Incompressible electronic states on the helium surface induced by millimeter wave irradiation

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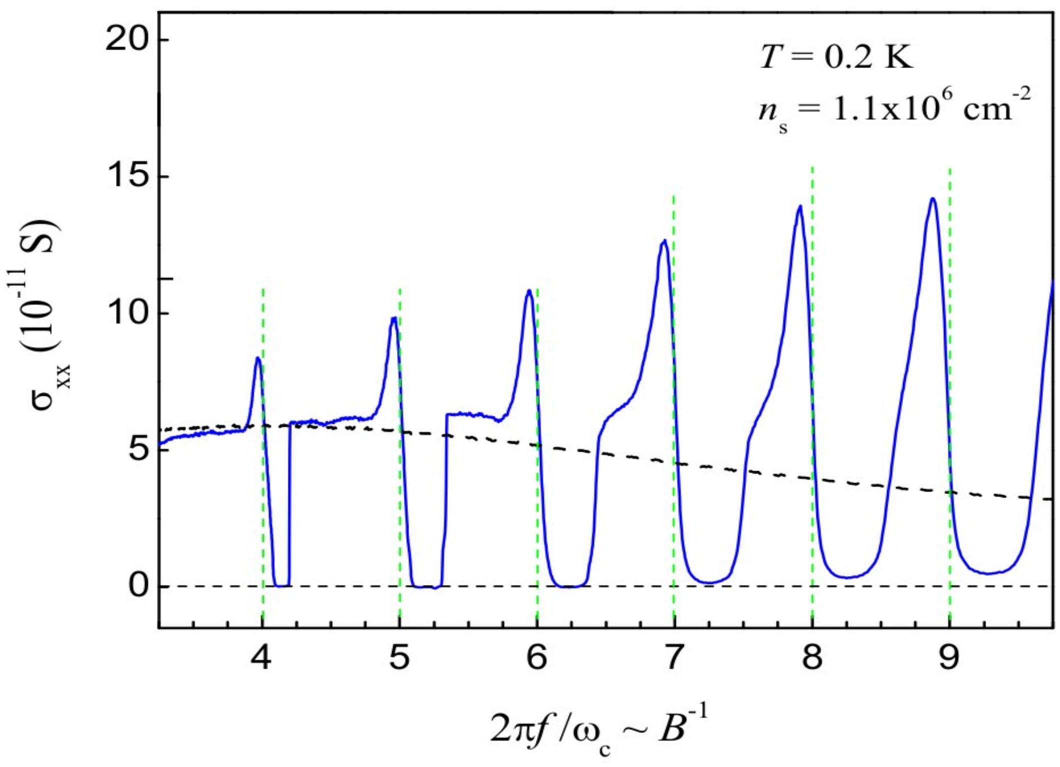
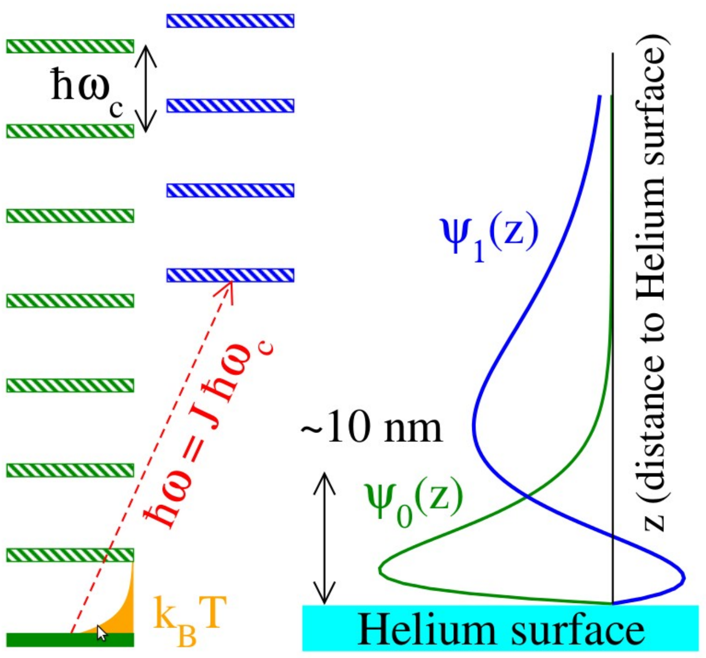
Electrons on helium under irradiation

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

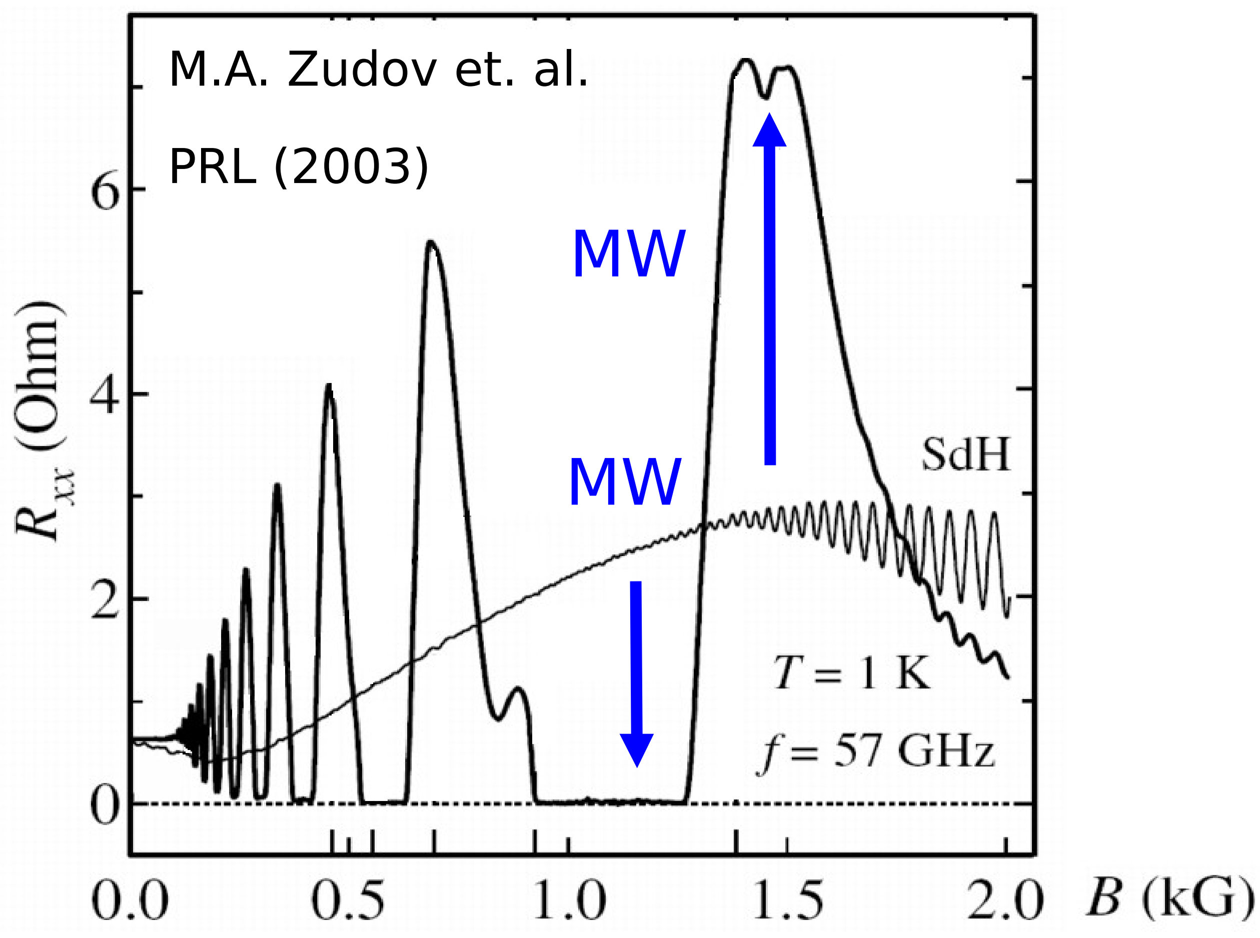




D. Konstantinov and K. Kono, PRL (2011) and (2012)

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,

  in GaAs at experiments by Jurgen Smet et. al. →

  ZRS behaviour seemingly inconclusive

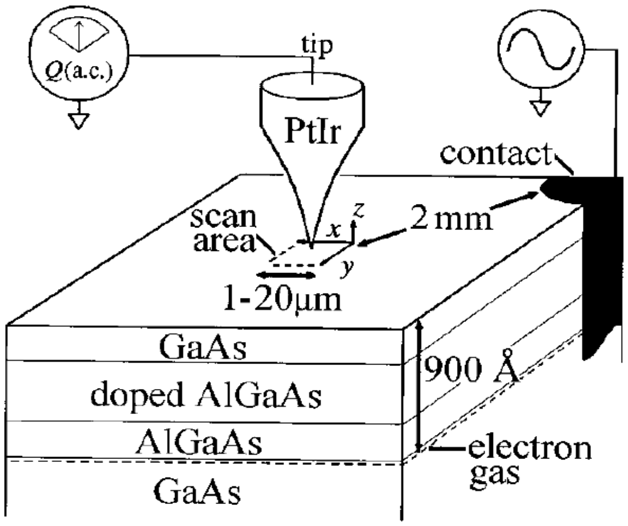
- Original motivation : edge vs bulk mechanisms ?

  (still puzzling: “bluk is important but edge is also”)

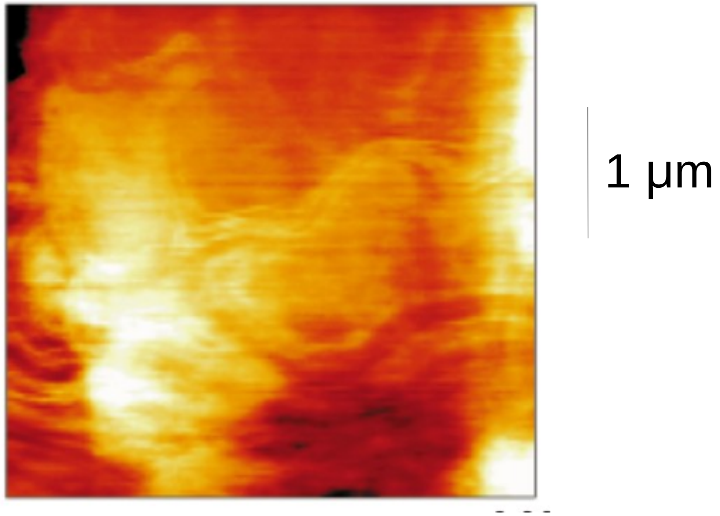
Compressibility in the quantum-Hall regime

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

  Visualisation of stripes, incompressible regions,...



Q in phase (i out of phase)



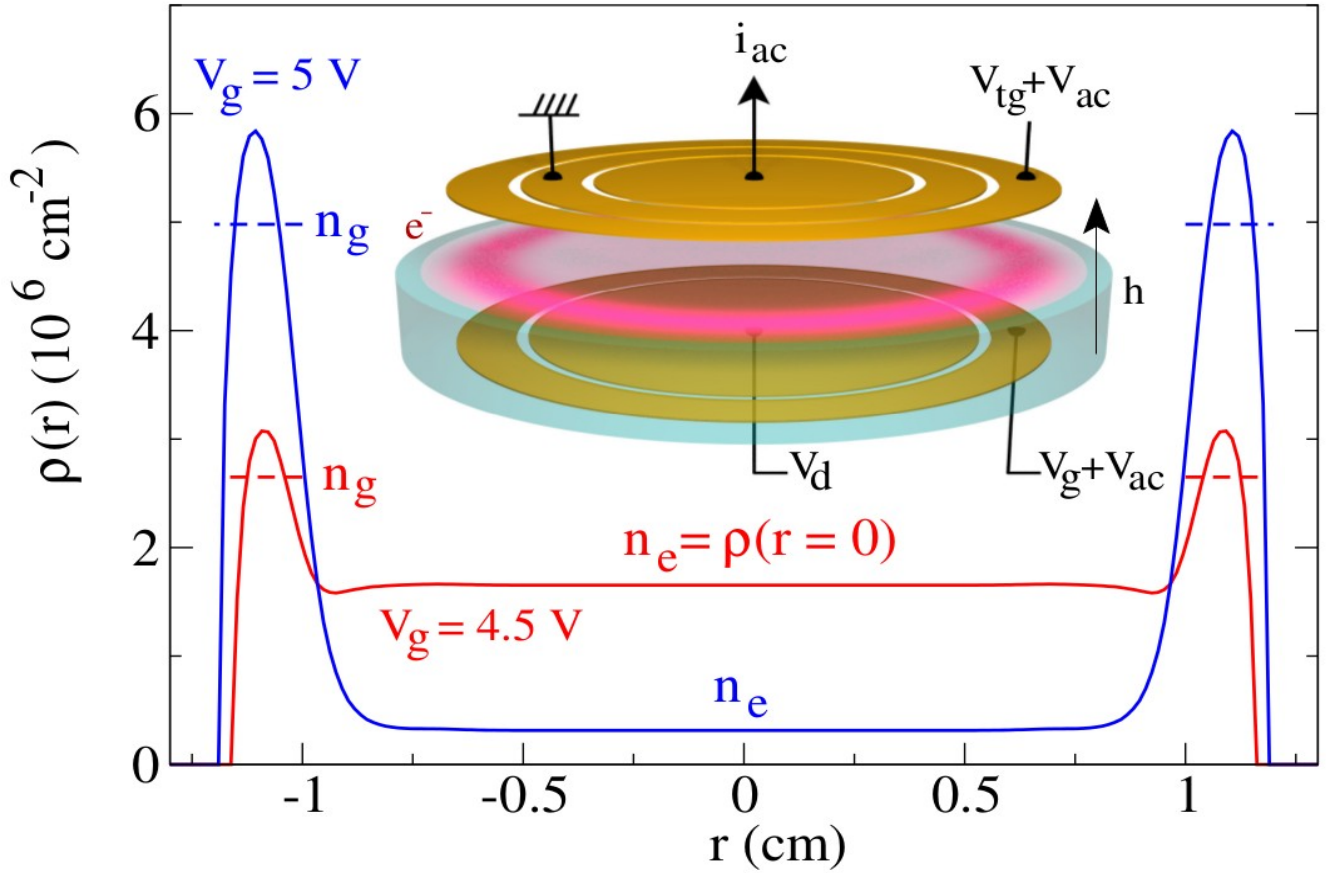
- Note the non local coupling geometry

- We cannot set the potential of electrons on Helium

  (no ohmic contacts)

Control of the density using the guard voltage

- A positive guard voltage attracts the electrons to the edge



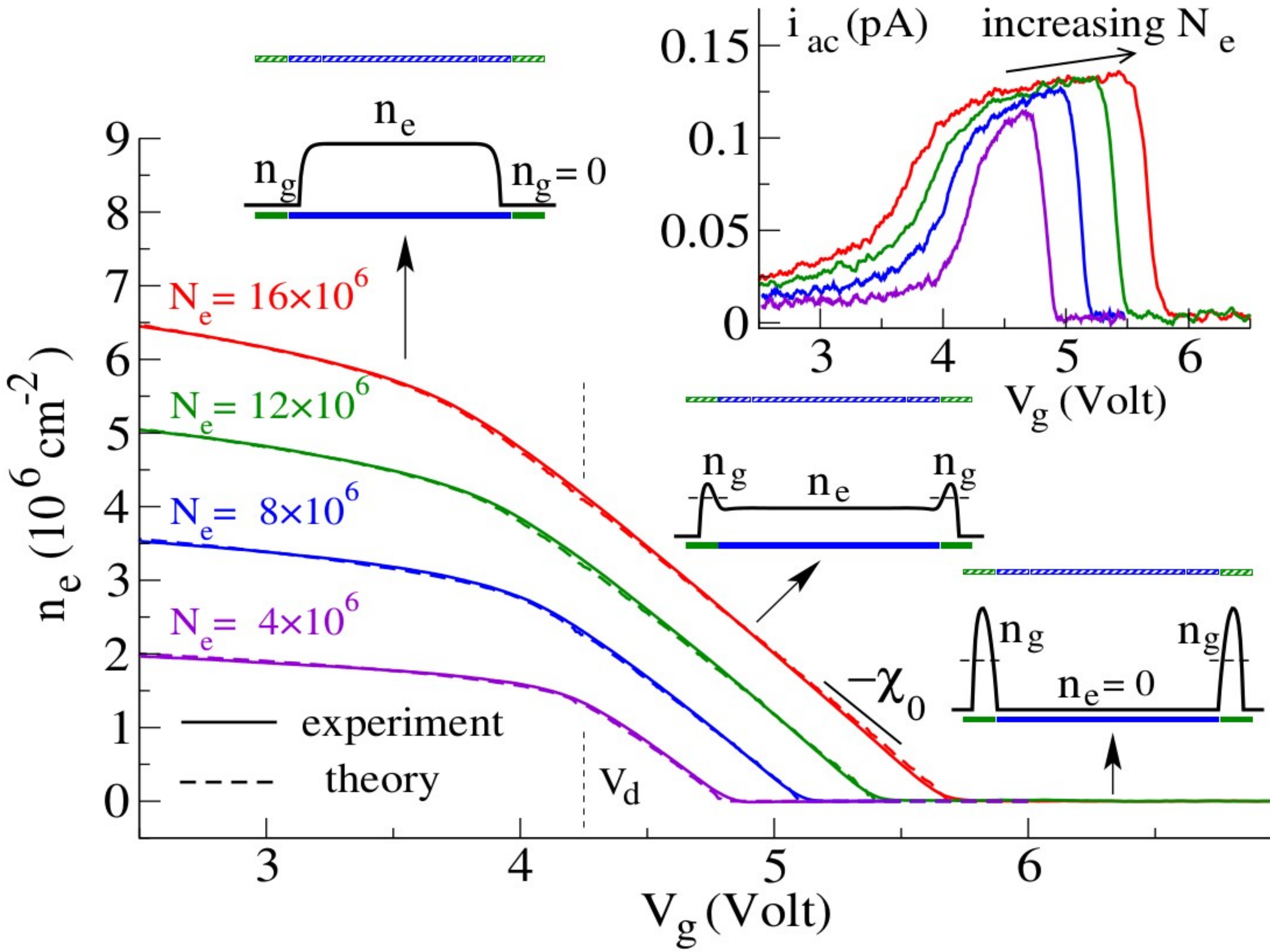
- We can directly measure the compressibility defined as:

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

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

Experimental densities vs FEM simulations

- The comparison (without irradiation) works extreemly well



- Only adjustable parameter, number of trapped electrons N_e

Compressibility in equilibrium :

- Compressibility given by the minimisation of the electrostatic energy

  Plane capacitor model →
  $$\chi_0 = -\frac{dn_e}{dV_g} = \frac{4\epsilon_0}{eh(1+S_d/S_g)}$$

- Compressibility perfectly understood in the dark

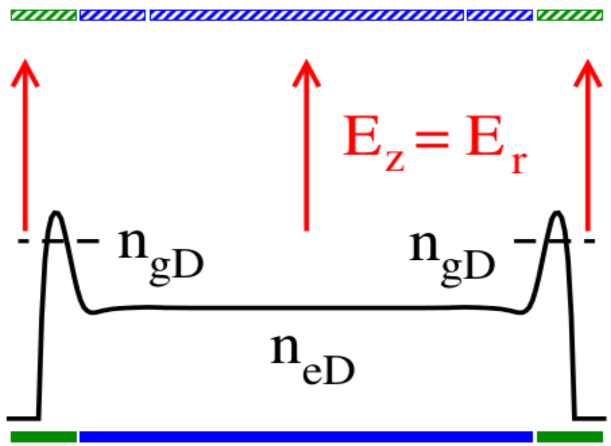
  No dependence on mobility when $\mu_{xx} > 0$

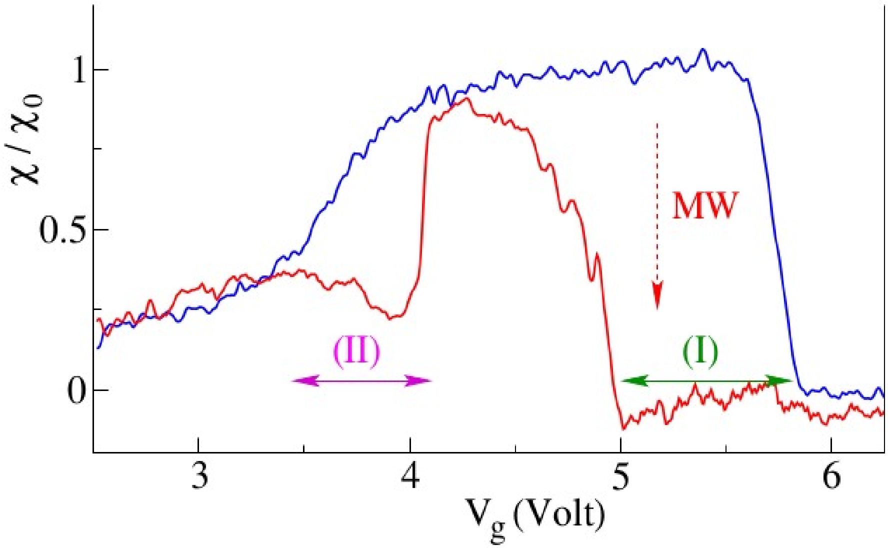
  → we can focus on ZRS regime

- We are now ready for microwaves !

Compressibility under irradiation $\omega/\omega_c = 6.25$

- Under microwaves : compressibiliy vanishes at some guard voltages



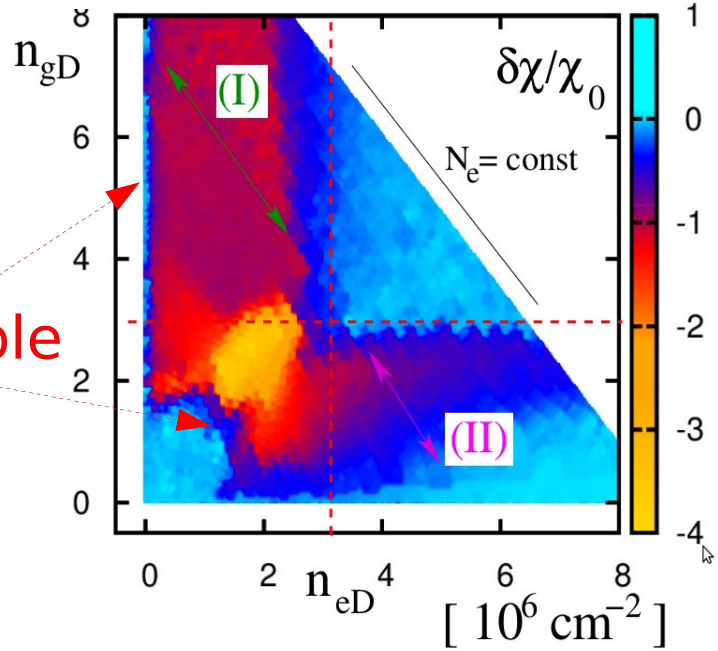


- Change of the compressibility

  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



Can we explain experiment with $\sigma_{xx} = 0$?

- For $\sigma_{xx} = 0$ any density profile is meta-stable

  (discussions with V. Shikin)

  We thus expect a strong dependence of the final

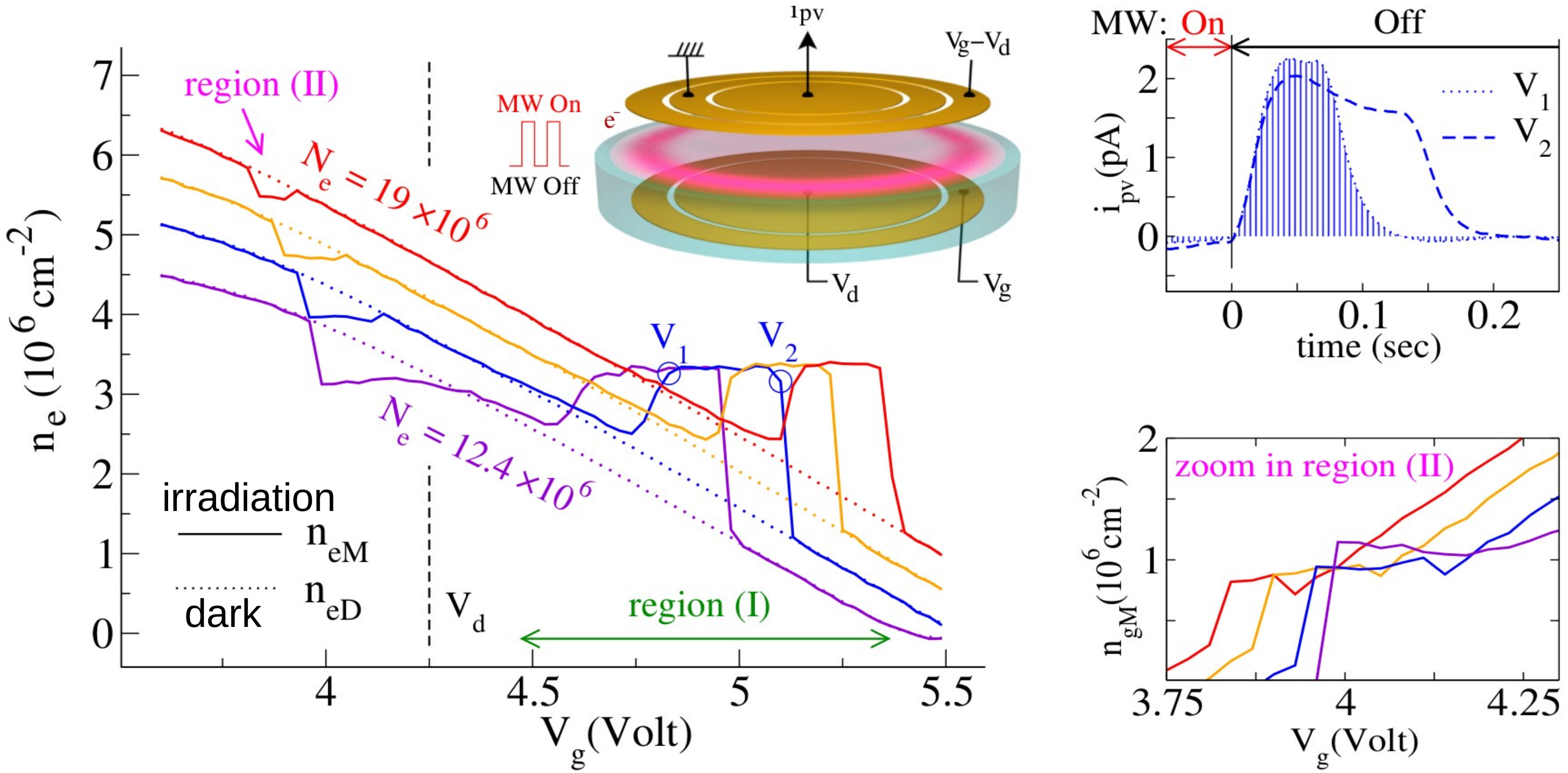
  state density on the initial density profile

- We determine the steady state density under irradiation

  starting from different equilibrium densities

Density from transient photo-current from 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

Two ways to measure zero

- $\chi = 0$: from low frequency AC technique

  but "It is easy to measure zero, just disconnect everything"

- $\chi = A - A = 0$: photo-current technique

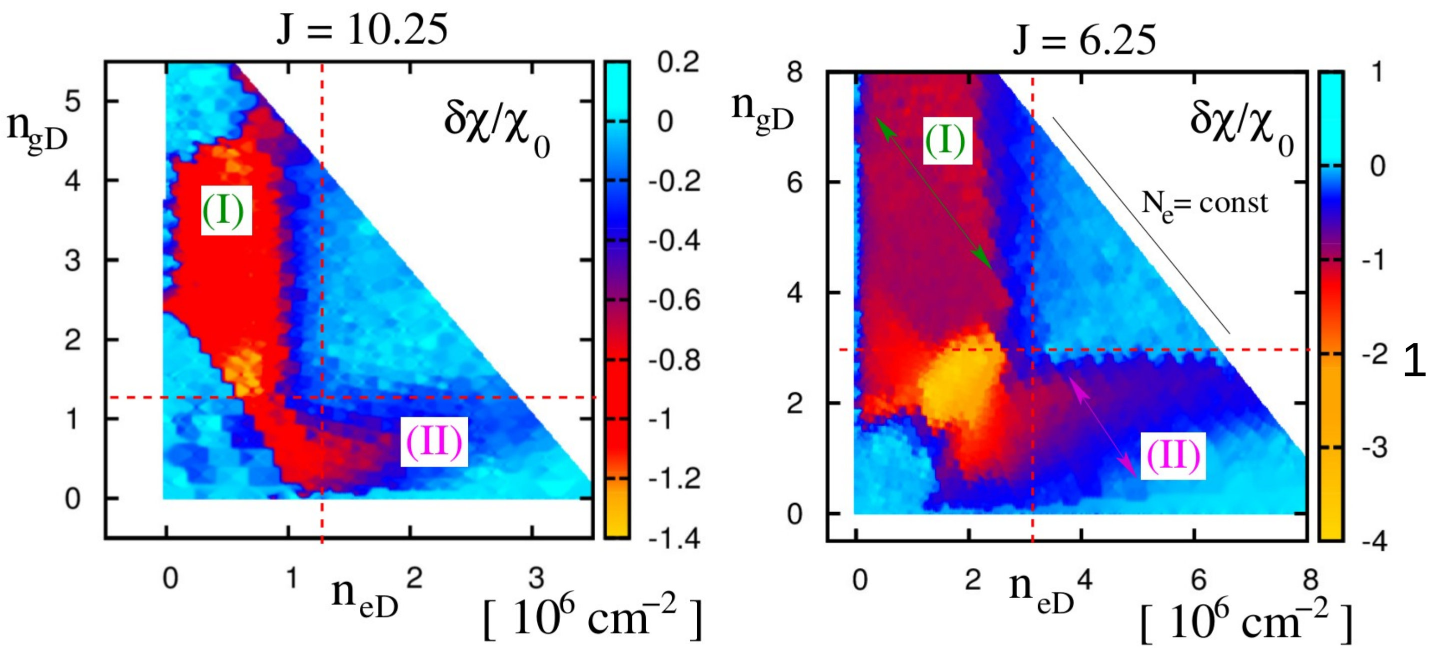
  Dark compressibility (no microwaves)

  Integration of photocurrent induced by microwave pulses

Two consistent signatures of incompressible behaviour

Compressibility at different $J = \omega/\omega_c$

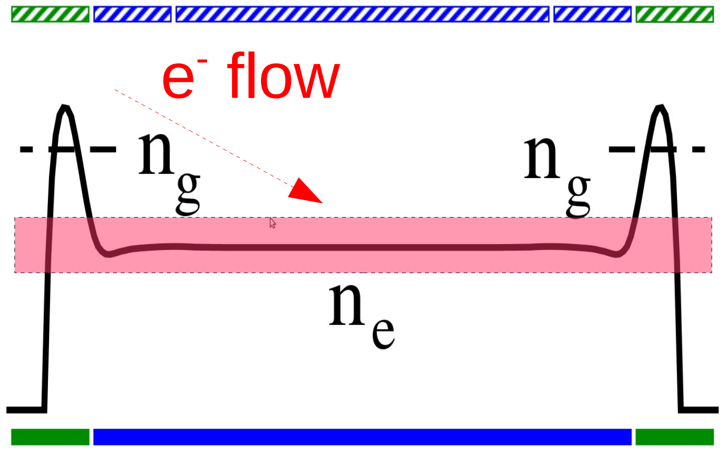
- Density boundaries almost the same at J = 6.25 and 5.25
- The density boundaries move to lower values at J = 10.25

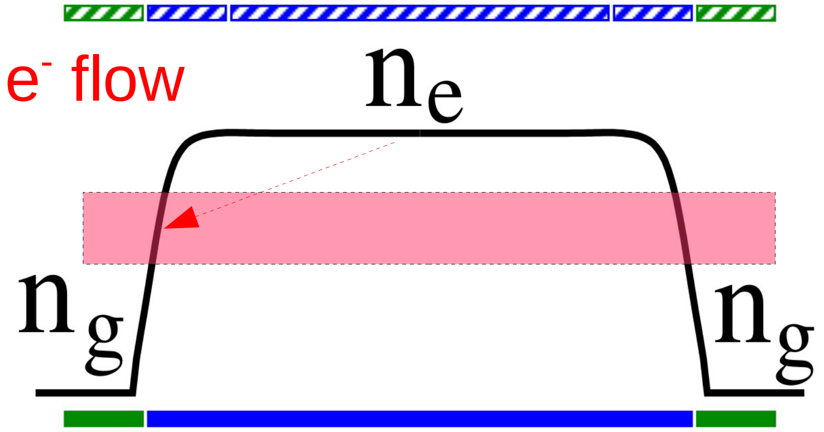


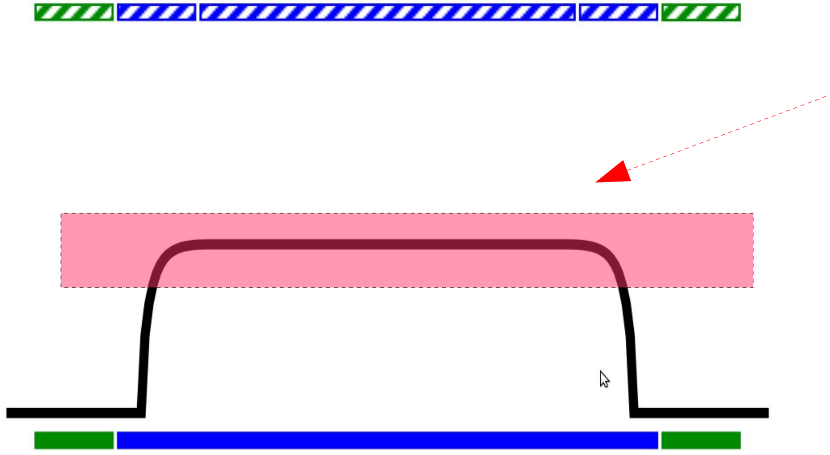
- Position of the density boundary consistent with :

$$n_e \propto \frac{1}{J} = \frac{\omega_c}{\omega} \propto B$$

Phenomenological description :







Almost all the system is in the unstable density region : self oscillations

Kimitoshi Kono's talk

Possible explanations

- 1) Domain theory
- 2) Photocurrent instability : Monarkha (MIRO) +
  Entin&Magaril theory (Photo-current)
- 3) Wishful and microscopic :
  Electron-riplon magneto-resonance
- 4) Non linear resonance
  (original motivation for
  experiments and D.L. Shepelyansky's talk)

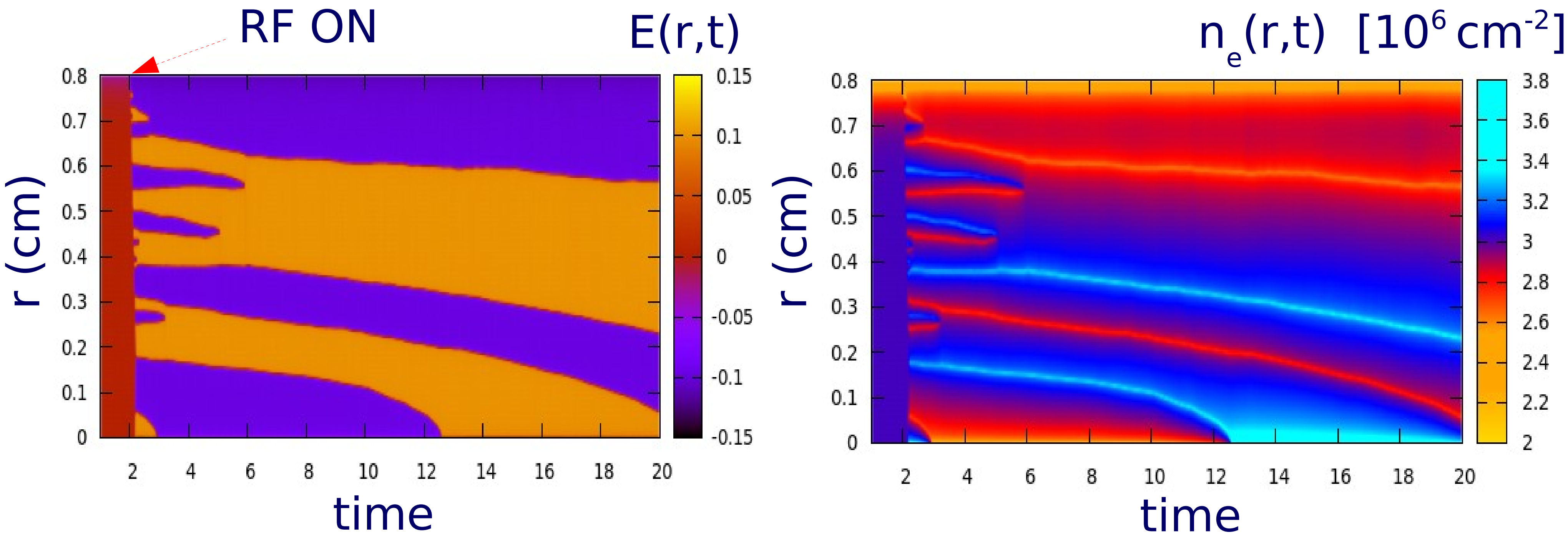
1) Domain model

$$\sigma(\mathbf{E}) = -|\sigma_{neg}| \left(1 - \frac{\mathbf{E}^2}{\mathbf{E}_0}\right)$$

Domain theory pins the electric field

$E = E_0 \sim \text{grad}(n_e)$ not n_e → no incompressibility

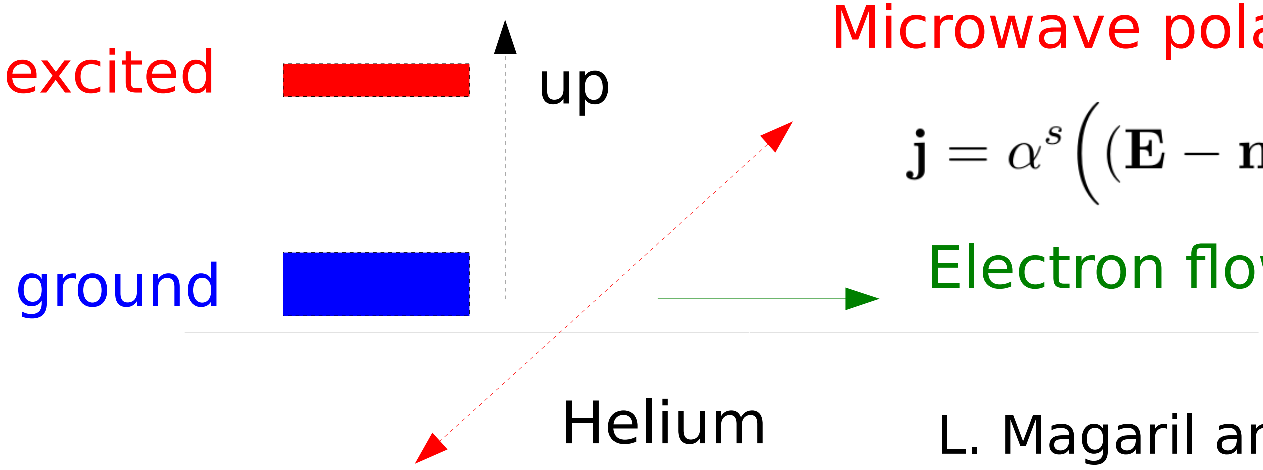
- Confirmation from FEM simulations [in interaction with Ivan Dmitriev]



- More work on domain theory is needed ...

2) M. Entin, L. Magaril : instability for $\mu_{xx}(B) > 0$

- Anomalous photo-current at inter-subband resonance



Microwave polarization **E**

$$\mathbf{j} = \alpha^s \Big((\mathbf{E} - \mathbf{n}(\mathbf{nE}))(\mathbf{nE}^*) + c.c. \Big)$$

Electron flow with velocity $V \sim \mathbf{E}^2$

L. Magaril and M. Entin JETP (2014)

- To reach steady state electrons need to create an electric field

$$V \sim \mu_{xx} E_{dc}$$

- Polarization fluctuates on the wavelength scale $\lambda \sim 1$mm

Maximal field is given by : $\max(E_{dc}) \sim e\, n_e / \varepsilon_0$

For $\mu_{xx} < \varepsilon_0 V/(e\, n_e)$ a catastrophe occurs : electron pockets ?

Before conductivity can even become negative !

3) Resonant plasmon-riplon interaction ?

- Excited electrons transfer their energy to riplons with wavenumber given by the inverse magnetic length : $k \sim \sqrt{\frac{\hbar}{eB}}$
- The riplons then oscillate at frequency : $\omega_r^2 \sim \frac{\gamma}{\rho} k^3$
- This creates a force which can become resonant with an electronic mode : $\Omega^2 \sim \omega_r^2$
- We consider magneto-shear modes $\Omega \sim \frac{\omega_p^2}{\omega_c}$

  Where we introduced the plasma frequency $\omega_p^2 \sim \frac{e^2 n_e^{3/2}}{\epsilon_0 m}$

$$n_e \sim \left[\frac{\gamma}{\rho} \frac{\epsilon_0^2 B^2}{e^2} \left(\frac{eB}{\hbar} \right)^{3/2} \right]^{1/3} \propto B^{7/6}$$

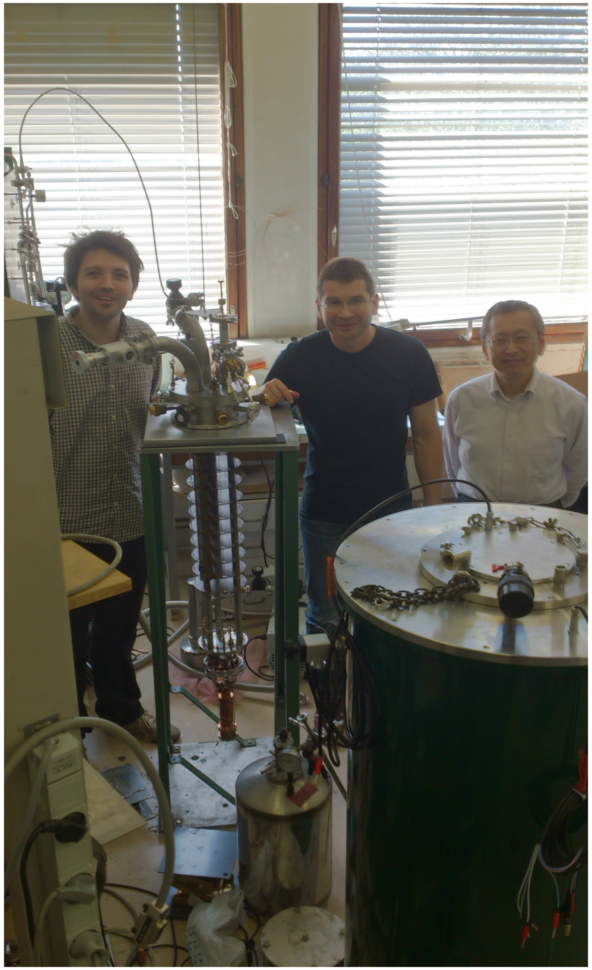
For B = 0.5 Tesla

n_e =3.4 x 10^6 cm^{-2}

Conclusions

- Evidence for incompressible behaviour of non degenerate electrons under microwave excitation
- Very clean system : only electrons and helium atoms
- Detailed experimental characterisation of ZRS steady state
  → constrains on theories
- Interaction effects (beyond mean-field theory) are important !

Thank you !



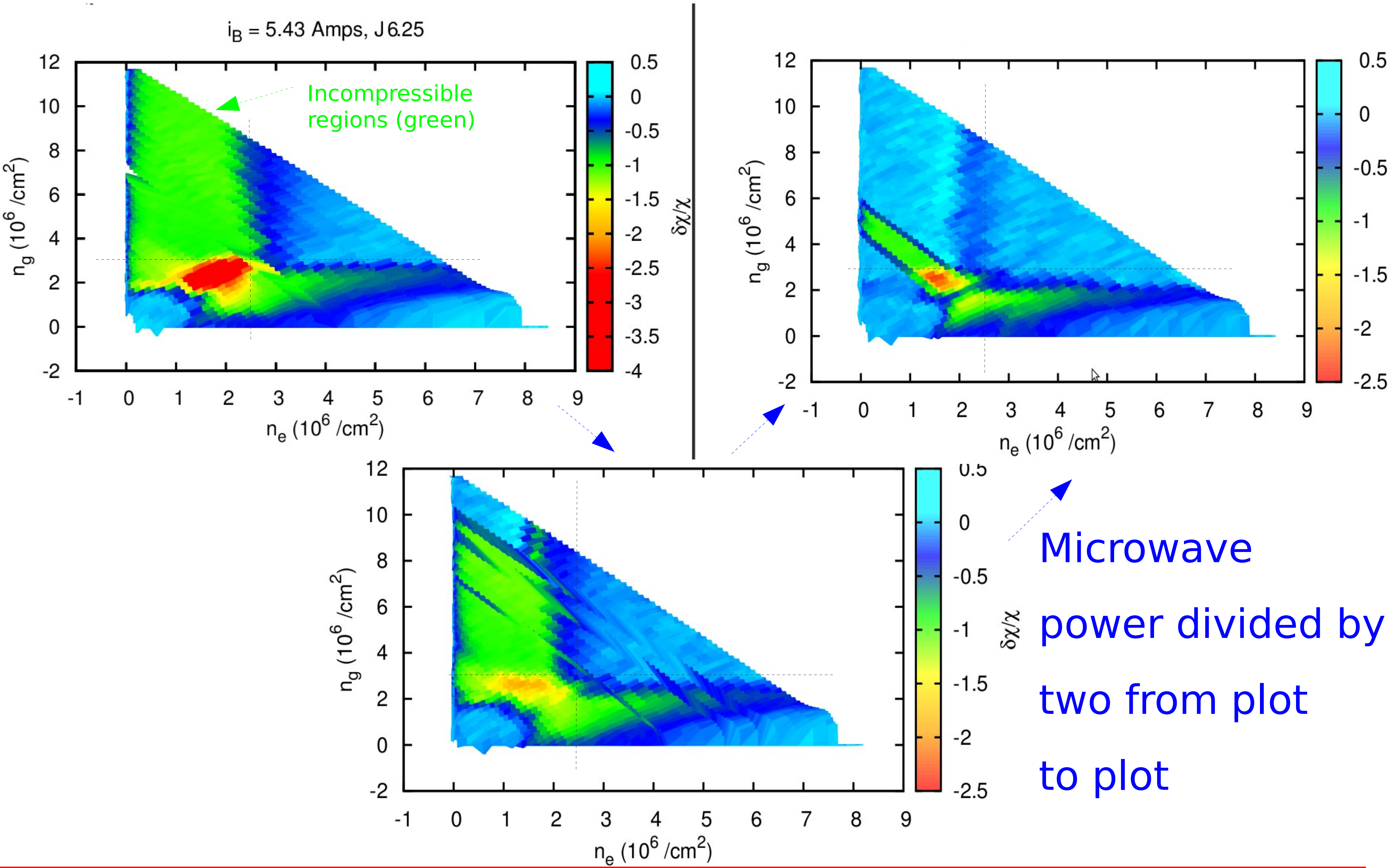
References:

D. Konstantionv, A.D. Chepelianskii, K. Kono, J. Phys. Soc. Japan (2012)

A.D. Chepelianskii, M. Watanabe, K. Nasyedkin, K. Kono and Denis Konstantinov

Published yesterday : Nature Communications 6, doi:10.1038/ncomms8210 (2015)

Dependence on microwave power

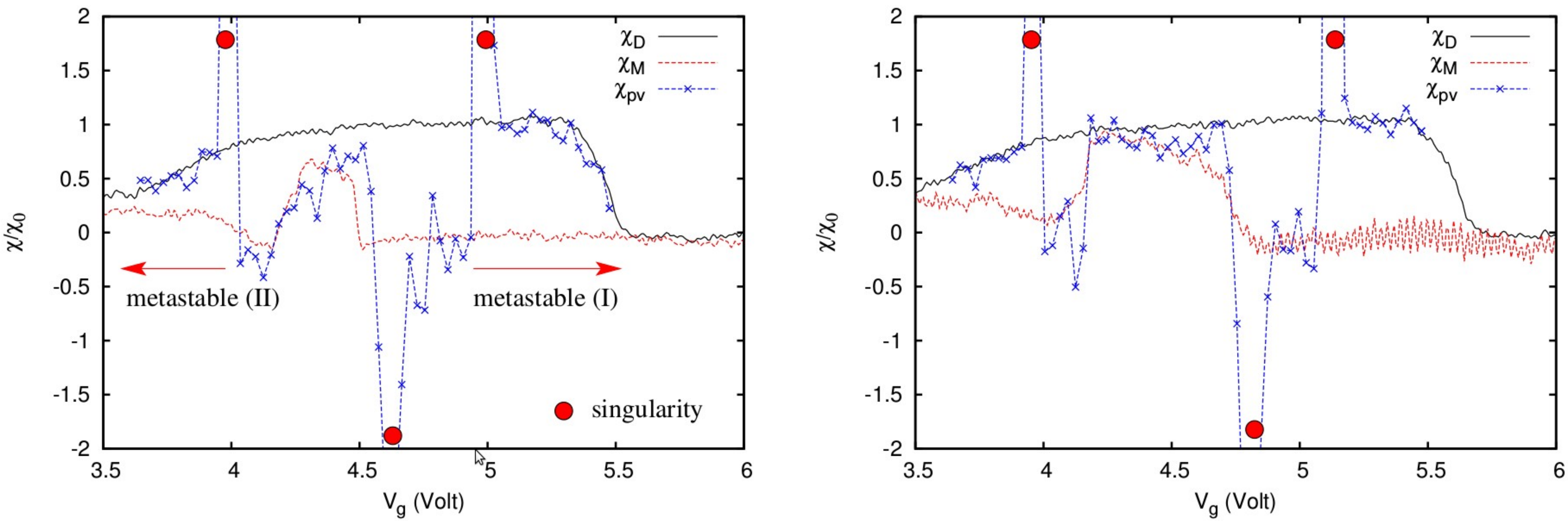


Microwave power divided by two from plot to plot

Vertical/horizontal boundaries are stable with microwave power

Consistency between the two techniques

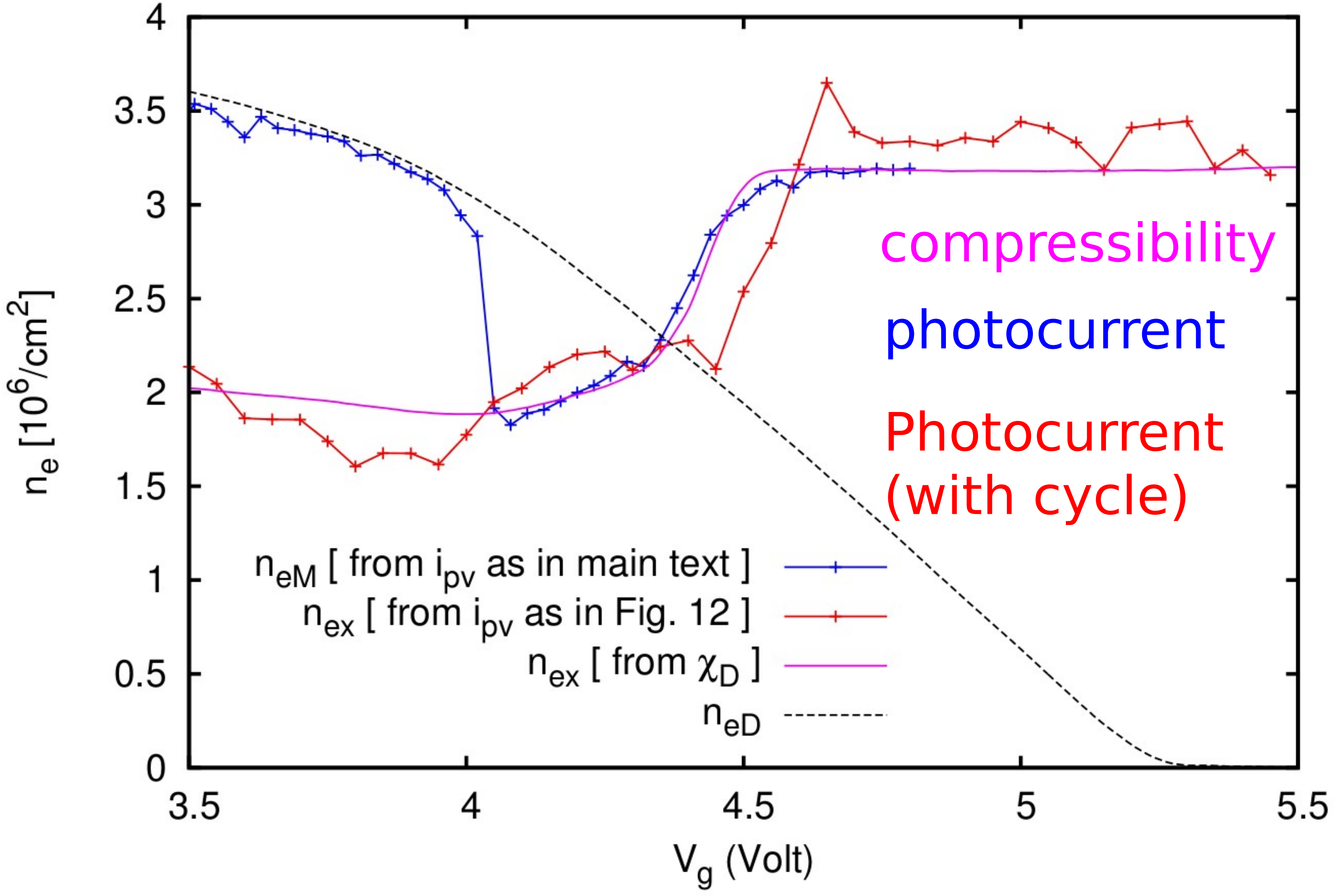
- We compare numerical differentiation of photocurrent data and compressibility measurement



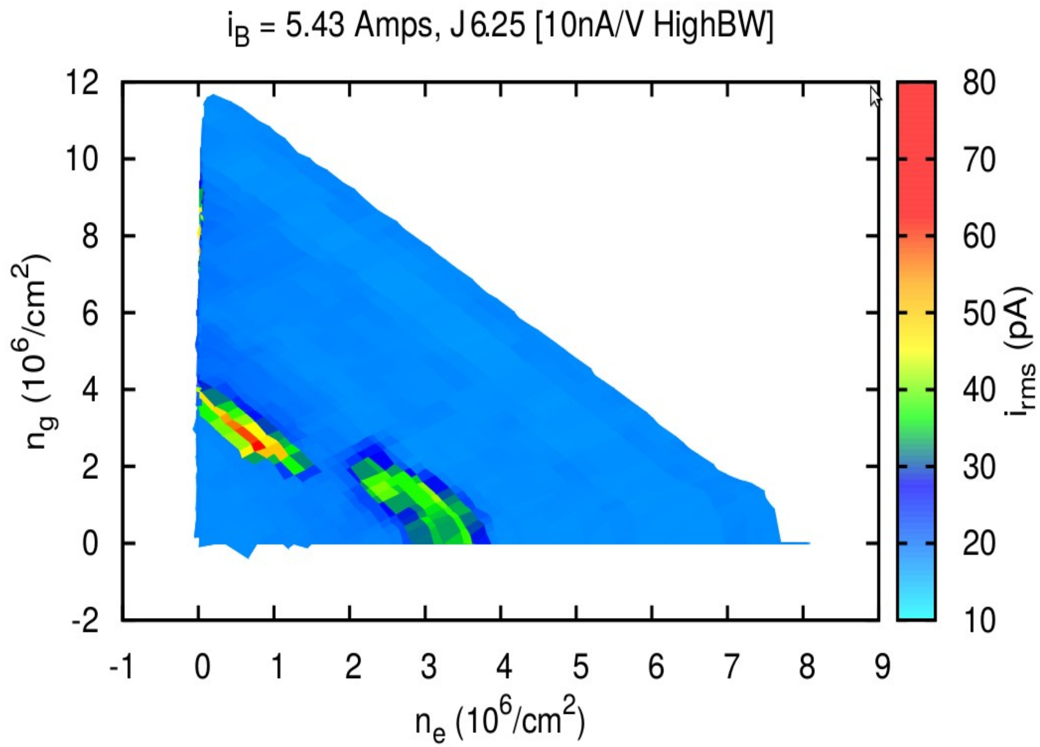
- Good agreement except at singular points (hysteresis)

Experimental data to be published in Nature Communications

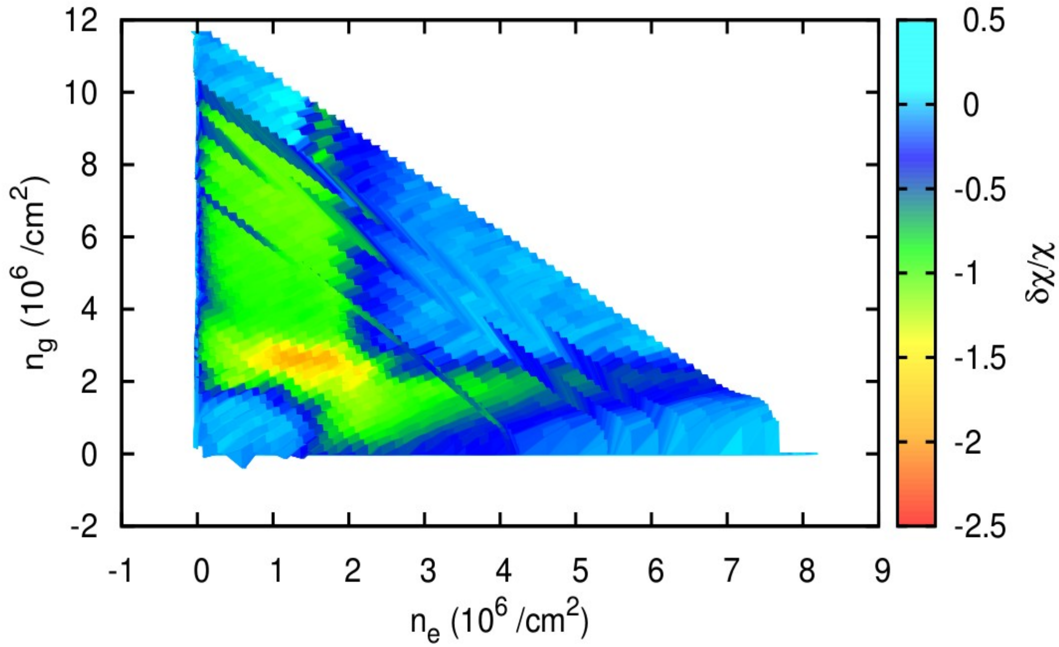
Density distribution under irradiation J = 6.25



- Density as function of gate using three different measurement techniques : good agreement



RMS current noise



Compressibility

Compressibility in equilibrium :

- Compressibility given by the minimisation of the electrostatic energy

  Plane capacitor model → $$\chi_0 = -\frac{dn_e}{dV_g} = \frac{4\epsilon_0}{eh(1+S_d/S_g)}$$

- Compressibility perfectly understood in the dark (much better than mobility and magnetoresistance)

- We are now ready for microwaves !

Incompressible electronic states

- In an incompressible electron gas the electron density n_e does not change with chemical potential μ_e

$$\frac{dn_e}{d\mu_e} = 0$$

  Experimentally μ_e can be controlled by a gate potential

- Example 1 : integer quantum Hall effect

  The energy cost to add an electron is: $\hbar\omega_c$

  it does not scale down with the size of the system (≠ Q. dot)

- Example 2 : fractional quantum Hall effect

VOLUME 50, NUMBER 18 PHYSICAL REVIEW LETTERS 2 MAY 1983

Anomalous Quantum Hall Effect: An Incompressible Quantum Fluid with Fractionally Charged Excitations

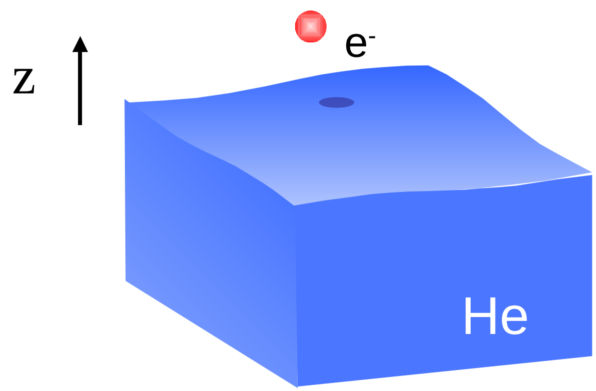
R. B. Laughlin

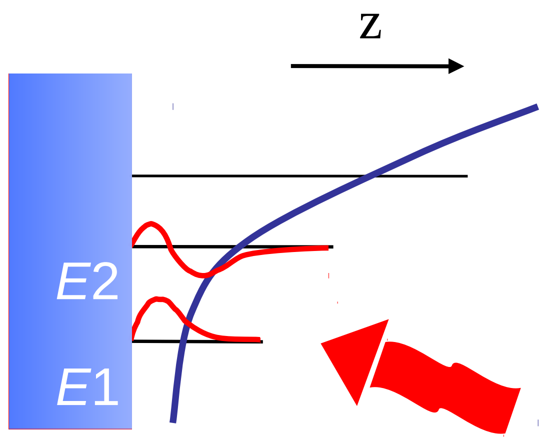
  The energy cost comes from electronic correlations: $\frac{e^2\sqrt{n_e}}{\epsilon}$

Probe edge theory on a different system : Electrons on liquid Helium surface

(visit to RIKEN 2010)

quasi-2D system





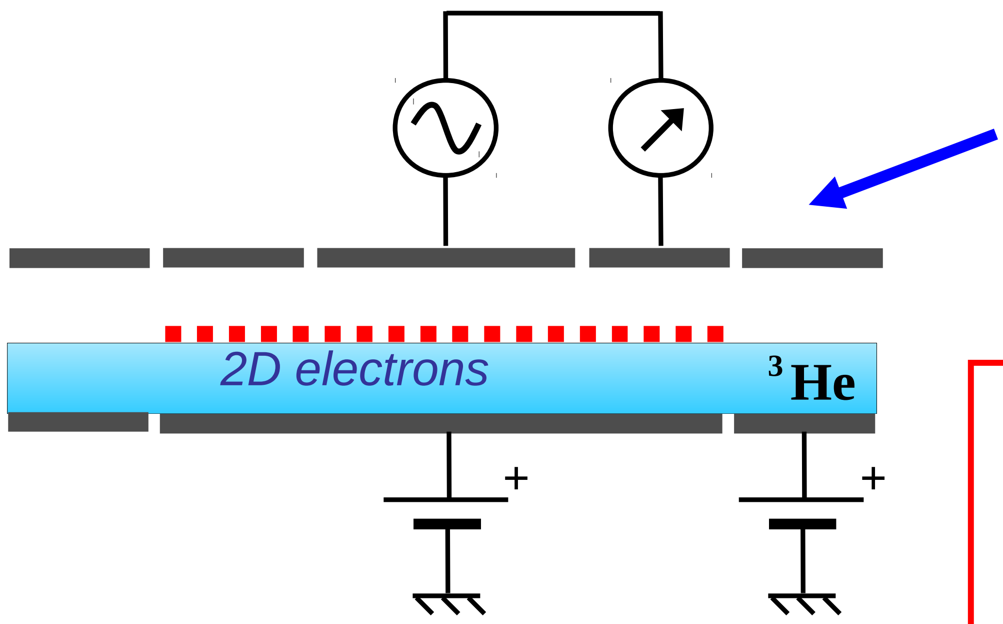
2D subbands

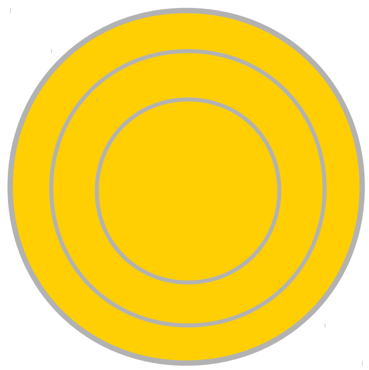
Discrete energy in z :

$$E_n, \quad n = 1, 2, ..$$

Attraction with

Image charge in liquid He





Top plate :

Corbino electrodes

Resistance measurement

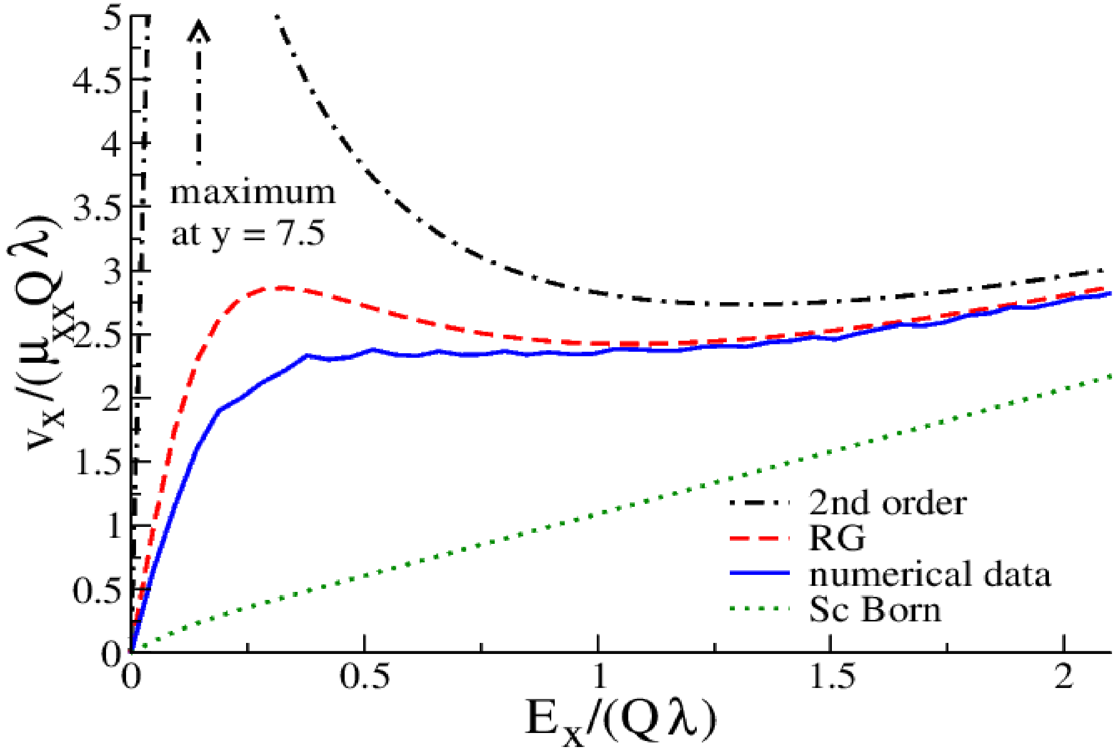
using capacitive coupling

Understanding e$^-$ transport properties

Drift/diffusion equation in magnetic field

$$\partial_t P = \mathrm{div}\,(\hat{\mu}[\mathrm{grad}\,U - \mathbf{E}]P) + D\Delta P$$

in presence of a random potential U(x,y)

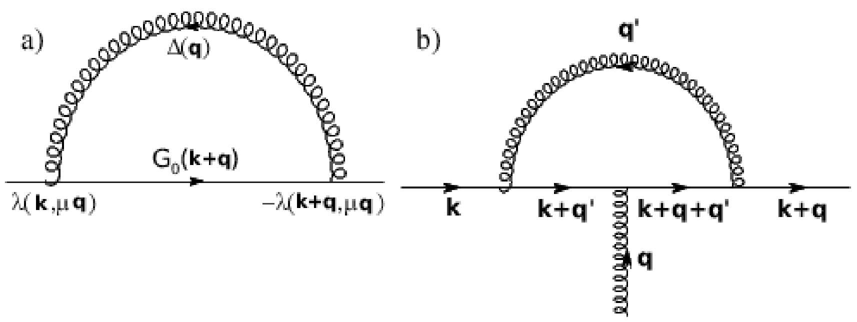


Treatment using

Numerical

and analytical methods

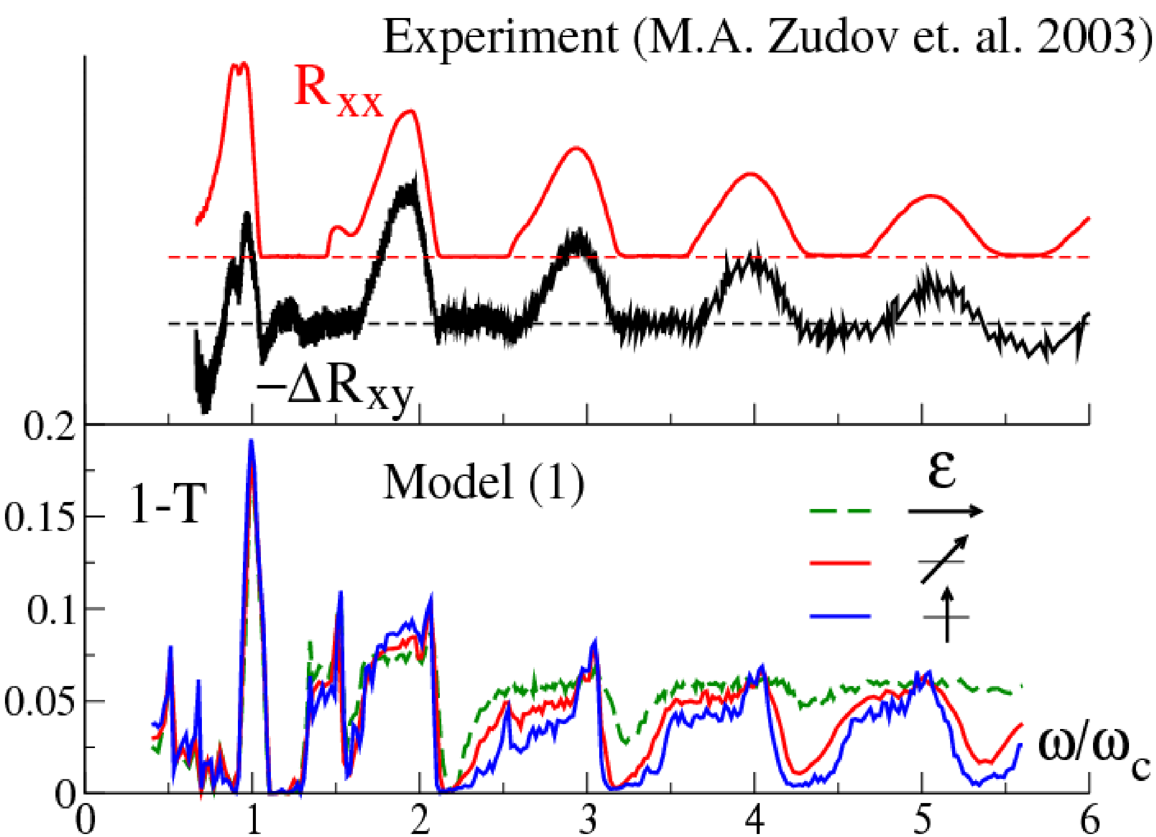
(Renormalization group)



Drift velocity (almost) independent on Electric field amplitude

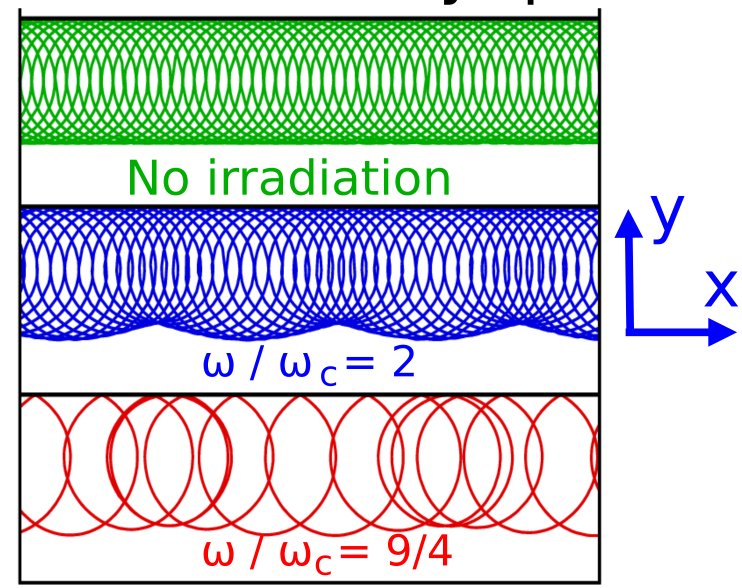
Theory : Microwave stabilization of edge transport

- Transmission → 1 along a sample edge in presence of microwaves
- Trapping at the edge ???

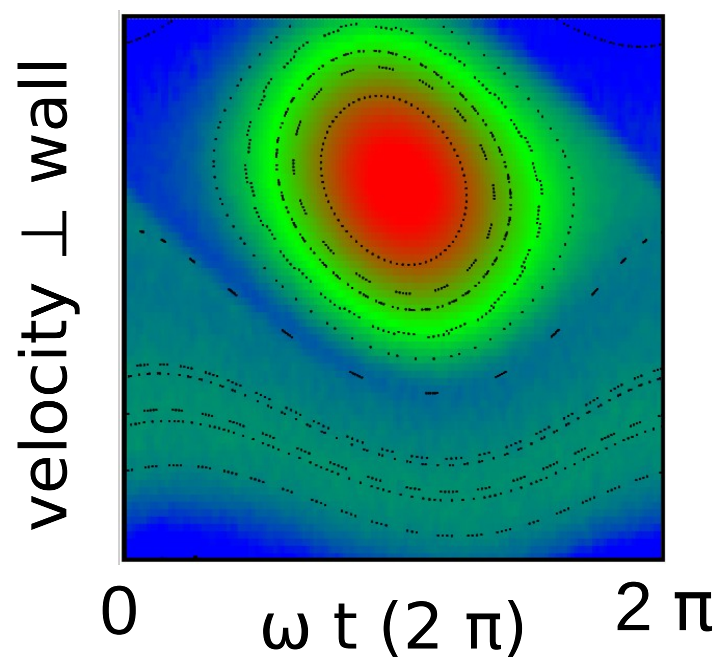


A.D. Chepelianskii, D.L. Shepelyansky PRB (2009)

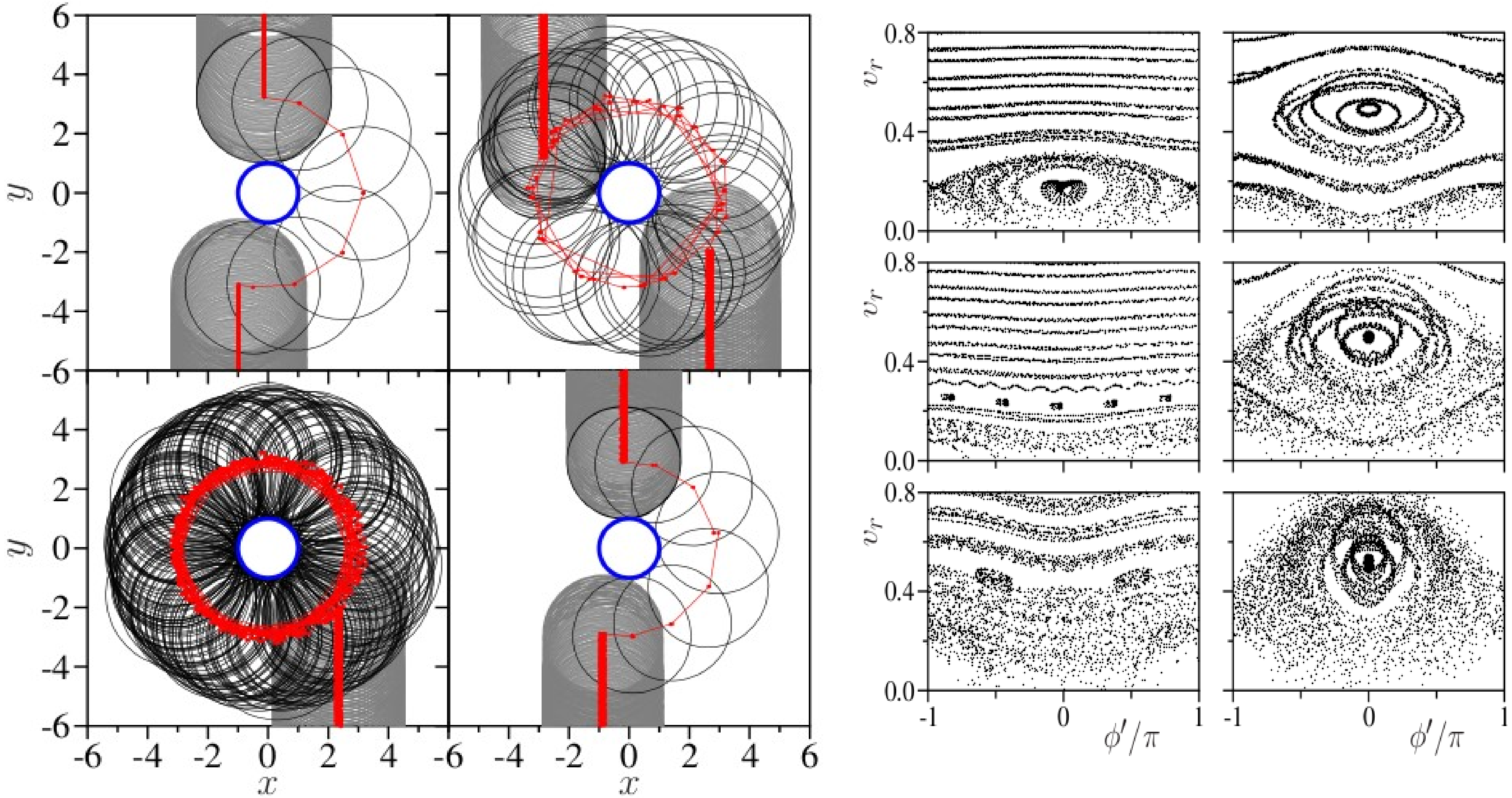
Trajectories in (x,y) plane



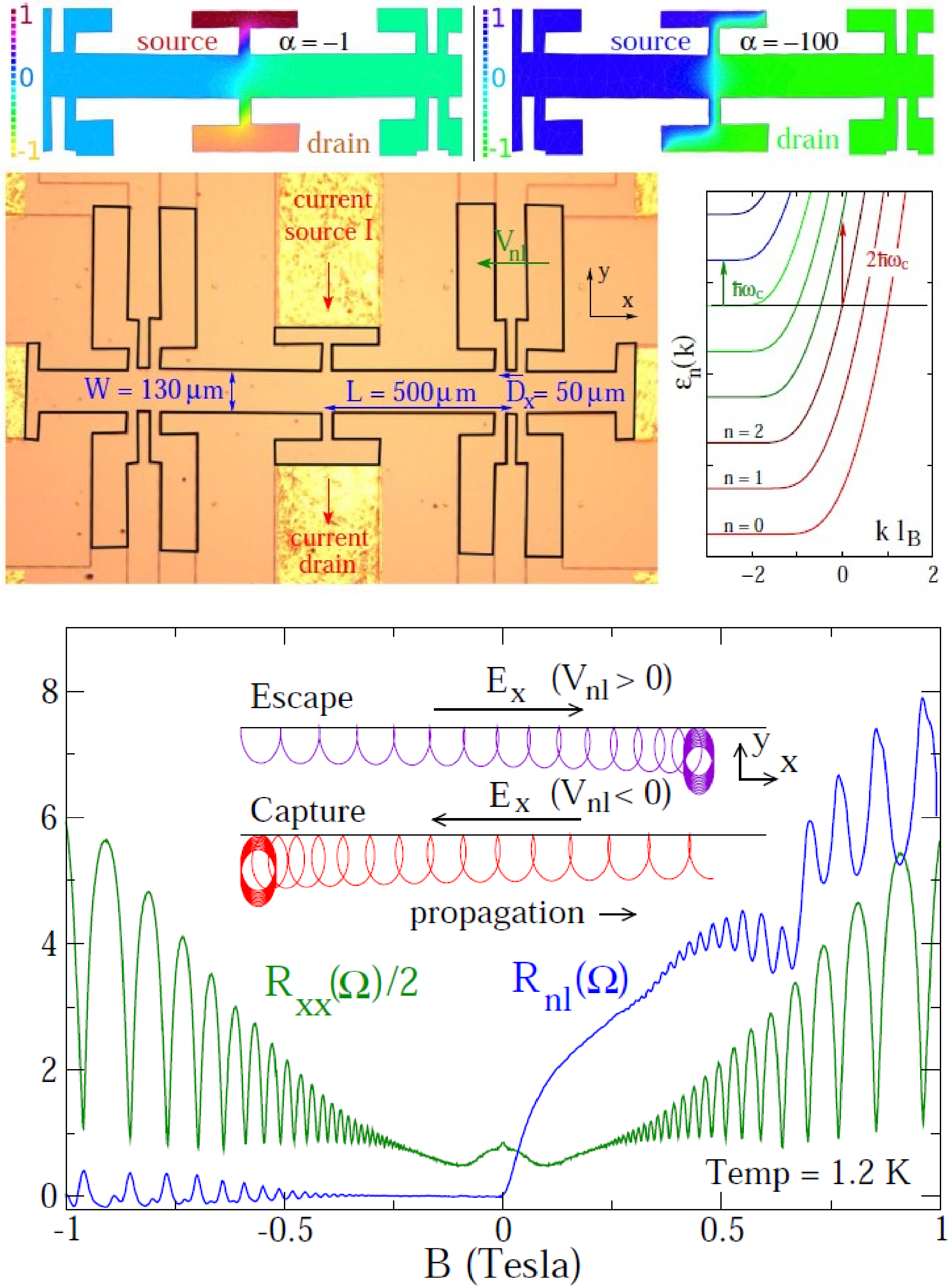
Chirikov standard map



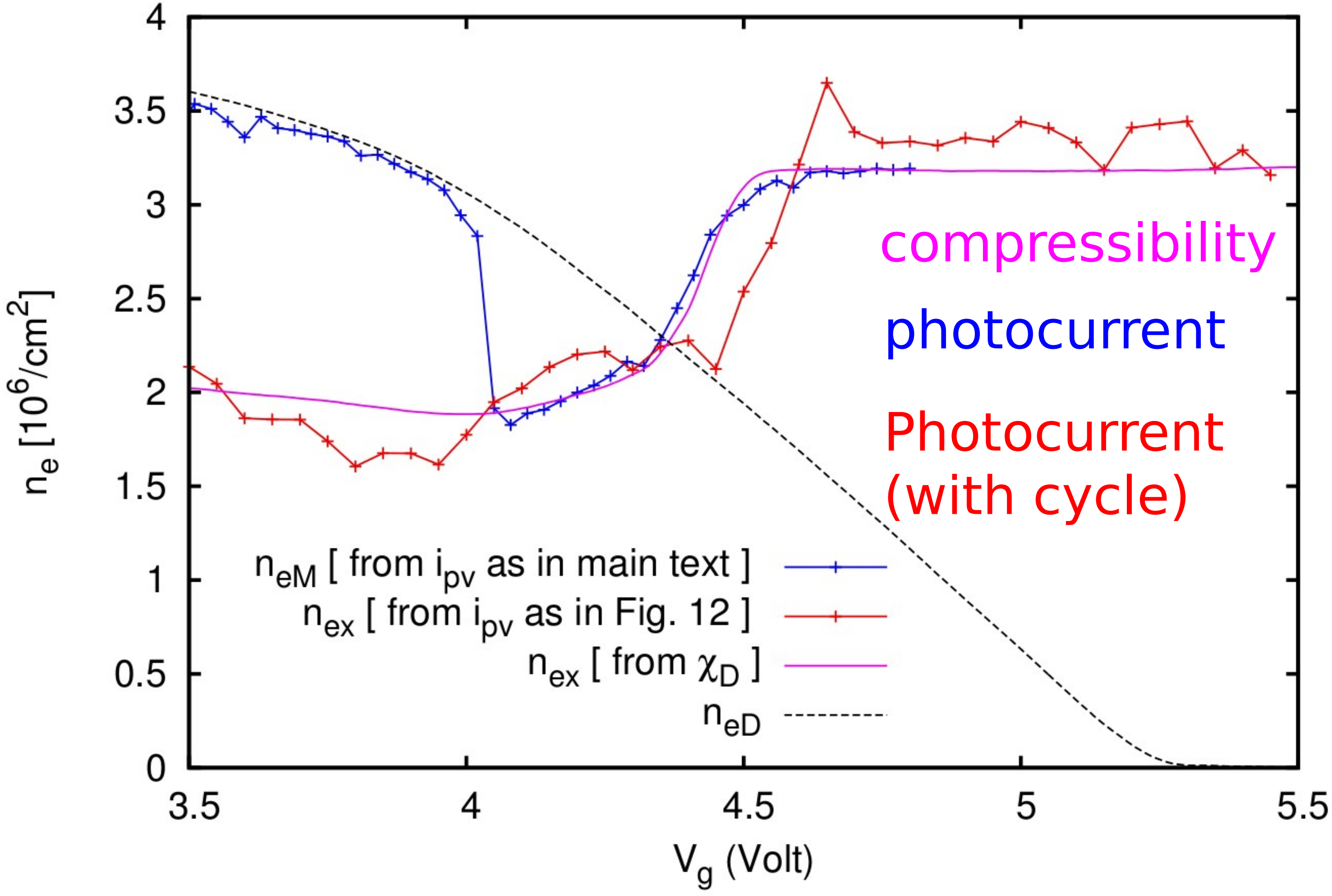
Non linear resonance on impurities



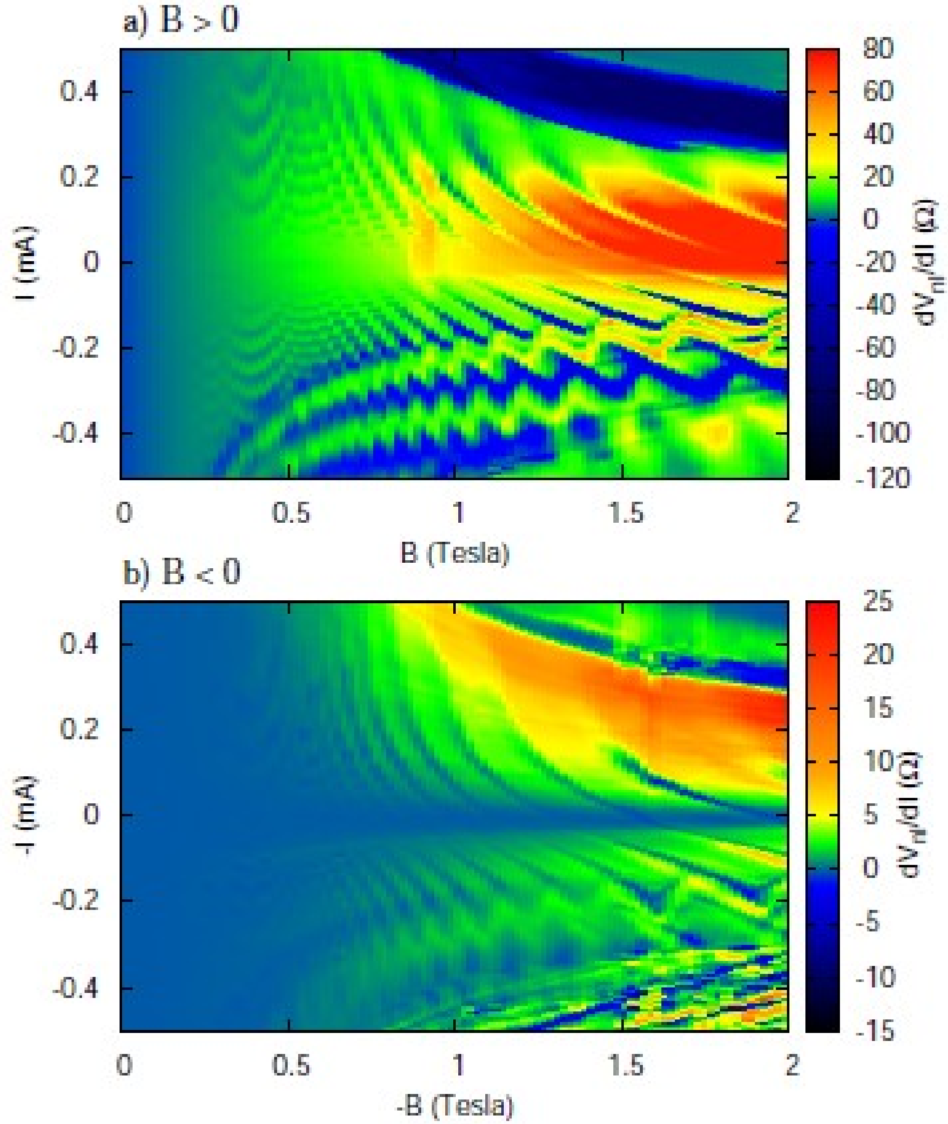
Non local effects

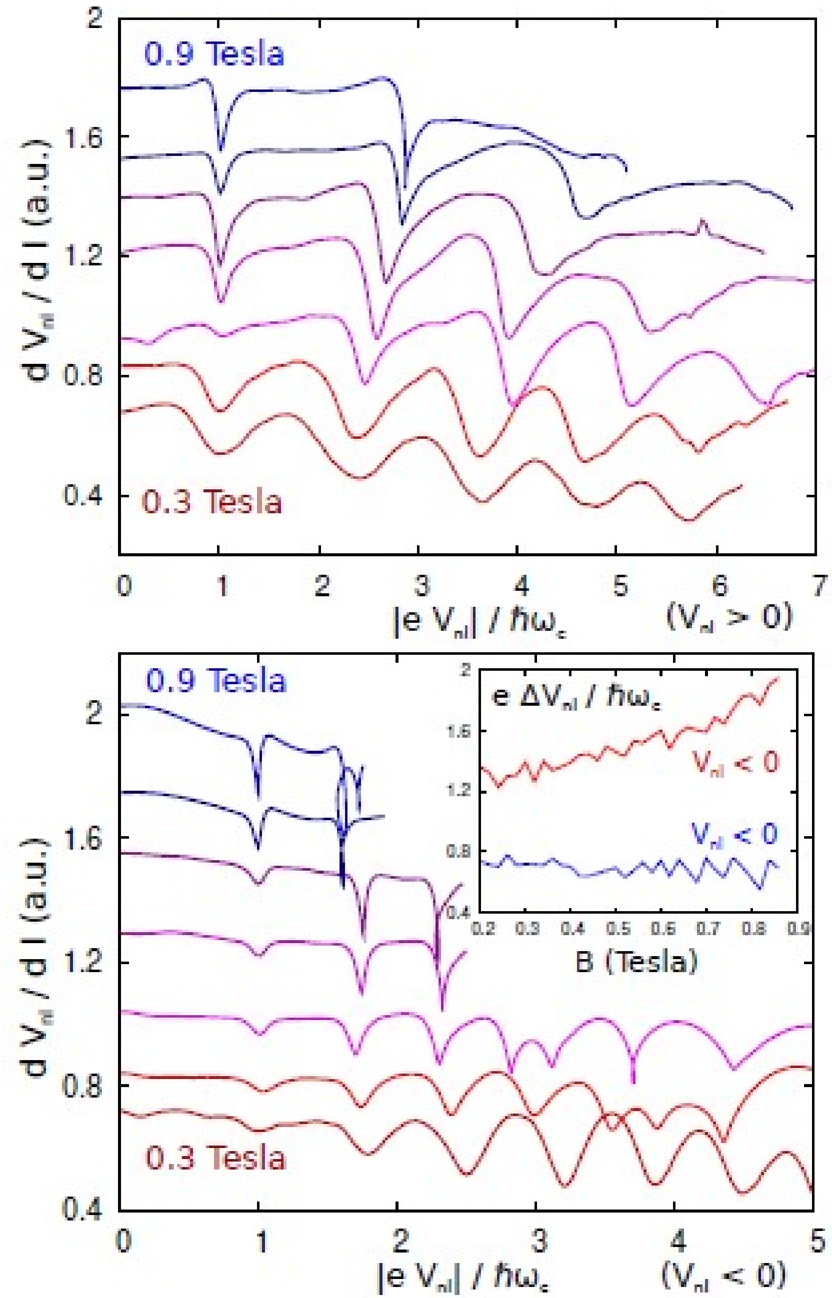


Density distribution under irradiation J = 6.25



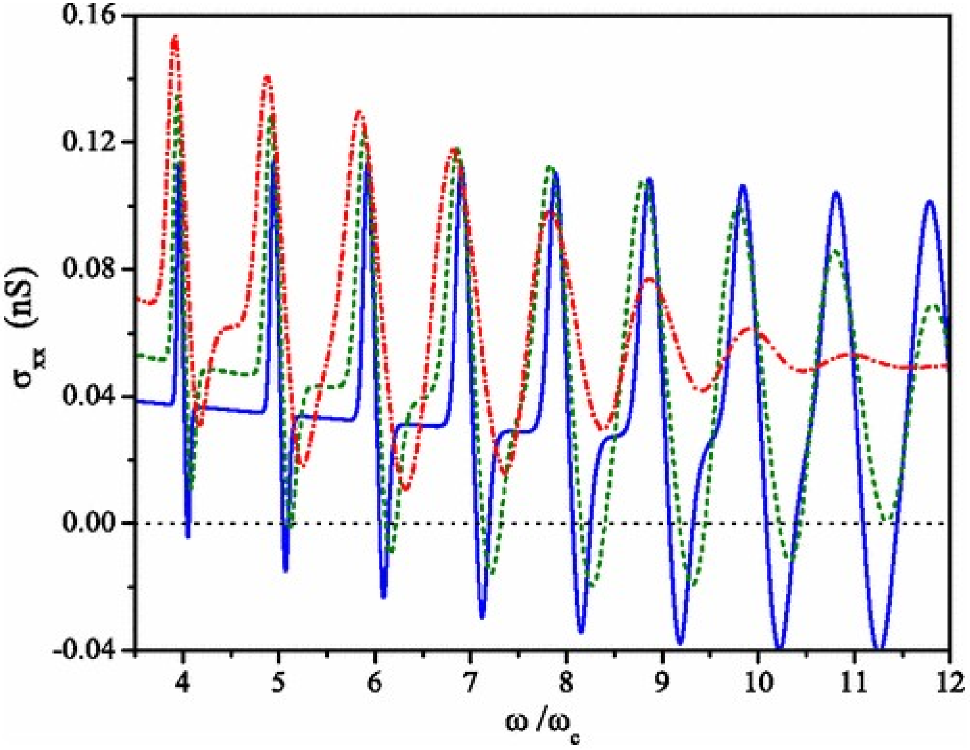
- Density as function of gate using three different measurement techniques : good agreement

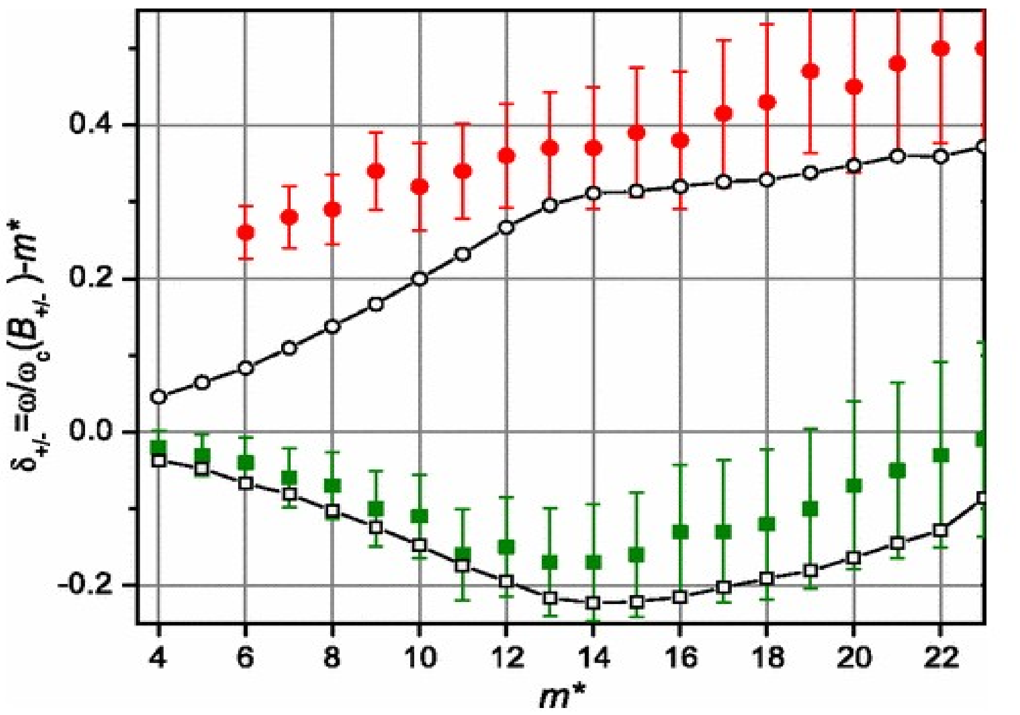

a) B > 0
I (mA)
B (Tesla)
dV_nl/dI (Ω)
b) B < 0
-I (mA)
-B (Tesla)
dV_nl/dI (Ω)


0.9 Tesla
0.3 Tesla
d V_nl / d I (a.u.)
|e V_nl| / ħω_c
(V_nl > 0)
0.9 Tesla
0.3 Tesla
e ΔV_nl / ħω_c
V_nl < 0
V_nl < 0
B (Tesla)
d V_nl / d I (a.u.)
|e V_nl| / ħω_c
(V_nl < 0)

2) Theory by Y. Monarkha

- Rate equations [ignores coherent effects: Floquet wave functions and memory effects]





- Seems to reproduce the position of $\sigma_{xx}(B)$ minima/maxima

- Gives $\sigma_{xx} < 0$ but no incompressible state/redistribution etc ...