Novel energy scale in correlated 2D electron system

V.M. Pudalov, L.A. Morgun, A.Yu. Kuntsevich

Lebedev Physical Institute, Moscow

Motivation

Electron-electron correlations in 2D systems manifest in:

- **"Metallic" *T*-dependent conduction,**
- **Metal-Insulator Transition (MIT),**
- **Giant positive MR in $B_{||}$ field,**
- **Negative Compressibility,**
- **Strong enhancement in m^*, χ, g-factor,** etc.

These effects are traditionally explained in the FL framework, presuming a homogeneous single-phase state of the 2D system

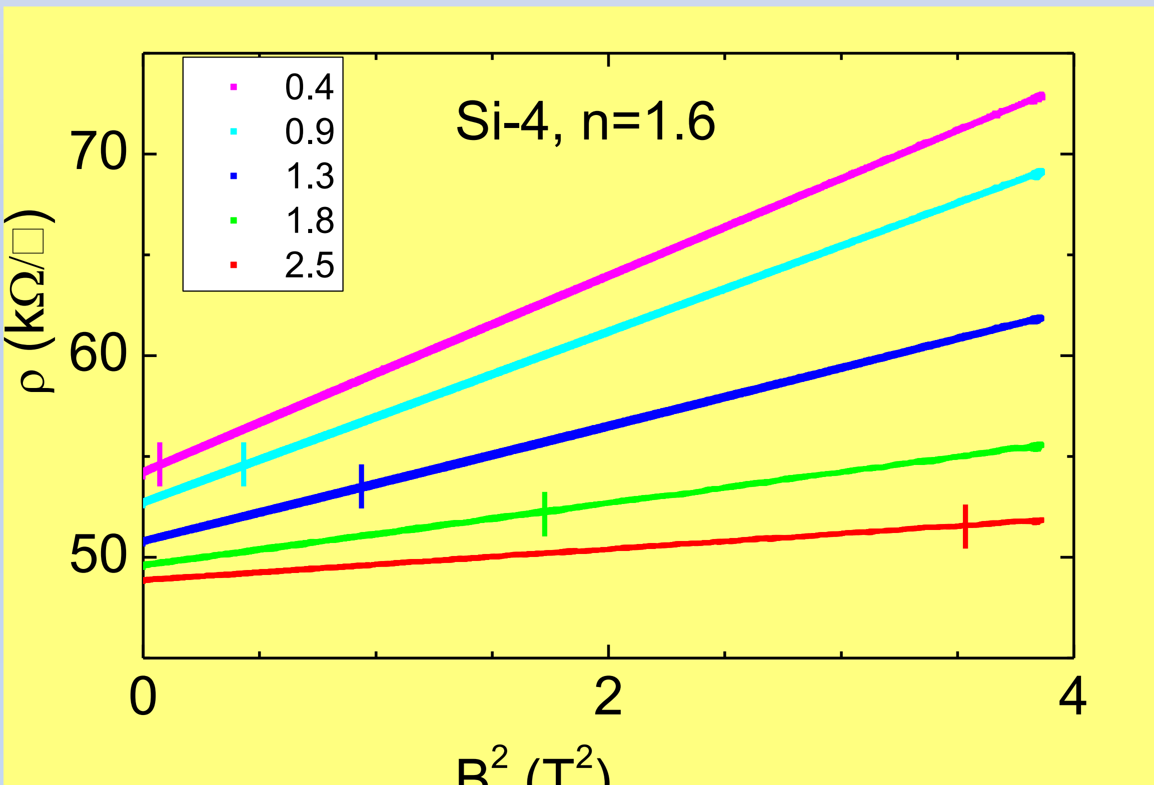
However, there are a number of theoretical suggestions and experimental data in favor of breaking homogeneous **FL-state** as r_s **increases.**

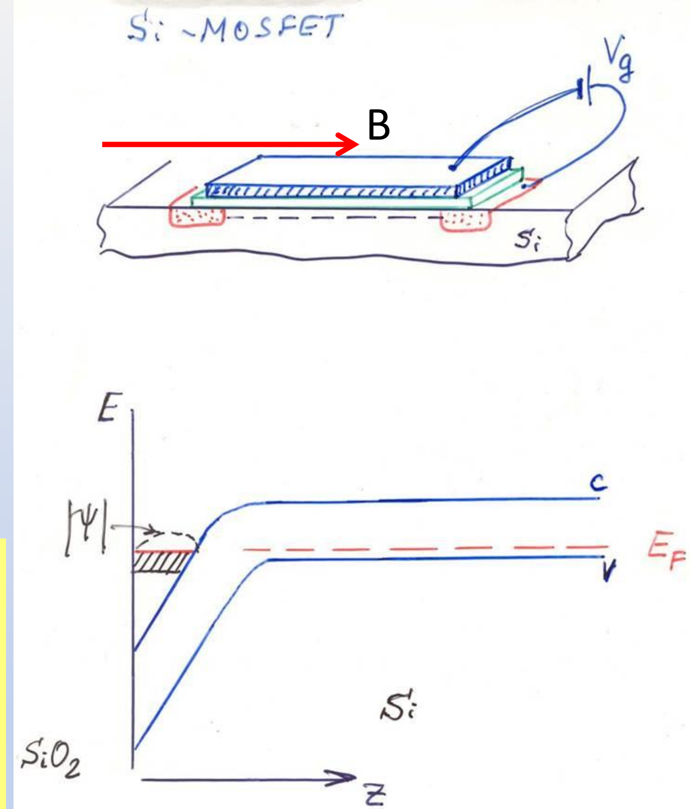
How these may be revealed in transport and thermodynamics ?

1. Magnetotransport

In weak ∥ field $g\mu B_{\parallel} << k_B T$

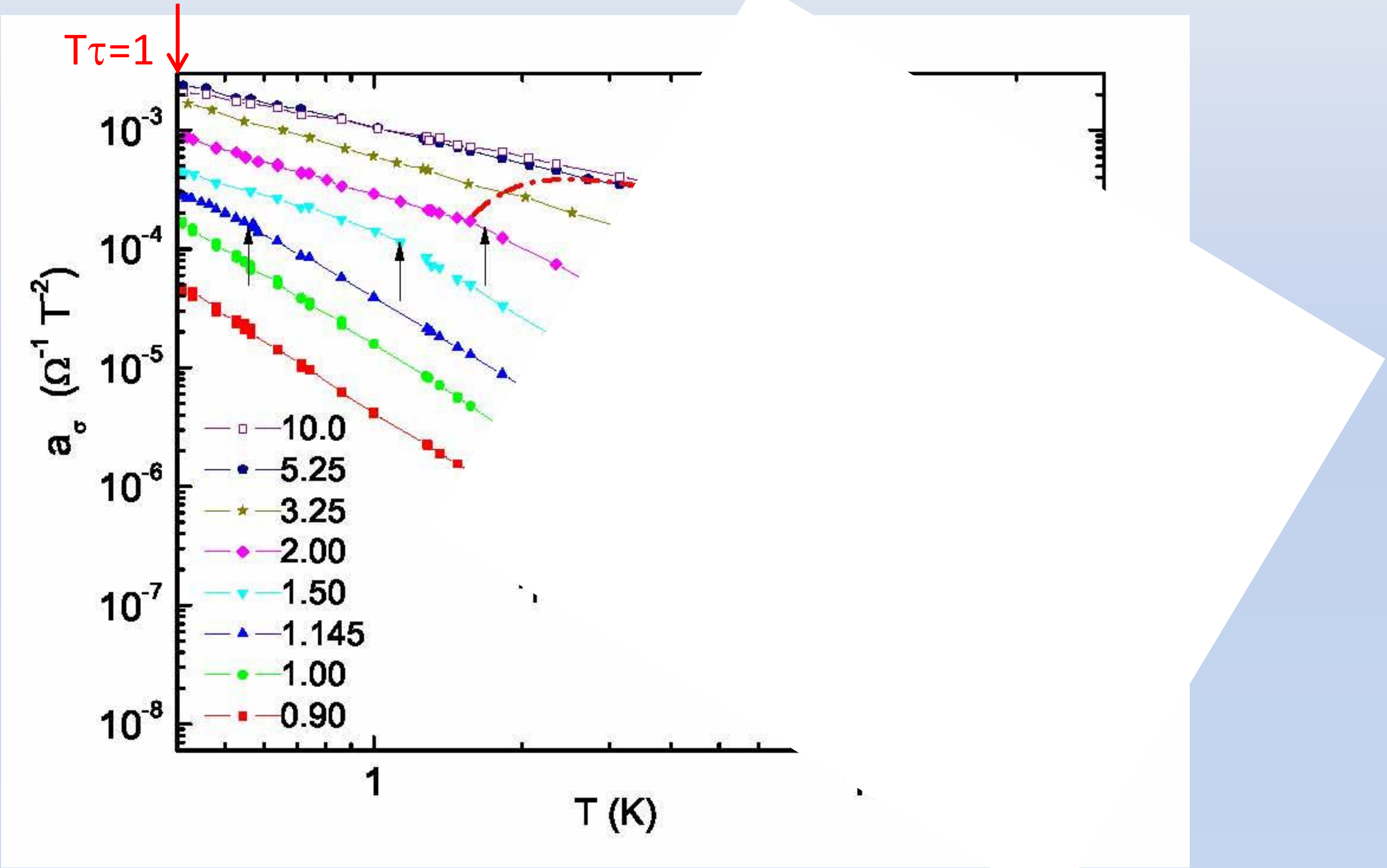
$$\sigma = \sigma_0 - a_\sigma B^2 + o\left(B^2\right)$$
$$\rho = \rho_0 + a_\rho B^2 + o(B^2),$$





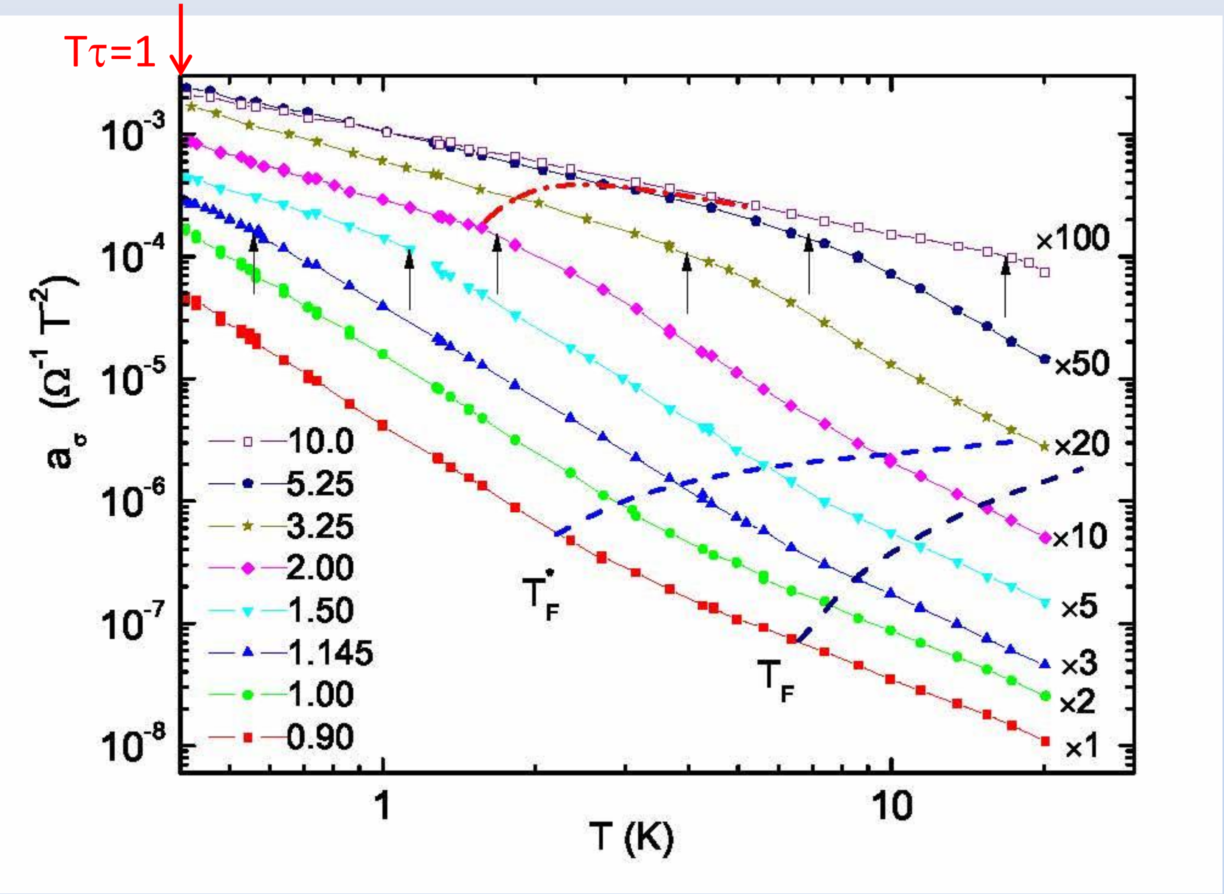
$$a_\sigma \equiv -\frac{1}{2}\partial^2\sigma/\partial B^2\Big|_{B=0}$$
$$a_\rho \equiv \frac{1}{2}\partial^2\rho/\partial B^2\Big|_{B=0},$$

$$a_\sigma = \left[\frac{1}{2\rho^2}\frac{\partial^2\rho}{\partial B^2} - \frac{1}{\rho^3}\left(\frac{\partial\rho}{\partial B}\right)^2\right]_{B=0} = \frac{1}{2\rho^2}\frac{\partial^2\rho}{\partial B^2}$$



an energy scale ***T*= T_kink < T_F*** ?

$$a_\sigma = \left[\frac{1}{2\rho^2}\frac{\partial^2\rho}{\partial B^2} - \frac{1}{\rho^3}\left(\frac{\partial\rho}{\partial B}\right)^2\right]_{B=0} = \frac{1}{2\rho^2}\frac{\partial^2\rho}{\partial B^2}$$



- ✓ Puzzling high-T regime sets at

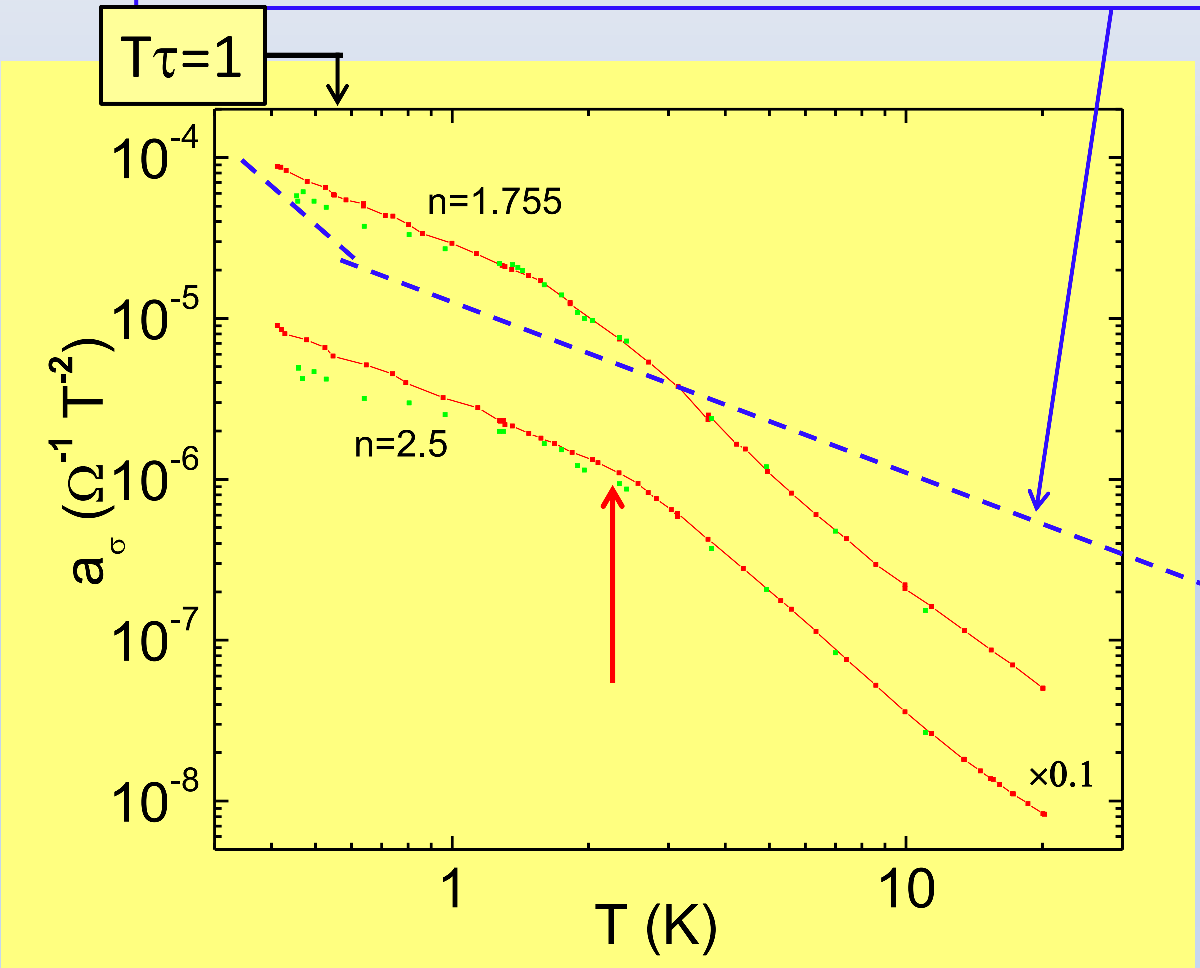
$\boxed{T > T_{kink}\,(n)}$

an energy scale $T^* = T_{kink} < T_F$?

FL theory:

$\delta\sigma \propto (B/T)^2 \longrightarrow a_\sigma \propto T^{-2}$ $\quad T << h/\tau k_B$

$\delta\sigma \propto (B/T)^2 T\tau \longrightarrow a_\sigma \propto T^{-1}$ $\quad T > h/\tau k_B$



- ✓ Origin of a controversy in FL parameters extracted from fitting the measured magnetoconductance

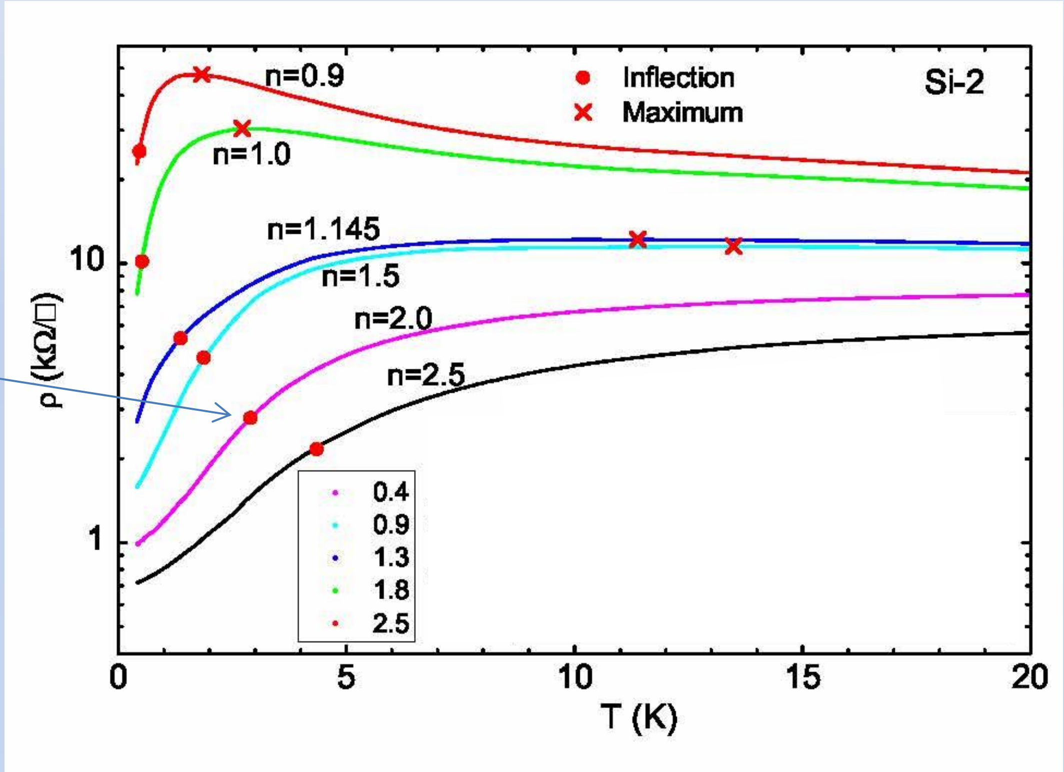
How *T may show up in other available low field data at *B<T* ?**

✓ 2. Transport in *B*=0

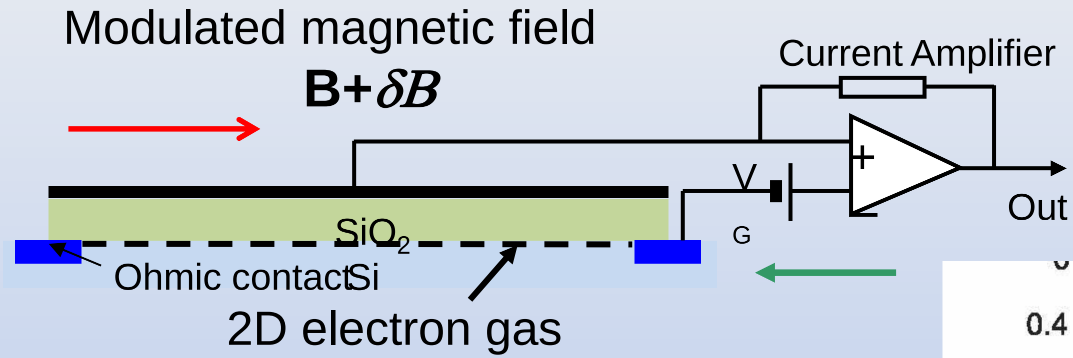
Inflection point

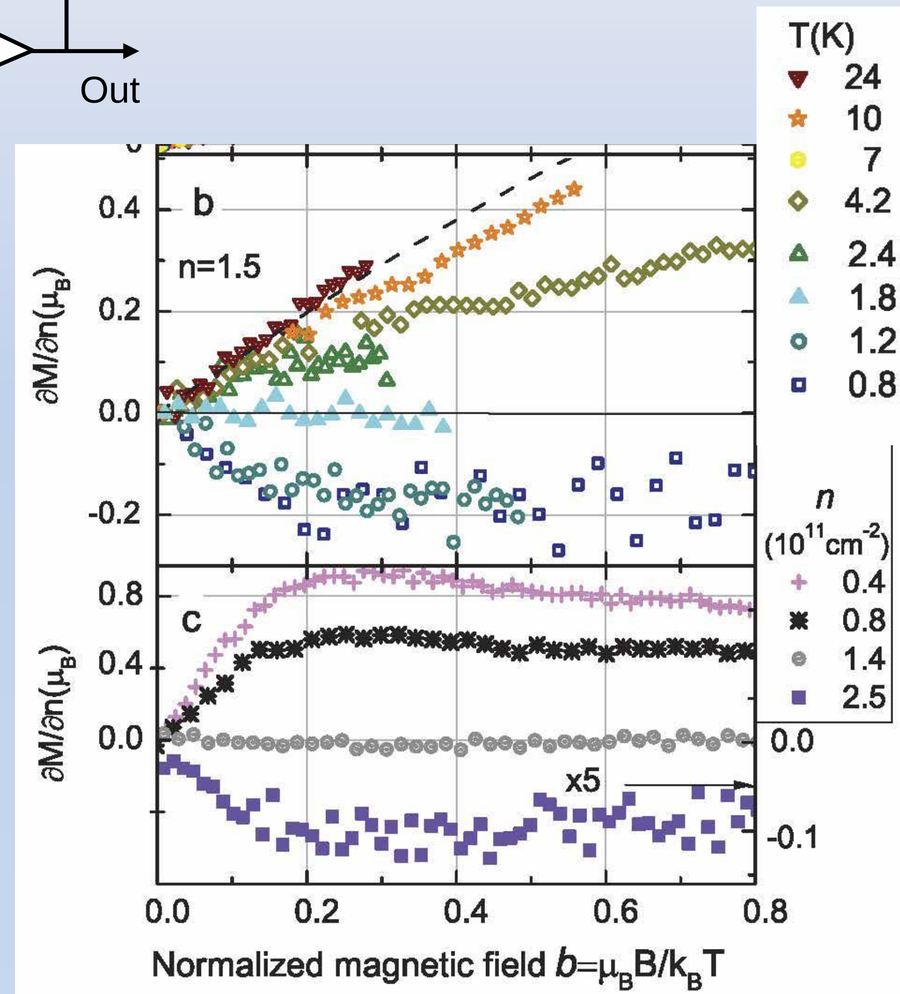
$d^2\rho/dT^2 = 0$

T_{infl}



✓ 3. Thermodynamic spin magnetization in weak field



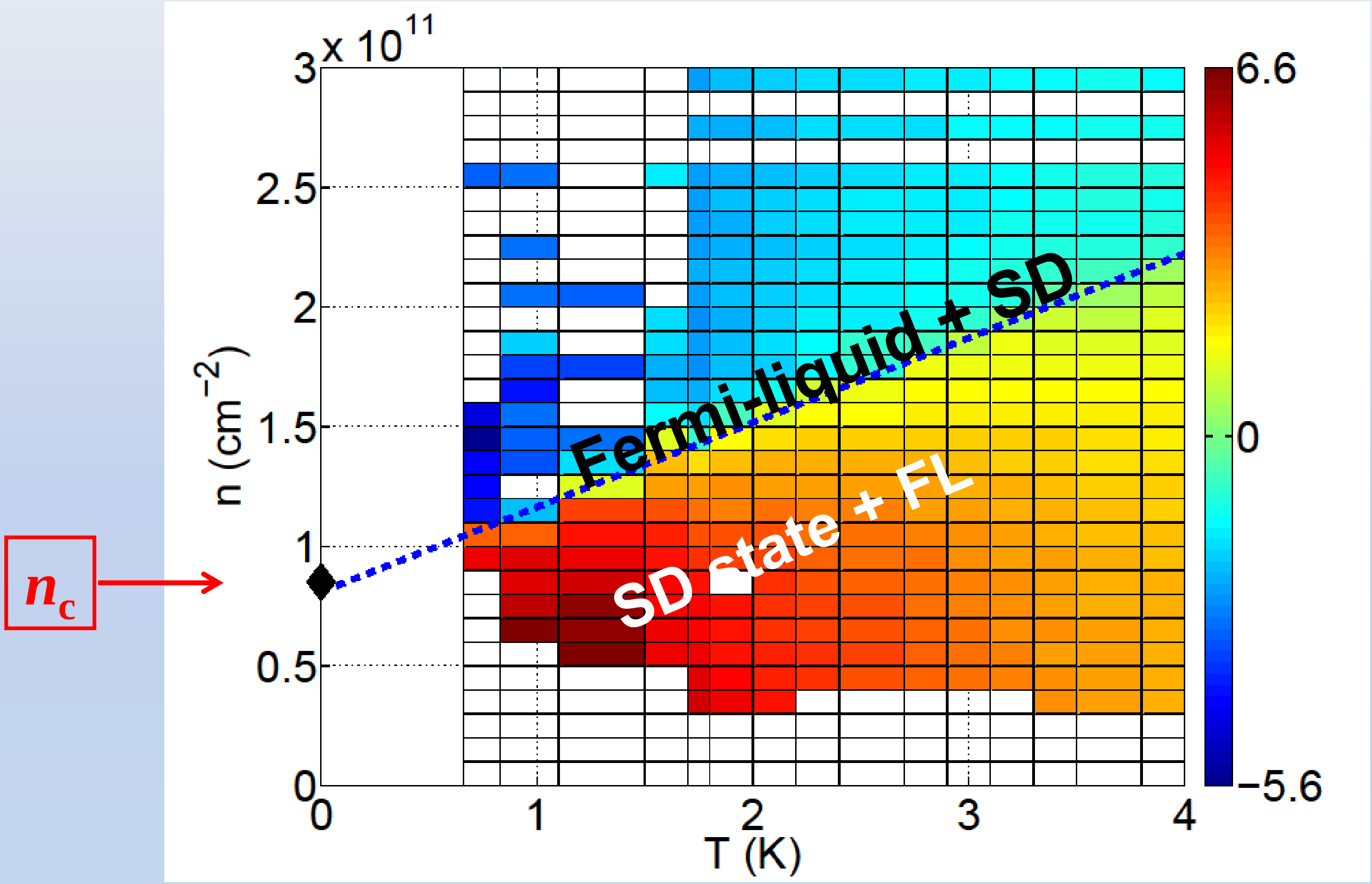


Sign change of dM/dn in weak field

$\longrightarrow$ $T(n)_{d\chi/dn}$

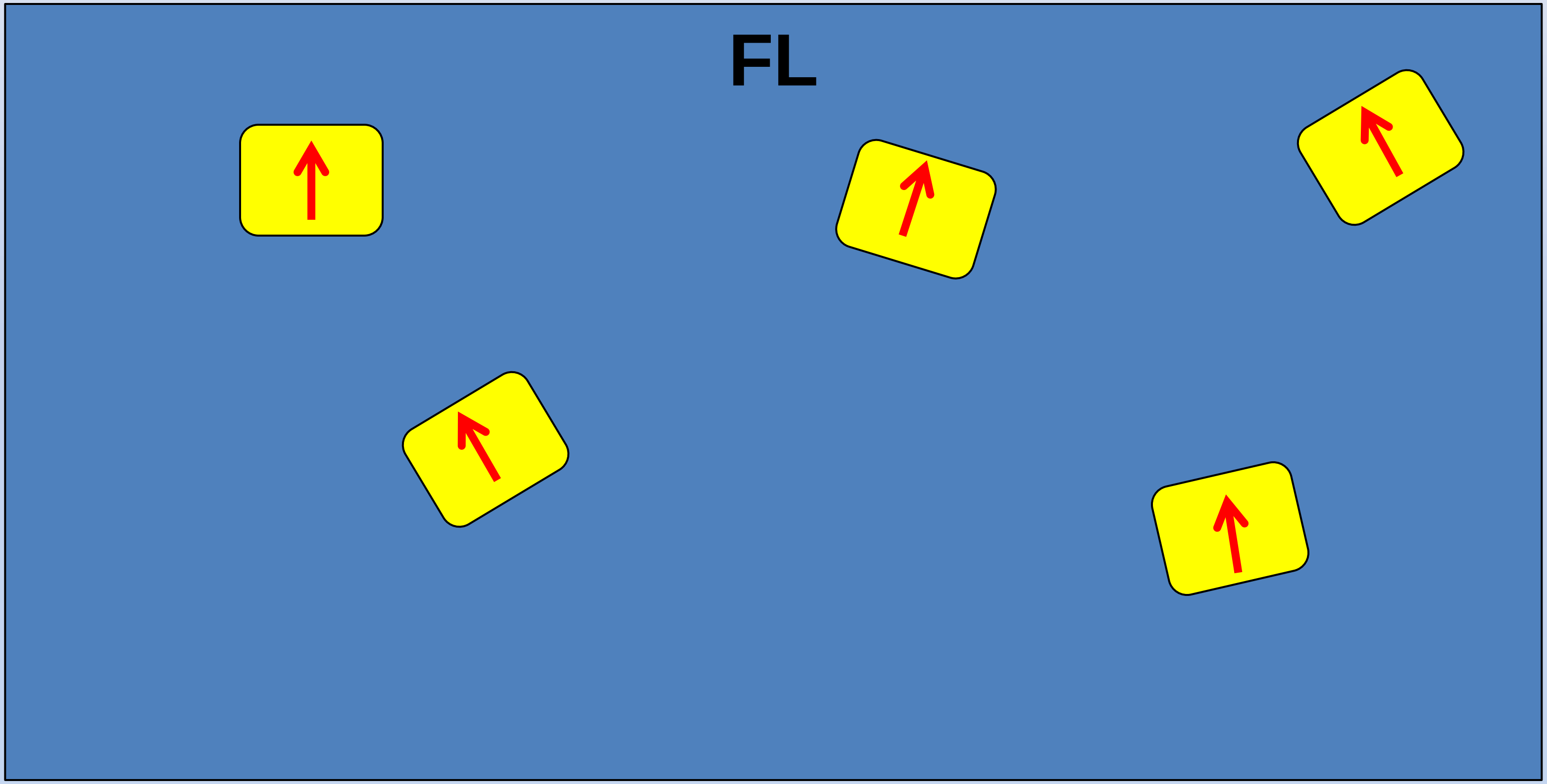
N.Teneh, AK, VP, M.Reznikov, PRL **109** (2012)

Sign change of $d\chi/dn$: critical behavior

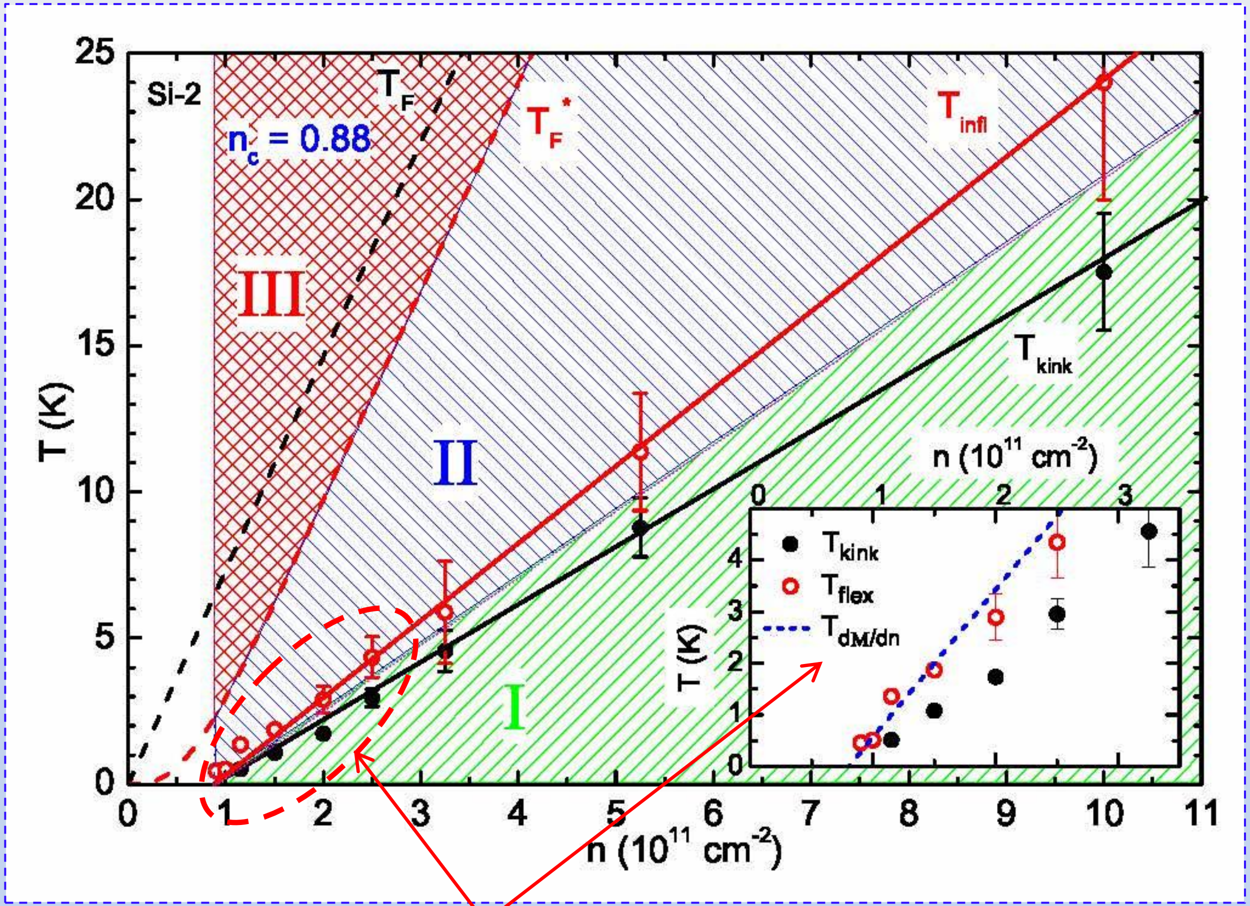


N.Teneh, AK, VP, M.Reznikov, PRL **109** (2012)

The two phase state



Phase diagram



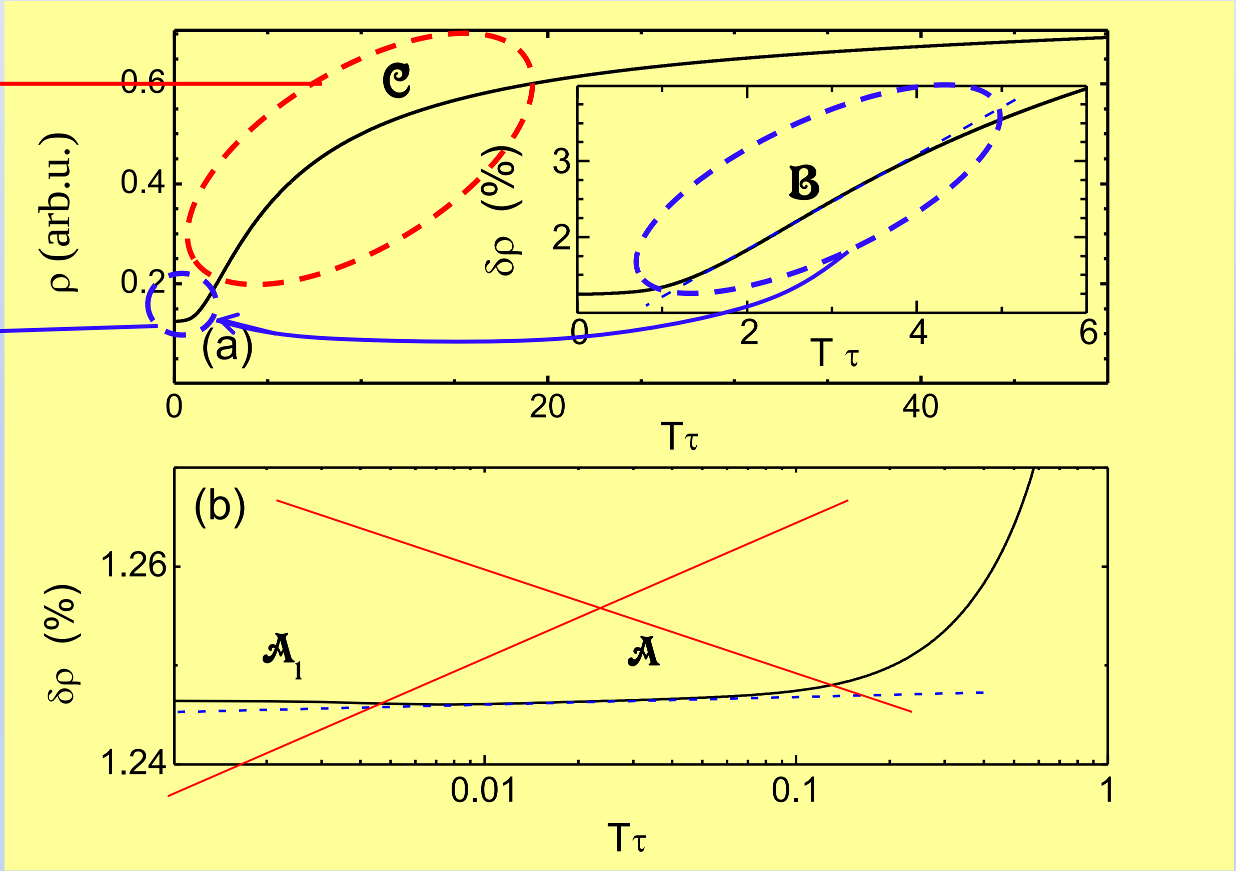
$T_{\text{infl}} \approx T_{\text{kink}} \approx T_{d\chi dn} \propto (n\text{-}n_c)$

Having no microscopic model, we consider ρ(T) and a_σ(T) phenomenologically, assuming 2 channel scattering

"High"-T physics

$$\rho = \rho_{LT}(T) + \rho_{HT}(T)$$

"Low-T" physics

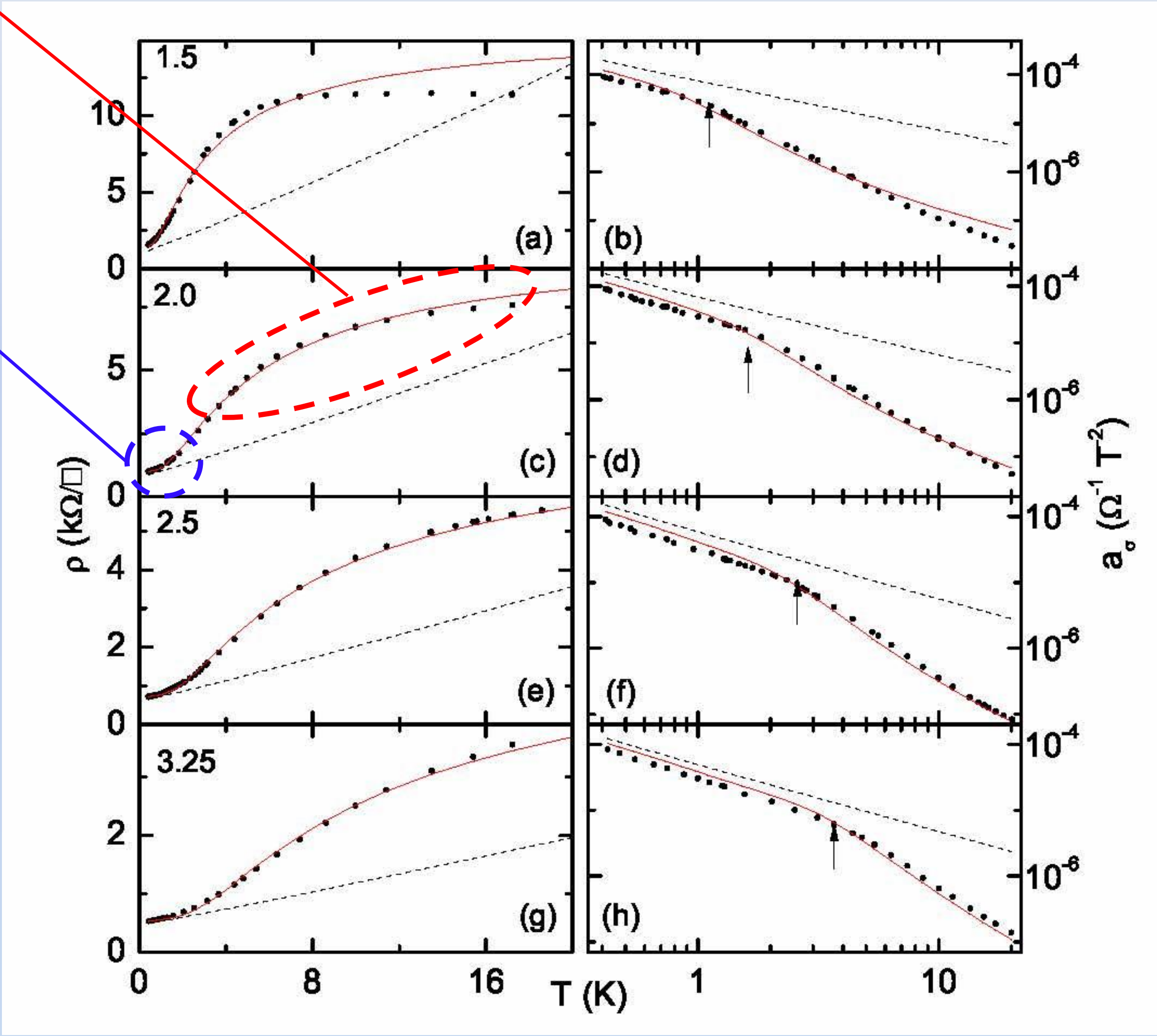


Having no microscopic model, we consider ρ(T) and a_σ(T) phenomenologically, assuming 2 channel scattering

$$\rho = \rho_{LT}(T) + \rho_{HT}(T)$$

"High"-T physics

"Low-T" physics



$\rho_{LT}(T)$ includes all QC

$\rho_{HT}(T)$ describes the steep $\rho(T)$ rise

Having no microscopic model, we consider $\rho(T)$ and $a_\sigma(T)$ phenomenologically, assuming 2 channel scattering

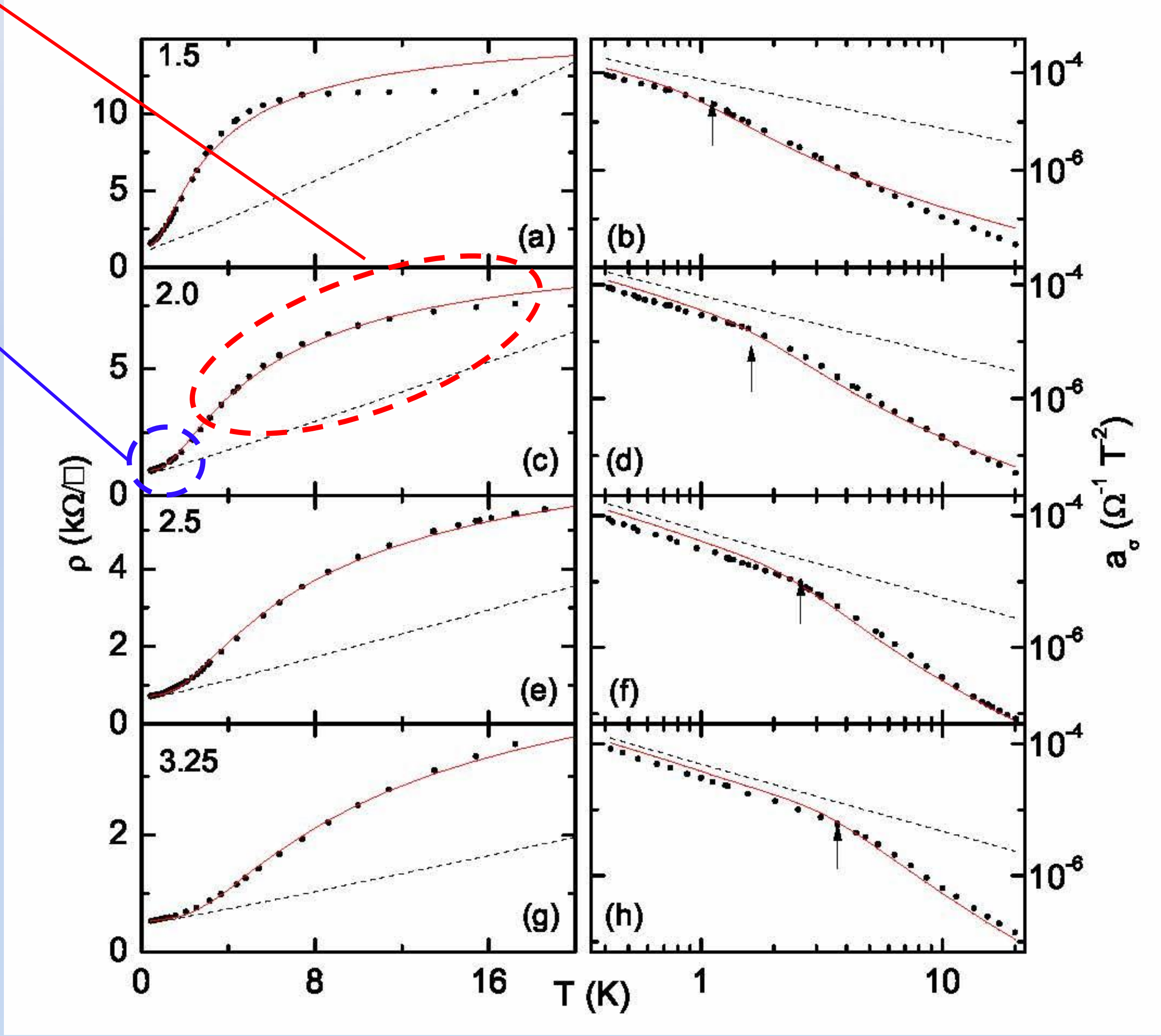
$$\rho = \rho_{LT}(T) + \rho_{HT}(T)$$

“High”-T physics

“Low-T” physics

$$\rho_{LT} = \frac{1}{\sigma_D + \delta\sigma_{qc}}$$

$\delta\sigma_{qc}$ is to be cut-off at $T > T_0$ where the quantum corrections die: $\boldsymbol{l_\varphi(T_0) = \lambda_F}$



Having no microscopic model, we consider $\rho(T)$ and $a_\sigma(T)$ phenomenologically, assuming 2 channel scattering

$$\rho = \rho_{LT}(T) + \rho_{HT}(T)$$

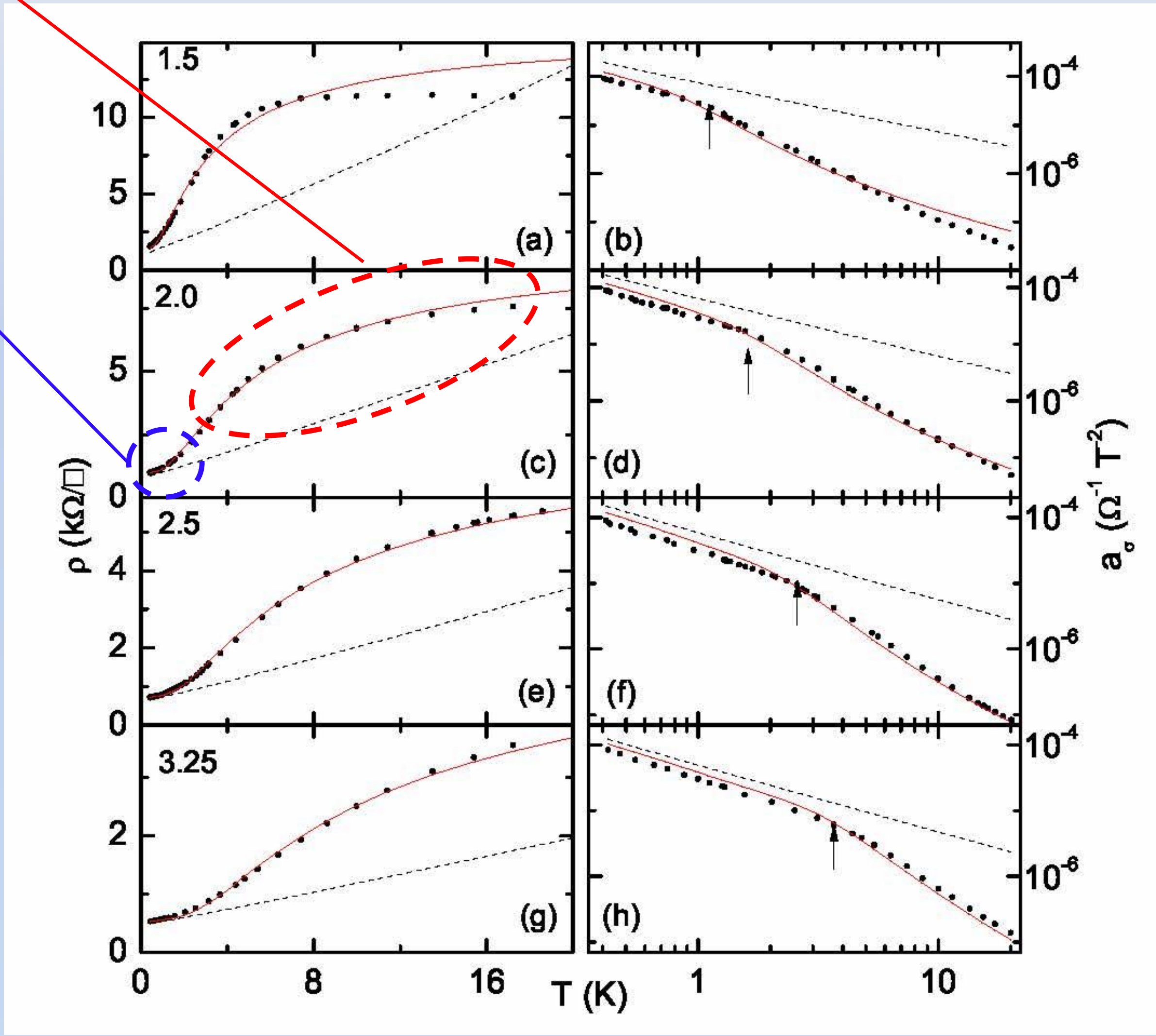
"Low-T" physics

"High"-T physics

$$\rho_{LT} = \frac{1}{\sigma_D + \delta\sigma_{qc}}$$

$$\rho_{HT} = \rho_1 \exp\left(-\frac{\Delta}{T}\right)$$

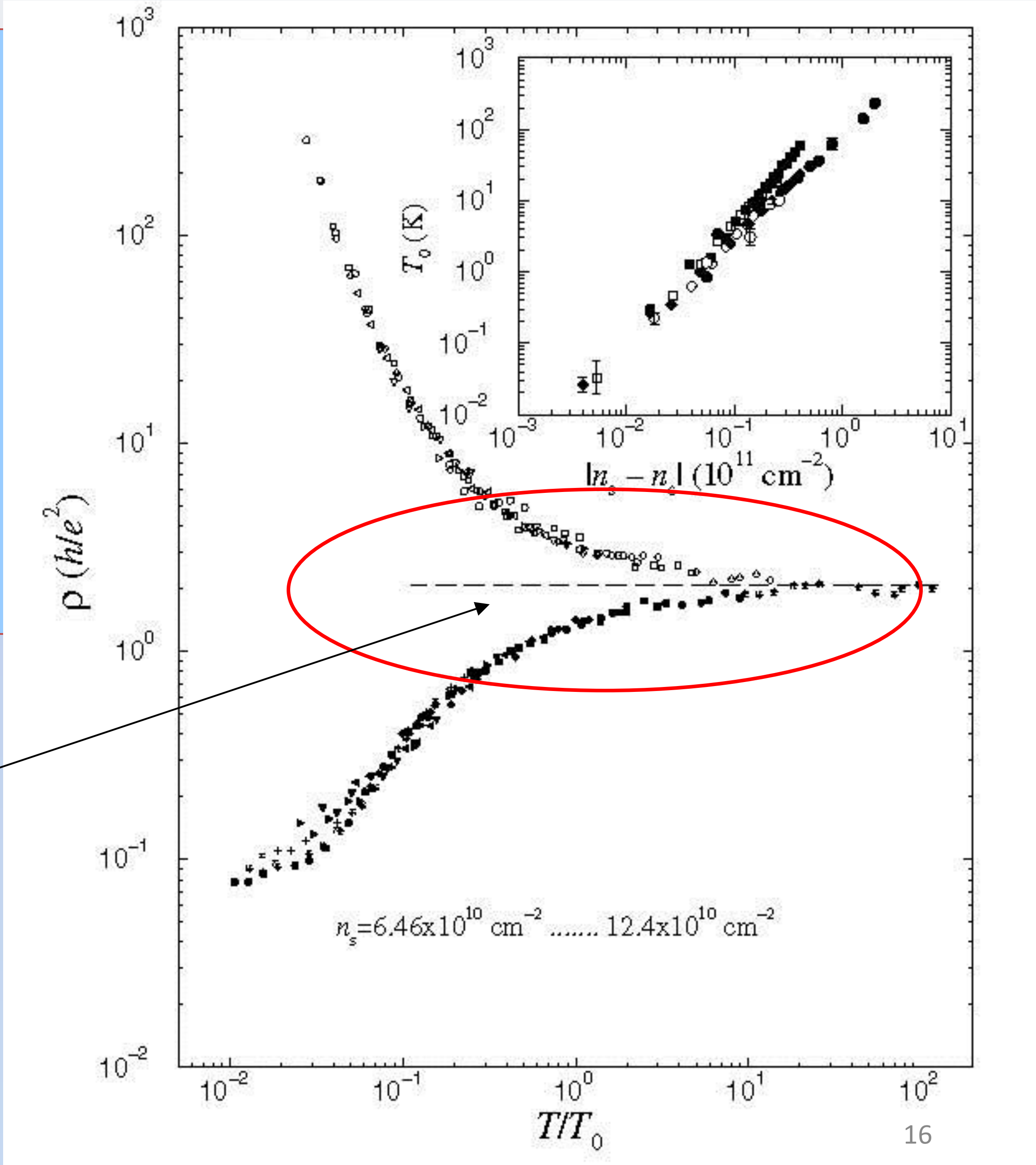
$\Delta(B=0) \propto (n-n_c)$



Attributes of the seeming critical phenomena (QPT)

- Mirror-reflection symmetry: $\rho(\Delta n, T)/\rho_c = \rho_c/\rho(-\Delta n, T)$
- Scaling $\rho/\rho_c = \boldsymbol{f}\,[\boldsymbol{T/T_0(n)}]$
- Critical behavior $T_0 \propto |n-n_c|^{-z\nu}$

Symmetry: holds here



S.V. Kravchenko, et al. *PRB* 1995

Having no microscopic model, we consider $\rho(T)$ and $a_\sigma(T)$ phenomenologically, assuming 2 channel scattering

$$\rho = \rho_{LT}(T) + \rho_{HT}(T)$$

"Low-T" physics

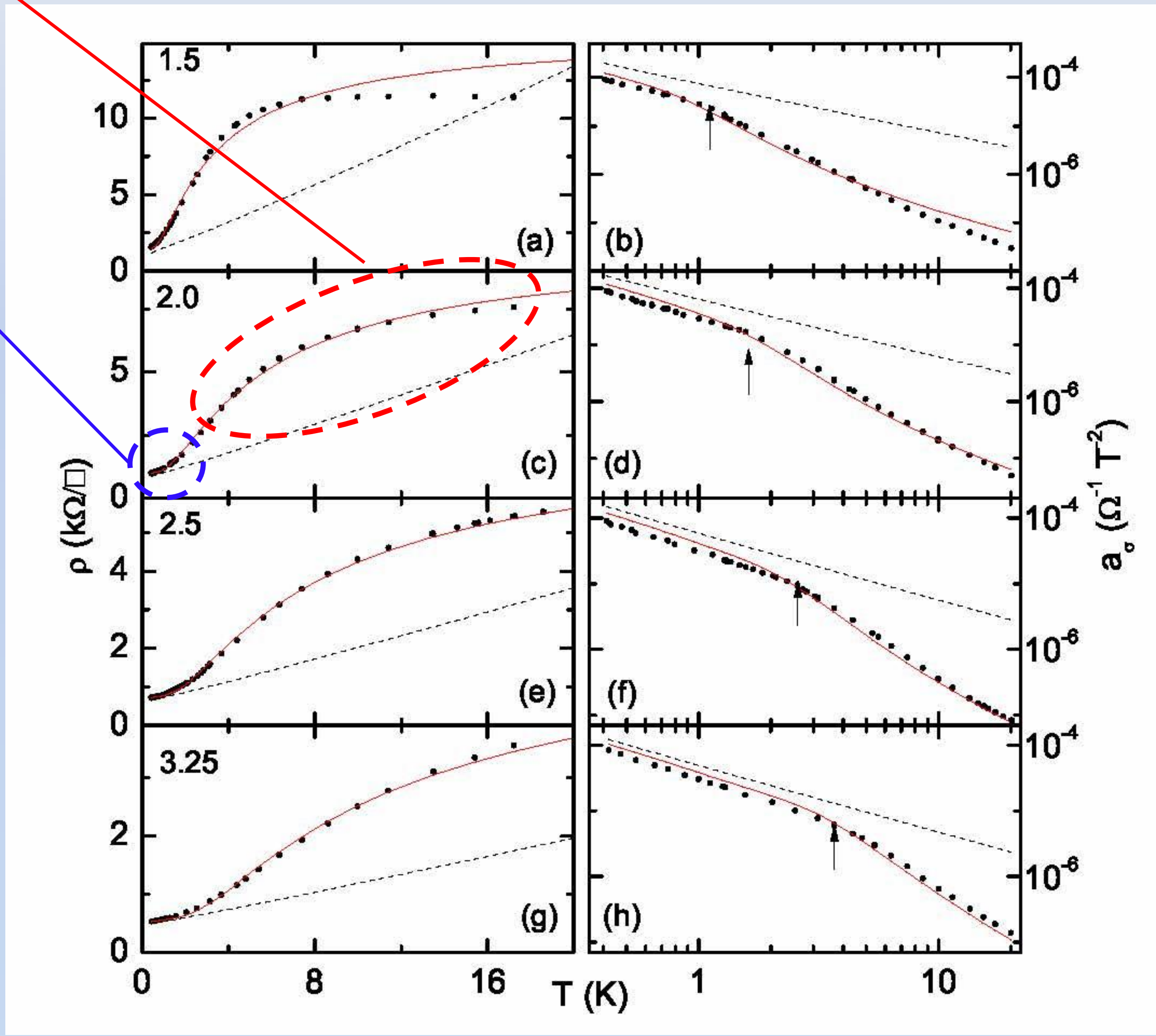
"High"-T physics

$$\rho_{LT} = \frac{1}{\sigma_D + \delta\sigma_{qc}}$$

$$\rho_{HT} = \rho_1 \exp\left(-\frac{\Delta}{T}\right)$$

$\Delta(B=0) \propto (n-n_c)$

$\Delta(B) = \Delta(0) + \beta B^2 + \zeta B^2/T$



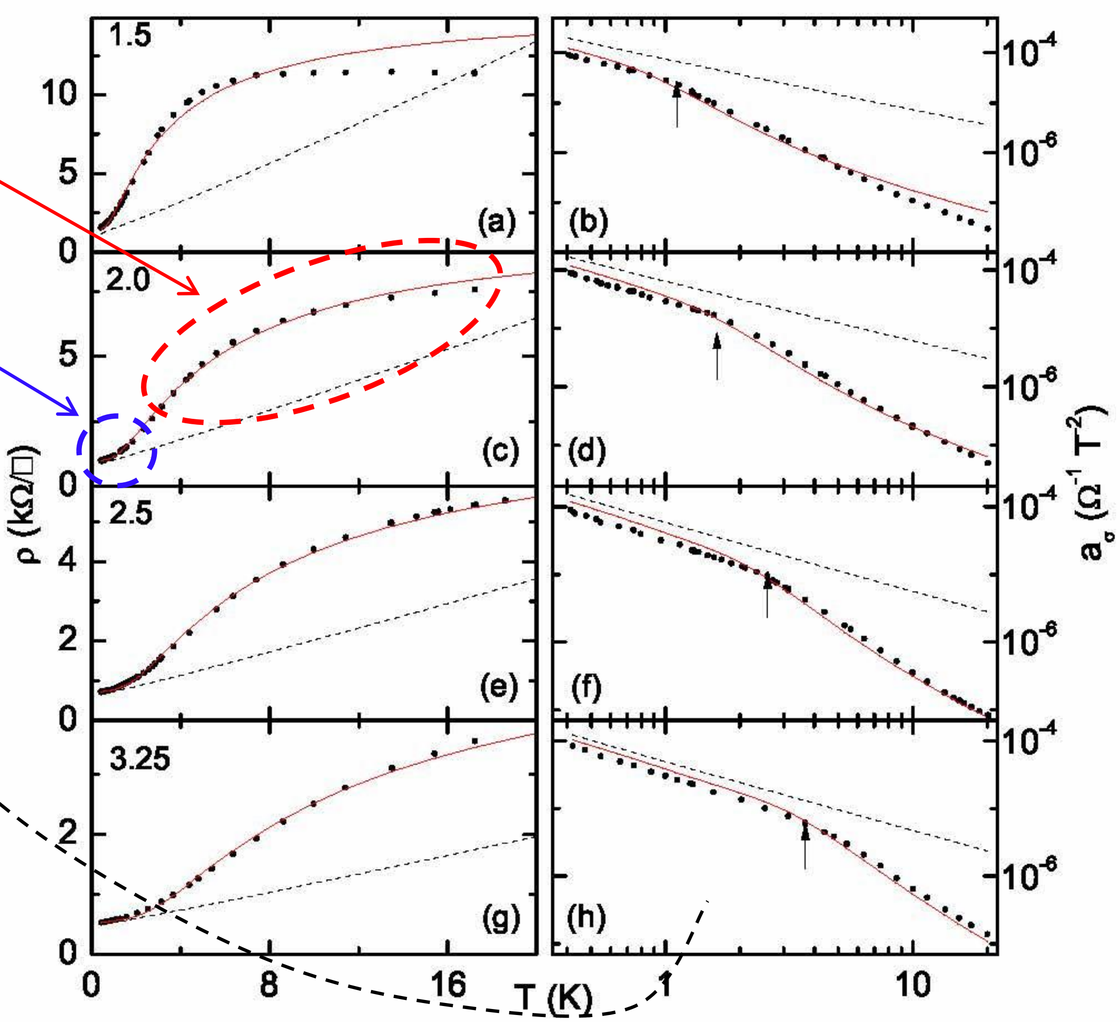
assuming 2 channel scattering

$$\rho(B,T) = \left[\sigma_D - \delta\sigma \cdot \exp\left(-T/T_B\right)\right]^{-1} + \rho_1 \exp\left(-\alpha\frac{n-n_c(0)}{T} - \beta\frac{B^2}{T} - \xi\frac{B^2}{T^2}\right)$$

2 fitting parameters: α and ρ_1

no fitting parameters

2 additional fitting parameters: β and ξ



Fitting parameters

ρ is in (kΩ/□), density - in 10^{11}cm^{-2},
$n_c = 0.88$, α - in K/10^{11}cm^{-2}

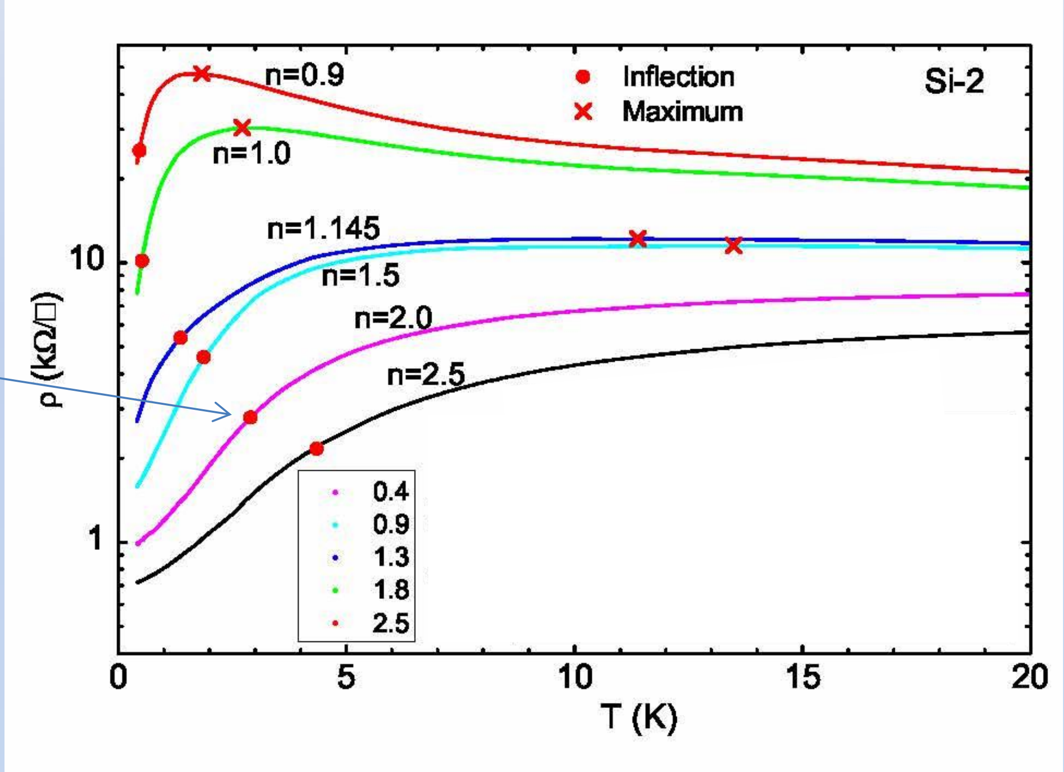
n	ρ_D	ρ_1	α	$\beta\,(\mathrm{K/T^2})$	$\xi\,(\mathrm{K^2/T^2})$
1.5	1268	14362	4.53	-0.0160	-0.08
1.996	901	9564	4.35	-0.0080	-0.09
2.5	662.2	6937	4.28	-0.0043	-0.11
3.25	501.5	5202	4.24	-0.0019	-0.15
5.252	336.14	3456.6	4.18	-0.0005	-0.19

Consequence 1: $\rho(T)$ data interpretation in the vicinity of n_c

Inflection point

$d^2\rho/dT^2 = 0$

$\boldsymbol{T_{infl}}$

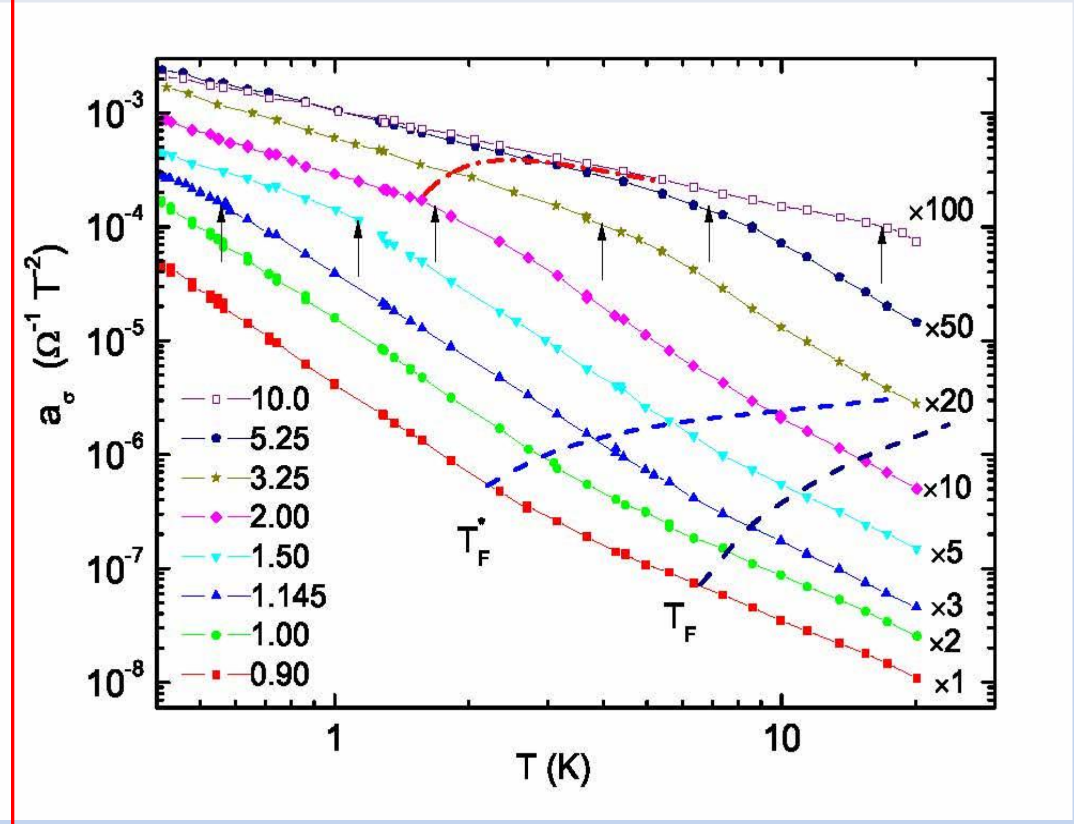


Consequence 1: $\rho(T)$ data interpretation in the vicinity of n_c

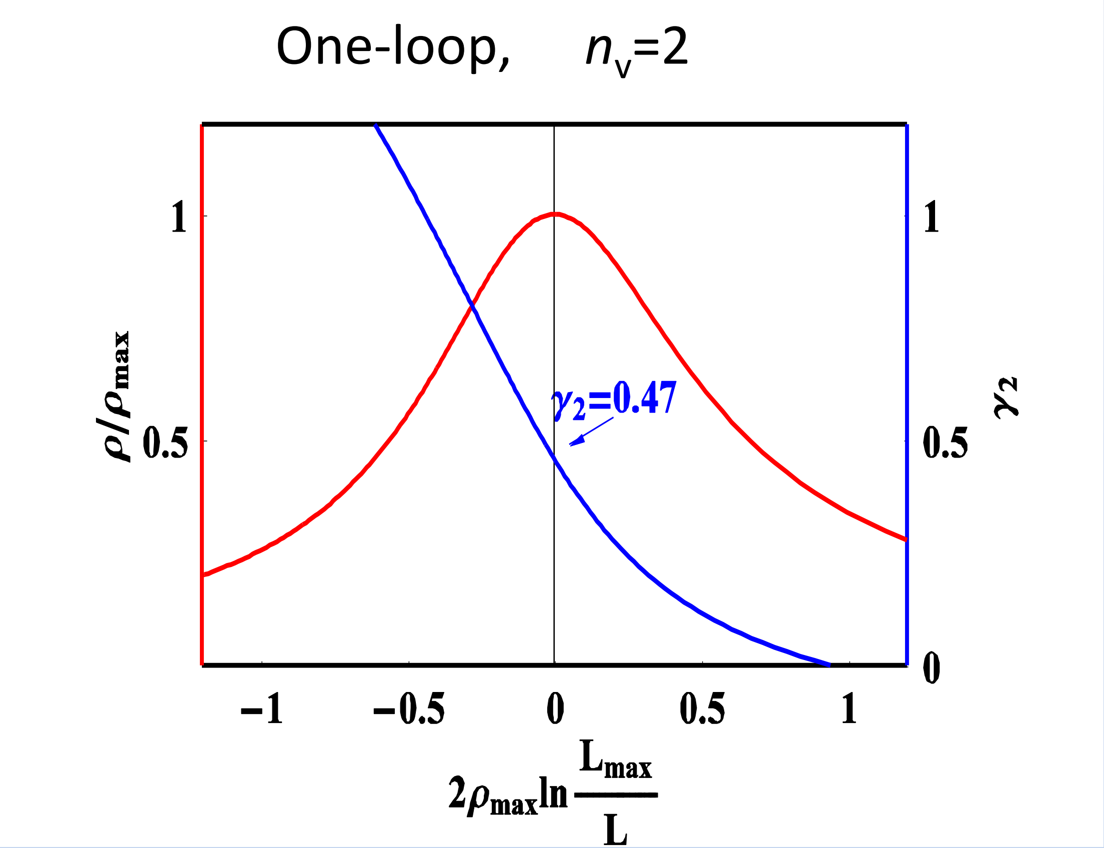
- $T_{kink} \approx T^*$ represents a **ballistic** physics
- $T^* < T_{max}$ always
- $T^* \rightarrow 0$ for $n \rightarrow n_c$,

Hence, T_{max} always belongs to the ballistic interaction regime

Hence, $\rho(T)$ maximum is not a hallmark of the RG flow



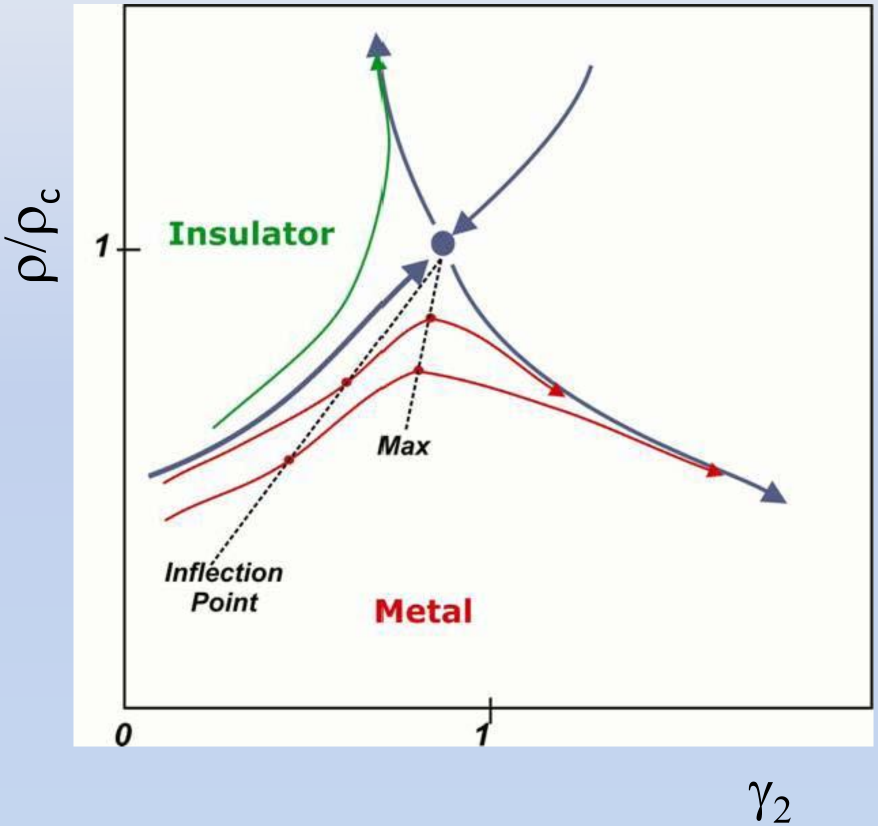
RG results



A.M.Finkelstein, A. Punnoose PRL (2002)

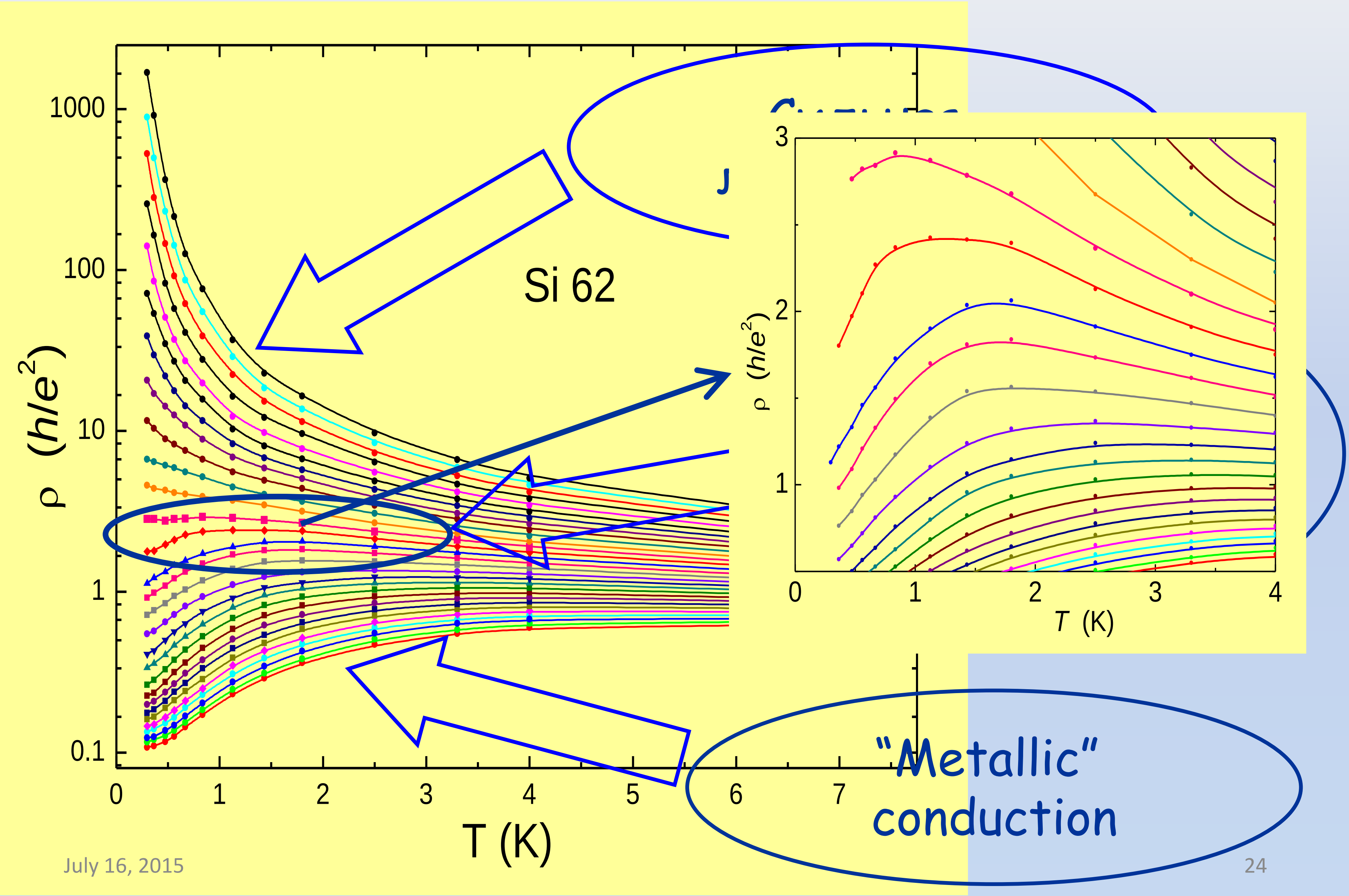
Fixed point

Two-loop, infinite n_v



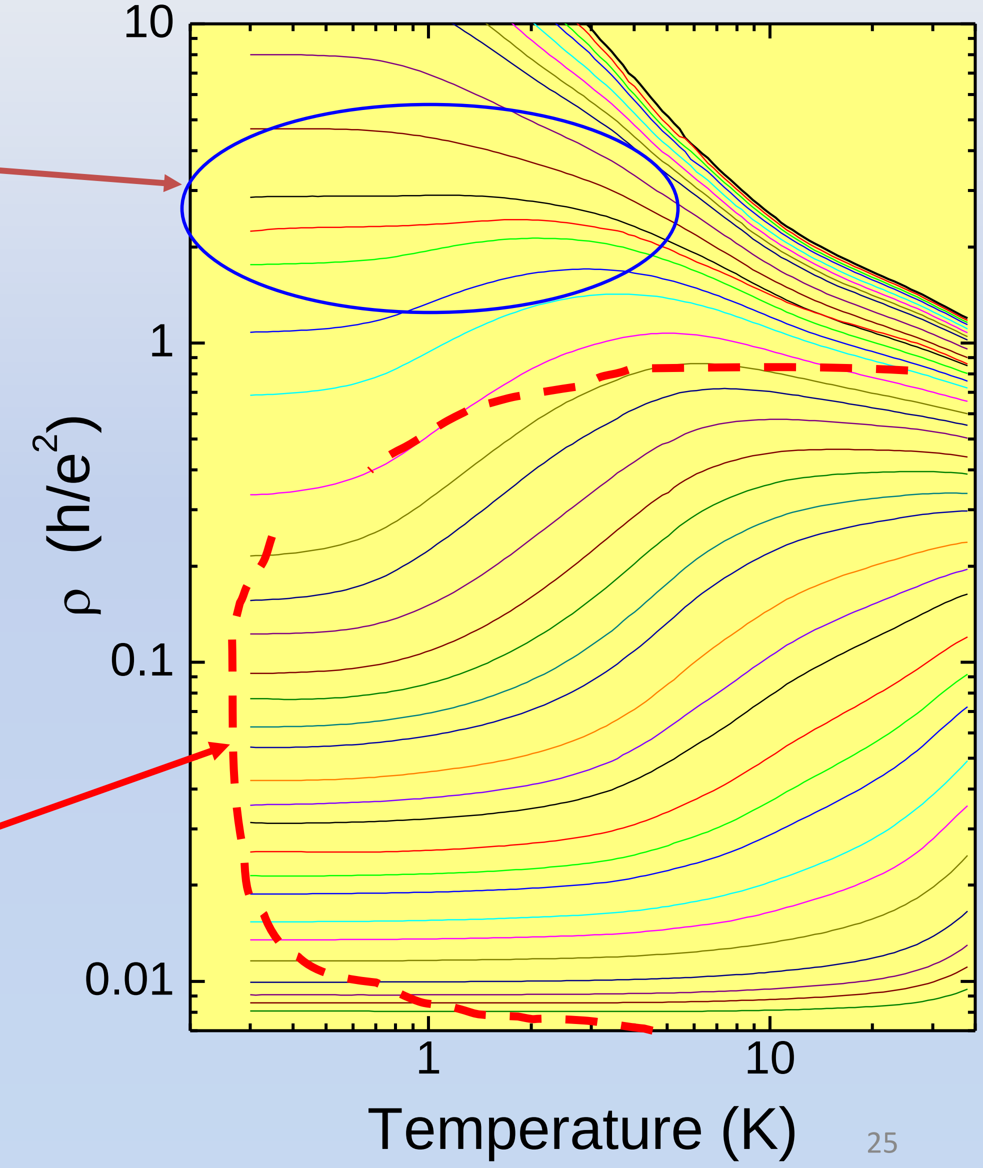
A. Punnoose , A.M.Finkelstein, Science (2005)

Zero field transport in the critical regime



Earlier believe: diffusive regime of interactions extends up to 10K !

Critical regime was considered to belong diffusive interaction regime



Diffusive-ballistic border:

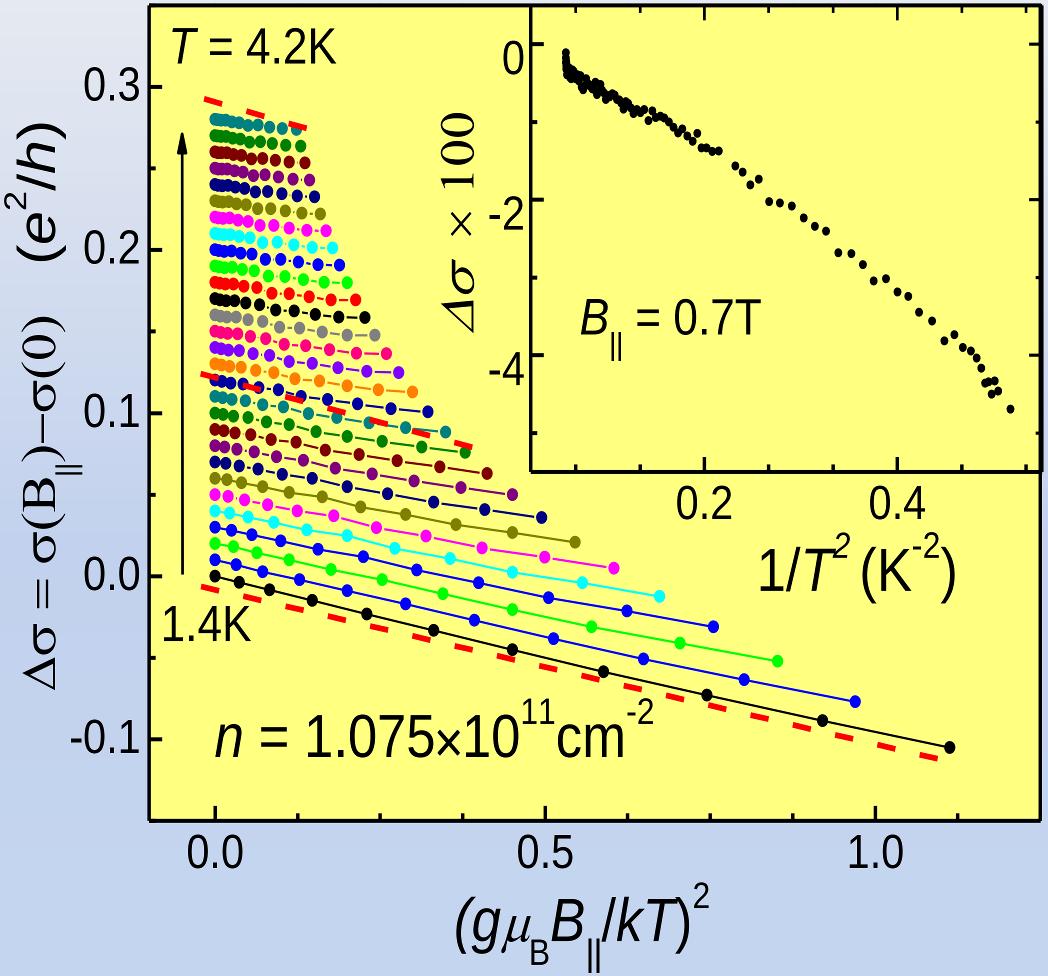
$$T^* = \frac{\hbar}{\tau}\frac{(1+F_0^\sigma)}{2\pi}$$

Consequence 2:

$\mathbf{a_\sigma(T) \propto 1/T^{2+\varepsilon}}$ dependence at $T^* < T \le T_{max}$ is a mimicry of the diffusive regime.

In fact, this is a high-T phenomenon

Excessive T-dependence of $\Delta\sigma$ was interpreted as $\gamma_2(T)$



For diffusive regime $T\tau < 1$

$$\delta\sigma \propto z^2 \propto \gamma_2(1+\gamma_2)\left(\frac{g\mu_B B_{||}}{kT}\right)^2$$

increasing ***$d\sigma/dz$* slope** with $1/T \Rightarrow$ T-dependence of $\gamma_2(\mathrm{T})$!

D. A. Knyazev, O. E. Omel'yanovskii, V. M. P., I. S. Burmistrov, JETP Lett. 84, 662 (2006).
S. Anissimova, S.V.Kravchenko , A. Punnoose, A.M.Finkelstein, T.M.Klapwijk, Nat.Phys. (2007)

Conclusions

✓ A novel energy scale ***T**** < T_F in a 2D electron system. It separates the "low-T" ballistic regime of interactions and a novel regime observed in transport at B=0 and B≠0, and in magnetization.

T* may be related with the energy level structure of the minority phase ("spin droplets"), revealed in magnetization measurements.

✓ ***T**** is a consequence of e-e correlations, since all these effects (i.e. T_{kink} , T_{infl} , $T_{d\chi/dn}$) are missing in low mobility samples (disordered, with a weak e-e interaction)

✓ Interpretation of preceding experimental data on the weak field MR in framework of the FL parameters needs to be refined

✓ MR in the regime T>T* mimics the behavior expected for the diffusive regime of interactions. This may affect interpretation of the MR in the critical regime of MIT

Thank you for attention!