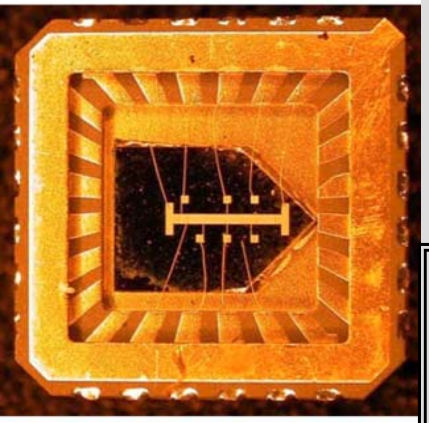
Физический институт имени П.Н.Лебедева

Ф И А Н

Temperature and field dependences of the spin susceptibility in 2DE liquid



Vladimir Pudalov

Lebedev Physics Institute, Moscow

Outline

- quantifying *e-e* interactions in 2D
- renormalized spin susceptibility χ^*. Low fields, $B_{||} << E_F$
- renormalized χ^*. High fields $B_{||} \sim E_F$

Argonne –

November 14, 2005

Contributors:

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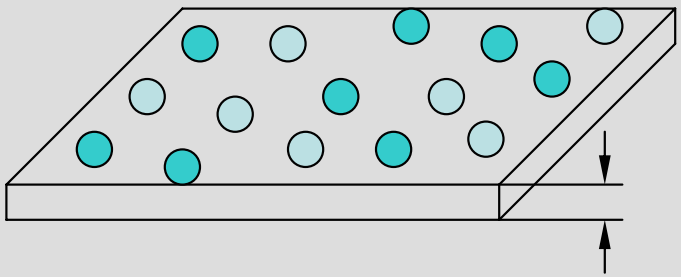
Gerhard Brunthaler, Adrian Prinz, Guenther Bauer JKU, Linz

The studied object: 2D sheet of electrons at a semiconductor-insulator interface



$\lambda_F \sim 5$nm

reside at the Si-SiO_2 inteface

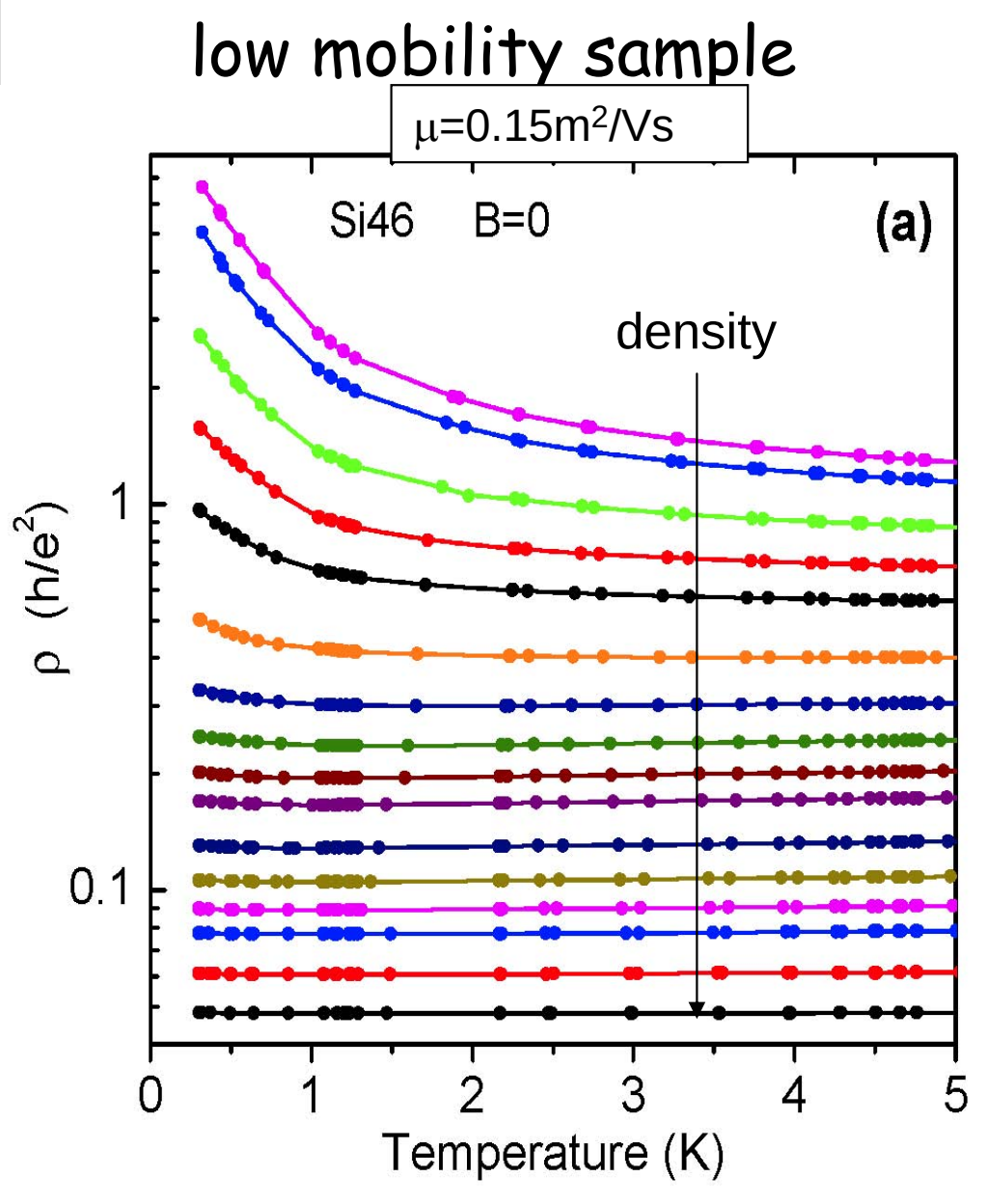
For a **clean defect-free** host lattice and interface, the very "dilute" 2D electron layer may be prepared, ~10^{10} cm^{-2}

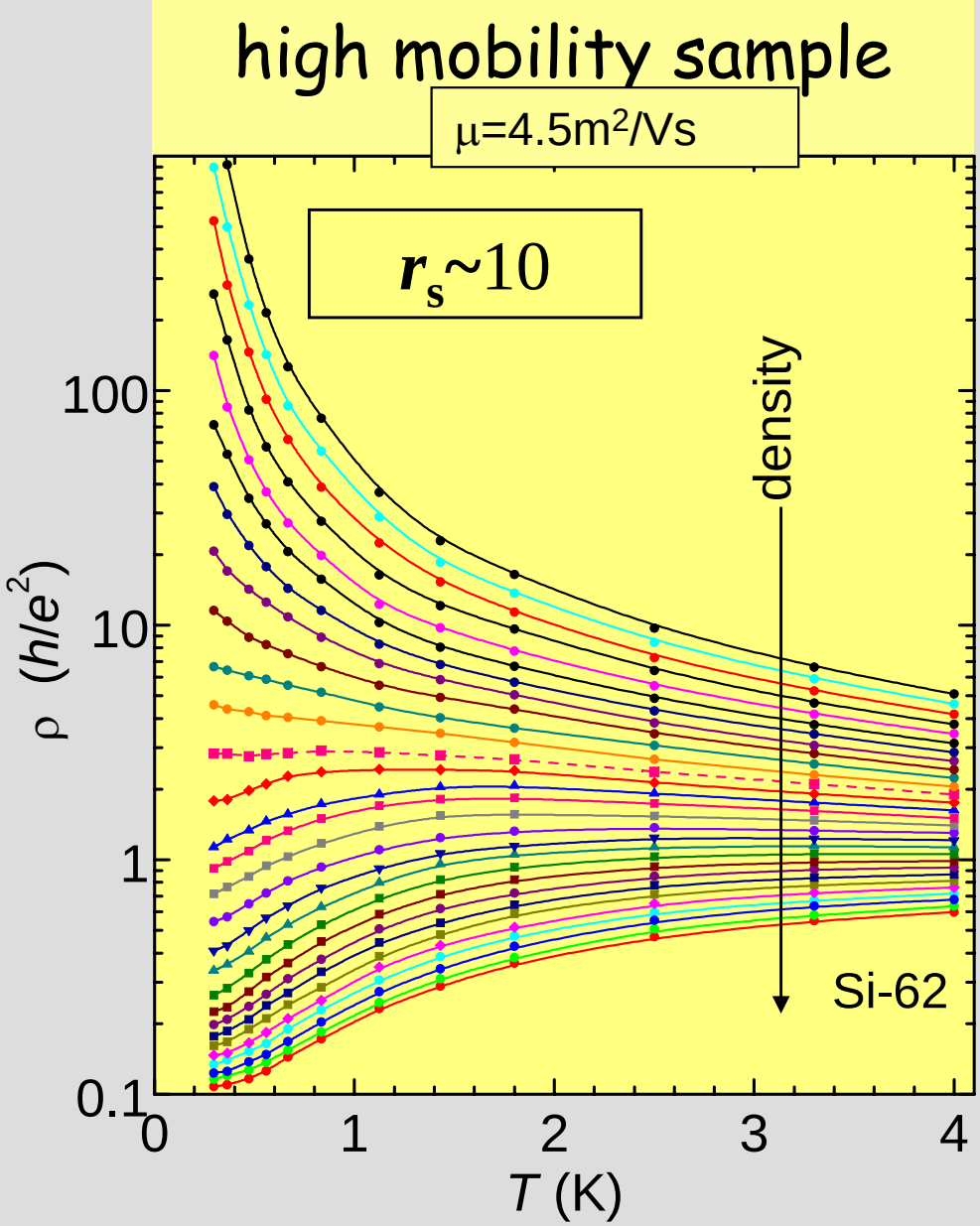
As a result, the e-e interaction energy $E_{ee} \propto e^2 n^{1/2}$ is extremely high ~ 70K, much exceeding the kinetic (Fermi) energy $E_F \propto n \sim 5K$

$$r_s = E_{ee}/E_F \propto 1/n^{1/2} >> 1$$

Motivation: The strongly correlated 2D electron system may exhibit new phases and new physics

Example of new physics:
MIT in 2D system



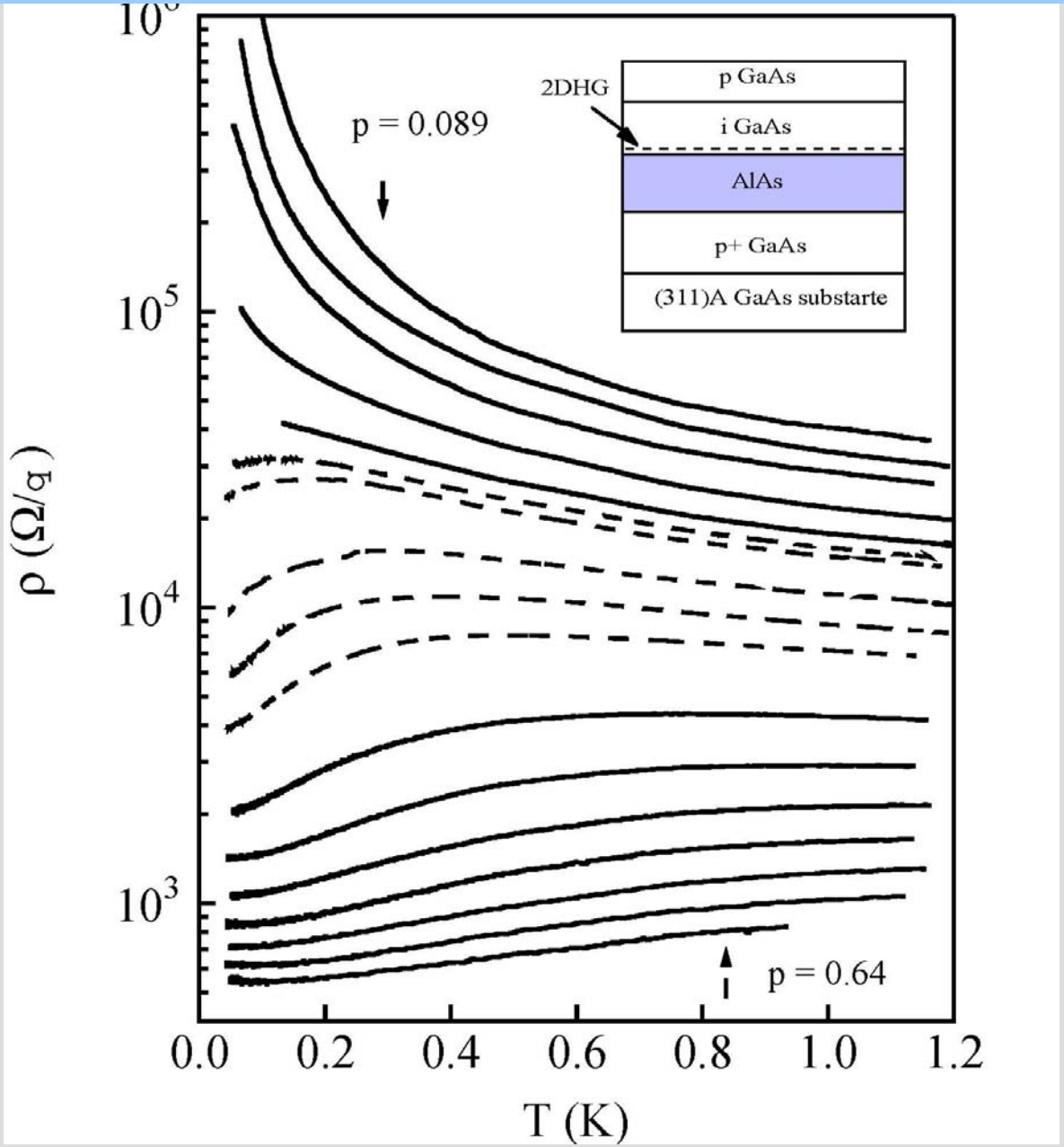


S.Kravchenko, V.P. et al. *Phys.Rev.B* 1994; 1995

Similar $\rho(T)$ behavior is found for other high-mobility/low density 2D systems :

p-GaAs,
n-GaAs,
p-Si/SiGe,
n-Si/SiGe,
n-SOI,

etc.



Y.Hanein et al. *Phys.Rev.Lett.* (1998)

There is no metallic state and MIT for non-interacting electrons

✓ ~~Spin-orbit interaction ?~~

Is unrenormalized

✓ ~~Electron-phonon interaction ?~~

Too low temperature and too weak *e-ph* coupling

Electron-electron interaction

Quantitative studies of the *e-e* interactions in 2D

The plan is:

- to use FL-theory
- to measure renormalization
- to quantify e-e interactions

$$\frac{g^*}{g_b} \equiv \frac{\chi^* m_b}{\chi_b m^*} = \frac{1}{(1+F_0^a)}, \tag{1}$$

$$\frac{m^*}{m_b} = 1 + \frac{1}{2}F_1^s, \tag{2}$$

$$\frac{\kappa^*}{\kappa} = \frac{m^*}{m_b}\frac{1}{(1+F_0^s)} \tag{3}$$

$$\frac{\chi^*}{\chi_b} = \frac{m^*}{m_b}\frac{1}{(1+F_0^a)}, \tag{4}$$

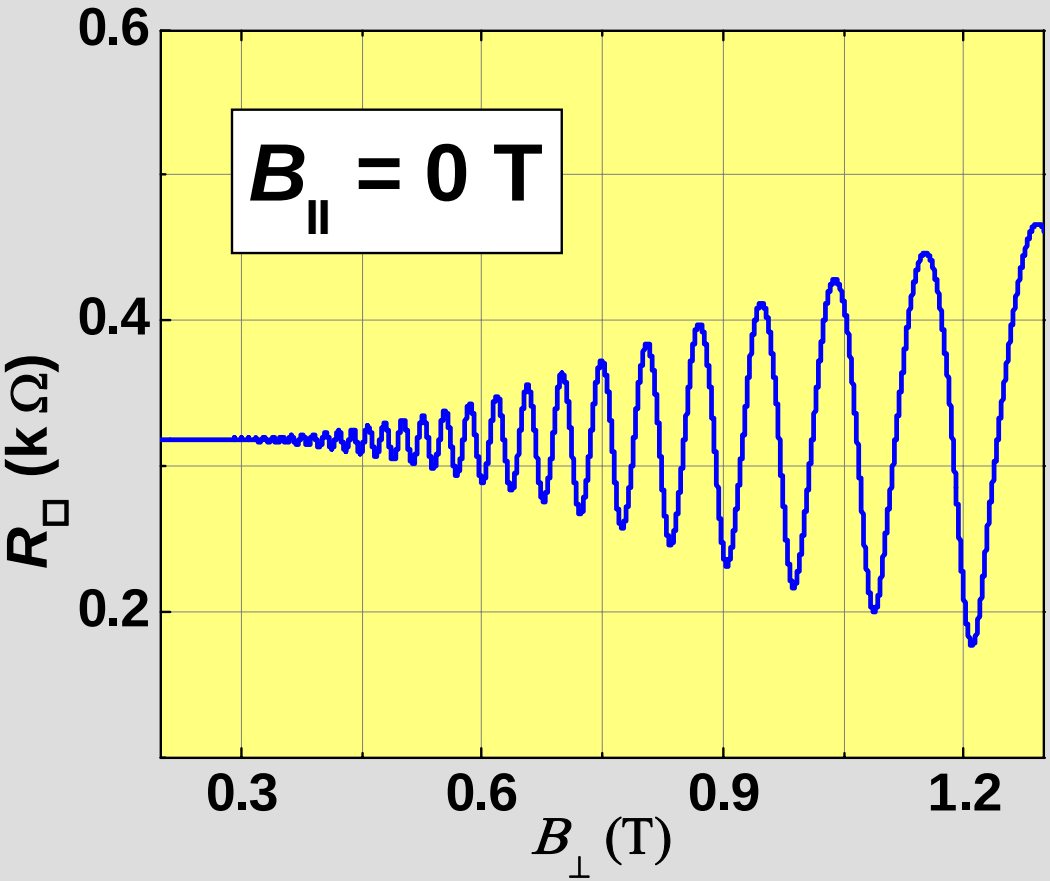
where g_b, m_b, κ_b, and χ_b are the corresponding bare values.

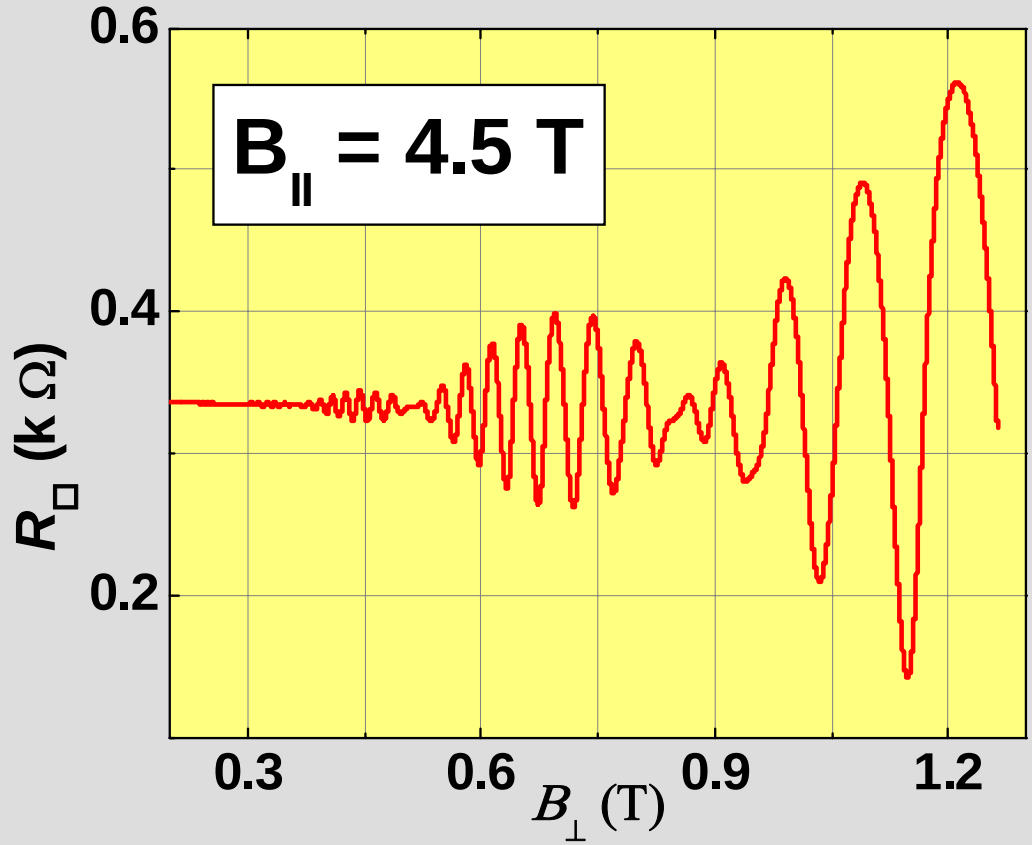
$F_i^{a,s}$ – coupling constants (harmonics) of e-e interaction

SdH oscillations for zero and non-zero $B_{||}$ field

$n = 10.8 \times 10^{11}$ cm^{-2},

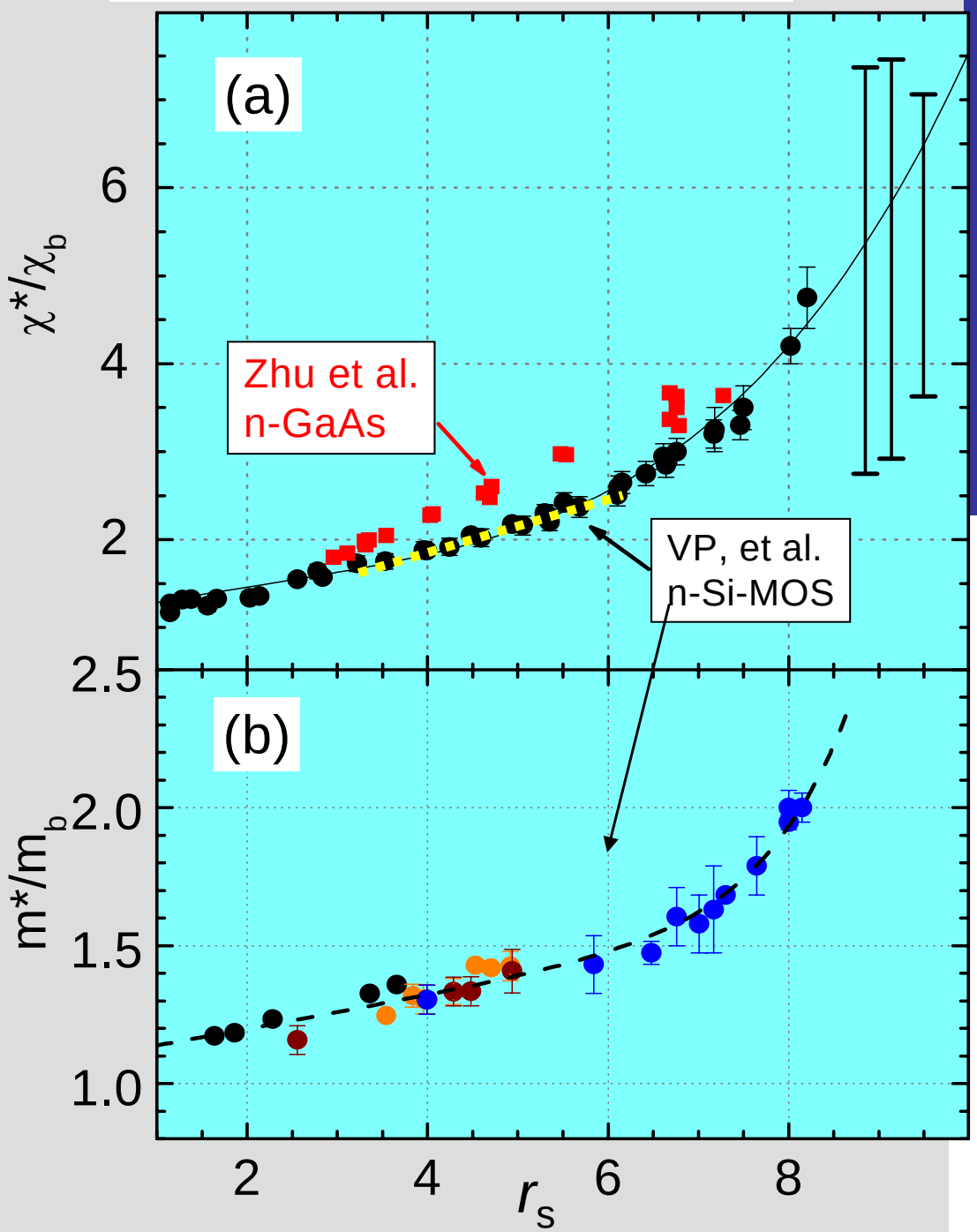
$r_s = 2.5$





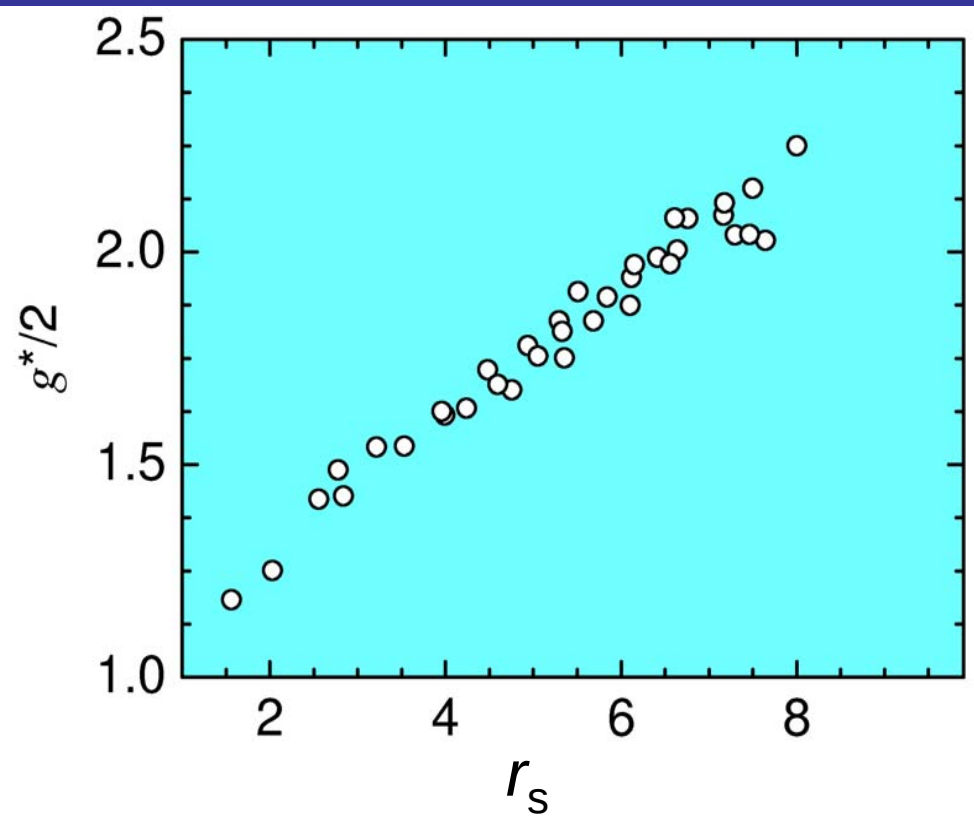
Gershenson et al., Physica E (2002)

VP et al., PRL (2002)



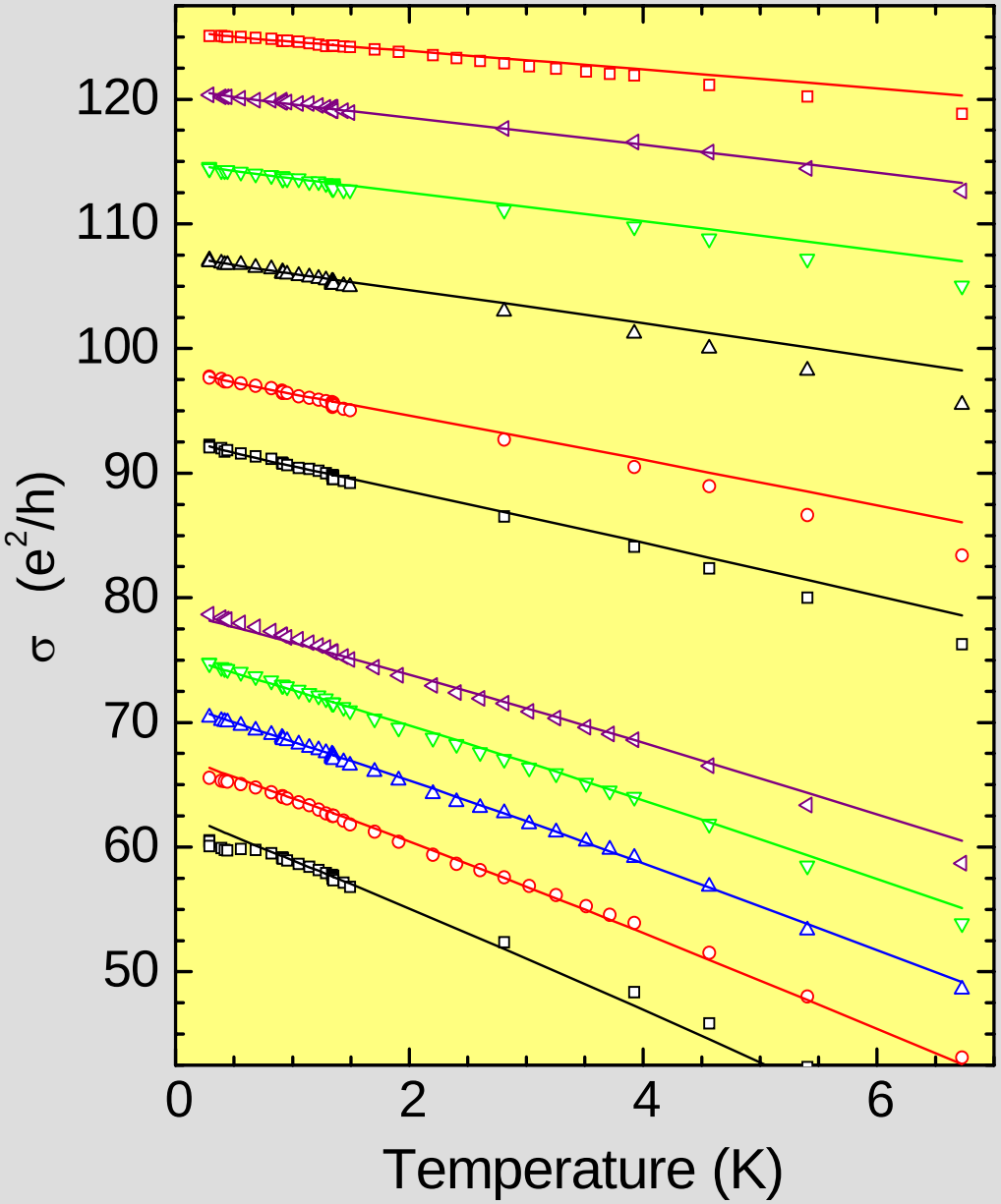
Renormalized χ^*, m^*, and g^* versus r_s determined from SdH oscillations in crossed fields ($g^*\mu B < kT$)

These are the data at $E = E_F$



V.P. et al., in: "*Fundamental Problems of Mesoscopic Physics*", Kluwer (2004)

Implementation of the measured g* and m* to the transport data (ballistic regime, $T\tau >> 1$)



No-parameter fit

$$\delta\sigma_T \approx 15\left(\frac{F_0^a}{1+F_0^a}\right)\frac{e^2}{\pi h}T\tau$$

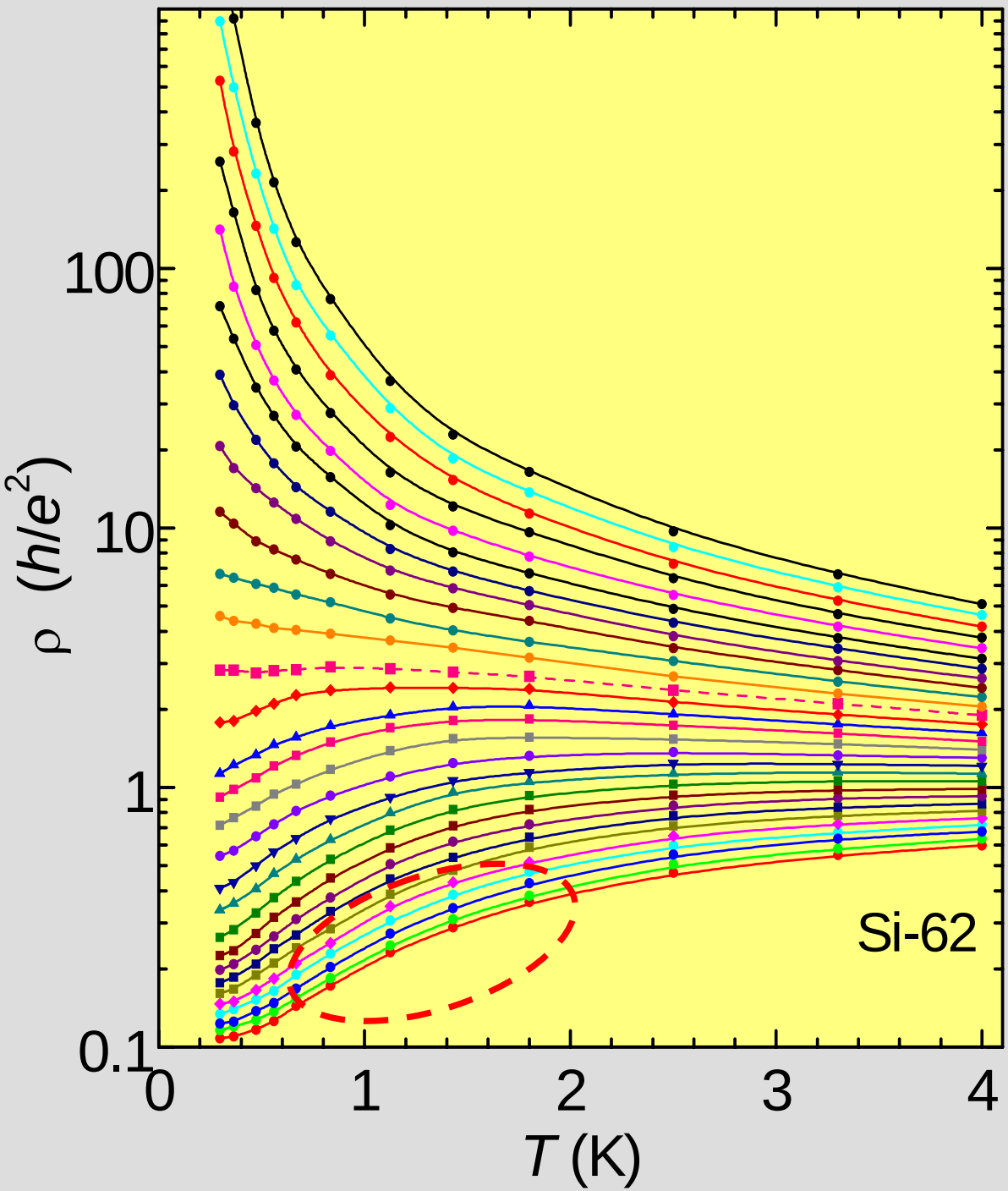
Conclusion:

at high temperature $T\tau$>>1, quasi-linear $\delta\rho(T)$, $\delta\sigma(T)$ is due to e-e interaction

VP et al. PRL (2003)

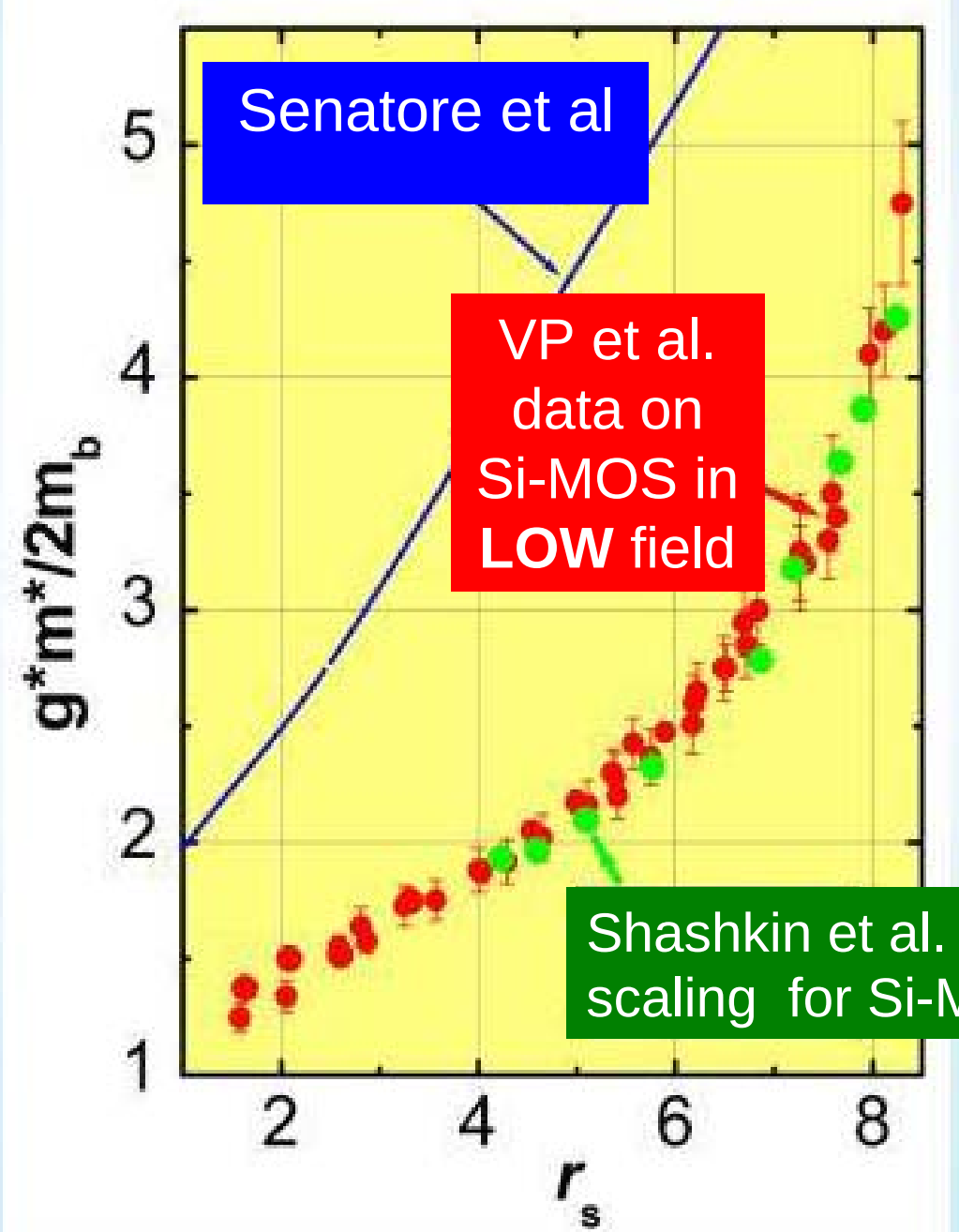
Conclusion:

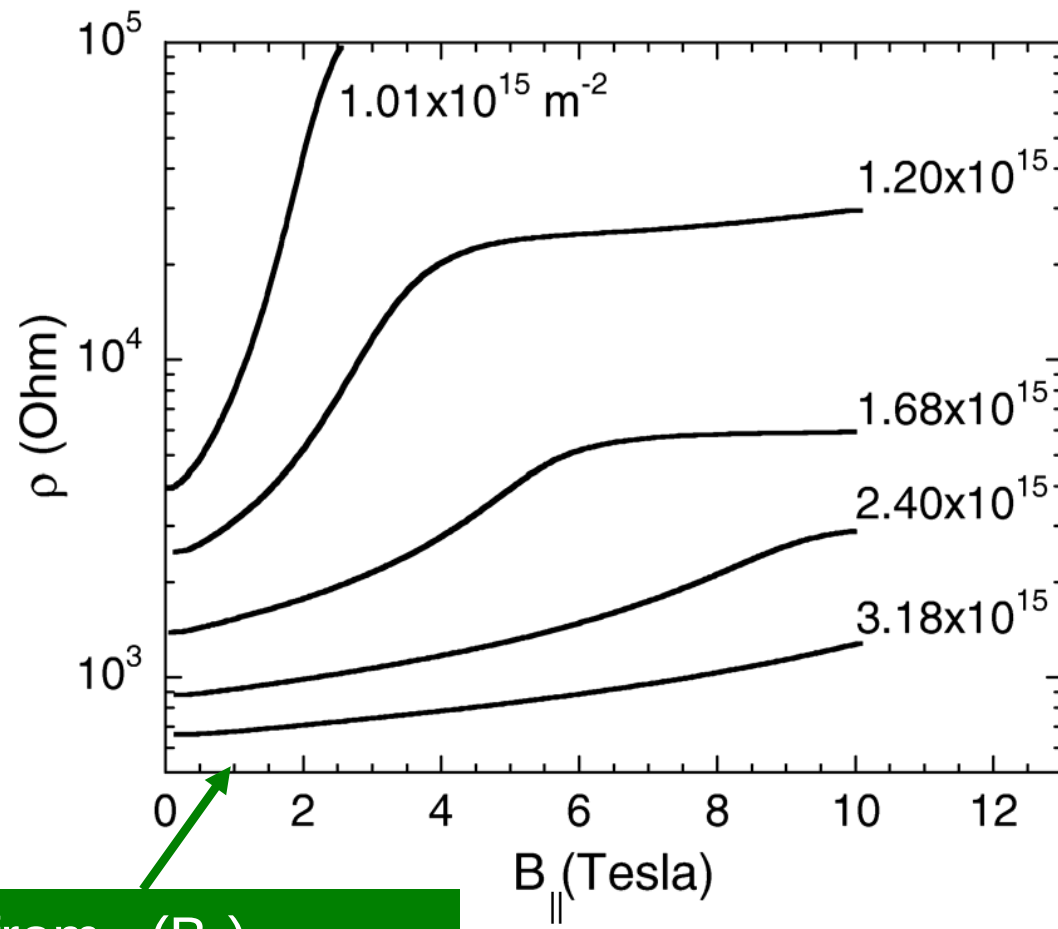
at high temperature
$T\tau$>>1,
quasi-metallic
$\delta\rho(T)$, $\delta\sigma(T)$
is due to e-e
interaction



Renormalization of χ^*:

overview of the data on Si-MOS



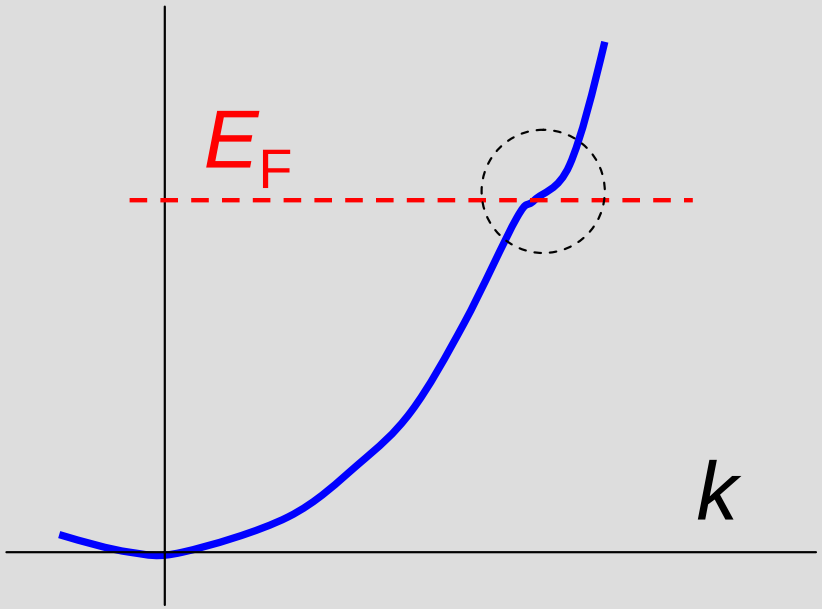


Shashkin et al. from $\rho(B_{||})$ scaling for Si-MOS in **HIGH** field

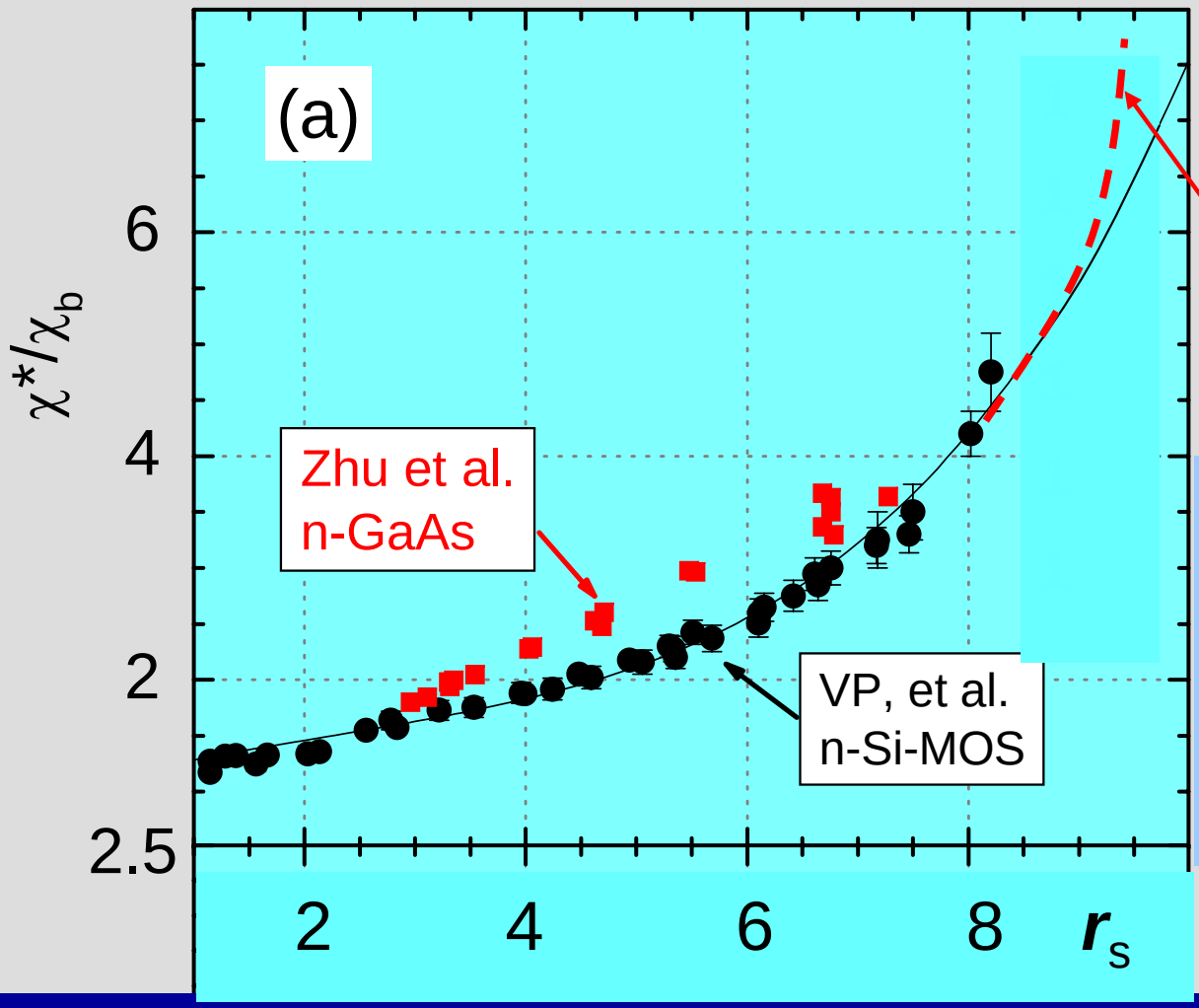
Consequence 1. Consistency of the experimental $\chi^*(r_s)$-data

- ✓ measured at E_F and
- ✓ in the overall energy interval $(0 - E_F)$

➢ e-e interaction is effective in a wide energy interval ($\delta E \sim E_F$, $\delta E \gg kT$), or is insensitive to spin



Consequence 2



χ^* is strongly renormalized.

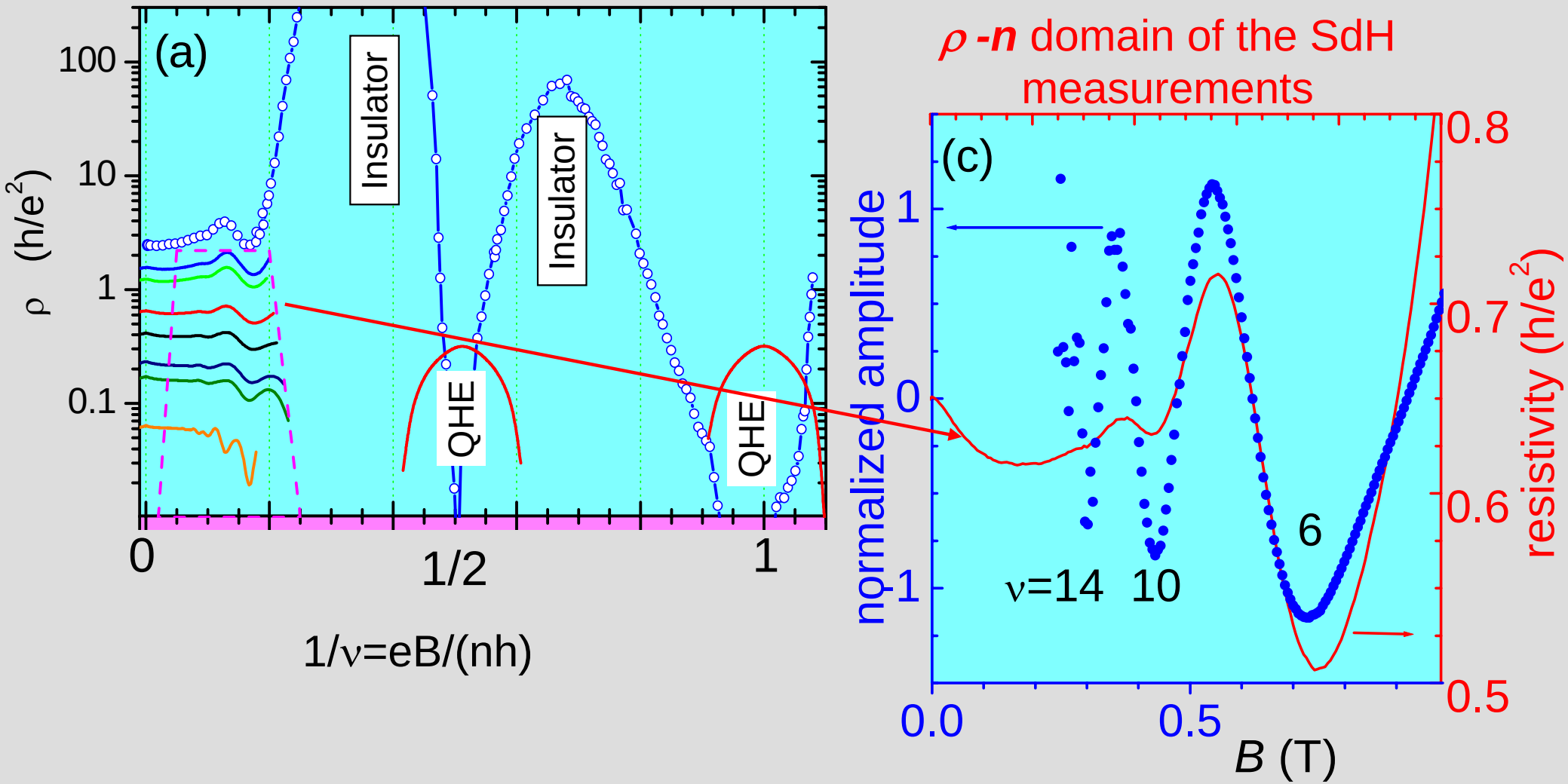
⇩

Does it diverge ?

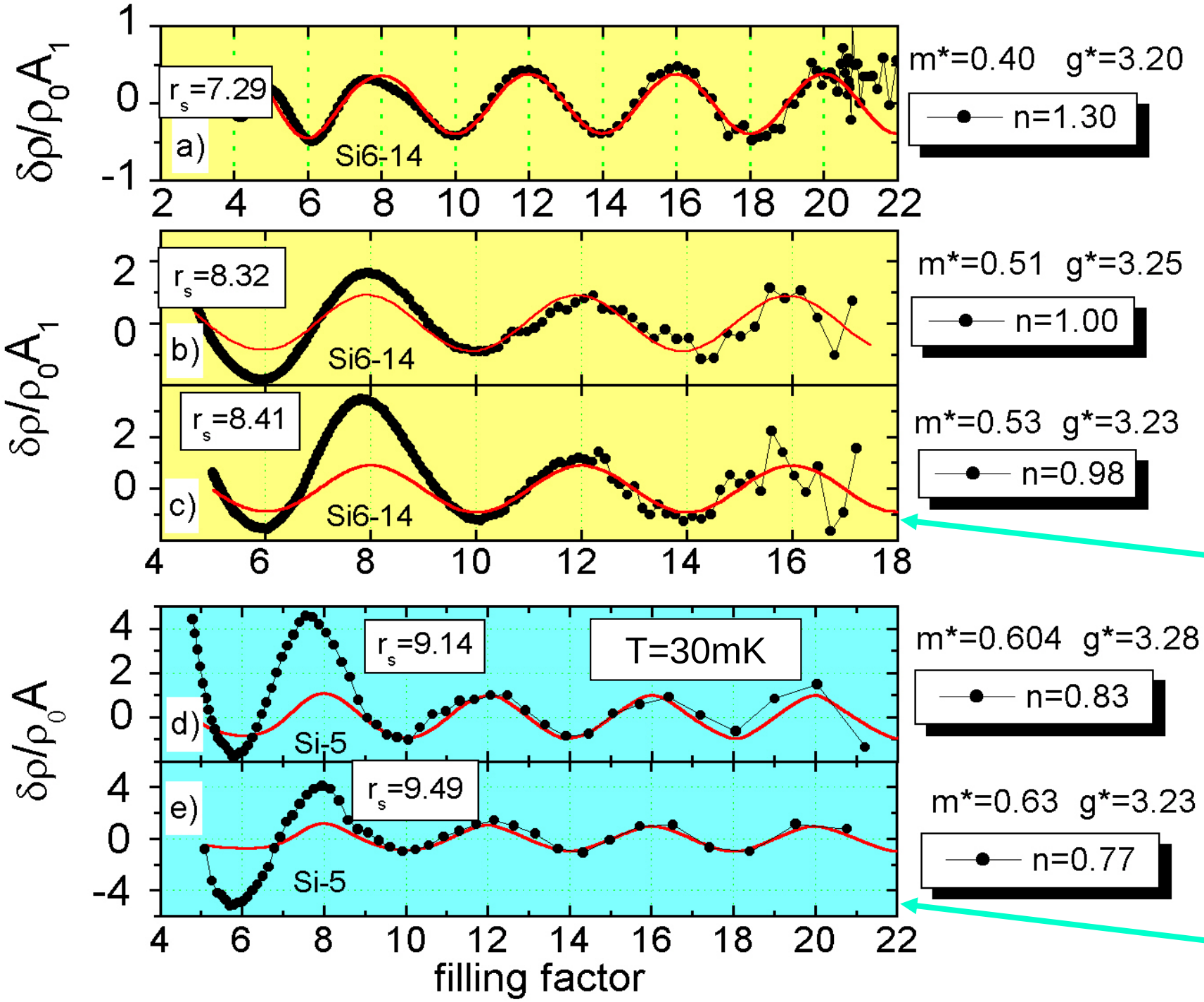
A spontaneous magnetic transition in 2D system of itinerant electrons ?

How can χ^* be tested at the lowest carrier density $n \sim n_c \cong 8\times10^{10}\text{cm}^{-2}$ (i.e. $r_s \approx 9.5$) ?

ρ-B-n phase space where SdH can be measured



VP, M.D'Iorio et al., PRB (1992); Phys.Lett. (1990).



Sample Si6-14
$n = n_c$

Sample Si15
$n = n_c$

V.P. et al., in: "*Fundamental Problems of Mesoscopic Physics*", Kluwer (04)

S.Kravchenko et al., SSC **116**, 495 (2000)

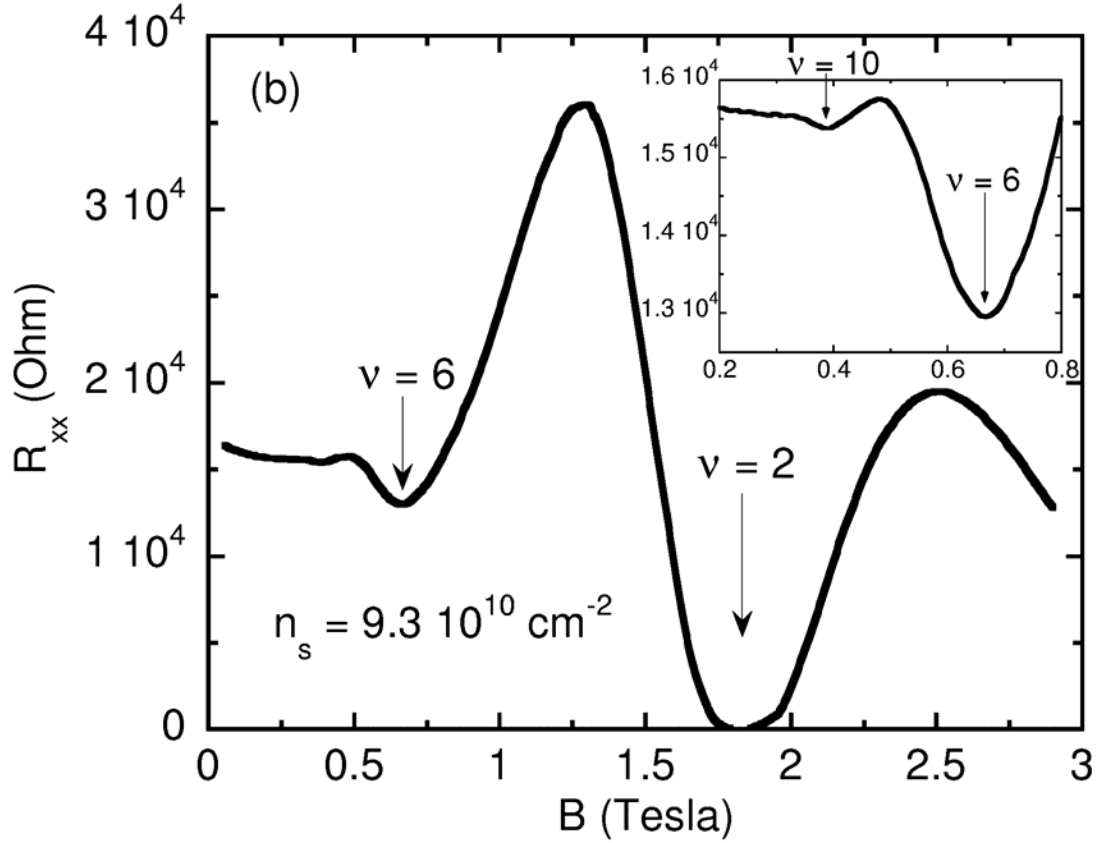


FIG. 1. Shubnikov-de Haas oscillations in the Si MOSFET at $T \approx 40$ mK (a) at a relatively high electron density $n_s = 5.43 \times 10^{11}$ cm^{-2} and (b) at low electron density $n_s = 9.3 \times 10^{10}$ cm^{-2}. The minima of the resistance at Landau level filling factors $\nu = 6$ and 10 are shown on an expanded scale in the inset.

S. Kravchenko et al., SSC **116**, 495 (2000)

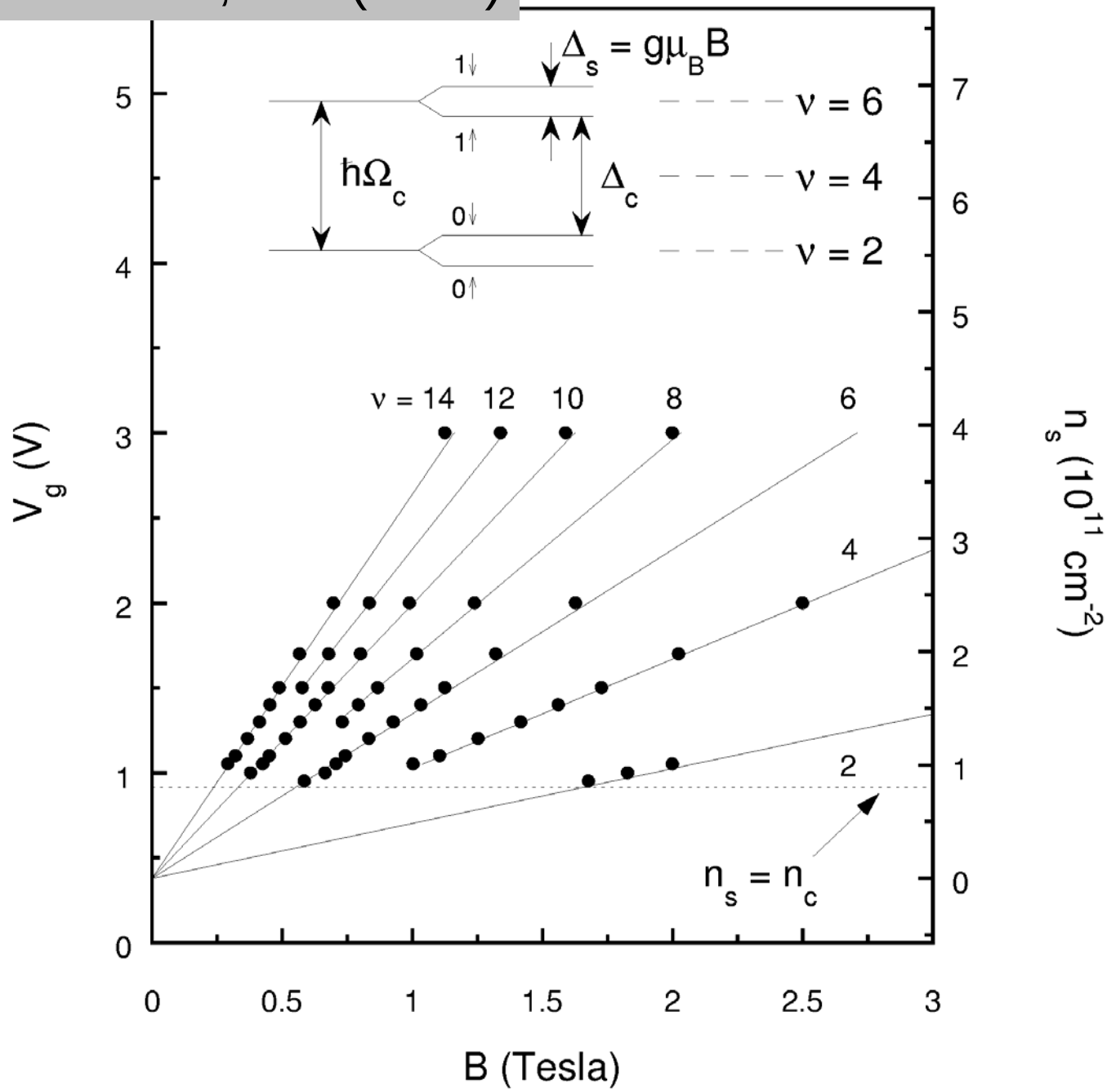
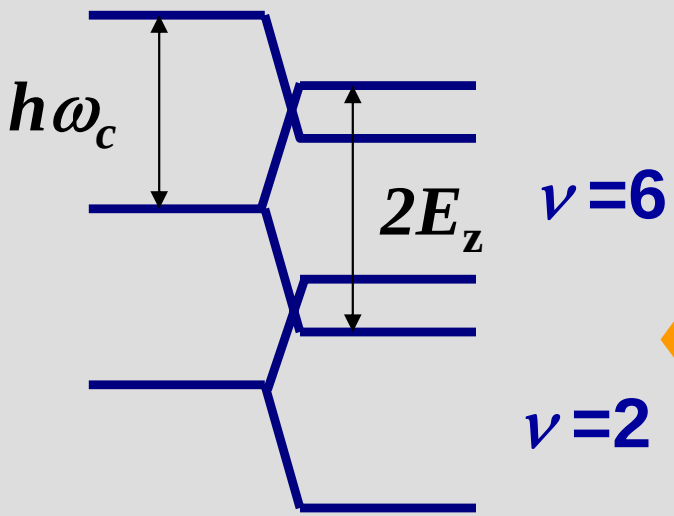
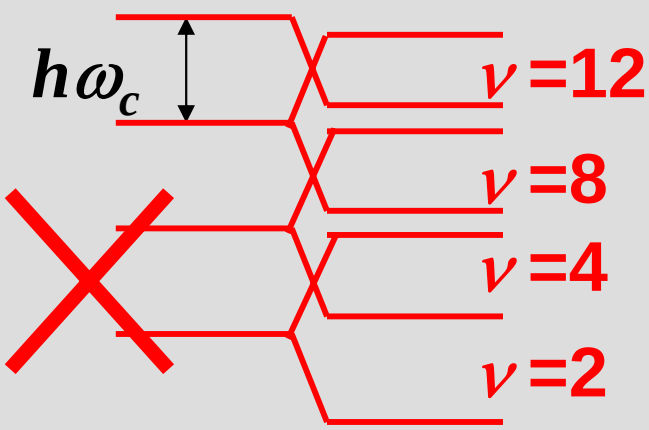


FIG. 3. Positions of the Shubnikov-de Haas oscillation minima in the (B, n_s) plane (dots) and the expected positions of the

ii) Estimation of the χ^* value from sign of the SdH oscillations





$$\cos\left(\pi\frac{E_z}{\hbar\omega_c}\right)=\cos\left(\pi\frac{\chi^*}{\chi_b}m_b\right)$$

ρ_{xx}-minima occur at ν = 2, 6, 10, etc

Hence,

$$2.6 = 1/(2m_b) < \chi^*/\chi_b < 3/(2m_b) = 7.9$$

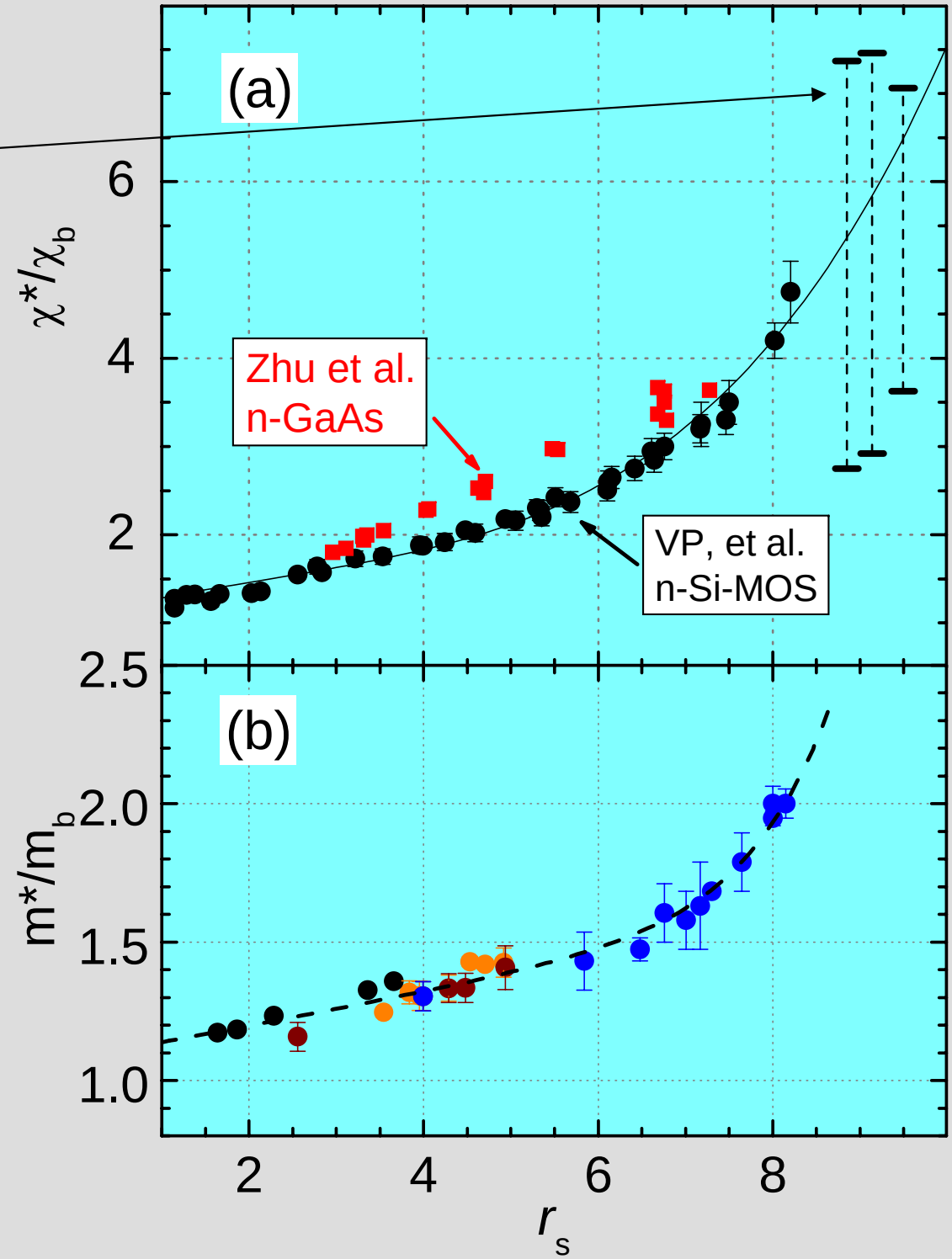
Periodicity and phase of the SdH oscillations corresponds to the presence of the **two** spin subbands for all densities (4-fold degeneracy)

The 2D system remains **unpolarized** down to

$n \approx 7.5 \times 10^{10} cm^{-2}$

Though the polarization can not be excluded at $n < 5 \times 10^{10} cm^{-2}$ (insulating phase)

Upper and lower estimates follow from period and sign of the oscillations

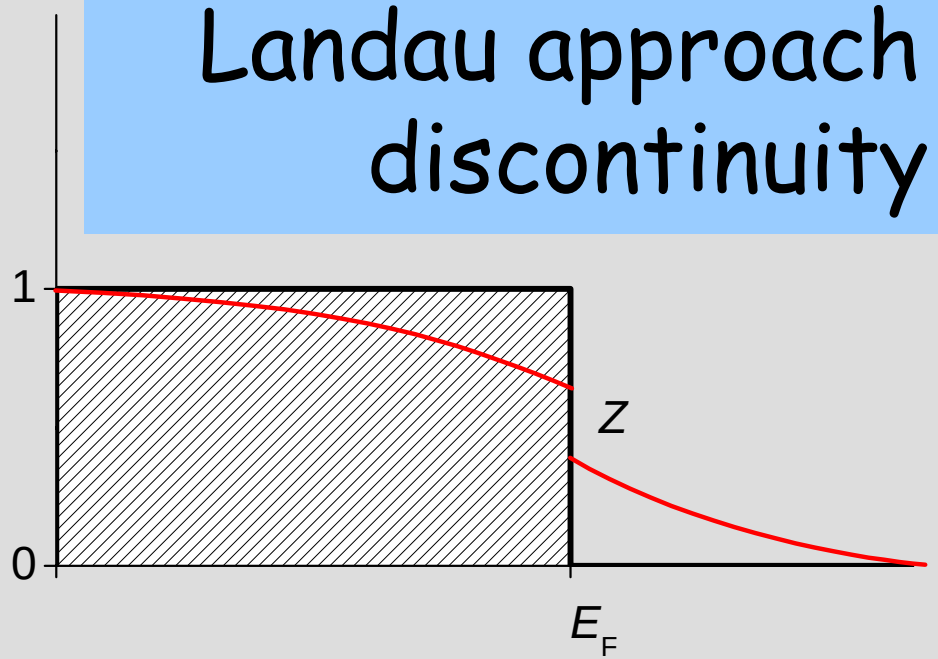


A factor of 7x enhancement

is now explained by:

- standard FL model,
- Dispersion instability,
- Two-phase model,
- disordered WC, etc

Landau approach works while there is a discontinuity at the Fermi level

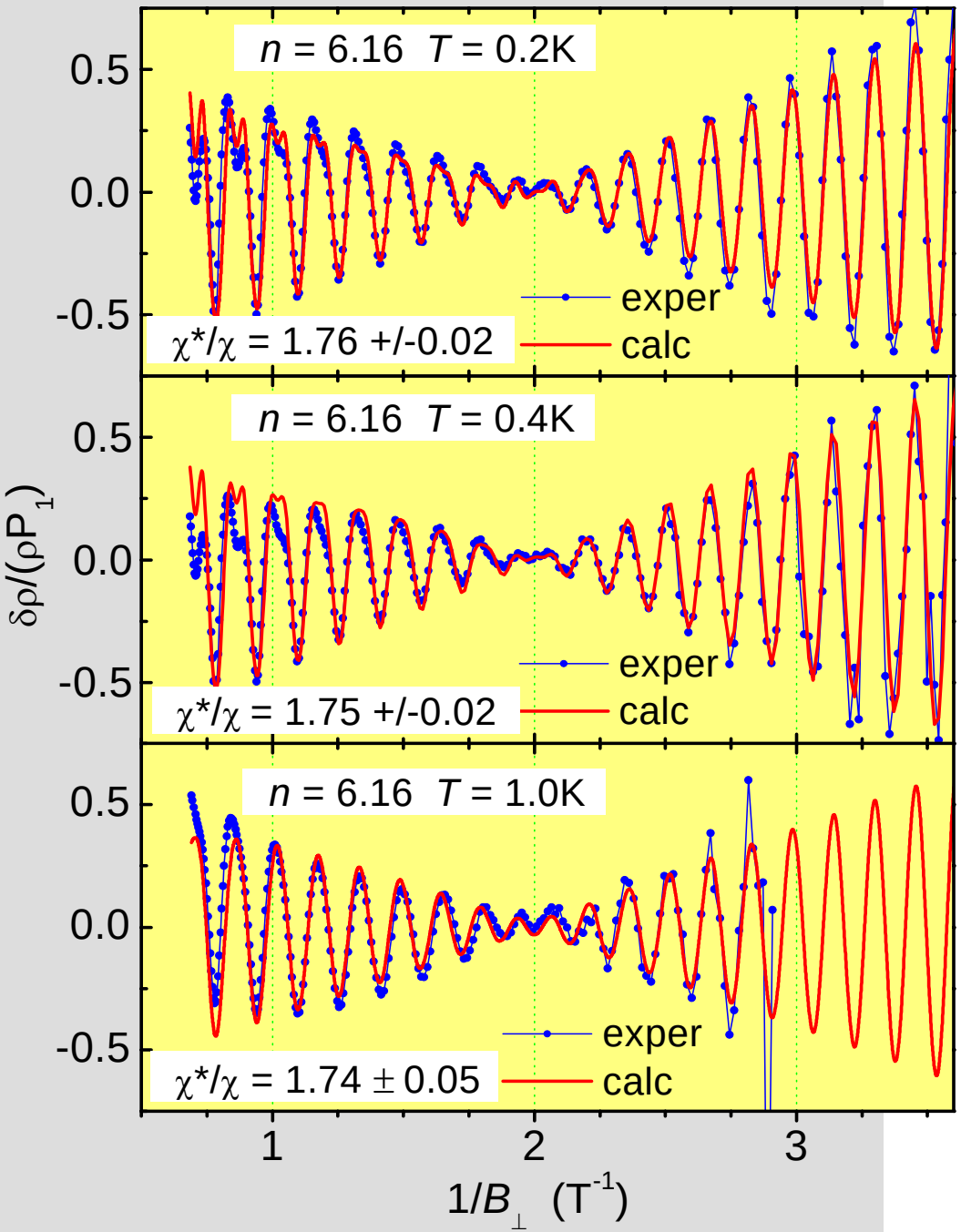


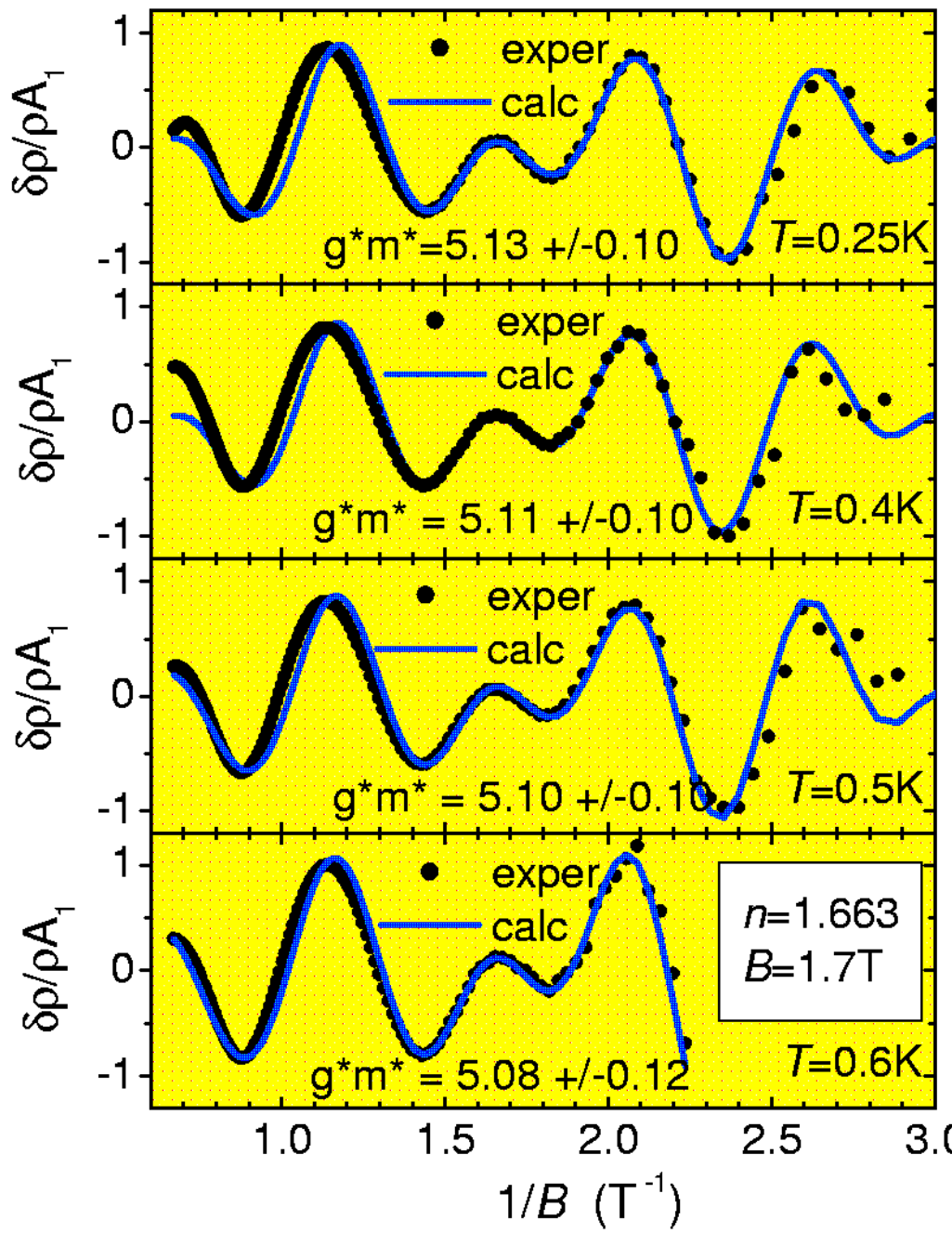
It doesn't work, e.g. for:

- marginal Fermi-liquid (Varma, Littlewood, Abrahams, et al.), $\boldsymbol{Z} \to 0$ logarithmically,

- "Fermion condensation" or "dispersion instability" model for strongly correlated fermions (Khodel, Shaginyan et al.).

How do the renormalized χ* varies with *T* ?





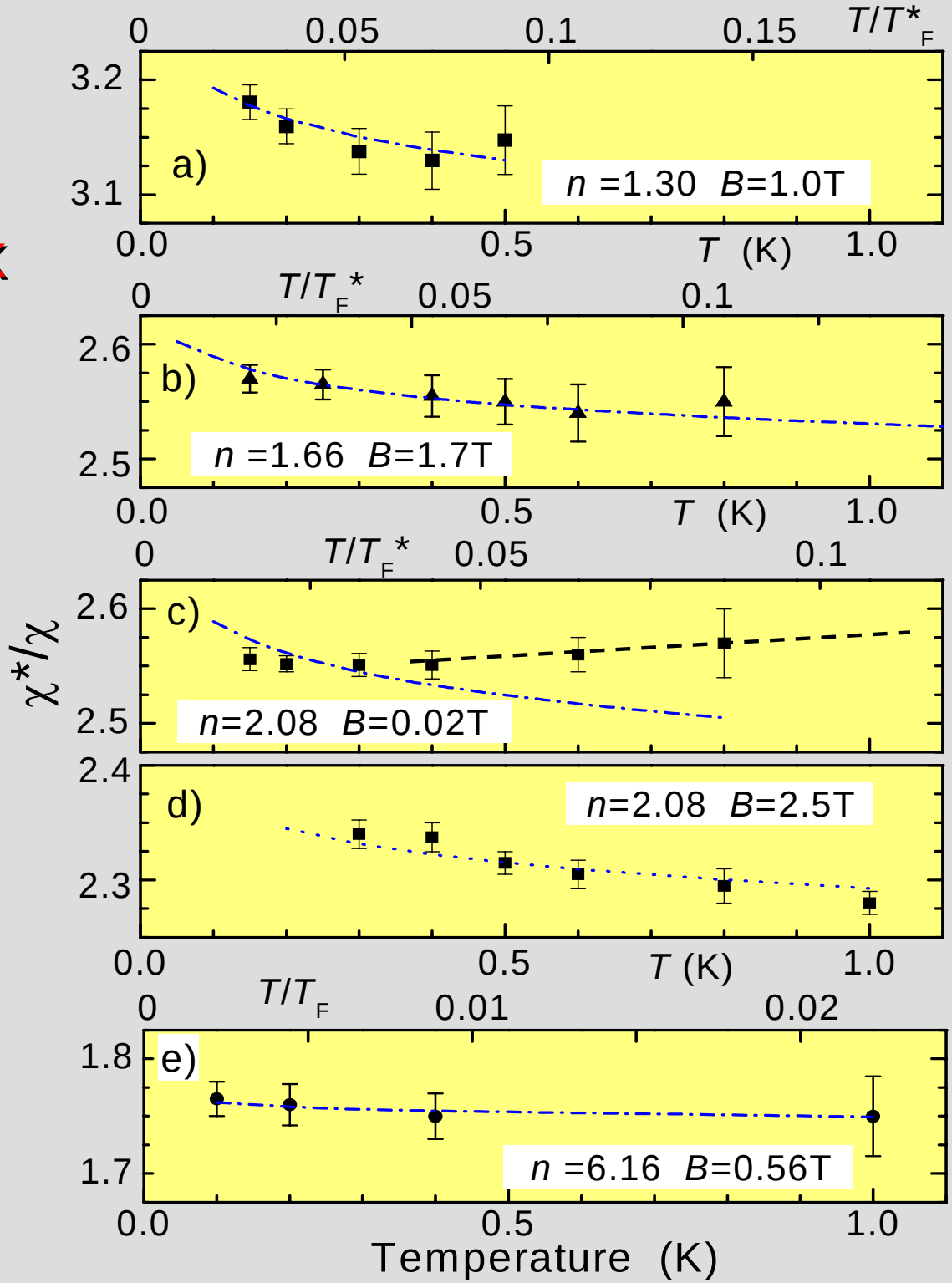
The results:

✓ $\chi(T)$-dependence is weak

✓ $d\chi/dT > 0$ for $T\tau << 1$

✓ $d\chi/dT$ tends to change sign at $T\tau \rightarrow 1$

✓ $\chi(T)$ significantly grows with $B_{||}$



(2b)
FL corrections for diffusive regime $T\tau$ <<1:
(Altshuler-Aronov, 1982)

$$\chi \equiv \frac{dM}{dH} = 2g^* \frac{dn}{dE}\mu_B^2 = \frac{4g^*\mu_B^2 m^*}{\pi \mathrm{h}^2} = \frac{g^*}{\pi}\frac{e^2}{m_0 c^2}\frac{m^*}{m_0}$$

$$\delta\chi \approx -\frac{n_v^2 (g\mu_B)^2}{2\pi^2 hD}\ln T\tau = -\frac{n_v^2 g^2 \mu_B^2 m^*}{\pi^2 2\pi \mathrm{h}^2 (k_F l)}\ln T\tau$$

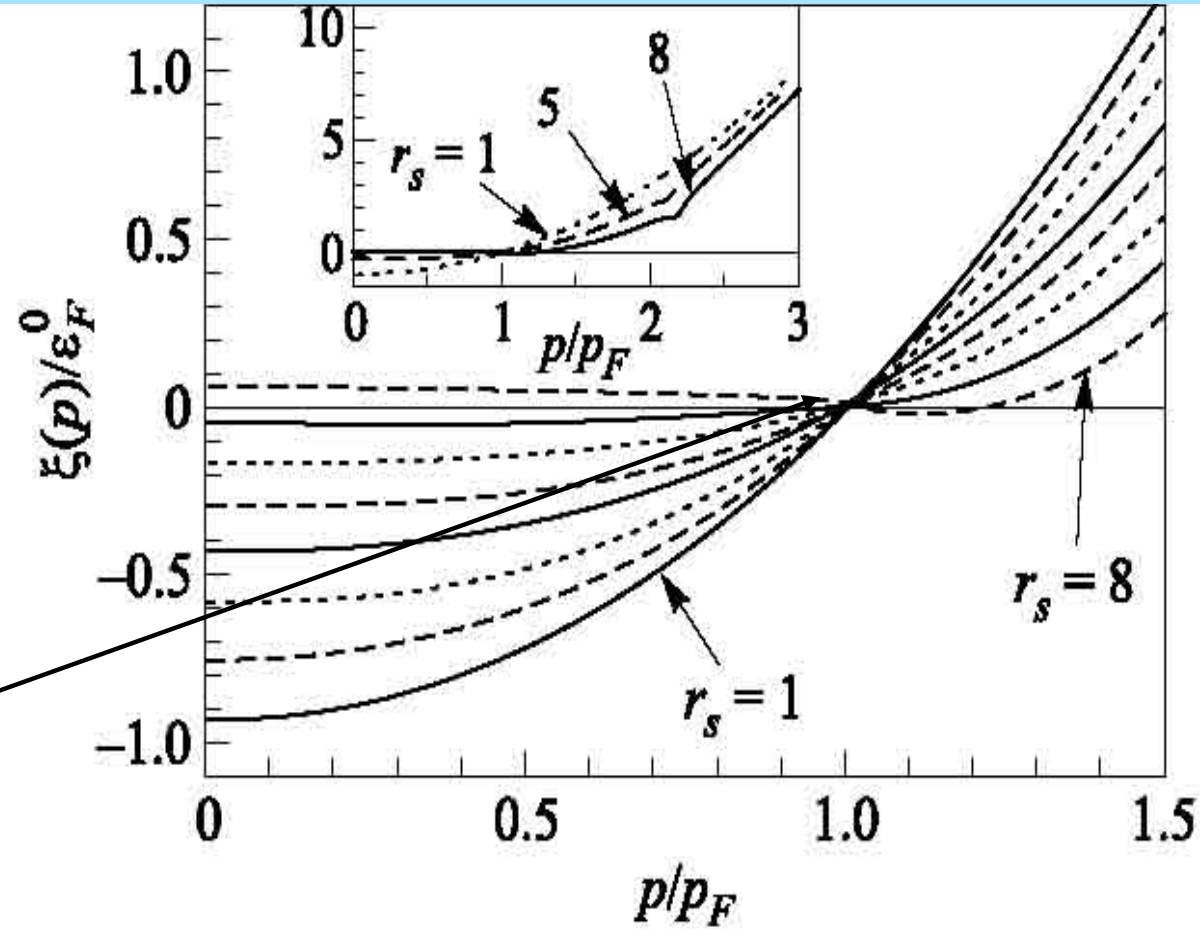
$$\frac{\delta\chi^*}{\chi_b} = -\frac{n_v^2 g^2 \mu_B^2 m^* \pi \mathrm{h}^2}{\pi^2 2\pi \mathrm{h}^2 (k_F l) 4g\mu_B^2 m_b}\ln T\tau = -\frac{g^* n_v^2}{8\pi^2 (k_F l)}\frac{m^*}{m_b}\ln T\tau$$

Weakness of the $\chi(T)$ dependence does not support the "dispersion instability" model

The "Fermion condensation" model predicts:
m^* or g^* to diverge $\propto 1/(n-n_c)^{3/8}$

$\chi^*(T) \propto T^{-2/3}$

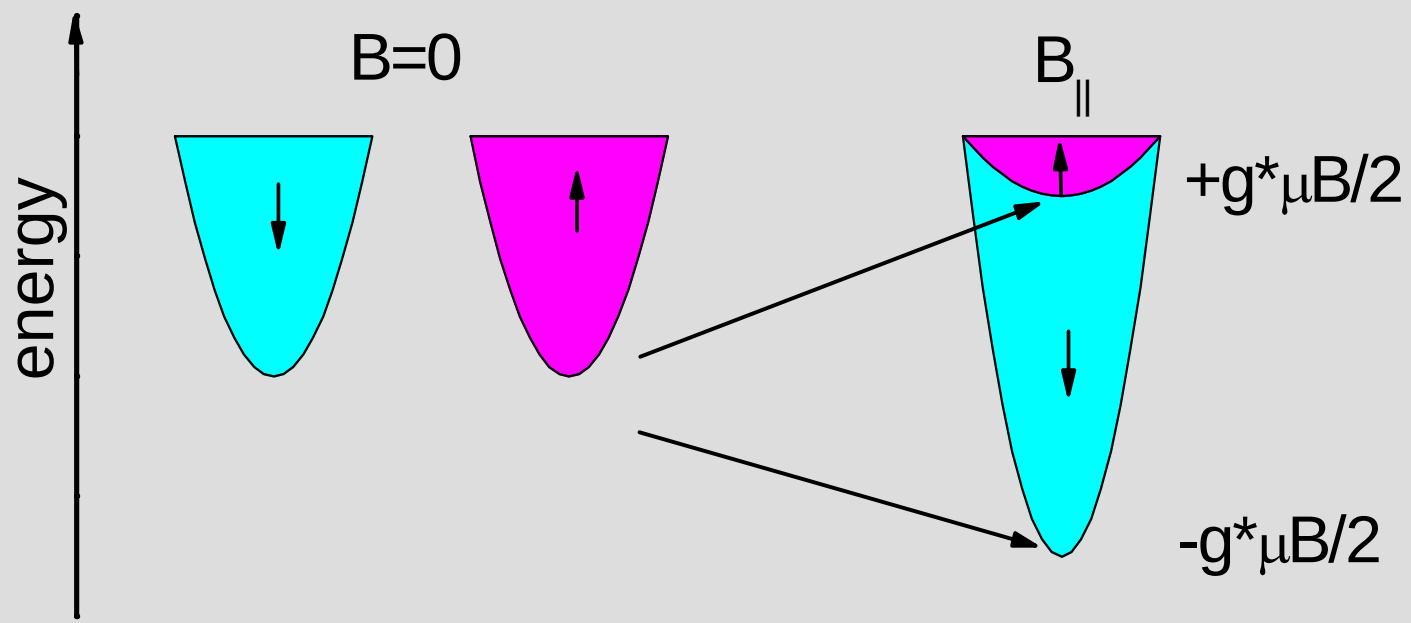
Note: an instability for $r_s \approx 7$



Single-particle spectra calculated for r_s= 1, 2, …8.

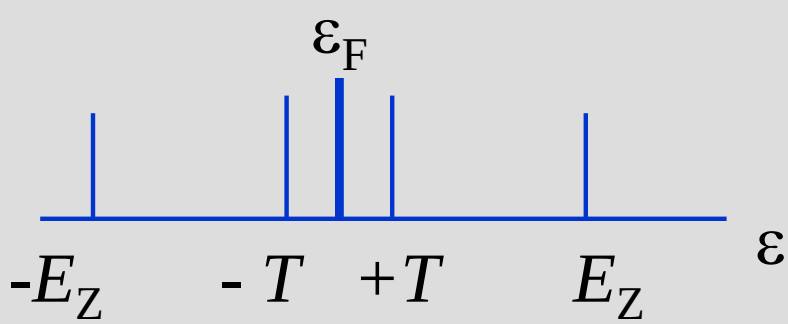
After:
Khodel, Shaginyan, JETP Lett. **51**(9), (1990).
Galiski, Khodel, cond-mat/0308203;
Baldo et al. J.Phys. Cond-mat, **16, 6431** (2004)

e-e interaction in partially spin-polarized 2D electron system: $g^*\mu B \sim E_F$



$m^*(1+\alpha)$
$T^D{}_0(1+\gamma)$
$g^*(1+\beta)$

$m^*(1-\alpha)$
$T^D{}_0(1-\gamma)$
$g^*(1-\beta)$



Anticipated splitting of up and down masses

RPA result for $r_s < 1$

$$\frac{m^*_{\uparrow/\downarrow}}{m} = \frac{1 - \frac{r_s}{\pi\sqrt{1\pm\zeta}} \int_0^\infty d\omega \left[\frac{\omega}{(1+\omega^2)^{3/2}}\right] \ln\left(1 - \frac{\omega}{2\sqrt{1+\omega^2}} - \frac{\omega}{2\sqrt{\left(\frac{1\mp\zeta}{1\pm\zeta}\right)+\omega^2}}\right)}{1 - \frac{r_s}{\pi\sqrt{1\pm\zeta}} \int_0^\infty d\omega \left[\frac{\omega}{(1+\omega^2)^{3/2}}\right] \ln\left(1 - \frac{\omega}{2\sqrt{1+\omega^2}} - \frac{\omega}{2\sqrt{\left(\frac{1\mp\zeta}{1\pm\zeta}\right)+\omega^2}}\right) - \frac{r_s}{\pi\sqrt{1\pm\zeta}}\left(\ln\left(\frac{r_s}{\sqrt{1\pm\zeta}}\right) + 1\right)}$$

$$\frac{m^*_{\uparrow/\downarrow}}{m} = 1 + \frac{r_S}{\pi}\ln(er_s) \mp \zeta\frac{r_S}{2\pi}\ln(e^2 r_s),$$

A.W.Overhauser, *PRB* (1971)
(for 3D)

Anticipated splitting of up and down masses

Gangadharaiah, Maslov (2005)

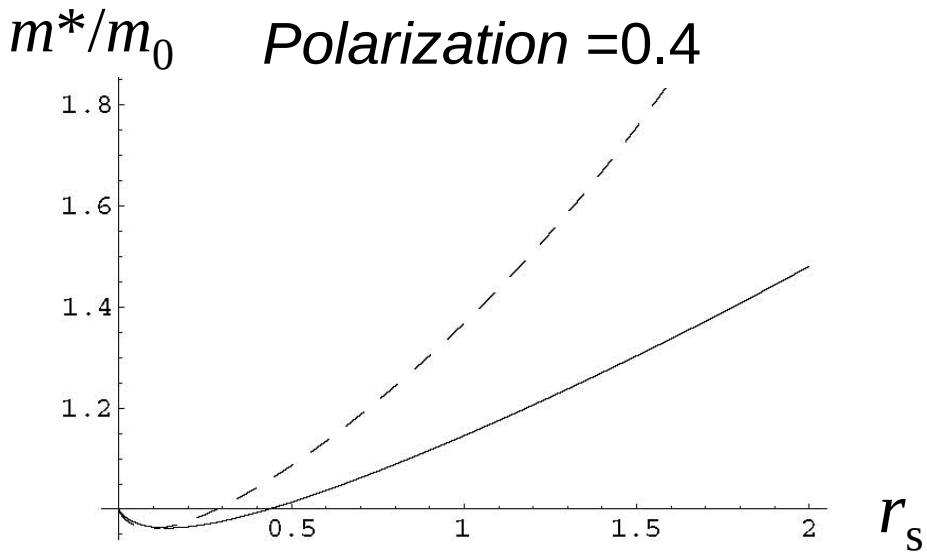


FIG. 1. The effective mass dependence on r_s for $\zeta = 0.4$. Solid: spin-up; dashed: spin-down.

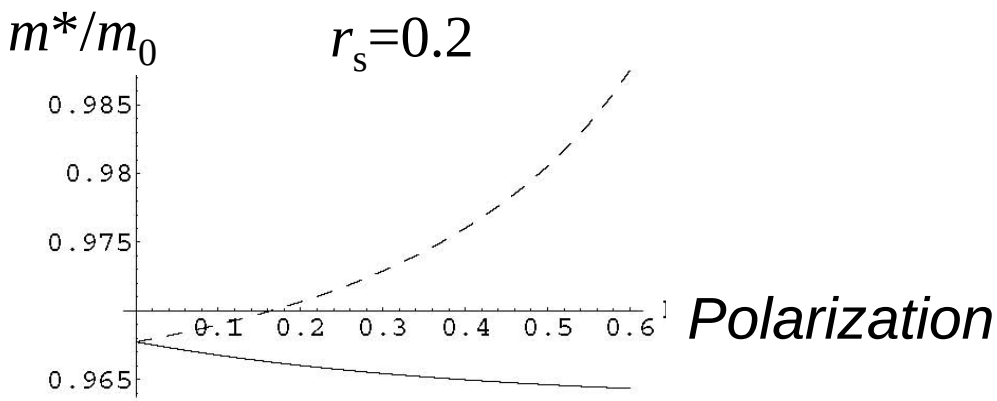
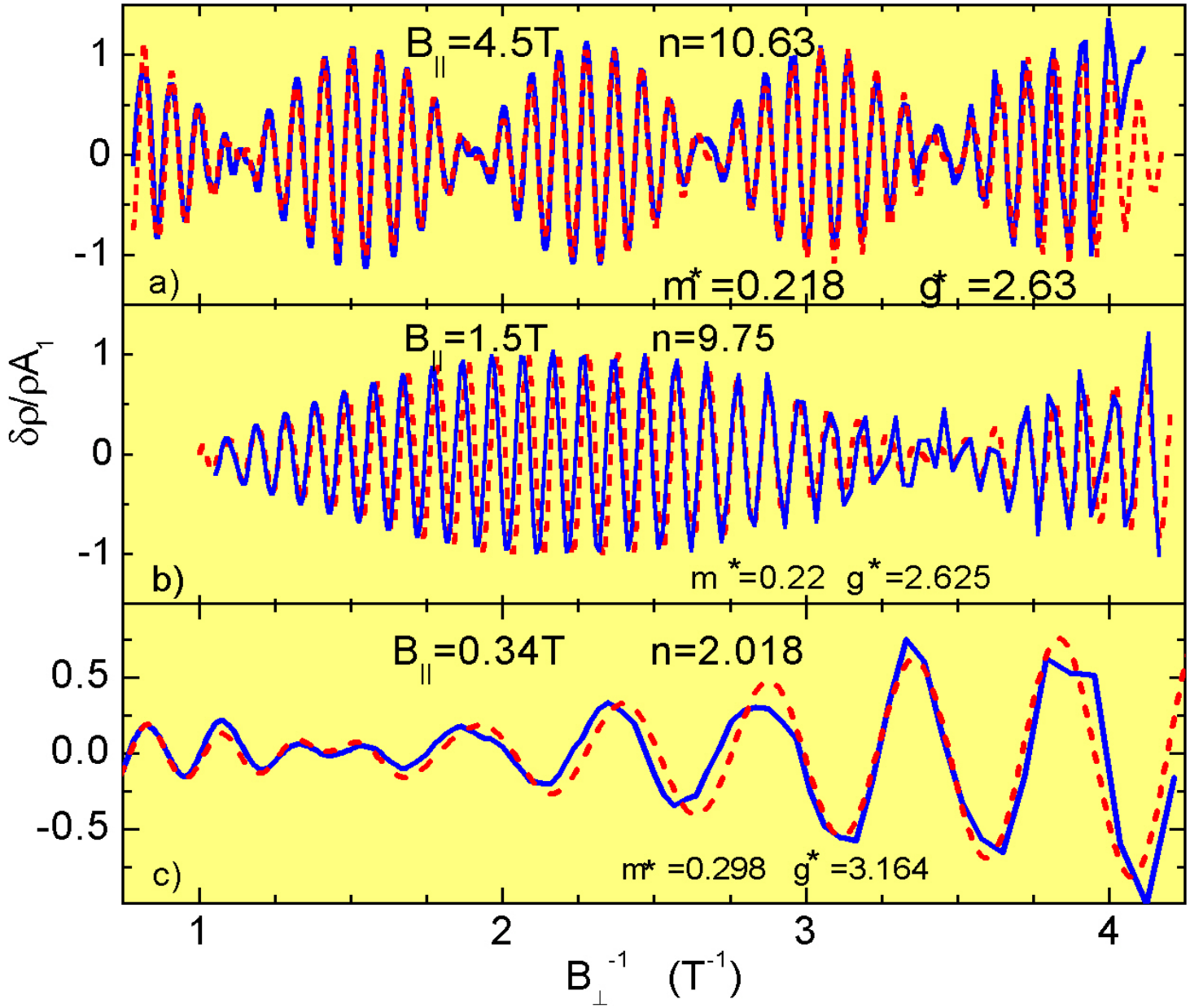
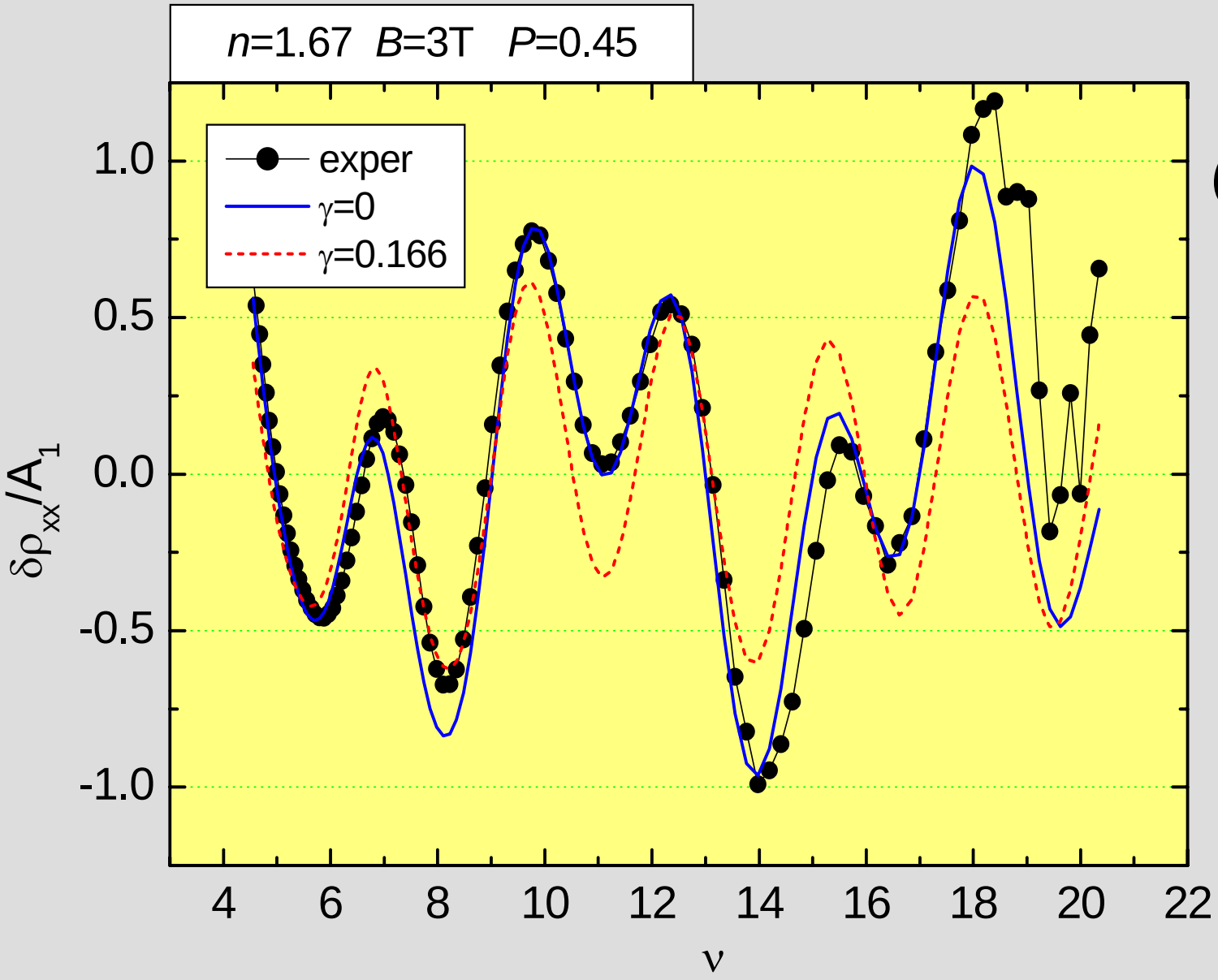


FIG. 2. The effective mass dependence on ζ for $r_s = 0.2$. Solid: spin-up; dashed: spin-down.

SdH oscillations with normalized amplitude



VP et al., *PRL* (2002)



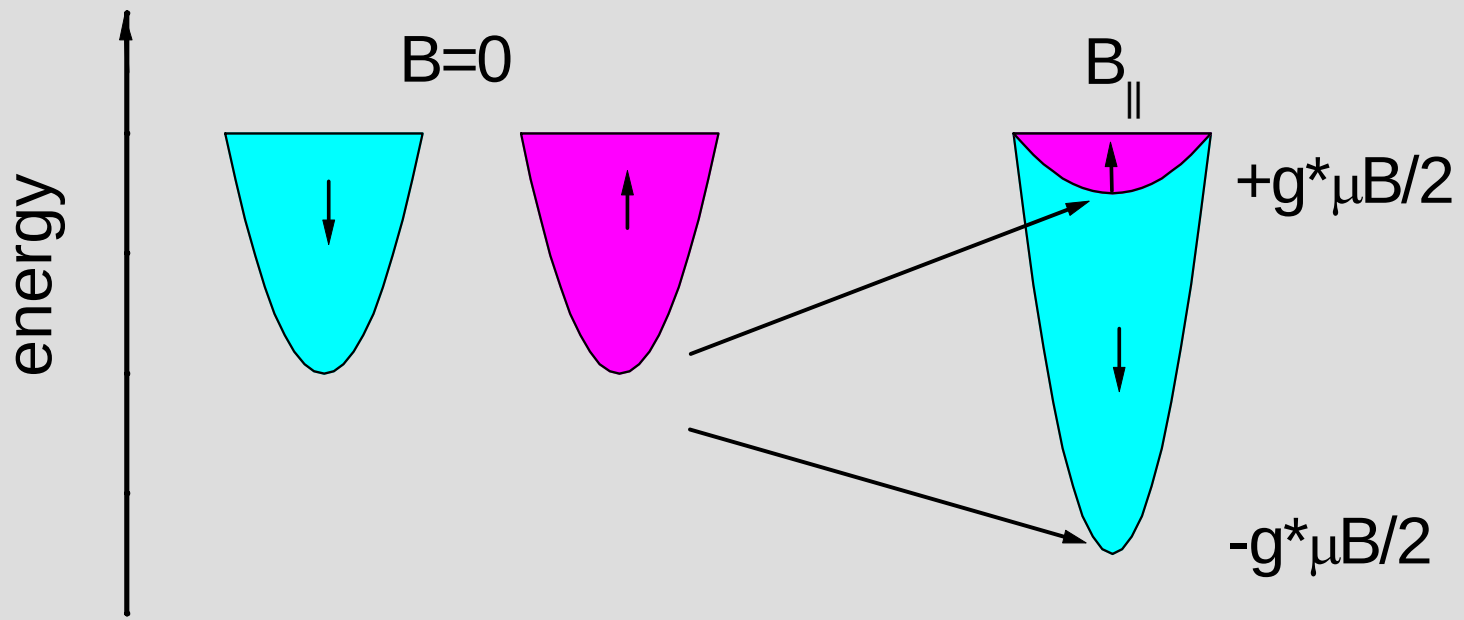
$(m^*/\tau_q)_{\uparrow\downarrow} = (1 \pm \gamma)$

The main result:

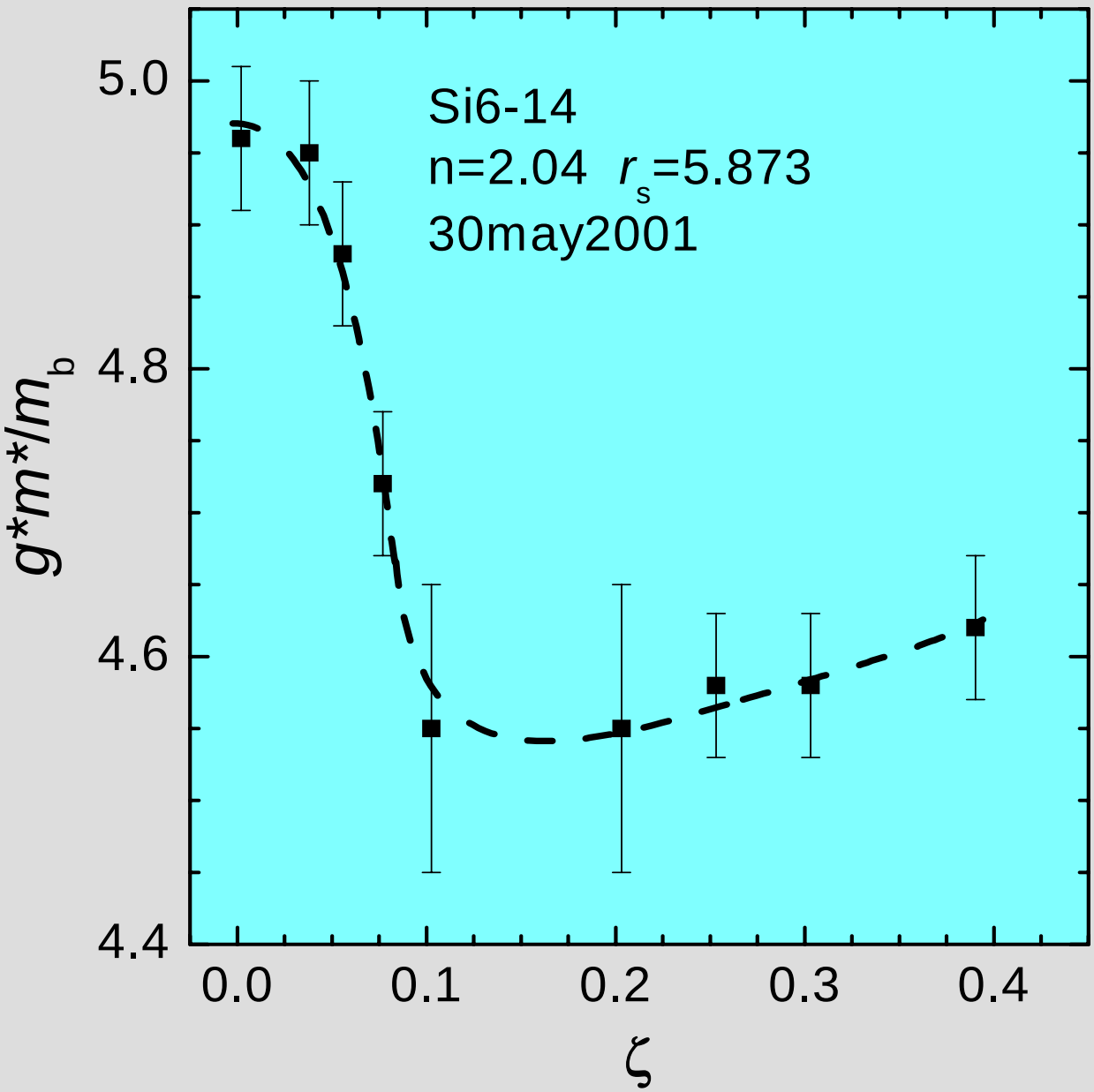
Electrons interact in the overall ensemble, rather than within each subbands

Possible interpretation:
The main channel of interaction is provided by spinless excitations with a wide energy spectrum ~ E_F

Non-linear effects: $g^*\mu B \sim E_F$



Renormalization of χ^* vs spin polarization $\zeta = (n_\uparrow - n_\downarrow)/n$



The sharp drop in $\chi^*(B_{||})$ is consistent with the thermodynamic measurements of the $M(B_{||})$ on Si-MOS

O.Prus, M.Reznikov et al. PRB (2003)

THERMODYNAMIC SPIN MAGNETIZATION OF . . .

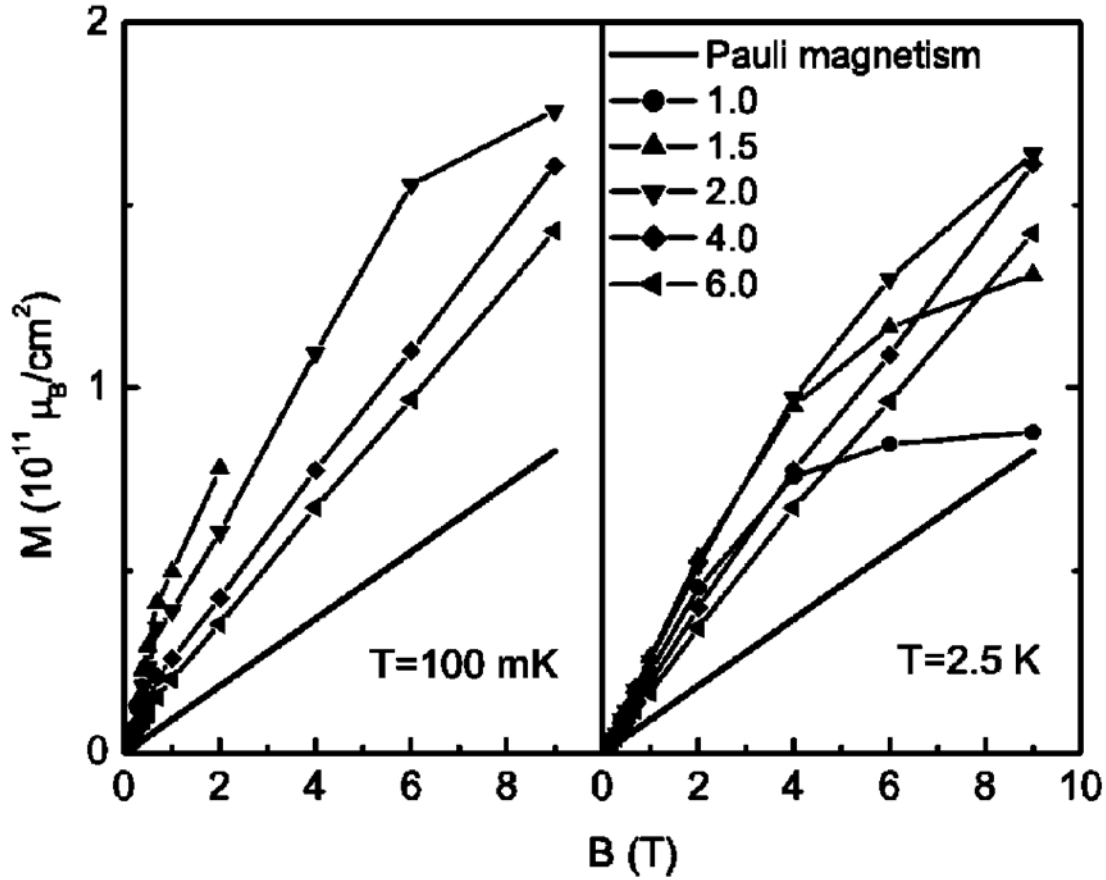
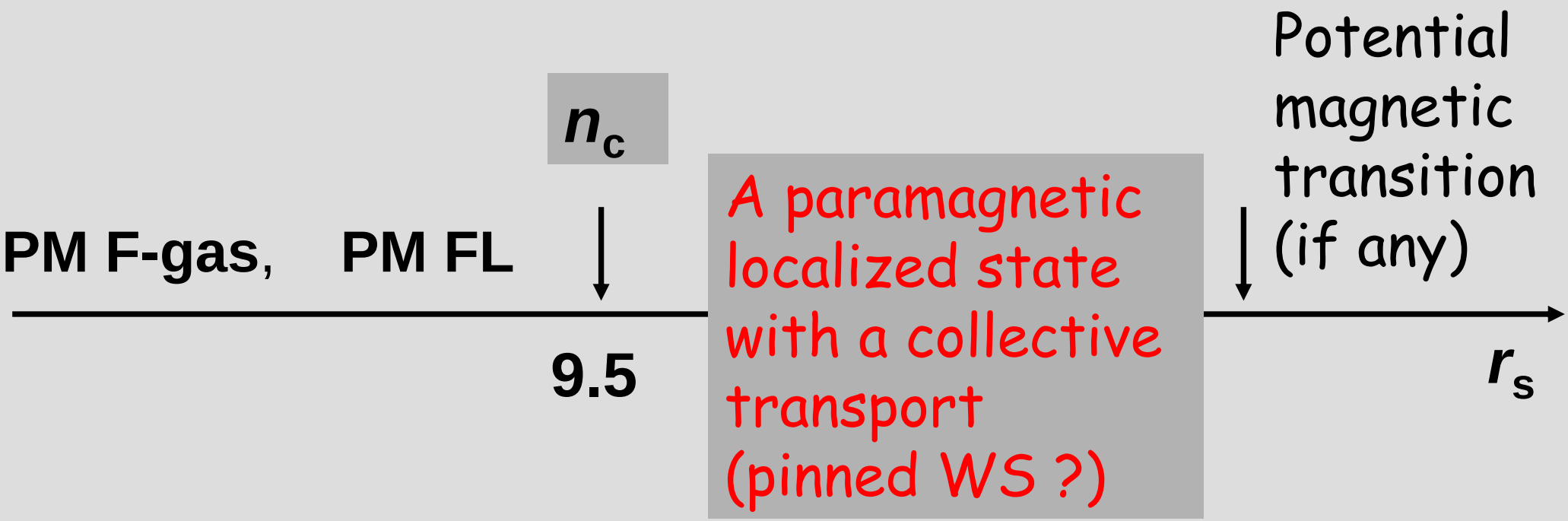


FIG. 5. Magnetization as a function of magnetic field at $T = 100$ mK and $T = 2.5$ K. Densities are given in 10^{11} cm^{-2} units. Bold line: Pauli magnetization for noninteracting degenerate fermions. As the temperature and magnetic field are reduced, the magnetization becomes increasingly nonlinear.

Summary

- Strong enchancement in χ^*, m^*, g^* as n decreases but FL remains paramagnetic
- No deviation from FL are seen so far
- e-e interactions takes place in a wide range of energies, and is insensitive to the Zeeman splitting
- Inconsistency with the non-FL "Fermion condensation" model

Thank you for attention !