Mechanism of giant microwave response of two-dimensional electron system near the second harmonic of the cyclotron resonance

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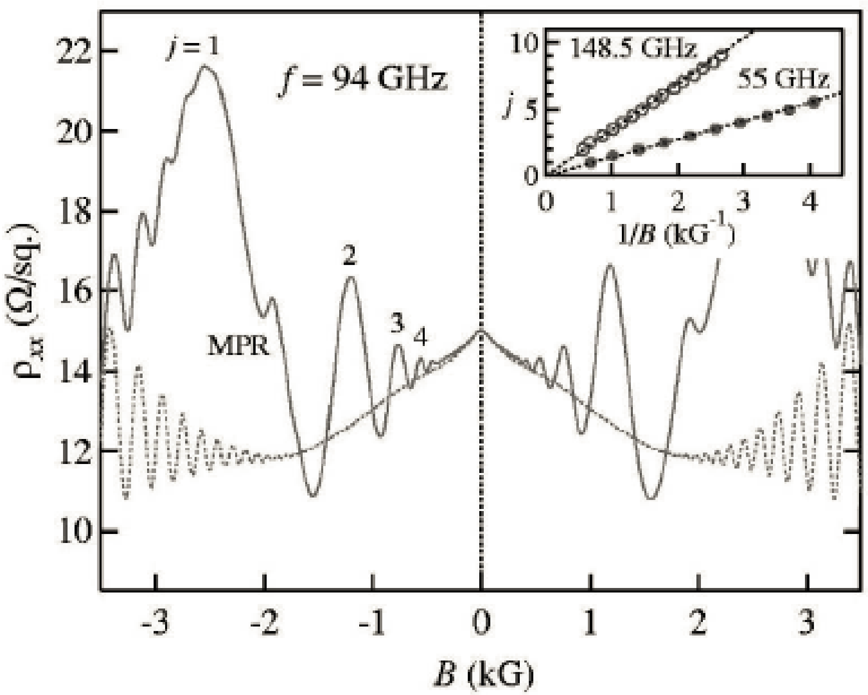
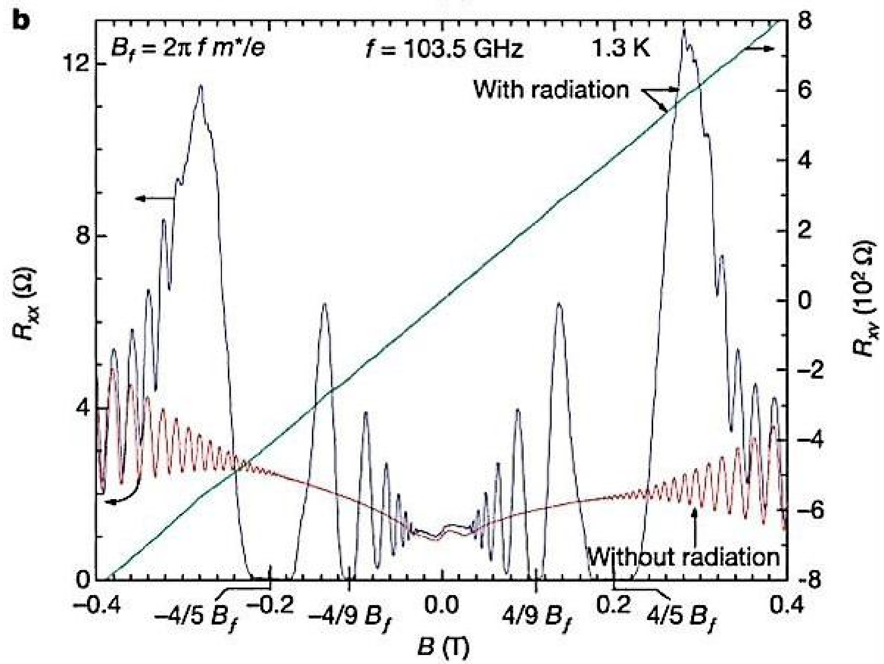
Microwave-induced magneto-oscillations and zero-resistance states in R_{xx}

"Low" mobility $\mu \approx 3x10^6$ cm^2/Vs



M. Zudov et al. PRB **64**, 201311 (2001)

High mobility AlGaAs/GaAs , μ~10^7 cm^2/Vs

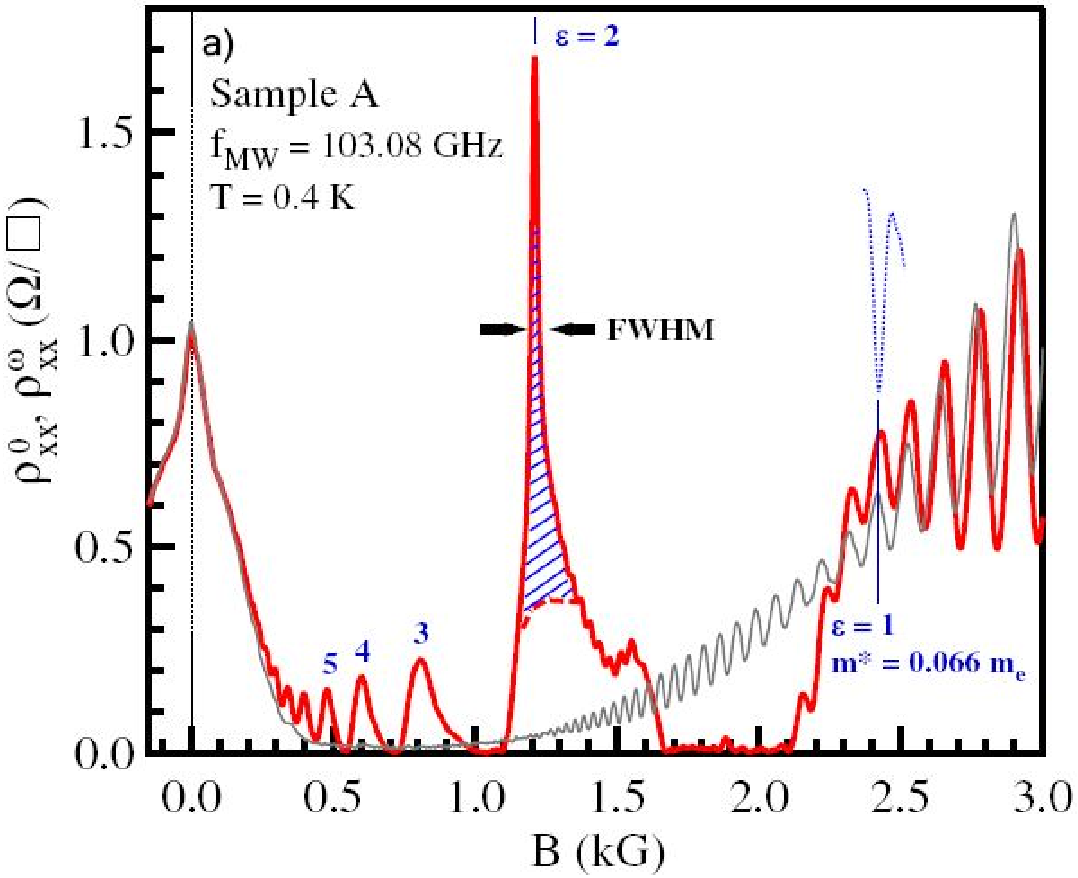


R. Mani et al., Nature **420**, 646 (2002)

The MIROs phase shift: $\omega/\omega_c = j \pm 1/4$

Motivation: giant microwave-induced photoresponse

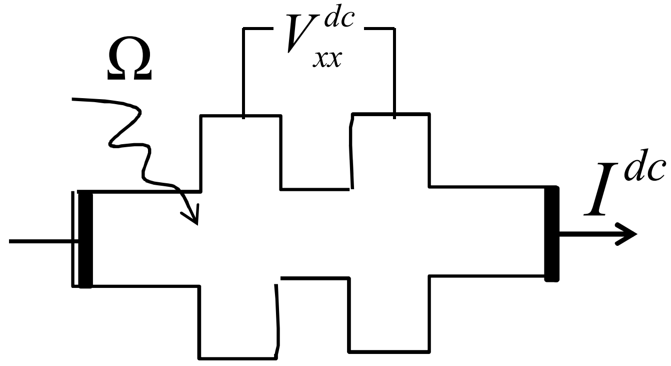
$$\mu \approx 3 \cdot 10^7\, cm^2/(V \cdot s)$$



$$\varepsilon = \frac{\Omega}{\omega_C}$$

The puzzle: narrow photoresistivity peak in the vicinity $\Omega = 2\omega_C$

$$\lambda_{MW} \gg L_x, L_y$$

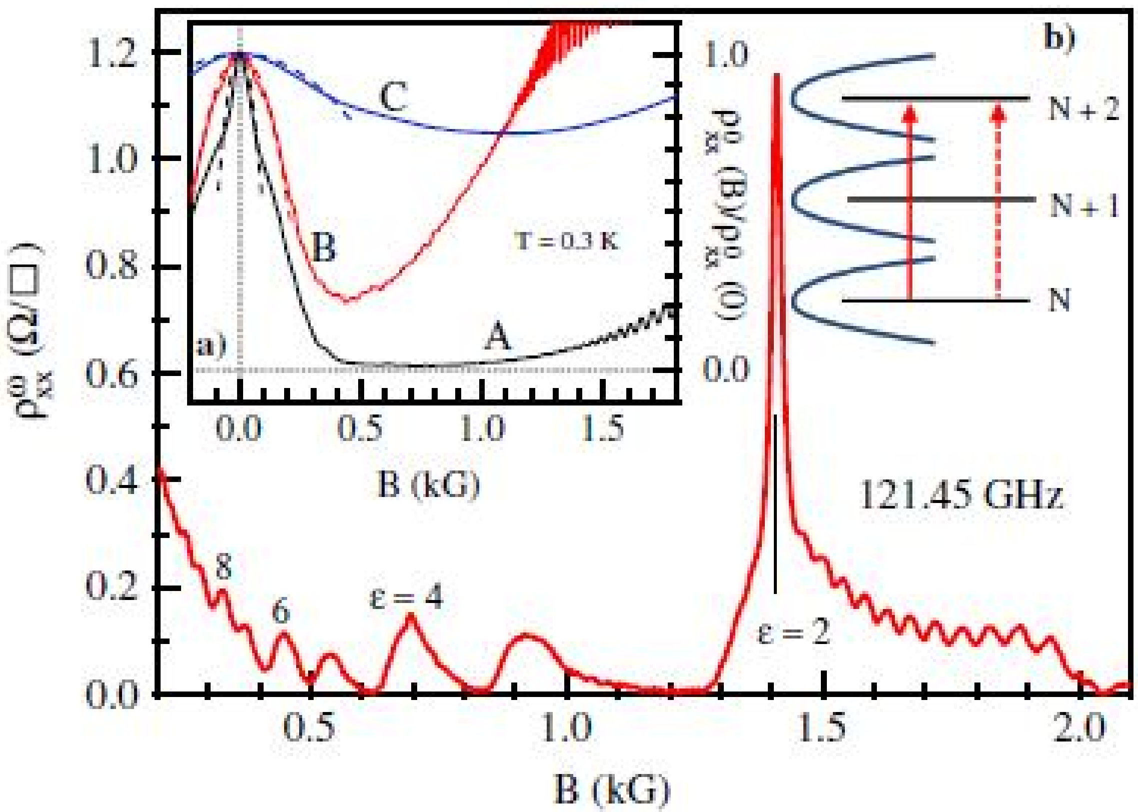


$$\rho_{xx} = \frac{V^{dc}_{xx}}{I^{dc}}$$

Ya. Dai, R.R. Du, L.N. Pfeiffer, K.W. West, PRL **105**, 246802 (2010); A.T. Hatke, M.A. Zudov, L.N. Pfeiffer, K.W. West, PRB **83**, 121301(R) (2011)

Dominating feature of samples w/o MW-irradiation:

a temperature-sensitive giant negative magnetoresistance (GNMR)



ABSTRACT

- Recent experiments [Du at al., Zudov et al.] on microwave-irradiated ultra-clean 2DES revealed a **colossal, narrow photoresistivity peak** in the vicinity of the second cyclotron resonance harmonic $\Omega \approx 2\omega_c$.
- Here we propose an explanation of this puzzle phenomenon in terms of

  a) ***the parametric cyclotron resonance*** in 2DES with the fundamental mode at $\Omega \approxeq 2\omega_c$

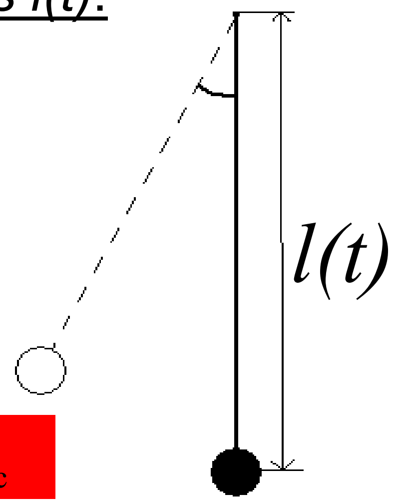
  +

  b) ***an anti-screening effect***: a strong enhancement of effective (acting on electrons) MW field by excitation of virtual "Bernstein" magnetoplasma modes at $\Omega \approx 2\omega_c$

An idea

Parametric resonance of a pendulum whose length *l* varies as *l(t)*:

$$l(t) = l_0 + h\cos\Omega t \qquad \omega_0 = \sqrt{\frac{g}{l_0}}$$



$\Omega = 2\omega_0$ - the fundamental parametric resonance!

If propose:

$\omega_0 \Rightarrow \omega_C$ ➡ Resonance in 2DEG is expected at $\Omega = 2\omega_c$

But : there are not any $2\omega_c$-resonance at homogeneous MW field !
So: inhomogeneous MW field ➡ excitation of 2D magnetoplasmons (real or virtual)

Scenario: Parametric resonance under inhomogeneous MW field ➡ Hydrodynamical instability ➡ 2DEG heating ➡ Sharp peak of resistance

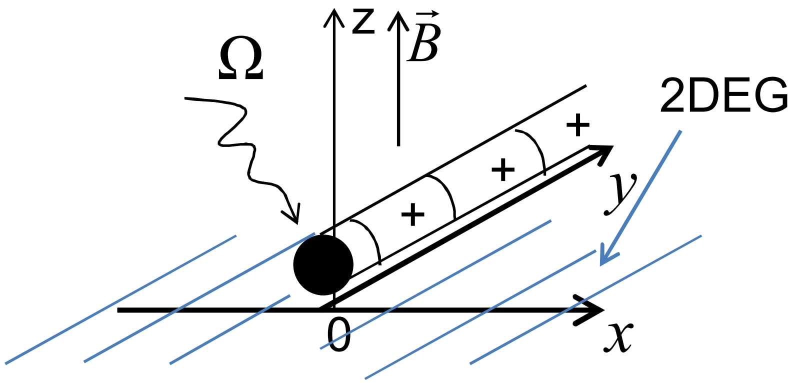
The aim: to study the effect of inhomogeneous MW field on 2DES stability

Simple model of inhomogeneous field: near-contact MW electric field

$$E_{ext}(x,t) = E_{ext}(x,\Omega)\cos\Omega t$$

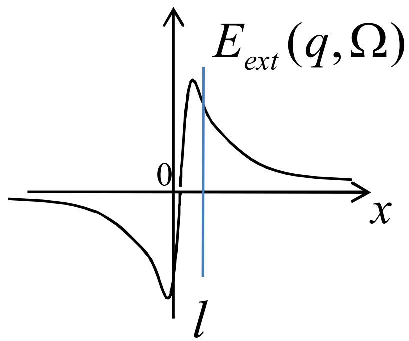
S.A. Mikhailov, PRB 83, 155303 (2011)

$E_{ext}(x,\Omega)$ - amplitude of non-screened near-contact MW field



$$E_{ext}(x,\Omega) = \frac{\varphi_0}{\sqrt{x^2+l^2}}$$

$$E_{ext}(q,\Omega) = 2\varphi_0 K_0(ql) \sim \ln(1/ql)$$



Linear screening of the ext. field $E_{ext}(q,\Omega)$

The resulting field is enhanced if $\varepsilon(q,\Omega) \approx 0$:

⇒

$$E_{\Omega}^{tot}(q) = \frac{E_{\Omega}^{ext}(q)}{\varepsilon(q,\Omega)}$$

Hydrodynamic approach: key points

The Euler Eq. for hydrodynamic velocity control the 2D electron liquid dynamics:

$$\frac{\partial \vec{V}}{\partial t} + \frac{\vec{V}}{\tau} + (\vec{V}\vec{\nabla})\vec{V} = \frac{e}{m} E_{tot}(x,t) + \vec{V} \times \vec{\omega}_C$$

1. Nonlinear term $(\vec{V}\vec{\nabla})\vec{V}$: local and instantaneous Doppler shift

$$\frac{\partial}{\partial t} + (\vec{V}_0 \vec{\nabla}) \rightarrow -i(\omega - \vec{q}\vec{V}_0)$$

2. An inhomogeneous external MW field: $E_{ext}(x,t) = E_{\Omega}^{ext}(x)\cos\Omega t$

3. Anti-screening of external field $E_{\Omega}^{ext}(x)$ *by magnetoplasmons*: $E_{\Omega}^{tot}(q) = \dfrac{E_{\Omega}^{ext}(q)}{\varepsilon(q,\Omega)}$

4. Non-locality $qR_c \sim 1$ *results in the appearance Bernstein magnetoplasma modes with gaps near* $N\omega_c$, $N=2,3,\ldots$

MW-induced forced oscillations
and
parametric Eqs for deviations

<u>The forced oscillations</u> under MW pumping:

$$V_{0x}(x,t) = V_{sx}(x)\sin\Omega t \qquad V_{sx}(x) = \frac{e}{m}\frac{\Omega}{\Omega^2 - \omega_C^2}E_{tot}(x,\Omega)$$

$$V_{0y}(x,t) = V_{cy}(x)\cos\Omega t \qquad V_{cy}(x) = \frac{e}{m}\frac{\omega_C}{\Omega^2 - \omega_C^2}E_{tot}(x,\Omega)$$

<u>Parametric Eqs. for small deviations</u> from forced oscillations.

After substitution $\vec{V}(x,t) = \vec{V}_0(x,t) + \delta\vec{V}(x,t)$

Eqs. for δV(x,t) can be obtained. These Eqs. contain **time-periodically coefficients.**

Consider the fundamental mode of parametric resonance at $\Omega \approx 2\omega_c$

$$\delta V_x(x,t) = e^{s_0 t}\left(A(x)\cos\frac{\Omega}{2}t + B(x)\sin\frac{\Omega}{2}t \right)$$

$$\tilde{A} = V_{sx}(x)A$$
$$\tilde{B} = V_{sx}(x)B$$

Effective Schrödinger Eq. for fundamental mode of PR:

$$(-\partial_x^2 + U(x))\tilde{A}(x) = 0$$

Effective potential energy:

$$U(x) = -\frac{\Omega^2}{s^2}\cdot\frac{(3V'_{sx}/8)^2 - \delta\omega^2}{V_{sx}^2}$$

$$\delta\omega = \frac{\Omega}{2} - \omega_C$$

$$V_{sx} \sim E_{tot}$$

Effective potential energy is proportional to the screened MW field:

$$E_{tot}(x,t) = \cos\Omega t \int_{-\infty}^{+\infty} \frac{dq}{2\pi} e^{iqx} \frac{E_\Omega(q)}{\varepsilon(q,\Omega)}$$

Non-local screening function at $qR_C \neq 0$ **:**

$$\varepsilon(q,\omega) = 1 + \frac{2m}{\pi\hbar^2} V_{ee}(q) \sum_{n=1}^{\infty} \frac{N^2\omega_C^2 J_n^2(qR_C)}{N^2\omega_C^2 - \omega^2 - i0\,\mathrm{sgn}\,\omega}$$

$$V_{ee}(q) = \frac{2\pi e^2}{\kappa|q|}$$

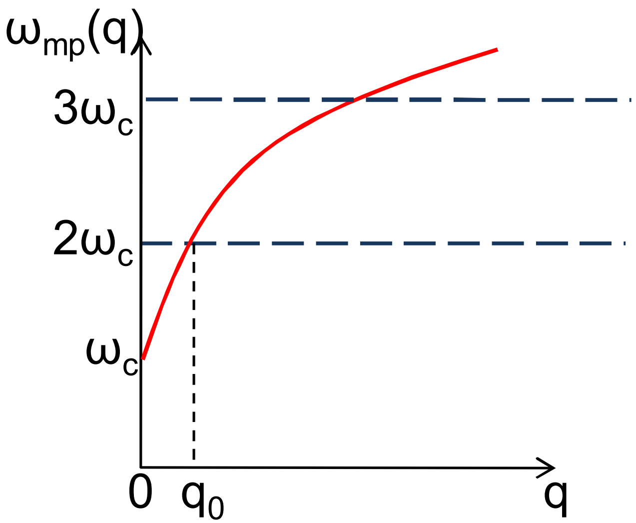
Let us find the U(x) and a solution of the "Schrödinger Eq."

2D magnetoplasmons: nonlocal effects

Classical 2D plasmons

F. Stern, 1967

$$\omega_P(q) = \sqrt{\frac{2\pi n_S e^2}{\kappa m} q}$$



Classical magnetoplasmons

$$\omega_C = \frac{eB_z}{cm}$$

1) Local limit: $qR_C \to 0$

$$\omega_{mp}^2(q) = \omega_C^2 + \omega_p^2(q)$$

2) Nonlocal effects: $qR_C \sim 1$

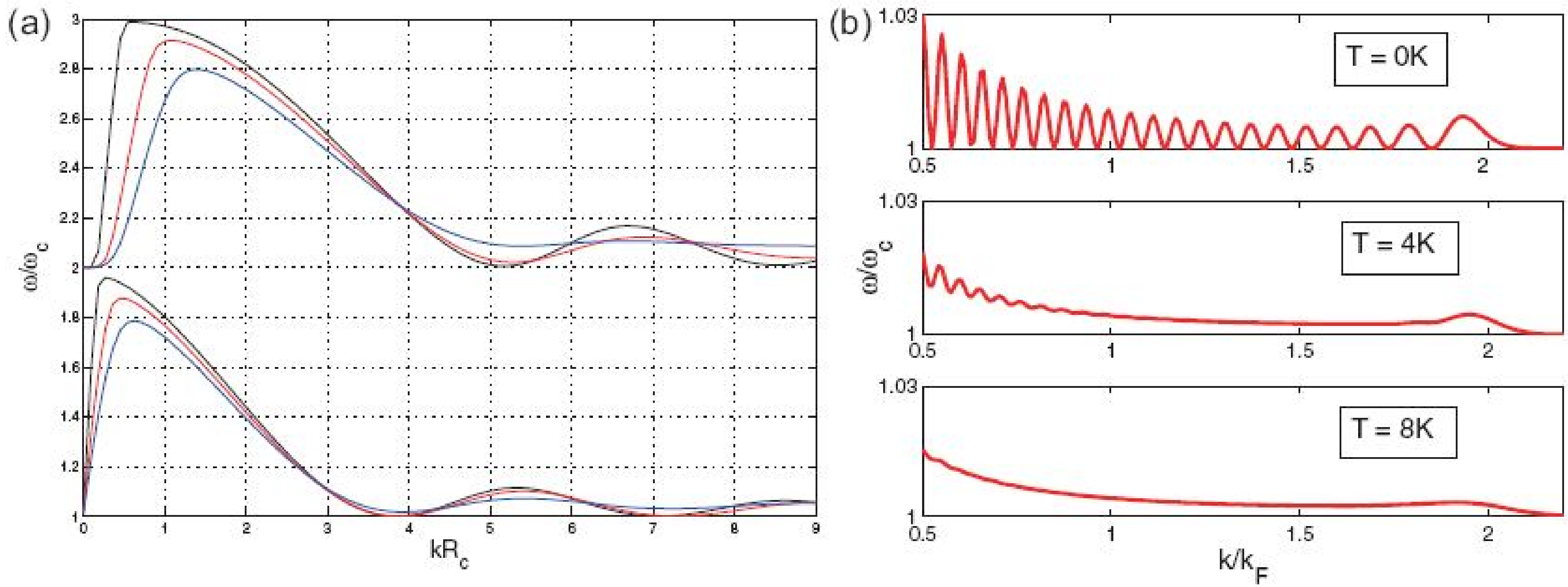
-> anticrossing at $\omega_{mp}(q) = N\omega_C$

The anticrossing results in the appearance of a number of branches (the “Bernstein modes”). **Important in 2DES !**

2D Bernshtein modes: RPA theory

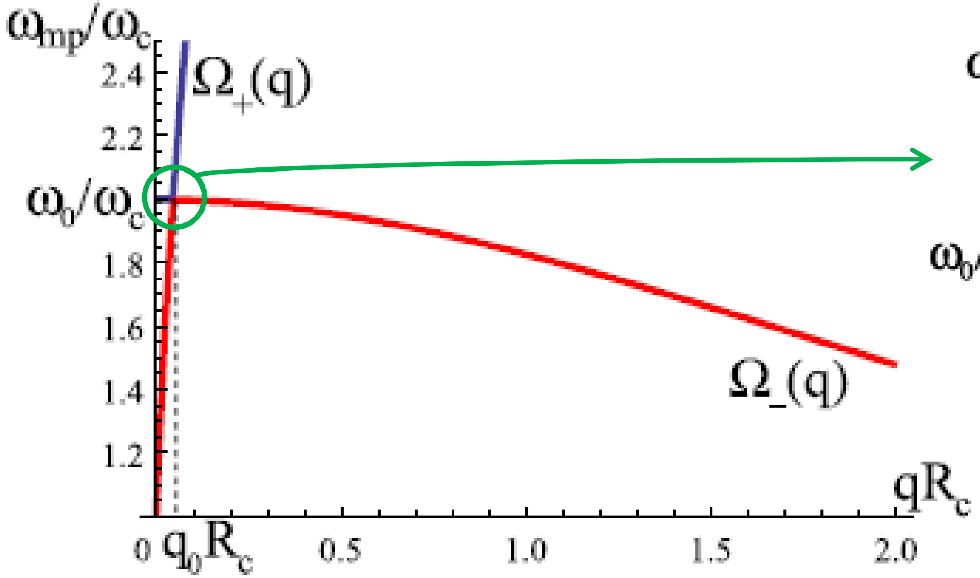
Classical local magnetoplasmons (kR=0): $\omega_{mp}(q,B) = \sqrt{\omega_p^2(q) + \omega_C^2}$

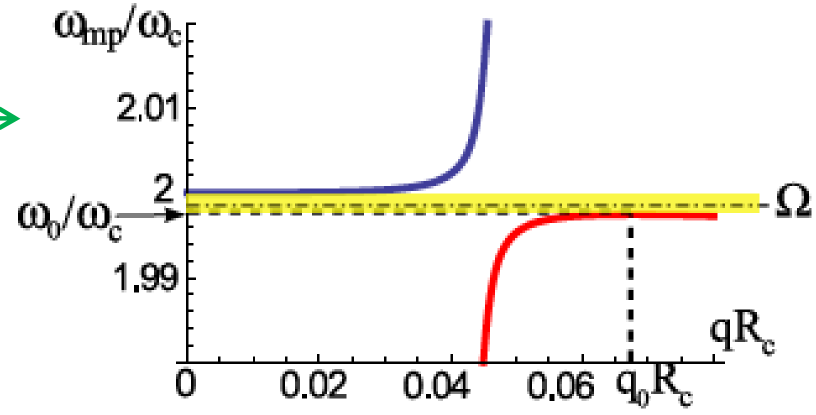
Nonlocal magnetoplasmons (nonzero kR):



$$\varepsilon(q,\omega) = 1 + \frac{V_{ee}(q)}{\pi\hbar\lambda^2} \sum_{N,N'} \frac{(f_N - f_{N'}) I_{N,N'}(q)}{\omega_C(N'-N) + \omega + i0}$$

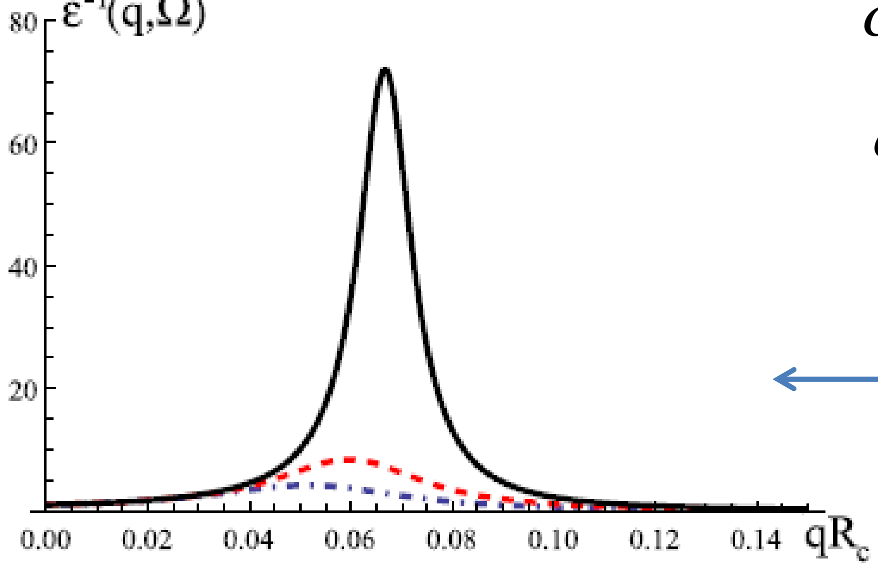
$$\lambda^2 = \frac{hc}{eB}$$





$$\delta\omega_{gap} = 2\omega_C - \omega_0 \approx 11.4\omega_C (a_B / R_C)^2$$

$$q_0 R_C = 4.5 a_B / R_C$$



The pumping frequency Ω lies in the Bernstein gap: $2\omega_c > \Omega > \omega_0$. Different lines correspond to the different values of the detuning $\delta\omega=\Omega/2-\omega_c$: $\delta\omega/\omega_c = -1.25 \cdot 10^{-3}$ (solid line), $\delta\omega/\omega_c = -10^{-3}$ (dashed line), $\delta\omega/\omega_c = -0.75 \cdot 10^{-3}$ (dash-dotted line). Parameters of 2DES: $\kappa=7$, $m=0.067m_0$, $n_s=3 \cdot 10^{11}$ cm^{-2}, $\omega_c/2\pi=10^{11}$Hz.

Maximal enhancement [$\varepsilon^{-1}(q, \Omega)$ ->inf.] **at the bottom of the gap:**

$$\Omega_{res} \approx 2\omega_C (1 - 5.7 (a_B / R_C)^2)$$

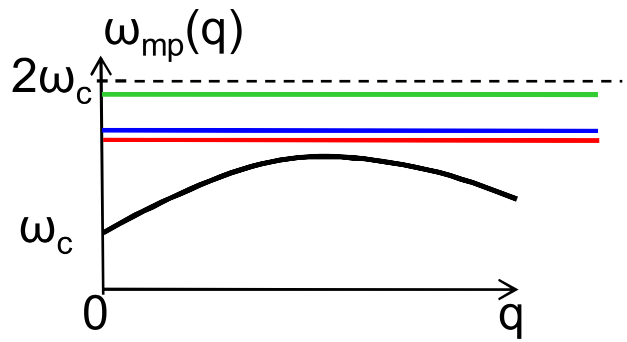
Threshold

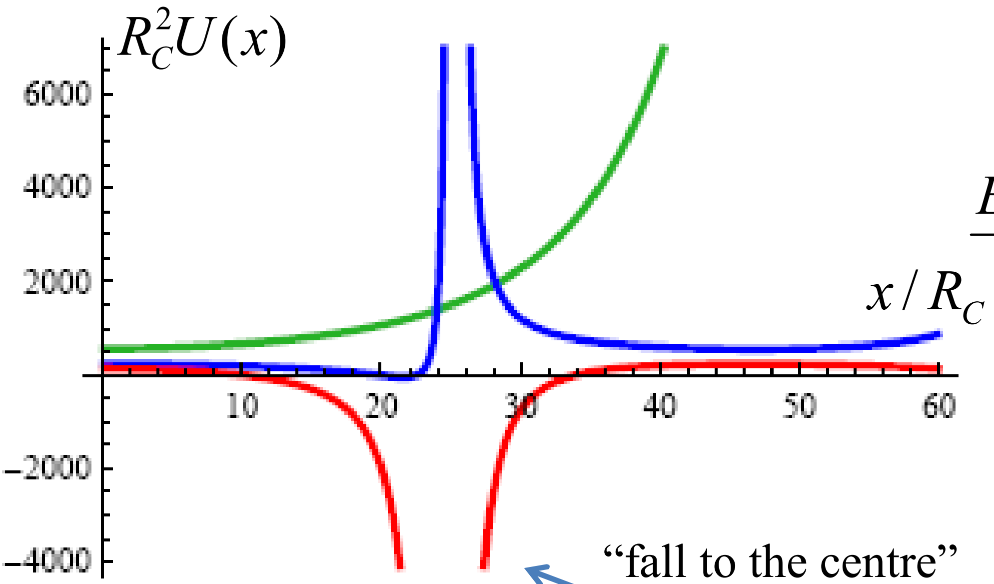
$$1/\tau^* \ll \delta\omega_{\max}$$

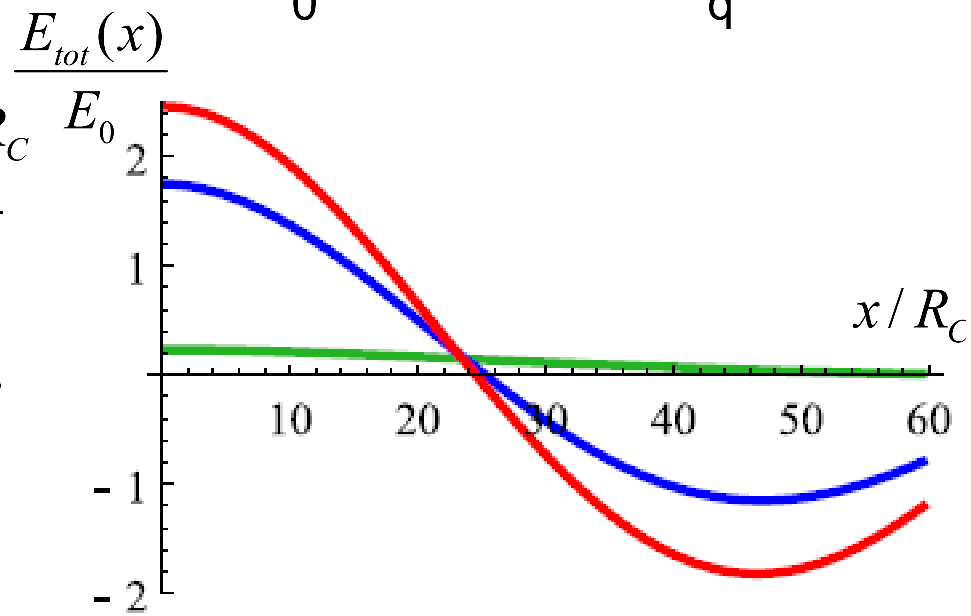
$$\delta V(x,t) = e^{s_0 t}\left(A(x)\cos\frac{\Omega}{2}t + B(x)\sin\frac{\Omega}{2}t \right)$$

Effective Schrödinger Eq.

$$(-\partial_x^2 + U(x))\tilde{A}(x) = 0\cdot\tilde{A}(x)$$







"fall to the centre"

$$U(x) \sim \frac{(3V'_{sx}/8)^2 - \delta\omega^2}{V_{sx}^2} \to -\frac{1}{(x-x_0)^2}$$

Instability develops at distance from contacts: $x_0 \sim 25R_c \approx 10\mu m$

Features of the mechanism (in agreement with experiment)

1. 2D parametric instability arises only in the samples of high quality.
   Condition: Bernstein gap > relaxation rate.
2. Threshold pumping is extra-low .
3. **There is threshold in quality of samples instead of the threshold in pumping .**

CONCLUSIONS

- We propose an explanation of colossal photoresistivity peak in the vicinity of $2\omega_c$ in terms of parametric instability of 2DES.
- We report the hydrodynamic theory of ***2D parametric cyclotron resonance*** in 2DES under an inhomogeneous electric field of the MW radiation with frequency **Ω**.
- The parametric instability arises when **Ω** is in the Bernstein gap of 2D MP spectrum. As result, the electrical field of the MW pumping enhances strongly by the virtual excitation of the Bernstein modes.
- The instability development leads to the heating of 2DES, which in turn leads to the sharp peak of photoresistivity, if the sample has the strong negative magnetoresistance.

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