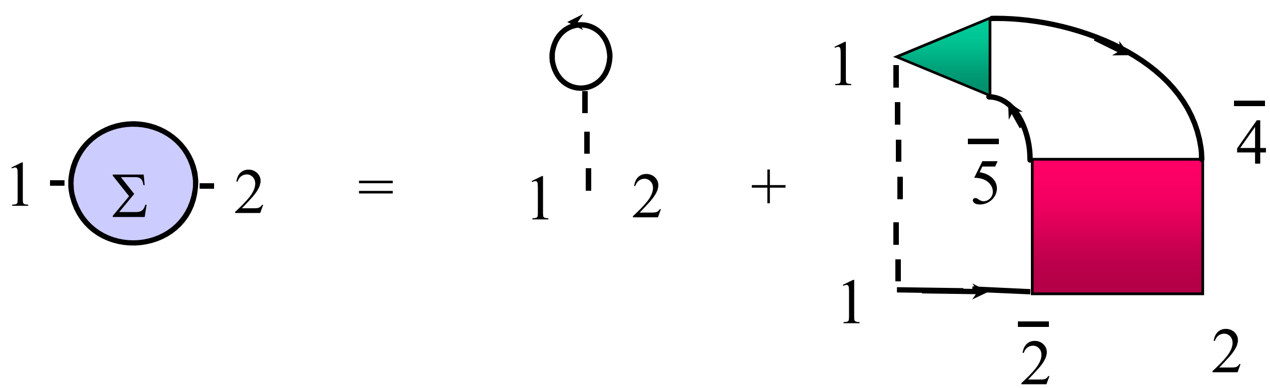
- General philosophy
  - Drop diagrams ($U < 6t$)
  - Impose constraints and sum rules
    - Conservation laws
    - Pauli principle ($\langle n_\sigma^2 \rangle = \langle n_\sigma \rangle$)
    - Local moment and local density sum-rules
- Get for free:
    - Mermin-Wagner theorem
    - Kanamori-Brückner screening
    - Consistency between one- and two-particle $\Sigma G = U \langle n_\sigma n_{-\sigma} \rangle$

Vilk, AMT J. Phys. I France, **7**, 1309 (1997); Allen et al.in *Theoretical methods for strongly correlated electrons* also cond-mat/0110130
(Mahan, third edition)

Two-Particle Self-Consistent Approach

A better approximation for single-particle properties (Ruckenstein)



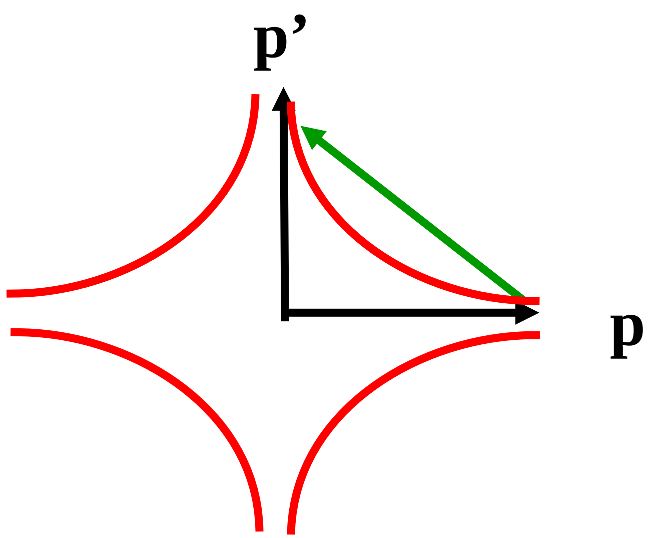


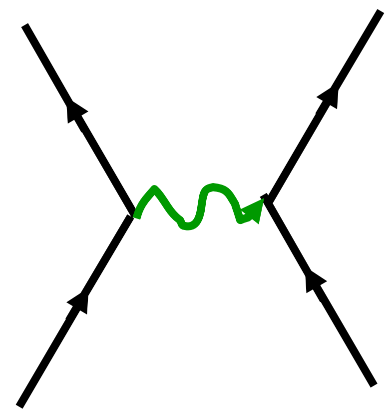
Y.M. Vilk and A.-M.S. Tremblay, J. Phys. Chem. Solids **56**, 1769 (1995).
Y.M. Vilk and A.-M.S. Tremblay, Europhys. Lett. **33**, 159 (1996);

N.B.: No Migdal theorem

Cartoon « BCS » weak-coupling picture

$$\Delta_{\mathbf{p}} = -\frac{1}{2V}\sum_{\mathbf{p}'} U(\mathbf{p}-\mathbf{p}')\frac{\Delta_{\mathbf{p}'}}{E_{\mathbf{p}'}}\left(1-2n\left(E_{\mathbf{p}'}\right)\right)$$





Béal–Monod, Bourbonnais, Emery
P.R. B. **34**, 7716 (1986).

Exchange of spin waves?
Kohn-Luttinger
T_c with pressure

D. J. Scalapino, E. Loh, Jr., and J. E. Hirsch
P.R. B **34**, 8190-8192 (1986).

Kohn, Luttinger, P.R.L. **15**, 524 (1965).

P.W. Anderson Science 317, 1705 (2007)

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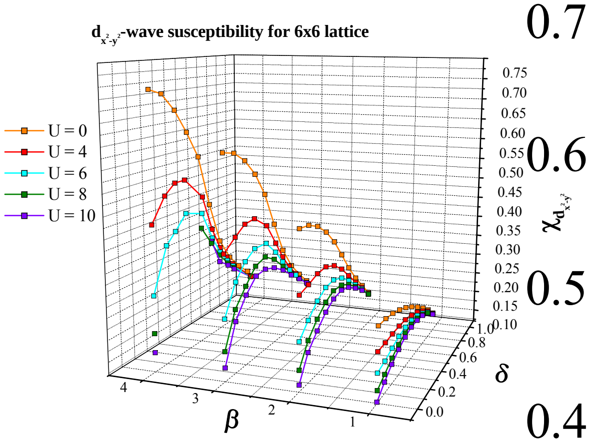

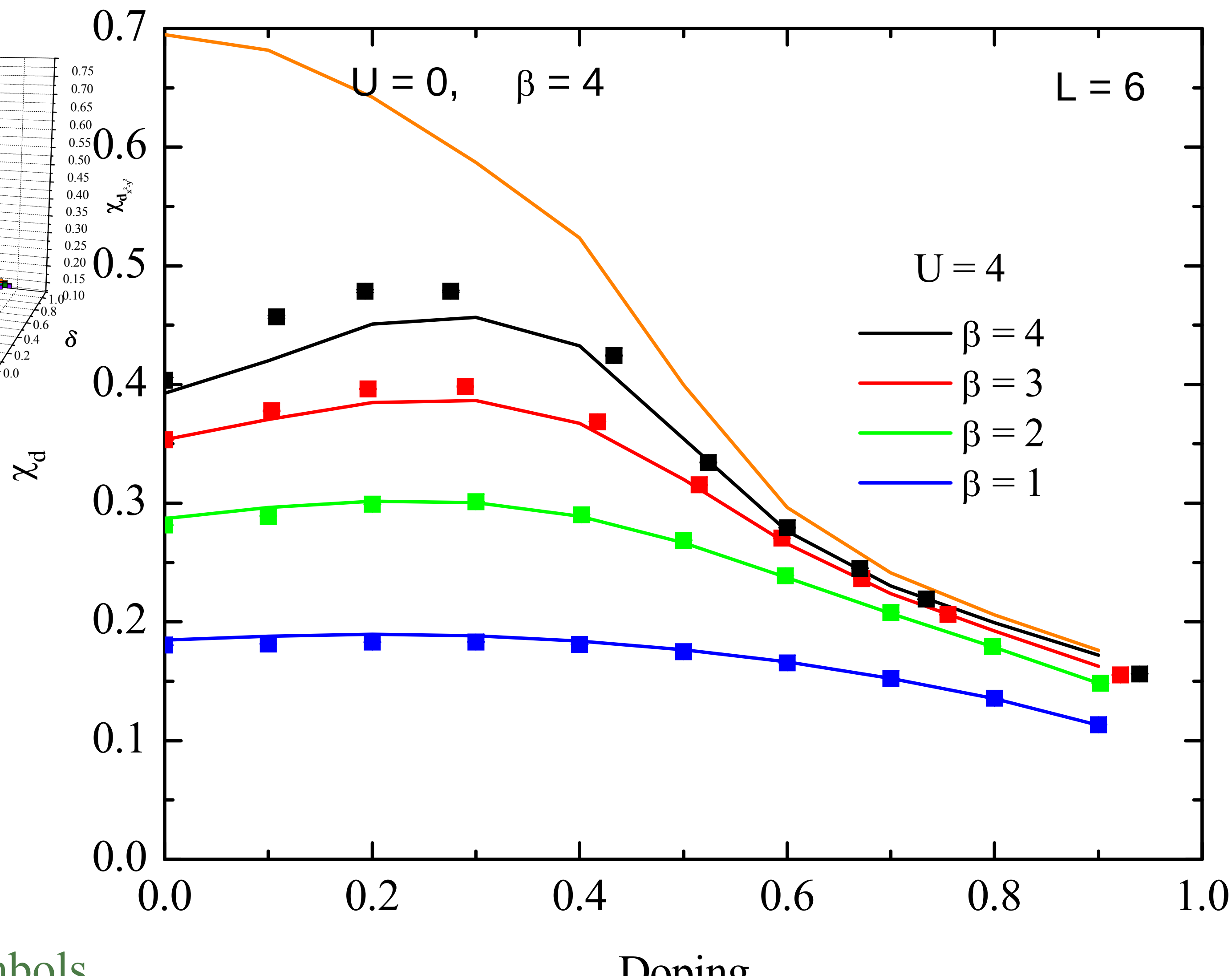

QMC: symbols.
Solid lines analytical.

Kyung, Landry, A.-M.S.T.

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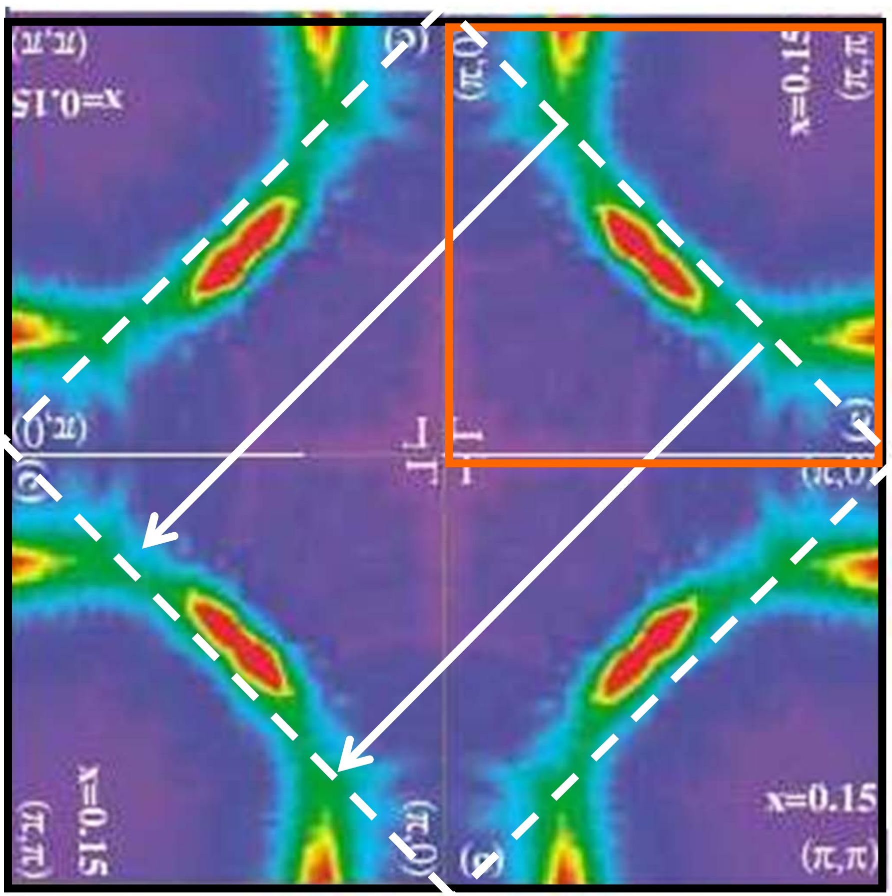
e-doped cuprates with TPSC

Hot spots from AFM quasi-static scattering

d = 2

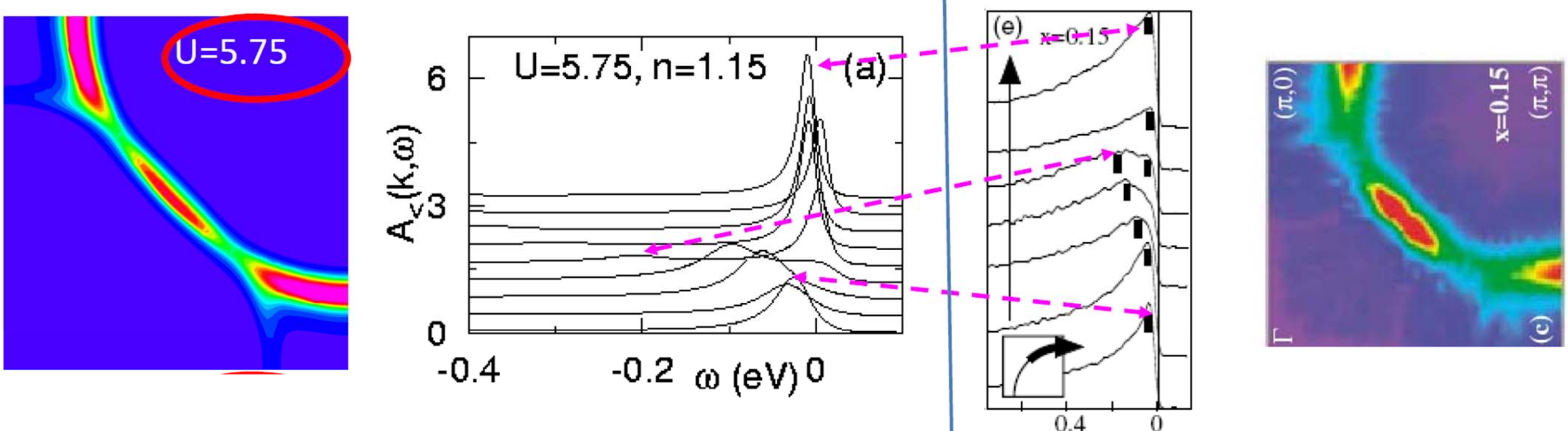


Armitage et al. PRL 2001

Pseudogap for e-doped curates

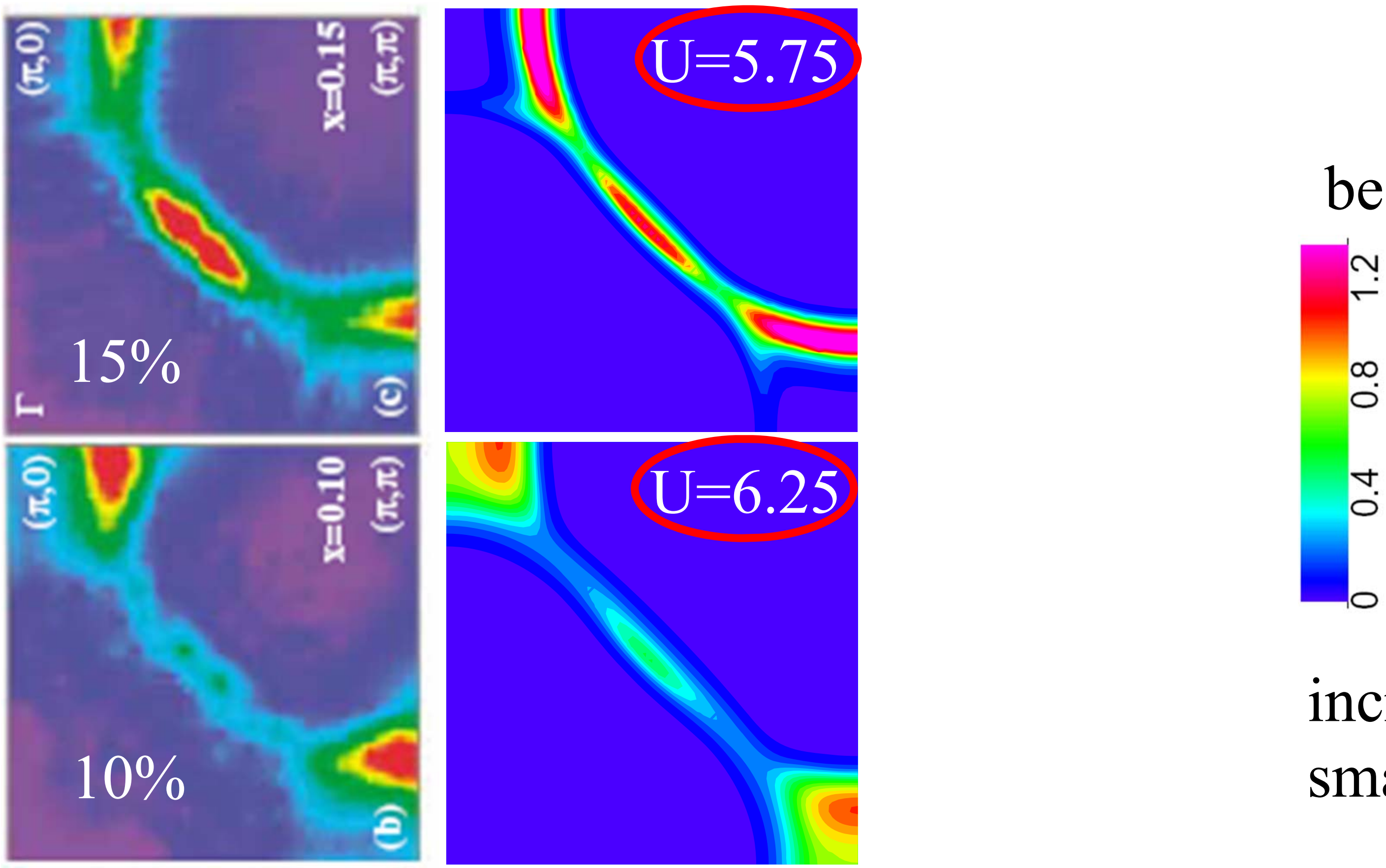
TPSC

ARPES



Fermi surface plots

Hubbard repulsion U has to…



be not too large

increase for smaller doping

Hankevych, Kyung, A.-M.S.T., PRL, sept. 2004

B.Kyung *et al.*,PRB **68**, 174502 (2003)

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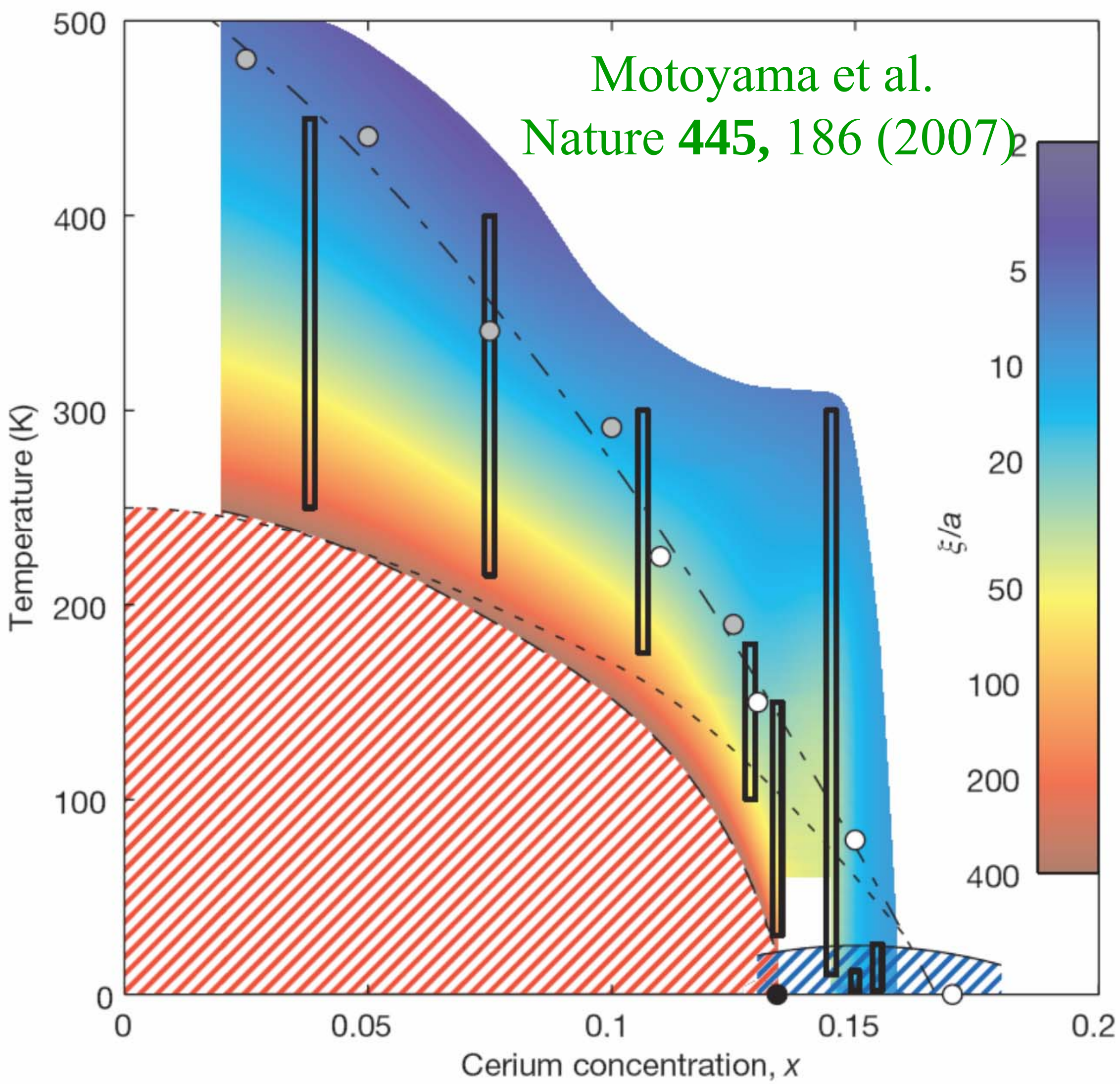
d = 2 precursors, e-doped



Motoyama et al.
Nature **445,** 186 (2007)

$$\xi^* = 2.6(2)\xi_{\text{th}}.$$

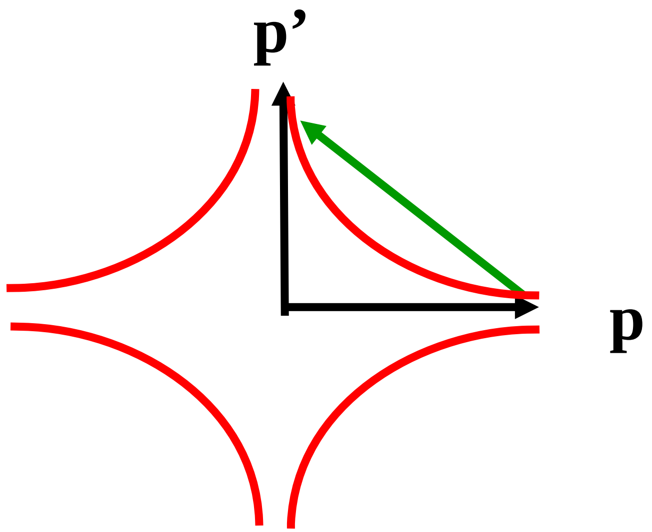
Vilk, A.-M.S.T (1997)

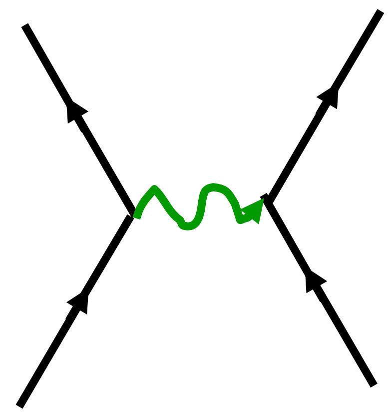
Kyung, Hankevych, A.-M.S.T., PRL, sept. 2004

Semi-quantitative fits of both ARPES and neutron

Cartoon « BCS » weak-coupling picture

$$\Delta_{\mathbf{p}} = -\frac{1}{2V}\sum_{\mathbf{p}'} U(\mathbf{p}-\mathbf{p}')\frac{\Delta_{\mathbf{p}'}}{E_{\mathbf{p}'}}\left(1-2n\left(E_{\mathbf{p}'}\right)\right)$$





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Kohn, Luttinger, P.R.L. **15**, 524 (1965).

P.W. Anderson Science 317, 1705 (2007)

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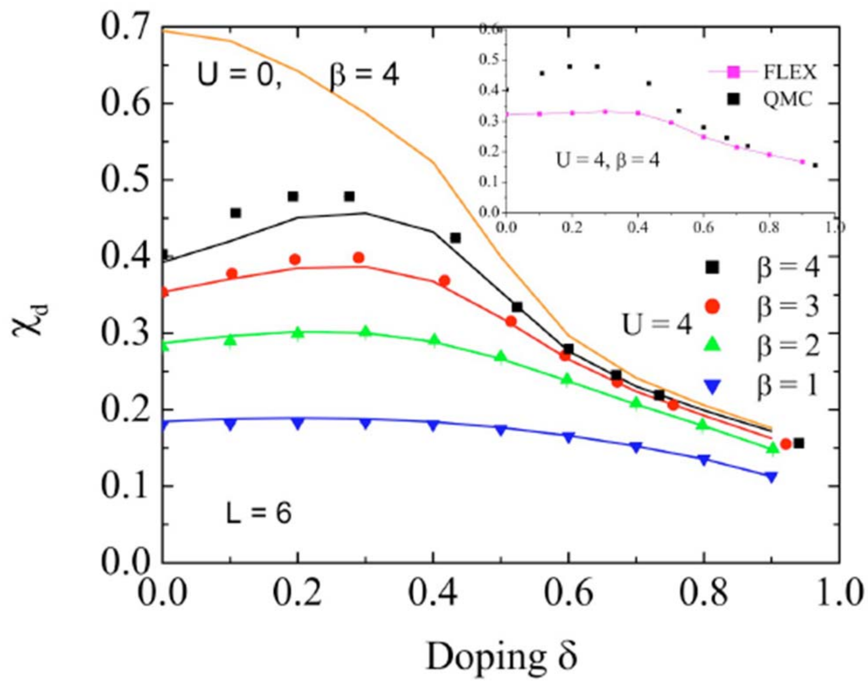
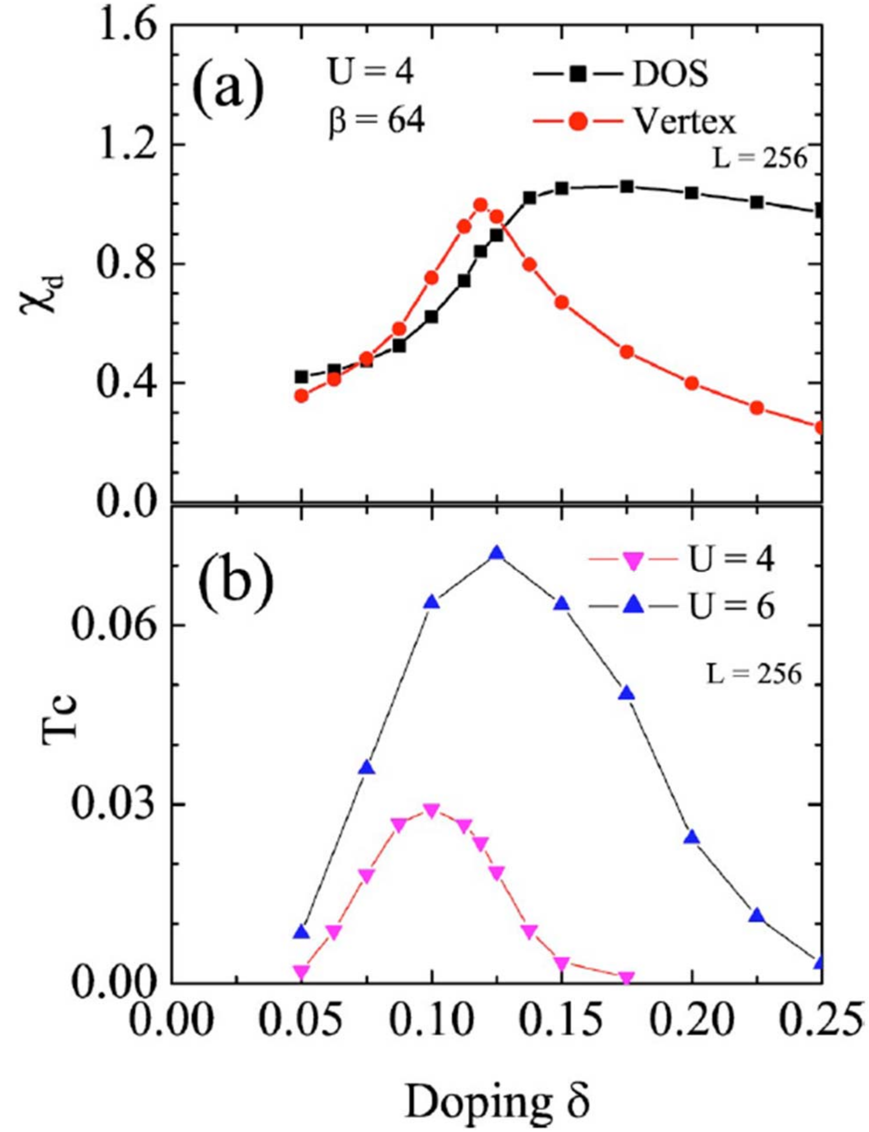
Superconductivity in TPSC



B. Kyung, J.S. Landry and A.-M.S.T., PRB **68**, 174502 (2003)



BCS vs AFM mediated SC

- Symmetry from wave vector of AFM
- Dominant wave vector from shape of Fermi surface
- For given shape of FS, T_c increases with U
- $N(0)$ not so important
- Competition with pseudogap => optimal t'
- T_c above or below RC regime, but $\xi > a$

Hassan, Davoudi, Kyung, A.-M.S.T.
Phys. Rev. B **77**, 094501 (2008)

Outline

- Weak to intermediate coupling
  - TPSC
  - e-doped cuprates
- **A phase at weak and at strong coupling**
- h-doped cuprates as doped Mott insulators
- Cluster Dynamical Mean-Field Theory
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  - Organics
  - High Tc

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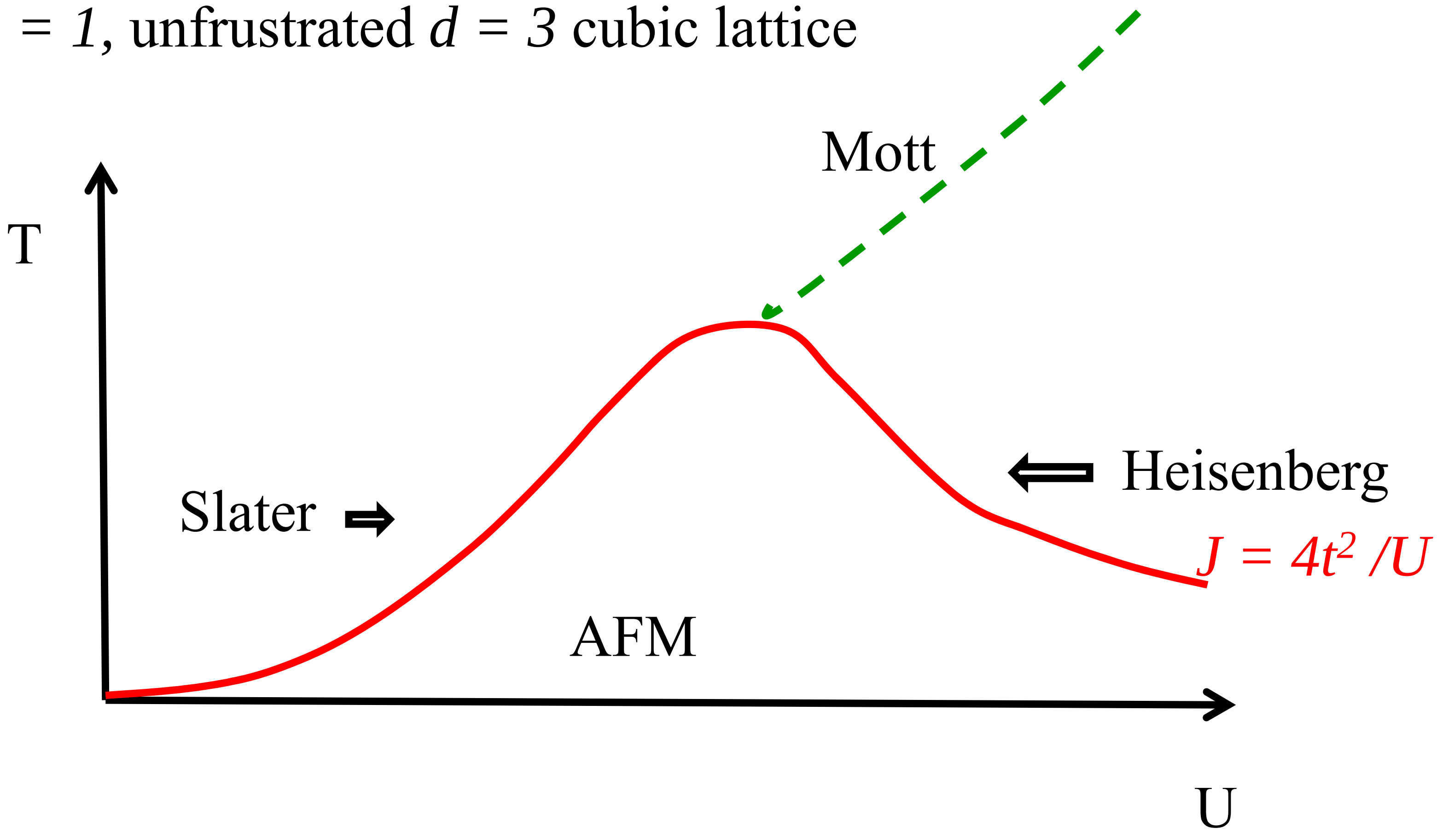
What is a phase?

Weak vs strong coupling

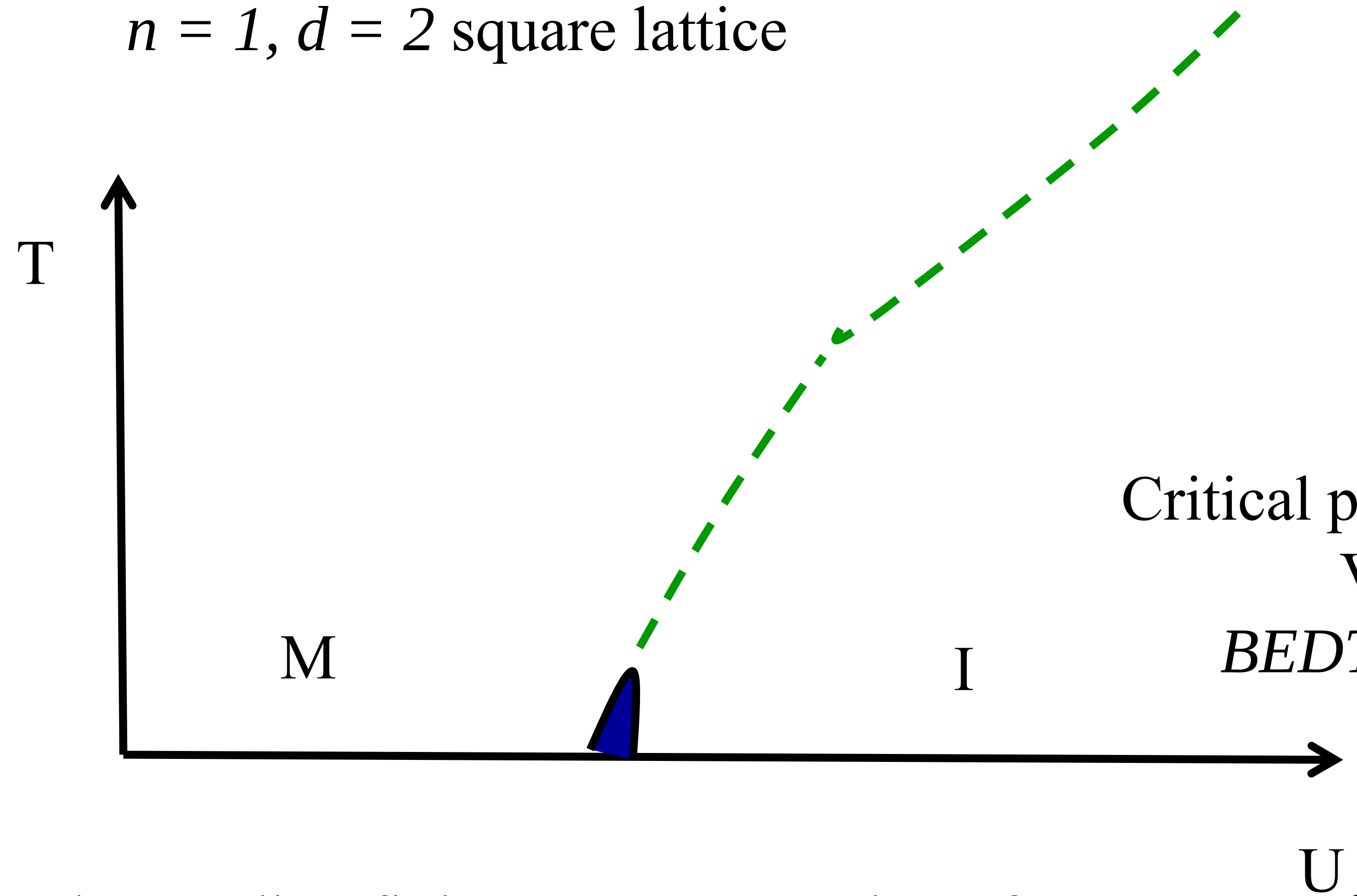
Local moment and Mott transition

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



Local moment and Mott transition

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 $T = 0$

Superconducting phase

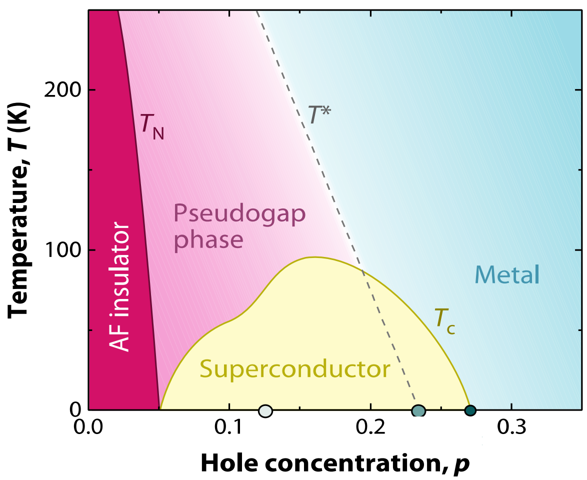
- Emergent:
  - Same broken symmetry *U(1)* for s-wave,
  - *U(1)* and C_{4v} for d-wave
  - Single-Particle gap, point or line node.
    - *T* dependence of C_p and κ at low *T*
  - Goldstone modes (Higgs)

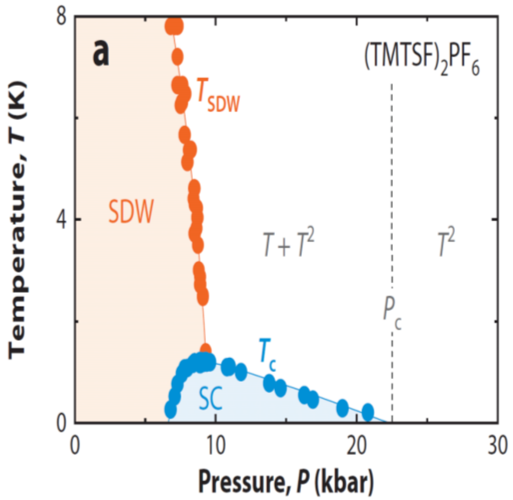
Superconductivity not universal even with phonons: weak or strong coupling

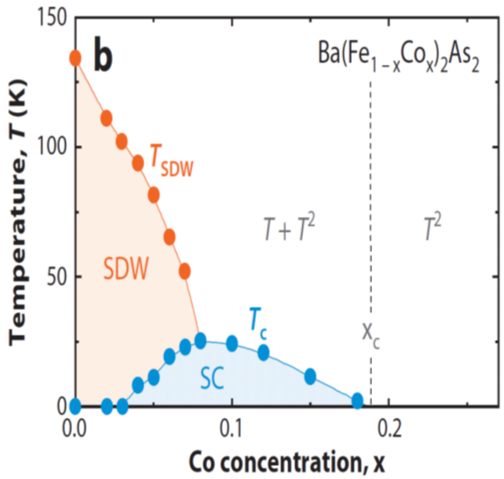
- In BCS universal ratios: e.g. $\Delta/k_B T_c$
  - Would never know the mechanism for sure if only BCS!

A phase: Superconducting

AFM and superconductivity







L. Taillefer, Annual Reviews of CMP 2010

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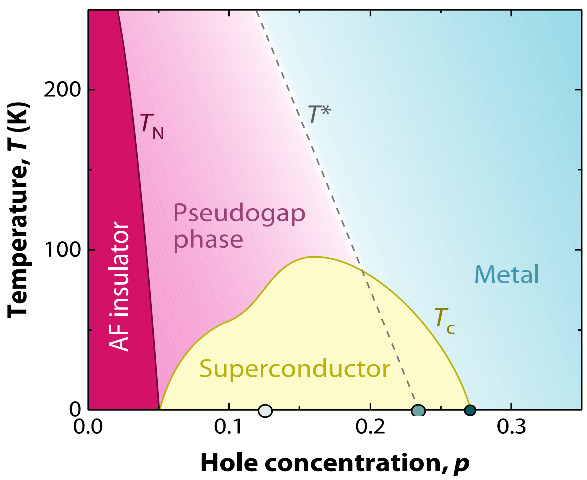
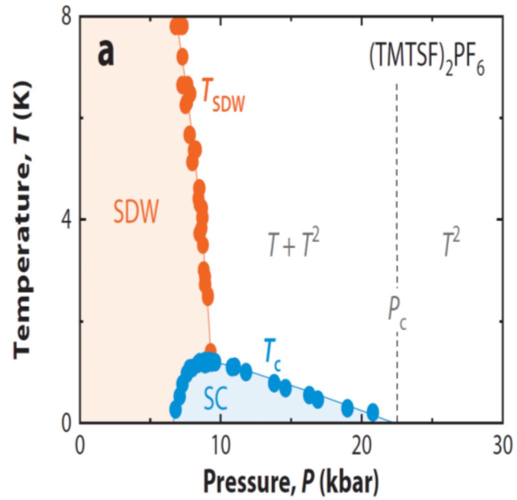
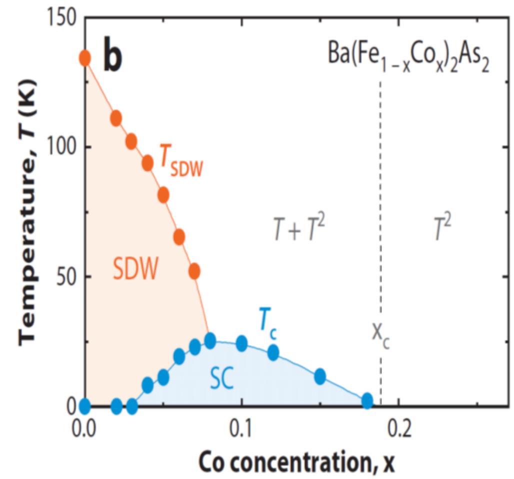
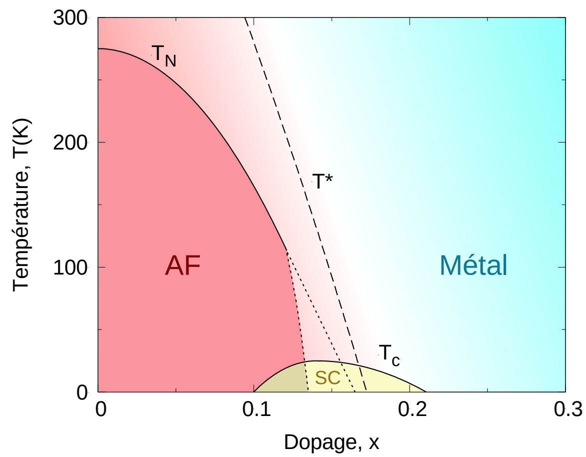
Weakly or strongly correlated?









L. Taillefer, Annual Reviews of CMP 2010

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Hole-doped cuprates as Mott insulators

Mott-Ioffe-Regel limit

$$\sigma = \frac{ne^2\tau}{m}$$

$$k_F\ell = \frac{2\pi}{\lambda_F}\ell \sim 2\pi$$

$$\sigma_{MIR} = \frac{e^2}{\hbar d}$$

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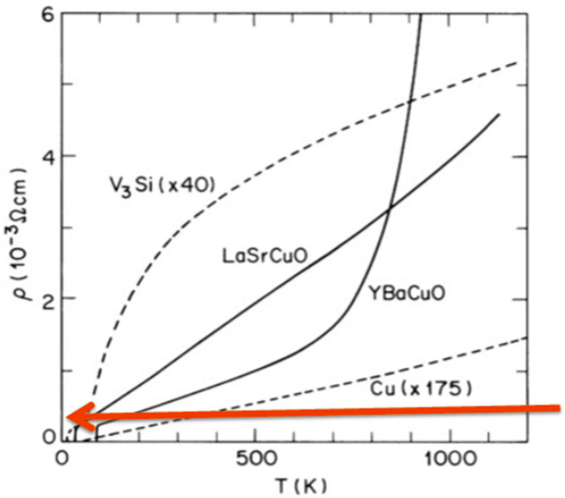
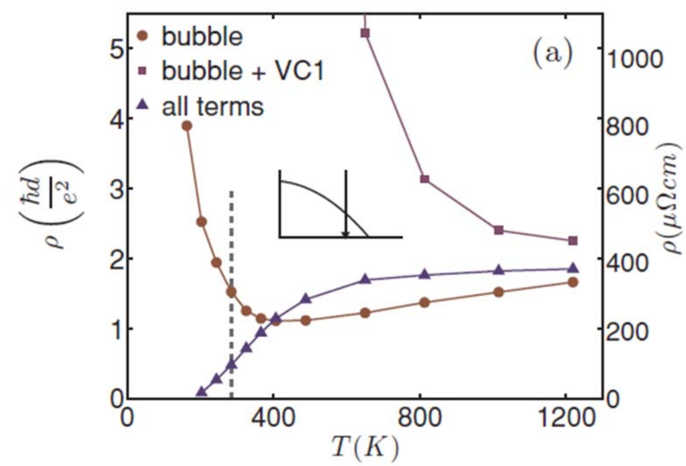
Hole-doped cuprates and MIR limit



Gurvitch & Fiory
PRL 59, 1337
(1987)

MIR limit
Mean-free path
~ Fermi wavelength



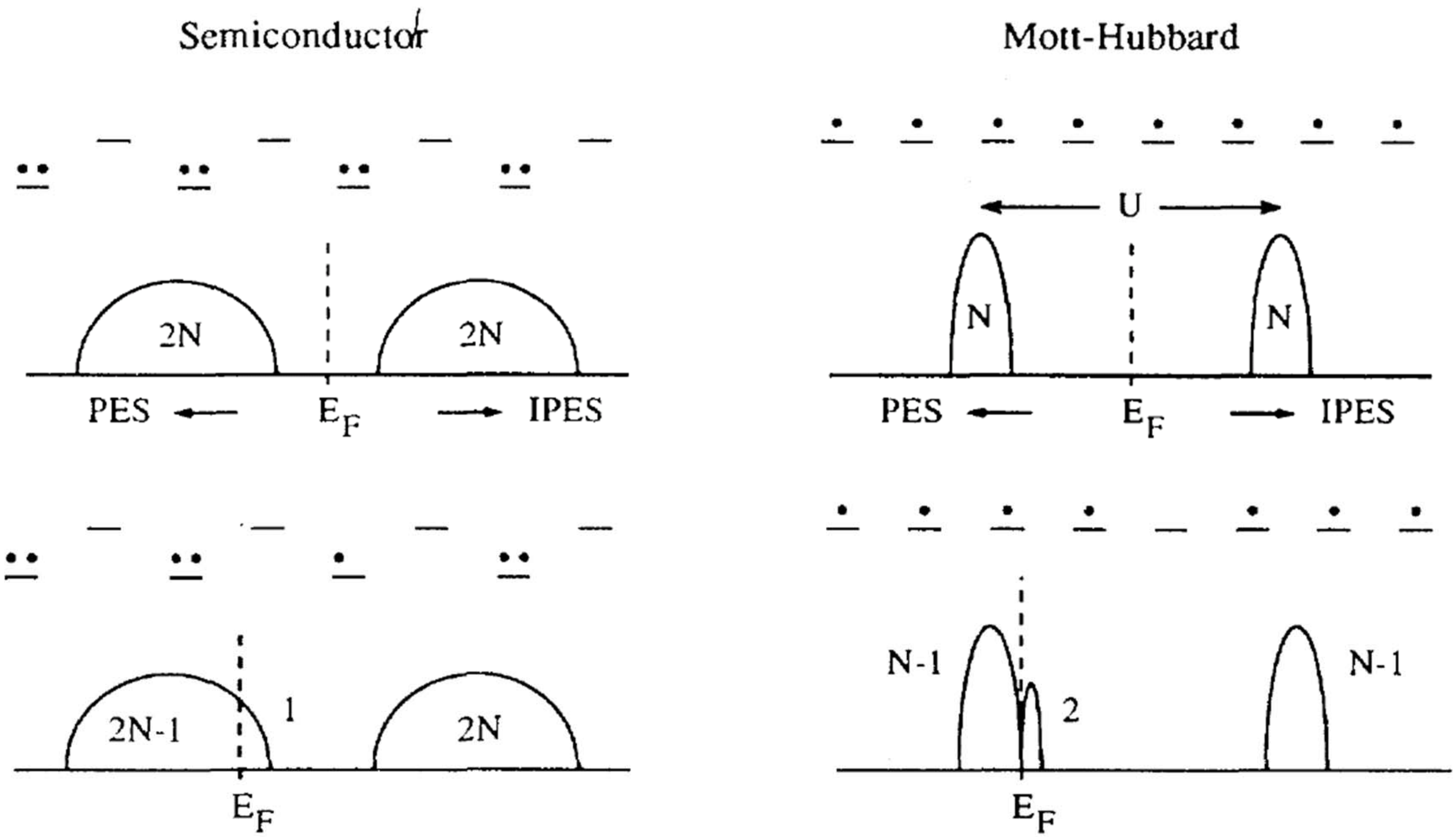
LSCO 17%, YBCO optimal

Dominic Bergeron et al. TPSC
PRB **84**, 085128 (2011)

PHYSICAL REVIEW B **84**, 085128 (2011)

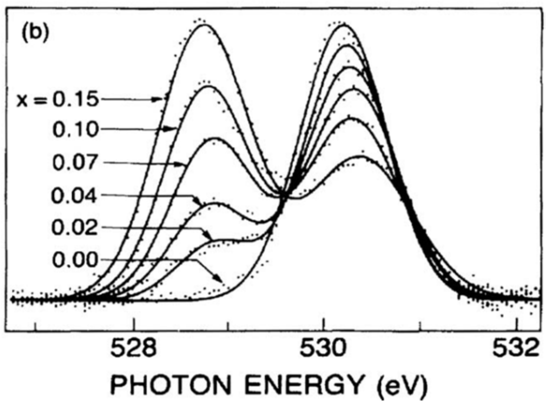
Optical and dc conductivity of the two-dimensional Hubbard model in the pseudogap regime and across the antiferromagnetic quantum critical point including vertex corrections

Spectral weight transfer

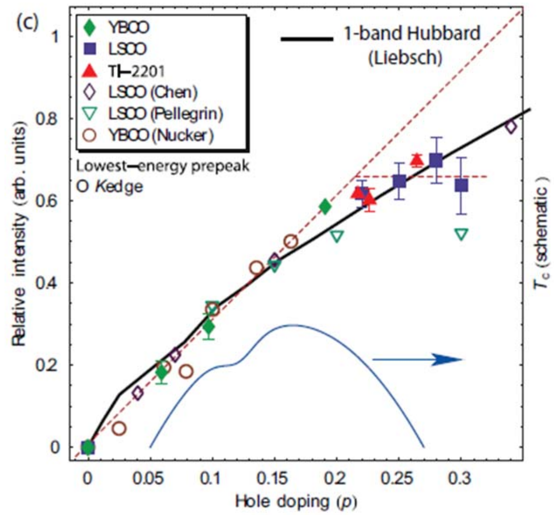


Meinders *et al.* PRB **48**, 3916 (1993)

Experiment: X-Ray absorption



Chen et al. PRL **66**, 104 (1991)



Peets et al. PRL **103**, (2009),
Phillips, Jarrell PRL , vol. **105**, 199701 (2010)

Number of low energy states above ω = 0 scales as *2x* +
Not as 1+x as in Fermi liquid

Meinders *et al.* PRB **48**, 3916 (1993)

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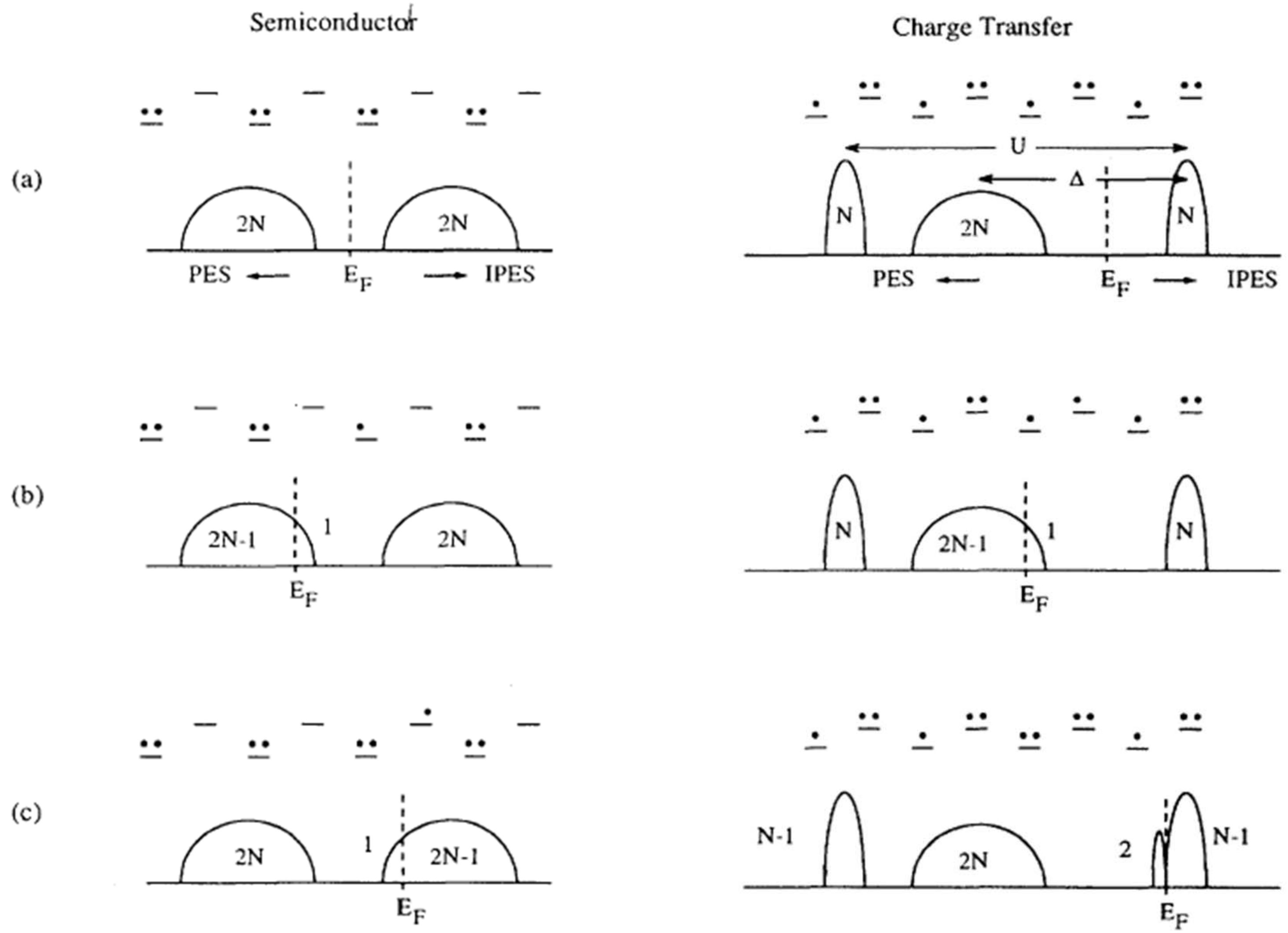
Charge-transfer insulator



Meinders *et al.* PRB **48**, 3916 (1993)

Strong coupling superconductivity

A cartoon strong coupling picture

P.W. Anderson Science 317, 1705 (2007)

$$J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j = J \sum_{\langle i,j \rangle} \left(\frac{1}{2} c_i^\dagger \vec{\sigma} c_i \right) \cdot \left(\frac{1}{2} c_j^\dagger \vec{\sigma} c_j \right)$$

$$d = \langle \hat{d} \rangle = 1/N \sum_{\vec{k}} (\cos k_x - \cos k_y) \langle c_{\vec{k},\uparrow} c_{-\vec{k},\downarrow} \rangle$$

$$H_{MF} = \sum_{\vec{k},\sigma} \varepsilon(\vec{k}) c_{\vec{k},\sigma}^\dagger c_{\vec{k},\sigma} - 4Jm\hat{m} - Jd(\hat{d} + \hat{d}^\dagger) + F_0$$

Pitaevskii Brückner:

Pair state orthogonal to repulsive core of Coulomb interaction

Miyake, Schmitt–Rink, and Varma
P.R. B **34**, 6554-6556 (1986)

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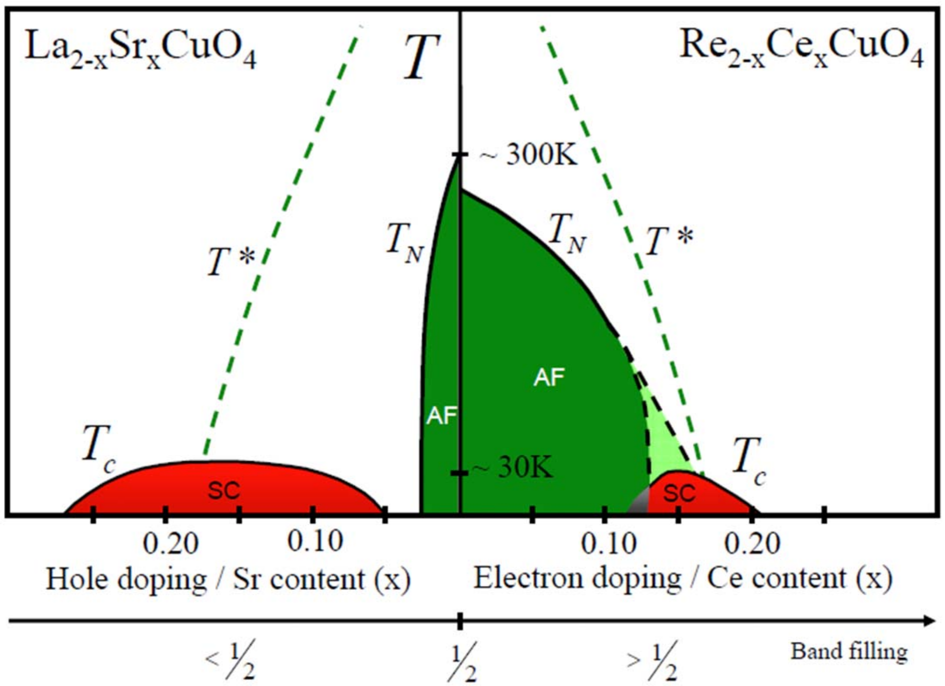
High-temperature superconductors

Armitage, Fournier, Greene, RMP (2009)



What is under the dome?
Mott Physics away from $n = 1$

- Competing order
  - Current loops: Varma, PRB **81,** 064515 (2010)
  - Stripes or nematic: Kivelson et al. RMP 75 1201(2003); J.C.Davis
  - d-density wave : Chakravarty, Nayak, Phys. Rev. B **63**, 094503 (2001); Affleck et al. flux phase
  - SDW: Sachdev PRB **80**, 155129 (2009) ...
- Or Mott Physics?
  - RVB: P.A. Lee Rep. Prog. Phys. **71,** 012501 (2008)

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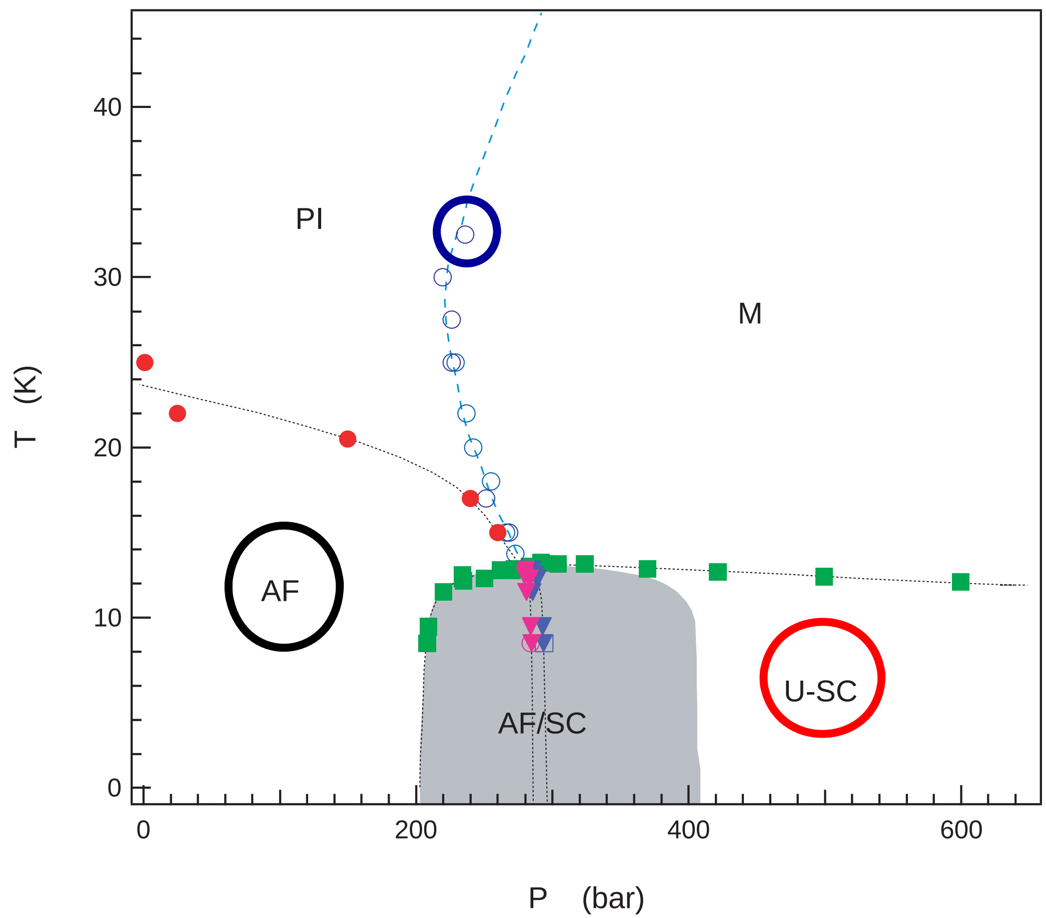
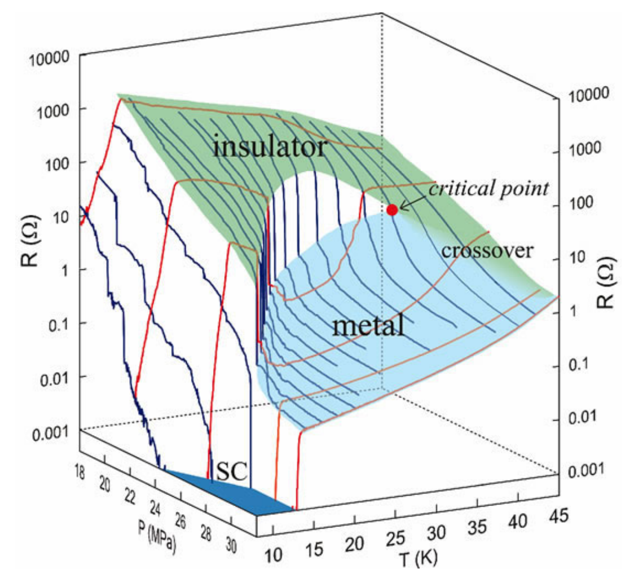
Another strongly correlated superconductor





F. Kagawa, K. Miyagawa, + K. Kanoda
PRB **69** (2004) +Nature **436** (2005)

Phase diagram (X=Cu[N(CN)$_2$]Cl)

S. Lefebvre et al. PRL **85**, 5420 (2000), P. Limelette, et al. PRL **91** (2003)

CIAR The Canadian Institute for Advanced Research

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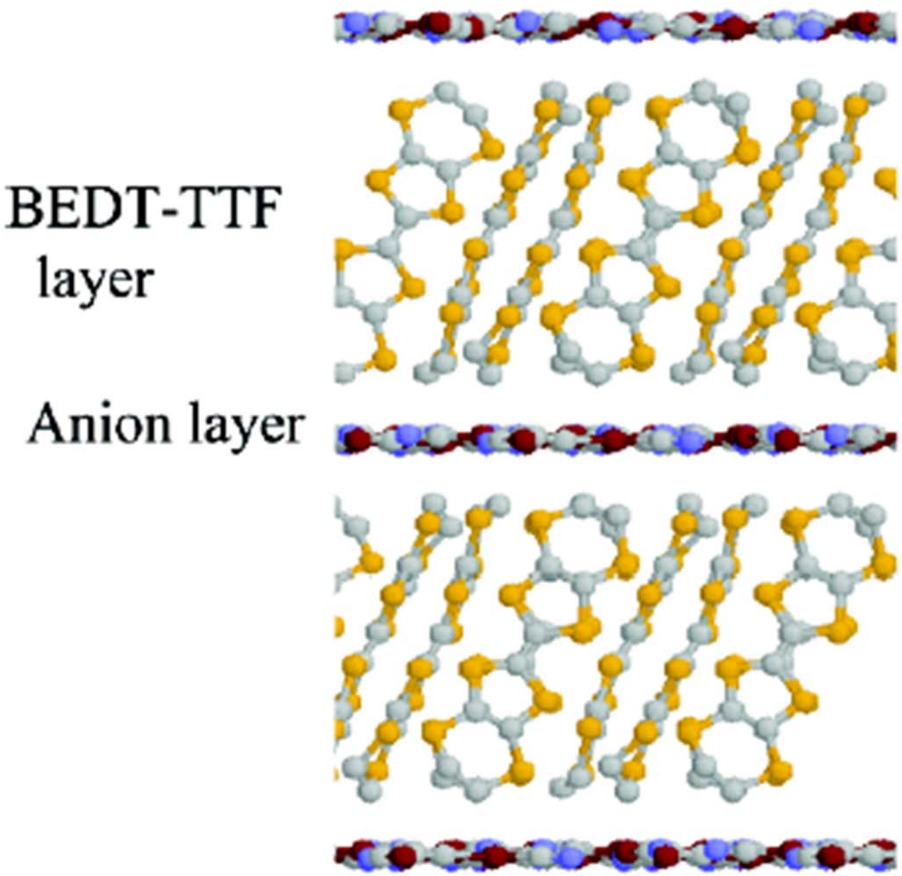
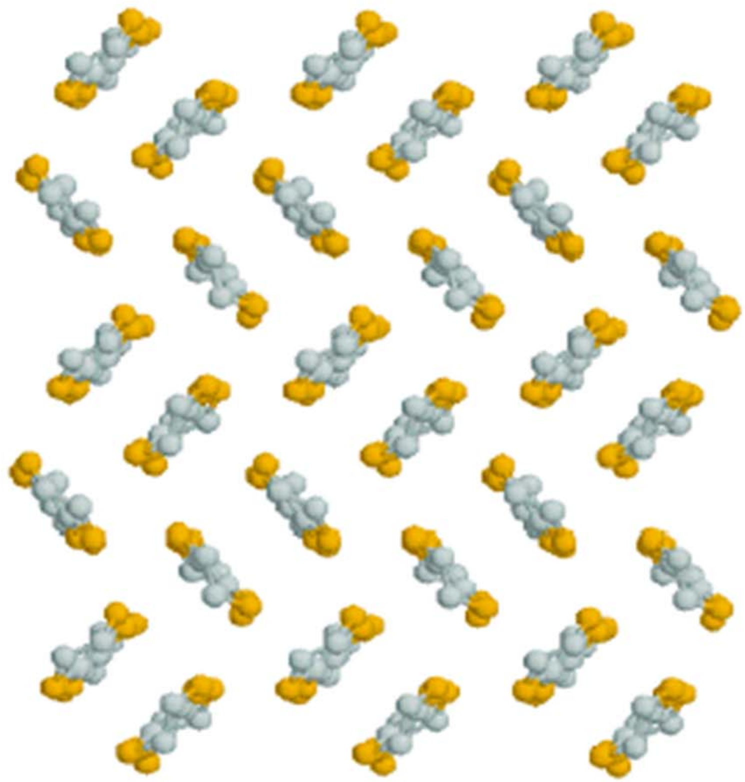
Layered organics (κ–BEDT-X family)





$t \approx 50\,\mathrm{meV}$

$\Rightarrow U \approx 400\,\mathrm{meV}$

$t'/t \sim 0.6 - 1.1$

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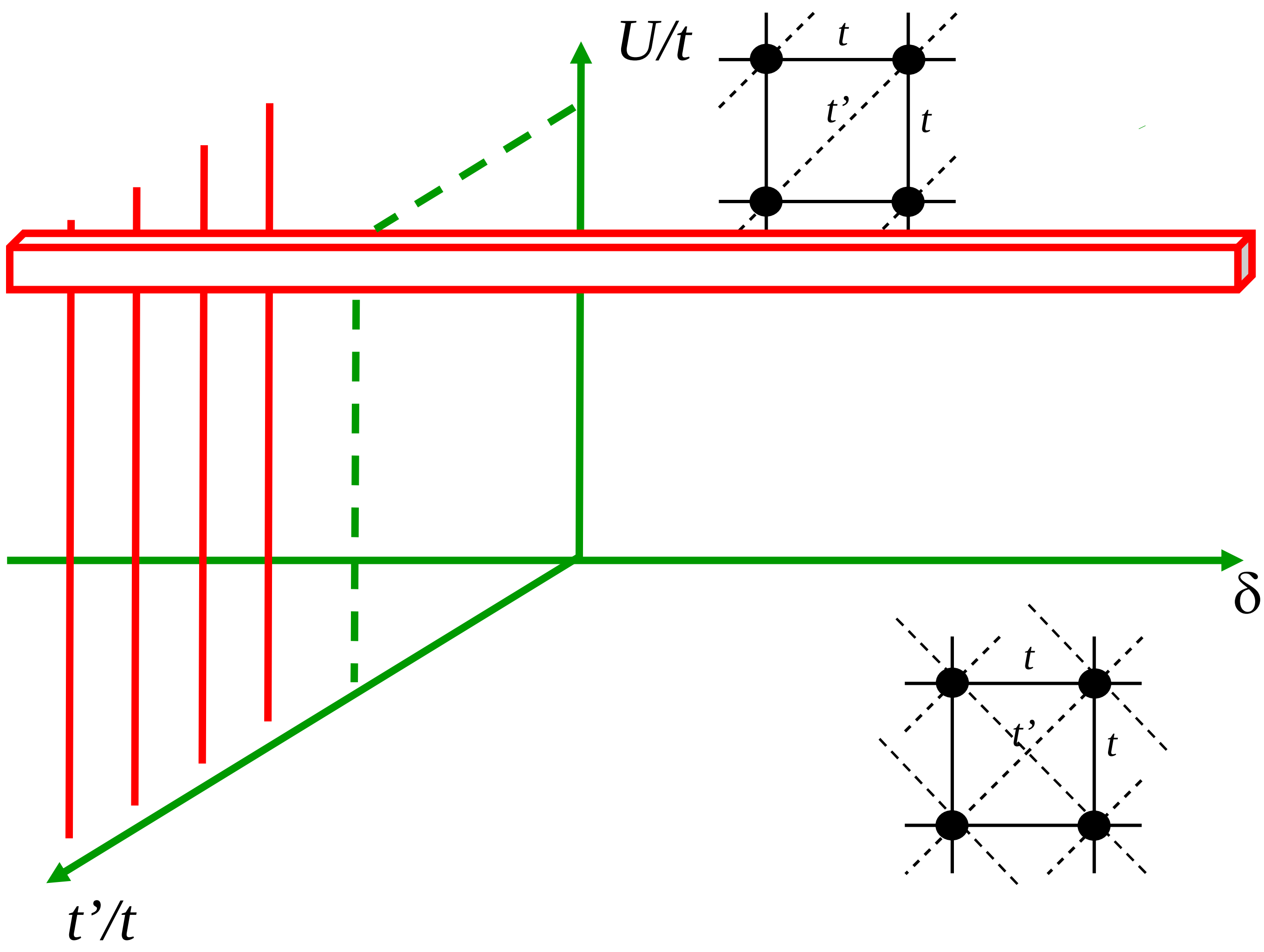
Perspective



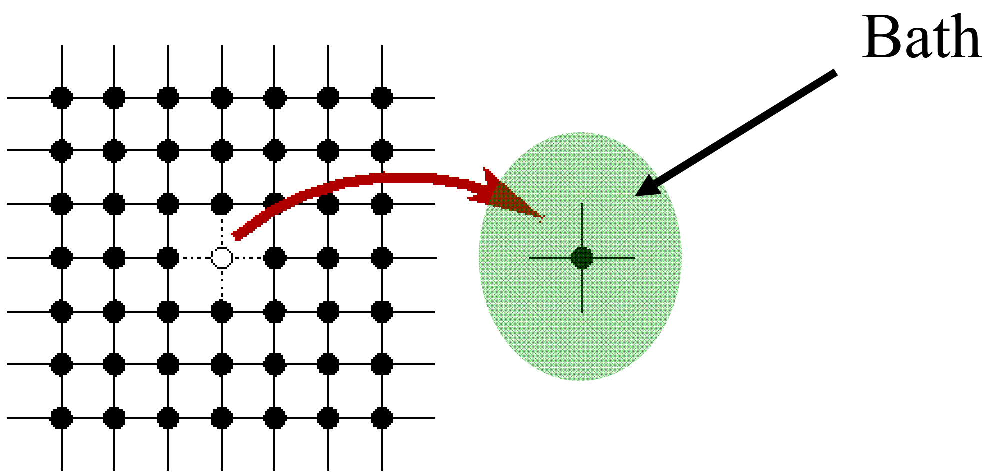
Outline

- Weak to intermediate coupling
  - TPSC
  - e-doped cuprates
- What is a phase
- h-doped as doped Mott insulators
- **Cluster Dynamical Mean-Field Theory**
- Strong coupling superconductivity
  - Organics
  - High Tc

Method

Mott transition and Dynamical Mean-Field Theory. The beginnings in *d = infinity*

- Compute scattering rate (self-energy) of impurity problem.
- Use that self-energy (ω dependent) for lattice.
- Project lattice on single-site and adjust bath so that single-site DOS obtained both ways be equal.

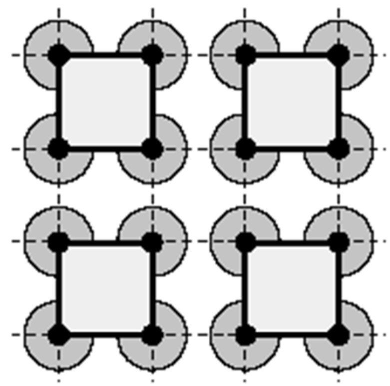


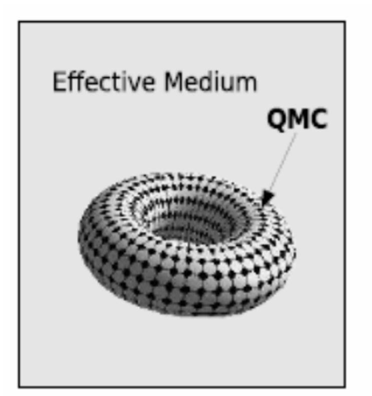
W. Metzner and D. Vollhardt, PRL (1989)
A. Georges and G. Kotliar, PRB (1992)
M. Jarrell PRB (1992)

DMFT, (d = 3)

2d Hubbard: Quantum cluster method

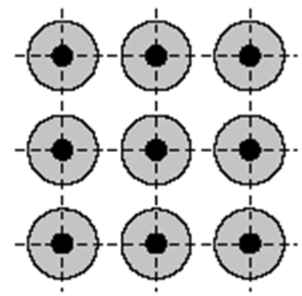
C-DMFT





DCA

DMFT



Hettler …Jarrell…Krishnamurty PRB **58** (1998)
Kotliar et al. PRL **87** (2001)
M. Potthoff *et al.* PRL **91,** 206402 (2003).

REVIEWS
Maier, Jarrell et al., RMP. (2005)
Kotliar *et al.* RMP (2006)
AMST *et al.* LTP (2006)

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Another way to look at this (Potthoff)

$$\Omega_{\mathbf{t}}[G] = \Phi[G] - Tr[(G_{0\mathbf{t}}^{-1} - G^{-1})G] + Tr\ln(-G)$$

$$\frac{\delta\Phi[G]}{\delta G} = \Sigma$$

$$\Omega_{\mathbf{t}}[\Sigma] = \Phi[G] - Tr[\Sigma G] - Tr\ln(-G_{0\mathbf{t}}^{-1} + \Sigma)$$

Still stationary (chain rule)

$$\Omega_{\mathbf{t}}[\Sigma] = F[\Sigma] - Tr\ln(-G_{0\mathbf{t}}^{-1} + \Sigma)$$

M. Potthoff, Eur. Phys. J. B 32, 429 (2003).

SFT : Self-energy Functional Theory

With $F[\Sigma]$ Legendre transform of Luttinger-Ward funct.

$$\Omega_{\mathbf{t}}[\Sigma] = F[\Sigma] + \mathrm{Tr}\ln(-(G_0^{-1} - \Sigma)^{-1})$$

is stationary with respect to Σ and equal to grand potential there.

$$\Omega_{\mathbf{t}}[\Sigma] = \Omega_{\mathbf{t}'}[\Sigma] - \mathrm{Tr}\ln(-(G_0'^{-1} - \Sigma)^{-1}) + \mathrm{Tr}\ln(-(G_0^{-1} - \Sigma)^{-1}).$$

Vary with respect to parameters of the cluster (including Weiss fields)

Variation of the self-energy, through parameters in $H_0(\mathbf{t'})$

M. Potthoff, Eur. Phys. J. B 32, 429 (2003).

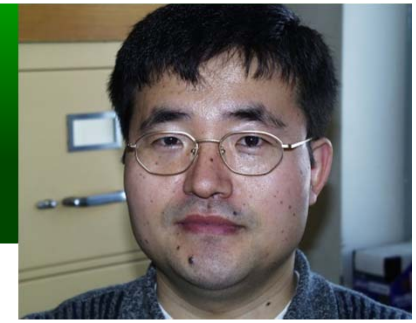
+ and -

- Long range order:
  - Allow symmetry breaking in the bath (mean-field)
- Included:
  - Short-range dynamical and spatial correlations
- Missing:
  - Long wavelength fluctuations

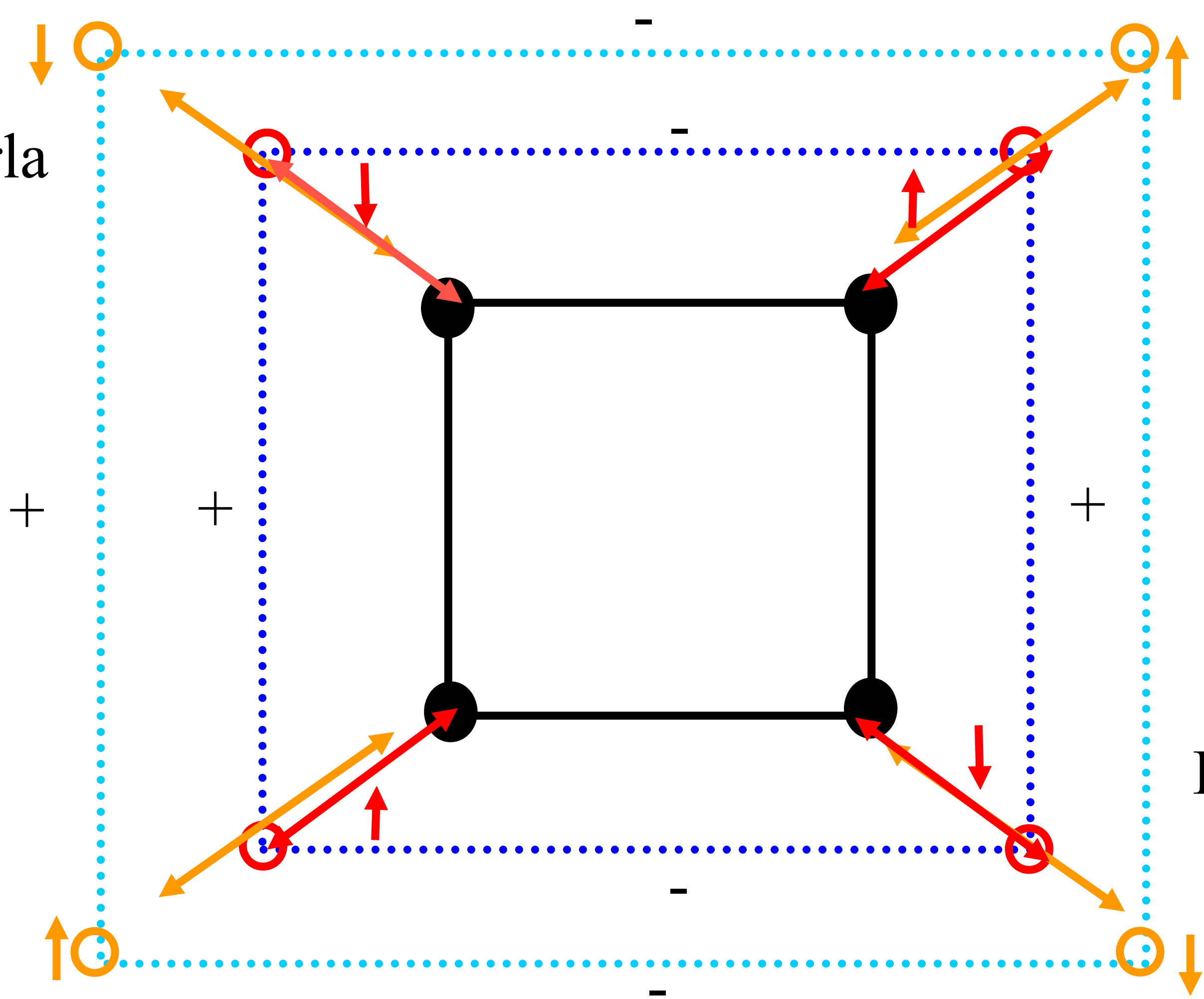
Two solvers for the cluster-in-a-bath problem

Competition AFM-dSC

S. Kancharla



B. Kyung



David Sénéchal

See also, Capone and Kotliar, Phys. Rev. B 74, 054513 (2006),
Macridin, Maier, Jarrell, Sawatzky, Phys. Rev. B 71, 134527 (2005)

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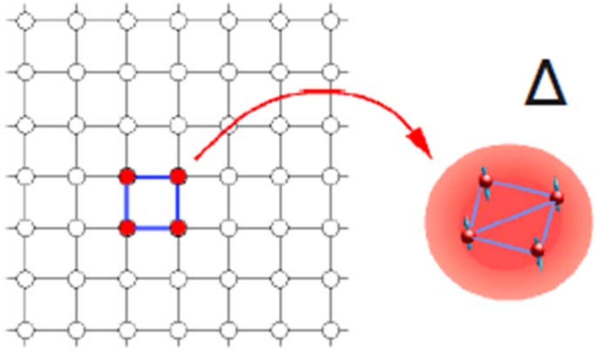
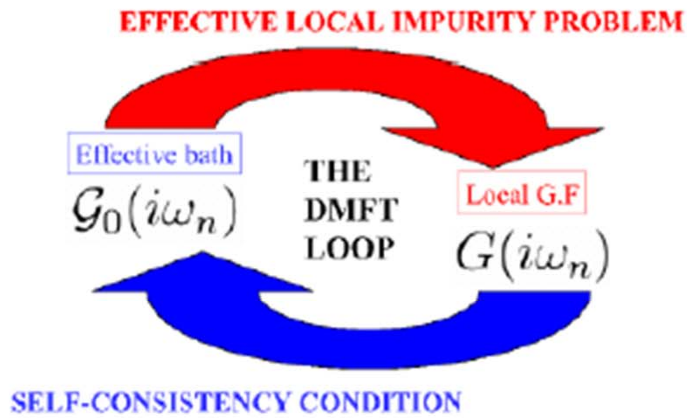
C-DMFT

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





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

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

At finite T, solving cluster in a bath problem

- Continuous-time Quantum Monte Carlo calculations to sum all diagrams generated from expansion in powers of hybridization.

  – P. Werner, A. Comanac, L. de' Medici, M. Troyer, and A. J. Millis, Phys. Rev. Lett. **97**, 076405 (2006).

  – K. Haule, Phys. Rev. B **75**, 155113 (2007).

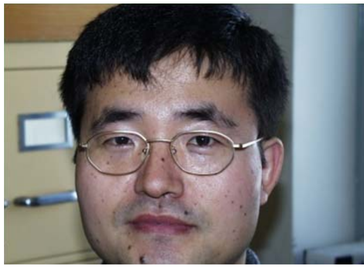
Outline

- Weak to intermediate coupling
  - TPSC
  - e-doped cuprates
- A phase at weak and at strong coupling
- h-doped cuprates as doped Mott insulators
- Cluster Dynamical Mean-Field Theory
- **Strong coupling superconductivity**
  - Organics
  - High Tc

$T = 0$ phase diagram $n = 1$

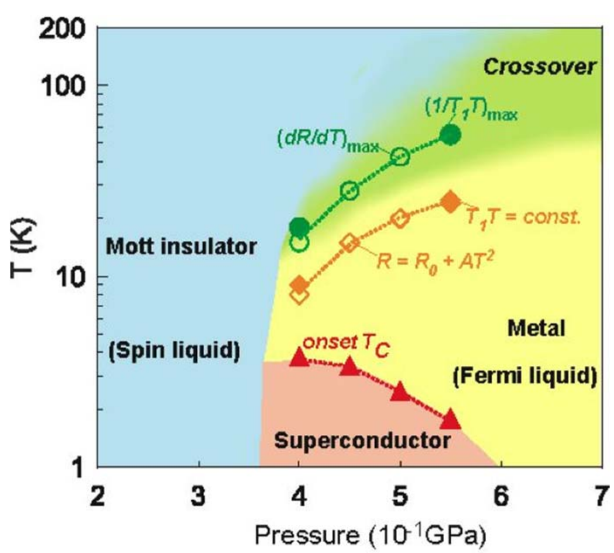
Phase diagram

Exact diagonalization as solver for cluster-in-a bath problem ($T=0$).

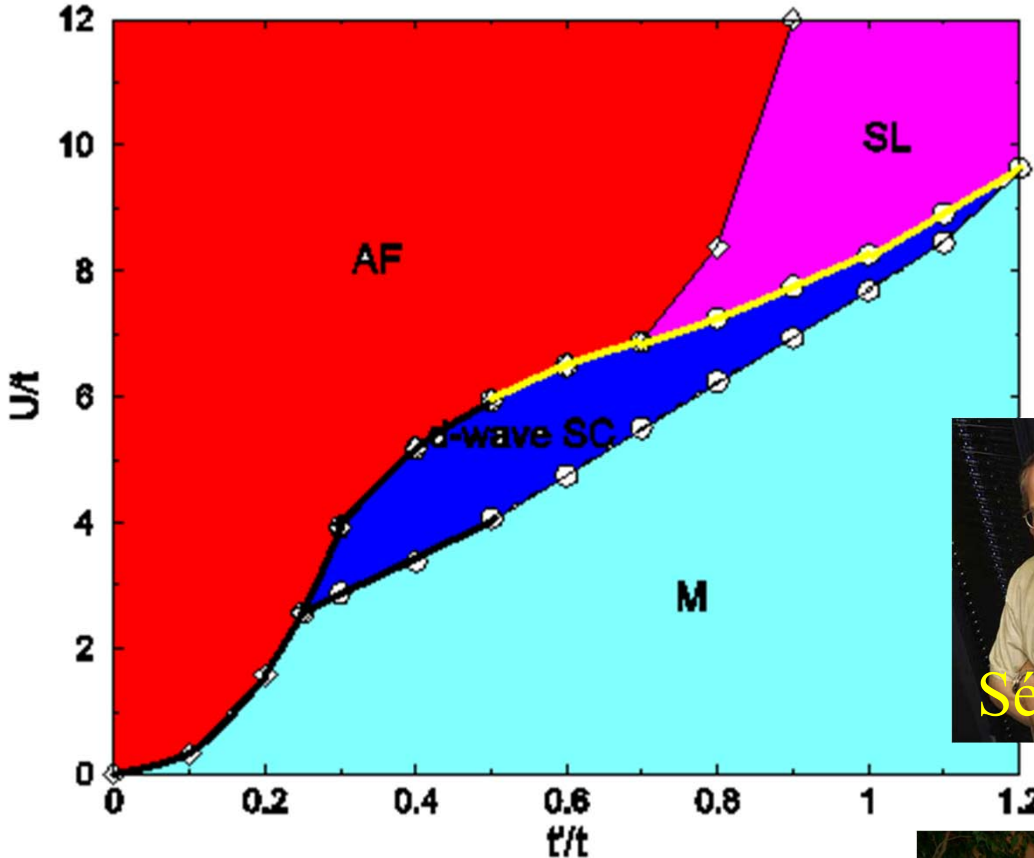


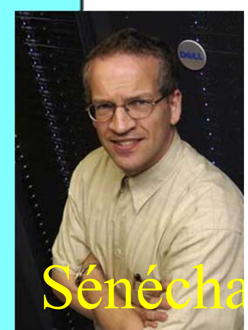
Theoretical phase diagram BEDT

X= $Cu_2(CN)_3$ (t'~ t)



Y. Kurisaki, et al.
Phys. Rev. Lett. **95**, 177001(2005)





Kyung, A.-M.S.T. PRL 97, 046402 (2006)

Sénéchal, Sahebsara, Phys. Rev. Lett. **97**, 257004

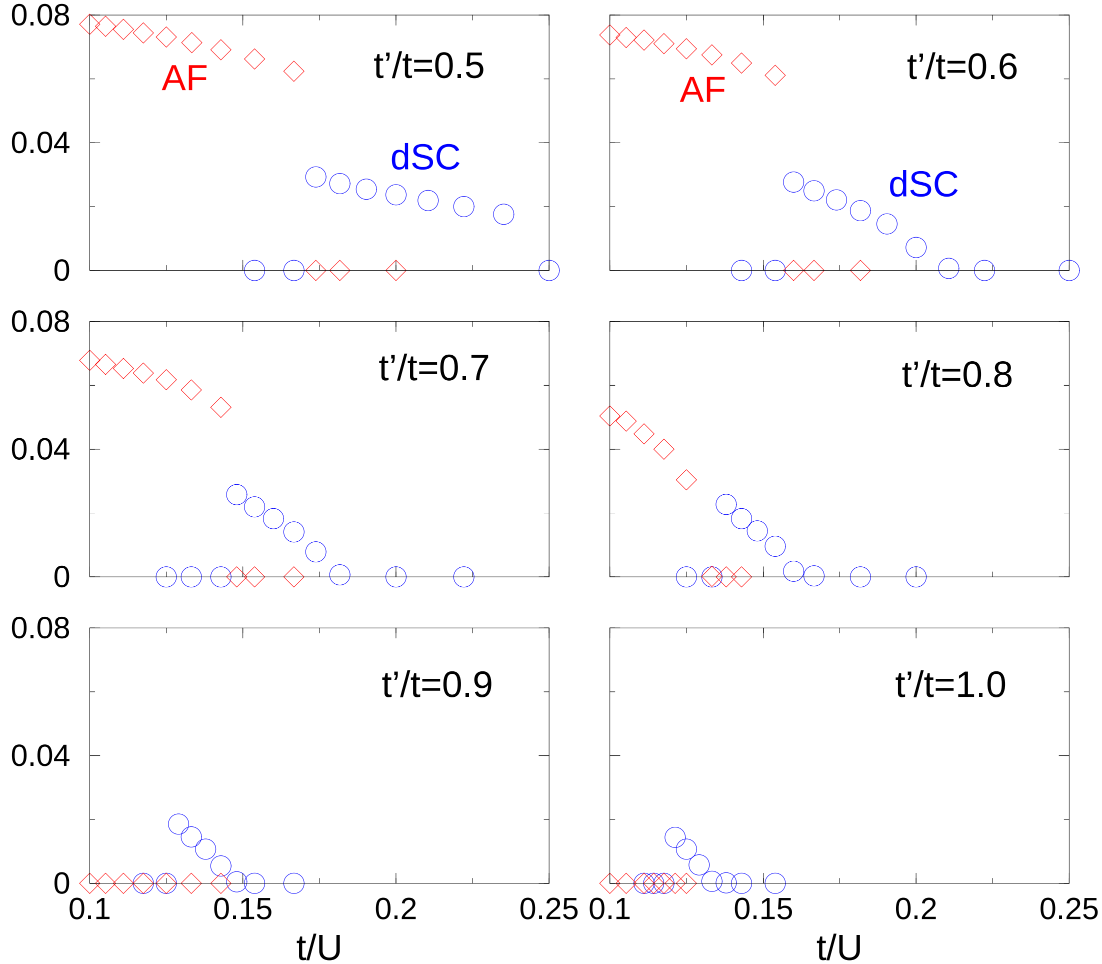
Y. Shimizu, et al. Phys. Rev. Lett. **91**, (2003)

AFM and dSC order parameters for various t'/t

- Discontinuous jump
- Strongest superconductivity near the Mott insulator!

X	$Cu[N(CN)_2]Br$	$Cu(NCS)_2$	$Cu_2(CN)_3$
t'/t	0.68	0.84	1.06
T_c	11.6	10.4	3.9

AF multiplied by 0.1



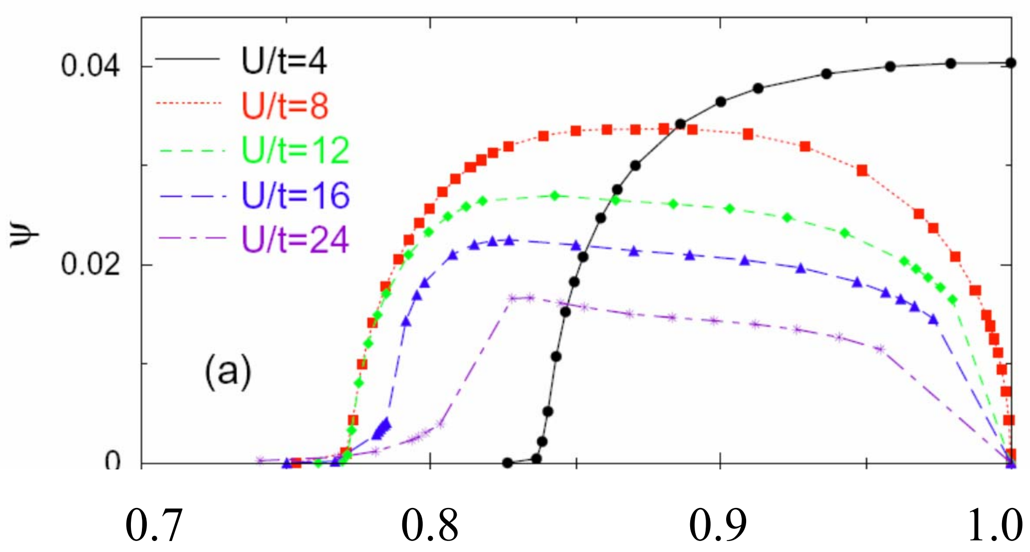
Kyung, A.-M.S.T. PRL 97, 046402 (2006)

$T = 0$ phase diagram: cuprates

Phase diagram

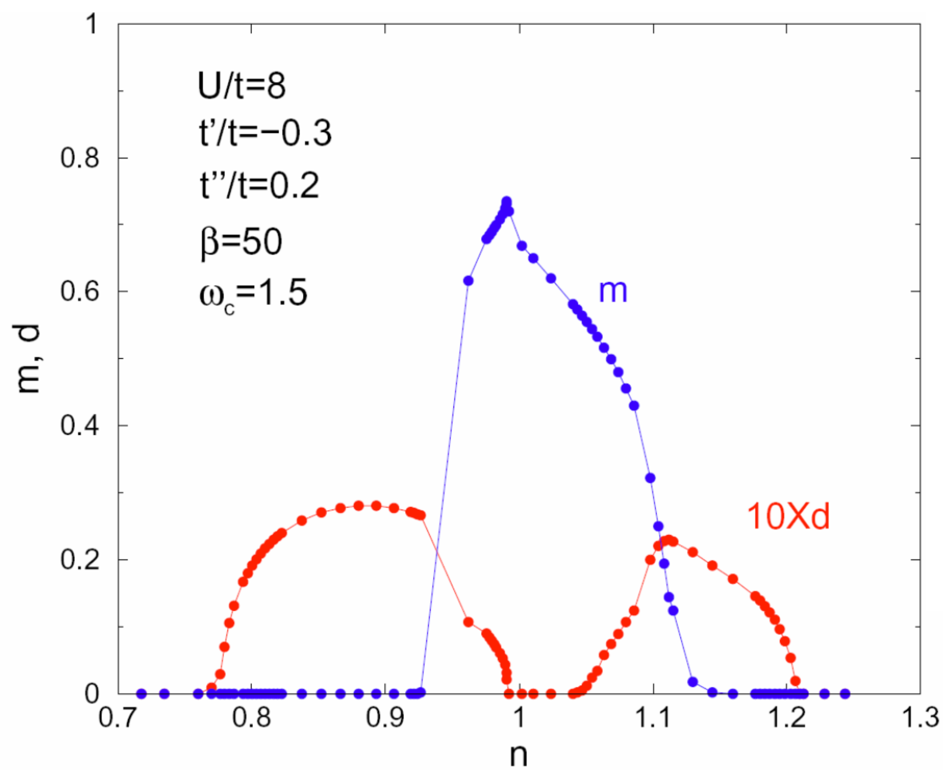
Exact diagonalization as impurity solver ($T=0$).

Dome vs Mott (CDMFT)

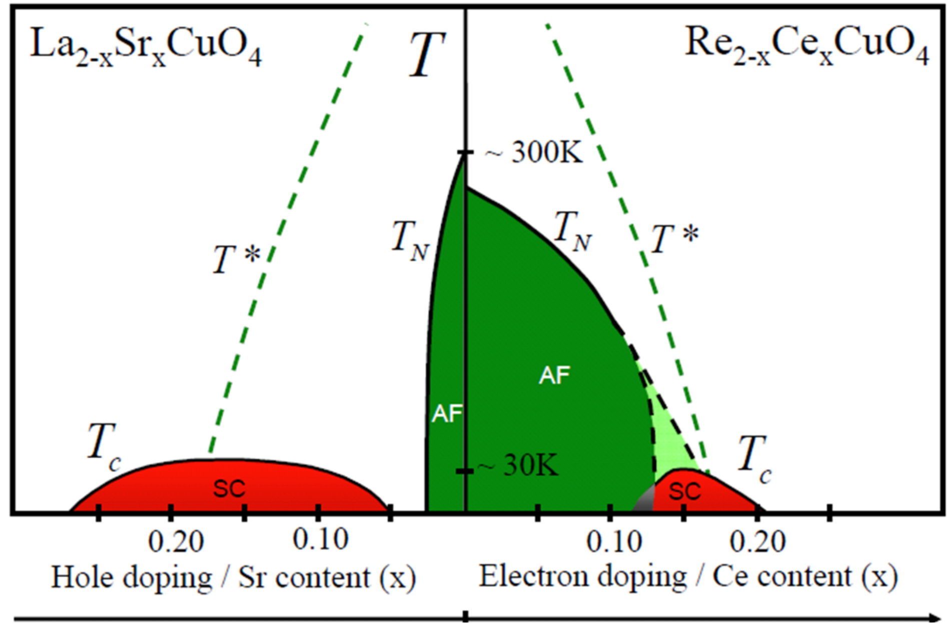


Kancharla, Kyung, Civelli, Sénéchal, Kotliar AMST Phys. Rev. B (2008)

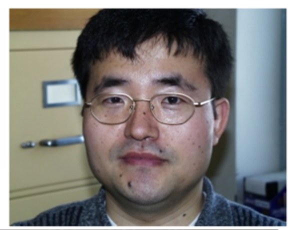
CDMFT global phase diagram



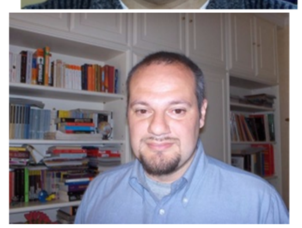
Kancharla, Kyung, Civelli, Sénéchal, Kotliar AMST Phys. Rev. B (2008)
AND Capone, Kotliar PRL (2006)



Armitage, Fournier, Greene, RMP (2009)





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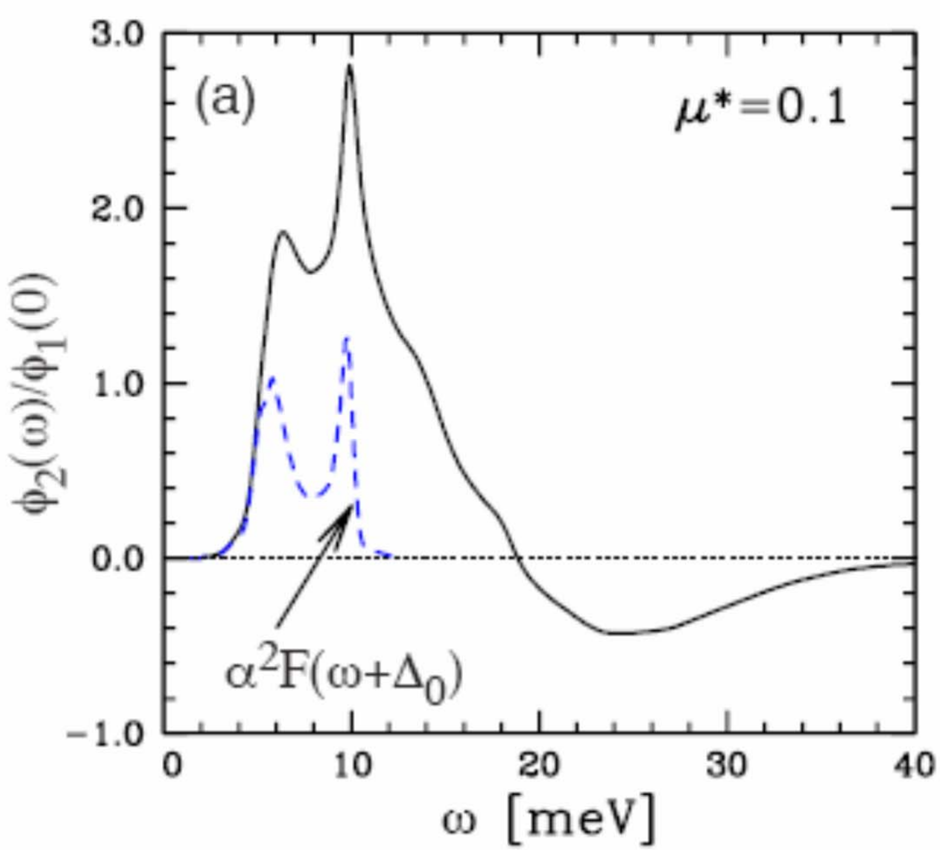
$T = 0$ phase diagram

The glue

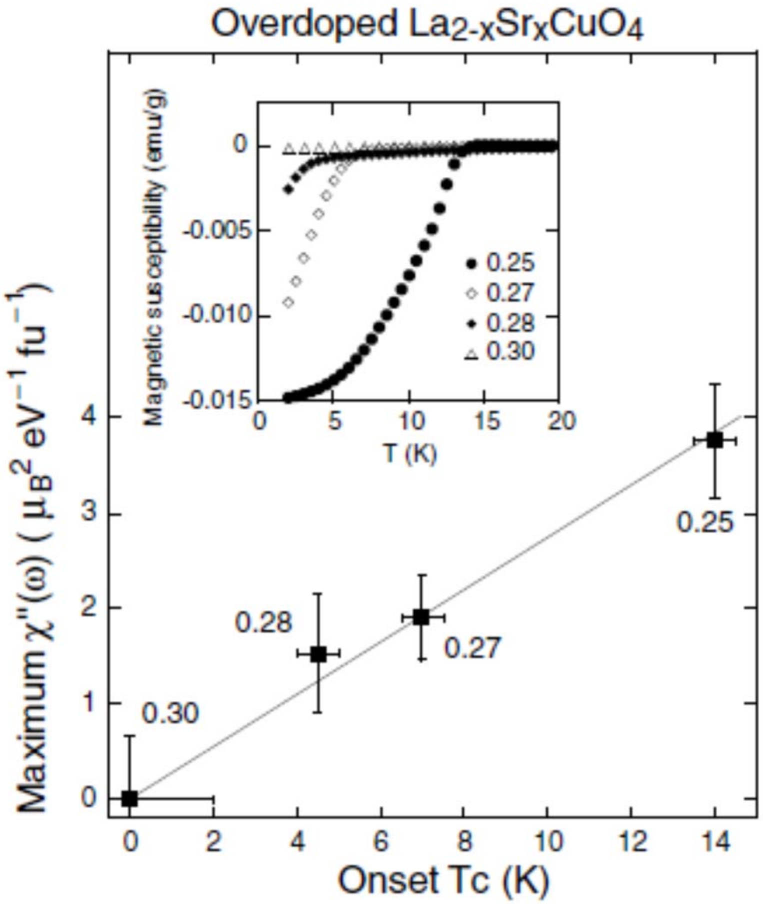
Im Σ_{an} and electron-phonon in Pb

Maier, Poilblanc, Scalapino, PRL (2008)

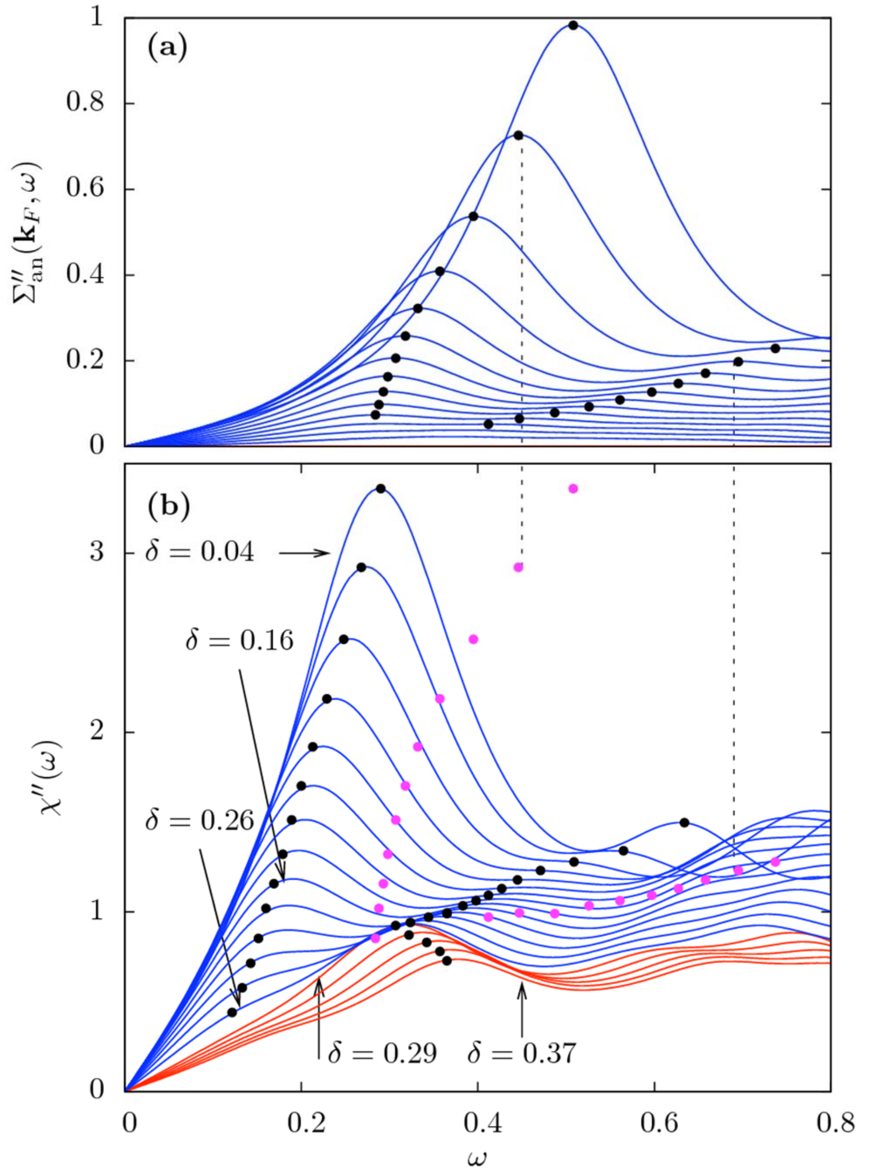


The glue

Kyung, Sénéchal, Tremblay, Phys. Rev. B **80,** 205109 (2009)



Wakimoto … Birgeneau PRL (2004)



The glue and neutrons

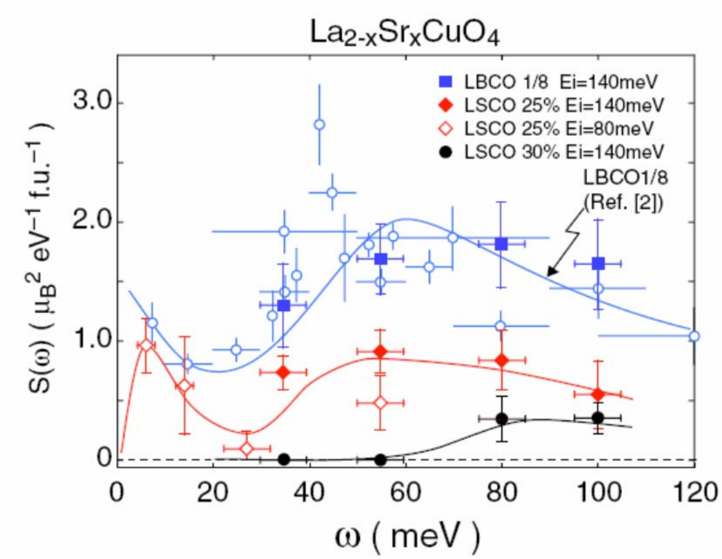
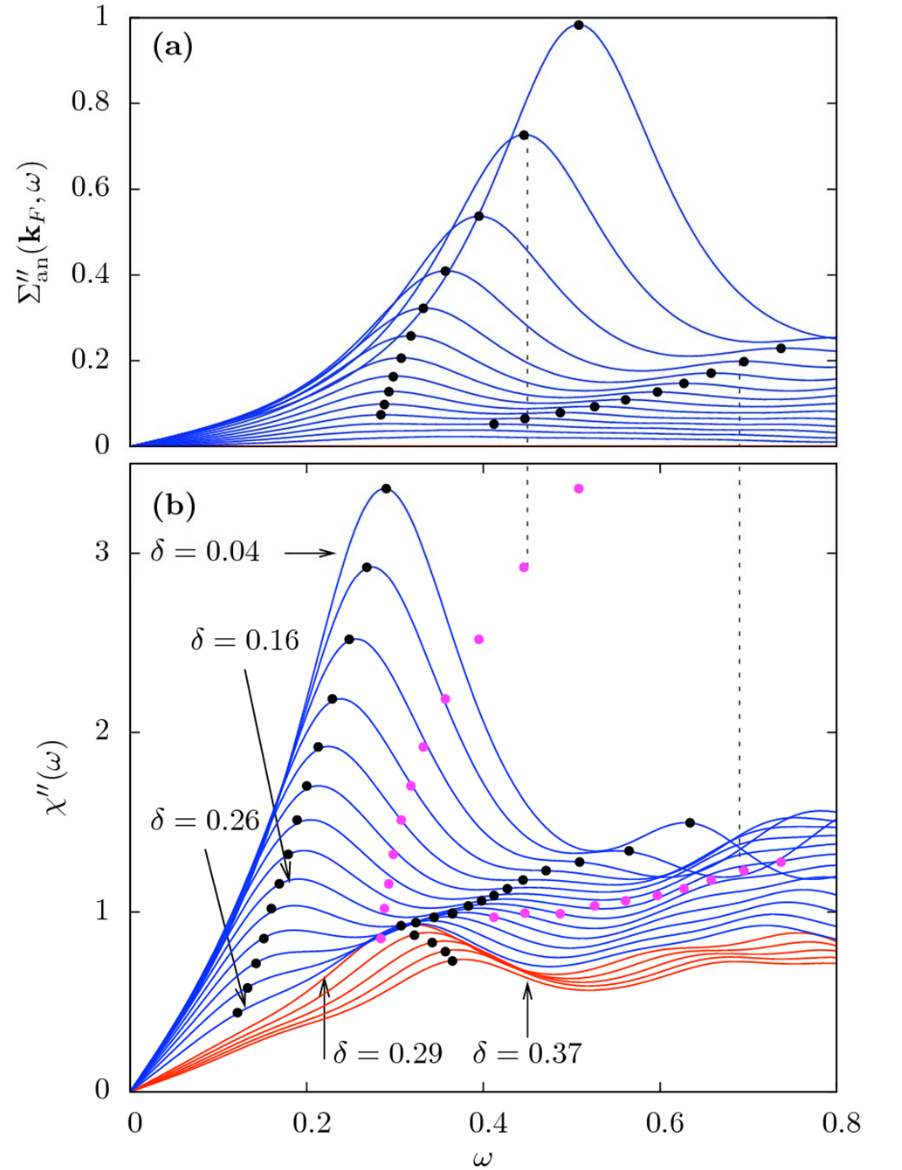


FIG. 3 (color online). **Q**-integrated dynamic structure factor $S(\omega)$ which is derived from the wide-H integrated profiles for LBCO $1/8$ (squares), LSCO $x = 0.25$ (diamonds; filled for E_i = 140 meV, open for E_i = 80 meV), and $x = 0.30$ (filled circles) plotted over $S(\omega)$ for LBCO 1/8 (open circles) from [2]. The solid lines following data of LSCO $x = 0.25$ and 0.30 are guides to the eyes.



Wakimoto … Birgeneau PRL (2007);
PRL (2004)

Frequencies important for pairing

Bumsoo Kyung

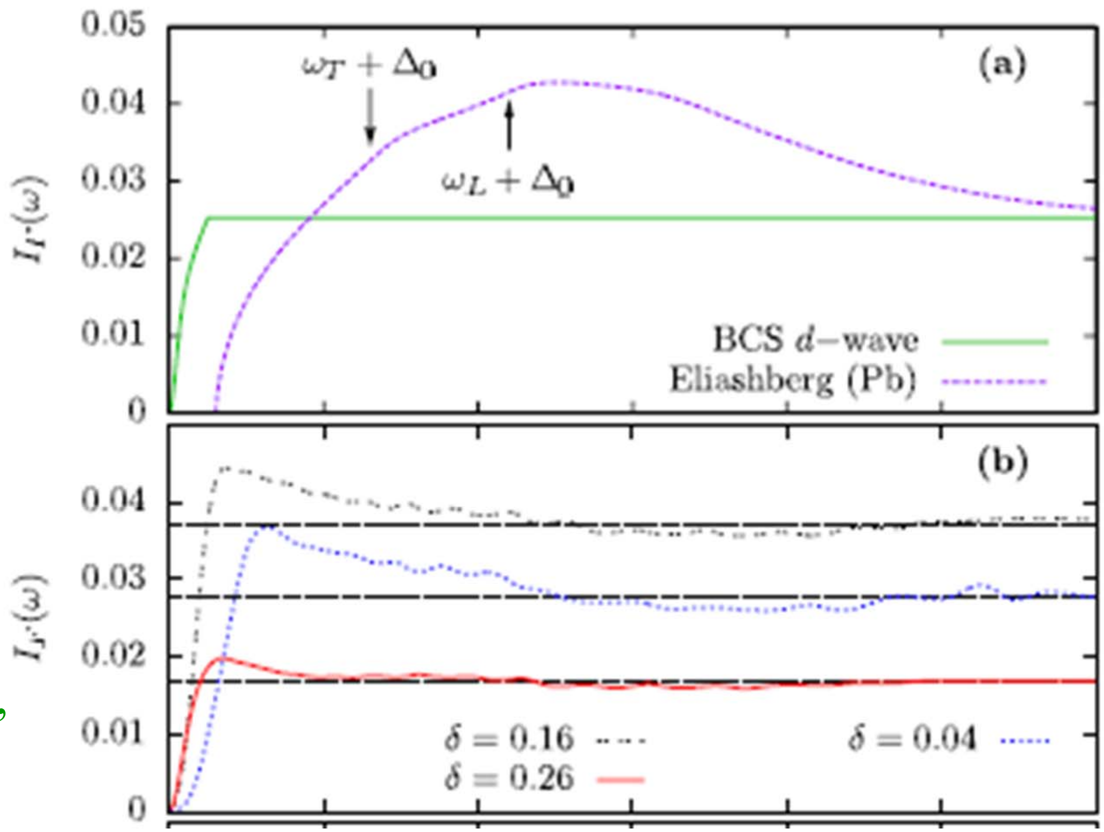
David Sénéchal

$$I_F(\omega) \equiv -\int_0^{\omega} \frac{d\omega'}{\pi} \mathrm{Im}\, F_{ij}^R(\omega')$$

Cumulative Order Parameter

$\langle c_{i\uparrow} c_{j\downarrow} \rangle$ for $\omega \to \infty$

B. Kyung, D. Sénéchal, and A.-M.S.T, Phys. Rev. B **80**, 205109 (2009).



Resilience to near-neighbor repulsion *V*

In mean-field, $J - V$

$J = 130\ meV$
$V = 400\ meV$

The $\ln(E_F/\omega_D)$ necessary to screen V, for μ^* not enough

Weak-coupling: $V < U\ (U/W)$ for survival of d-wave

S. Raghu, E. Berg, A. V. Chubukov, and S. A. Kivelson, PRB **85**, 024516 (2012).
S. Onari, R. Arita, K. Kuroki, and H. Aoki, PRB **70**, 094523 (2004).

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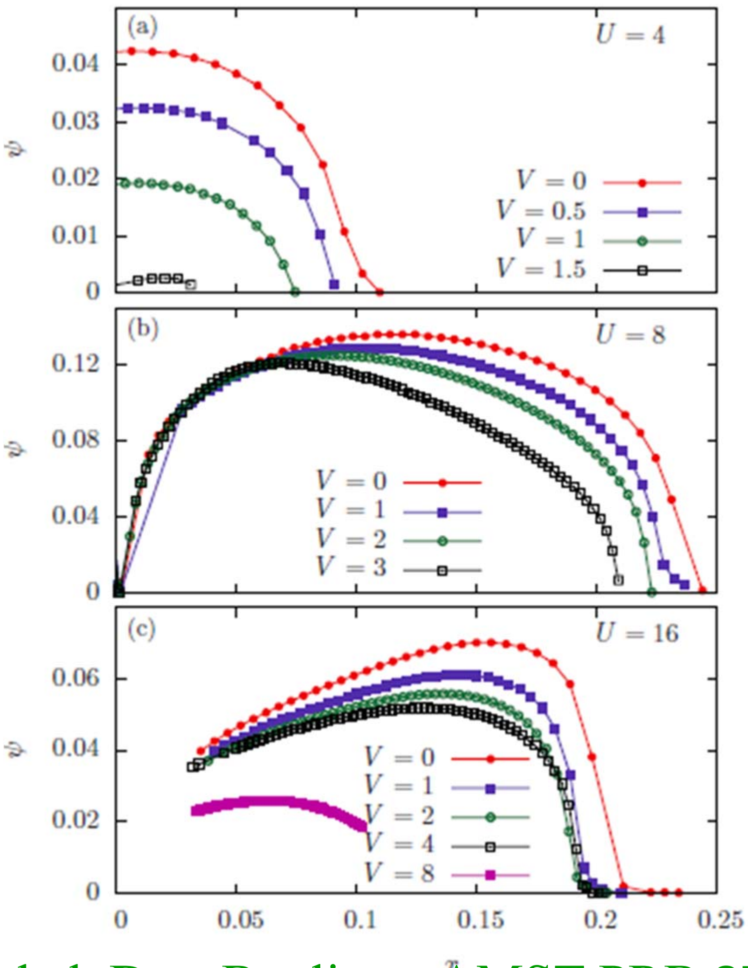
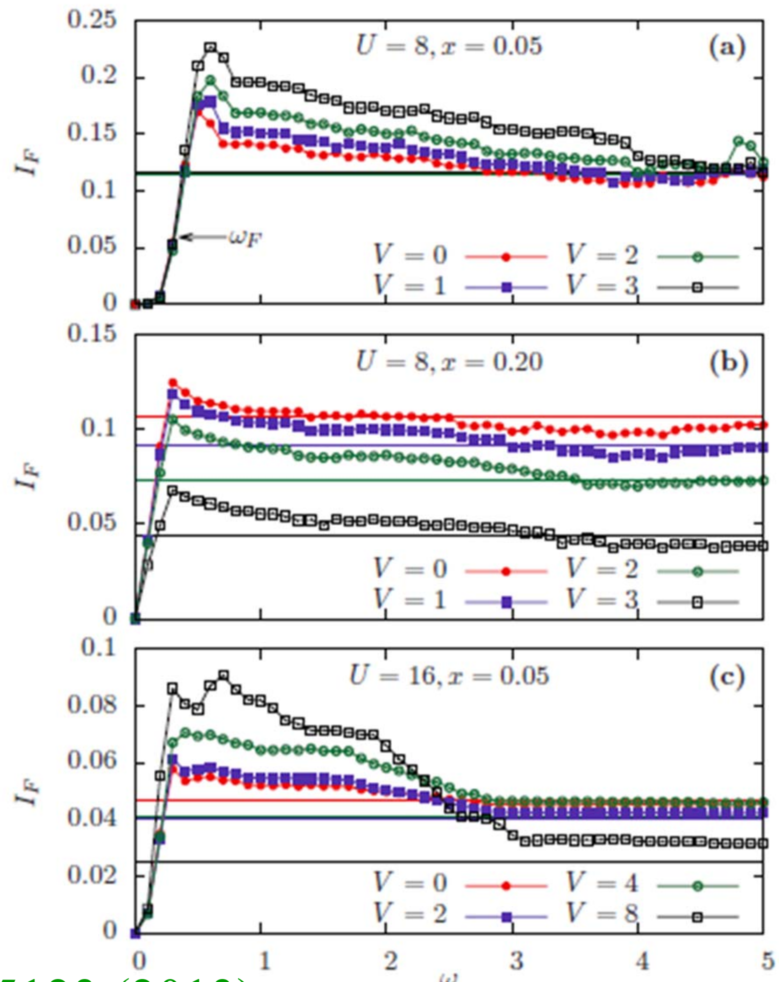
Resilience to near-neighbor repulsion

David Sénéchal

$$J = \frac{4t^2}{U - V}$$





Sénéchal, Day, Bouliane, AMST PRB **87**, 075123 (2013)

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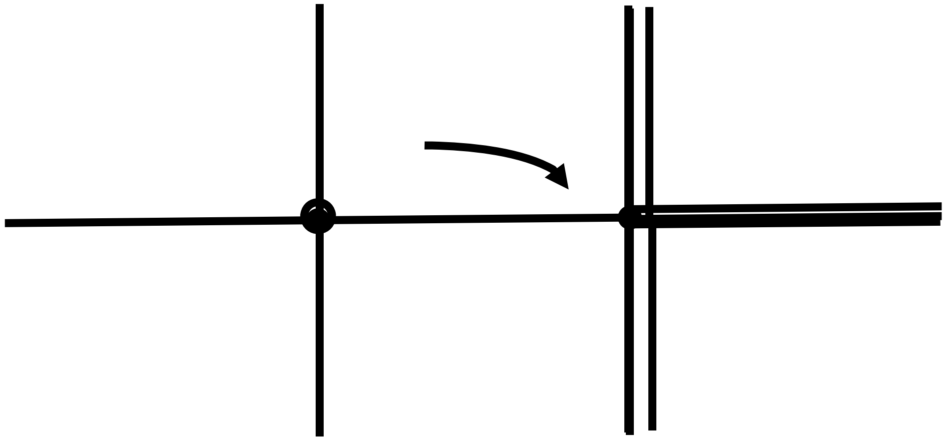
J in the presence of V

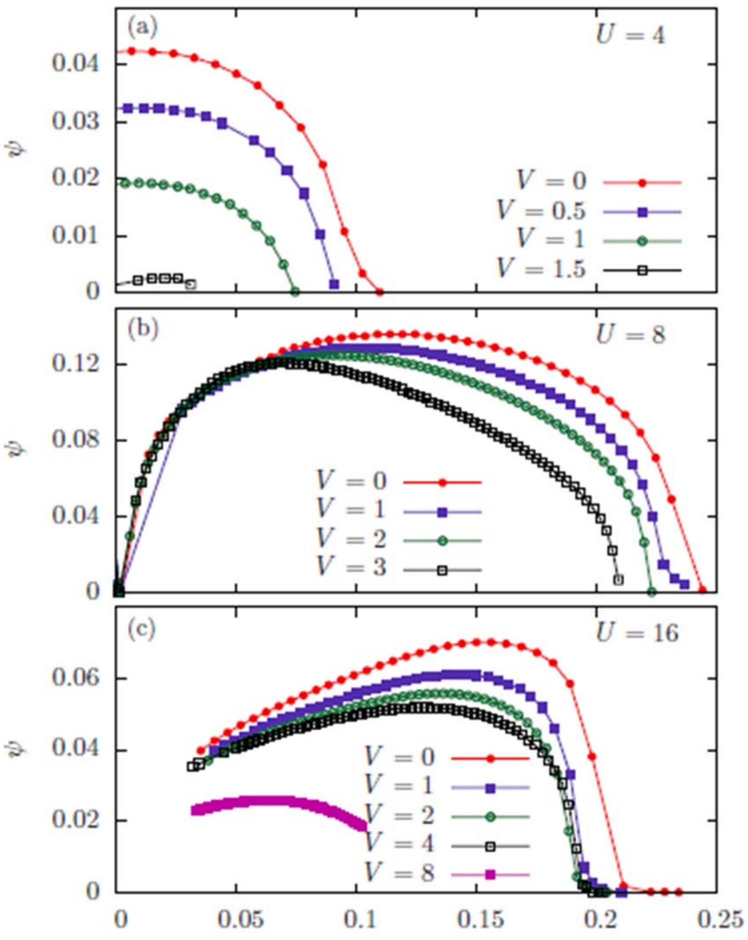


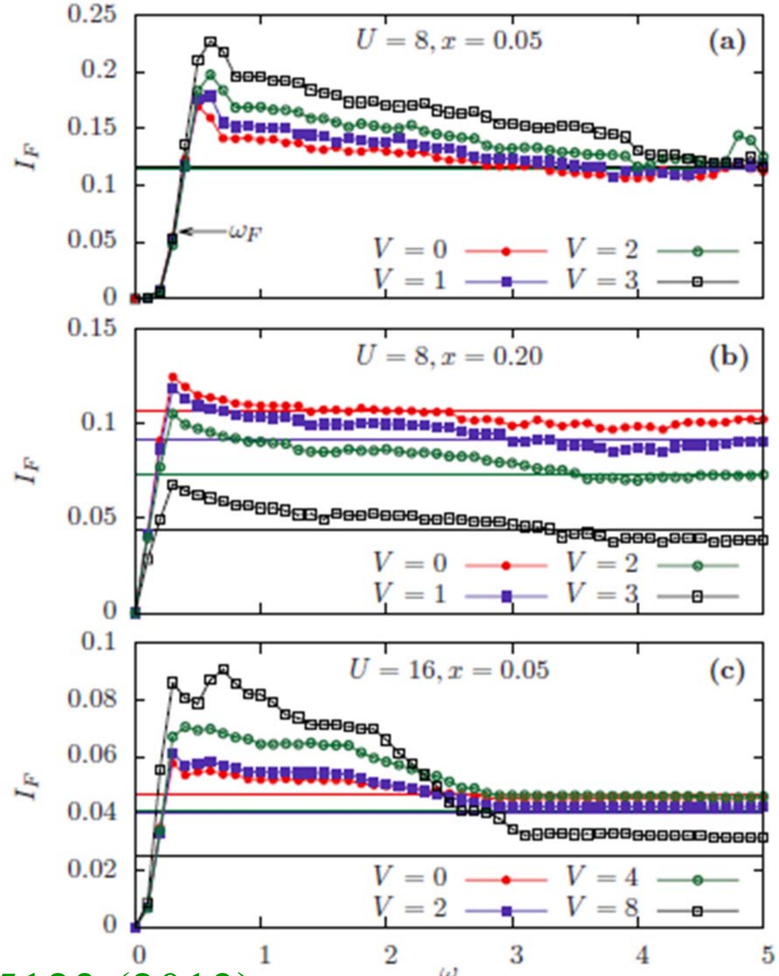
$$J = \frac{4t^2}{U-V}$$

Resilience to near-neighbor repulsion

David Sénéchal

$$J = \frac{4t^2}{U-V}$$





Sénéchal, Day, Bouliane, AMST PRB **87**, 075123 (2013)

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Giovanni Sordi

Patrick Sémon

Kristjan Haule

Finite *T* phase diagram

Superconductivity

PRL 2012

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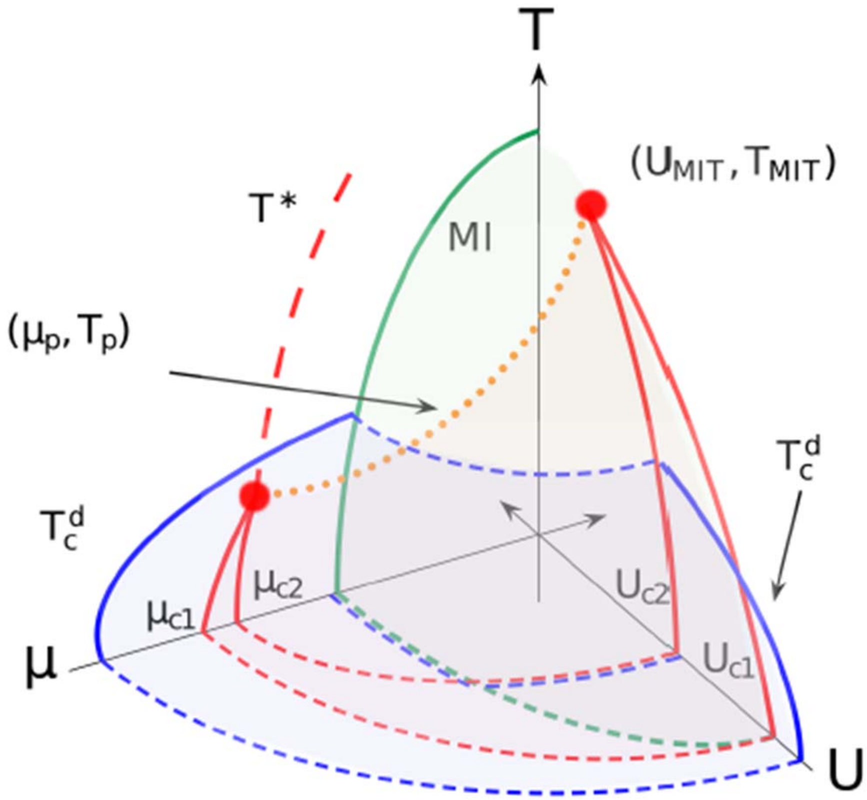
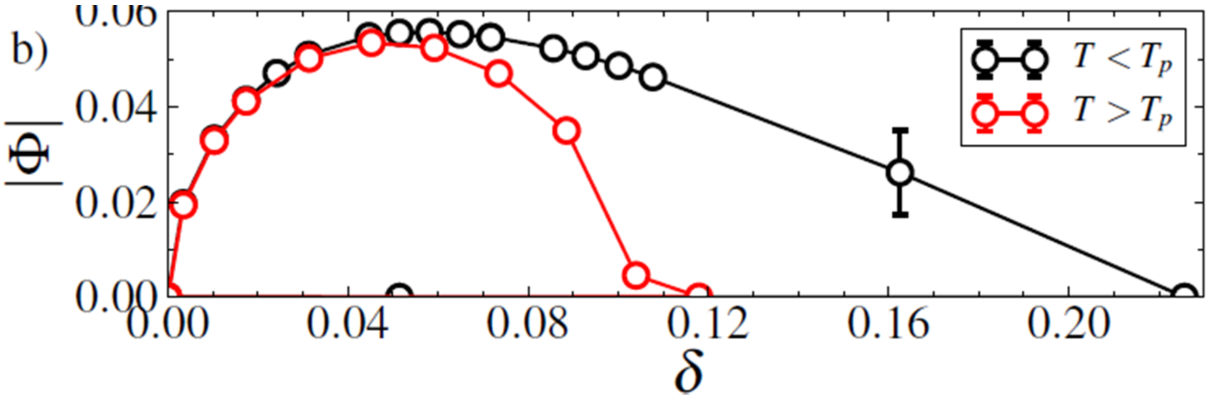
Unified phase diagram



Cuprates (doping driven transition)

Giovanni Sordi



Patrick Sémon

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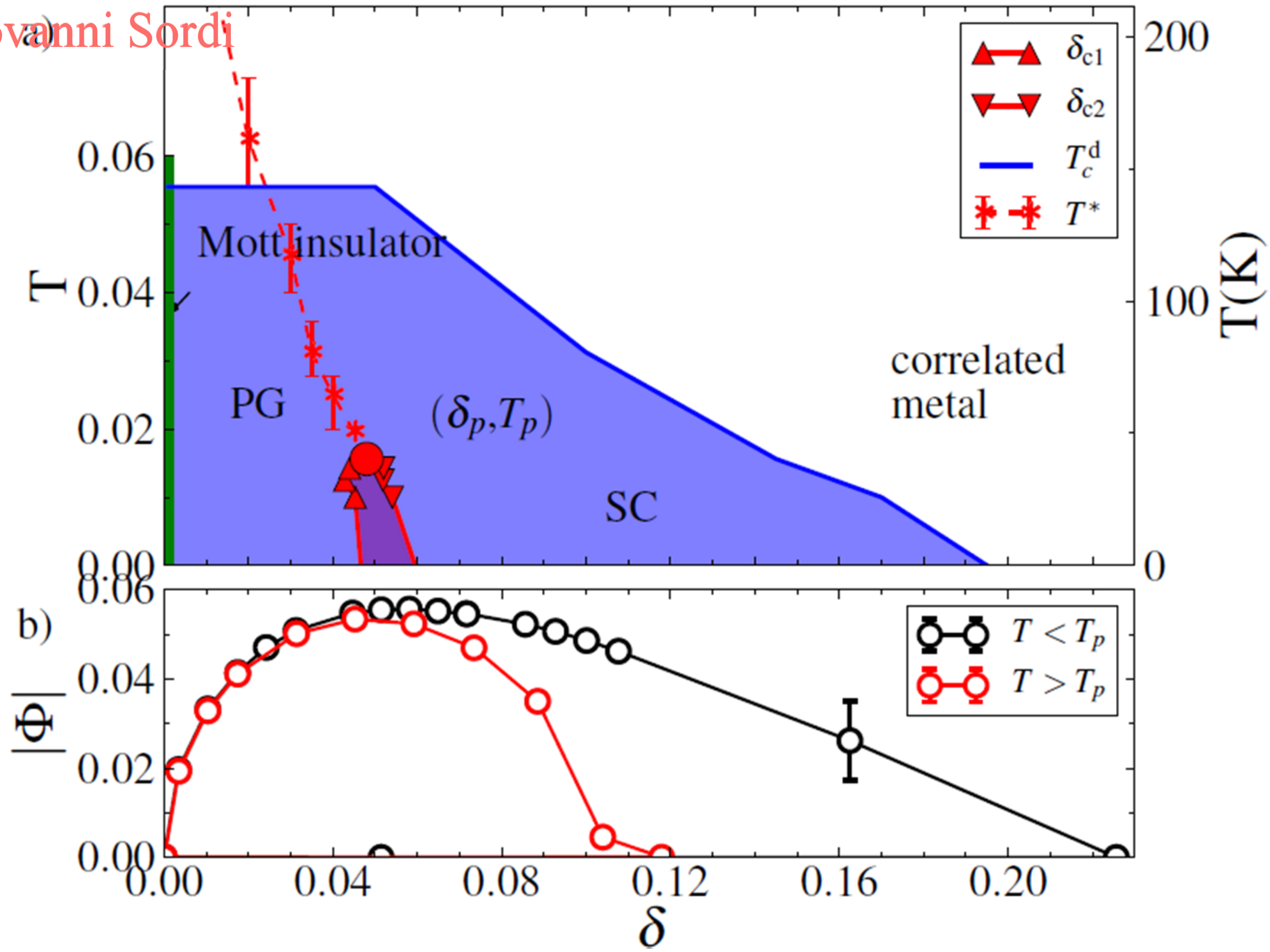
Cuprates (doping driven transition)

Giovanni Sordi



Patrick Sémon

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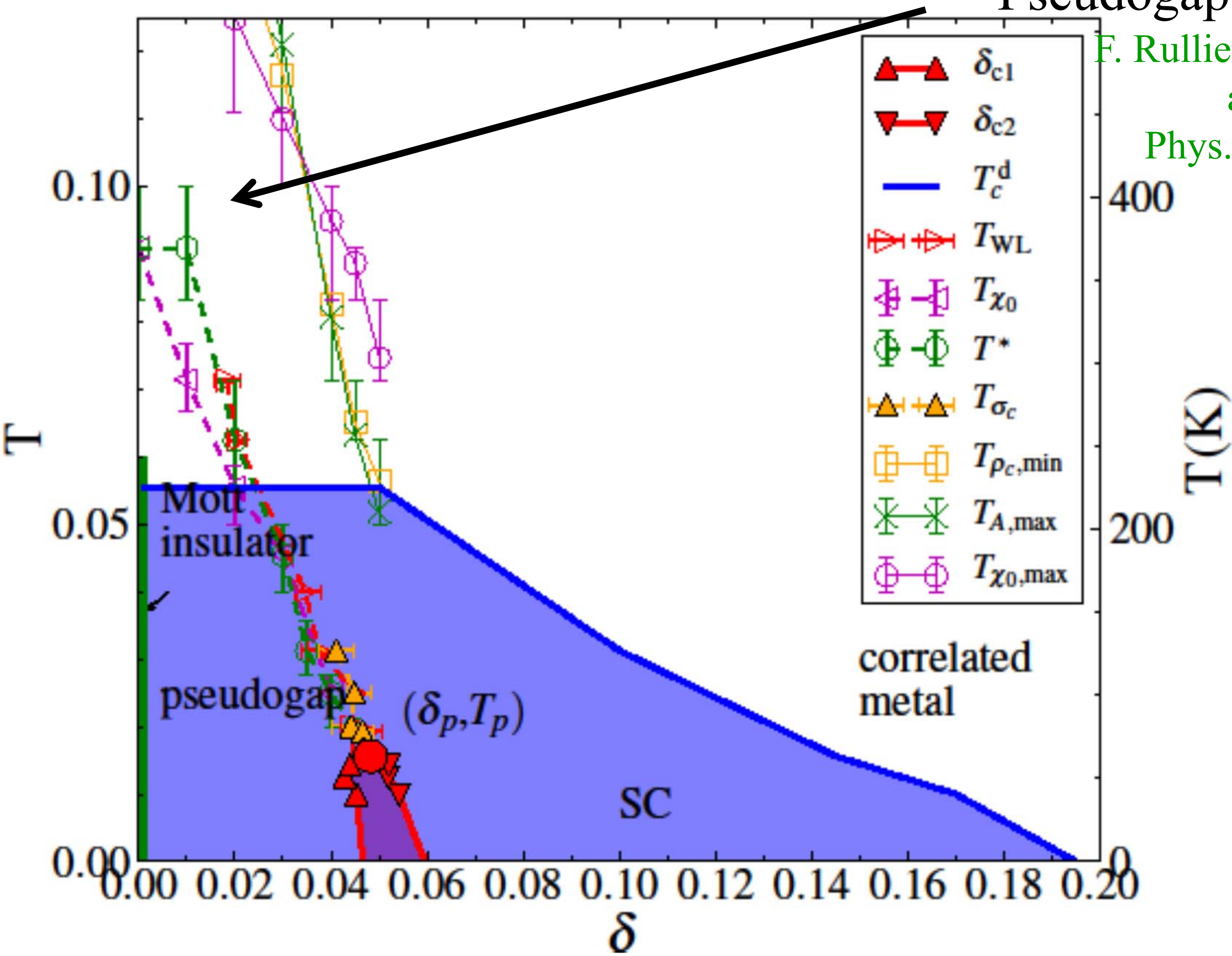
SC vs pseudogap

Pseudogap vs pair

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



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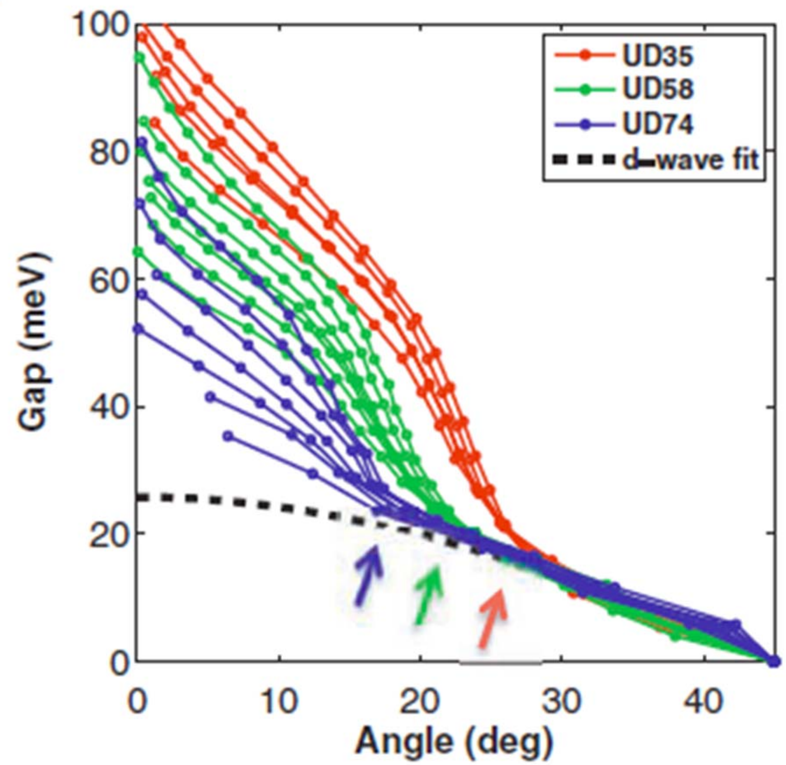
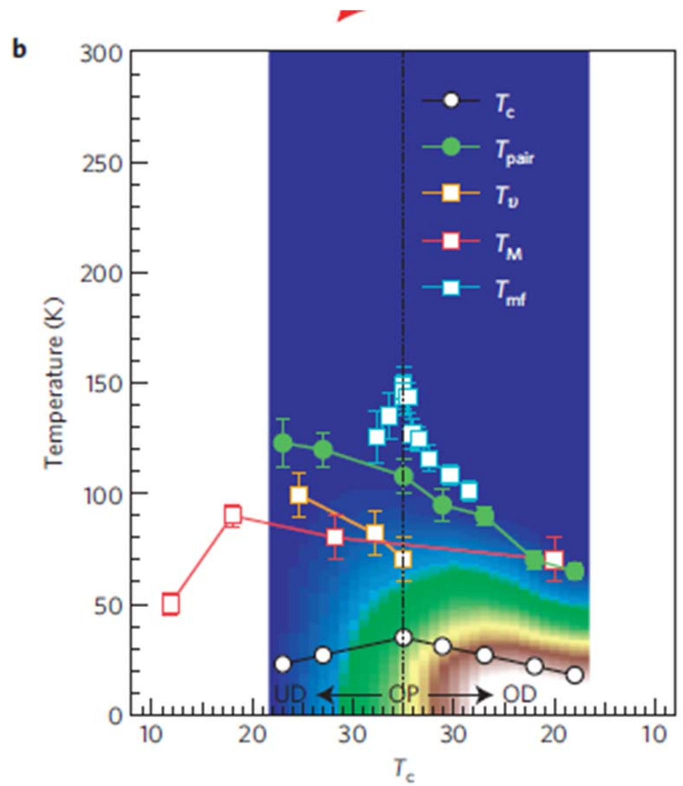
Nodal gap



Pushp, Yazdani Science 26 June 2009:
Vol. 324 no. 5935 pp. 1689-1693

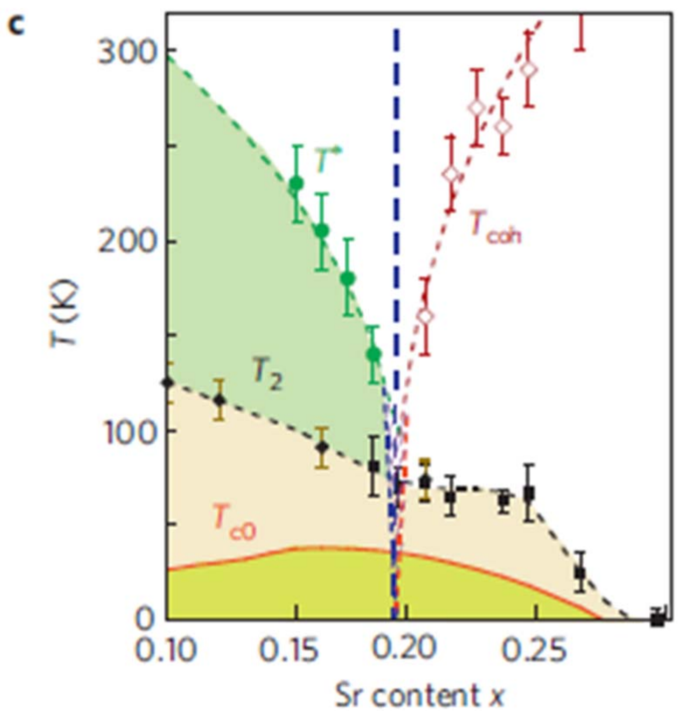
Tpair



ARPES
Bi2212

Kondo, Takeshi, et al. Kaminski Nature Physics **2011**, *7*, 21-25

T_2



Magnetoresistance, LSCO
Fluctuating vortices

Patrick M. Rourke, et al. Hussey Nature Physics 7, 455–458 (2011)

Giant proximity effect

$T_c = 32\ K$
$T_c < 5K$

Morenzoni et al.,
Nature Comms. **2** (2011)

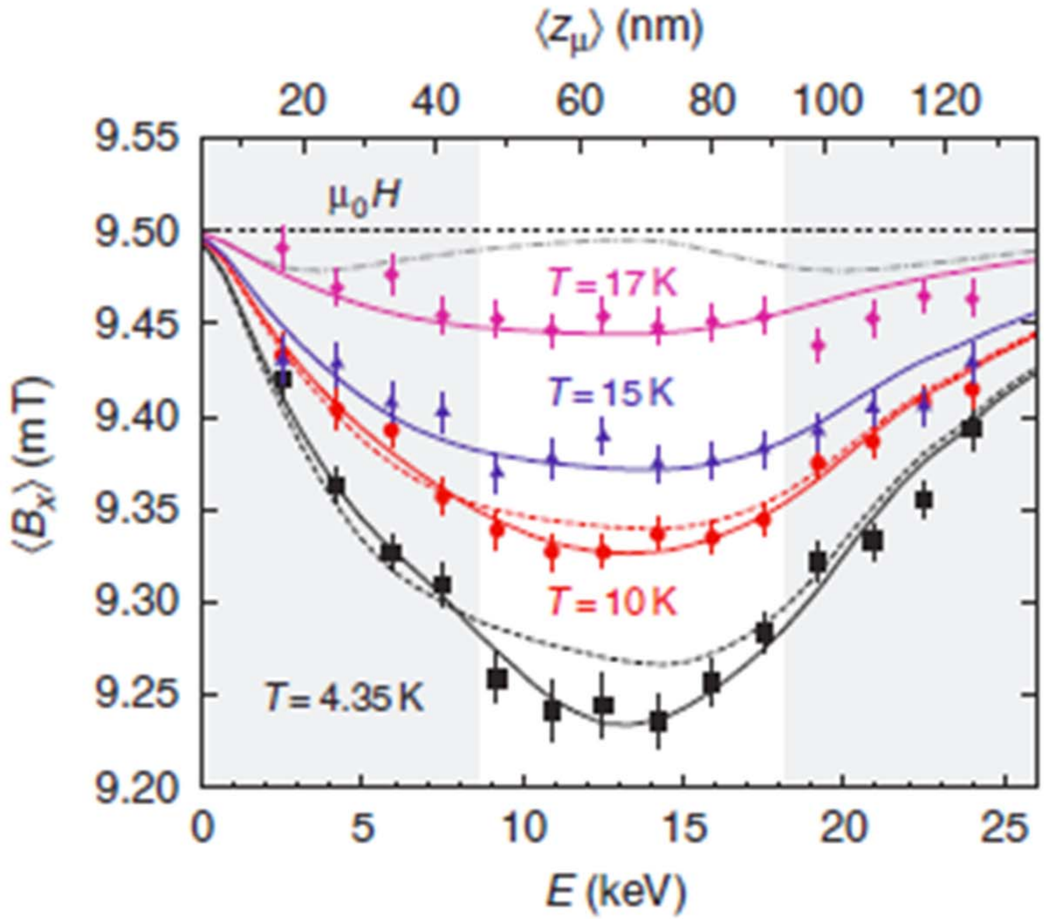


Figure 6 | Depth profile of the local field at different temperatures. The

Actual T_c in underdoped

- Quantum and classical phase fluctuations
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  - D. Podolsky, S. Raghu, and A. Vishwanath, Phys. Rev. Lett. **99**, 117004 (2007).
  - Z. Tesanovic, Nat Phys **4**, 408 (2008).
- Magnitude fluctuations
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- Competing order
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- Disorder
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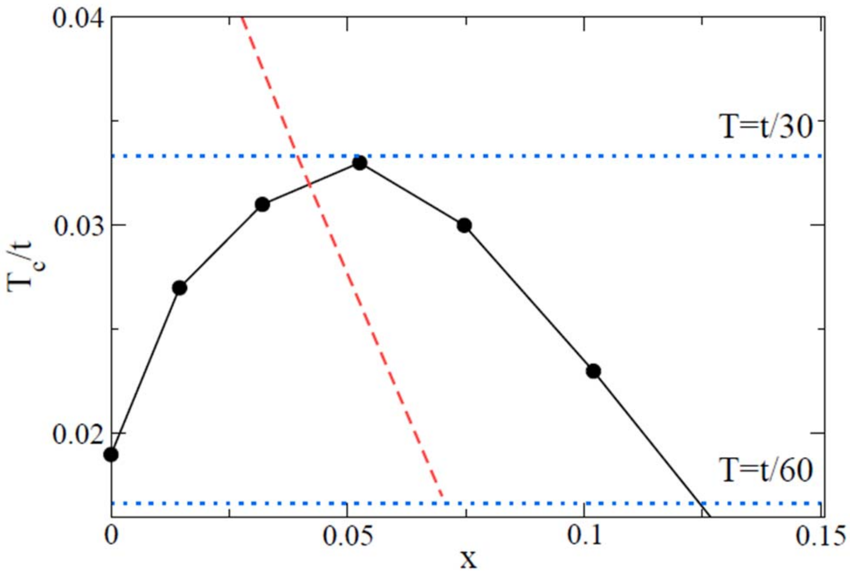
Larger clusters

- Is there a minimal size cluster where T_c vanishes before half-filling?
- Learn something from small clusters as well
  - Local pairs in underdoped

Larger cluster 8 site DCA



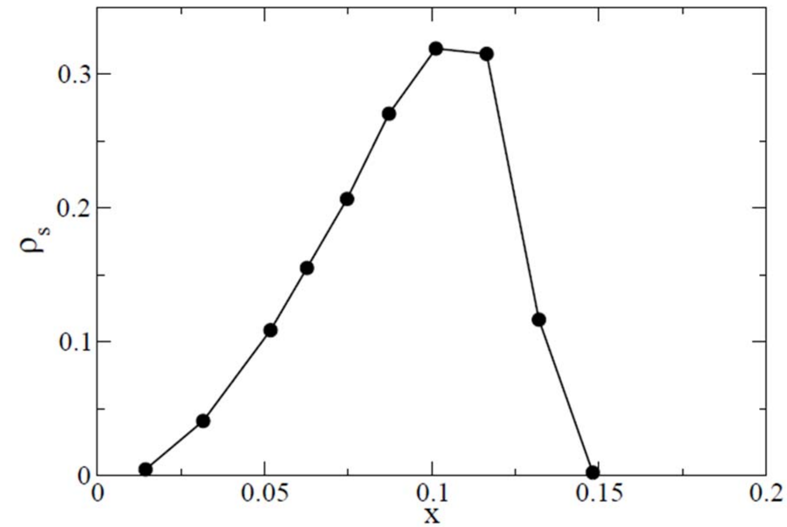


FIG. 8. Superfluid stiffness ρ_s determined in the superconducting state at $T = t/60$ from Eq. 15, as a function of doping.

Gull, Millis, arxiv.org:1304.6406

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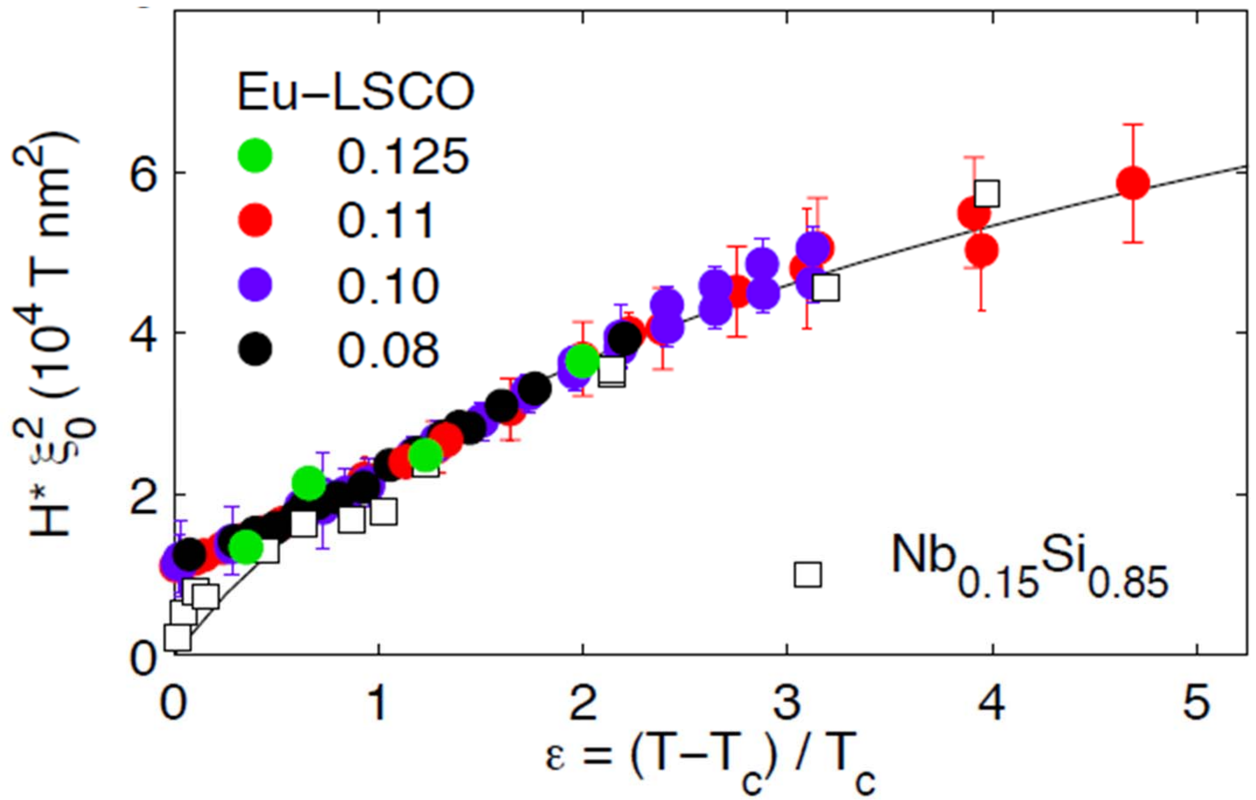
Gaussian amplitude fluctuations in Eu-LSCO



Chang, Doiron-Leyraud et al.

Phase fluctuations and disorder?

Monolayer LSCO, field doped

A. T. Bollinger et al. & I. Božović, Nature **472**, 458–460

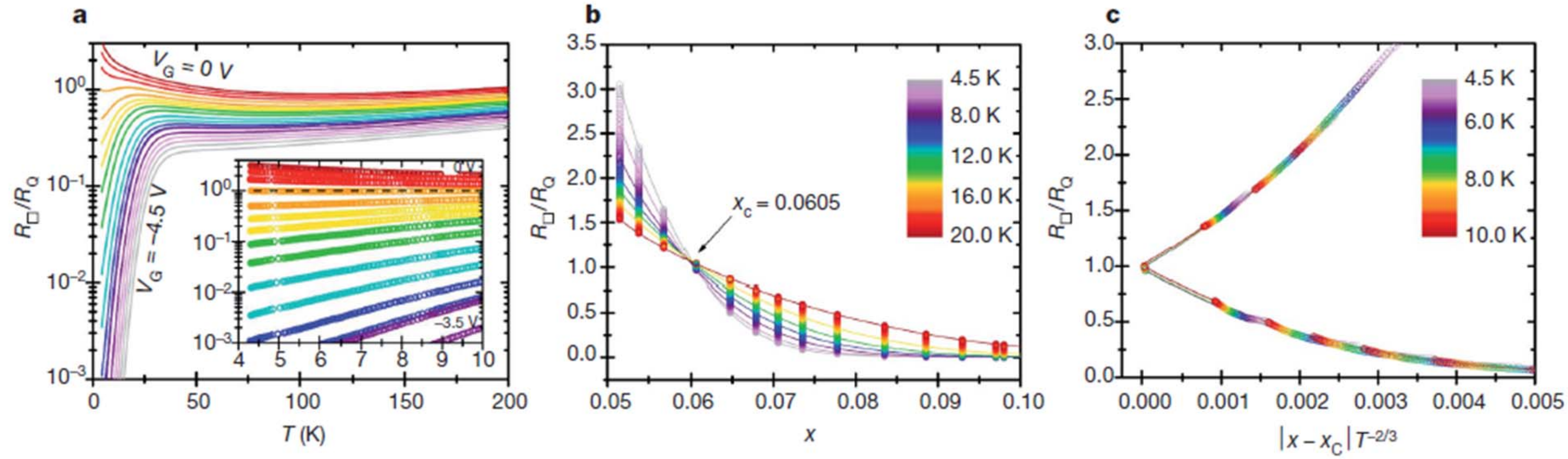


Figure 2 | Superconductor–insulator transition driven by electric field. a, Temperature dependence of normalized resistance $r = R_\square(x,T)/R_Q$ of an initially heavily underdoped and insulating film (see Supplementary Fig. 12 for linear scale). The device (Supplementary section B) employs a coplanar Au gate and DEME-TFSI ionic liquid. The carrier density, fixed for each curve, is tuned by varying the gate voltage from 0 V to −4.5 V in 0.25 V steps; an insulating film becomes superconducting via a QPT. The inset highlights a separatrix independent of temperature below 10 K. The open circles are the actual raw data points; the black dashed line is $R_\square(x_c,T) = R_Q = 6.45$ kΩ. **b**, The inverse representation of the same data, that is, the $r_T(x)$ dependence at fixed temperatures below 20 K. Each vertical array of (about 100) data points corresponds to one fixed carrier density, that is, to one $r_x(T)$ curve in Fig. 2a. The colours refer to the temperature, and the continuous lines are interpolated for selected temperatures (4.5, 6.0, 8.0, 10.0, 12.0, 15.0 and 20.0 K). The crossing point defines the critical carrier concentration $x_c = 0.06 \pm 0.01$, and the critical resistance $R_c = 6.45 \pm 0.10$ kΩ. **c**, Scaling of the same data with respect to a single variable $u = |x - x_c| T^{-1/z\nu}$, with $z\nu = 1.5$. This figure is derived by folding panel **b** at x_c and scaling the abscissa of each $r_T(|x - x_c|)$ curve by $T^{-2/3}$. For 4.3 K < T < 10 K, the discrete groups of points of Fig. 2b collapse accurately onto a two-valued function, with one branch corresponding to x larger and the other to x smaller than x_c. The critical exponents are identical on both sides of the superconductor–insulator transition. The raw data points cover the interpolation lines almost completely, except close to the origin.

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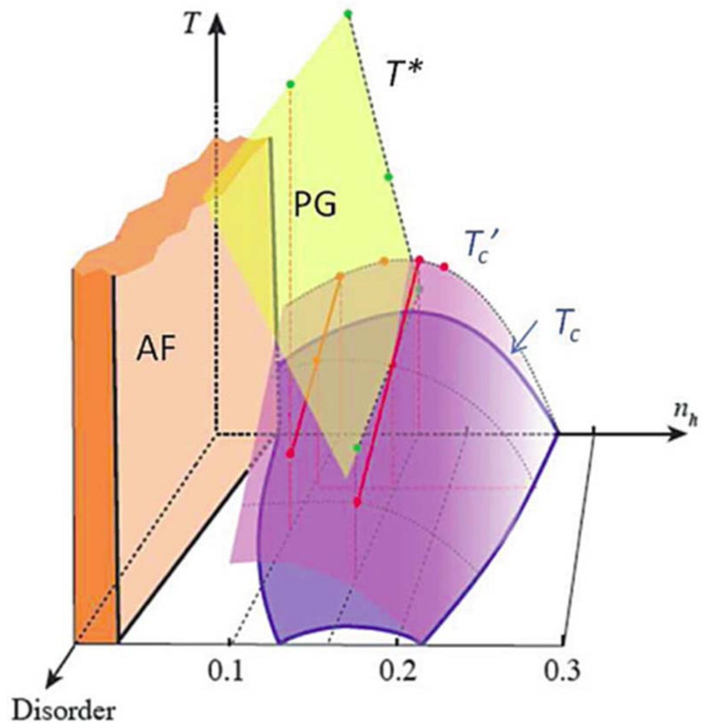
E

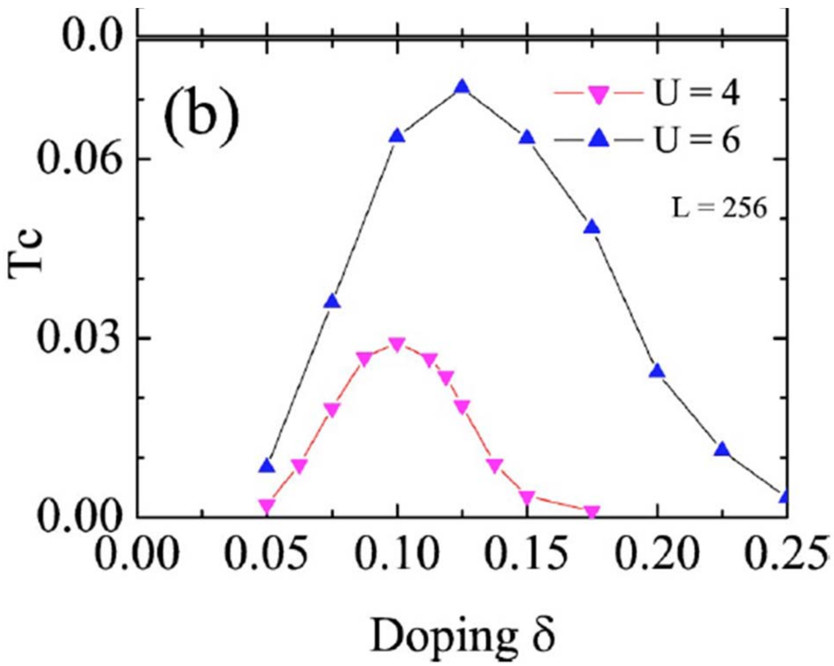
Effect of disorder



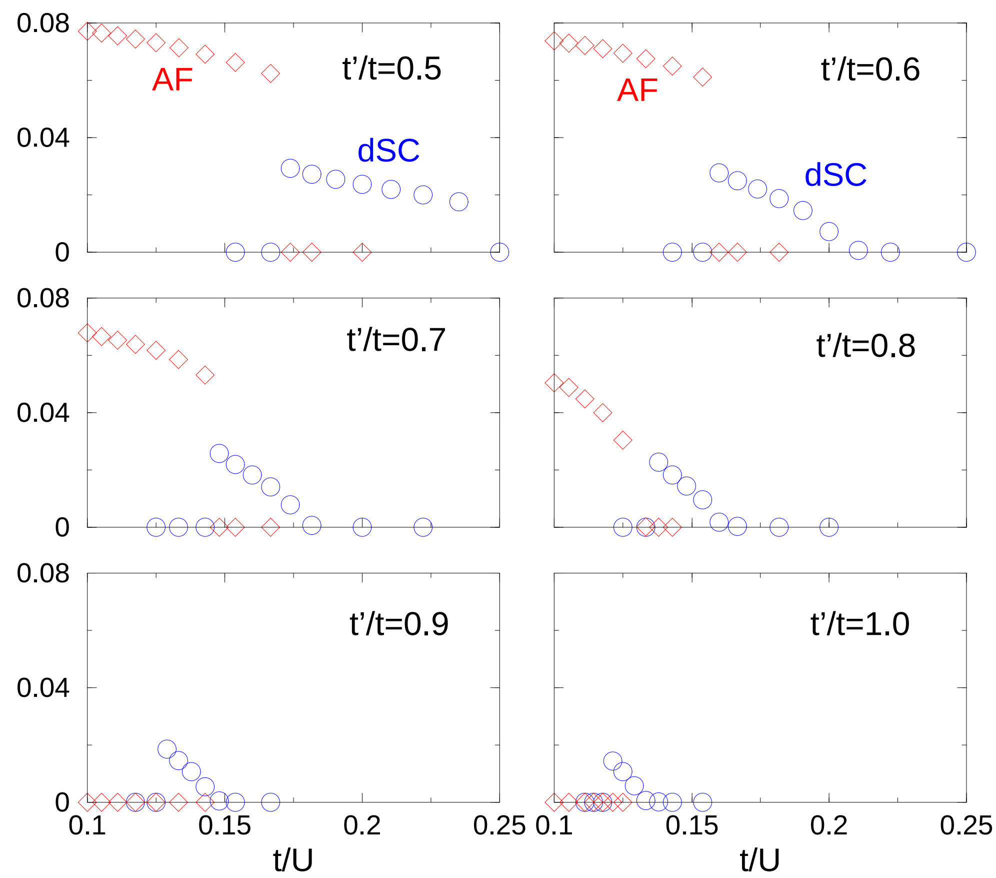
F. Rullier-Albenque, H. Alloul, and G.Rikken,
Phys. Rev. B **84**, 014522 (2011).

Superconductivity in underdoped vs BCS

Summary

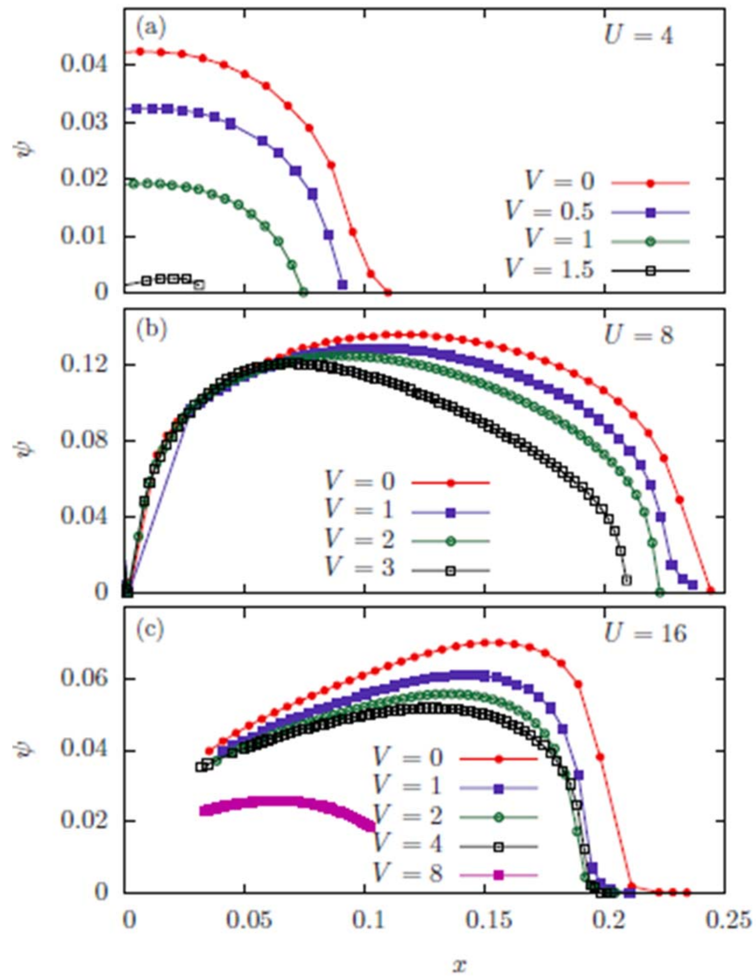


(b)
U = 4
U = 6
L = 256
Tc
0.0
0.06
0.03
0.00
0.00 0.05 0.10 0.15 0.20 0.25
Doping δ



t'/t=0.5
t'/t=0.6
t'/t=0.7
t'/t=0.8
t'/t=0.9
t'/t=1.0
AF
dSC
0.08
0.04
0
0.1 0.15 0.2 0.25
t/U

Summary



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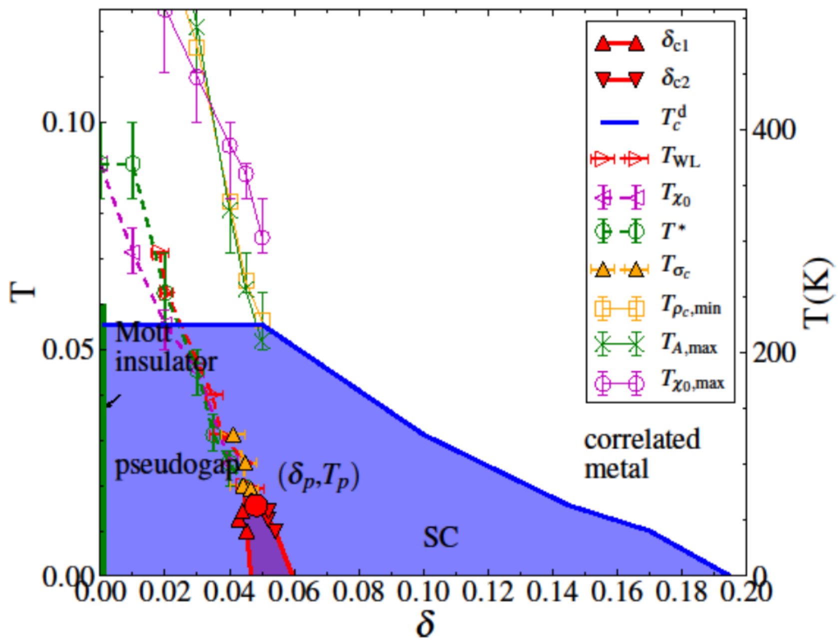
Rutherford



- Below the dome finite T critical point (not QCP) controls normal state
- First-order transition destroyed but traces in the dynamics
- T^* different from T_c^d
- Actual T_c in underdoped
  - Competing order
  - Long wavelength fluctuations (see O.P.)
  - Disorder

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Conclusions

- Tools for Hubbard model,
  - weak to intermediate coupling
  - Strong coupling
- The influence of Mott Physics extends way beyond half-filling

Main collaborators


Giovanni Sordi


Kristjan Haule


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Bumsoo Kyung


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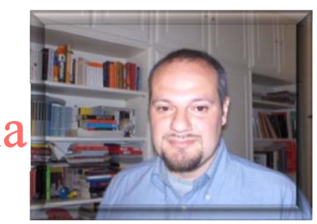
Dominic Bergeron


Sarma Kancharla


Marcello Civelli


Massimo Capone


Gabriel Kotliar

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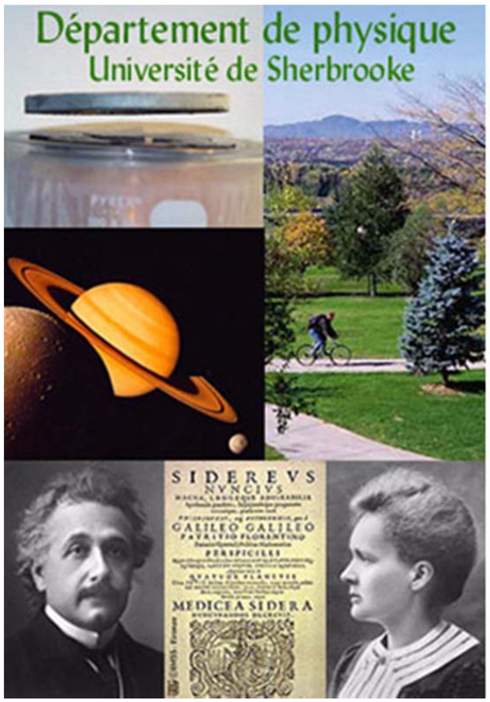

André-Marie Tremblay

CANADA RESEARCH CHAIRS
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Merci

Thank you