Lectures 3-4

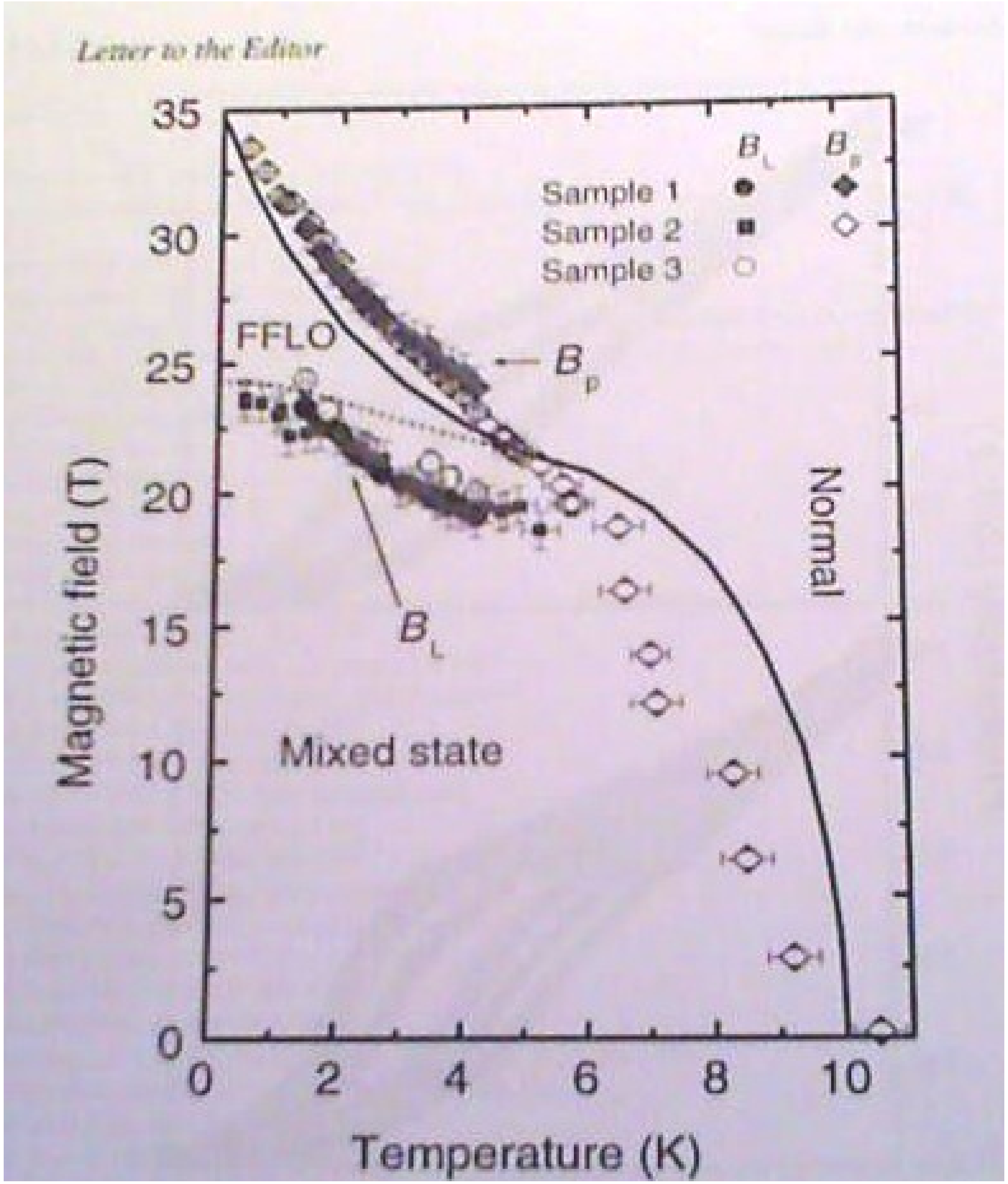
١. **Almost localized Fermi liquid (ALFL): a paradigm for non-Landau Fermi liquid composed of strongly correlated electrons:**
   - **Spin-dependent masses**
   - **Effective field driven by the correlations**

٢. **Cooper pair instability: from indistinguishable to distinguishable particles**

٣. **H_a – T phase diagram: BCS vs. FFLO phases stability for 3D and 2D gas**

٤. **BCS vs FFLO phase for two-dimensional lattice**

J. Singleton et al., J. P. CM 12, L641 (2000)



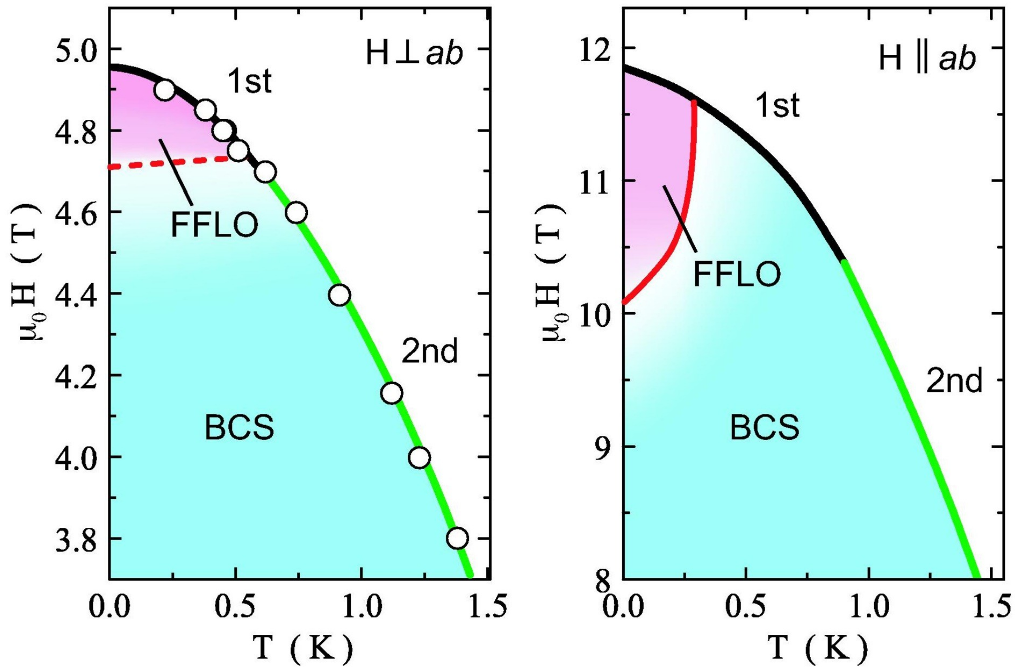
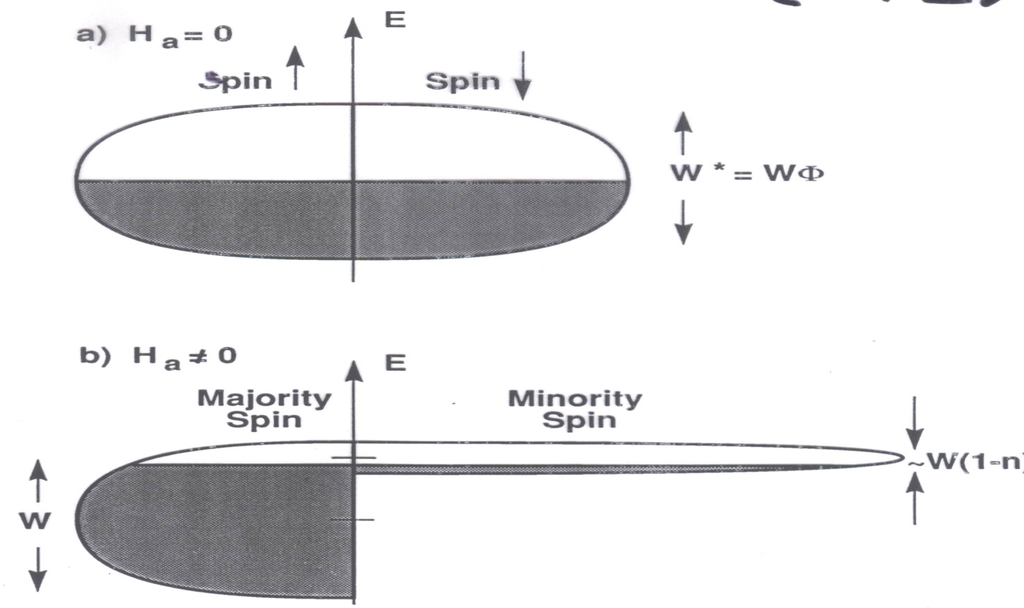


FIG. 3: H-T phase diagrams at low temperatures and high fields for $\boldsymbol{H} \perp ab$ (left) and for $H \parallel ab$ (right). The colored portions display the FFLO (pink) and BCS (blue) regions. The open circles are $H_{c2}^{\perp}$ determined by the NMR experiments. The black and green lines represent the upper critical fields which are in the first order and in the second order, respectively. The red dashed and solid lines represent the phase boundary separating the FFLO and BCS states.@For $\boldsymbol{H} \perp ab$, precise determination of the phase boundary between the FFLO and the BCS states is difficult by the present experiments.

K. Kumagai et al., cond-mat/0605394

Spin dependent masses of quasiparticles

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



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

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

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

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

Spin-dependent masses quantitatively: infinite U, narrow-band limit

- $$m^*_\sigma / m_{BAND} \underset{U\to\infty}{=} \frac{١ - n_f / ٢}{١ - n_f} - \sigma \frac{\langle S^z_f \rangle}{١ - n_f} \quad \Rightarrow$$
- $$m^*_\downarrow - m_\uparrow \sim \frac{١}{١ - n_f} * \quad \text{magnetization} \;\Rightarrow$$
- The masses depend on the field (weakly above the metamagnetic point)
- $$\gamma(H_a) = \gamma_{BAND} \frac{m^*_\uparrow + m^*_\downarrow}{m_{BAND}} \to \gamma_{BAND} \quad \text{for } H_a >> H_C$$
- Masses depend on temperature:

$$\frac{m^*}{m_{BAND}} = m^*(T = ٠)\left[١ + \zeta(٢)\left(\frac{T}{T_K}\right)^٢ \right] + \ldots$$

Physical origin of heavy masses:

In the magnetically polarized state the majority electrons ($\sigma=\uparrow$) scatter less effectively on a fewer spin-minority electrons. The opposite is true for the spin-minority particles.

In effect, the particles in the spin – minority subband (much) heavier than those in the majority subband

Reviews: (J. S.):

- Encyclopedia of Condensed Matter Physics, Elsevier, vol.3, 126 - 136 (2005);
- phys. stat. sol. (b), Editor's choice, 243, 78-88 (2006);
- Physica B (sces'05), 378-380, 1185-1190 (2006).

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	30 ± 13	3.14
α_3	17.6 ± 0.8	40 ± 4	3.14

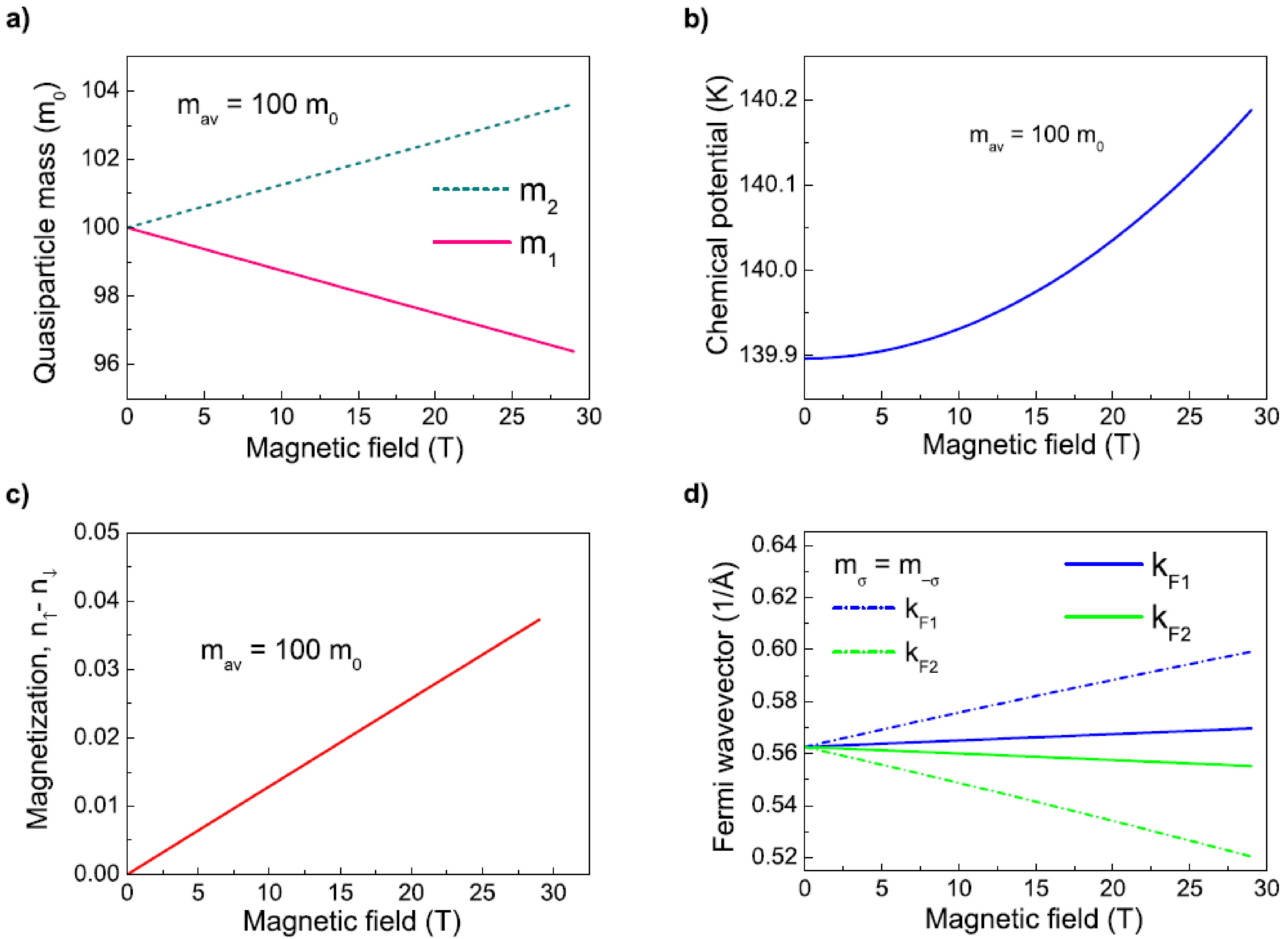
Anomalous de Haas-van Alphen Oscillations in CeCoIn5
A. McCollam, S. R. Julian, P. M. C. Rourke, D. Aoki, and J. Flouquet
Phys. Rev. Lett., 94, 186401 (2005); Physica B (2005).
See also: I. Sheikin, et al., Phys. Rev. B 67, 094420 (2003)

Quasiparticle states II

$$\xi_{\mathbf{k}\sigma} = \frac{\hbar^2 k^2}{2m_\sigma} - \sigma h - \mu - \sigma h_{\mathrm{cor}}$$

$$\frac{m_\sigma}{m_B} = \frac{1 - n_\sigma}{1 - n} = \frac{1 - n/2}{1 - n} - \sigma \frac{\bar{m}}{2(1 - n)} \equiv \frac{1}{m_B}(m_{\mathrm{av}} - \sigma \Delta m/2)$$

$$\mathcal{H} = \sum_{\mathbf{k}\sigma} \xi_{\mathbf{k}\sigma} a^\dagger_{\mathbf{k}\sigma} a_{\mathbf{k}\sigma} - \frac{V_0}{N} \sum_{\mathbf{k}\mathbf{k}'\mathbf{Q}} a^\dagger_{\mathbf{k}+\mathbf{Q}/2\uparrow} a^\dagger_{-\mathbf{k}+\mathbf{Q}/2\downarrow} a_{-\mathbf{k}'+\mathbf{Q}/2\downarrow} a_{\mathbf{k}'+\mathbf{Q}/2\uparrow} + \frac{N}{n} \bar{m} h_{\mathrm{cor}}$$


a)
m_{av} = 100 m_0
m_2
m_1
Quasiparticle mass (m_0)
Magnetic field (T)
b)
m_{av} = 100 m_0
Chemical potential (K)
Magnetic field (T)
c)
m_{av} = 100 m_0
Magnetization, $n_\uparrow - n_\downarrow$
Magnetic field (T)
d)
$m_\sigma = m_{-\sigma}$
k_{F1}
k_{F2}
k_{F1}
k_{F2}
Fermi wavevector (1/Å)
Magnetic field (T)

Anderson-lattice Hamiltonian in the large U limit

$$H = \sum_{mn} (t_{mn} - \mu\delta_{mn})\, c^\dagger_{m\sigma} c_{n\sigma} + \epsilon_f \sum_{i\sigma} N_{i\sigma}(1 - N_{i\bar{\sigma}})$$

$$+ \sum_{i\sigma} V_{im} \;*\; (1 - N_{i\bar{\sigma}})(f^\dagger_{i\sigma} c_{m\sigma} + c^\dagger_{m\sigma} f_{i\sigma})$$

$$- 2 \sum_{imn} \frac{2V_{im}V_{in}}{U+\epsilon_f}\, b^\dagger_{im} b_{in}.$$

Real-space pairing operators

$$b^\dagger_{im} = \frac{1}{\sqrt{2}}\left[a^\dagger_{i\uparrow}(1 - N_{i\downarrow})c_{m\downarrow} - a^\dagger_{i\downarrow}(1 - N_{i\uparrow})c_{m\uparrow}\right]$$

ArXiv:cond-mat/0809.1799

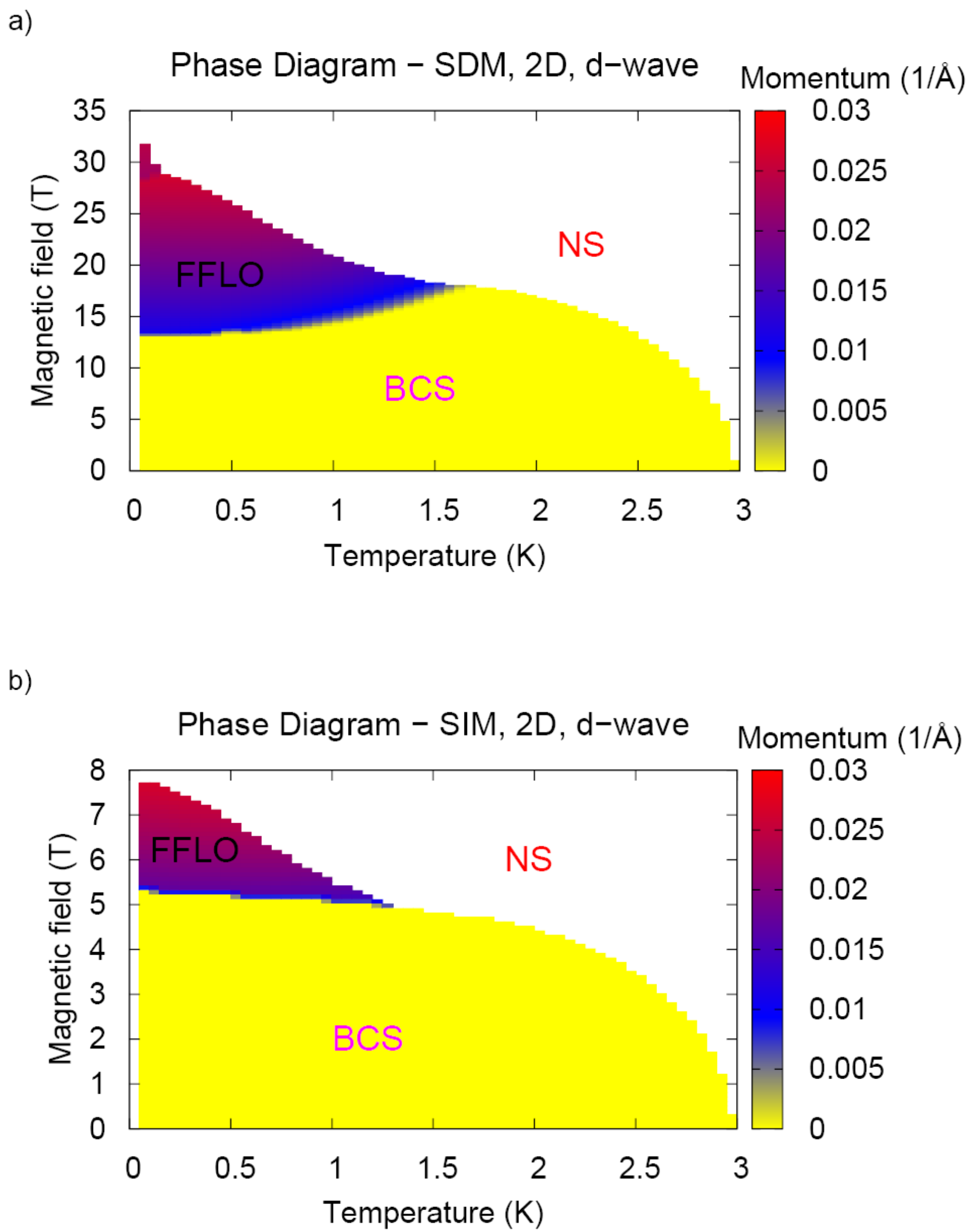
Effective quasiparticle Hamiltonian with effective pairing

(Gutzwiller approximation for quasiparticle states)

$$\mathcal{H} = \sum_{\mathbf{k}\sigma} (q_\sigma \epsilon_{\mathbf{k}} - \sigma \mu_B H) \psi^\dagger_{\mathbf{k}\sigma} \psi_{\mathbf{k}\sigma}$$

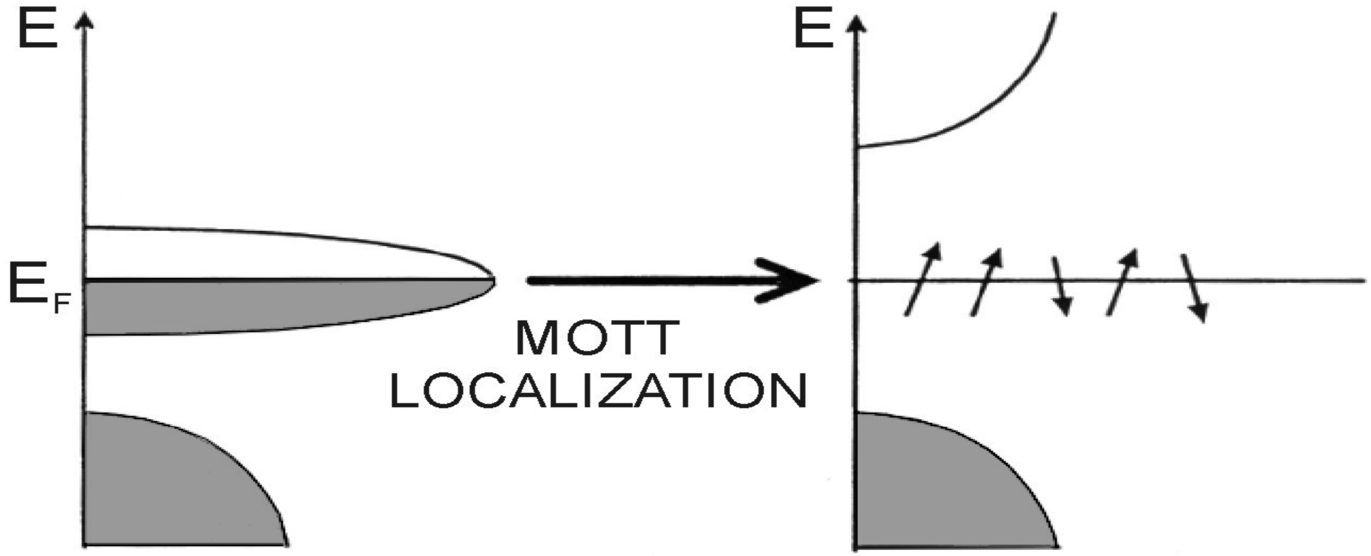
$$-\frac{1}{N} \sum_{\mathbf{k}\mathbf{k}'} \frac{4V_{\mathbf{k}}^2 V_{\mathbf{k}'}^2}{\epsilon_f^2(\epsilon_f + U)} R_{\sigma\bar{\sigma}} \gamma_{\mathbf{k}} \gamma_{\mathbf{k}'} \psi^\dagger_{\mathbf{k}\uparrow} \psi^\dagger_{-\mathbf{k}\downarrow} \psi_{-\mathbf{k}'\downarrow} \psi_{\mathbf{k}'\uparrow}$$

$$\Psi_{\mathbf{k}\sigma} \approx f_{\mathbf{k}\sigma}$$

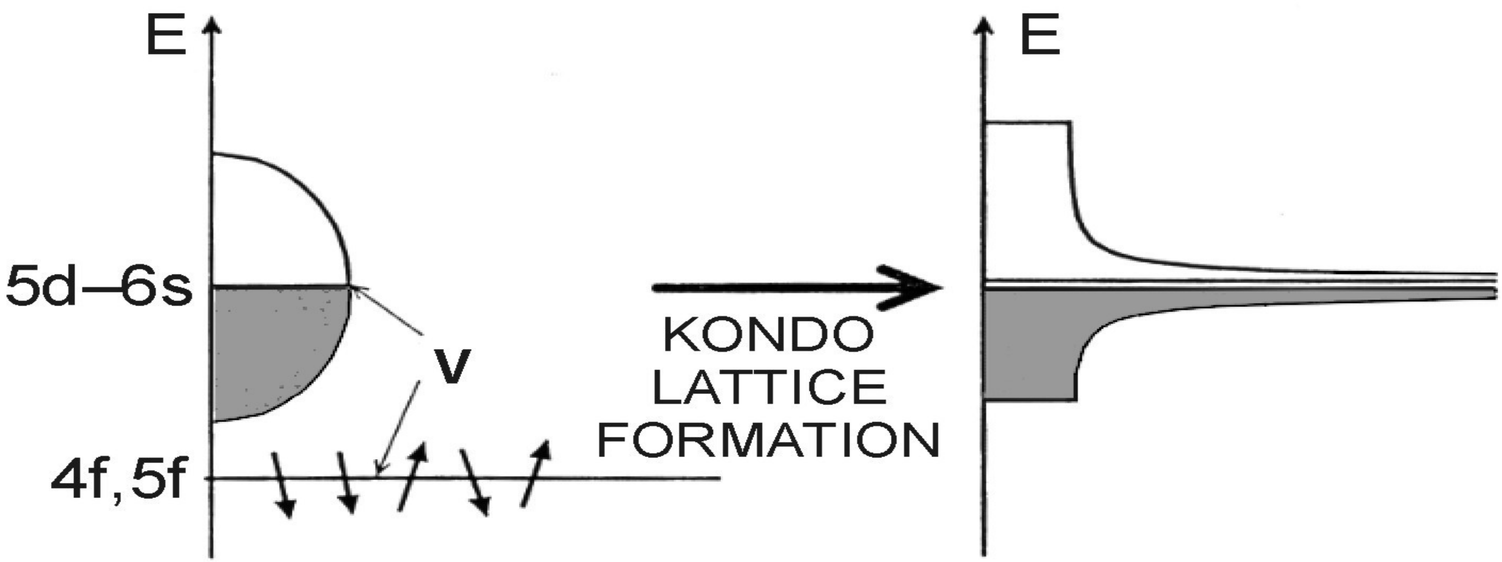


J. Kaczmarczyk and J. Spałek (2009), unpublished

Narrow–band systems (3d)



Hybridized systems (f)



Contents

1. Concept of spin-dependent quasiparticle mass (1990 → 2005):

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

2. Cooper pair with the spin-dependent masses of quasiparticles:

Układy skorelowanych fermionów:

1. Co oznacza "silnie skorelowane?"

Punkt startowy: en. oddziaływania >> en. pasmowa

U >> W

Przybliżenie H-F nawet jakościowo niepoprawne (LDA)

Przybliżenie Gutzwillera = MFA

(Gutzwiller projection)

2. Model t-J (sieci Andersona) punktem startowym, albo model Hubbarda z U>>W

Dlaczego ważne? **AF -> SC** (ewolucja ze stanu izol. Motta)

3. Paired states:

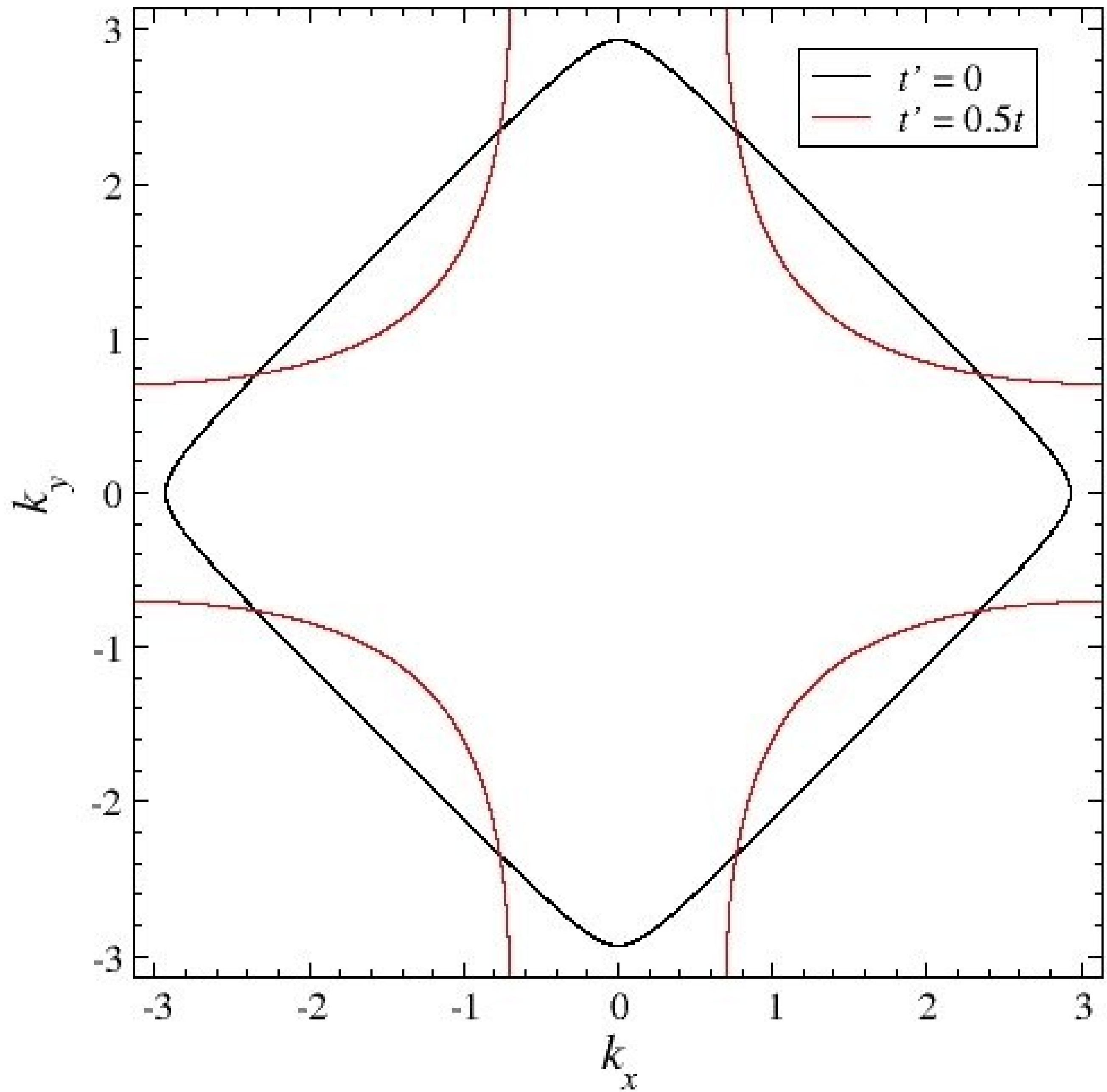
- BCS state (condensate at rest)
- FFLO state (moving condensate of pairs)

$$
\begin{aligned}
H \; = \; & \sum_{ij\sigma} \left(-t_{ij\sigma}\left(\mathbf{A}\right) - \delta_{ij}\mu\right) c^{\dagger}_{i\sigma} c_{j\sigma} + g\mu_{\mathrm{B}} H \sum_{i} \left(c^{\dagger}_{i\uparrow} c_{i\uparrow} - c^{\dagger}_{i\downarrow} c_{i\downarrow}\right) \\
+ \; & \sum_{i} \left(\Delta_i^{*} c_{i\uparrow} c_{i\downarrow} + \mathrm{H.c.}\right)
\end{aligned}
$$

$$
\Delta_i = V \langle c_{i\downarrow} c_{i\uparrow} \rangle
$$

$$
t_{ij\sigma}\left(\mathbf{A}\right) = t_{ij\sigma} \; \exp\left(\frac{ie}{\hbar c} \int_{\mathbf{R}_j}^{\mathbf{R}_i} \mathbf{A} \cdot d\mathbf{l} \right)
$$

$$
t_{ij\sigma} = t_{ij} \frac{1-n}{1-n_{\sigma}}, \quad n = n_{\uparrow} + n_{\downarrow}
$$



t' = 0
t' = 0.5t
k_y
k_x
3
2
1
0
-1
-2
-3

Fulde–Ferrell–Larkin–Ovchinnikov phase:

- **Two-dimensional case (H || c)**
- **Tight-binding approximation: t'/t = -0.5**
- **Pauli term dominant (Zeeman term only)**

f

- **Results: n = const,**
  μ = const (quark-gluon plasma),
  F. Wilczek, PRL (2003).

$$
\begin{aligned}
H &= \sum_{\mathbf{k},\sigma} \left(\varepsilon_{\mathbf{k},\sigma} - \mu\right) c^{\dagger}_{\mathbf{k},\sigma} c_{\mathbf{k},\sigma} + g\mu_{\mathrm{B}} H \sum_{\mathbf{k}} \left(c^{\dagger}_{\mathbf{k},\uparrow} c_{\mathbf{k},\uparrow} - c^{\dagger}_{\mathbf{k},\downarrow} c_{\mathbf{k},\downarrow} \right) \\
&+ \sum_{\mathbf{k}} \left(\Delta^{*}_{\mathbf{Q}} c_{\mathbf{k},\uparrow} c_{-\mathbf{k}+\mathbf{Q},\downarrow} + \mathrm{H.c.} \right)
\end{aligned}
$$

$$
\Delta_{\mathbf{Q}} = \frac{V}{N} \sum_{\mathbf{k}} \langle c_{-\mathbf{k}+\mathbf{Q},\downarrow} c_{\mathbf{k},\uparrow} \rangle
$$

$$
\varepsilon_{\mathbf{k},\sigma} = -2t_{\sigma} \left(\cos k_x + \cos k_y\right) + 4t'_{\sigma} \cos k_x \cos k_y
$$

$$
\Delta_{\mathbf{Q}} = -\frac{1}{N} \sum_{\mathbf{k}} \Delta_{\mathbf{Q}} \frac{f\left(E_{\mathbf{k},\mathbf{Q},1}\right) - f\left(E_{\mathbf{k},\mathbf{Q},2}\right)}{E_{\mathbf{k},\mathbf{Q},1} - E_{\mathbf{k},\mathbf{Q},2}}
$$

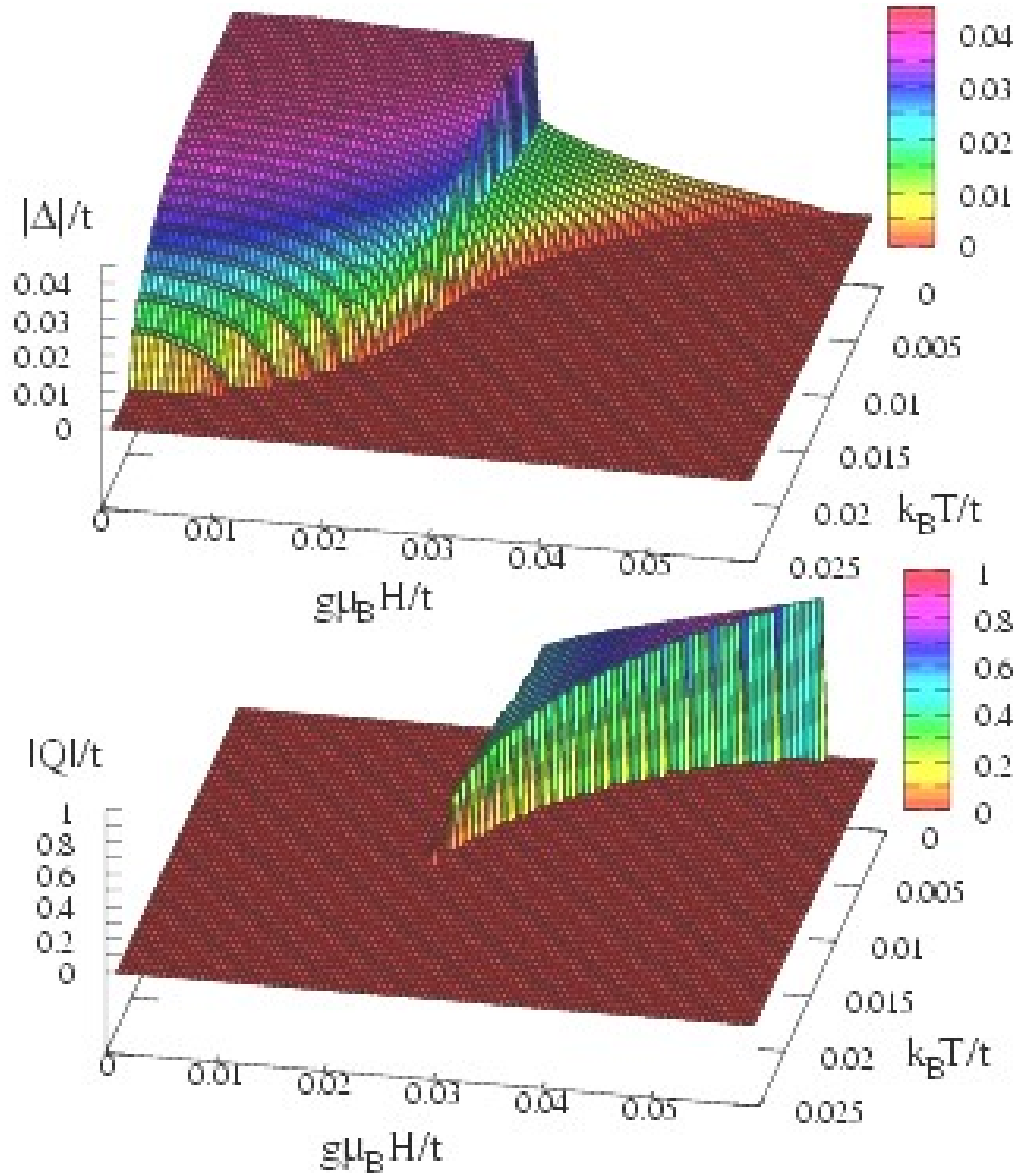
$$
\begin{aligned}
E_{\mathbf{k},\mathbf{Q},1/2} &= g\mu_{\mathrm{B}} H + \frac{1}{2} \left(\varepsilon_{\mathbf{k},\uparrow} - \varepsilon_{-\mathbf{k}+\mathbf{Q},\downarrow}\right) \\
&\pm \frac{1}{2} \sqrt{\left(\varepsilon_{\mathbf{k},\uparrow} + \varepsilon_{-\mathbf{k}+\mathbf{Q},\downarrow} - 2\mu\right)^2 + 4|\Delta_{\mathbf{Q}}|^2}
\end{aligned}
$$

$$
\begin{aligned}
n_\uparrow &= \frac{1}{N}\sum_{\mathbf{k}}\frac{1}{E_{\mathbf{k},\mathbf{Q},1}-E_{\mathbf{k},\mathbf{Q},2}} \\
&\quad\times\left[\left(E_{\mathbf{k},\mathbf{Q},1}+\varepsilon_{-\mathbf{k}+\mathbf{Q},\downarrow}-\mu-g\mu_{\mathrm{B}}H\right)f\left(E_{\mathbf{k},\mathbf{Q},1}\right)\right. \\
&\quad\left.-\left(E_{\mathbf{k},\mathbf{Q},2}+\varepsilon_{-\mathbf{k}+\mathbf{Q},\downarrow}-\mu-g\mu_{\mathrm{B}}H\right)f\left(E_{\mathbf{k},\mathbf{Q},2}\right)\right]
\end{aligned}
$$

$$
\begin{aligned}
n_\downarrow &= 1-\frac{1}{N}\sum_{\mathbf{k}}\frac{1}{E_{\mathbf{k},\mathbf{Q},1}-E_{\mathbf{k},\mathbf{Q},2}} \\
&\quad\times\left[\left(E_{\mathbf{k},\mathbf{Q},1}-\varepsilon_{\mathbf{k},\uparrow}+\mu-g\mu_{\mathrm{B}}H\right)f\left(E_{\mathbf{k},\mathbf{Q},1}\right)\right. \\
&\quad\left.-\left(E_{\mathbf{k},\mathbf{Q},2}-\varepsilon_{\mathbf{k},\uparrow}+\mu-g\mu_{\mathrm{B}}H\right)f\left(E_{\mathbf{k},\mathbf{Q},2}\right)\right]
\end{aligned}
$$

$$
\begin{aligned}
\Omega(\Delta_{\mathbf{Q}},\mathbf{Q}) &= -k_{\mathrm{B}}T\sum_{\mathbf{k}}\sum_{\alpha=1}^{2}\ln\left[1+\exp\left(-E_{\mathbf{k},\mathbf{Q},\alpha}/k_{\mathrm{B}}T\right)\right] \\
&\quad+\sum_{\mathbf{k}}\left(\varepsilon_{-\mathbf{k}+\mathbf{Q},\downarrow}-\mu-g\mu_{\mathrm{B}}H\right)+\frac{N|\Delta|^2}{V}
\end{aligned}
$$

$$
F(\Delta_{\mathbf{Q}},\mathbf{Q}) = \Omega(\Delta_{\mathbf{Q}},\mathbf{Q})+\mu n N
$$



|Δ|/t
0.04
0.03
0.02
0.01
0
0
0.01
0.02
0.03
0.04
0.05
gμ_B H/t
0
0.005
0.01
0.015
0.02
0.025
k_B T/t
0.04
0.03
0.02
0.01
0
|Q|/t
1
0.8
0.6
0.4
0.2
0
0
0.01
0.02
0.03
0.04
0.05
gμ_B H/t
0
0.005
0.01
0.015
0.02
0.025
k_B T/t
1
0.8
0.6
0.4
0.2
0

Outlook:

1. Pair momentum Q nonzero, FFLO

a

1. H $\neq$ 0: indistinguishable quasiparticles transforming into distinguishable !!!

↑ ↓

2. m $\neq$ m : wide range of the FFLO appearance.

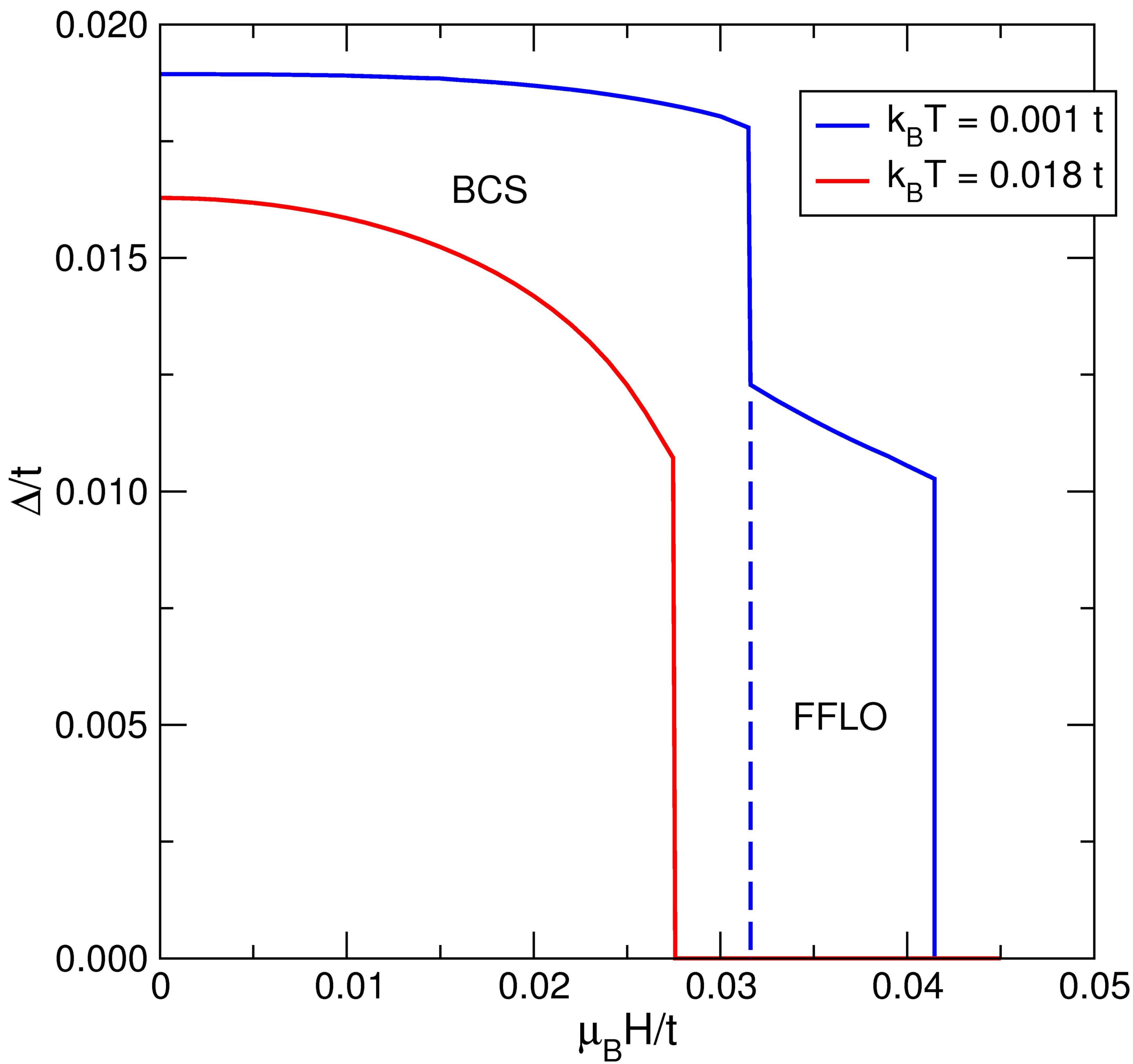
f

1. μ = const or n = const

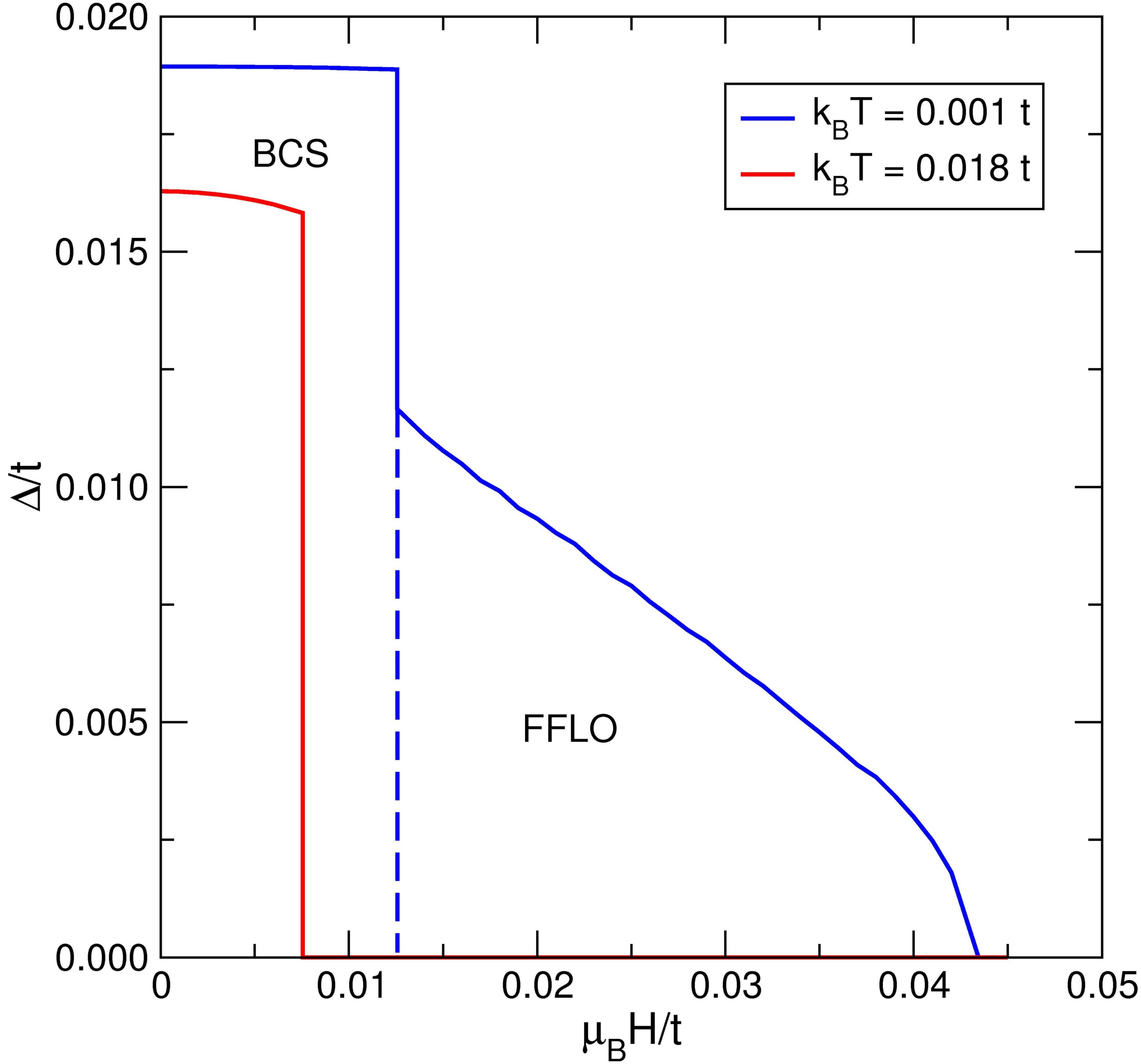
1. s wave or d wave?

1. Cooper pair for the case with spin dependent masses:

- $Q = 0$ versus $Q \neq 0$
- Indistinguishable → distinguishable

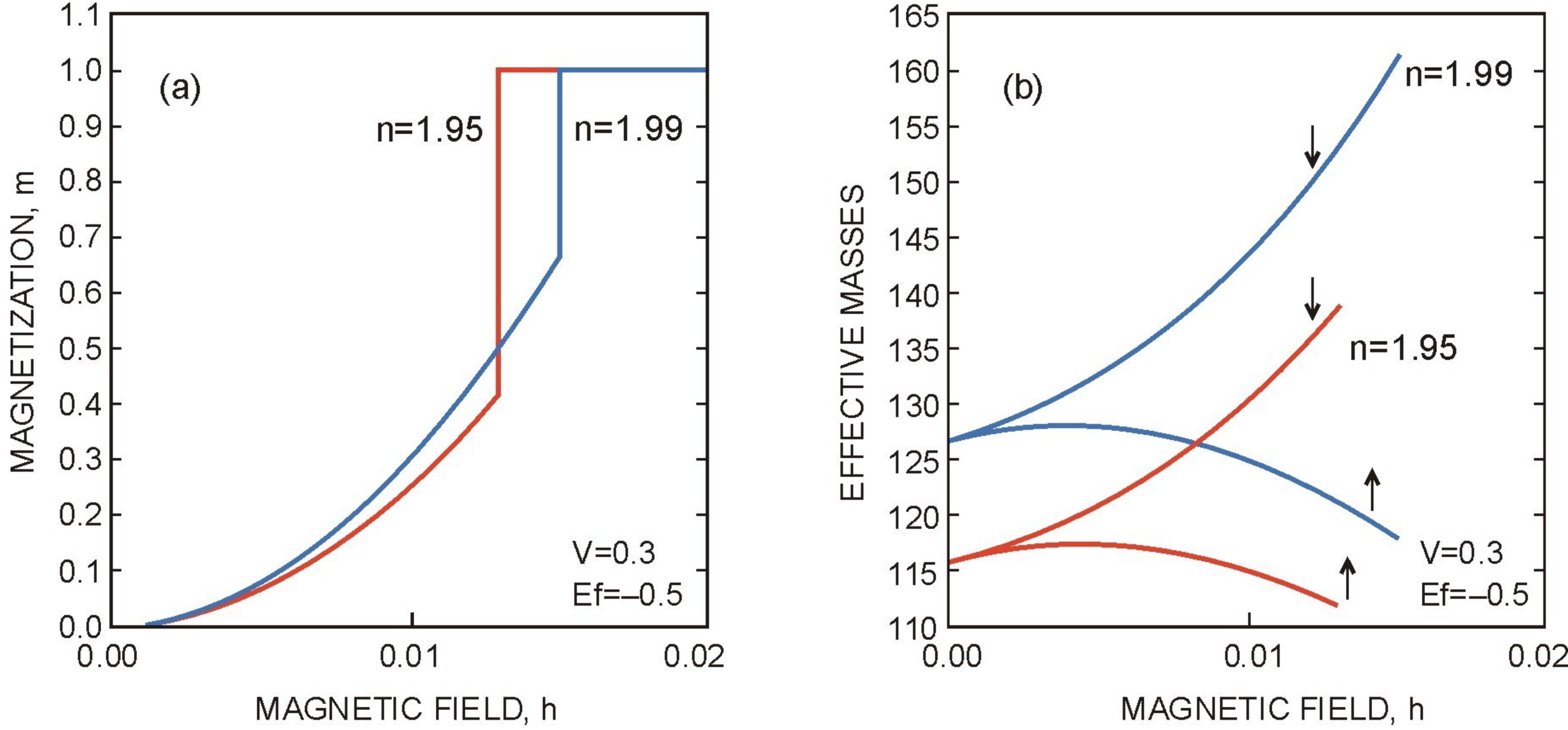


0.020
0.015
0.010
0.005
0.000
Δ/t
0
0.01
0.02
0.03
0.04
0.05
μBH/t
kBT = 0.001 t
kBT = 0.018 t
BCS
FFLO



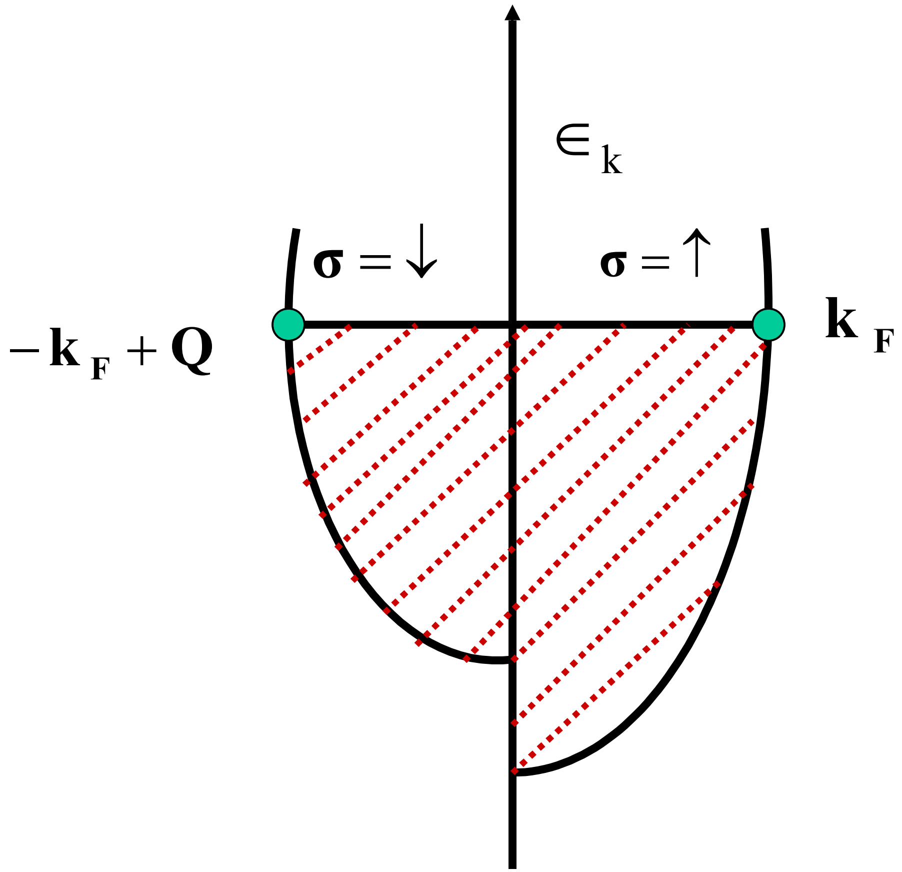
0.020
0.015
0.010
0.005
0.000
Δ/t
0
0.01
0.02
0.03
0.04
0.05
μBH/t
kBT = 0.001 t
kBT = 0.018 t
BCS
FFLO

Sieć Kondo: $U \to \infty$



(a) Magnetization curve ($m=n_\uparrow - n_\downarrow$) for $n \to 2$ and in the Kondo-lattice limit;
(b) spin-split masses for majority ($\sigma=\uparrow$) and minority ($\sigma=\downarrow$) spin subbands

R. Citro, A. Romano & J.S., Physica B **259-261**, 213 (1999)



a

Fermi wavevector mismatch for H $\neq 0$:

$$\alpha_{\mathbf{k}\uparrow} = u_{\mathbf{k}} a_{\mathbf{k}+\mathbf{Q}/2\uparrow} - v_{\mathbf{k}} a^{\dagger}_{-\mathbf{k}+\mathbf{Q}/2\downarrow}$$

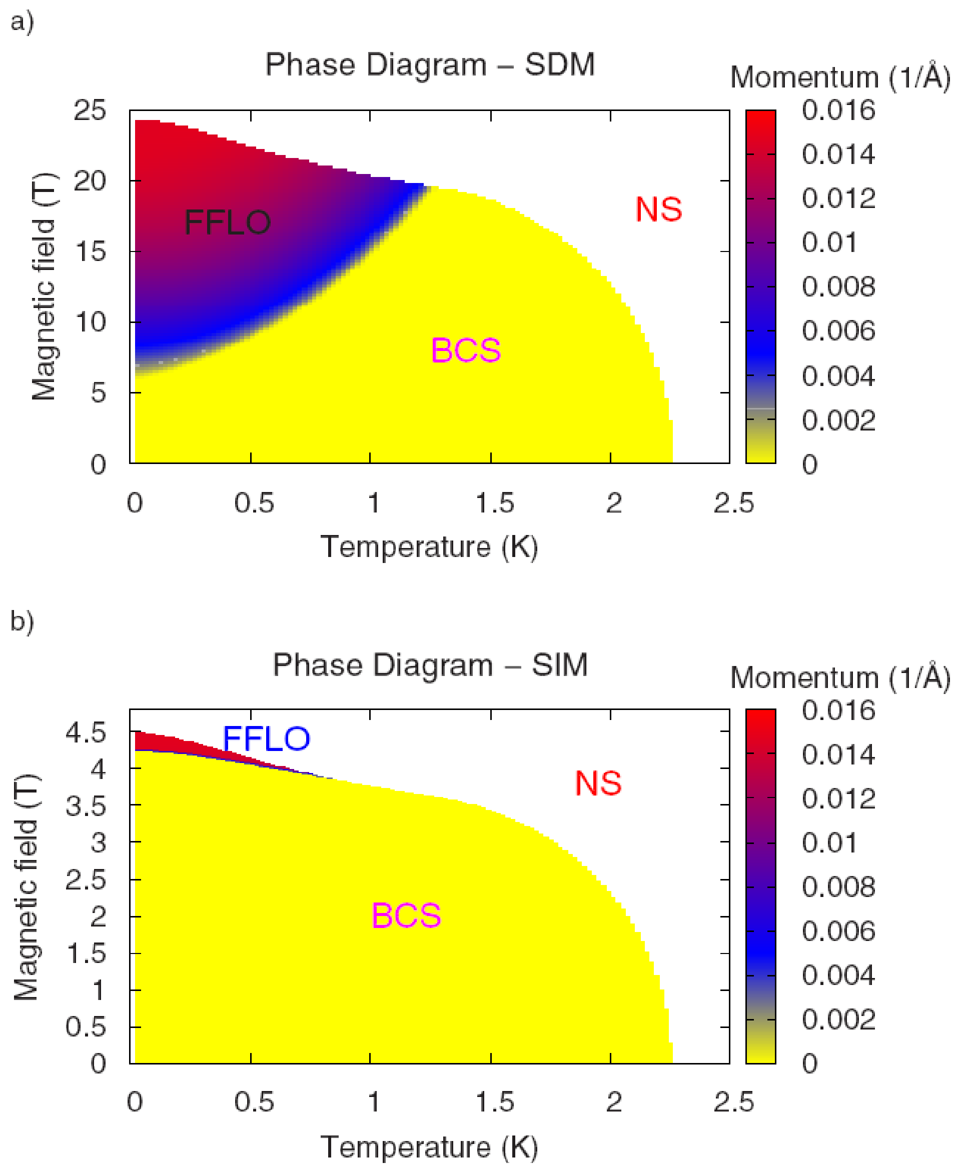
$$\alpha^{\dagger}_{\mathbf{k}\downarrow} = v_{\mathbf{k}} a_{\mathbf{k}+\mathbf{Q}/2\uparrow} + u_{\mathbf{k}} a^{\dagger}_{-\mathbf{k}+\mathbf{Q}/2\downarrow}$$

$$\mathcal{H} = \sum_{\mathbf{k}\sigma} E_{\mathbf{k}\sigma} \alpha^{\dagger}_{\mathbf{k}\sigma} \alpha_{\mathbf{k}\sigma} + \sum_{\mathbf{k}} \left(\xi^{(s)}_{\mathbf{k}} - E_{\mathbf{k}}\right) + N\frac{\Delta^2_{\mathbf{Q}}}{V_0} + \frac{N}{n}\bar{m}h_{\mathrm{cor}}$$

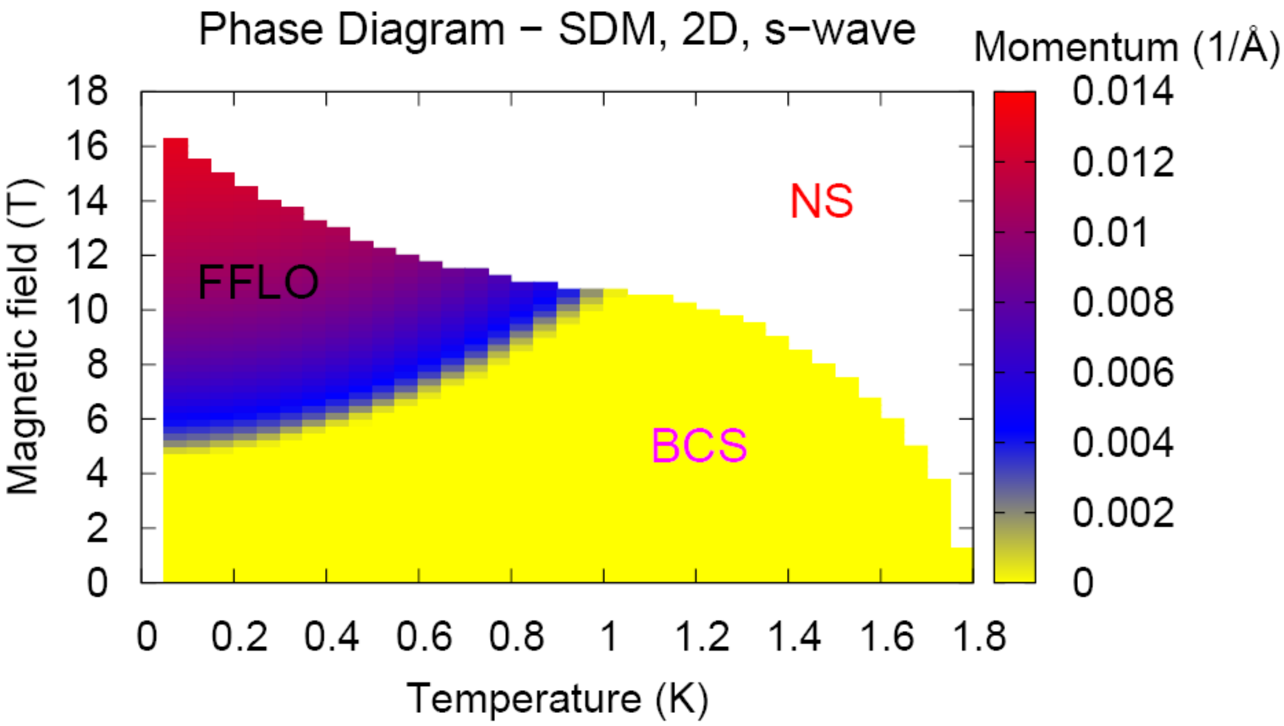
$$E_{\mathbf{k}\sigma} = E_{\mathbf{k}} + \sigma\xi^{(a)}_{\mathbf{k}}, \qquad E_{\mathbf{k}} = \sqrt{\xi^{(s)2}_{\mathbf{k}} + \Delta^2_{\mathbf{Q}}}$$

$$\xi^{(s)}_{\mathbf{k}} \equiv \frac{1}{2}\left(\xi_{\mathbf{k}+\mathbf{Q}/2\uparrow} + \xi_{-\mathbf{k}+\mathbf{Q}/2\downarrow}\right), \qquad \xi^{(a)}_{\mathbf{k}} \equiv \frac{1}{2}\left(\xi_{\mathbf{k}+\mathbf{Q}/2\uparrow} - \xi_{-\mathbf{k}+\mathbf{Q}/2\downarrow}\right)$$

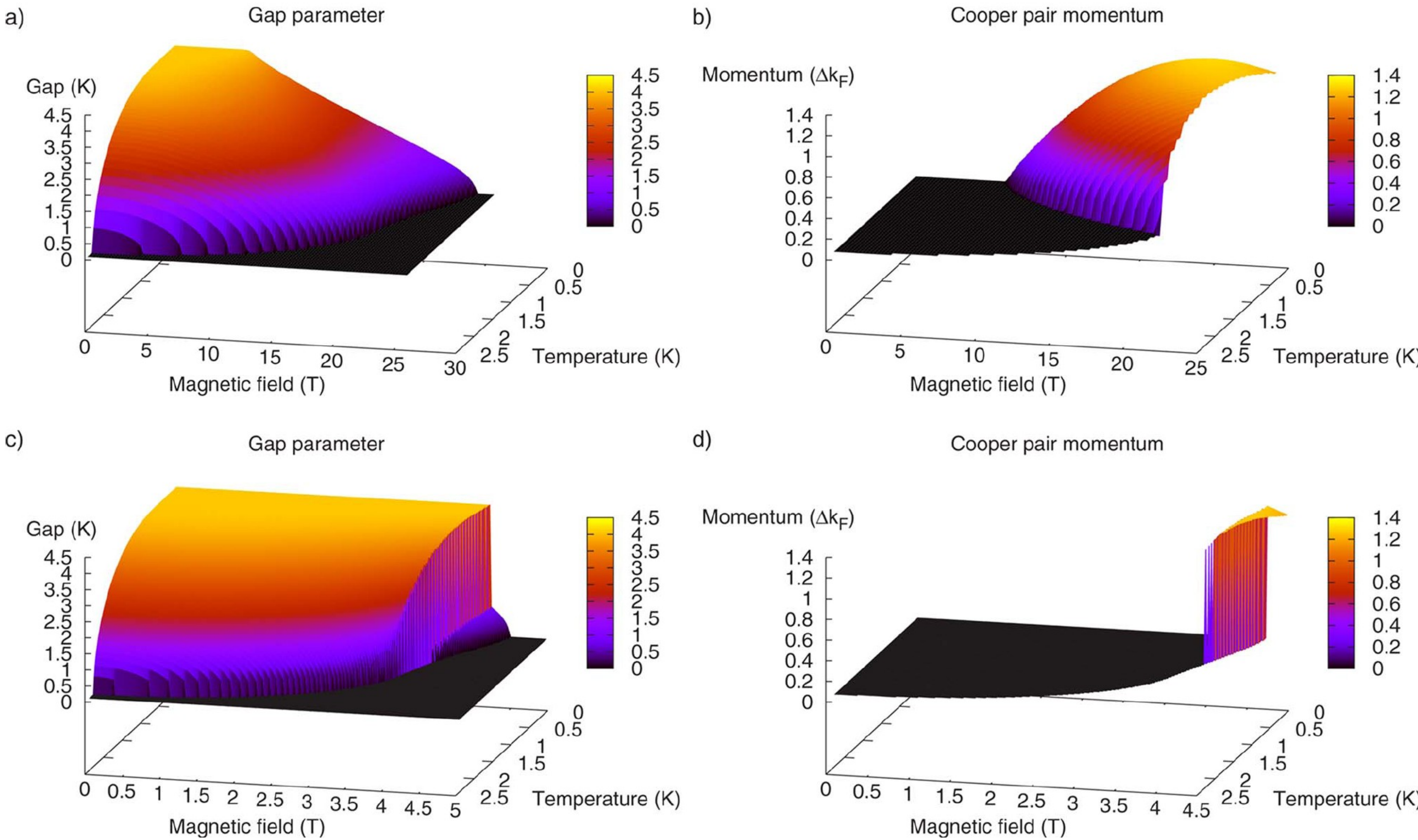
$$\Delta_{\mathbf{Q}} \equiv \frac{1}{N}\sum_{\mathbf{k}} \langle a_{-\mathbf{k}+\mathbf{Q}/2\downarrow} a_{\mathbf{k}+\mathbf{Q}/2\uparrow} \rangle$$



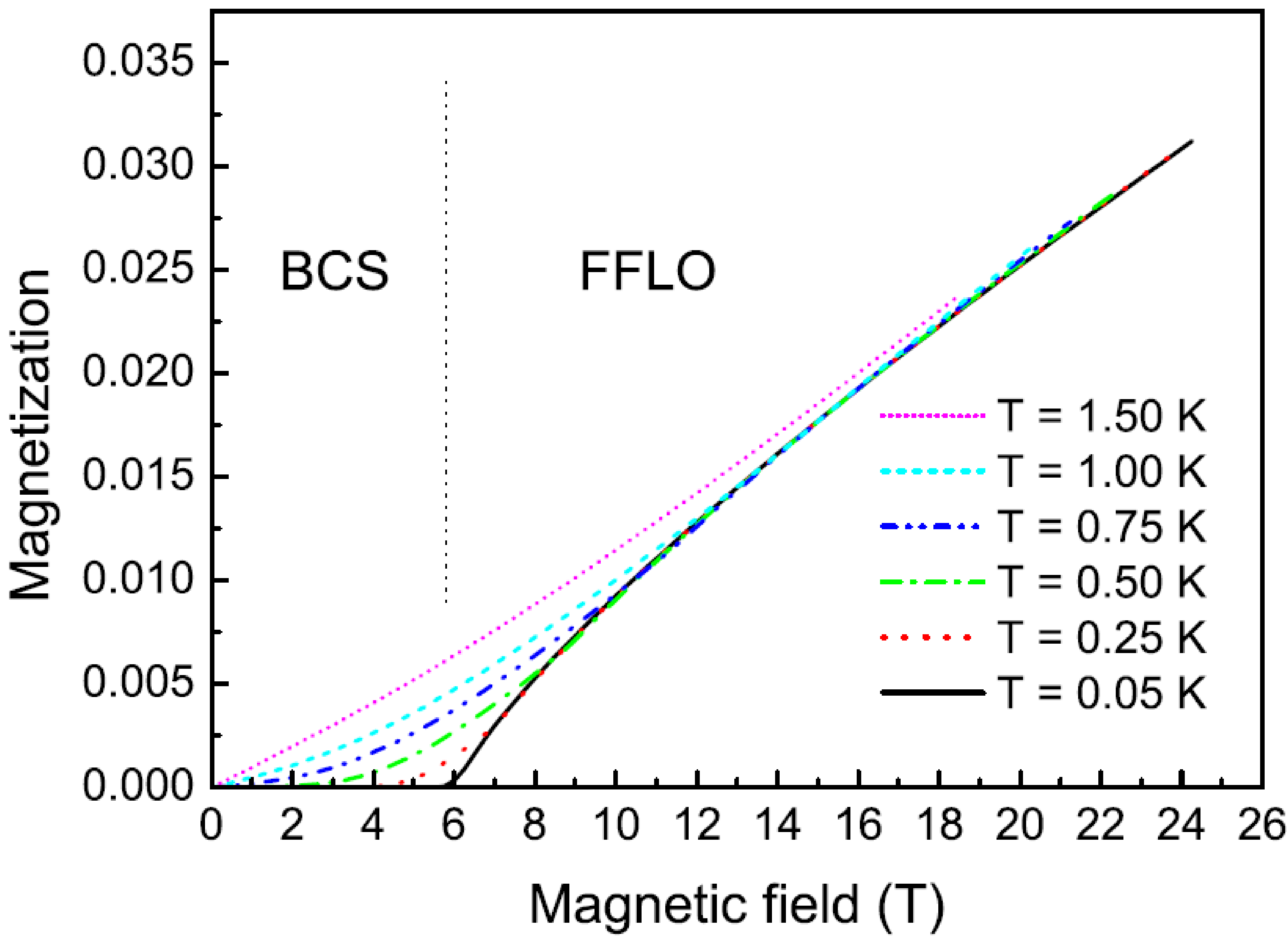
J. Kaczmarczyk and J. Spałek, PRB 79, 214519, pp. 1-15 (2009)



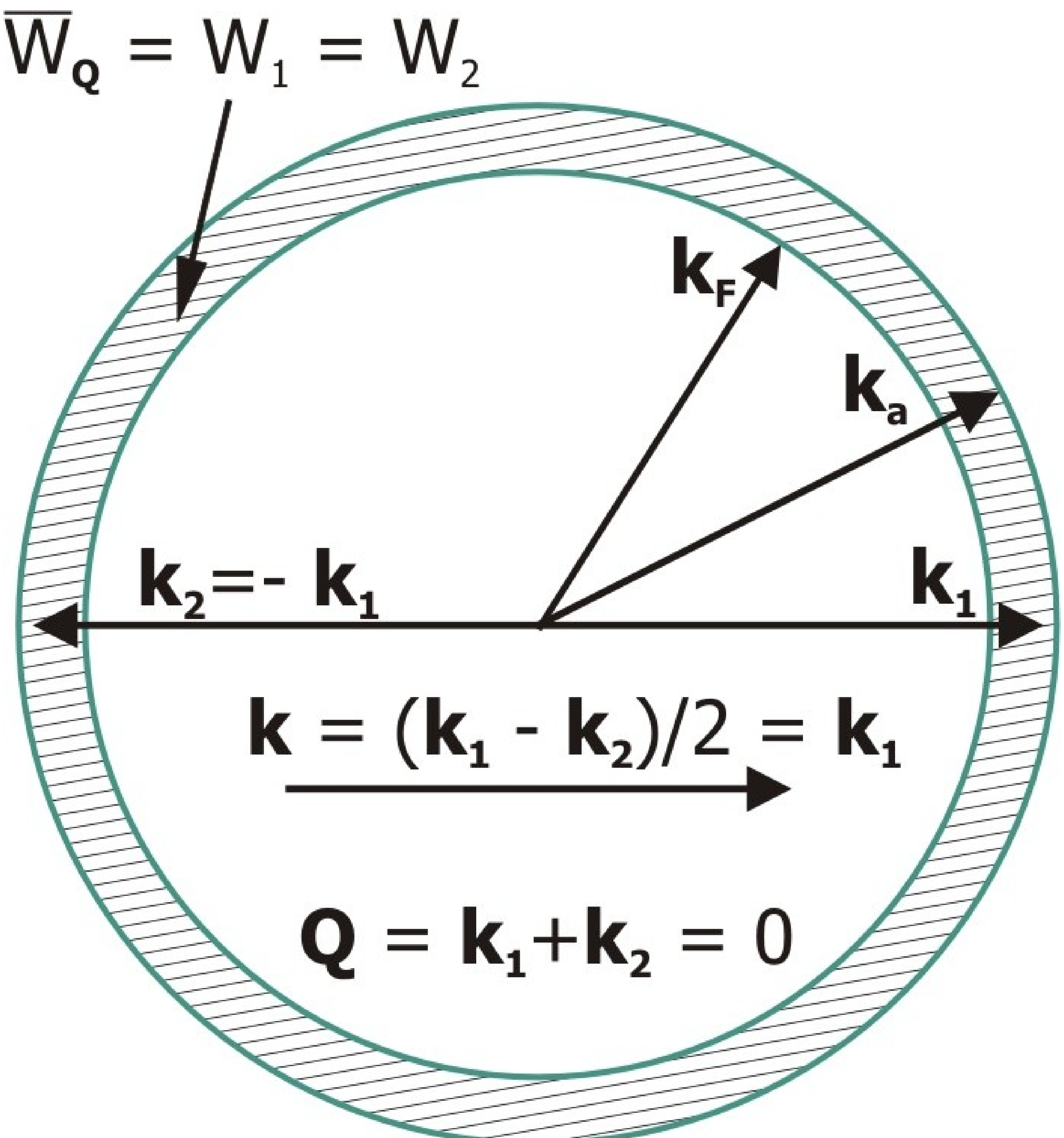
J. Kaczmarczyk and J. Spałek (2009), unpublished



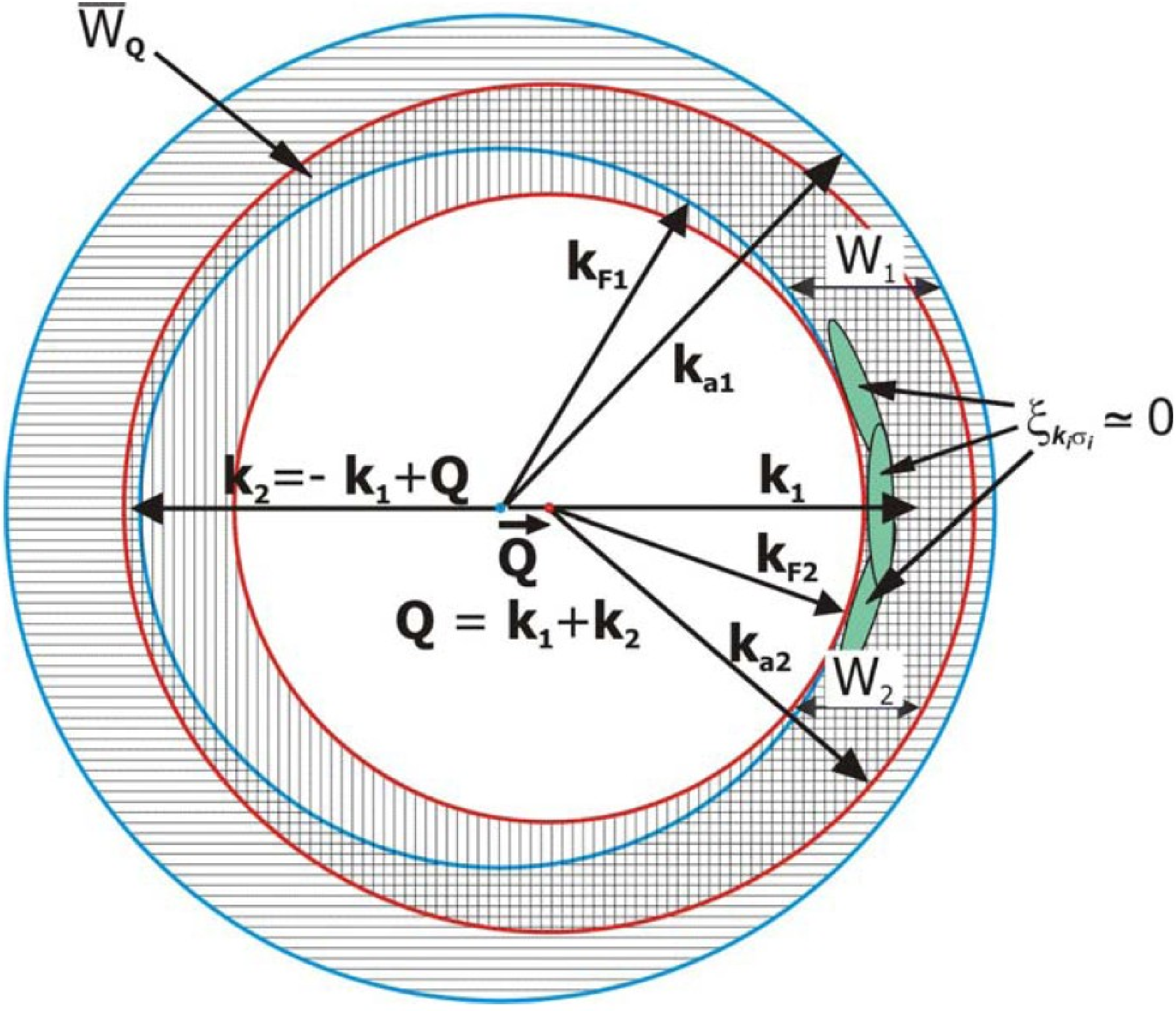
J. Kaczmarczyk and J. Spałek, PRB 79, 214519, pp. 1-15 (2009)



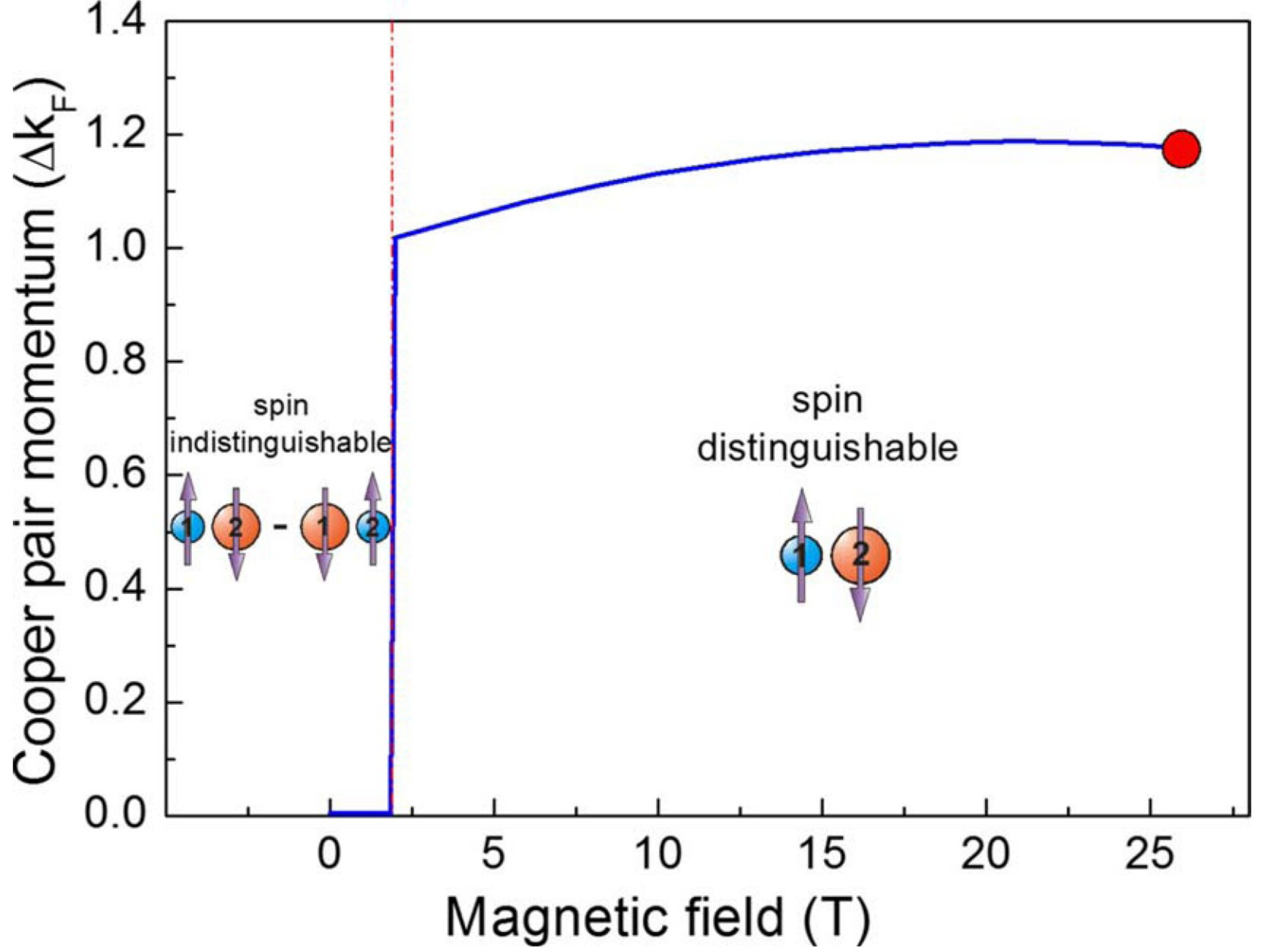
BCS
FFLO
T = 1.50 K
T = 1.00 K
T = 0.75 K
T = 0.50 K
T = 0.25 K
T = 0.05 K
Magnetization
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
Magnetic field (T)
0
2
4
6
8
10
12
14
16
18
20
22
24
26



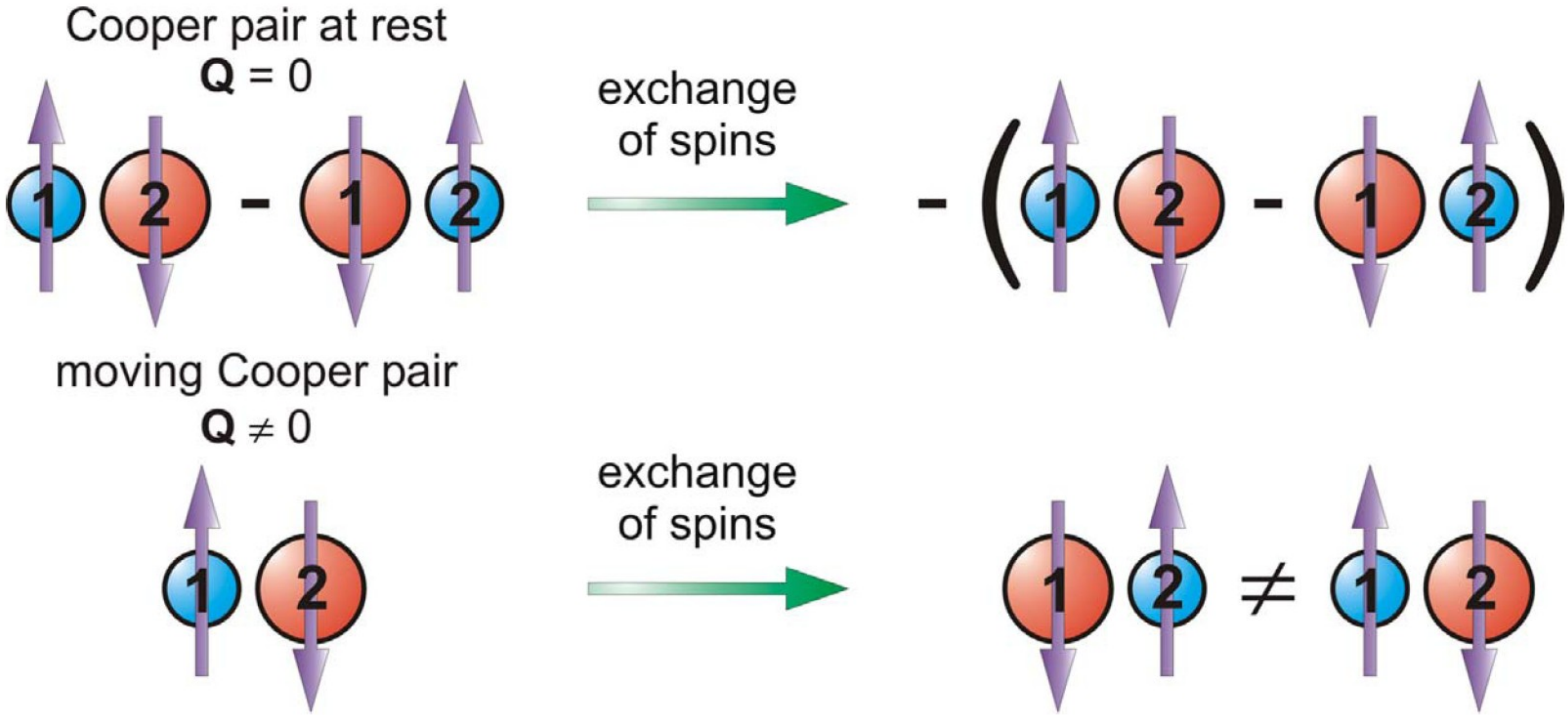
$\overline{W}_Q = W_1 = W_2$
k_F
k_a
$k_2 = - k_1$
k_1
$k = (k_1 - k_2)/2 = k_1$
$Q = k_1 + k_2 = 0$



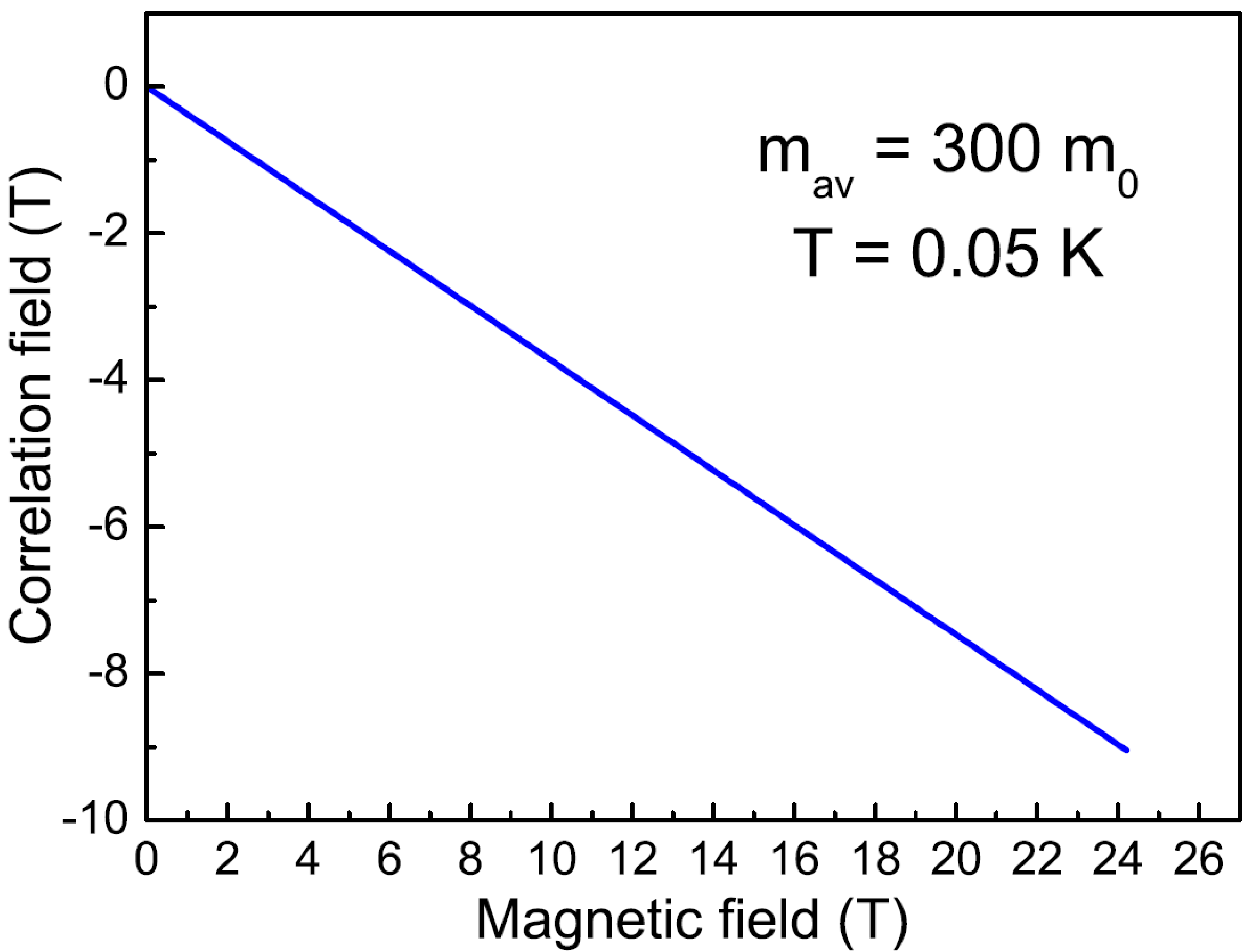
$\overline{W}_Q$
k_{F1}
k_{a1}
W_1
$\xi_{k_i\sigma_i} \simeq 0$
$k_2 = - k_1 + Q$
k_1
$\vec{Q}$
k_{F2}
$Q = k_1 + k_2$
k_{a2}
W_2



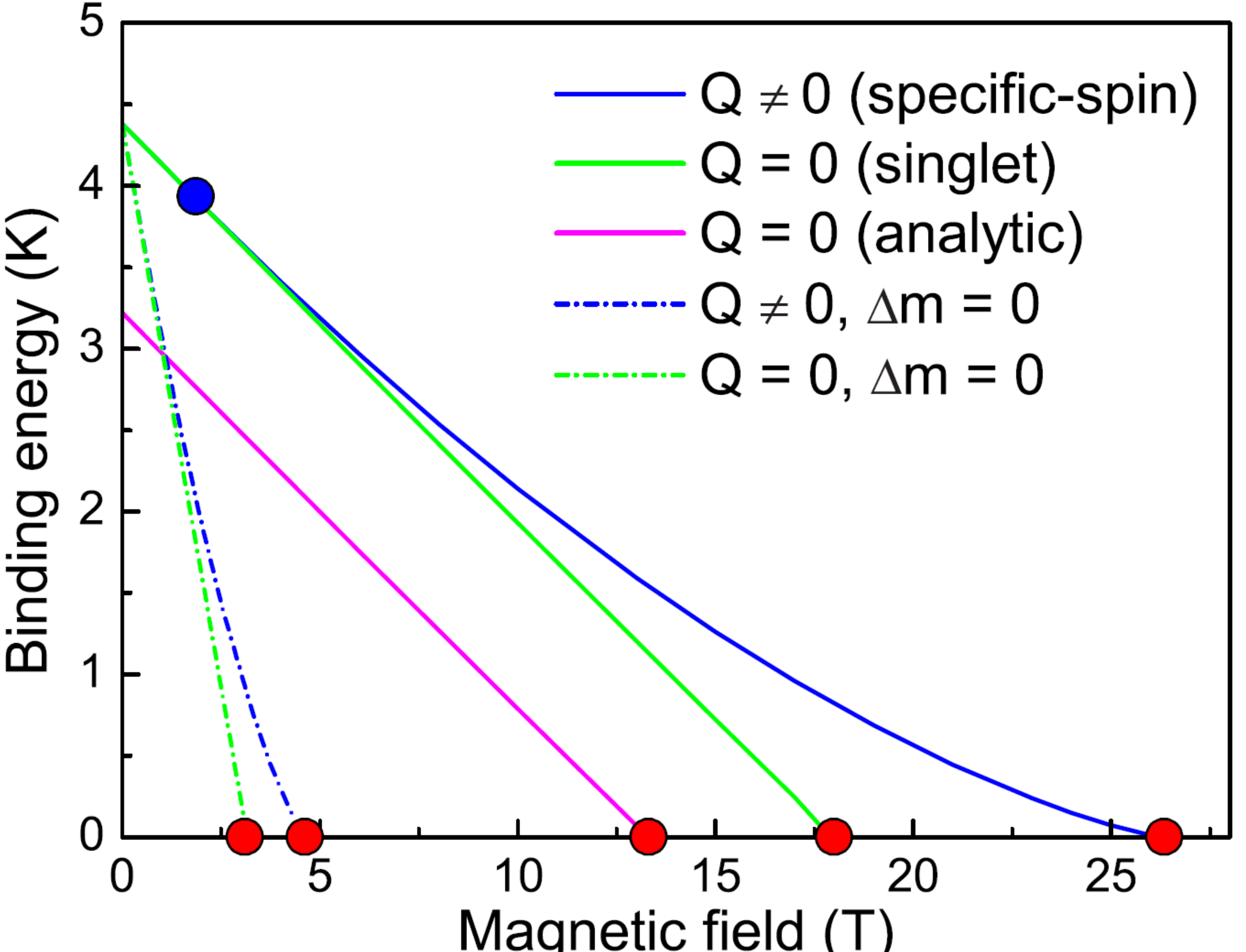
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Cooper pair momentum (Δk_F)
spin
indistinguishable
1 2 - 1 2
spin
distinguishable
1 2
0
5
10
15
20
25
Magnetic field (T)



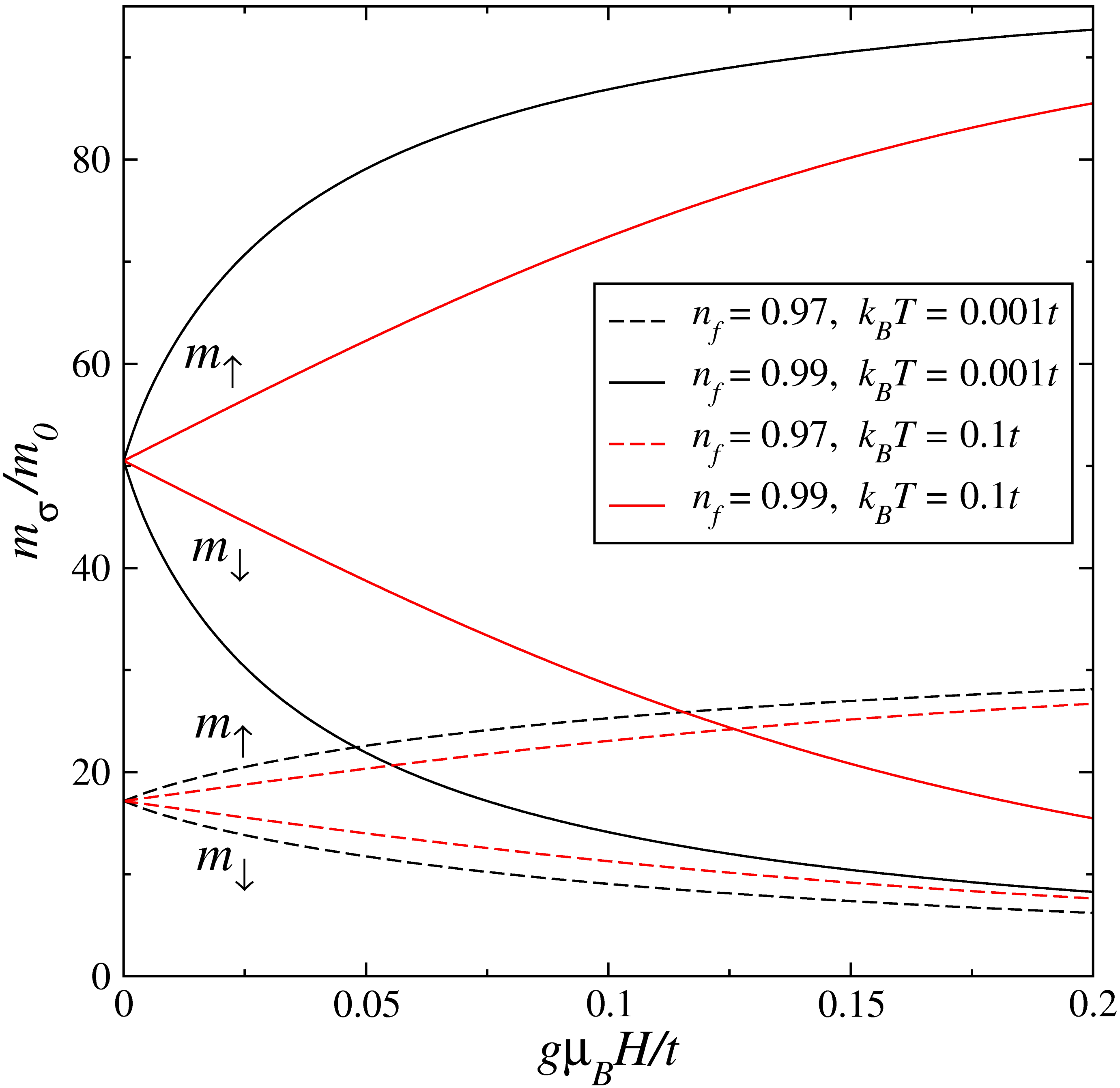
$$\chi_1(\uparrow)\chi_2(\downarrow)=\frac{1}{2}\left[\chi_1(\uparrow)\chi_2(\downarrow)-\chi_1(\downarrow)\chi_2(\uparrow)\right]+\frac{1}{2}\left[\chi_1(\uparrow)\chi_2(\downarrow)+\chi_1(\downarrow)\chi_2(\uparrow)\right]$$



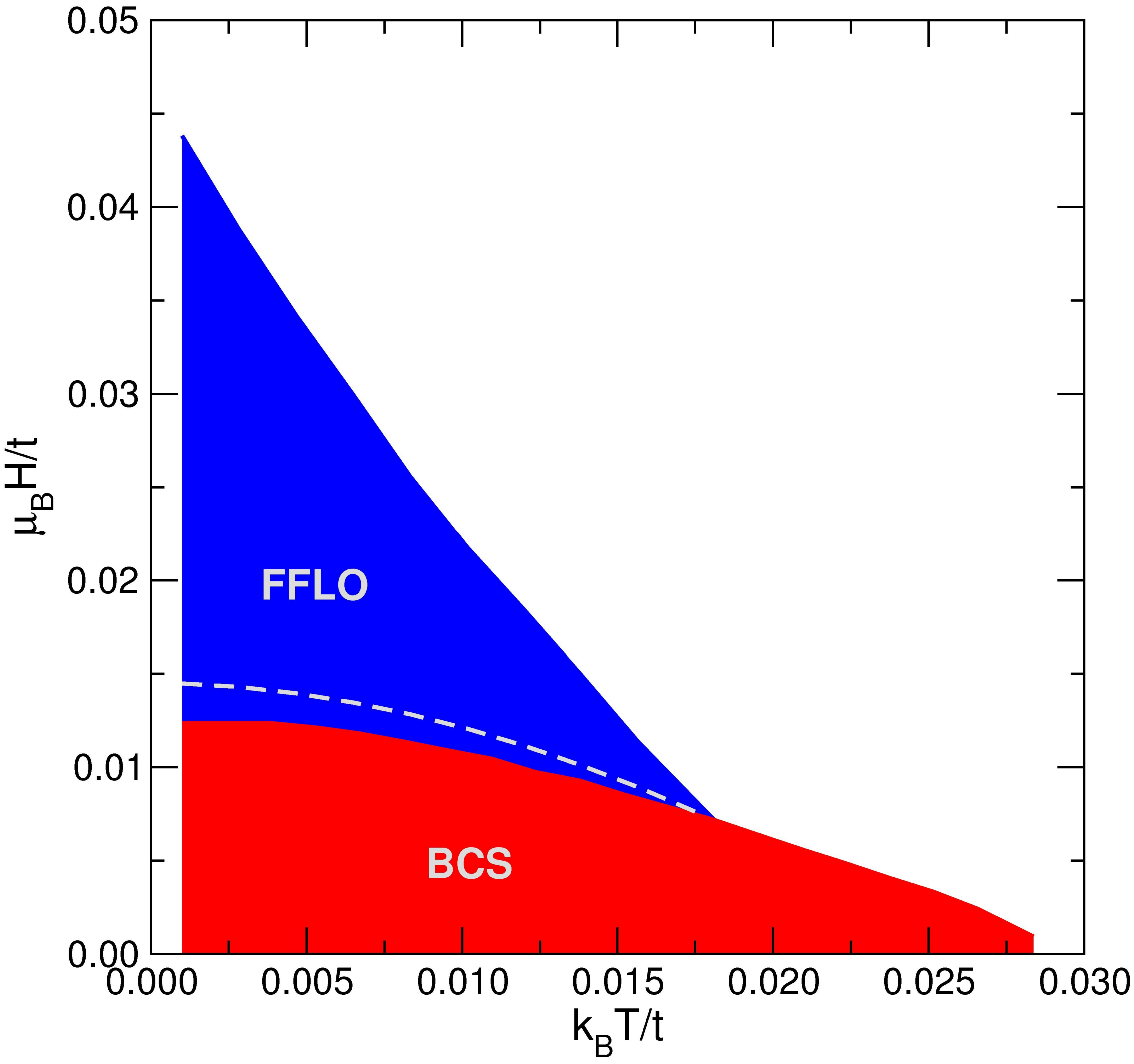
m_av = 300 m_0
T = 0.05 K
Correlation field (T)
Magnetic field (T)
0
-2
-4
-6
-8
-10
0 2 4 6 8 10 12 14 16 18 20 22 24 26



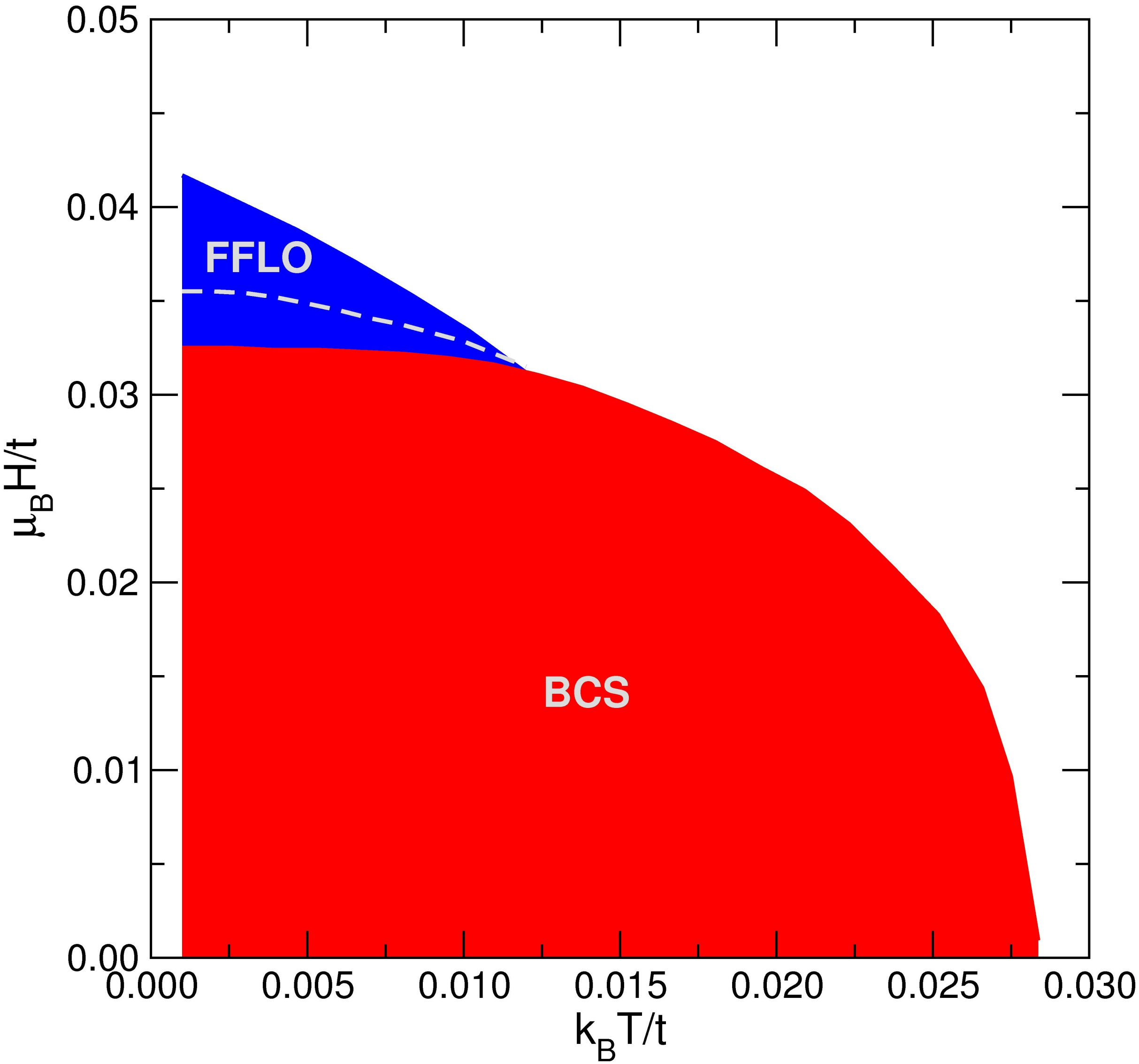
Q ≠ 0 (specific-spin)
Q = 0 (singlet)
Q = 0 (analytic)
Q ≠ 0, Δm = 0
Q = 0, Δm = 0
Binding energy (K)
Magnetic field (T)
0
1
2
3
4
5
0
5
10
15
20
25



80
60
40
20
0
0
0.05
0.1
0.15
0.2
m_σ / m_0
$g\mu_B H/t$
$m_\uparrow$
$m_\downarrow$
$m_\uparrow$
$m_\downarrow$
$n_f = 0.97,\ k_B T = 0.001t$
$n_f = 0.99,\ k_B T = 0.001t$
$n_f = 0.97,\ k_B T = 0.1t$
$n_f = 0.99,\ k_B T = 0.1t$

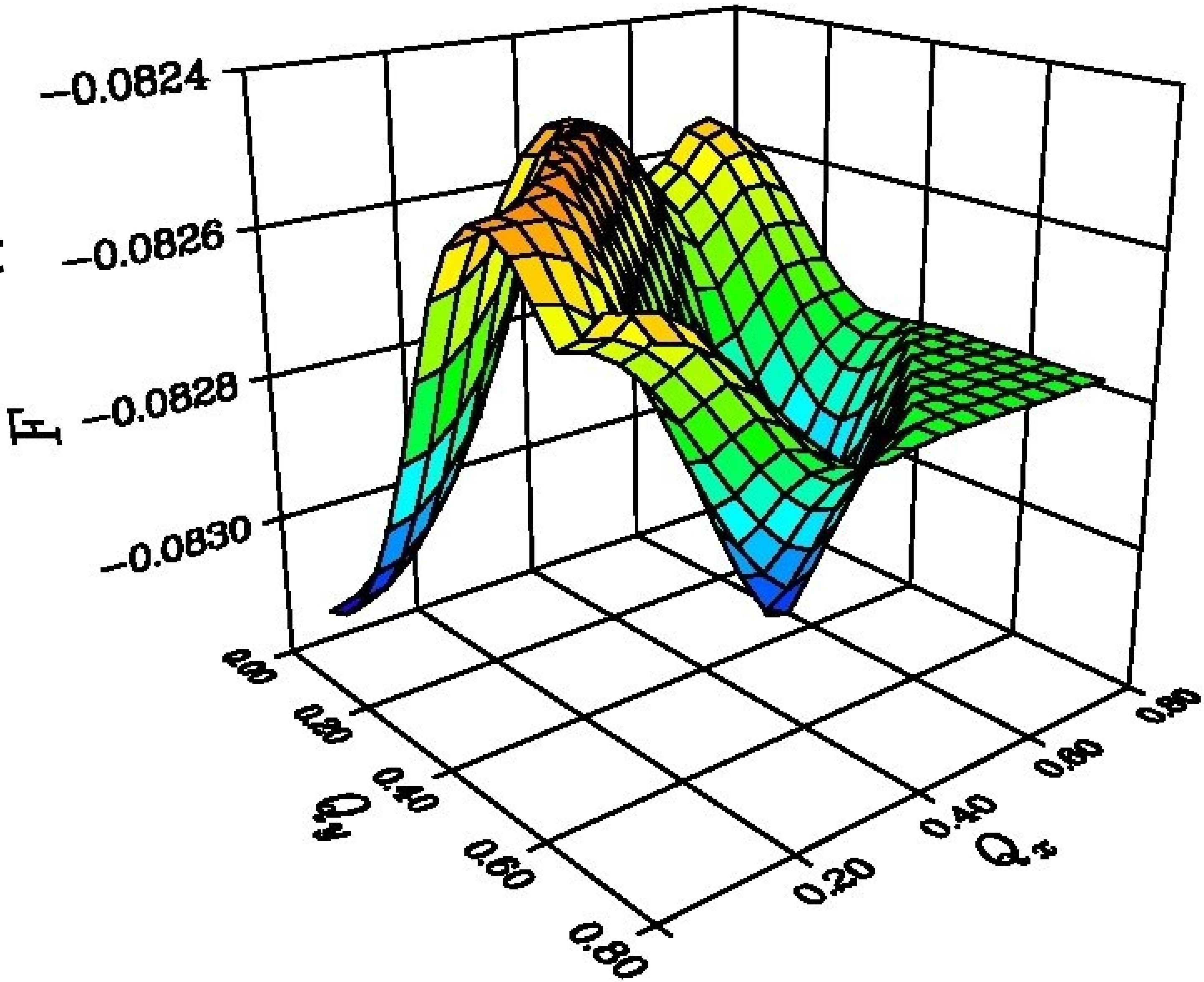


M. Maśka, M. Mierzejewski, J. Kaczmarczyk, J. S. (2009), unpubl.

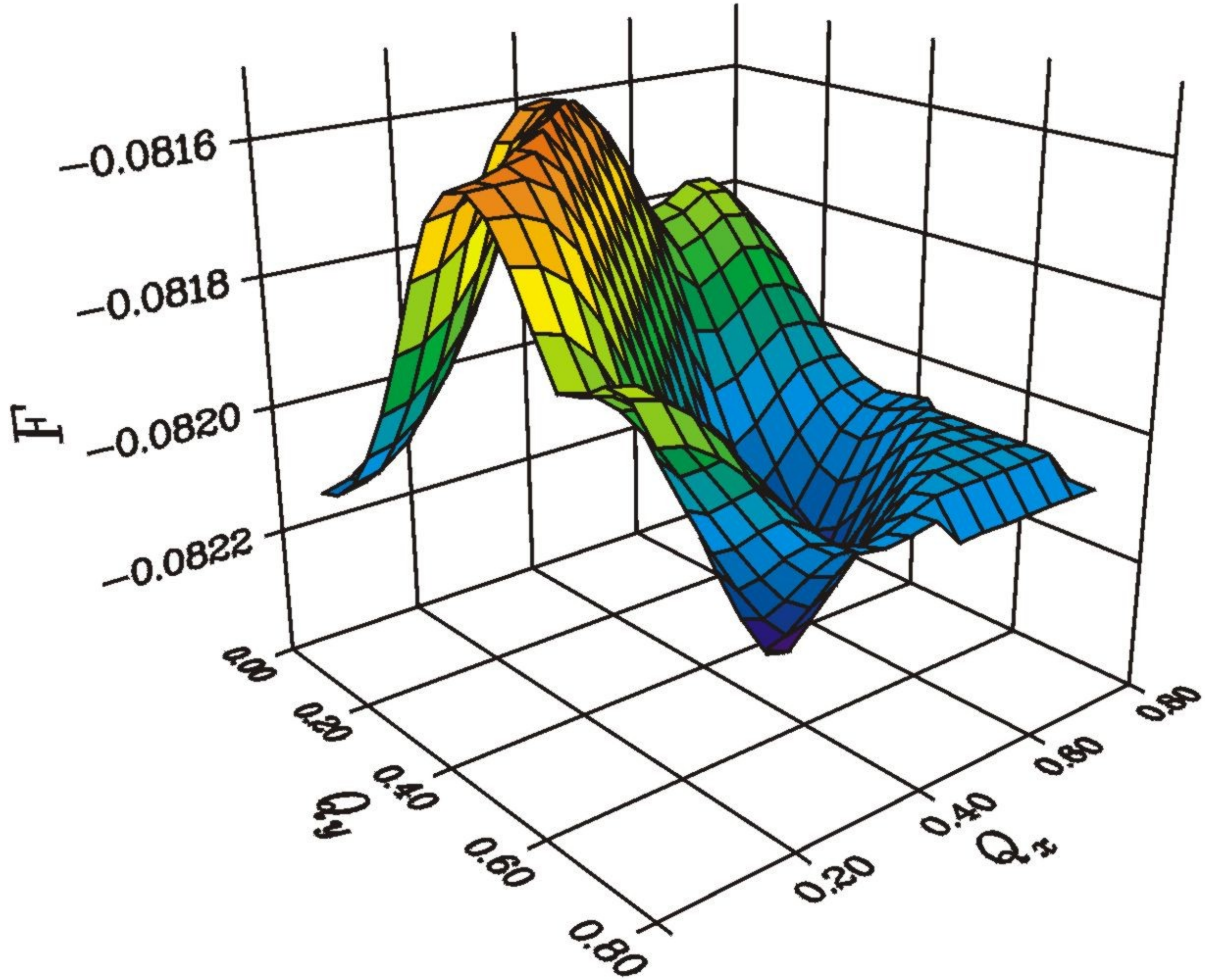


M. Maśka, M. Mierzejewski, J. Kaczmarczyk, J. S. (2009), unpubl.

F/t



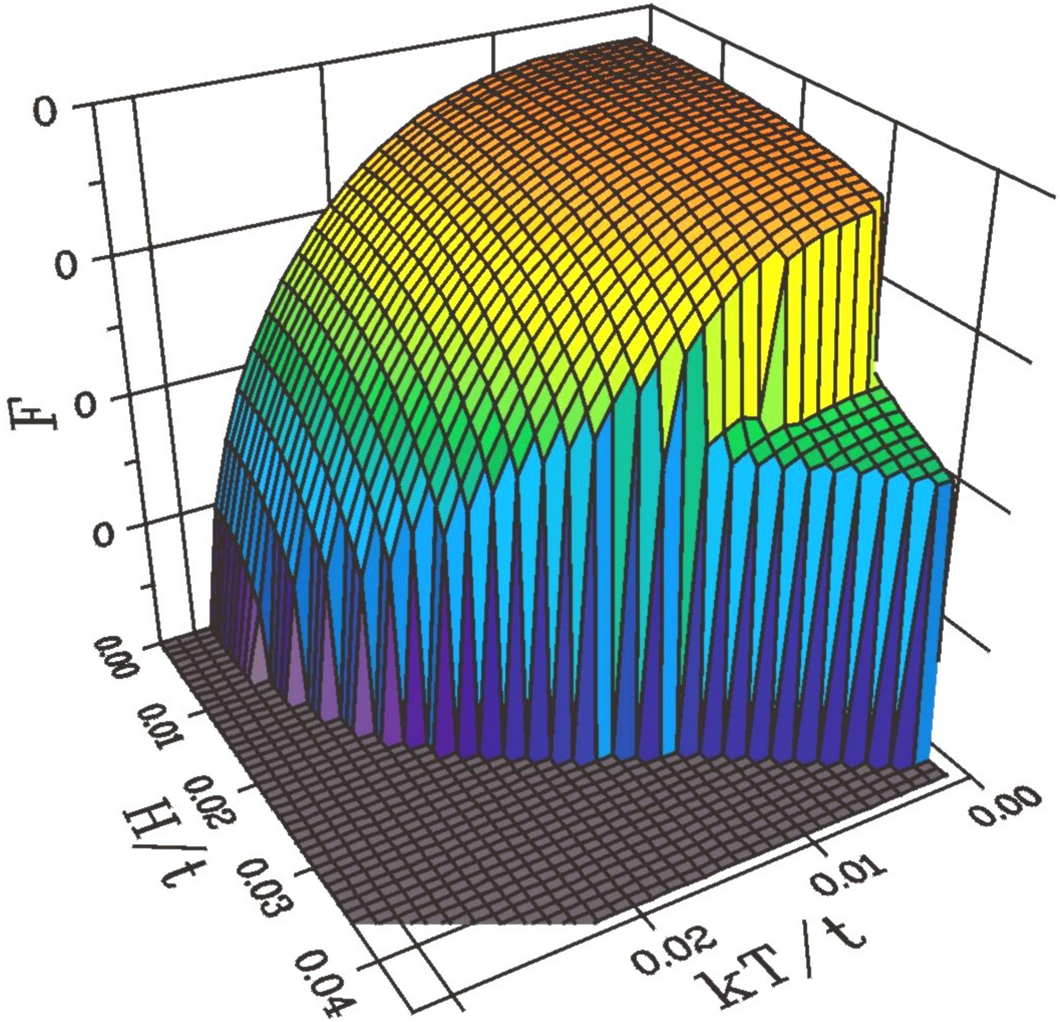
M. Maśka, M. Mierzejewski, J. Kaczmarczyk, J. S. (2009), unpubl.

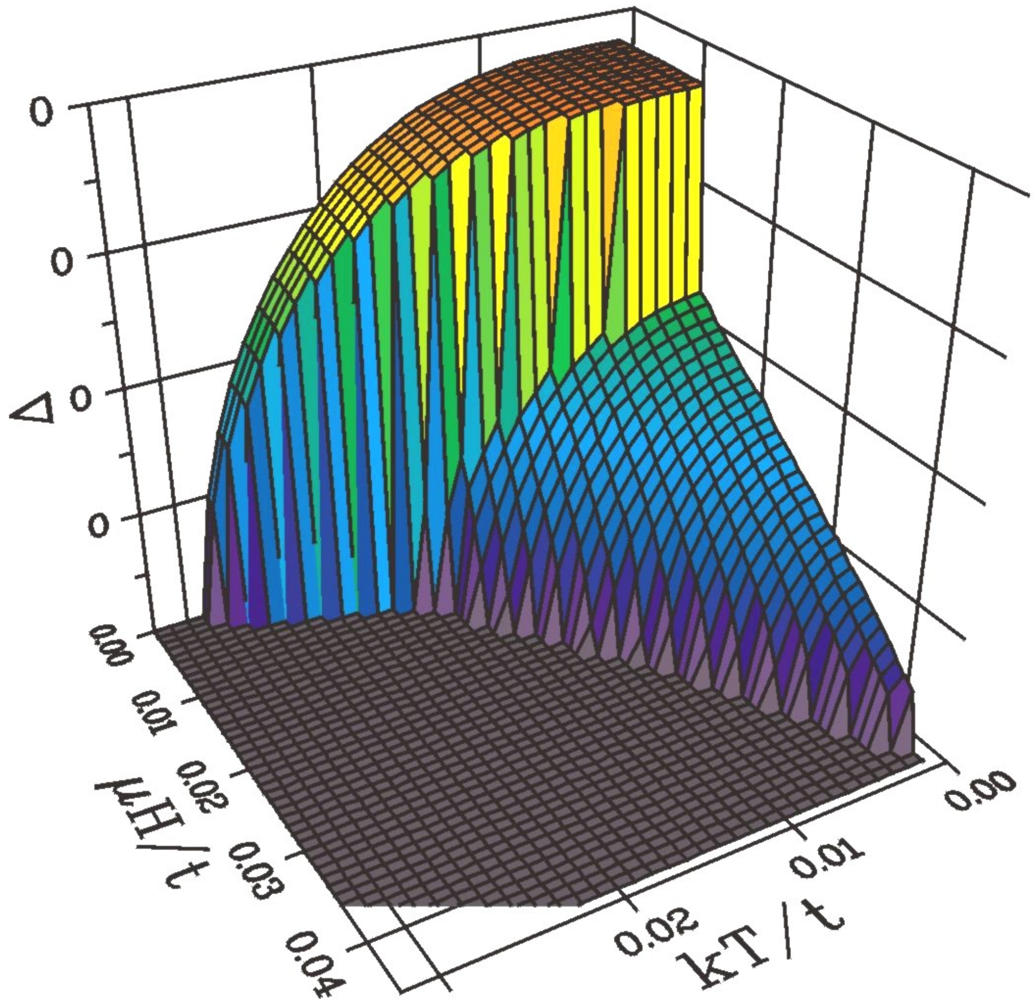


M. Maśka, M. Mierzejewski, J. Kaczmarczyk, J. S. (2009), unpubl.

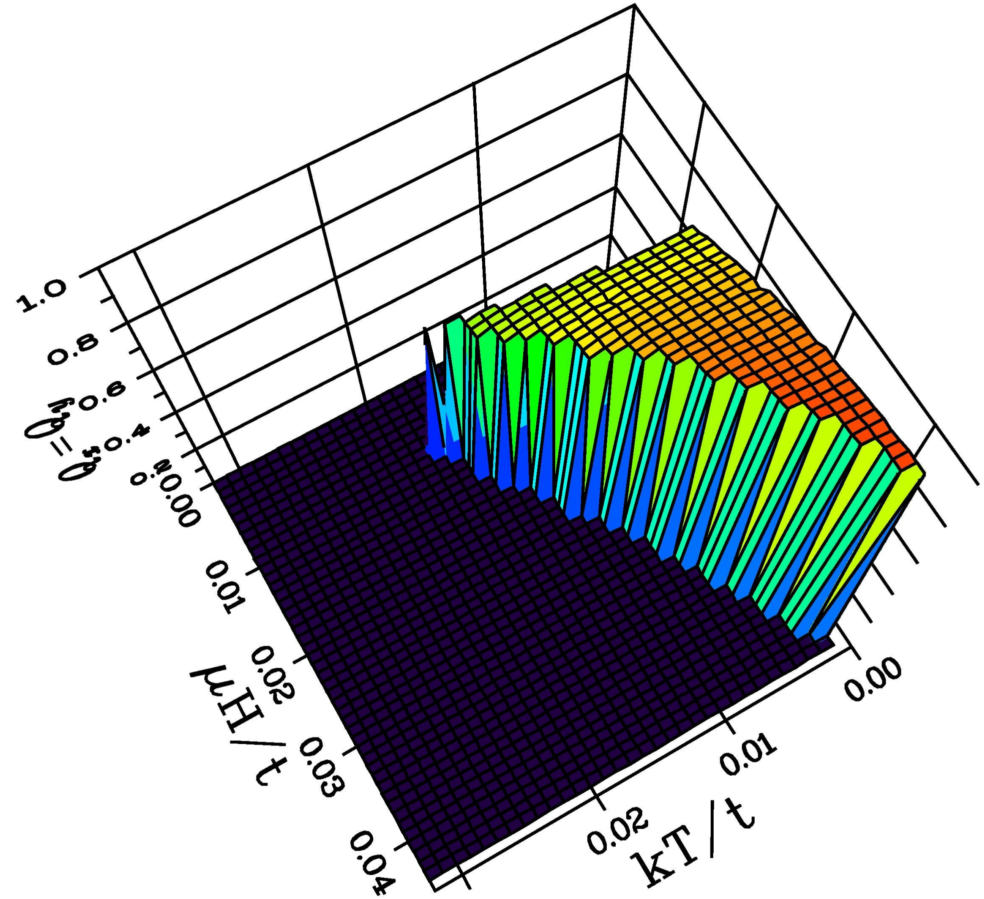
Conclusions

1. **Transition to distinguishable quasiparticles in Cooper pair in an applied field**
2. **FFLO phase is robust when the masses are spin-dependent**
3. **Effective field driven by correlations compensates partially the applied field**
4. **Generalization of the concept of the Landau quasiparticle**

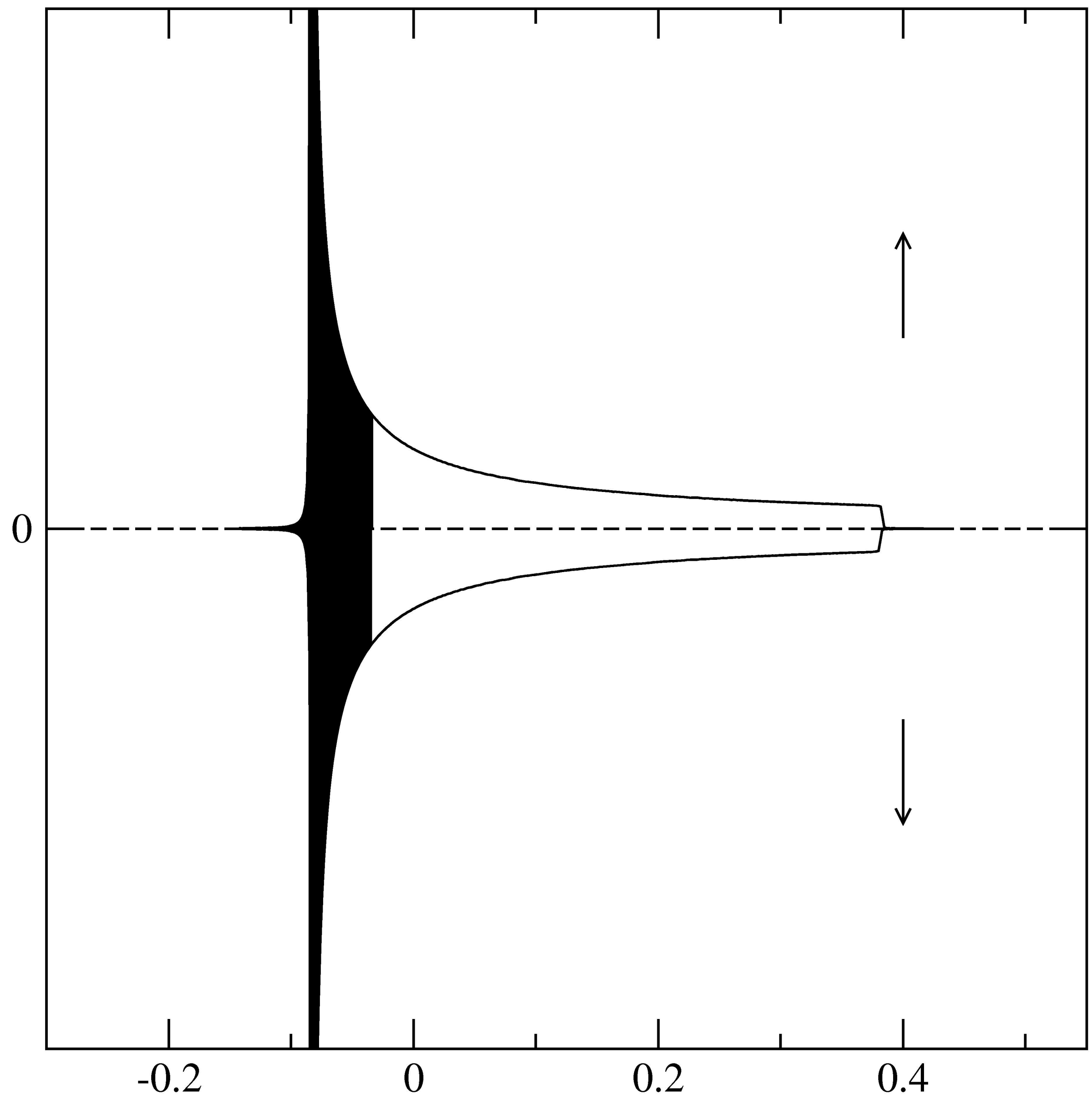

0
0
0
0
F
0.00
0.01
0.02
0.03
0.04
H / t
0.00
0.01
0.02
kT / t



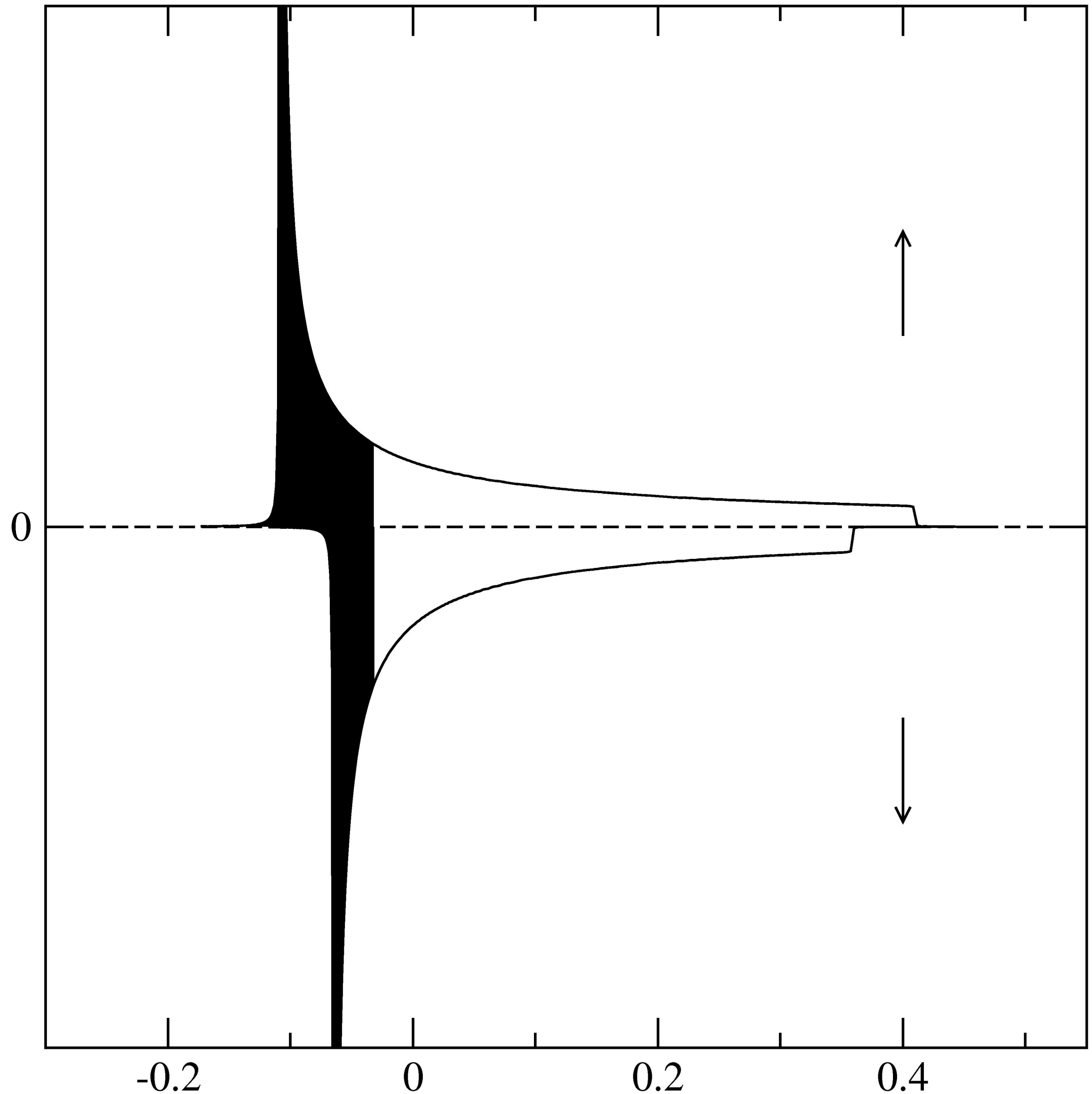
0
0
0
0
Δ
0.00
0.01
0.02
0.03
0.04
μH / t
0.00
0.01
0.02
kT / t



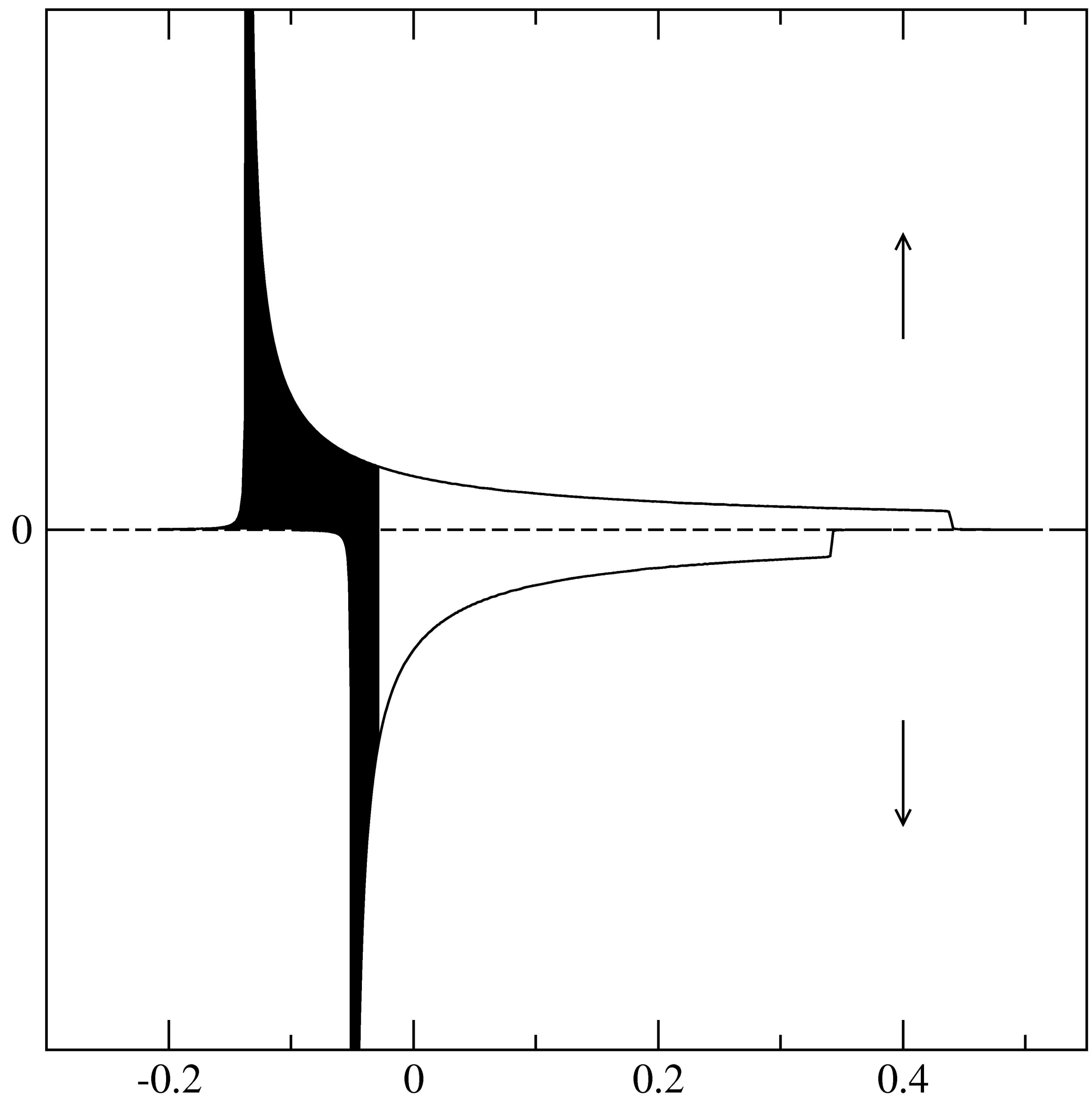
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.01
0.02
0.03
0.04
μH/t
0.00
0.01
0.02
kT/t



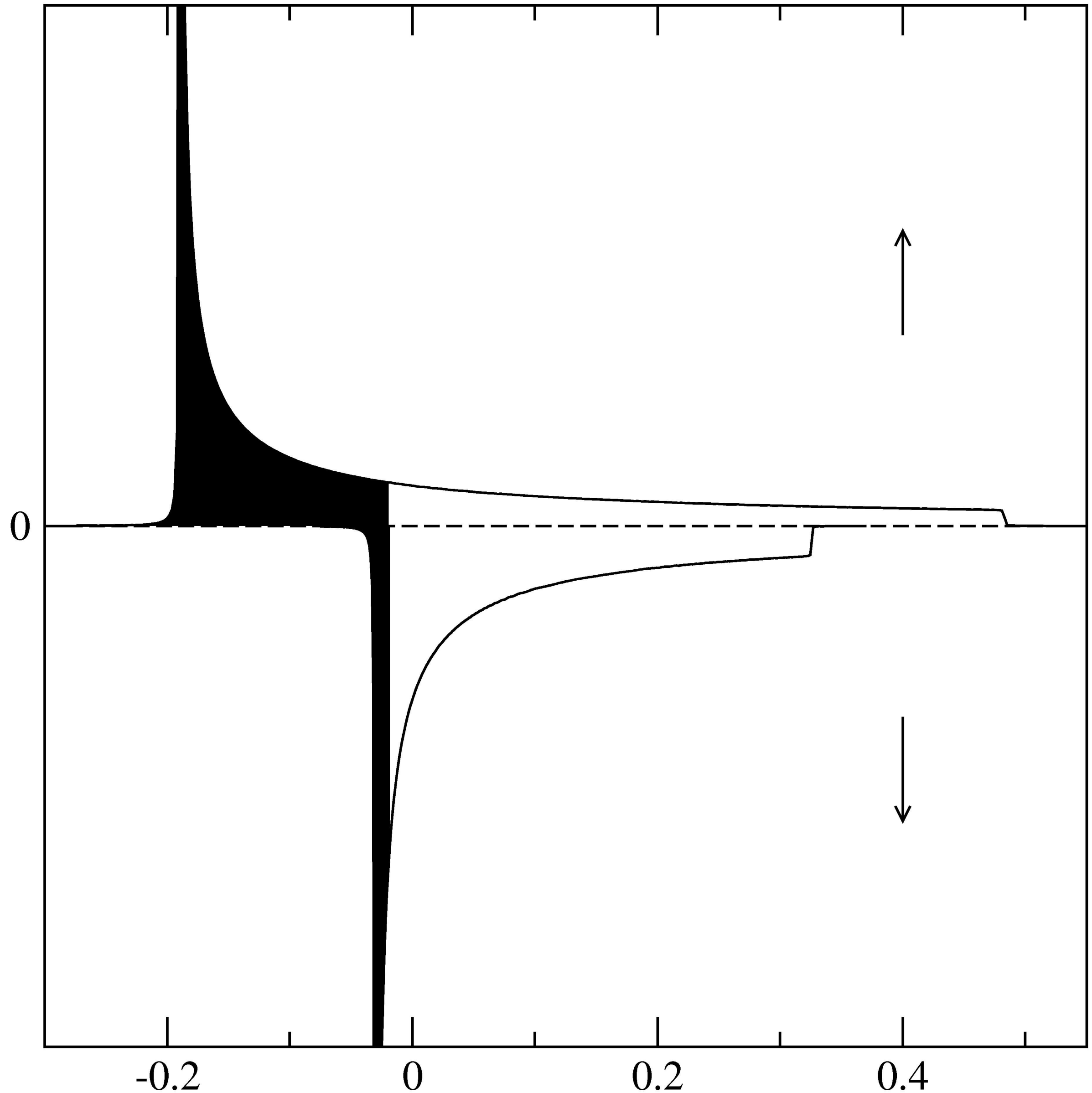
0
-0.2
0
0.2
0.4



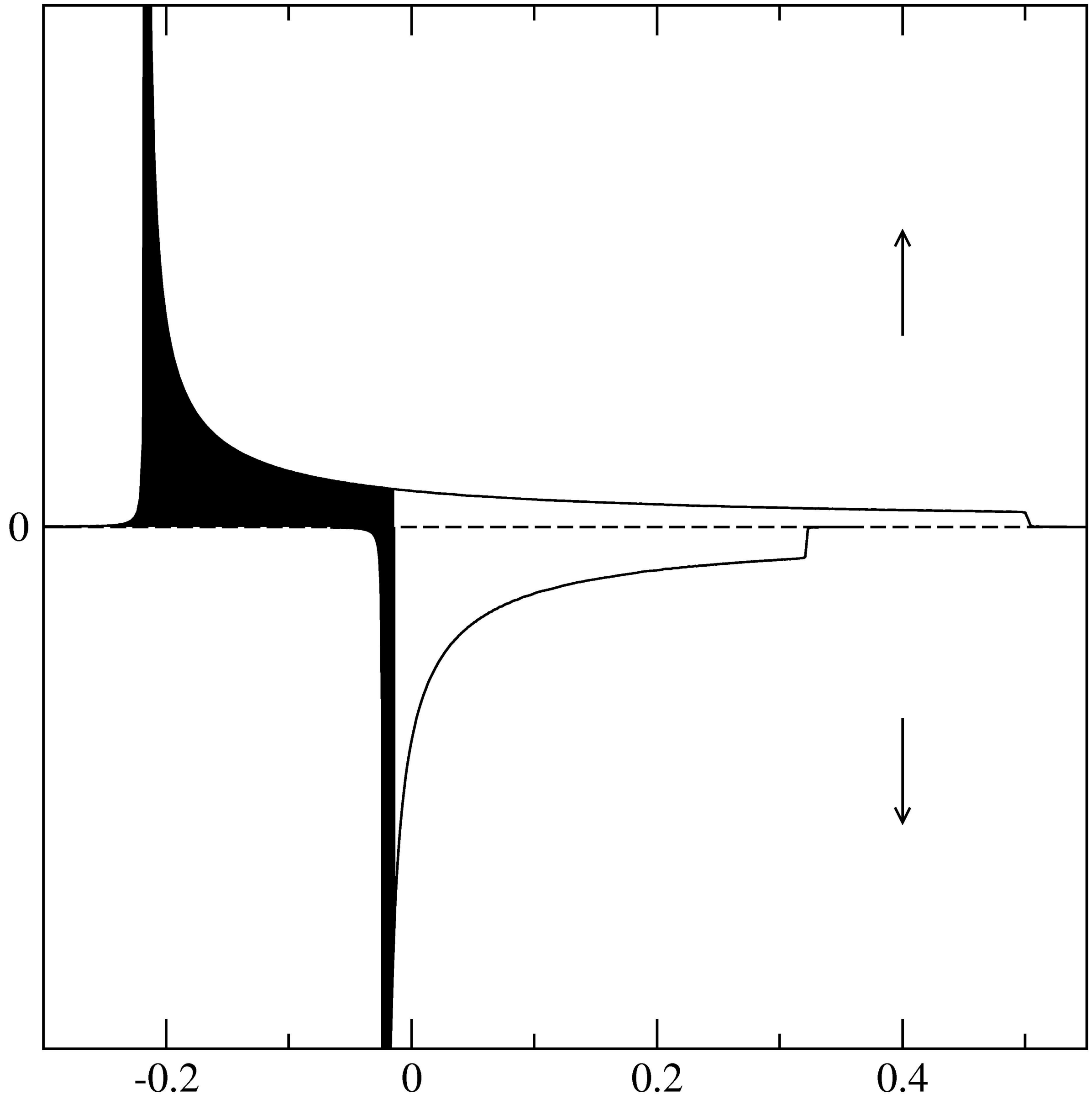
0
-0.2
0
0.2
0.4

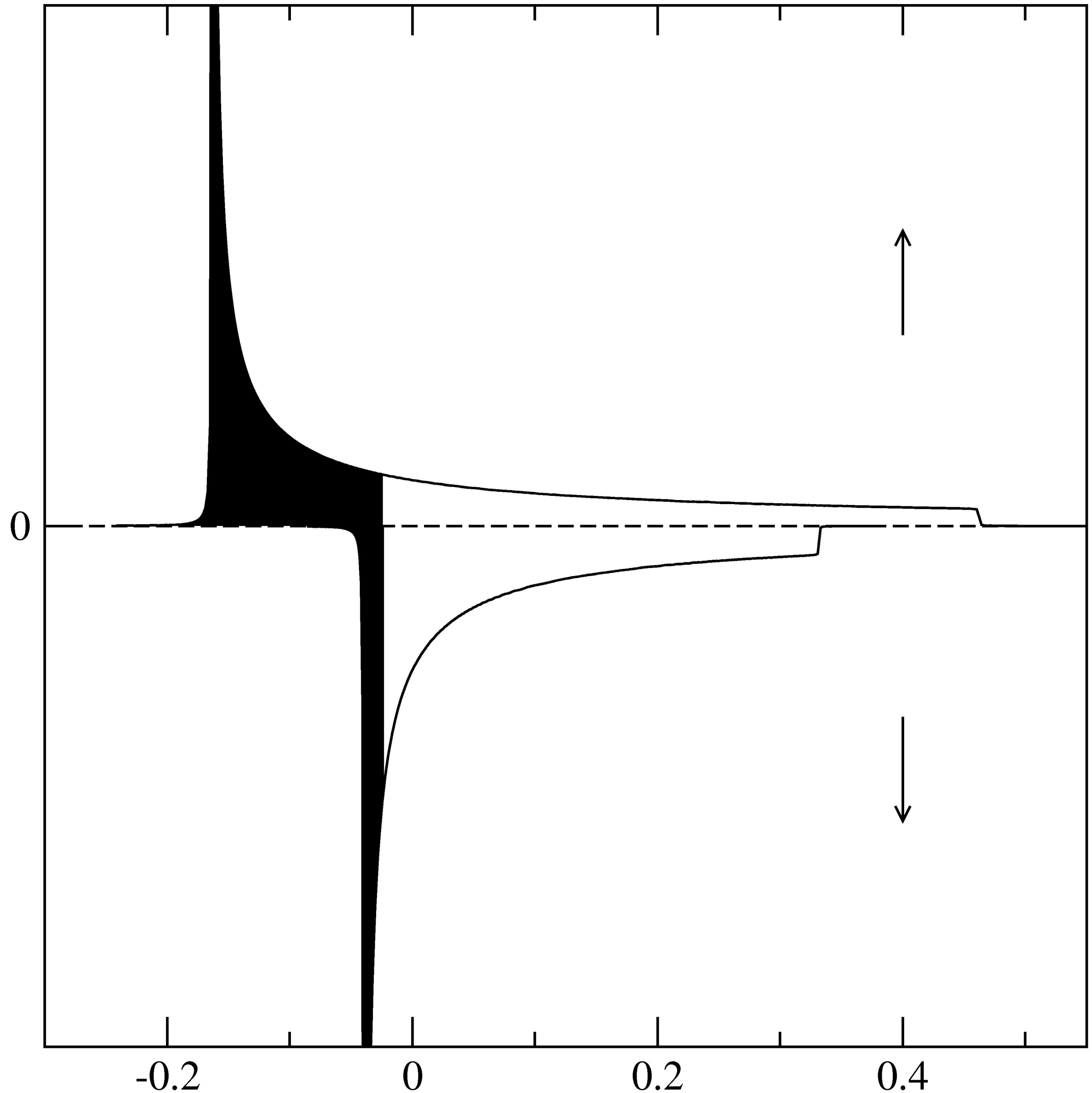


0
-0.2
0
0.2
0.4



0
-0.2
0
0.2
0.4


0
-0.2
0
0.2
0.4


0
-0.2
0
0.2
0.4

3. Struktura elektronowa? **LDA + U, LDA + DMFT, Gutzwiller LDA**

Gutzwiller + wave function readj.: beyond the parametrized models

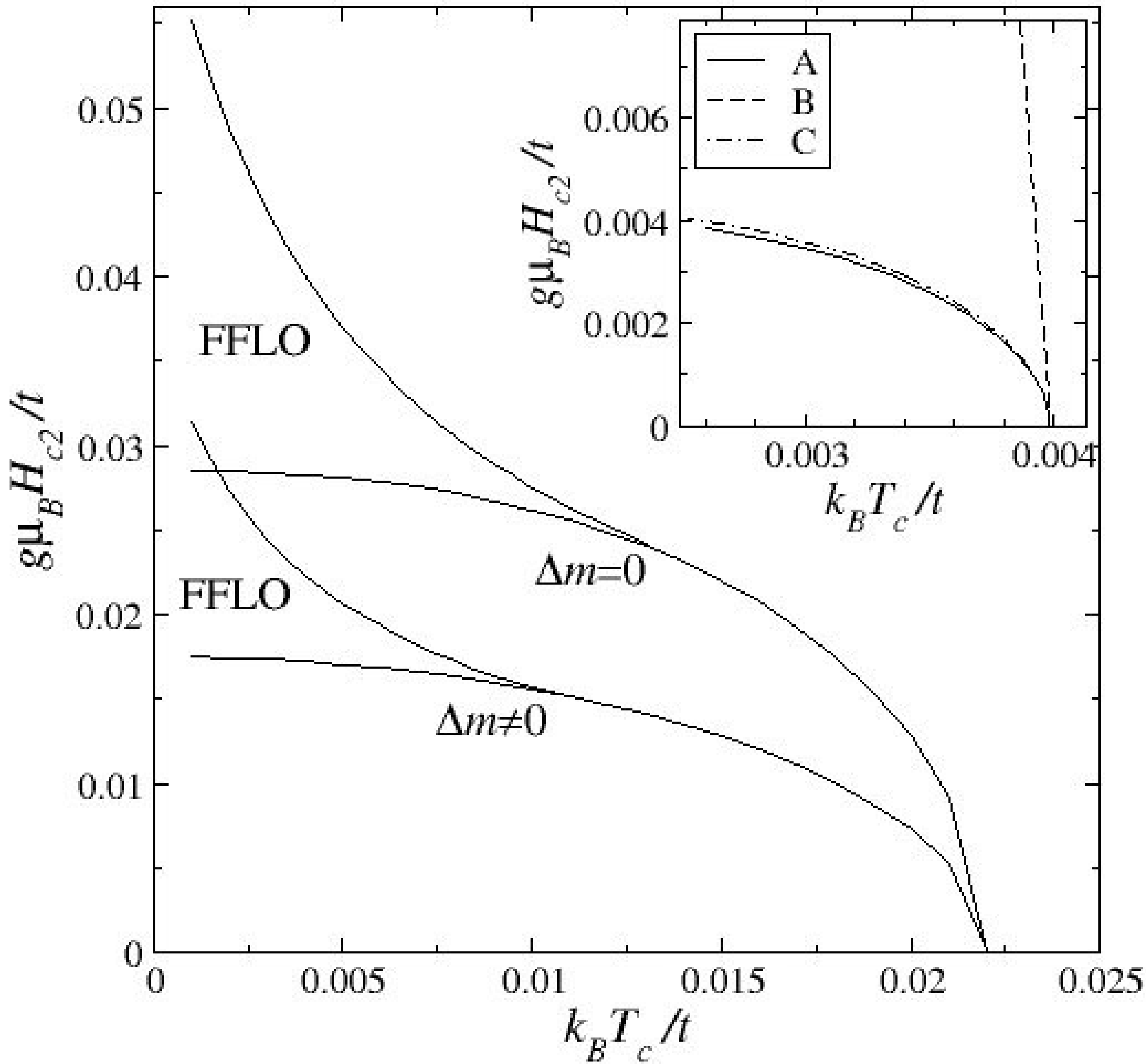
4. Efektywna temperatura Kondo: **temperatura koherencji**

Lokalizacja zaindukowana ruchem termicznym dla rosnącej temperatury, korelacje typu Kondo (lub nie) dla T -> 0

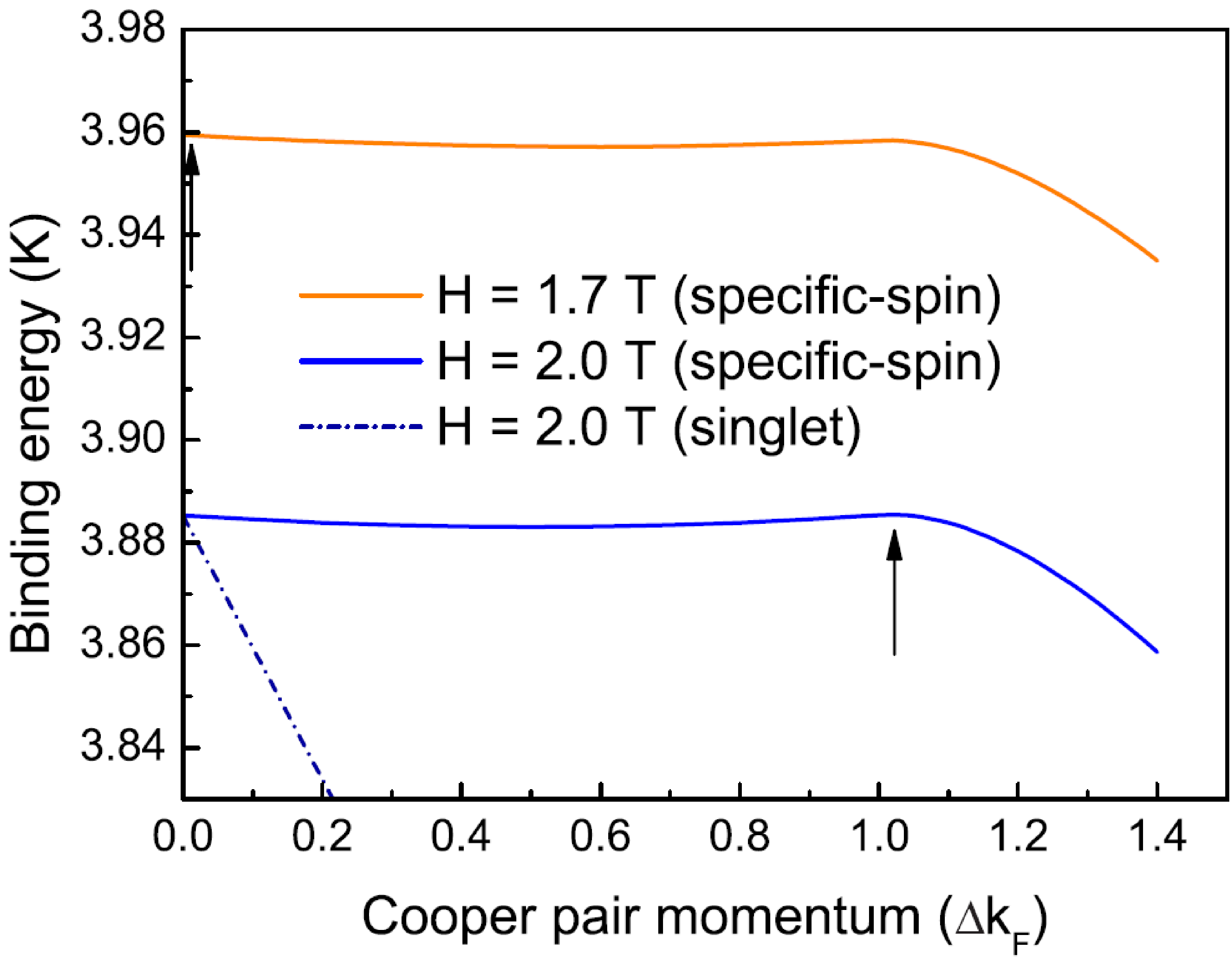
5. **Kwantowe zjawiska krytyczne** czyli wyjście poza paradygmat prawie zlokalizowanej cieczy Fermiego;

Kwantowe punkty krytyczne na progu lokalizacji Motta, metalizacja magnetytu (A. Kozłowski, jutro)

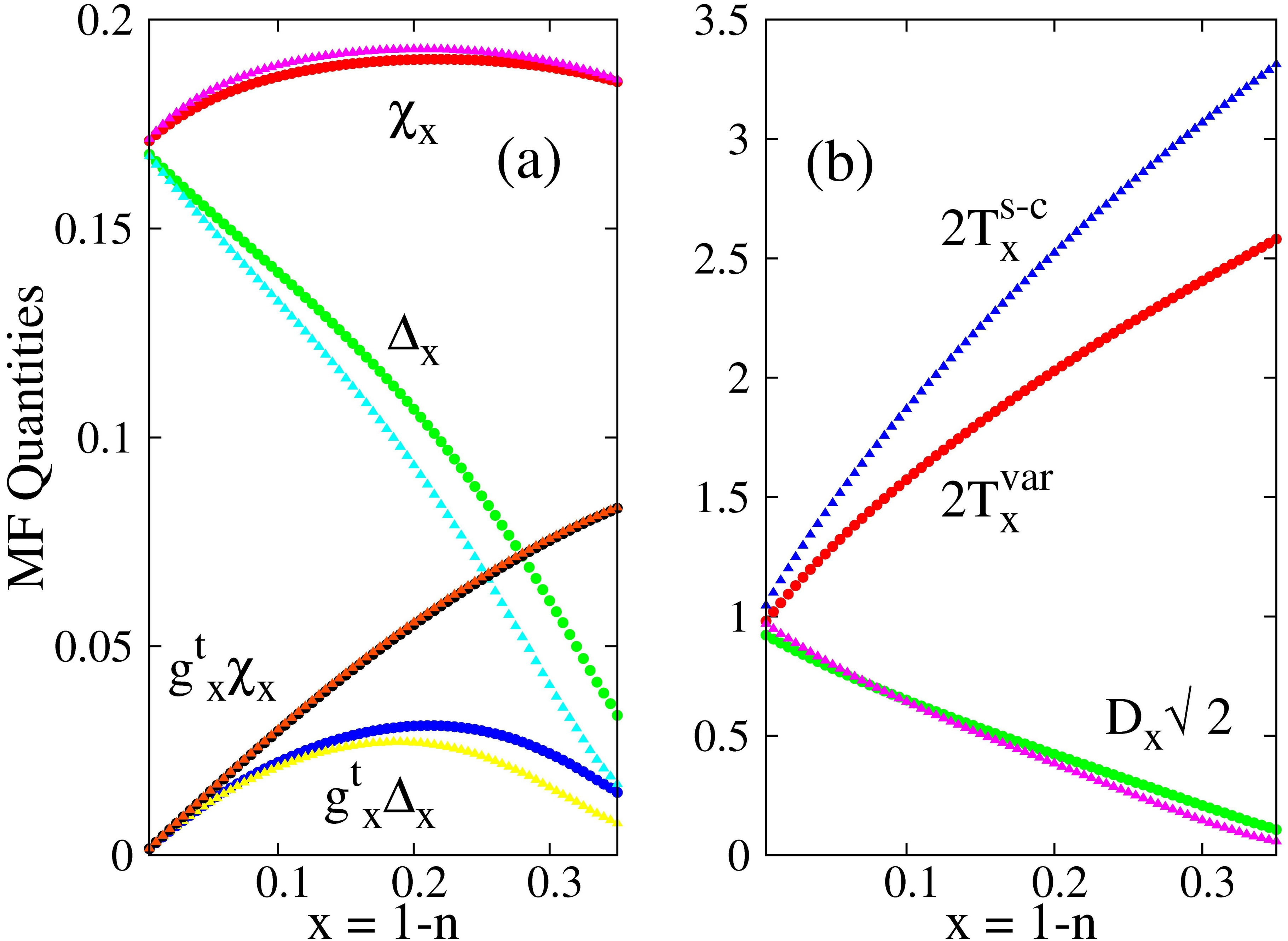
6. Uwaga metodologiczna: **wzajemne cytowanie**



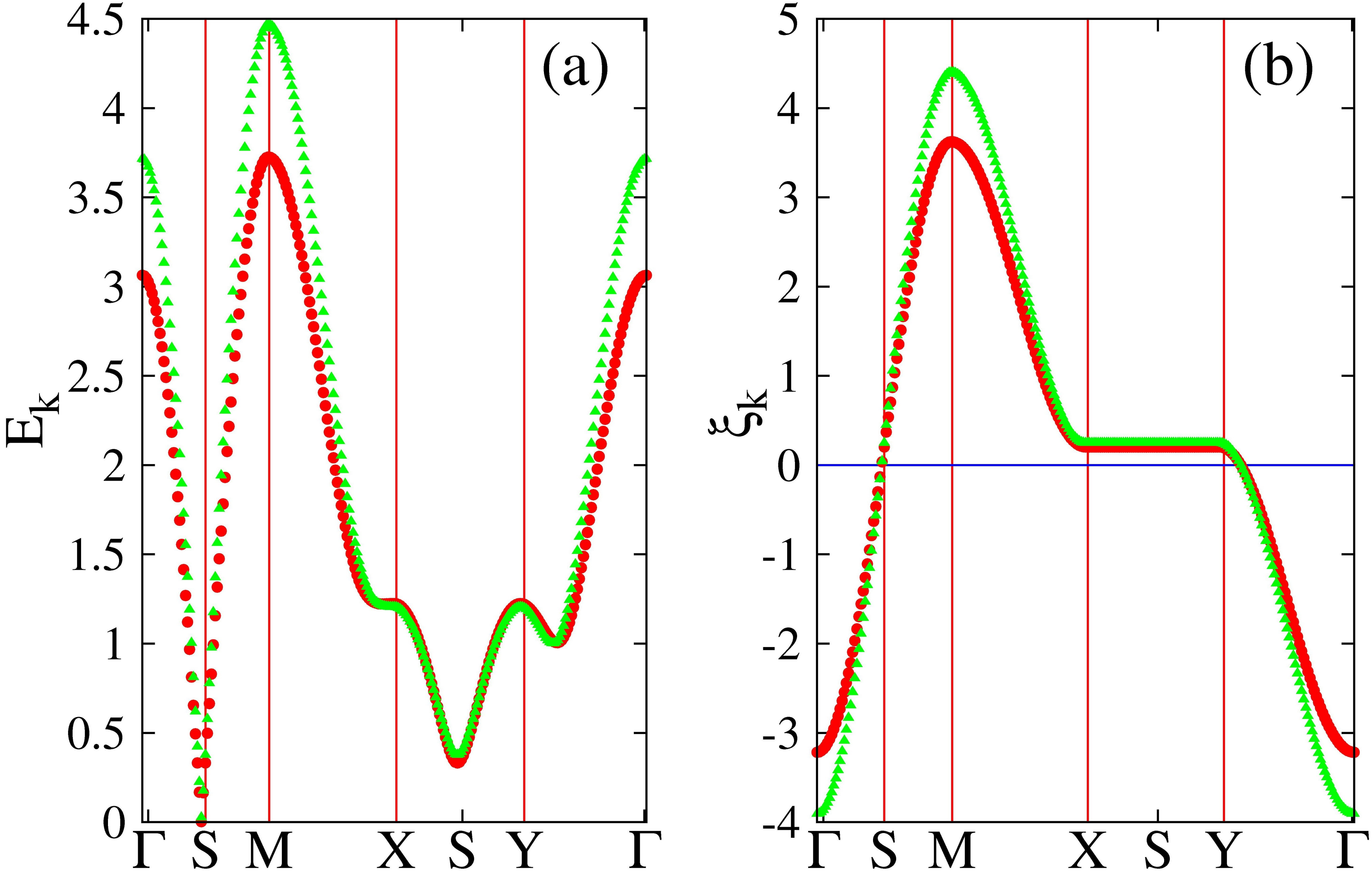
0.05
0.04
0.03
0.02
0.01
0
$g\mu_B H_{c2}/t$
FFLO
FFLO
$\Delta m=0$
$\Delta m\neq 0$
0
0.005
0.01
0.015
0.02
0.025
$k_B T_c/t$
A
B
C
0.006
0.004
0.002
0
0.003
0.004



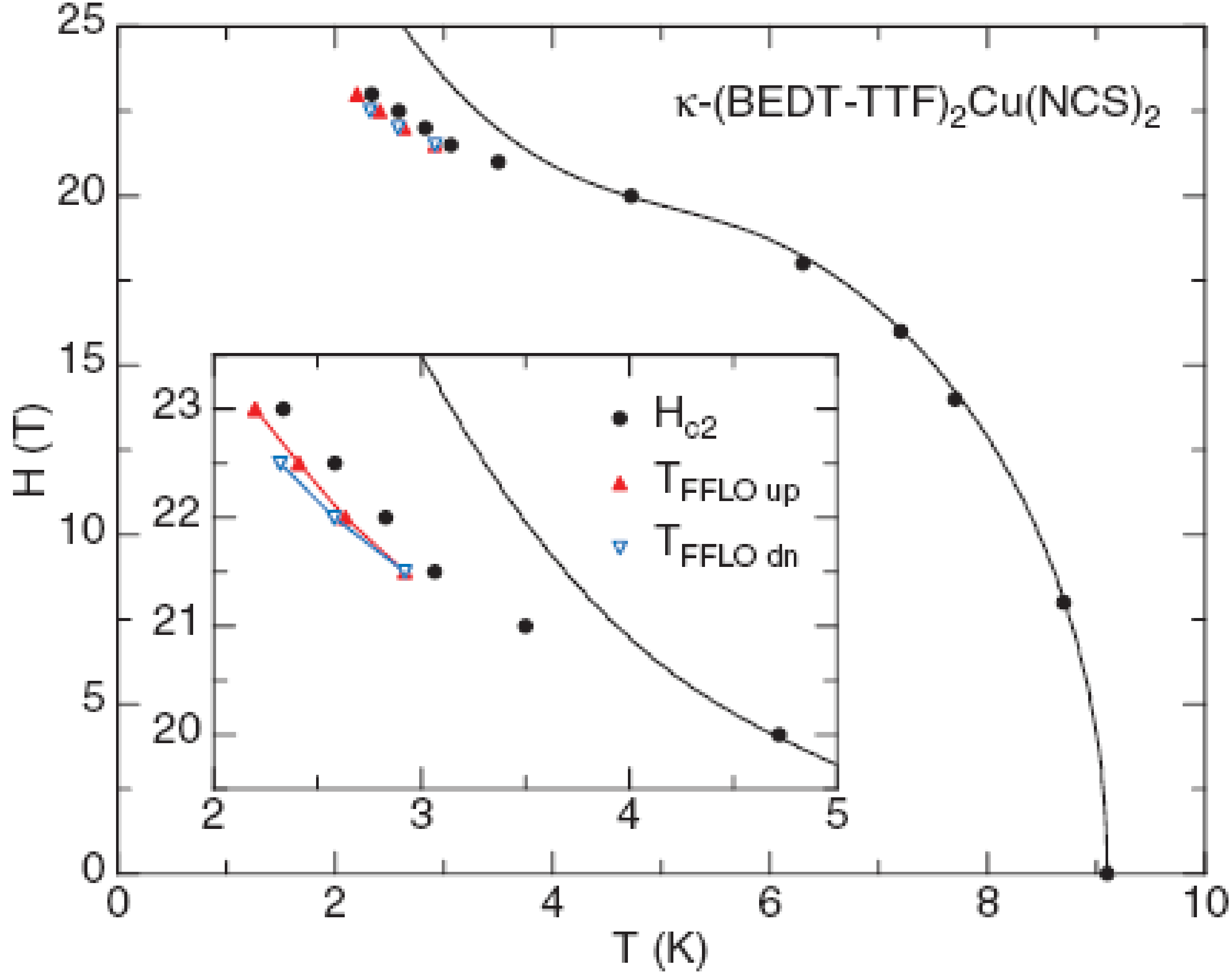
3.98
3.96
3.94
3.92
3.90
3.88
3.86
3.84
Binding energy (K)
H = 1.7 T (specific-spin)
H = 2.0 T (specific-spin)
H = 2.0 T (singlet)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cooper pair momentum (Δk_F)



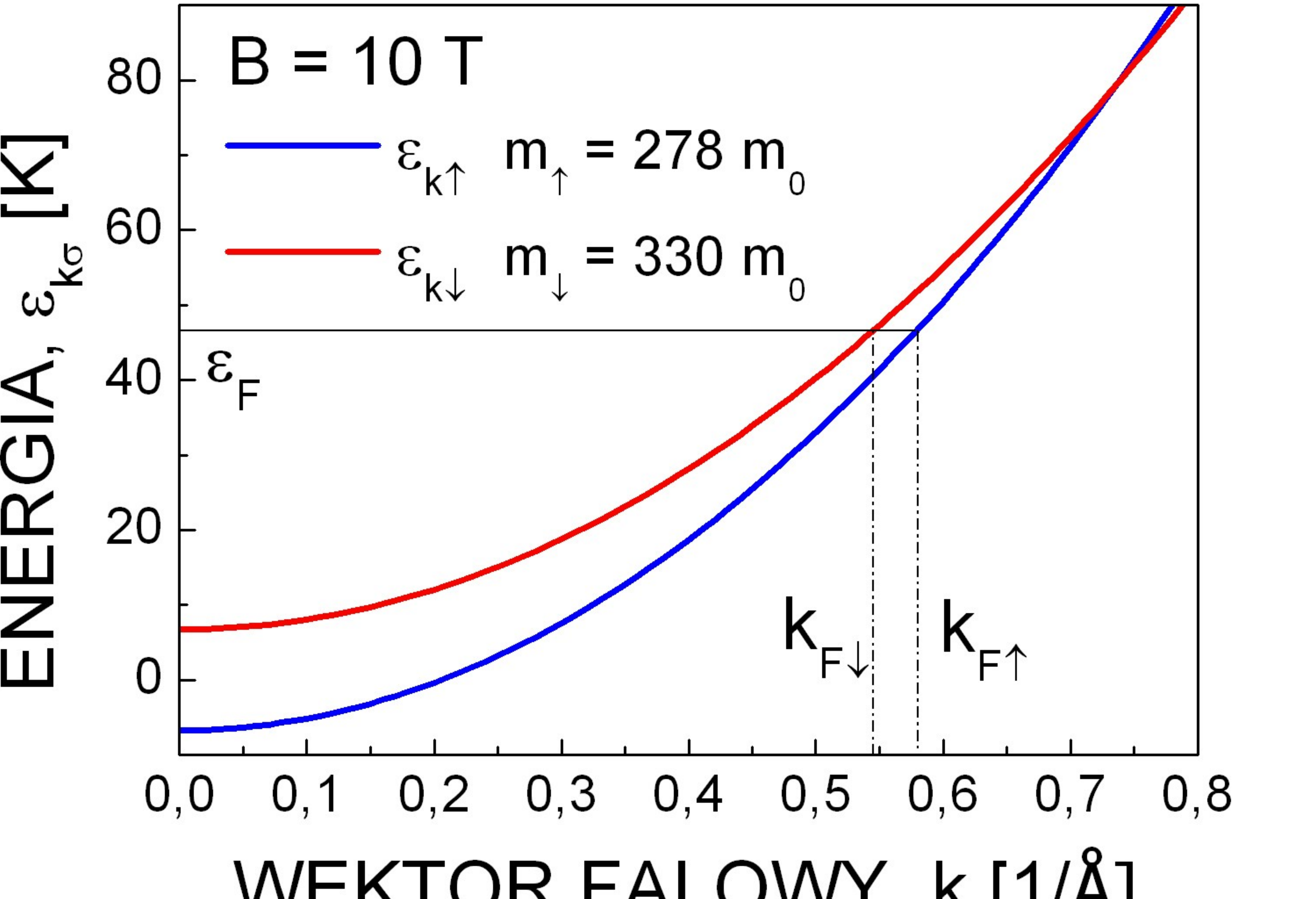
MF Quantities
0.2
0.15
0.1
0.05
0
0.1
0.2
0.3
x = 1-n
χ_x
(a)
Δ_x
$g^t_x\chi_x$
$g^t_x\Delta_x$
3.5
3
2.5
2
1.5
1
0.5
0
0.1
0.2
0.3
x = 1-n
(b)
$2T_x^{s\text{-}c}$
$2T_x^{var}$
$D_x\sqrt{2}$



(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



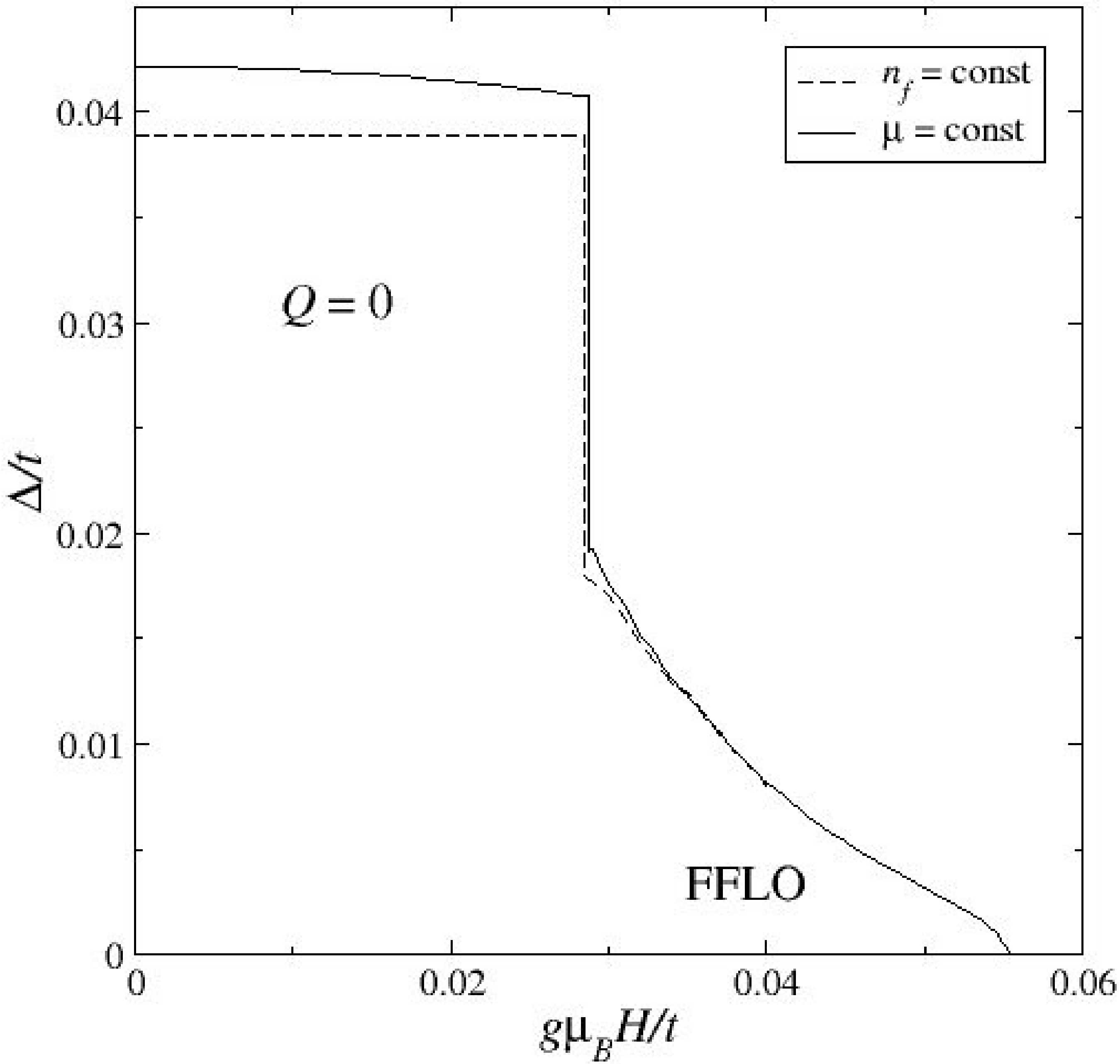
κ-(BEDT-TTF)$_2$Cu(NCS)$_2$
H (T)
T (K)
H_{c2}
$T_{FFLO\ up}$
$T_{FFLO\ dn}$
0
2
4
6
8
10
5
15
20
25
21
22
23
3


B = 10 T
$\varepsilon_{k\uparrow}$ $m_\uparrow$ = 278 m_0
$\varepsilon_{k\downarrow}$ $m_\downarrow$ = 330 m_0
ε_F
$k_{F\downarrow}$
$k_{F\uparrow}$
80
60
40
20
0
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
ENERGIA, $\varepsilon_{k\sigma}$ [K]
WEKTOR FALOWY, k [1/Å]

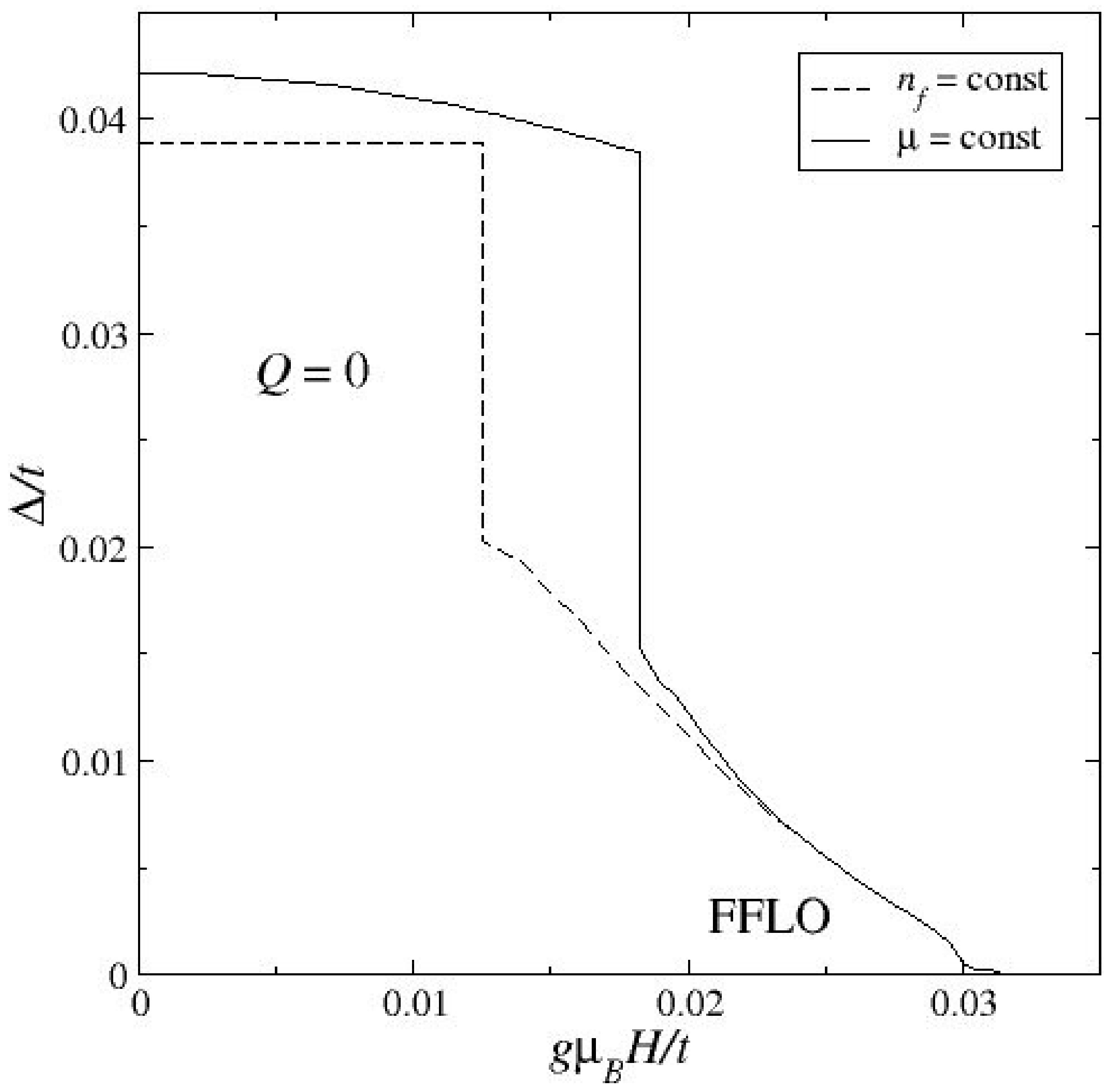
Fulde-Ferrell-Larkin-Ovchinnikov superconducting phase for paired quasiparticles with spin-dependent masses and their distinguishability

University of Silesia

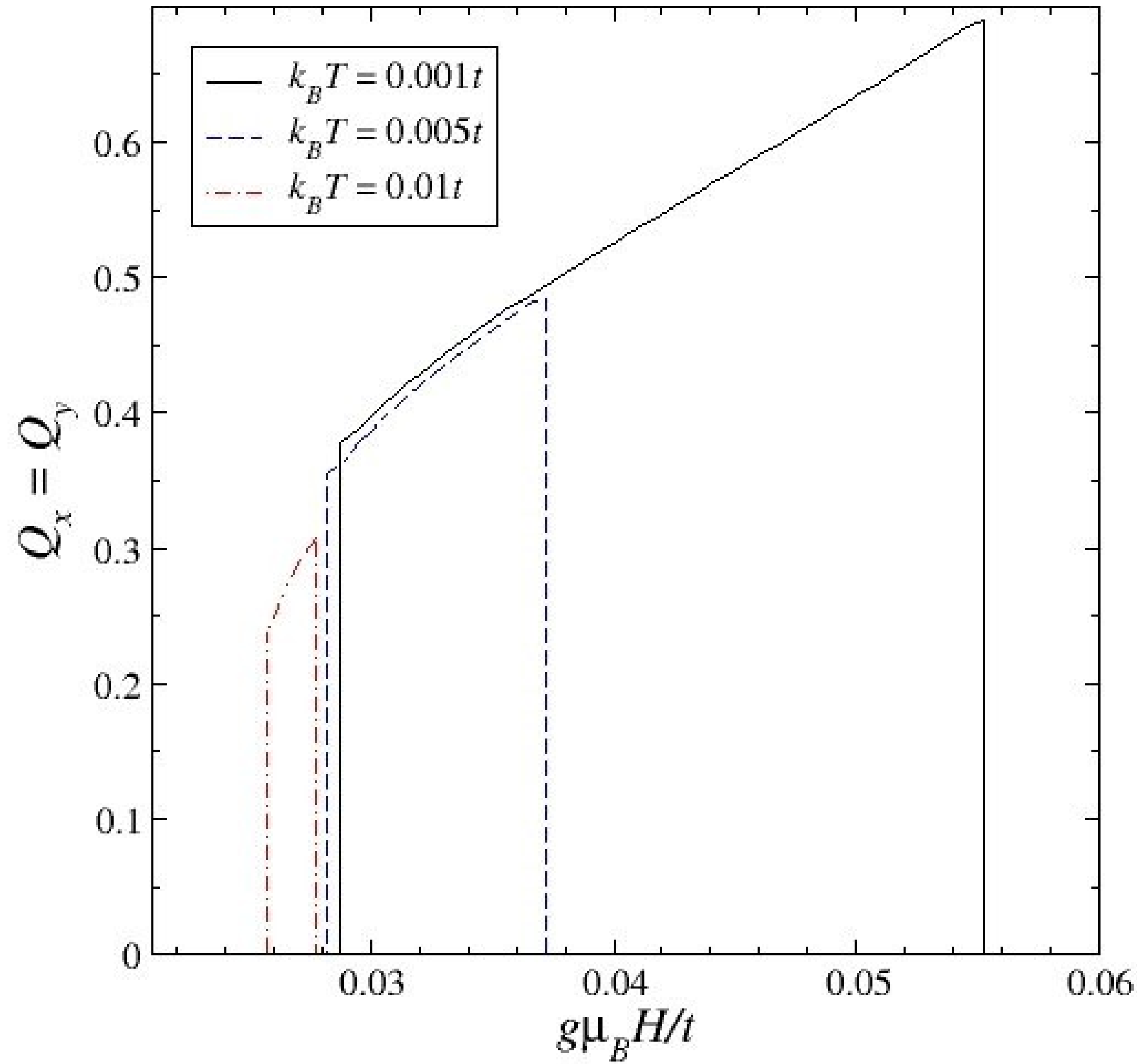
od 1364 r.



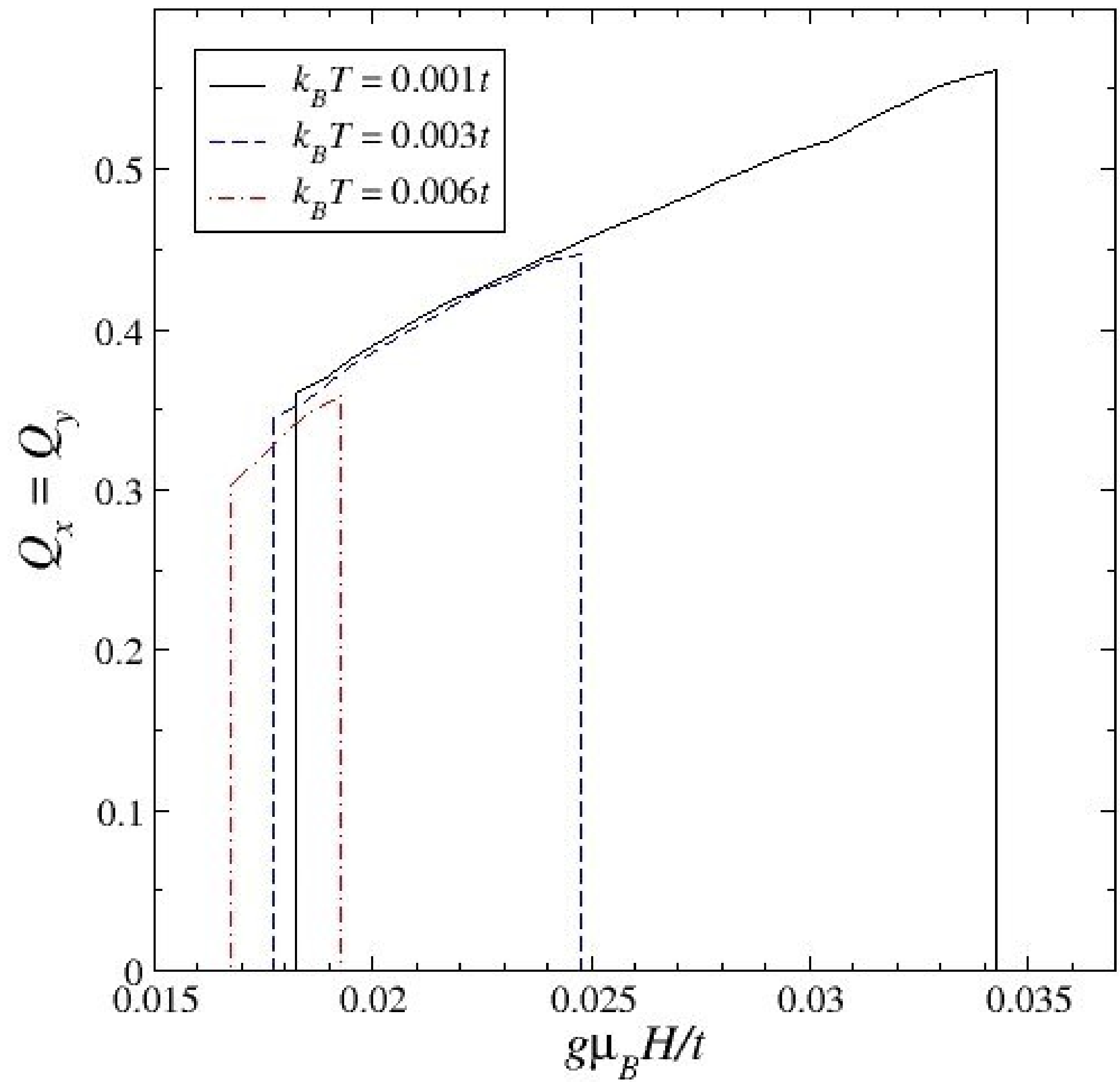
n_f = const
μ = const
$Q = 0$
FFLO
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
Δ/t
$g\mu_B H/t$



n_f = const
μ = const
0.04
0.03
0.02
0.01
0
Δ/t
Q = 0
FFLO
0
0.01
0.02
0.03
$g\mu_B H/t$



$k_B T = 0.001t$
$k_B T = 0.005t$
$k_B T = 0.01t$
0
0.1
0.2
0.3
0.4
0.5
0.6
$Q_x = Q_y$
0.03
0.04
0.05
0.06
$g\mu_B H/t$



$k_B T = 0.001t$
$k_B T = 0.003t$
$k_B T = 0.006t$
$Q_x = Q_y$
$g\mu_B H/t$
0
0.1
0.2
0.3
0.4
0.5
0.015
0.02
0.025
0.03
0.035

Unconventional superconductivity of quasiparticles with spin-dependent masses

Jan Kaczmarczyk and Jozef Spałek

Marian Smoluchowski Institute of Physics, Jagiellonian University, ul. Reymonta 4, 30-059 Kraków, Poland
Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, ul. Reymonta 19, 30-059 Kraków, Poland