Signatures expérimentales des interactions électroniques dans le transport mésoscopique

Introduction :ordres de grandeur, rappels transport cohérent

Interactions et cohérence de phase

Désordre, dimensionnalité, environnement électromagnétique, géométrie
Comment déterminer le temps de cohérence de phase dans un système fini

Interactions et propriétés thermodynamiques

Correction à la densité d'états d'un système diffusif ; rôle de la dimensionalité
Système localisé : gap de Coulomb
Magnétisme orbital

Transport hors d'équilibre
Rectification mésocopique et interactions

Que se passe t'il à la limite 1D ?

Instabilité du liquide de Fermi,

Exemple fils quantiques et nanotubes de carbone

Peut on parler de comportement liquide de Luttinger dans les conducteurs 1D

Blocage de Coulomb dynamique et environnement électromagnétique

Interactions dans les boîtes quantiques

Du blocage de Coulomb à l'effet Kondo

Contacts supraconducteurs : compétition entre effet Kondo et effet Josephson

Interactions et densité d'états

$$G^{R,A}_\epsilon = (\epsilon - H \pm i0)^{-1} \qquad \delta(\epsilon - H) = Im(G^R_\epsilon)/2\pi = (G^R_\epsilon - G^A_\epsilon)/2\pi$$

Régime diffusif sans interactions: ν =Tr ($\delta(\varepsilon$-H)) ~ N/E_F
Pas de correction quantique à la DOS moyenne

En présence d'interactions:
Perturbation des niveaux électroniques à l'ordre 1:

$$\delta\epsilon_i^H = \sum_j f(\epsilon_j) \int U(r-r')\phi_j^*(r')\phi_j(r')dr'\phi_i^*(r)\phi_i(r)dr$$

Terme de Hartree

$$\delta\epsilon_i^F = \sum_j f(\epsilon_j) \int U(r-r')\boxed{\phi_j^*(r')\phi_j(r)}\phi_i^*(r)\phi_i(r')drdr'$$

Terme de Fock (échange)

• Interactions et densité d'états

$$\Delta_\epsilon = \frac{1}{\nu_0}\sum_i \delta(\epsilon - \epsilon_i)\delta\epsilon_i \qquad \frac{\delta\nu}{\nu_0} = -\partial\Delta_\epsilon/\partial\epsilon$$

Terme de Fock

$$\delta\epsilon_i^F = \sum_j f(\epsilon_j)\int U(r-r')\phi_j^*(r')\phi_j(r)\phi_i^*(r)\phi_i(r')drdr'$$

$$\Delta_\epsilon^F = -\frac{1}{\nu_0}\int_{-\infty}^{+\infty} f(\epsilon-\omega)d\omega\sum_q U_q Re\frac{1}{i\omega + Dq^2}$$

Diffuson: contribution dominante

$$\boxed{\delta\nu^F = -\, U\left[\frac{\epsilon}{D}\right]^{d/2}\Omega/\epsilon}$$

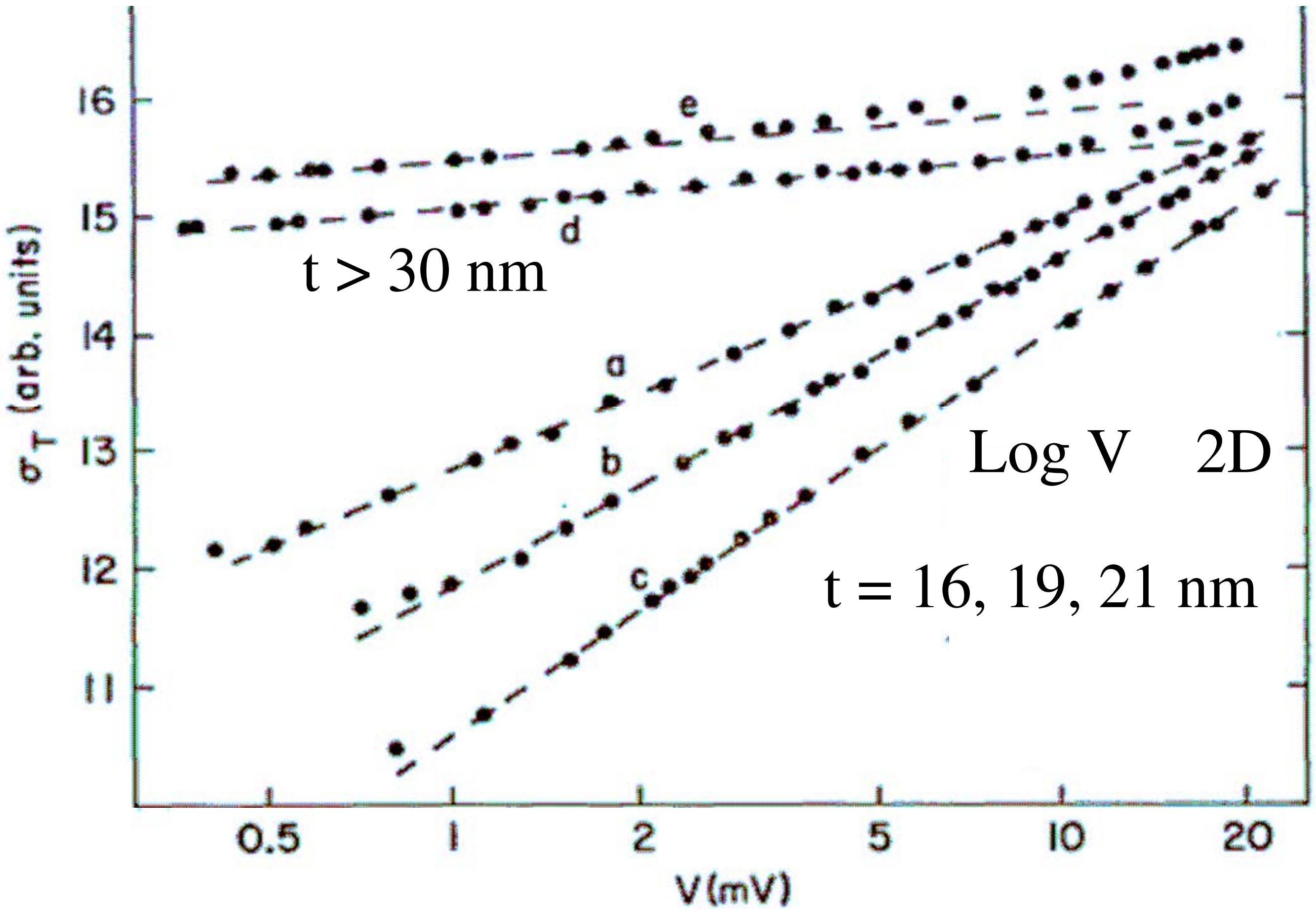
Anomalie en:
$$\begin{cases} -\varepsilon^{1/2} & \text{à 3D} \\ -\mathrm{Log}(\varepsilon) & \text{à 2D} \\ -\,\varepsilon^{-1/2} & \text{à 1D} \end{cases}$$

Longueur caractéristique

$L_\varepsilon = (\hbar\, D / \varepsilon\ )^{1/2}$

$\delta\nu^H < \delta\nu^F$ si écrantage modéré

Observation expérimentale: Conductance tunnel

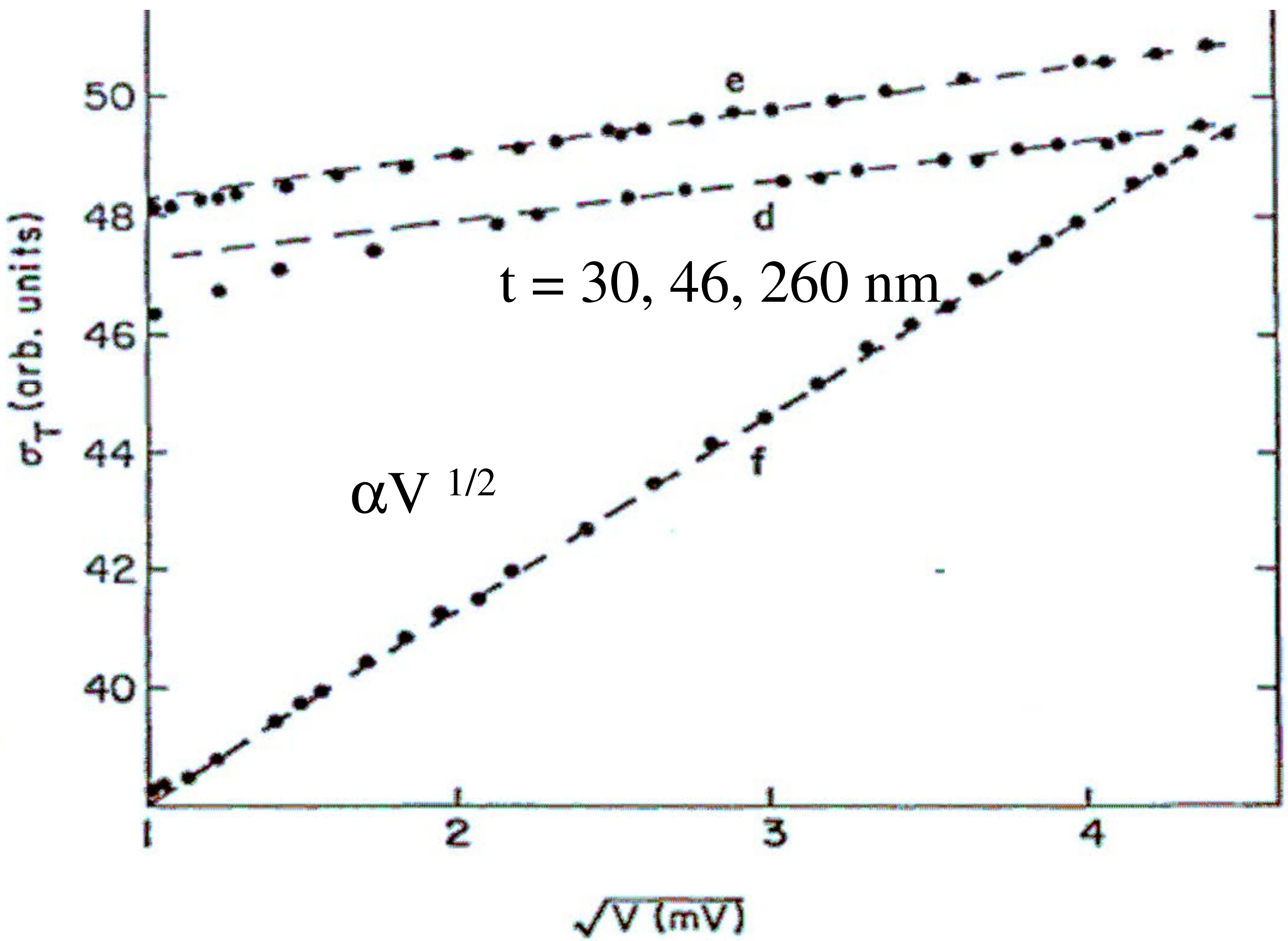


Films In ox épaisseur t: Imry, Ovadyau PRL 1982

$eV > k_B T$

Crossover 2D 3D $t > L_V = (\hbar D / eV)^{1/2}$

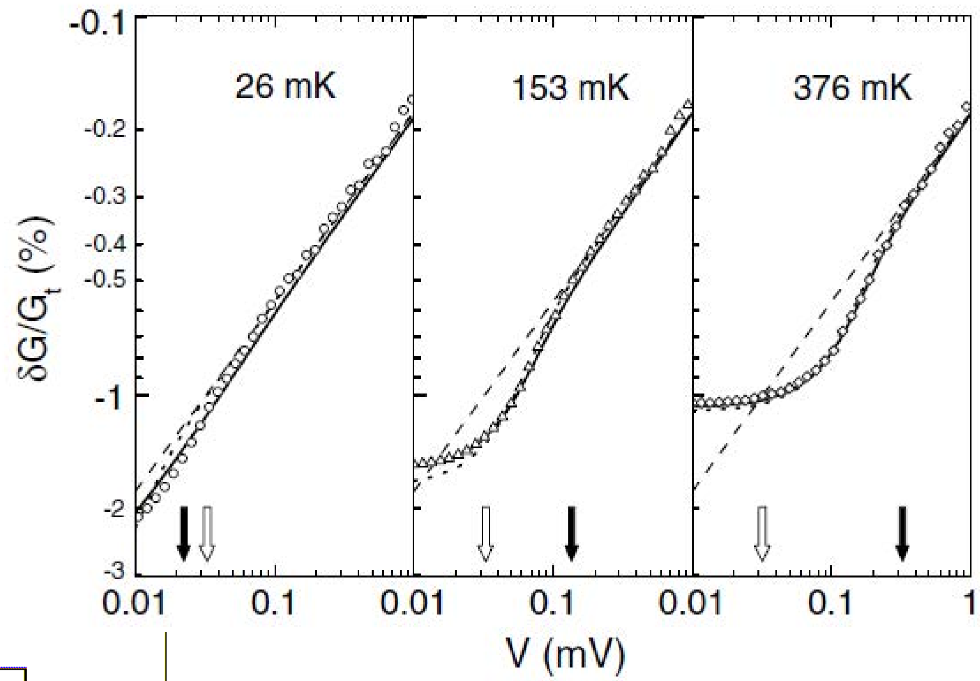
Observation expérimentale: Conductance tunnel



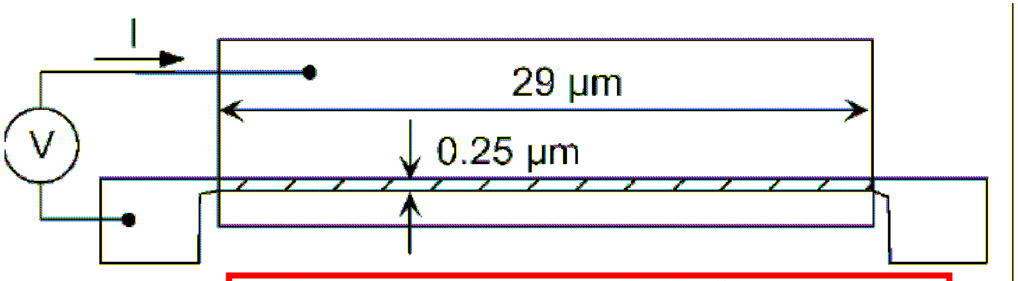
Films In ox épaisseur t: Imry, Ovadyau PRL 1982

Tunneling into a 1D wire

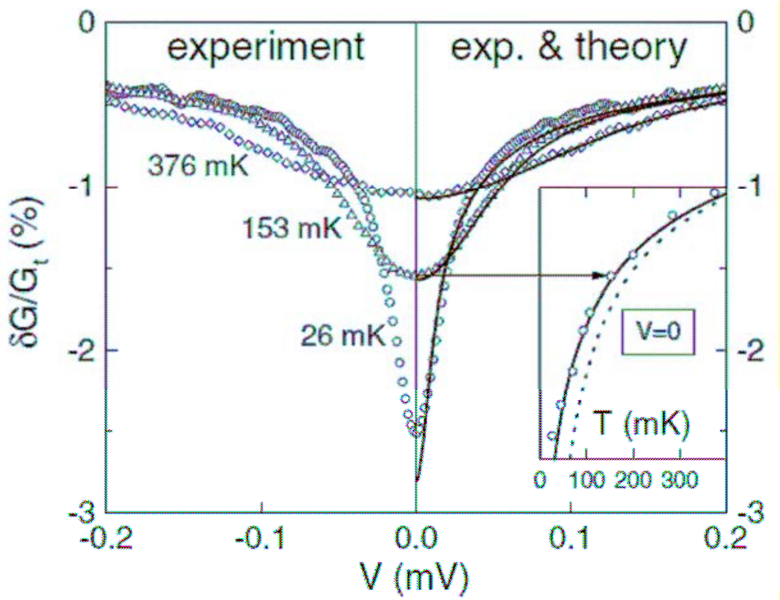
Pierre et al. PRL 2001



Influence de l’environnement électromagnétique



$$\boxed{D^* = (R_\square C_s)^{-1} \quad >> \mathrm{D}}$$

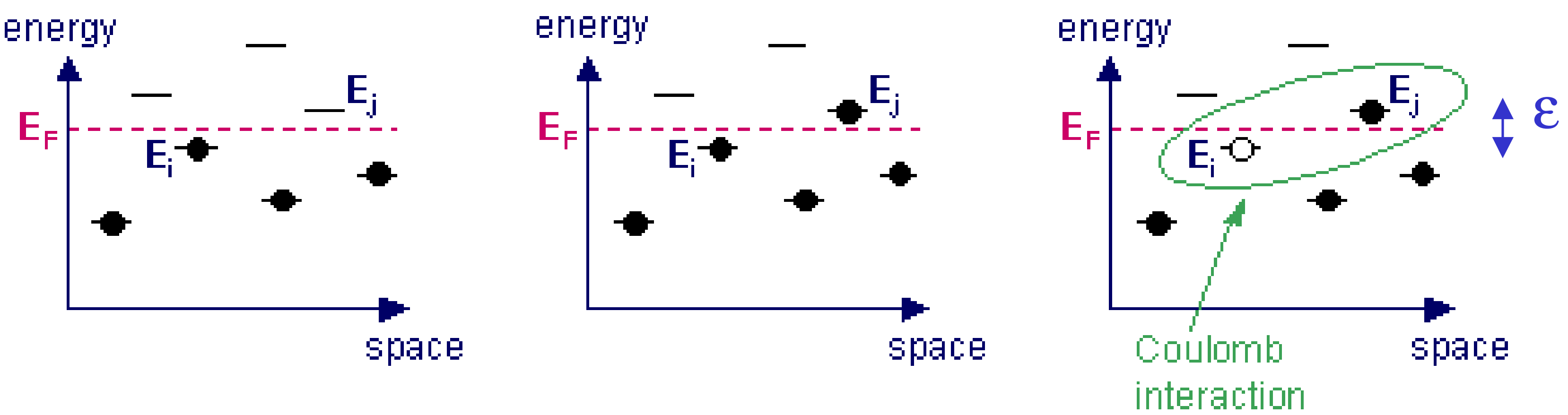


$$\delta G/G_t \simeq -1.56 \frac{R_l}{R_K}\sqrt{\frac{\hbar D^*}{k_B T}} \quad \text{for } \frac{eV}{k_B T} \to 0$$

$$\delta G/G_t = -\sqrt{2}\,\frac{R_l}{R_k}\sqrt{\frac{\hbar D^*}{eV}} \quad \text{for } \frac{eV}{k_B T} \to \infty$$

Localisation et interactions électroniques

Efros Shklowskii J phys C 75



Limite $k_F l_e$ ~1

La conductance s'effectue par sauts entre état localisés.

variation d'énergie correspondant à un saut de i vers j au voisinage de E_F

$\Delta E = E_j - E_i - e^2/R_{ij}$ $R_{ij} \sim (\varepsilon \nu(\varepsilon_F)/ V)^{1/d}$

La condition $\Delta E > 0$ implique $e^2/R_{ij} < \varepsilon$ $\boxed{\nu(\varepsilon_F) = 0 \quad \text{et} \quad \nu(\varepsilon) \sim |\varepsilon - \varepsilon_F|^{d-1}}$

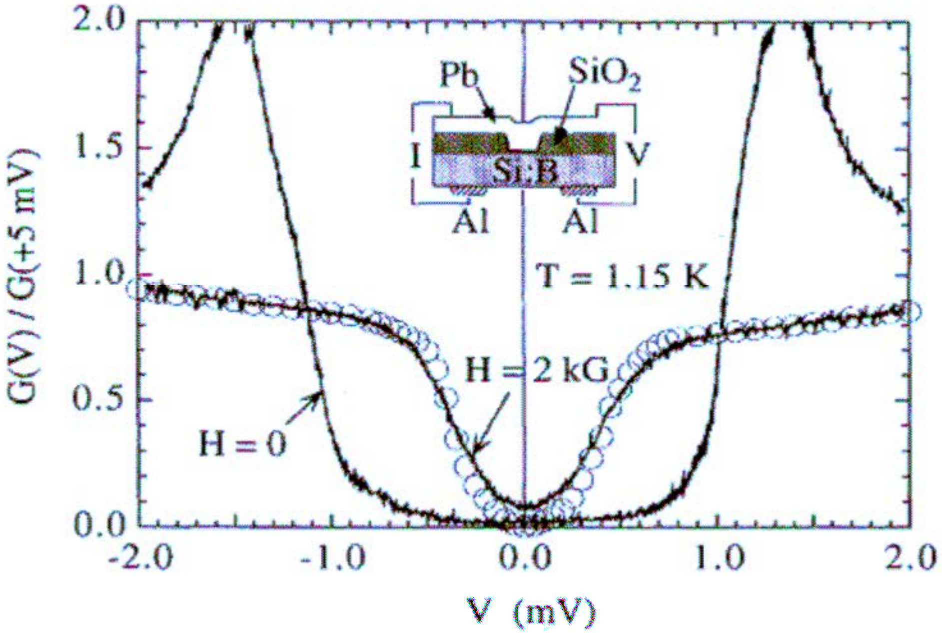
Forte perturbation de la densité d'états par les interactions

Mise en évidence du gap d'Efros et Shklowskii

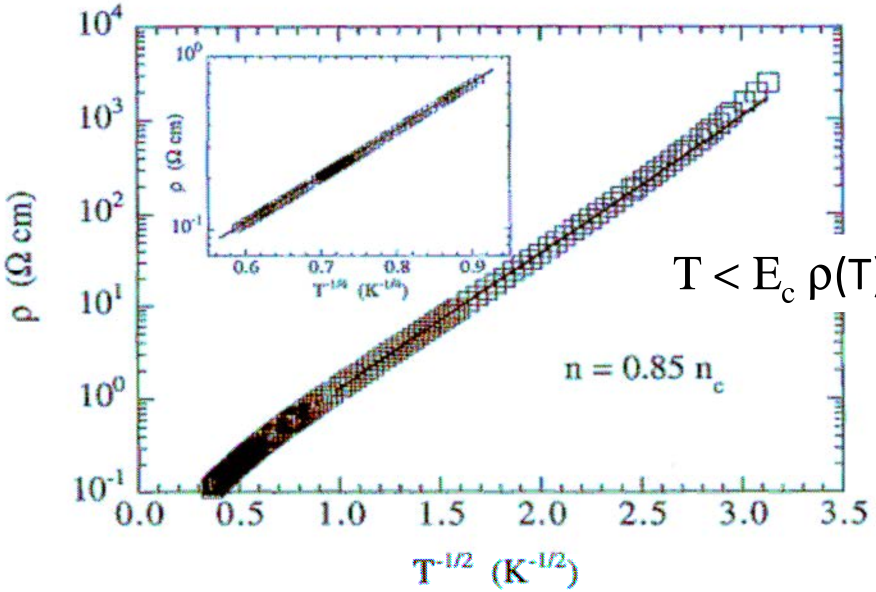
3D

$$\frac{G(V)}{G_0} = \int_{-0}^{+\infty} \frac{N(\varepsilon)}{N_0}\left[-\frac{\partial f(\varepsilon - eV)}{\partial(eV)}\right] d\varepsilon$$

Mesures de conductance tunnel
sur Si:B   Electrode Pb



$T > E_c$ $\rho(T) \sim \exp -b/T^{1/4}$



$T < E_c$ $\rho(T) \sim \exp -a/T^{1/2}$

$$N(\varepsilon) = \frac{3}{\pi}\left(\frac{\kappa}{e^2}\right)^3 (\varepsilon - \varepsilon_F)^2$$

Massey, Lee PRL 95

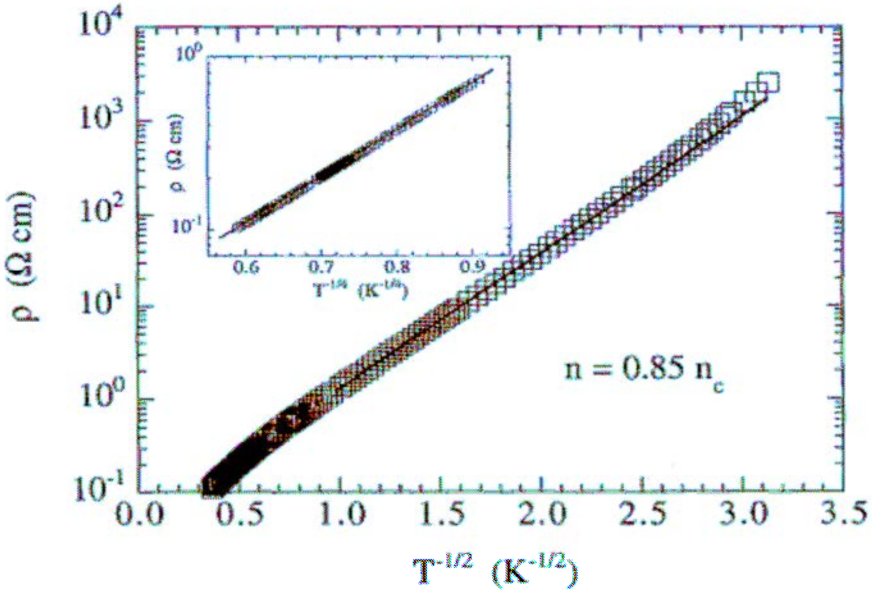
Mise en évidence du gap d'Efros et Shklowskii

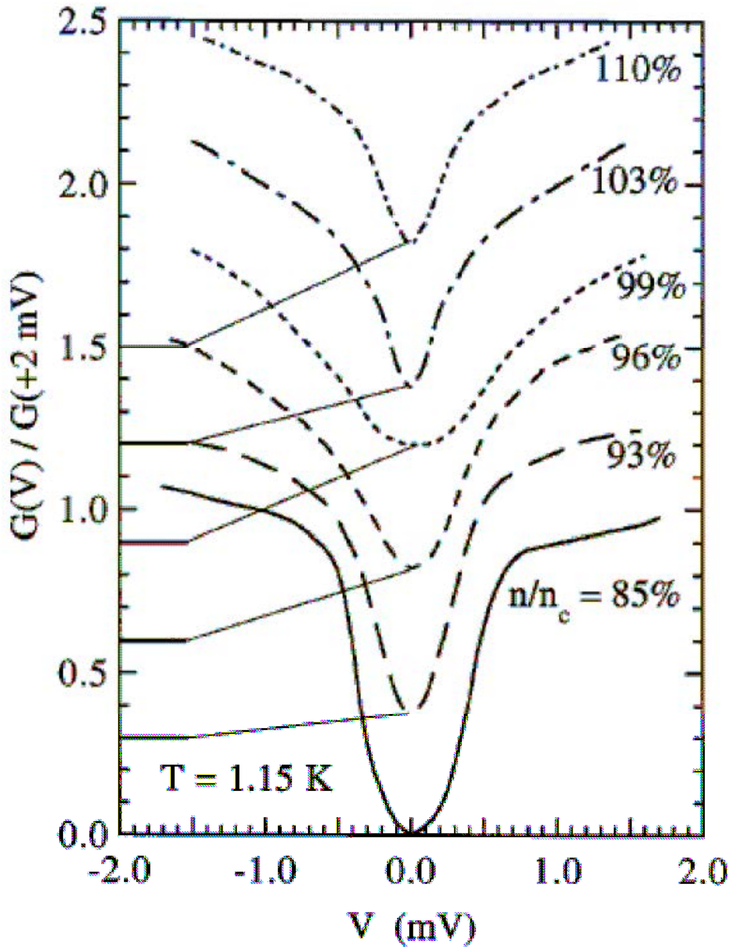
3D

Fort dopage: Anomalie Altshuller Aronov
LogV

$$\frac{G(V)}{G_0} = \int_{-0}^{+\infty} \frac{N(\varepsilon)}{N_0}\left[-\frac{\partial f(\varepsilon - eV)}{\partial(eV)}\right] d\varepsilon .$$

Mesures de conductance tunnel
sur Si:B   Electrode Pb

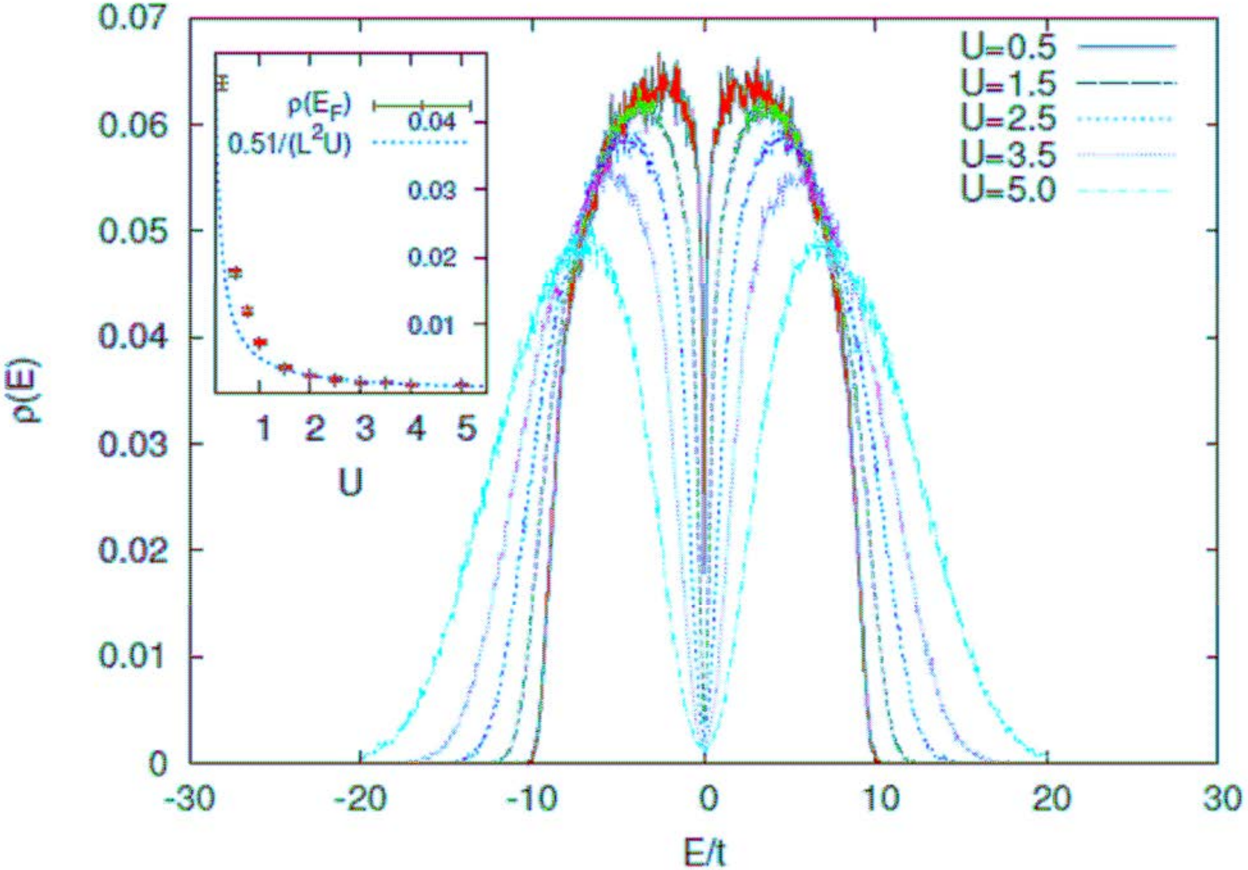




Faible dopage: gap de Coulomb

Massey, Lee PRL 96

Simulations numériques

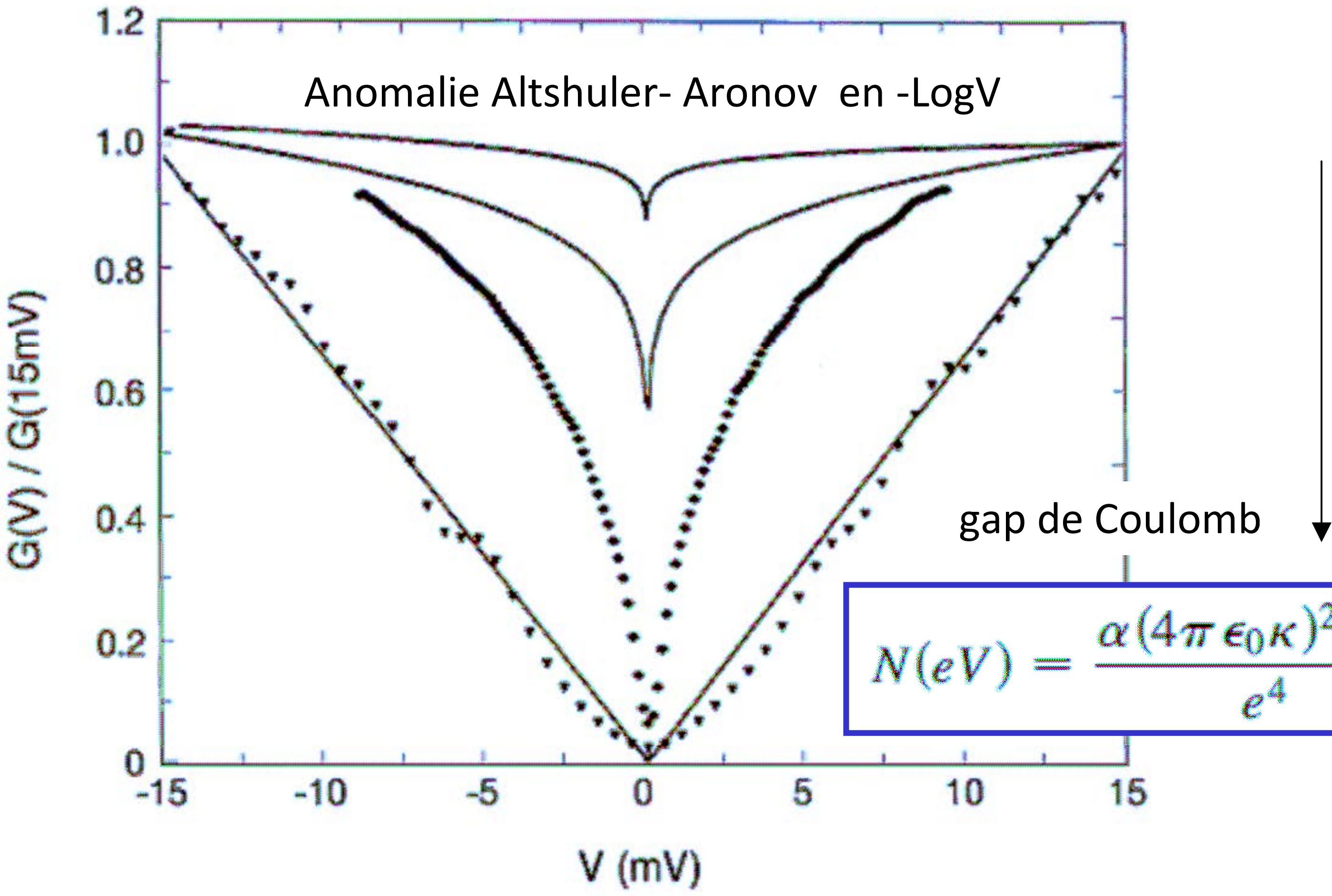


Amini et al. 2013

$$H_0 = \sum_i (\epsilon_i - \mu)\, c_i^\dagger c_i - t \sum_{\langle ij \rangle} c_i^\dagger c_j + \mathrm{h.c.}, \quad H_1 = \frac{U}{2} \sum_{i,j} \frac{n_i n_j}{r_{ij}}.$$

Mise en évidence du gap d'Efros et Shklowskii

2D



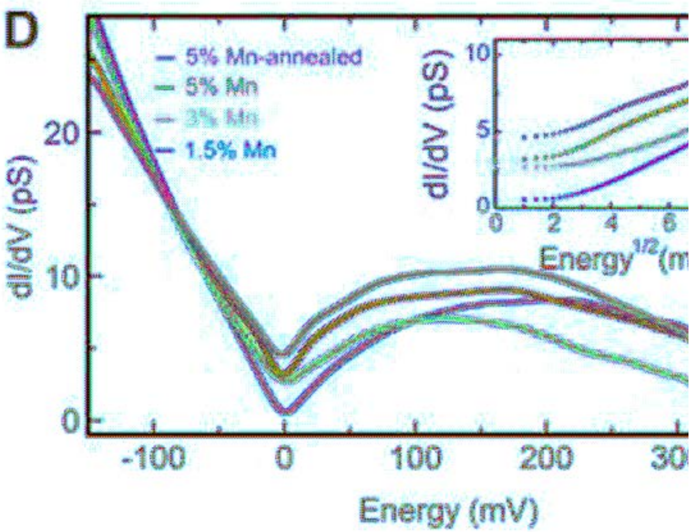
$$N(eV) = \frac{\alpha(4\pi\epsilon_0\kappa)^2|eV|}{e^4}$$

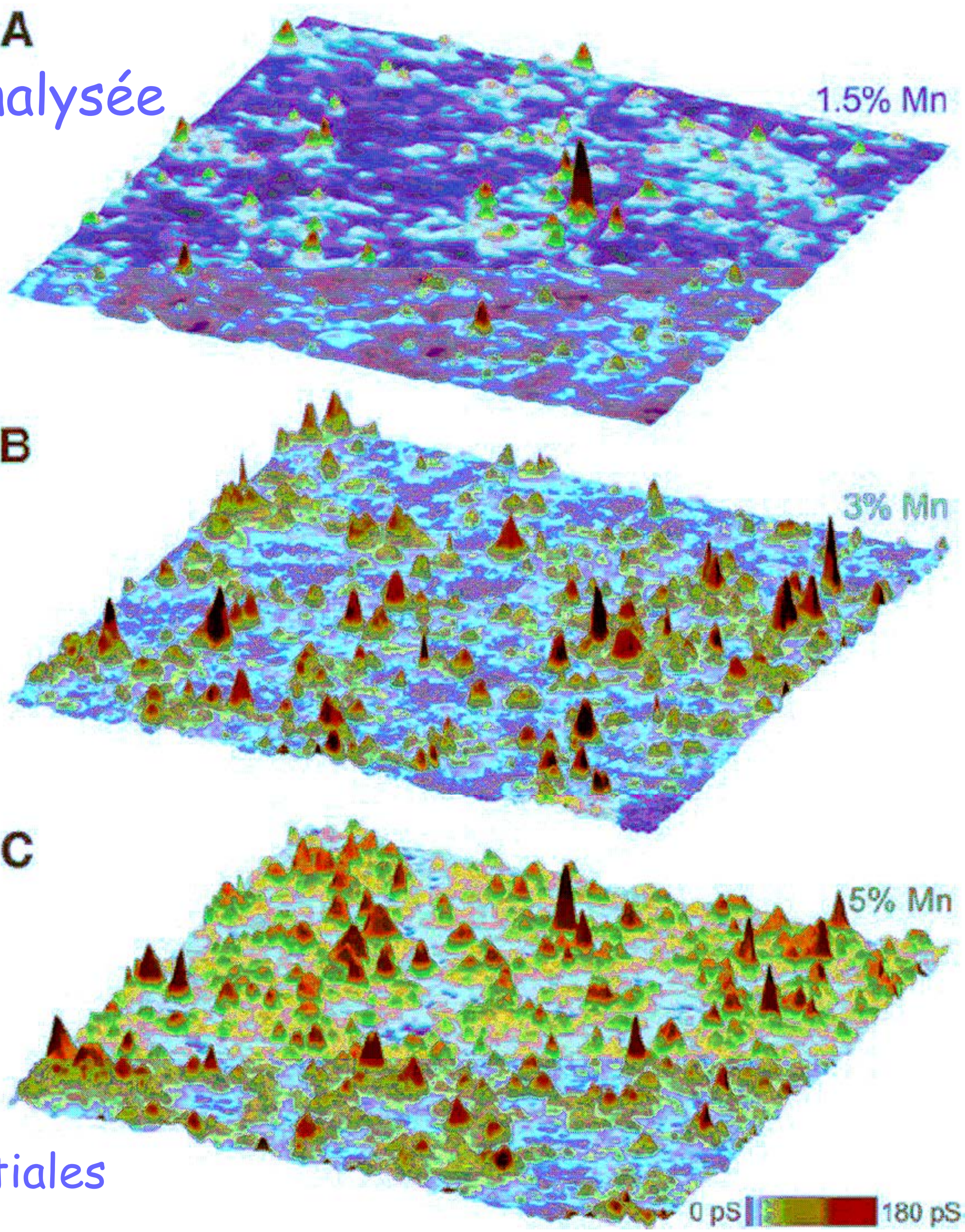
Films de Be différentes épaisseurs Butko et al. 2000

Transition métal isolant analysée par spectroscopie tunnel

GaAsMn

Richardella et al. Science 2012





Analyse des corrélations spatiales

Interactions et magnétisme orbital

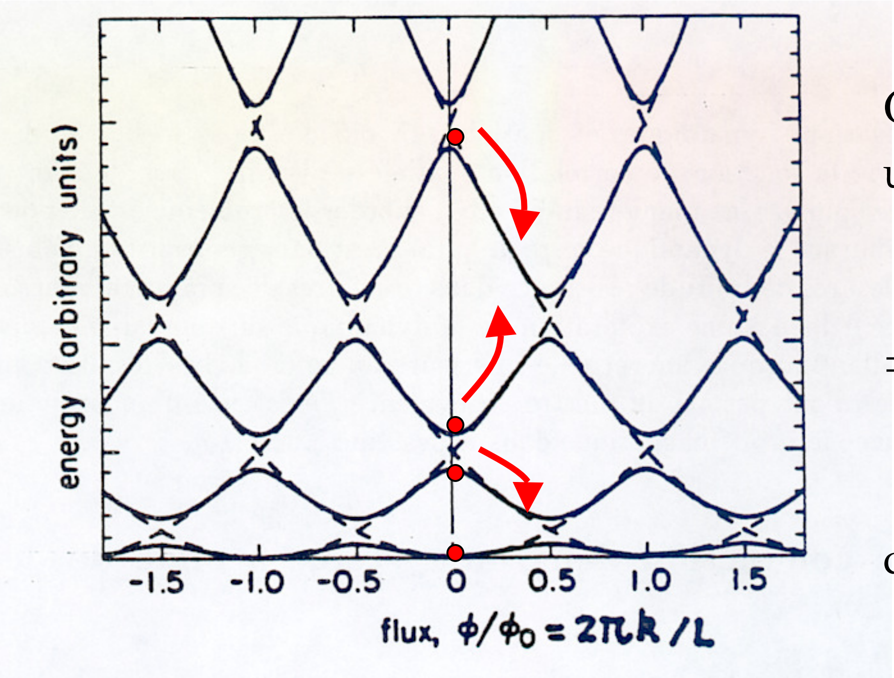
Courants permanents et effet Aharonov Bohm

Problème de la moyenne d'ensemble

Rôle des interactions en relation avec les corrections quantiques à la DOS (Cooperon)

Spectre d'un anneau 1D

$k=(2\pi/L)(\Phi/\Phi_0)$
Ondes de Bloch sur une maille du réseau réciproque $2\pi/L$,
niveaux d'énergie de l'anneau décrit les bandes
$E_n[k=(2\pi/L)(\Phi/\Phi_0)]$



Chacun des niveaux d'énergie de l'anneau porte un courant **$i_n = ev_n/L$**

où $v_n = \langle n'|\mathbf{P}/m|n'\rangle = \langle n|(\mathbf{P} - e\mathbf{A})/m|n\rangle$

$= \partial En/\partial k\ |k(\Phi) = -(2\pi/L)(\Phi/\Phi 0)$

d'où $\boxed{i_n(\Phi) = ev_n/L = -\partial En/\partial\phi}$

Ondes de Bloch
dans un potentiel de période $L=2\pi R$

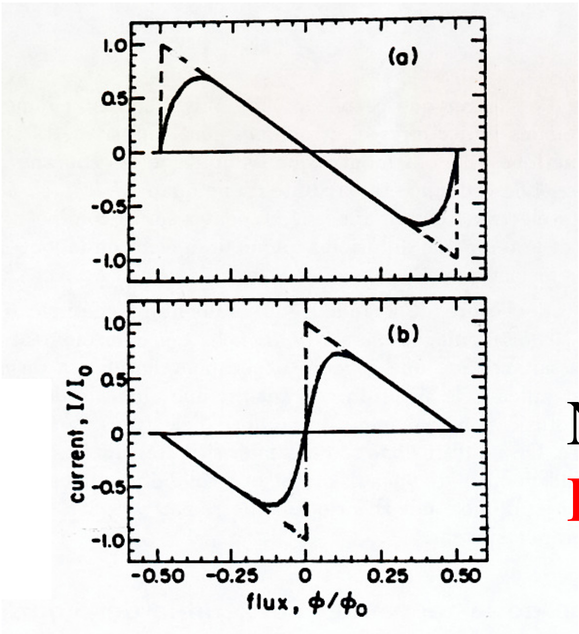
Courant permanent

$I(N) = \Sigma_1^N \, s \, i_n(\Phi) = -\partial E(N)/\partial\phi$ où $E(N)$ est l'énergie totale de l'anneau contenant N électrons,

$M(N) = I(N) \times S$ cette relation thermodynamique est équivalente à celle reliant l'aimantation au champ magnétique dans un système :

$M(N) = -\partial E(N)/\partial B$

Molécules Aromatiques!

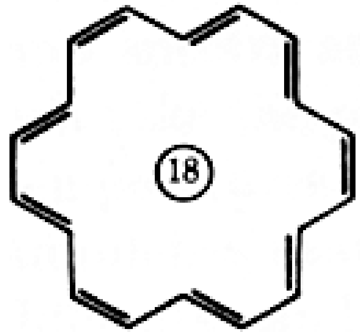


$$I = -\frac{\partial E}{\partial \Phi}$$

$\sim ev_F/L$

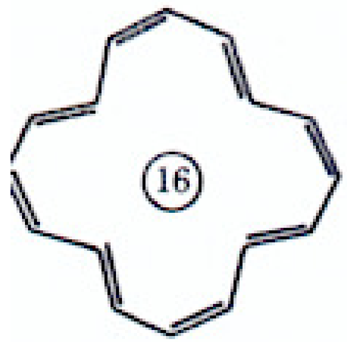
N=4n+2

Diamagnétisme



N=4n

Paramagnétisme



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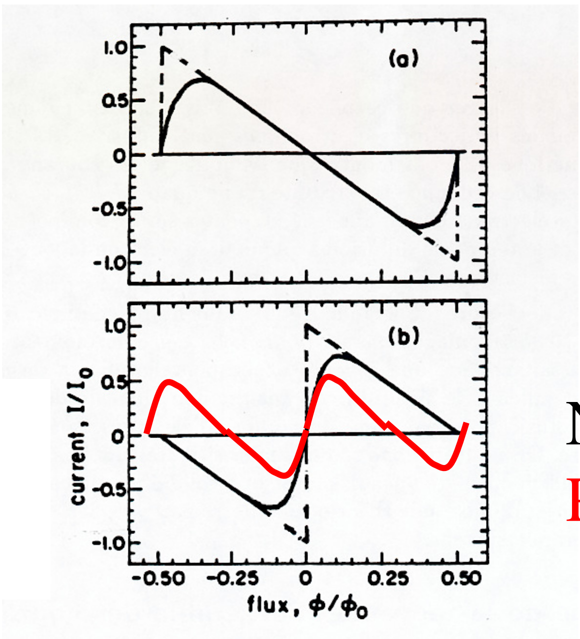
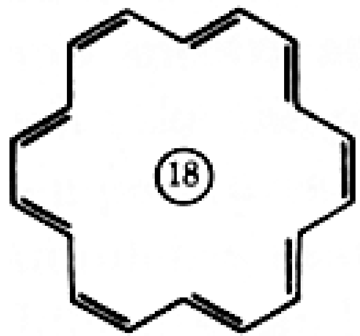


$$I = -\frac{\partial E}{\partial \Phi}$$

$\sim ev_F/L$

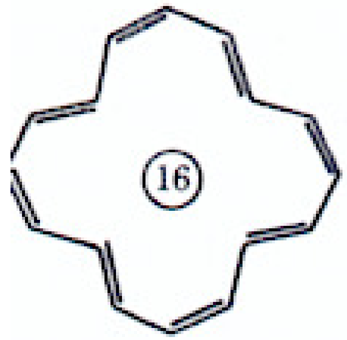
N=4n+2

Diamagnétisme



N=4n

Paramagnétisme

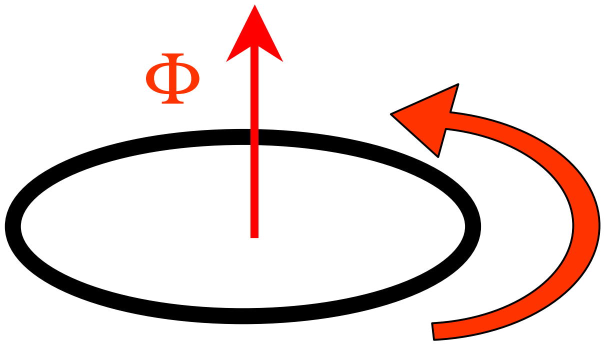


$I_{N+1}(\Phi) = I_N(\Phi + \Phi_0/2)$

Moyenne non nulle périodique en $\Phi_0/2$

Courant Permanent d'un anneau mésocopique

Energie totale : $E(\Phi) = \Sigma_{n\ \text{occupé}}\ E_n(\Phi)$ oscille avec le flux



Courant permanent $I = \langle I \rangle = \langle -\partial H/\partial \phi \rangle$

$$I = -\frac{\partial E}{\partial \Phi} = I_0 \sin(2\pi\Phi/\Phi_0) + \text{harm}$$

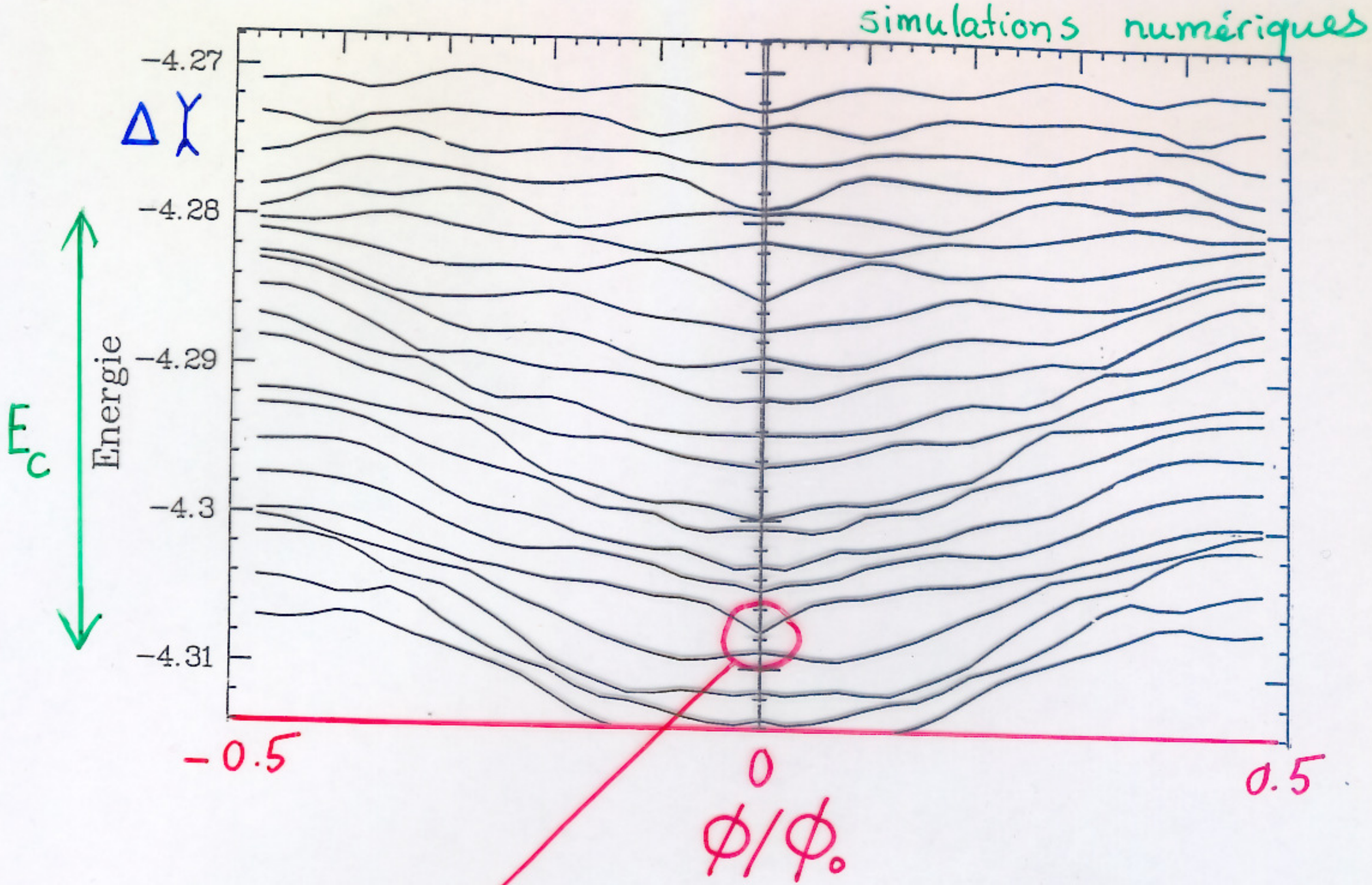
Résiste au désordre !

Existe dans un anneau de résistance finie!

Moment magnétique:

$M = -dE/dB = I\,S$ ~ 100 spins mesurable!

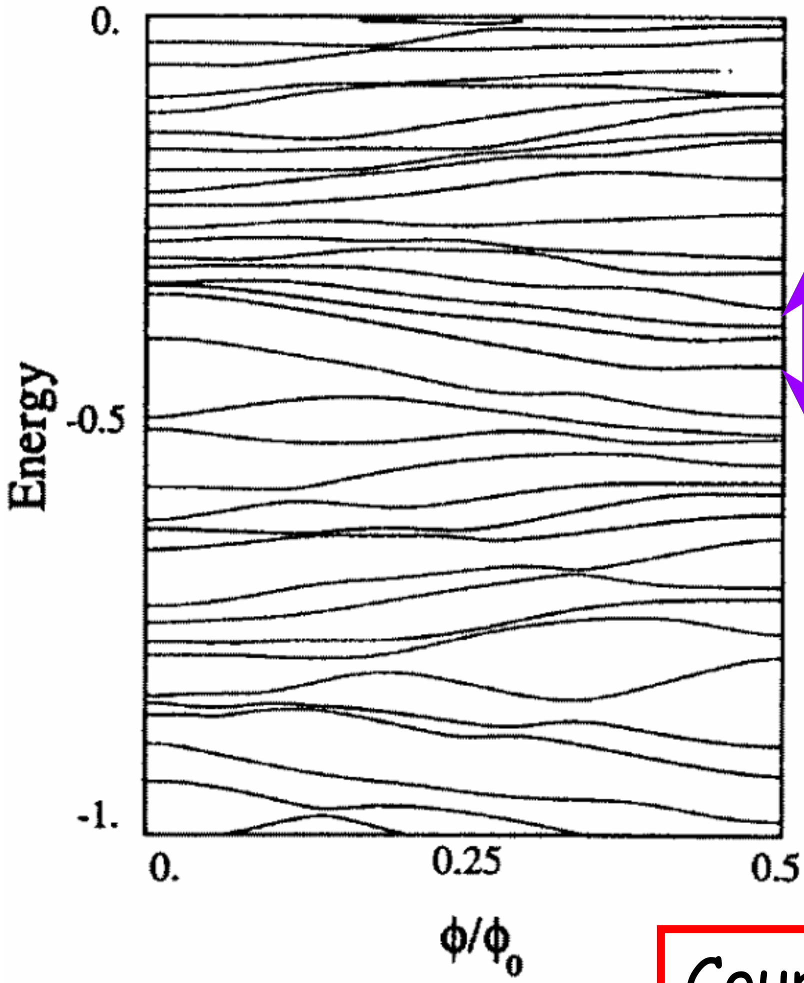
SPECTRE D'UN ANNEAU DIFFUSIF 3D $l_e < L$



ENERGIE DE CORRELATION:

$$E_c = h/\tau_D = hD/L^2$$

Spectre d'un anneau désordonné



Spectre corrélé

Energie de Thouless

$E_c = h\, D/L^2 = h/\tau_D$

$\tau_D = L^2/D$ temps de diffusion autour de l'anneau

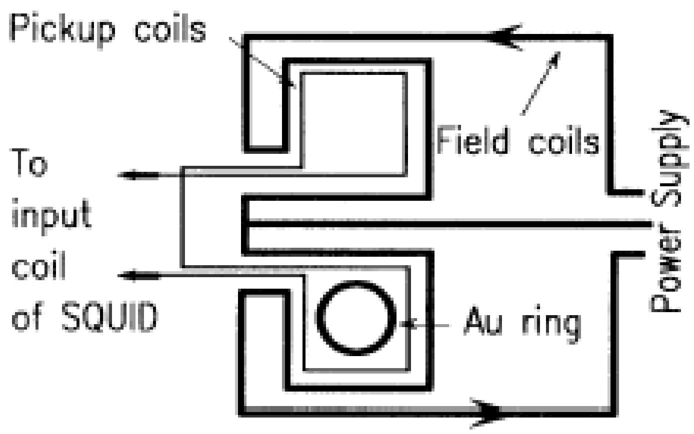
Décrit par la théorie des matrices aléatoires sur cette échelle d'énergie

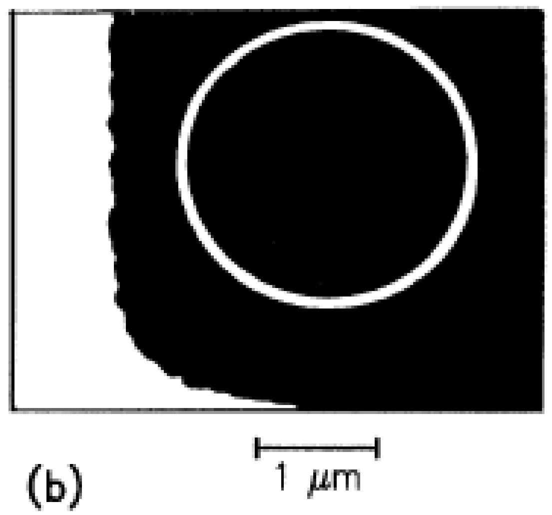
Courant permanent: variable aléatoire

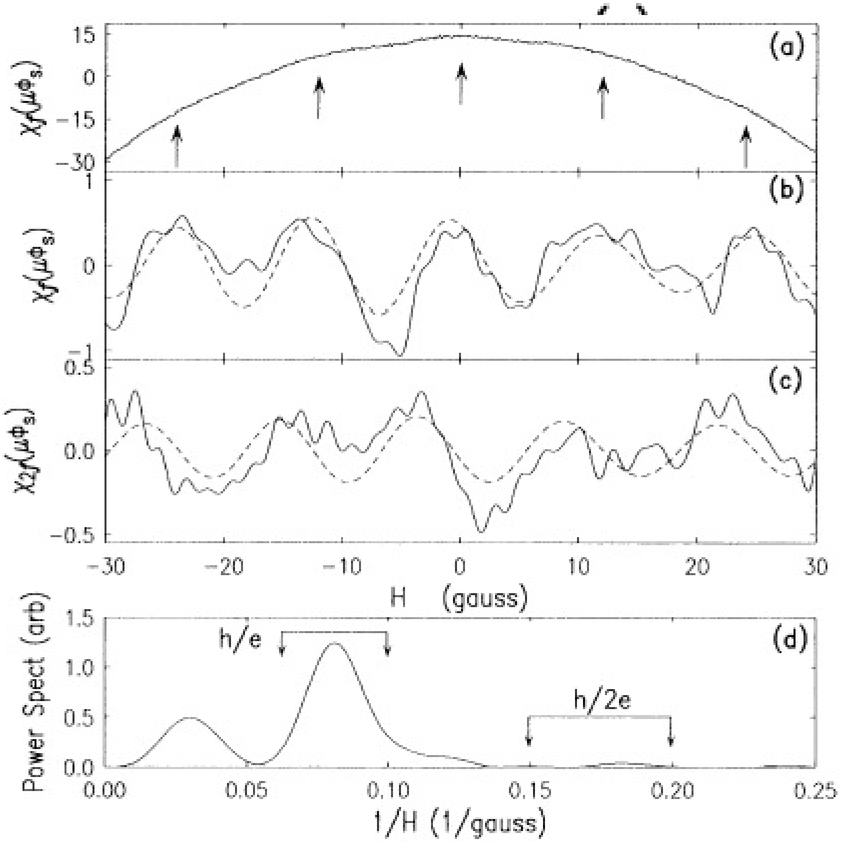
$$\langle I^2 \rangle^{1/2} = e/\tau_D = I_0\, l_e/L$$

Magnetic moment of an individual ring:

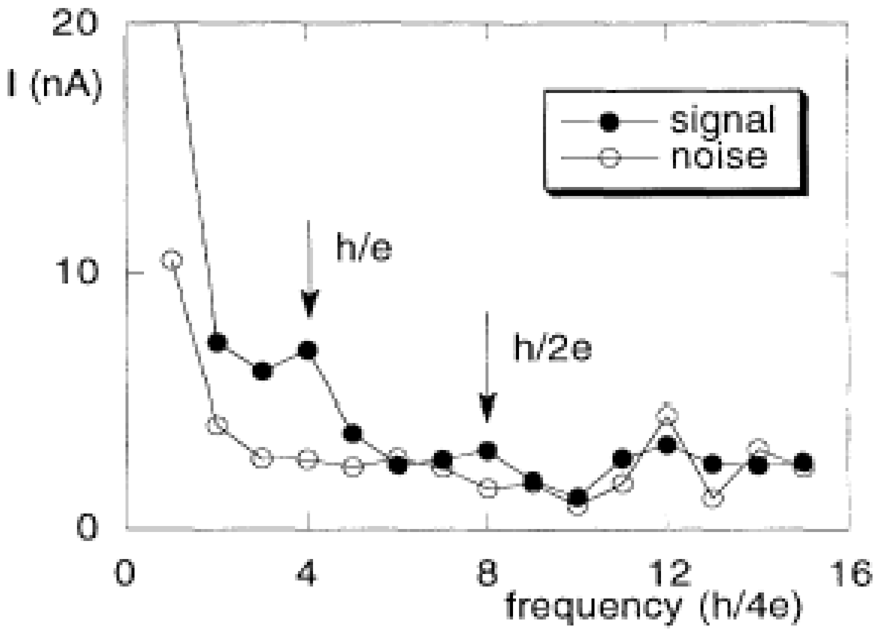
Chandrasekar,Webb (1991)

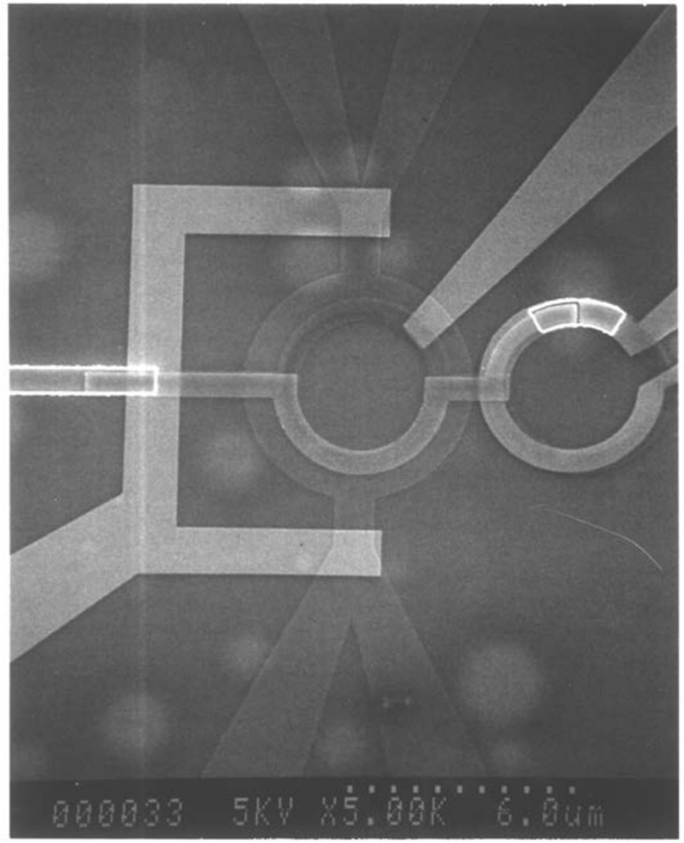


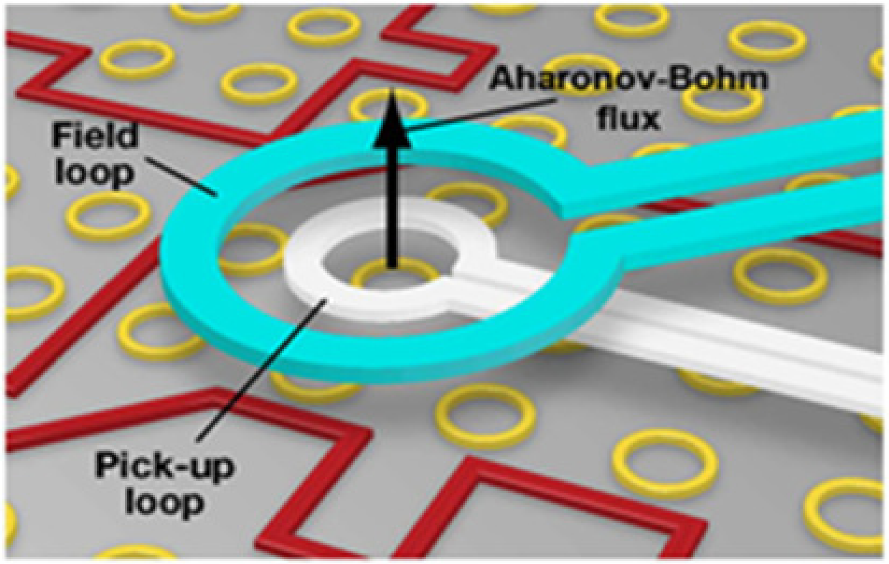




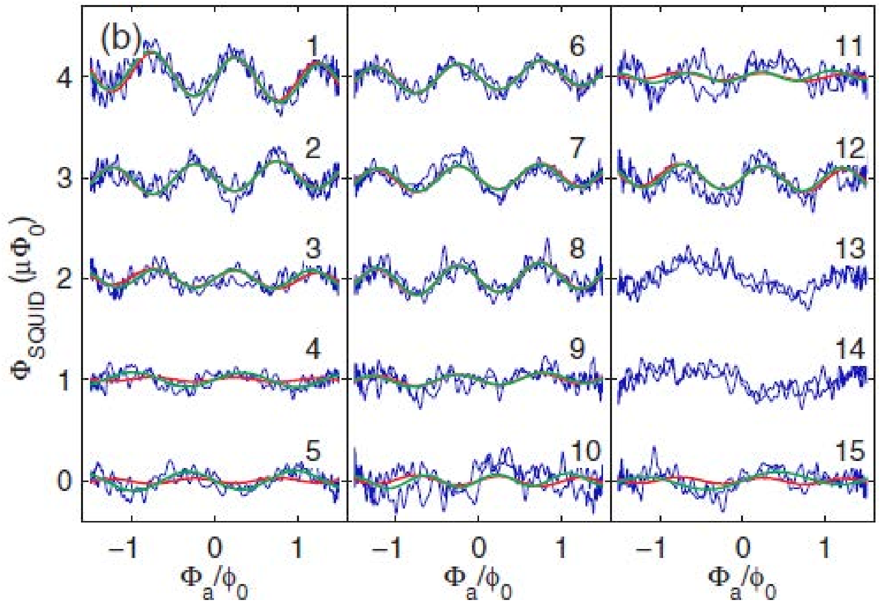
Experimental set up for the detection of the magnetic moment of an individual mesoscopic ring (D.Mailly et al. 1993)



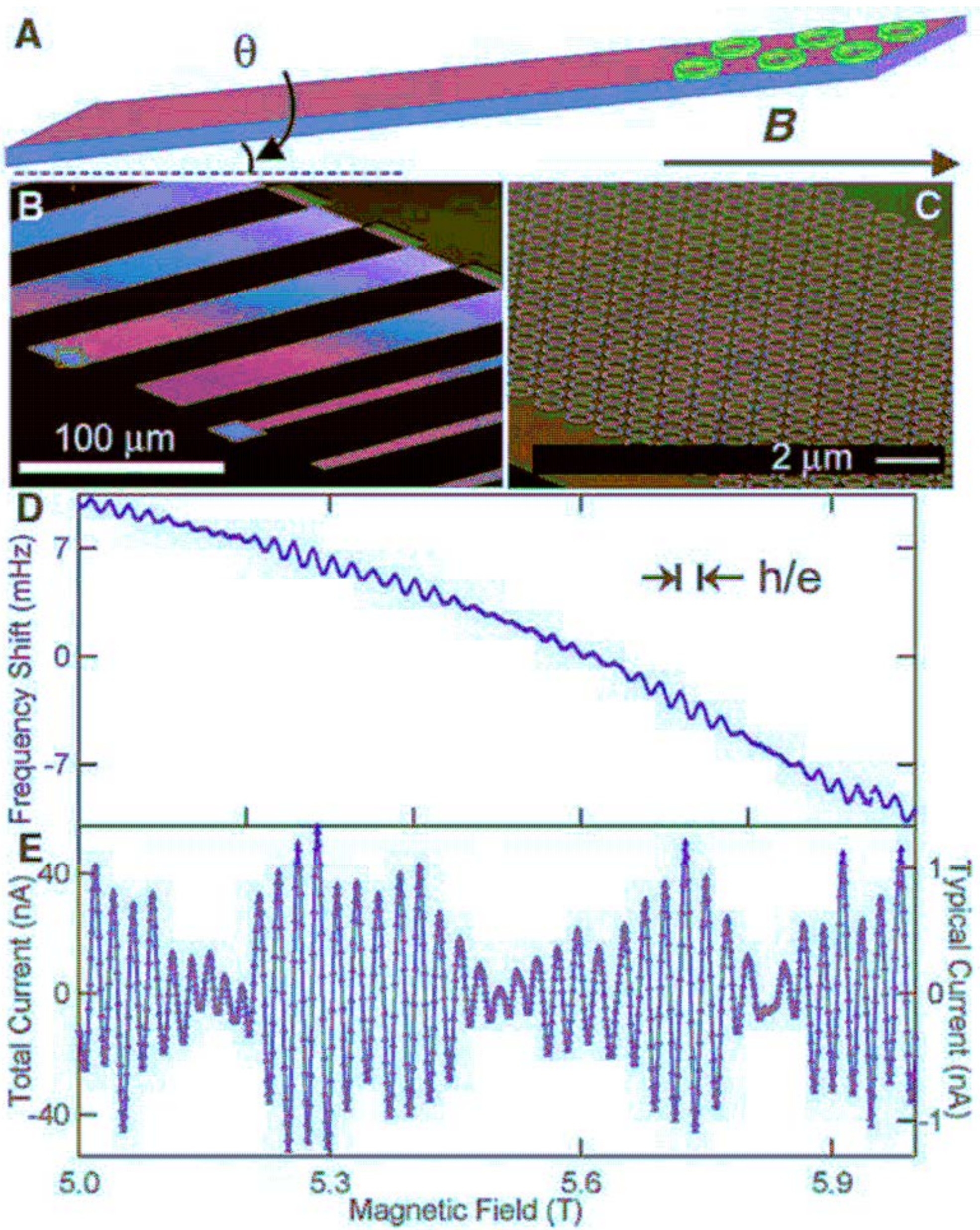




Set up for magnetic detection of persistent currents
(Bluhm et al. PRL 2008)



Mesures de couple en fort champ magnétique

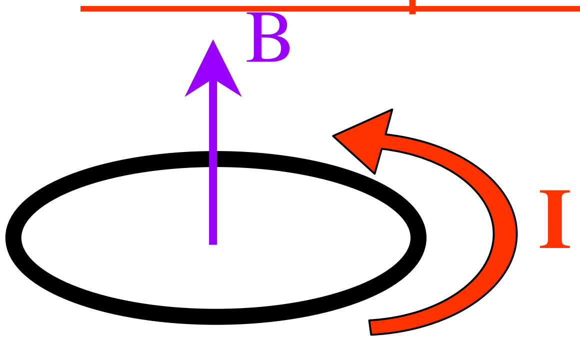


Oscillateur mécanique
fréquence de résonance
α **M** x **B**
Signal mesuré α N $^{1/2}$

Périodique en h/e
Correspond à
$\pm$ e/ τ_D par anneau

A. Beya Bleszynski et al.2009

Courants permanents et Moyenne d'ensemble



Echelle de courant : e/τ_D

avec $\tau_D = L^2/D$

Mesure sur un échantillon

$\neq$

Moyenne

Courant typique : $I_{typ} = \sqrt{< I^2 >}$

- mesure sur un anneau
- périodique en Φ_0

Courant moyen : $I_{moy} =< I >$

- mesure sur une assemblée d'anneaux
- périodique en $\Phi_0/2$

2 contributions :

1- Moyenne « canonique » N fixe ind de F = $<I> = \Delta/\Phi_0 \sin 4\pi\Phi/\Phi_0$

Anneau métallique $\Delta \sim$ qqμK

2-Interactions e-e

$\delta E = e^2 \int V(\mathbf{r-r'})\, n(\mathbf{r}) n(\mathbf{r'}) \mathbf{drdr'}$

$V(\mathbf{r}) = U\, \delta(\mathbf{r})$

$$\boxed{<I> = - e^2 U \; d/d\Phi \left[\int <n(\mathbf{r})^2> dr \right]}$$

Magnétisme orbital et interactions électroniques

$$\boxed{M_{ee} = -\frac{\nu U}{2\pi}\partial_B \int_0^{+\infty} \omega \underbrace{Re P_c(\omega, B)}\, d\omega}$$ $= -\partial_B\, \delta E_{ee}(B)$

Correction quantiques à l'énergie liée aux interactions

Dans un anneau : $\sum_n Re \frac{1}{i\omega + Dq_n^2 + 1/\tau_\phi}$ Cooperon

$$q_n = n2\pi/L + 4\pi\phi/\phi_0$$

Ressemble à la correction de localisation faible à la conductance moyenne:

$$\delta G_Q(\omega) = (4e^2/h)\frac{D}{L^2}\sum_n Re\frac{1}{i\omega + Dq_n^2 + 1/\tau_\phi} \propto \int_0^{+\infty} \exp(-t/\tau_\phi)\; P_c(r,r,B,t)dt$$

$E_c = \hbar/\tau_D = \hbar\, D/L^2$

$$\boxed{I_{ee} = M_{ee}/S = U\nu\, E_{Th}/\phi_0 \;\; \sin(4\pi\phi/\phi_0) + \text{harm}\ldots}$$

Susceptibilité magnétique $\chi_{ee} = dI_{ee}/dB\,|_{B=0} = U\nu\,(e^2/4\pi^2 m)\, k_F l_e \sim \chi_L\, k_F l_e$

$\chi_L = -\, e^2/12\pi m = -2/3\, \mu_B{}^2 \rho_0$

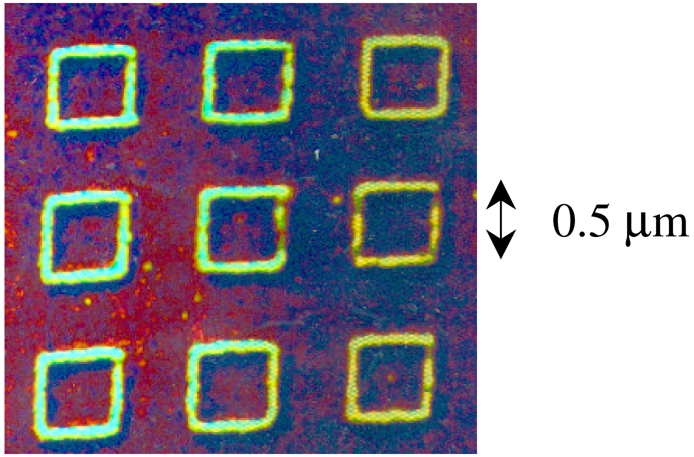
Signe donné par celui des interactions

Ackermans, Montambaux

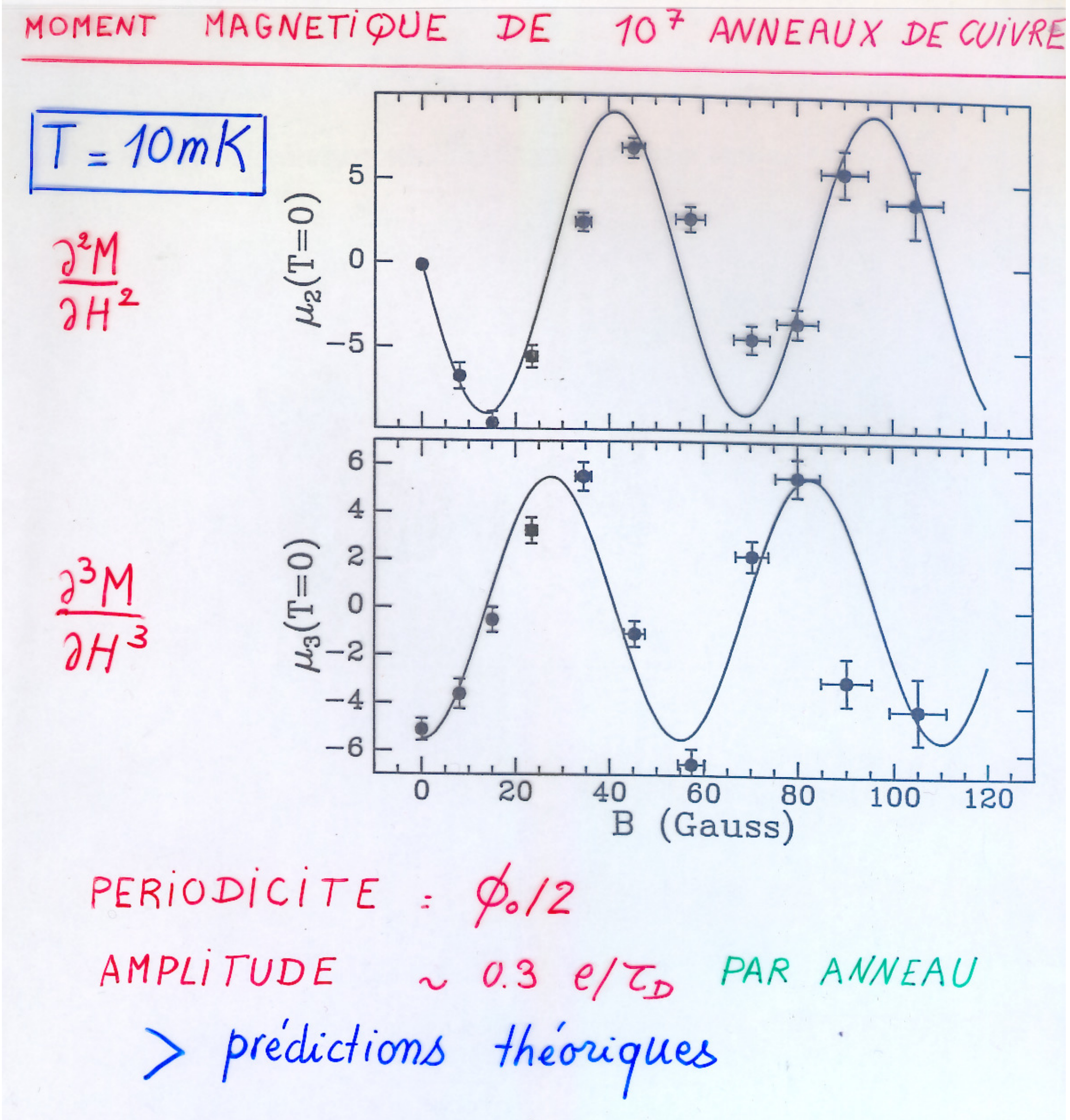
Expérimentalement signe diamagnétique!

Rôle des fluctuations supraconductrices?

Mesure du courant moyen



Magnétométrie à SQUID



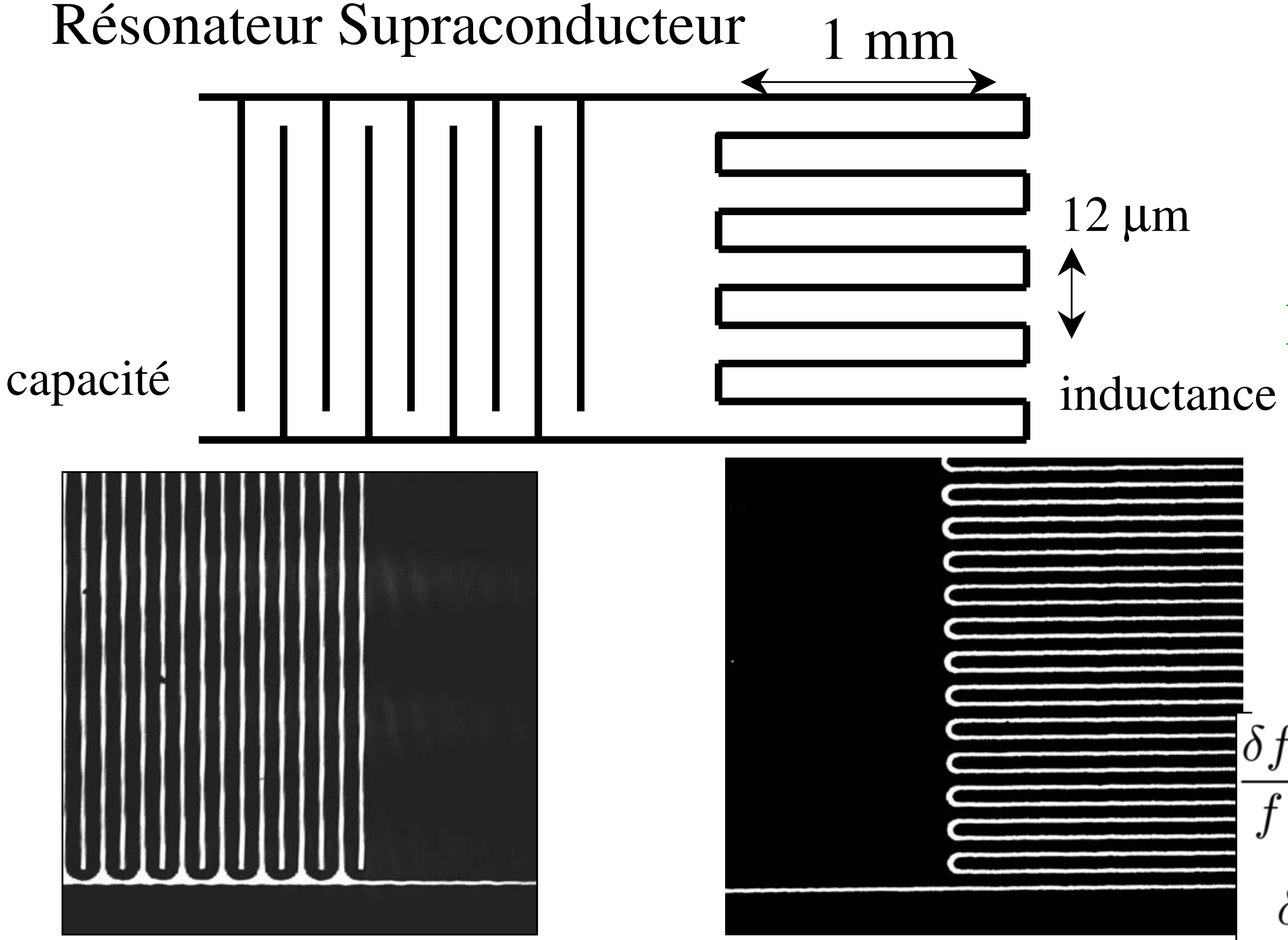
Lévy *et al.*, PRL (1990)

10^7 anneaux de cuivre :

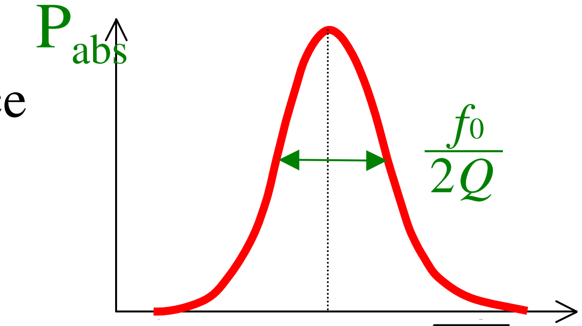
- courant moyen (Φ_0 /2)
- courant de l'ordre de e/τ_D
- signe diamagnétique

Mesures ac sur des anneaux isolés

Résonateur Supraconducteur



f_0= 200-400 MHz
Q=2.10^5 T<1K

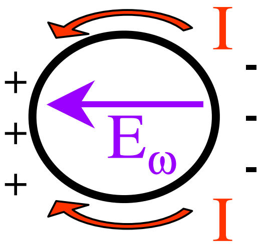


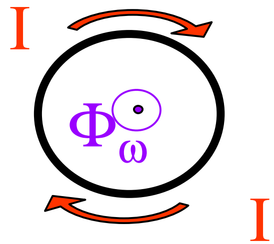
$$f = 1/(2\pi\sqrt{LC})$$

$$\frac{\delta f}{f} = -\frac{1}{2} N k_m \chi' \quad \text{~Im G}$$

$$\delta(\frac{1}{Q}) = N k_m \chi'' \quad \text{~Re G}$$

Polarisabilité Electrique

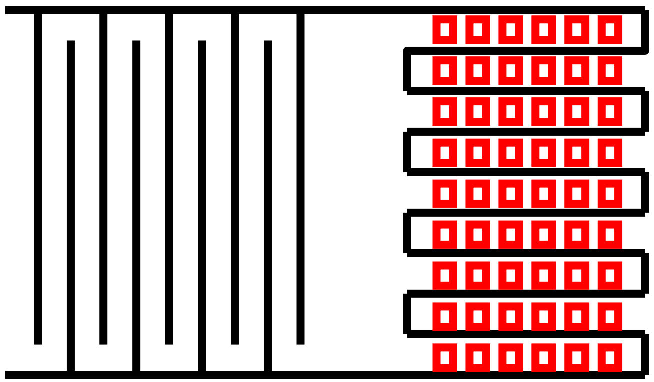




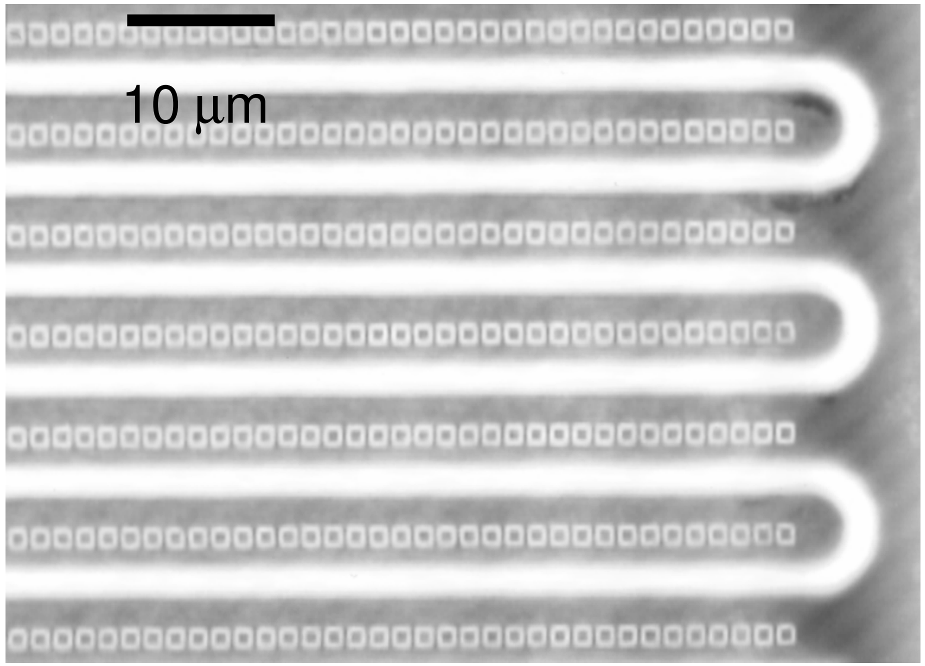
Susceptibilité Magnétique

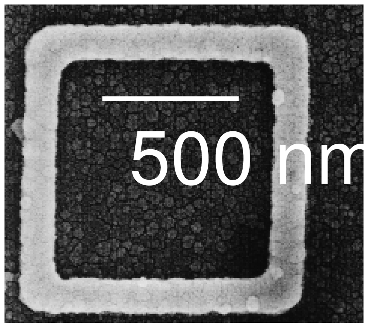
Mesures sans contacts!

Réponse magnétique d'Anneaux d' Argent



résonateur





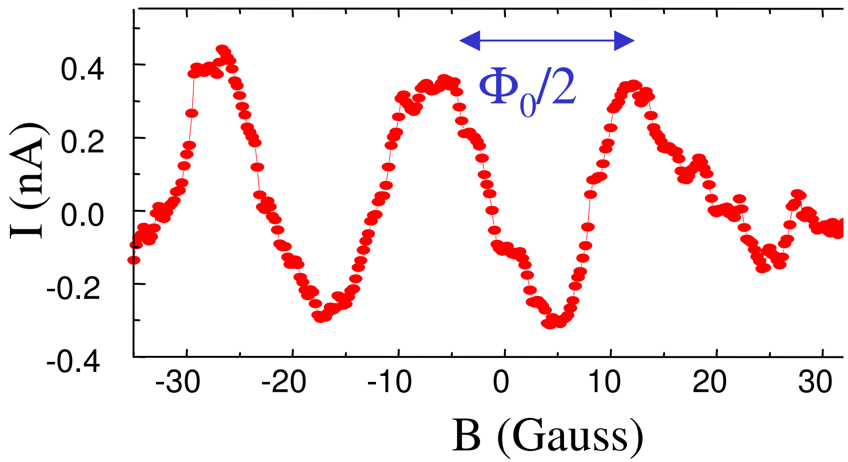
anneaux d'argent

Deblock et al. 2002

Susceptibilité magnétique : $\chi_m = dI/d\phi$

- periodique en $\Phi_0/2$
- diamagnetique à bas champ
- amplitude : $I = 0.3$ nA $= e/\tau_D$

T= 40mK



Mesoscopic rectification

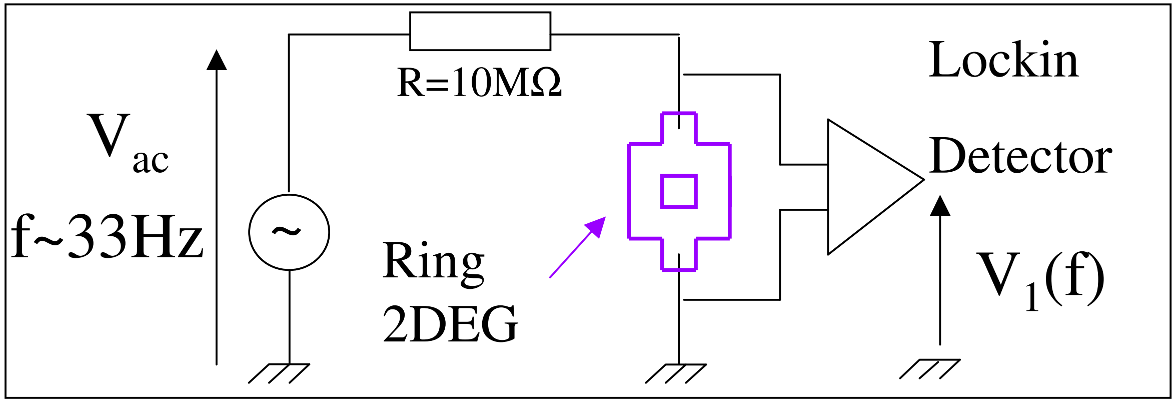
Why is non linear mesoscopic transport interesting?
What kind of diodes are mesoscopic systems?

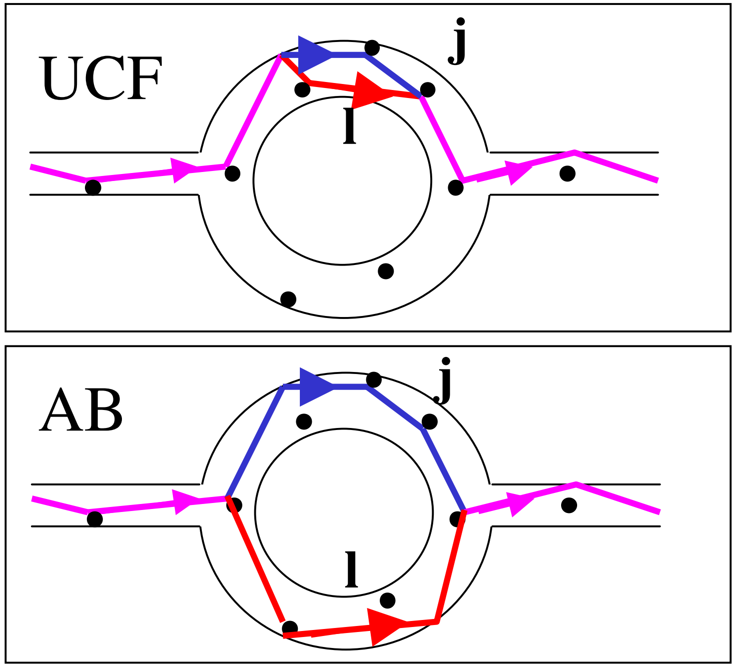
Field Asymmetry related to electron-electron interactions
<u>Amplitude of electron-electron interactions can be measured!</u>

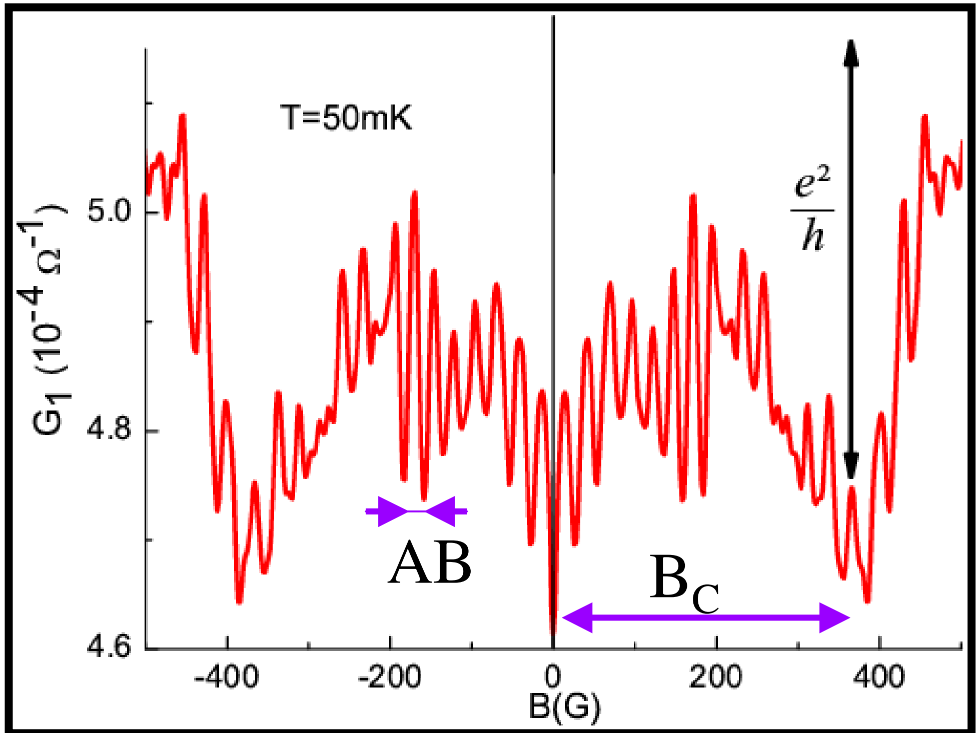
Linear Conductance

$I = G_1 V$

2 wires mesurement







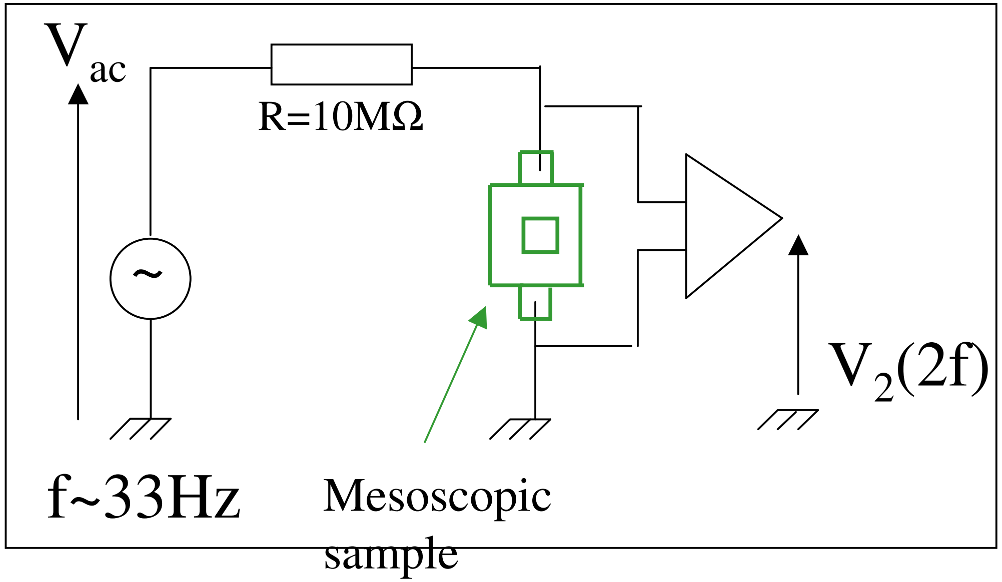
AB Oscillations and UCF even function of field

Non Linear Conductance of second Order

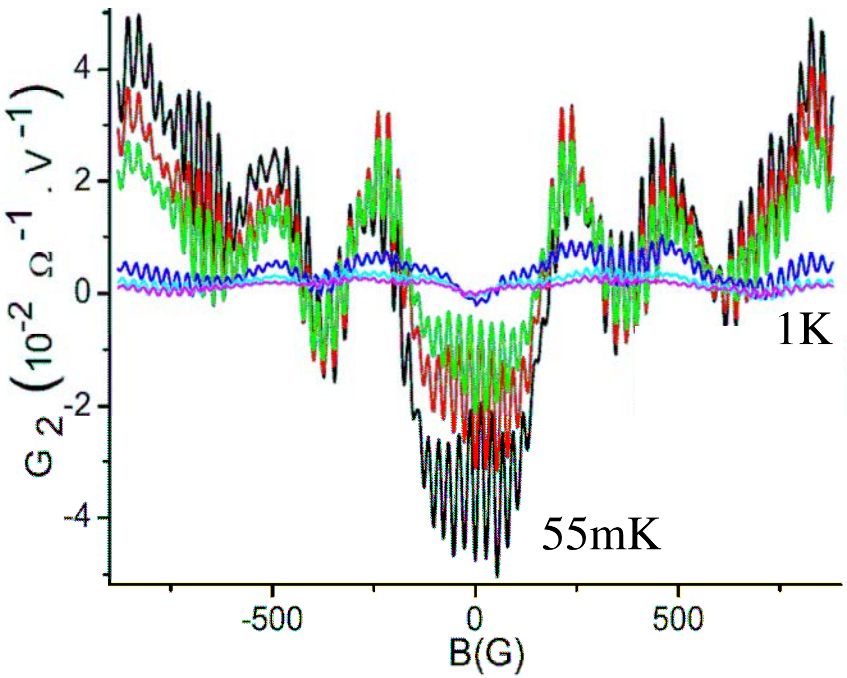
In a non centrosymmetric sample

$$\boxed{I = G_1 V + G_2 V^2}$$

G_2 is a mesoscopic quantity



$$\langle G_2 \rangle = 0$$

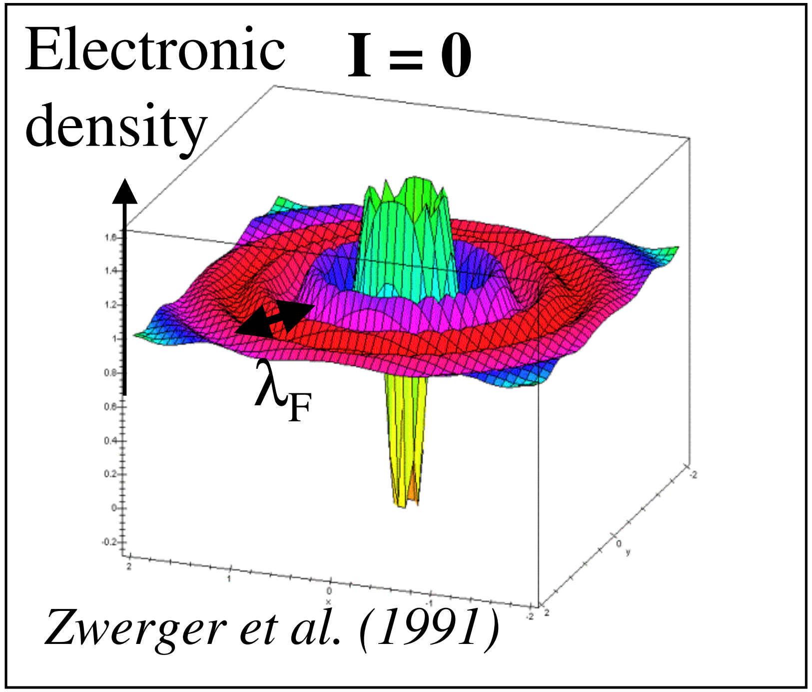


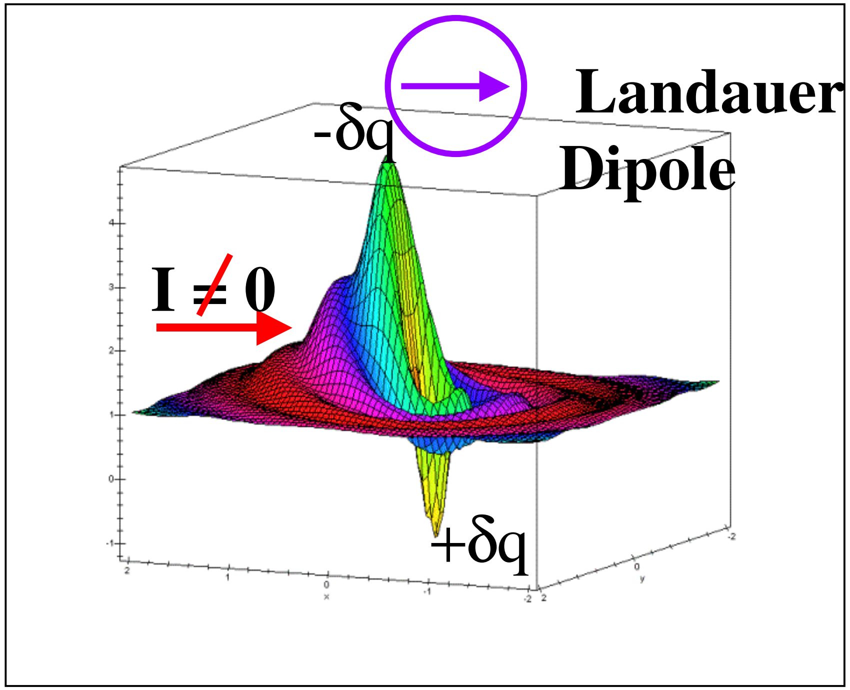
G_2 is not an even function of magnetic field

Observations on GaAS/GaAlAs ballistic systems *Angers 07*

Electron-electron interactions at the single impurity level

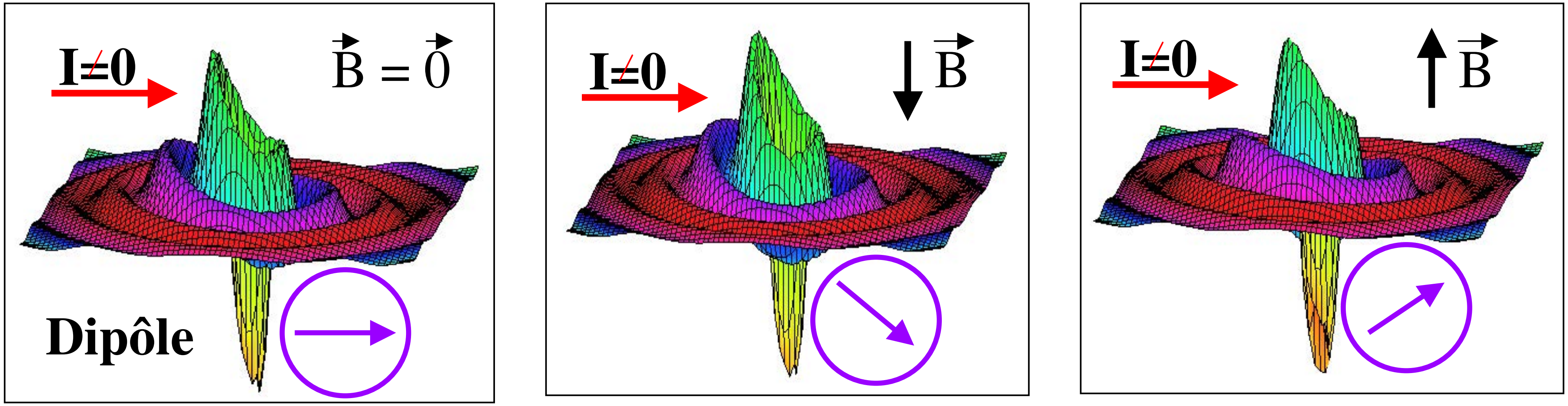
$$\boxed{dn(I) \neq dn(-I)}$$





Electron-electron interactions at the single impurity level

$$\boxed{dn(\vec{B}) \neq dn(-\vec{B})}$$



$$H_{\mathrm{int}} = \frac{\gamma_{\mathrm{int}}}{\nu} \int d\vec{r}\; n^2(\vec{r})$$

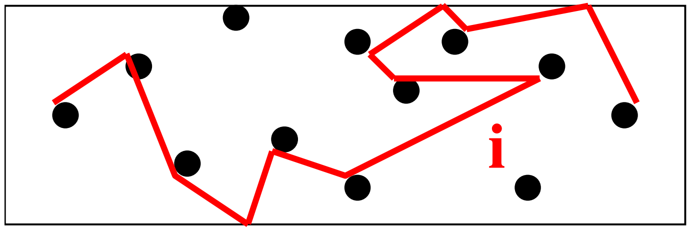
$$\boxed{dU_{\text{dés}}(\vec{r}) = \frac{\gamma_{\mathrm{int}}}{2\nu} dn(\vec{r})}$$

Bias induced Modification of the scattering potential
has an odd component in I and B

Mesoscopic Effect

$V(\vec{r})$

Origin of $\boxed{G_2}$ **and** $\boxed{G_2^{AS}}$



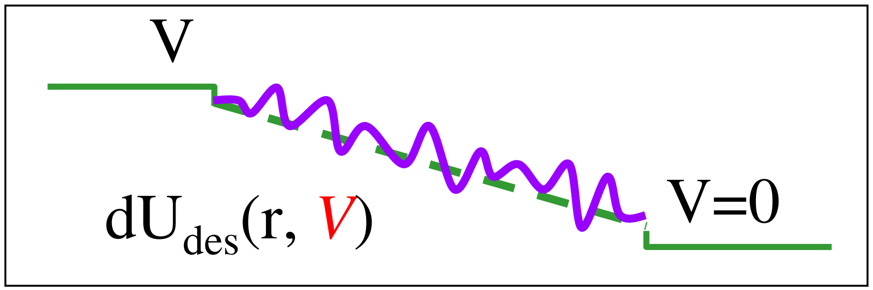
$$d\phi_i = \int dU_{\text{dés}}(\vec{r}(t), V(r))\, dt$$

Modification of the spatial charge distribution and potential landscape with bias

(c.f. M. Büttiker,)

Bias

$$V \longrightarrow dn(\vec{r}, V) \xrightarrow{\gamma_{int}} dU_{des}(\vec{r}, V) \xrightarrow{\text{Diffusive trajectories}} d\phi_i(V) \xrightarrow{\text{Phase coherence}} dG(V)$$



$$G_2 = \left(\frac{\partial dG\left[dU_{dis}, V, \gamma_{int}\right]}{\partial V} \right)_{V=0}$$

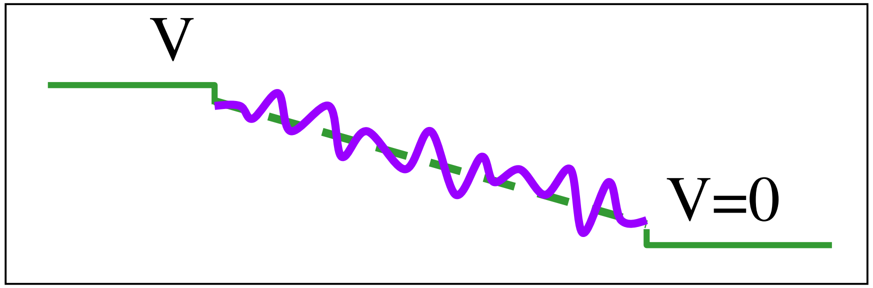
- Existence of a contribution odd in magnetic field in dn and G_2

Importance of interactions

Büttiker, Sanchez, Polianski 2004,2006

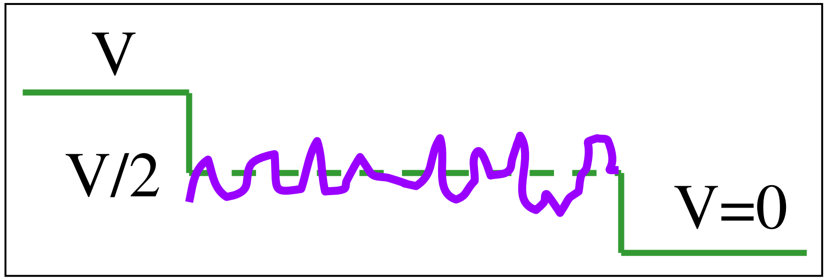
$\boxed{\delta G_2^S}$ depends on the potential landscape

➤ Diffusive regime



➤ Ballistic regime

symmetrical contacts,
strong interactions



No average voltage drop through the sample !

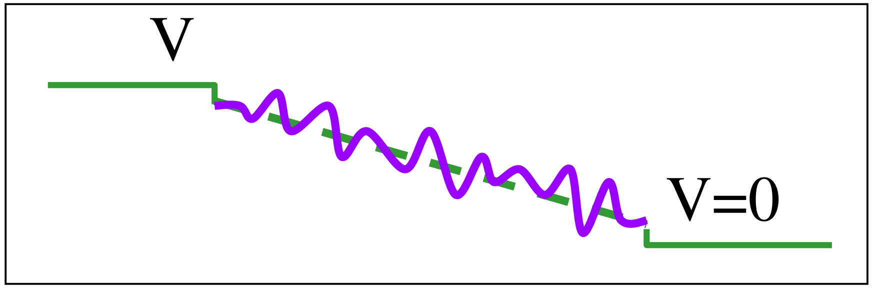
$$\boxed{< d\phi_i(V) >= eV\tau_D/h}$$

$$\boxed{< d\phi_i(V) >=0}$$

$$\boxed{G_2 = dG(V)/dV = \Sigma_i\, (dG/ d\phi_i\,)(d\phi_i(V)/dV)}$$

$\boxed{\delta G_2^S}$ depends on the potential landscape

- Diffusive regime

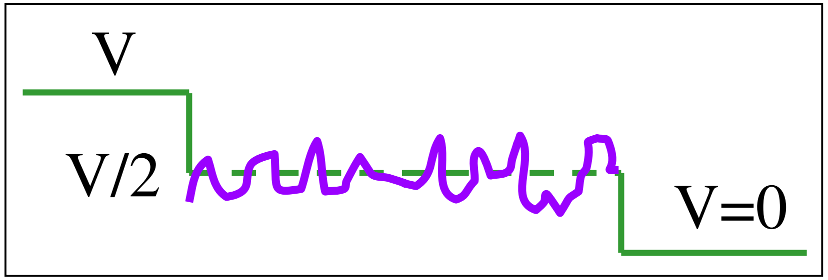


$$\delta G_2^S \cong \boxed{\frac{e\tau_D}{\hbar}\delta G_1} + \boxed{\frac{e\tau_D}{\hbar}\frac{\gamma_{\text{int}}}{g}(\delta G_1)^2}$$

$$\Rightarrow \boxed{\frac{\delta G_2^{AS}}{\delta G_2^S} \cong \frac{\gamma_{\text{int}}}{g}\delta G_1}$$

- Ballistic regime

symmetrical contacts,
strong interactions

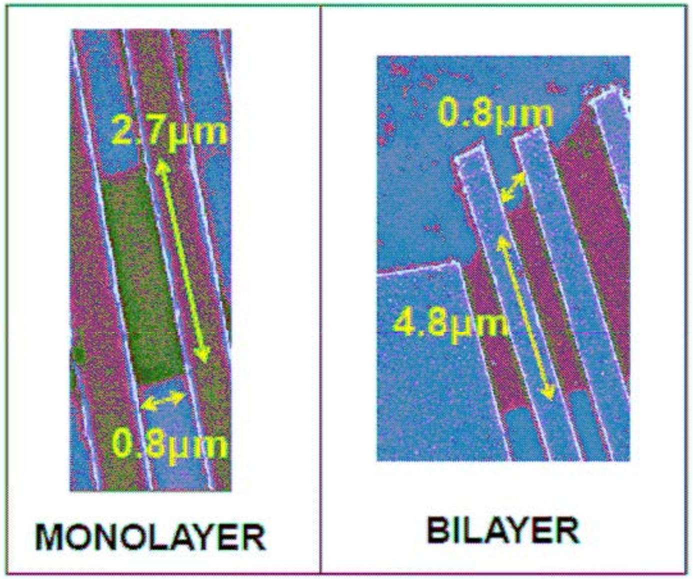


No average voltage drop through the sample !

$$\delta G_2^S \cong \boxed{0} + \boxed{\frac{e\tau_D}{\hbar}\frac{\gamma_{\text{int}}}{g}(\delta G_1)^2}$$

Polianski et al. (2006 et 2007)

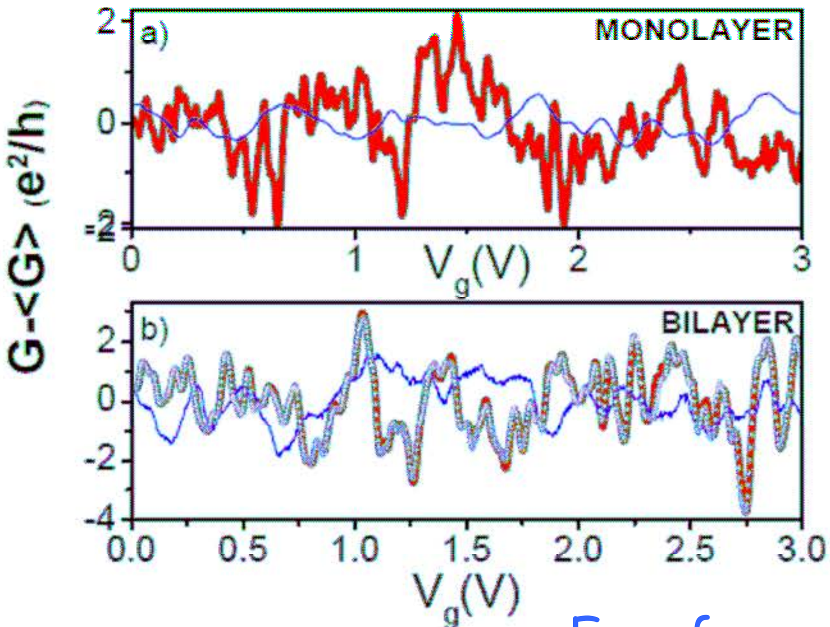
$$\Rightarrow \boxed{\frac{\delta G_2^{AS}}{\delta G_2^S} \cong 1}$$

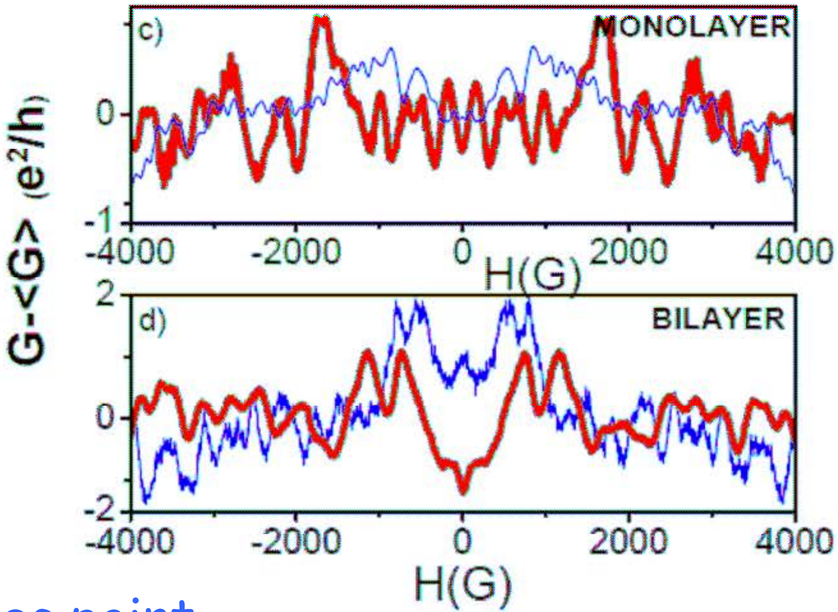


Conductance fluctuations in graphene

Correlation fields and energies
depend on doping level

Ojeda et al. PRL 2010





Far from the Dirac point

Close the Dirac Point

G_2 contains an antisymmetric component in magnetic field

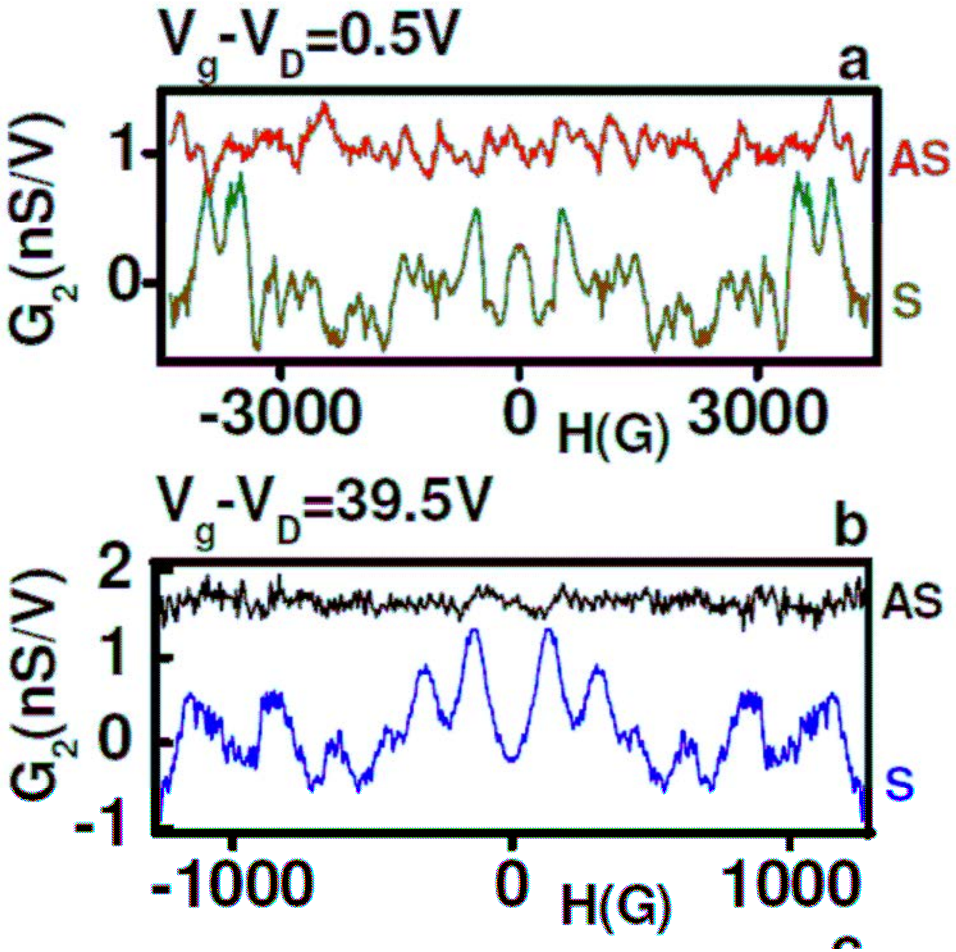
Casimir Onsager Symmetry rules: $G_1(B)=G_1(-B)$

Do not apply for $G_2(B)$

$$G_1^{AS}=0 \quad G_2^{AS} \neq 0$$

$$G_2^{S,AS}=(G_2(B) \pm G_2(-B))/2$$

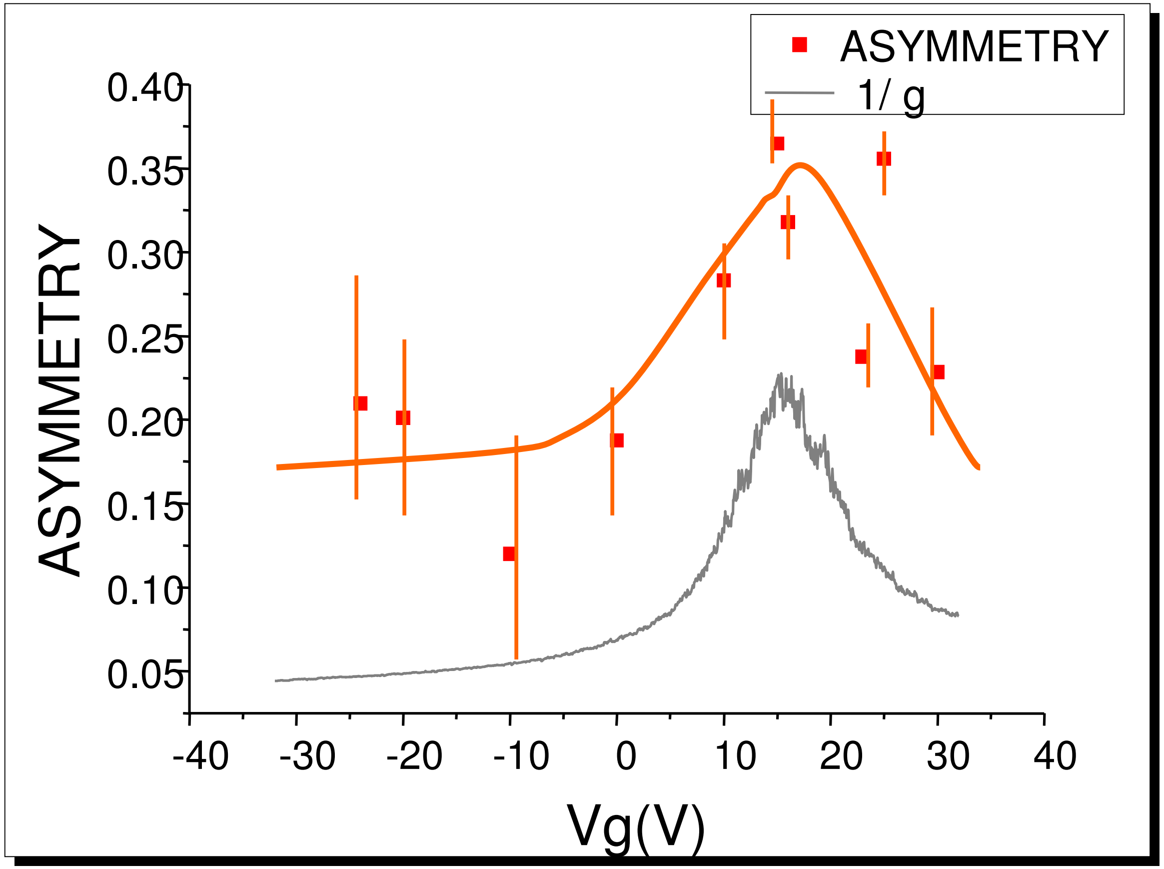
GRAPHENE
T=50mK



At neutrality point

Far from neutrality point

Conductance dependence of the field asymmetry



$$\frac{\delta G_2^{AS}}{\delta G_2^{S}} \cong \frac{\gamma_{int}}{g}$$

In qualitative agreement
With theoretical predictions
For diffusive systems

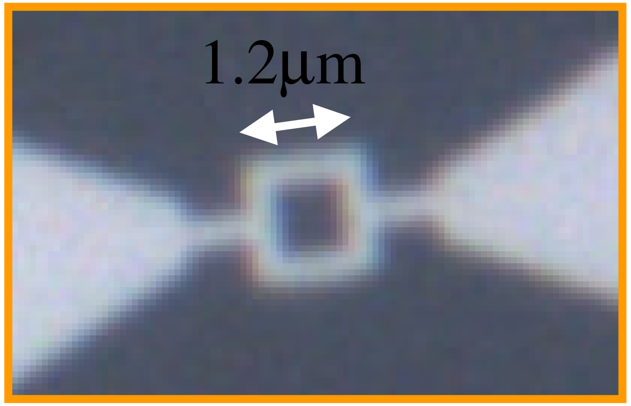
γ_{int}

0 no interactions No screening

1 Interactions Good screening

Aharonov-Bohm Ring 2D e gas

2 contacts
No gate



LPS, Orsay Angers et al. 2006

with 2DEG U. Gennser LPN

Other experiments :

Zumbühl et al. (2006) quantum boxes g~1
Leturcq et al. (2006) small rings g <1

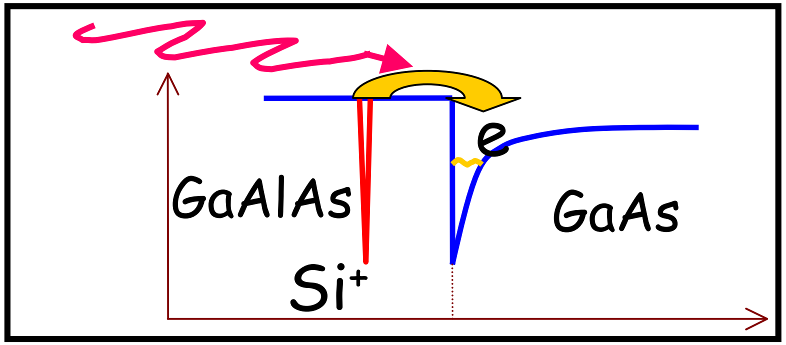
Expected rectification asymmetry: $\boxed{\propto \frac{1}{g}}$ $g=G/(e^2/h)$

Current pulses
10 à 50 mA

decrease of g

Illumination

Increase of g



➢With 2 samples conductance is varied from: **g = 1 to 21**

Symmetry in magnetic field of G_2 and G_1

Casimir Onsager
Symmetry rules:

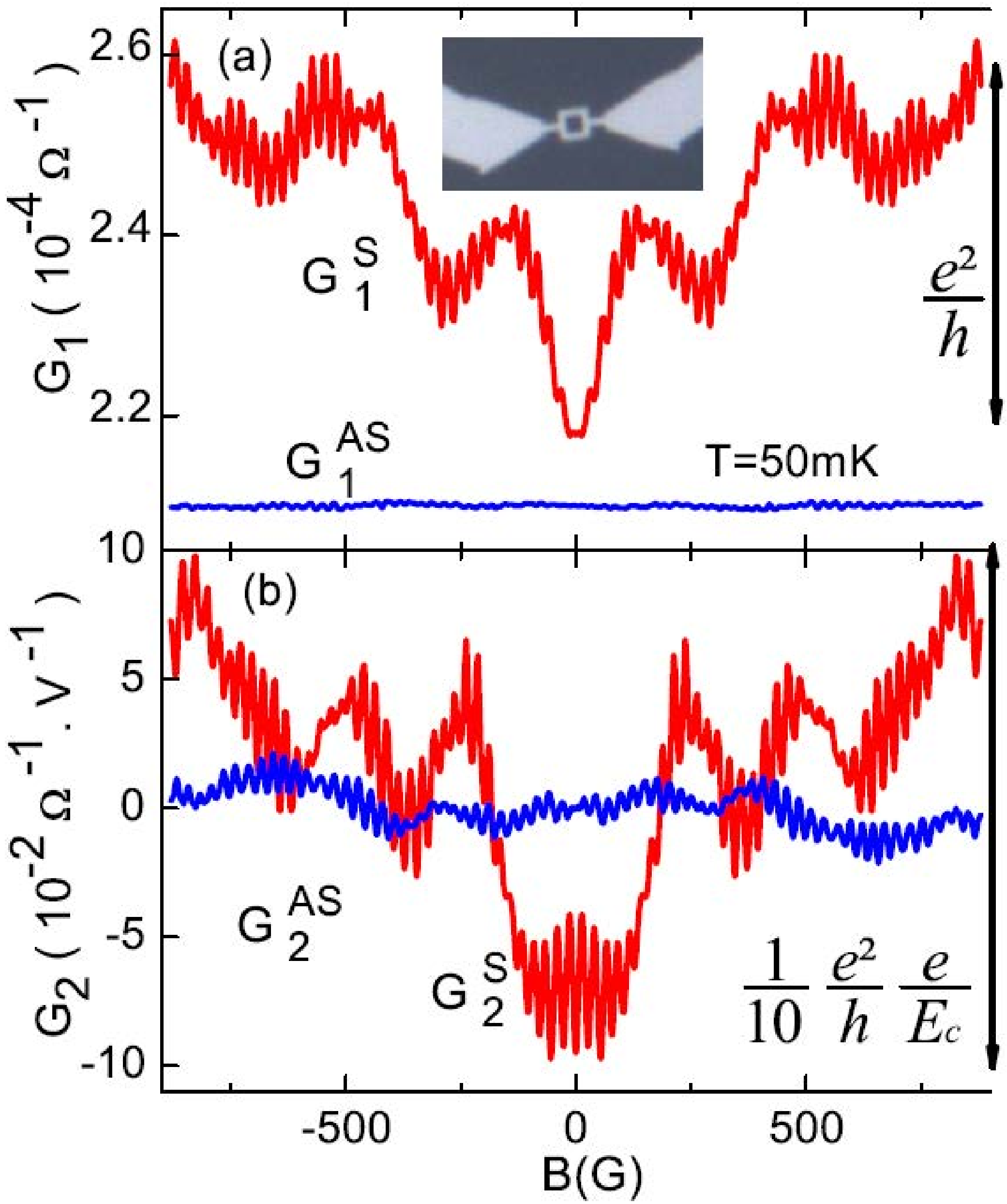
$G_1(B)=G_1(-B)$

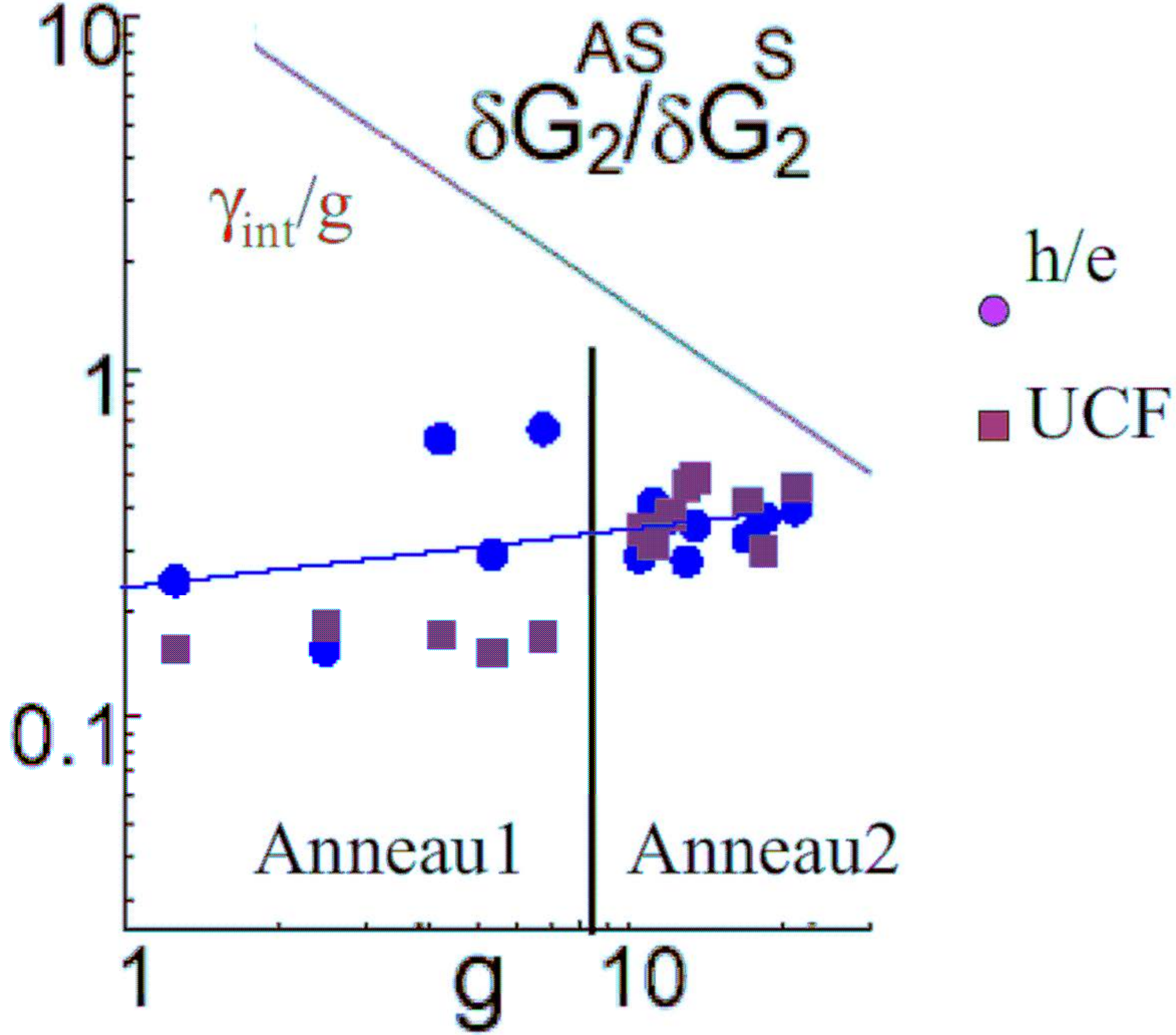
Do not apply for $G_2(B)$

$$G^{S,AS} = \frac{G(B) \pm G(B)}{2}$$

$G_1^{AS} = 0$

$G_2^{AS} \neq 0$





10
1
0.1
$\delta G_2^{AS}/\delta G_2^{S}$
γ_{int}/g
h/e
UCF
Anneau1
Anneau2
1
g
10