Non equilibrium transport In ultra clean systems

A.D. Chepelianskii

Experiments on surface electrons :
D. Konstantinov, K. Kono

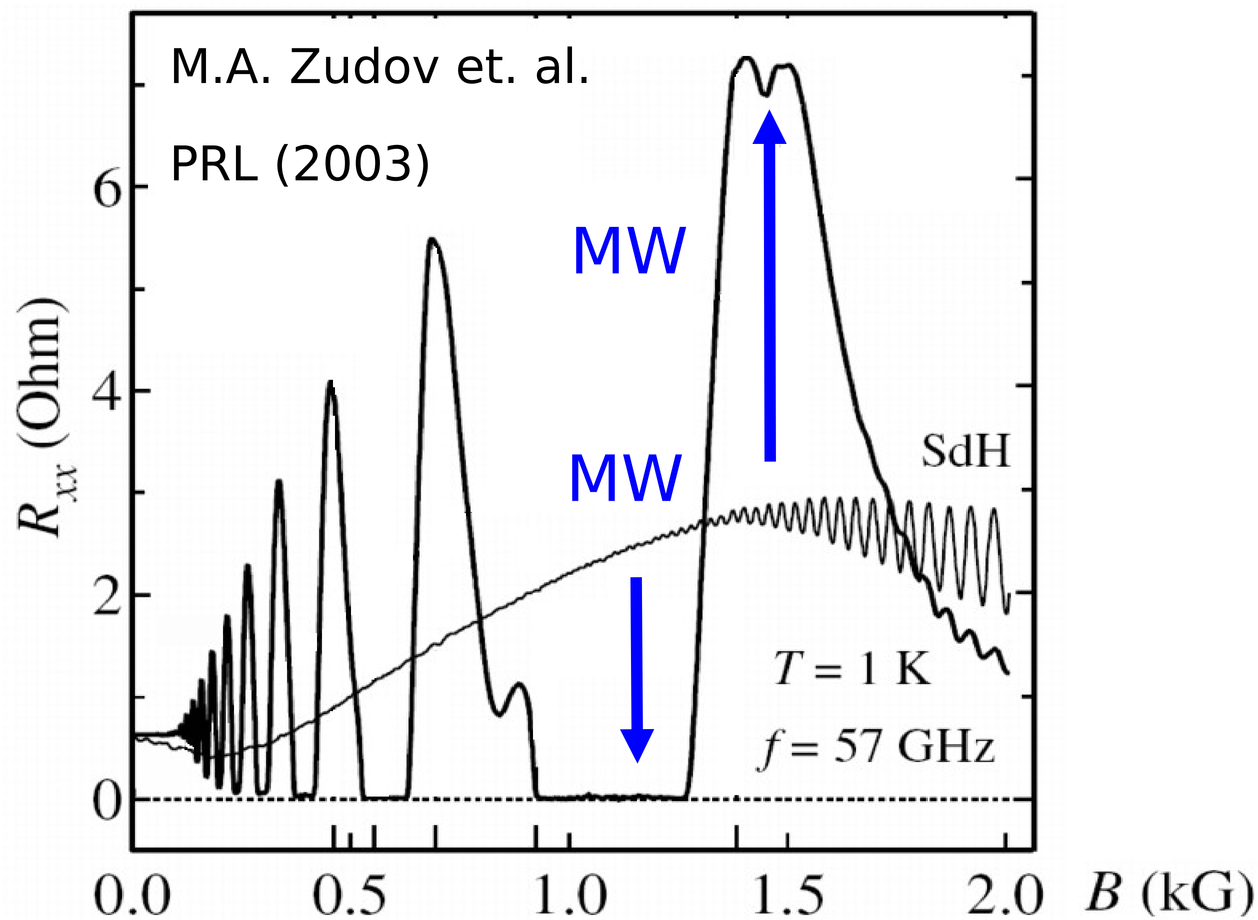
Experiments in Orsay :
J.Laidet, H. Bouchiat
groupe de physique mesoscopique

Theory: **D.L. Shepelyansky**

Experiments in Cambridge :
A. Brewer, I. Farrer, H.E Beere, D.A. Ritchie
R.H Friend

Microwave induced zero-resistance states

- 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

Existing theories :

- Most developed theory (elastic/inelastic) :
  negative resistance & domains theory
  outstanding contributors in the audience

- J. Inarrea theory (a bulk theory as well)

- Microwave effect on edge channels (“home” theory)

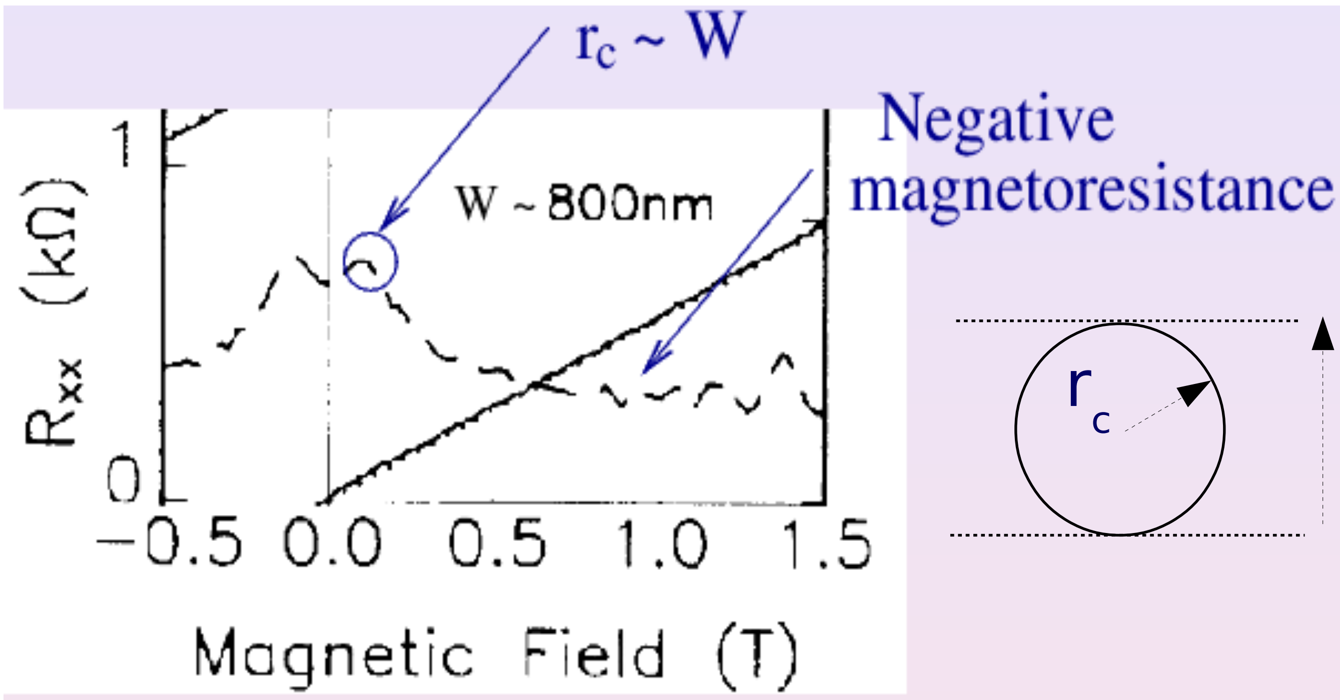
- Microwave effect on contact regions ! S.A. Mikhailov (2011)

Bulk transport/edges/contacts ...

All possibilities offered by Solid State physics were tried !

Commensurably effects in transport

When the Larmor Radius r_c is commensurable with the channel width W magneto-transport changes



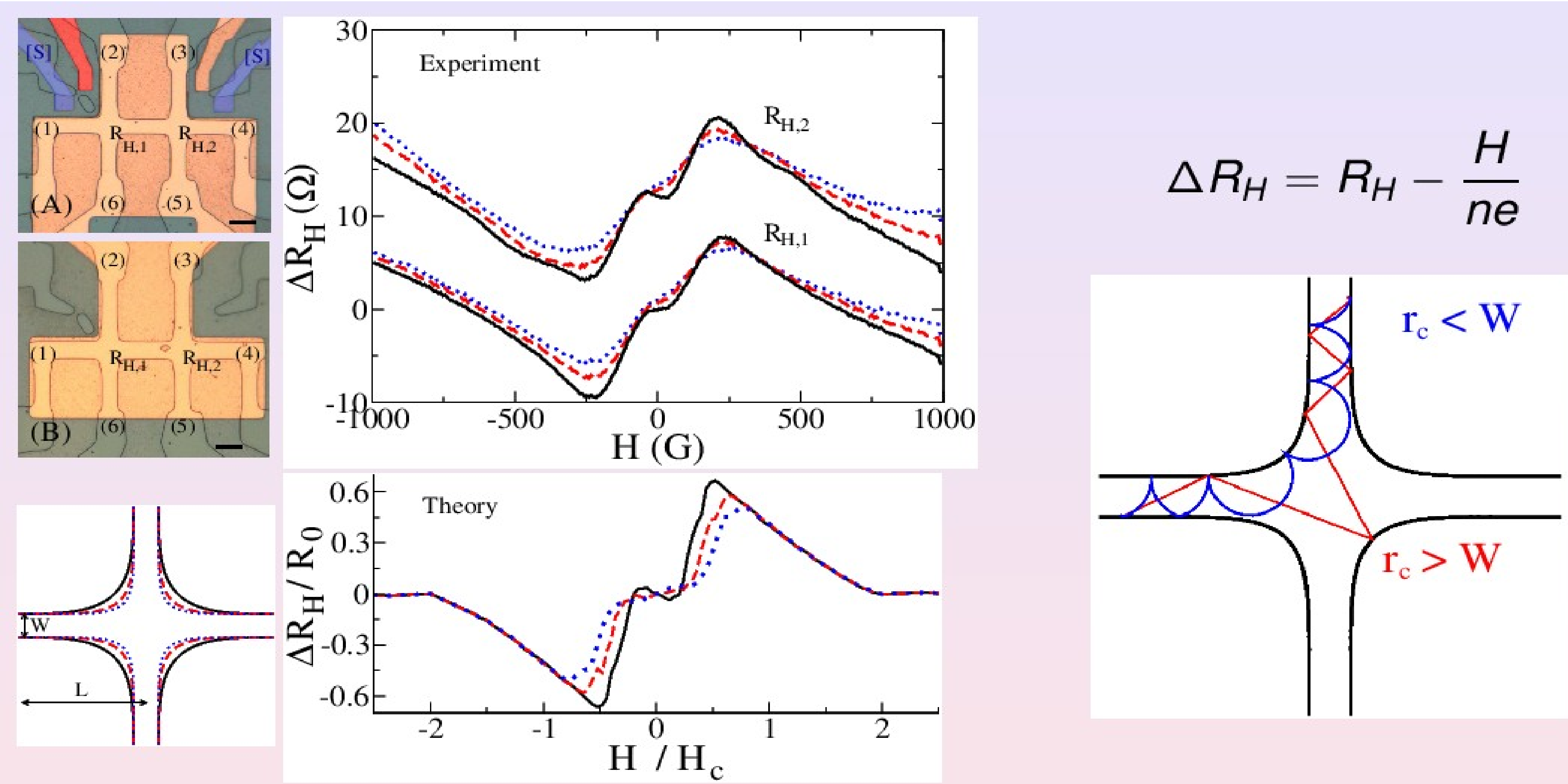
M.L. Roukes et. al. PRL 1987

- Peaks when $r_c \sim W$
- Suppression of R_{xx} when $r_c < W$

Understanding using a billiard model

- Determine Hall resistance R_H, R_{xx} from the classical

Transmission probabilities from one contact to another



$$\Delta R_H = R_H - \frac{H}{ne}$$

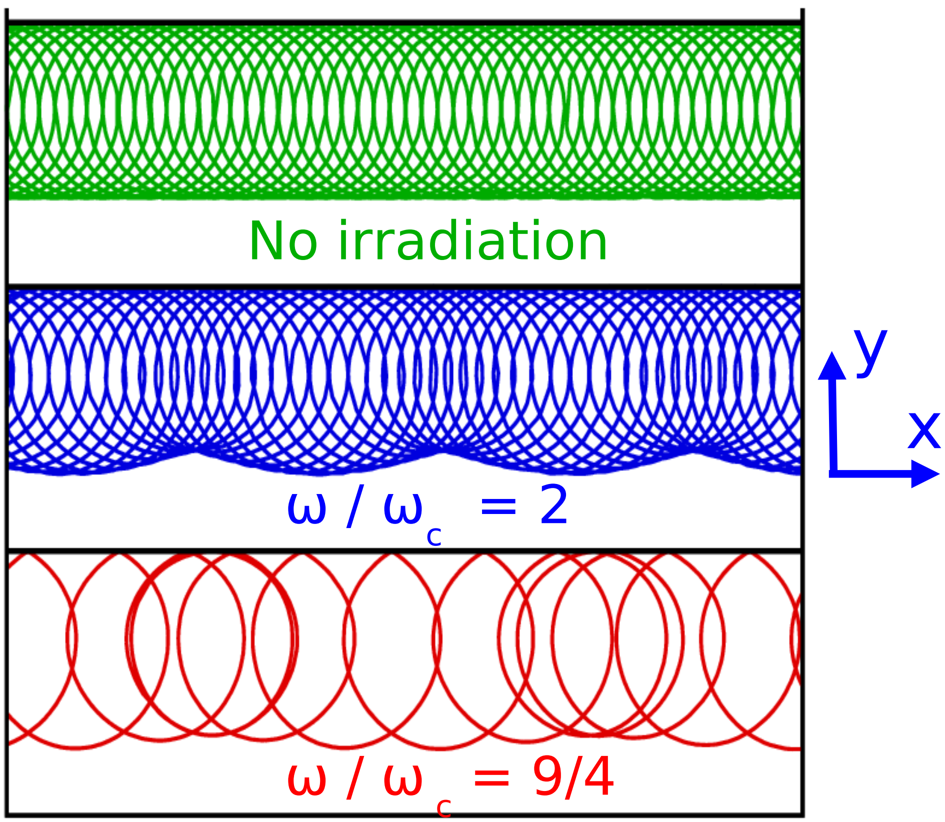
Billiard model C.W. Beenakker et. al. PRL 1989; Experiments A.C. PRL 2009

If guiding becomes perfect $R_{xx} \to 0$!?

Theory : Microwave stabilization of edge transport

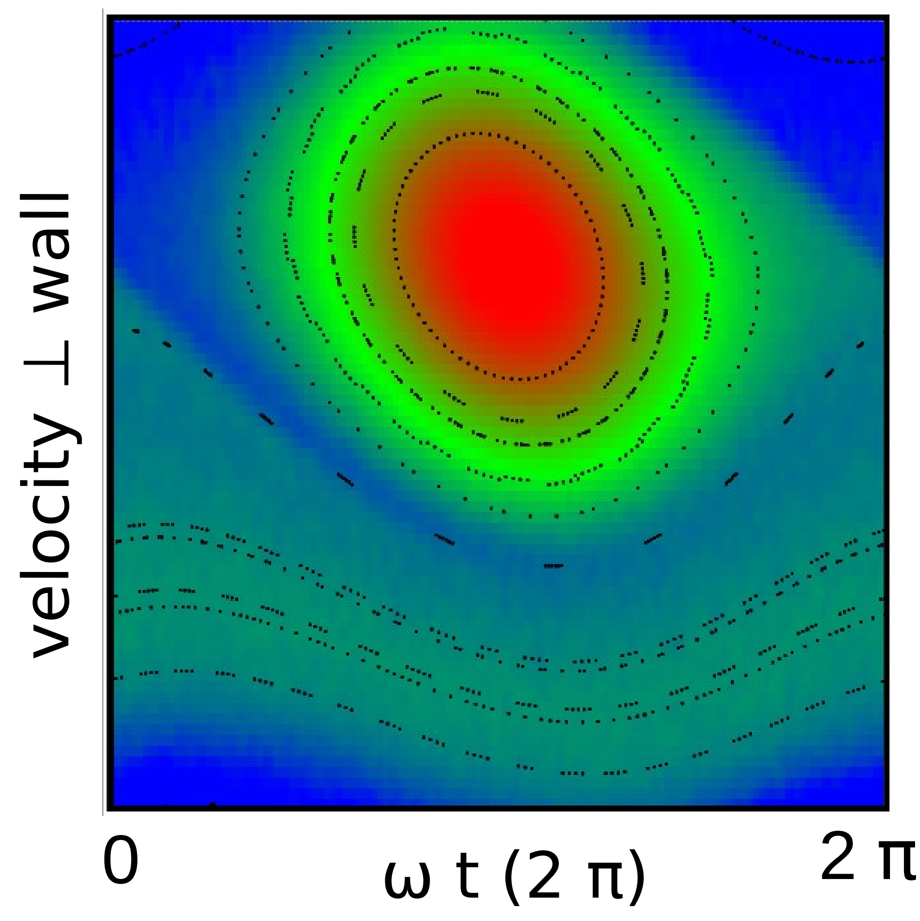
- Non linear resonance under microwave irradiation
- With dissipation → attractor and trapping

Trajectories in (x,y) plane



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

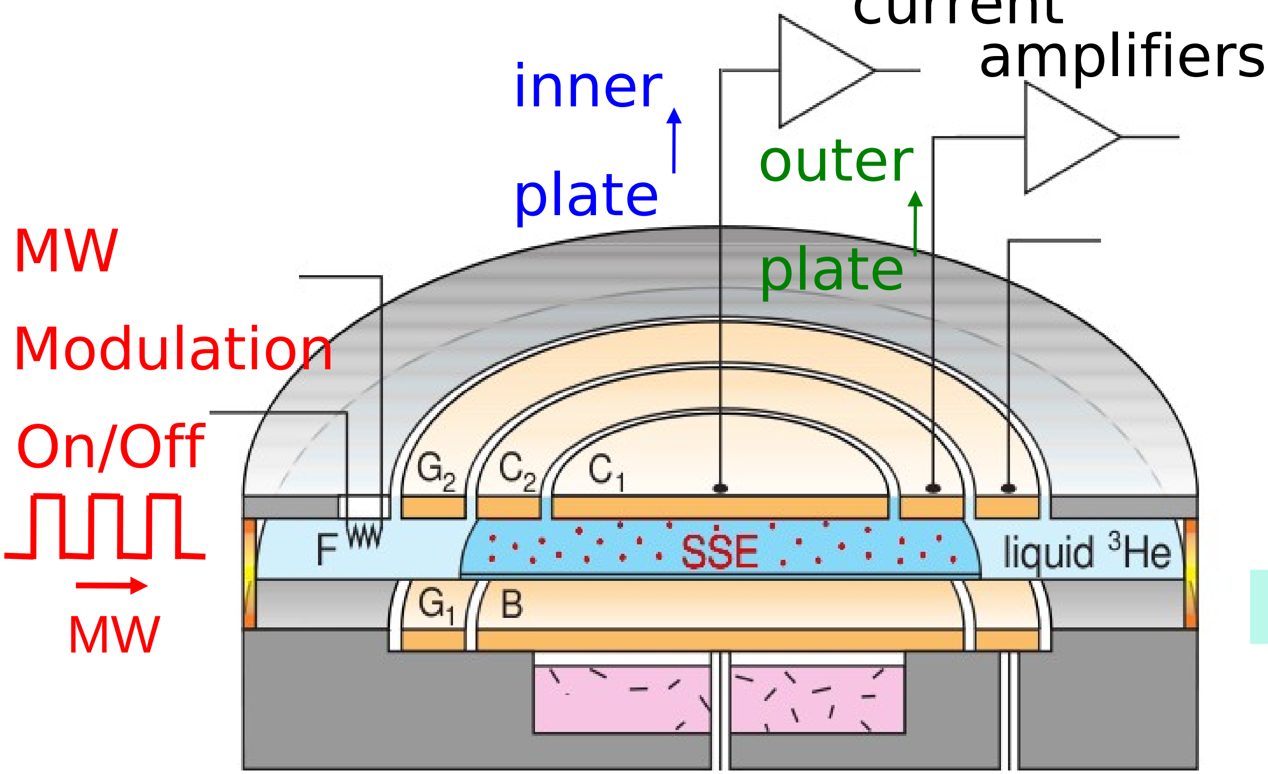
Chirikov standard map



How to detect trapping at the edge ?

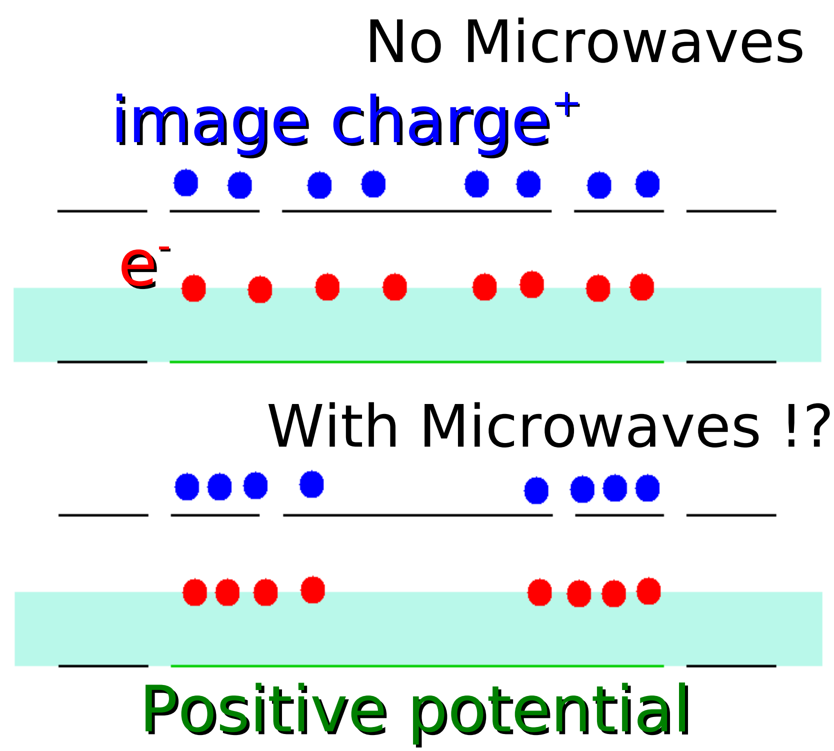
Modulate the microwave power without external bias !

Detect transient currents due to motion of image charge



70GHz amplitude

modulated at 1 Hz



When MW switched on

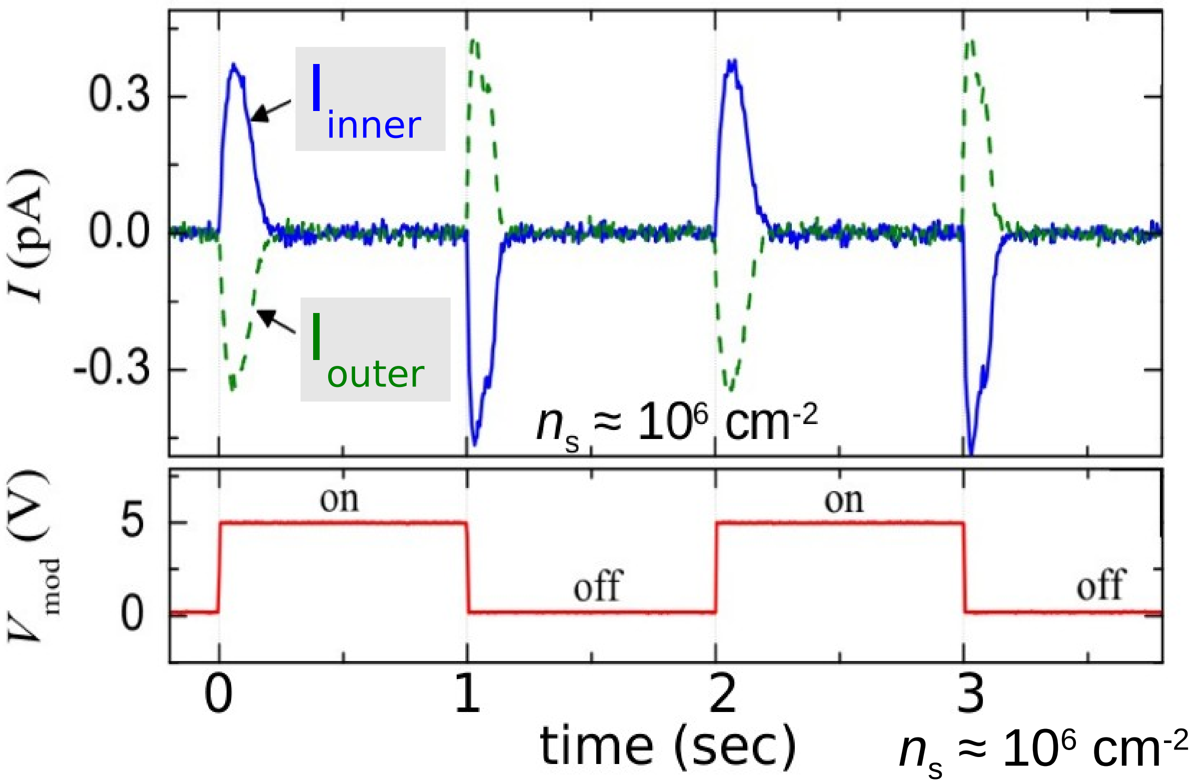
Positive image charge released

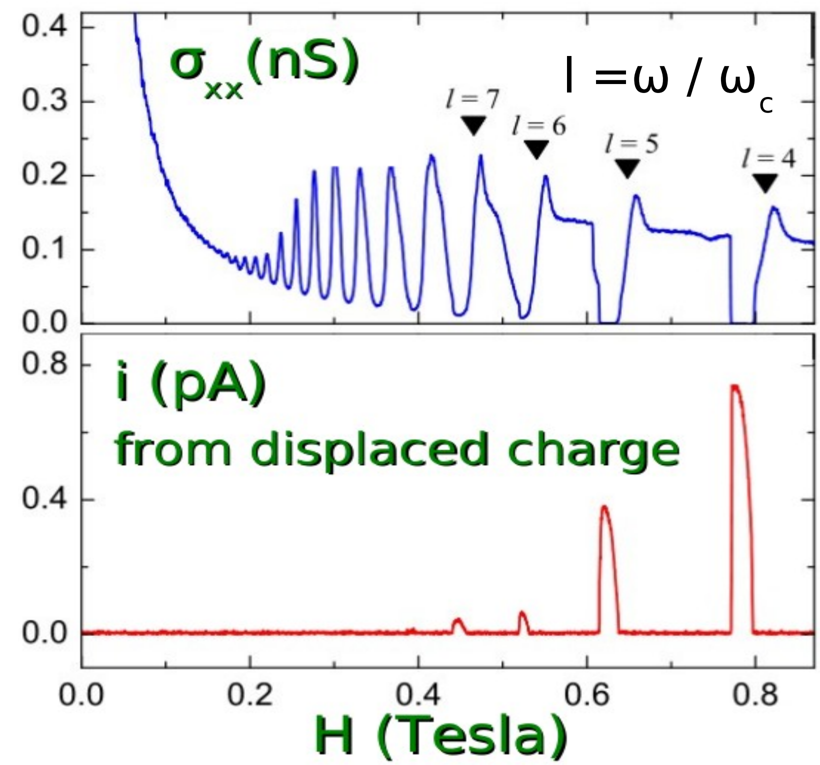
Positive inner transient current

Transient radial currents !

Under the experimental conditions for ZRS

current from inner to outer plate when MW ON



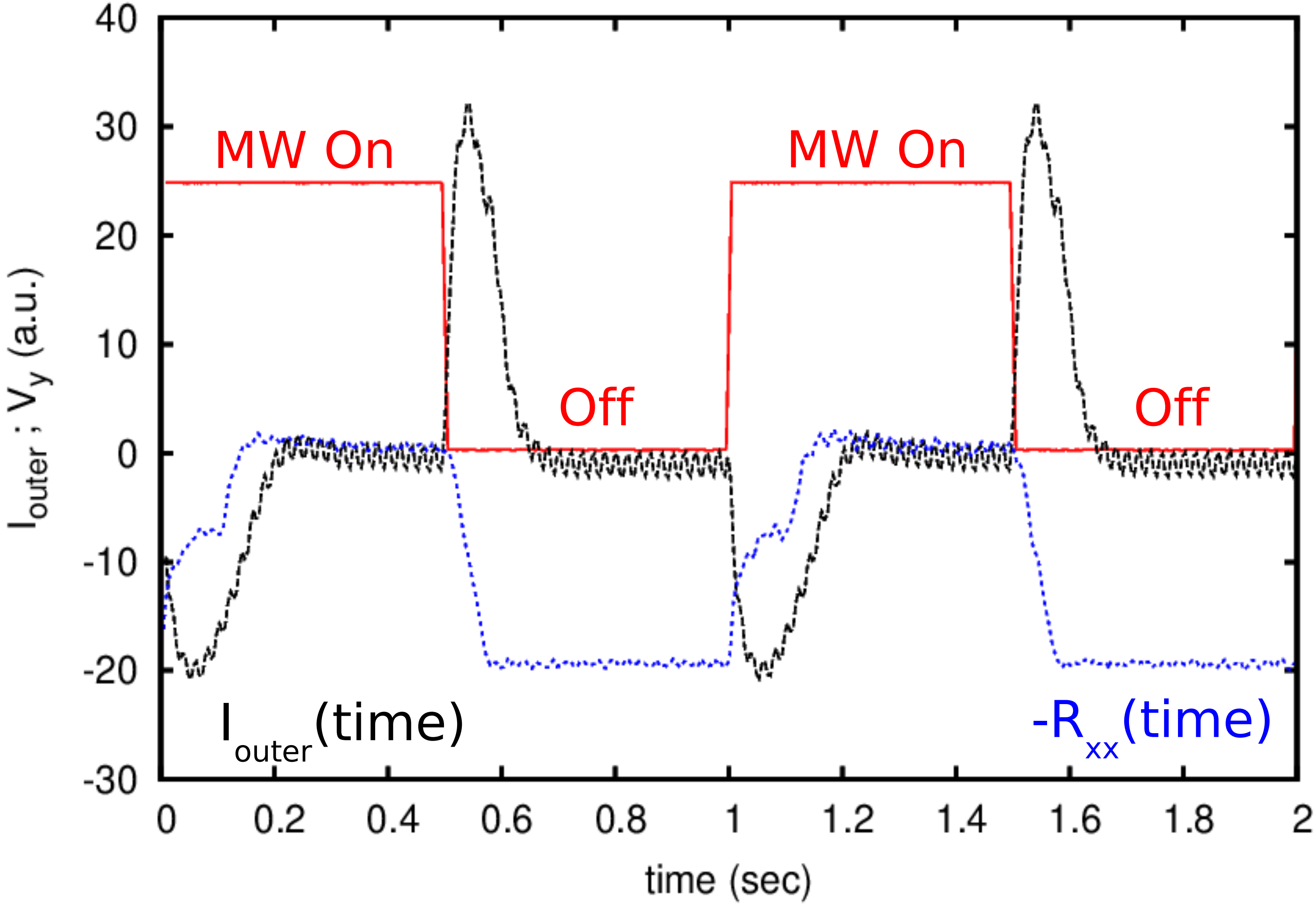


Large fraction of electrons (20 to 100%) move to the edge

Demonstration of trapping at the edges !

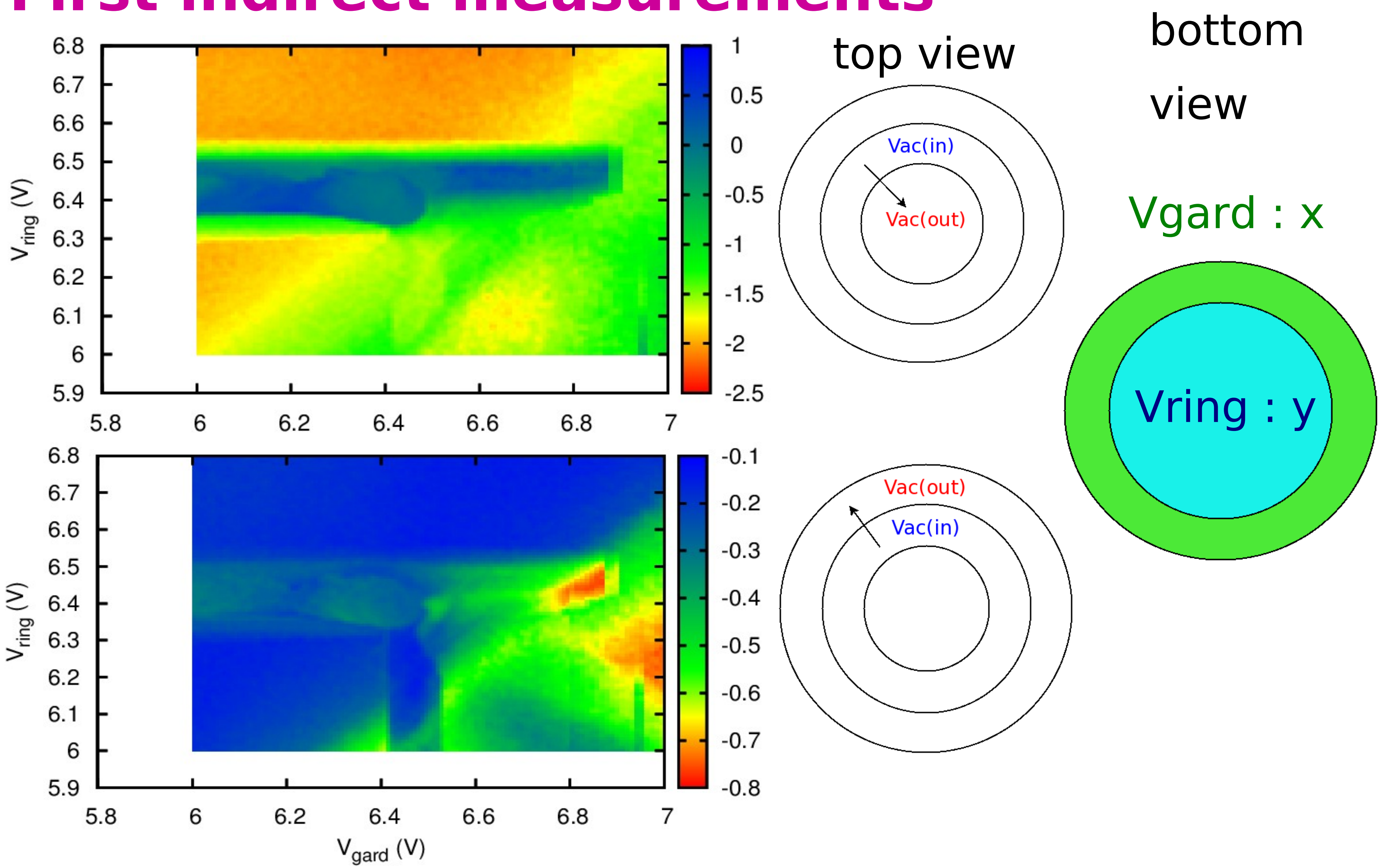
D. Konstantionv, A.D. Chepelianskii, K. Kono, arxiv:1101.5667 submitted to PRL (2011)

Transient conductivity measurements



Zero resistance appears only when the charge redistribution is completed

First indirect measurements

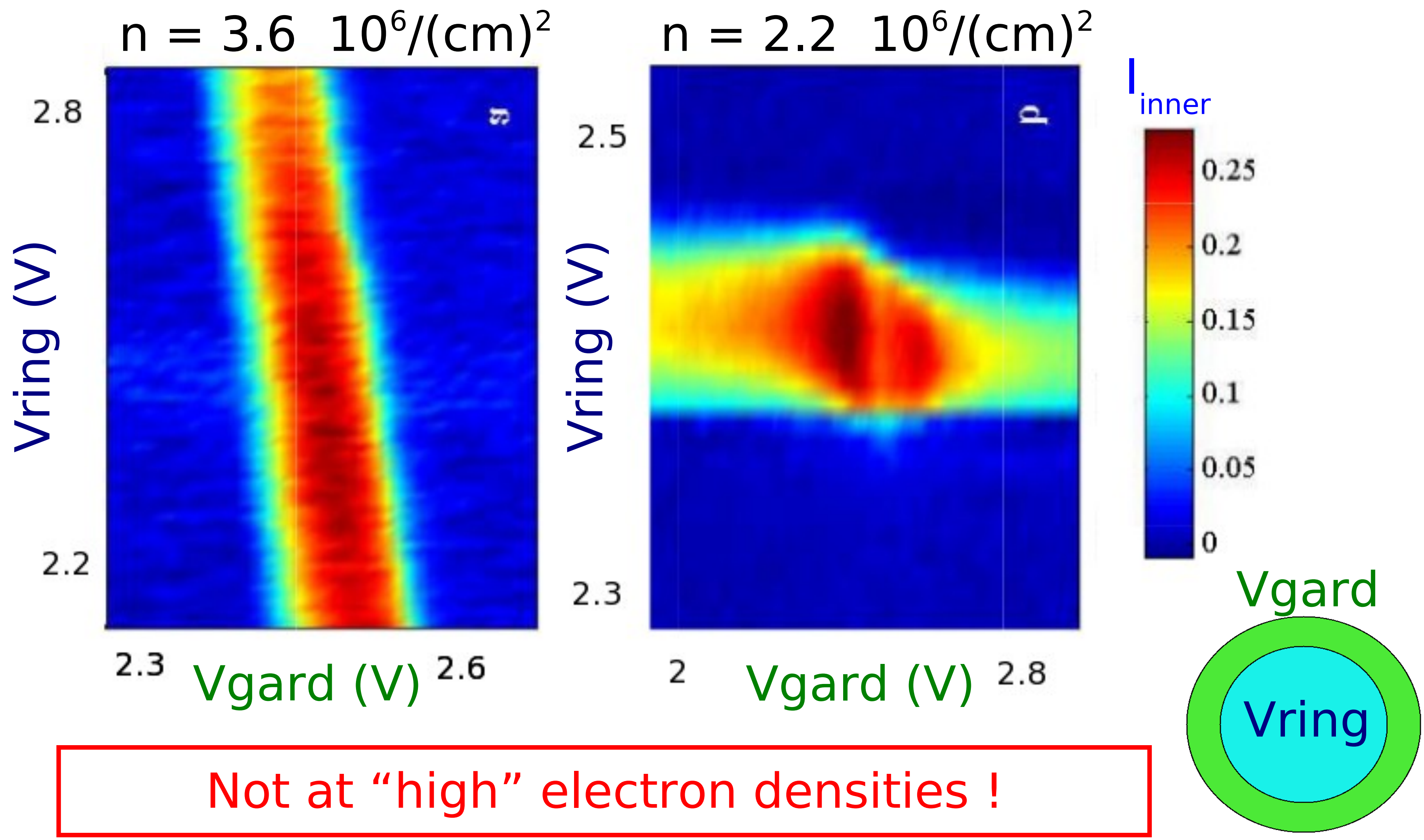


Zero resistance in the center but not at the edge !

Local resonant excitation

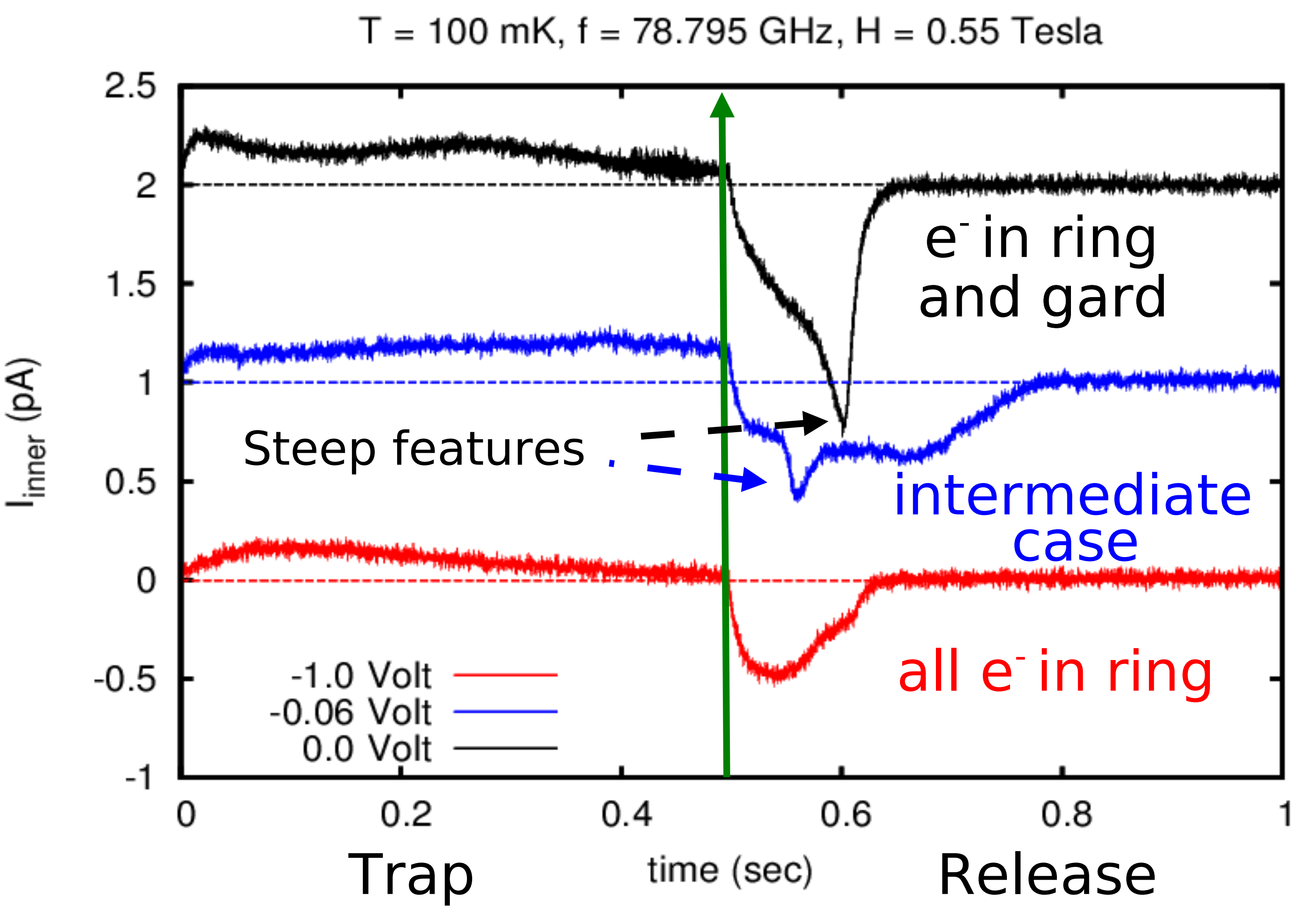
Since electrons are trapped at the edge,

do we really need resonant excitation in the center ?

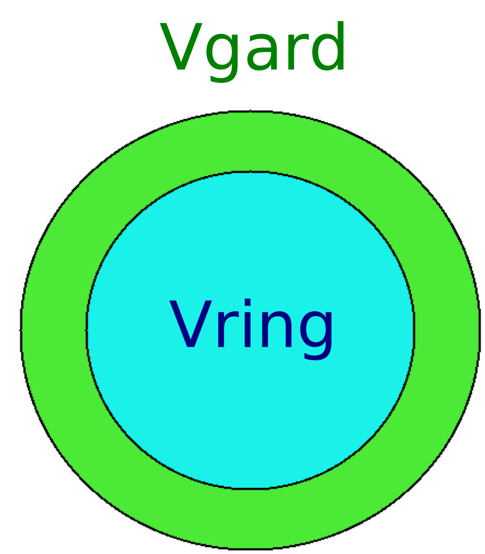


Not at “high” electron densities !

Reconstruction of the density profile from the decay kinetics ?



Change Vgard - Vring



Indications of a steep density distribution ?

Multi-photon absorption

High repulsion energy per trapped e^- ~ 1eV

Conservation of energy : many 0.4meV photons per e^-

Model Hamiltonian (at short times) :

$$\hat{H} = \hbar\omega_c(\hat{a}^+\hat{a} + \frac{1}{2}) + \sum_k \epsilon_k |k><k| + \hat{H}_{angle} + \hat{W} + \hat{H}_{ac}(t)$$

Landau levels z levels

$$\hat{H}_{angle} = i\alpha\sqrt{\frac{\hbar m\omega_c^3}{2}} \sum_{k,k'} z_{kk'}(\hat{a} - \hat{a}^+)|k><k'|$$

tilt in the magnetic field

$$\hat{W} = \sum_{l,l';k,k'} W_{l,l';k,k'} |l><l'| \otimes |k><k'|$$

Riplons

$$\hat{H}_{ac}(t) = eE_z \sum_{l,n} z_{ln} |l><n| \cos\omega t + eE_x\sqrt{\frac{\hbar}{2m\omega_c}}(\hat{a} + \hat{a}^+)\cos\omega t$$

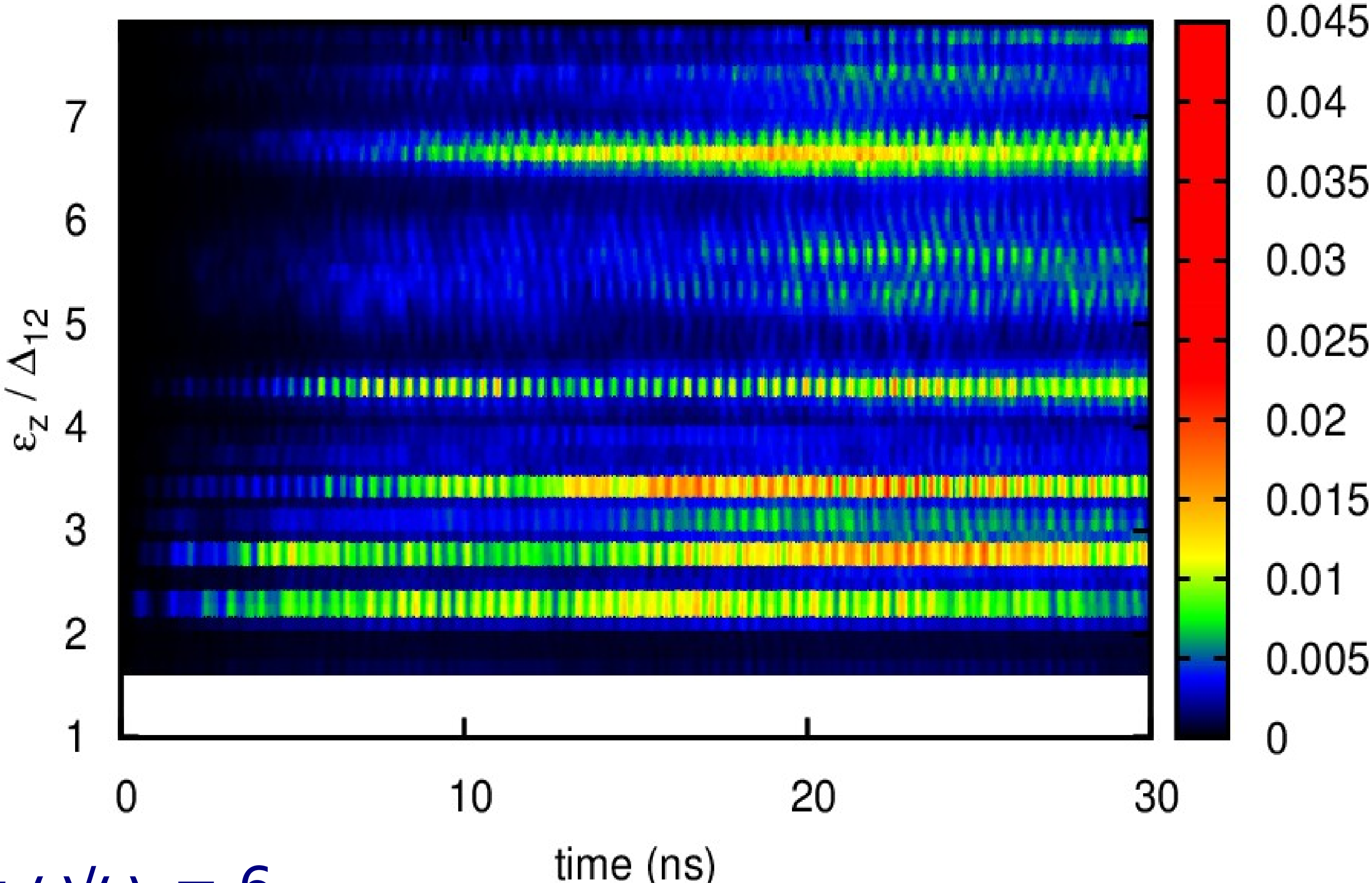
AC driving

$$a = \sqrt{\frac{m\omega_c}{2\hbar}}\left(\hat{x} + \frac{i}{m\omega_c}\hat{p}\right)$$

$z_{ln} = <l|z|n>$ dipolar transition elements in the z direction

Numerical integration of dynamics (1)

$$P(\epsilon_z;t) = \sum_l |\psi(l, n_z;t)|^2$$



$J = \omega/\omega_c = 6$

$\omega = \Delta_{12}$

$B \sim 0.5$ Tesla

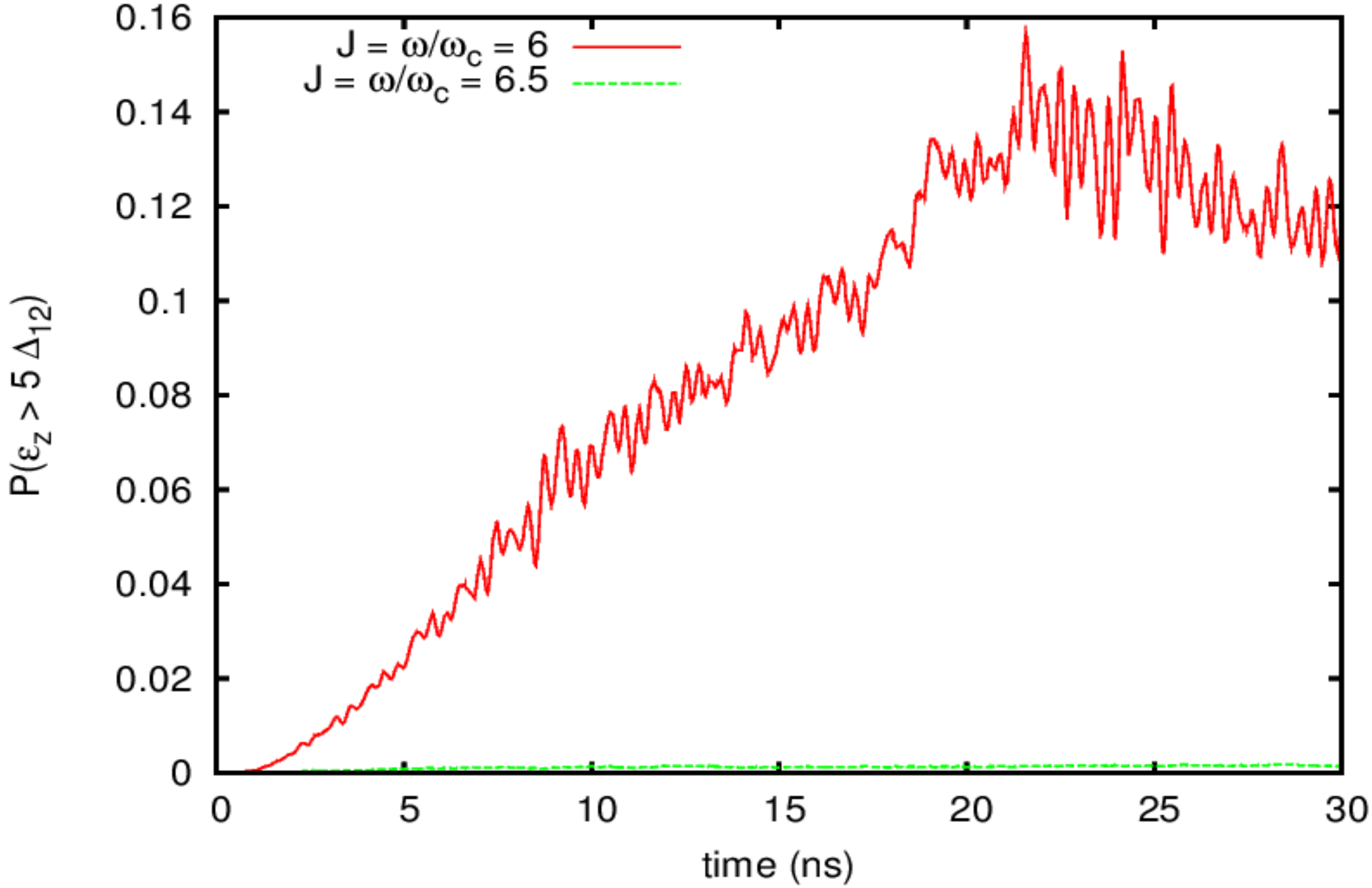
$E_{z;dc} = 3$ V/mm

$E_{x;ac} = E_{z;ac} = 1$ V/mm

$\alpha = 6$ deg

$W = 0.02\ \hbar\omega_c$

Numerical integration of dynamics (2)



The highly excited z-states should be very long lived; they are far from the surface

Summary for e^- on liquid Helium

In ZRS electrons accumulate on the edge

Repulsion energy per trapped e^- ~ 1eV

Photon energy ~ 0.4 meV, Temperature ~ 100 mK

Transient conductivity measurements suggest :

e^- Redistriubtion → ZRS (and not the other way around!)

At high densities :

Resonant excitation at the edge induces redistribution

Resonant excitation in the center : <u>no effect</u> !

In this story I focused on the first second after turnon off MW,

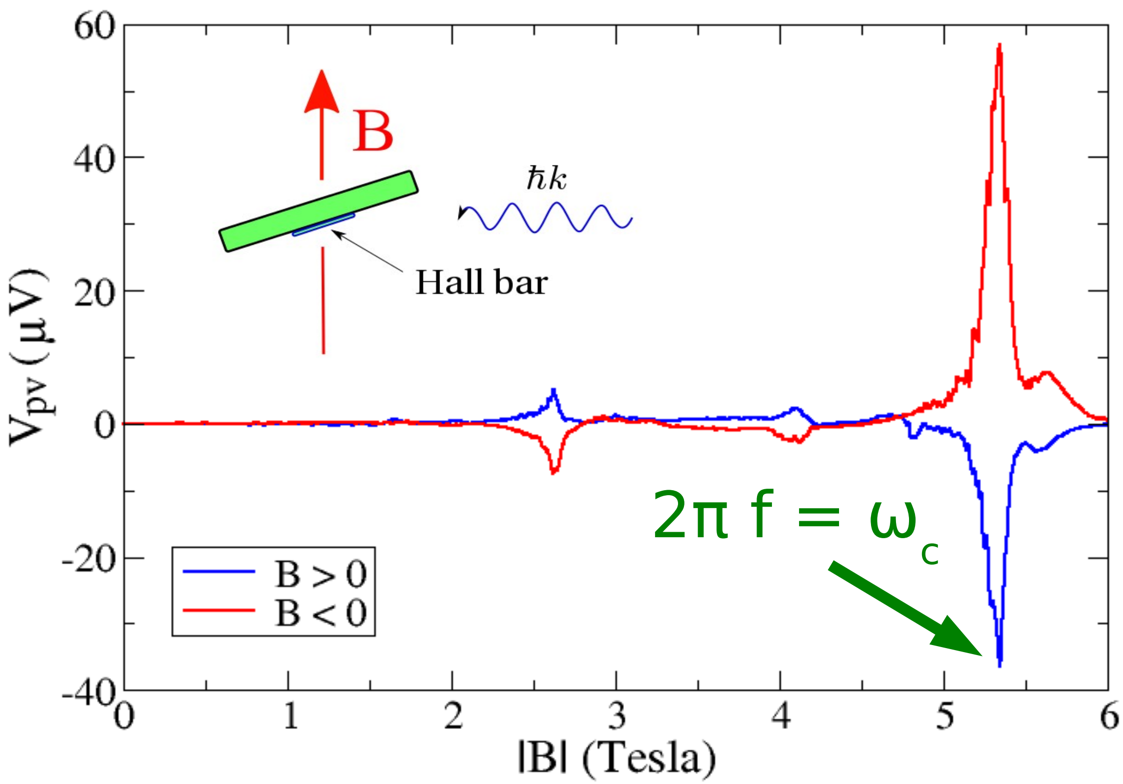
More non trivial effects at later times (but not only)

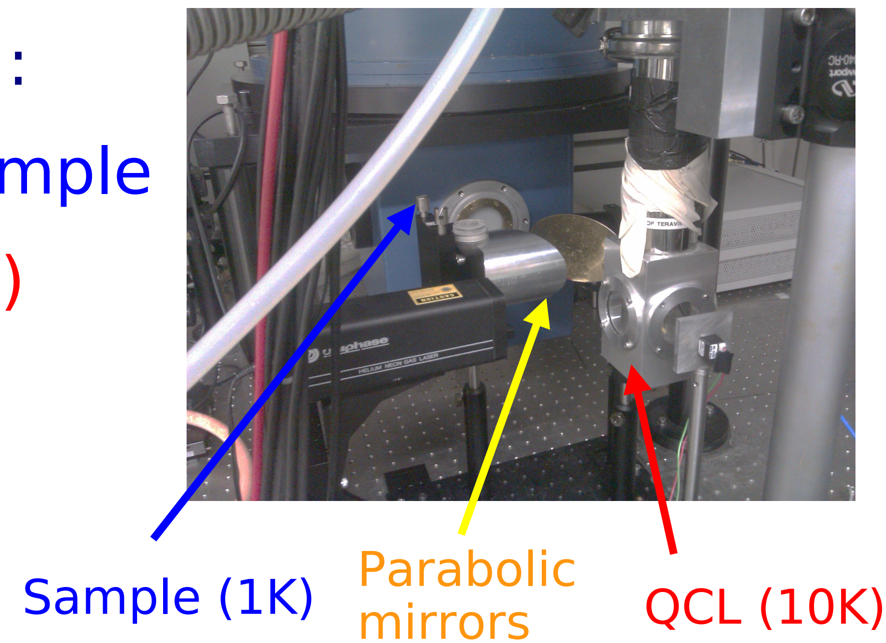
“Photo-voltage under THz light

Photo-transport at THz frequencies :

Coupling between a mesoscopic sample

and a Quantum cascade laser (QCL)





Photovoltage across

ultra-high mobility

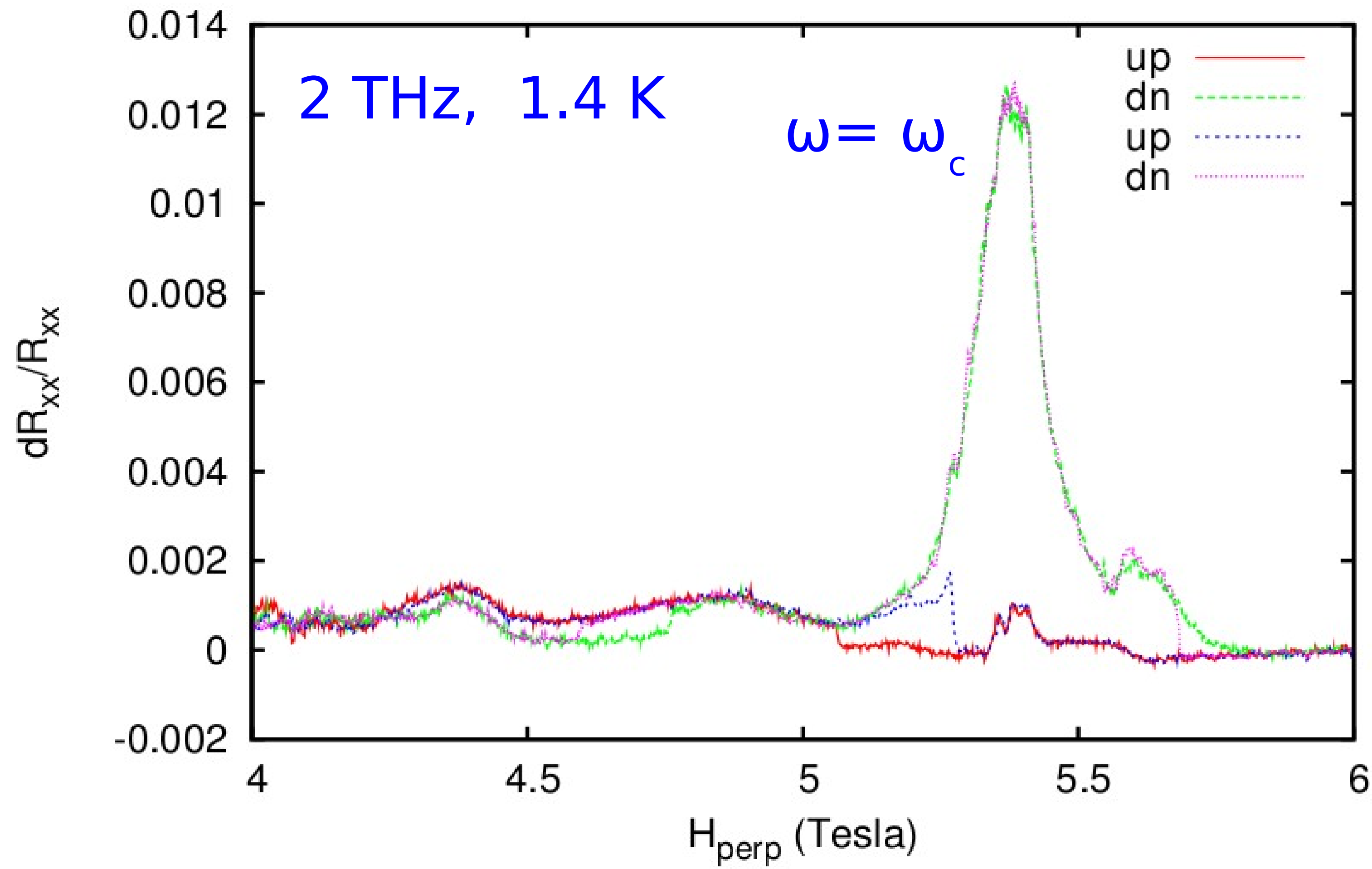
Hall bar under irradiation

$f = 2.25$ THz

(Cambridge 2011-2012)

Interesting B symmetry properties of photo-photovoltage

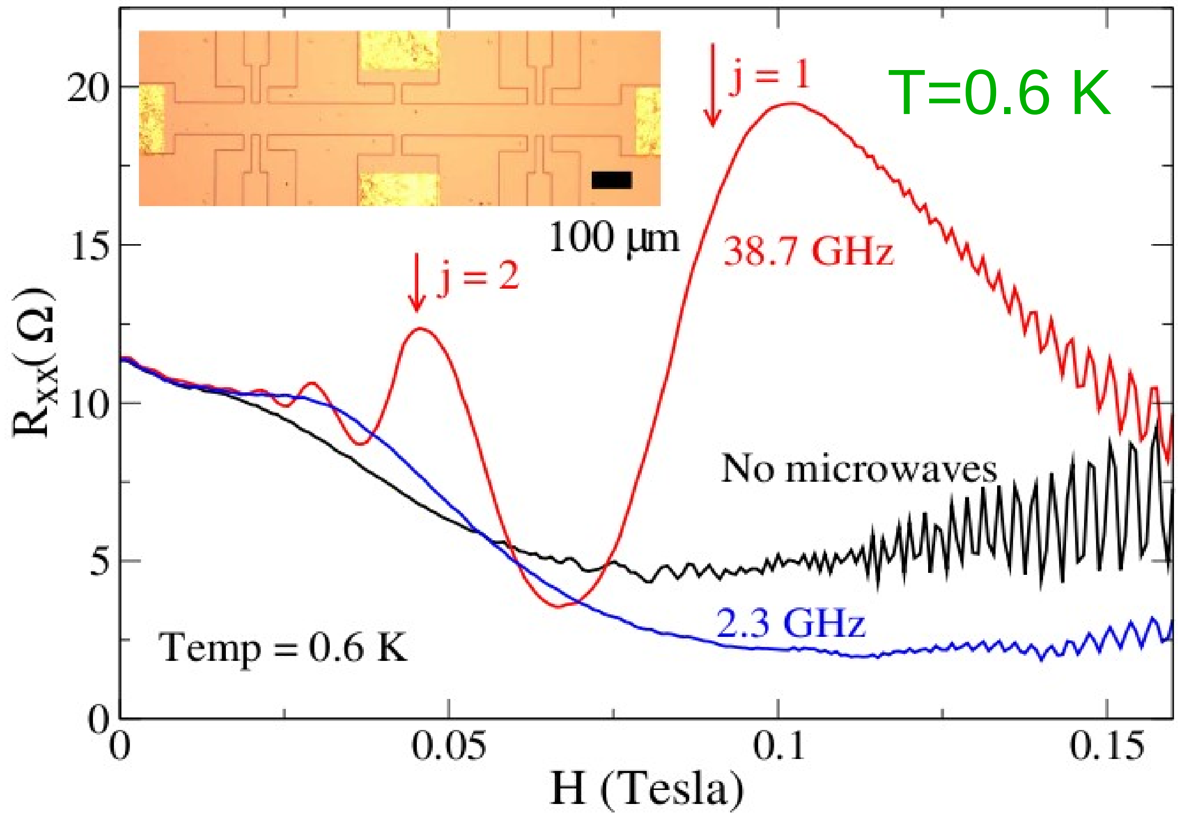
Bi-stable photo-resistance



- bi-stability under THz illumination (“domains” if one wishes)
- but no zero-resistance ...

Even if one detects “domains” in ZRS, this is not a proof that the “domains” are the cause of ZRS

Transport under low frequency irradiation (2DEG)



High frequency

$\omega > \omega_c$

Low frequency

$\omega \ll \omega_c$

Even a low frequency irradiation can reduce R_{xx}

This effect was not anticipated in bulk transport theories (?)

$\omega \ll \omega_c$: no transitions between LL in the bulk

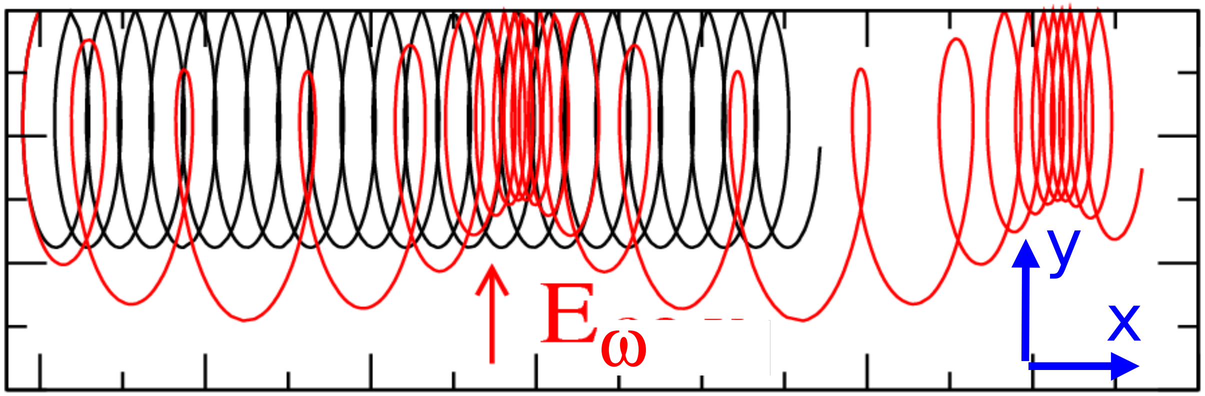
plasma regime $\omega \tau \sim 10$: no bulk magnetoplasmons

for $\omega < \omega_c$ RF field should not penetrate sample bulk

Ultra high mobility sample : H. Beere, D. Ritchie (Cambridge); Internship : J. Laidet

A simple edge channel explanation ?

- Low frequency accelerates drift along edges :



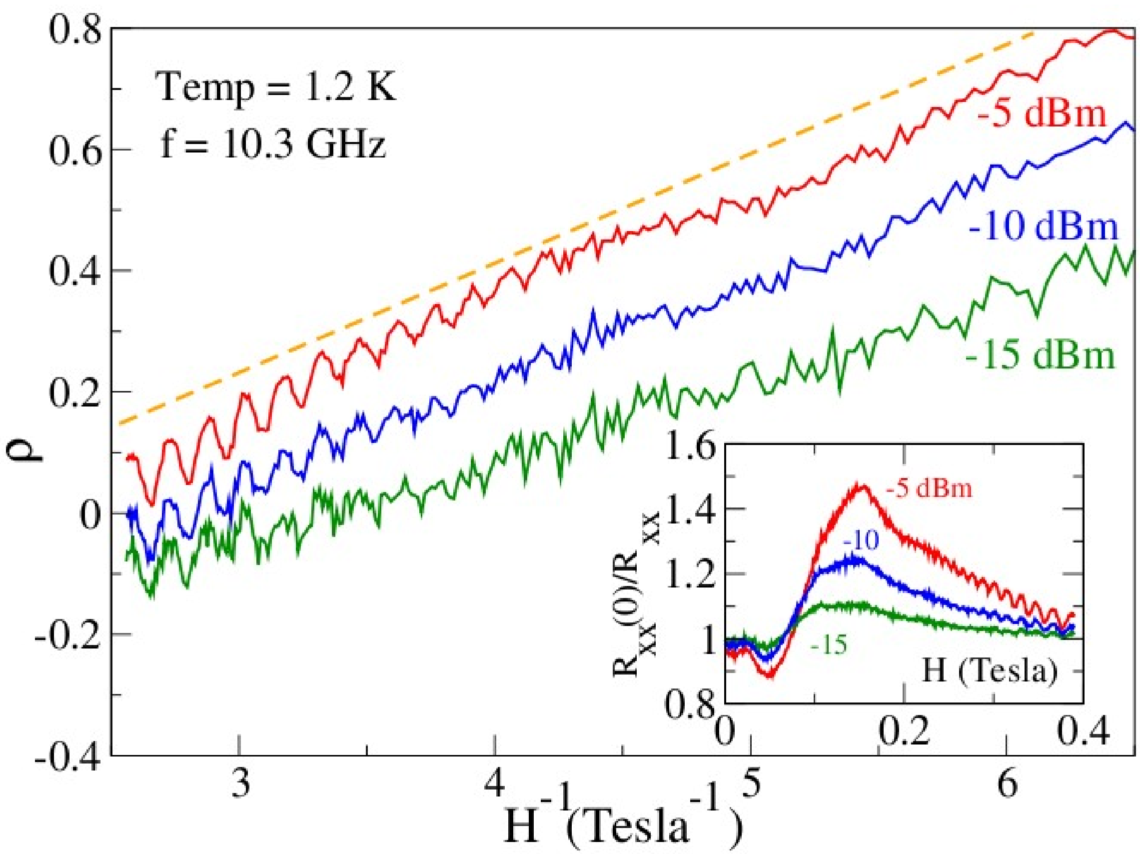
Better guiding

and lower R_{xx}

$$\frac{R_{xx}(0)}{R_{xx}} = \frac{< v_g >}{v_g(0)}$$

with microwave

$$\frac{< v_g >}{v_g(0)} - 1 \propto \frac{E_\omega}{\omega_c} \propto \frac{\sqrt{P_\omega}}{H}$$

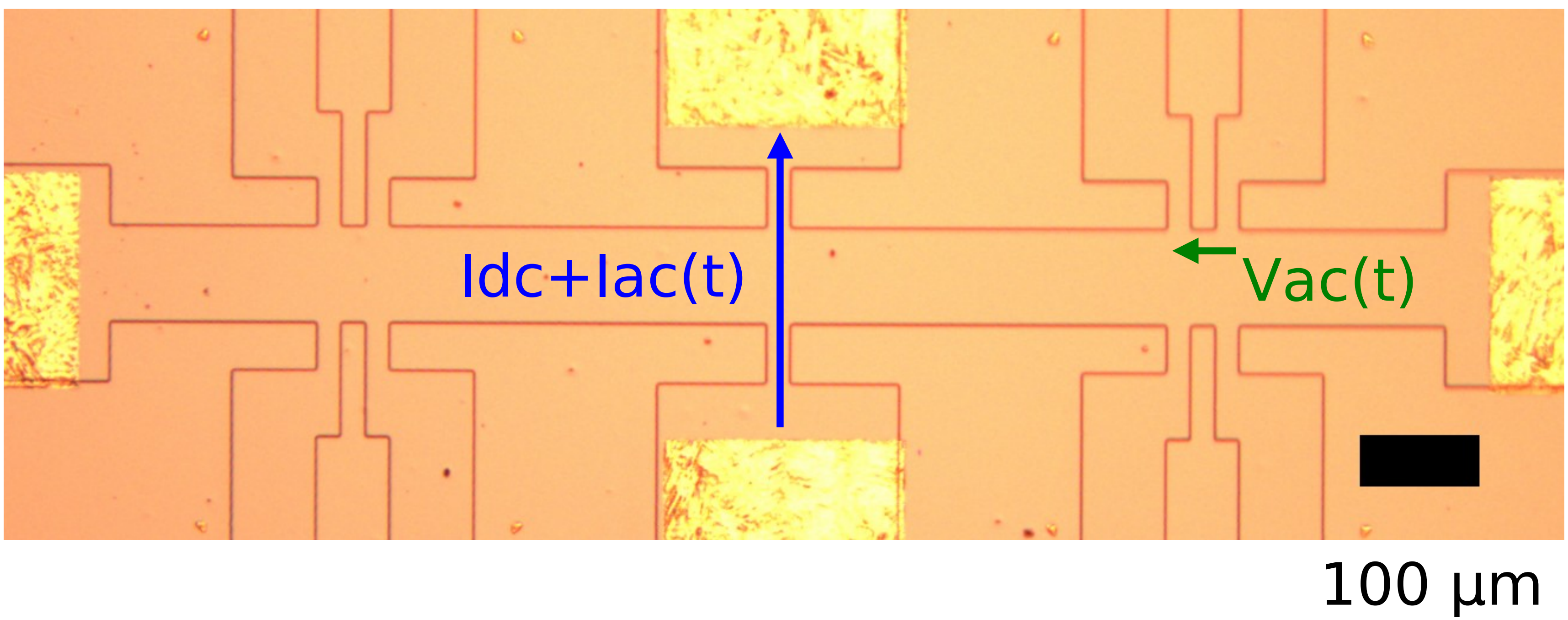


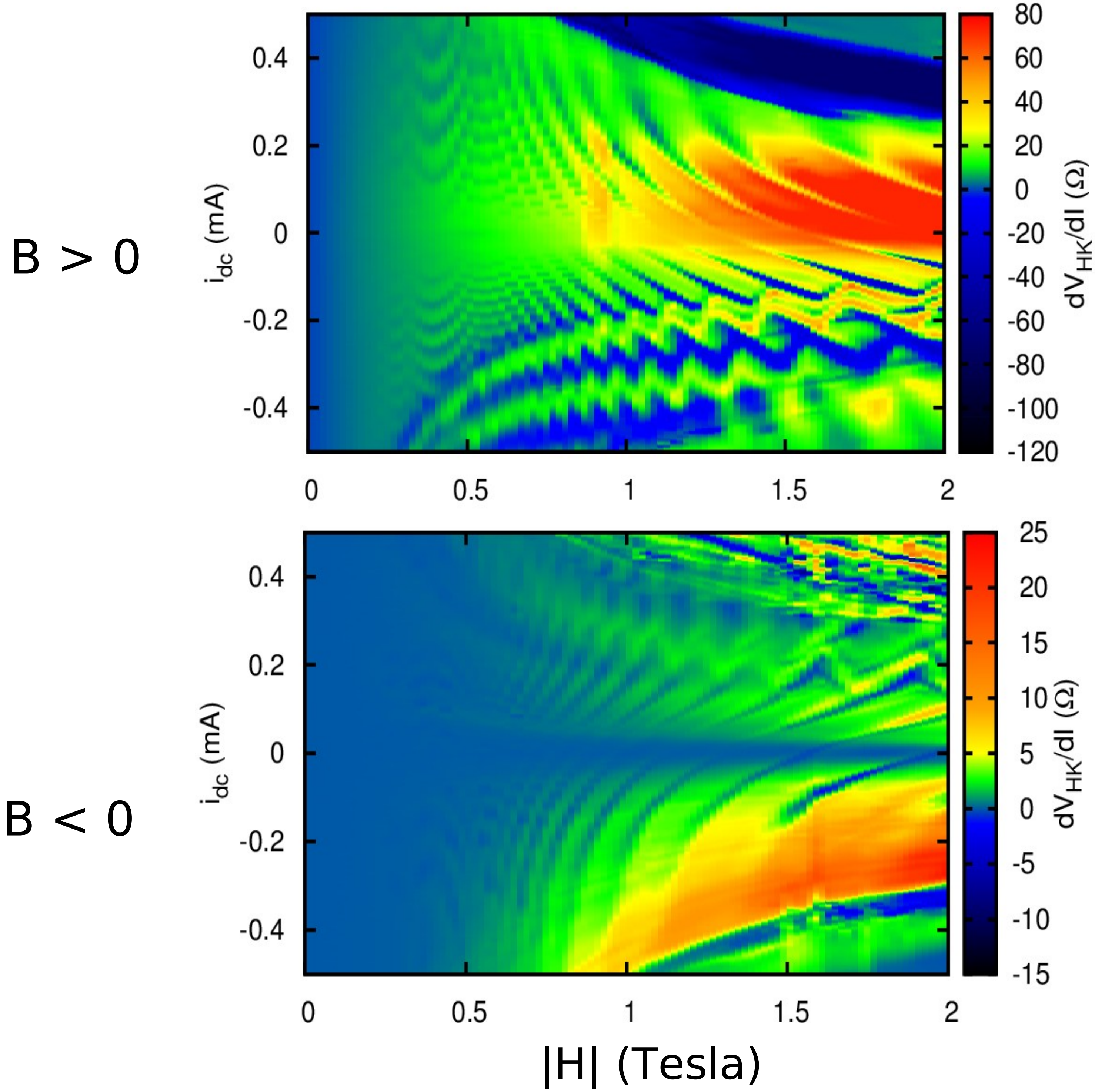
$$\rho = \frac{1}{\sqrt{P_\omega}} \left(\frac{R_{xx}(0)}{R_{xx}} - 1 \right) \propto \frac{1}{H}$$

It works !

Role of edge channels ?

- Objection : I overestimate the role of edge channels in the transport
- Experiment : Try non local measurements ...





Idc = 0

Strong B → -B asymmetry

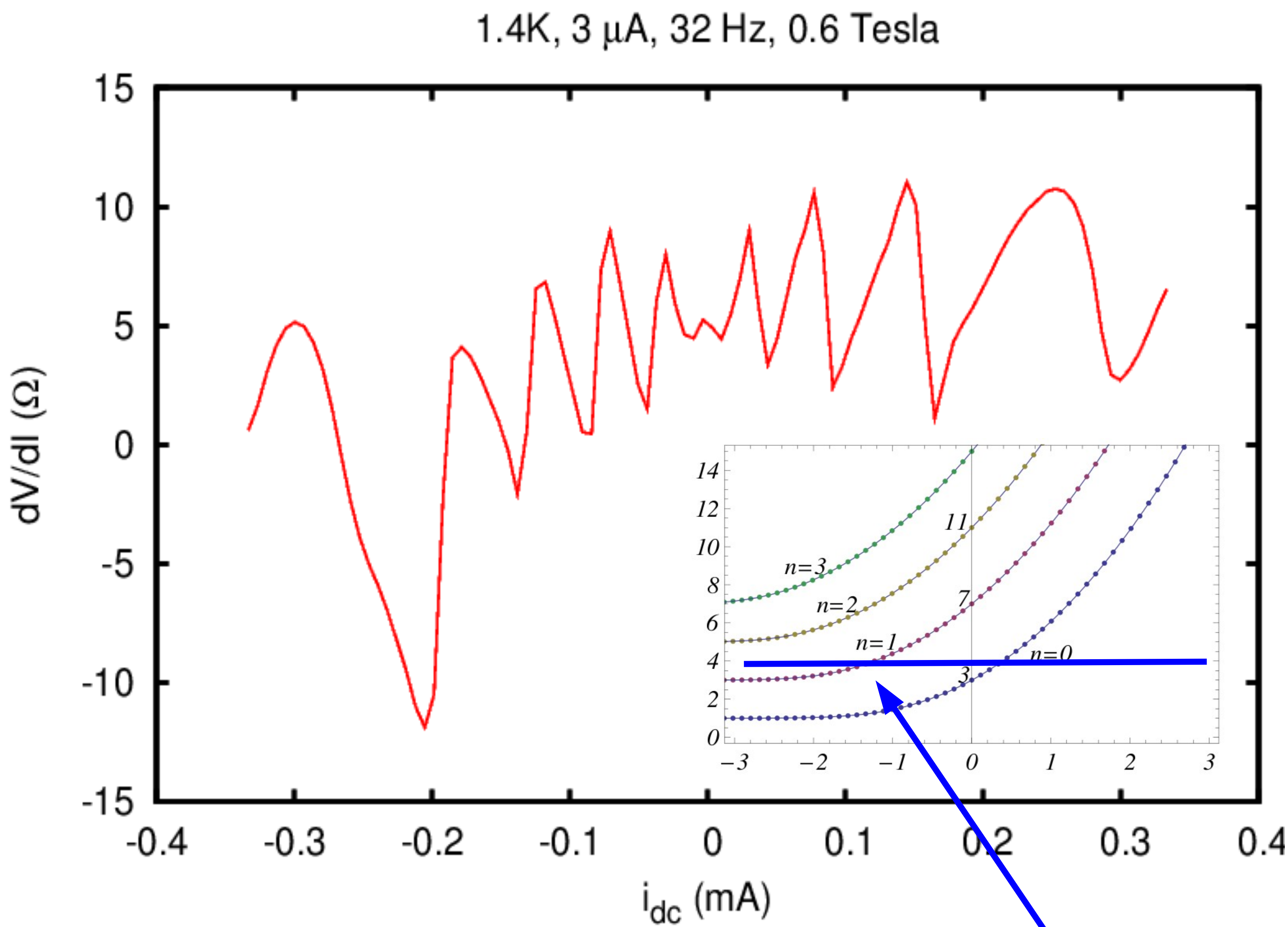
Finite Idc

Weak symmetry

B → -B

Idc → -Idc

Very non harmonic features in dV/dI

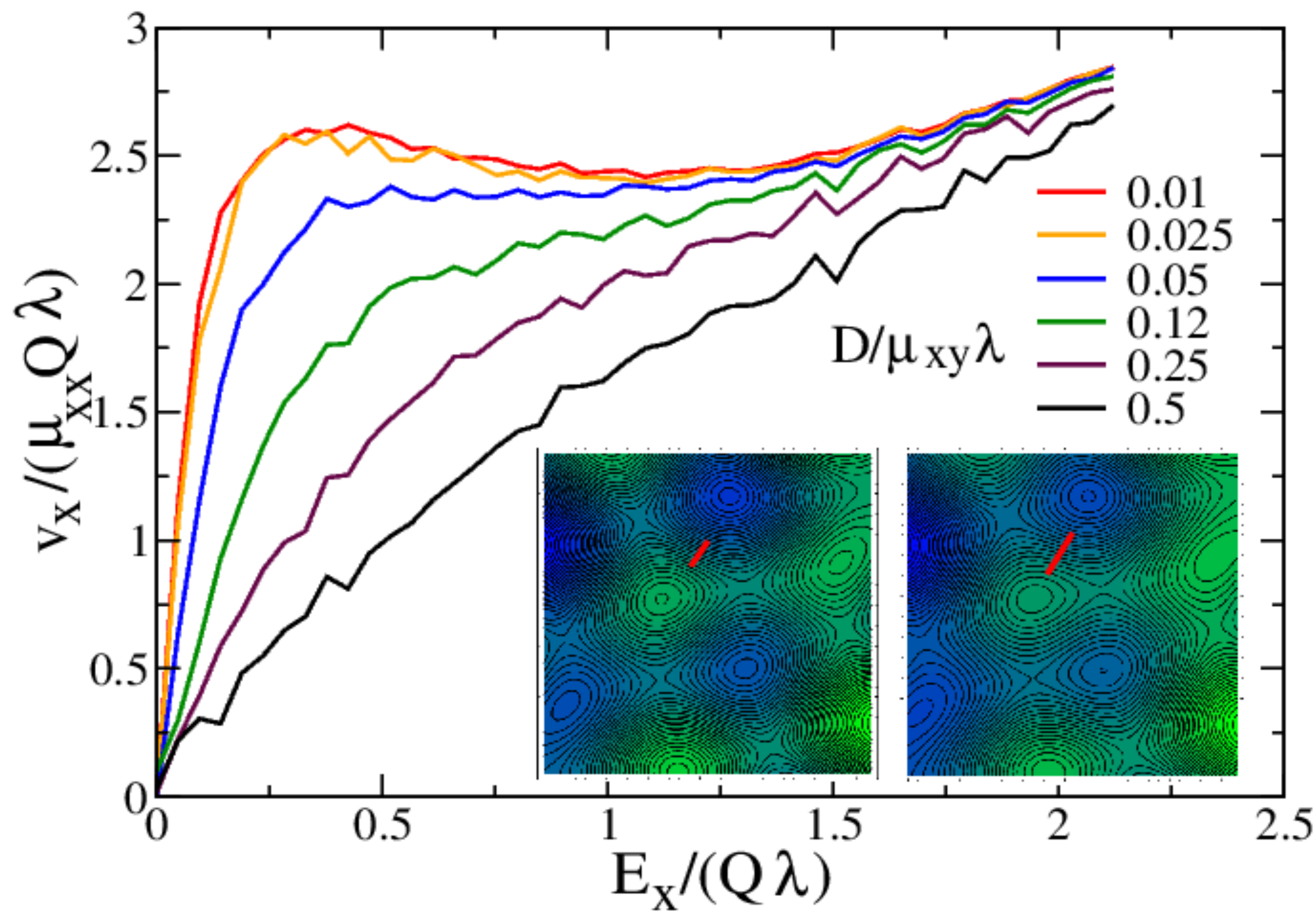


An electric field will tilt the edge states,

and suppress the intersection with the Fermi level

Non linear transport in the sample bulk

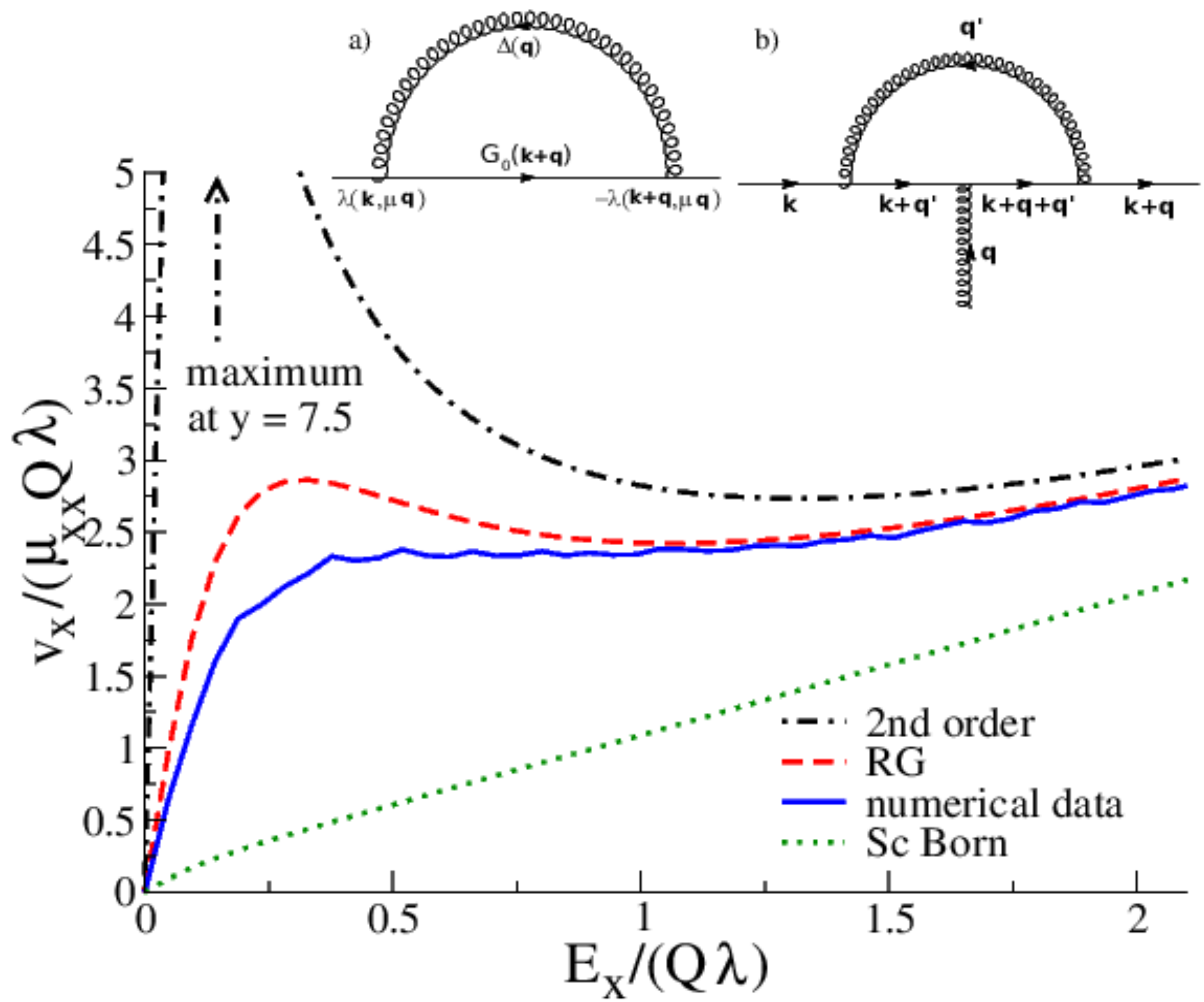
$$\partial_t P = \mathrm{div}\,(\hat{\mu}[\mathrm{grad}\,U - \mathbf{E}]P) + D\Delta P$$



U(x,y) Gaussian correlated disorder potential

Potential λ RMS amplitude; Q^{-1} correlation length

Theoretical modelling



Theory does not work great, comparison with simulation important !

Summary on 2DEG

- THz illumnation → photovoltage/“bistability”
  but no ZRS/MIRO so far
- Experiments in the low frequency limit,
  and non local transport (spectroscopy of edge channels ?)
- Theory of non linear transport in drift diffusion equations
  in random media (macroscopic diffusion rate determined
  by long range and not microscopic noise)
- Probably ZRS in GaAs non trivial mixture
  of edge and bulk effects
  (as QHE : edge channels vs percolating paths)
  Many questions, not many answers …

Thank you !

A Cambridge experimentalist !