Fermi Liquid Interaction-Induced Metallic Transport of Dilute 2D Holes in GaAs: A Critical Examination by the Hall Effect

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Outline

- 2D metal-insulator transition basics: the “anomalous” metallic transport and parallel magnetic field effect

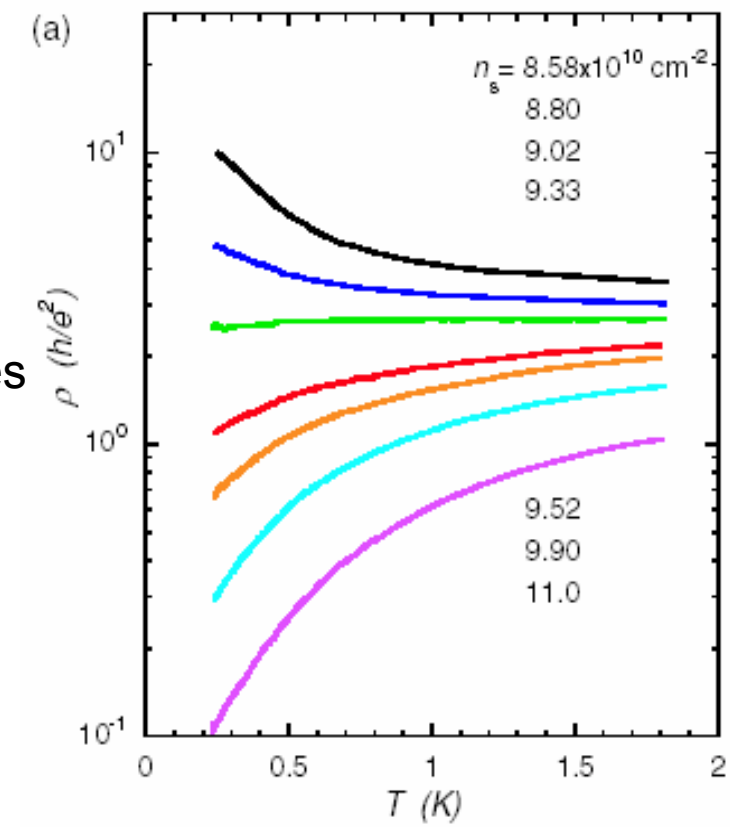
- Can the Fermi liquid interaction theory explain the 2D metallic transport? --- An examination by the Hall effect for dilute *p*-GaAs system

- Zero field spin polarization of low density 2D holes in *symmetric* GaAs quantum well

The “anomalous” metallic transport and MIT in dilute 2D systems

Si-MOSFET, Kravchenko and Sarachik data

Density decreases

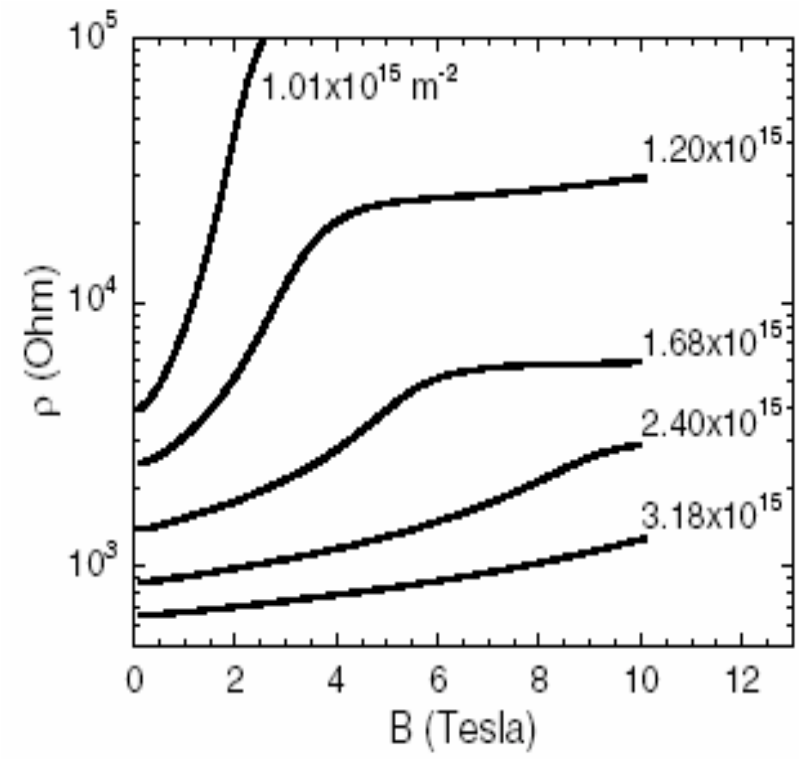


Critical density

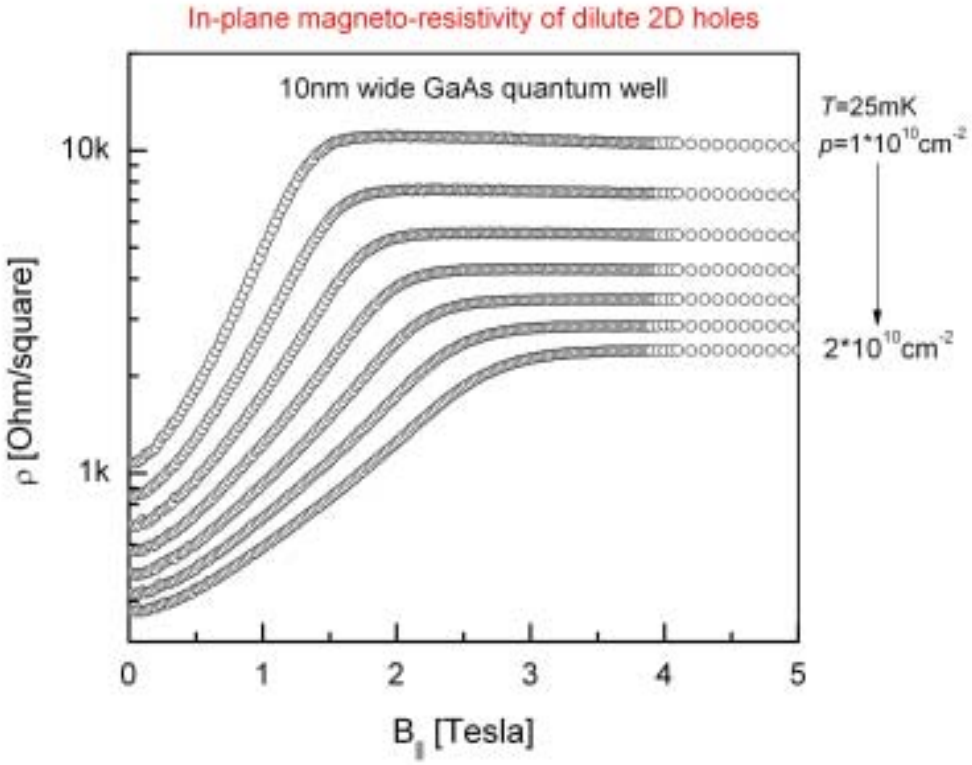
Low density (large r_s), high mobility (high τ)

The destruction of 2D metallic state in $B_{||}$

Si-MOSFET, Shashikin *et al.,* PRL 2001



p-GaAs, Gao *et al.* unpublished data



Interaction corrections to the conductivity of 2D Fermi liquids

1. Diffusive regime, $k_B T < \hbar/\tau$ (Altshuler, Aronov, 1980's):

$$\Delta\sigma = 1/\pi\ e^2/h\ \{1+3(1-\ln(1+F_o^\sigma)/F_o^\sigma)\}\ \ln(k_B T\ \tau/\hbar)$$

F_o^σ : Fermi liquid parameter

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2. Ballistic regime, $k_B T > \hbar/\tau$ (Zala, Narozhny, Aleiner/ZNA 2001):

Easily satisfied for 2D metallic samples

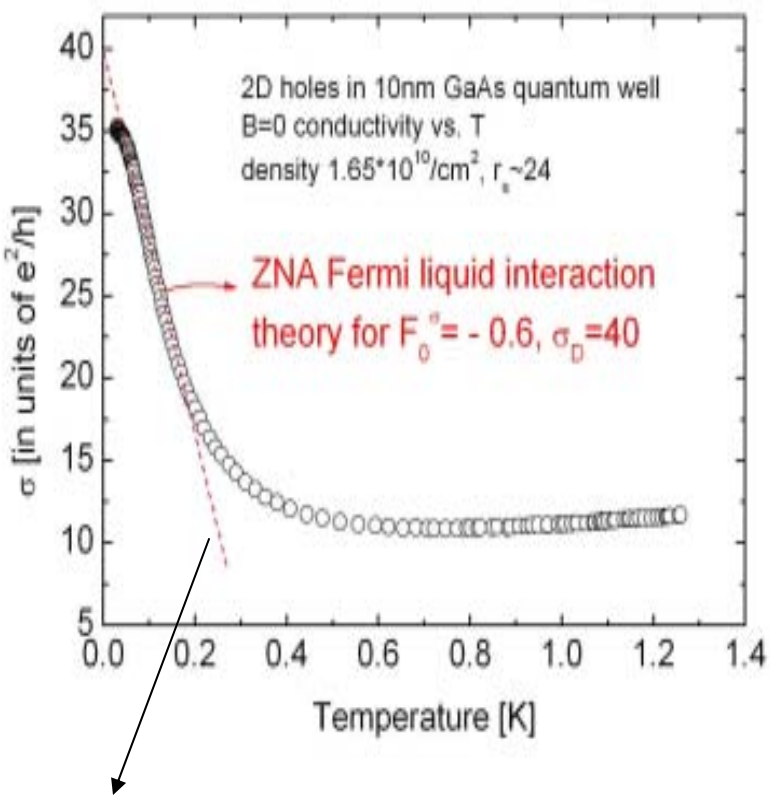
$$\Delta\sigma = 1/\pi\ e^2/\hbar\ k_B T\ \tau/\hbar\ \{1+3\ F_o^\sigma/(1+F_o^\sigma)\}$$

F_o^σ : Fermi liquid parameter

Note: valid for $T \ll T_F$!!

The 2D metallic conductivity explained as the Fermi liquid interaction correction

Exemplary analysis from Gao *et al.* PRL, 2004

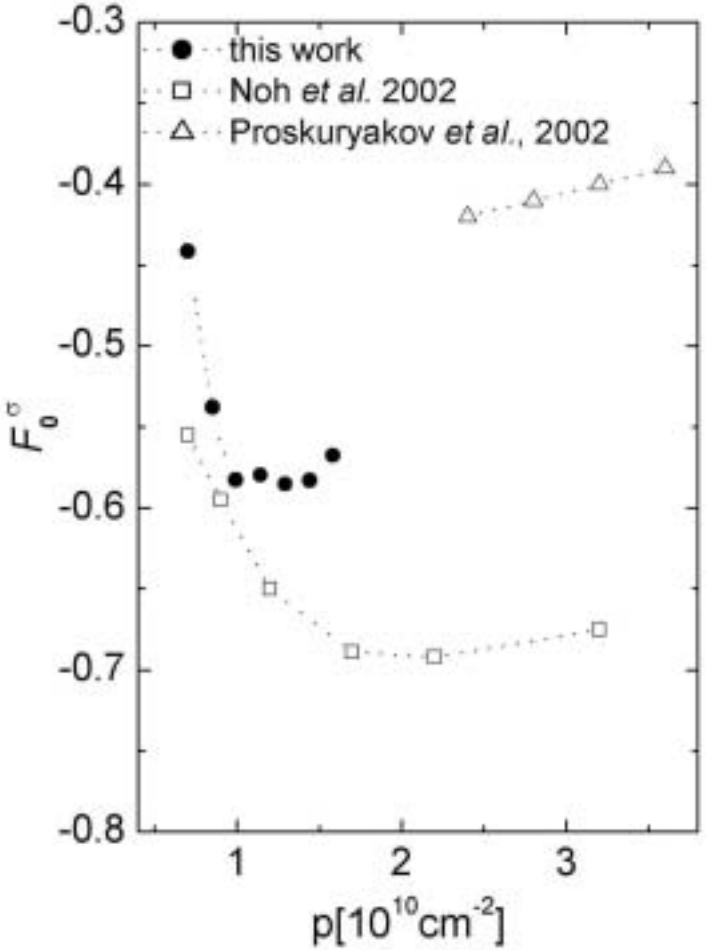


$$\sigma(T) = \sigma_D + \sigma_D \times T / T_F \{1+3 F_o^\sigma /(1+ F_o^\sigma)\}$$

Proskuryakov *et al.*, PRL2002
Coleridge *et al.*, PRB 2002
Kvon *et al.*, PRB 2002
Shashkin *et al.*, PRB 2002
Noh *et al.*, PRB 2003
Pudalov *et al.*, PRL 2003
Vitkalov *et al.*, PRB 2003

and more….

How consistent are the fitted F_o^σ's ?



$$\Delta\sigma(T) = \sigma_D \times T / T_F \{1+3 F_o^\sigma /(1+ F_o^\sigma)\}$$

For metallic $\sigma(T)$, $-1<F_o^\sigma<-0.25$.

F_0^σ's by fitting metallic $\sigma(T)$ to interaction theory from different groups for *p*-GaAs system

Interaction corrections to the Hall coefficient of 2D Fermi liquids

Zala, Narozhny &Aleiner PRB, 64, 201201(2001)

Hall resistivity correction:

$\Delta\rho_{xy}(T)/\rho_{xy} \propto 1/\sigma_D \times \ln(1+11\pi/192 \times \hbar/T\tau) \times f(F_o^\sigma) \propto 1/T$ at high T

Longitudinal conductivity correction:

The same F_0^σ

$\Delta\sigma(T) = \sigma_D \times T/T_F \{1+3 F_o^\sigma/(1+F_o^\sigma)\}$

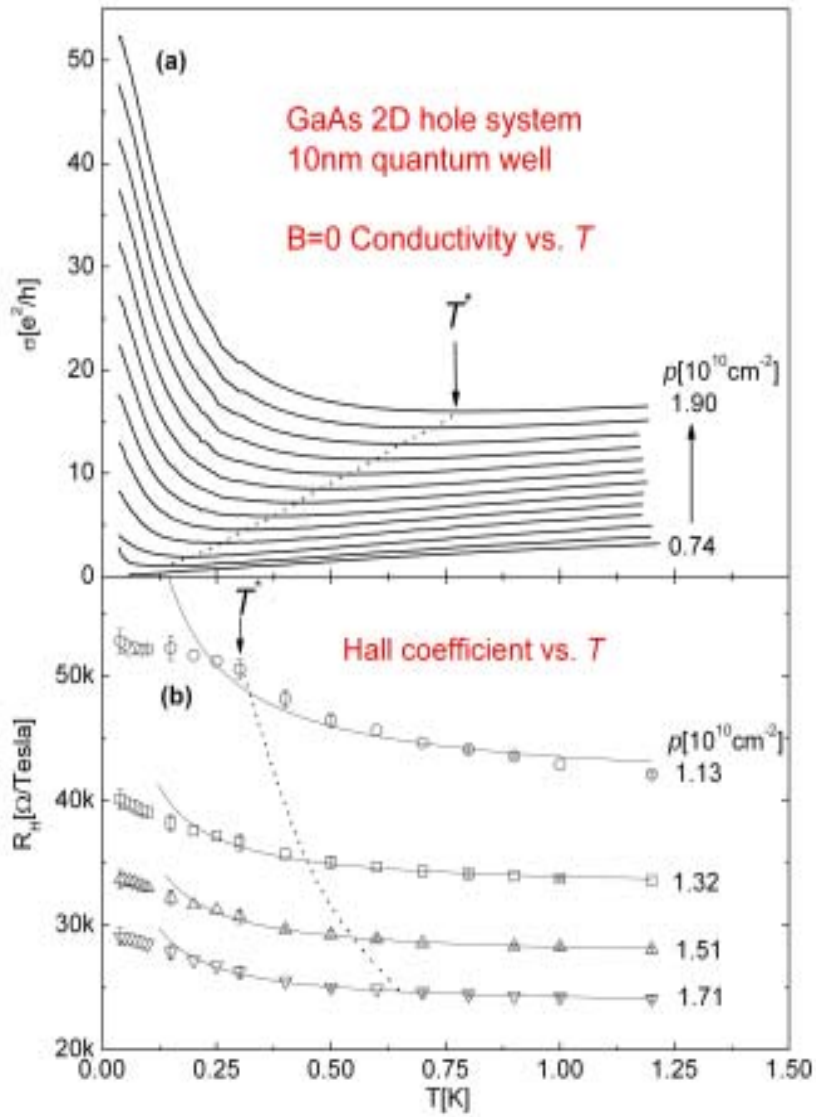
$\sigma(T)$ vs. $R_H(T)$ of dilute 2D holes in p-GaAs

Gao *et al.* PRL, 93, 256402 (2004)

~ a factor of 3 conductivity enhancement below T^* when $p>p_c$ ~$0.78*10^{10}/cm^2$

~ 20% Hall coefficient enhancement for metallic densities

Hall coefficient $R_H=\rho_{xy}/B$

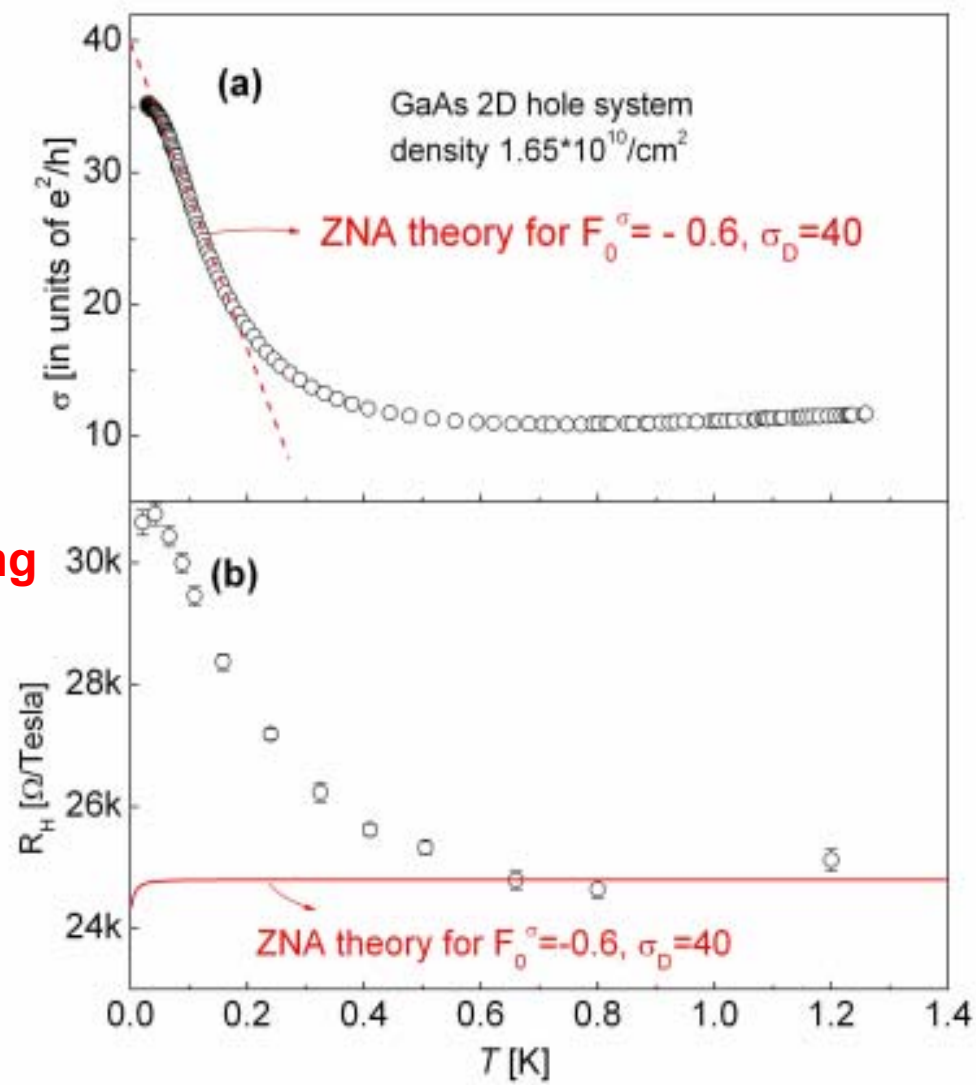


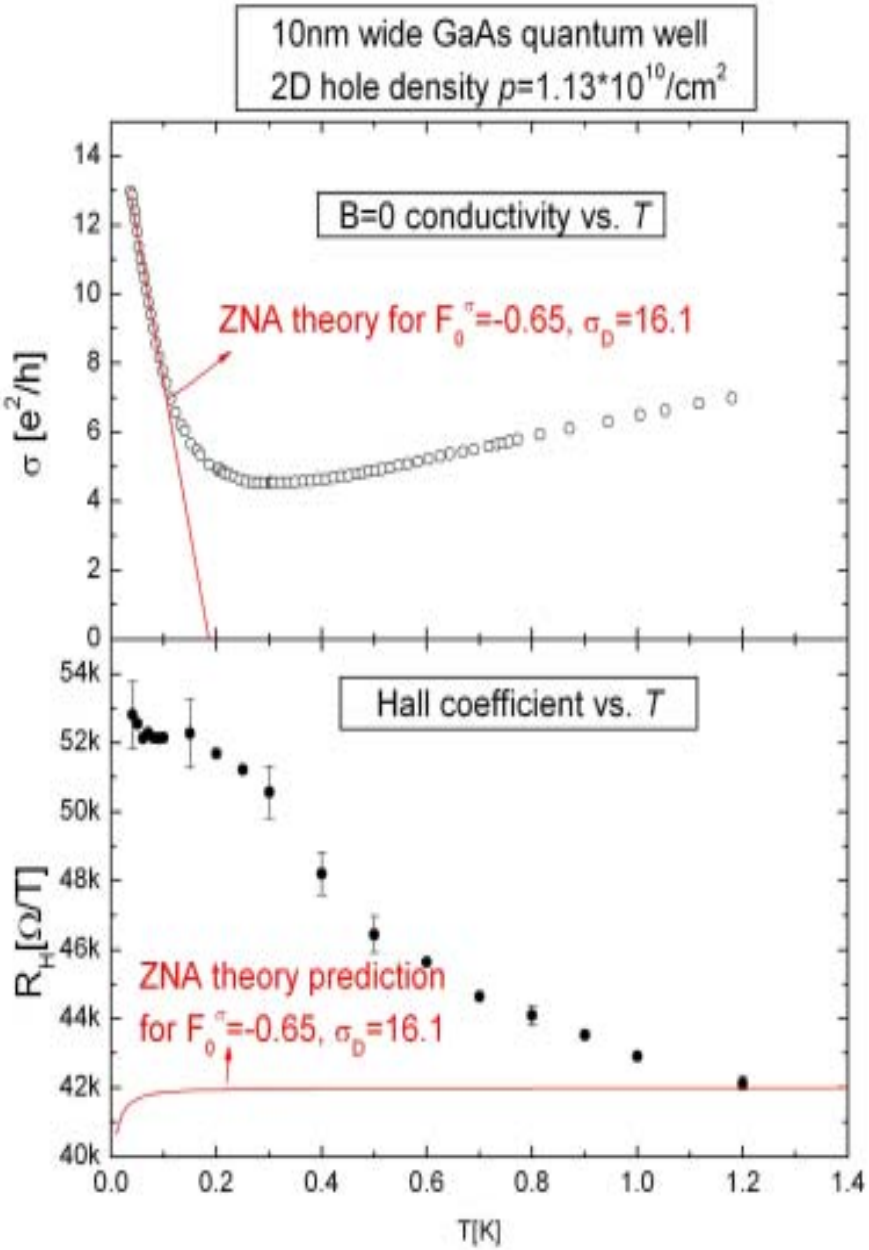
Fermi liquid interaction theory can **not** explain the $R_H(T)$ for 2D holes in GaAs

Inconsistencies between theory and data:

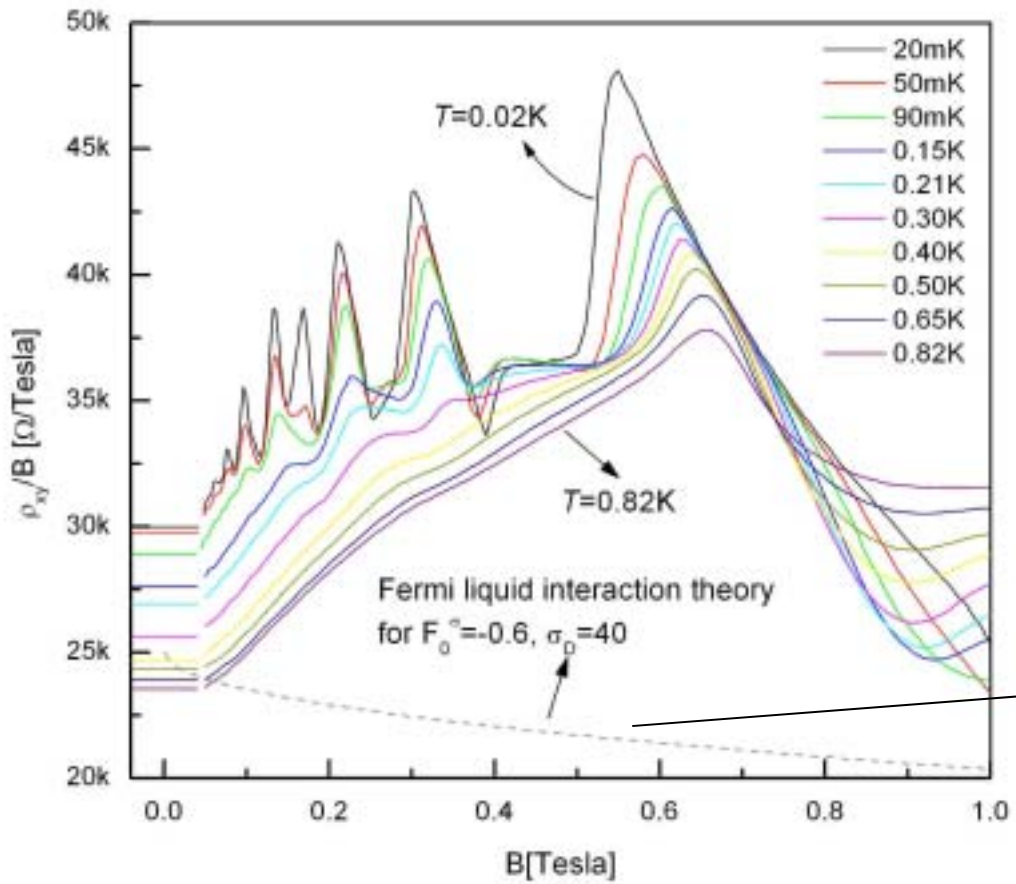
wrong sign for $\Delta\rho_{xy}$

the observed *T*-dependence is too strong




10nm wide GaAs quantum well
2D hole density p=1.13*10^10/cm^2
B=0 conductivity vs. T
ZNA theory for F_0^σ=-0.65, σ_D=16.1
σ [e^2/h]
Hall coefficient vs. T
ZNA theory prediction
for F_0^σ=-0.65, σ_D=16.1
R_H [Ω/T]
T[K]

Magnetic field enhanced slope of ρ_{xy} at high field ($\omega_c\tau$>1) regime



Slope of Hall resistivity vs. Perpendicular magnetic field Of 2D holes in GaAs

Density $1.65*10^{10}/cm^2$

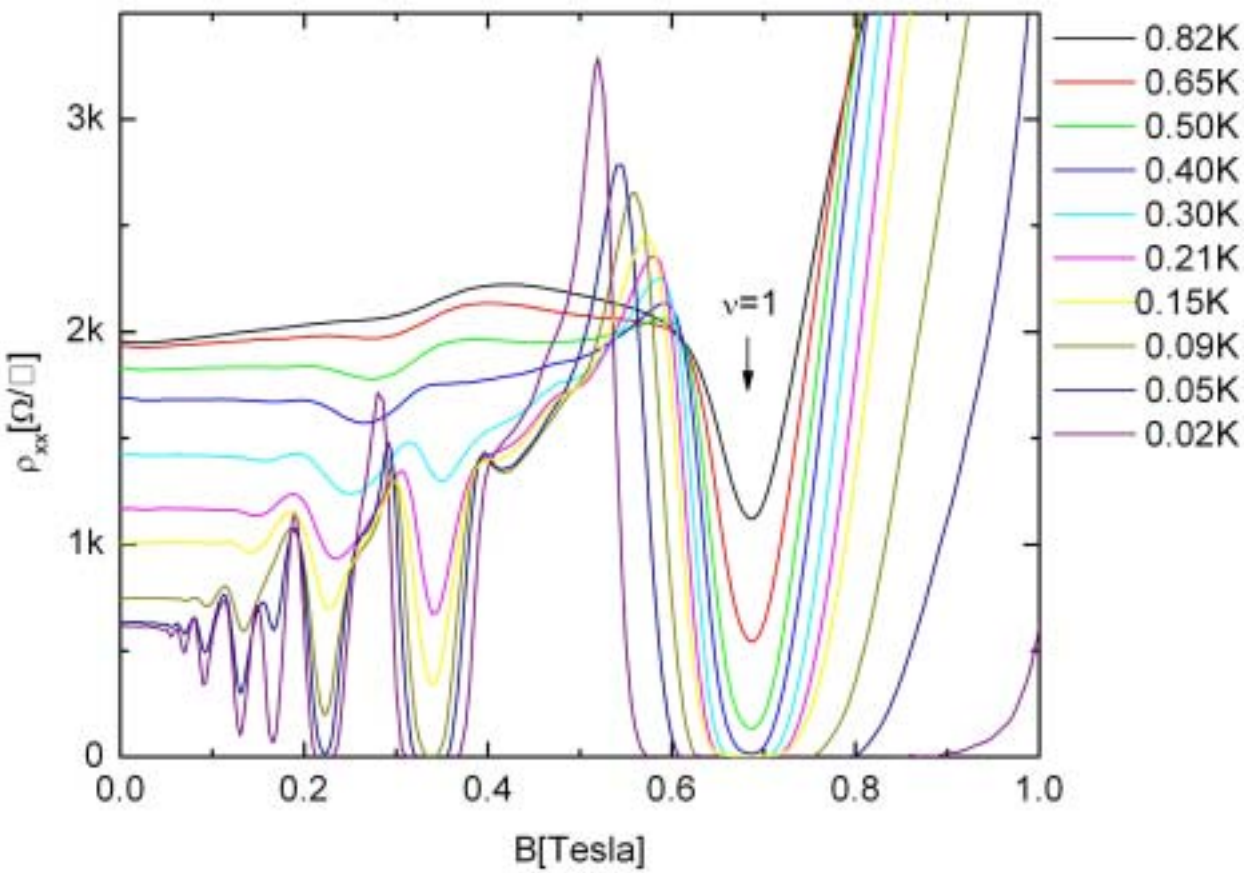
Gornyi and Mirlin's Fermi liquid Interaction theory (PRL 2003, PRB 2004) for $\omega_c\tau$>1 predicts a **negative** correction

Comparing the Hall resistivity of metallic 2D holes with Fermi liquid interaction theory

If the metallic $\sigma(T)$ is due to Fermi liquid interaction correction:

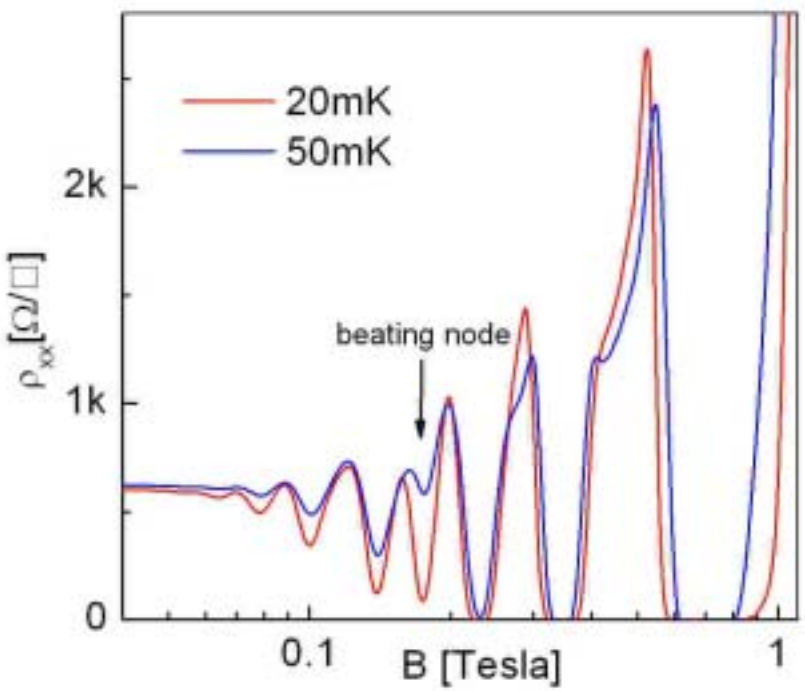
1. Low B regime: a decreasing $R_H(=\rho_{xy}/B)$ is expected as *T* drops — but we observed an enhanced R_H
2. High B regime: ρ_{xy}/B is expected to decrease as B increases — but we observed an increasing ρ_{xy}/B

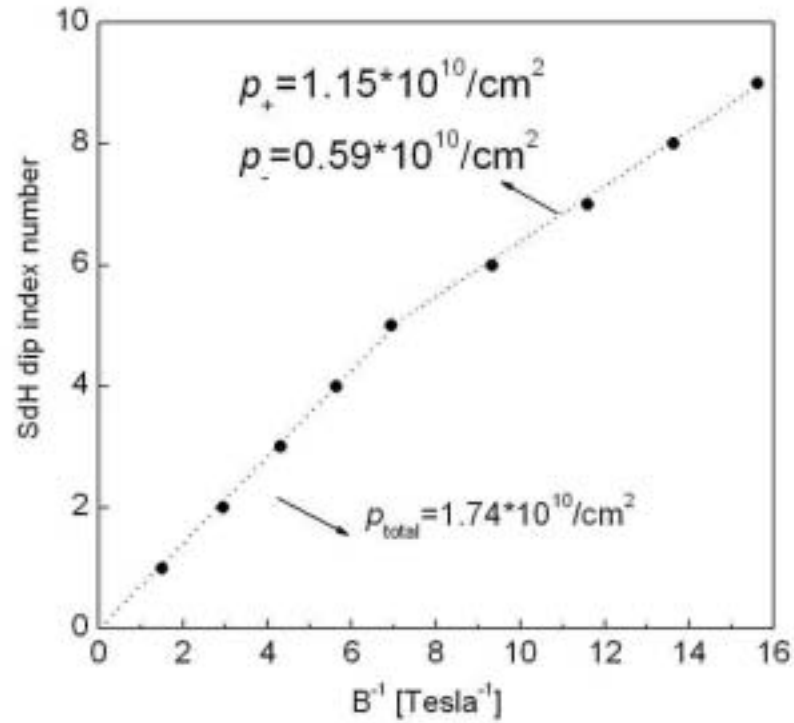
Temperature dependent Shubnikov de-Haas oscillations



2D holes in GaAs quantum well, density =1.65*10^{10}/cm^2

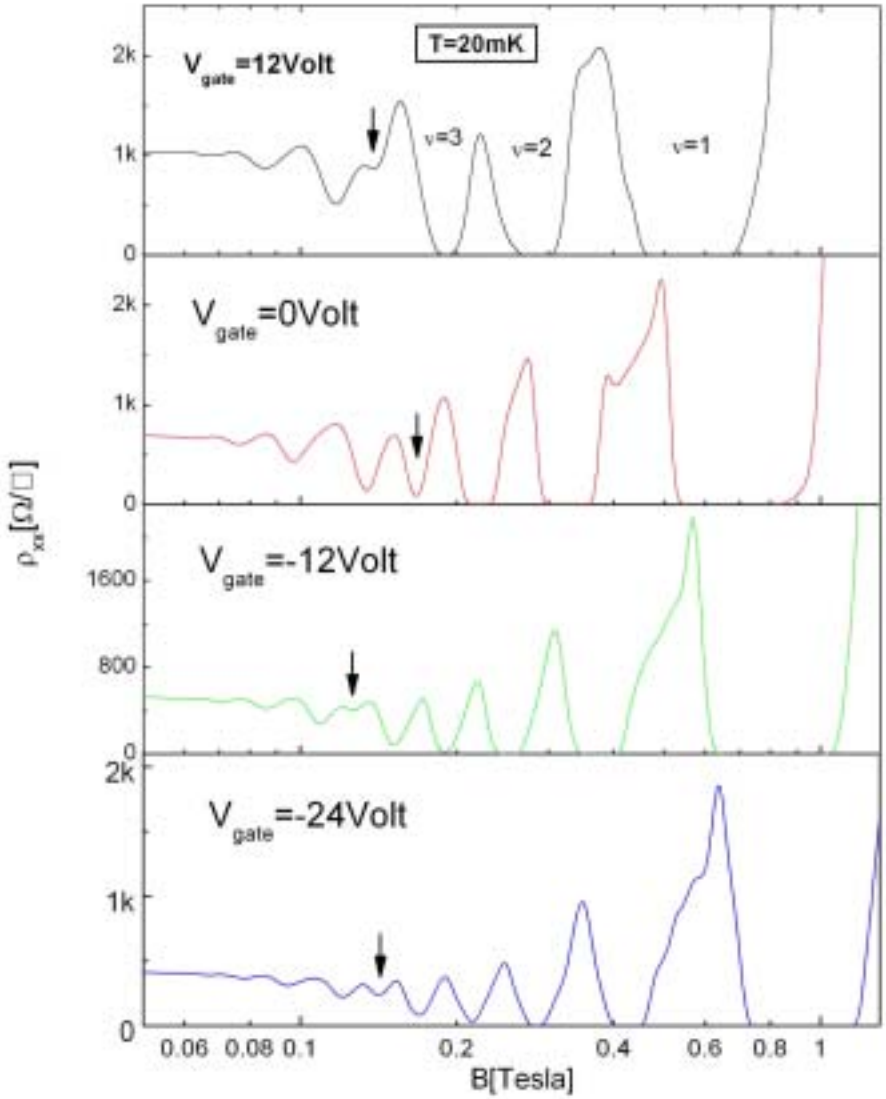
B=0 spin polarization of low density 2D holes in symmetric GaAs quantum well





~30% spin splitting at B=0

B=0 spin polarization of low density 2D holes in symmetric GaAs quantum well



density [10^{10}/cm^2]	B=0 spin splitting
1.4	28%
1.65	30%
1.9	26%
2.15	20%

Summary

Magneto-transport and Hall effect of dilute metallic 2D holes in GaAs quantum well:

- Low *B* Hall coefficient of is enhanced as *T* reduces
- Slope of ρ_{xy} further increases when *B* increase in the high field ($\omega_c\tau>1$) regime

Contradicts the Fermi liquid interaction theory, awaits explanation (a semi-classical screening model: Das Sarma & Hwang, cond-mat/0412670)

- Evidence of significant *B*=0 spin splitting