Coulomb Shift of the Intersubband Resonance and Temperature Bistability of Electrons on He

D. Konstantinov, M. Dykman, M. Lea, Y. Monarkha,

Kimitoshi Kono

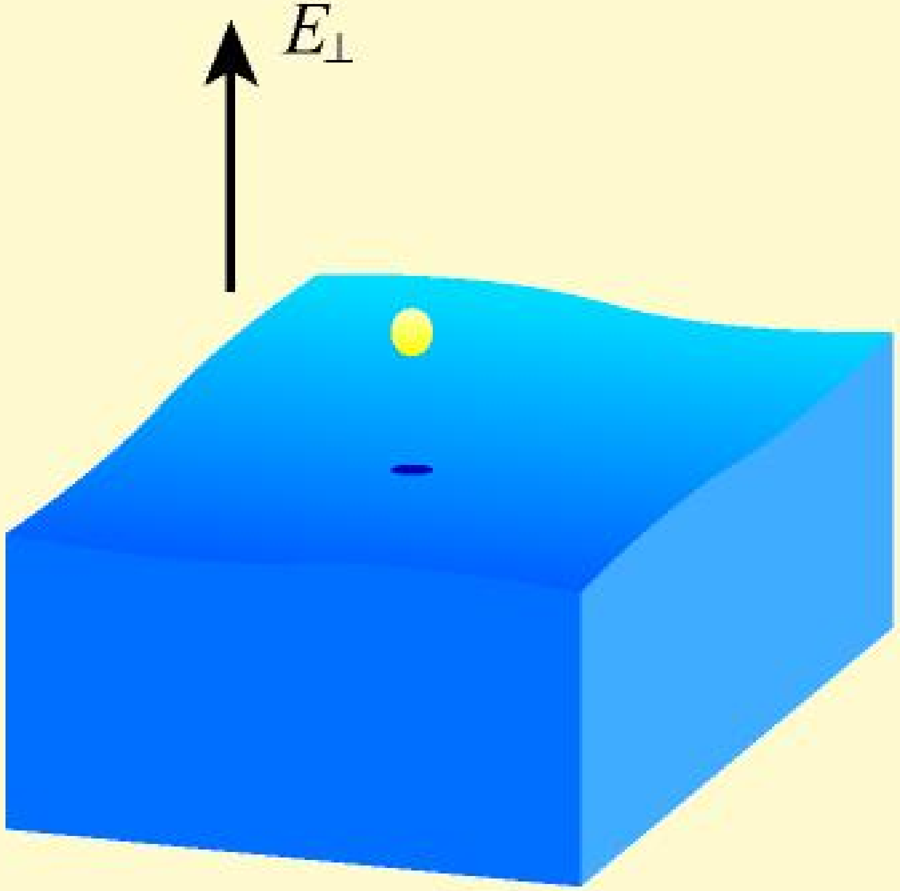
May 22, 2010, Princeton

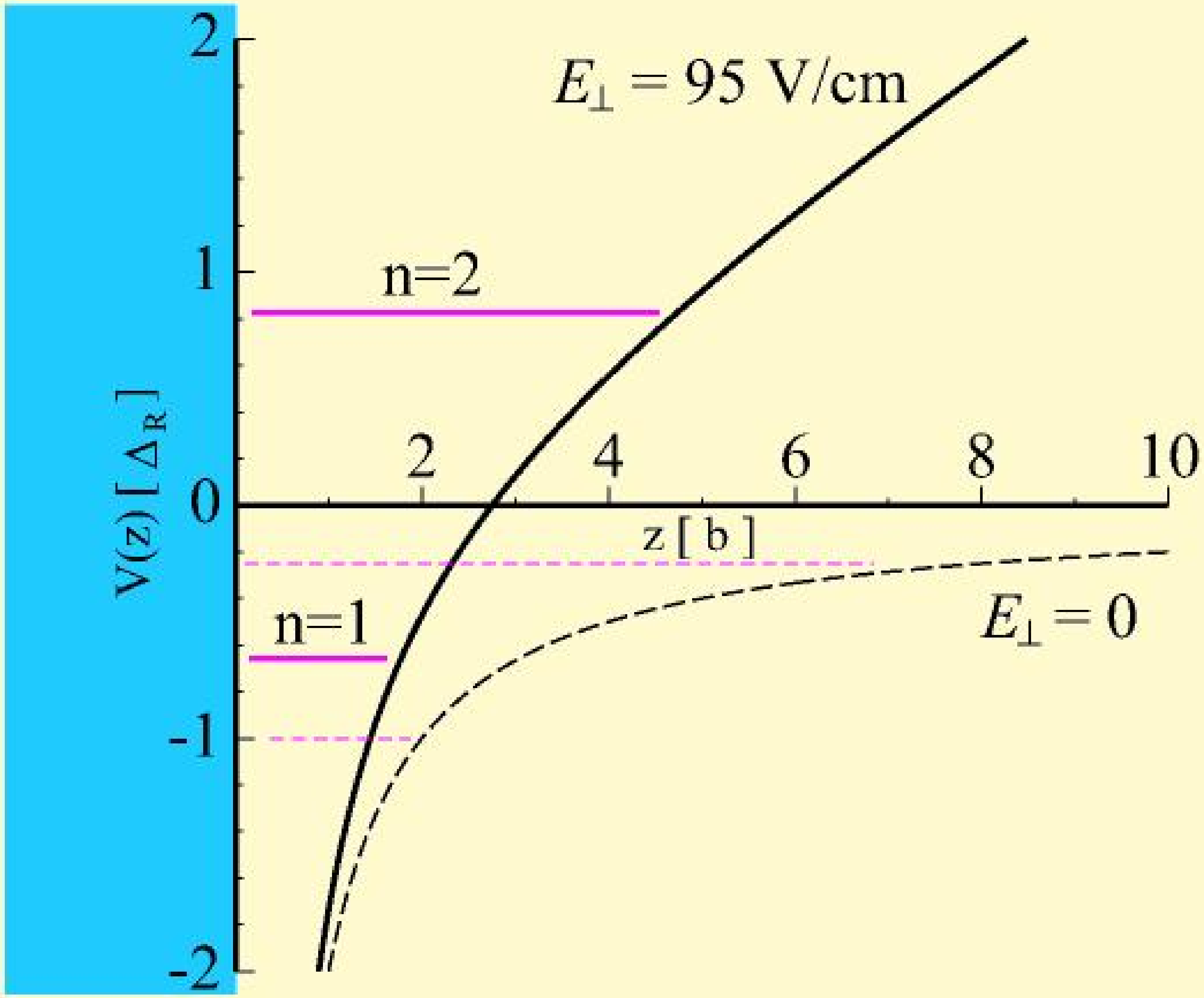
Outline

- Introduction
- Experiment
- Results
  - Microwave (MW) absorption induced hot-electron effect
  - Frequency shift due to Coulomb interaction
  - Bistability
- Summary

D. Konstantinov et al.: Phys. Rev. Lett. 98, 235302 (2007).
D. Konstantinov et al.: Phys. Rev. Lett. 103, 096801 (2009).

Surface states

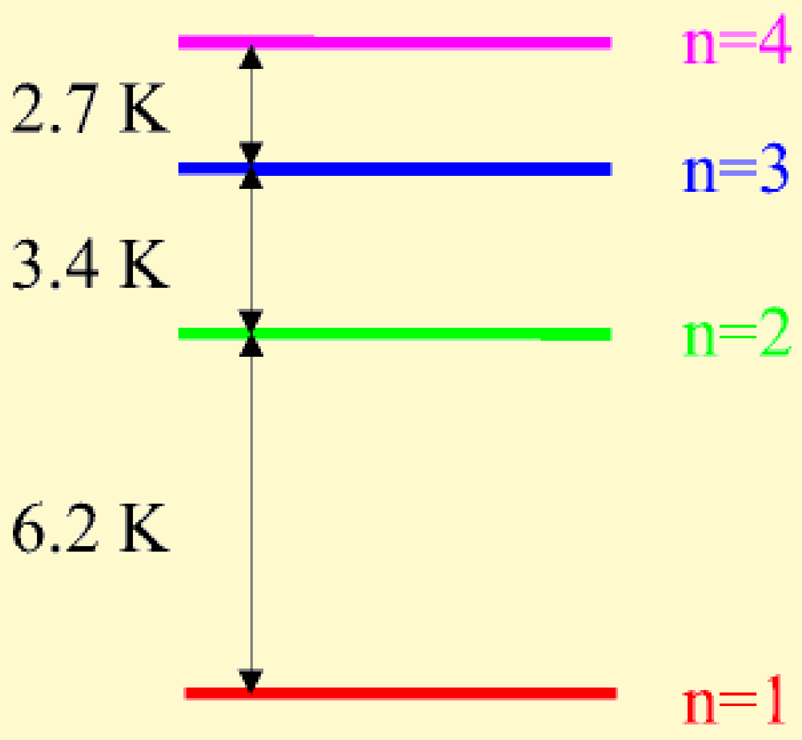




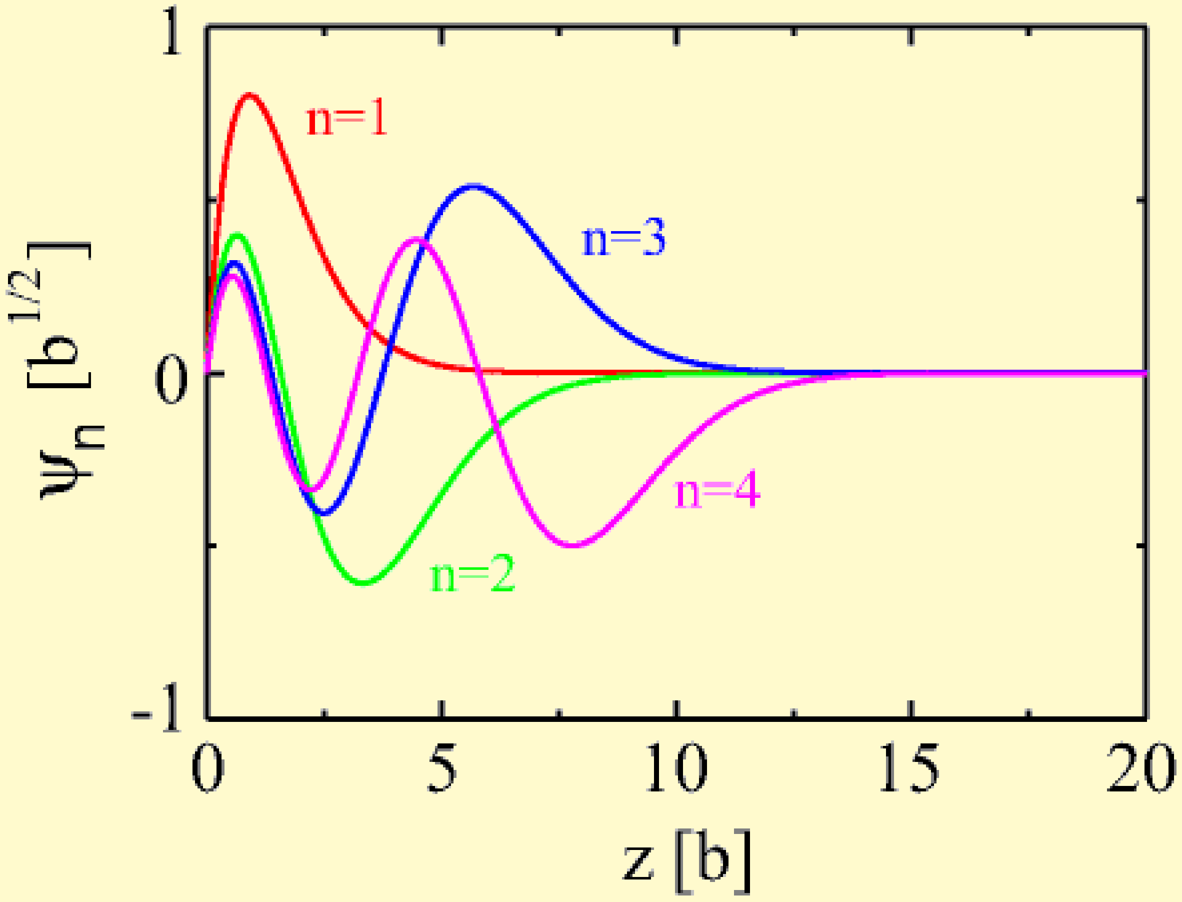
$$V(z) = -\frac{\Lambda e^2}{z} + eE_\perp z$$

Wave functions

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2}-\frac{\Lambda e^2}{z}+eE_\perp z\right]\psi_n(z)=\epsilon_n\psi_n(z)$$

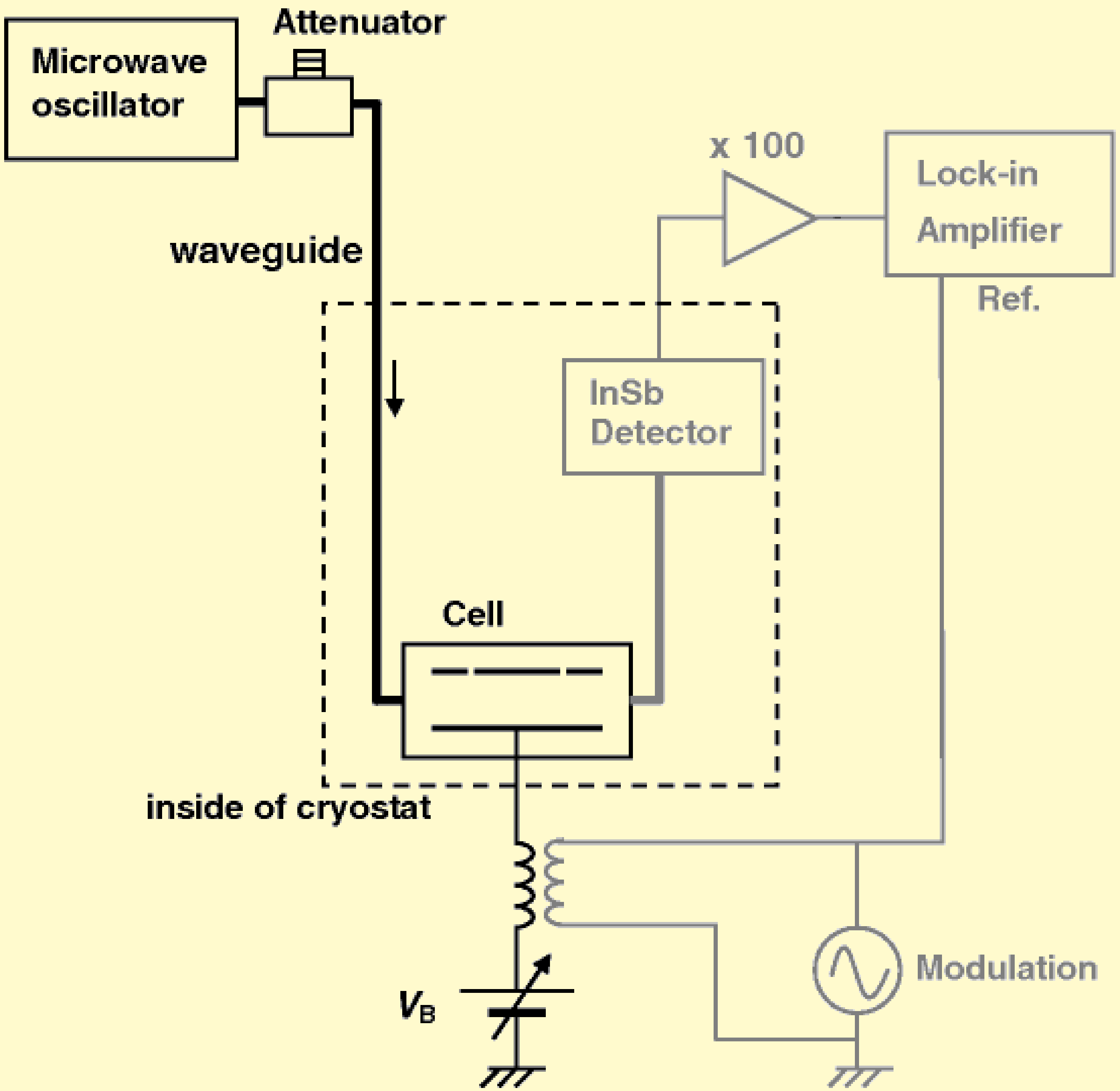


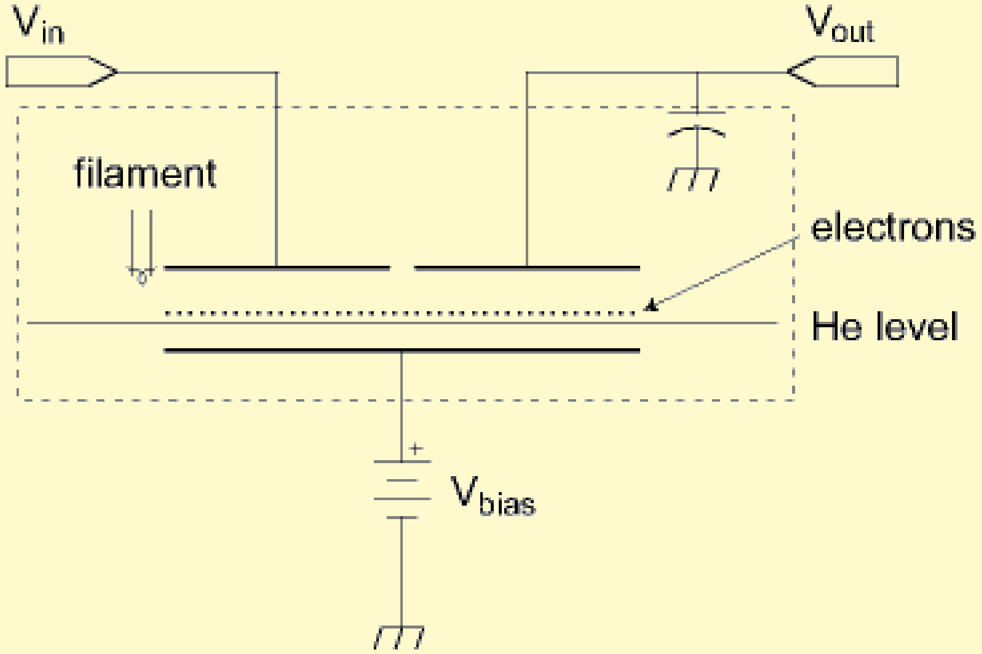
$E_\perp = 95$ V/cm

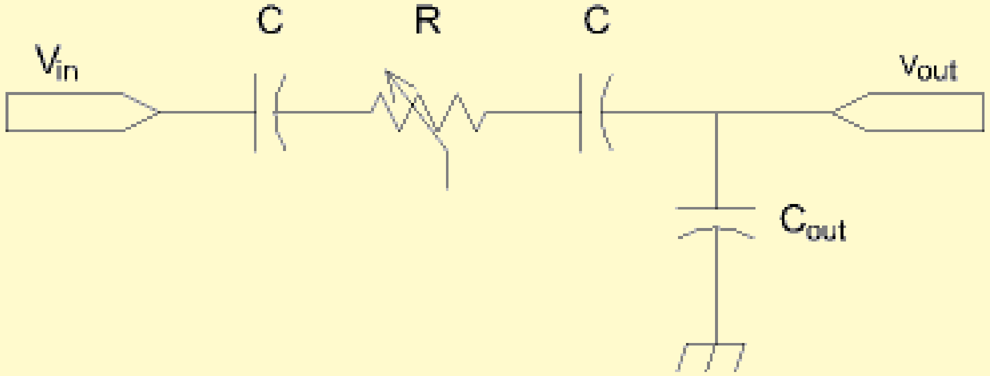


Experimental block diagram

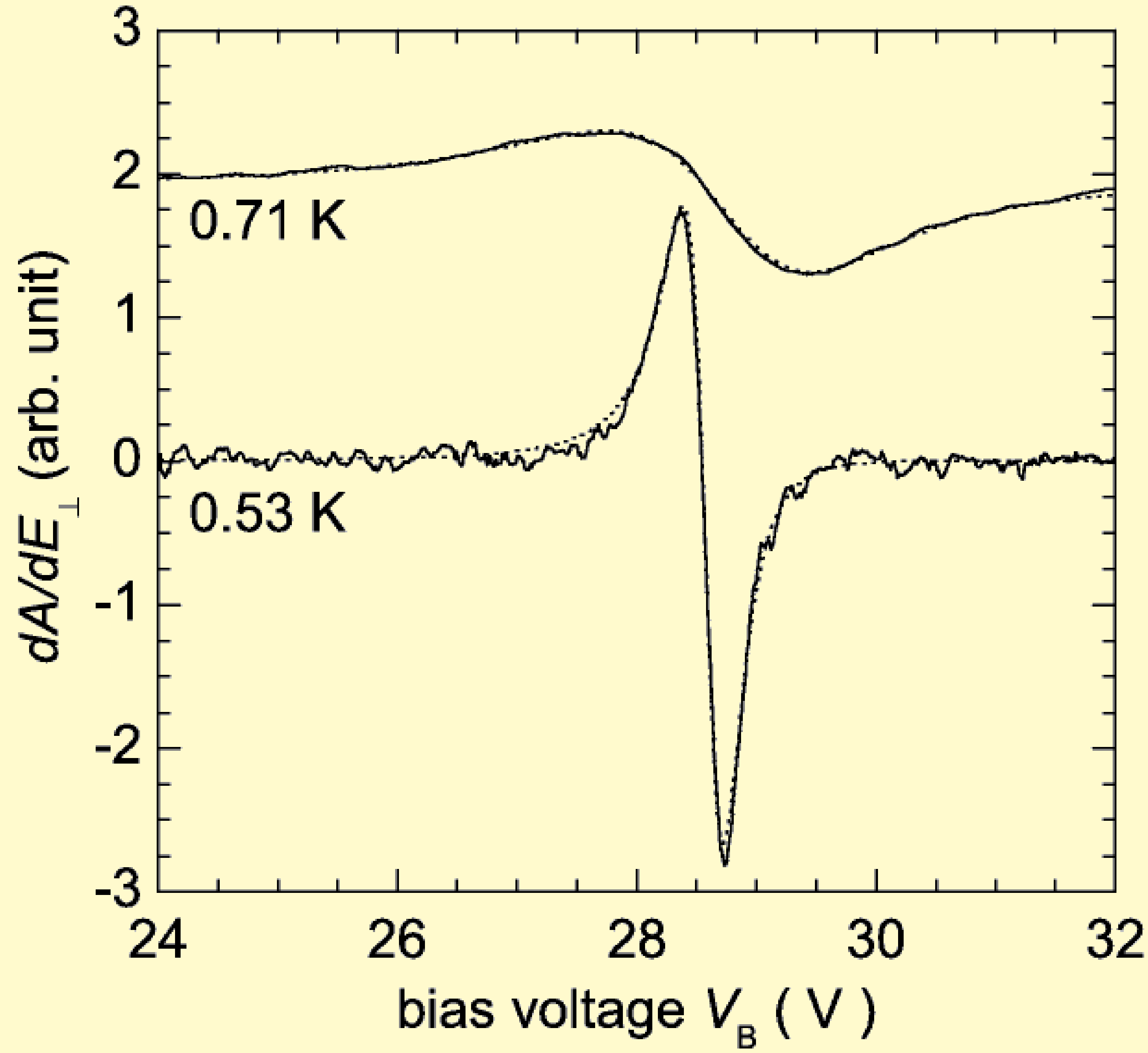
C. C. Grimes and T. R. Brown: Phys. Rev. Lett. 32 (1974) 280.
E. Collin et al.: Phys. Rev. Lett. 89 (2002) 245301.



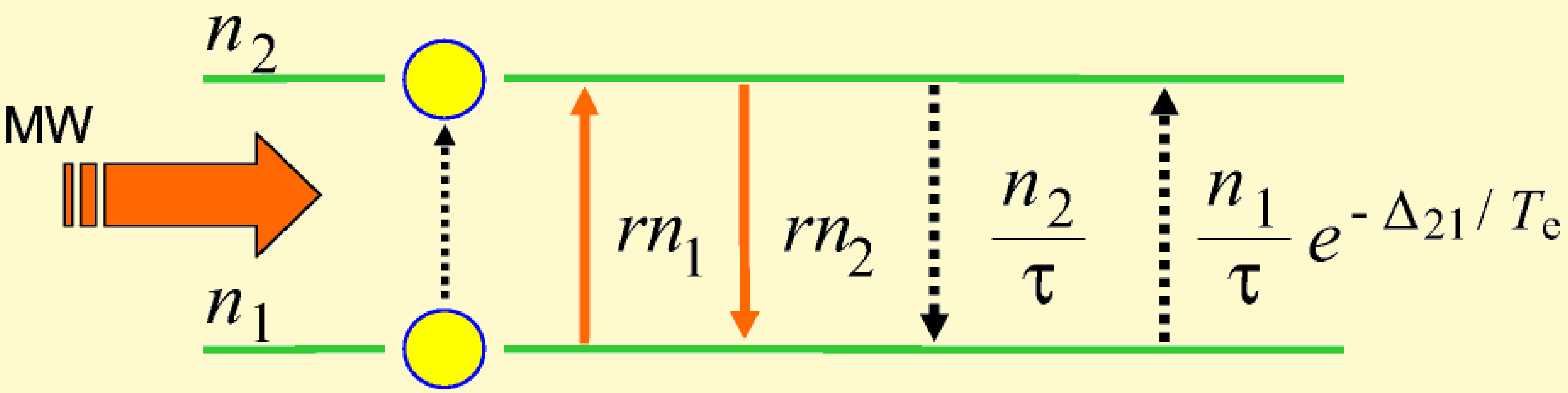




Absorption signal



MW Absorption dynamics



Rate equation

$$\frac{dn_2}{dt} = r(n_1 - n_2) - \frac{1}{\tau}(n_2 - n_1 e^{-\Delta_{21}/T_e})$$

$$n_1 + n_2 = 1$$

$$\Delta_{mn} = \epsilon_m - \epsilon_n$$

r : Stimulated absorption (emission) rate

τ : Relaxation time

Absorption rate

$$r = \frac{1}{2}\frac{\Omega_{\mathrm{R}}^2\gamma}{\delta^2+\gamma^2}$$

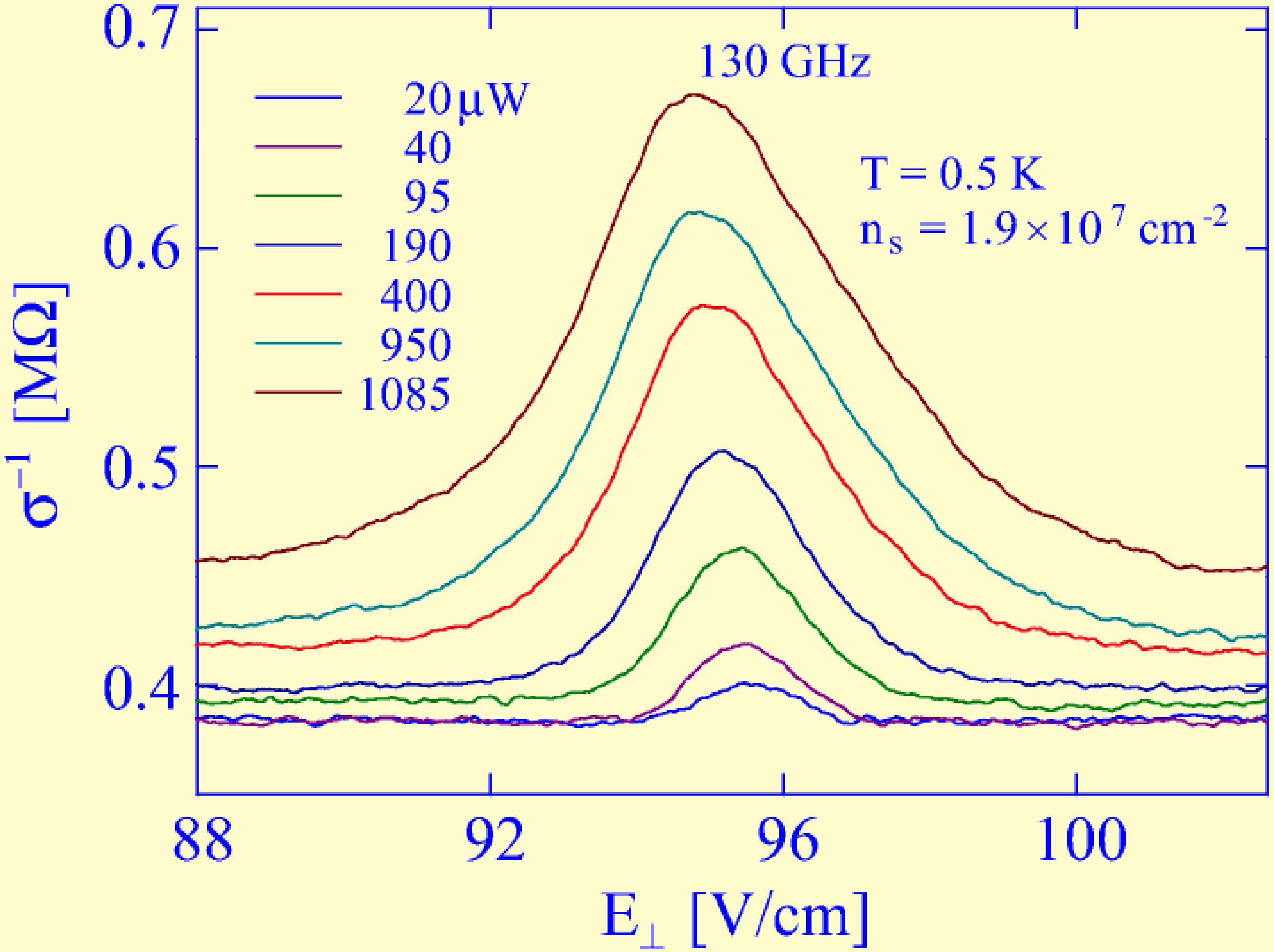
$$\delta = \omega_0 - \omega, \quad \hbar\omega_0 = \Delta_{21}$$

γ Linewidth

$$\hbar\Omega_{\mathrm{R}} = eE_0\langle 1|z|2\rangle \quad \text{(Rabi frequency)}$$

E_0 Microwave electric field

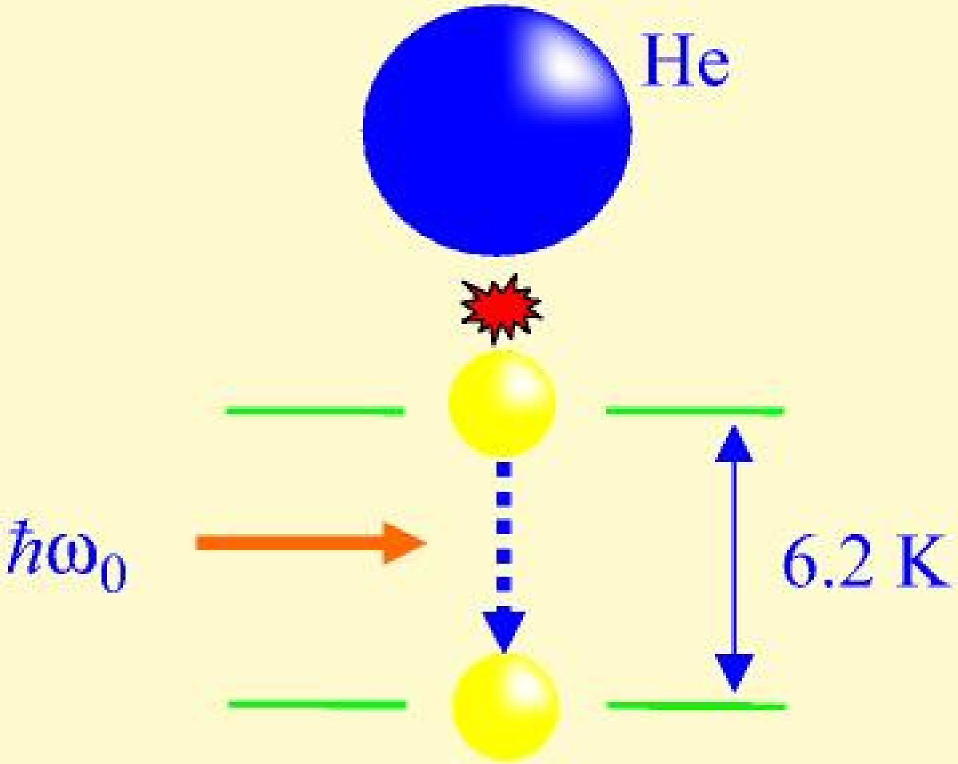
MW induced resisitivity

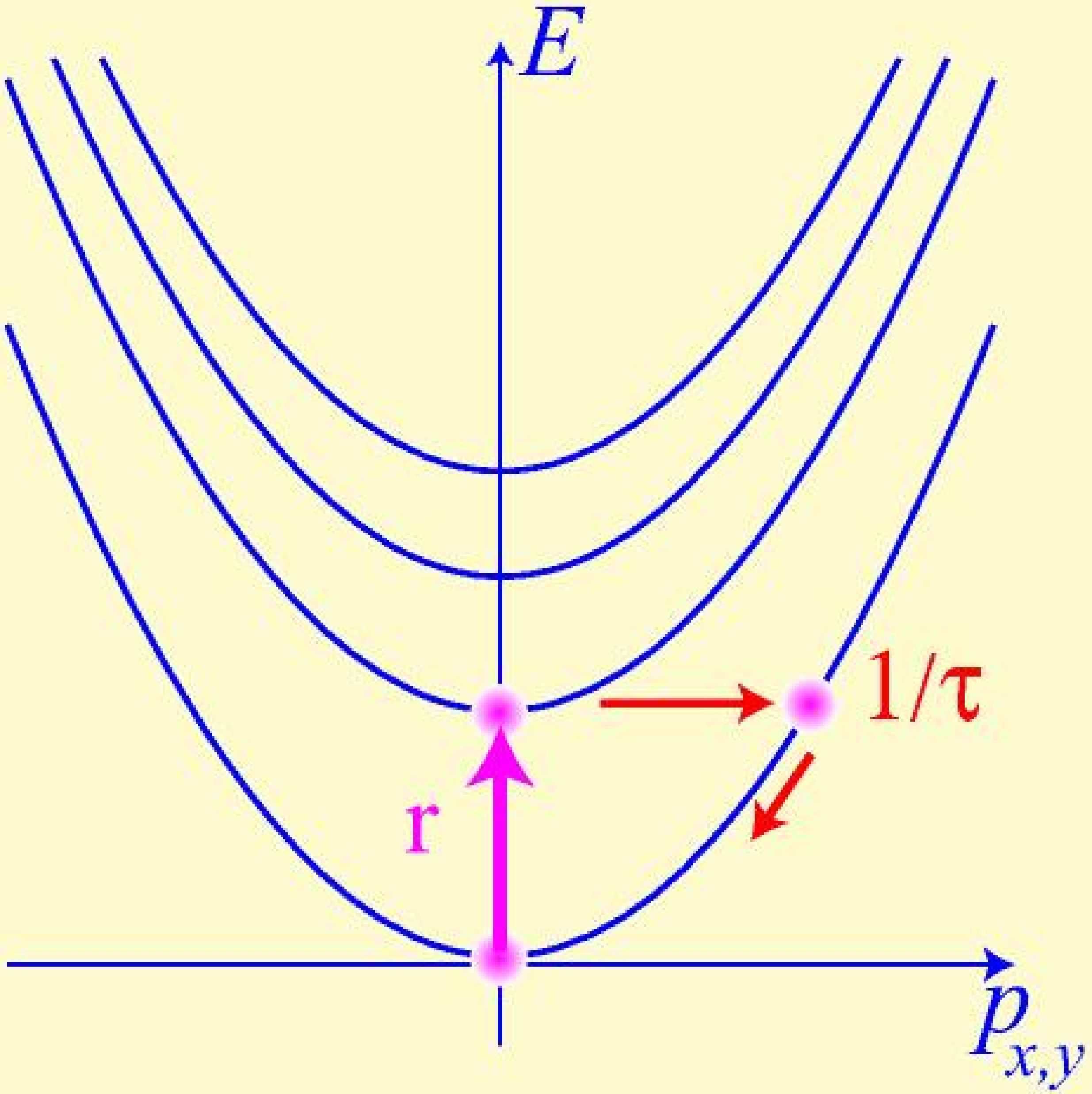


Relaxation dynamics

Total energy

$$E_n = \epsilon_n + \frac{p_\parallel^2}{2m}$$





To calculate Te

Rate equation:

$$r\,(n_1 - n_2) = \frac{1}{\tau}\left(n_2 - n_1\,e^{-\Delta_{21}/T_e}\right)$$

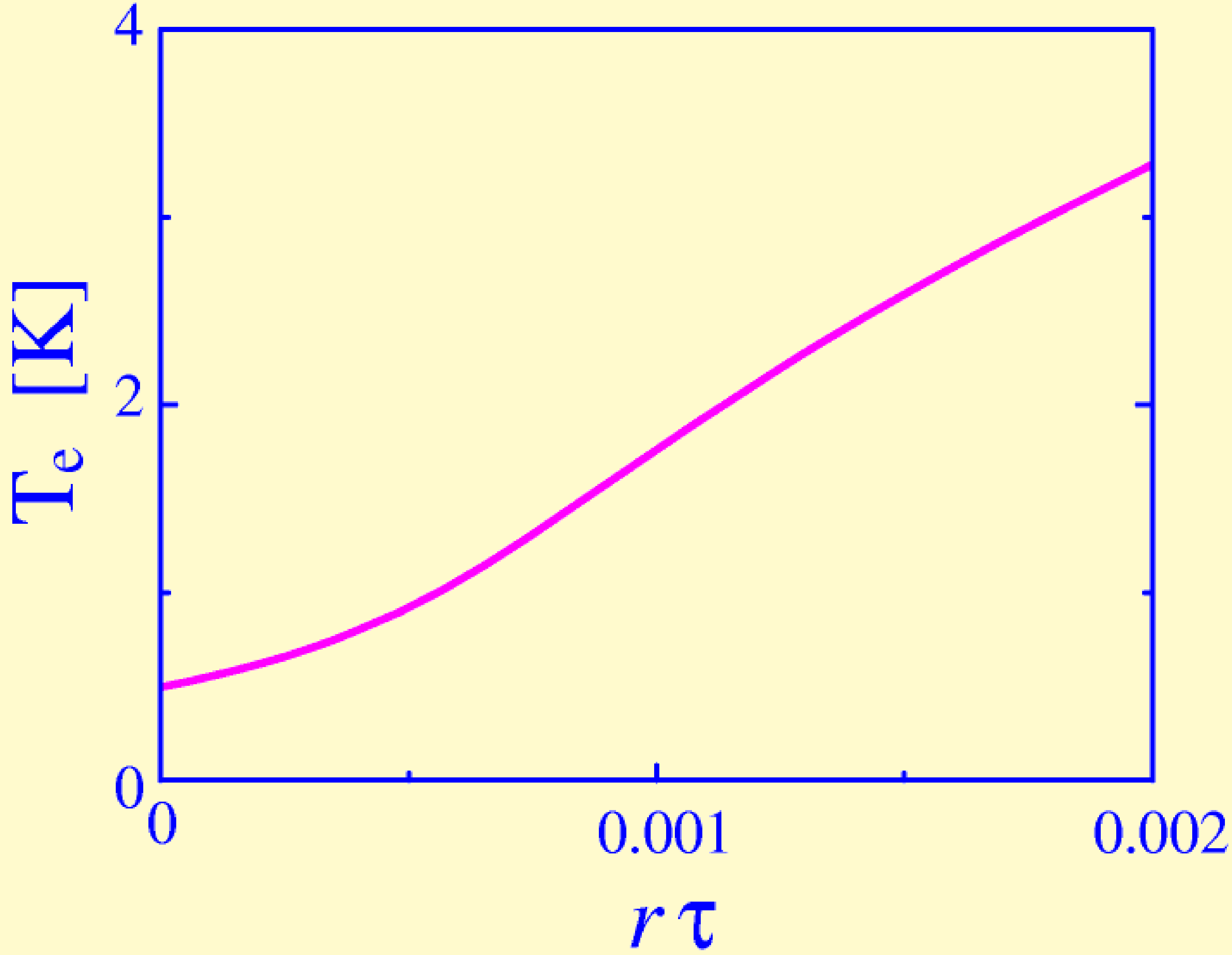
$$n_i = Z^{-1} e^{-\frac{\Delta_{i1}}{T_e}} \quad (i \geq 3), \quad Z = \sum_{i=1}^{\infty} e^{-\frac{\Delta_{i1}}{T_e}}$$

Energy balance equation:

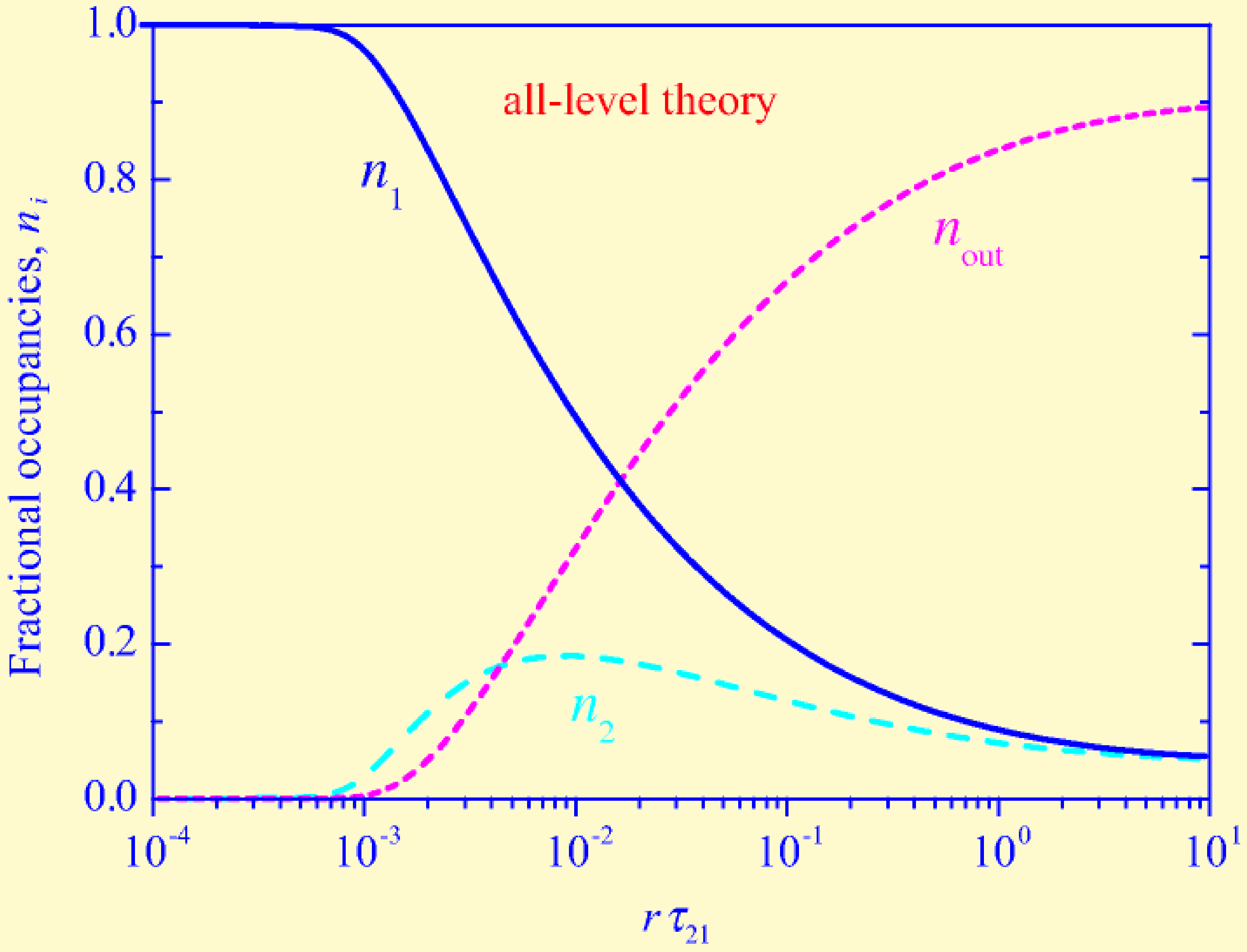
$$(T_e - T)\,\nu_{\mathrm{E}}(T_e) = \hbar\omega\,r\,(n_1 - n_2)$$

$$\nu_{\mathrm{E}}(T_e) \approx \frac{m}{M}\frac{1}{\tau}$$

Te



Fractional occupancy



Mobility vs. Te

$$\mu = \frac{e}{m\nu_{\mathrm{M}}}$$

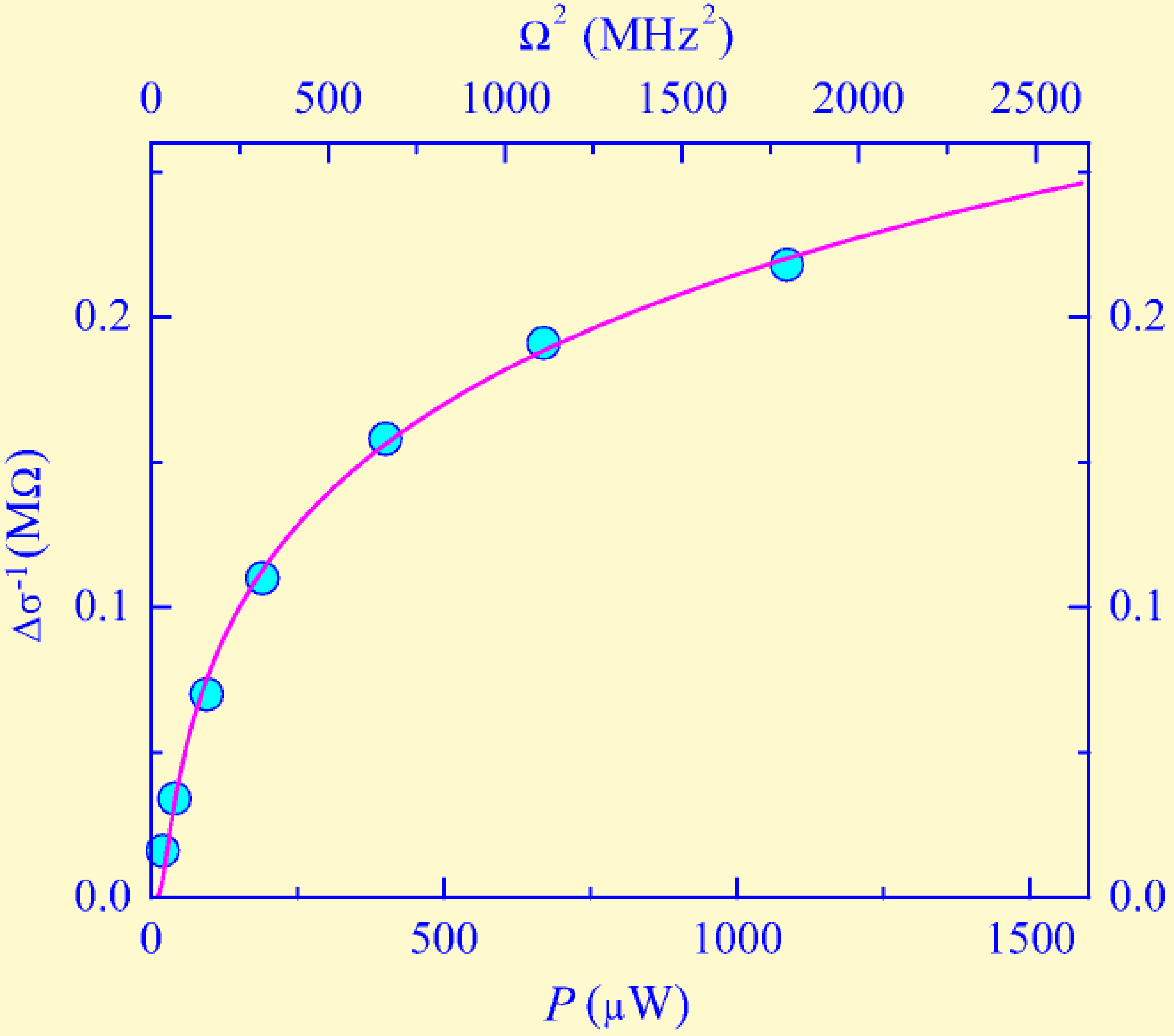
$$\nu_{\mathrm{M}}(T_e) = \nu_{\mathrm{M}}^0 \sum_{ij} s_{ij}\, n_j\, e^{-(|\Delta_{ij}|+\Delta_{ij})/2T_e} [1 + \frac{|\Delta_{ij}| + \Delta_{ij}}{2T_e}]$$

$$s_{ij} = \frac{\int_0^\infty dz\, [\psi_i(z)\psi_j(z)]^2}{\int_0^\infty dz\, \psi_1(z)^4}$$

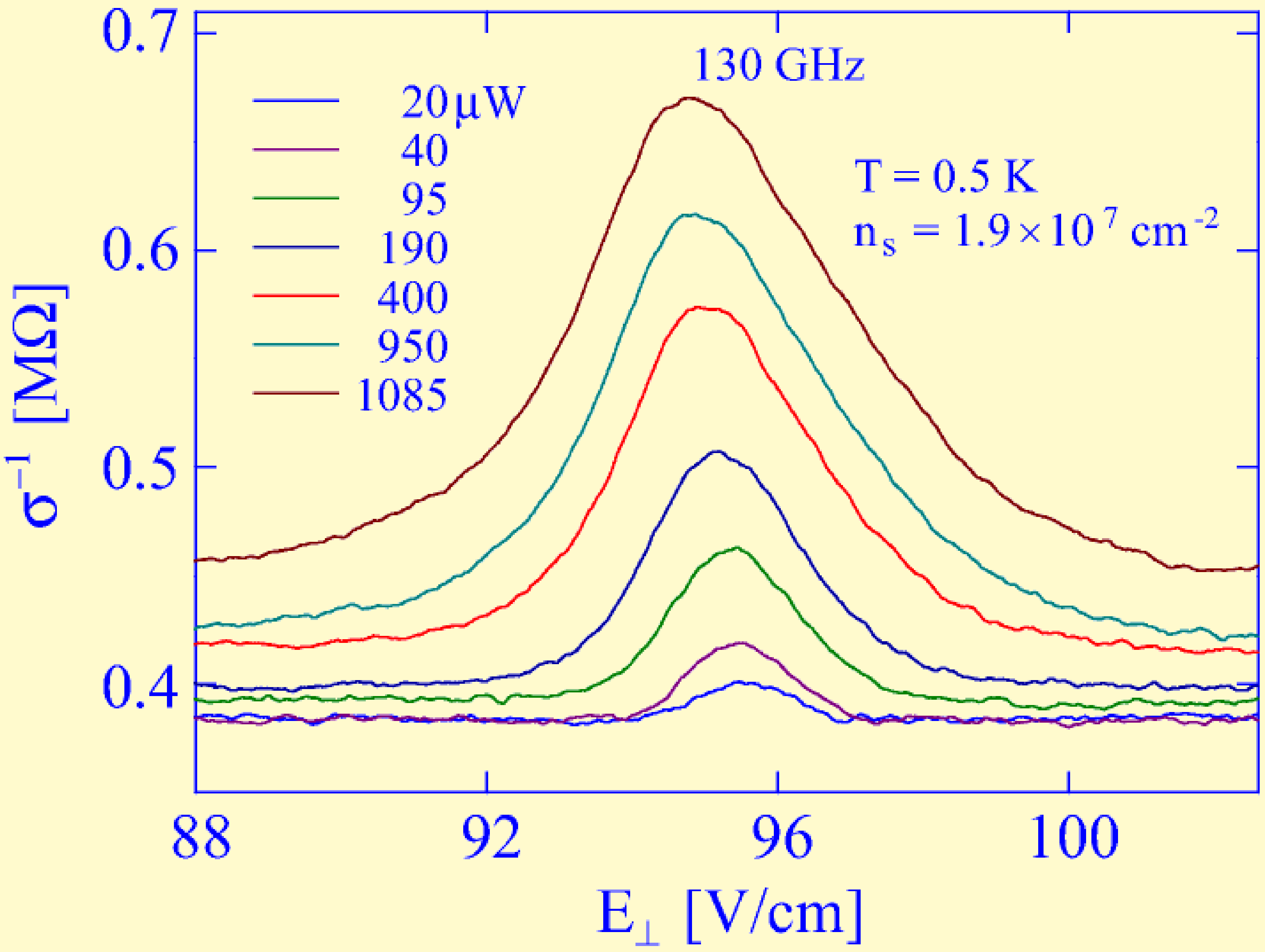
$$\Delta_{ij} = \epsilon_i - \epsilon_j$$

M. Saitoh and T. Aoki: J. Phys. Soc. Jpn 44 (1977) 71.
Yu. P. Monarkha et al.: J. Phys. Soc. Jpn 76 (2007) 124702.

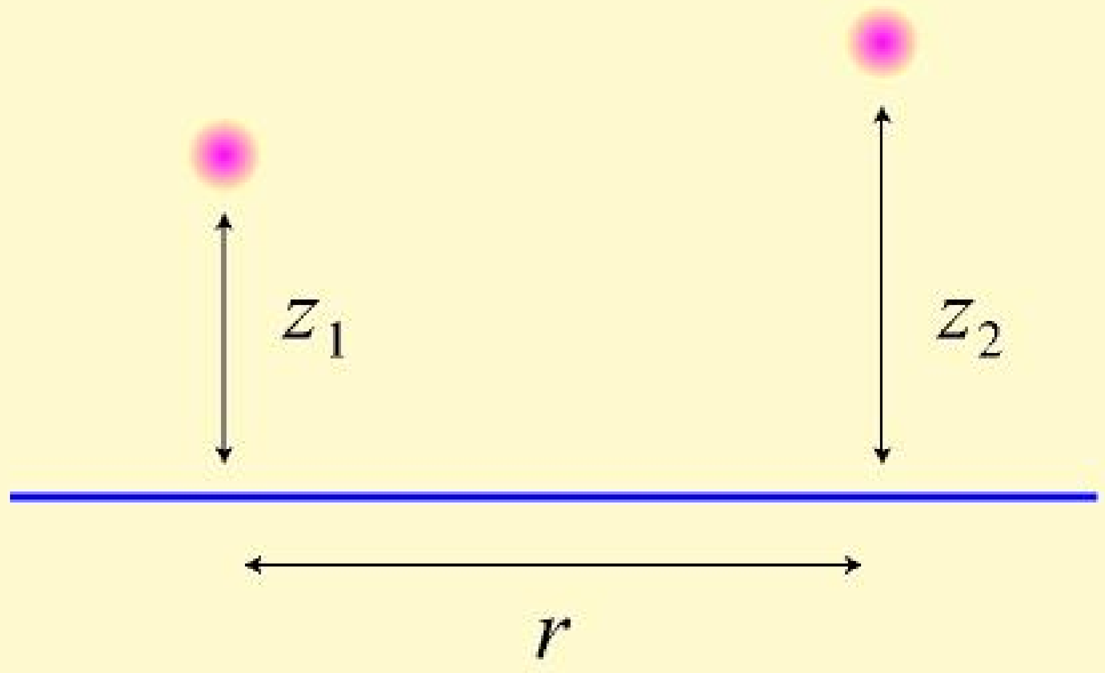
Resistance peak height



Resonance frequency shift



Coulomb interaction



$$V(z_1, z_2) \approx \frac{e^2}{r}\left(1 - \frac{(z_1 - z_2)^2}{2r^2}\right)$$

$$H_I = -\frac{e^2}{2r^3}(z_1 - z_2)^2$$

A correction to Δ_{21} from the neighboring electron in the lth-state

$$\Delta E \approx \langle 2|\langle l|H_I|l\rangle|2\rangle - \langle 1|\langle l|H_I|l\rangle|1\rangle$$

$$= -\frac{e^2}{2r^3}\left[\langle 2|z^2|2\rangle - \langle 1|z^2|1\rangle - 2\Big(\langle 2|z|2\rangle - \langle 1|z|1\rangle\Big)\langle l|z|l\rangle\right]$$

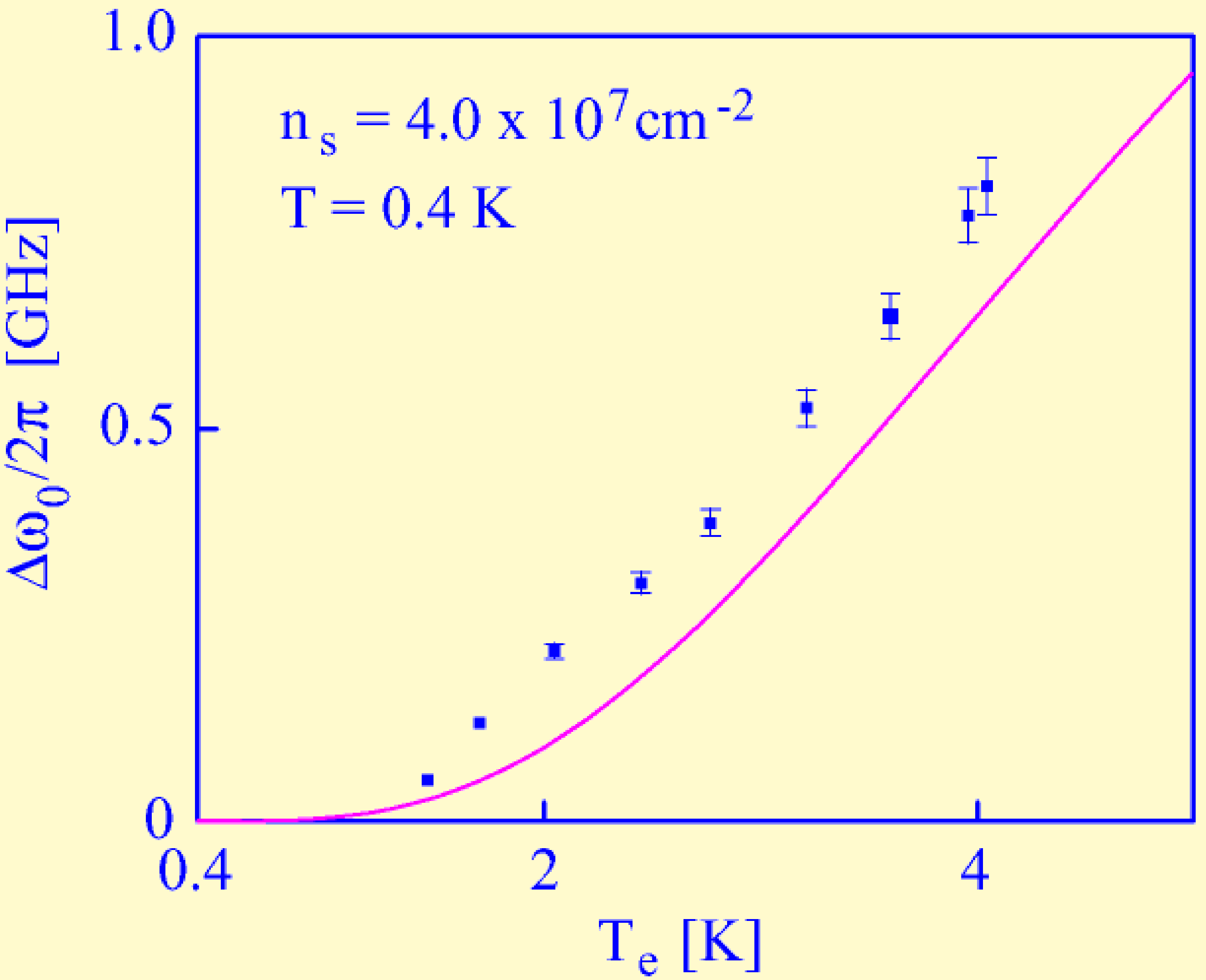
MW power dependent shift:

$$\Delta\omega_0 = \frac{Fe^2 n_s^{3/2}}{\hbar} \Big(\langle 2|z|2\rangle - \langle 1|z|1\rangle \Big) \Big(\sum_l \langle l|z|l\rangle \, n_l - \langle 1|z|1\rangle \Big)$$

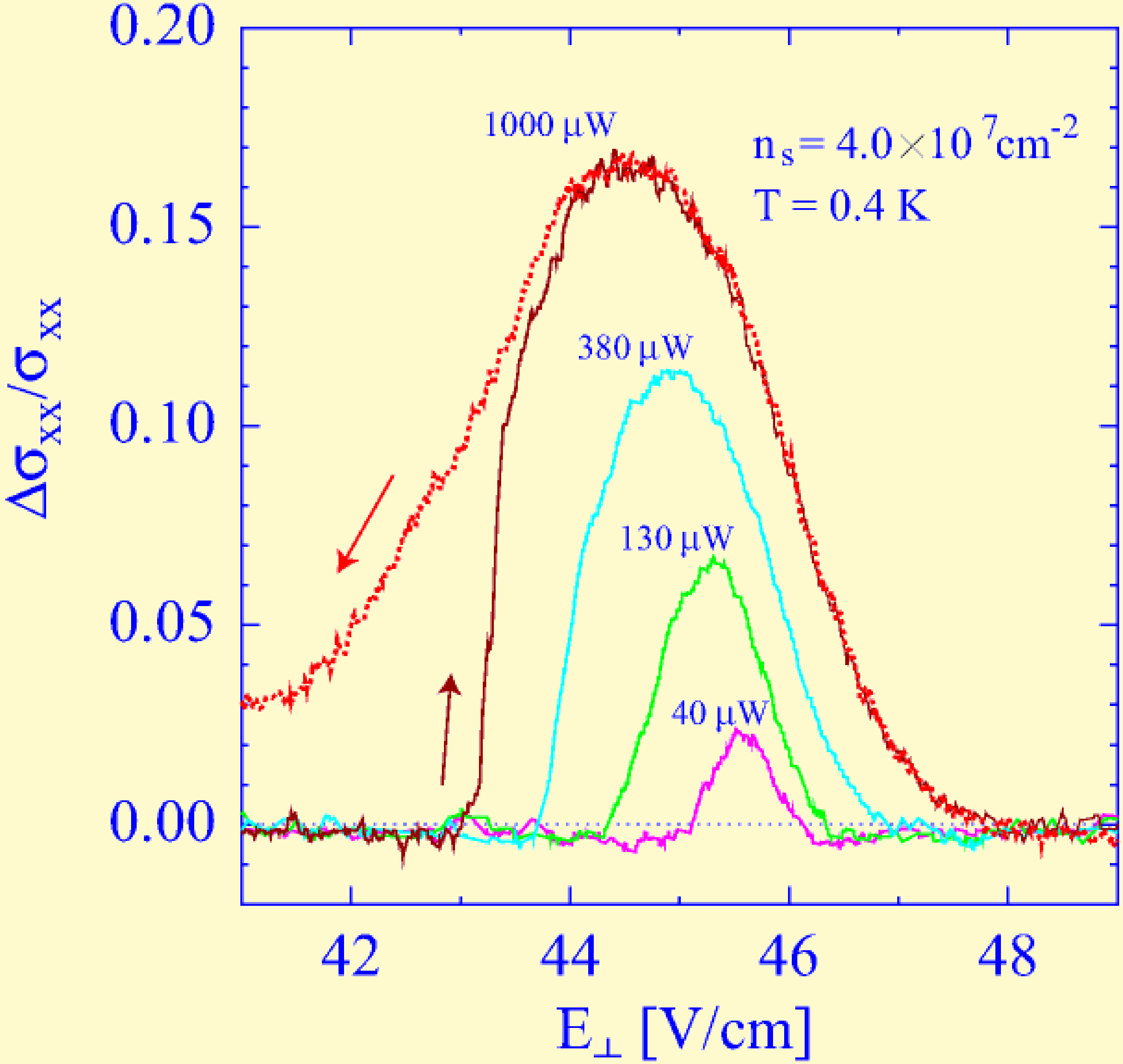
$$F = \frac{1}{\sqrt{n_s}} \int_0^\infty \frac{g(r)}{r^3} 2\pi r dr$$

$$\approx 8.91 \quad \text{for triangular lattice}$$

Shift of resonance frequency

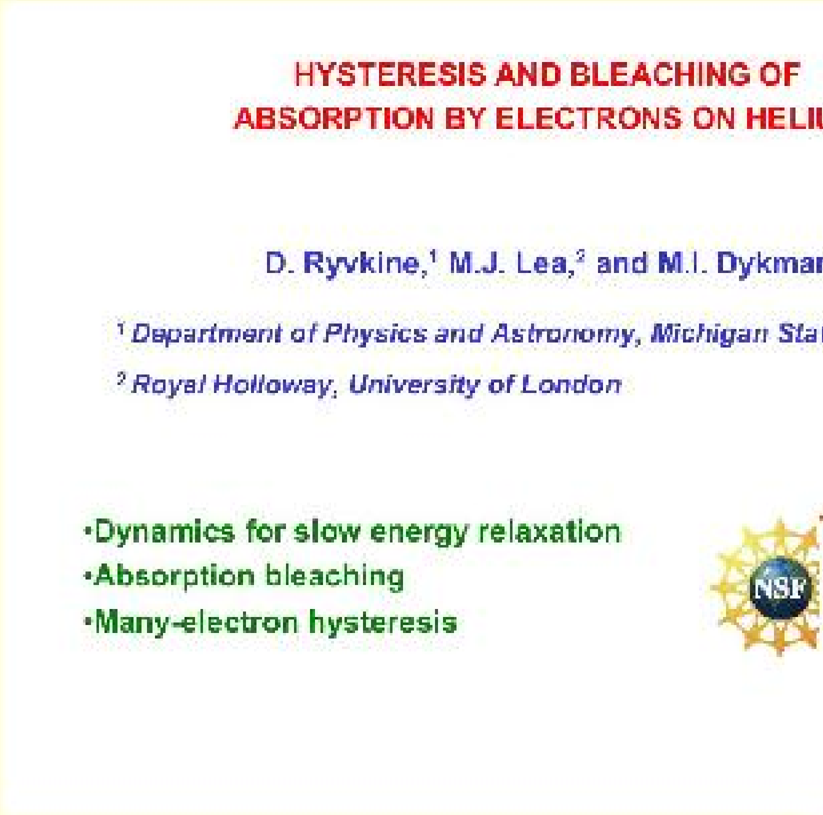


Hysteresis



0.20
0.15
0.10
0.05
0.00
$\Delta\sigma_{xx}/\sigma_{xx}$
42
44
46
48
$E_\perp$ [V/cm]
1000 μW
380 μW
130 μW
40 μW
$n_s = 4.0\times10^7 \text{cm}^{-2}$
T = 0.4 K

Paris in 2006



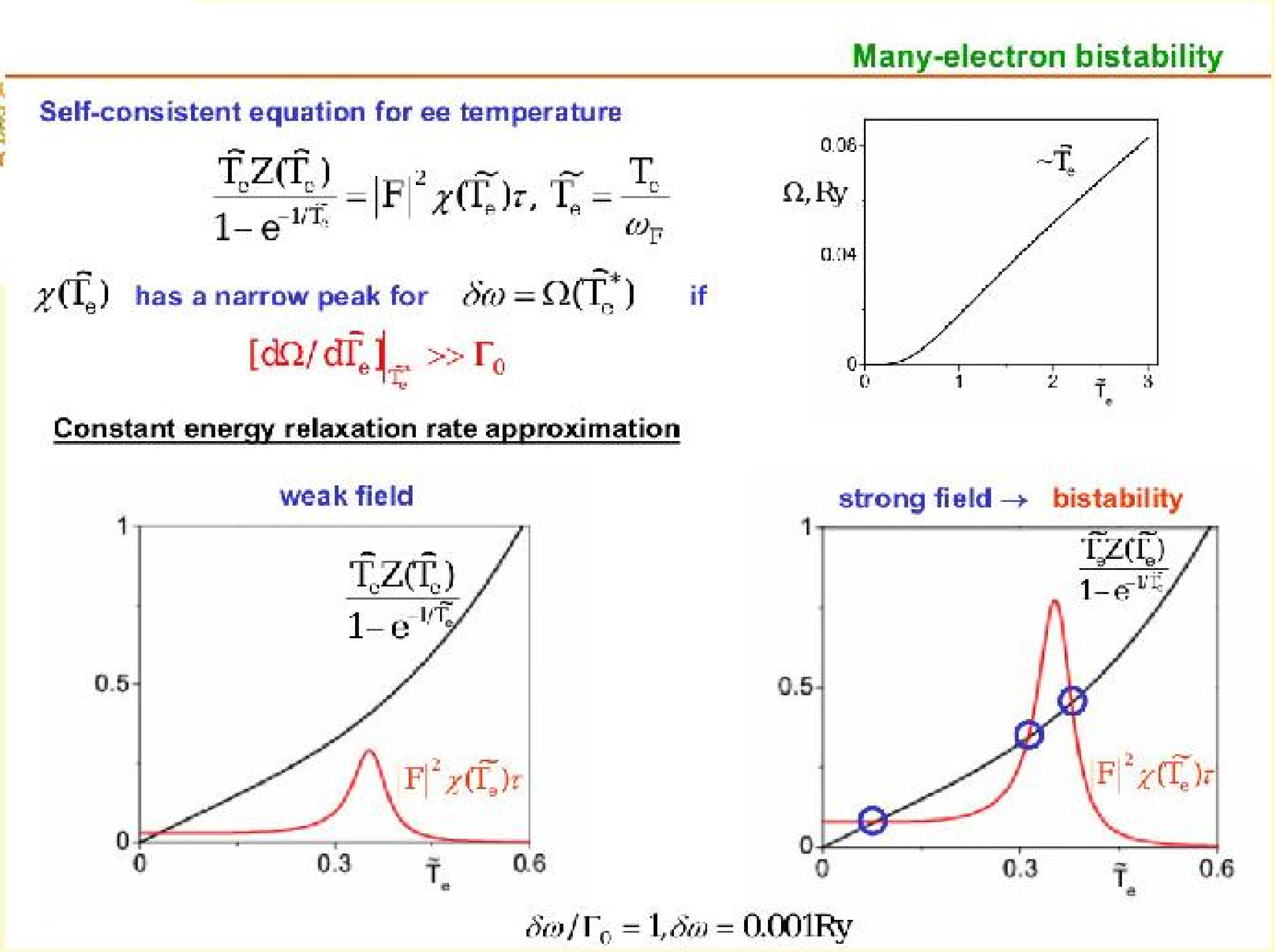
HYSTERESIS AND BLEACHING OF
ABSORPTION BY ELECTRONS ON HELIUM

D. Ryvkine,[1] M.J. Lea,[2] and M.I. Dykman[1]

[1] *Department of Physics and Astronomy, Michigan State University*

[2] *Royal Holloway, University of London*

- Dynamics for slow energy relaxation
- Absorption bleaching
- Many-electron hysteresis



Many-electron bistability

Self-consistent equation for ee temperature

$$\frac{\tilde{T}_e Z(\tilde{T}_e)}{1-e^{-1/\tilde{T}_e}} = |F|^2 \chi(\tilde{T}_e)\tau,\ \tilde{T}_e = \frac{T_e}{\omega_\Gamma}$$

$\chi(\tilde{T}_e)$ has a narrow peak for $\delta\omega = \Omega(\tilde{T}_e^*)$ if

$$[d\Omega/d\tilde{T}_e]\big|_{\tilde{T}_e^*} \gg \Gamma_0$$

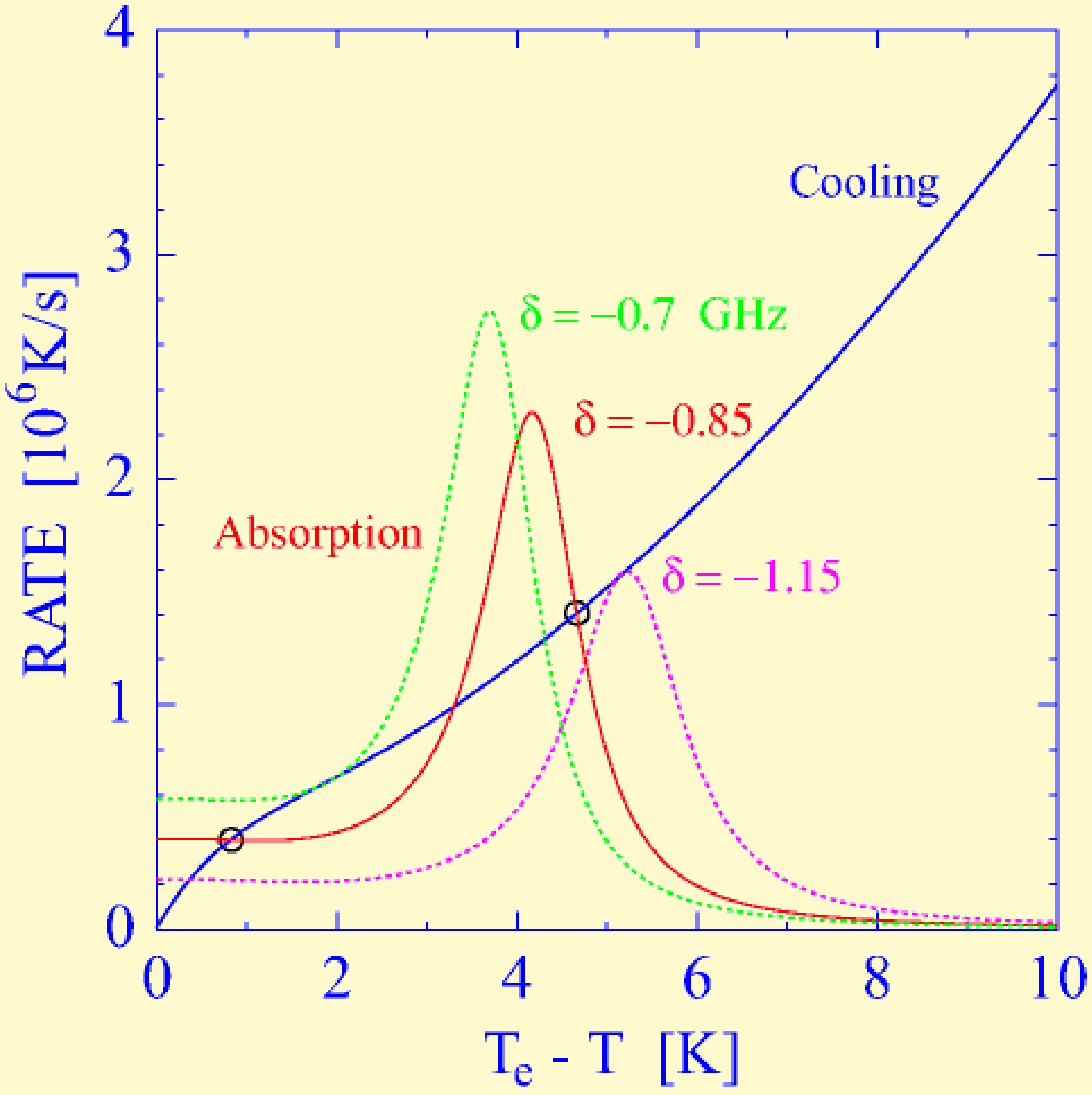
Constant energy relaxation rate approximation

weak field

strong field → bistability

$\delta\omega/\Gamma_0 = 1, \delta\omega = 0.001\text{Ry}$

Energy balance and bistability

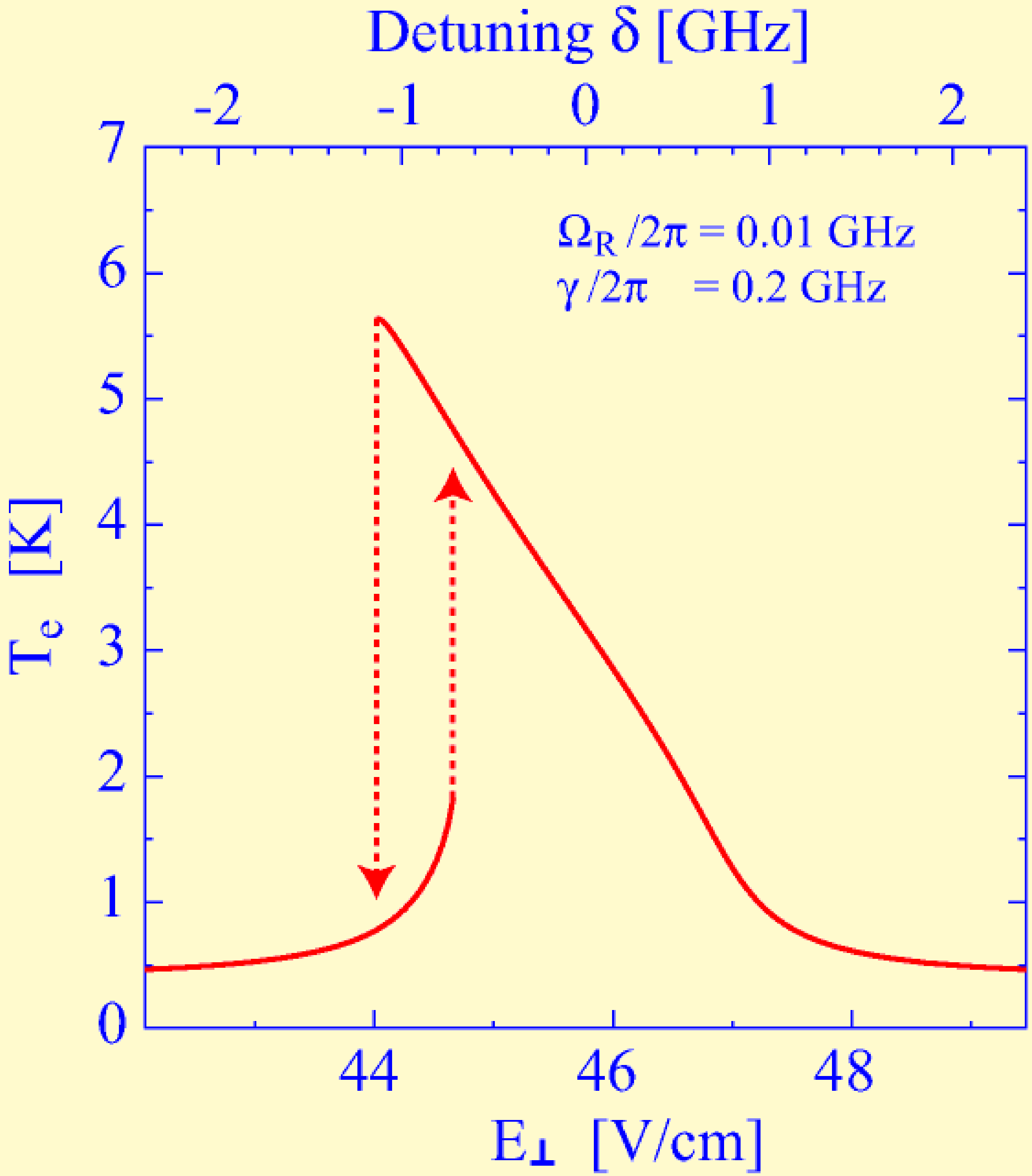


$$r = \frac{1}{2}\frac{\Omega_{\mathrm{R}}^2\gamma}{(\delta + \Delta\omega_0(T_e))^2 + \gamma^2}$$

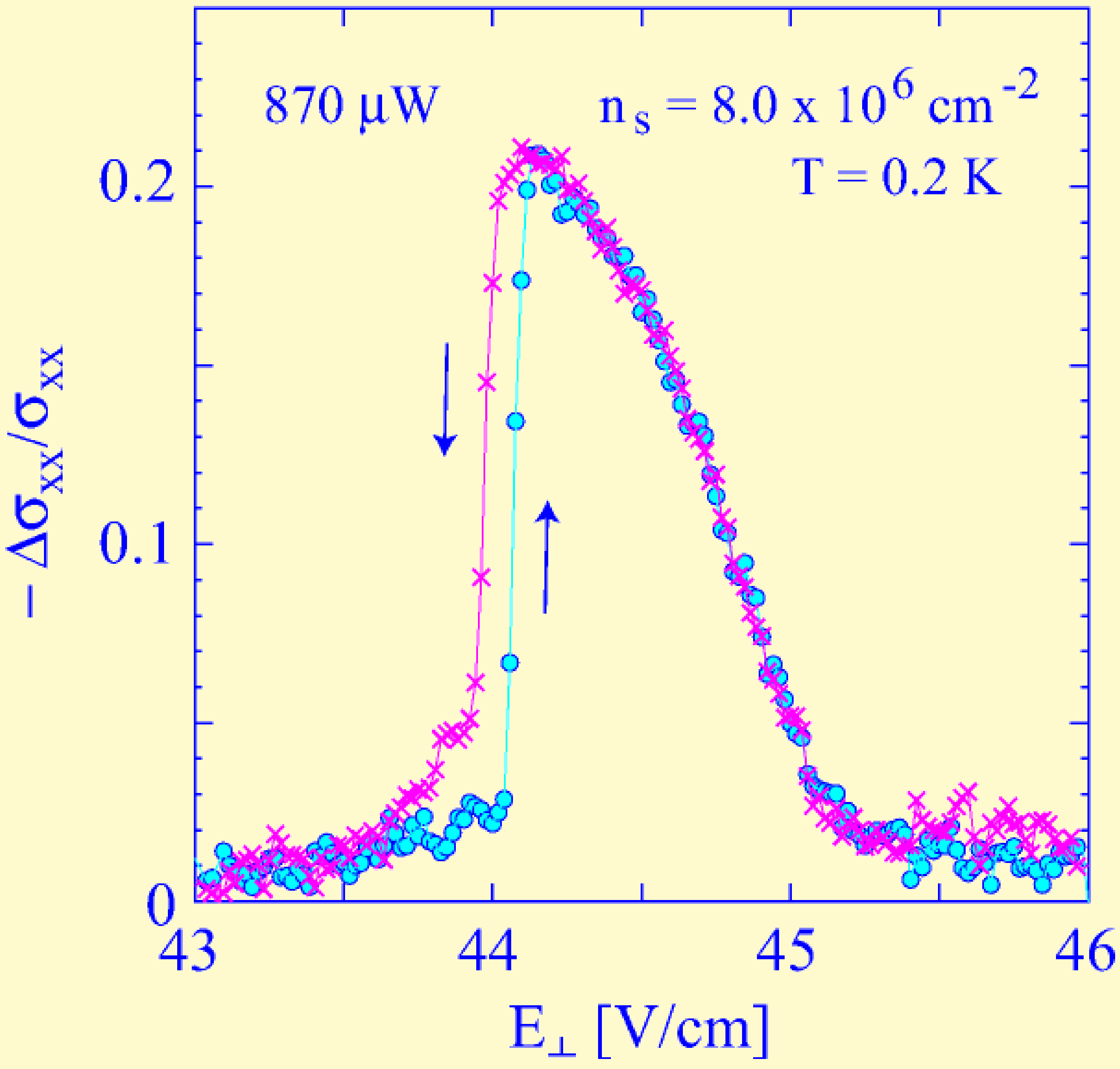
$$\delta = \omega_0 - \omega$$

$$\hbar\omega r(n_1 - n_2) = \nu_{\mathrm{E}}(T_e)(T_e - T)$$

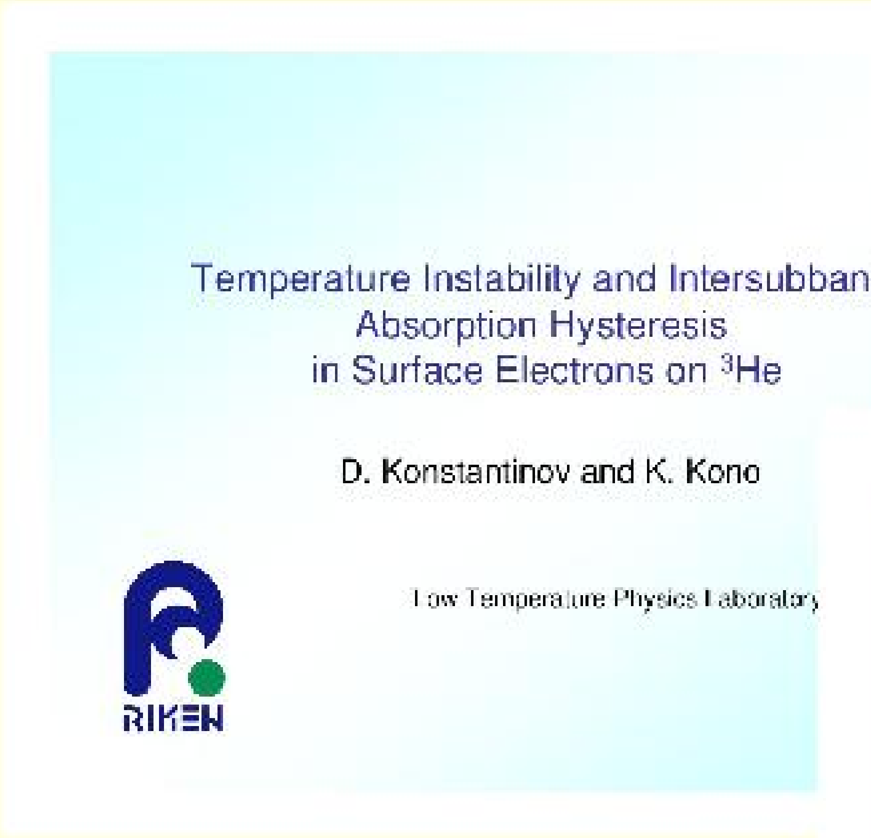
Hysteresis (model)



Hysteresis (0.2K)



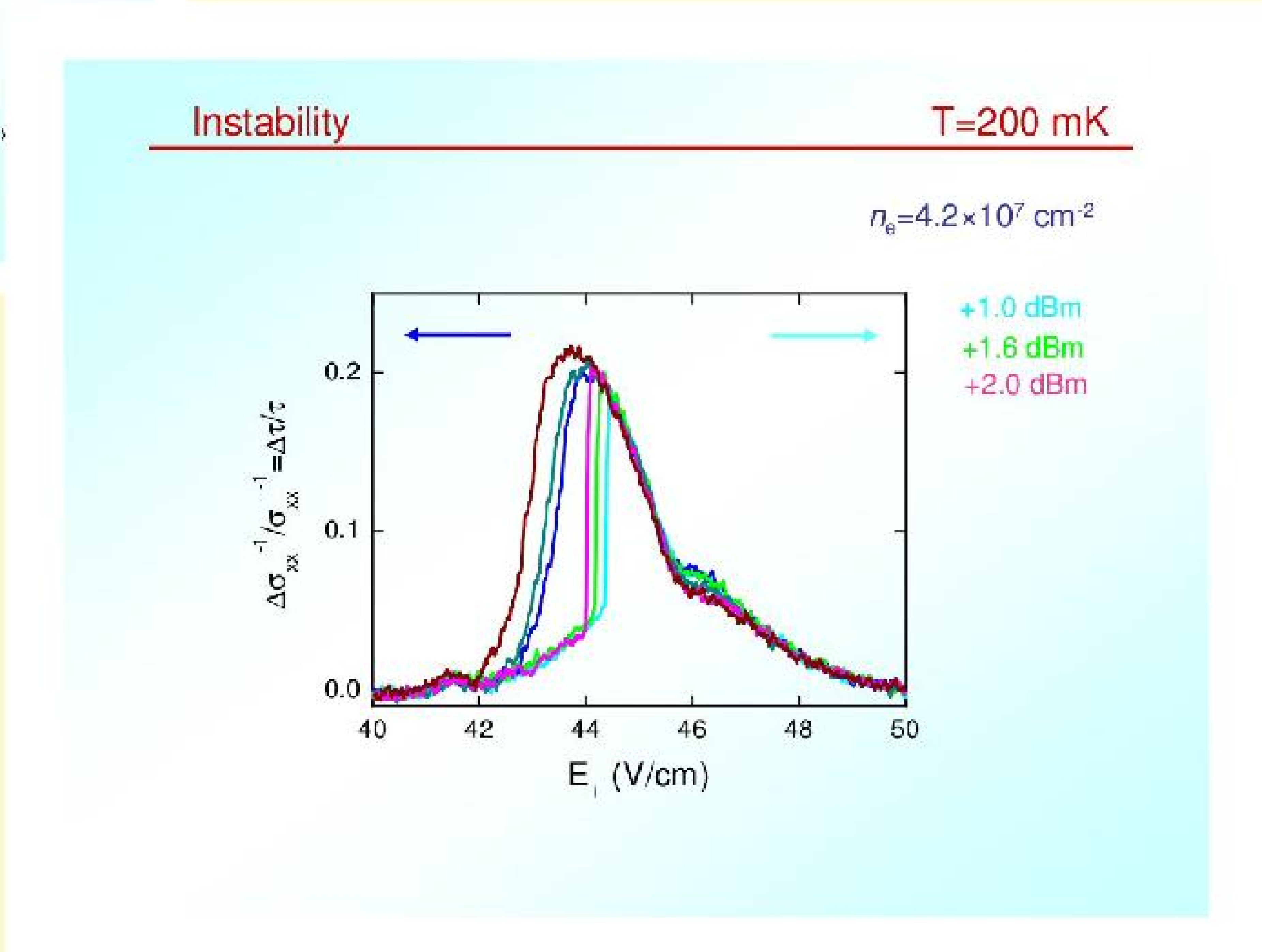
Wako in 2008



Temperature Instability and Intersubband
Absorption Hysteresis
in Surface Electrons on ^{3}He

D. Konstantinov and K. Kono

Low Temperature Physics Laboratory

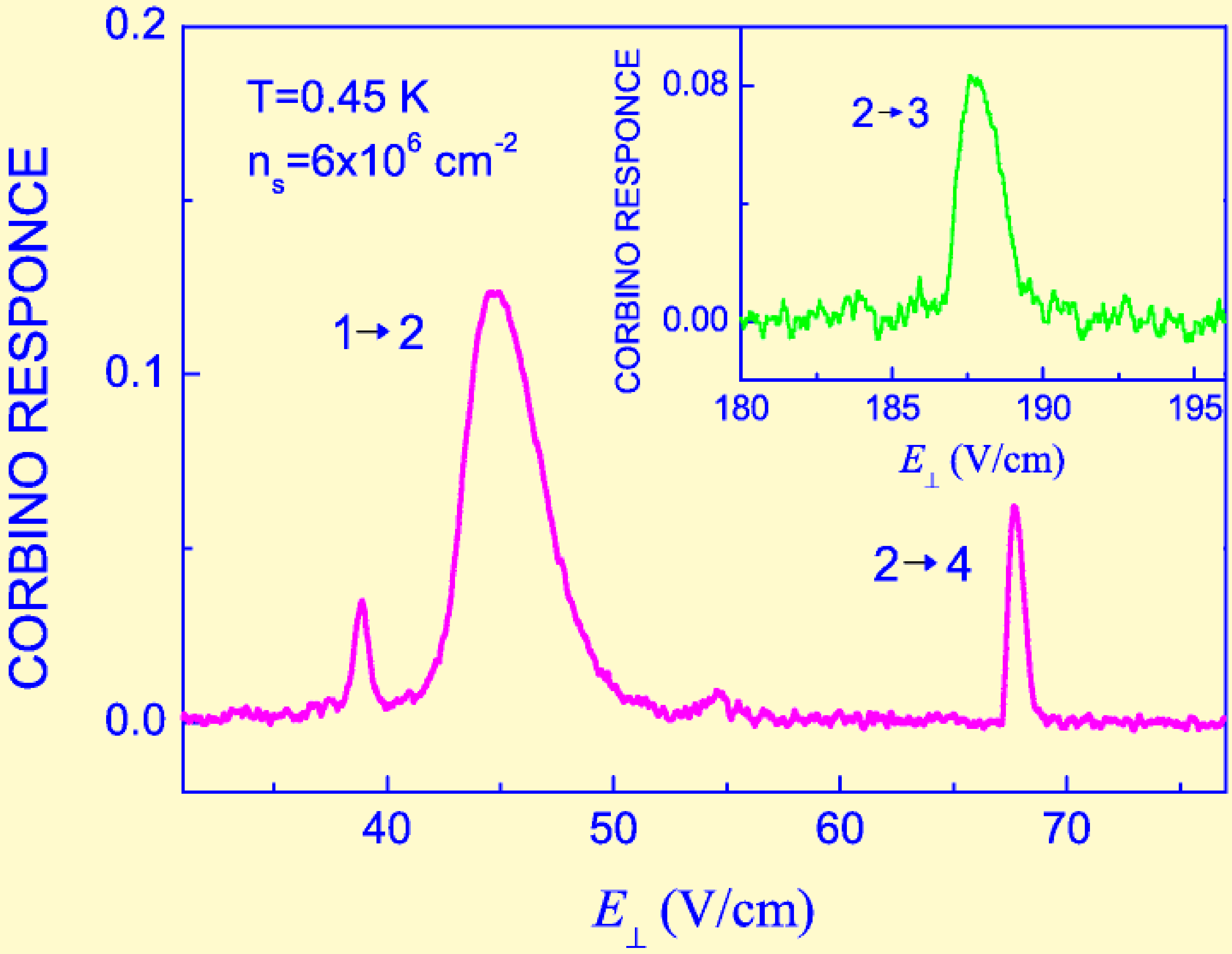


Instability

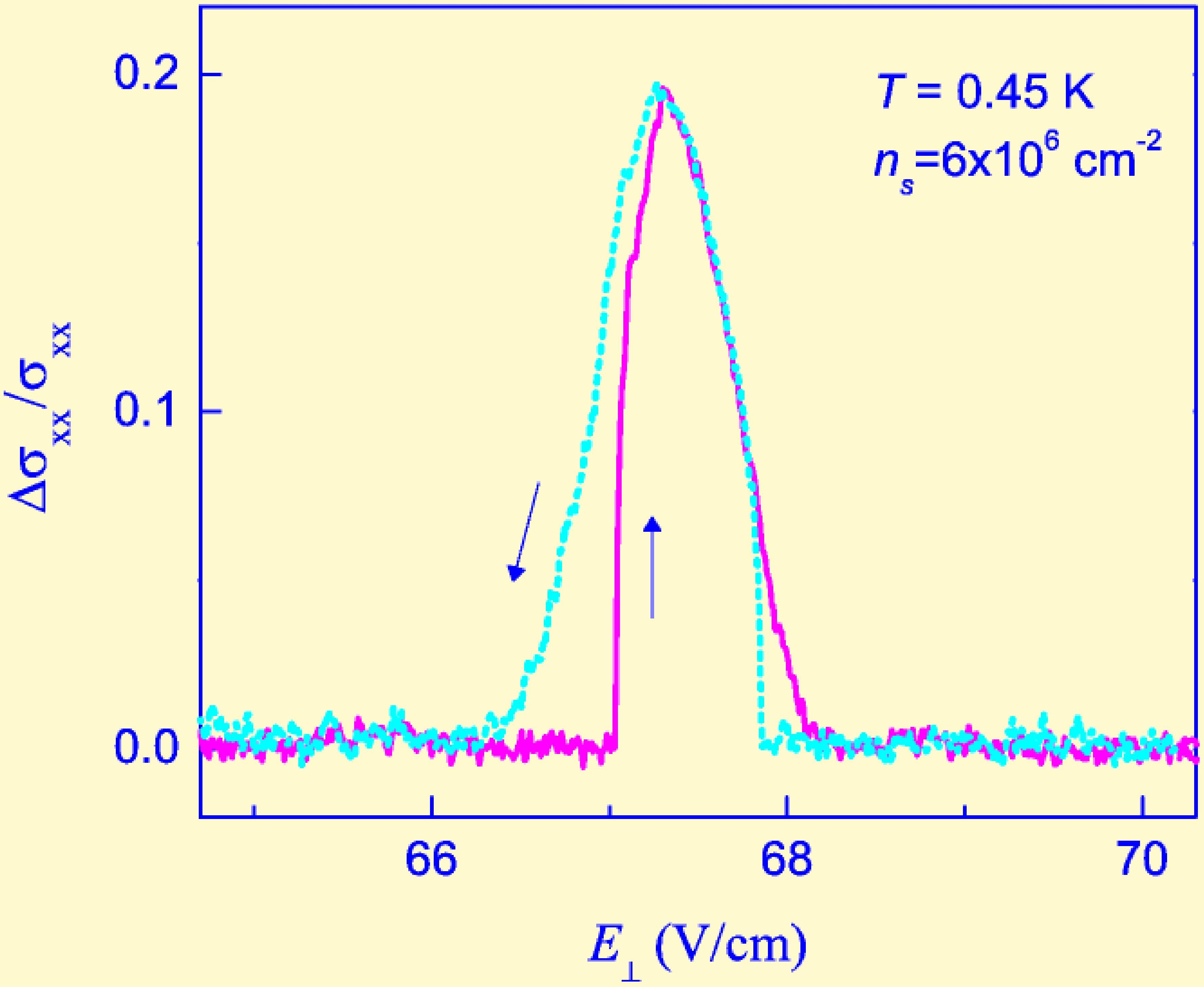
T=200 mK

n_e=4.2×10^7 cm^{-2}

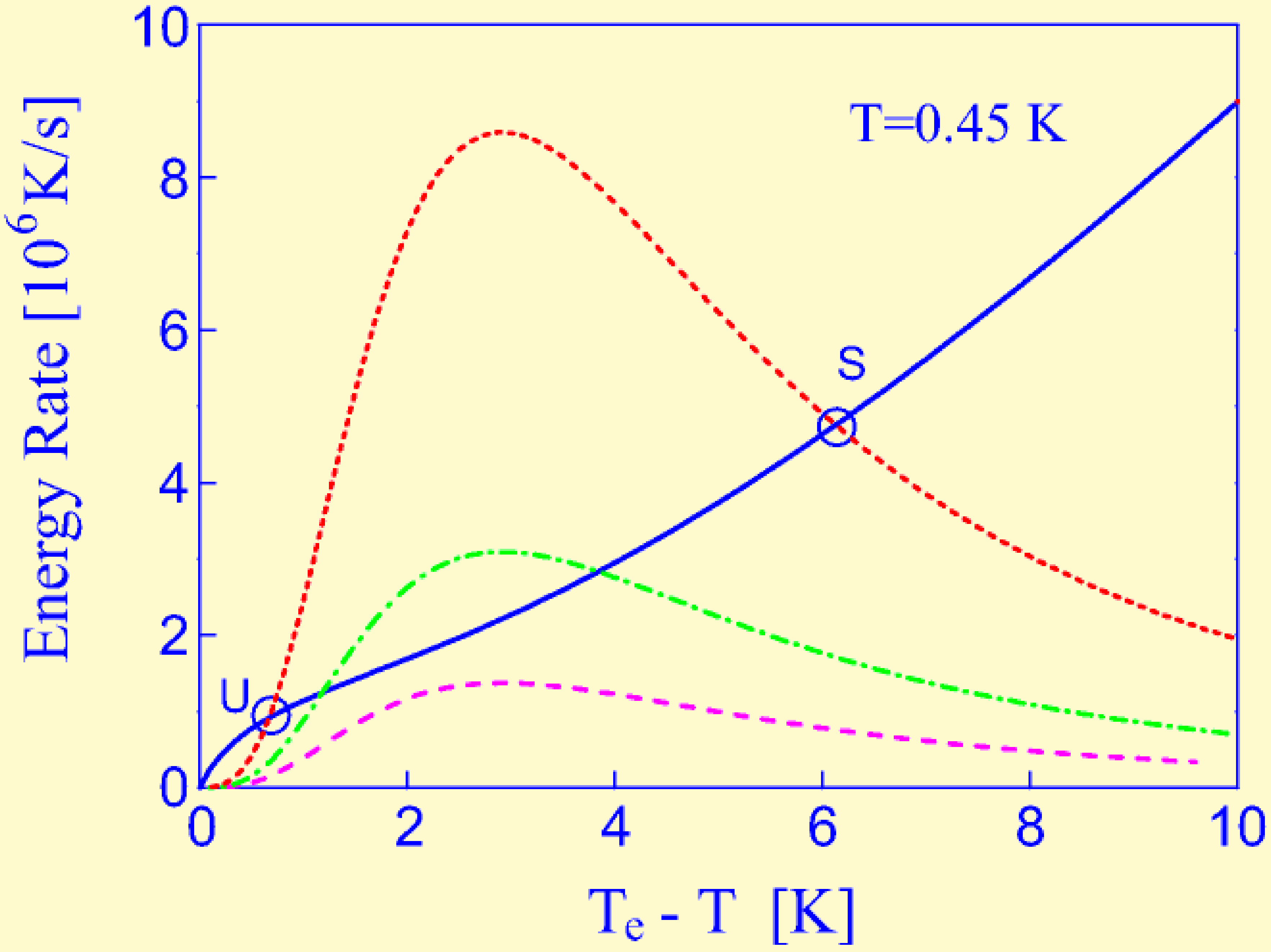
Self-sustained absorption



Hysteresis


T = 0.45 K
$n_s = 6\text{x}10^6$ cm^{-2}
$\Delta\sigma_{xx}/\sigma_{xx}$
0.0
0.1
0.2
66
68
70
$E_\perp$ (V/cm)

Model



Conclusion

- Microwave-induced hot-electron effect is important
- Coulomb interaction causes a frequency shift
- Resonance line-shape shows hysteresis at high MW power
- The hysteresis is attributed to temperature bistability
- Self-sustained MW absorption is found
- This series of workshops is really productive