Ginzburg Conference on Physics

May 28 - June 2, 2012

Lebedev Institute / Moscow

Ferromagnetic spin droplets in 2D strongly correlated electron system

Experiment:

Alex Kuntsevich (LPI)
Michael Reznikov (ISSP, Haifa)
Nimrod Teneh (ISSP, Haifa)
Vladimir Pudalov (LPI)

Theory:

Igor Burmistrov - Landau ITP

Физический институт имени П.Н.Лебедева
ФИАН

ИТФ им. Л.Д.Ландау

Ginzburg' List of Outstanding Problems in Physics and Astrophysics

#4 Two dimensional electron systems,
#5 Metal-insulator transitions, etc

Motivation

- Ground state of the 2D electron system in the presence of interactions and disorder. Particularly, spin arrangement
- Experimental observation of a strong growth in spin susceptibility with r_s ($F_0^\sigma \to -1$). Stoner instability ?
- Lack of observation of any $\chi(T)$ -dependence

Possible ground sates:

- Liquid(=metal)
  - Paramagnetic Fermi-liquid
  - Non-Fermi liquid
  - FM liquid
- Superfluid
- Solid (=Insulator)
  - Wigner crystal (AFM),
  - SDW, CDW,
  - Mott insulator (AFM)
  - Individual strongly localized states (AFM)

Non-uniform states:

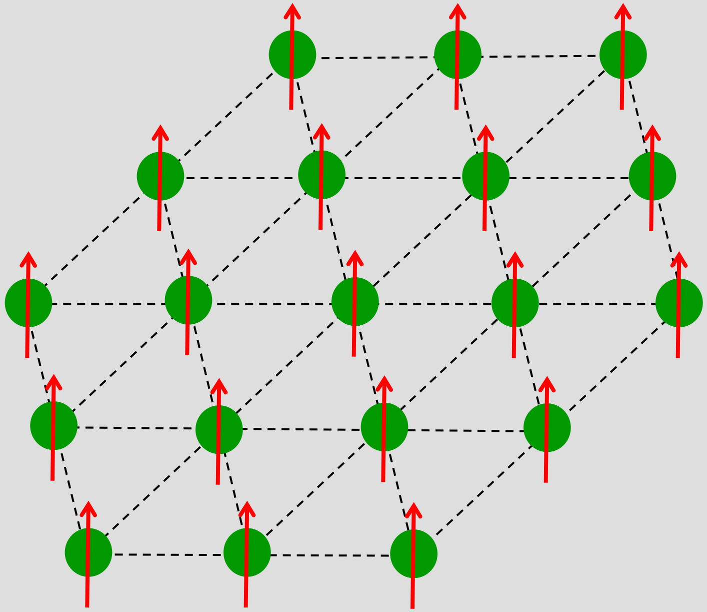
WC bubbles + electron liquid

Nematic phases, etc

Clean Very low density system:

Wigner Crystal

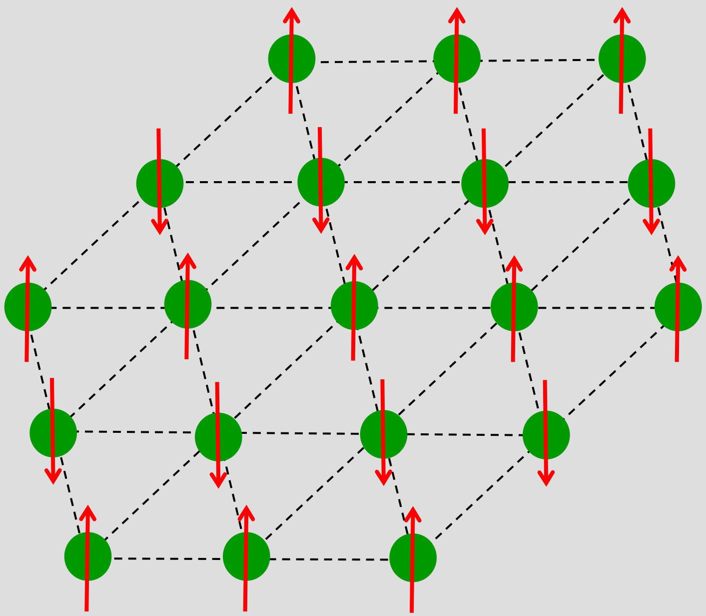
r_s~37 B. Tanatar and D.C. Ceperley (1989)



ferromagnetic

Clean Very low density system:

Wigner Crystal



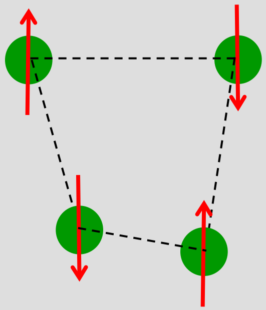
ferromagnetic

↕

antiferromagnetic

Very small
energy difference!

Dirty System:



S=0

Antiferromagnetic coupling: Bhatt and Lee (1982)

Strong growth in $\chi^* \propto m^*g^*$ with density lowering (growth of r_s)

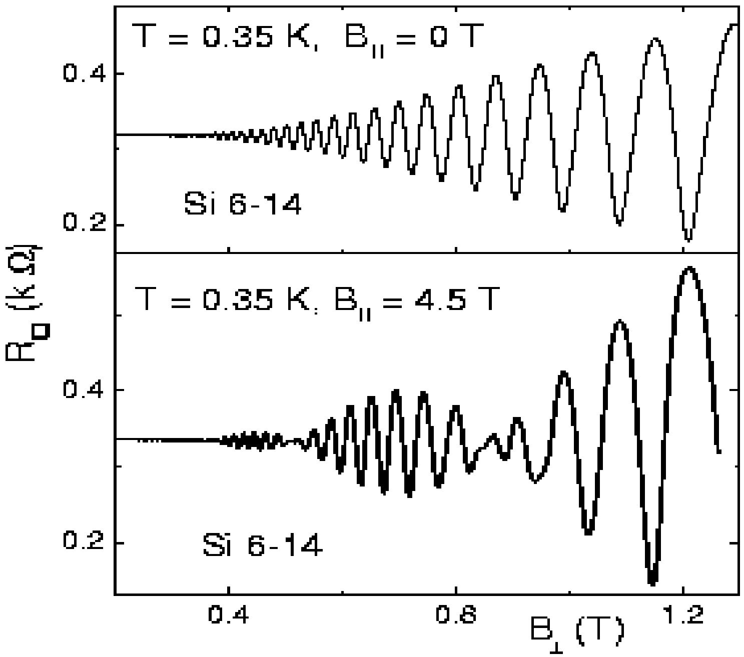
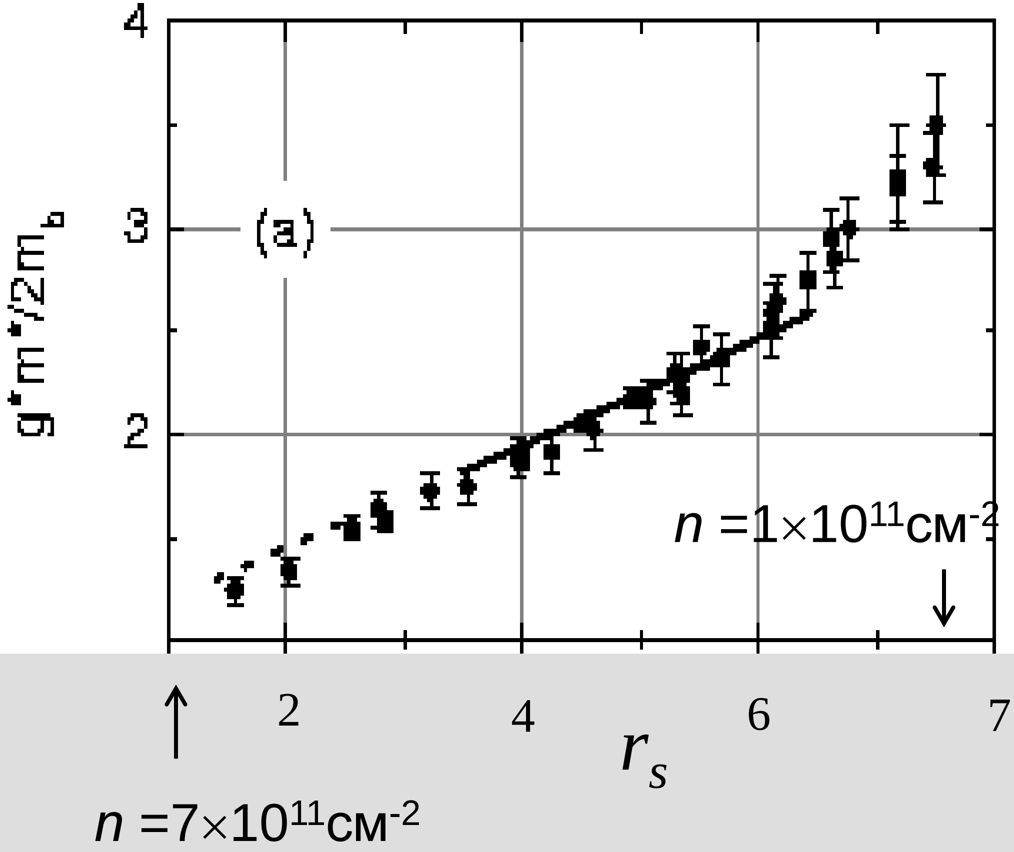


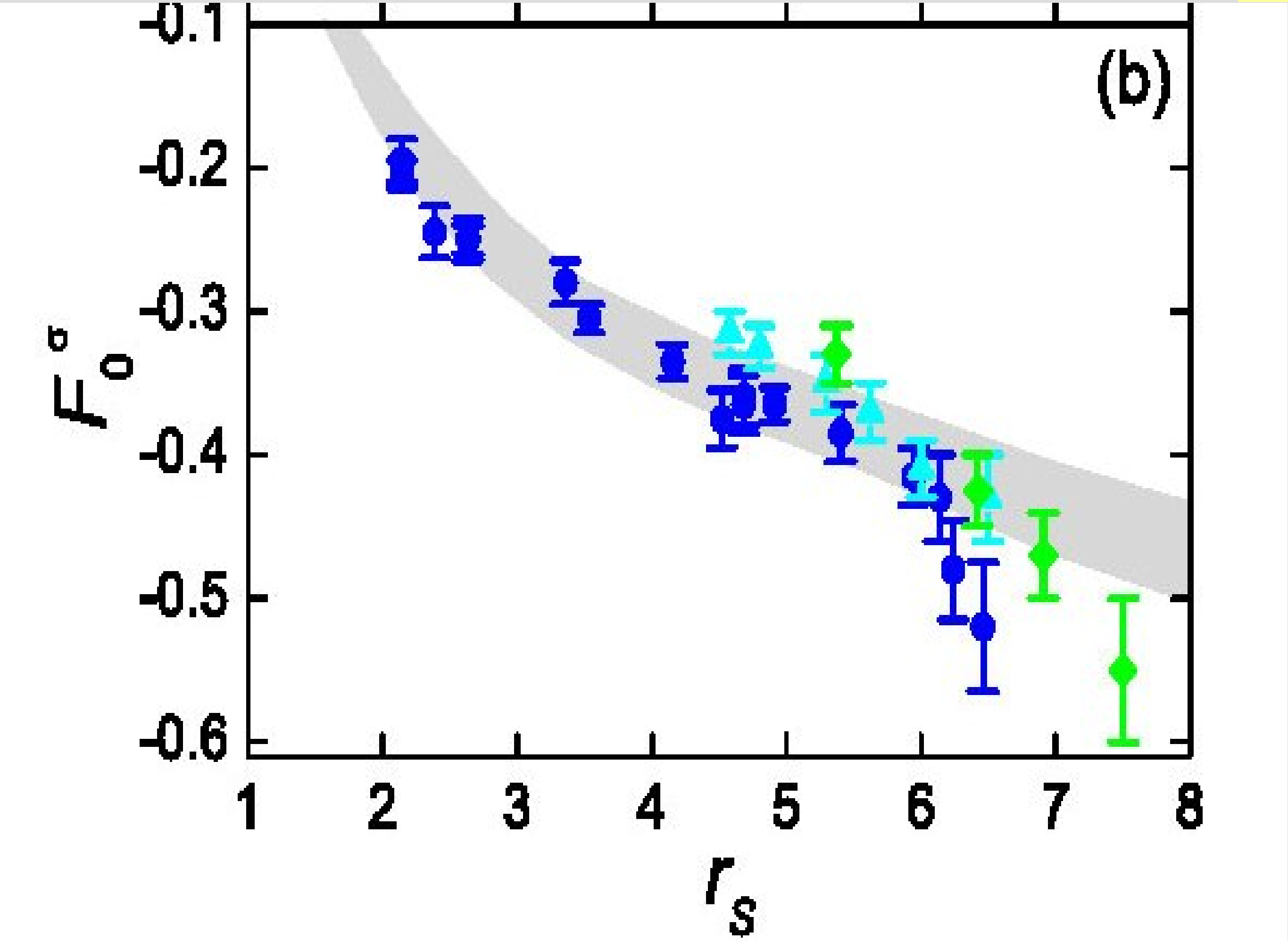
FIG. 1. Shubnikov–de Haas oscillations for $n = 10.6 \times 10^{11}\,\mathrm{cm}^{-2}$: (a) $B_{\parallel} = 0$ and (b) $B_{\parallel} = 4.5$ T.



V.M.Pudalov, M.E.Gershenson, H.Kojima, *Phys.Rev.Lett.* **88**, 196404 (2002)

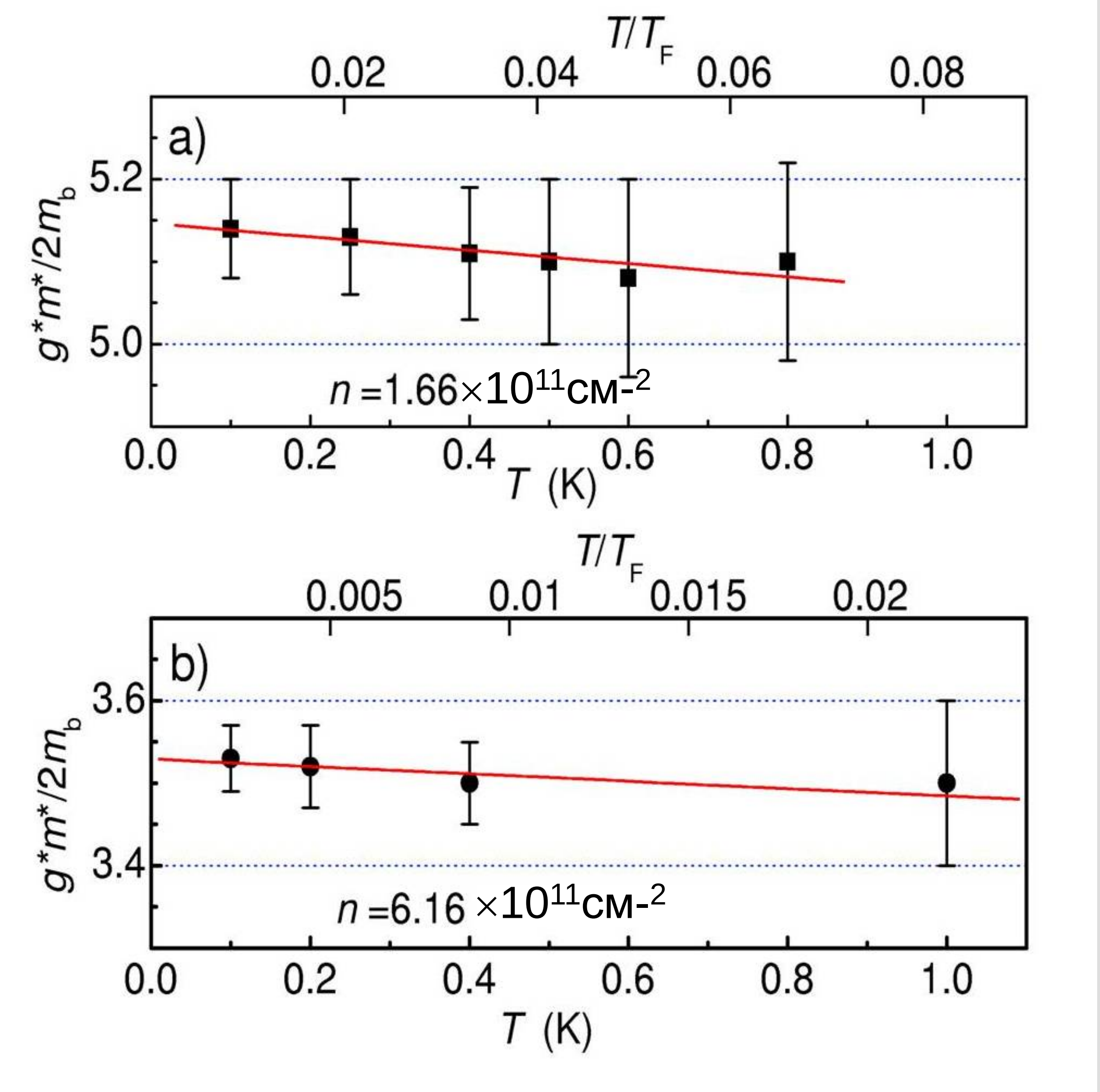
Strong growth of F_0^a with lowering n (increase of r_s)

$$g^* = \frac{g_b}{1 + F_0^\sigma}$$



N.N. Klimov, D.A. Knyazev, O.E. Omel'yanovskii, V.M. Pudalov, H.Kojima, M.E. Gershenson, PRB 78, 195308 (2008)

The absence of *T*-dependence of $\chi^* \propto g^* m^*$, measured from SdH oscillations



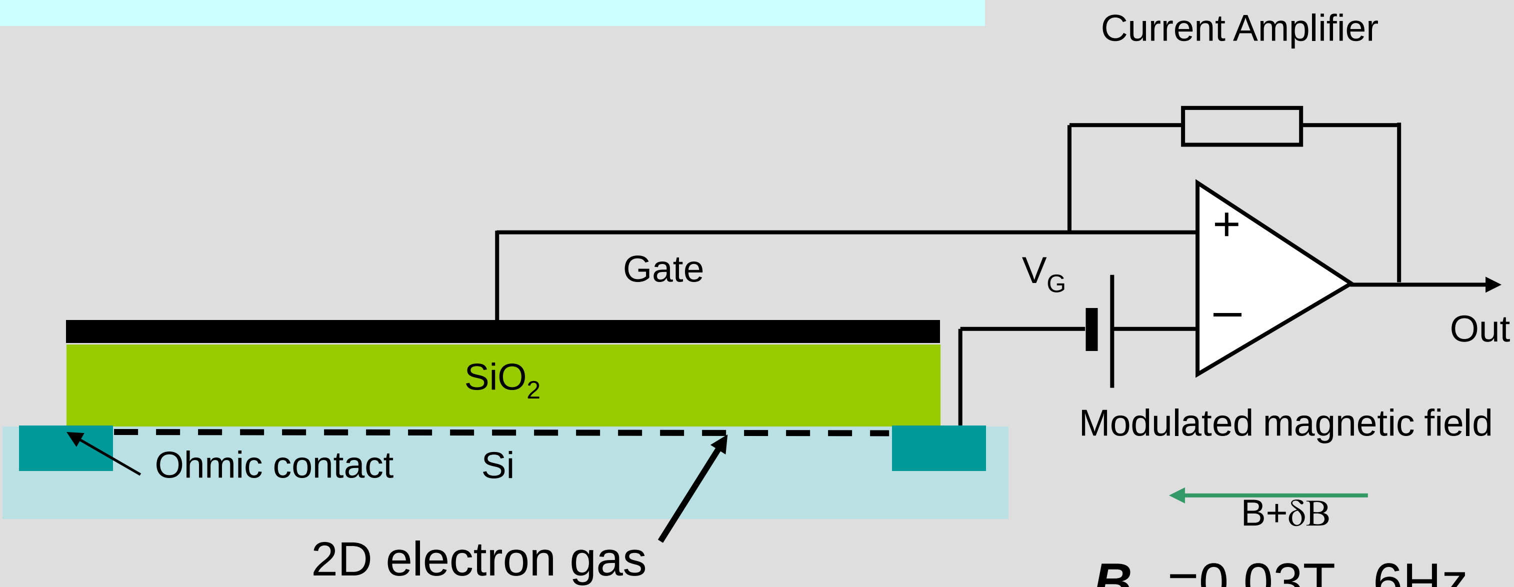
Experimental Task:

to measure the thermodynamic spin magnetization of electrons in 2D system in Si with a total number of spins 10^8 - 10^9, in weak fields ($B_{||}<T$)

Samples – Si-MOSFET structures, μ^{peak}=1-3 m^2/Vs

Density range – (10^9 – 10^{12})/$см^2$

Experimental setup



$\boldsymbol{B}_{\sim}$ =0.03T, 6Hz

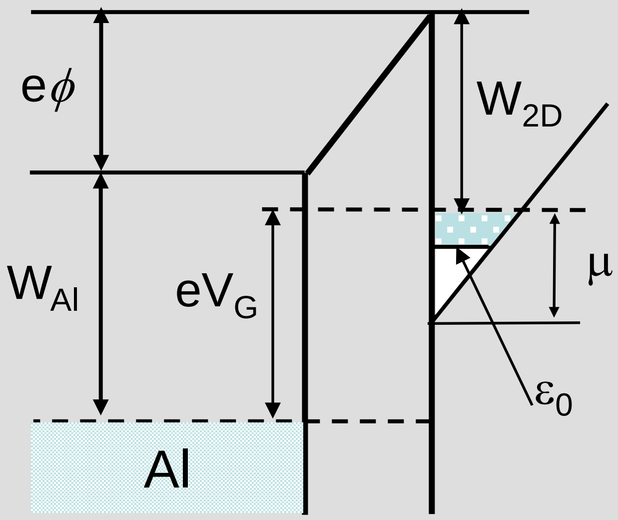
Advantages

- Measures thermodynamic magnetization
- Accessibility of the "Insulating phase"
- Low-field measurements

Disadvantages

- Measures $\partial M / \partial n$, which is unknown at small *n*;
- Requires assumptions for the integration to reconstruct $\boldsymbol{M}$

Principle of the Measurements



$$U = \Delta\varphi + \Delta\mu / e$$

$$\Delta\tilde{\varphi} = -\Delta\tilde{\mu} / e = -\frac{\partial\mu}{\partial B}\frac{\Delta B\cos(\omega t)}{e}$$

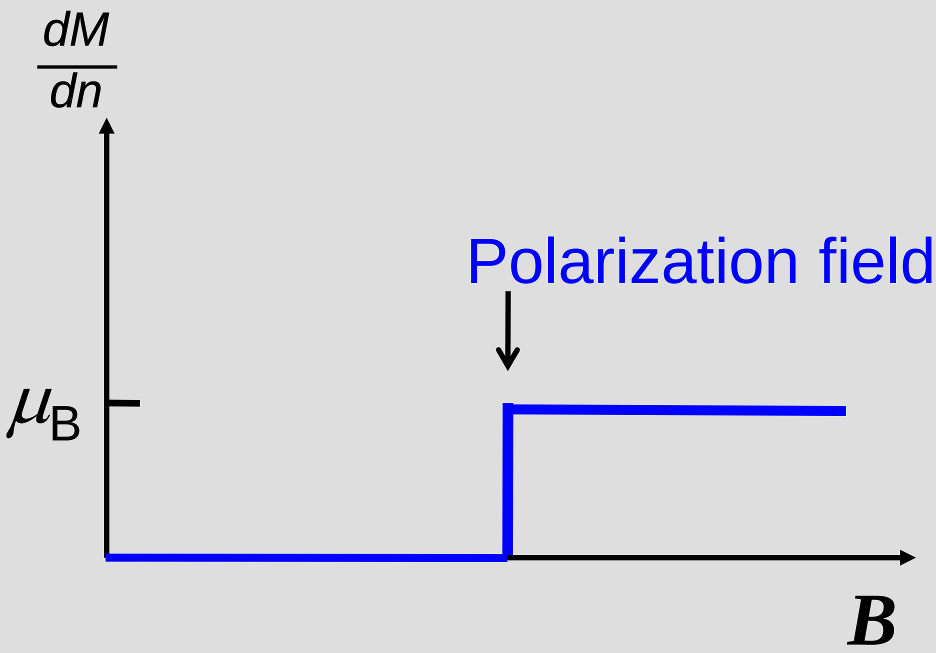
$$\tilde{I} = \frac{\partial\mu}{\partial B}\frac{\Delta B\omega C\sin(\omega t)}{e}$$

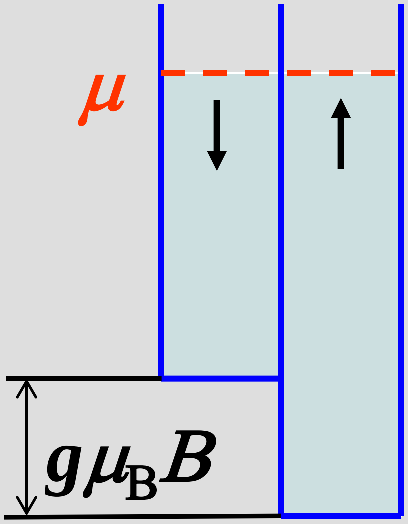
$$\left.\frac{\partial\mu}{\partial B}\right|_n = -\left.\frac{\partial M}{\partial n}\right|_B$$

$$f(n, B) \text{ - free energy}$$

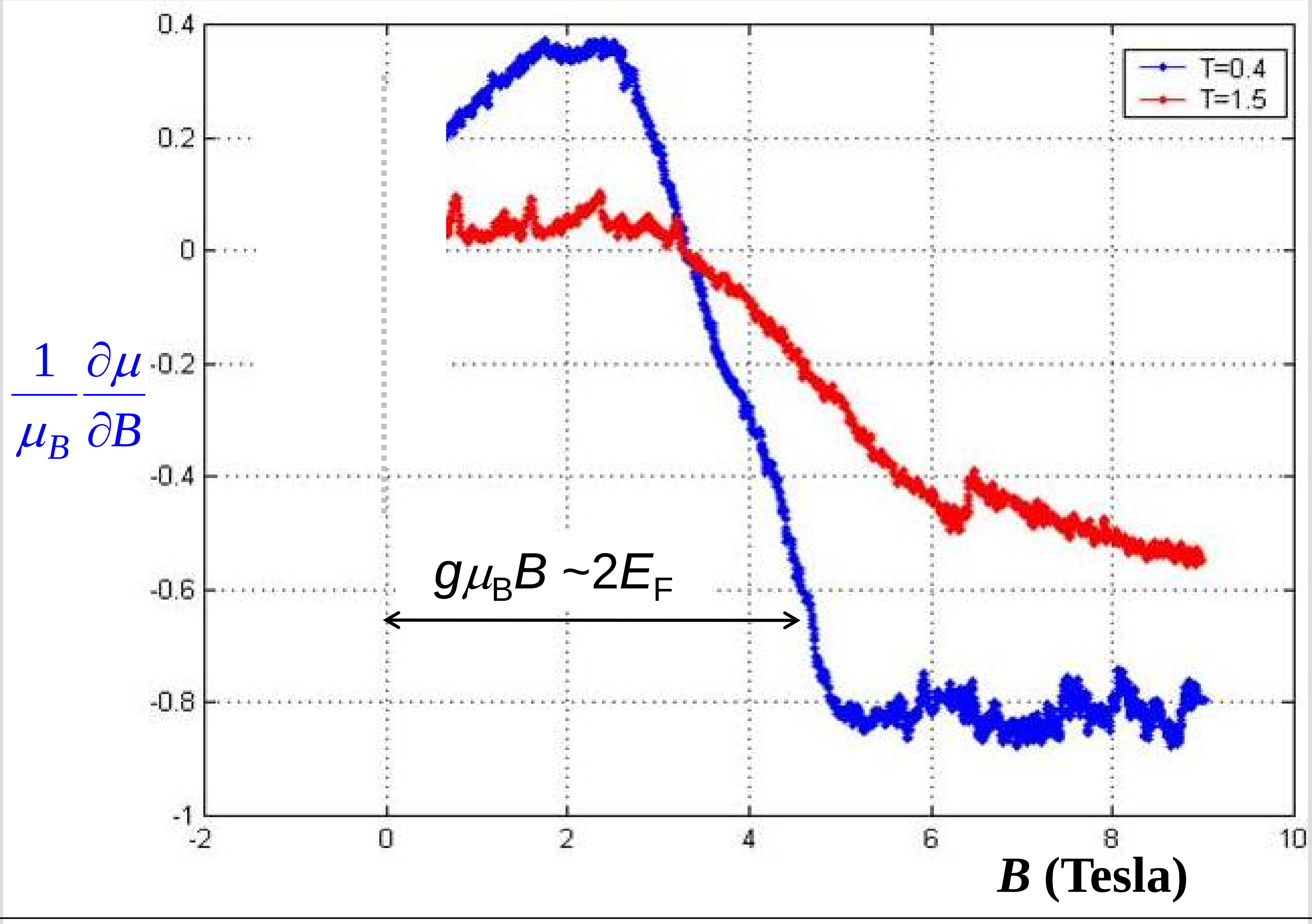
Maxwell relation: $\mu = \frac{\partial f}{\partial n}, \quad \mathrm{m} = -\frac{\partial f}{\partial B} \quad \Rightarrow \quad \frac{\partial\mu}{\partial \mathrm{B}} = -\frac{\partial m}{\partial n}$

dM/dn, expectations for the degenerate Fermi-gas (no interactions)



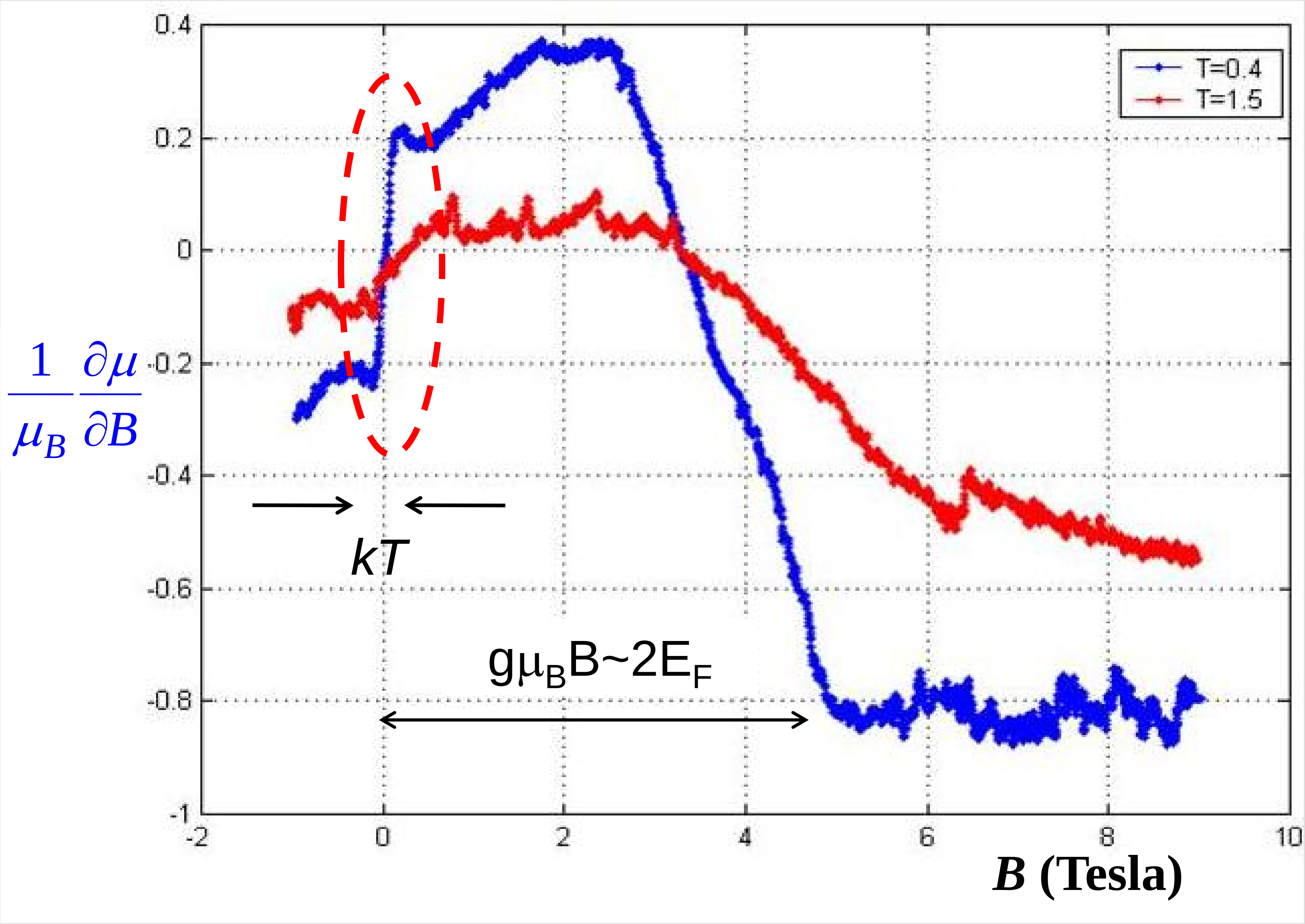


Earlier measurements. n = 1.5 10^{11} cm^{-2}



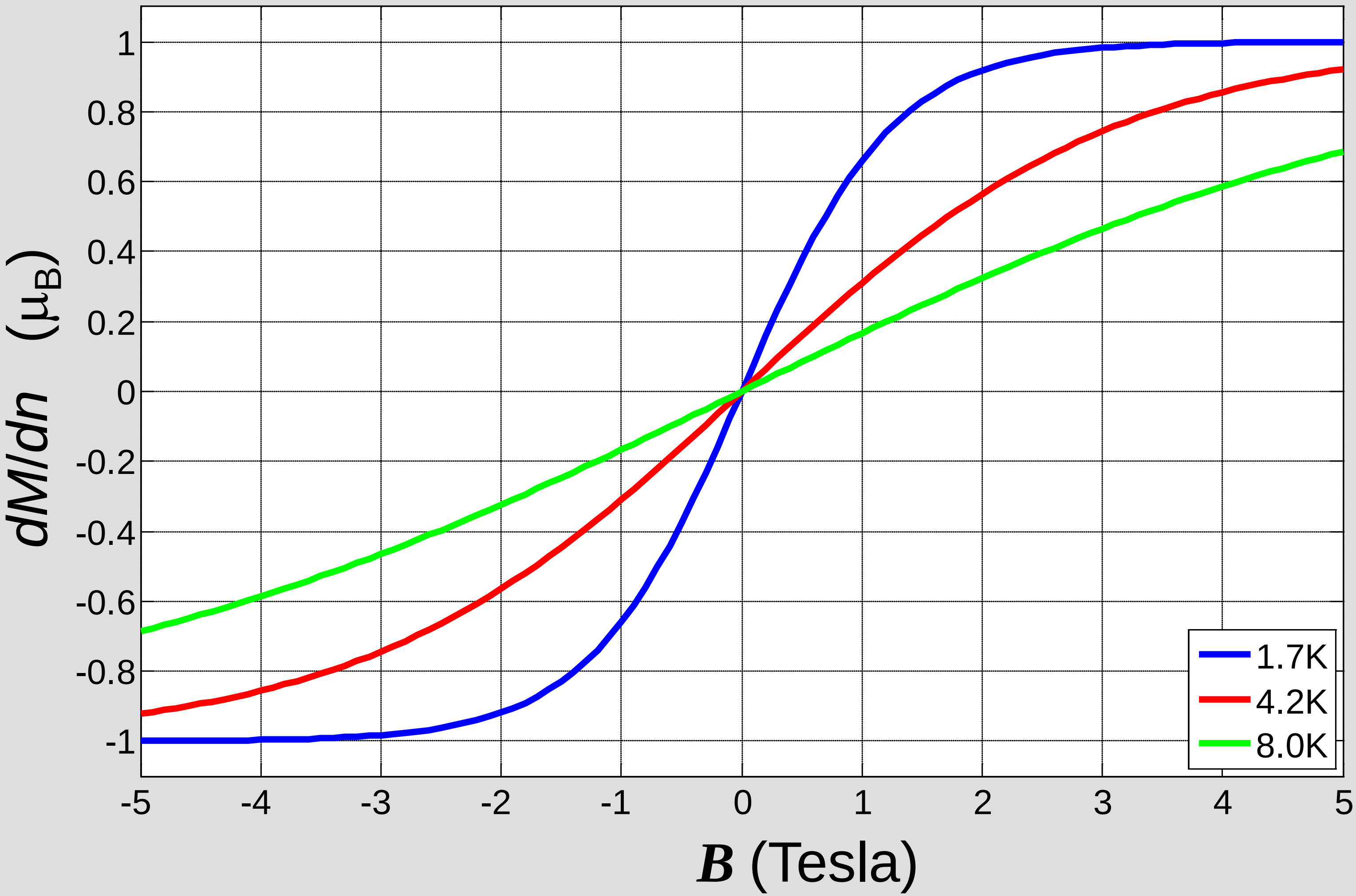
O.Prus, Y.Yaish, M.Reznikov, U.Sivan, V.Pudalov, PRB, 67, 205407 (2003)

New measurements: *B<T*, *n*= 1.5 10^{11} cm^{-2}

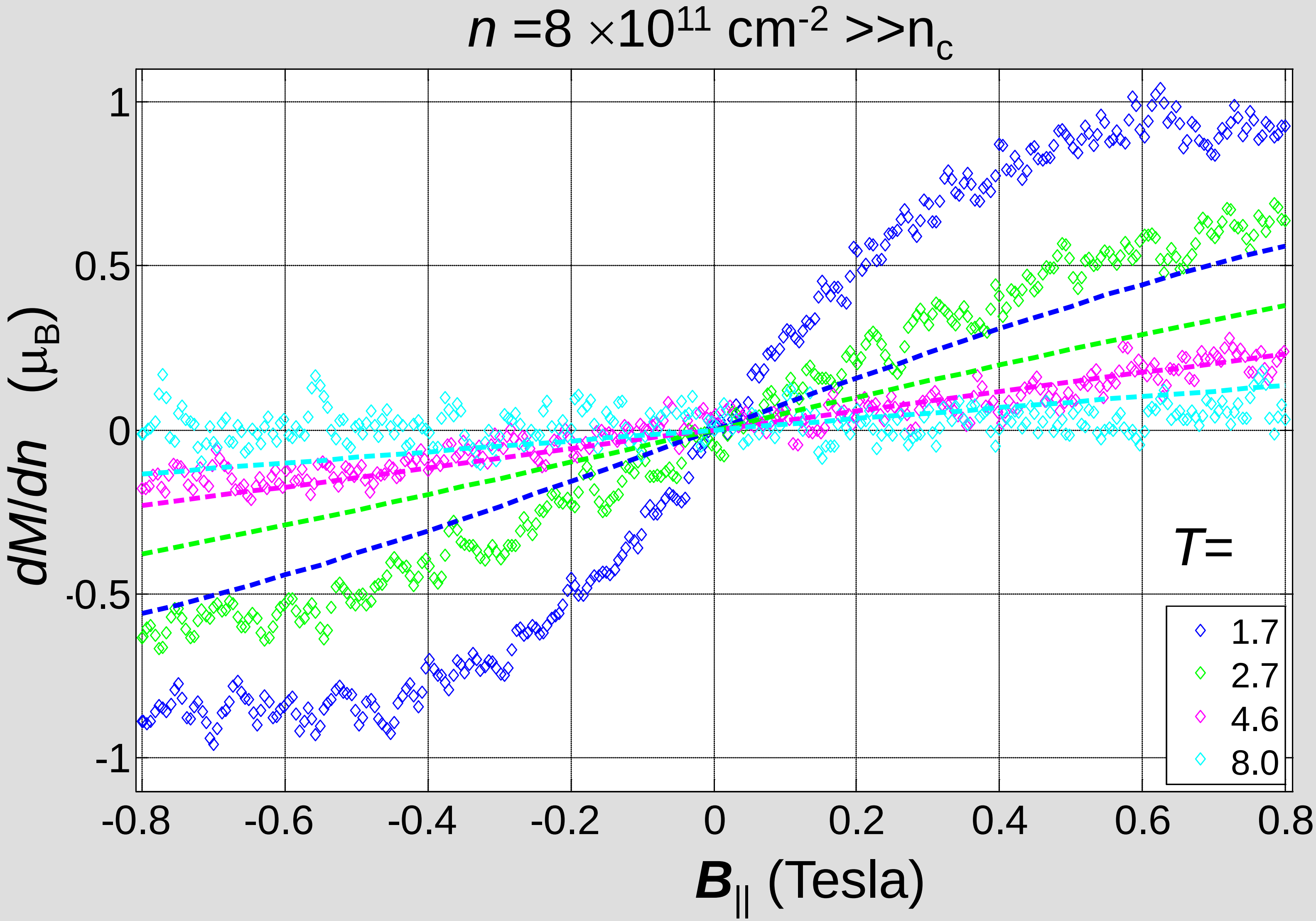


dM/dn, expectations for a single spin

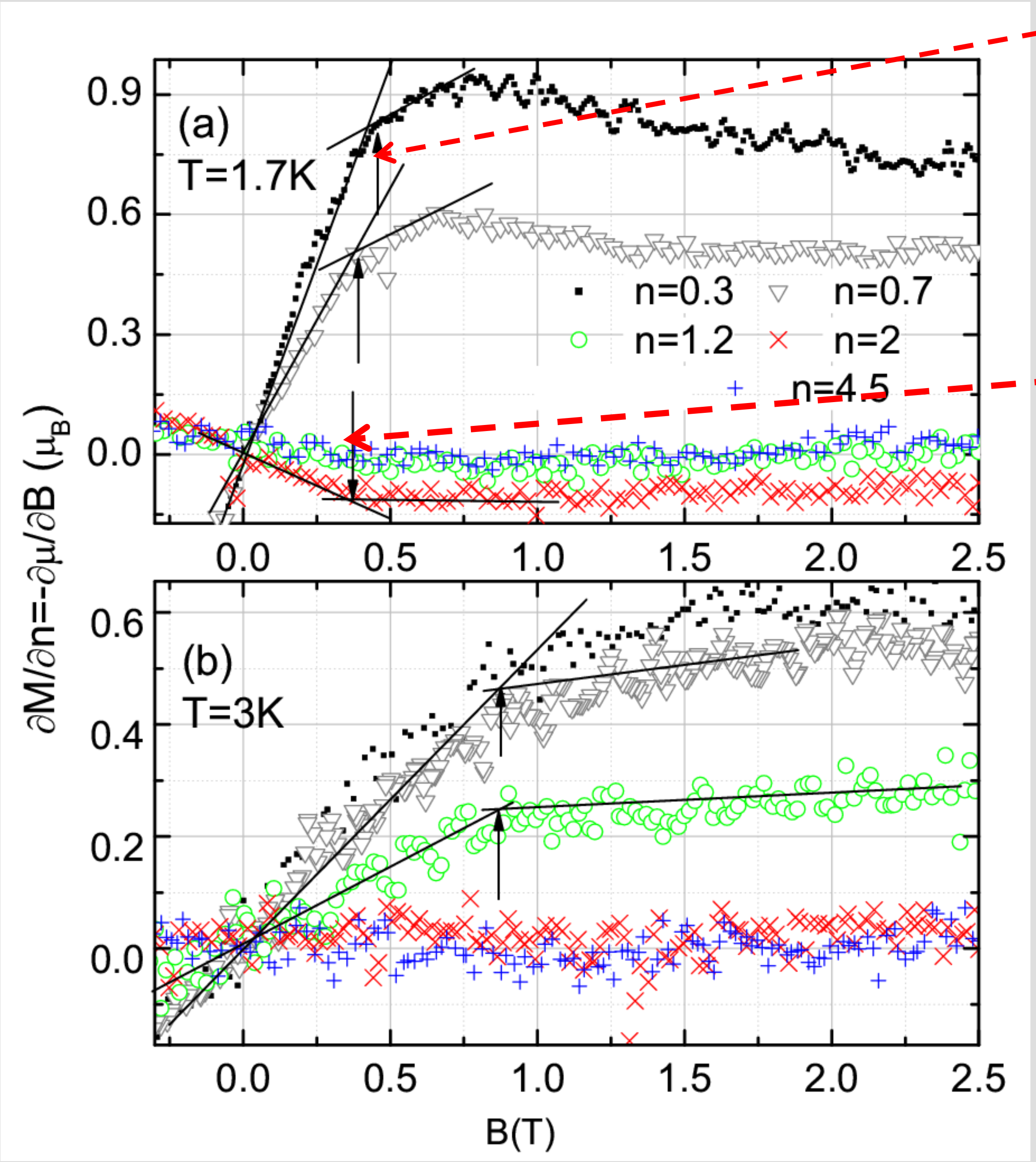
$$M = n\mu_B \tanh\left(\frac{\mu_B B}{k_B T}\right) \quad \Rightarrow \quad \frac{dM}{dn} = \mu_B \tanh\left(\frac{\mu_B B}{k_B T}\right)$$



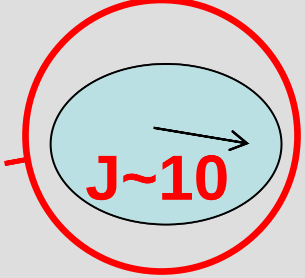
Raw data, low fields



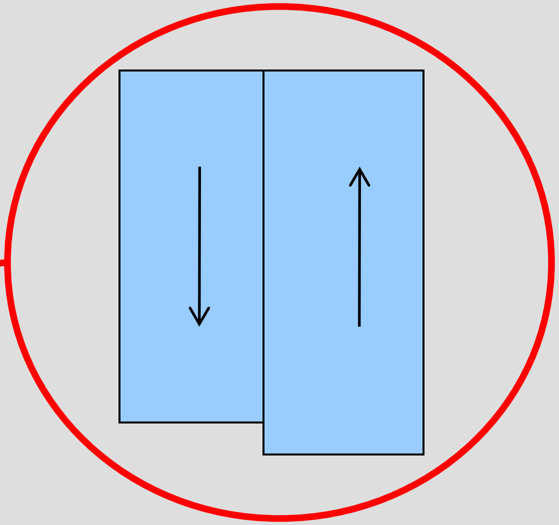
Raw data



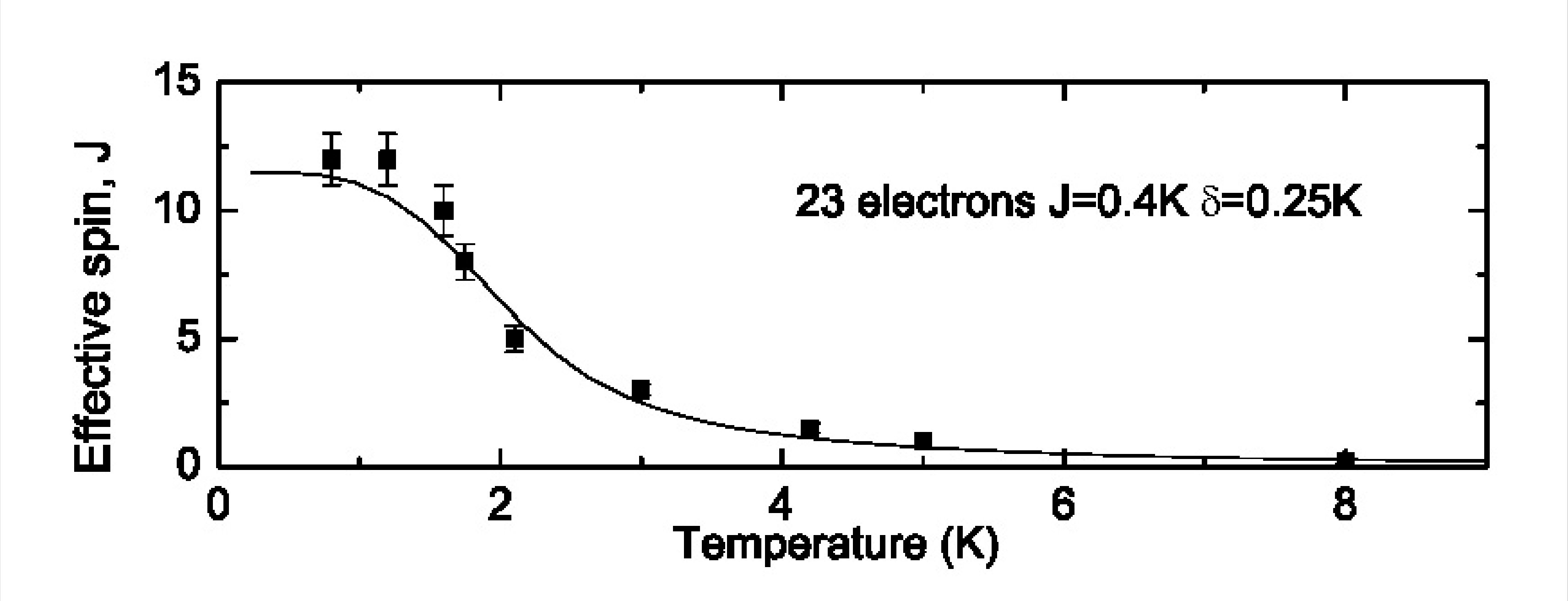
(a)
T=1.7K
0.9
0.6
0.3
0.0
n=0.3
n=0.7
n=1.2
n=2
n=4.5
(b)
T=3K
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
∂M/∂n=-∂μ/∂B (μ_B)
B(T)



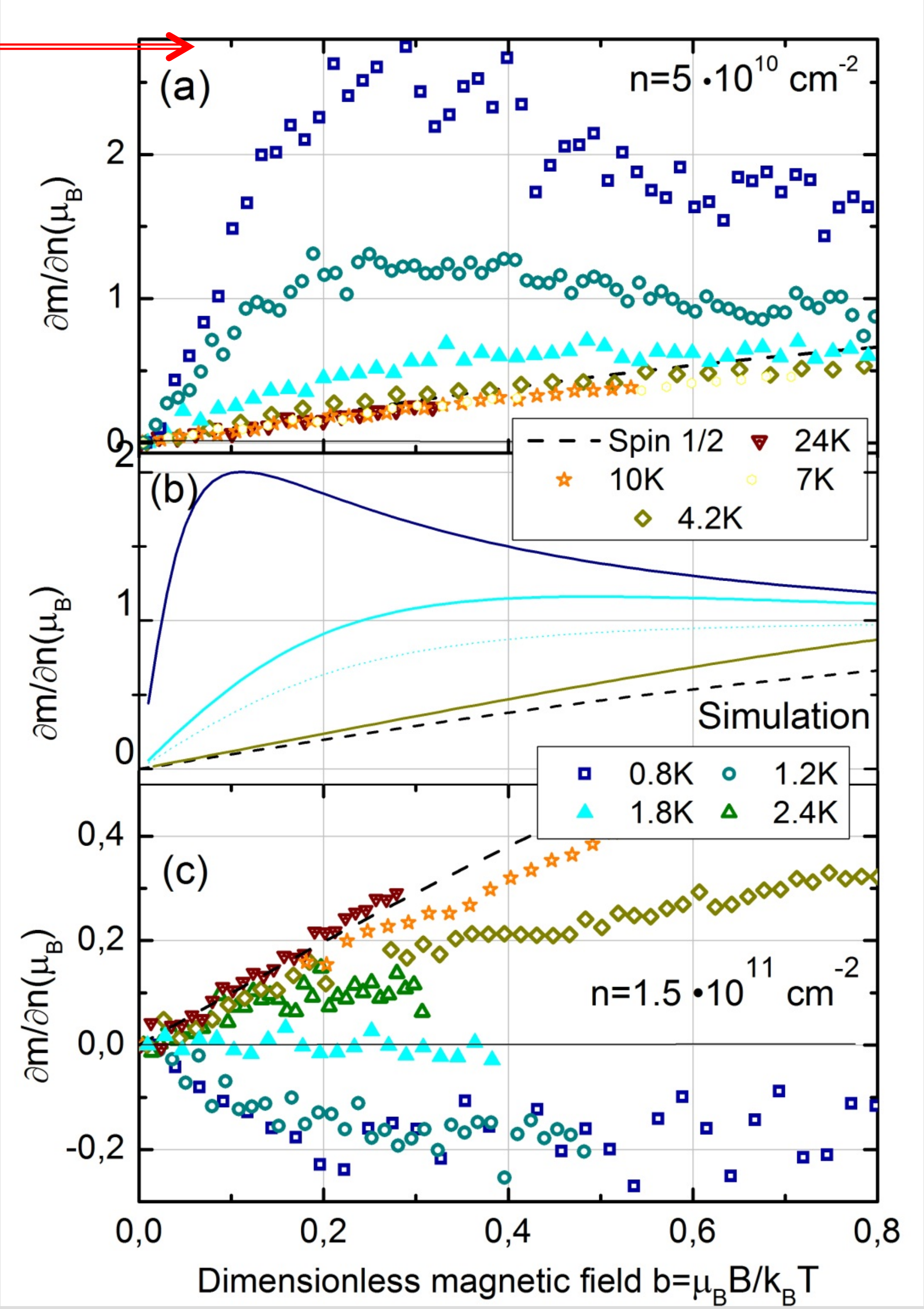
J~10



Total effective spin: fitting of the experiment with a theory

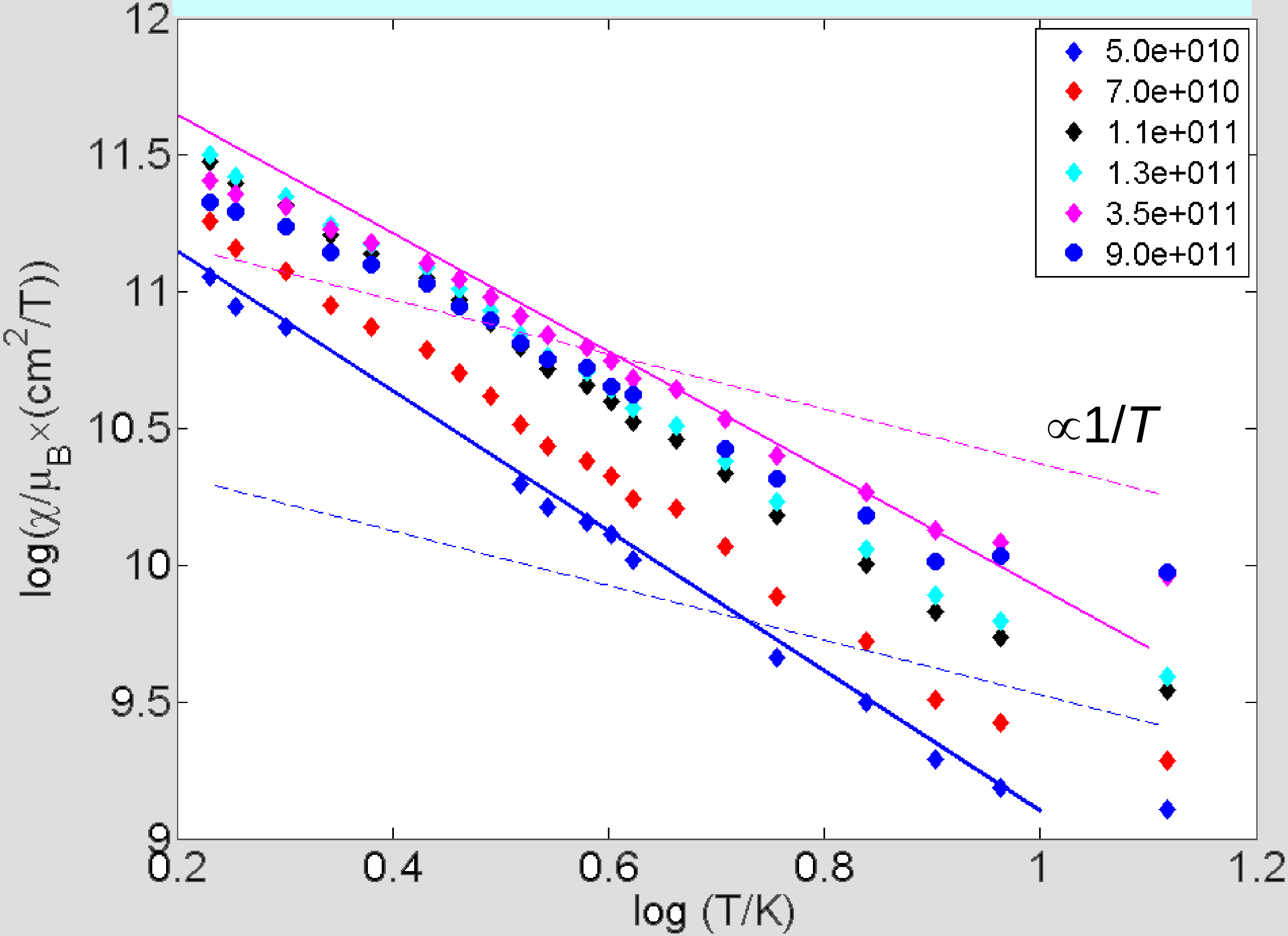


$dM/dn > \mu_B$

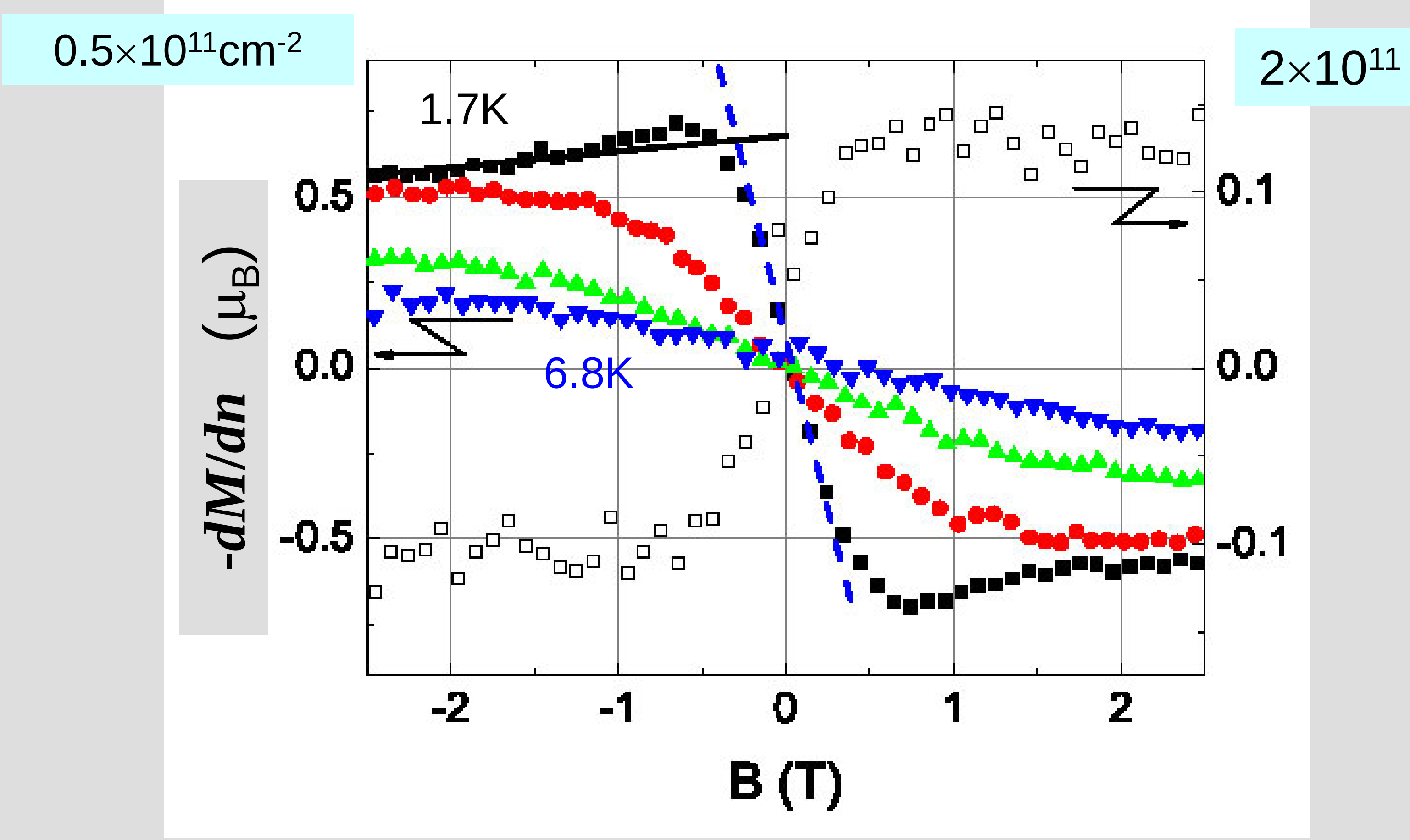


(a)
n=5 •10^10 cm^-2
∂m/∂n(μB)
Spin 1/2
24K
10K
7K
4.2K
(b)
Simulation
0.8K
1.2K
1.8K
2.4K
(c)
n=1.5 •10^11 cm^-2
Dimensionless magnetic field b=μBB/kBT

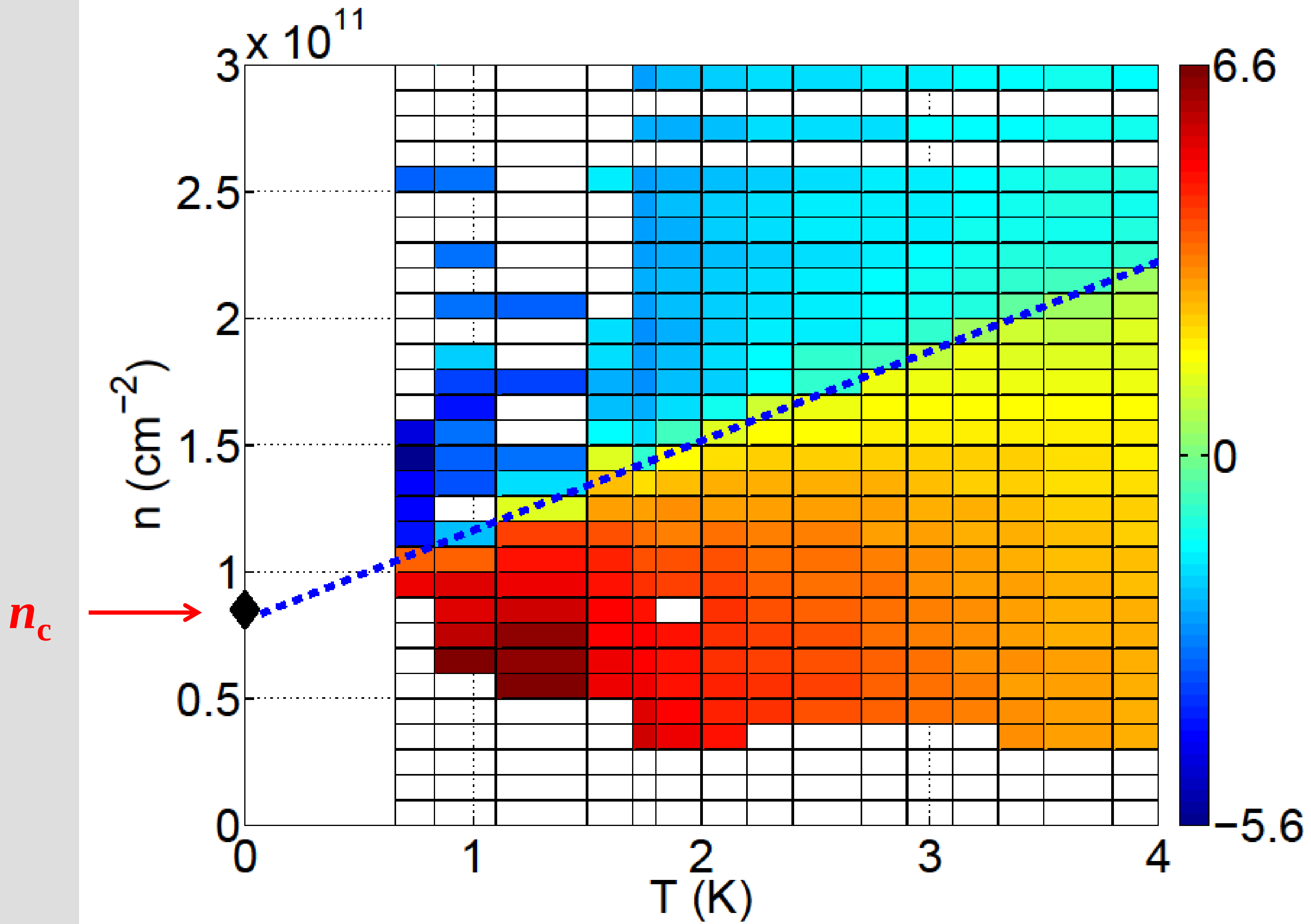
Susceptibility vs temperature



Sign change of *dM/dn*



Sign change of *dM/dn*



Conclusions

- In the Insulating state of the correlated 2D electron system: spontaneous formation of the “nanomagnets” - **spin droplets** with a large spin $\boldsymbol{S}$=2.

- The low field spin susceptibility is strongly temperature dependent ($\mathbf{1/\boldsymbol{T}^{2.5}}$) even at high densities ($\boldsymbol{n} > \boldsymbol{n}_{\mathbf{c}}$)

- The spin droplets are detected up to well metallic phase, coexisting with electron liquid

- The spin droplets “melt” as density and/or temperature increases, remaining of a constant size

- $\boldsymbol{dM/dn}$ changes sign as density increases. For $T \rightarrow 0$ this happens right at $\boldsymbol{n}=\boldsymbol{n}_{\mathbf{c}}$

Thank you for attention !

Magnetization is given as

$$\frac{M}{g\mu_B} = \frac{1}{Z}\sum_{n_{\uparrow,\downarrow}\in\mathbb{Z}} \frac{n_\uparrow - n_\downarrow}{2} B_{(n_\uparrow-n_\downarrow)/2}\left(\frac{(n_\uparrow - n_\downarrow)b}{2T}\right) Z_{n_\uparrow} Z_{n_\downarrow} e^{J(n_\uparrow-n_\downarrow)(n_\uparrow-n_\downarrow+2)/(4T)]}. \quad (1) \quad \{eq1\}$$

Here, summation over integer numbers $n_\uparrow$ and $n_\downarrow$ is restricted by constaint: $n_\uparrow + n_\downarrow = N$, where N is the number of electrons in the puddle. Next, $b = g\mu_B B$ and the grand partition function

$$Z = \sum_{n_{\uparrow,\downarrow}\in\mathbb{Z}} \frac{\sinh[b(n_\uparrow - n_\downarrow + 1)/(2T)]}{\sinh[b/(2T)]} Z_{n_\uparrow} Z_{n_\downarrow} e^{J(n_\uparrow-n_\downarrow)(n_\uparrow-n_\downarrow+2)/(4T)]}. \quad (2) \quad \{eq2\}$$

and

$$B_m(x) = \frac{2m+1}{2m}\coth\left(\frac{2m+1}{2m}x\right) - \frac{1}{2m}\coth\frac{x}{2m} \quad (3)$$

denotes the Brillouin function. The quantities Z_n stands for the canonical partition functions for spectrum ϵ_γ:

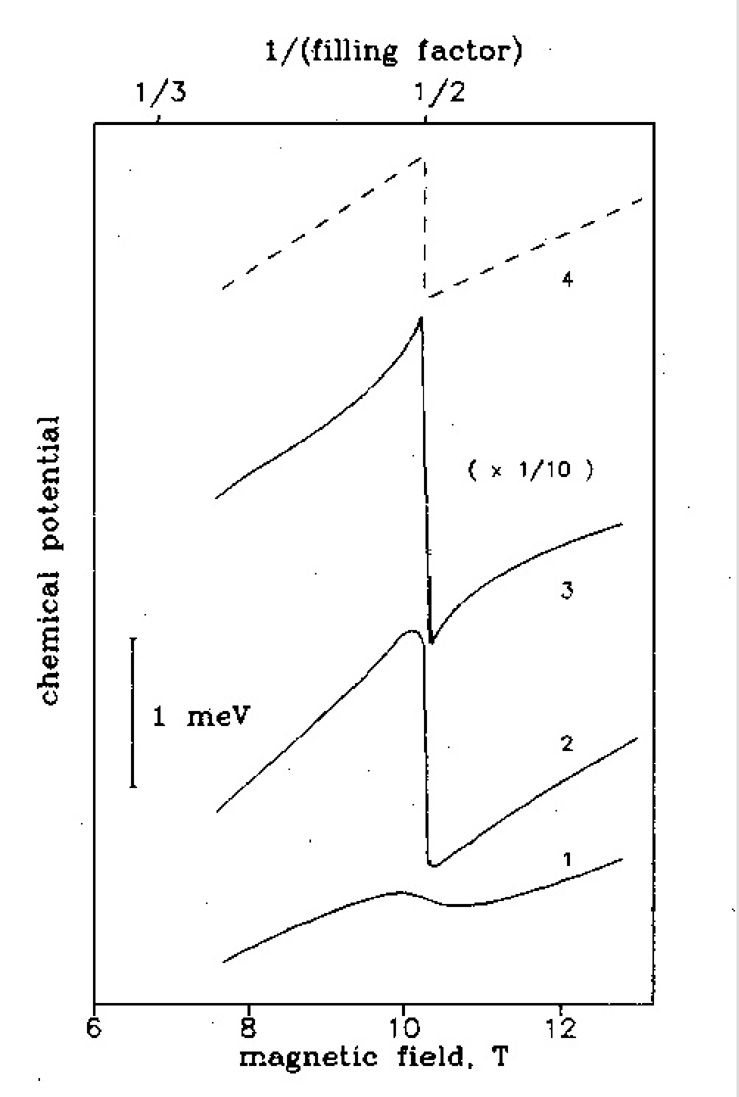
$$Z_n \equiv \int_0^{2\pi} \frac{d\theta}{2\pi} e^{-i\theta n} \prod_\gamma \left(1 + e^{i\theta - \epsilon_\gamma/T}\right). \quad (4)$$

Initial parameters:

- single-particle leves: $\{\epsilon_\gamma\} = \epsilon_1, \ldots \epsilon_K$ [if equidistant, then $\epsilon_j = \epsilon_{j-1} + \delta$]
- exchange interaction $J > 0$. Physically, it is proportional to δ. So parameter is J/δ.
- temperature and magnetic field

О чем не будет рассказано:

орбитальный магнетизм 2D системы электронов и магнетизм в $B_{\perp}$ поле



Почему не видна Ферми-жидкостная поправка в спиновую восприимчивость ?

A. Finkelstein, A. Shekhter, 2006)

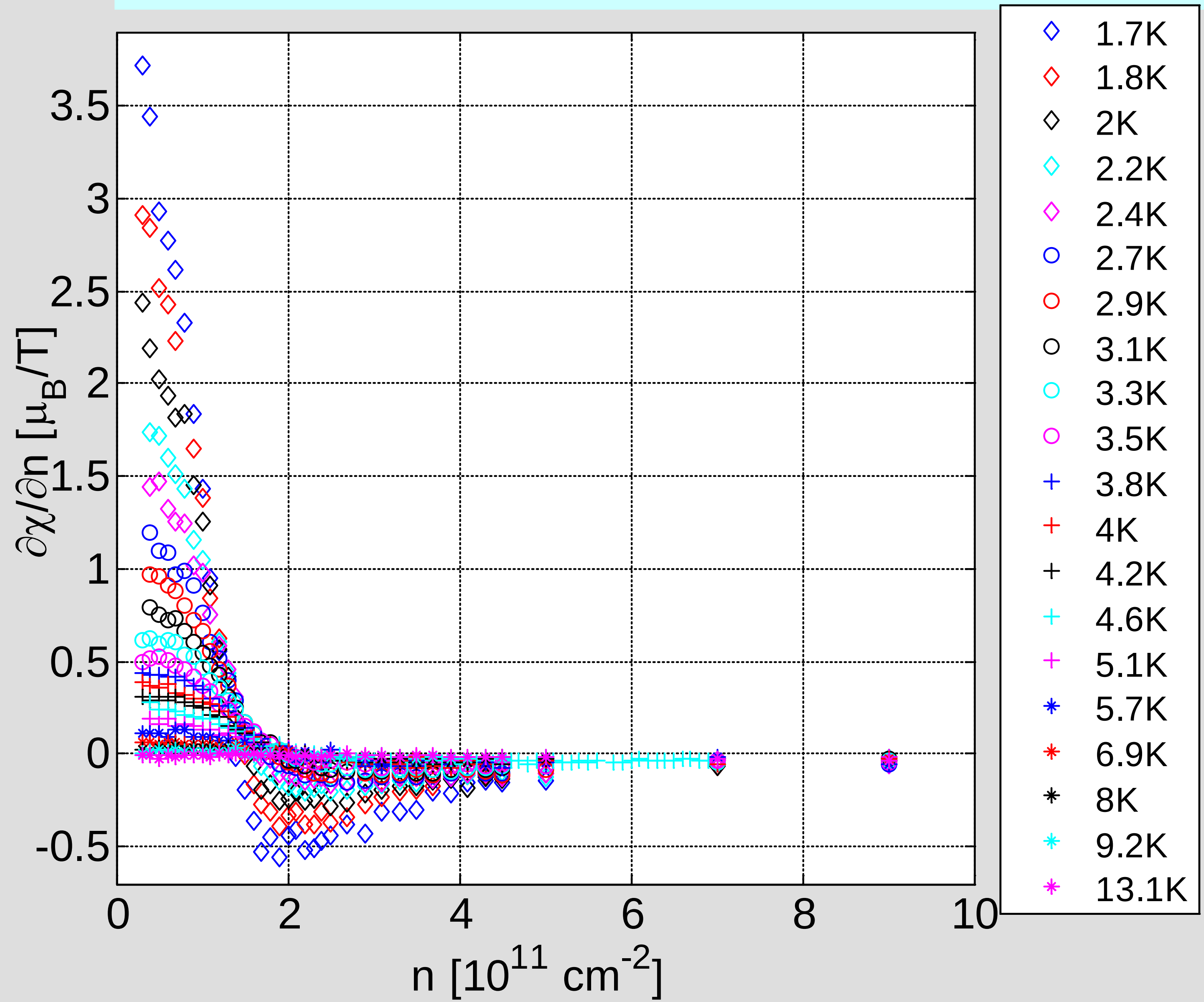
$$\delta\chi(T,H=0) = \left[\ln(1-f_{s,0}) + \frac{f_{s,0}}{1-f_{s,0}}\right]\left(\frac{\tilde{\mu}_B}{\mu_B}\right)^2 \frac{T}{\tilde{\epsilon}_F}\chi_0^{2D}$$

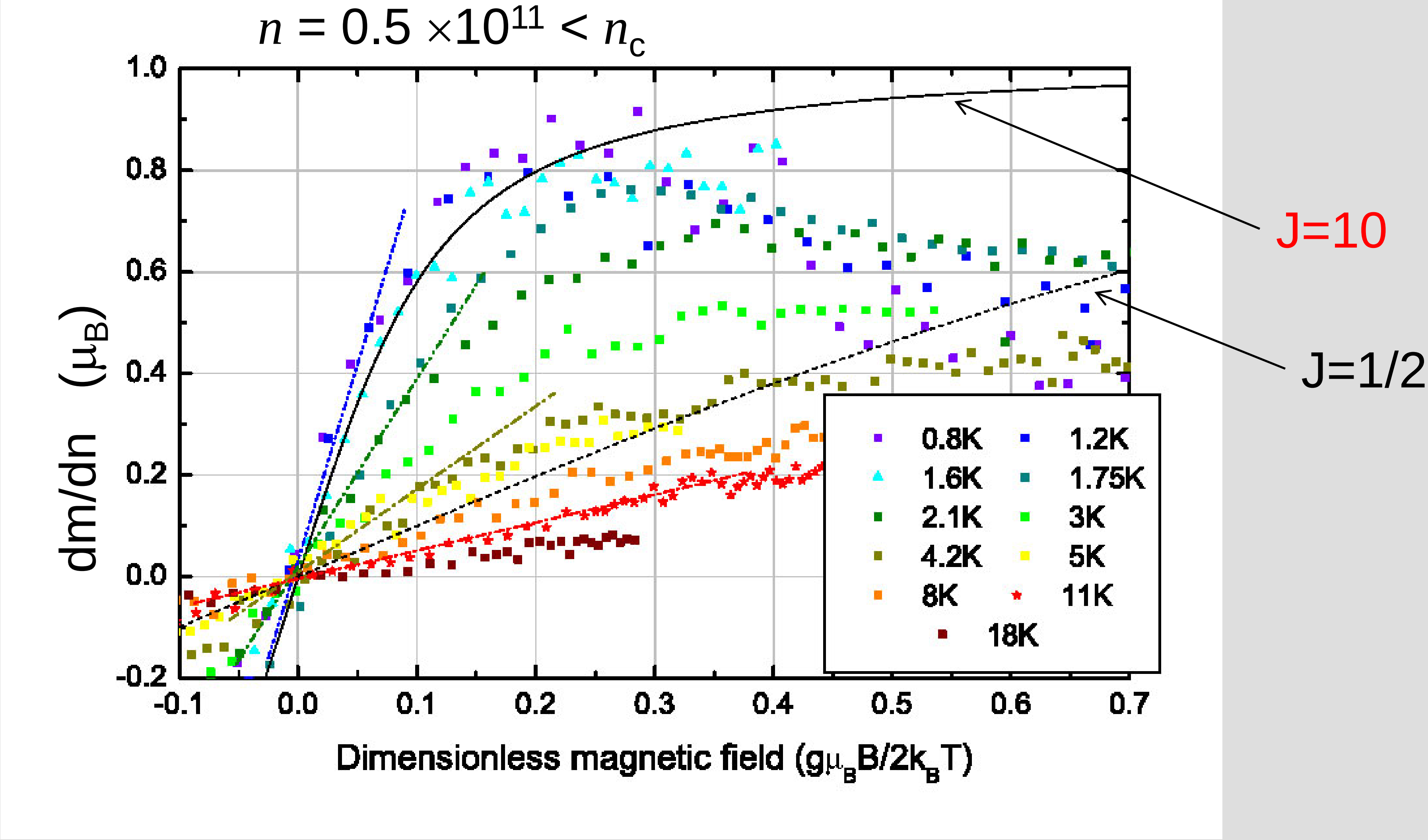
$$= [\ln(1+g_{s,0})^{-1} + g_{s,0}]\left(\frac{\tilde{\mu}_B}{\mu_B}\right)^2 \frac{T}{\tilde{\epsilon}_F}\chi_0^{2D}.$$

A. Chubukov, D. Maslov, 2009

$$\delta\chi(T,H=0) = \left[F_0(f_{s,0}) - 2\frac{f_{s,1}}{f_{s,0}}F_1(f_{s,0})\right]\left(\frac{\tilde{\mu}_B}{\mu_B}\right)^2 \frac{T}{\tilde{\epsilon}_F}\chi_0^{2D},$$

dχ/dn versus ***n*** @*T*=1.7 -13K

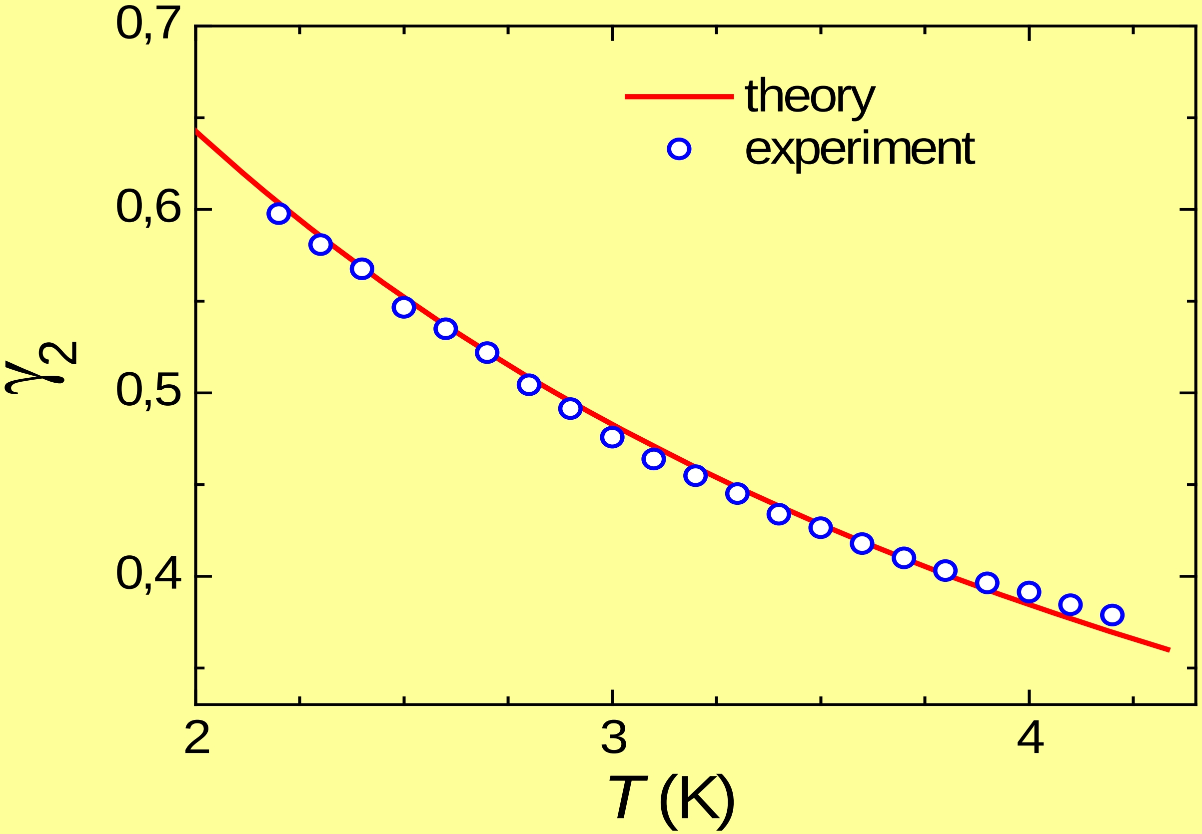




n = 0.5 ×10^11 < n_c
dm/dn (μ_B)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Dimensionless magnetic field (gμ_B B/2k_B T)
0.8K
1.2K
1.6K
1.75K
2.1K
3K
4.2K
5K
8K
11K
18K
J=10
J=1/2

Strong growth of $\gamma_2(T)$, indirectly obtained from RG-analysis of the ρ(T) data

$$\gamma_2 = \frac{g^*}{g_b} - 1 \equiv \frac{-F_0^\sigma}{1+F_0^\sigma}$$



D.Knyazev, V.Pudalov, I.Burmistrov, JETP Lett, **84**, 780 (2006)