Surface electrons on helium under microwave excitation

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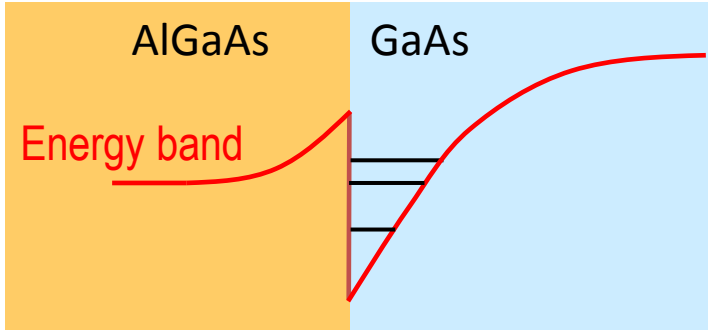
NPCQS2012, April 23-25, 2012

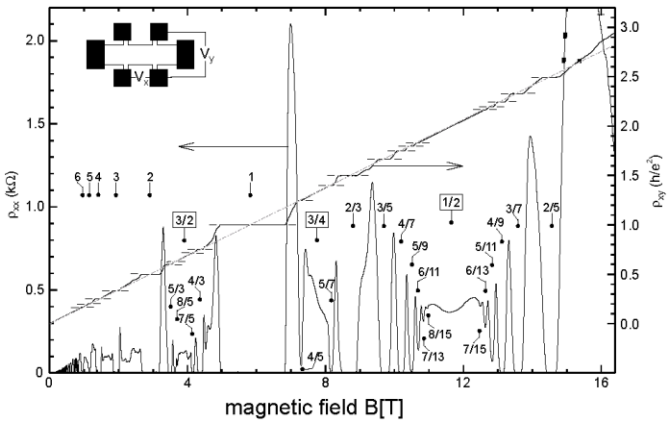
2D electron systems



GaAs/AlGaAs heterostructures

- impurity scattering limits mobility

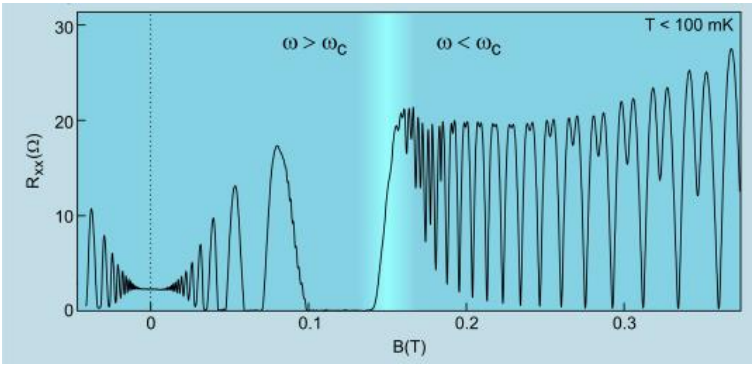
$\mu \approx 37 \cdot 10^6 \quad \frac{cm^2}{V \cdot s}$ - highest mobility



I/F Quantum Hall Effects

- vanishing dissipative conductivity

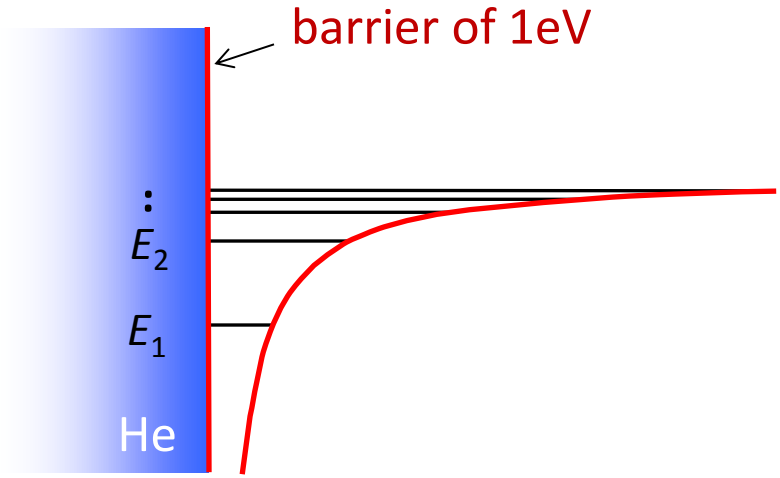
$$\sigma_{xx} = \frac{\rho_{xx}}{\rho_{xx}^2 + \rho_{xy}^2} \to 0, \quad \rho_{xx} \to 0$$



Radiation-induced zero-resistance states

R. Mani et al., Nature 2002
M. Zudov et al., PRL 2003

Electrons on He



Electrons on surface of liquid He

- no impurities, smoothest surface

$$\sqrt{\langle \xi^2 \rangle} \approx 0.2\ \text{Å}$$

$$\mu \gtrsim 100 \cdot 10^6 \ \frac{\text{cm}^2}{\text{V}\cdot\text{s}}$$ - the highest mobility!

T-dependent scattering

Vapor-atoms: $N_{vapor} \propto T^{3/2} \exp(-Q/kT)$

Ripplons: $n_q = \dfrac{1}{\exp(\hbar\omega_q / kT) - 1} \propto T$

Elastic scattering

$$\frac{M_{\text{He}}}{m_e} \sim 10^4$$

$$\omega_q \approx \sqrt{\frac{\sigma}{\rho}} q^{3/2} \qquad \hbar\omega_q << \frac{\hbar^2 q^2}{2m}$$

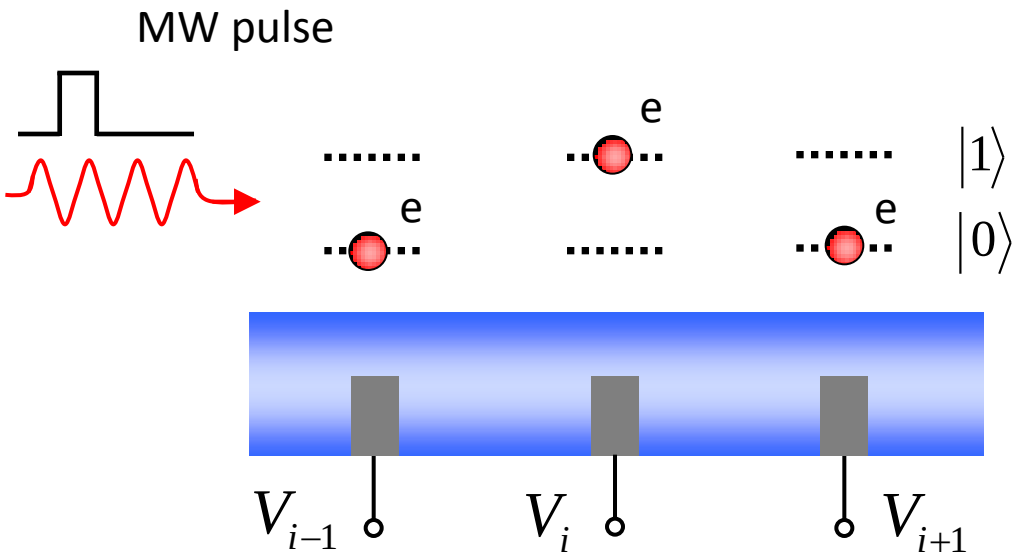
Qubits on He

SCIENCE VOL 284 18 JUNE 1999

Quantum Computing with Electrons Floating on Liquid Helium

P. M. Platzman[1]* and M. I. Dykman[2]

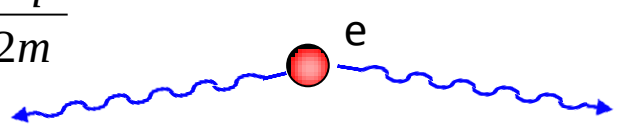
A quasi–two-dimensional set of electrons ($1 < N < 10^9$) in vacuum, trapped in one-dimensional hydrogenic levels above a micrometer-thick film of liquid helium, is proposed as an easily manipulated strongly interacting set of quantum bits. Individual electrons are laterally confined by micrometer-sized metal pads below the helium. Information is stored in the lowest hydrogenic levels. With electric fields, at temperatures of 10^{-2} kelvin, changes in the wave function can be made in nanoseconds. Wave function coherence times are 0.1 millisecond. The wave function is read out with an inverted dc voltage, which releases excited electrons from the surface.



- Long decoherence time

Inelastic 2-ripplon decay

$$2\hbar\omega_q = \frac{\hbar^2 q^2}{2m}$$



- Scalability

Microwave absorption

Mike Lea, Royal Holloway

Single electron manipulation

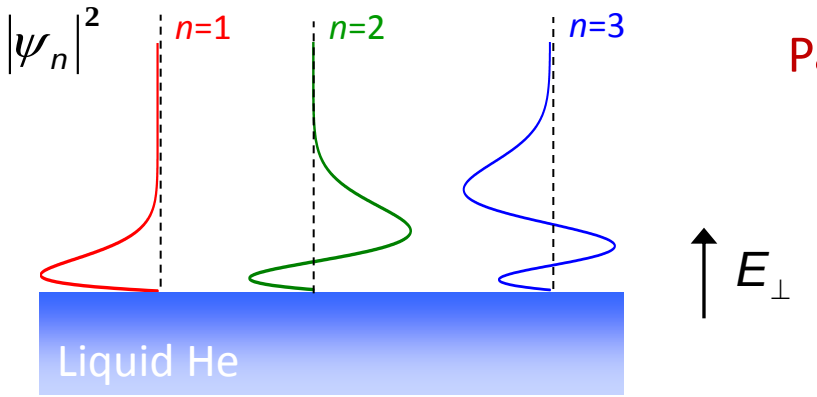
Yury Mukharsky, Saclay
Mike Lea, Royal Holloway

Spin qubits, Circuit QED

Steve Lyon, Princeton University
David Schuster, University of Chicago

+ many others

Rydberg levels

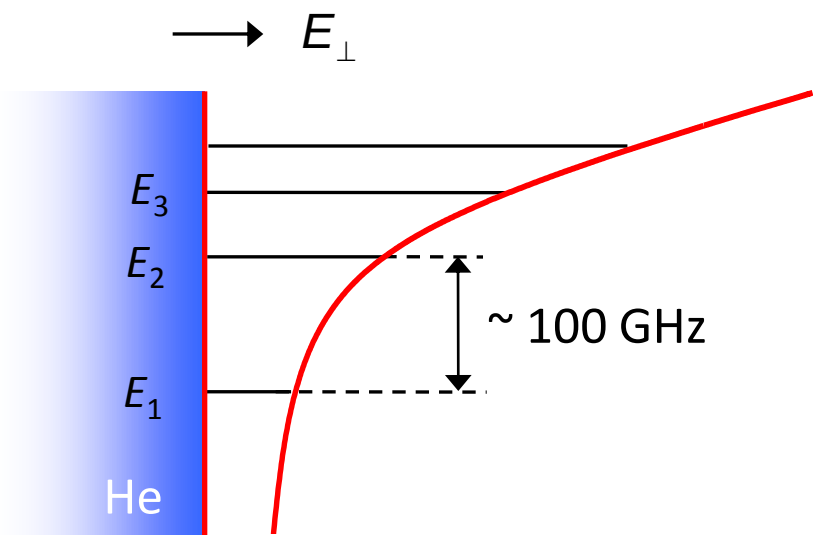


Parity symmetry-breaking of states ψ_n :

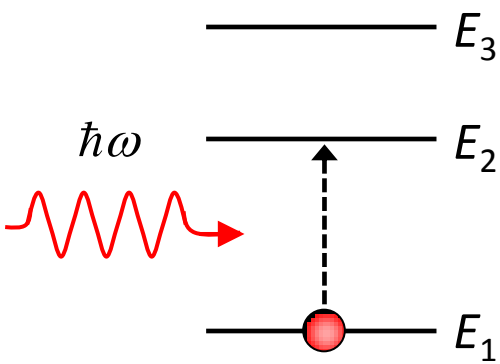
$$\langle n|z|n\rangle \neq 0$$

Lian-Fu Wei (talk on Monday)

linear Stark effect

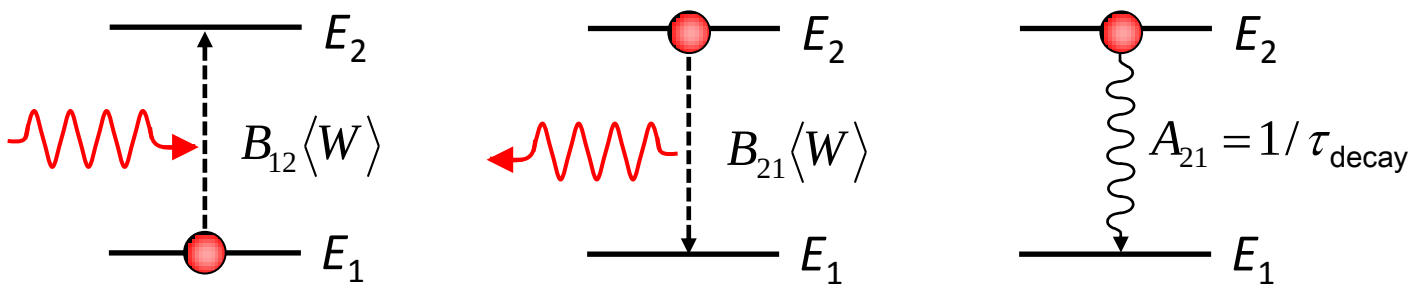


MW resonance: $\hbar\omega = E_2 - E_1$



<u>2-level system</u>

Microwave absorption

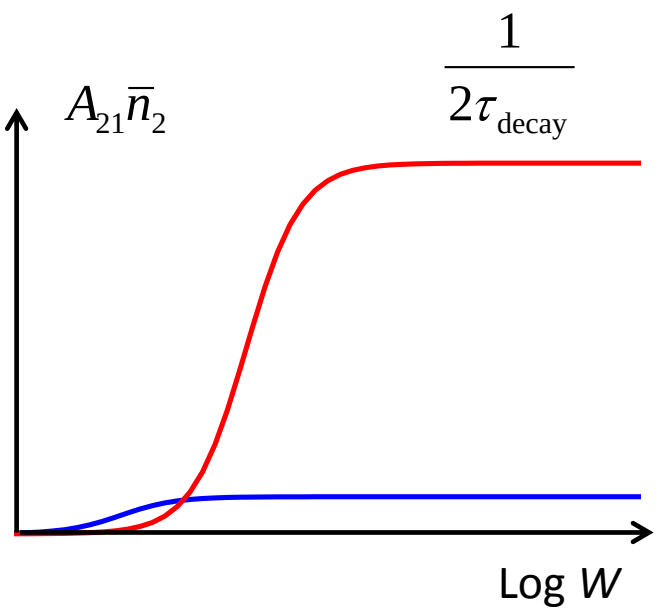


Transition rate equations:

$$\frac{\partial \bar{n}_2}{\partial t} = B_{12}\bar{n}_1 - B_{21}\bar{n}_2 - A_{21}\bar{n}_2 = 0$$

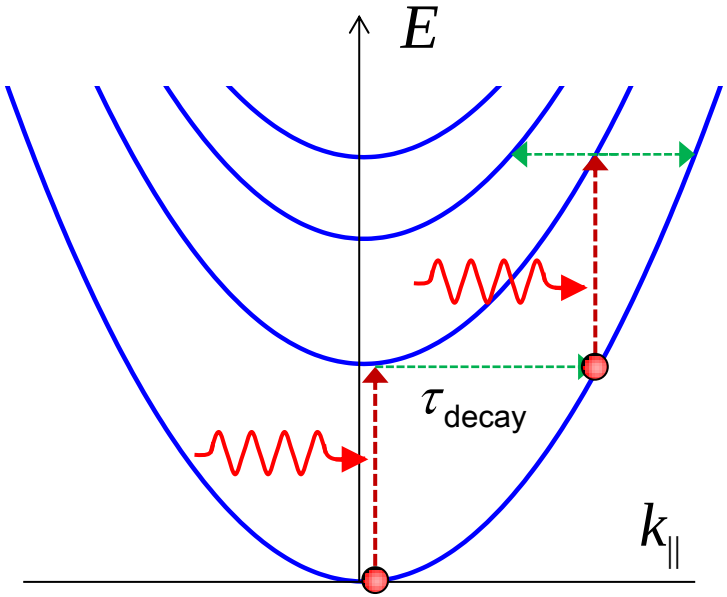
$$\bar{n}_1 + \bar{n}_2 = 1$$

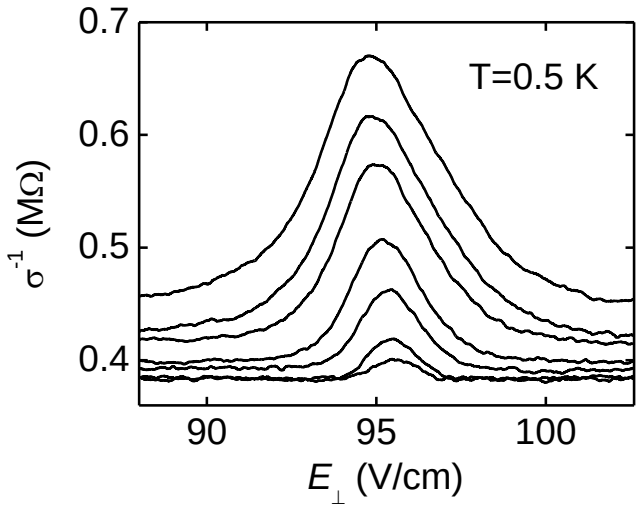
$$B_{12} = B_{21} \propto W$$



2-level system

Electron heating





2D energy subbands

$$E = E_n + \frac{\hbar^2 k_{\parallel}^2}{2m}$$

Very fast thermalization with $T_e >> T$

$$\tau_{\text{ee}} \sim \omega_p \approx 10^{-11}\,\text{s}$$

Energy balance

$$\hbar\omega \frac{\bar{n}_2}{\tau_{\text{decay}}} = \frac{T_e - T}{\tau_{in}}$$

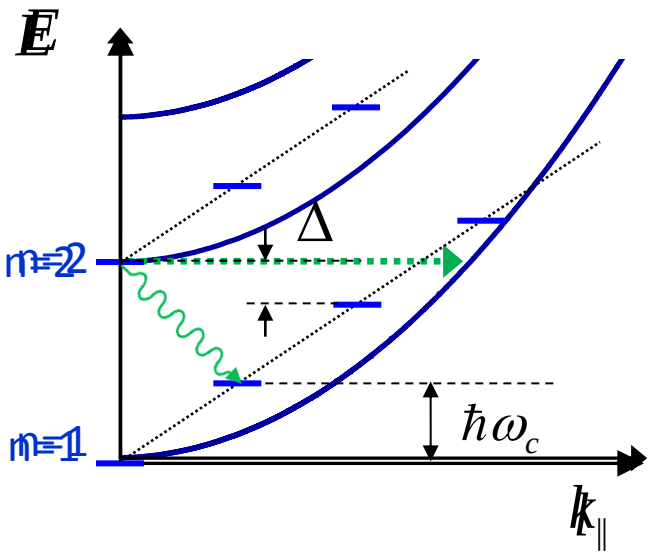
5 K

10^{-9} s

10^{-6} s

Poster by Olesya Sarajlic yesterday

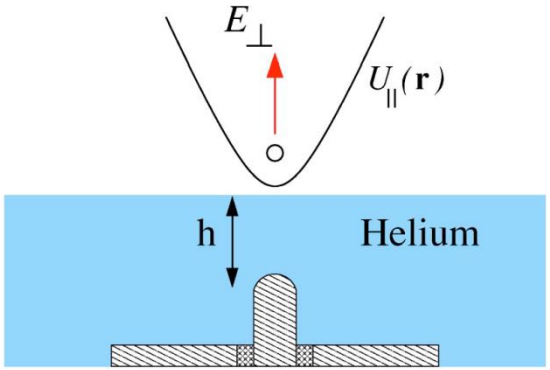
Landau quantization



PHYSICAL REVIEW B **67**, 155402 (2003)

Qubits with electrons on liquid helium

M. I. Dykman,[1,*] P. M. Platzman,[2] and P. Seddighrad[1]

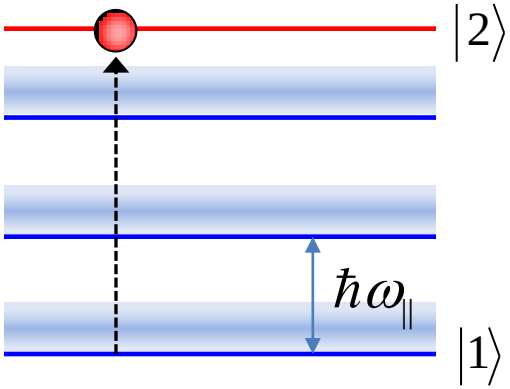


2D energy subbands

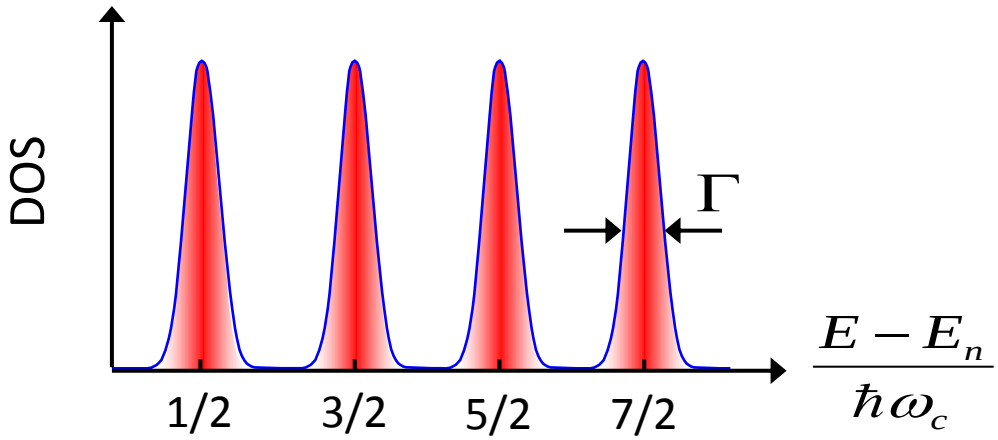
$$E = E_n + \frac{\hbar^2 k_{\parallel}^2}{2m}$$

What is we apply magnetic field?

$$E = E_n + \hbar\omega_c (l + 1/2)$$



Magneto-transport



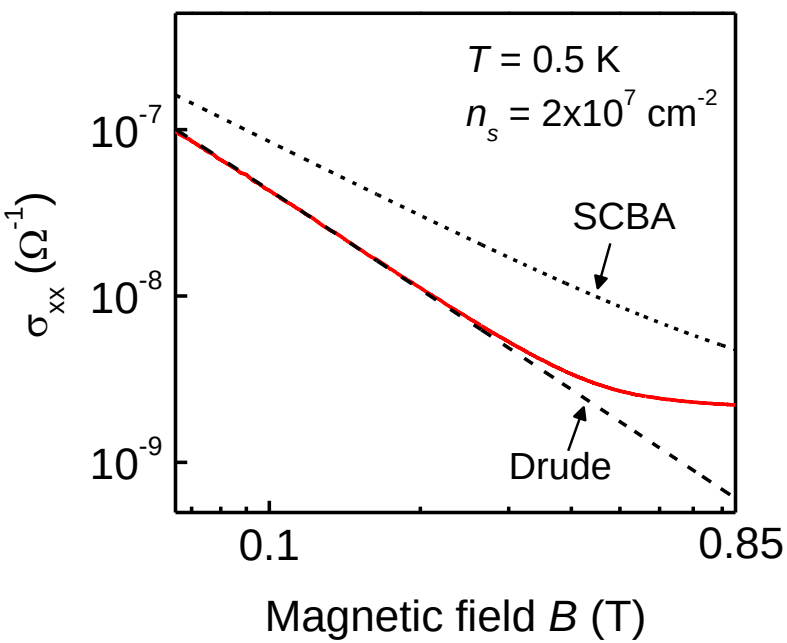
ν_0 - scattering rate in B=0

ν_B - scattering rate in $B\neq 0$

$\Gamma = \hbar\nu_B$ and $\frac{\nu_B}{\nu_0} \approx \frac{\hbar\omega_c}{\Gamma}$ $\Rightarrow$

$$\Gamma = \hbar\sqrt{\frac{2}{\pi}\omega_c\nu_0(T)}$$

Ando and Uemura, 1974



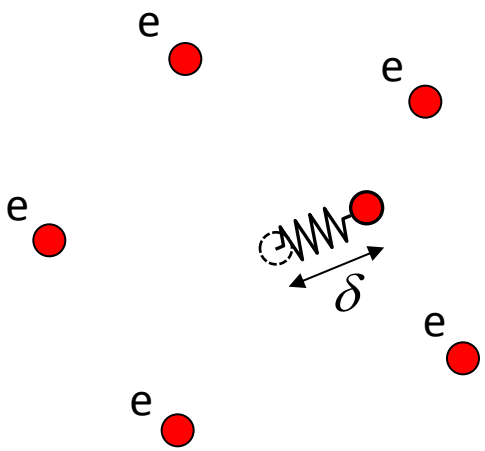
$\omega_c << \nu_0$ - Drude model

$$\frac{\sigma_{xx}}{\sigma_0} = \frac{\nu_0^2}{\omega_c^2 + \nu_0^2}$$

$\omega_c >> \nu_0$ - deviation from Drude model

Many-electron effects

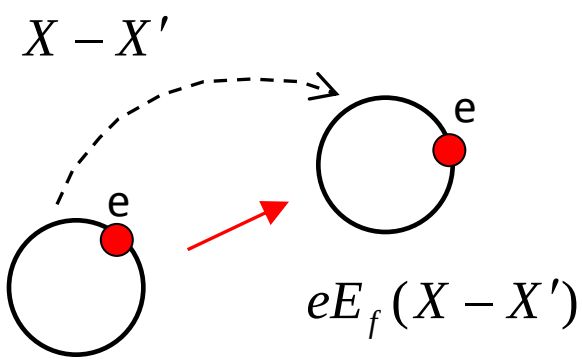
Dykman, Khazan 1979

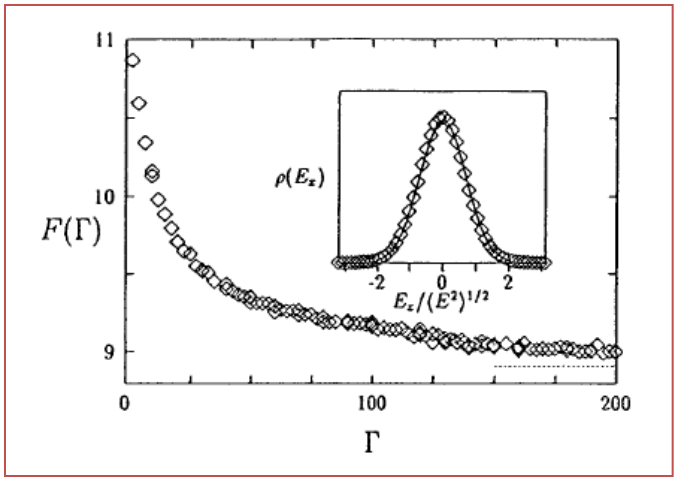


Average force on electron: $e\overline{E}_f = k\delta$

Typical frequency : $\frac{m}{k} = \omega_p = \sqrt{\frac{2\pi e^2 n_s^{3/2}}{m}}$

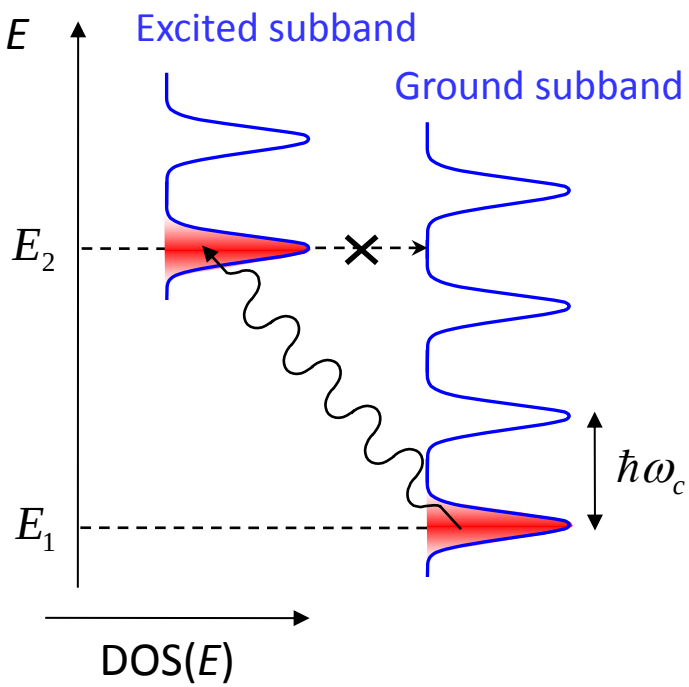
$$\boxed{\frac{k\delta^2}{2} \approx k_B T_e} \quad \Rightarrow \quad \boxed{\overline{E}_f \approx n_s^{3/4}\sqrt{4\pi k_B T_e}}$$





Fang-Yen, Dykman, Lea PRB 1997

Inter-subband dynamics



Decay rate (short-range scattering)

$$\nu_{2\to1} = \frac{\nu^{(0)}_{2\to1}}{\sqrt{\pi}} \frac{\hbar\omega_c}{\Gamma_{1,2}} \sum_m \exp\left[- \frac{(E_2 - E_1 - \hbar\omega_c m)^2}{\Gamma_{1,2}^2} \right]$$

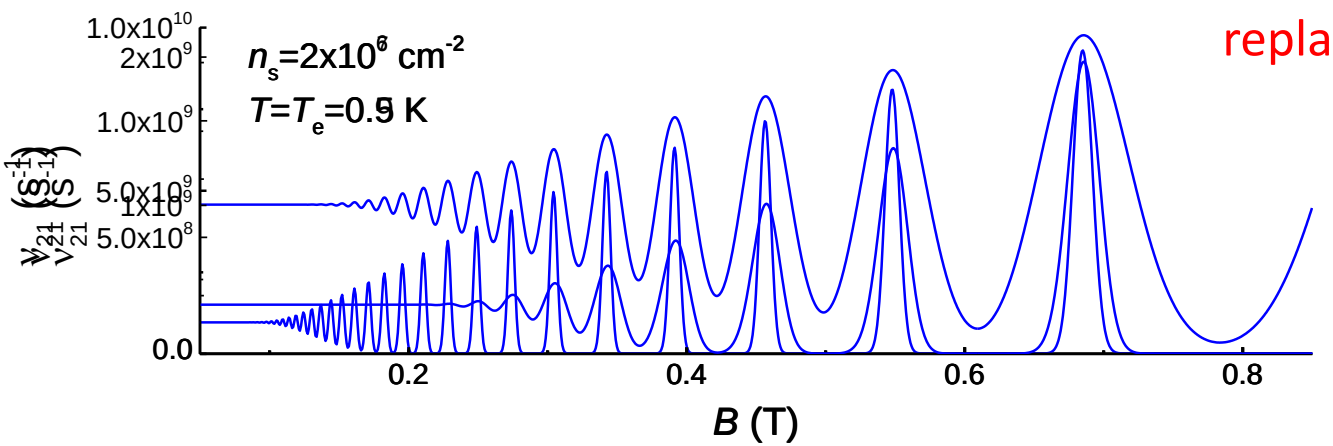
$2\Gamma_{1,2}^2 = \Gamma_1^2 + \Gamma_2^2$ - overlapping of LLs

Add $eE_f L$ to energy change

typical scattering length

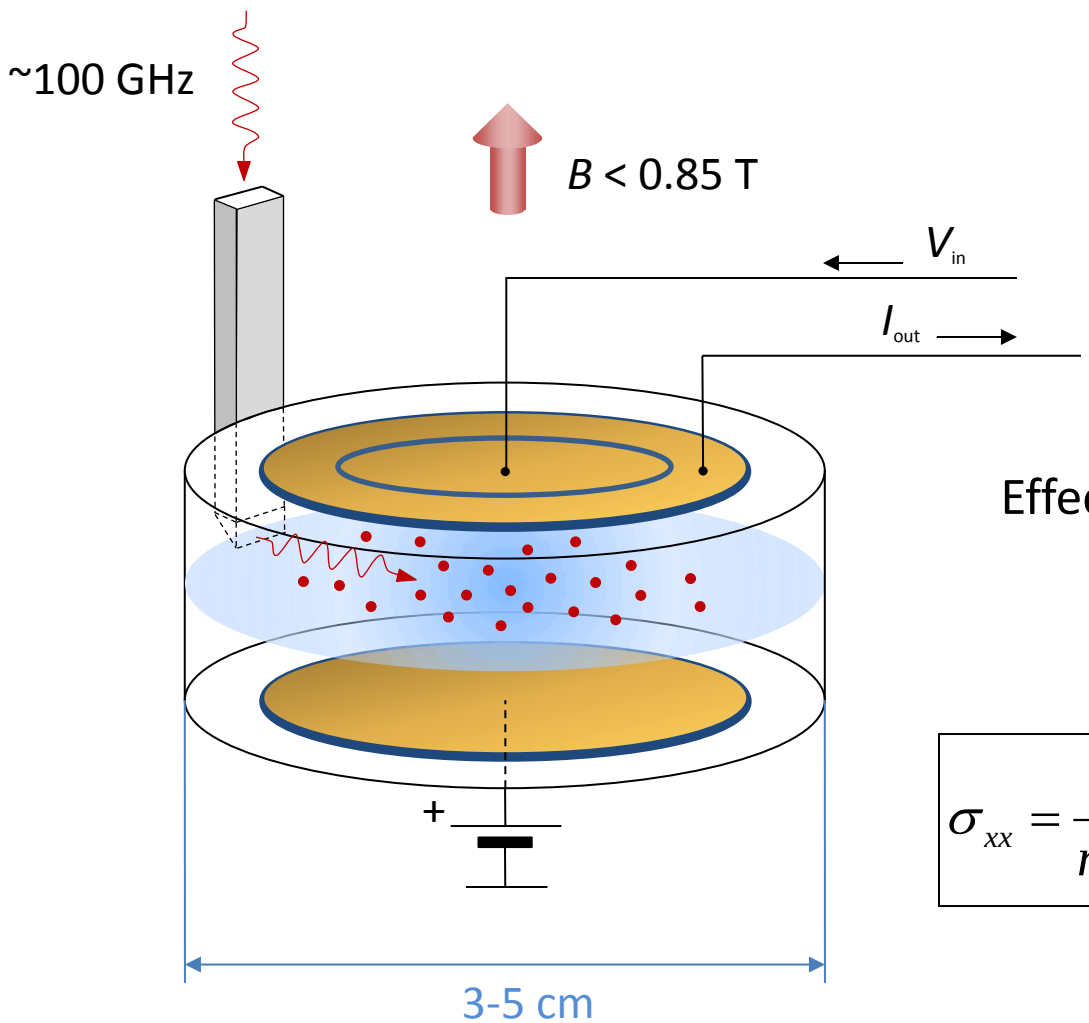
and average over distribution $\rho(E_f) \sim e^{-E_f^2/\bar{E}_f^2}$

replace $\Gamma_{1,2}^2 \to \Gamma_{1,2}^2 + 2(e\bar{E}_f L)^2$



Experimental method

Sommer-Tanner method (*1971*)



$$\frac{I_{out}}{V_{in}} = G(\sigma_{xx})$$

complex admittance

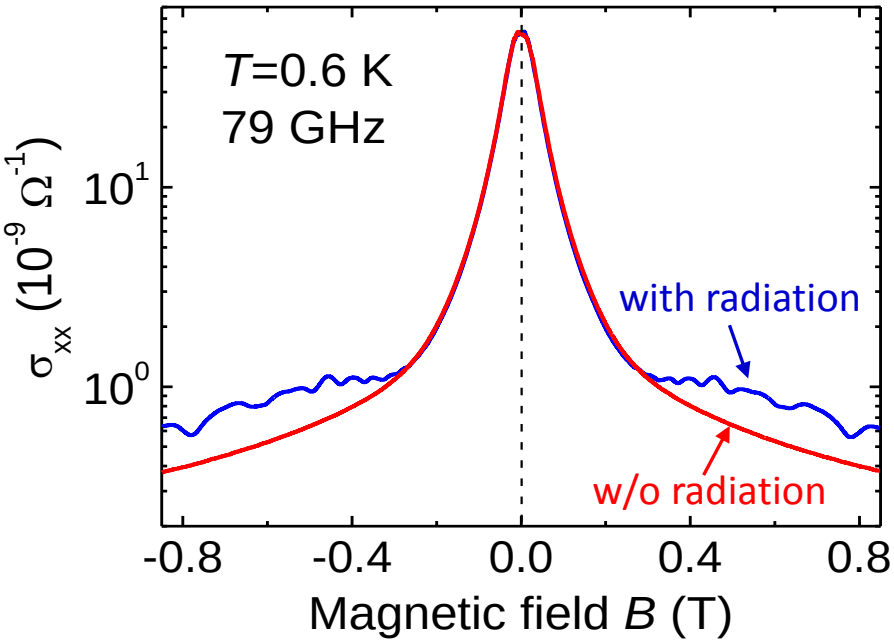
Effective scattering rate

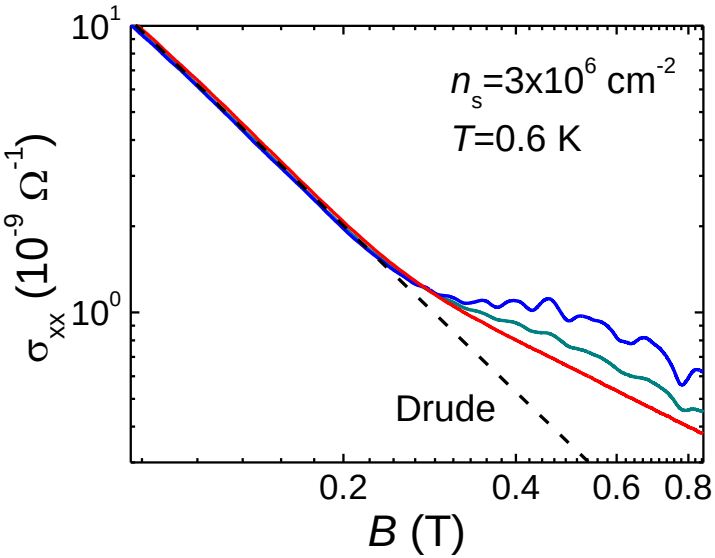
$$\vec{F}_{friction} = -N_e m \nu_{eff} \langle \vec{\upsilon}_e \rangle$$

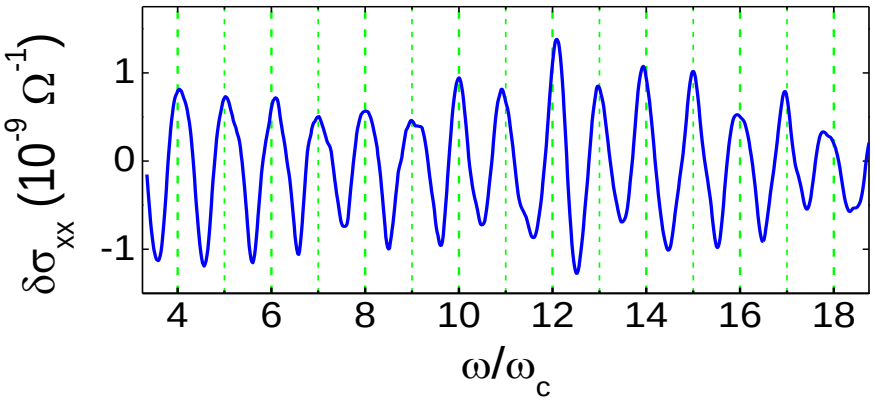
$$\sigma_{xx} = \frac{e^2 n_s \nu_{eff}}{m_e(\omega_c^2 + \nu_{eff}^2)}$$

$$\sigma_{xy} = \frac{\omega_c}{\nu_{eff}} \sigma_{xx}$$

Magneto-oscillations







$$\sigma_{xx} \approx \frac{e^2 n_s \nu_{eff}}{m_e \omega_c^2}$$

Enhancement of scattering $\frac{\omega}{\omega_c} = i$

Short-range scattering

Effective collision rate $\nu_{eff} = \nu_{\text{intra}} + \nu_{\text{inter}}$

Yuriy Monarkha

$$\nu_{\text{inter}} = \frac{(\hbar\omega_c)^2}{2\sqrt{\pi}k_B T_e}\sum_l \rho_l \left[\bar{n}_1 \frac{\lambda_{11}}{\Gamma_1} + \bar{n}_2 \frac{\lambda_{22}}{\Gamma_2}\right]$$

ρ_l - Boltzmann occupancy of LLs

$$\nu_{\text{inter}} = \left(\bar{n}_2 + \bar{n}_1 e^{-\frac{E_2 - E_1}{k_B T_e}}\right)\frac{(\hbar\omega_c)^2}{2\sqrt{\pi}k_B T_e}\sum_l \rho_l \frac{\lambda_{21}}{\Gamma_{1,2}} \exp\left[-\frac{(E_2 - E_1 - \hbar\omega_c m^*)^2}{\Gamma_{1,2}^2}\right]$$

$$\Gamma_{1,2}^2 \to \Gamma_{1,2}^2 + 2(eE_f L)^2$$

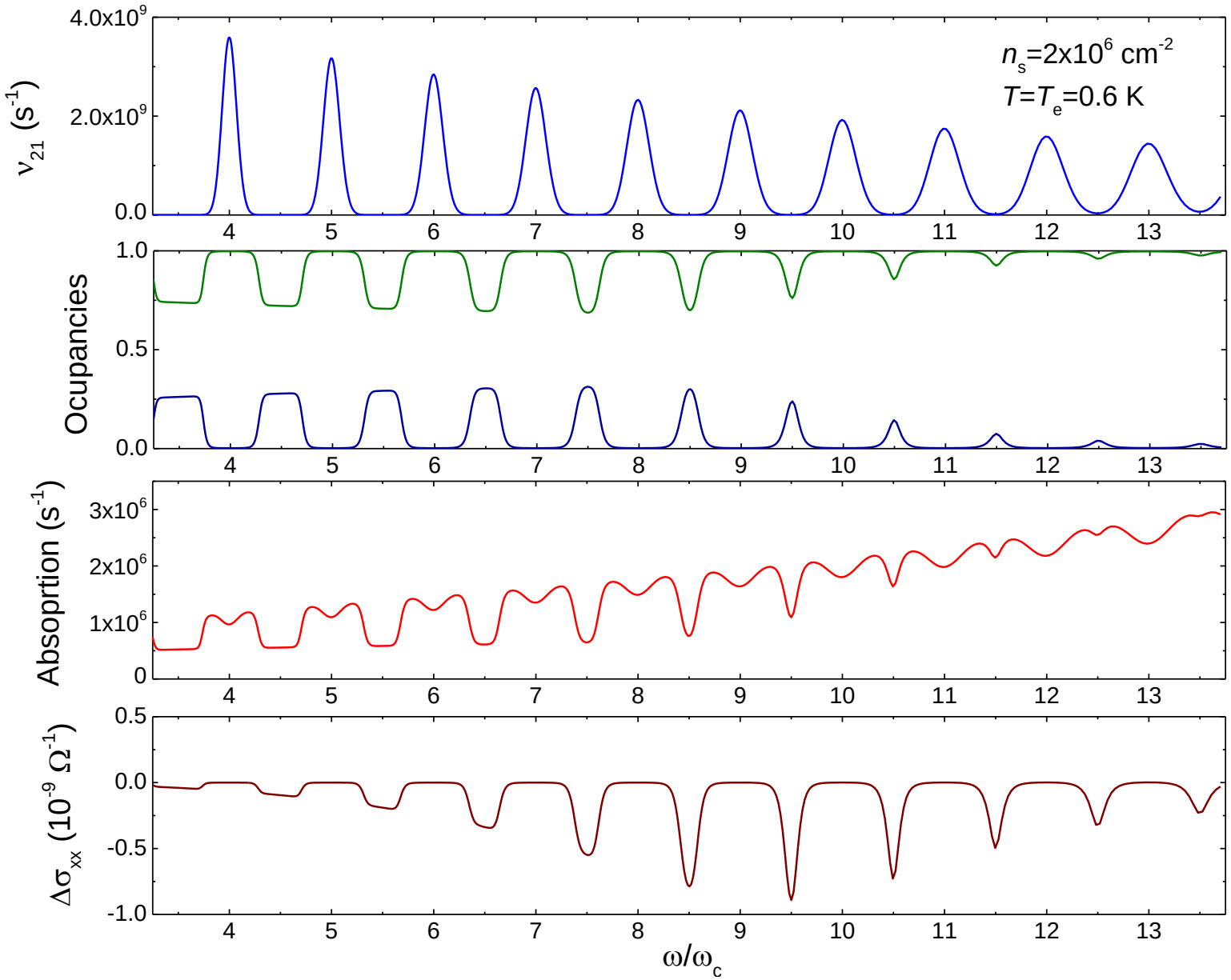
$$m^* = \text{round}\left(\frac{E_2 - E_1}{\hbar\omega_c}\right)$$

Very dynamical and nonlinear process!

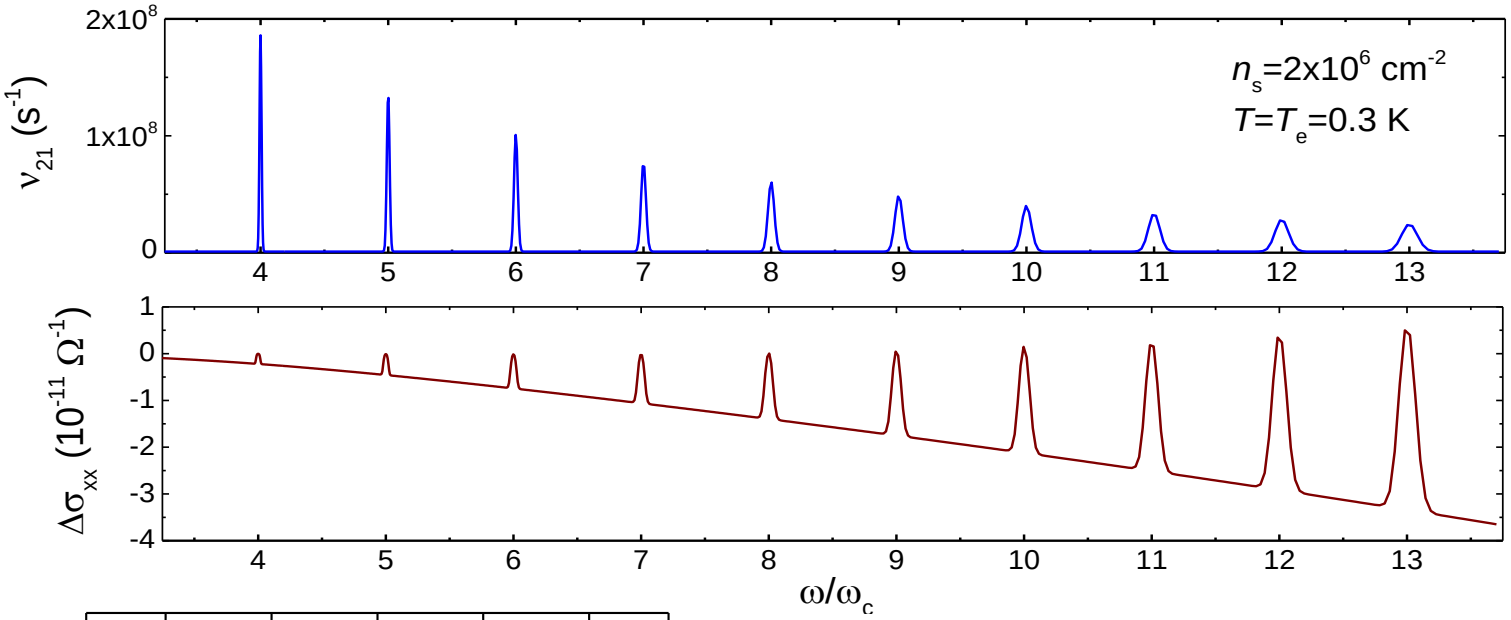
$$\nu_{2\to1} \Rightarrow \bar{n}_1, \bar{n}_2 \Rightarrow B_{12}(\bar{n}_1 - \bar{n}_2) \Rightarrow k_B T_e \Rightarrow E_f \sim \sqrt{T_e}$$

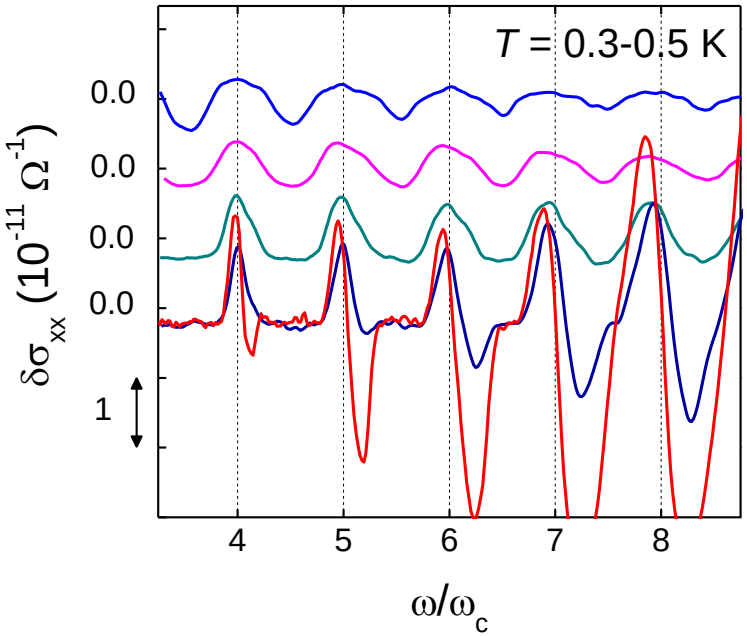
decay rate — subband population — absorption rate — electron temperature — fluctuating field

Population dynamics



Density-of-states





Sign-changing contribution?!

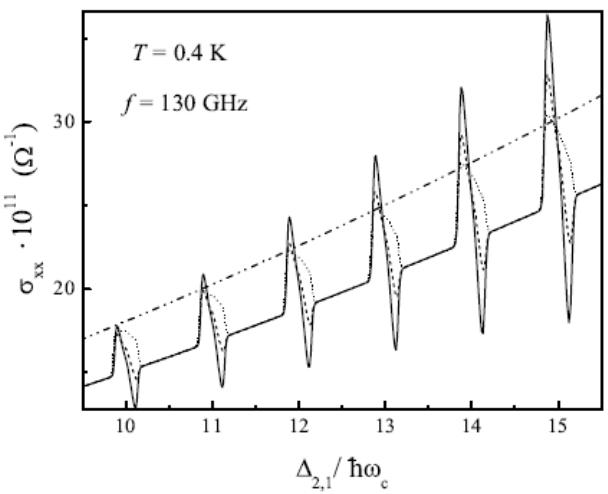
Theory of Monarkha

Effective collision rate $\nu_{eff} = \nu_{\text{intra}} + \nu_{\text{inter}}$

Anomalous contribution $\nu_{\text{inter}} = \nu_N + \nu_A$

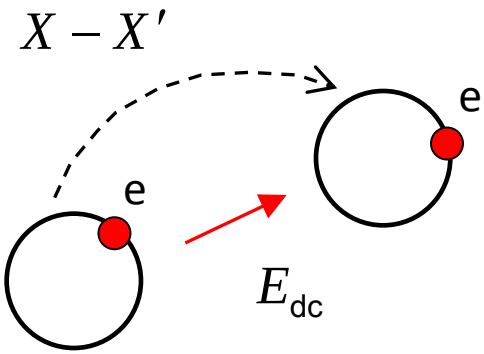
$$m^* = \text{round}\left(\frac{E_2 - E_1}{\hbar\omega_c}\right)$$

$$\nu_{\text{A}} = -\boxed{\left(\bar{n}_2 - \bar{n}_1 e^{-\frac{E_2 - E_1}{k_B T_e}}\right)} \frac{(\hbar\omega_c)^2}{\sqrt{\pi}} \sum_l \rho_l \frac{\lambda_{21}}{\Gamma_{1,2}^2} \exp\left[-\frac{(E_2 - E_1 - \hbar\omega_c m^*)^2}{\Gamma_{1,2}^2}\right] \boxed{\frac{(E_2 - E_1 - \hbar\omega_c m^*)}{\Gamma_{2,1}}}$$



Yu. Monarkha, 2011

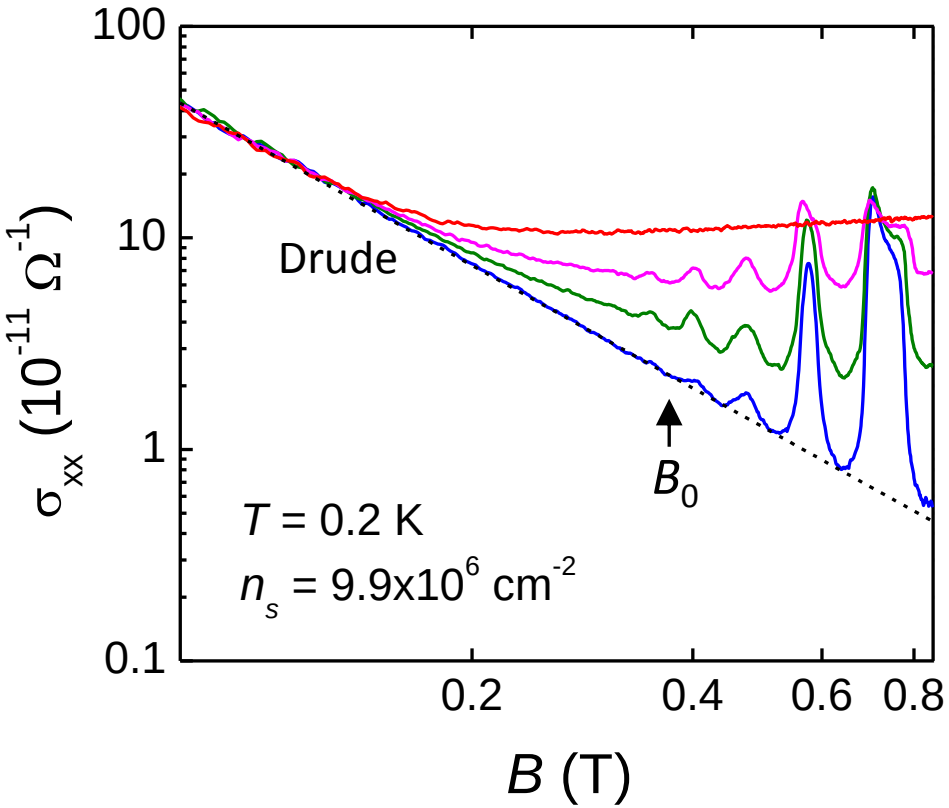
Simple picture



$$\hbar\omega_c(l - l') + \hbar\omega - eE_{\text{dc}}(X - X') = 0$$

$$eE_{\text{dc}}(X - X') > 0$$

Electron temperature



Onset of oscillations

$$eE_f R_c \geq \hbar\omega_c$$

onset magnetic field

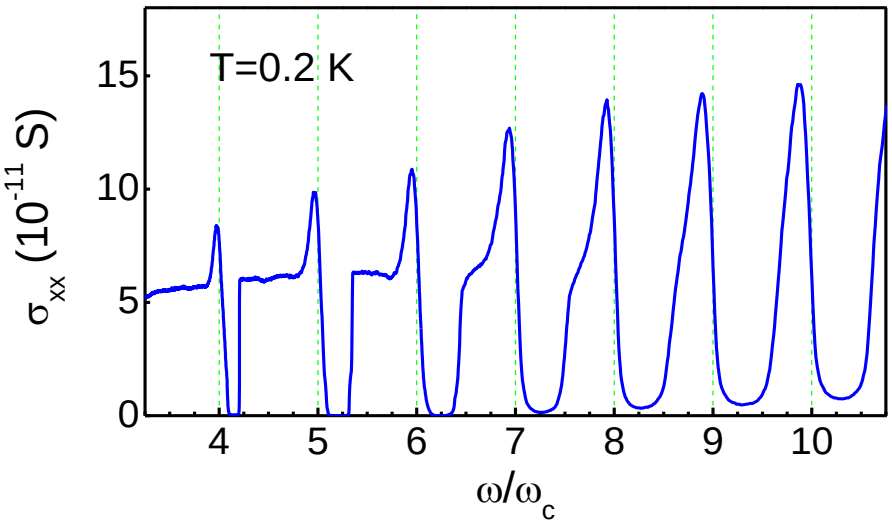
$$B_0 \approx 1.7\times10^{-5} n_3^{3/8} T_e^{1/2}$$

Lea, Dykman 1994

Electron temperature

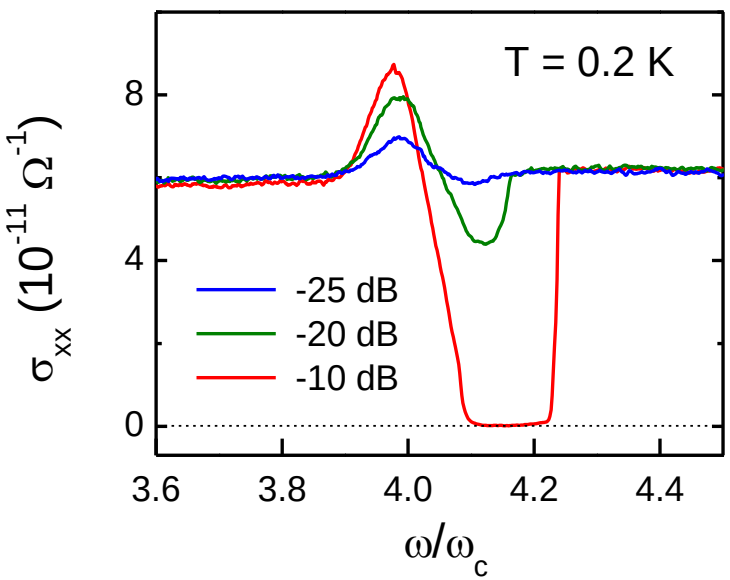
$$T_e \approx 1.7 \text{ K}$$

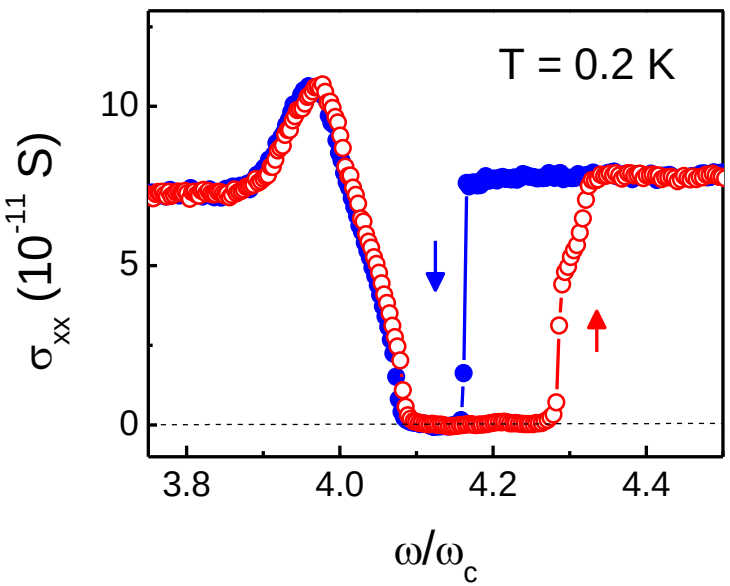
Zero conductivity



Tensor relation

$$\sigma_{xx} = \frac{\rho_{xx}}{\rho_{xx}^2 + \rho_{xy}^2} \to 0, \quad \rho_{xx} \to 0$$

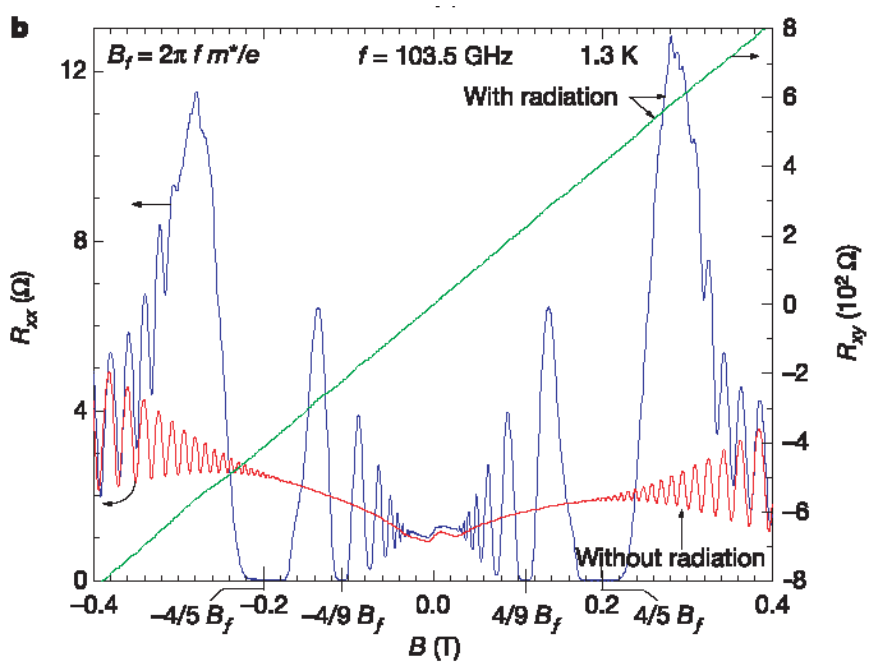




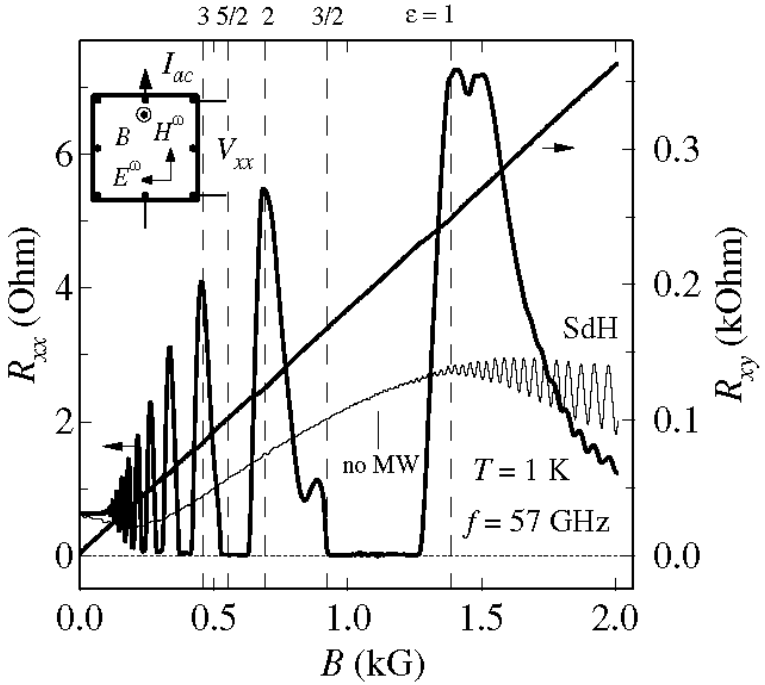
ZRS in GaAs/AlGaAs

Radiation-induce zero-resistance states (ZRS) in high-mobility 2DEG

R. Mani et al., Nature 2002

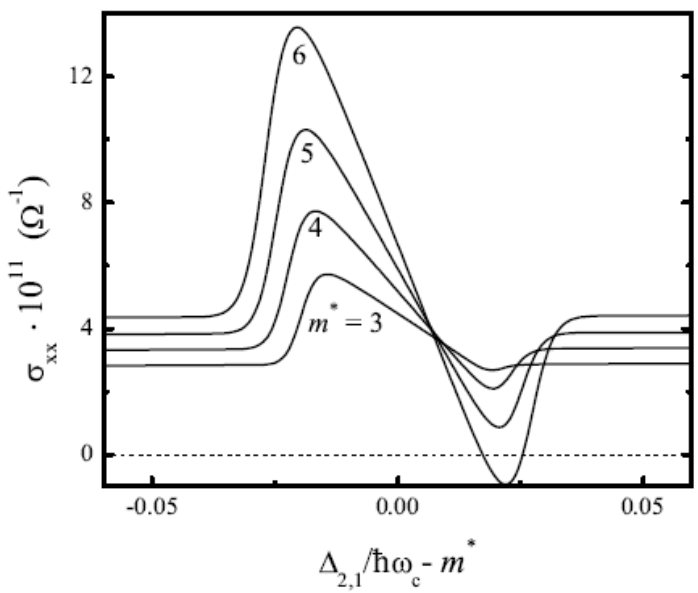


M. Zudov et al., PRL 2003



More on theory today: *Ivan Dmitriev*
Maxim Khodas
Alexei Chepelianskii

Negative linear conductivity



In 2D at zero magnetic field:

$$\begin{cases} \dfrac{\partial \rho_s}{\partial t} = -\nabla \vec{j} = \sigma \nabla_r^2 V \\ \nabla^2 V = -\rho_s \delta(z) \end{cases}$$

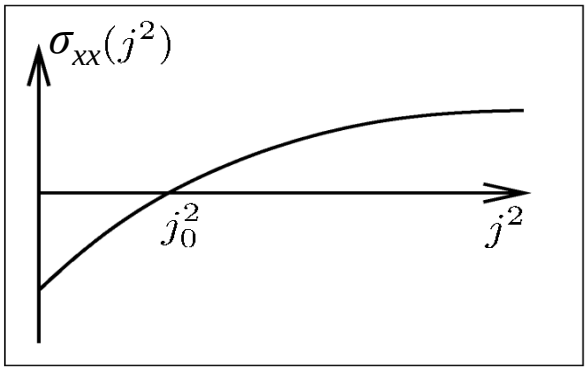
$$\rho_k \sim \exp\left(-\frac{\sigma k}{2} t\right) \to \infty$$

Yu. Monarkha, 2011

Instability and spontaneous formation

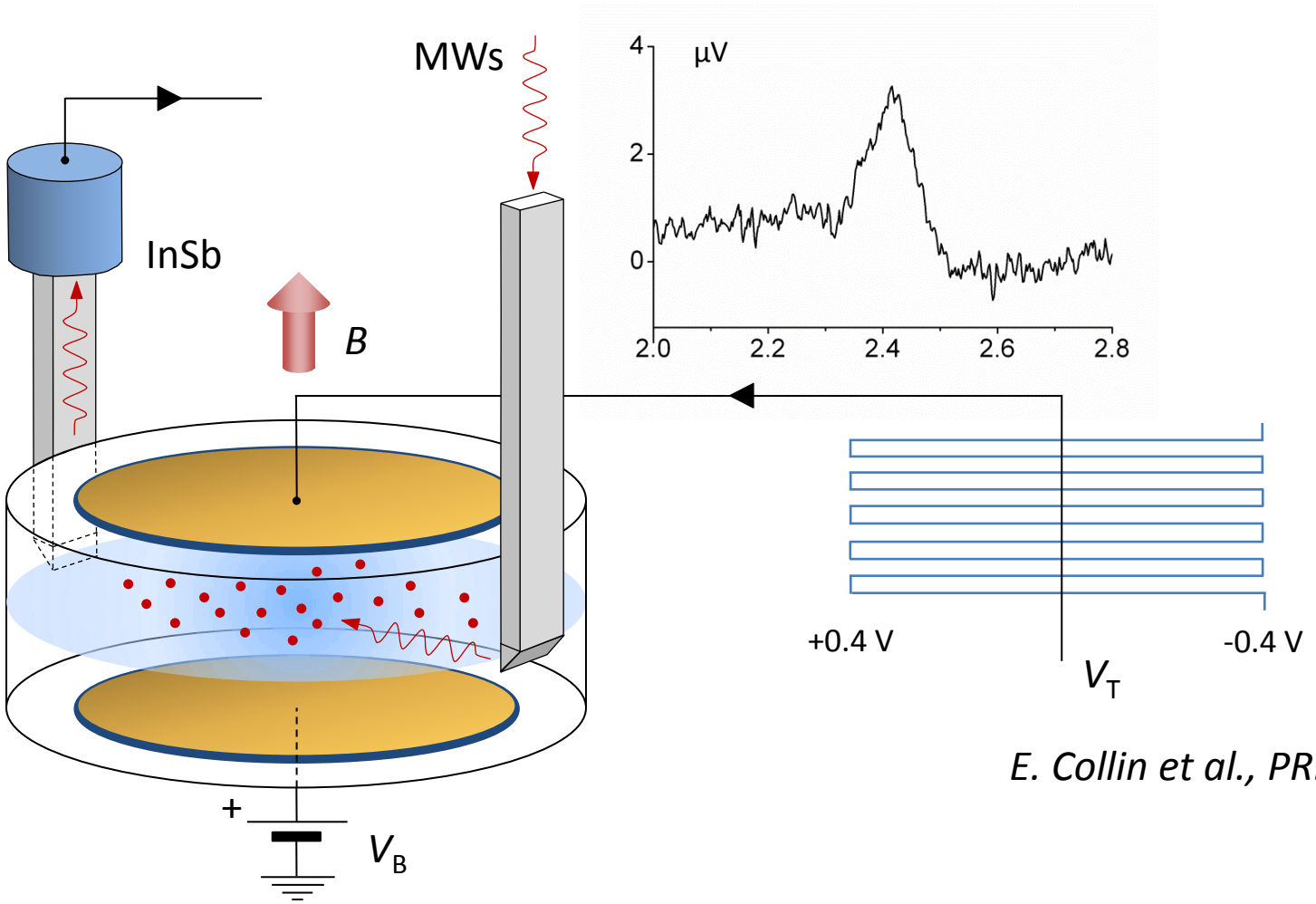
of current domains at $\sigma_{xx} < 0$

Andreev, Aleiner, Millis PRL 2003



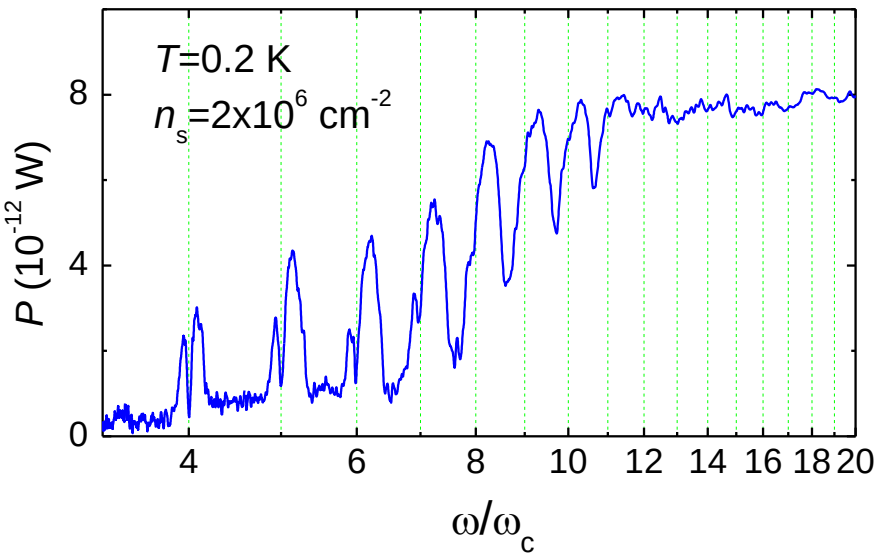
MW absorption

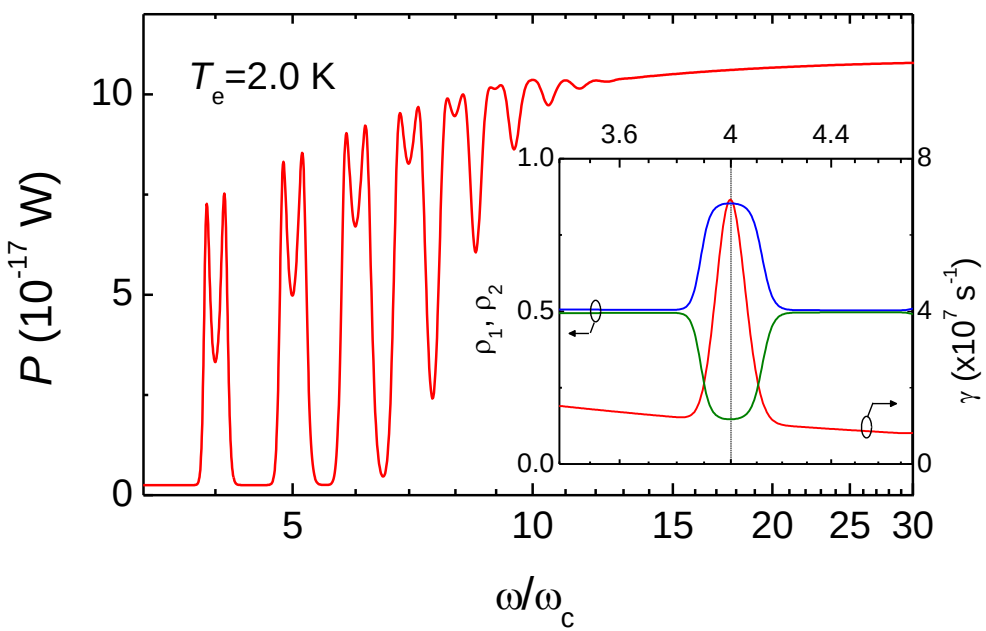
What about absorption saturation?



E. Collin et al., PRL 2002

MW absorption





Onset magnetic field

$$B_0 \approx 1.7\times10^{-5} n_3^{3/8} T_e^{1/2}$$

Overheating of electrons $T_e \approx 2$ K

Absorption saturation

$$\bar{n}_1, \bar{n}_2 \to 1/2$$

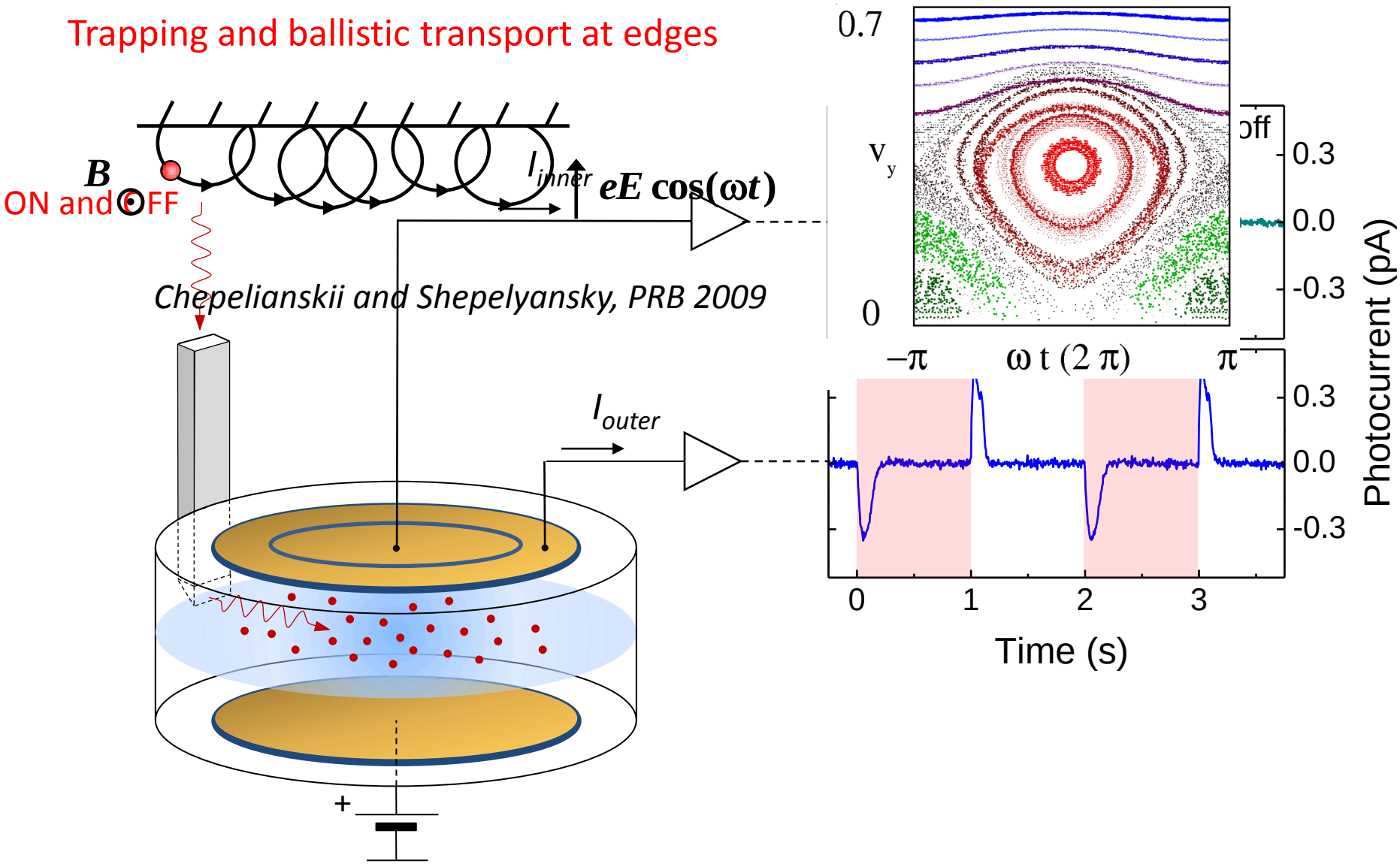
Sharp feature at ω/ω_c=i

$$p \sim \frac{|\langle 2|H_{\text{int}}|1\rangle|^2}{\gamma}(\bar{n}_1 - \bar{n}_2)$$

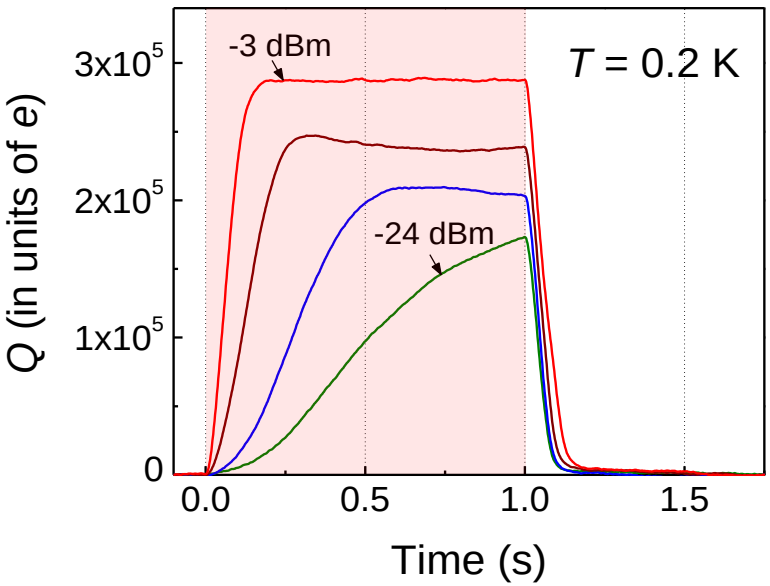
But what about inhomogenious broadening?!

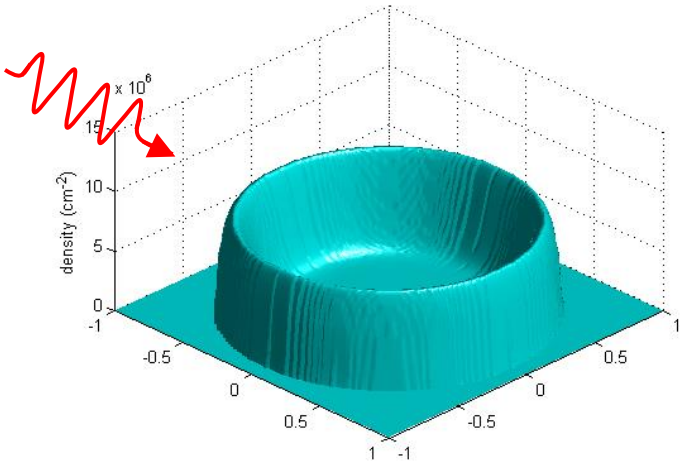
Edge trapping

Trapping and ballistic transport at edges



Redistribution of charge

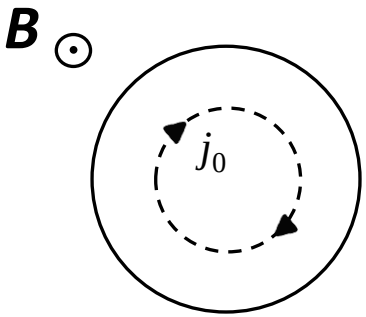




Charge trapping leading to zero σ_{xx}?

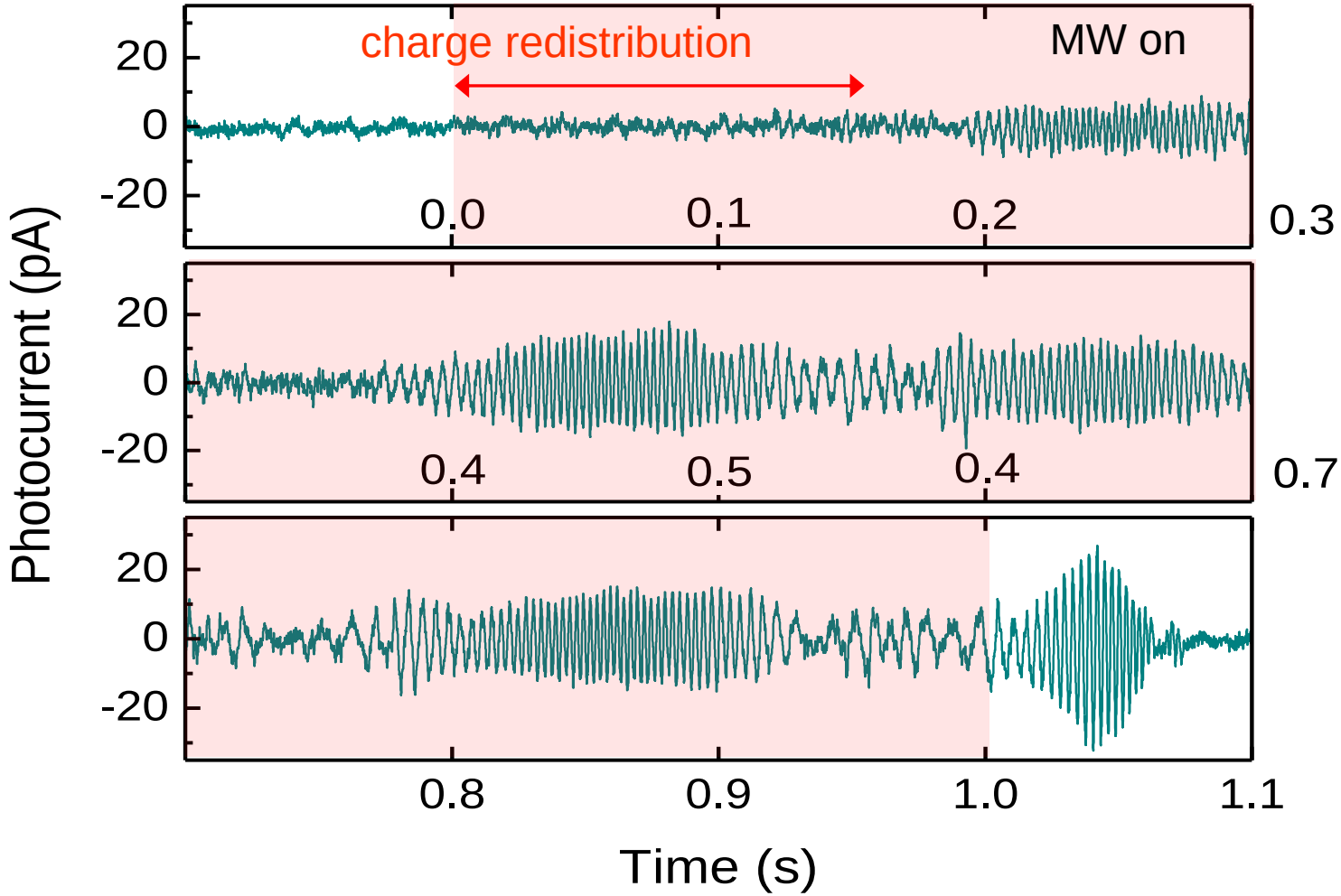
OR

Negative σ_{xx} leading to redistribution?



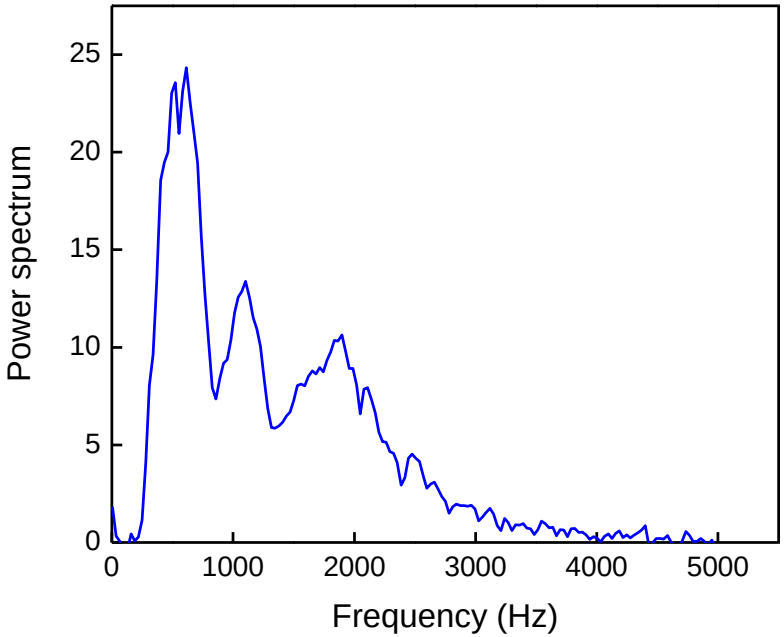
Current domains (Corbino)

Self-organized oscillations



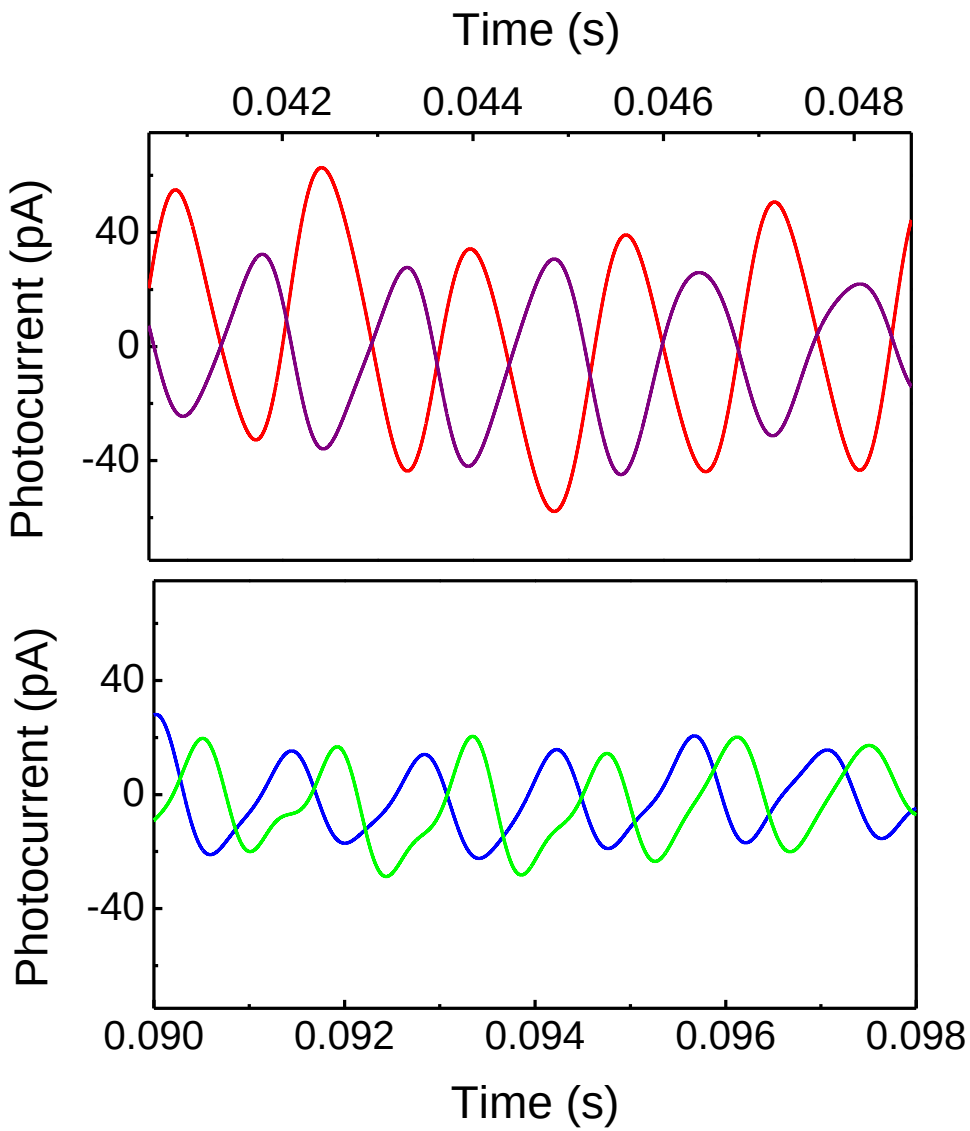
Sound of electrons

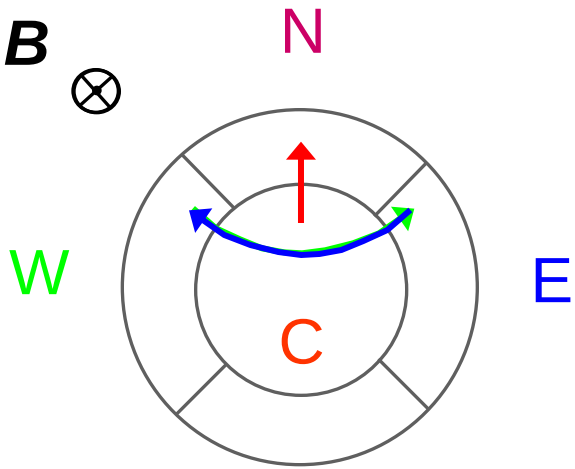
Recoded by Masamitsu Watanabe



Thank you!

Phase relation





Hall gyrator (?)

M. Lea et al. LT18, Kyoto 1987

$$I_x Z - I_y R_H = 0$$

$$I_x R_H + I_y Z = 0$$

Resonance at $\omega \approx (R_H C)^{-1} \sim 100$ Hz

due to inductance $L = R_H^2 C$

Time-dependent frequency: $R_H = \dfrac{B}{n_s e}$