Interaction effects in the electrons on helium : from microscopic to macroscopic scales

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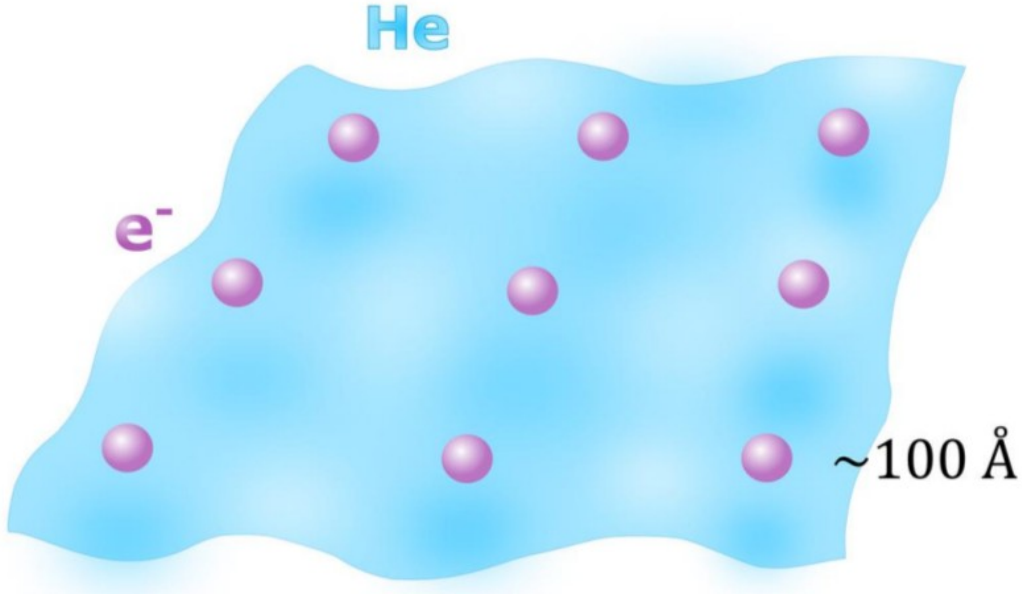
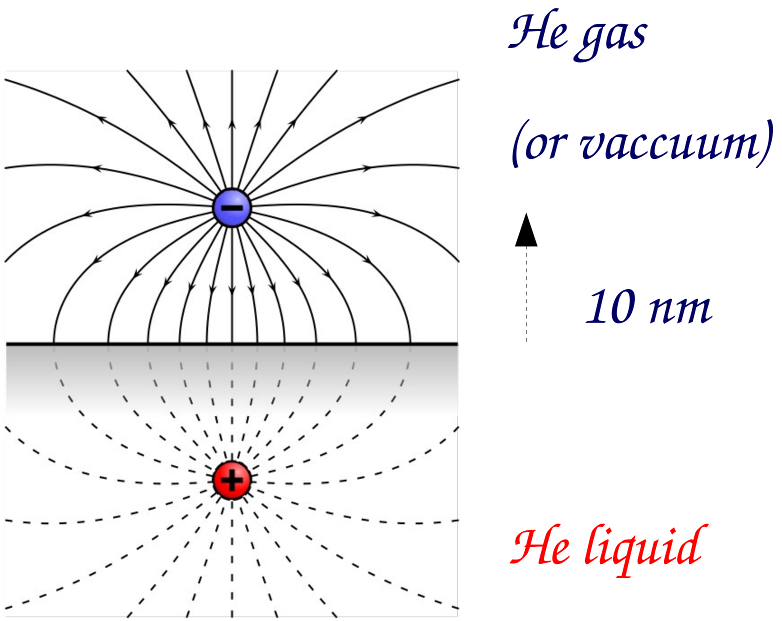
arXiv:1910.08026

Electrons on Helium :





- Two dimensional electron gas
- Very high mobilities $\mu > 10^7$ $cm^2/(V \cdot s)$
- Low densities $n_e \approx 10^6$ cm^{-2} to $n_e \approx 10^9$ cm^{-2}

  Fermi energy is usually much smaller than temperature
- Almost no screening : long range Coulomb interactions

Towards single electron physics

- Previous research focussed on high density electron gases :

  Wigner crystal formation : k_BT << Coulomb energy

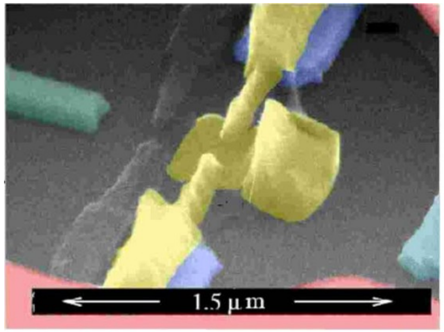
  Quantum melting : k_BT << Fermi Energy < Coulomb Energy

  P. Leiderer et. al. Surface Science (1996)

- Recently renewed interest for the low density limit in the context of quantum computing

  PM Platzman, MI Dykman, Science (1999)

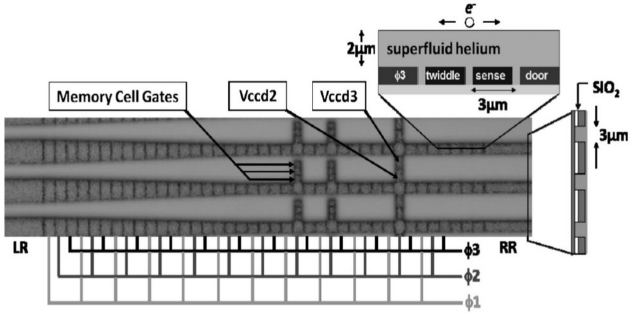
Electron counting with a SET



M. Lea, Y. Mukharsky et. al.

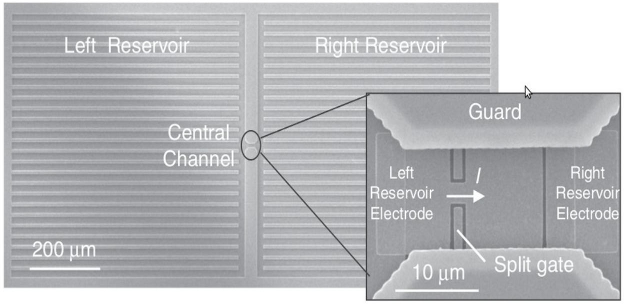
(APL 2005, PRB 2009)

Efficient clocked e^- transfer



S. A. Lyon et. al. (PRL 2011)

1D channels



D.G. Rees, K. Kono et. al

(PRL 2012)

Coulomb interactions for electrons on helium

- Short range view – Coulomb potential :

$$V(r) = \frac{1}{4\pi\epsilon_0} \sum_i \frac{-e}{|r - r_i|}$$

- Describes : Wigner crystallization, quantum effects, ...

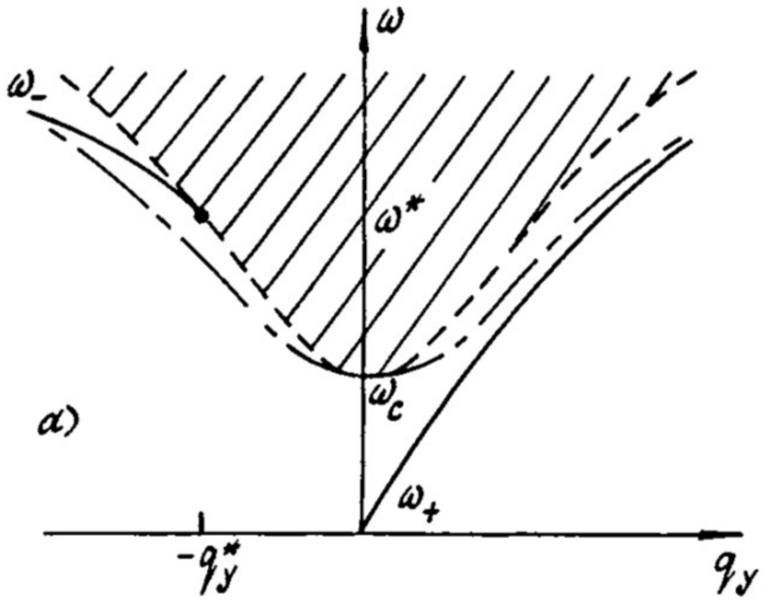
- Long range view – Laplace equation :

$$\Delta V(r) = \frac{e\, n_e}{\epsilon_0}$$

- Describes : density profile, plasmons, screening, ...

Magnetoplasmons in 2DEG

- Magnetoplasmon = resonant oscillations of the electronic density under magnetic field



Delocalized (bulk) magnetoplasmons have frequencies $\omega > \omega_c$

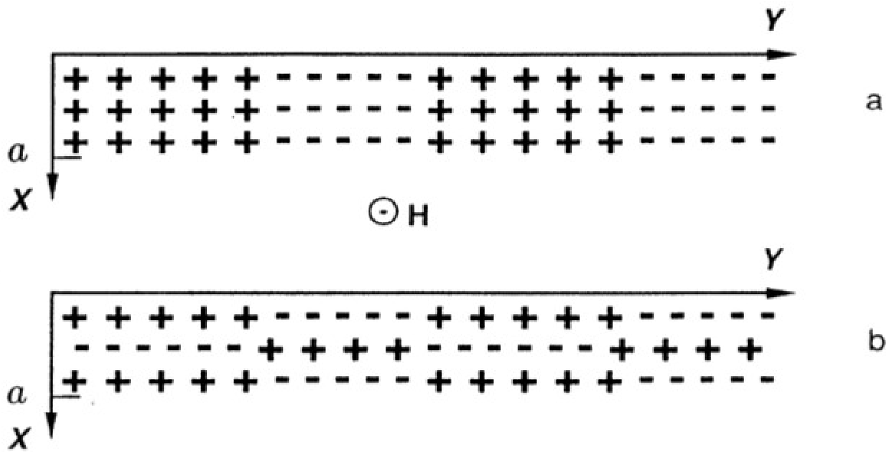
picture from Volkov, Mikhailov (1991)

- Low frequency magnetoplasmons are localized at the edge of the system (first experiments with electrons on helium !)

C.C. Grimes, G. Adams PRL (1976),

D. C. Glattli, E. Y. Andrei et.al. PRL (1985) and Mast, Dahm et. al. PRL (1985)

Acoustic magnetoplasmons



Edge magnetoplasmon

Acoustic magnetoplasmon

From I. L. Aleiner et. al. Phys. Rev. B 51, 13467 (1995).

VOLUME 75, NUMBER 20 PHYSICAL REVIEW LETTERS 13 NOVEMBER 1995

Novel Edge Magnetoplasmons in a Two-Dimensional Sheet of $^4He^+$ Ions

P. L. Elliott, C. I. Pakes, L. Skrbek,* and W. F. Vinen
School of Physics and Space Research, University of Birmingham, Birmingham B15 2TT, United Kingdom
(Received 10 July 1995)

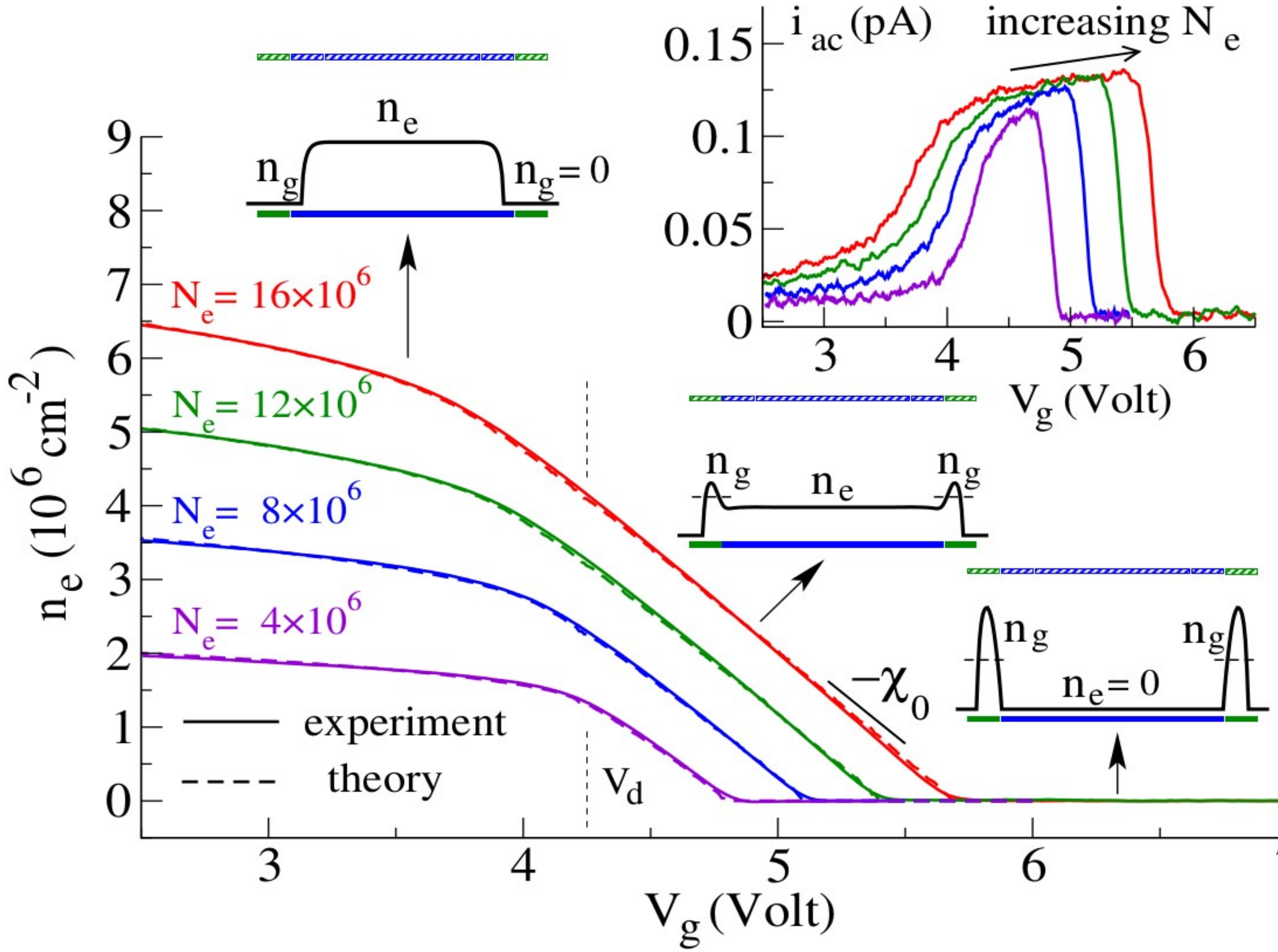
We report the experimental observation of novel low-frequency edge magnetoplasma waves in circular pools of positive ions trapped below the surface of superfluid ^{4}He. The modes were detected through a nonlinear coupling with an axisymmetric plasma mode of the pool, when both types of modes were driven simultaneously. The observed frequencies of the new modes and their dependence on magnetic field and pool radius allow us to identify them with those predicted to exist by Nazin and Shikin [Sov. Phys. JETP **67**, 288 (1988)] when account is taken of the correct density profile at the edge of the pool.

Magneto-plasmon summary

- high frequency delocalized magnetoplasmons $\omega > \omega_c$
- Low frequency magnetoplasmons $\omega \ll \omega_c$ confined near the edge of the system
- We show a magneto-plasmon with frequency $\omega \ll \omega_c$ that is not localized near the edge
- We describe it theoretically and study its interaction with edge magnetoplasmons

Experimental density profiles

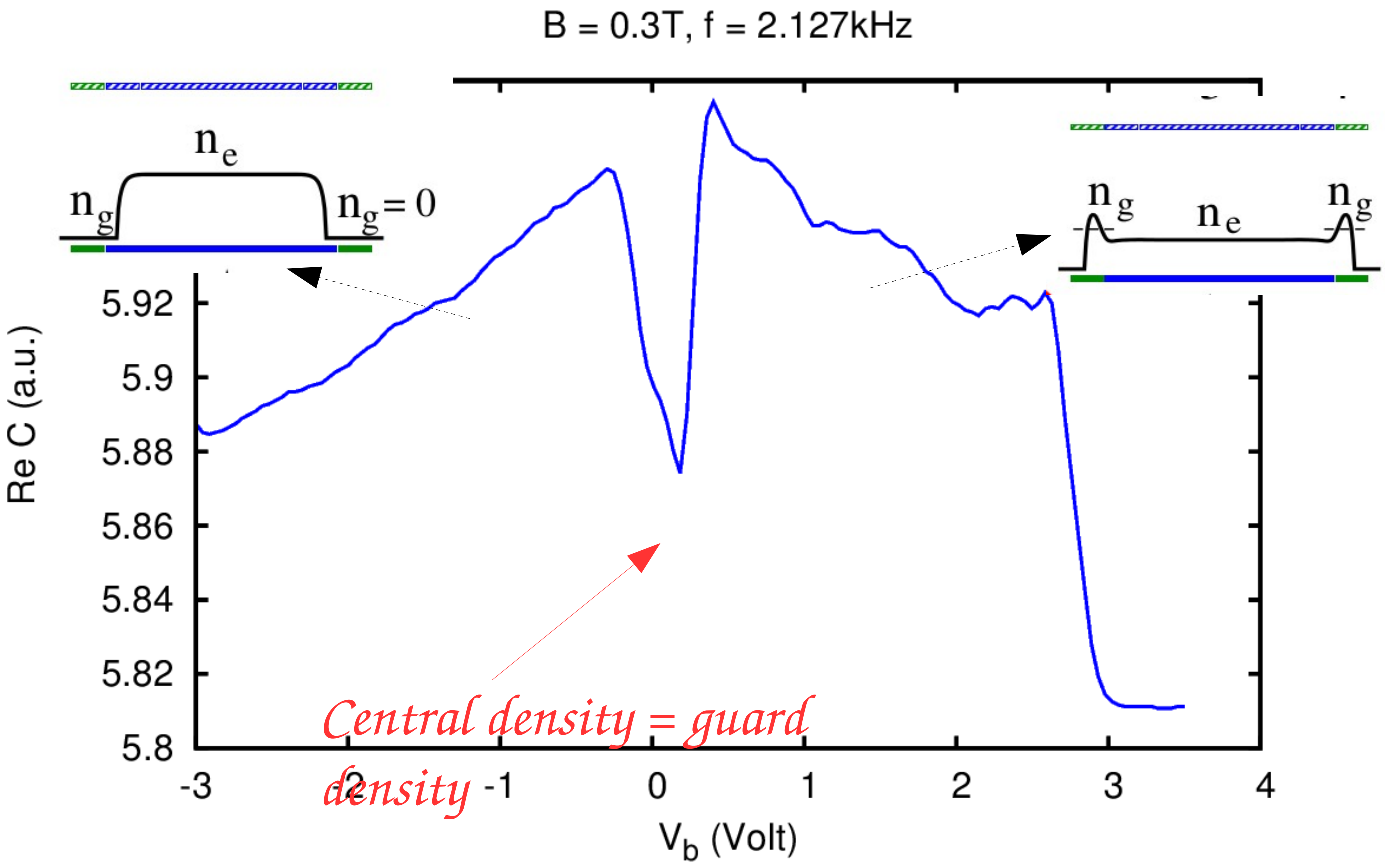
- *The comparison between experimental and theoretical profile works extremely well*



The electron cloud profile as function of gates is well understood

Resonance between center/guard densities

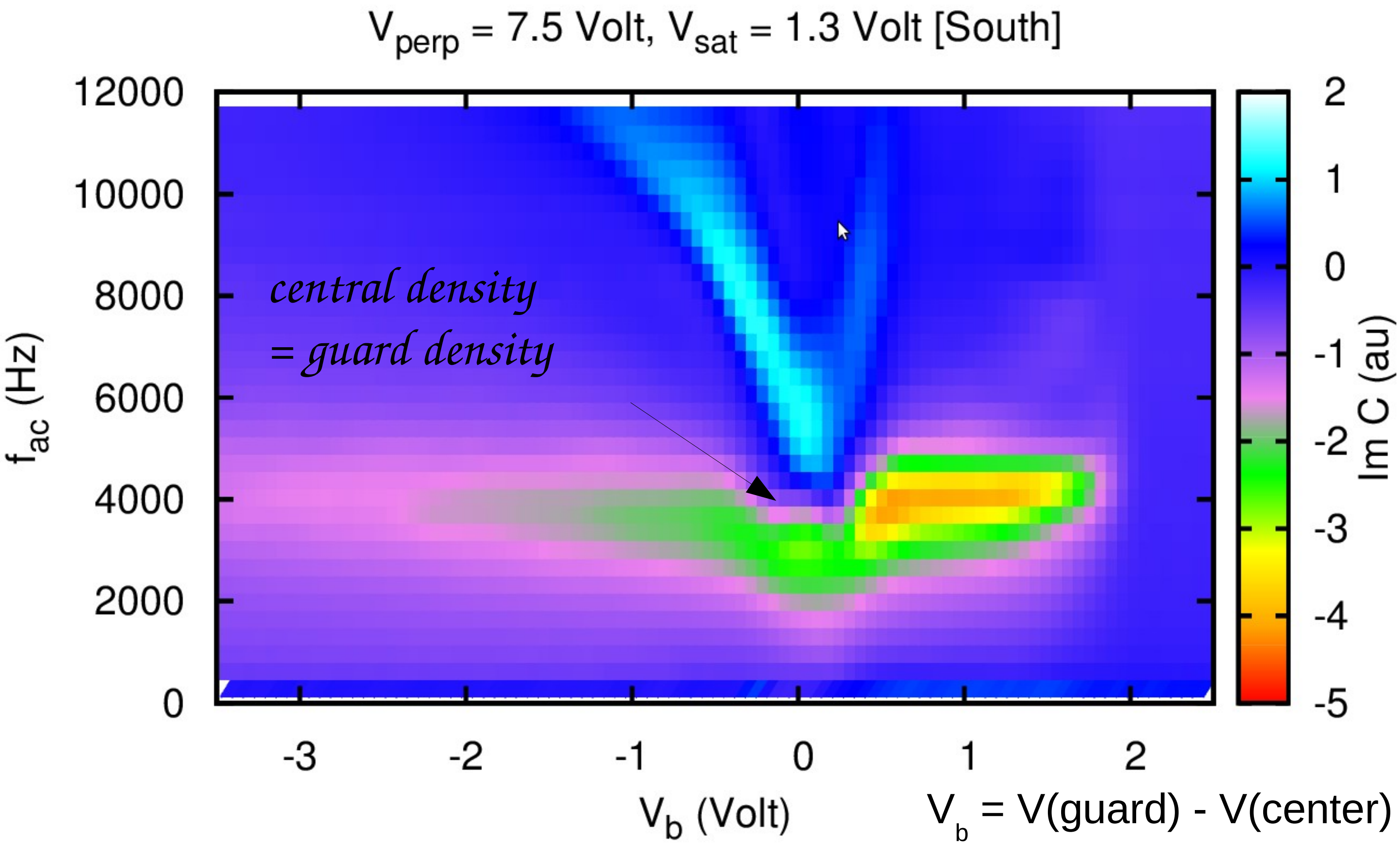
- *At magnetic field B > 100mT a resonance appears (puzzle from 2011)*



- *Central and guard reservoirs can see each other -*

  A low frequency bulk magnetoplasmon mode ?

The resonance between reservoirs is also a resonance in frequency

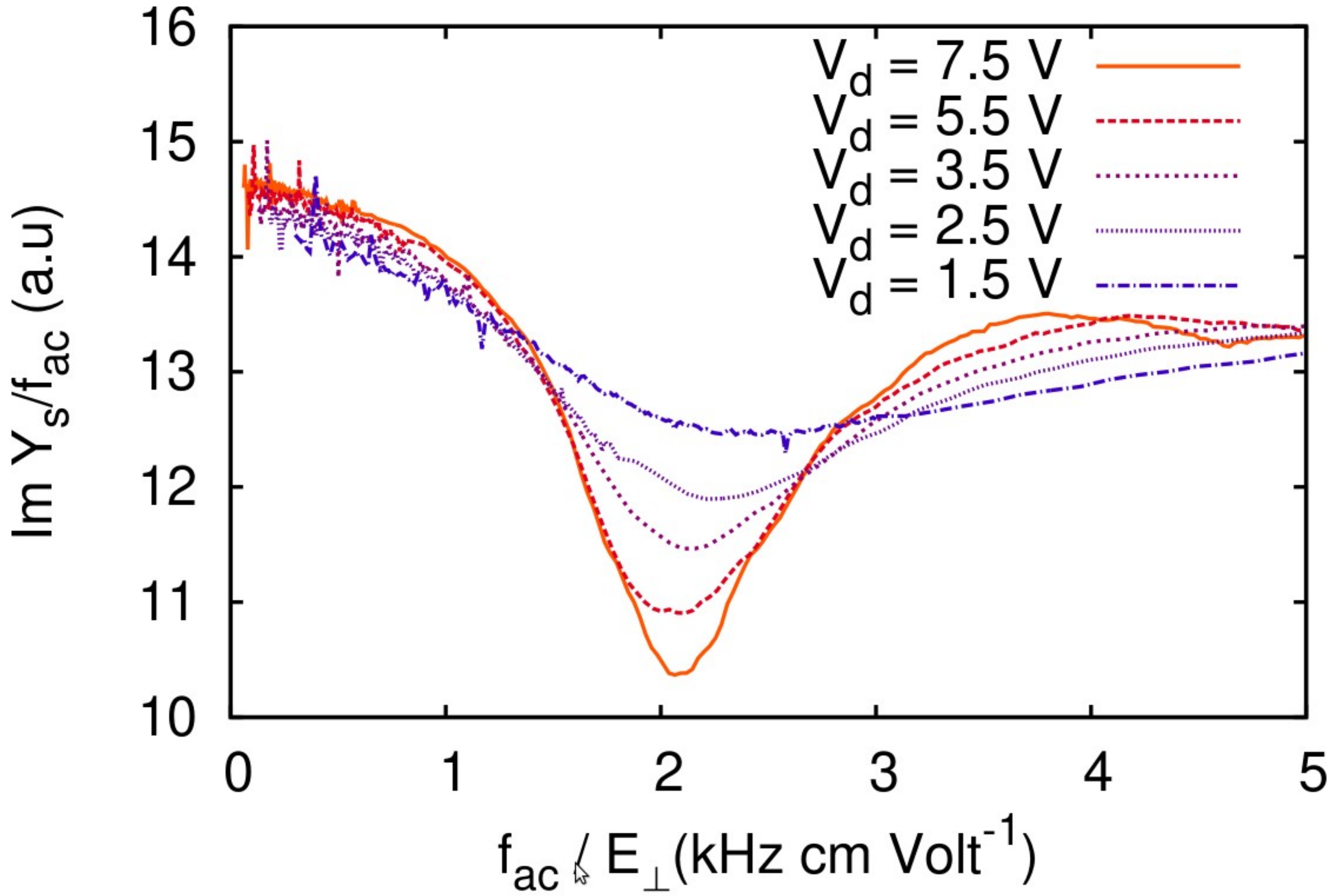


V_b = V(guard) - V(center)

- *A resonance that depends on the shape of the electron cloud*
- *But not at all on the local electronic density (!)*

Experimental characterization of the resonance

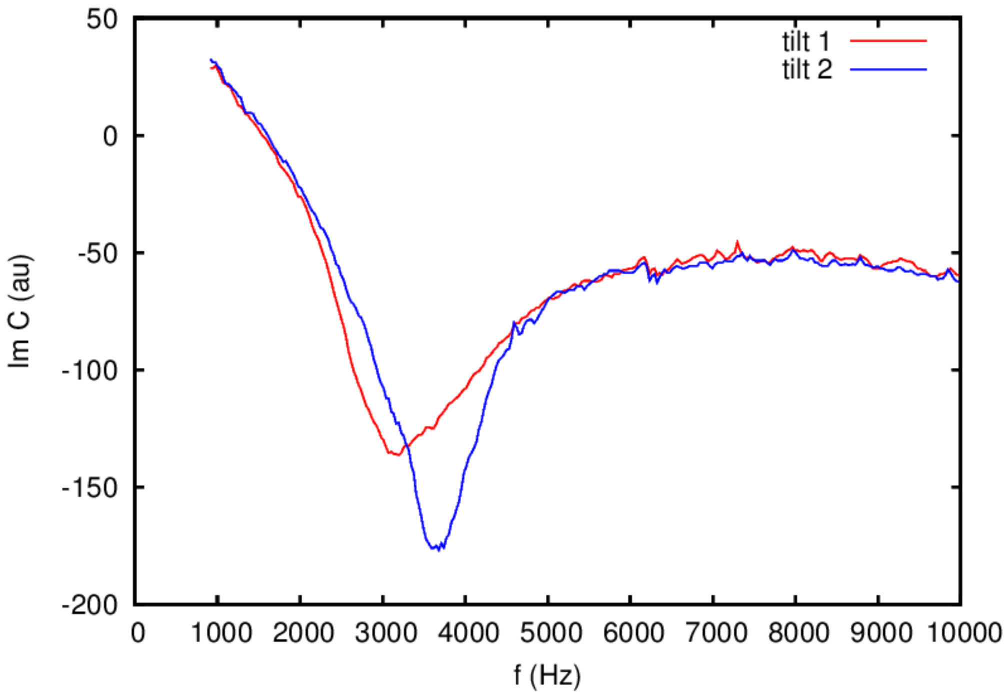
- *What are the remaining parameters : "hidden" parameter perpendicular electric field*

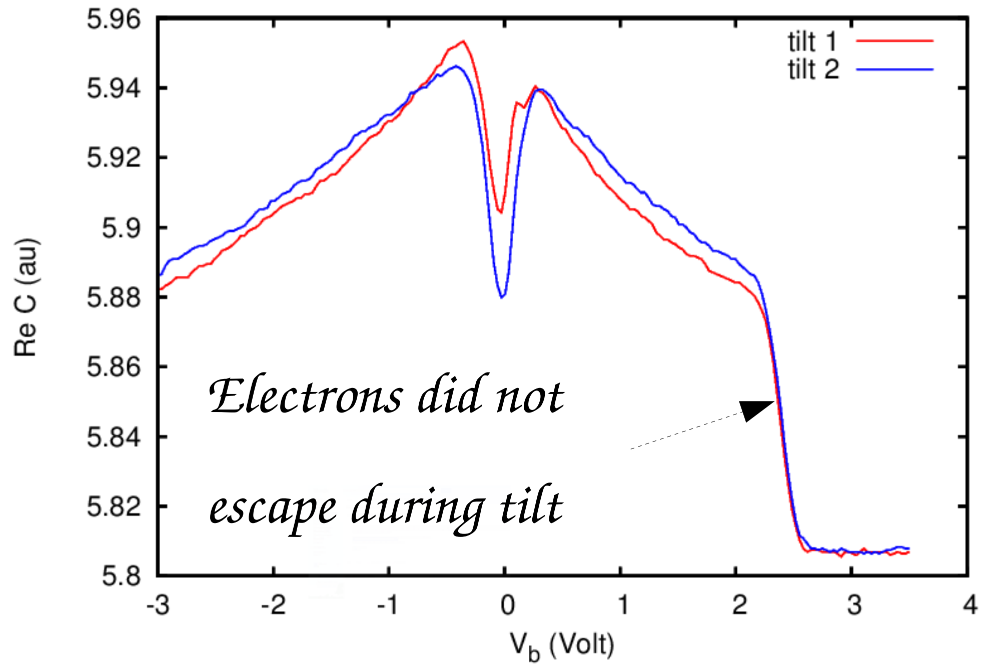


Resonance $f \sim E_\perp / B$ → tilt of the cell is important

Experimental confirmation by tilting the fridge

- *When we tilt the fridge by ~ 0.1 deg the resonance moves indeed !*





Theoretical understanding of this resonance

- *Electrostatic modelling of the tilt of the helium cell*

  → *we show that the tilt creates an almost uniform density gradient*

- *A density gradient creates a low frequency magnetoplasmon mode*

  → *Simplified model (analytic) effective Schrodinger equation*

  → *formula for the propagation velocity*

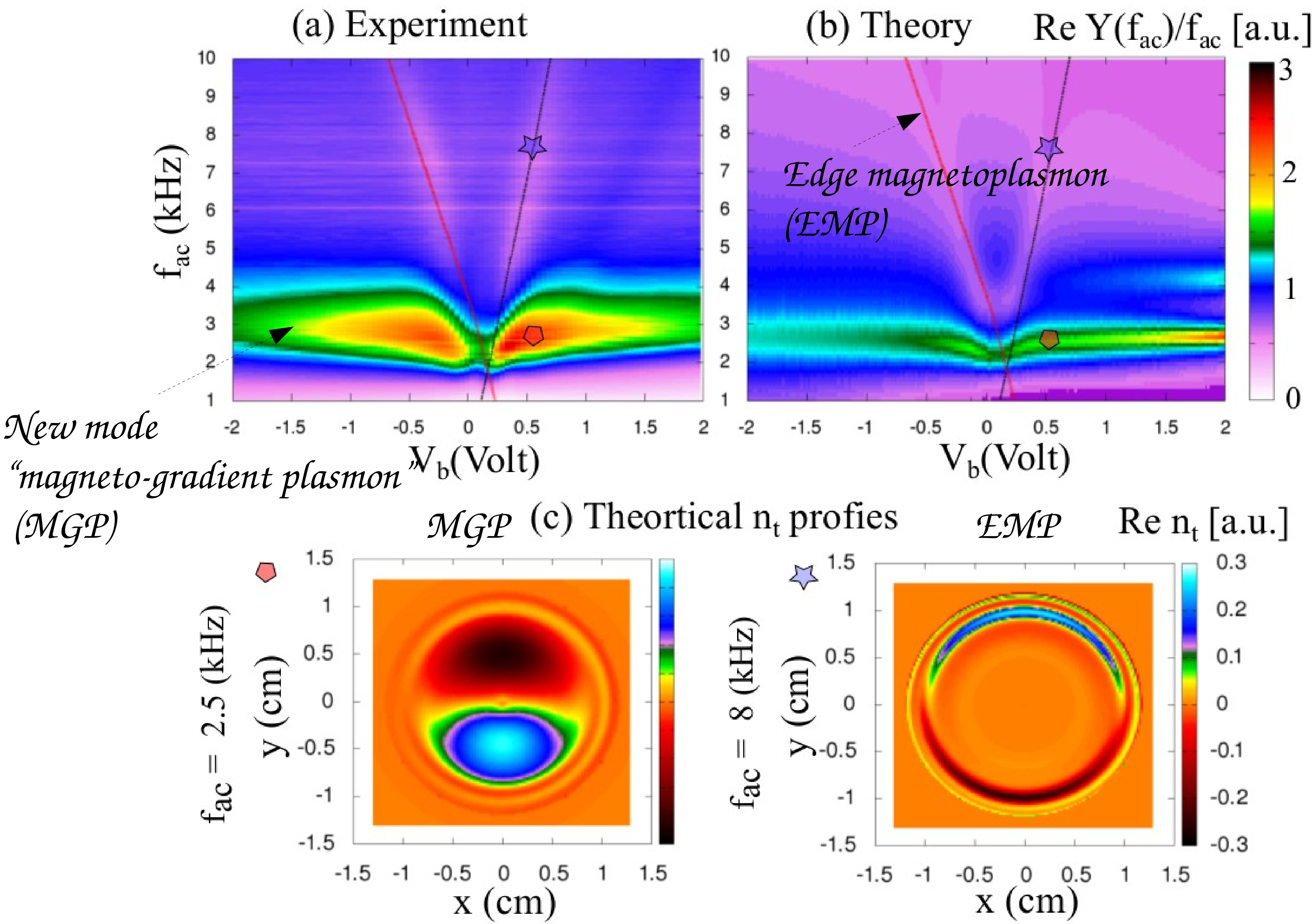
$$v_{MGP} \simeq \frac{\alpha E_{\perp}}{B\sqrt{2}}$$ (α tilt angle)

- *Detailed finite elements model*

  → *experimental confirmation of the mode spacial structure*

Finite element simulations

$$\Delta V(r)=\frac{e\,n_e}{\epsilon_0};\; j=-\sigma\nabla V$$



Magneto-plasmon summary

- Long range electro-statics describes well magneto-plasmon modes with large wave-numbers
  (distance between electrons much smaller than the plasmon-wavelength)

- Understanding the origin of an unidentified plasmon-mode can take a long time
  but models work well once the physical ingredients are identified

- Interesting aspect : study the coupling between a
  single 1D and a single 2D mode in a controlled environment

Phys. Rev. B 103, 075420 (2021) , arXiv:1910.08026

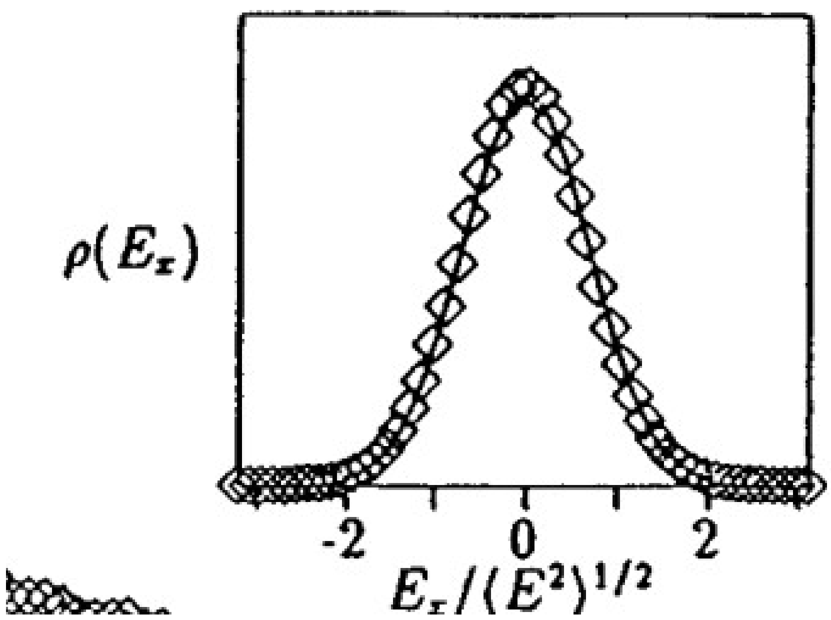
Coulomb interactions on the microscopic scale

$$V(r) = \frac{1}{4\pi\epsilon_0} \sum_i \frac{-e}{|r - r_i|}$$

- Thermal motion of electrons creates a fluctuating electric field E_x

Gaussian distribution of fluctuating electric fields E_x

(with theoretically known variance)



Allows the understanding of magnetoresistance saturation.

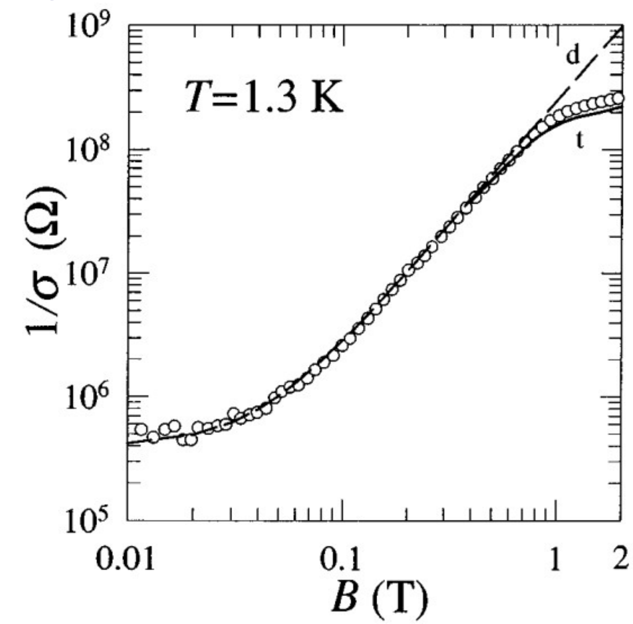
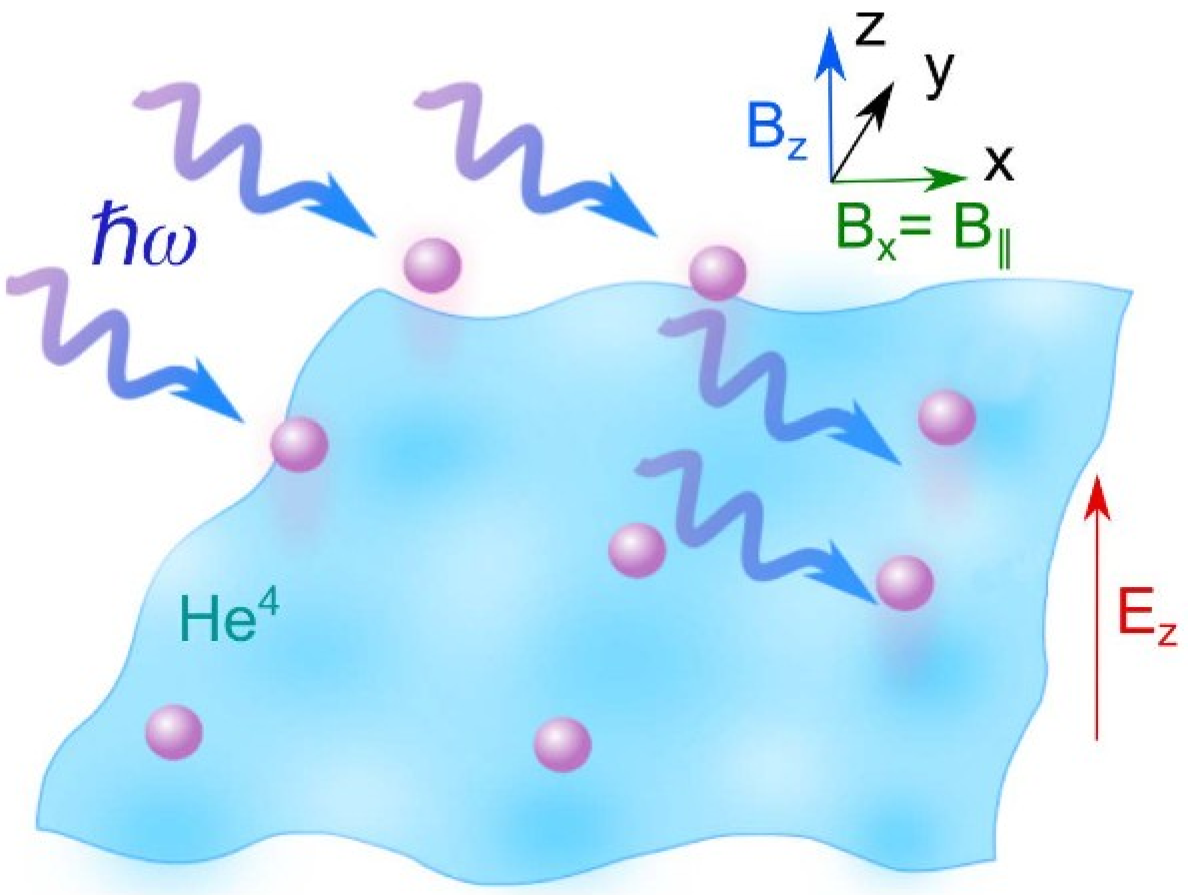


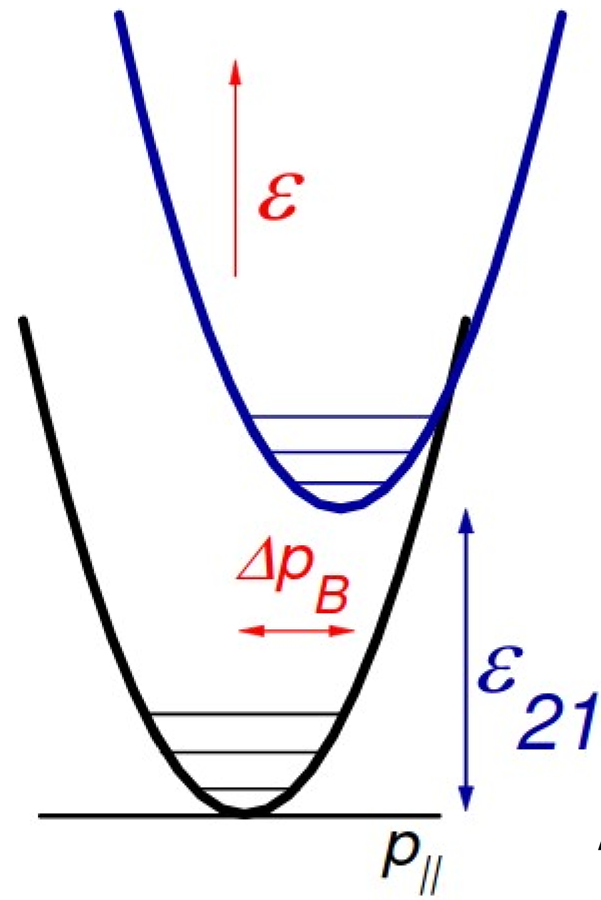
FIG. 7. The Drude region for magnetoconductivity, showing $1/\sigma(B)$ vs B at 1.3 K for $n = 0.64 \times 10^{12}$ m^{-2}. Line **d** shows the fit to the Drude model while line **f** is the full theory including many-electron and single-particle scattering effects.

M. J. Lea, P. Fozooni, A. Kristensen, M. I. Dykman et. al. PRB, 16280 (1997)

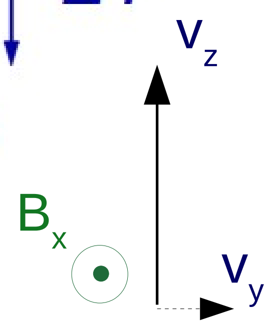
Spectroscopic measurement of the fluctuating electric field distribution

- Ground and first excited subband are separated by ε_{12}
- B_z quantizes the subbands into Landau levels



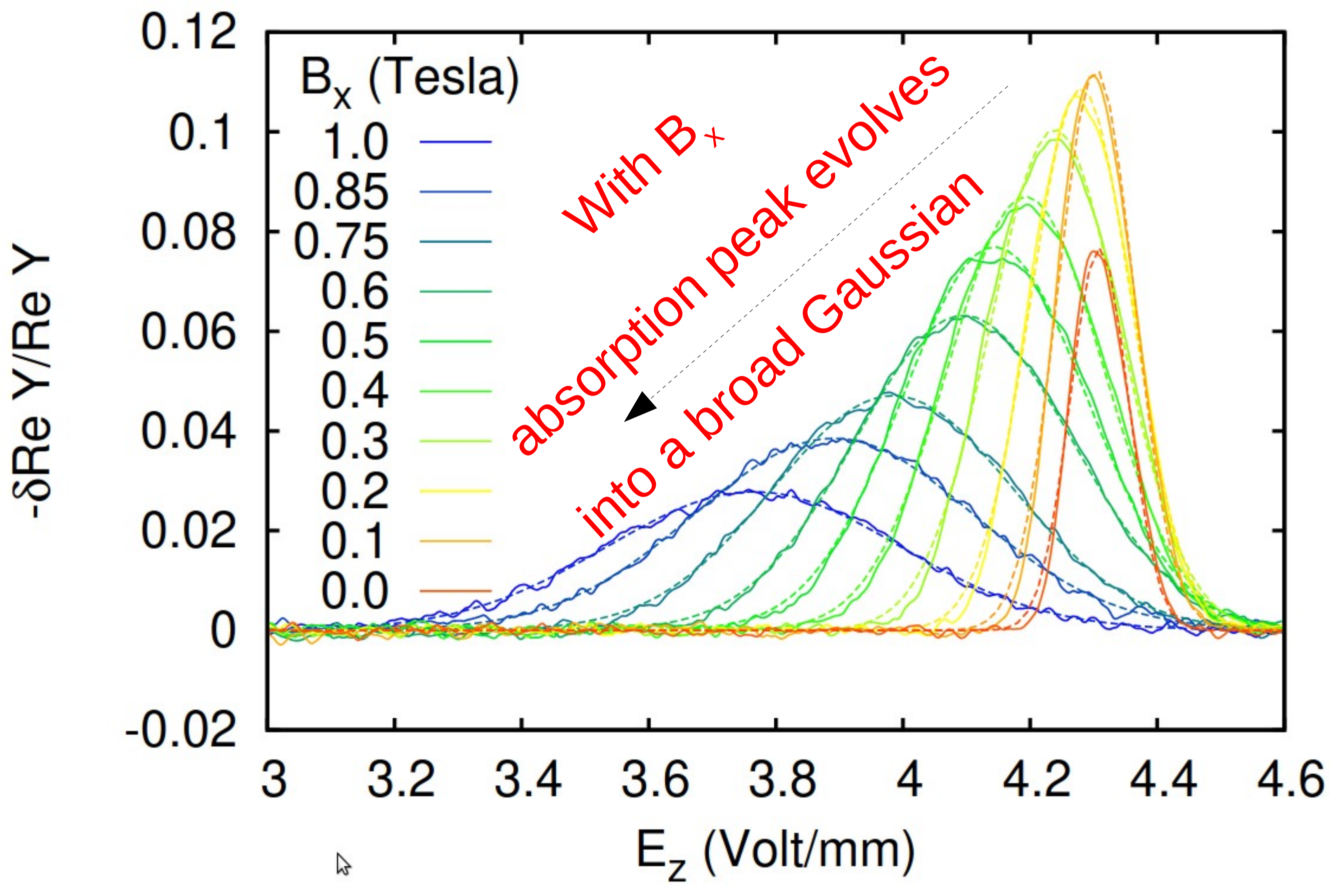


- B_x creates a coupling between in plane and vertical motion



Spectroscopic measurement of the fluctuating electric field distribution

- For large B_x the interaction between in plane and vertical motion is so strong that the ε_{12} absorption shows in plane force fluctuations
- Experiment resonant f = 150 GHz absorption as function of Stark field E_z



Spectroscopic measurement of the fluctuating electric field distribution

- This broad Gaussian is actually an image of the Coulomb fluctuating field

- Quantitative theory by M. I. Dykman :

  In the limit where classical dynamics correlation time is longer than quantum life time

$$\delta E_z(measured) = \frac{B_x}{B_z\sqrt{2}}\,\delta E_x(fluctuating\ field\ RMS)$$

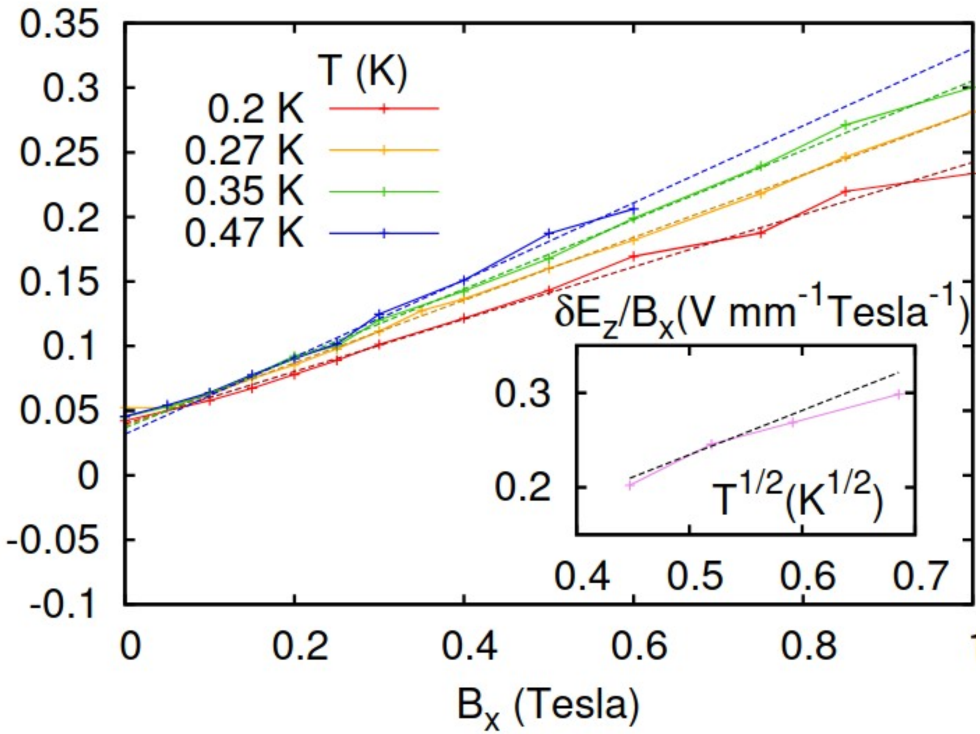
$$\delta E_z \approx \frac{3\,B_x}{B_z\sqrt{2}}\sqrt{k_B T\, n_e^{3/2}}$$

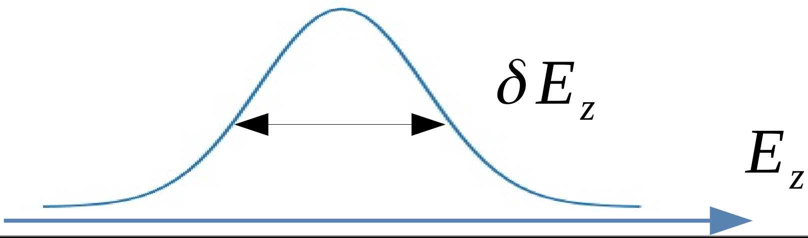
Experimental confirmation

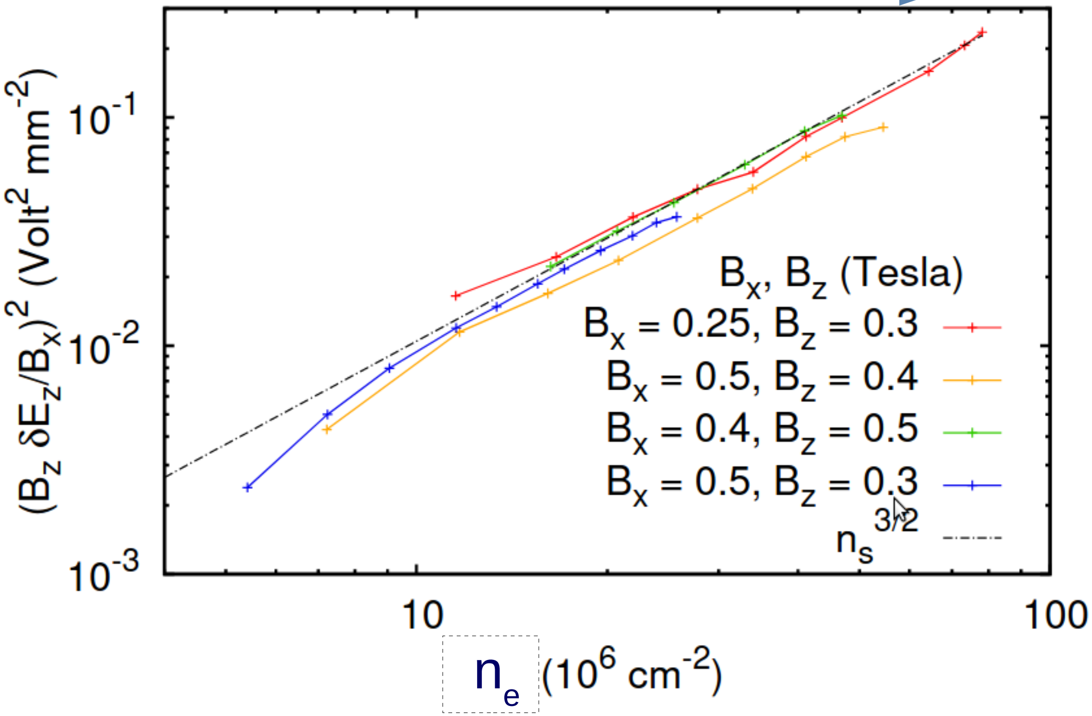
- This relation is confirmed without any fitting parameters in the experiment

$$\delta E_z \approx \frac{3 B_x}{B_z \sqrt{2}} \sqrt{k_B T n_e^{3/2}}$$

δE_z (V mm^{-1})







- Checks $\delta E_z \propto \sqrt{k_B T}$
- Checks $\delta E_z \propto B_x$
- Checks prefactor
- Checks $\delta E_z \propto \sqrt{n_e^{3/2}}$
- Checks $\delta E_z \propto B_z^{-1}$

Fluctuating field summary

- Spectroscopy allows to visualize the fluctuation of the local Coulomb force
- Good agreement with theoretical predictions of many body theory

  Arxiv:2011.05282
- This gives us a thermometer for electrons on helium

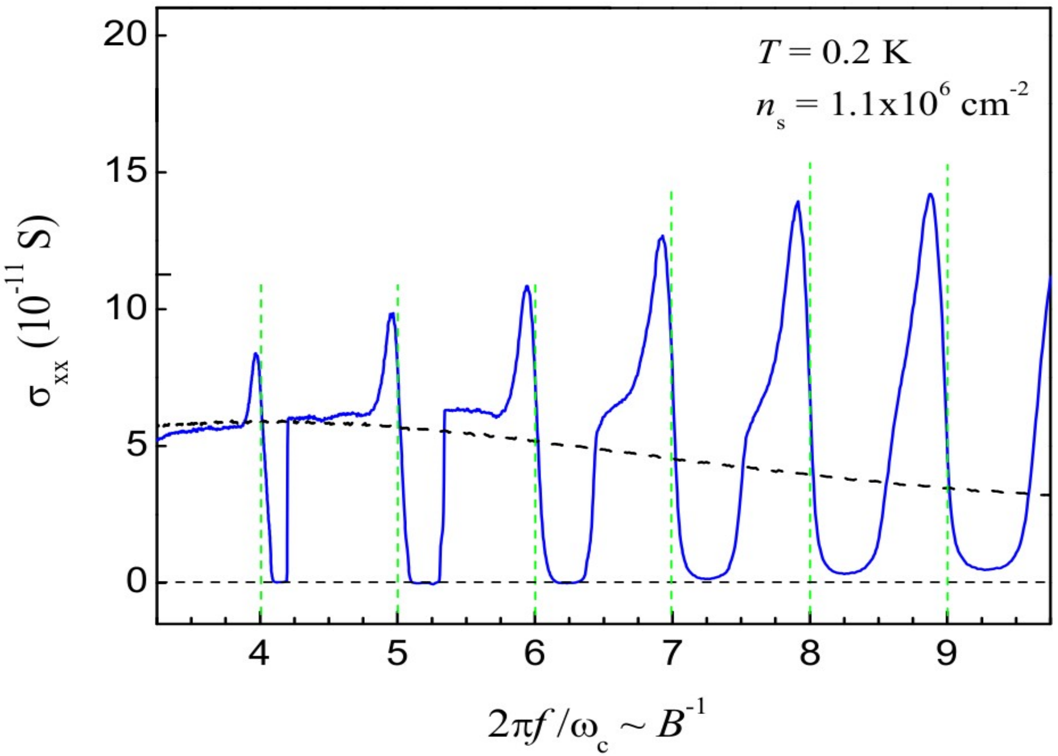
  (opens a possibility for heat transport experiments)

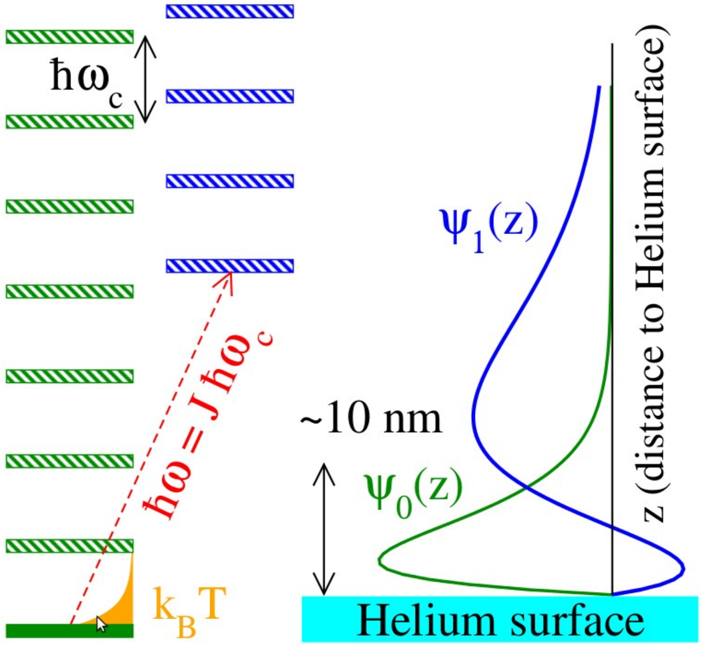
General conclusions ?

- Microscopic level : good agreement with many body theory
- Macroscopic level : good agreement with electrostatic equations
- Conclusion : no surprises ?

Electrons on helium under irradiation

- Excitation of the inter-subband resonance
- Appearance of zero-resistance states

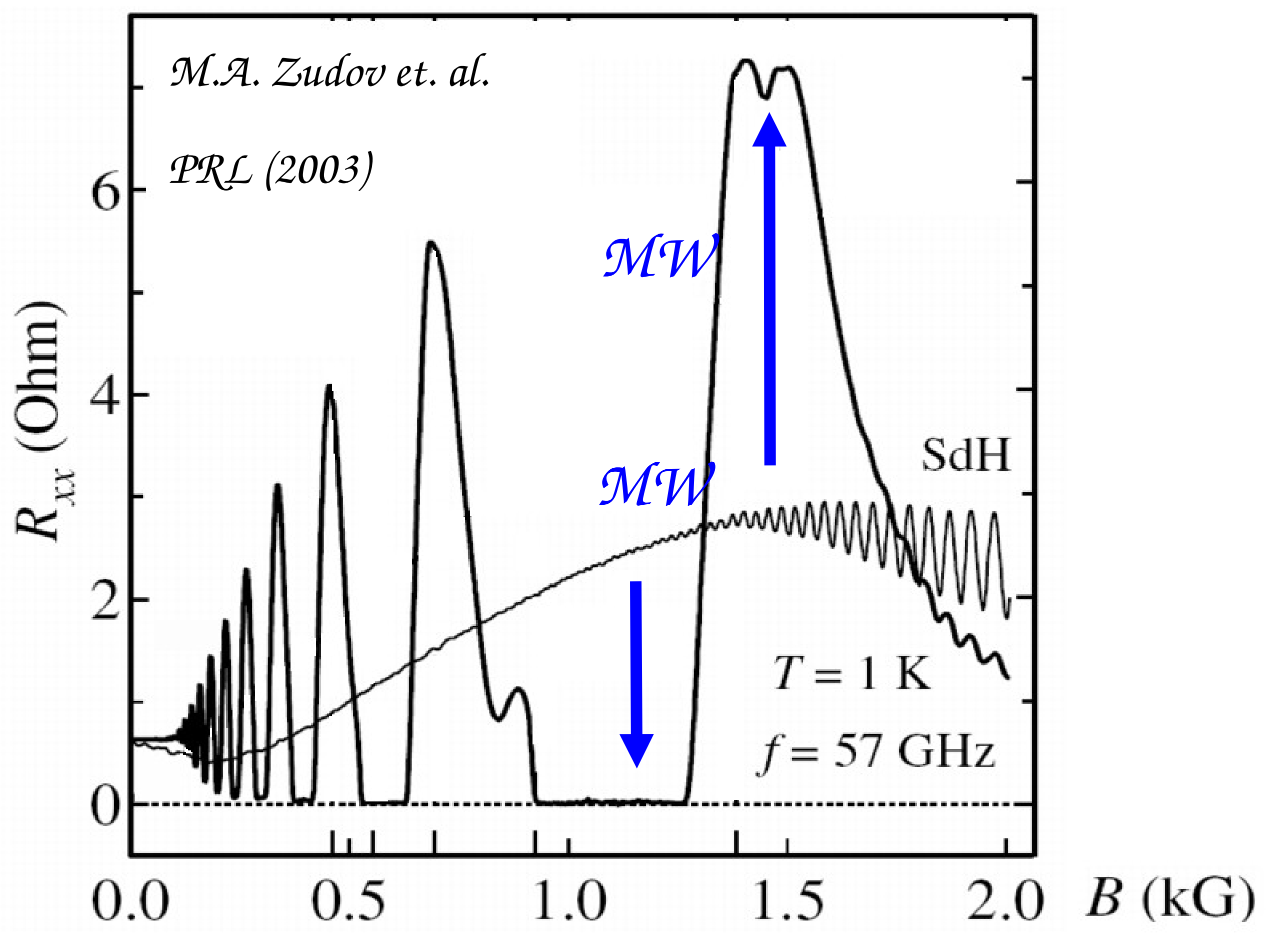




D. Konstantinov and K. Kono, PRL (2011) and (2012)

Similarity with physics in GaAs/GaAlAs

- R.G. Mani et al. (2002) and M.A. Zudov et. al. (2003)
- Complete suppression of R_{xx} under irradiation at 1 kGauss



Position of zeros determined by ω / ω_c ; ω_c cyclotron frequency

Understanding the steady state ZRS

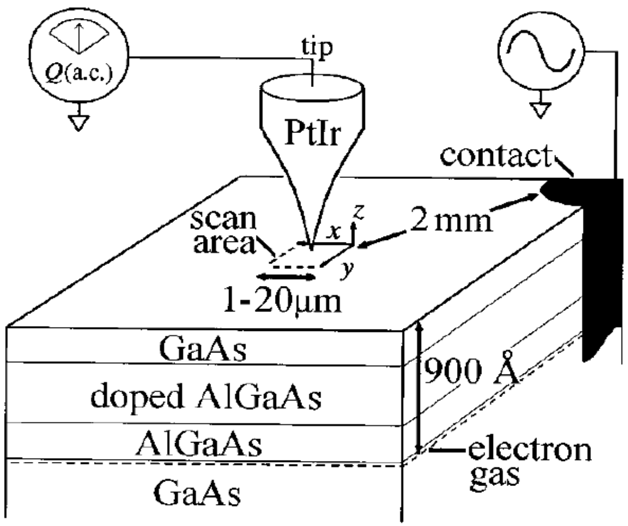
- We want to understand what governs the electron density distribution under “zero resistance” conditions

- The compressibility $\chi = dn_e / d\mu_e$ is an informative steady state quantity

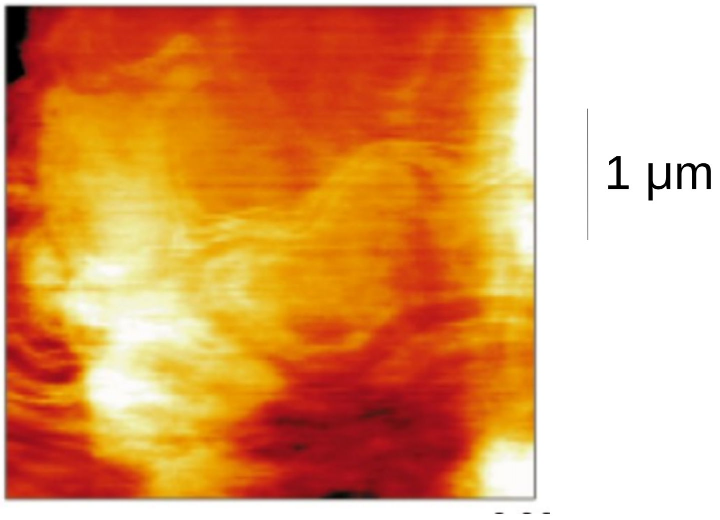
Compressibility in the quantum-Hall regime

- Example : S.H. Tessemer et. al., Nature **392**, 51 (1998)

  Visualisation of stripes, incompressible regions,...



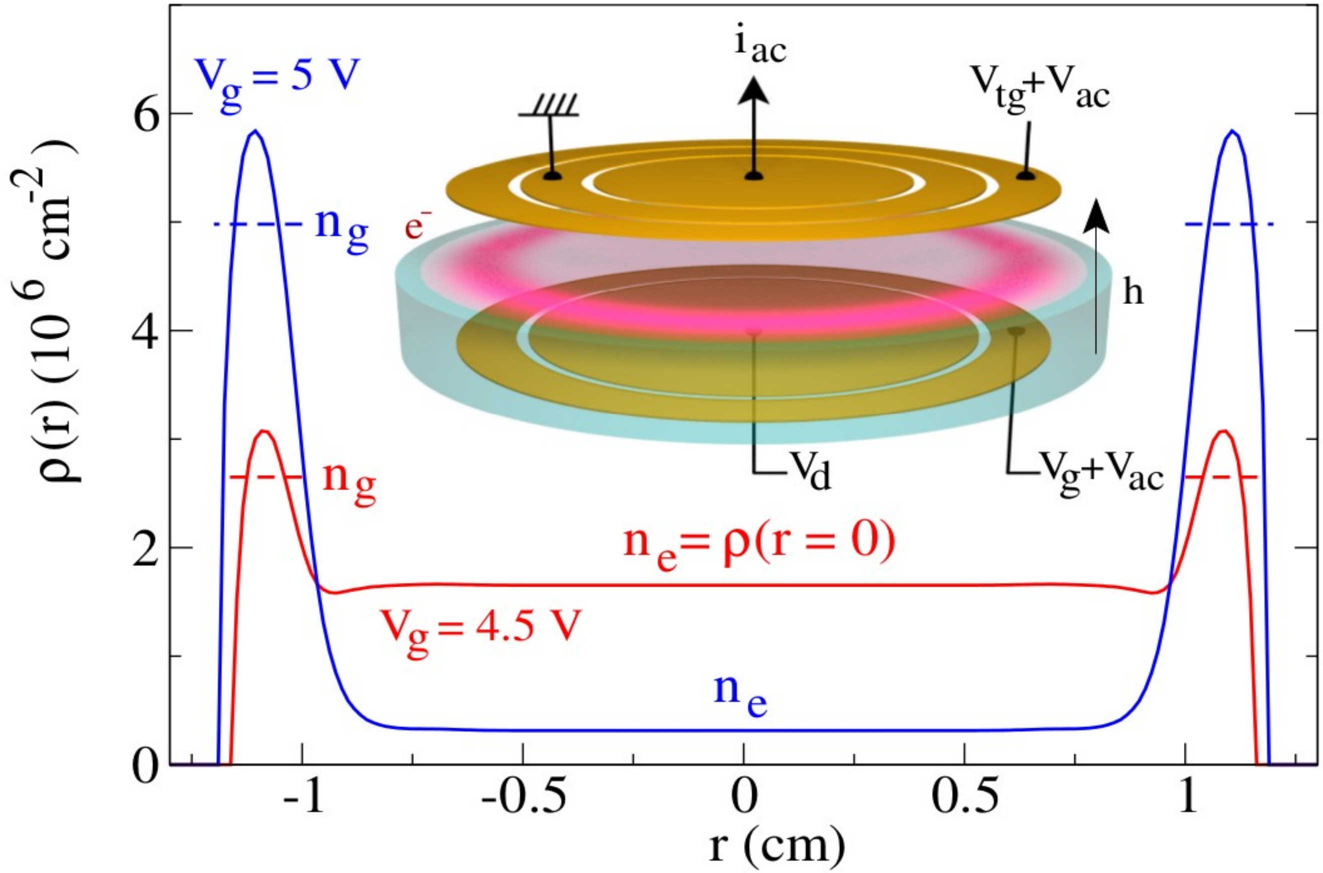
Q in phase (i out of phase)



- Note the non local coupling geometry

Control of the density using the guard voltage

- A positive guard voltage attracts the electrons to the edge



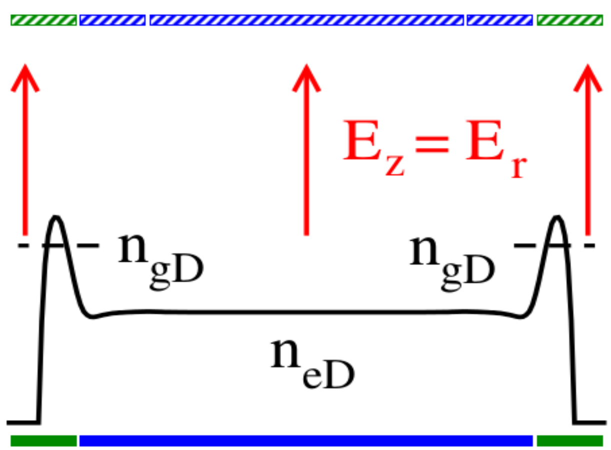
- We can directly measure the compressibility defined as:

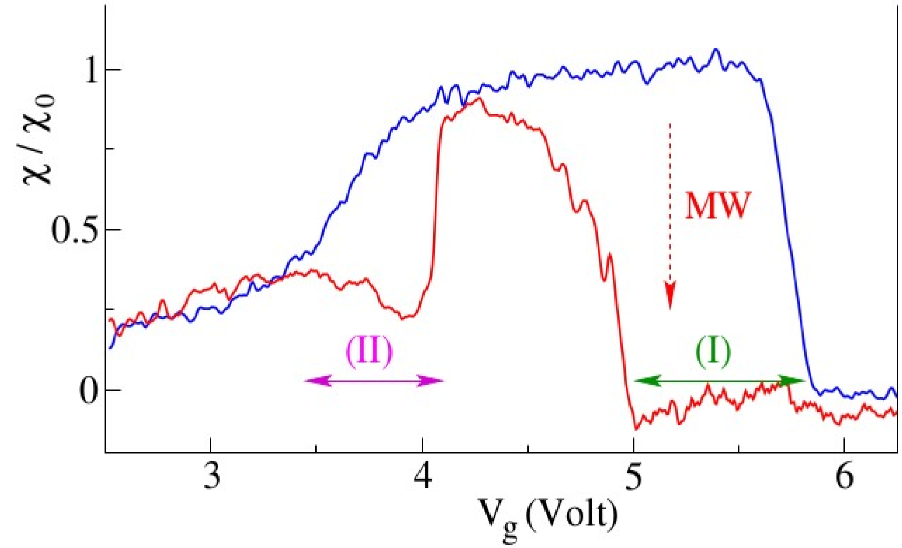
$$\chi = -\frac{dn_e}{dV_g} = \frac{i_{ac}}{e\pi^2 f_{ac} R_i^2 V_{ac}}$$

[f_{ac} ~ 2 Hz, V_{ac} ~ 25mV]

Compressibility in a zero resistance state

- *Under microwaves : compressibiliy vanishes at some guard voltages*



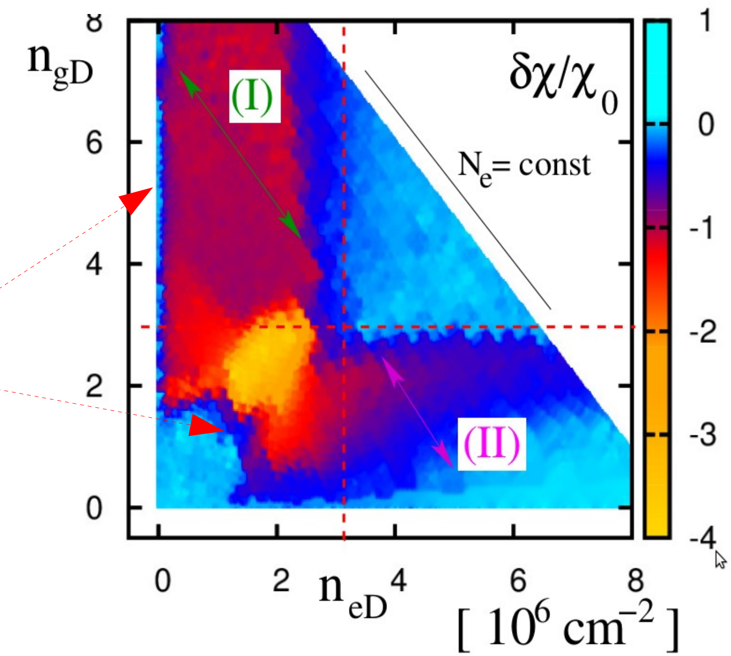


- *Change of the compressibility*

  on the n_{eD} , n_{gD} *plane*

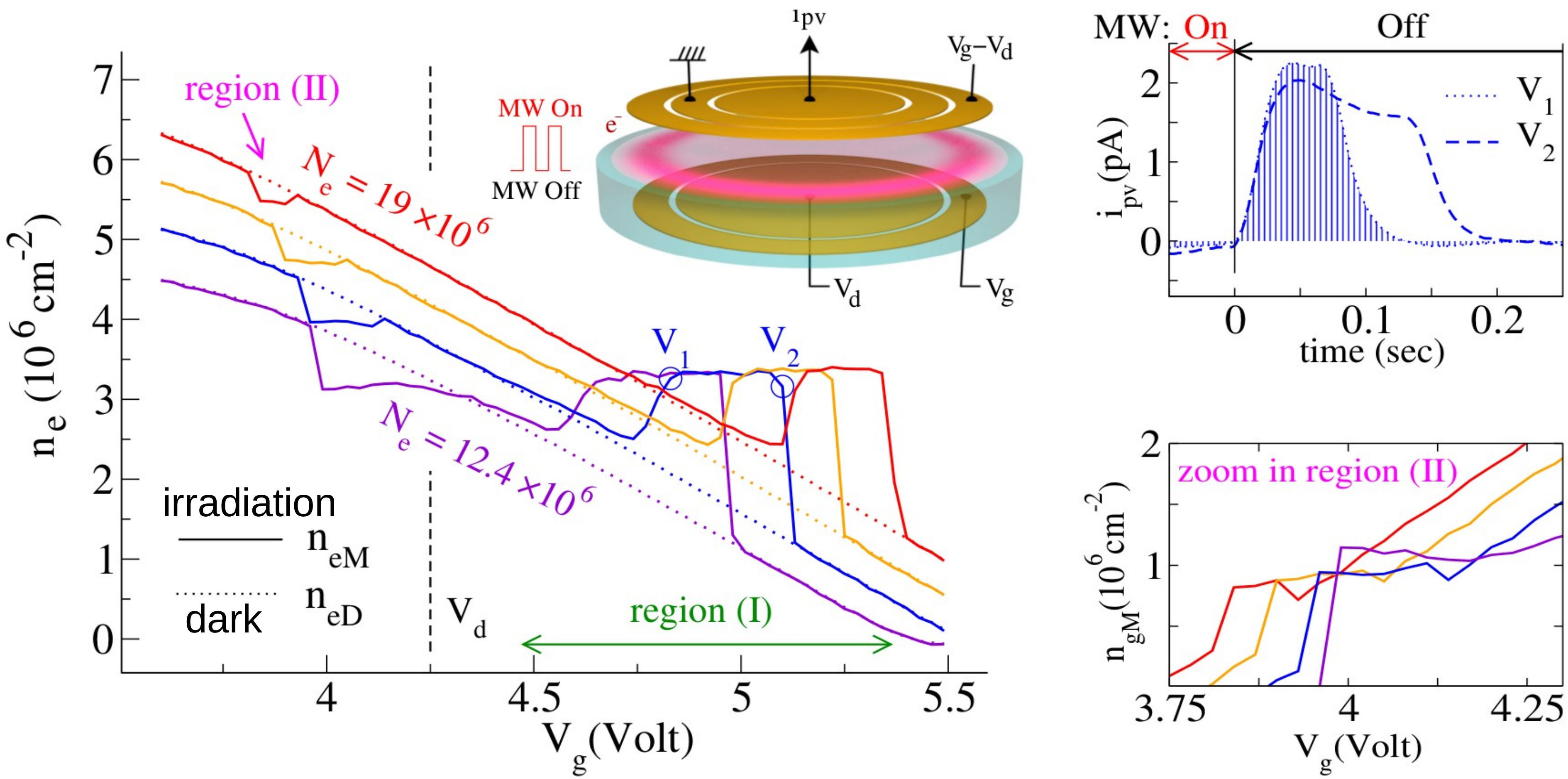
Color $\delta\chi/\chi_0$: $\delta\chi/\chi_0 = -1$ *incompressible*

n_{eD}, n_{gD} *denisty in equilibrium*



Density from transient photo-current on/off MW pulses

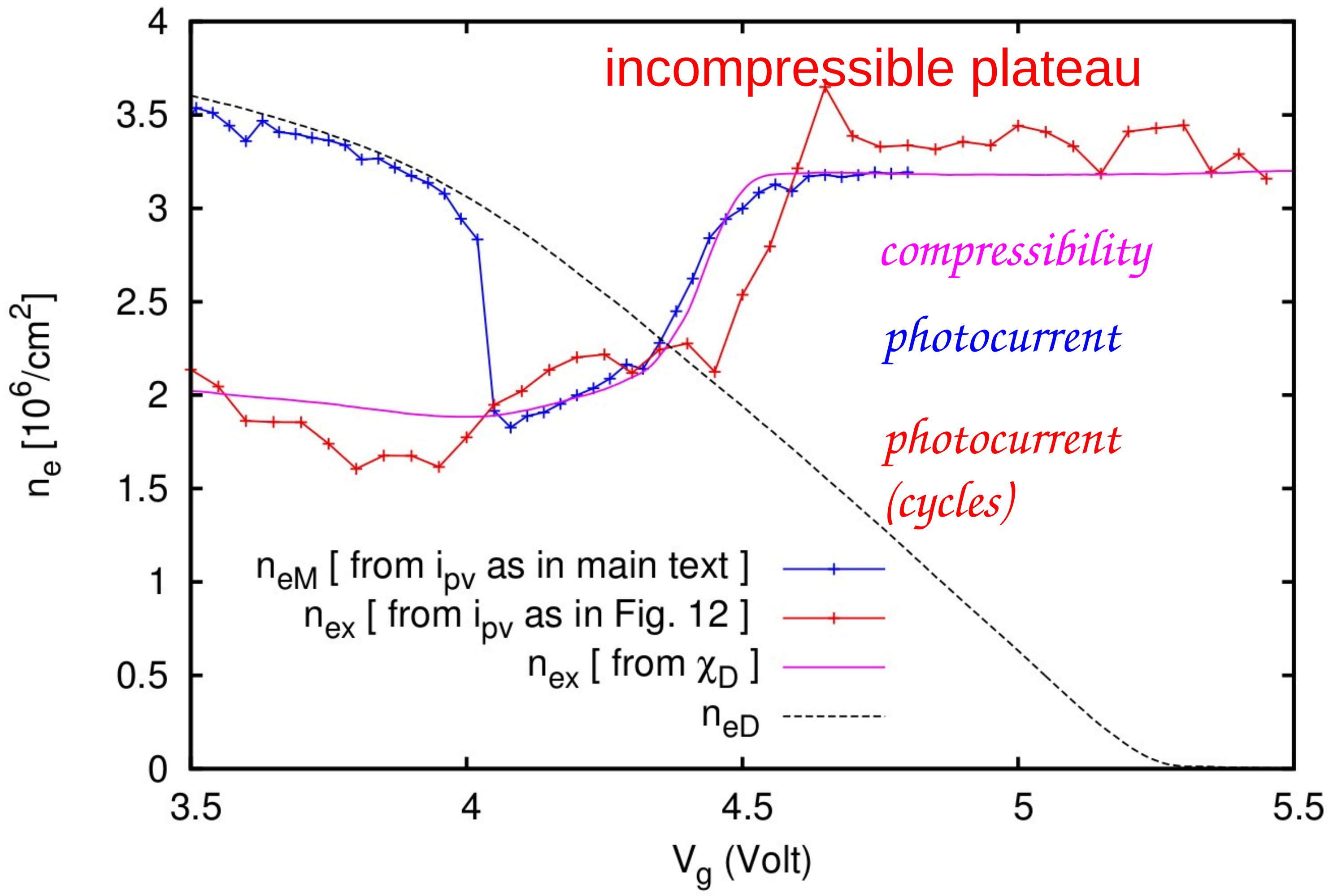
- Reconstruct density from $$\delta n_e = n_e(1) - n_e(0) = \frac{2}{e\pi R_i^2}\int_{Off} i_{pv}(t)dt$$



- Region (I) : plateau independent on initial conditions !

Dynamical mechanism pinning the density at a fixed value

Density distribution in zero resistance state



- Density as function of gate : very different from equilibrium
- Puzzle – incompressible plateau / charge inversion ?

Conclusions

- Interesting coexistence between very quantitative physics and spectacular effects without a microscopic physical explanation for now

  A.D. C., M. Watanabe, K. Nasyedkin, K. Kono and Denis Konstantinov
  Nature Com. 6, 8210 (2015) doi:10.1038/ncomms8210

- Probably a theory for the zero-resistance state has to bridge the gap between

  Microscopic photo-induced transport with its short range electron-electron electron-riplon fluctuations

  And macroscopic photo-transport with its long range density gradients etc ...