Spin susceptibility near metal-insulator transition in 2D

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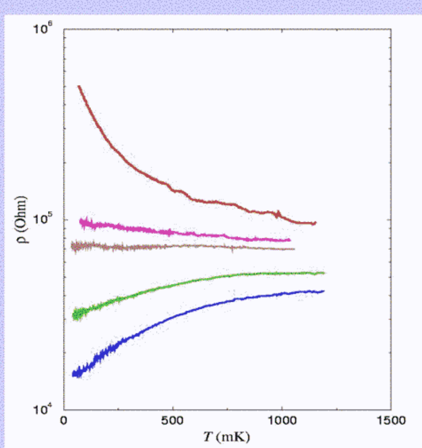
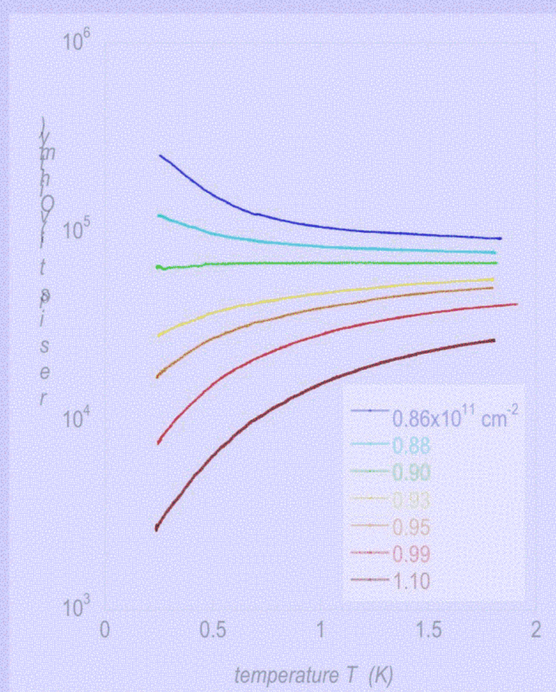
In very clean samples, practically universal metal-insulator transition is seen:

Klapwijk's sample:



(Note: samples from different sources, measured in different labs)

Pudalov's sample:



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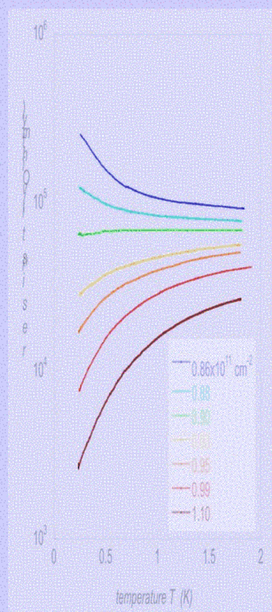
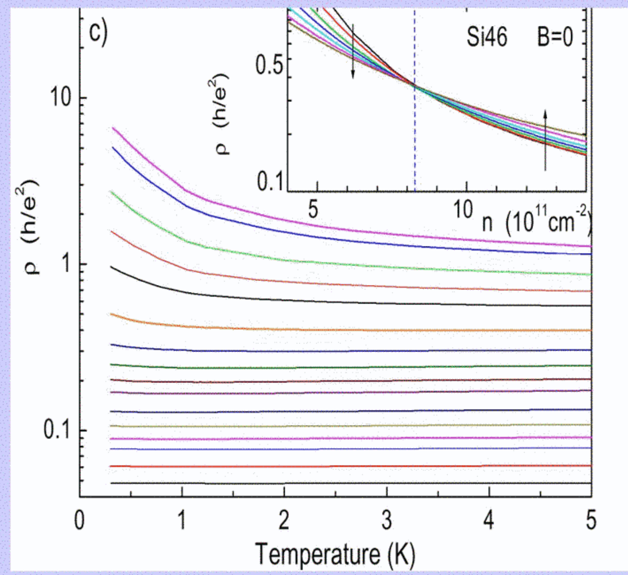
… in contrast to strongly disordered samples:

clean sample:

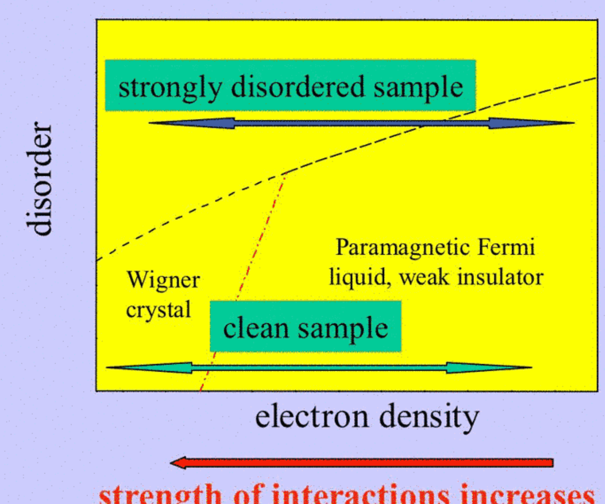


dirty sample:

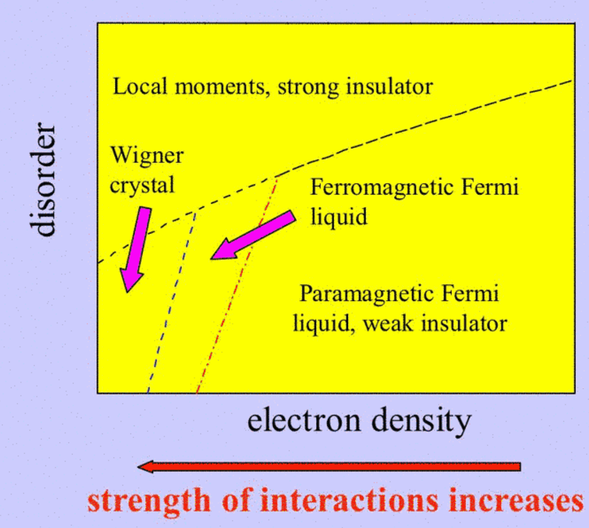


Suggested phase diagrams for strongly interacting electrons in two dimensions

Tanatar and Ceperley,
Phys. Rev. B **39**, 5005 (1989)



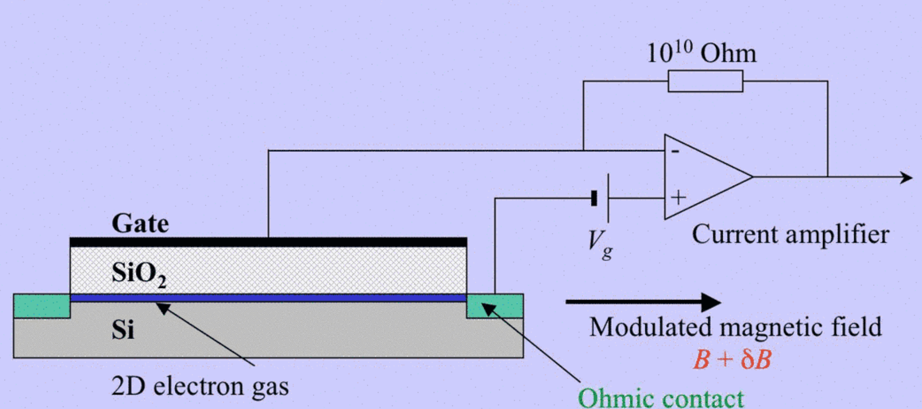
Attaccalite *et al*.
Phys. Rev. Lett. **88**, 256601 (2002)



In clean samples, is it a phase transition, or just something funny happens to conductivity?

Measurements of thermodynamic magnetization

suggested by B. I. Halperin (1998); first implemented by O. Prus, M. Reznikov, U. Sivan *et al.* (2002)



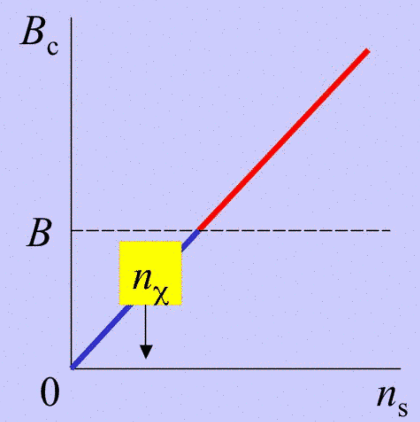
$$i \sim d\mu/dB = -\,dM/dn_s$$

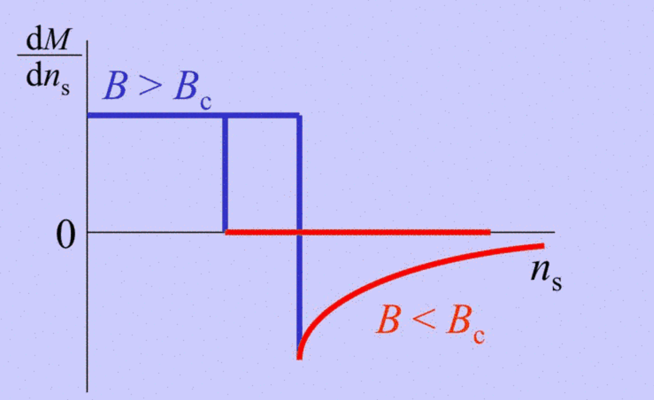
Magnetic field of the full spin polarization B_c vs. n_s

spontaneous spin polarization at n_χ:

$$B_c = \pi\hbar^2 n_s / 2\mu_B g^* m^*$$

$$M = \mu_B \xi n_s = \begin{cases} \mu_B n_s B/B_c \text{ for } B < B_c \\ \mu_B n_s \text{ for } B > B_c \end{cases}$$





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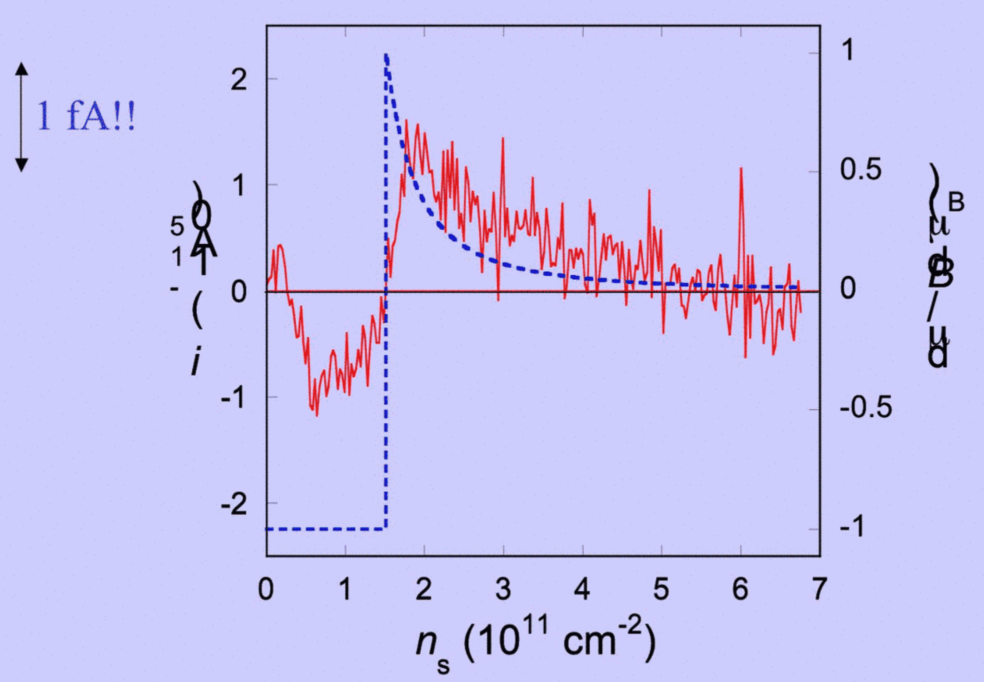
Expected *vs.* measured dμ/dB = - dM/dn



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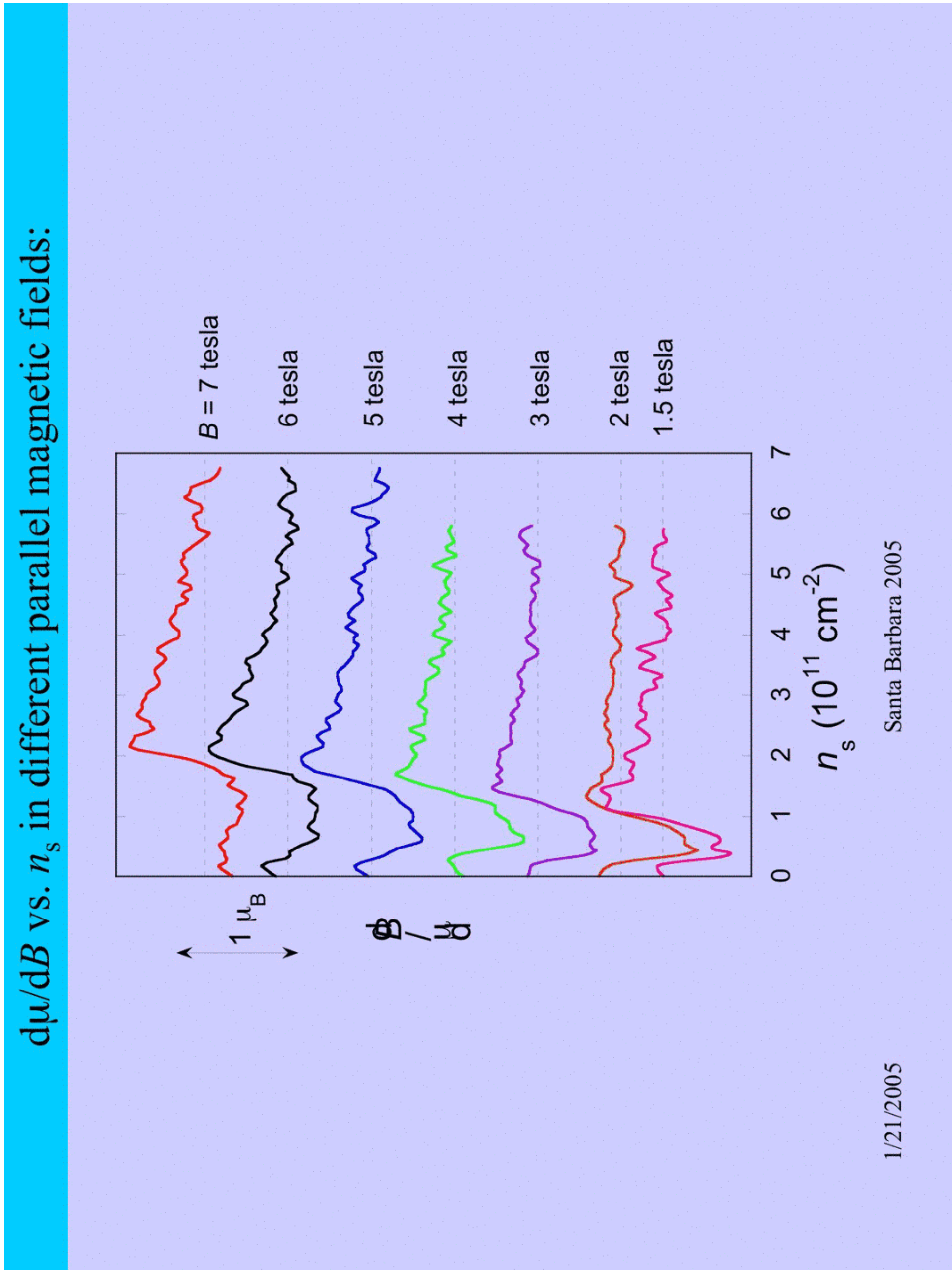
dμ/dB vs. n_s in different parallel magnetic fields:
B = 7 tesla
6 tesla
5 tesla
4 tesla
3 tesla
2 tesla
1.5 tesla
1 μ_B
dμ/dB
0 1 2 3 4 5 6 7
n_s (10^{11} cm^{-2})
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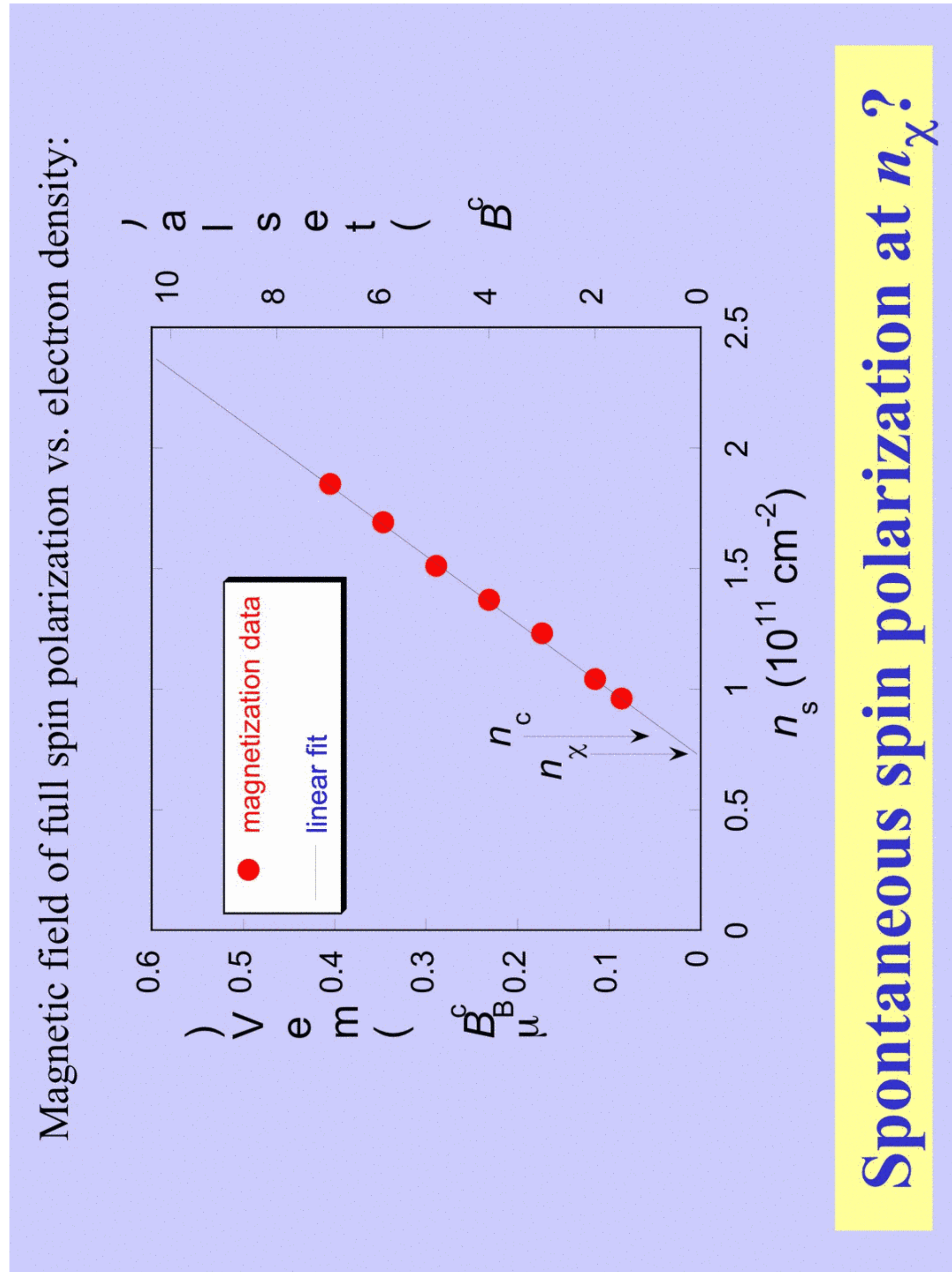
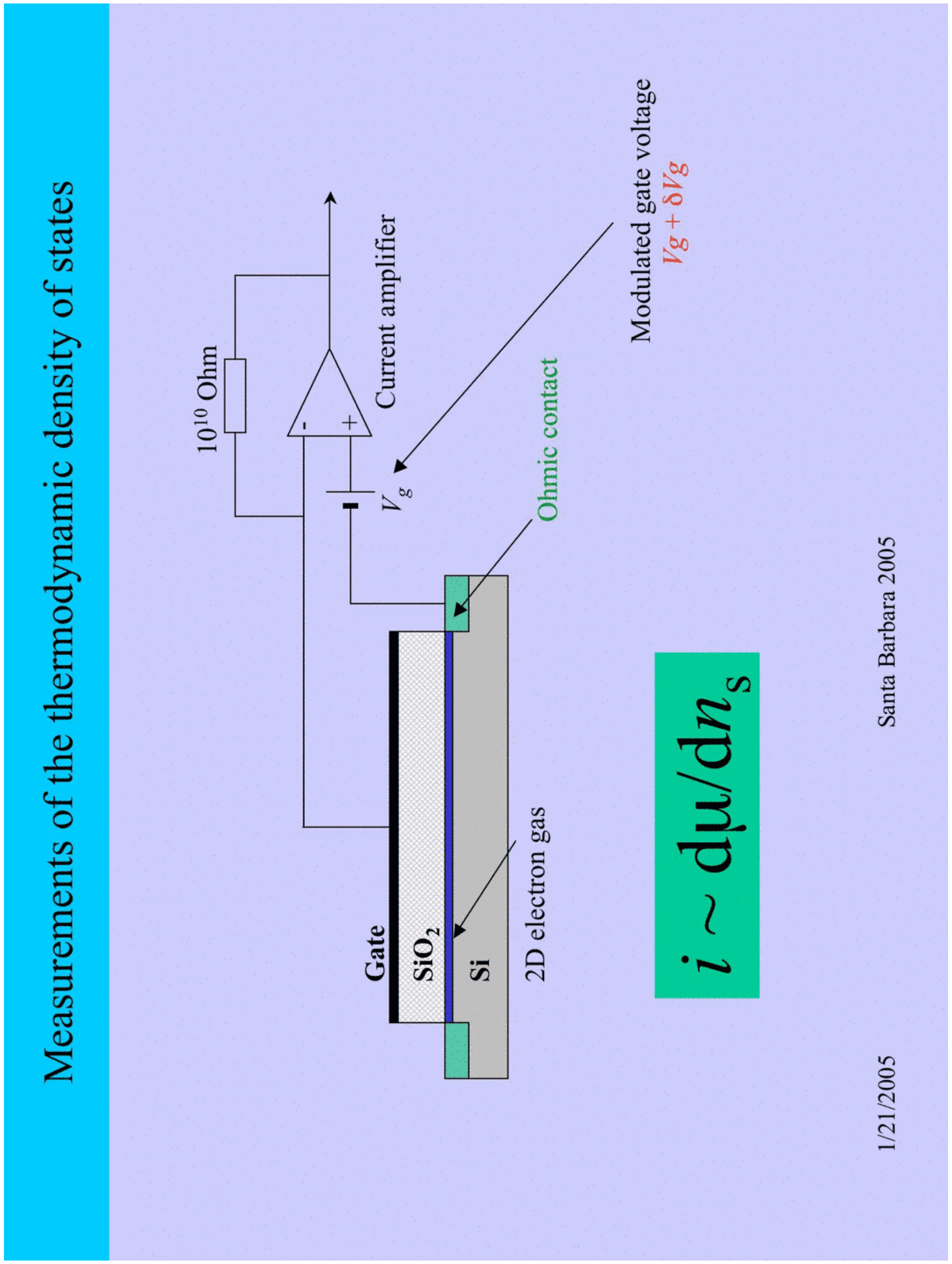

Magnetic field of full spin polarization vs. electron density:
B_c (tesla)
0 2 4 6 8 10
$\mu_B B_c$ (meV)
0 0.1 0.2 0.3 0.4 0.5 0.6
magnetization data
linear fit
n_c
n_χ
0 0.5 1 1.5 2 2.5
n_s (10^{11} cm^{-2})
Spontaneous spin polarization at n_χ?


Measurements of the thermodynamic density of states
10^{10} Ohm
Current amplifier
Modulated gate voltage
$Vg + \delta Vg$
V_g
Ohmic contact
Gate
SiO_2
Si
2D electron gas
$i \sim d\mu/dn_s$
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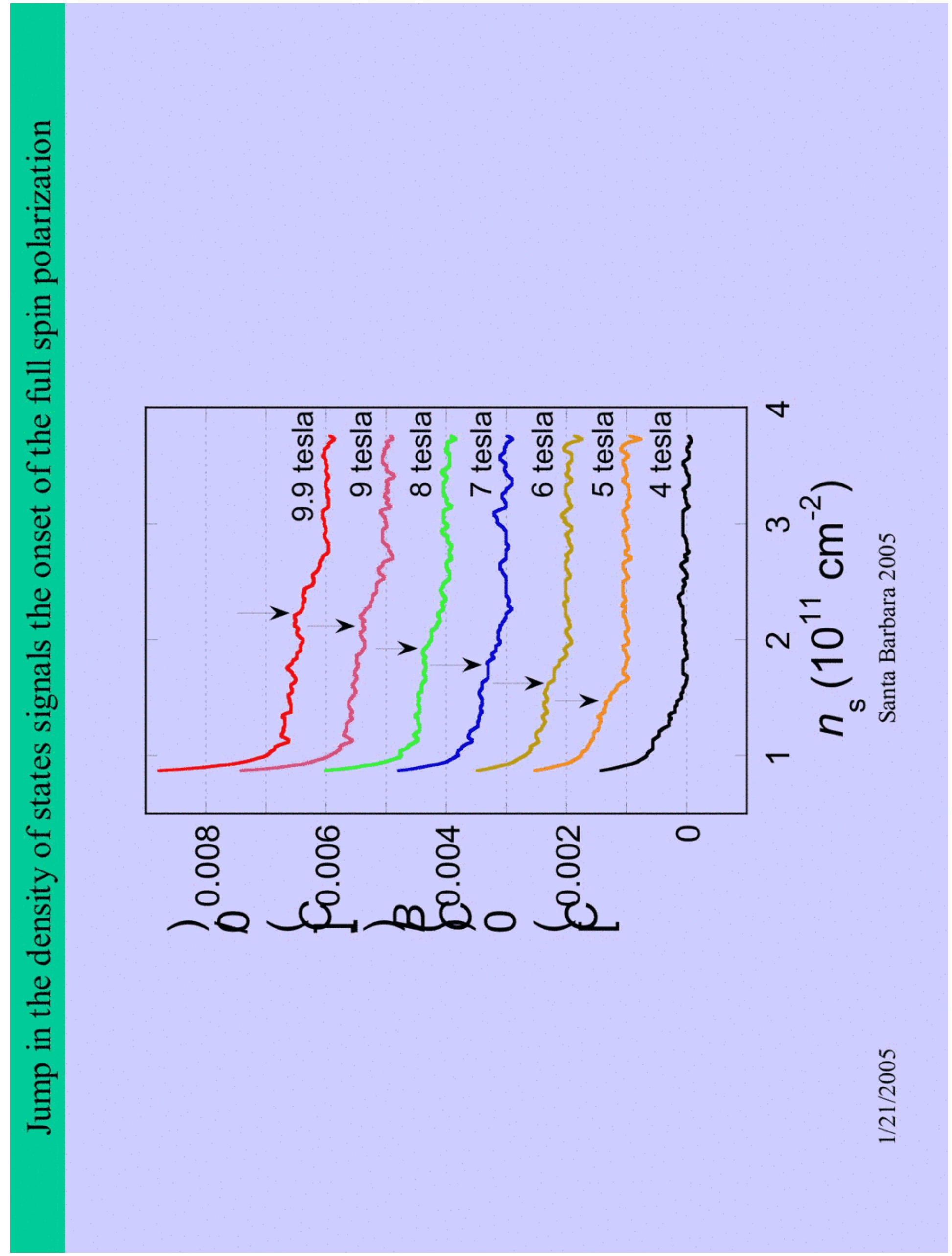
Jump in the density of states signals the onset of the full spin polarization
9.9 tesla
9 tesla
8 tesla
7 tesla
6 tesla
5 tesla
4 tesla
0.008
0.006
0.004
0.002
0
1
2
3
4
n_s (10^{11} cm^{-2})
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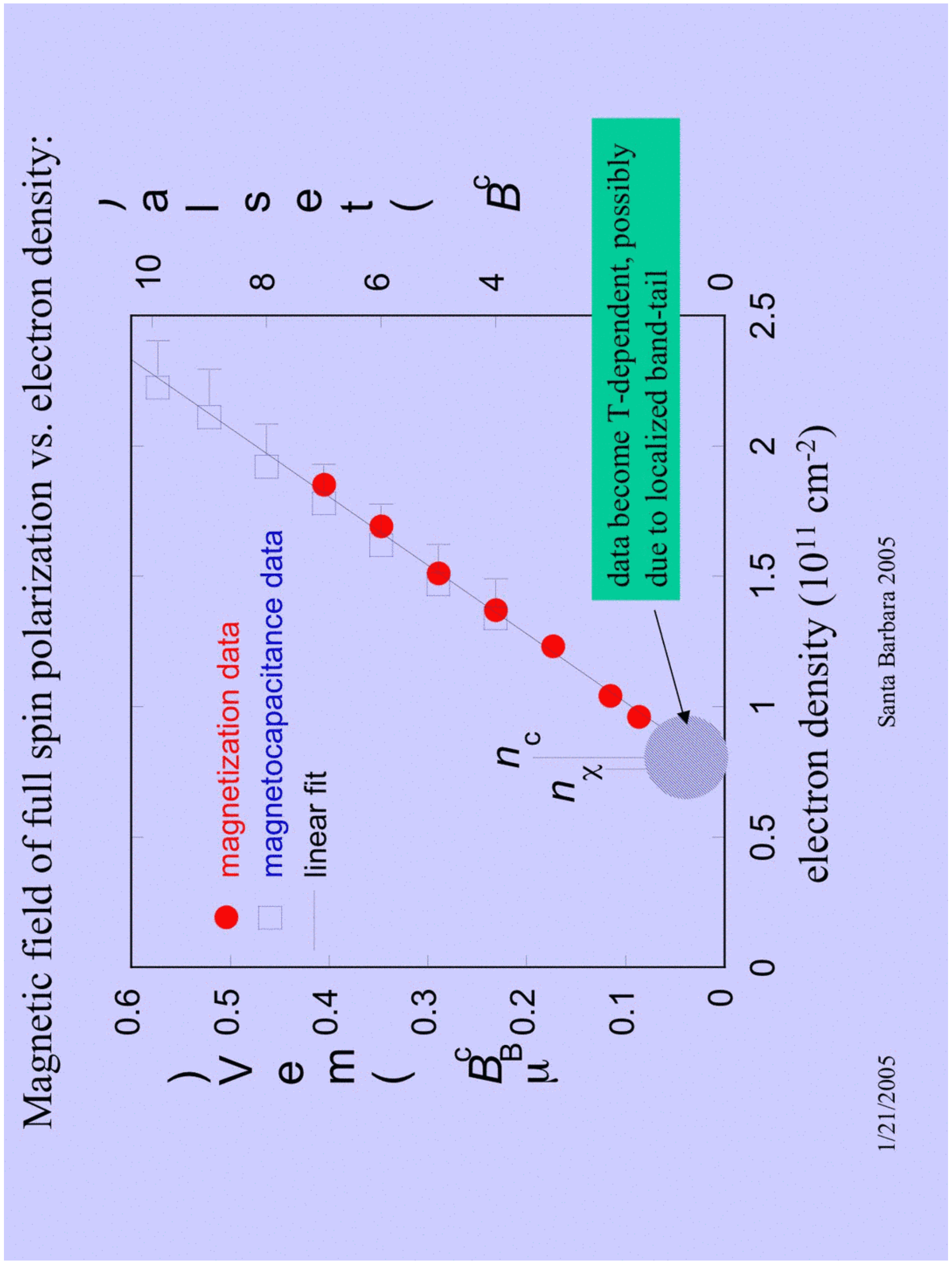
Magnetic field of full spin polarization vs. electron density:
magnetization data
magnetocapacitance data
linear fit
data become T-dependent, possibly due to localized band-tail
n_c
n_χ
$\mu_B B^c$ (meV)
B^c (tesla)
electron density (10^{11} cm^{-2})
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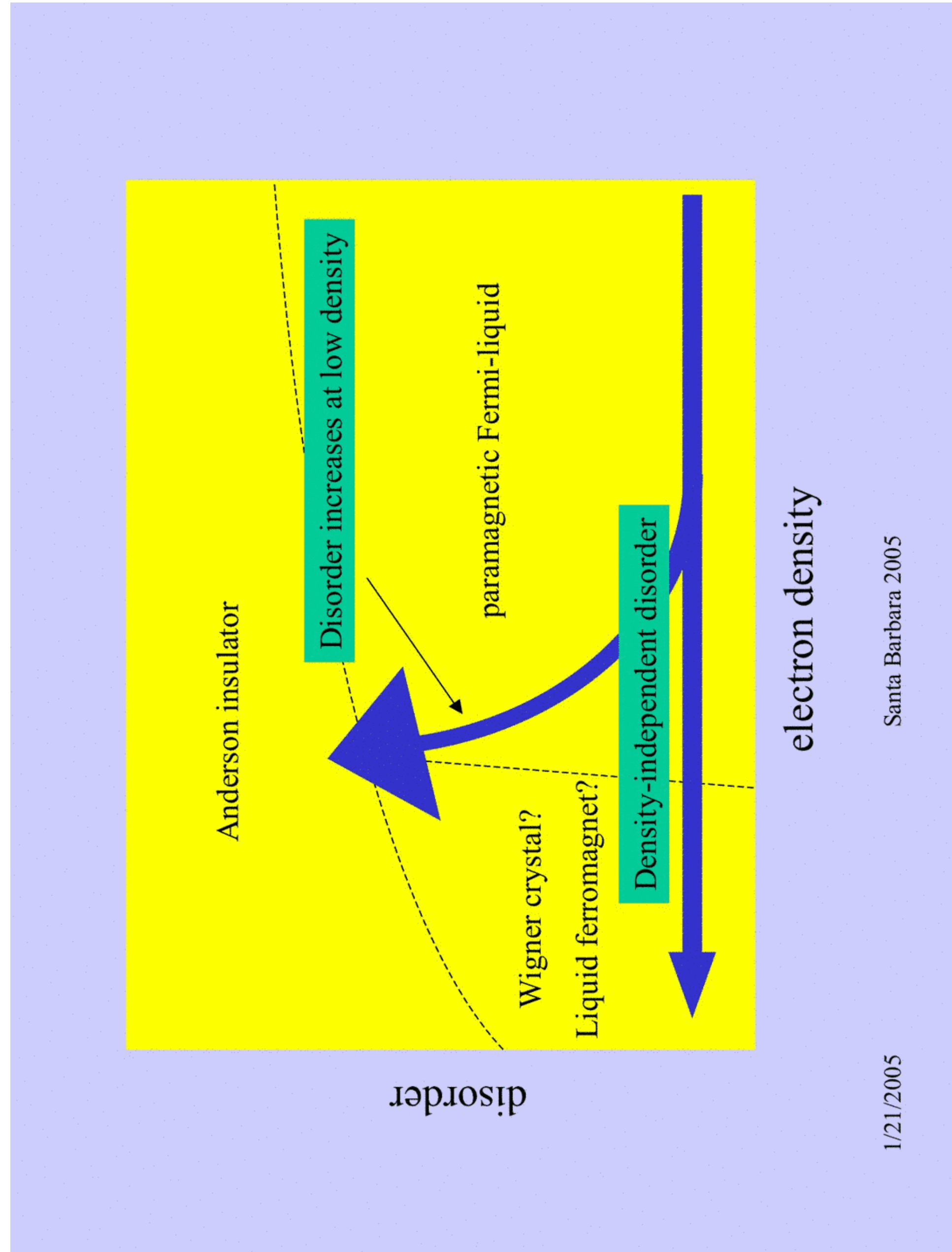
Anderson insulator
Disorder increases at low density
paramagnetic Fermi-liquid
Wigner crystal?
Liquid ferromagnet?
Density-independent disorder
electron density
disorder
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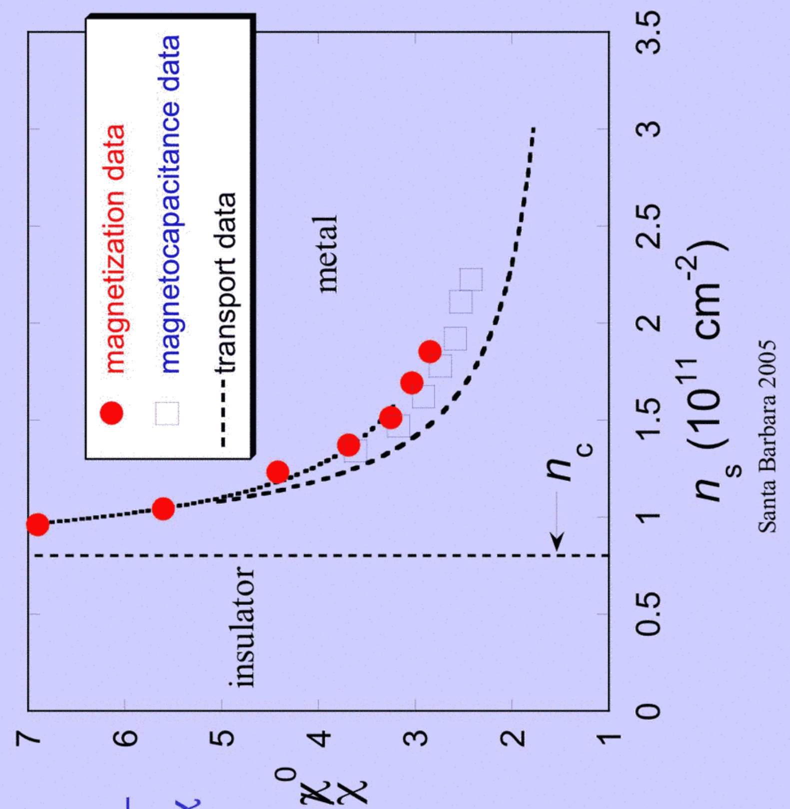
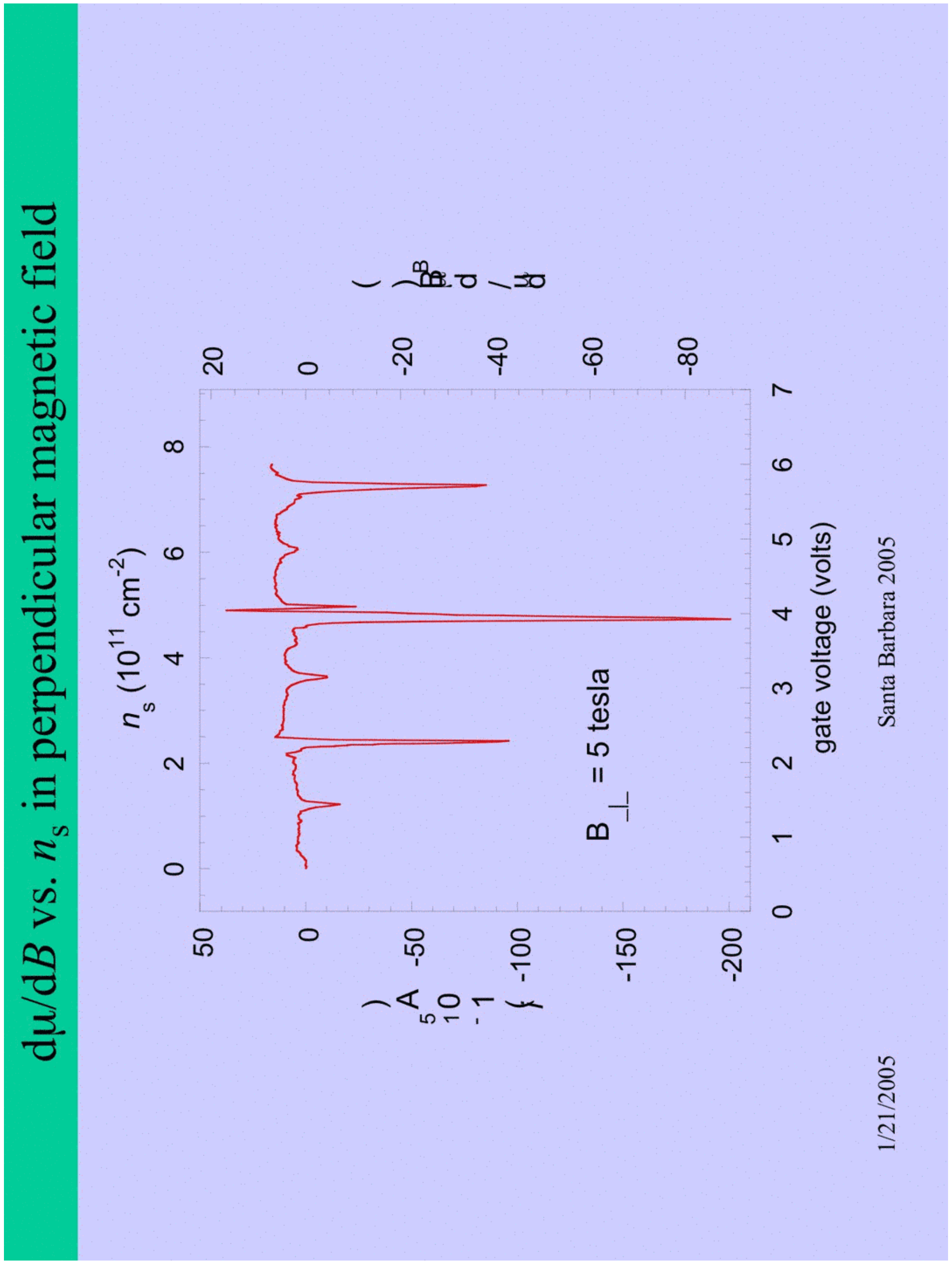
Spin susceptibility exhibits critical behavior near the metal-insulator transition:

$$\chi \sim \frac{n_s}{n_s - n_\chi}$$



g-factor or effective mass?


dμ/dB vs. n_s in perpendicular magnetic field
n_s (10^11 cm^-2)
B_⊥ = 5 tesla
gate voltage (volts)
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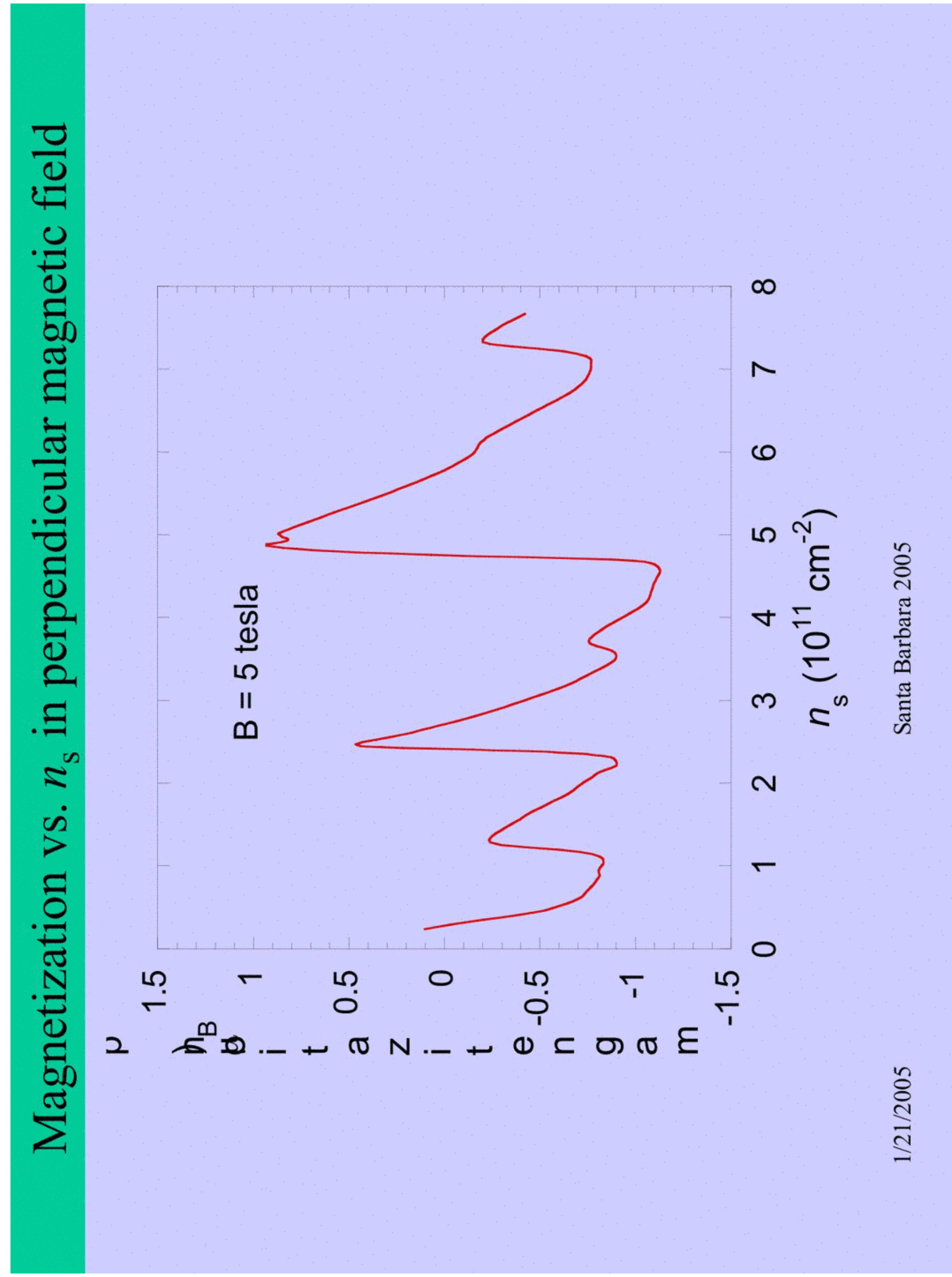
Magnetization vs. n_s in perpendicular magnetic field
B = 5 tesla
n_s (10^11 cm^-2)
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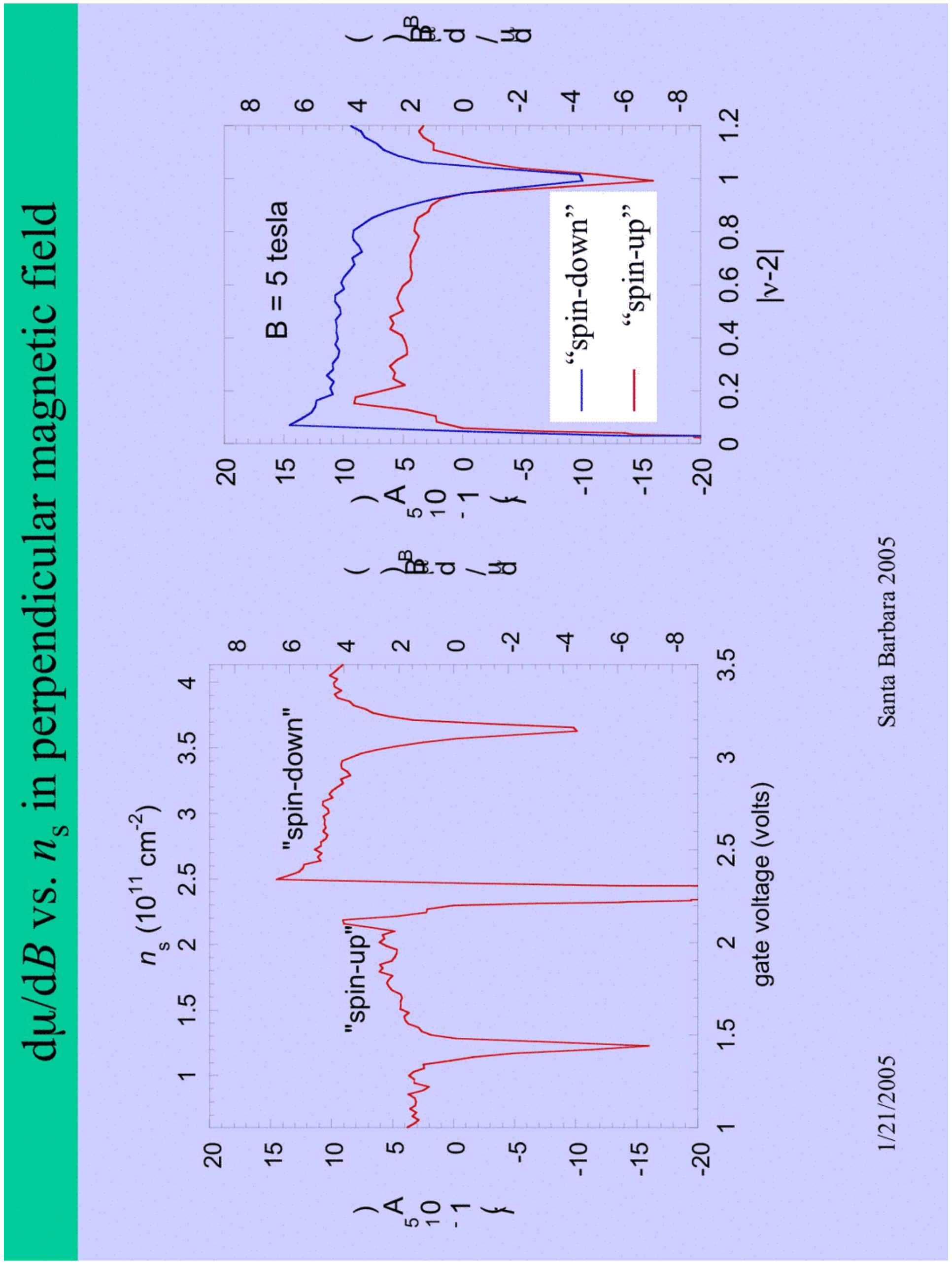
dμ/dB vs. n_s in perpendicular magnetic field
n_s (10^{11} cm^{-2})
"spin-down"
"spin-up"
gate voltage (volts)
B = 5 tesla
"spin-down"
"spin-up"
|ν-2|
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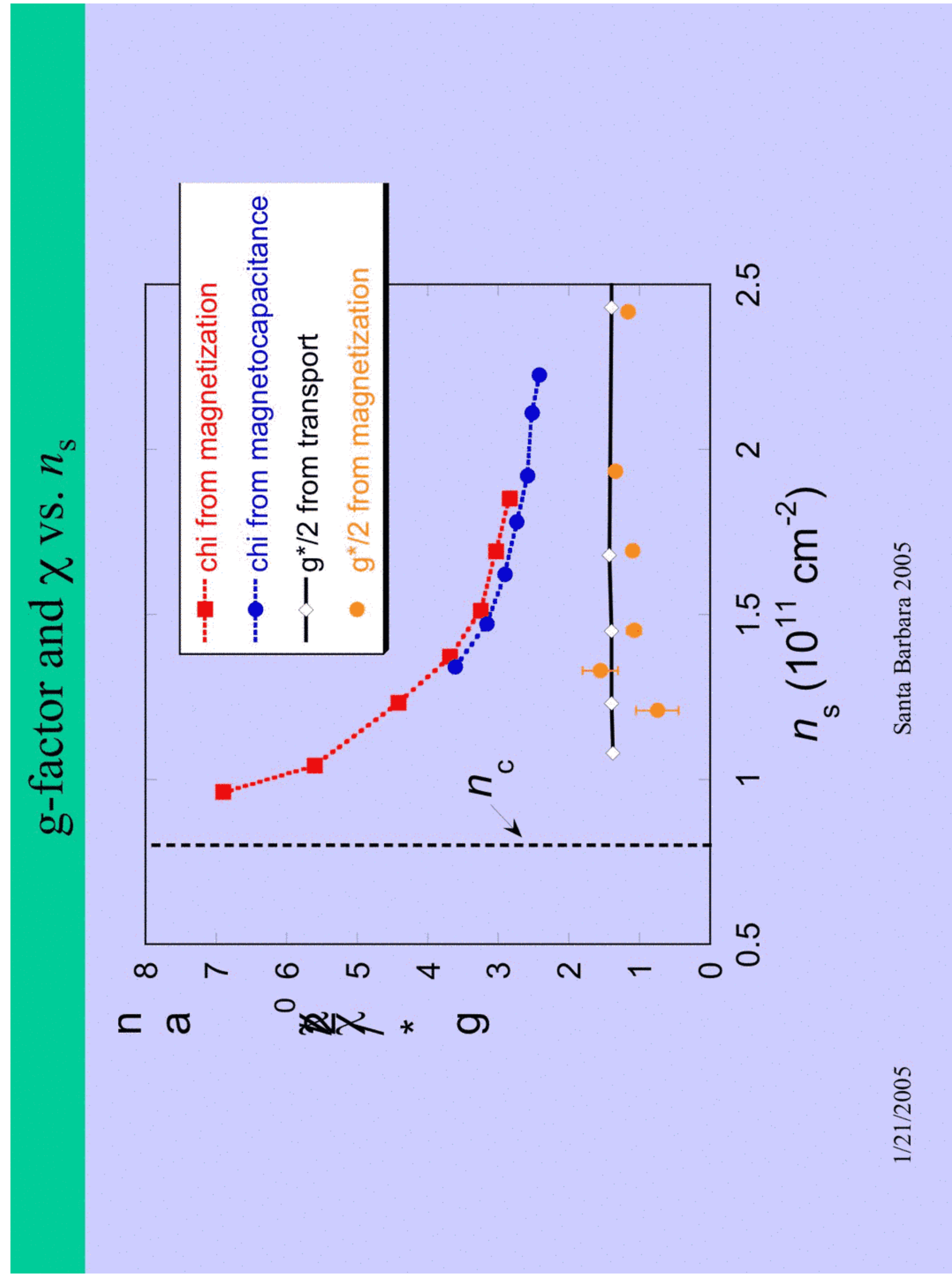
g-factor and χ vs. n_s
chi from magnetization
chi from magnetocapacitance
g*/2 from transport
g*/2 from magnetization
n_c
n_s (10^{11} cm^{-2})
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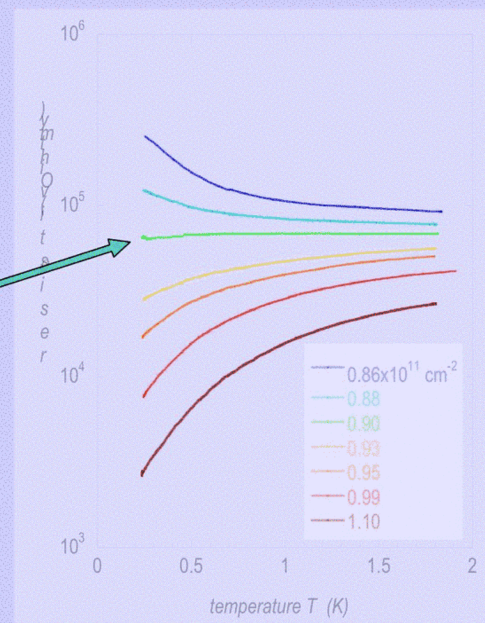
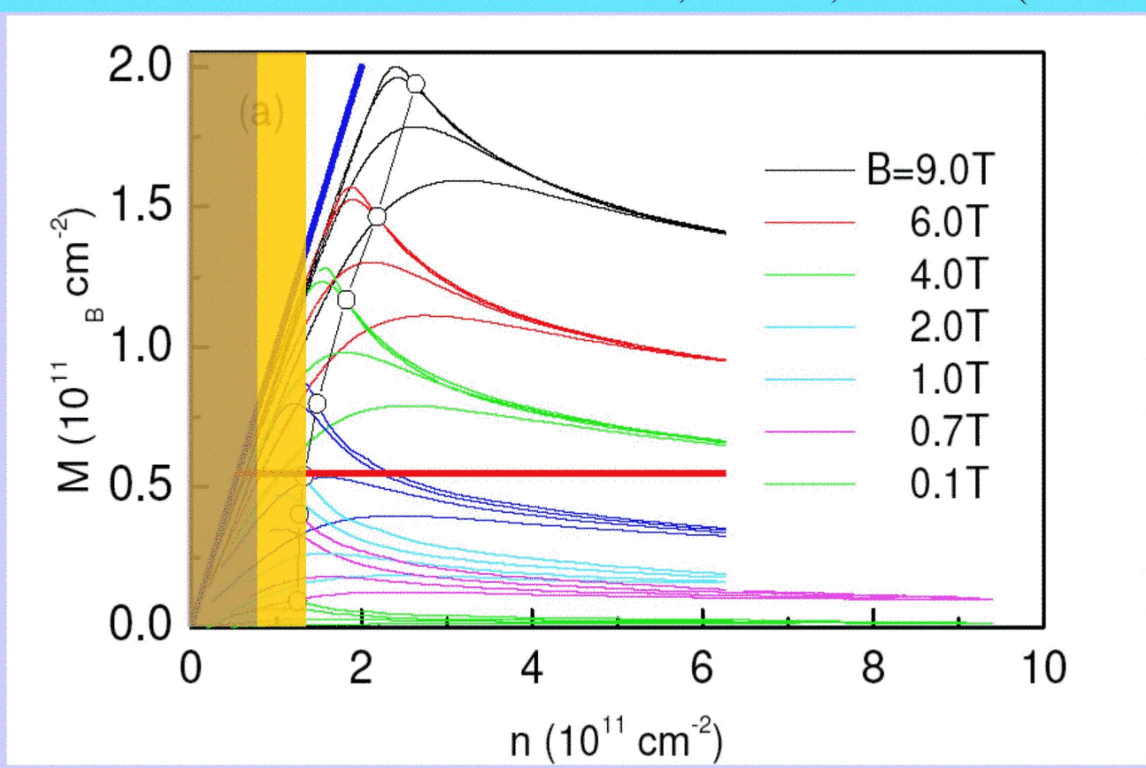
CONCLUSIONS:

- **In strongly interacting 2D electron system in silicon, spin susceptibility sharply rises with a tendency to diverge at a sample-independent density n_χ.**
- **We find no evidence of increasing g-factor: it must be the effective mass that is responsible for the effect**
- **In clean samples, n_χ practically coincides with the metal-insulator transition.**

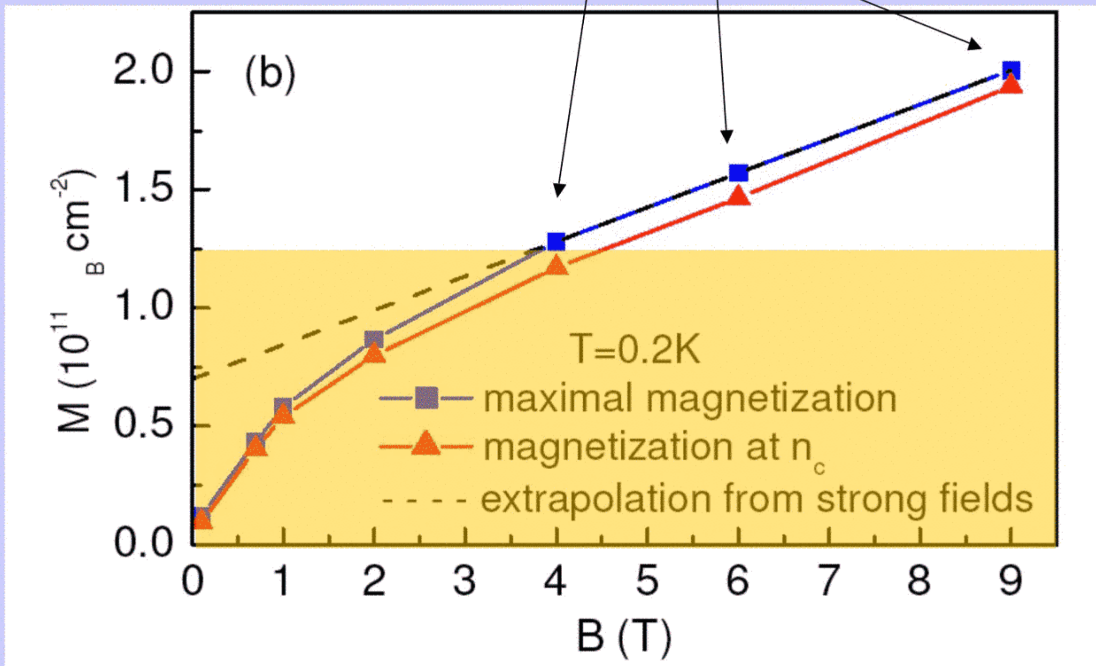


Appendix:

Difference between our results and those of Prus, Reznikov, Sivan *et al*. (*PRB* 2003):



Only three data points are relevant to the metallic regime



Data of Prus, Reznikov, Sivan *et al.* *PRB* 2003

Indeed, the (inverse) spin susceptibility has a Curie form characteristic of local moments

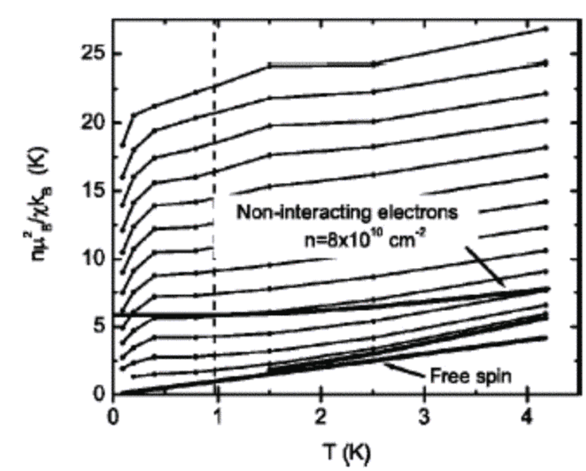


FIG. 4. Inverse susceptibility as determined from $M(B)$ at $B = 0.7$ T. Experimental points from bottom to top correspond to densities $0.8–6\times10^{11}$ cm^{-2} in 4×10^{10} cm^{-2} steps. The thick straight line depicts Curie law and the dashed line marks $T = (g\mu_B/k_B)\times0.7$ T. The experimental points at $n=8\times10^{10}$ are connected by a thick line for comparison with the expectation for noninteracting electrons of the same density.

Data of Prus, Reznikov, Sivan *et al.* *PRB* 2003