Physics of Strongly Correlated Electrons: Selected Topics

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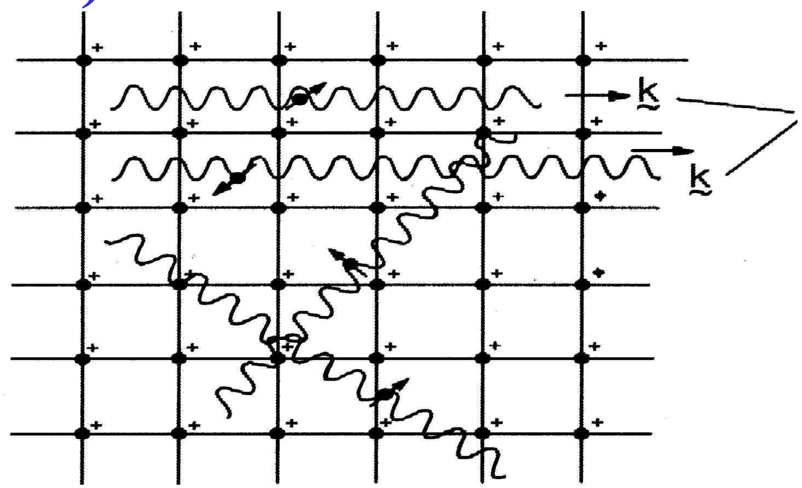
Contents

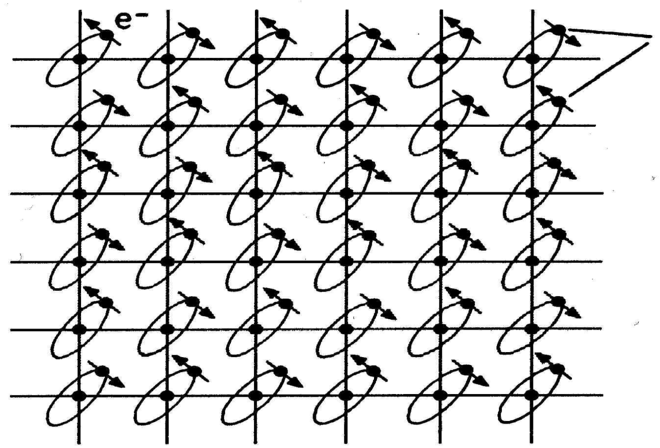
Lecture I: Metal-insulator transition at T>0

Delocalized versus localized

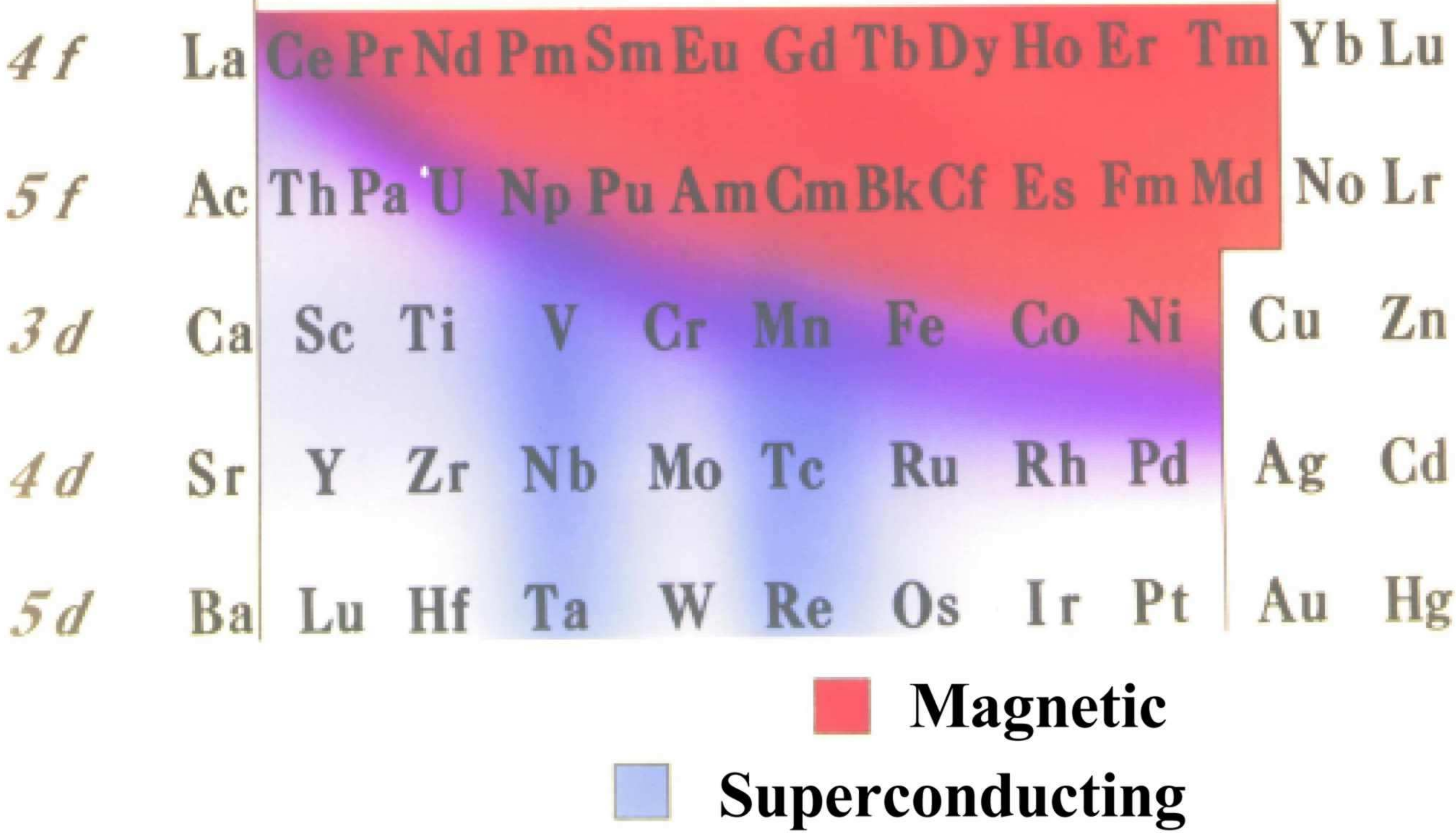
a) Metal



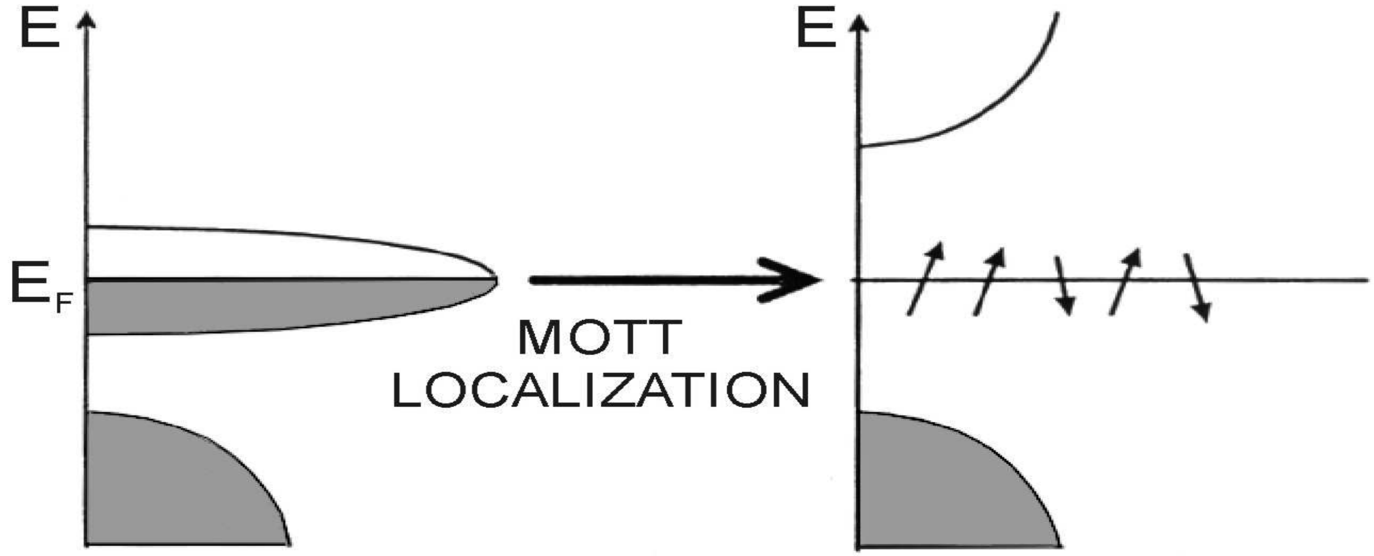
b) Mott-Hubbard insulator



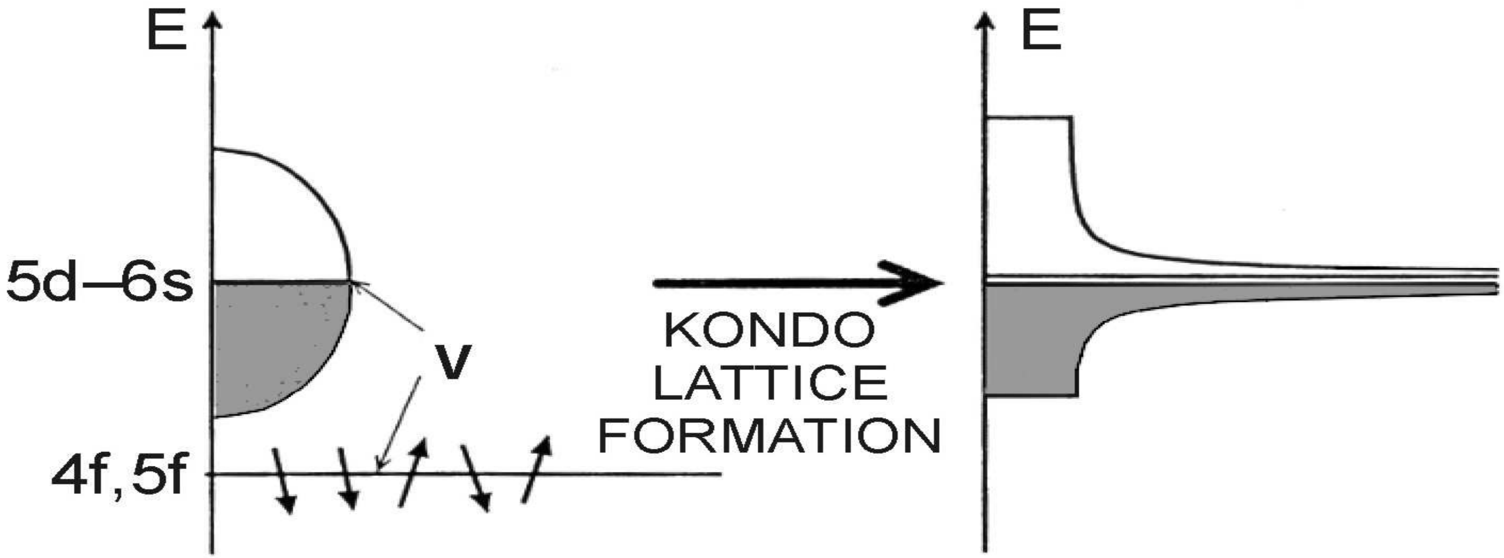
Magnetic versus superconducting



Narrow–band systems (3d)



Hybridized systems (f)



Localization criterion: Mott (Wigner)

Kinetic energy in e⁻ gas/particle

$$\overline{\epsilon} = \frac{3}{5}\epsilon_F = \frac{3}{5}\frac{\hbar^2}{2m^*}\left(3\pi^2\frac{N}{V}\right)^{2/3} \sim \rho^{2/3}$$

Electron-electron repulsion energy/particle

$$\epsilon_{e-e} = \frac{1}{2}\frac{e^2}{\varepsilon d_{e-e}} = \frac{e^2}{2\varepsilon}\rho^{1/3}$$

Where the classical interparticle distance is

$$d_{e-e} = \left(\frac{V}{N}\right)^{1/3}$$

Instability of the electron gas concept if:

$\overline{\epsilon} = \epsilon_{e-e}$ → **gas instability**

Note: e-e interaction dominates if $\epsilon_{e-e} > \overline{\epsilon}$ **, i.e.** $\rho < \rho_c$

$$\underbrace{\left(\frac{\hbar^2}{m^* e^2}\varepsilon\right)}_{a_B}\rho_c^{1/3} = \frac{5}{3}\frac{1}{\left(3\pi^2\right)^{2/3}} \cong 0.17$$

a_B → effective Bohr radius

$$a_B \cdot \rho_c^{1/3} \cong 0.17 \sim 0.2$$

Other effects $\Rightarrow$ Fermi - sphere collaps?

In one dimension:

$$\mathbf{a_B \, \rho_C \cong 1 \quad \Rightarrow \quad R_C \cong a_B}$$

Yet another Mott criterion of localization

A different derivation by Mott (1961).

Attractive potential screened by gas (Kittel,1990)

$$V(\mathbf{r}) = -\frac{e^2}{\kappa\, r}\ \exp(-q\, r)$$

q is the inverse Thomas-Fermi screening length

$$q = \frac{4\, m^*\, e^2\, n_c^{1/3}}{\varepsilon\, \hbar^2}$$

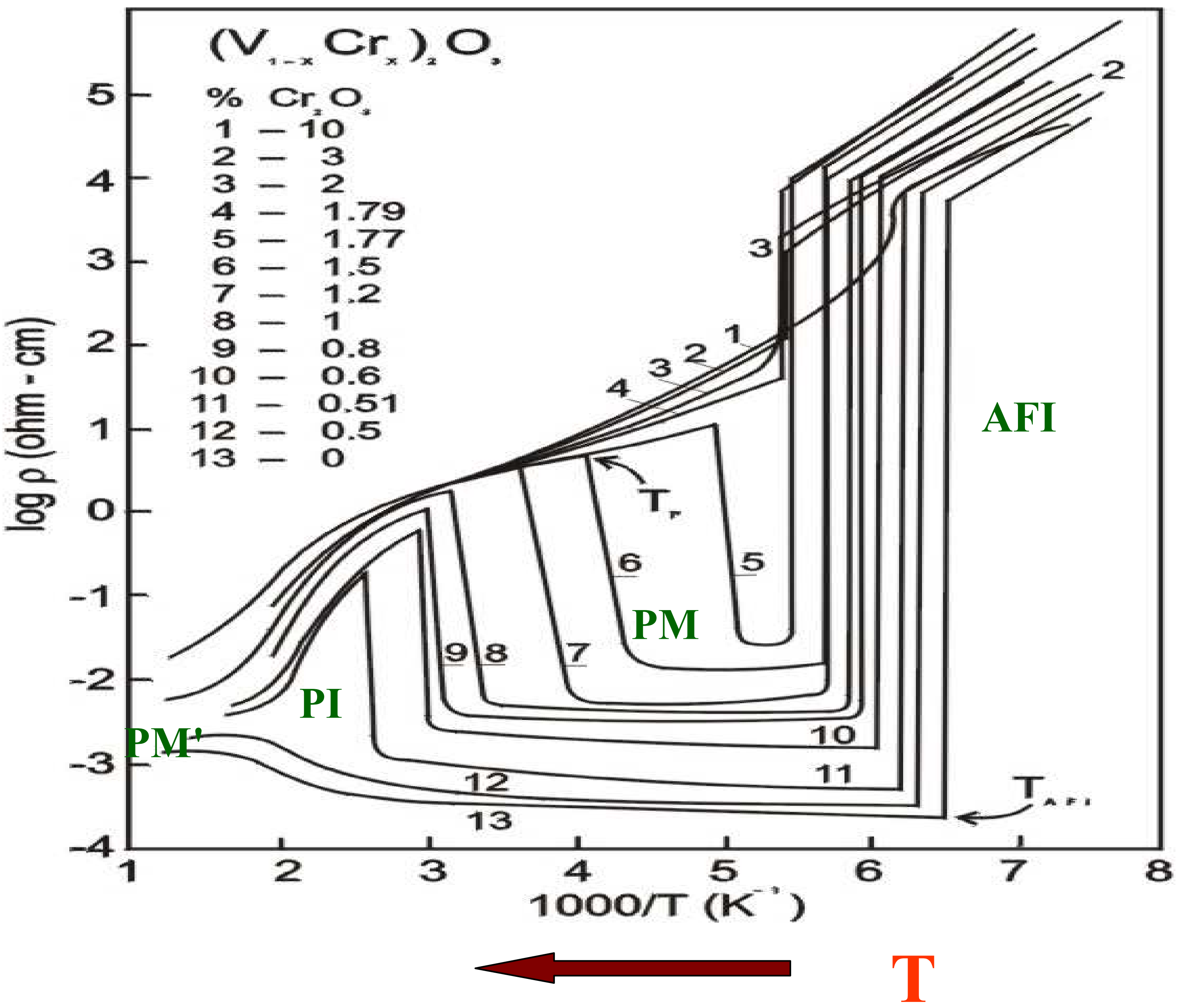
A screened potential does not lead to a bound state if (Landau, Lifshitz, 1990):

$$q > \frac{m^*\, e^2}{\varepsilon\, \hbar^2} = a_B^{-1}$$

$$q^{-1} = a_B \quad \Rightarrow \quad n_c^{1/3}\, a_B = 0.25$$

First period: 1980-2000

J.S. Eur. J. Phys. 21, 511-34 (2001)



H. Kuwamoto et al., PRB 22 (1980) 2626

$$H = \epsilon_a^{\text{eff}} \sum_j n_j + t \sum_{j\sigma} \left(e^{-i\phi/N} c_{j\sigma}^\dagger c_{j+1\sigma} + \text{h.c.} \right) + U \sum_i n_{i\uparrow} n_{i\downarrow} + \sum_{i<j} K_{ij} \delta n_i \delta n_j ,$$

$$\delta n_i \equiv n_i - 1, \epsilon_a^{\text{eff}} = \epsilon_a + N^{-1} \textstyle\sum_{i<j} (2/R_{ij} + K_{ij})$$

$$\mathrm{t}_{\langle \mathrm{ij} \rangle} \equiv \mathbf{t} \equiv \left\langle \mathrm{w}_\mathrm{i} \middle| \mathrm{H}_1 \middle| \mathrm{w}_\mathrm{j} \right\rangle$$

$$\mathrm{U} \equiv \left\langle \mathrm{w}_\mathrm{i} \ \mathrm{w}_\mathrm{i} \middle| \mathrm{V}_{12} \middle| \mathrm{w}_\mathrm{i} \ \mathrm{w}_\mathrm{i} \right\rangle$$

$$\mathrm{K}_\mathrm{ij} \equiv \left\langle \mathrm{w}_\mathrm{i} \ \mathrm{w}_\mathrm{j} \middle| \mathrm{V}_{12} \middle| \mathrm{w}_\mathrm{i} \ \mathrm{w}_\mathrm{j} \right\rangle$$

Atomic functions

$$\Phi_i(\mathbf{r}) = \left(\pi\alpha^3\right)^{1/2} \exp\left(-\alpha\left|\mathbf{r} - \mathbf{R}_i\right|\right)$$

$$\left\langle \Phi_i \middle| \Phi_j \right\rangle = S_{ij}$$

Wannier functions

$$w_i(\mathbf{r}) = \sum_j \beta_{ij} \Psi_j(\mathbf{r})$$

$$\left\langle w_i \middle| w_j \right\rangle = \delta_{ij}$$

Qualitative characteristics:

1) Bare band width $W = 2z|t| \quad ; \quad t = \int d^3r \; w_i(\mathbf{r}) \; H_1 \; w_j(\mathbf{r})$

2) Coulomb repulsion $U = \int d^3r \; d^3r' \; |w_i(\mathbf{r})|^2 \; \frac{e^2}{|\mathbf{r}-\mathbf{r}'|} \; |w_i(\mathbf{r}')|^2$

$$\left(K_{ij} = \int d^3r \; d^3r' \; |w_i(\mathbf{r})|^2 \; \frac{e^2}{|\mathbf{r}-\mathbf{r}'|} \; |w_j(\mathbf{r}')|^2 \right)$$

3) Band filling $n = \sum_{\sigma} \langle a^{\dagger}_{i\sigma} a_{i\sigma} \rangle = \frac{1}{N} \sum_{\sigma, \mathbf{k} \le k_F} \langle a^{\dagger}_{\mathbf{k}\sigma} \, a_{\mathbf{k}\sigma} \rangle$

(empty) $0 \le n \le 2$ **(full)**

Metallic limit:	MIT:	Strong correlations:
$U, K \ll W$	$U \cong W$	$W \ll U$
		$(U-K)$

Physically U/W – important parameter

The concept of band narrowing (renormalization) and competition between band and Coulomb energies

Why electronic transition?

- **Band (kinetic) energy**: $W = 1 \div 2$ eV
- **Coulomb repulsion energy**: $U \sim$ few eV
- **Thermal energy**: $k_B T \sim 10$ meV ($T \sim 100$ K)
- **Why phase transition possible?** For $U \sim U_C \sim W$

$$W \rightarrow \tilde{W} = W q \leq 0.1\,\text{eV}$$

$$U \langle n_{i\uparrow} n_{i\downarrow} \rangle \sim 0.1\,\text{eV}$$

$$\frac{E_G}{N} = -\frac{q W}{4} + U \langle n_{i\uparrow} n_{i\downarrow} \rangle \sim k_B T, \; g \mu_B H_a, \text{disorder}$$

Canonical model: Hubbard (resuts):

$$\frac{E_G}{N} \equiv \frac{\langle H \rangle}{N} = \frac{1}{N}\sum_{k\sigma} E_k f(E_k) + U \underbrace{\langle n_{i\uparrow} n_{i\downarrow} \rangle}_{\equiv d^2}$$

$$\begin{cases} E_k = q\left(d^2\right) \in_k \\ q\left(d^2\right) = 8 d^2 \left(1 - 2 d^2\right) < 1 \end{cases}$$

$U_c \equiv 8|\in|$:

$E_G = E_{min}$:

$$\begin{cases} d^2 = \frac{1}{4}\left(1 - \frac{U}{U_C}\right), \quad 8|\overline{\in}| = U_C \\ \frac{E_G}{N} = \left(1 - \frac{U}{U_C}\right)^2 \overline{\in} \\ \frac{m^*}{m_0} = \frac{1}{1 - \left(\frac{U}{U_C}\right)^2} \sim \gamma \to \infty \\ \frac{\chi}{\gamma} = \frac{1 + \frac{U}{2U_C}}{\left(1 + \frac{U}{U_C}\right)^2} \sim 4 \end{cases}$$

Simplest model: Hubbard model at half filling (n=1): classical regime for fermion systems –

Nonzero temperature (statistical physics): consequences of mass renormalization, etc.

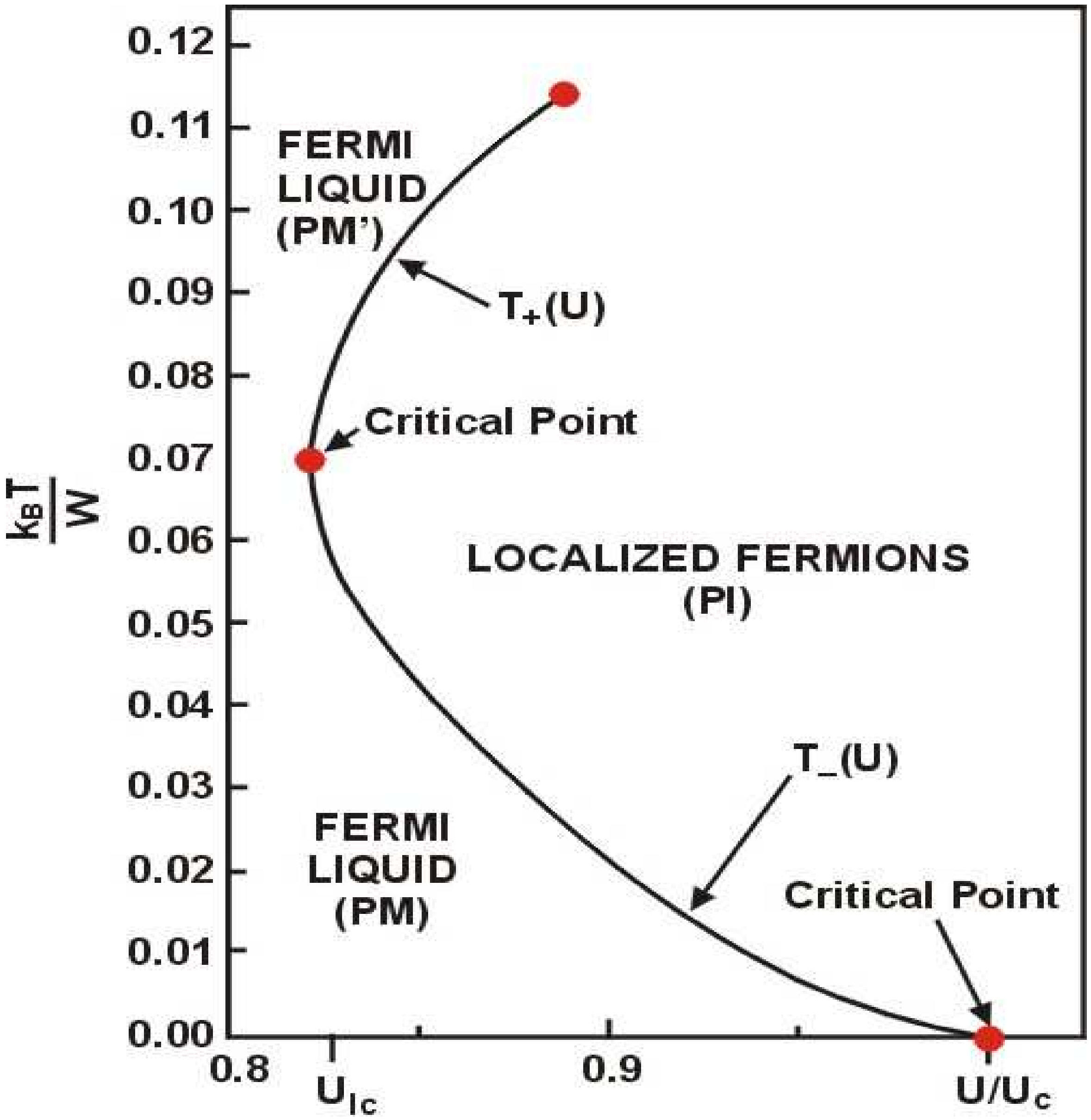
THERMODYNAMICS:

$$\begin{cases} F_{metal} = \left(1 - \dfrac{U}{U_C}\right)^2 \overline{\in} - \dfrac{1}{2} \dfrac{\gamma_0 T^2}{1 - \left(\dfrac{U}{U_C}\right)^2} \\ F_{\substack{insulator \\ (param)}} = -k_B T \ln 2 \qquad\qquad (E_{ex} = 0) \end{cases}$$

Coexistence: $F_{metal} = F_{insulator}$
(PM – PI)

$$k_B T_{\pm} = \frac{3\Phi_0}{2\pi\rho} \left\{ \ln 2 \pm \left[(\ln 2)^2 - \frac{4}{3}\pi^2 \rho |\overline{\in}| \frac{\left(1 - \dfrac{U}{U_C}\right)^2}{\Phi_0} \right]^{1/2} \right\}$$

Important:
Two transitions



J. S. et al., PRL **59**, 728 (1987) – orbitally nondegenerate;
A. Klejnberg & J. S., PRB **57**, 12 041 (1998) – degenerate.

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Discontinuous Metal-Insulator Transitions and Fermi-Liquid Behavior of Correlated Electrons

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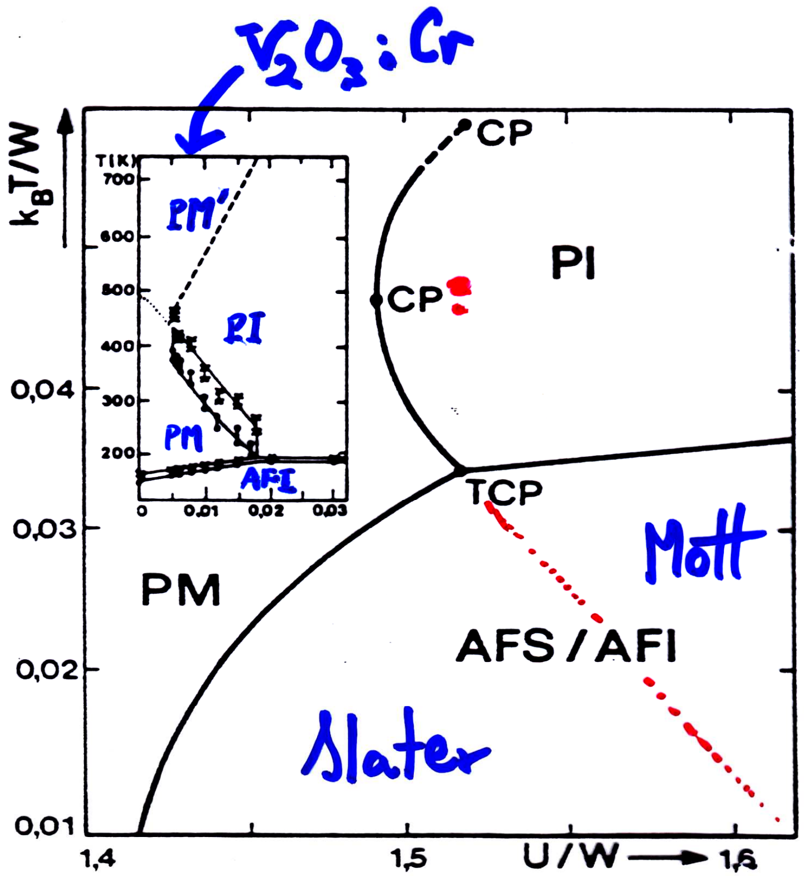
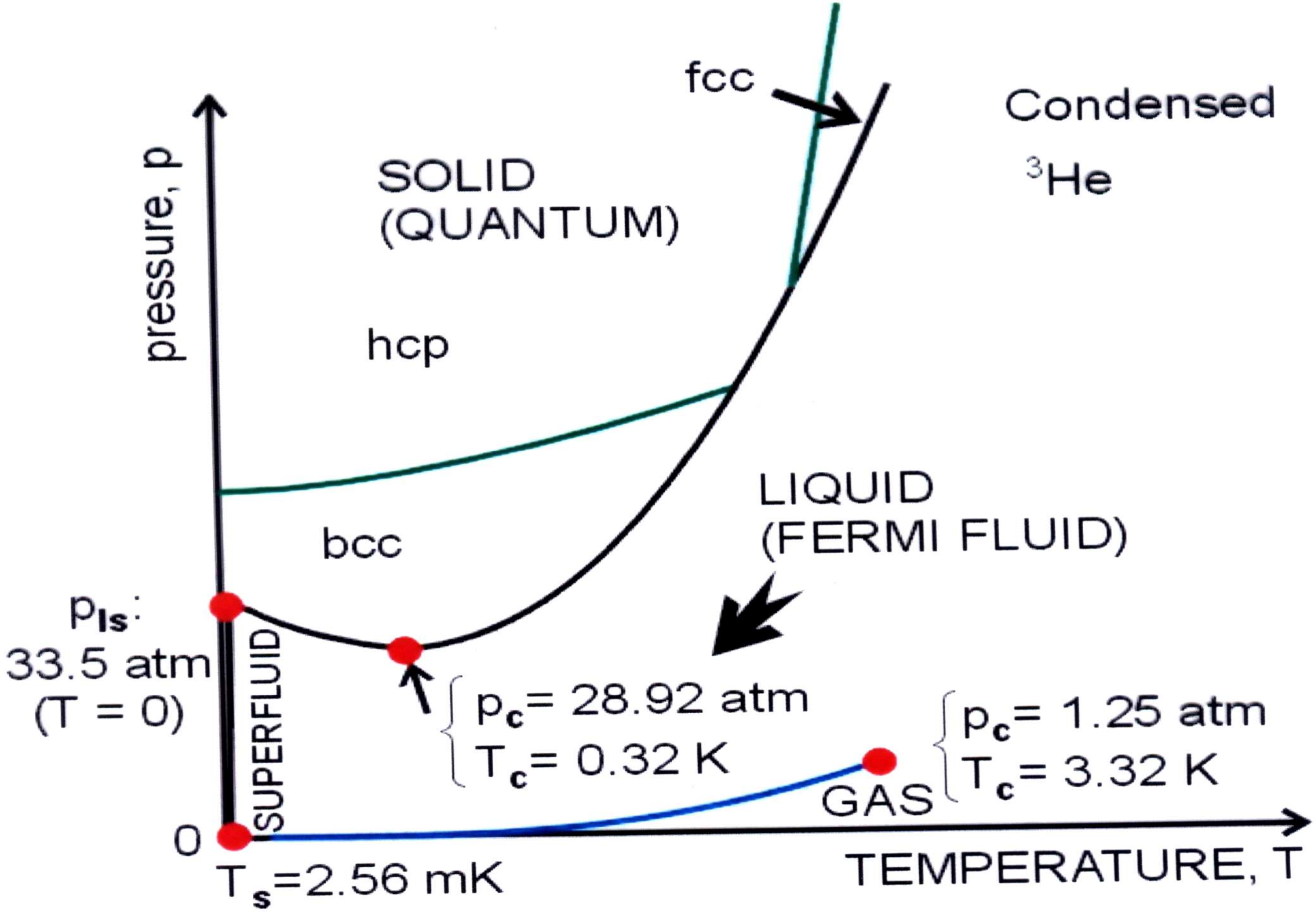
(Received 2 June 1986)

Cf. also Korbel et al.., EPJ B 32, 315 (2003)



Liquid helium-3 as a continuous Mott system: similar behavior as foe electrons



J.S., in: Encycl. of Condens.Matter Phys., vol.3, 126-36 (2005)

Conclusions I:

1. The concept of (narrow) band narrowing-> quasiparticle-mass renormalization
2. First-order MIT with critical (quantum) points
3. Theory valid below Uc - in the metallic phase
4. Double occupancy d as an mean-field order parameter

Extension I: Almost localized Fermi liquid (ALFL)

Landau – Fermi liquids of fermions

For $T \rightarrow 0$

- **Electrical resistivity:** $\rho = \rho_0 + AT^2$
- **Magnetic susceptibility:** $\chi = \chi_0 + aT^2$
- **Specific heat:** $c_p = \gamma T + \delta \; T^3 \ln T / T_0$ $\quad \gamma \propto m^*$
- **Wilson ratio:** $R = \chi / \chi_0 / \gamma / \gamma_0$
- **Kadowaki – Woods scaling** $A \sim \gamma^2$
- **Quasiparticle lifetime:** $\tau^{-1} = \tilde{a}\,\omega^2 + bT^2$

ALFL: Important novel points:

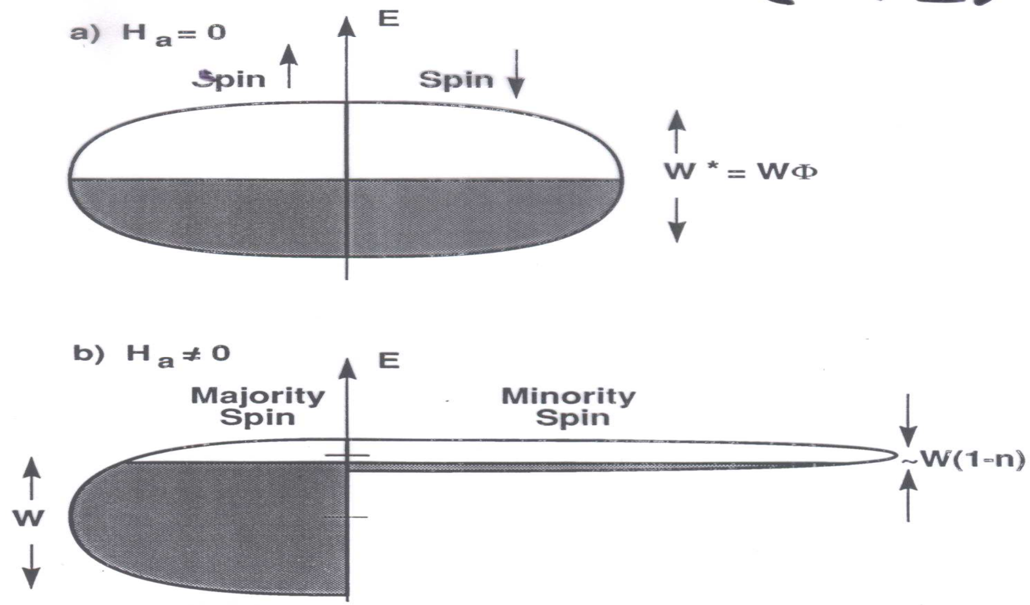
1. Concept of spin-dependent quasiparticle mass (1990 $\rightarrow$ 2005):

   $$m_\sigma / m_0 = 1/Z_\sigma$$

2. Moving Cooper pair: Q nonzero

3. Discontinuous BCS – FFLO transition

D. SPIN DEPENDENT EFFECTIVE MASS ($n \neq 1$)



J. Spałek & P. Gopalan, Phys. Rev. Lett. (1990) **64**, 2823

$$\frac{m_\sigma}{m_B} = \frac{1}{q_\sigma}$$

$$q_\sigma = \frac{1}{n_\sigma(1-n_\sigma)}\left\{\left[(n_\sigma - d^2)(1-n+d^2)\right]^{1/2} + d(n_{\bar{\sigma}} - d^2)^{1/2}\right\}^2$$

$$\frac{1}{N}E_G = \frac{1}{N}\sum_{\underset{\sim}{k}\sigma}(q_\sigma \epsilon_{\underset{\sim}{k}} - \mu_B H_a \sigma - \mu)\,\bar{n}_{\underset{\sim}{k}\sigma} + U d^2$$

Spin-dependent masses from the de Haas-van Alphen effect

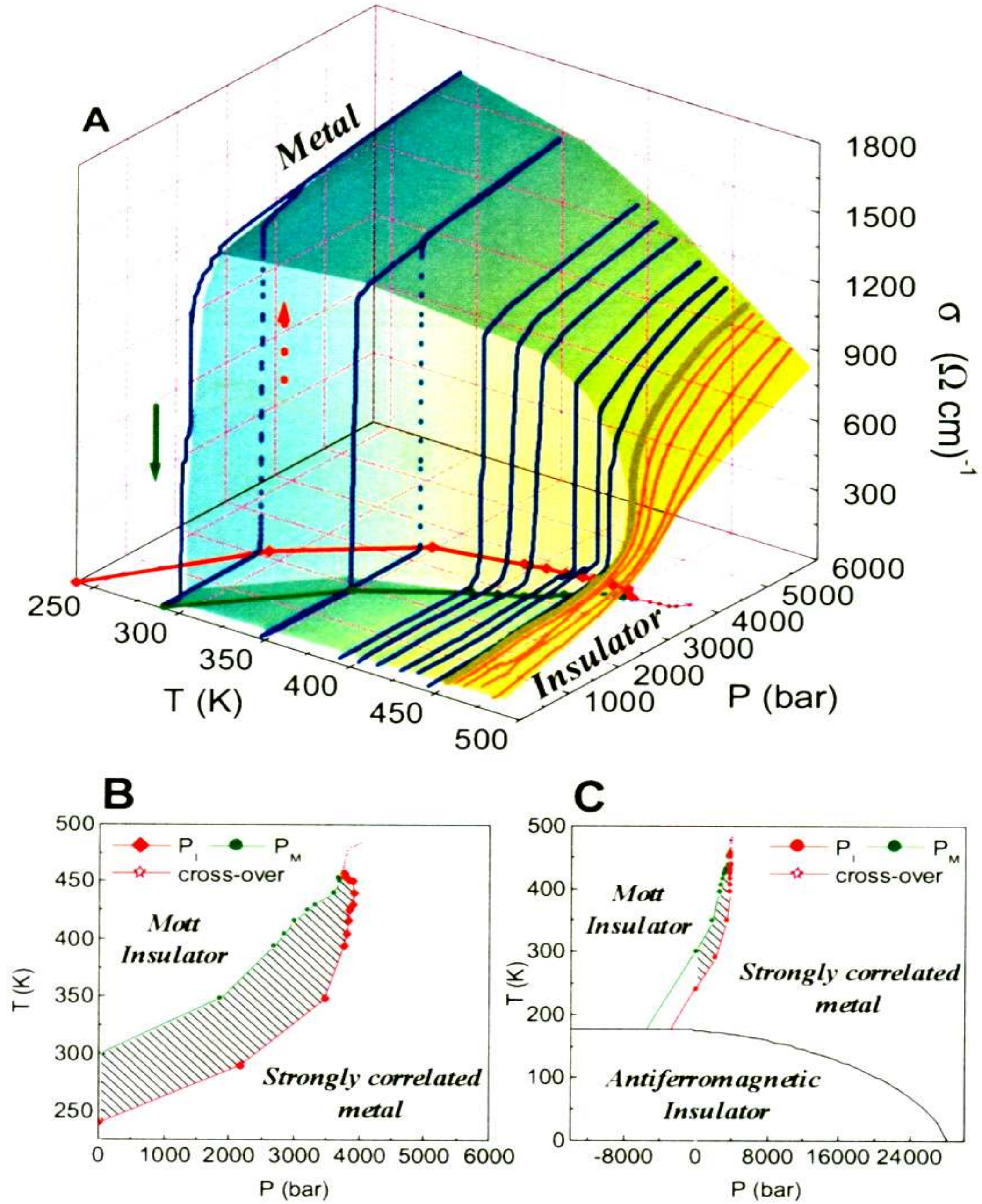
	$m_{\uparrow}$	$m_{\downarrow}$	ϕ_x
$\theta = 0^o$			
α_1	21.2 ± 0.2	94 ± 7	3.14
α_2	24.2 ± 0.4	94 ± 8	3.14
α_3	14.5 ± 0.6	30 ± 8	2.42
$\theta = 10^o$			
α_1	21.3 ± 2.4	39 ± 5	3.14
α_2	24.7 ± 3.5	50 ± 13	3.14
α_3	17.6 ± 0.8	40 ± 4	3.14

Anomalous de Haas–van Alphen Oscillations in CeCoIn5 A. McCollam, S. R. Julian, P. M. C. Rourke, D. Aoki, and J. Flouquet
Phys. Rev. Lett., 94, 186401 (2005); Physica B (2005).

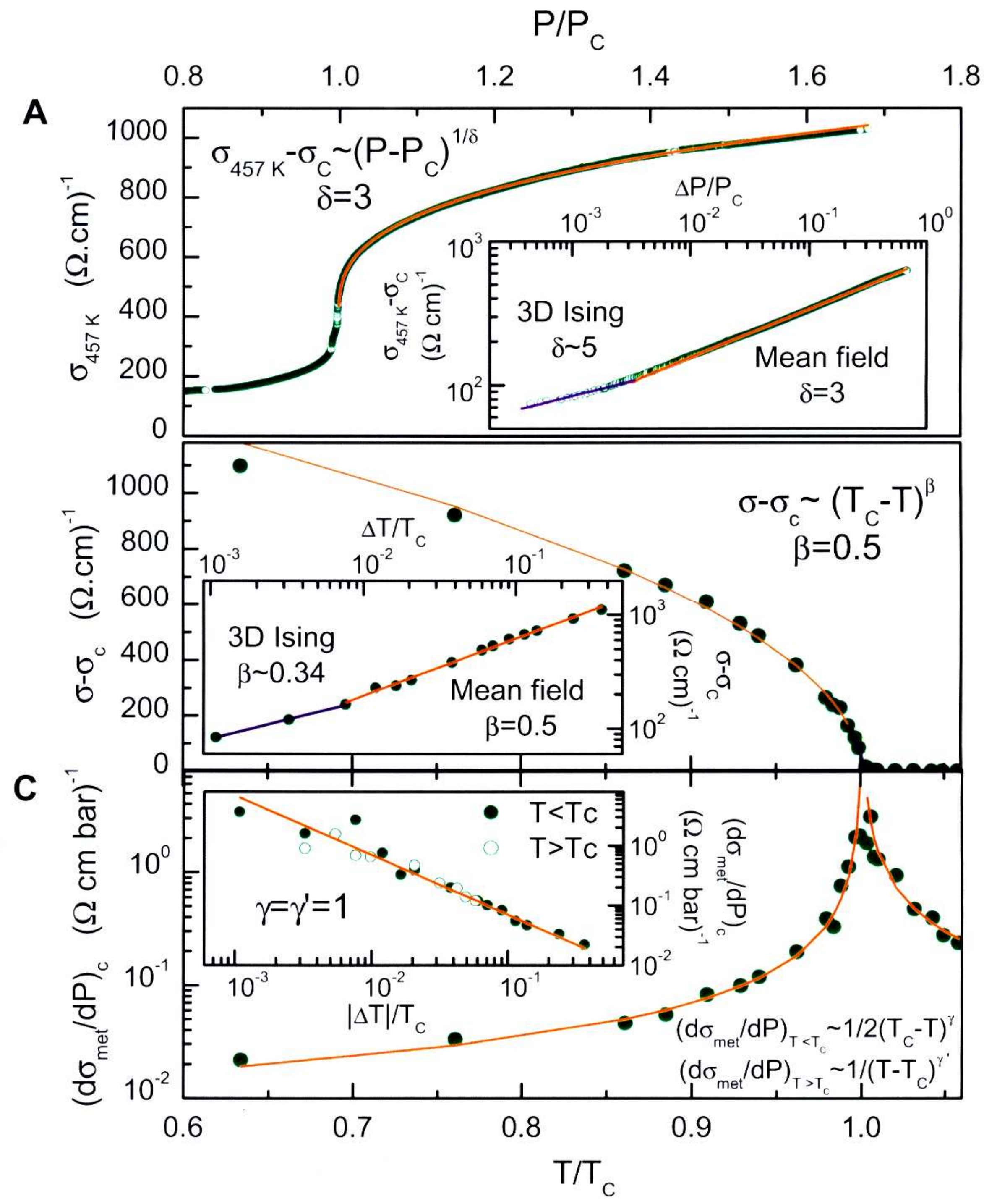
See also: I. Sheikin, et al., Phys. Rev. B 67**, 094420 (2003)**

Extension II:
(Classical) critical behavior

P. Limelette et al..,
Science **302**, 89-92 (2003)

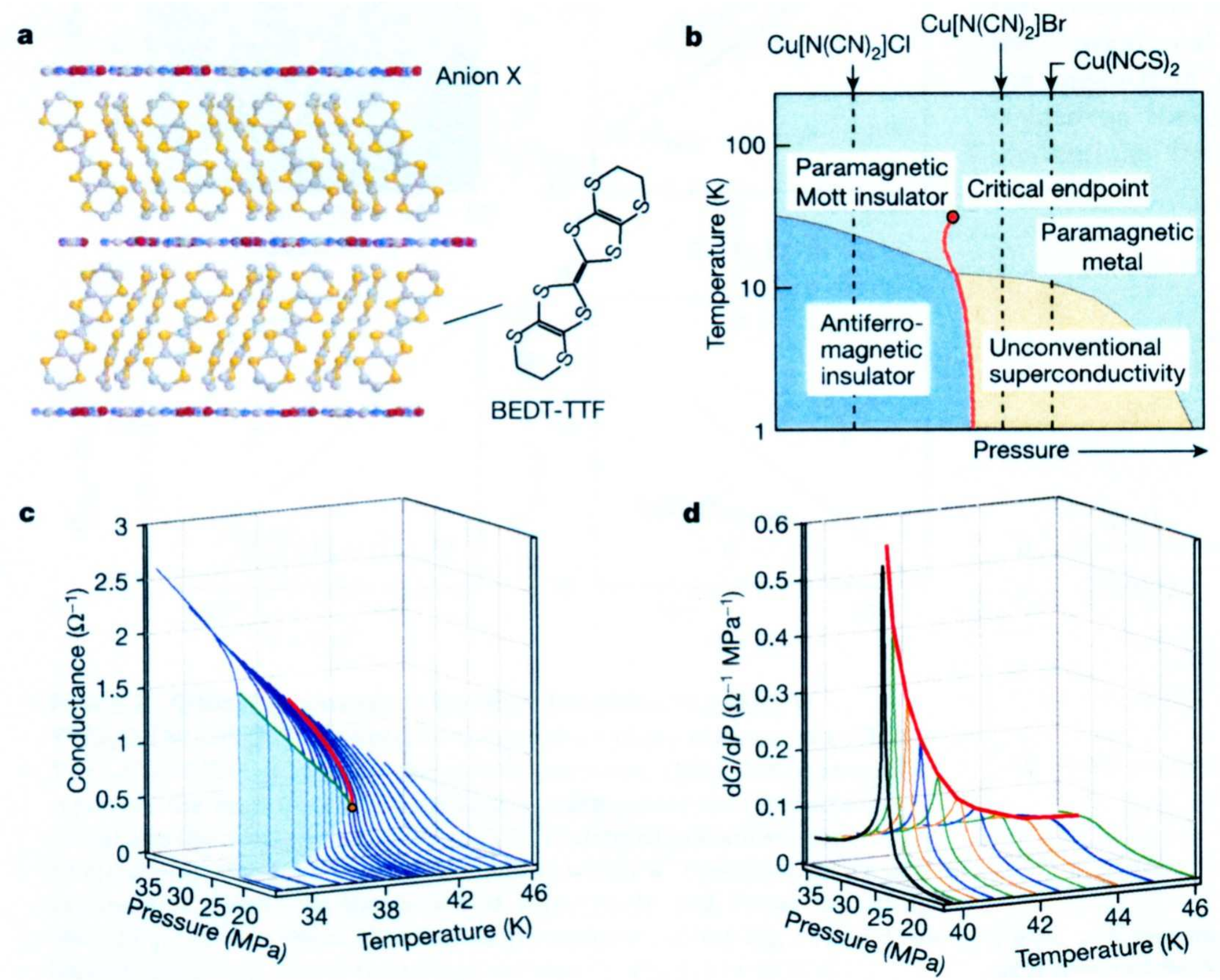


V_2O_3:Cr

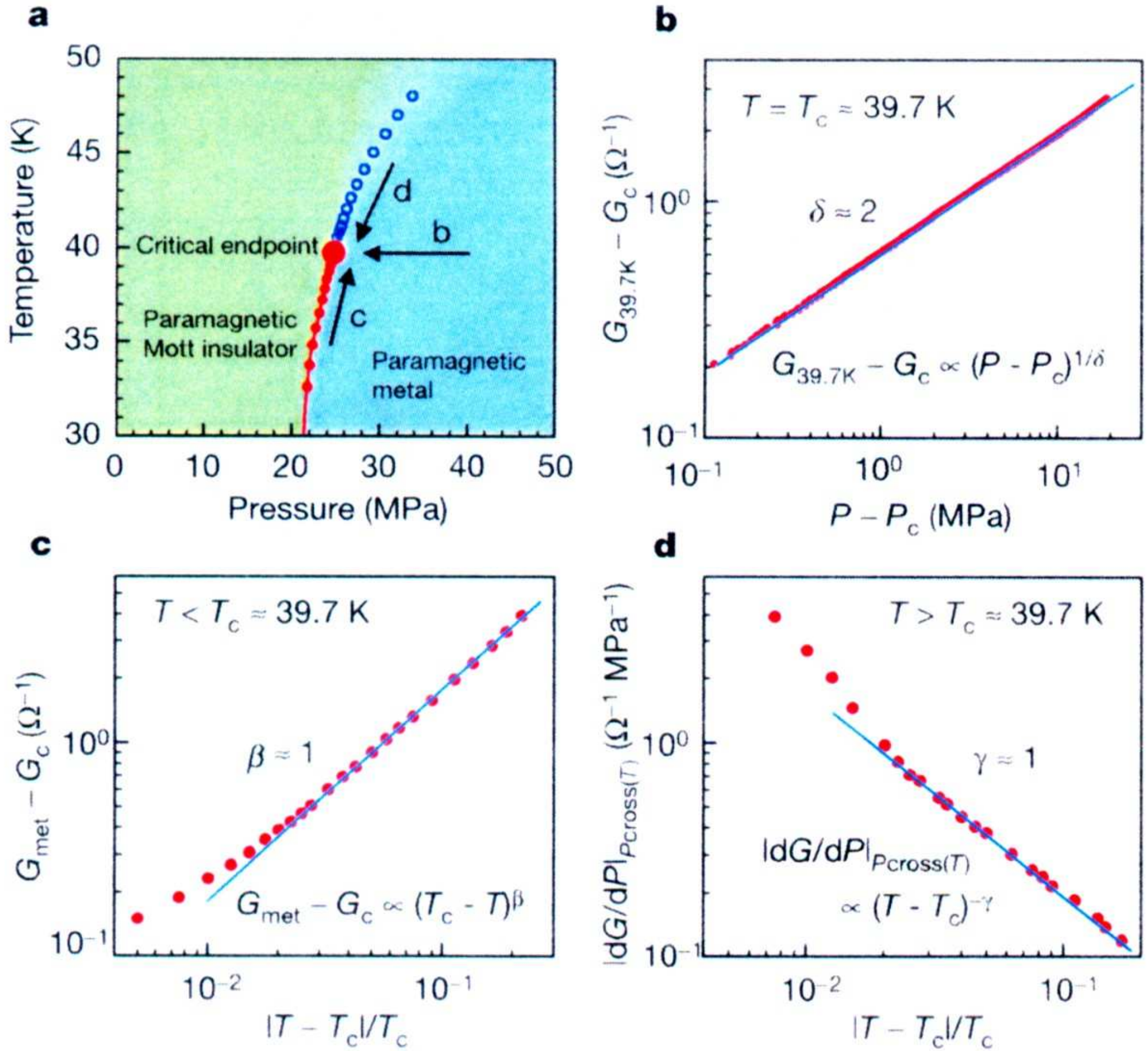


P/P_C
A
σ_457 K-σ_C~(P-P_C)^1/δ
δ=3
σ_457 K (Ω.cm)^-1
ΔP/P_C
σ_457 K-σ_C (Ω cm)^-1
3D Ising
δ~5
Mean field
δ=3
σ-σ_c~ (T_C-T)^β
β=0.5
σ-σ_c (Ω.cm)^-1
ΔT/T_C
3D Ising
β~0.34
Mean field
β=0.5
σ-σ_C (Ω cm)^-1
C
(dσ_met/dP)_c (Ω cm bar)^-1
T<Tc
T>Tc
γ=γ'=1
|ΔT|/T_C
(dσ_met/dP)_c (Ω cm bar)^-1
(dσ_met/dP)_T<T_C~1/2(T_C-T)^γ
(dσ_met/dP)_T>T_C~1/(T-T_C)^γ'
T/T_C

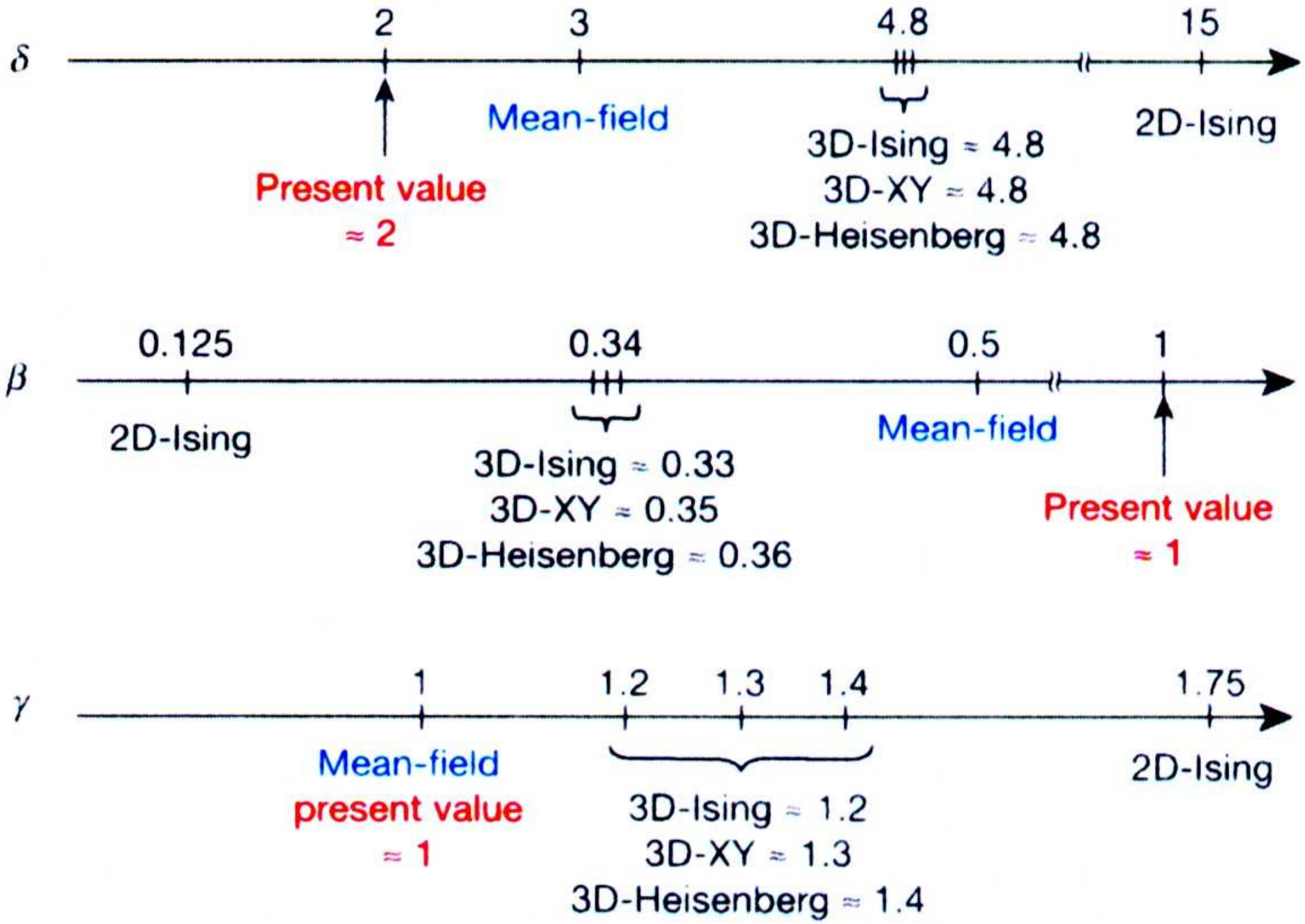
Critical point for 2D system:
organic metal
a novel behavior



F. Kagawa et al., Nature 436, 534 (2005)



a
b
c
d
Temperature (K)
Pressure (MPa)
Critical endpoint
Paramagnetic
Mott insulator
Paramagnetic
metal
T = T_c ≈ 39.7 K
δ ≈ 2
G_39.7K − G_c ∝ (P − P_c)^1/δ
G_39.7K − G_c (Ω^−1)
P − P_c (MPa)
T < T_c ≈ 39.7 K
β ≈ 1
G_met − G_c ∝ (T_c − T)^β
G_met − G_c (Ω^−1)
|T − T_c|/T_c
T > T_c ≈ 39.7 K
γ ≈ 1
|dG/dP|_Pcross(T)
∝ (T − T_c)^−γ
|dG/dP|_Pcross(T) (Ω^−1 MPa^−1)
|T − T_c|/T_c


δ
2
3
4.8
15
Mean-field
3D-Ising ≈ 4.8
3D-XY ≈ 4.8
3D-Heisenberg ≈ 4.8
2D-Ising
Present value
≈ 2
β
0.125
0.34
0.5
1
2D-Ising
3D-Ising ≈ 0.33
3D-XY ≈ 0.35
3D-Heisenberg ≈ 0.36
Mean-field
Present value
≈ 1
γ
1
1.2
1.3
1.4
1.75
Mean-field
present value
≈ 1
3D-Ising ≈ 1.2
3D-XY ≈ 1.3
3D-Heisenberg ≈ 1.4
2D-Ising

Critical point in magnetic system:

NiSSe system

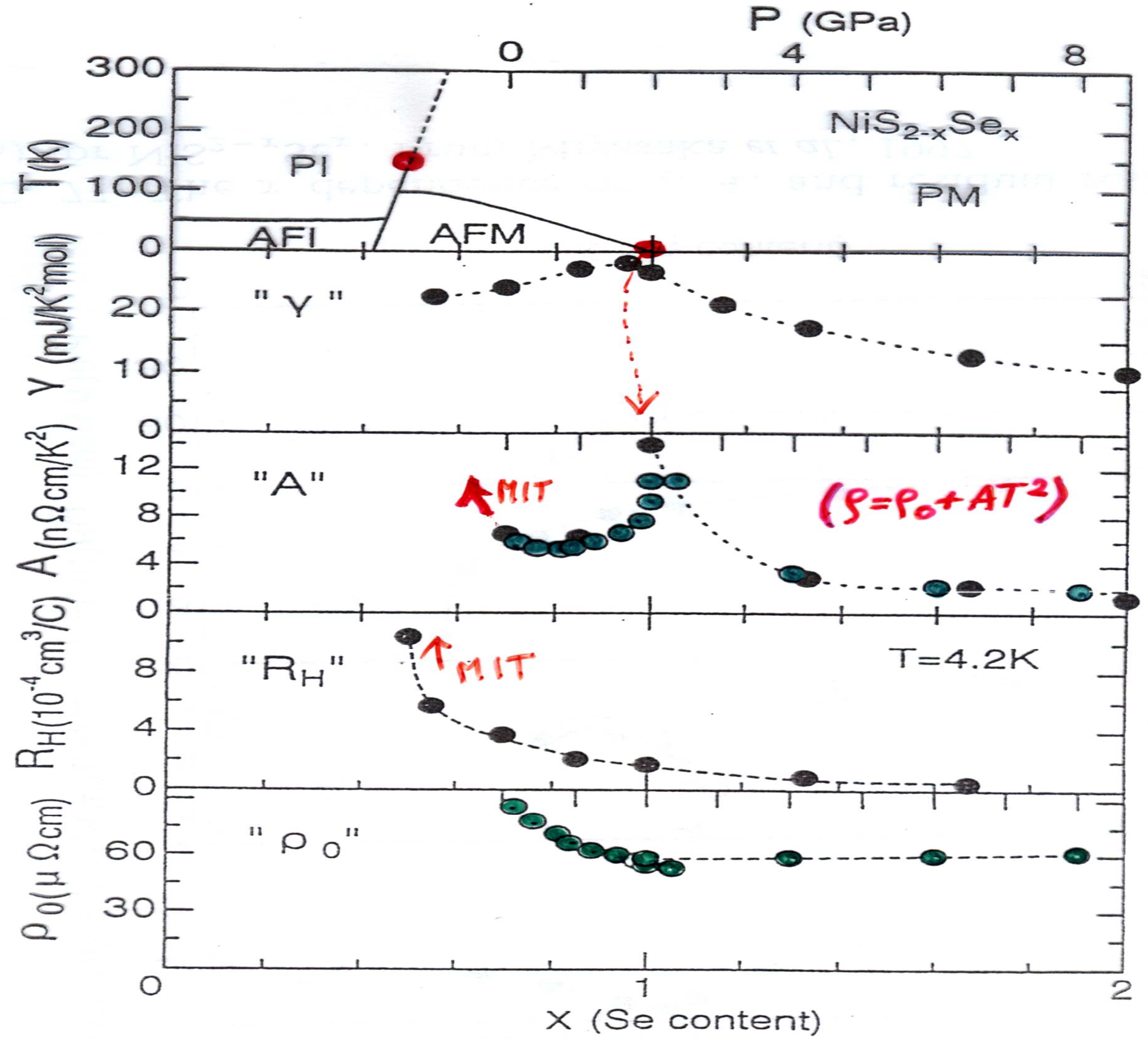


FIG. 77. The x dependence of χ, A, and residual resistivity (ρ_0) for $NiS_{2-x}Se_x$. From Miyasaka *et al.*, 1997.

— Imada/Fujimori/Tokura, RMP (1998)

A. Husmann et al.,
PRL **84**, 2465 (2000)

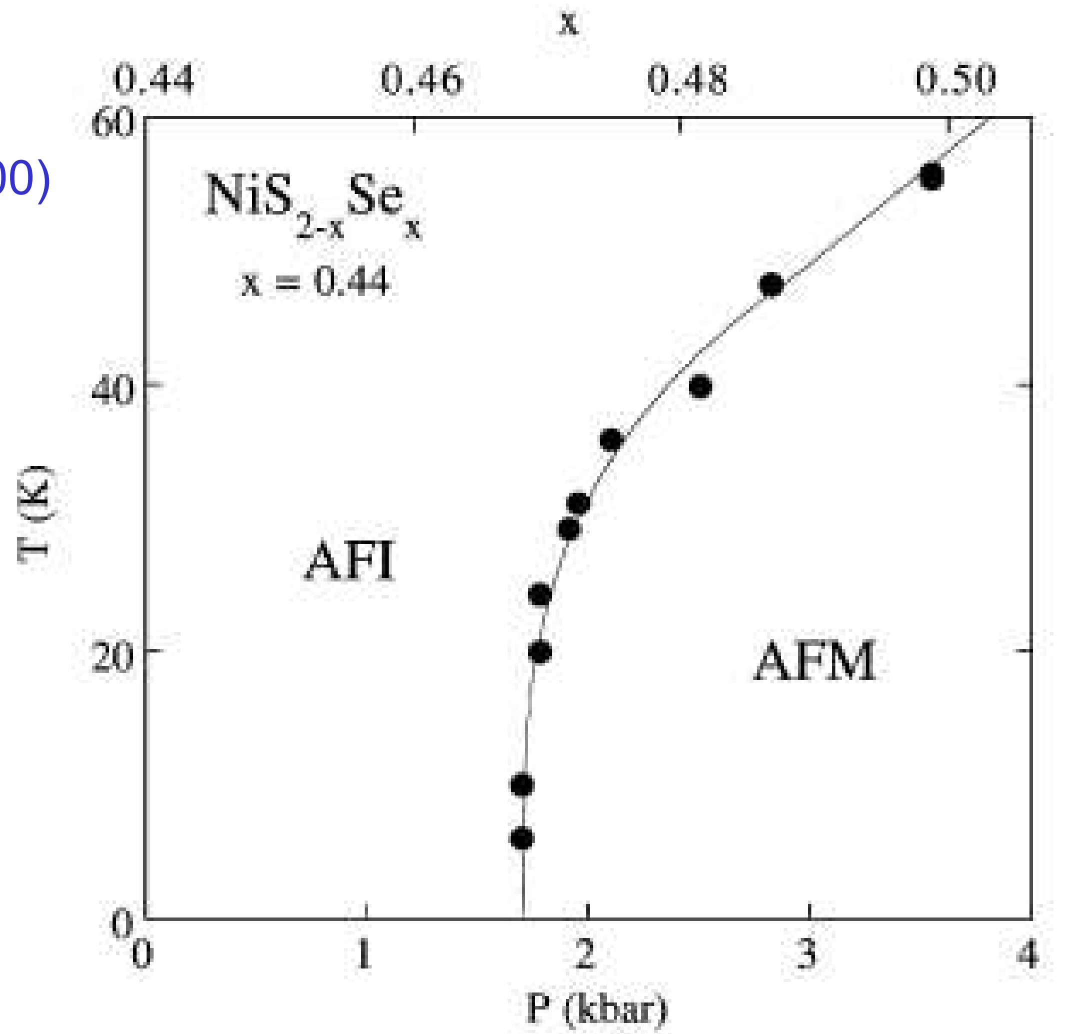


FIG. 1. Pressure-temperature phase diagram for crystals of $NiS_{1.56}Se_{0.44}$. The critical pressure for the $T = 0$ metal-insulator transition is less than 2 kbar. Each kbar of external pressure corresponds to a chemical pressure $\Delta x = 0.017$. AFI = antiferromagnetic insulator; AFM = antiferromagnetic metal.

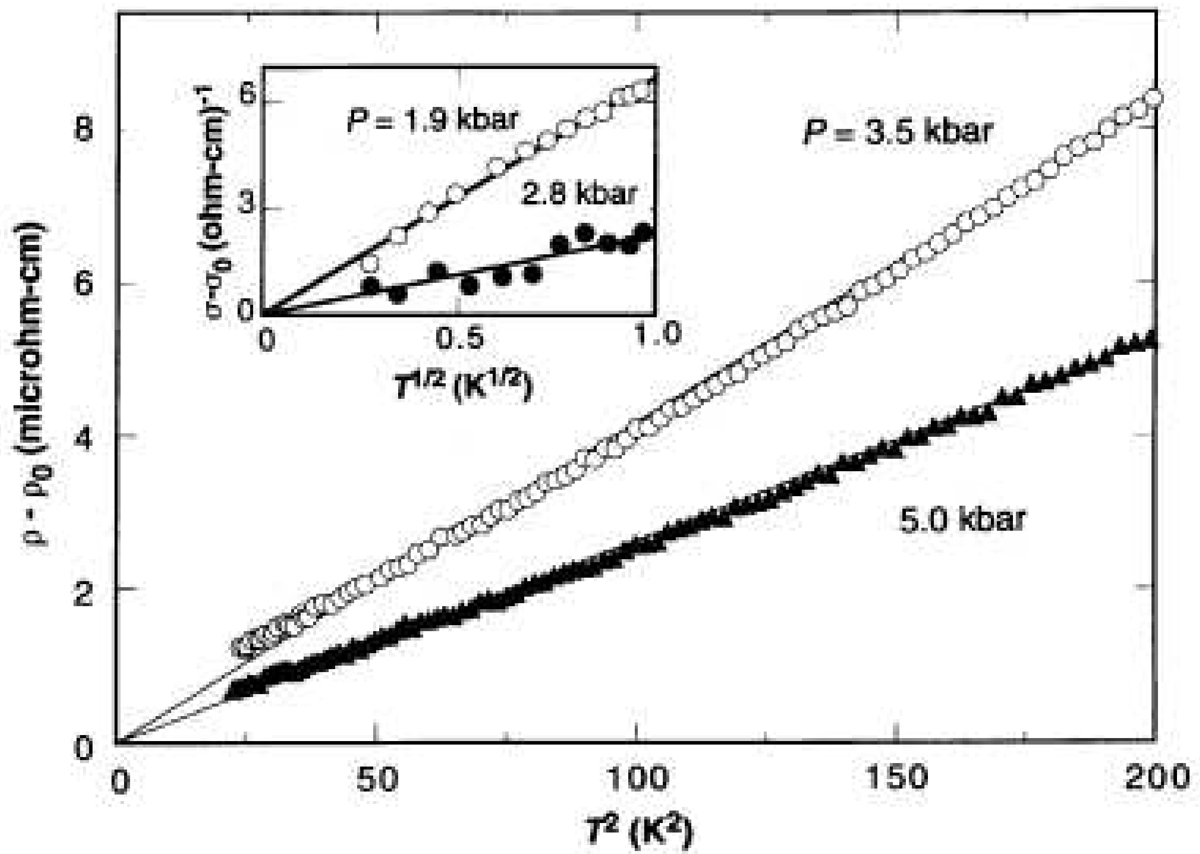


Fig. 2. The large T^2 dependence of the resistivity ρ with slope increasing at the approach to the MI transition indicates a greatly enhanced electronic effective mass. Inset: The effective mass enhancement is revealed as well by the changing slope of the $T^{1/2}$ dependence of the conductivity σ for $T < 1$ K, characteristic of electron-electron interactions in the presence of disorder.

A. Husmann et al., Science **274**, 1875 (1996)

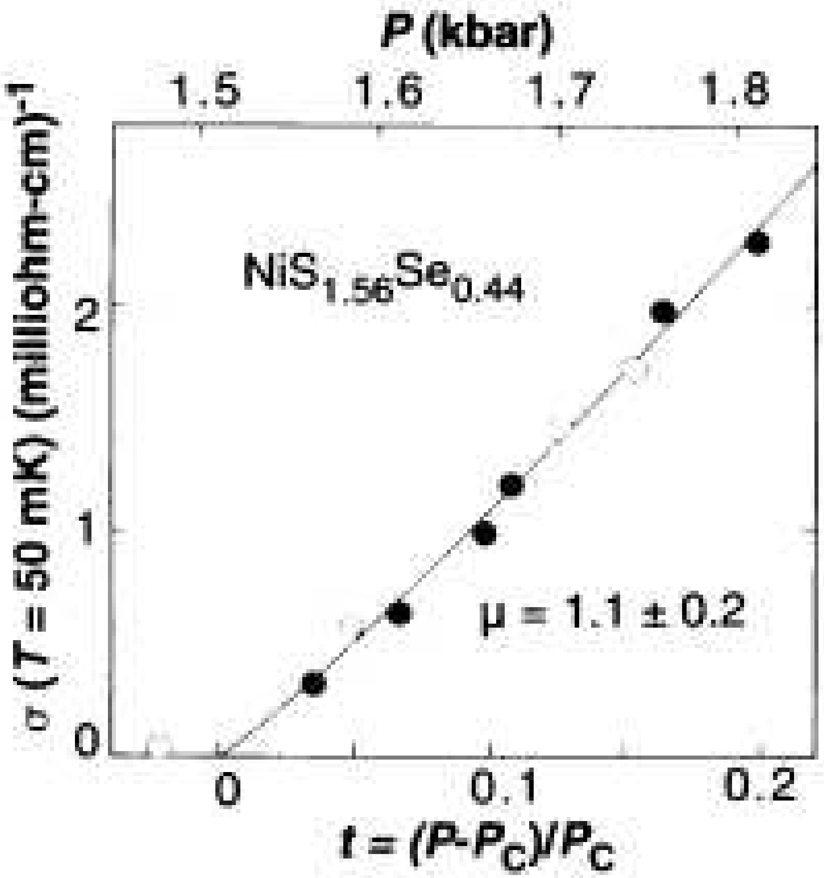
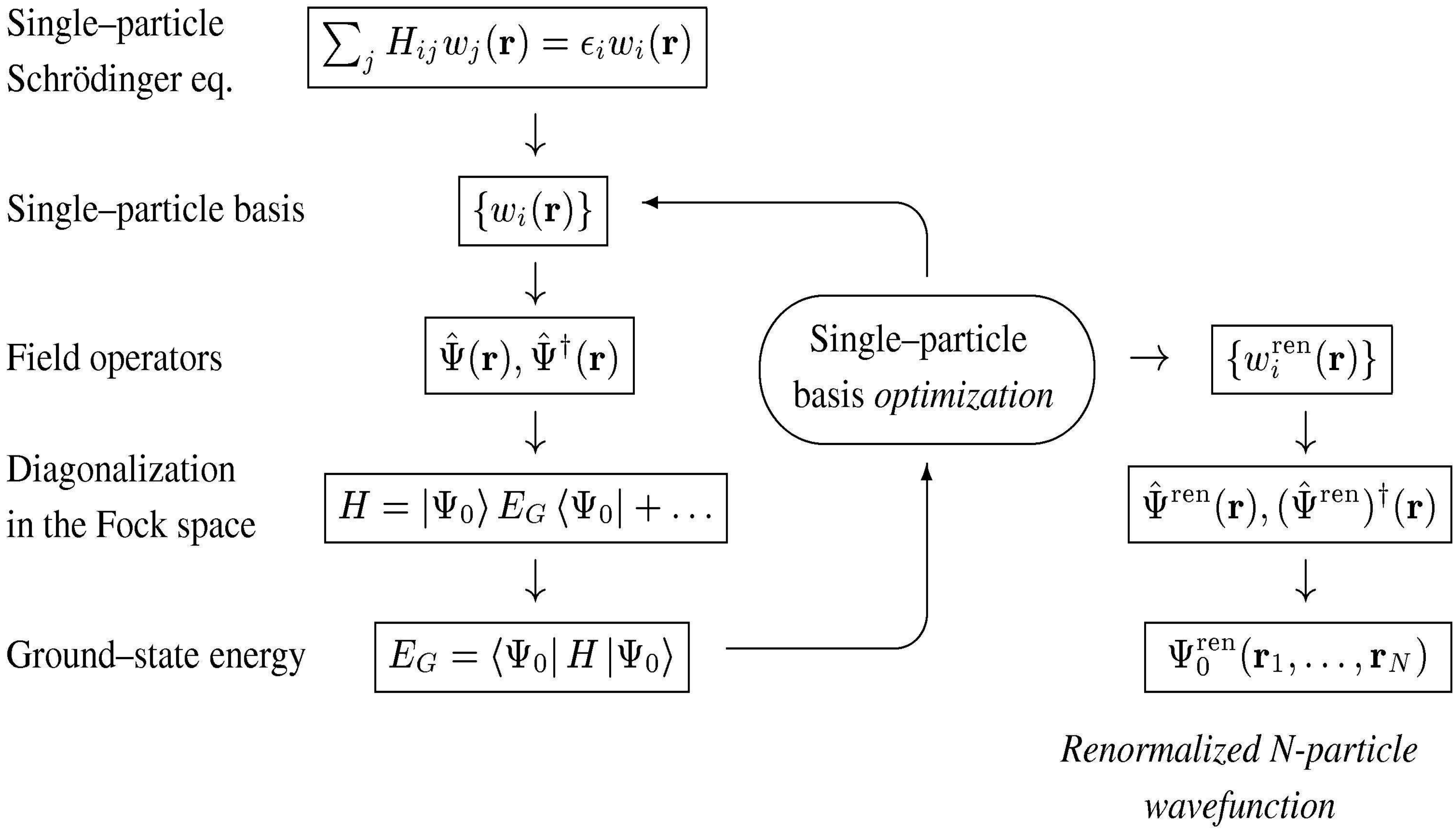


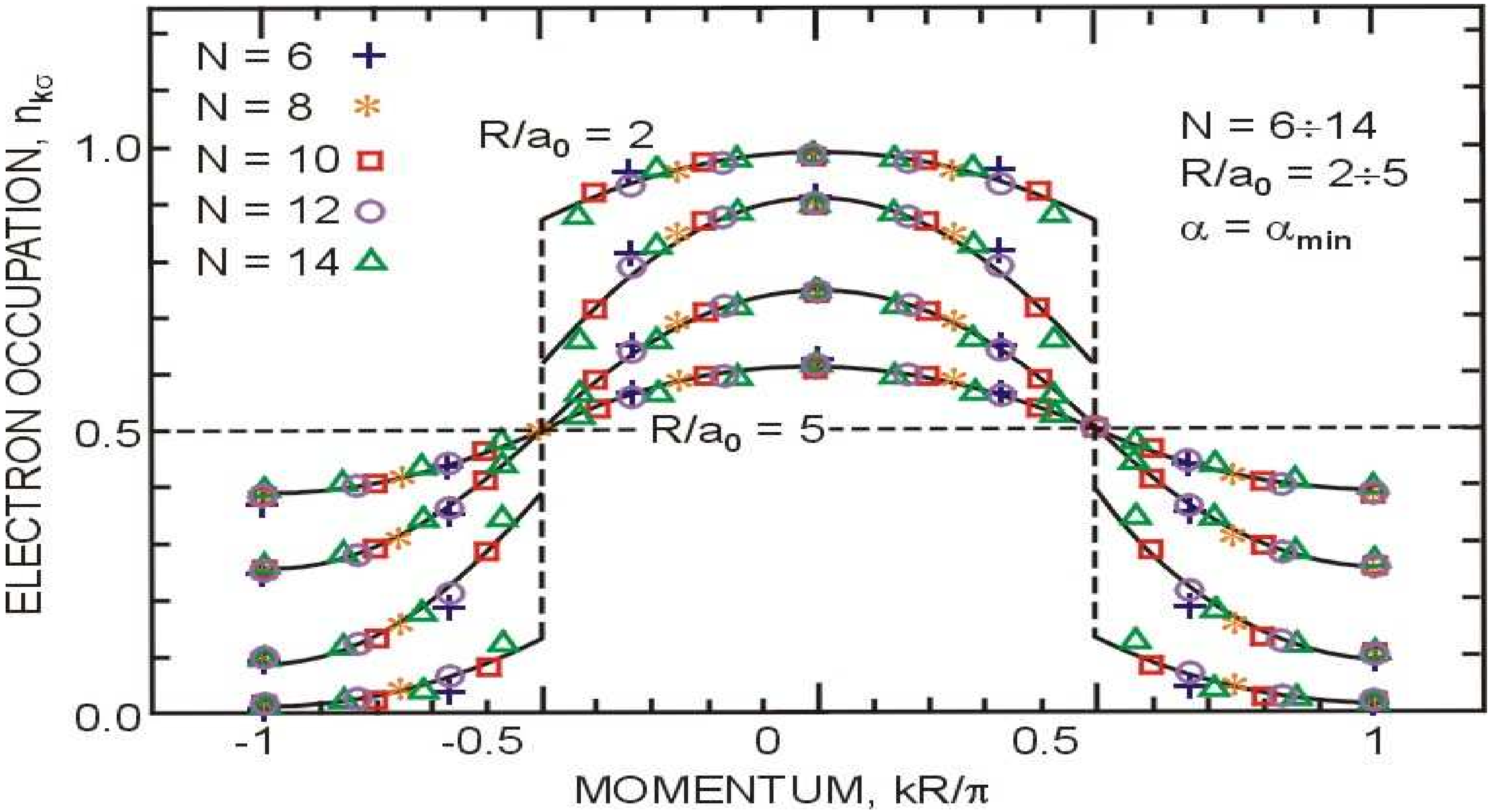
Fig. 1. The $T \rightarrow 0$ conductivity σ_0 as a function of reduced pressure t for two crystals with P_c = 1.51 kbar (filled circles) and P_c = 1.67 kbar (open circles) at the MI transition. The conductivity falls smoothly to zero, $\sigma_0 \sim t^{\mu}$, where 1 (milliohm-cm)$^{-1}$ is of order the Mott conductivity.

Extension III:
Correlations + wave function
renormalization (2008-9)



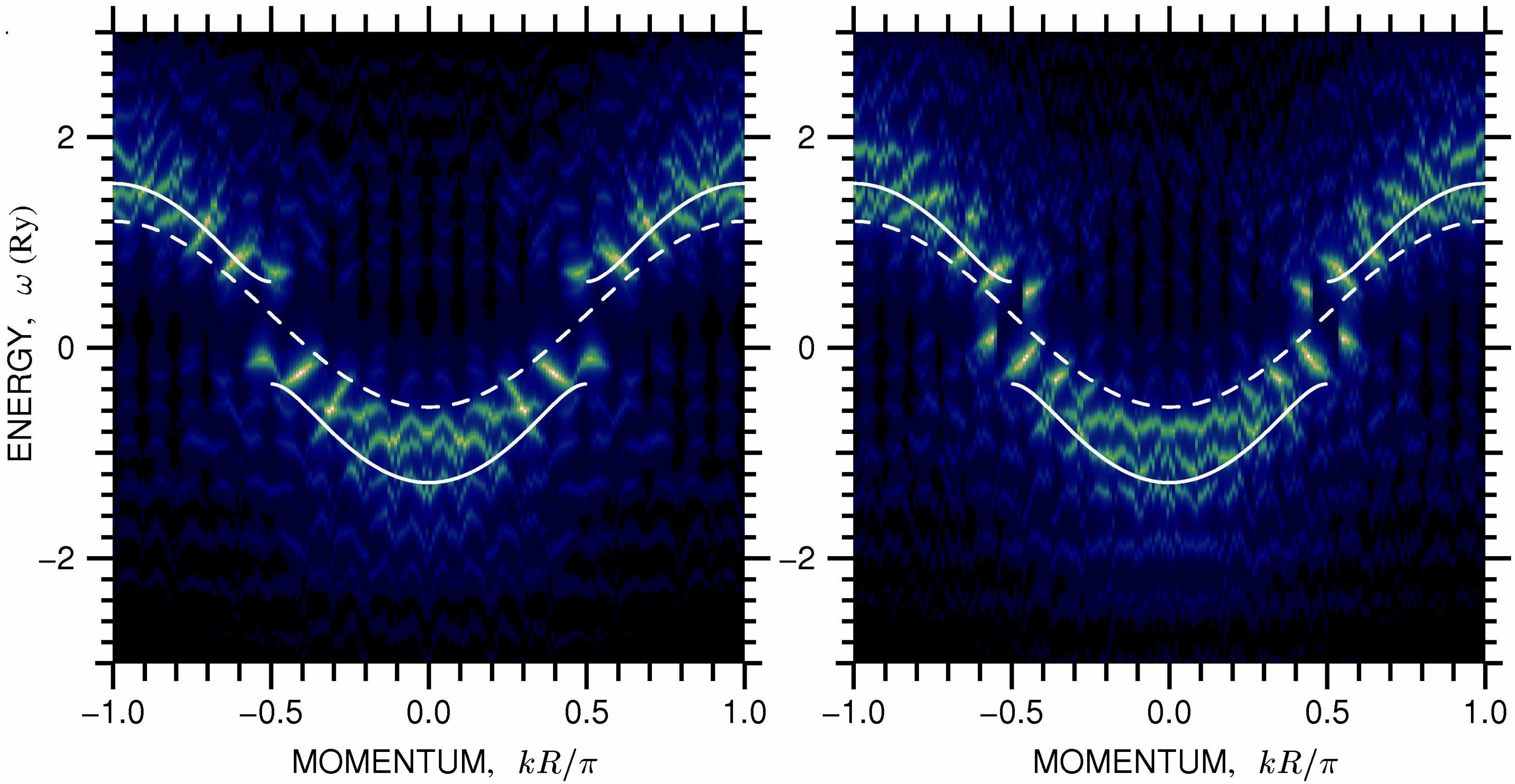
EDABI: J. Spałek, R. Podsiadły, W. Wójcik, and A. Rycerz, Phys.Rev. B 61, 15676 (2000);→ (2001-2007); J. Kurzyk et al. (2008-9)

Momentum distribution:Fermi-Dirac vs continuous

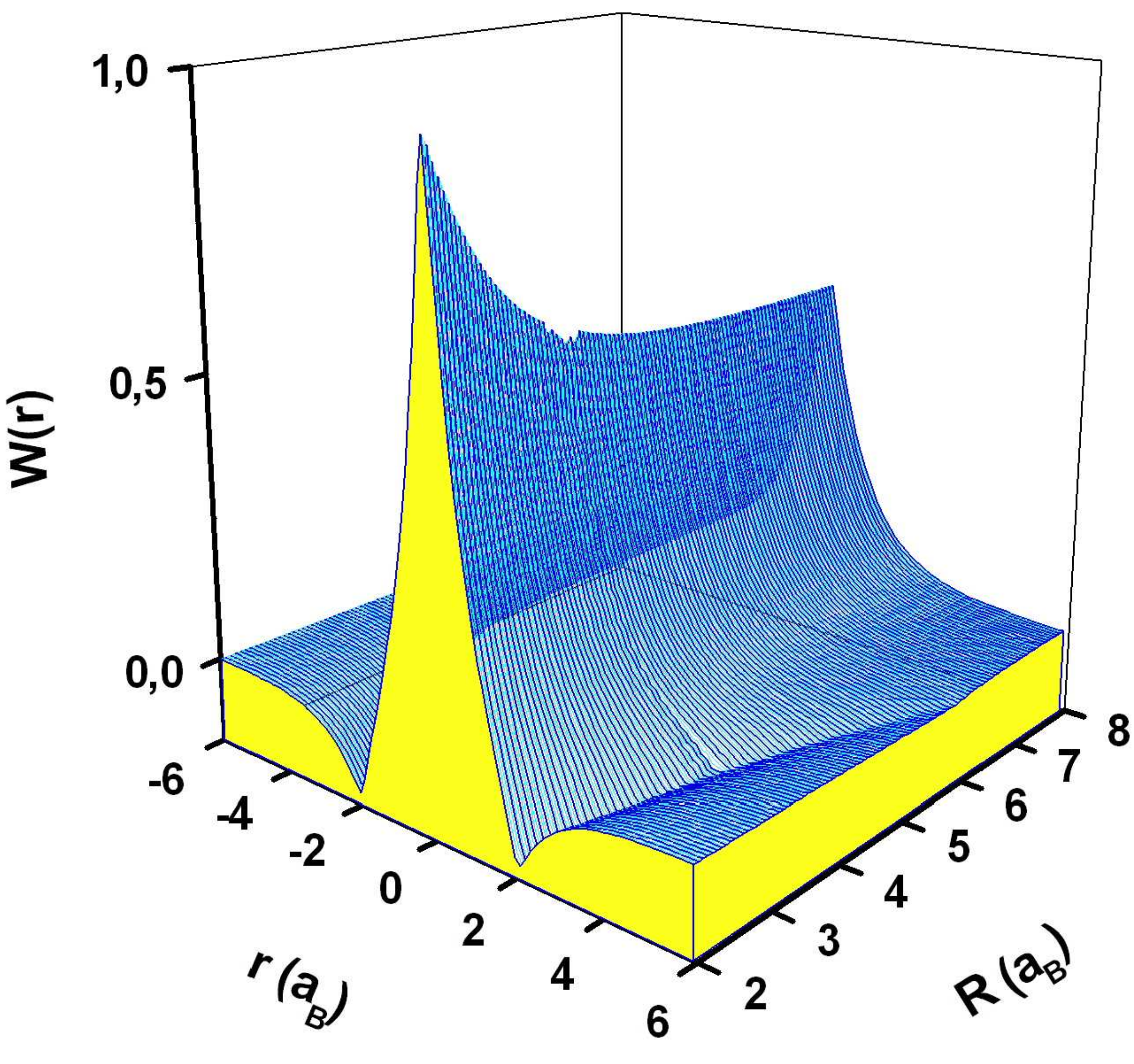


J. S. & A. Rycerz, PRB-R (2001);
J.S., in Encyclopedia of Condensed Matter Physics, Elsevier, vol. 3, pp. 126-136 (2005)

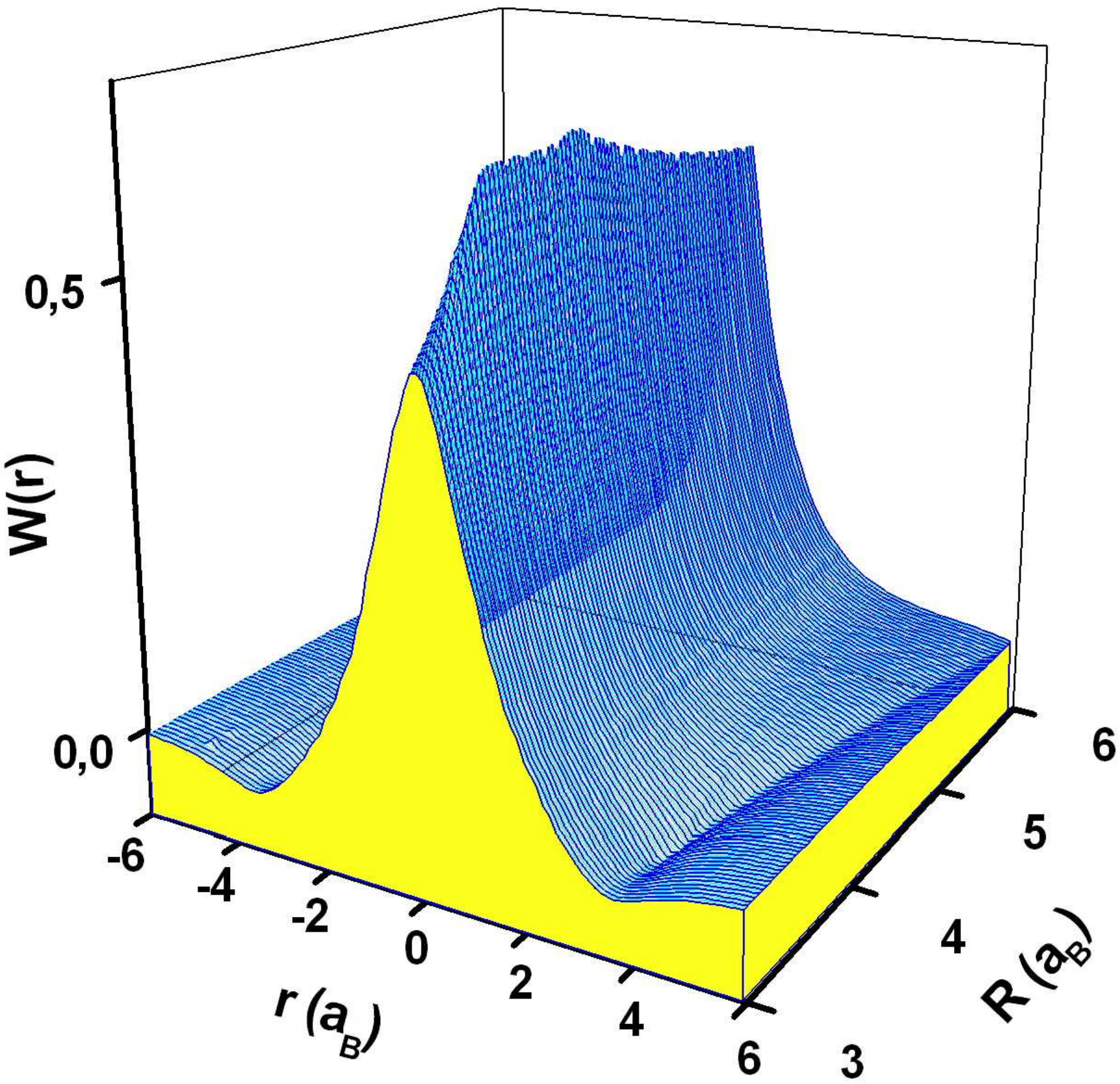
Renormalized band energies: even and odd

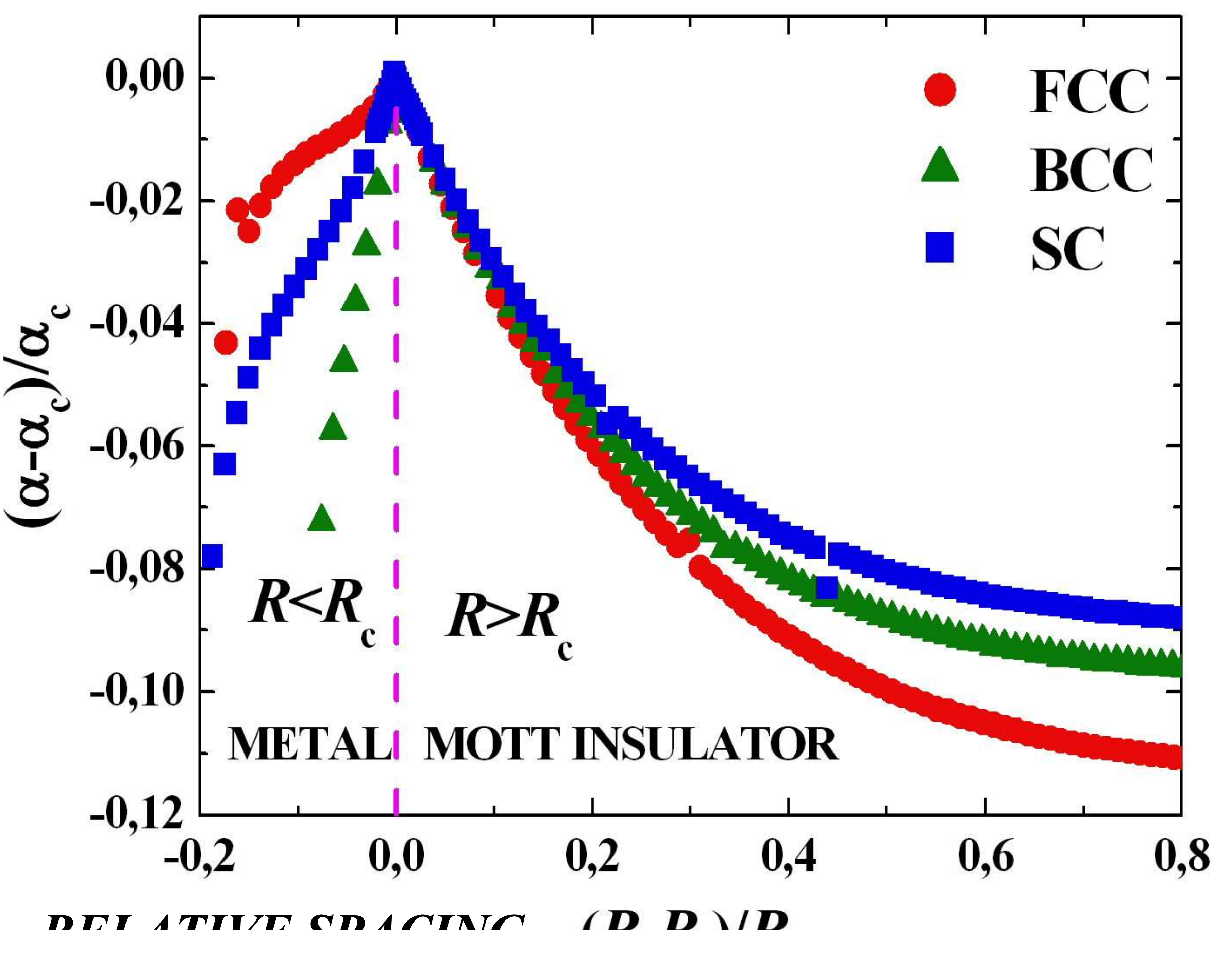


Square lattice

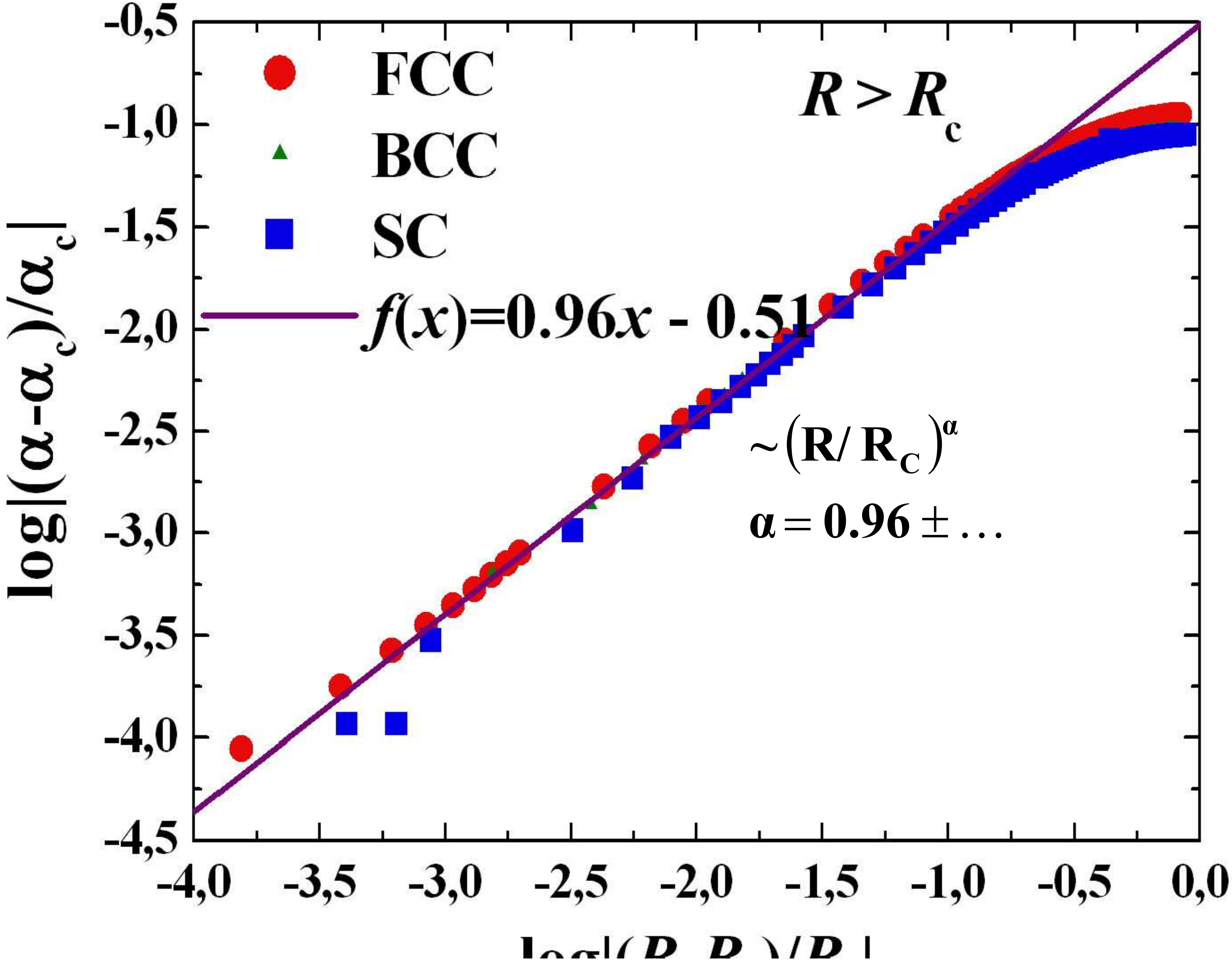


Simple Cubic lattice

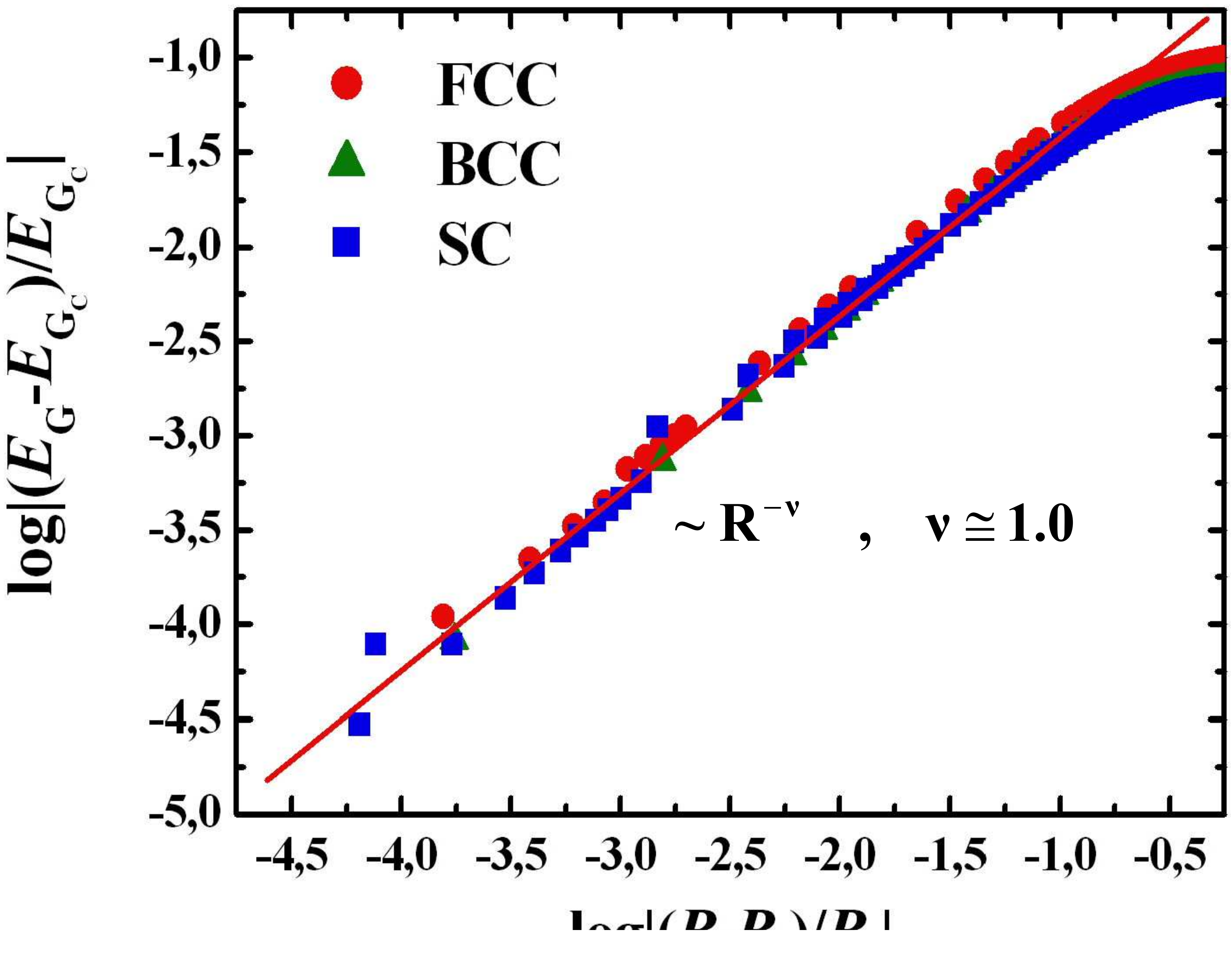




FCC
BCC
SC
$(\alpha-\alpha_c)/\alpha_c$
0,00
-0,02
-0,04
-0,06
-0,08
-0,10
-0,12
-0,2
0,0
0,2
0,4
0,6
0,8
$R<R_c$
$R>R_c$
METAL
MOTT INSULATOR



FCC
BCC
SC
R > R_c
f(x)=0.96x - 0.51
~(R/R_C)^α
α = 0.96 ± …
log|(α-α_c)/α_c|
-0,5
-1,0
-1,5
-2,0
-2,5
-3,0
-3,5
-4,0
-4,5
-4,0
-3,5
-3,0
-2,5
-2,0
-1,5
-1,0
-0,5
0,0



FCC
BCC
SC
~ R^−ν , ν ≅ 1.0
log|(E_G-E_Gc)/E_Gc|
-1,0
-1,5
-2,0
-2,5
-3,0
-3,5
-4,0
-4,5
-5,0
-4,5
-4,0
-3,5
-3,0
-2,5
-2,0
-1,5
-1,0
-0,5

Microscopic parameters at the critical point for GA solutions and for the lattices considered

Struct.	α / a_0	R_C / a_0	$(U/W)_C$
CH	1.021	3.288	2.547
SQ	1.051	3.622	1.621
TR	1.054	3.569	1.318
SC	1.099	4.236	1.337
BCC	1.109	4.384	1.080
FCC	1.128	4.351	0.880

Conclusions II:

Wave function renormalization + Two-particle correlations combined

Extension IV: Orbitally degenerate model

$$H_1 = \frac{1}{2} U \sum_i n_i^2 - J \sum_i \mathbf{S}_i^2 + \frac{1}{4} J \sum_{il} n_{il}^2 - J \sum_{il} (\mathbf{S}_{il}^z)^2$$

E.M. Goerlich et al. (2009)

l = 1,…, L - the orbital index

Hubbard-Stratonowich transformation

$$\exp\left\{\frac{\hat{\alpha}^2}{2}\right\} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx \exp\left\{-\frac{x^2}{2} \pm \hat{\alpha} x\right\}$$

To be continued …

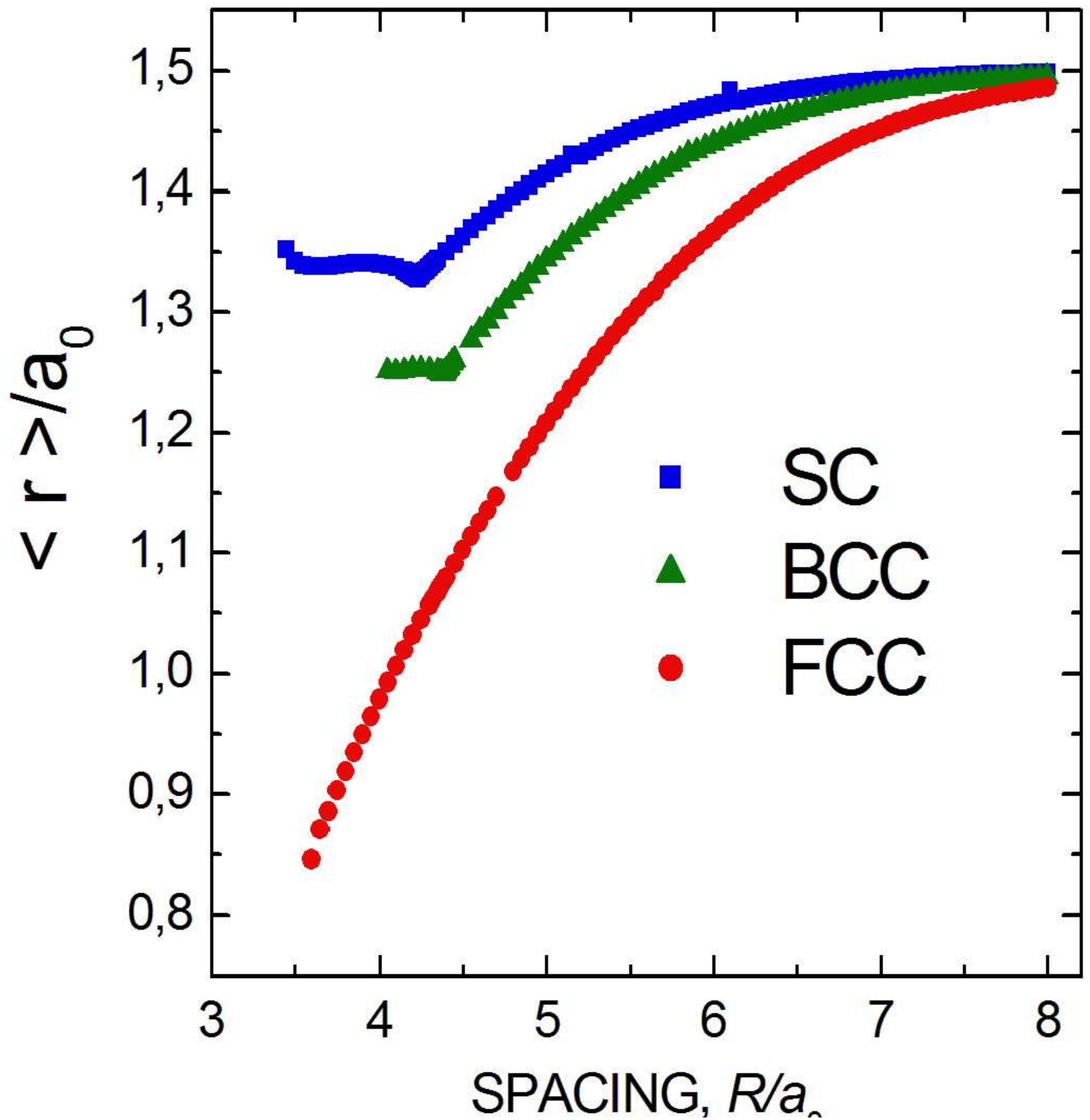
Supplement: Infinite Hubbard chain vs. nanochain

Ground state energy functional:

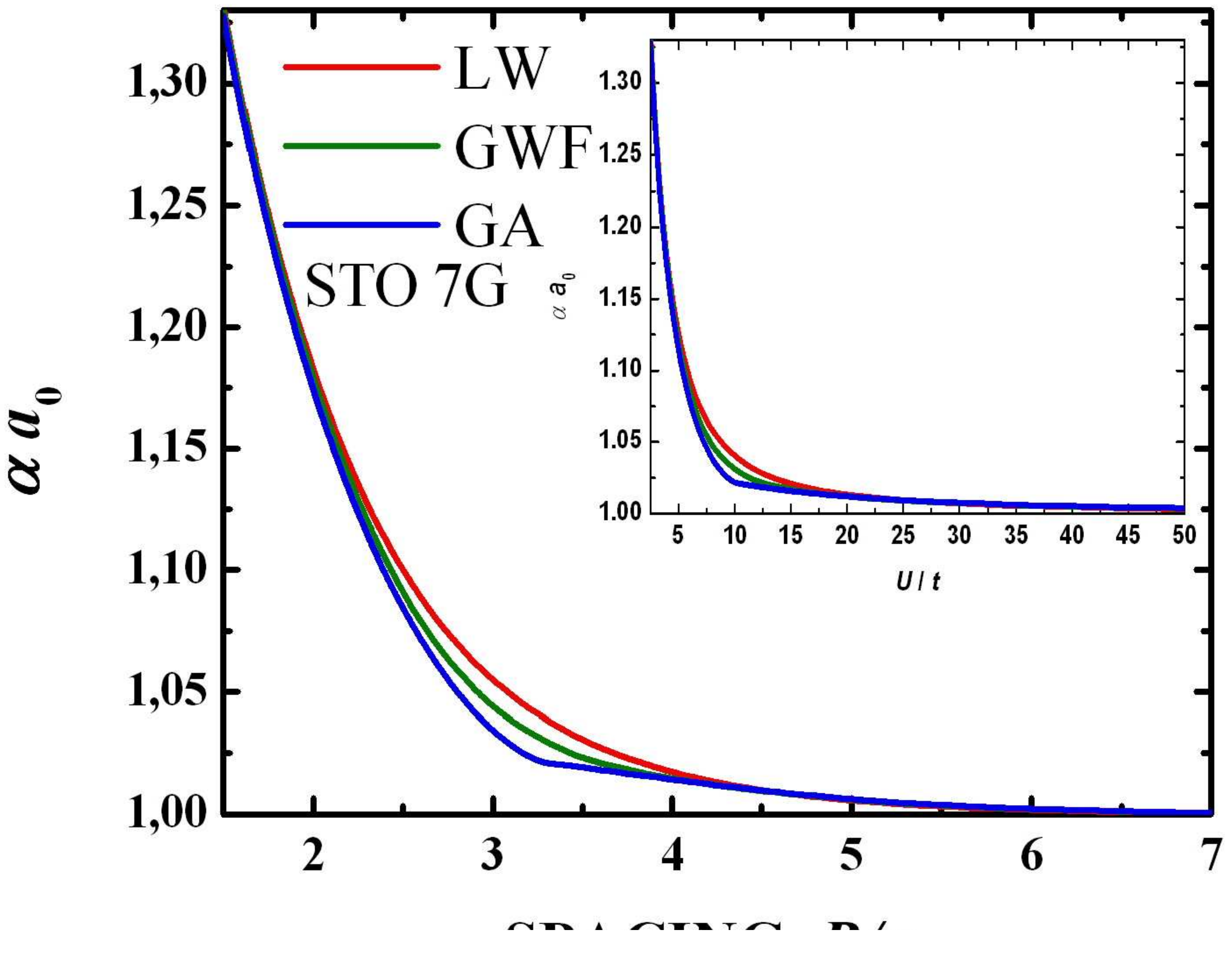
$$\frac{E}{N} = \epsilon_a^{eff} - 4t\int_0^{\infty} \frac{J_0(\omega)J_1(\omega)}{\omega\left[1+\exp(\omega U/2t)\right]}\,d\omega$$

$$\delta n_i \equiv 1 - n_i \equiv 0$$

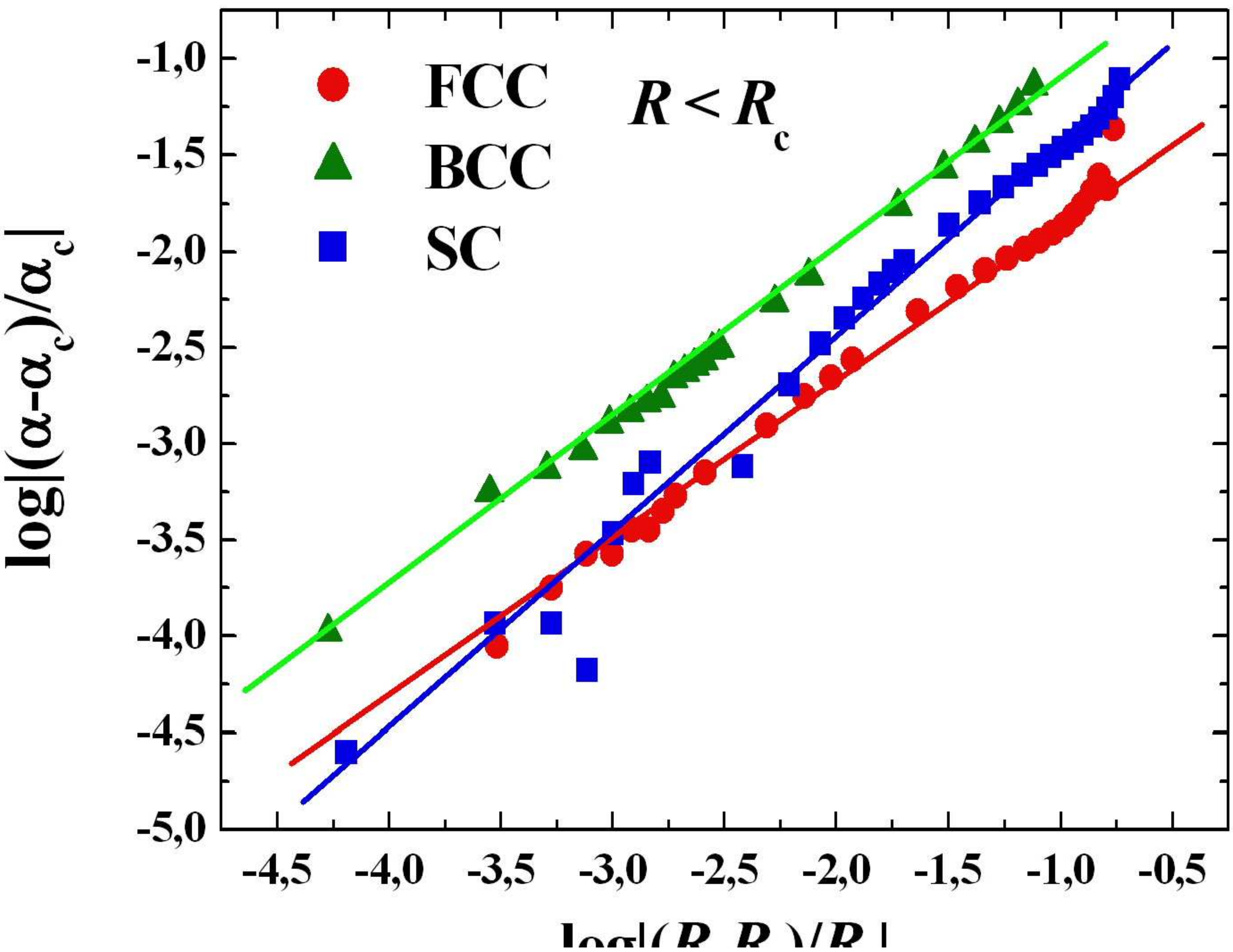
Periodic bound cond.



1,5
1,4
1,3
1,2
1,1
1,0
0,9
0,8
< r >/a0
SC
BCC
FCC
3
4
5
6
7
8
SPACING, R/a0

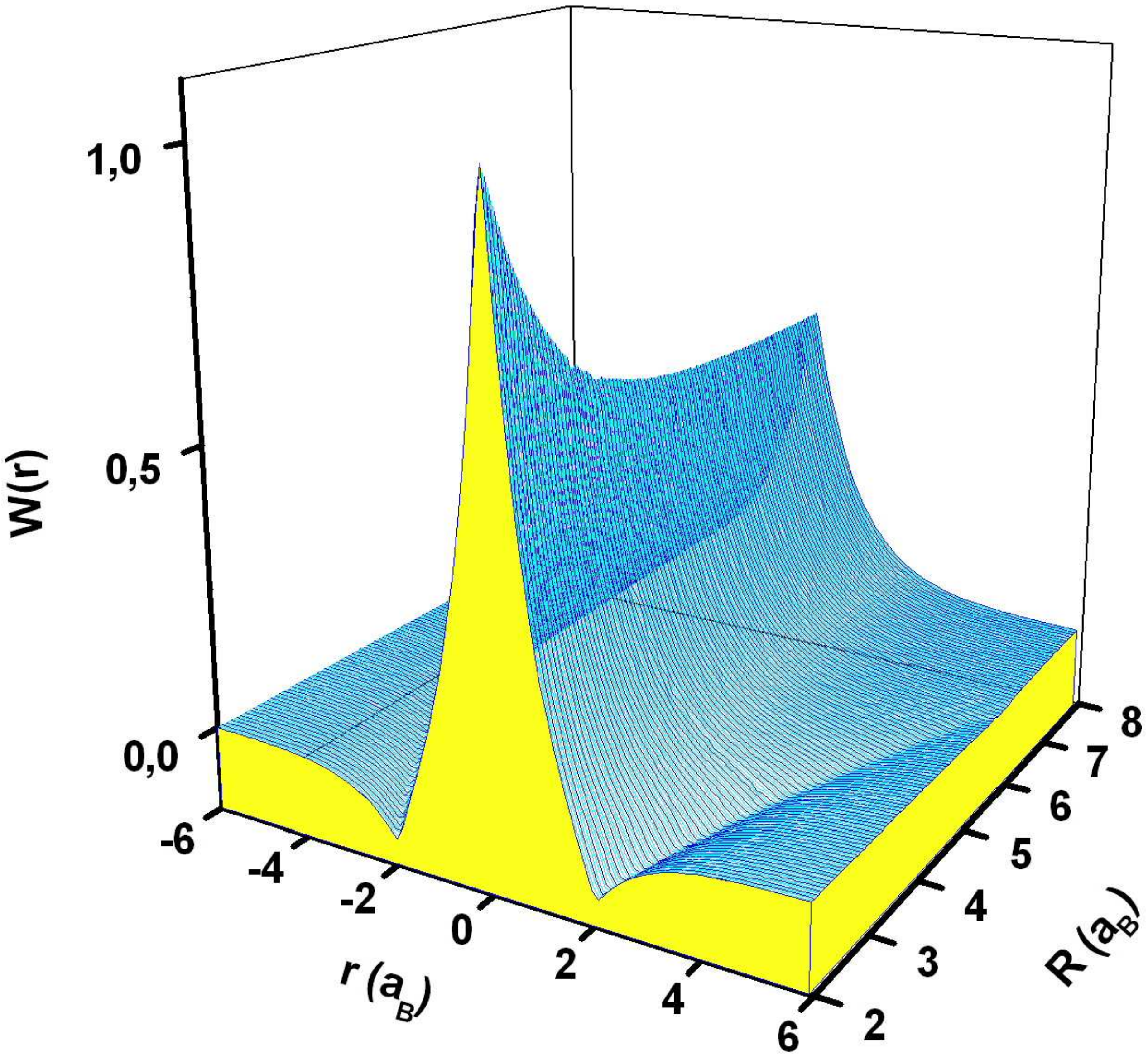


LW
GWF
GA
STO 7G
α a0
1,30
1,25
1,20
1,15
1,10
1,05
1,00
2
3
4
5
6
7
α a0
1.30
1.25
1.20
1.15
1.10
1.05
1.00
5
10
15
20
25
30
35
40
45
50
U / t

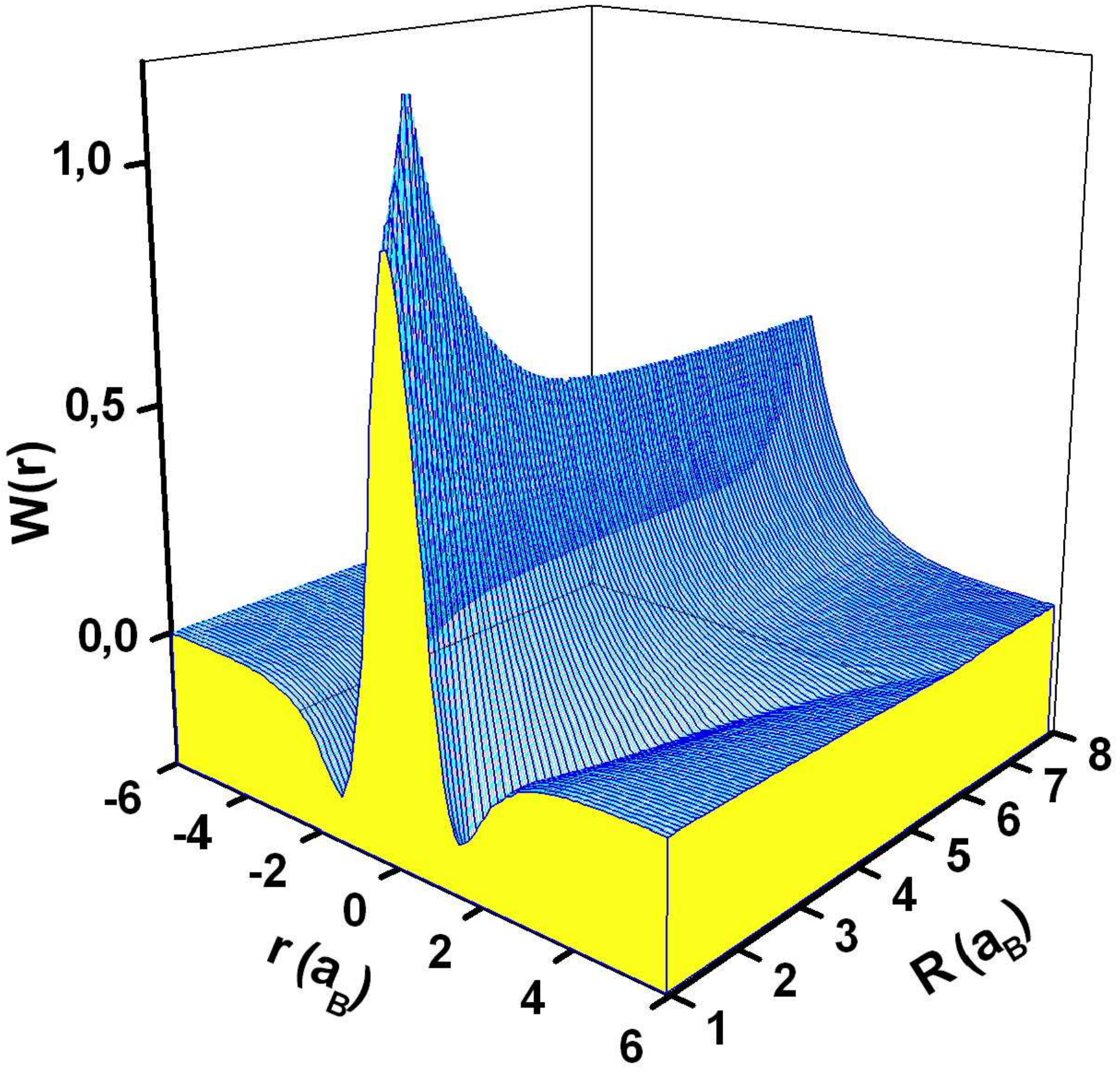


FCC
BCC
SC
R < Rc
log|(α-αc)/αc|
-1,0
-1,5
-2,0
-2,5
-3,0
-3,5
-4,0
-4,5
-5,0
-4,5
-4,0
-3,5
-3,0
-2,5
-2,0
-1,5
-1,0
-0,5

Triangle lattice



Chain



$$t = \langle w_i | H_1 | w_j \rangle$$

$$U = \langle w_i^2 | V_{12} | w_i^2 \rangle$$

↓

Renormalized wave equation:

$$\frac{\delta(E - \mu N_e)}{\delta w_i^*(\mathbf{r})} - \nabla \cdot \frac{\delta(E - \mu N_e)}{\delta(\nabla w_i^*(\mathbf{r}))} = \sum_{i \geq j} \lambda_{ij} w_j(\mathbf{r})$$

Adjustable Slater or STO-3G basis forms a trial Wannier function obtained variationally

Collaboration

Jan Kurzyk – Tech. Univ., Krakow

Robert Podsiadły – Jag. Univ., Krakow

Włodek Wójcik – Tech. Univ., Krakow

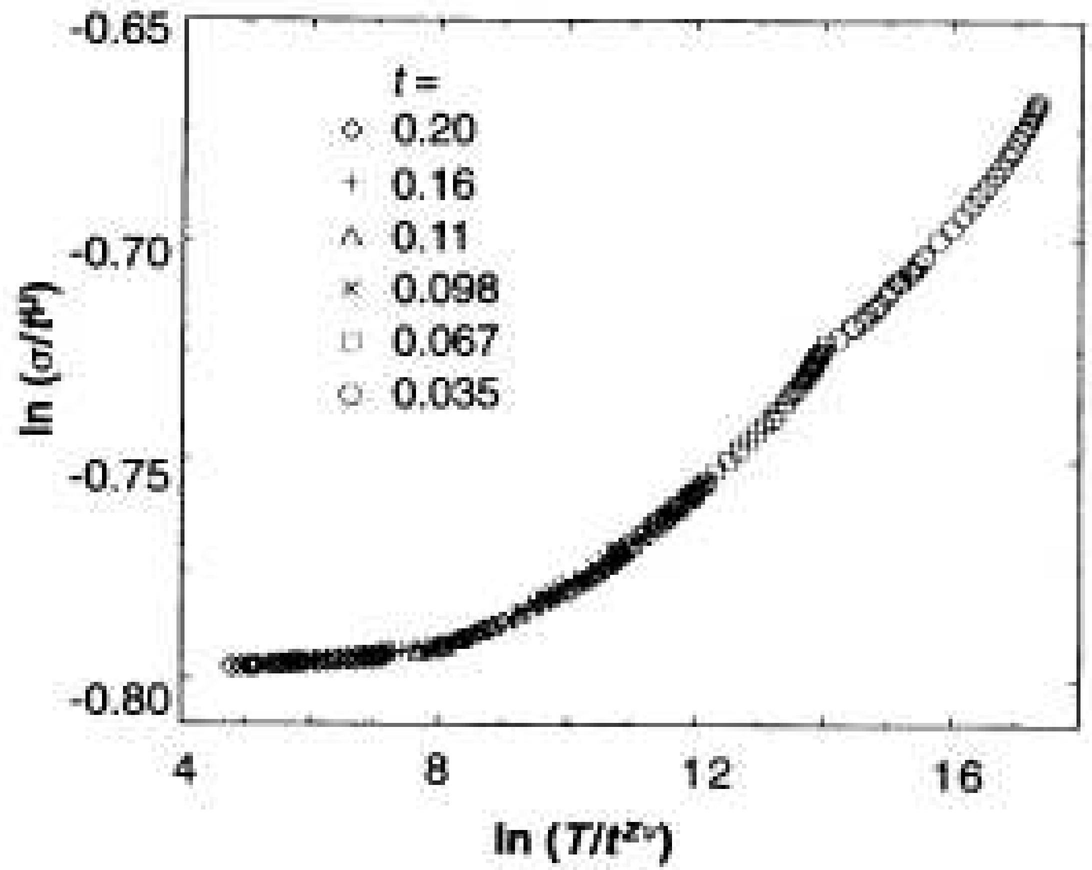


Fig. 4. Dynamical scaling curve for the six closest reduced pressures t to the $T = 0$ Mott-Hubbard MI transition. The ability to collapse the data onto a universal curve reflects the measurable influence of the quantum critical point.

$$[(\Phi_i)_{\sigma\sigma'}] = \begin{pmatrix} \imath\eta_i + \upsilon_i^z & \upsilon_i^- \\ \upsilon_i^+ & \imath\eta_i - \upsilon_i^z \end{pmatrix}$$

$$N = N(U,J,L) = \frac{1}{4U} + \frac{L}{2J} - \frac{\left(\frac{1}{4U} - \frac{L}{2J}\right)^2}{\frac{1}{4U} + \frac{L}{2J}} = \frac{2L}{J + 2LU} \sim \frac{1}{U}$$

$$V = V(U,J,L) = \frac{1}{2J} - \frac{1}{2J(1+L)} = \frac{L}{2J}$$

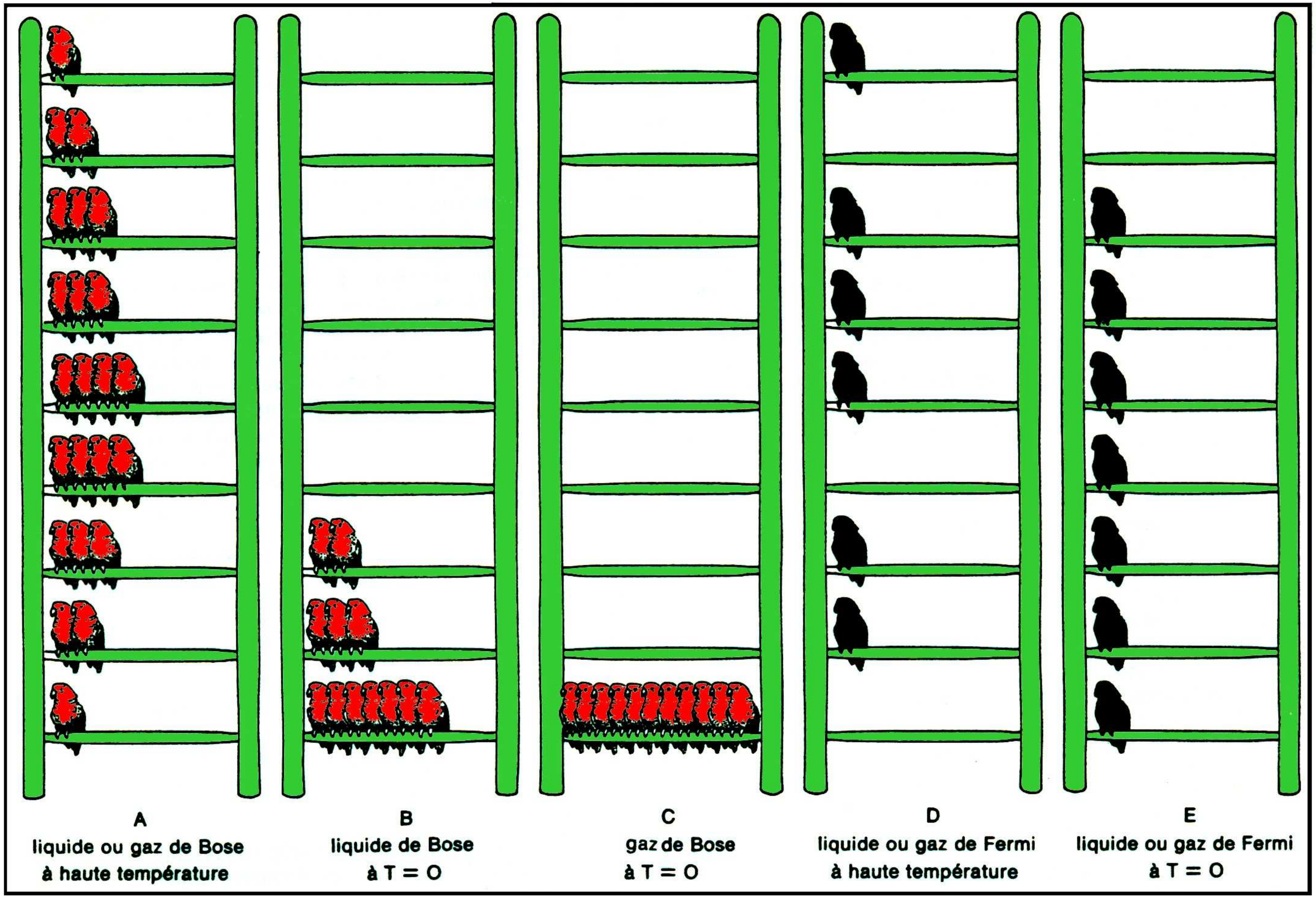
$$Z = \int D[\bar{a},a]_k \int d\eta d^3\upsilon \exp\left\{-\frac{\beta}{2}\sum_n \left(N\eta^2 + V\upsilon^2\right)\right\}$$
$$\times \exp\left\{-\sum_{klmn} (\bar{a}_{kln\uparrow}, \bar{a}_{kln\downarrow}) \left((-\imath\omega_n + \epsilon_k - \mu)\delta_{mn}\mathbf{1} + \hat{\Phi}_{m-n}\right) \begin{pmatrix} a_{klm\uparrow} \\ a_{klm\downarrow} \end{pmatrix}\right\}$$

$$\begin{aligned} Z &= \exp\left\{-\frac{1}{2}\beta(N\eta_0^2 + V\upsilon_0^2) + \underbrace{2\ln(\beta\upsilon_0)}_{*} + \sum_{kn} \ln\left[\beta^2(\epsilon_k - \mu + \imath\eta_0 + \imath\omega_n)^2 - \beta^2\upsilon_0^2\right]\right\} \\ &= \exp\{-S_{eff}\} \end{aligned}$$

Extension III: Effective Landau-Hertz functional

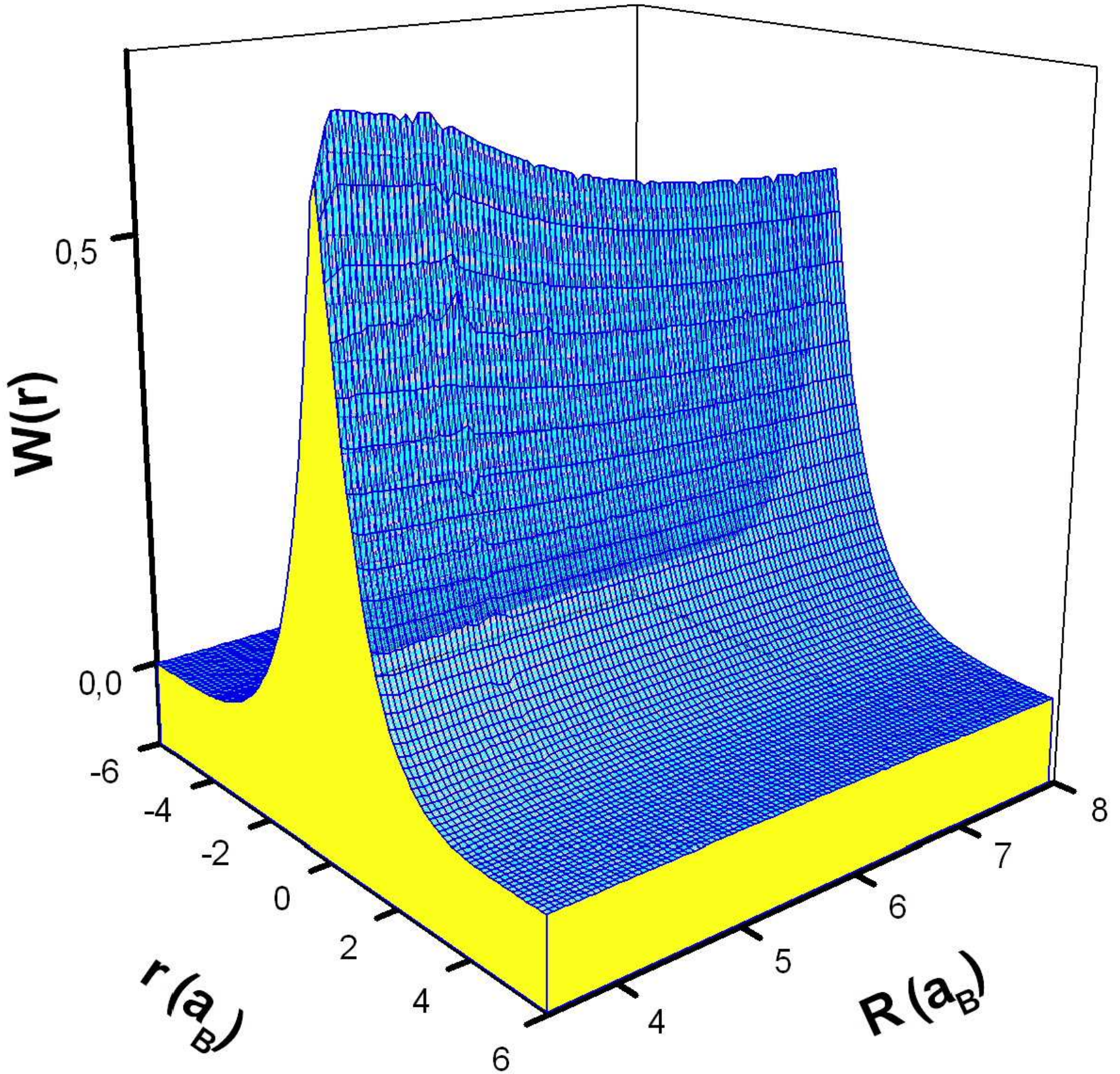
$\Omega_{eff} =$

$\Omega_{free} + (N/2+LC_0)\eta^2 + (V/2-LC_0)v^2 + L\beta^2C_1(\eta^4+v^4- 6\eta^2v^2)$

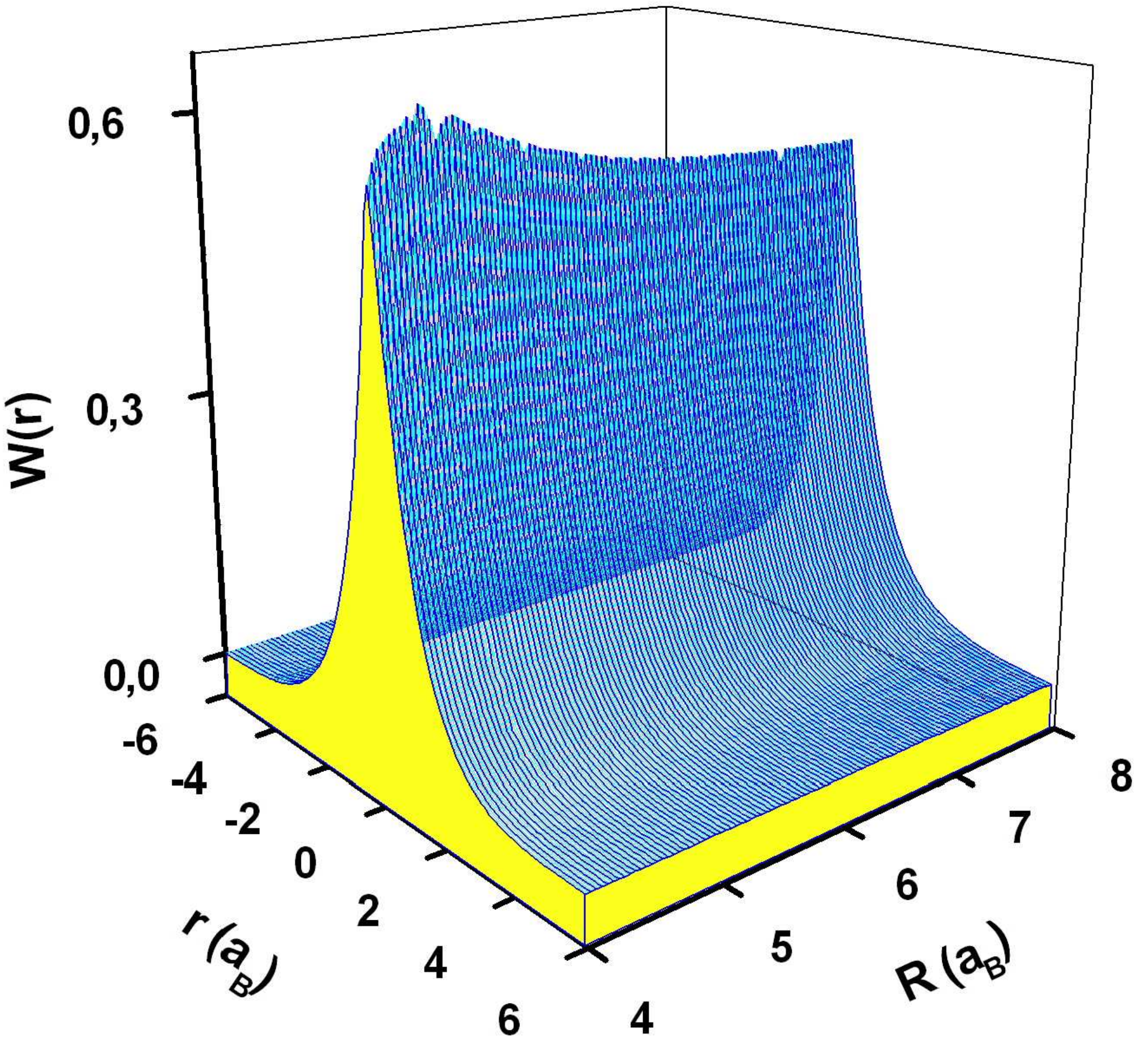


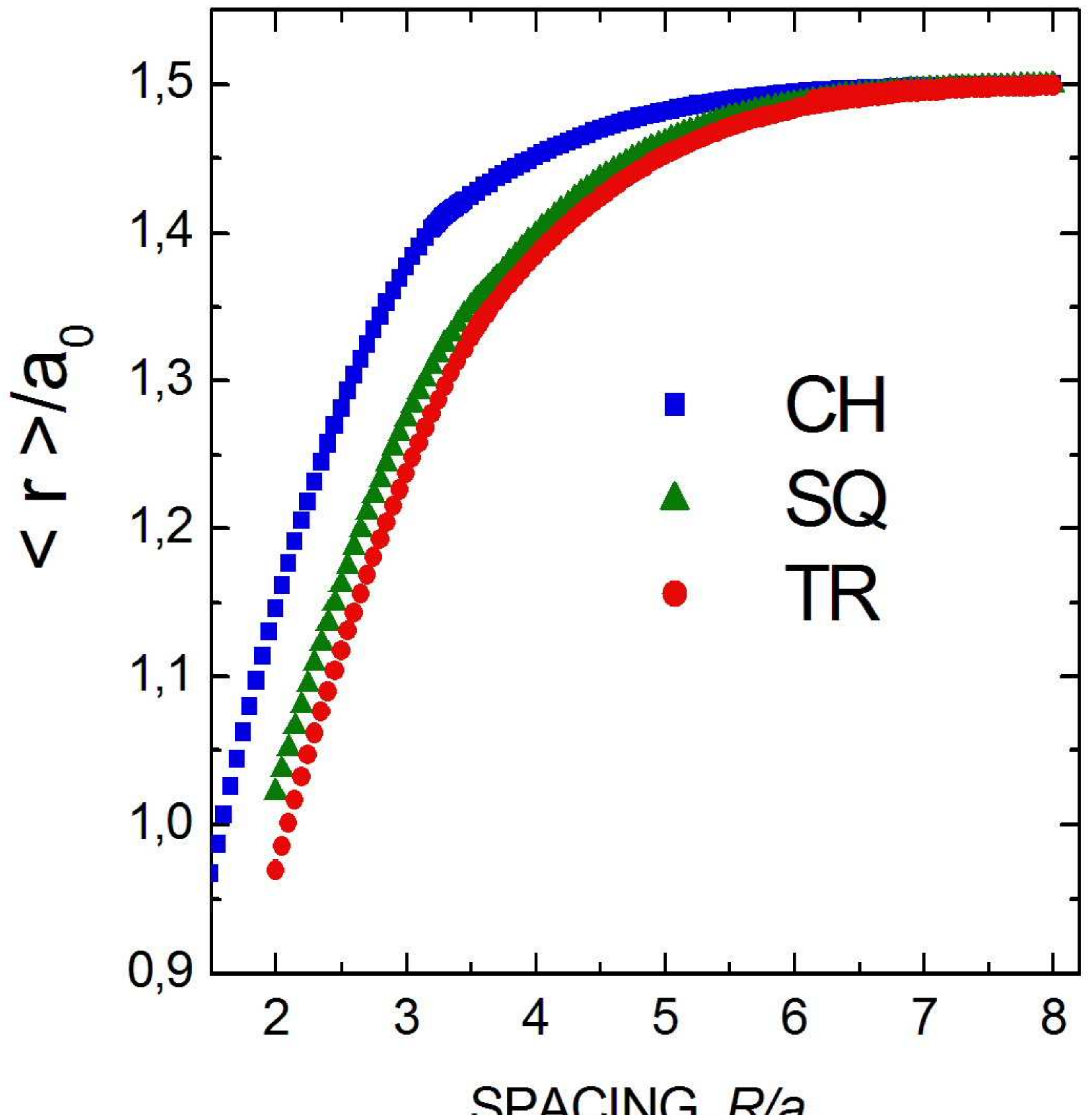
S. Balibar, La Recherche

Face Centered Cubic lattice

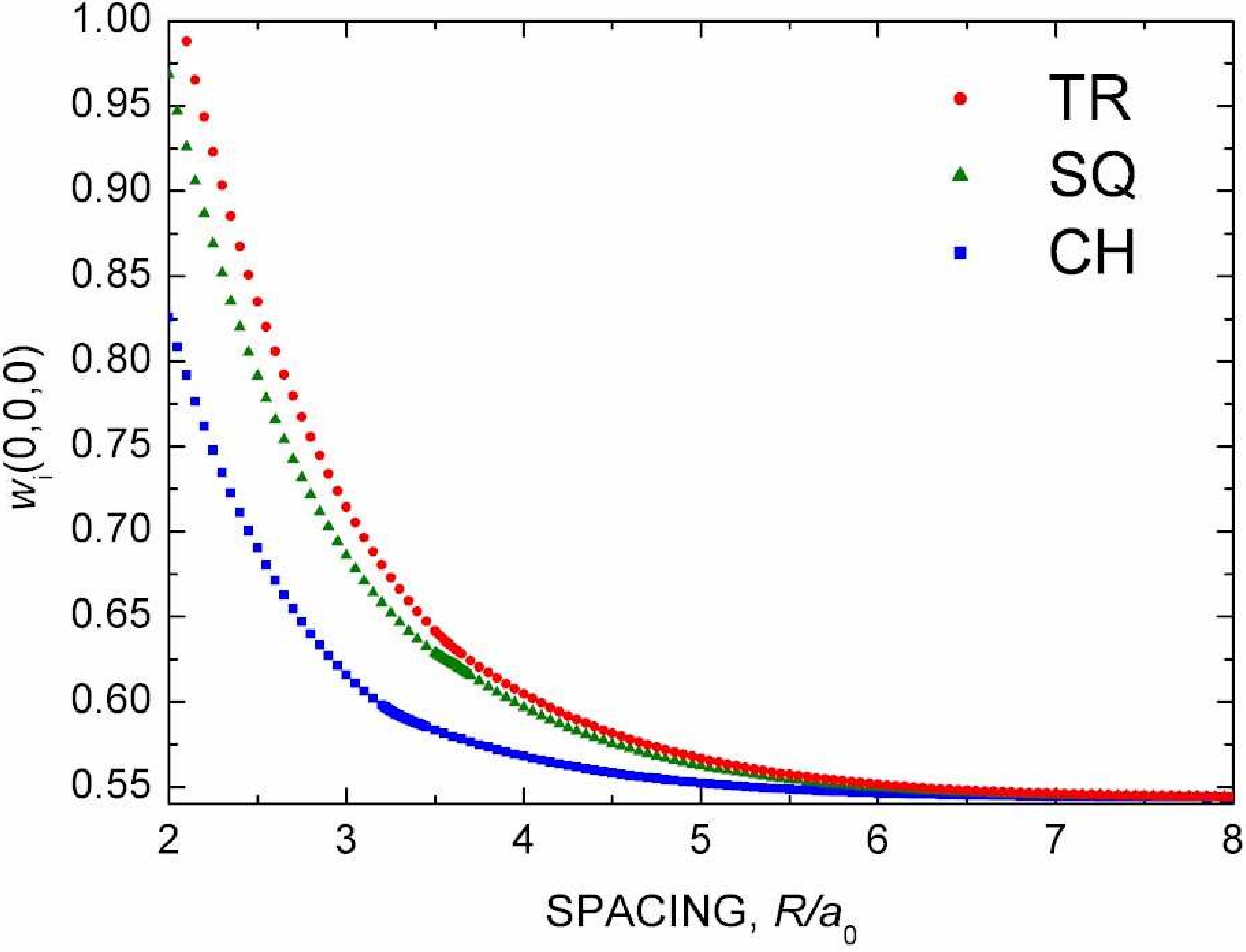


Body Centered Cubic lattice





1,5
1,4
1,3
1,2
1,1
1,0
0,9
2
3
4
5
6
7
8
< r >/a0
CH
SQ
TR
SPACING R/a

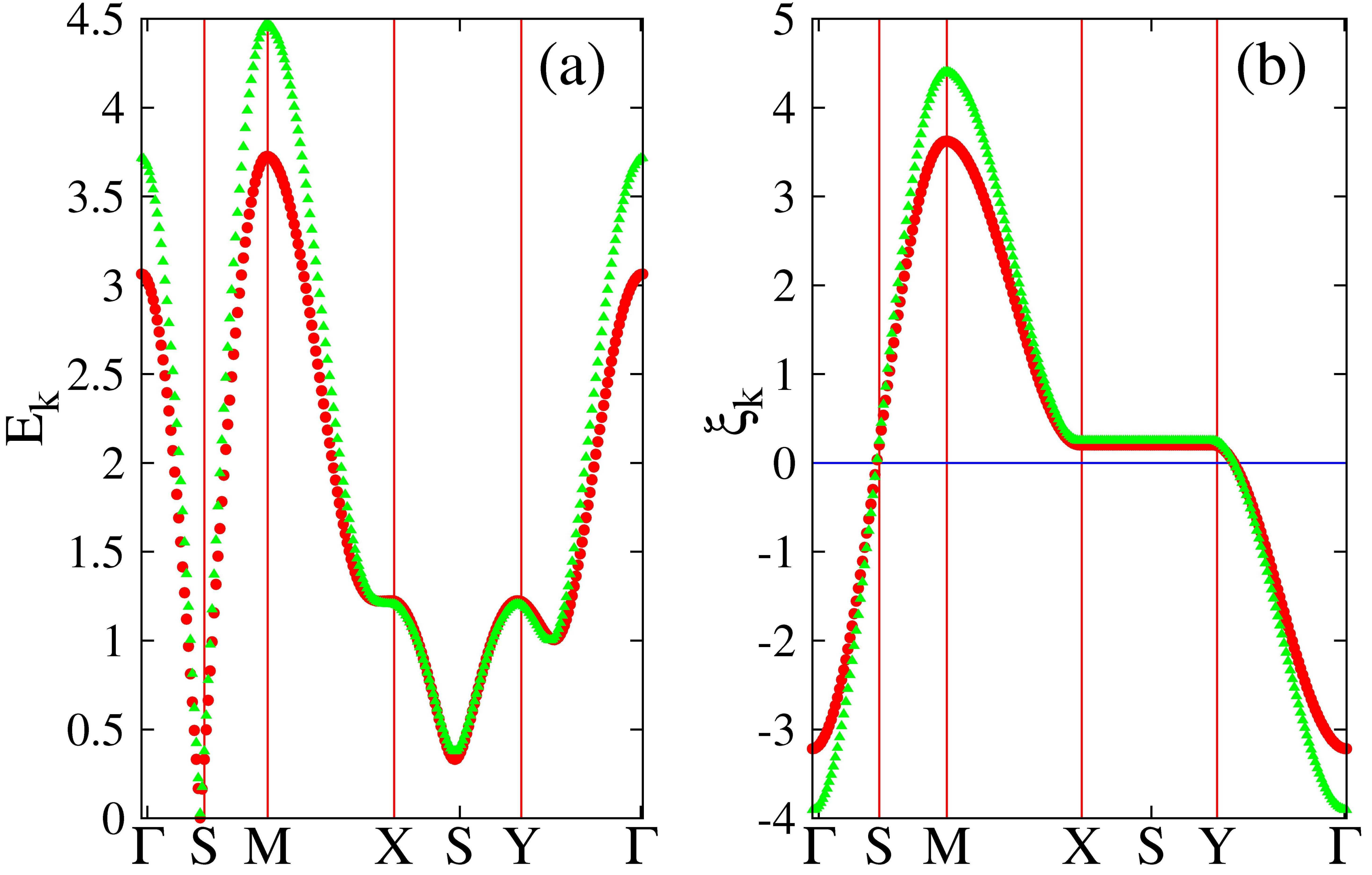


1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
$w_i(0,0,0)$
2
3
4
5
6
7
8
SPACING, R/a_0
TR
SQ
CH

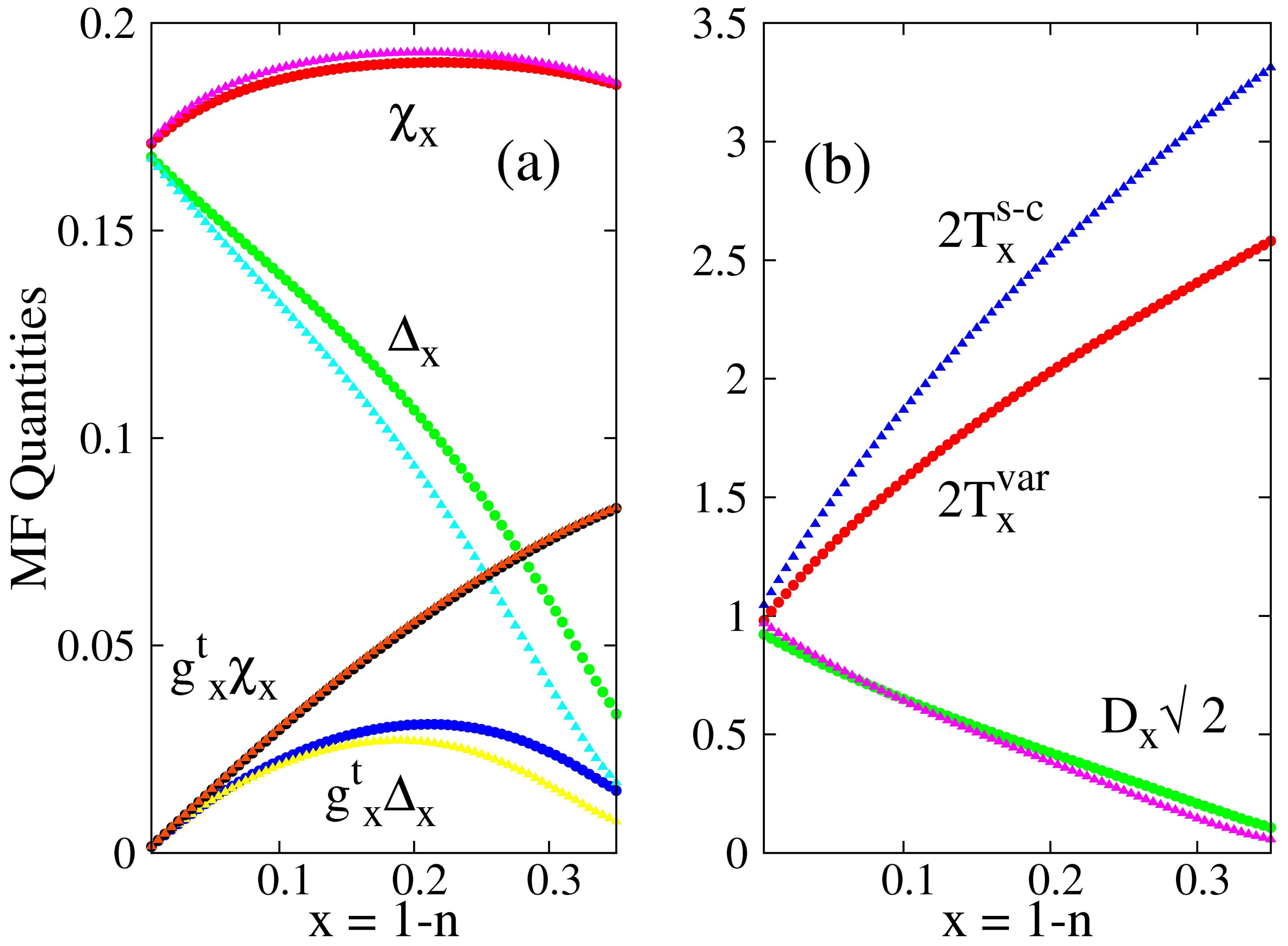
Contents

Part II: Real space pairing and d-wave superconductivity

1. Derivation of t-J model from the Hubbard model
2. Real-space pairing operators vs. magnetism
3. Mean-field solution(s)
4. Interorbital pairing: heavy fermions
5. Spin-triplet pairing(?)



(a)
(b)
E_k
ξ_k
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
5
4
3
2
1
0
-1
-2
-3
-4
Γ S M X S Y Γ
Γ S M X S Y Γ



MF Quantities
χ_x
(a)
Δ_x
$g^t_x\chi_x$
$g^t_x\Delta_x$
0
0.05
0.1
0.15
0.2
0.1
0.2
0.3
x = 1-n
(b)
$2T_x^{s-c}$
$2T_x^{var}$
$D_x\sqrt{2}$
0
0.5
1
1.5
2
2.5
3
3.5
0.1
0.2
0.3
x = 1-n