Photon-induced zero-resistance states in electrons on He

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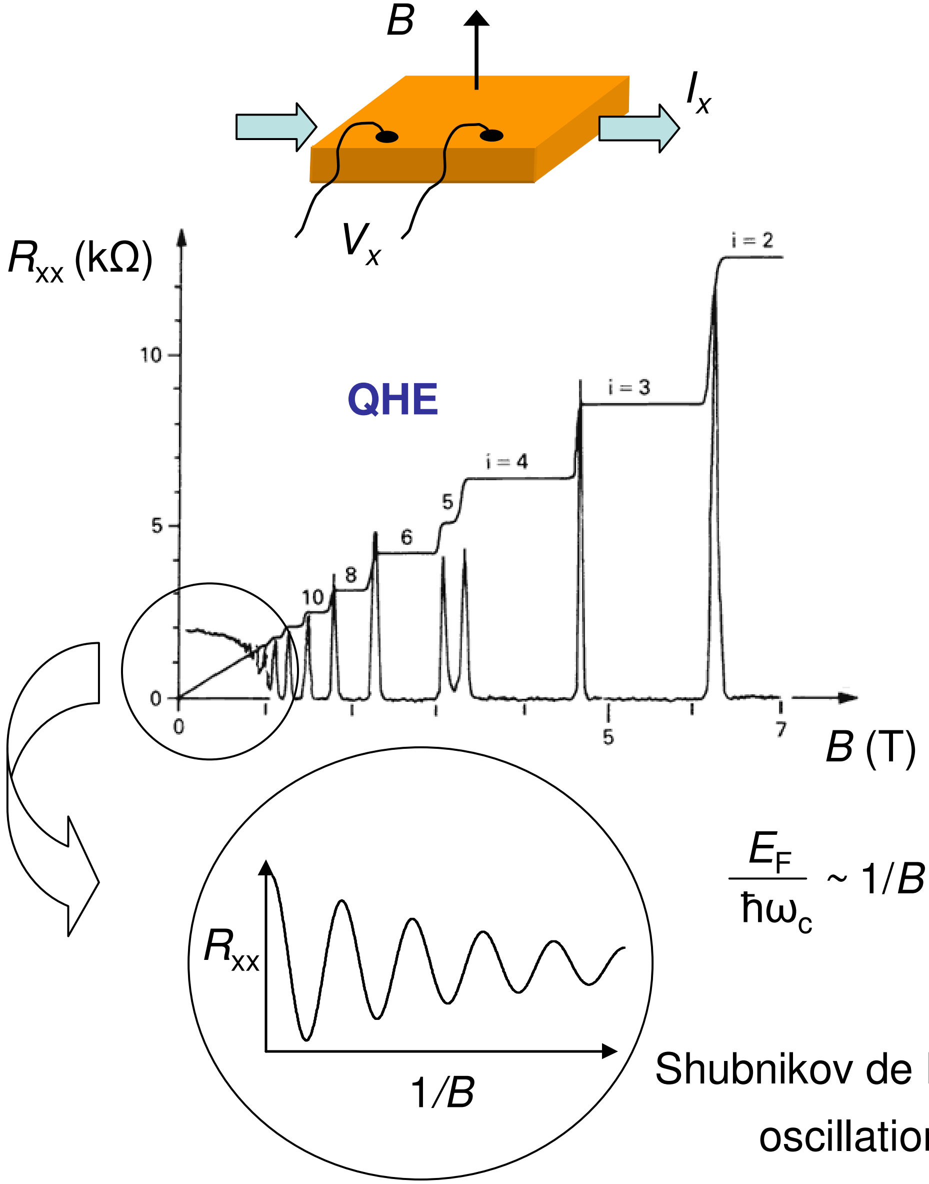
Talk outline

Subject: novel transport phenomena in nondegenerate 2D electrons subjected to perpendicular magnetic fields

- Quantum oscillations in degenerate 2DEG in semiconductors
- Radiation-induced ZRS in GaAs/AlGaAs
- Inter-subband resonance in electrons on He
- Quantum oscillations in electrons on He
- ZRS in electrons on He
- Conclusions and future plans

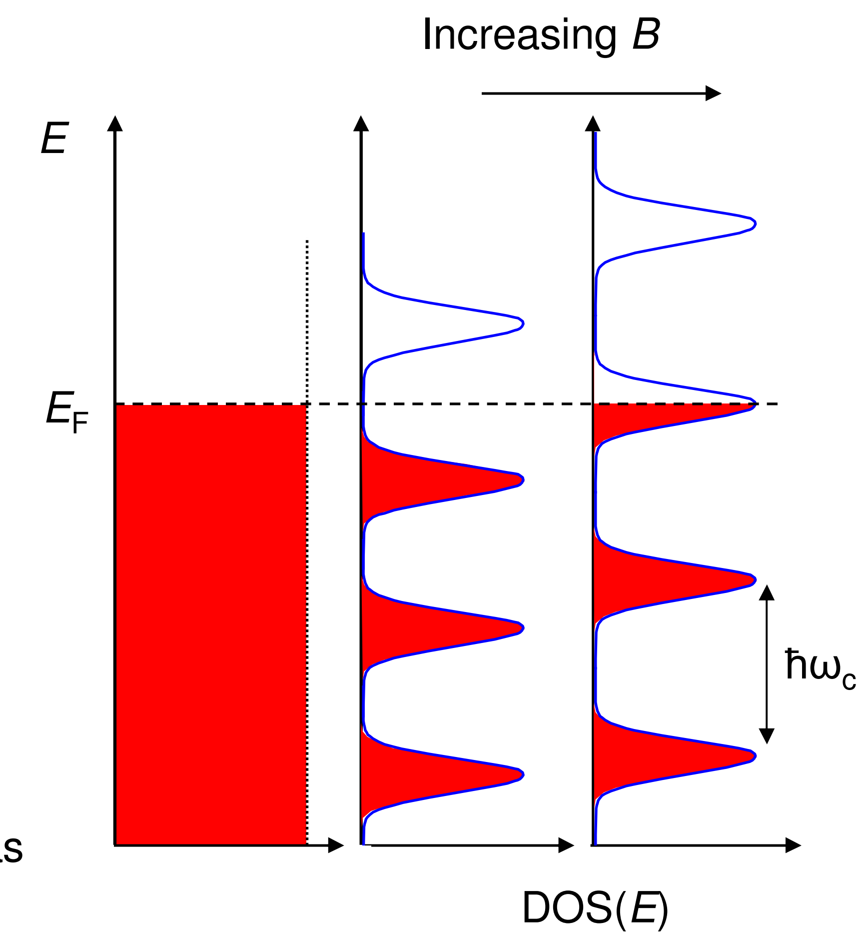
Degenerate 2DEG in magnetic fields



$$\frac{E_F}{\hbar\omega_c} \sim 1/B$$

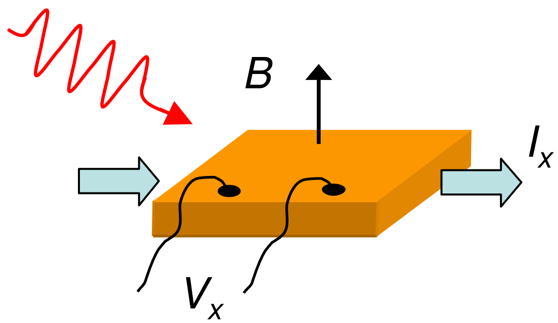
Shubnikov de Haas oscillations

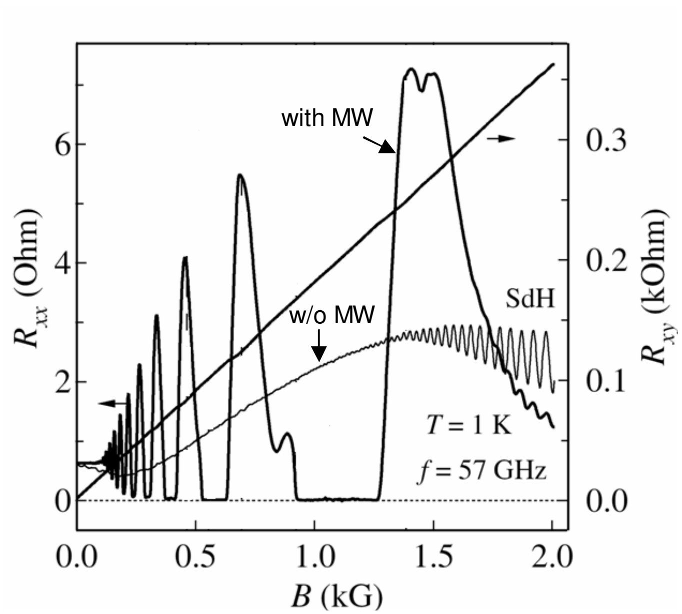
Fermi statistics + Landau quantization



Radiation-induced ZRS in GaAs/AlGaAs

f = 10-100 GHz





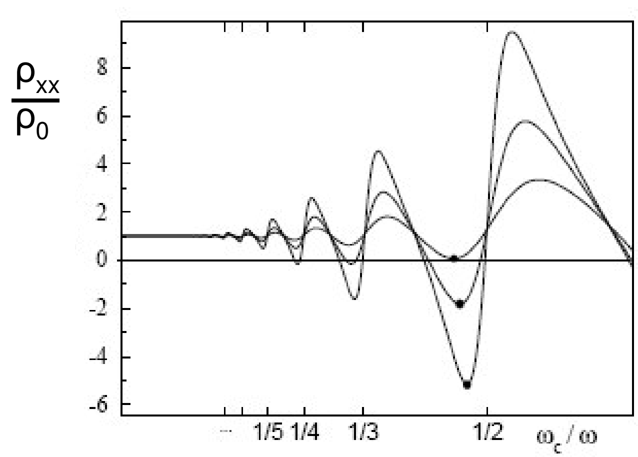
From Zudov et al. PRL 2003

$$\frac{hf}{\hbar\omega_c} = j$$ - no change in resistance

Kohn's theorem

$$\frac{hf}{\hbar\omega_c} = j \pm \frac{1}{4}$$ - resistance minima/maxima

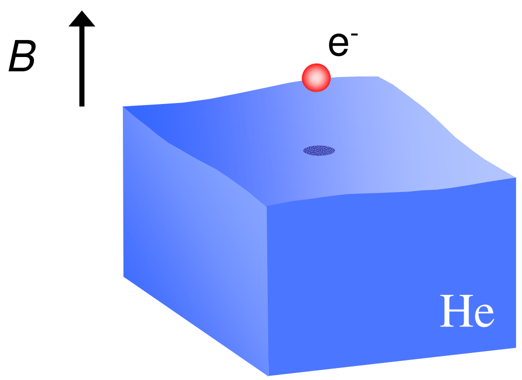
Great number of theoretical proposals!



1. Negative-resistivity minima!
2. $\sigma_{xx} < 0$ - spontaneous symmetry breaking

Andreev et al. PRL 2003

Non-degenerate 2D electrons on He

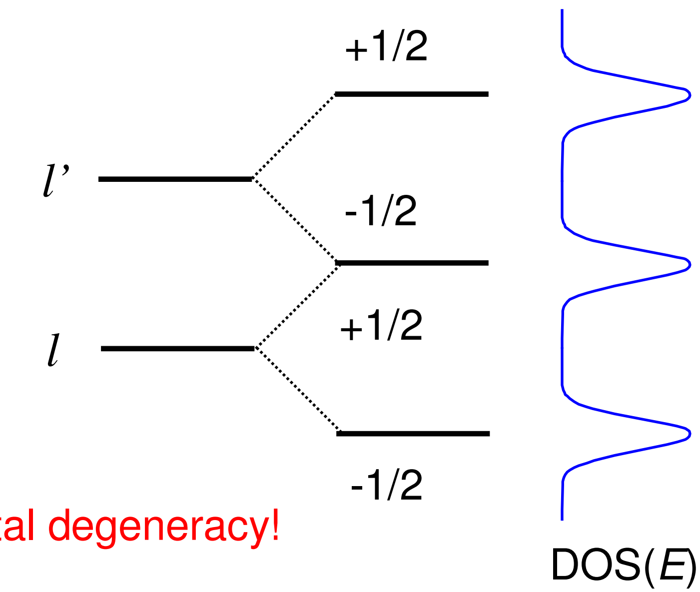


- Ultra-clean system with the highest mobility ~10^8 cm^2/Vs
- Unscreened Coulomb interaction
- Low areal density < 2×10^8 cm^{-2}

→ At T=0 classical Wigner solid rather than degenerate gas!

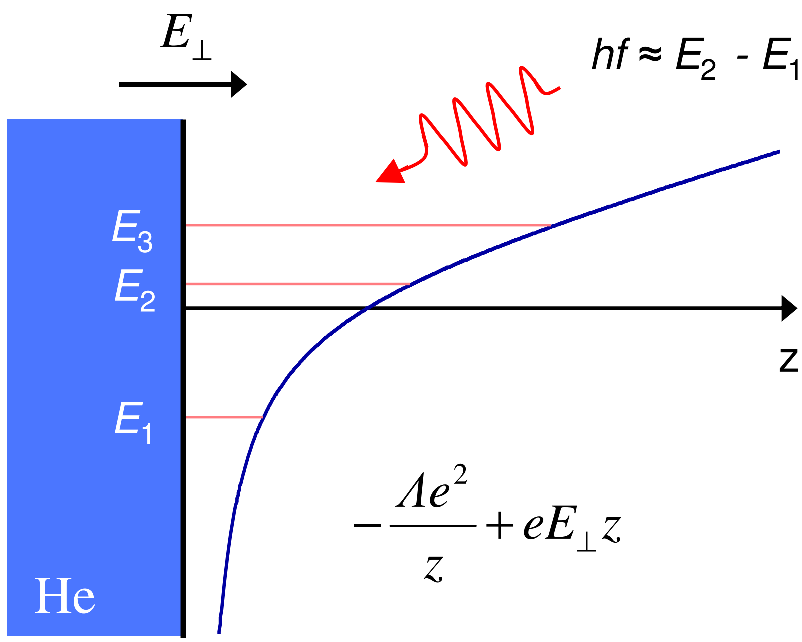
In perpendicular B: $E = \hbar\omega_c(l+\frac{1}{2}) \pm \frac{1}{2} g\mu_B B$

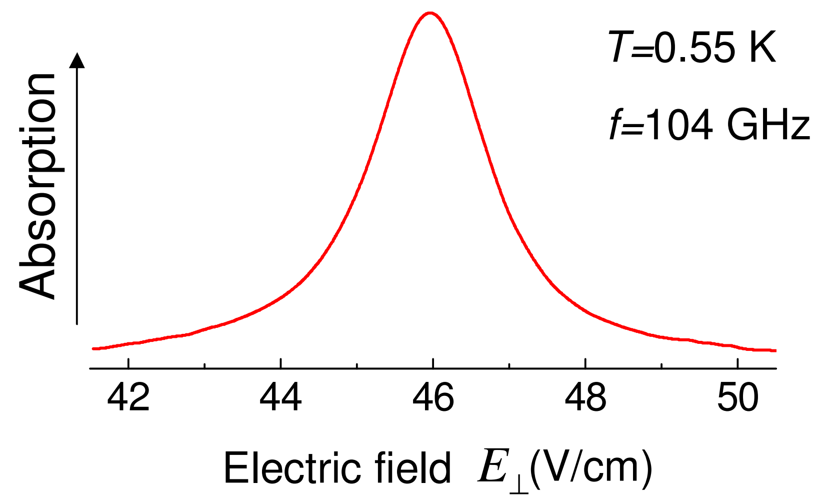
- Free-electron mass $m^* \approx m_e$
- Free-electron g-factor: g=2.0023



Accidental degeneracy!

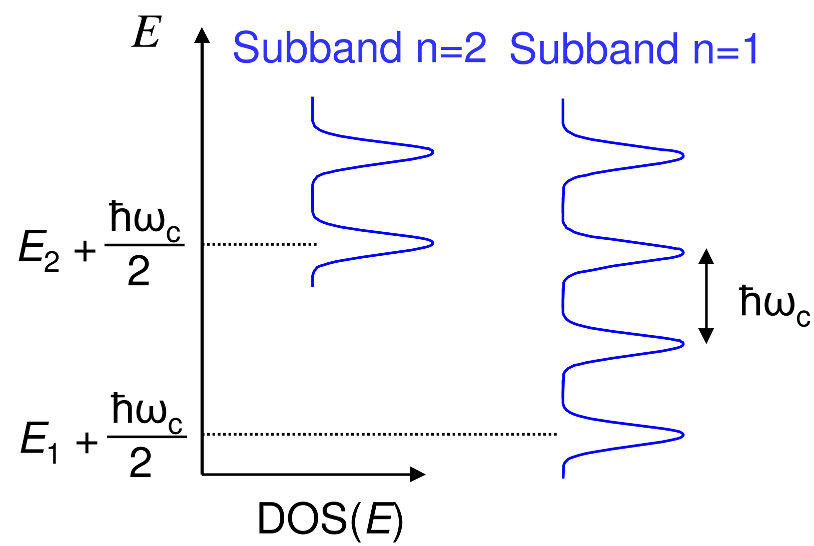
Inter-subband resonance





Total energy in magnetic fields:

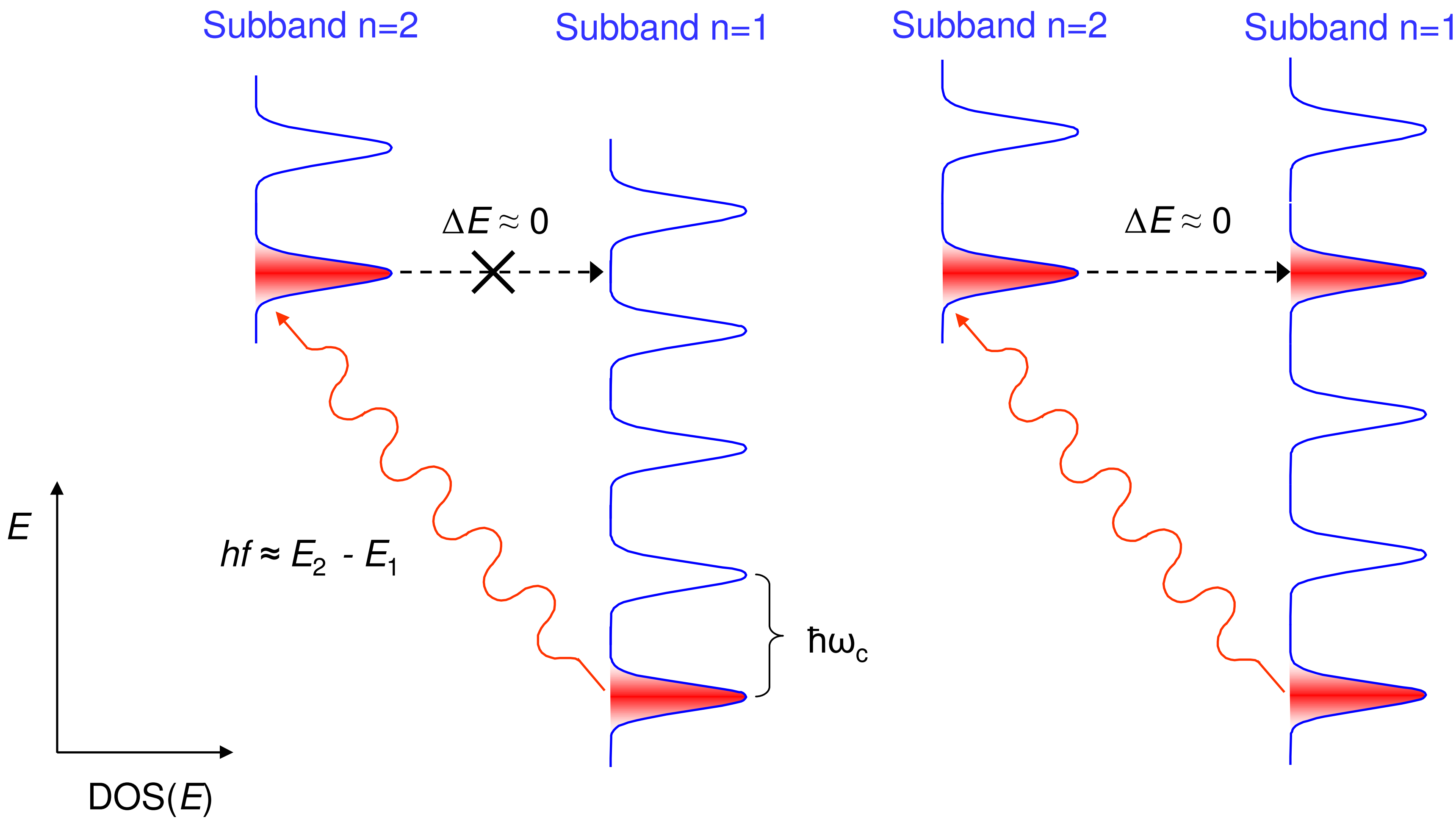
$$E = E_n + \hbar\omega_c(l+\frac{1}{2}), \quad l = 0, 1, 2, ..$$



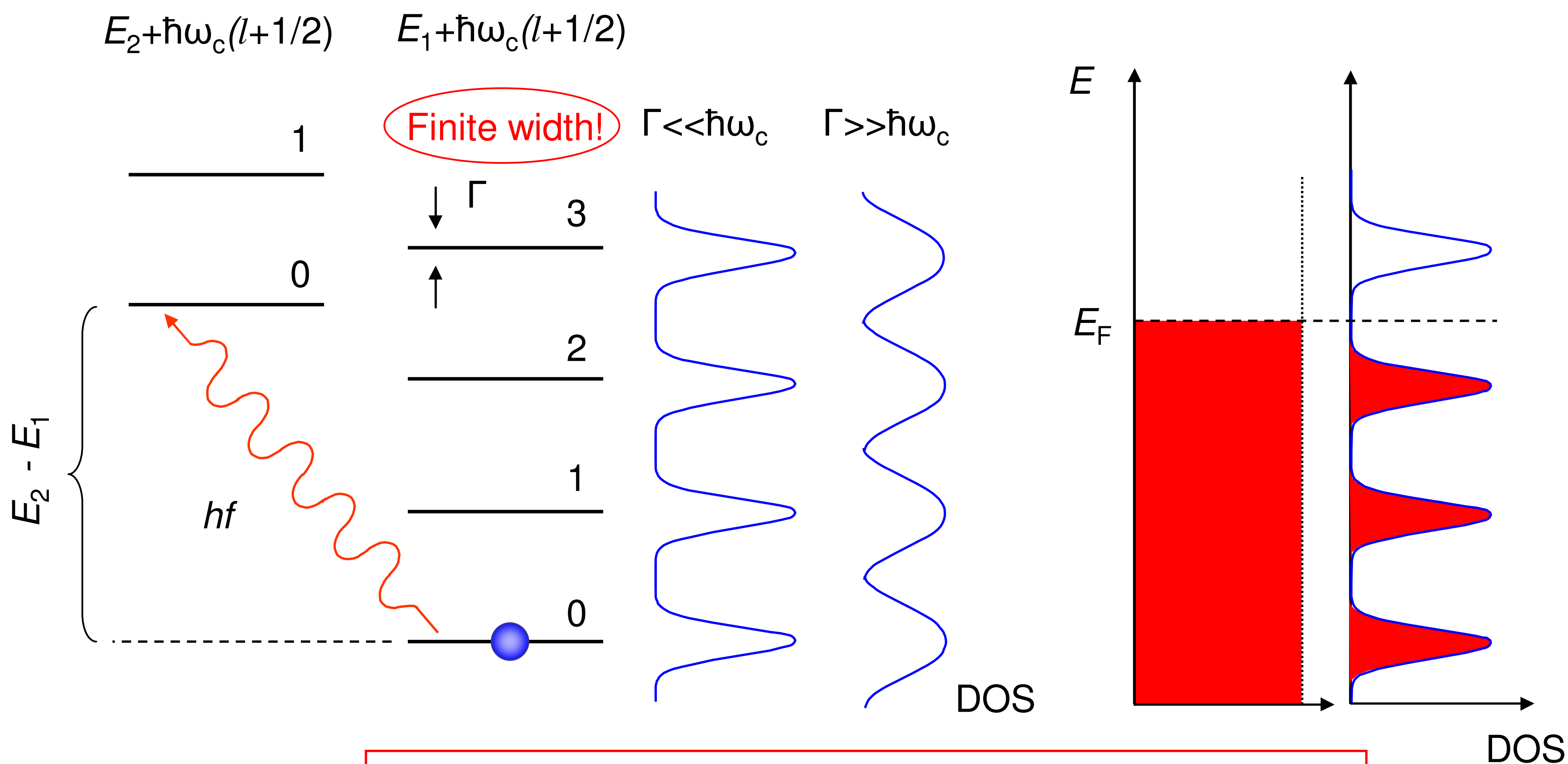
Electron dynamics in magnetic fields

Microwave excitation + scattering-mediated transitions. Scattering is quasi-elastic!

$$\frac{E_2 - E_1}{\hbar\omega_c} \approx \frac{2\pi f}{\omega_c} = N+1/2 \qquad\qquad \frac{E_2 - E_1}{\hbar\omega_c} \approx \frac{2\pi f}{\omega_c} = N$$



Magneto-resistance oscillations

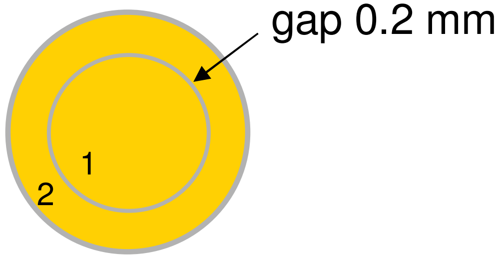


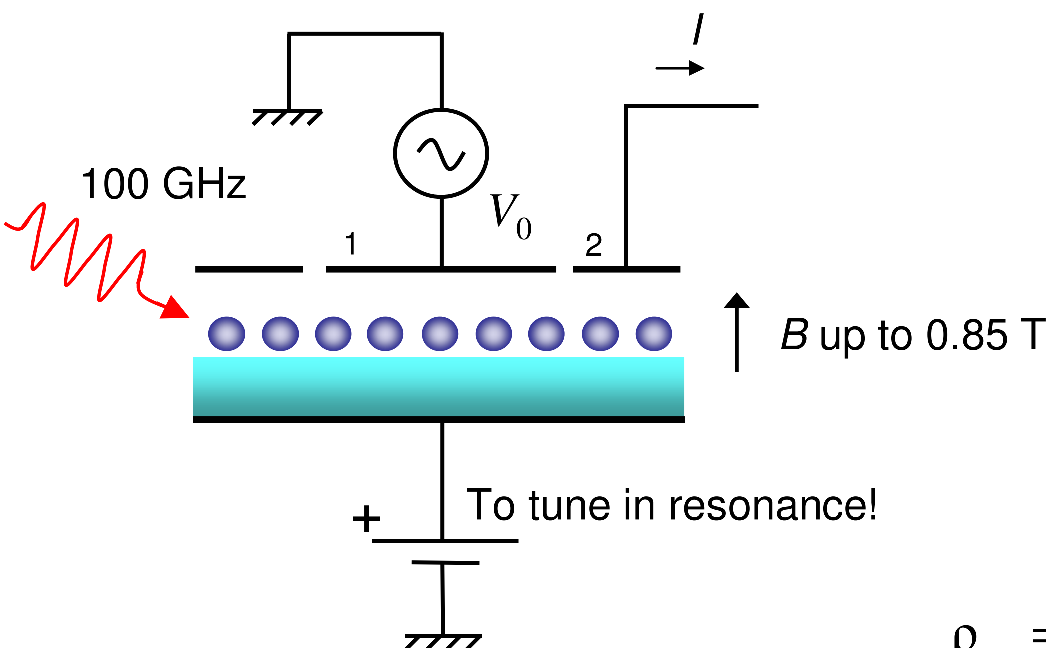
$\frac{E_2 - E_1}{\hbar\omega_c}$ versus $\frac{E_F}{\hbar\omega_c}$

Somewhat similar to Shubnikov de Haas effect

Experiment

Au plated Corbino disk





Magneto-transport measurements:

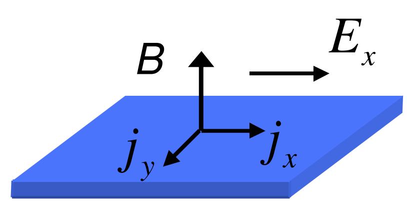
$$I = \left(\mathrm{Re}(G) + j\,\mathrm{Im}(G)\right)V_0$$

Determine complex admittance *G*

$$G = G(\sigma_{xx})$$

Find relationship between *G* and σ_{xx}

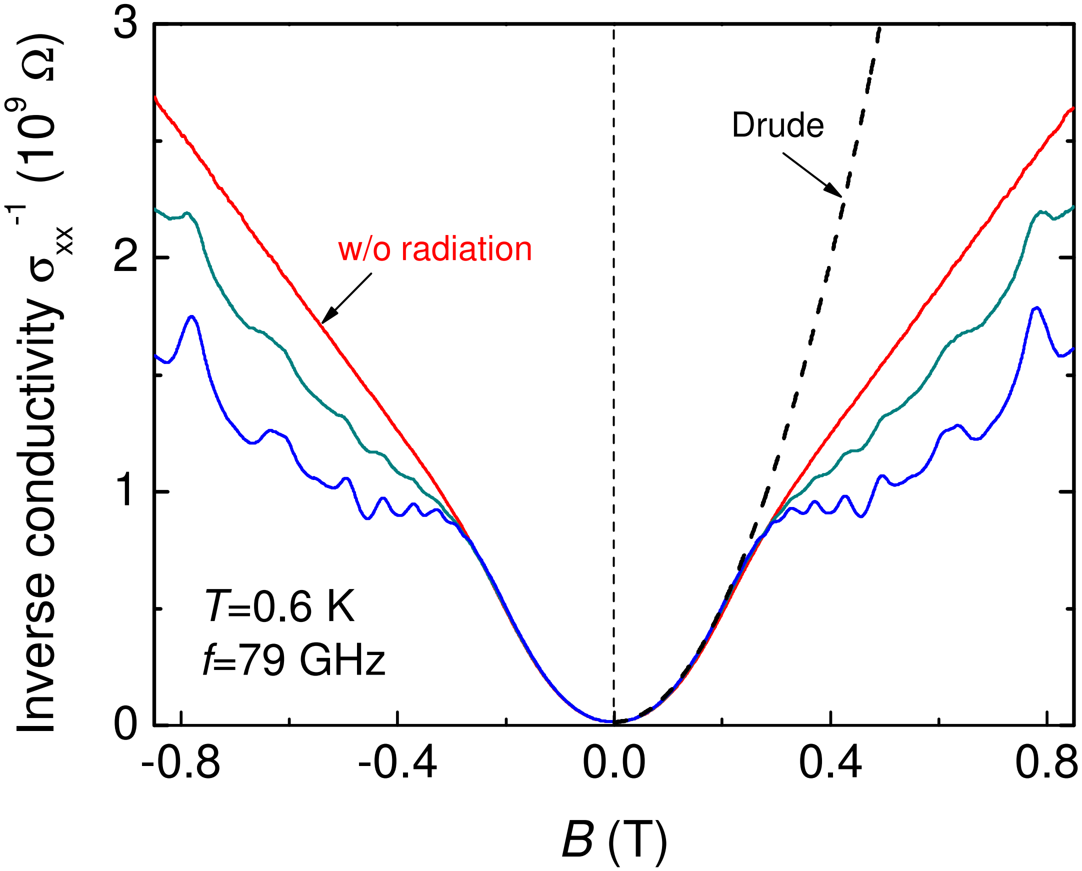
More details on the poster!



$$\vec{j} = \begin{pmatrix} \sigma_{xx} & \sigma_{yx} \\ \sigma_{xy} & \sigma_{yy} \end{pmatrix} E_x$$

$$\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \approx \frac{\sigma_{xx}}{\sigma_{xy}^2} \sim \sigma_{xx}$$

Oscillations



Without (w/o) radiation:

Drude low: $\sigma_{xx} \approx \frac{\mu B^2}{e n_s}$, $\mu B >> 1$

Many-electron effects

Dykman and Lea

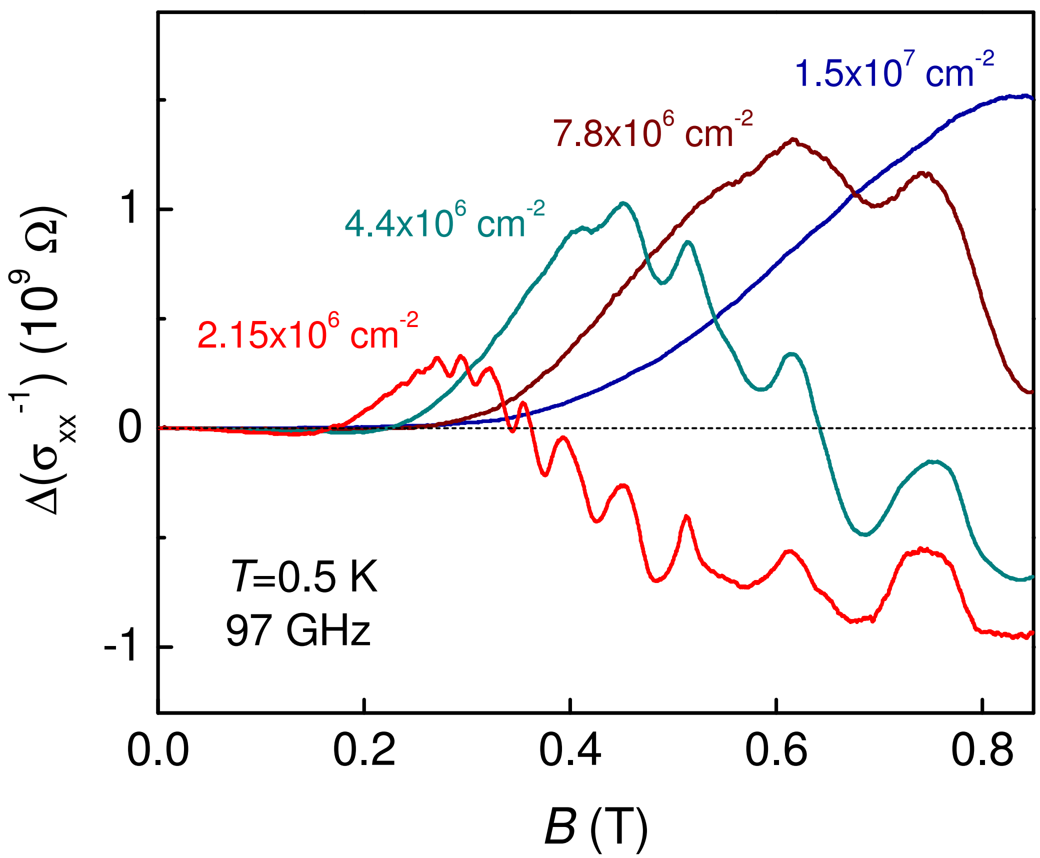
New result:

Radiation-induced

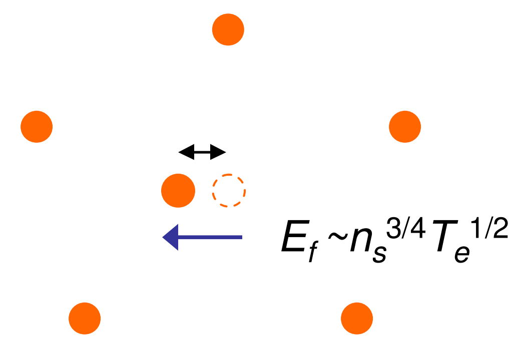
resistivity oscillations!

Many-electron effects

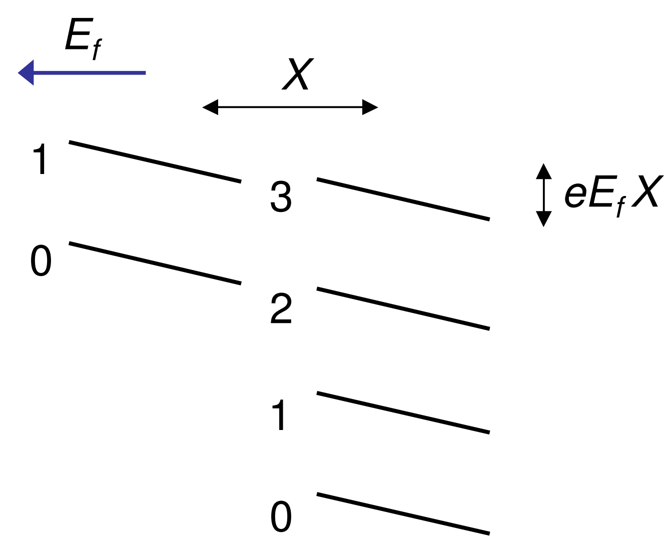
$\Delta(\sigma_{xx}^{-1}) = \sigma_{xx}^{-1}|_{with} - \sigma_{xx}^{-1}|_{w/o}$



Fluctuating electric field E_f

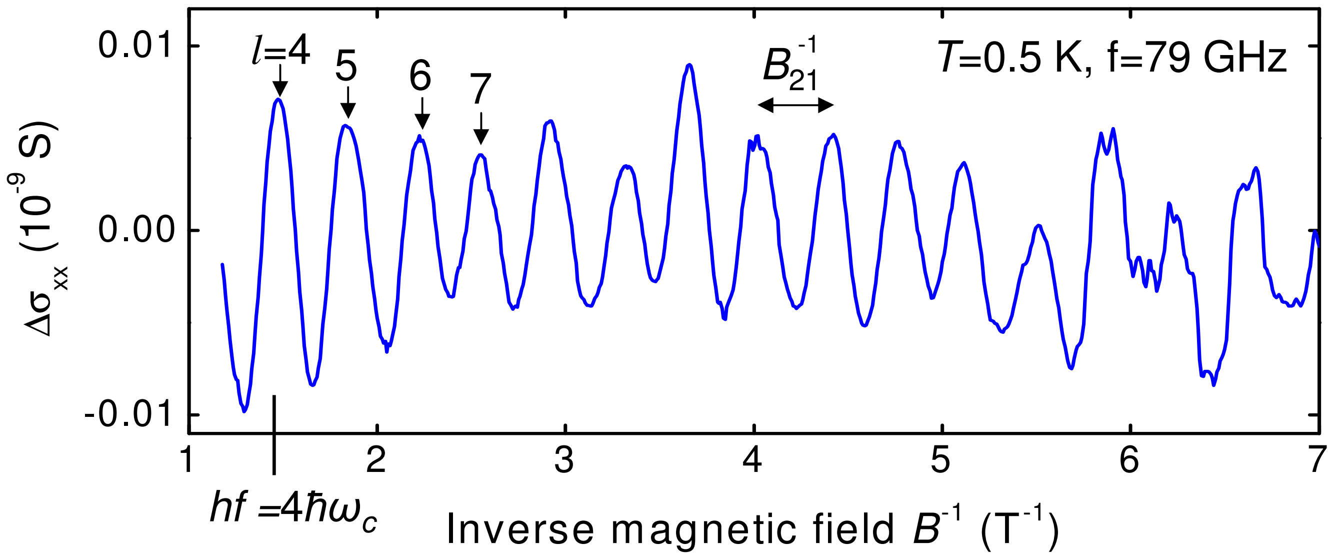


Dykman and Khazan (1979)



Tilting of Landau levels!

Periodicity

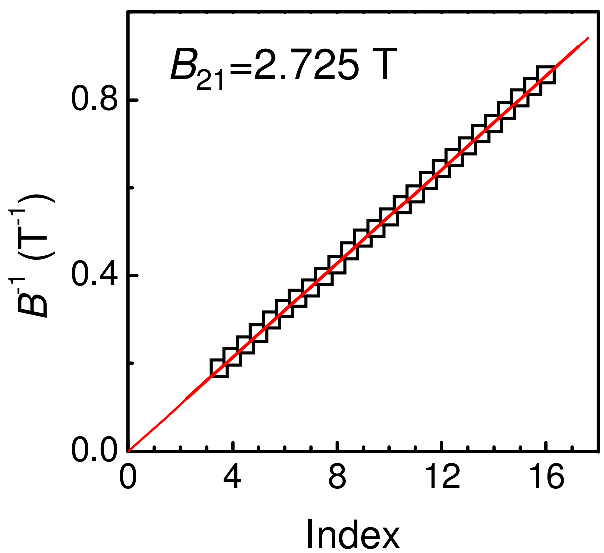


l =4,5, .. - Landau index

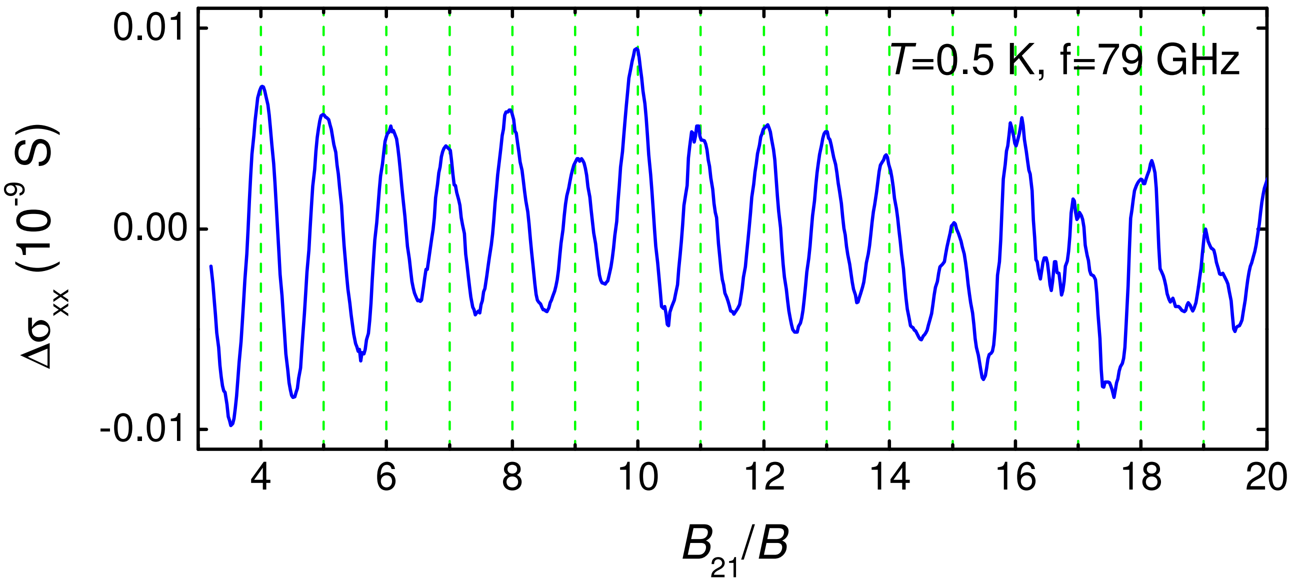
l - index for maxima

l +1/2 - index for minima

$$\Delta\sigma_{xx} \sim \cos[2\pi \frac{B_{21}}{B}]$$



Periodicity

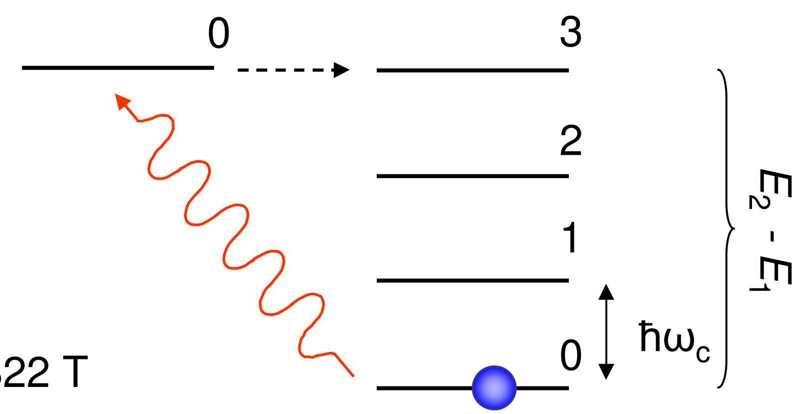


Maxima at $\frac{B_{21}}{B}$ = integer number

$$\sigma_{xx} = \frac{n_s e^2}{m_e} \frac{\nu}{\nu^2 + \omega_c^2} \sim \nu$$ - scattering rate

$$\frac{B_{21}}{B} = \frac{E_2 - E_1}{\hbar\omega_c} \approx \frac{2\pi f}{\omega_c} \longrightarrow B_{21} \approx \frac{2\pi f m}{e} = 2.822 \text{ T}$$

Good agreement!

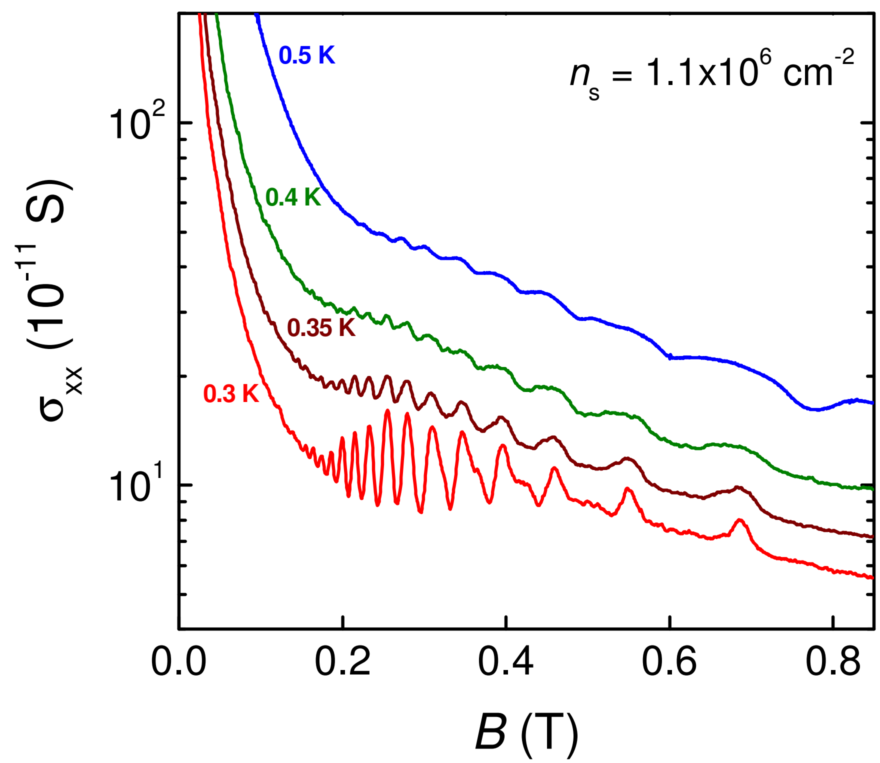


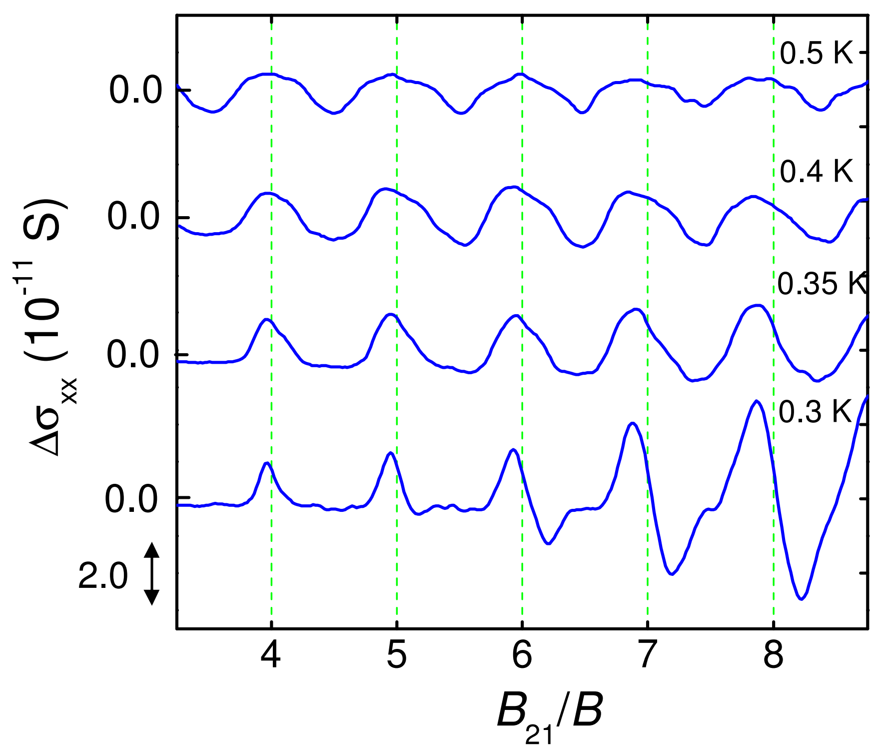
Thermal broadening of LLs

Low density and sufficiently high fields → ignore many-electron effects

Self-consistent Born approximation (SCBA): $\Gamma \sim \hbar(\omega_c \nu)^{1/2}$

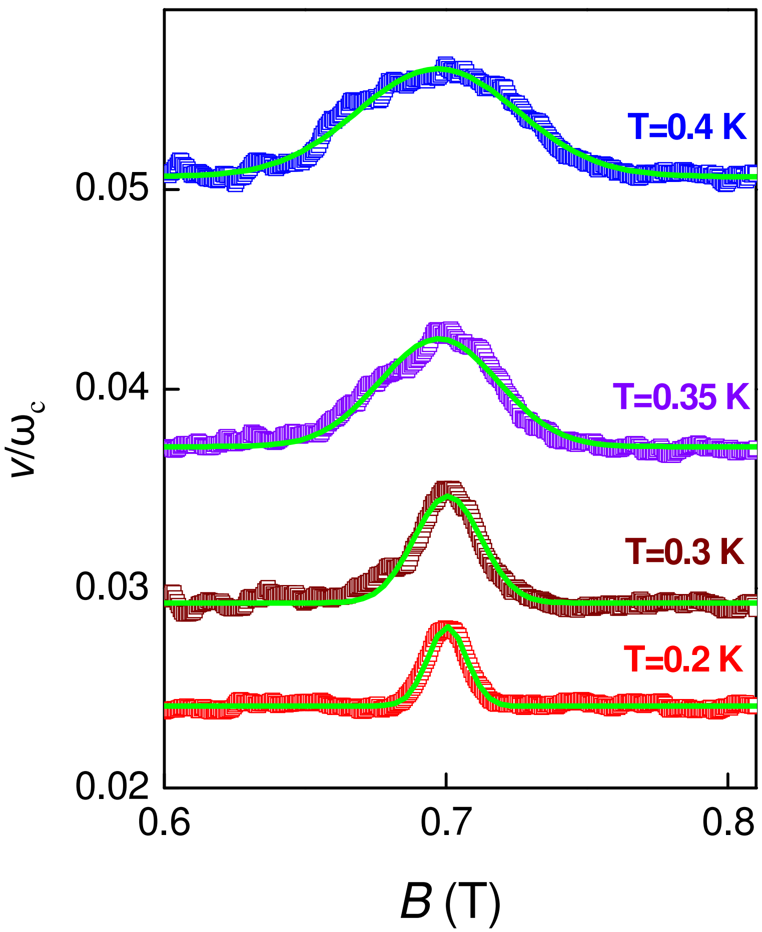
Decrease scattering by lowering *T* !





Thermal broadening of LLs

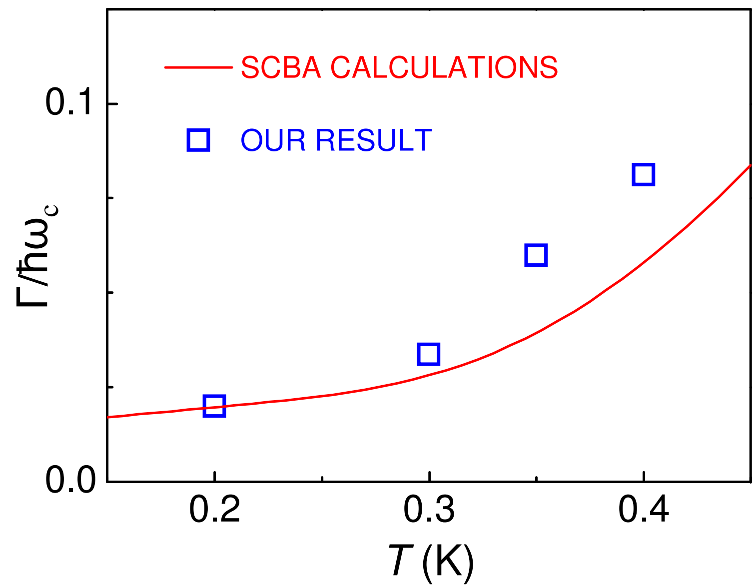
Fit with Gaussian lineshape:



Broadening due to vapor atoms

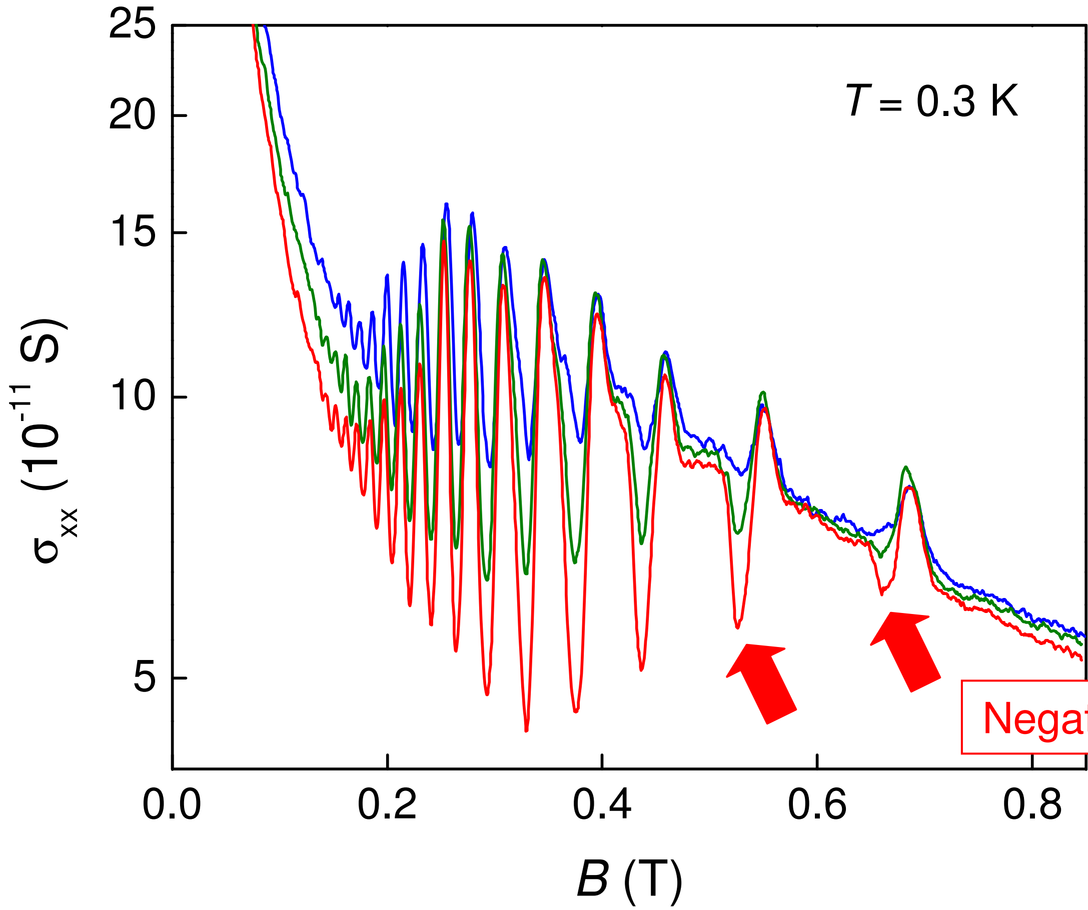
and ripplons in SCBA:

$$\Gamma^2 = \Gamma^2_{\text{atom}} + \Gamma^2_{\text{rippl}}$$



Conductivity decrease

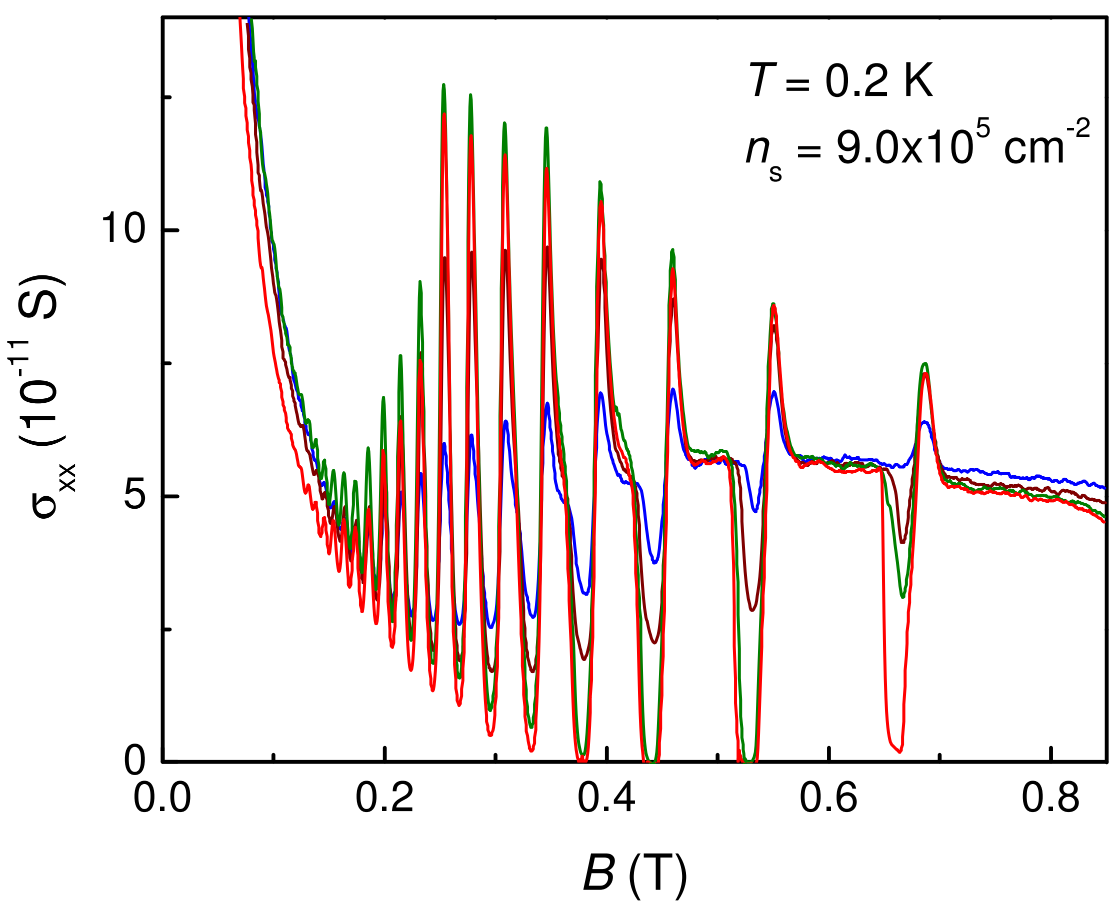
Upon increasing radiation power, there appears a negative contribution to σ_{xx}!



Negative contribution to σ_{xx}!

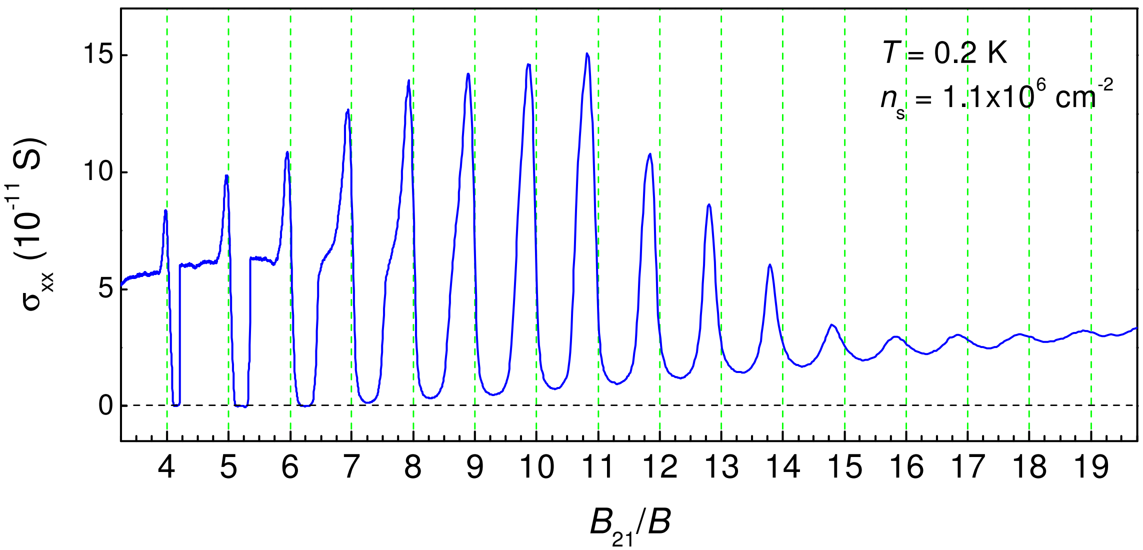
ZRS at T=0.2 K

The effect becomes stronger at lower *T* !



Vanishing conductivity σ_{xx} and resistivity ρ_{xx} at the minima!

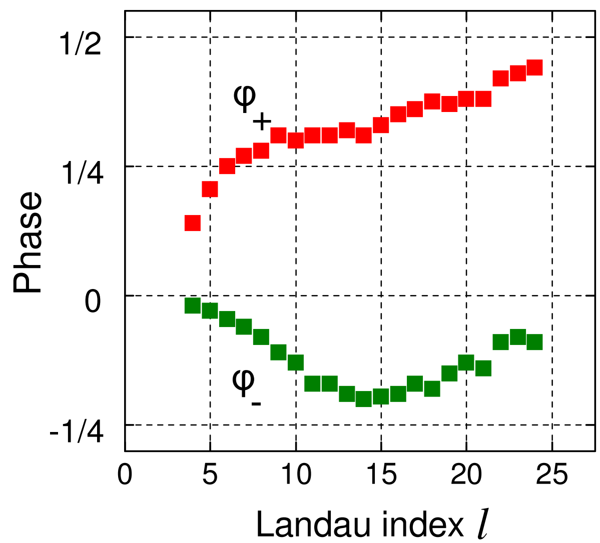
Phase of oscillations



$\frac{B_{21}}{B_+}$ - position of minima

$\frac{B_{21}}{B_-}$ - position of maxima

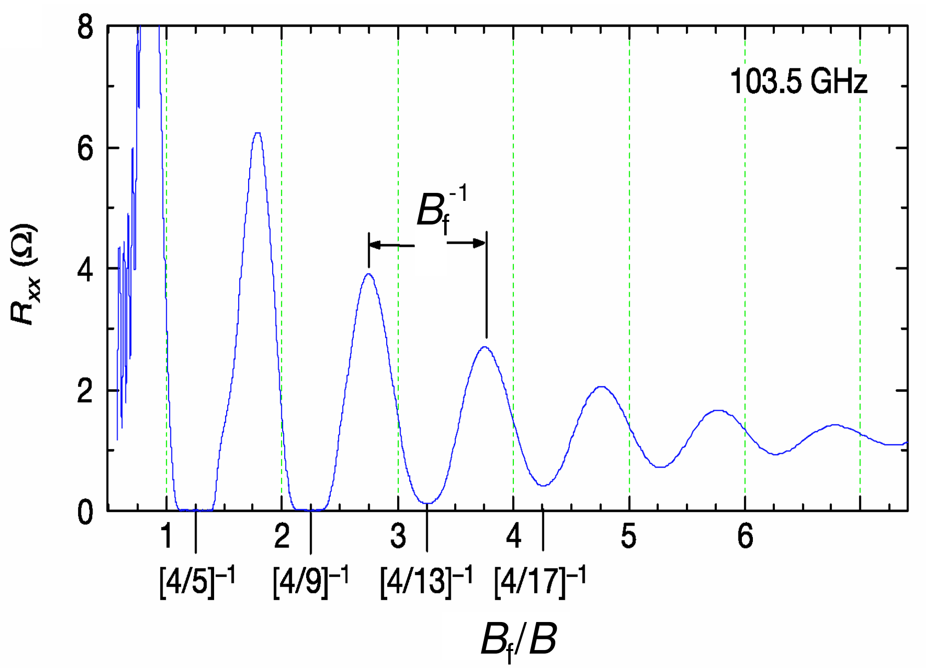
$$\frac{B_{21}}{B_\pm} = l + \varphi_\pm(l)$$



Oscillations in GaAs/AlGaAs

In GaAs/AlGaAs herterosctructures:

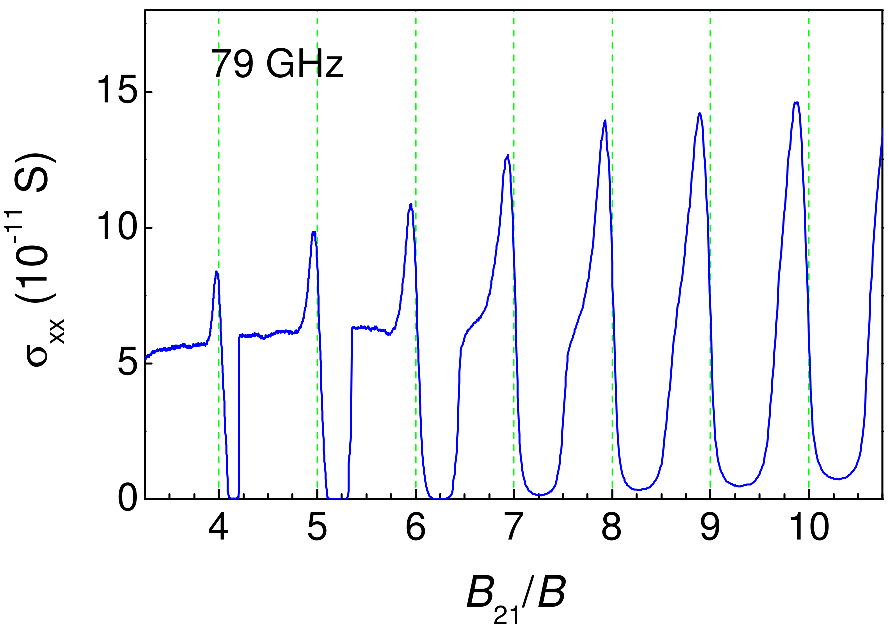
$$\frac{B_f}{B_\pm} = j \pm \frac{1}{4} \quad , \quad j = 1,2,\ldots \,.$$



From Mani et.al. Nature 420, 646 (2002)

In our system:

$$\frac{B_{21}}{B_\pm} = l + \varphi_\pm(l) \quad , \quad l = 4,5,\ldots \,.$$

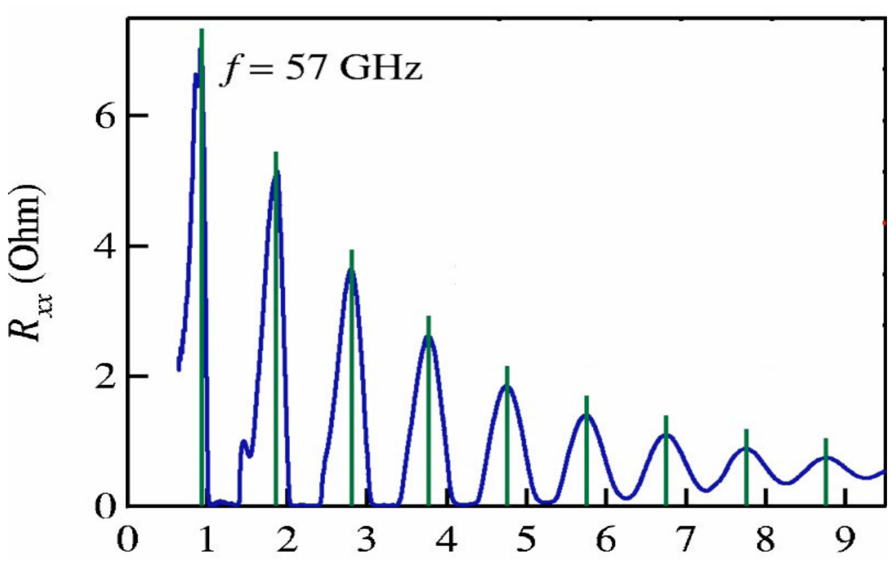


Oscillations in GaAs/AlGaAs

In GaAs/AlGaAs heterosctructures:

$$\varepsilon_{\pm} = j + \alpha_{\pm}\, j \ , \ \text{for} \ j \leq 4$$

$$\varepsilon_{\pm} = j + \frac{1}{4} \ , \ \text{for} \ j > 4$$

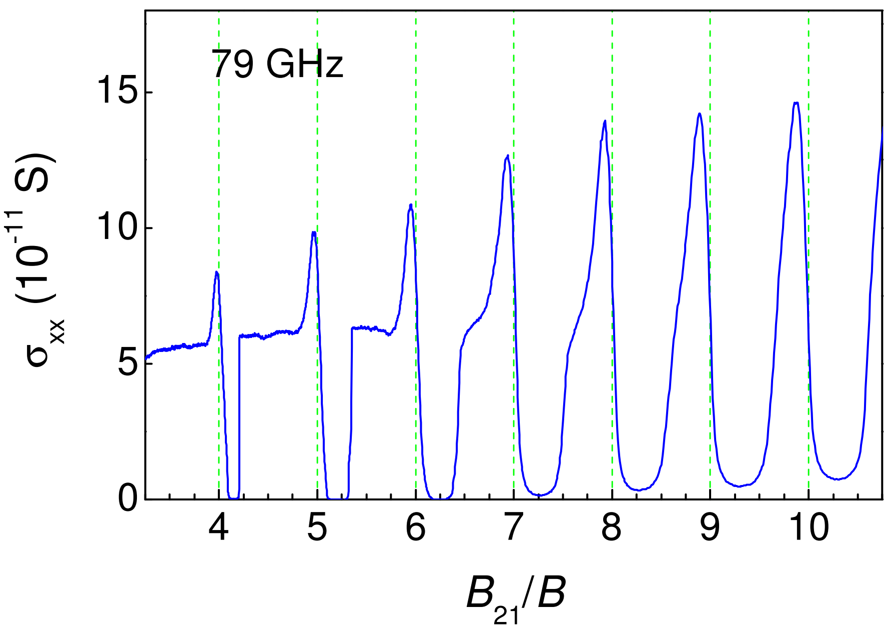


$$\varepsilon = \frac{2\pi f}{\omega_c}$$

From Zudov PRB, 69 (2004)

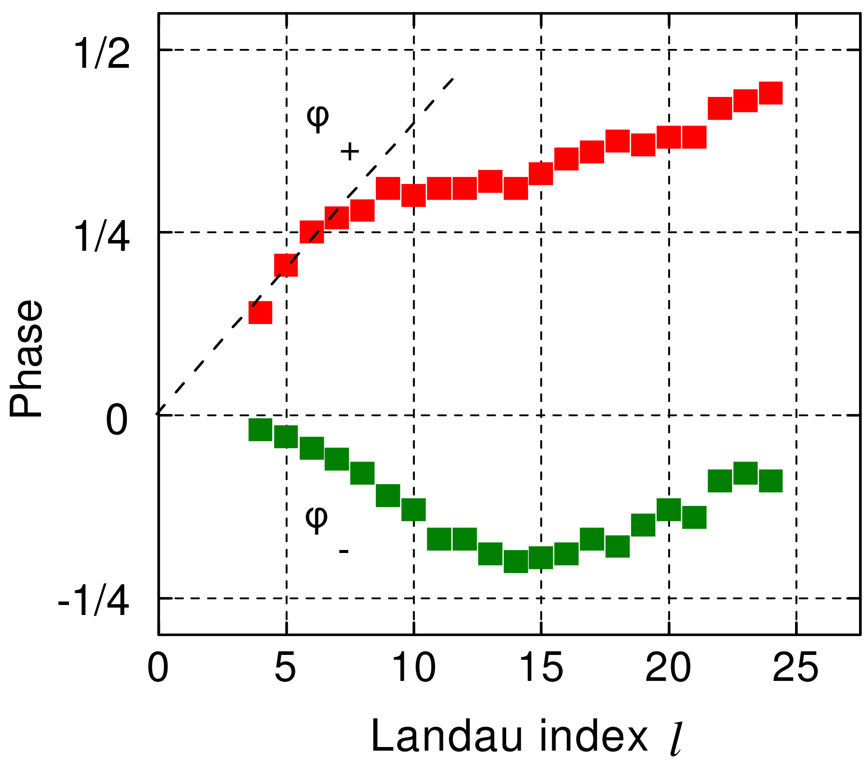
In our system:

$$\frac{B_{21}}{B_{\pm}} = l + \varphi_{\pm}(l) \ , \quad l = 4,5,\ldots .$$



Phase for minima

$$\frac{B_{21}}{B_+} = l + \varphi_+(l) \quad , \quad l = 4,5,\ldots$$

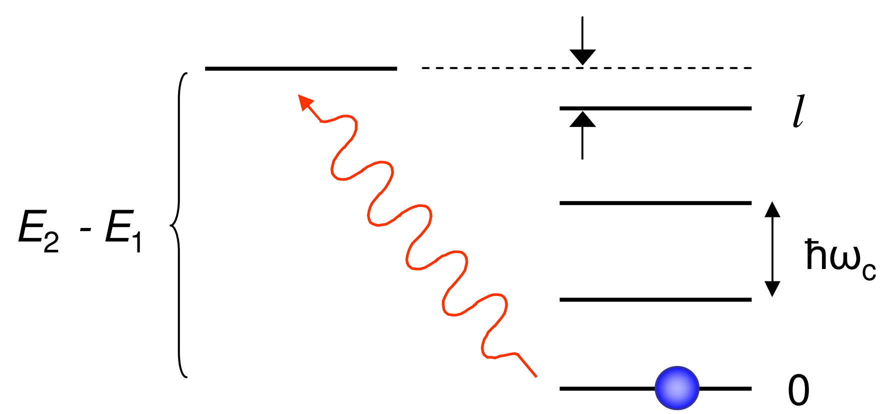


Suppose $\varphi_+ = \alpha\, l$, for $l \leq 4$

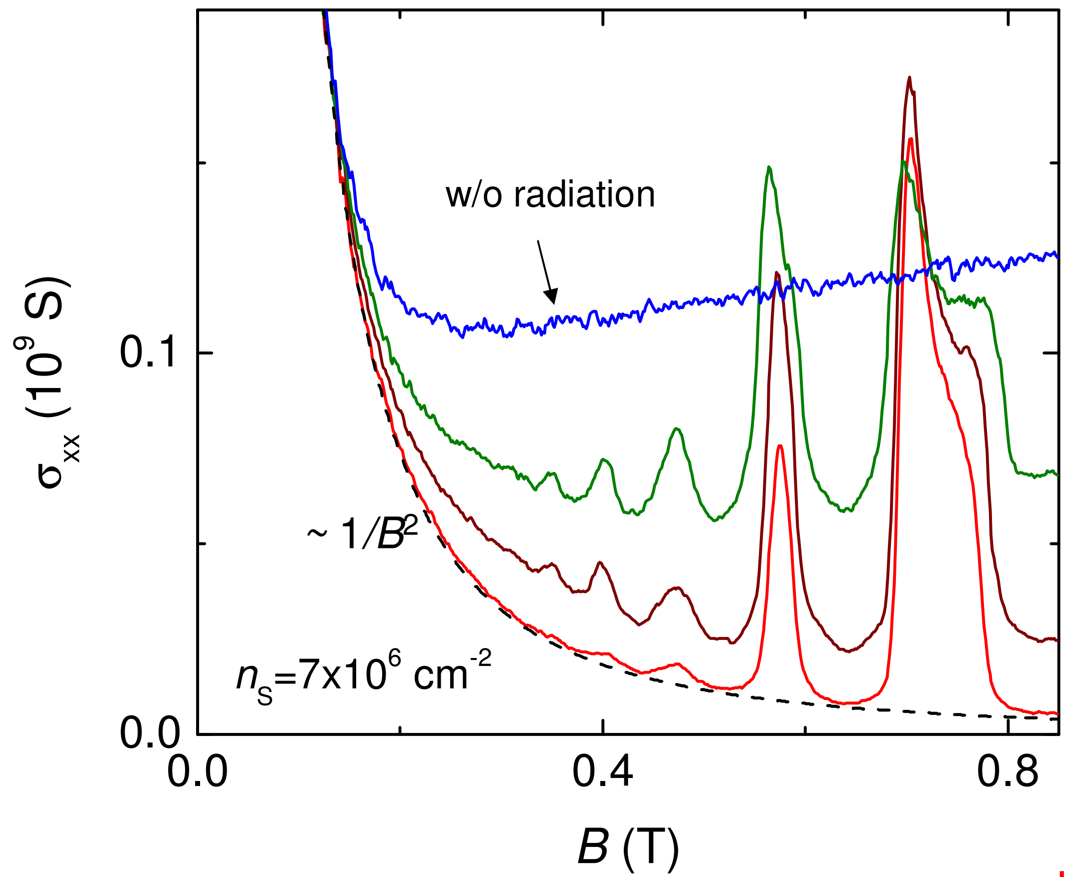
Because $\frac{B_{21}}{B} = \frac{E_2 - E_1}{\hbar\omega_c}$

Then at the minima:

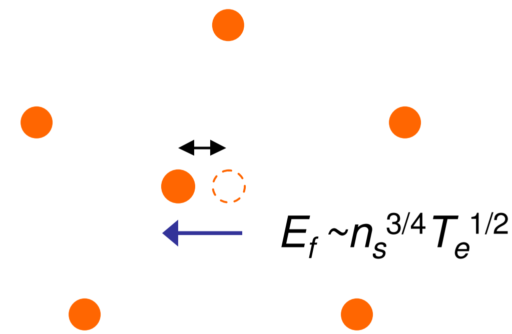
$$E_2 - E_1 - l\,\hbar\omega_c = \frac{\alpha}{\alpha + 1}\,(E_2 - E_1)$$



Density dependence (T=0.2 K)



Fluctuating electric field E_f



Dykman and Khazan (1979)

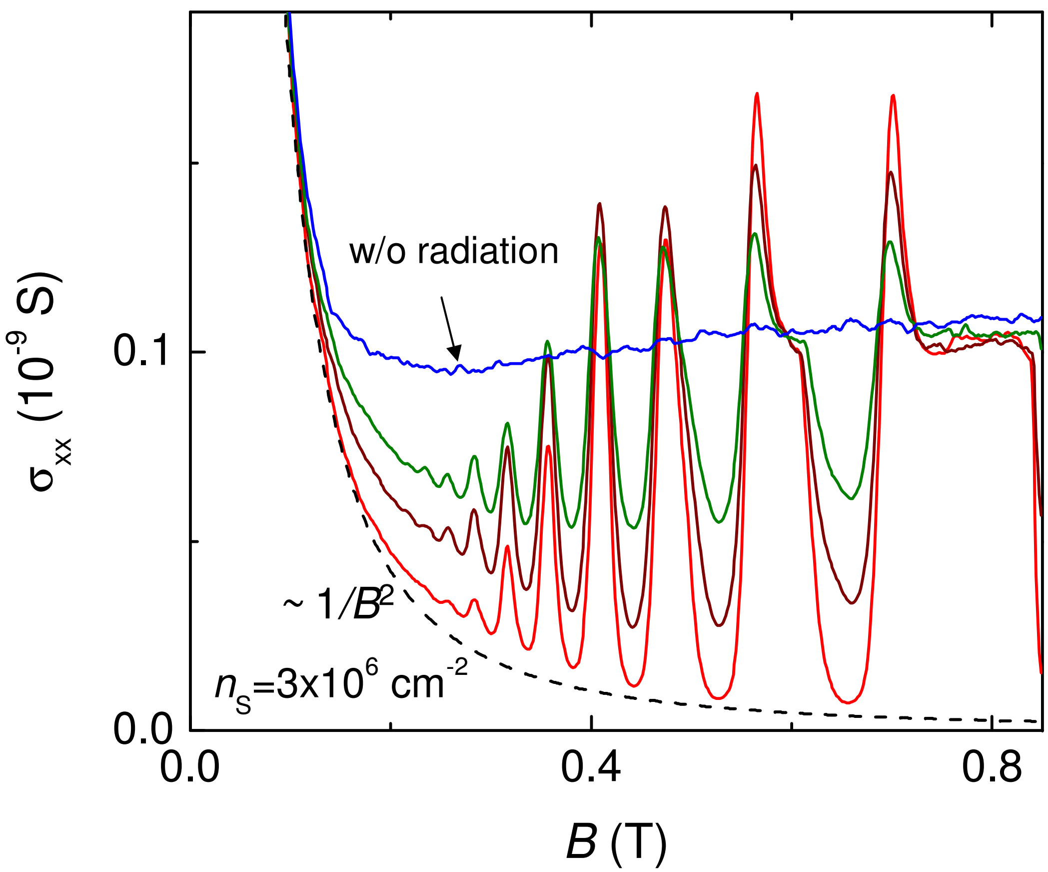
Electron heating at the resonance:

$T_e >> T$

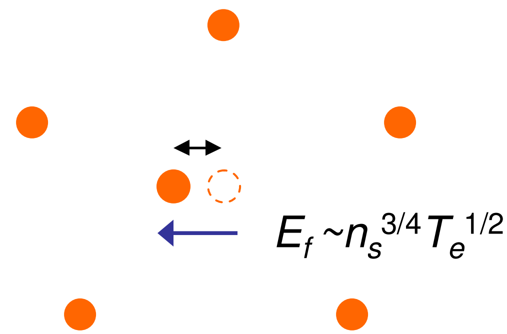
Konstantinov et al. PRL 2007

Heating restores Drude ($1/B^2$) regime!

Density dependence (T=0.2 K)



Fluctuating electric field E_f



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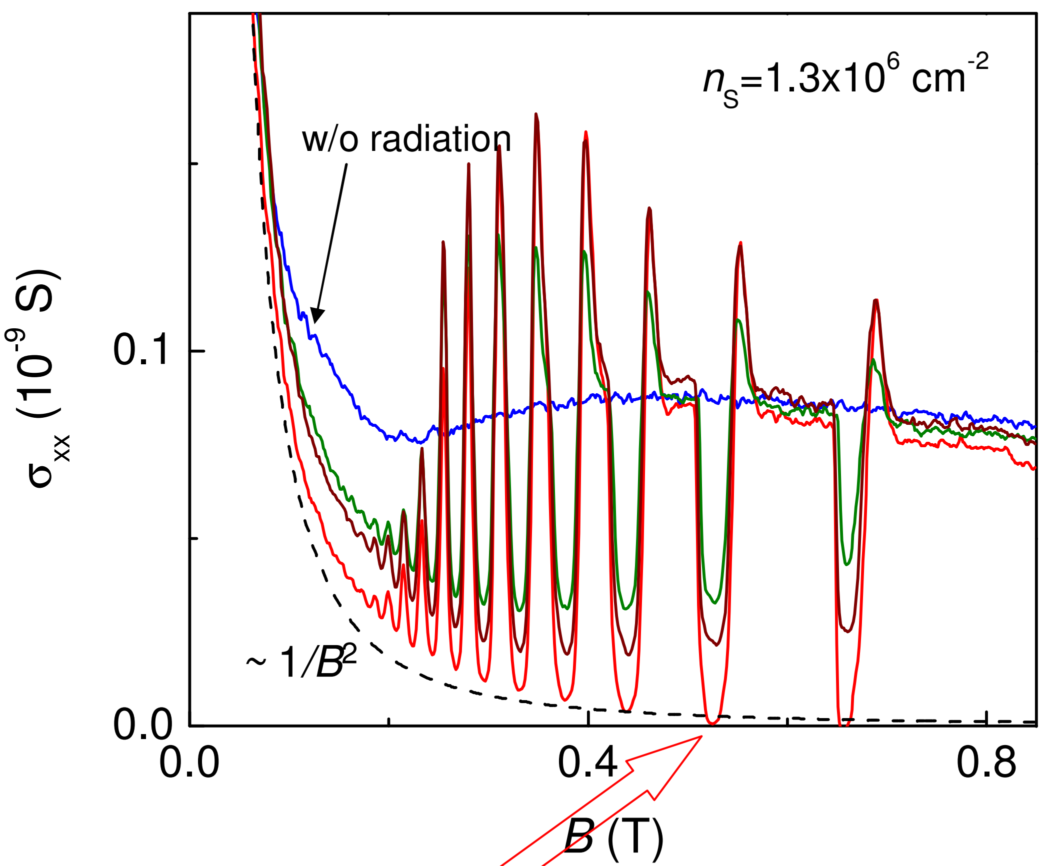
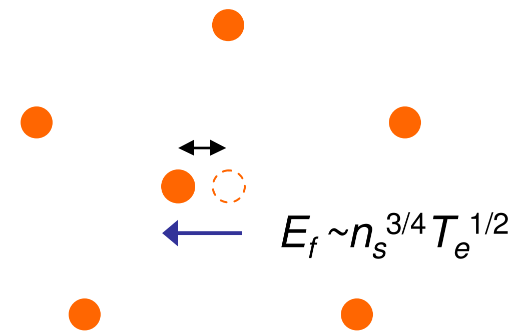


Something else is happening!

Fluctuating electric field E_f



Dykman and Khazan (1979)

Electron heating at the resonance:

$T_e >> T$

Konstantinov et al. PRL 2007

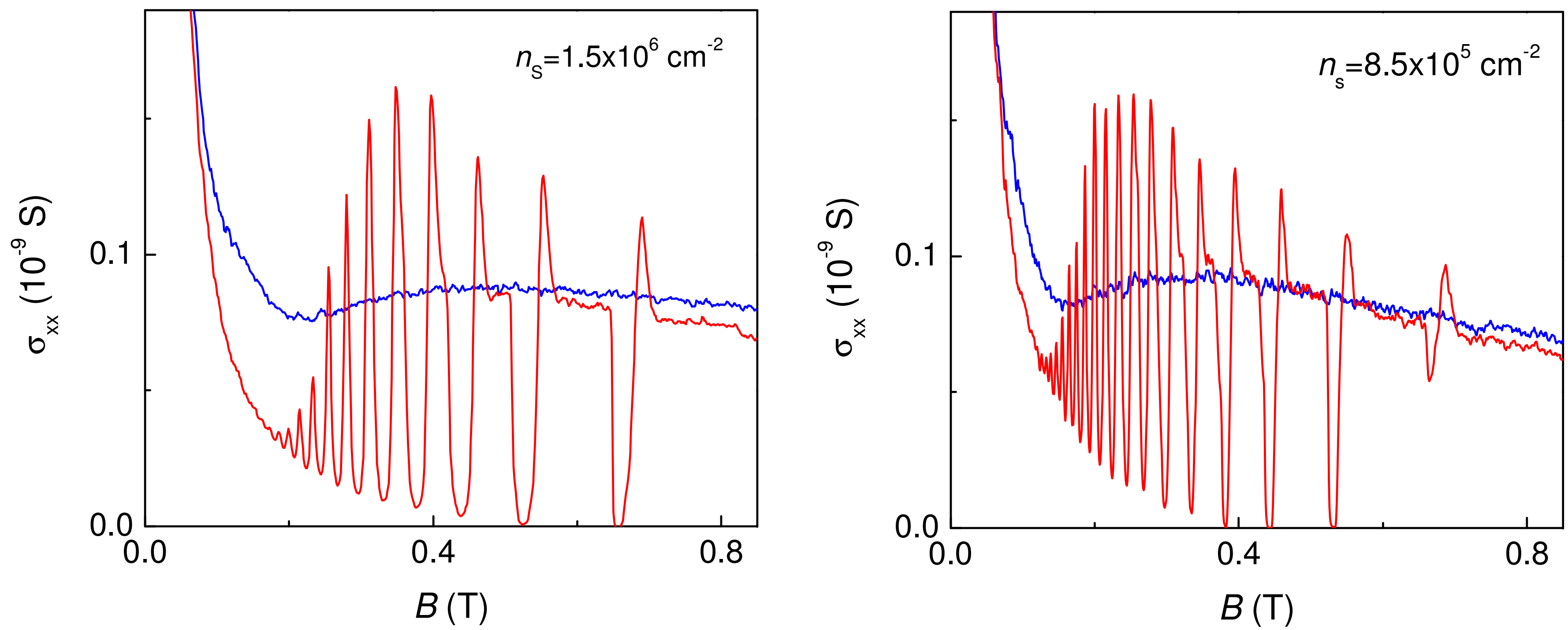
Competition between many-electron effects

and quantization of energy spectrum!

Density dependence (T=0.2 K)

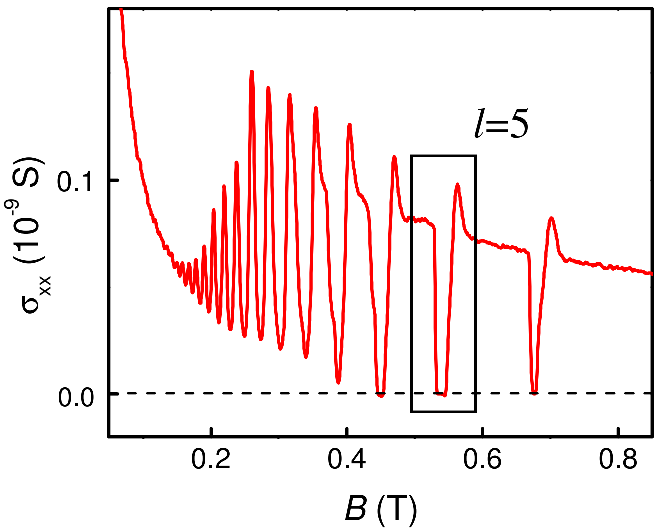
Electron-electron interaction → determines thermalization rate

Further decrease of density seems to eliminate the effect!



Will it disappear at very low density?!

Instability and hysteresis



Experiment:

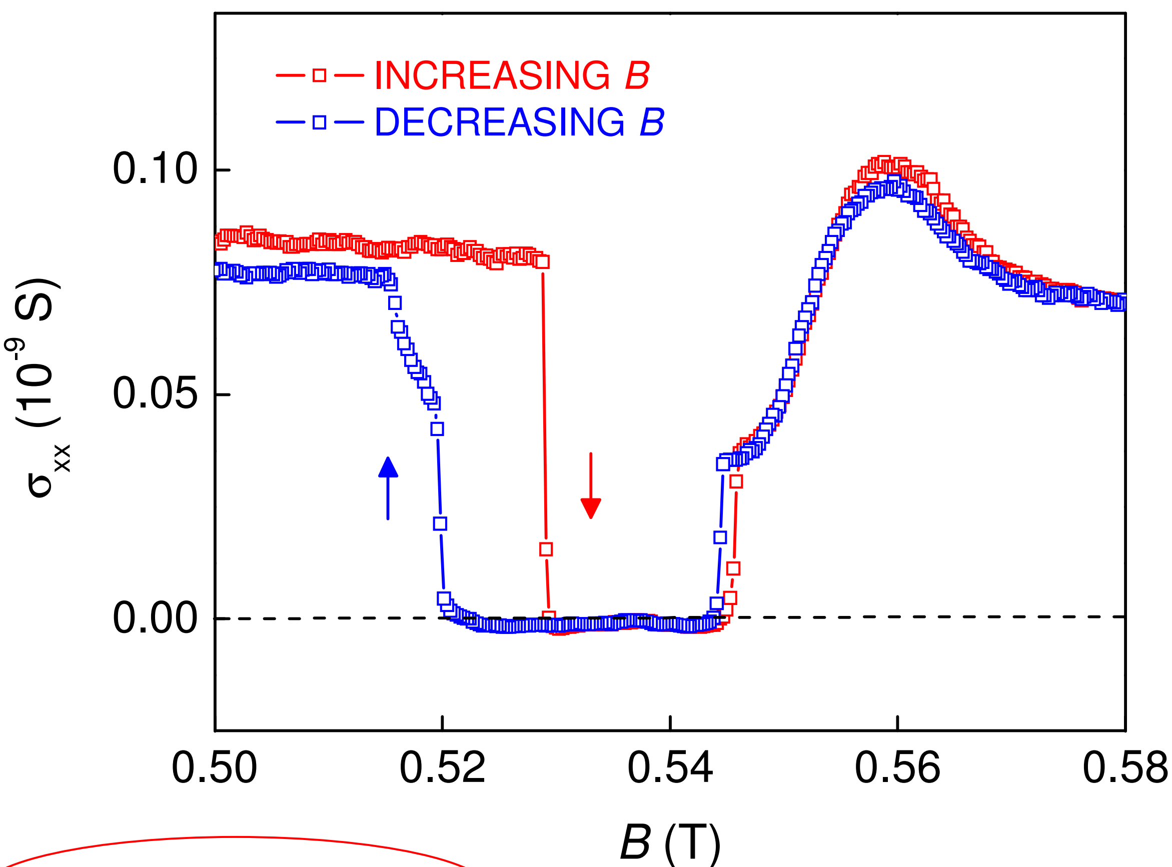
Willett *et al* (PRL 2004)

Theory:

Durst *et al* (PRL 2003)

Dmitriev *et al* (PRB 2005)

Andreev *et al* (PRL 2003)



Slightly negative σ_{xx}!

Summary and plans

- Inter-subband magneto-oscillations in nondegenerate 2D electrons
- Allows to study dynamics of electrons in magnetic fields,
  e.g. collision broadening, many electron effects etc.
- Observed ZRS show striking similarities with zero-resistance effect in GaAs/AlGaAs heterostructures

- Study mechanism of zero-resistance effect in an ultra-clean system of classical electrons
- Extend to higher magnetic fields to cover regime $hf = \hbar\omega_c$
- Microwave absorption in ZRS regime
- Quantum oscillations as a probe to resolve density of states