



# Isolants topologiques: transport électronique

Laurent Lévy

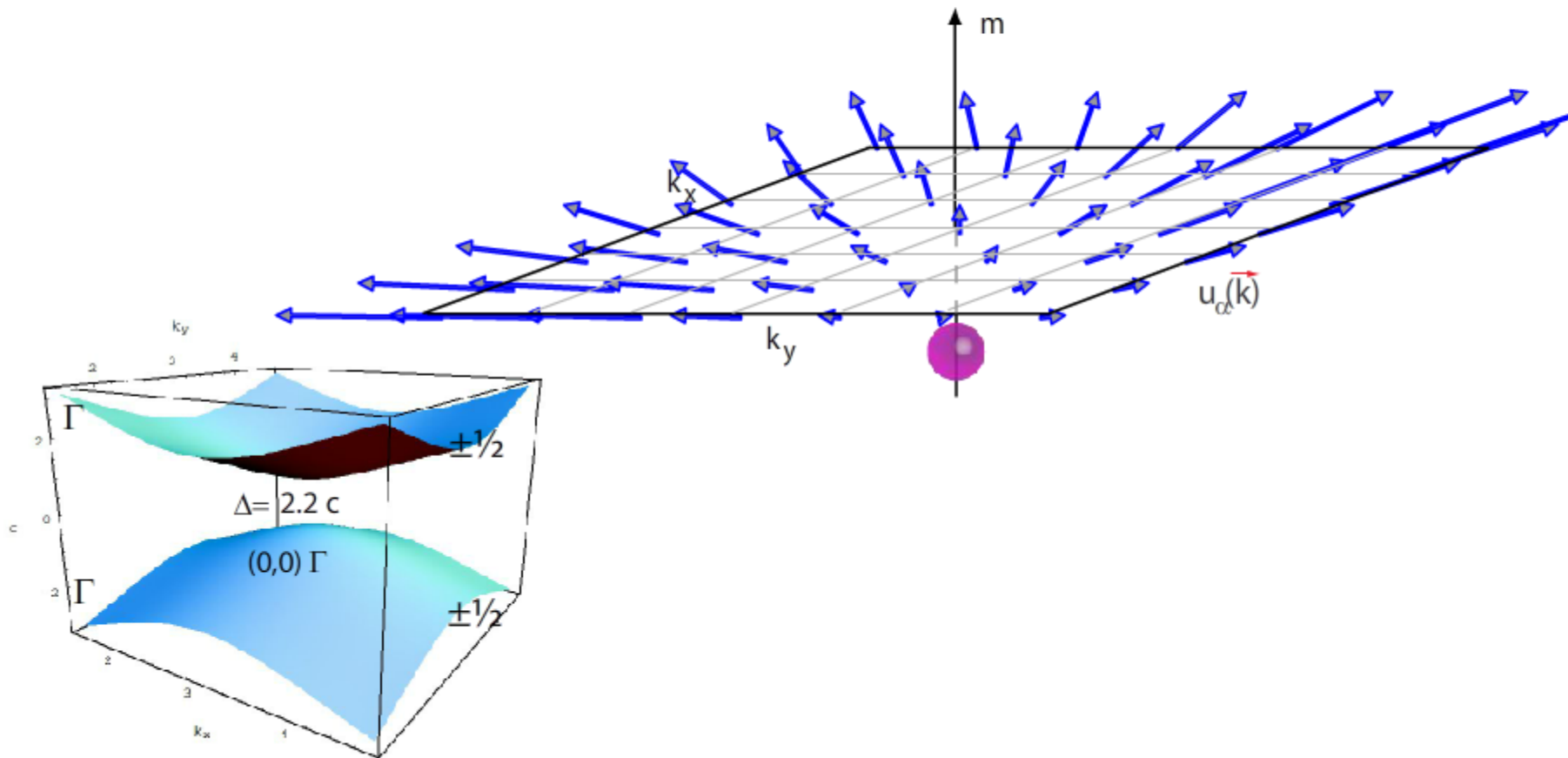
Institut Néel, Univ. de Grenoble

# Exemple: modèle BHZ de l'effet Hall de spin

Zhang model Hamiltonian

$$H = 2.2c - c[\cos k_x + \cos k_y]\sigma_z + \underbrace{\sin k_x \sigma_x + \sin k_y \sigma_y}_{\text{Spin-Orbit}} = \sigma \cdot \vec{d}(\vec{k})$$

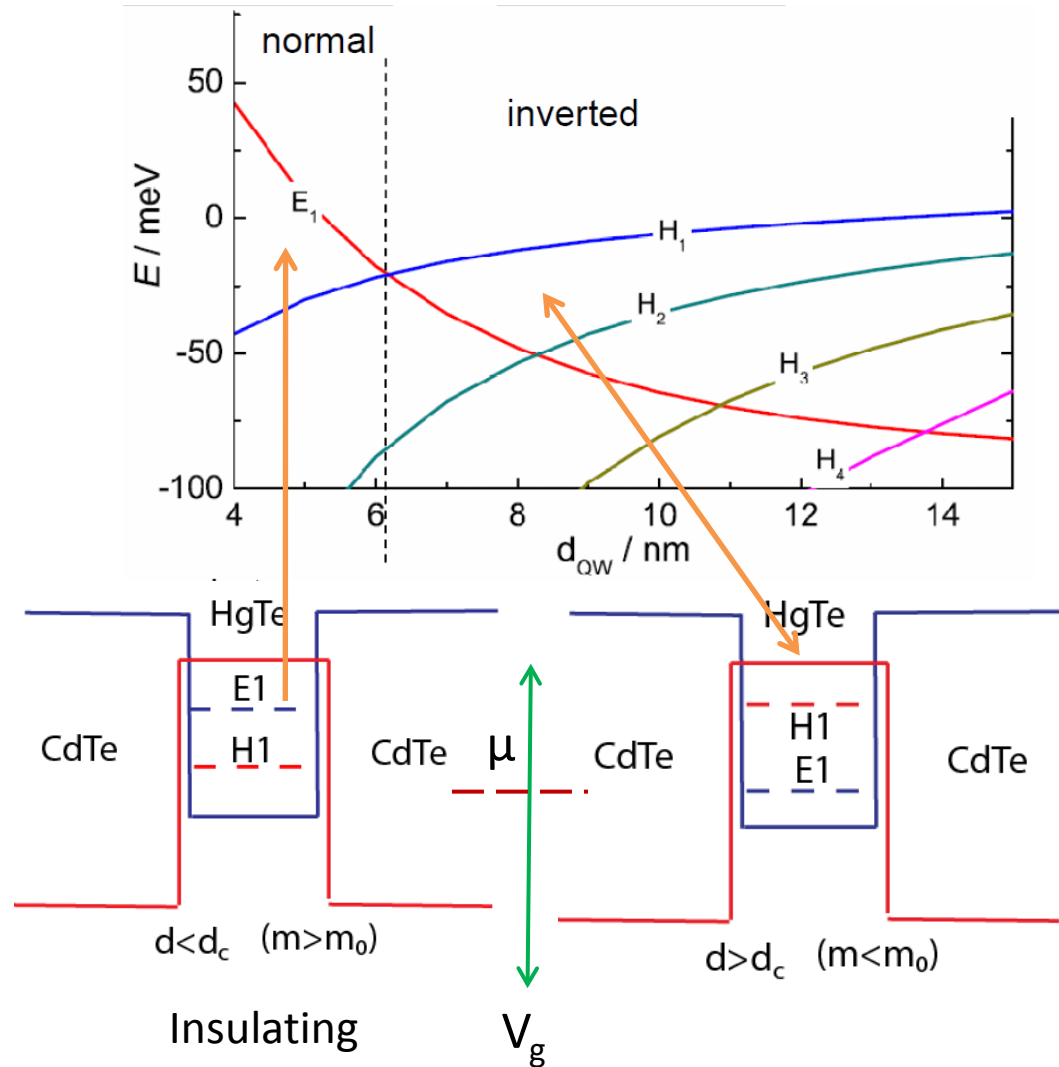
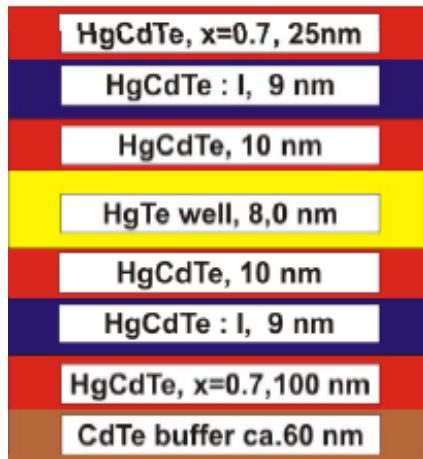
$$\varepsilon = \pm |d| = m - 2c \quad \vec{d}(\vec{k}) = (\sin k_x, \sin k_y, m - c[\cos k_x + \cos k_y])$$



# Effet du confinement dans un puit quantique

Transition gap normal aux faibles épaisseurs a un gap inverse au dessus de 6.7nm

Croissance MBE



# Formation des états de bord du quantum spin-Hall

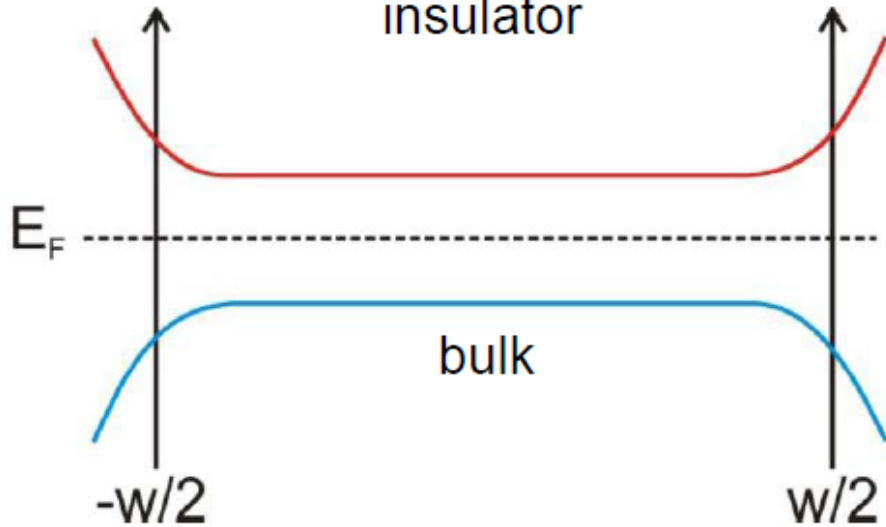
$m > 0$

Gap « normal »

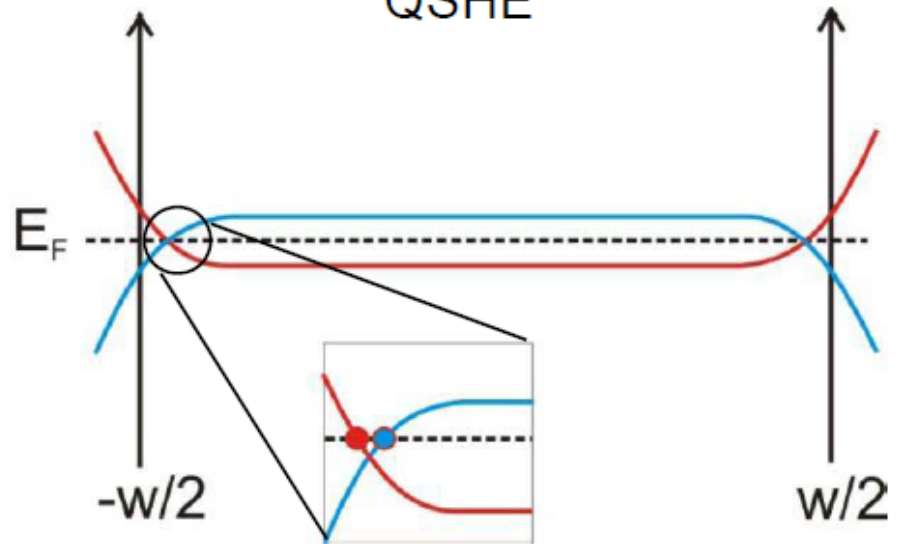
$m < 0$

Gap « inversé »

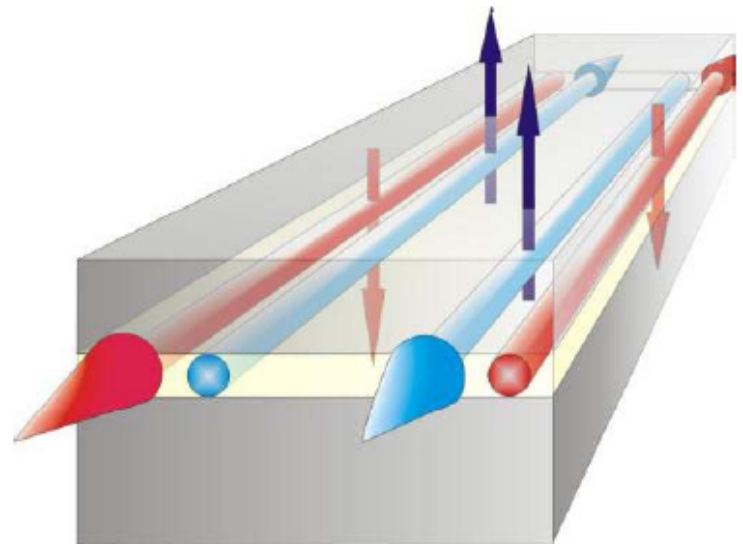
normal  
insulator



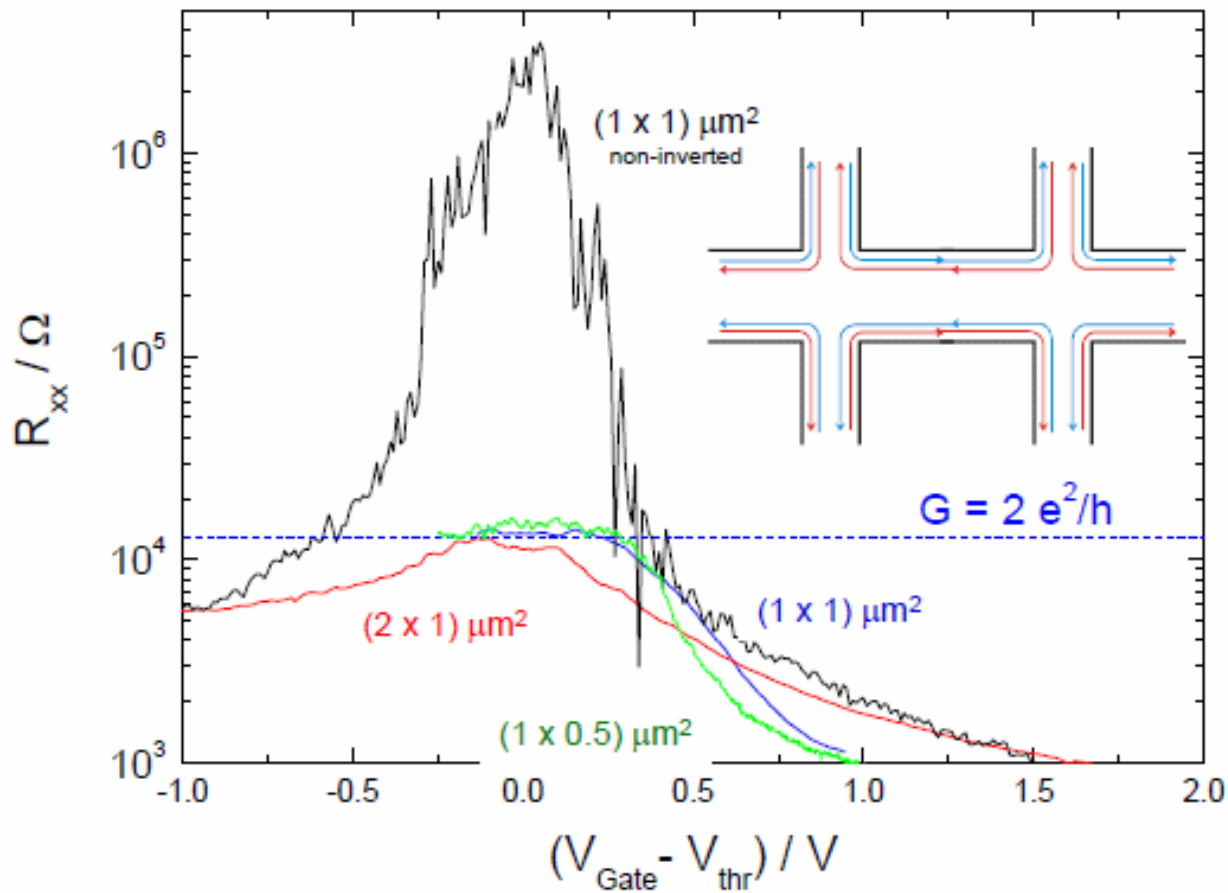
QSHE



entire sample  
insulating

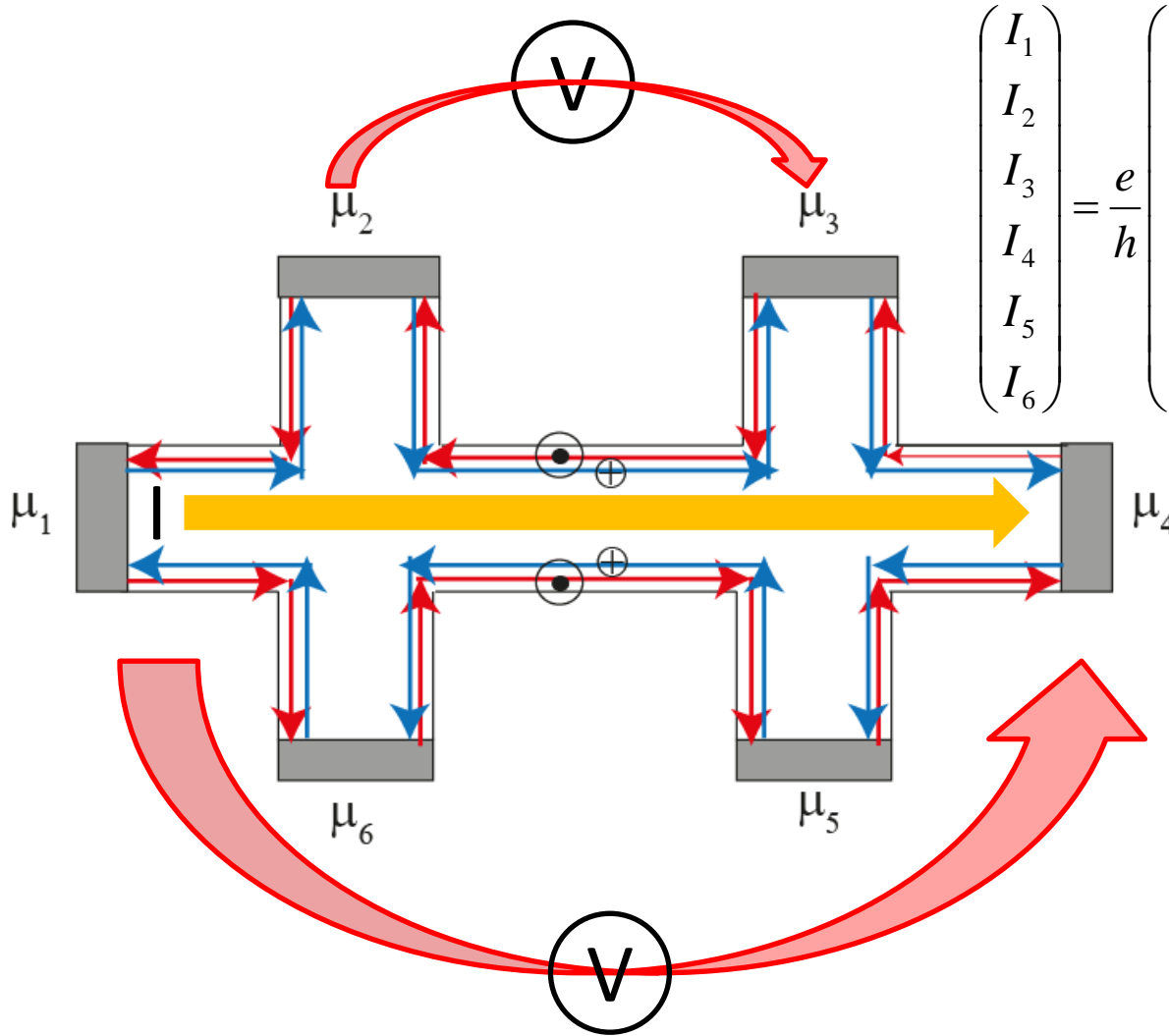


# L'effet Hall de spin



HgCdTe, $x=0.7$ , 25nm
HgCdTe : I, 9 nm
HgCdTe, 10 nm
HgTe well, 8,0 nm
HgCdTe, 10 nm
HgCdTe : I, 9 nm
HgCdTe, $x=0.7$ , 100 nm
CdTe buffer ca.60 nm

# Conductance multi-terminaux (barre de Hall)



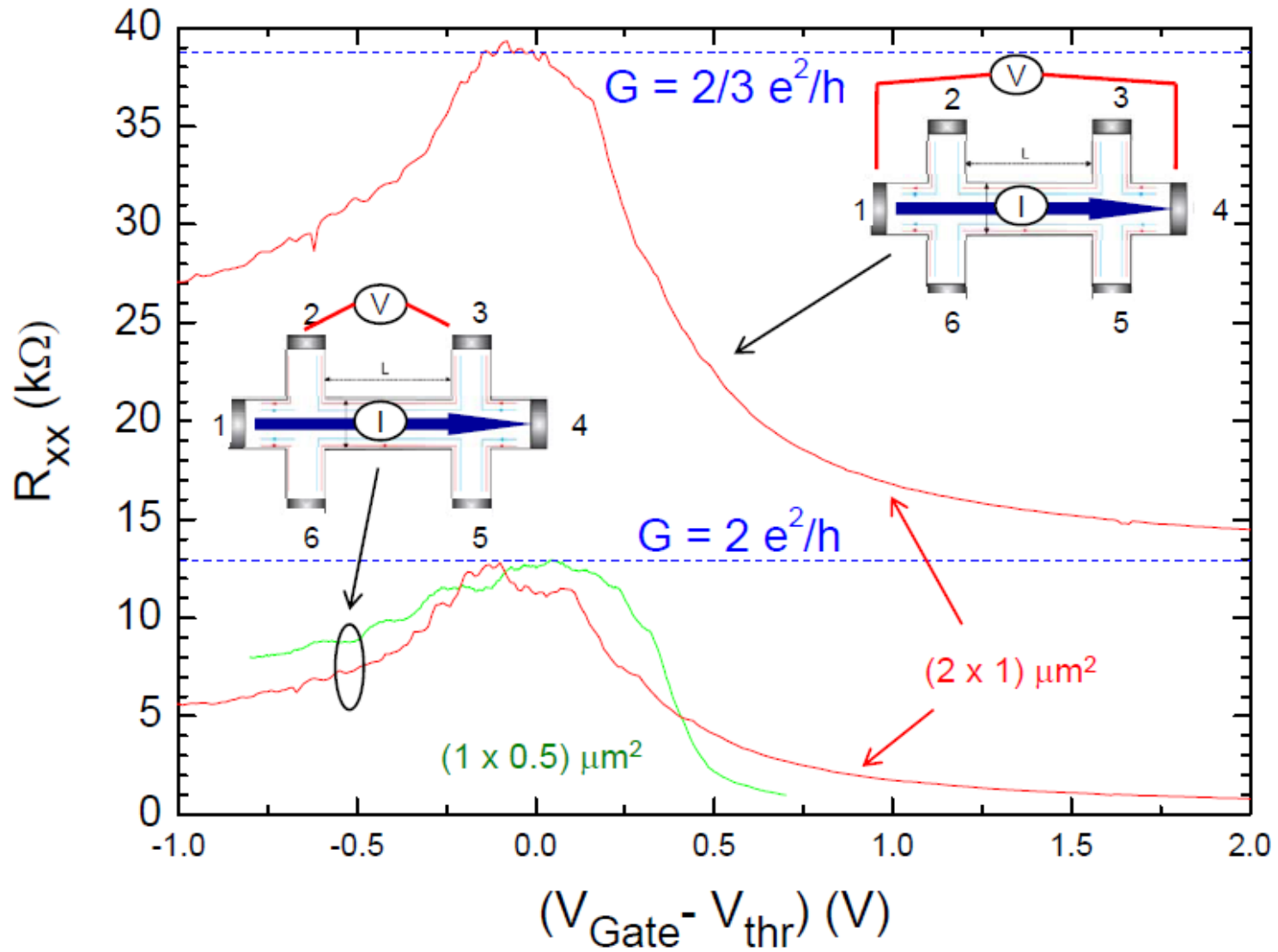
$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{pmatrix} = \frac{e}{h} \begin{pmatrix} -2 & 1 & 0 & 0 & 0 & 1 \\ 1 & -2 & 1 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & 0 \\ 0 & 0 & 1 & 2 & 1 & 0 \\ 0 & 0 & 0 & 1 & -2 & 1 \\ 1 & 0 & 0 & 0 & 1 & -2 \end{pmatrix} \begin{pmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \\ \mu_5 \\ \mu_6 \end{pmatrix}$$



$$G_{4t} = \frac{eI}{\mu_2 - \mu_3} = 2 \frac{e^2}{h}$$

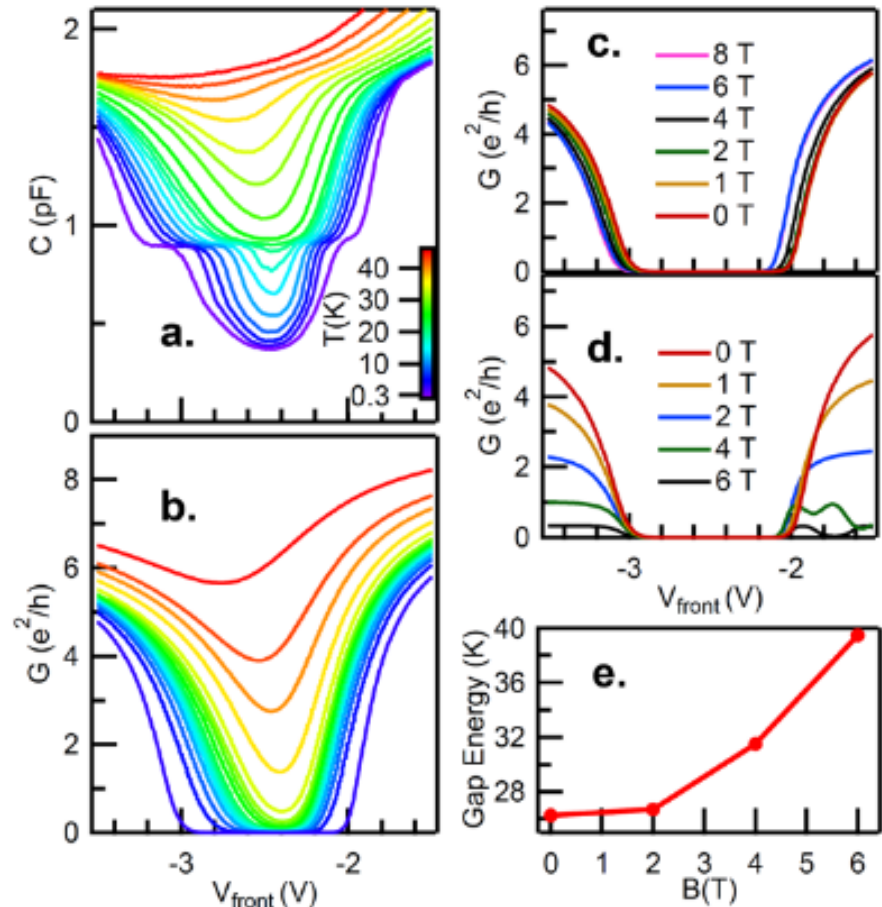
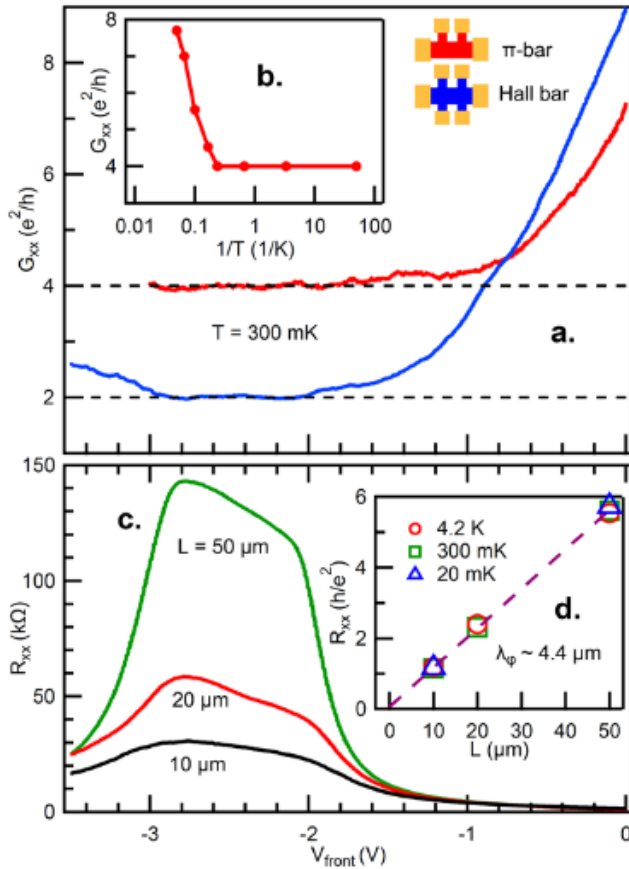
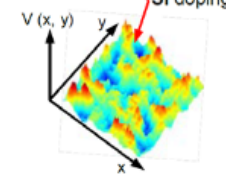
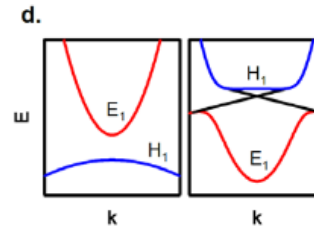
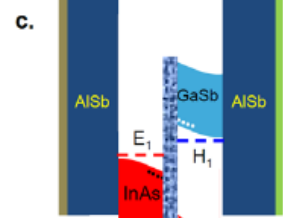
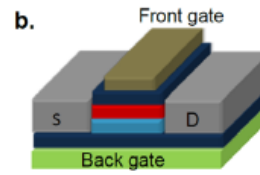
$$G_{2t} = \frac{eI}{\mu_1 - \mu_4} = \frac{2}{3} \frac{e^2}{h}$$

# Résultat (Konig et al)



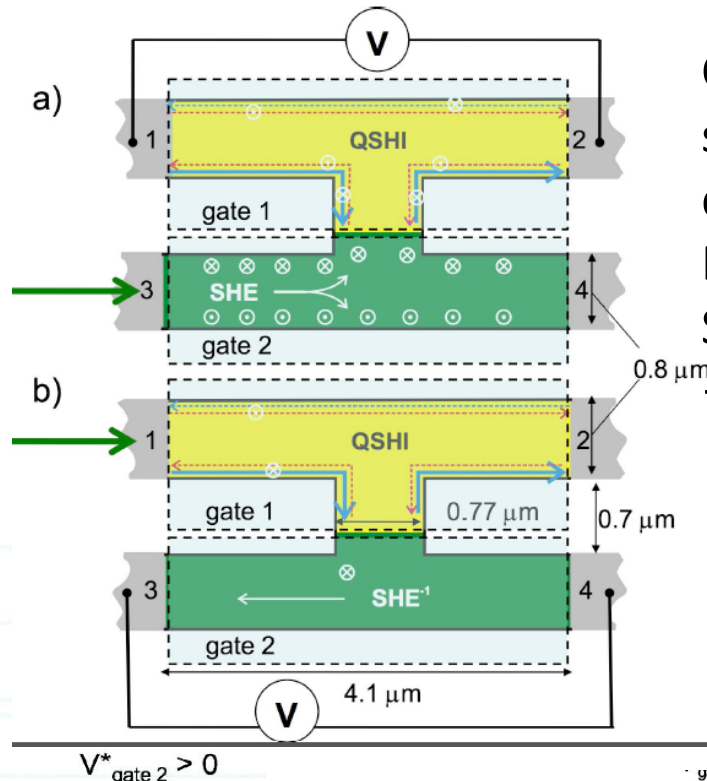
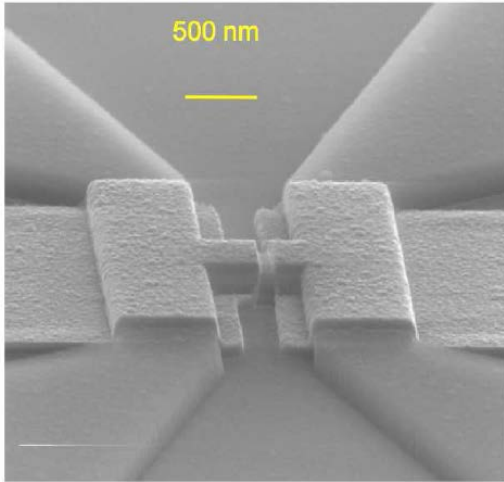
# Autre système: InAs-GaSb

Rui-Rui Du, Cond-Mat 2013



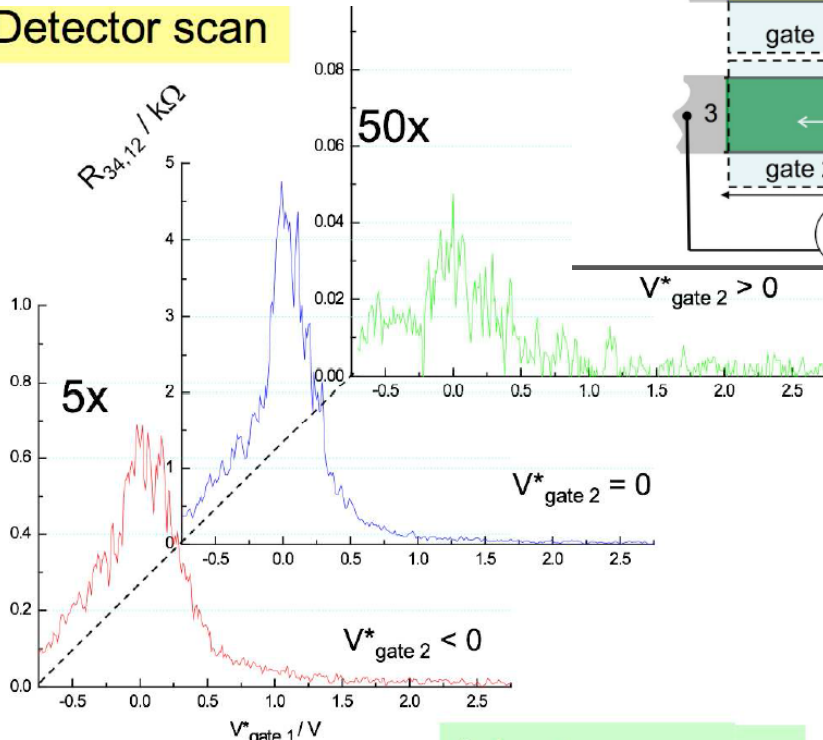


# Premiers pas vers les applications en spintronique: le filtre « H » de spin

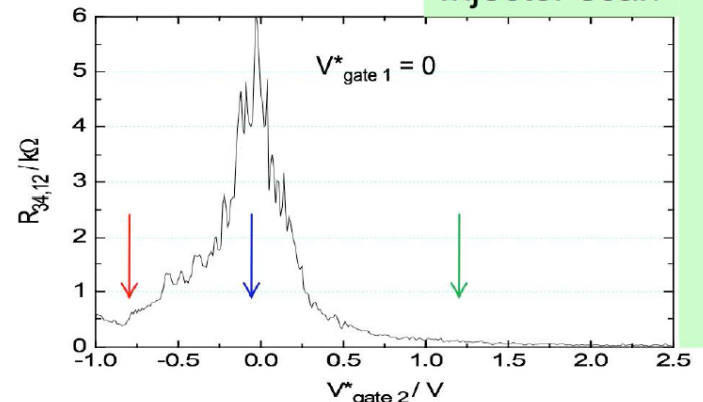


Couplage spin-orbite  
ségrégation des spins  
de chaque cote du canal  
EHQS → transfère  $\mu_{\uparrow}$   $\mu_{\downarrow}$   
Sur les électrodes 1 et 2  
→ tension  $V = (\mu_{\uparrow} - \mu_{\downarrow}) / e$

## Detector scan

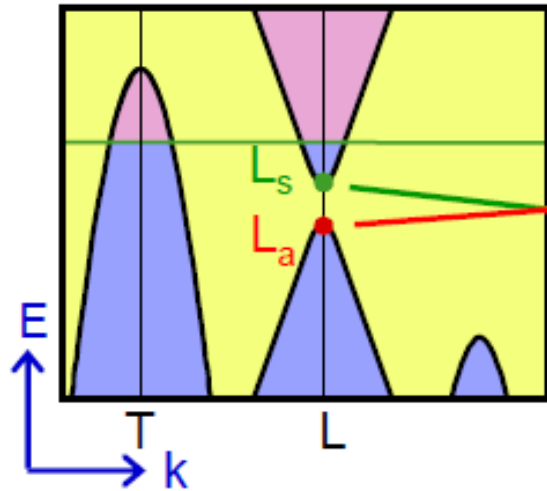


## Injector scan

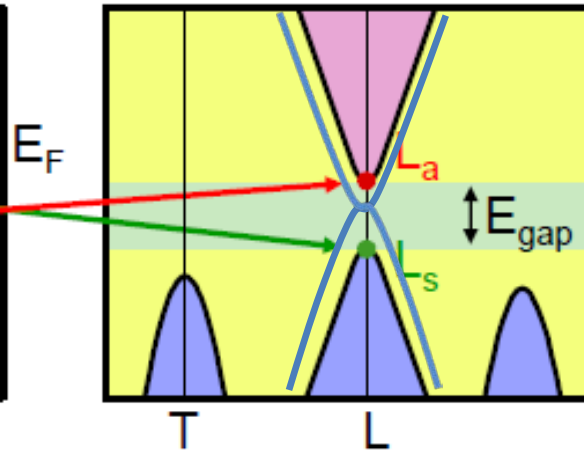


# Material tuning: example of $\text{Bi}_{1-x}\text{Sb}_x$

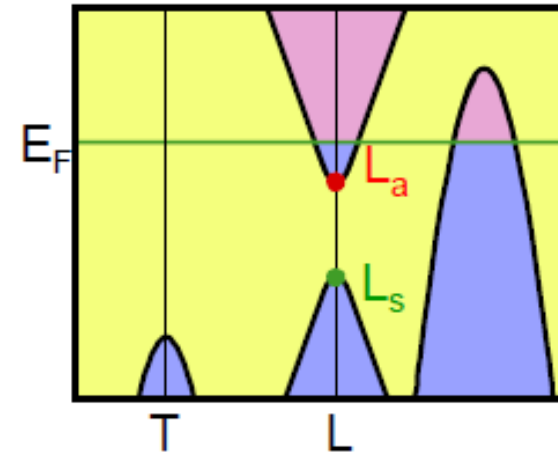
Pure Bismuth:  
semi-metal



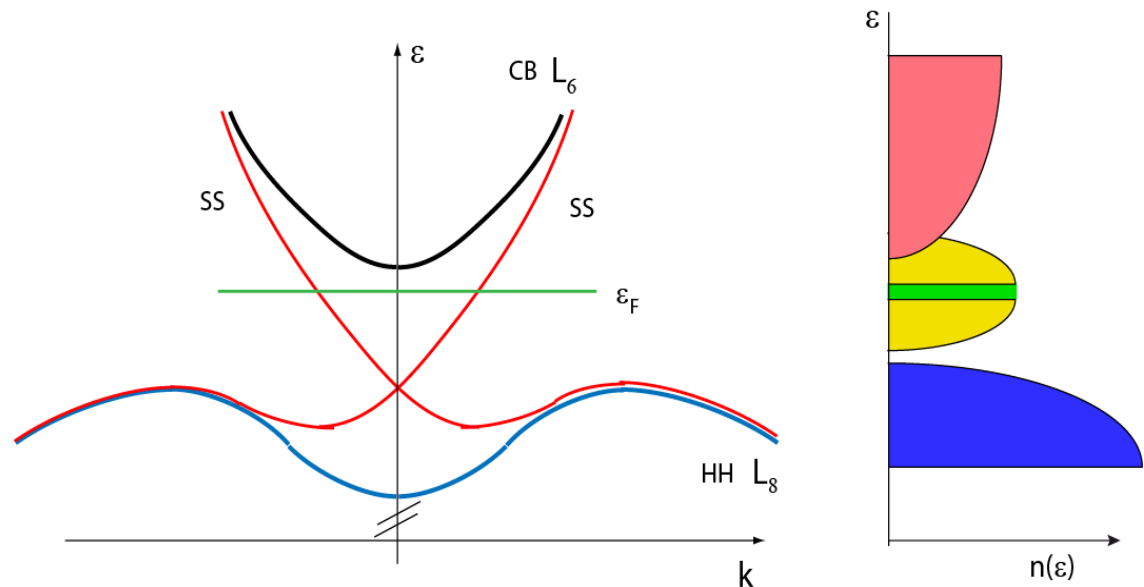
Alloy:  
Semiconductor  $0.09 < x < 0.18$



Pure Antimony:  
semi-metal



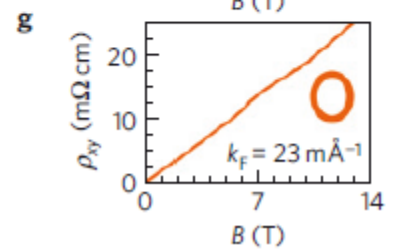
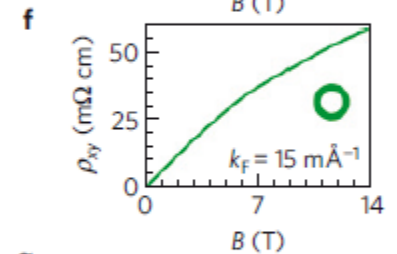
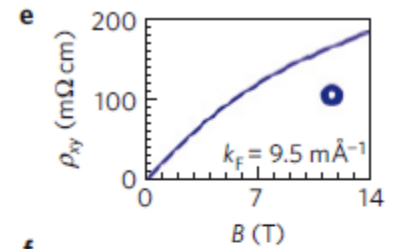
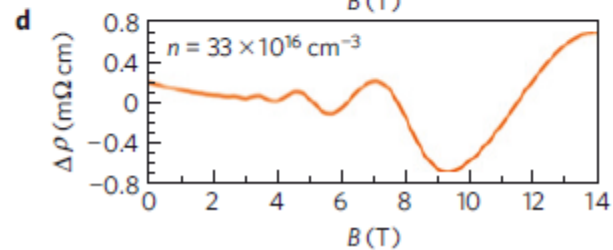
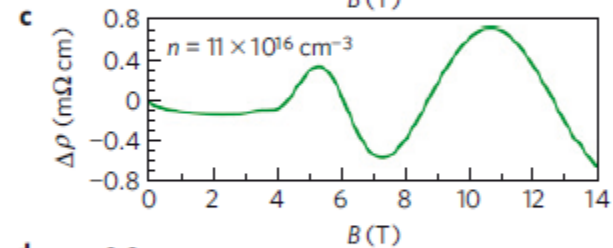
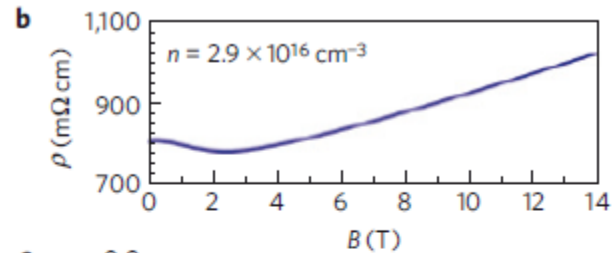
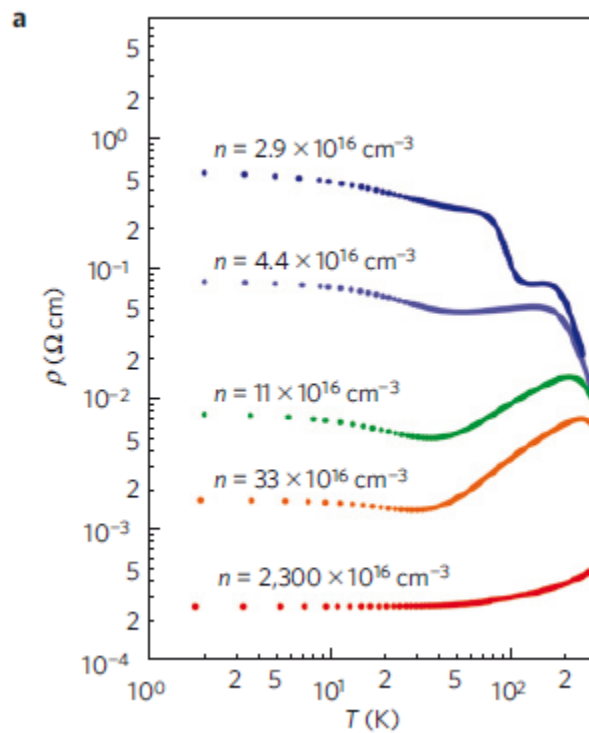
In fact



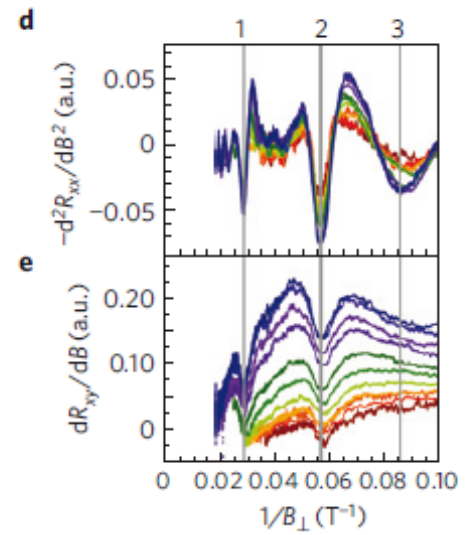
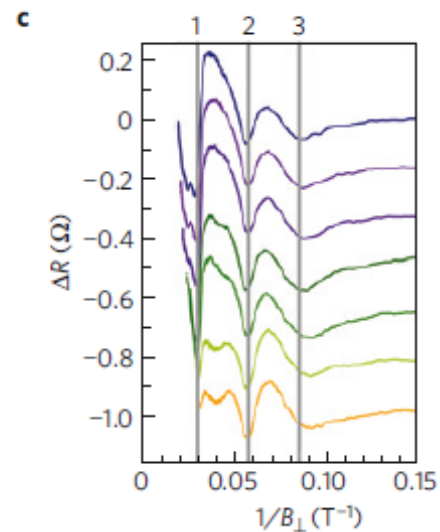
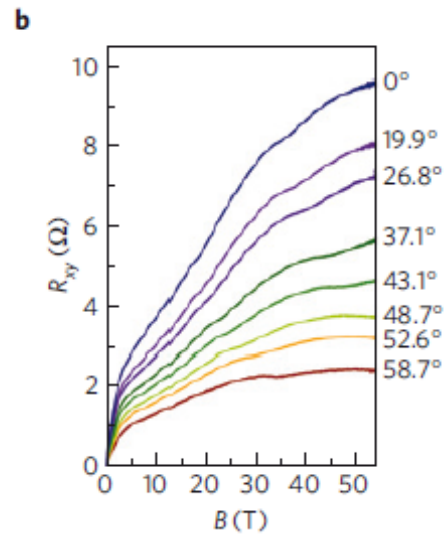
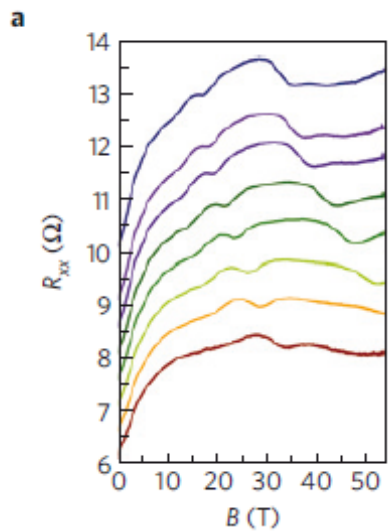
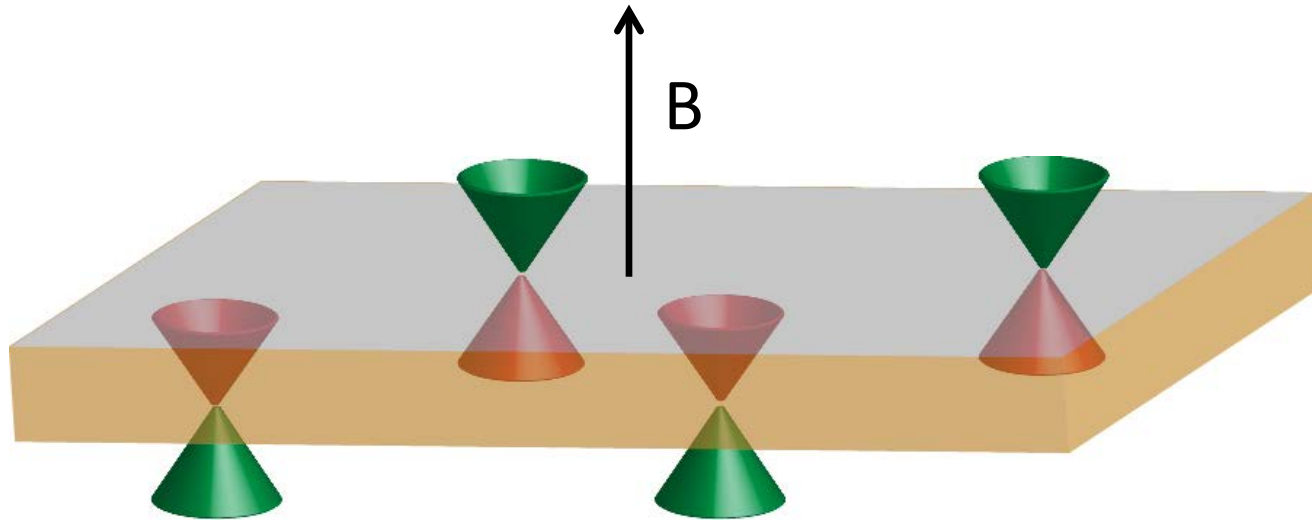
# Comment réduire la conductivité de volume ?

Ajouter des accepteurs (Ca..)

Sb in Bi<sub>2</sub>Se<sub>3</sub> (Analytis et al Nat Phys 2010)

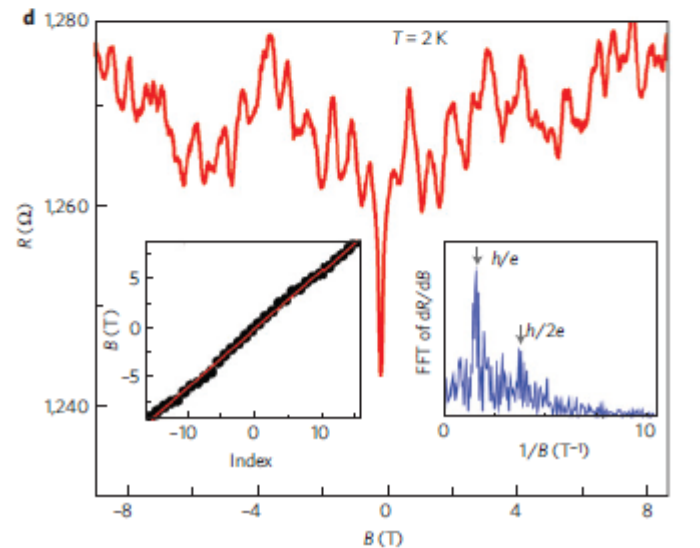
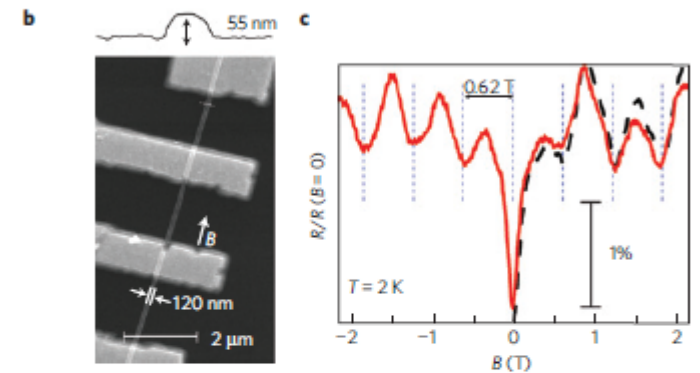
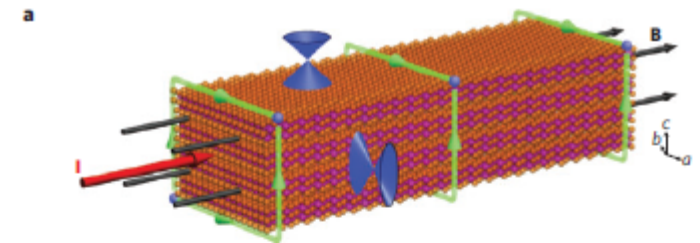
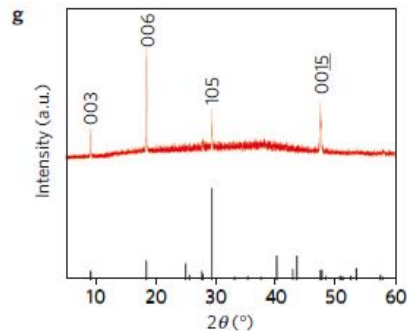
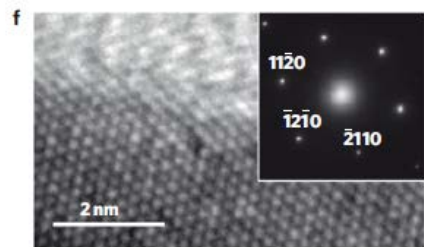
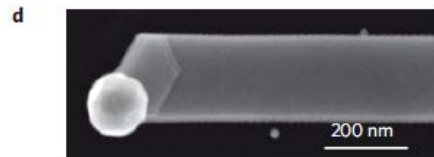
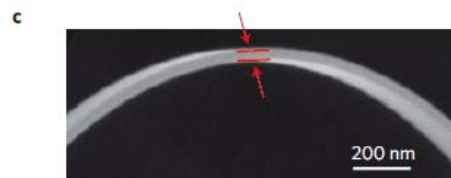


# Extraction des états de surface: oscillations de SdH



# Autre approche: réduction dimensionnelle

$\text{Bi}_2\text{Se}_3$  nanowires (Peng et al Nat. Mat.)

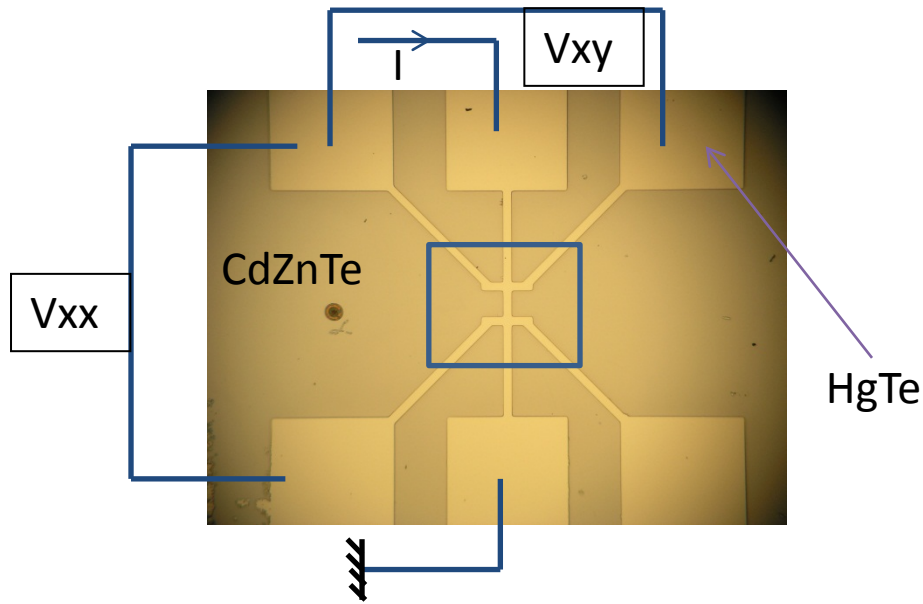


Aharonov-Bohm effect  
of surface states

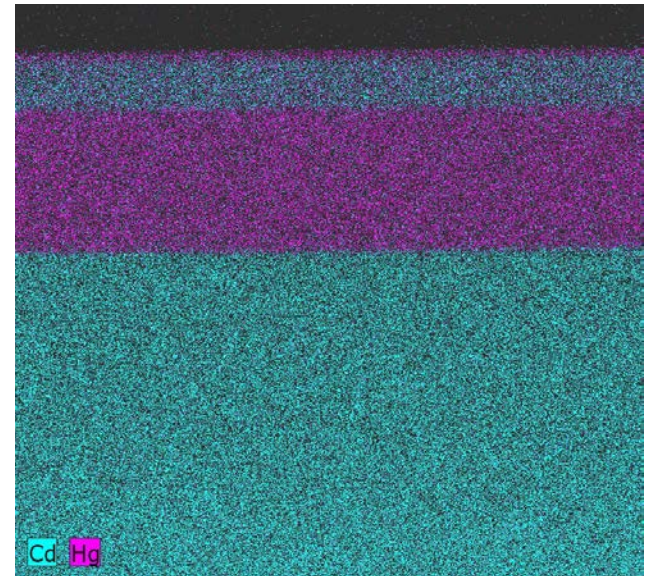
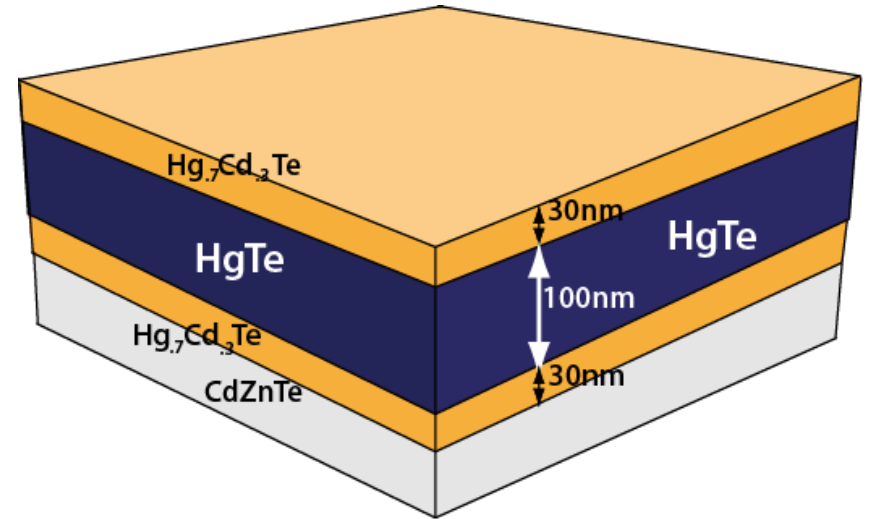


# Systeme 3D avec grilles HgTe-contraint

Magneto-transport measurements:  
Gated Hall-bar structures



Optical lithography (Nanofab)  
+ chemical etching (CEA-LETI)  
Strained HgTe 0,07%



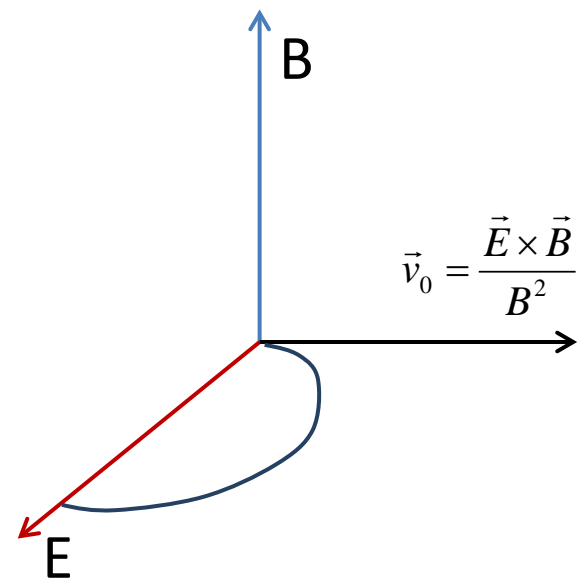
# Magnéto-conductance classique

$$\hbar \frac{d\vec{r}}{dt} = \vec{\nabla}_q \varepsilon_n(\vec{q})$$

$$\hbar \frac{d\vec{q}}{dt} = e\vec{E} + e \frac{d\vec{r}}{dt} \times \vec{B}$$

$$r = r' + v_0 t$$

$$\vec{v}_0 \times \vec{B} + \vec{E} = 0$$



$$\hbar \frac{d\vec{r}'}{dt} = \vec{\nabla}_q \varepsilon_n(\vec{q}) - \vec{q} \cdot \vec{v}_0$$

$$\hbar \frac{d\vec{q}}{dt} = e \frac{d\vec{r}'}{dt} \times \vec{B}$$

petit  $\begin{pmatrix} \dot{x}(t) \\ \dot{y}(t) + \frac{E}{B} \end{pmatrix} = \begin{pmatrix} \cos(\omega_c t) & \sin(\omega_c t) \\ -\sin(\omega_c t) & \cos(\omega_c t) \end{pmatrix} \begin{pmatrix} \dot{x}(0) \\ \dot{y}(0) + \frac{E}{B} \end{pmatrix}$

limite  $\omega\tau \gg 1$   $P(t) = \frac{1}{\tau} e^{-t/\tau}$  relaxation Poissonnienne de la vitesse moyenne a 0  
(pas de mémoire)

$$\langle \dot{x} \rangle = \frac{E}{B} \sin \omega_c t \rightarrow \frac{E}{B} \int_0^\infty \frac{dt}{\tau} e^{-t/\tau} \sin \omega_c t = \frac{E}{B} \frac{\omega_c \tau}{1 + (\omega_c \tau)^2}$$

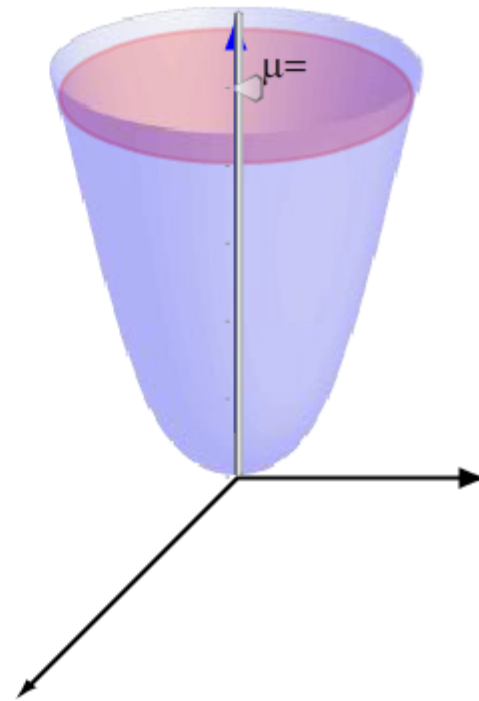
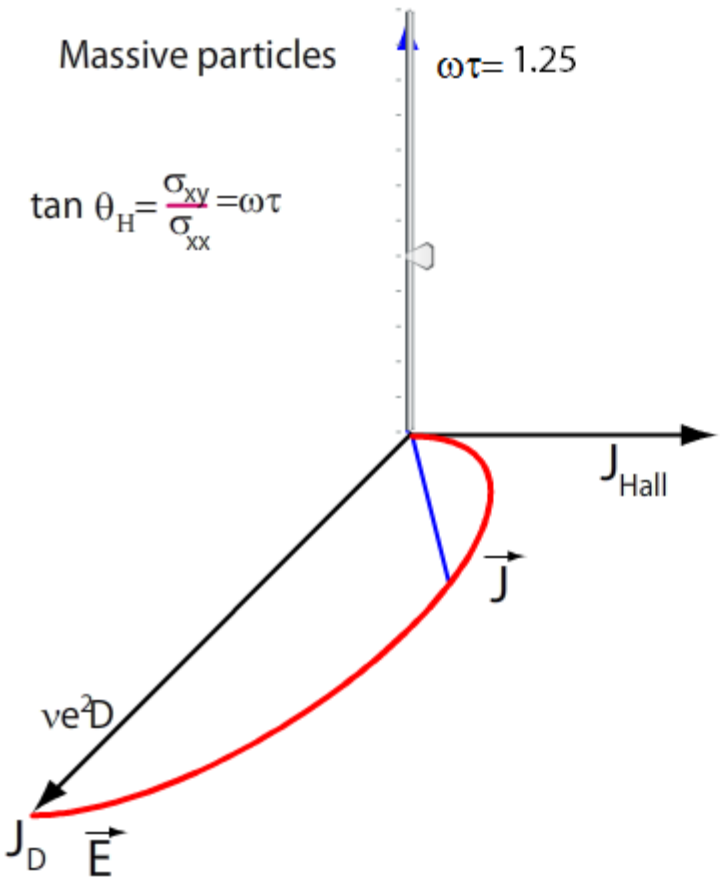
$$\langle \dot{y} \rangle = -\frac{E}{B} (1 - \cos \omega_c t) \rightarrow \frac{E}{B} \int_0^\infty \frac{dt}{\tau} e^{-t/\tau} (1 - \cos \omega_c t) = -\frac{E}{B} \frac{(\omega_c \tau)^2}{1 + (\omega_c \tau)^2}$$

$$\begin{pmatrix} j_x \\ j_y \end{pmatrix} = \frac{\sigma_0}{1 + (\omega_c \tau)^2} \begin{pmatrix} 1 & \omega_c \tau \\ -\omega_c \tau & 1 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

Courant transverse compense par un champ électrique transverse

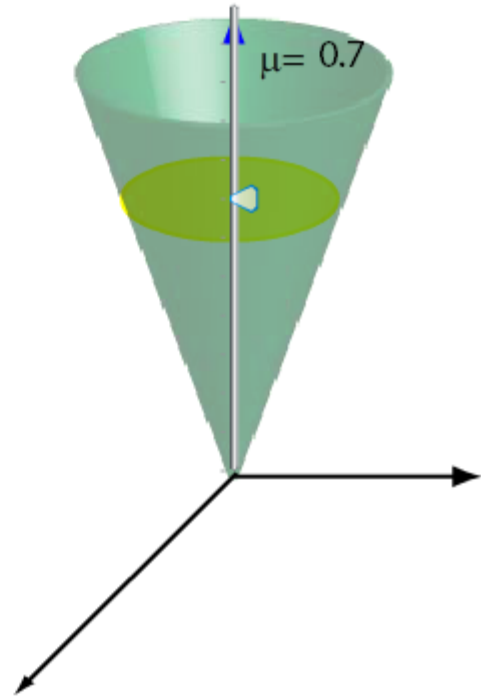
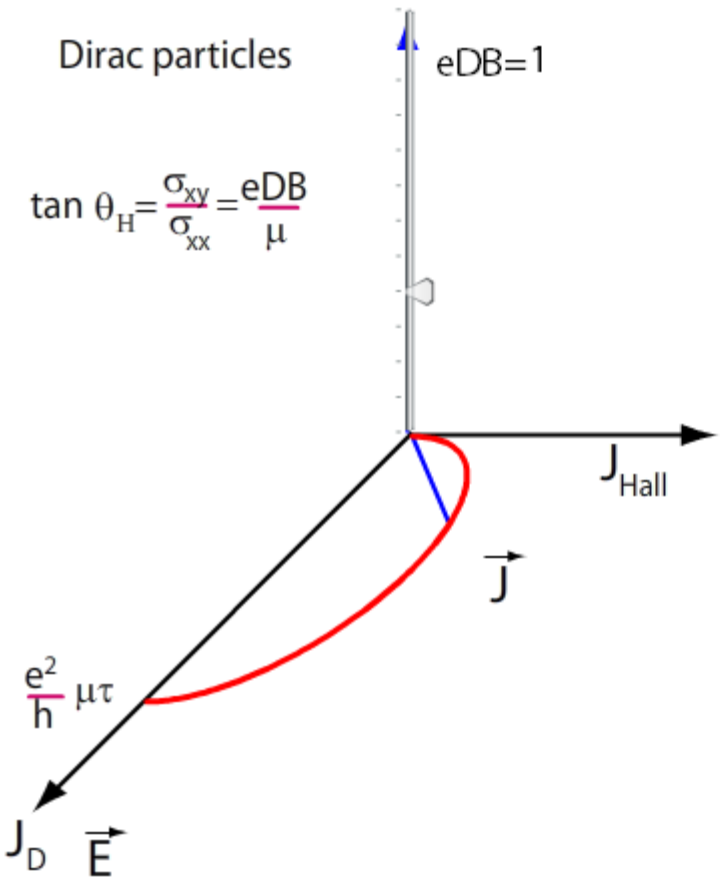
densité et signe des porteurs  $\leftarrow R_H = \frac{E_y}{j_x B} = \frac{1}{ne} \leftarrow E_y = \frac{j_x}{ne} B \leftarrow E_y - \langle v \rangle B = 0$

# Animation: magnéto-galvanométrie porteur massif

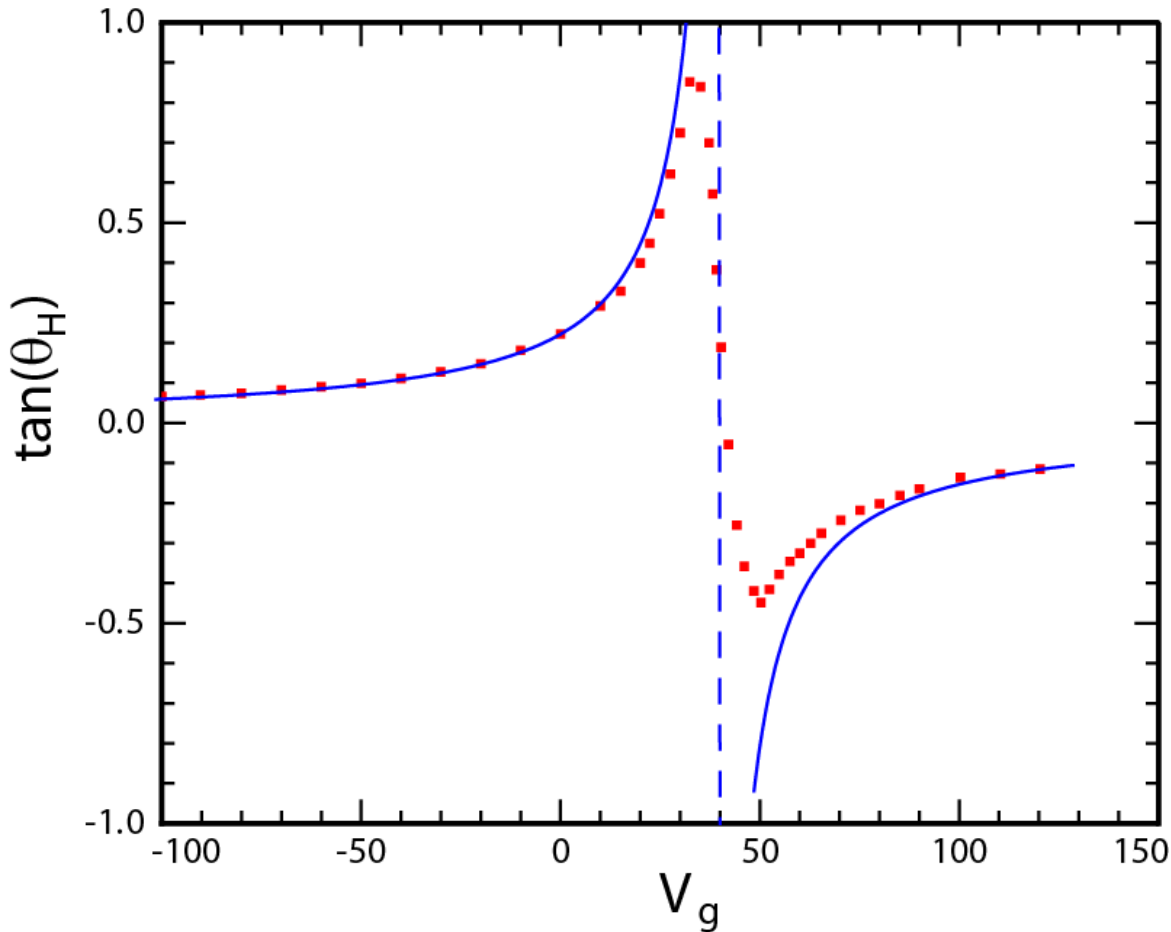




# Animation: magnéto-galvanométrie fermions de Dirac



# Magnetoconductance bas champ dans le modèle de Dirac



$$\sigma_{xx} = k_F l \frac{B_*^2}{B^2 + B_*^2}, \sigma_{xy} = k_F l \frac{BB_*}{B^2 + B_*^2},$$

$$\tan(\theta_H) = \frac{B}{B_*}$$

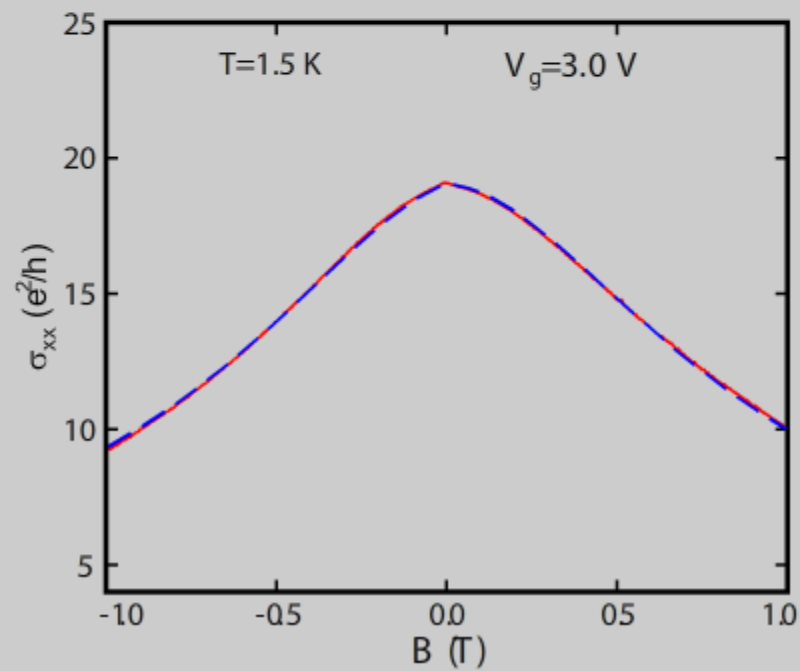
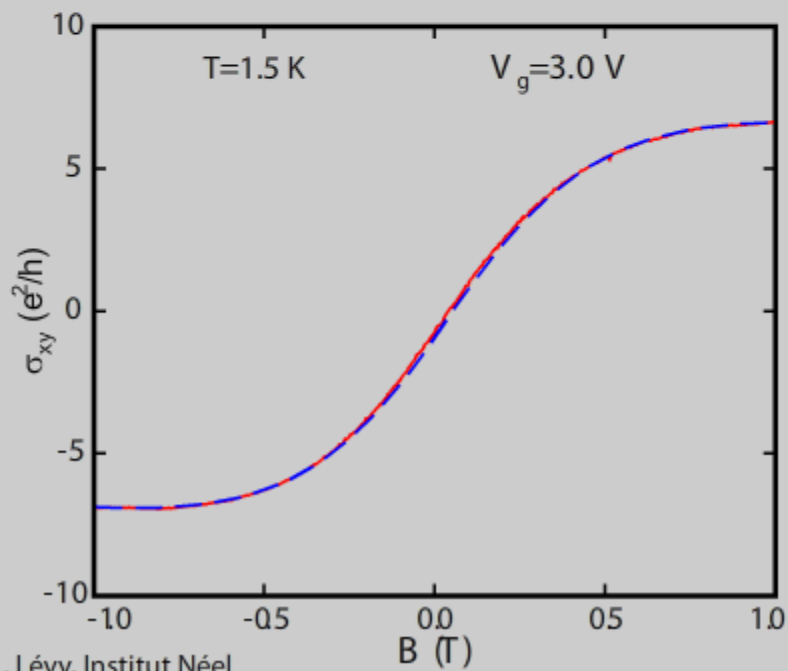
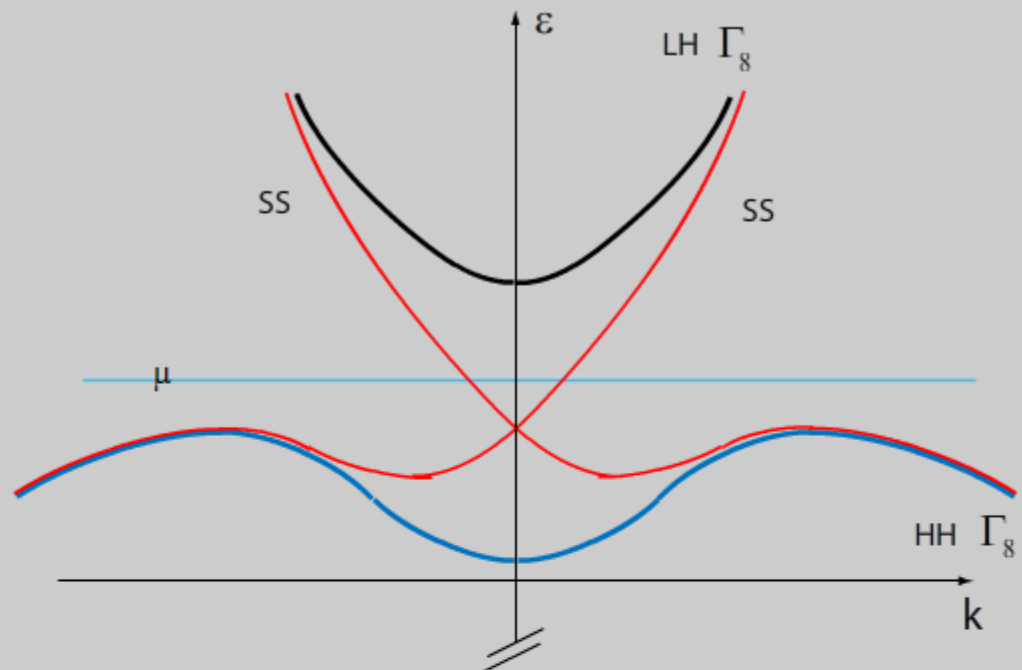
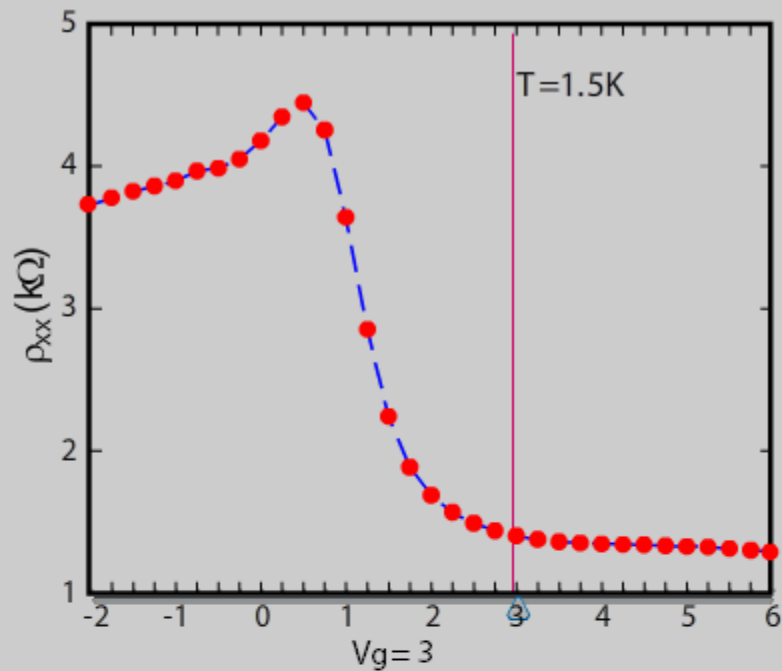
$$B_* = \frac{\mu}{2eD}$$

Magnetic field at which

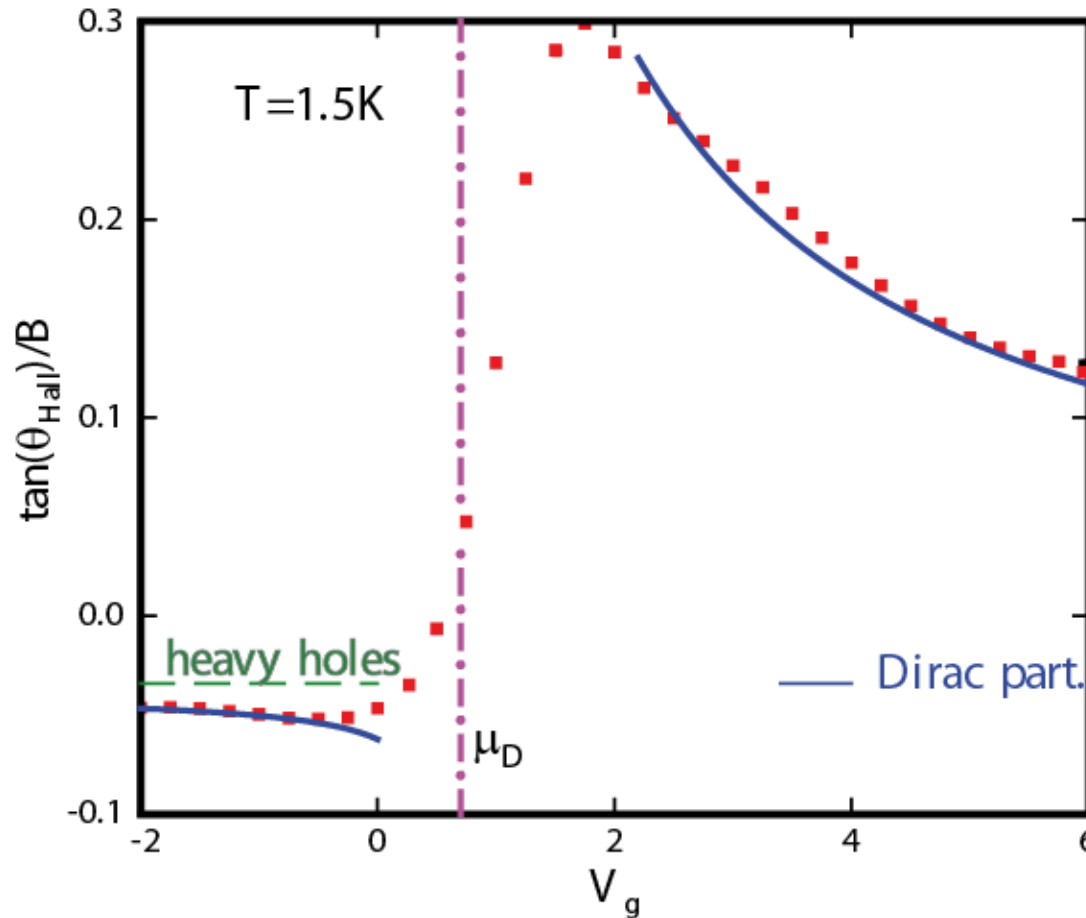
$$E_c(\ell_B) = \mu$$

Graphene

Novosolov-Geim, Science 2005



# Angle de Hall angle, point de Dirac



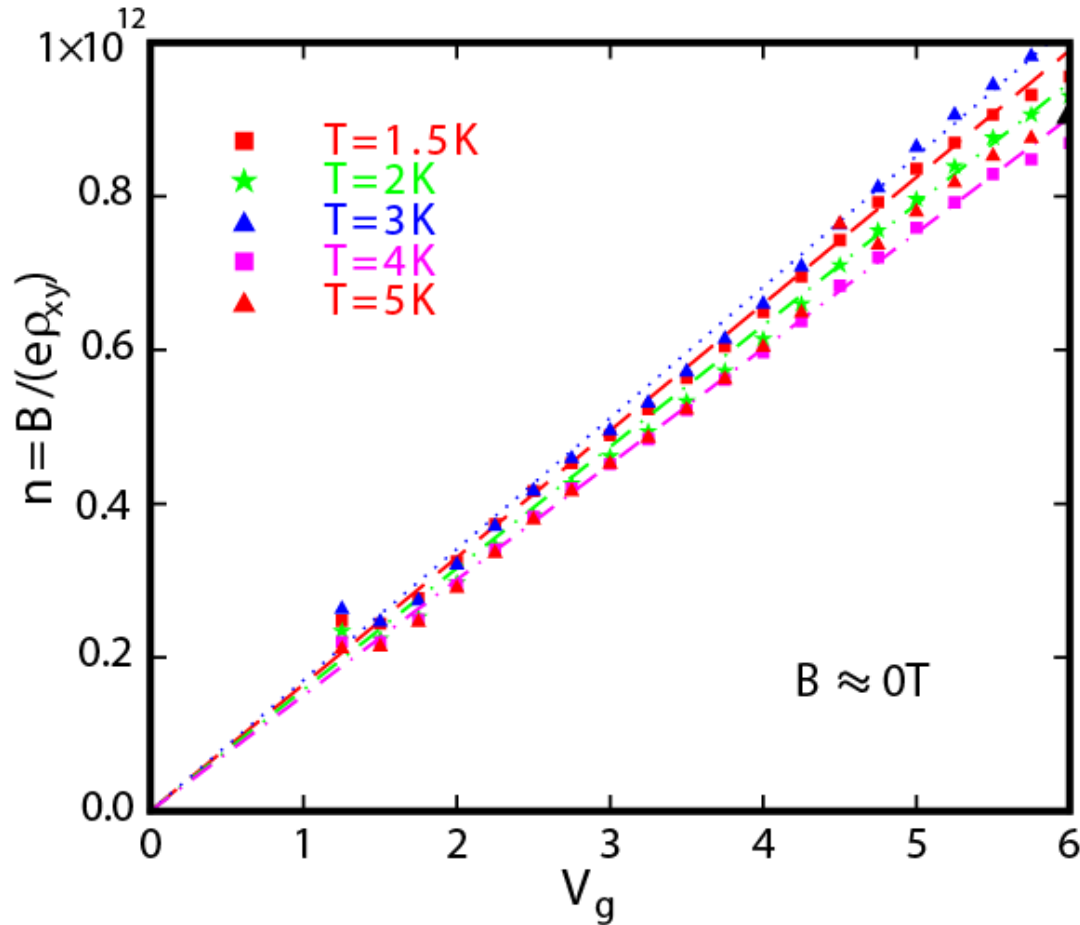
Fit:  $\mu_D = 0.7 \pm 0.1\text{V}$

Other measurement:  
n=0 QH state extrapolate  
to  $V_g = 0.8\text{V}$   $B \rightarrow 0$

Assuming  $D(V_g, T)$ ,  $\sigma_0(V_g, T)$   
All data fits accurately, this  
2 fluid model

Key to WL measurement: cannot subtract high-T data as  $\sigma_{xx}(T)$

# Correspondance densité-Vg

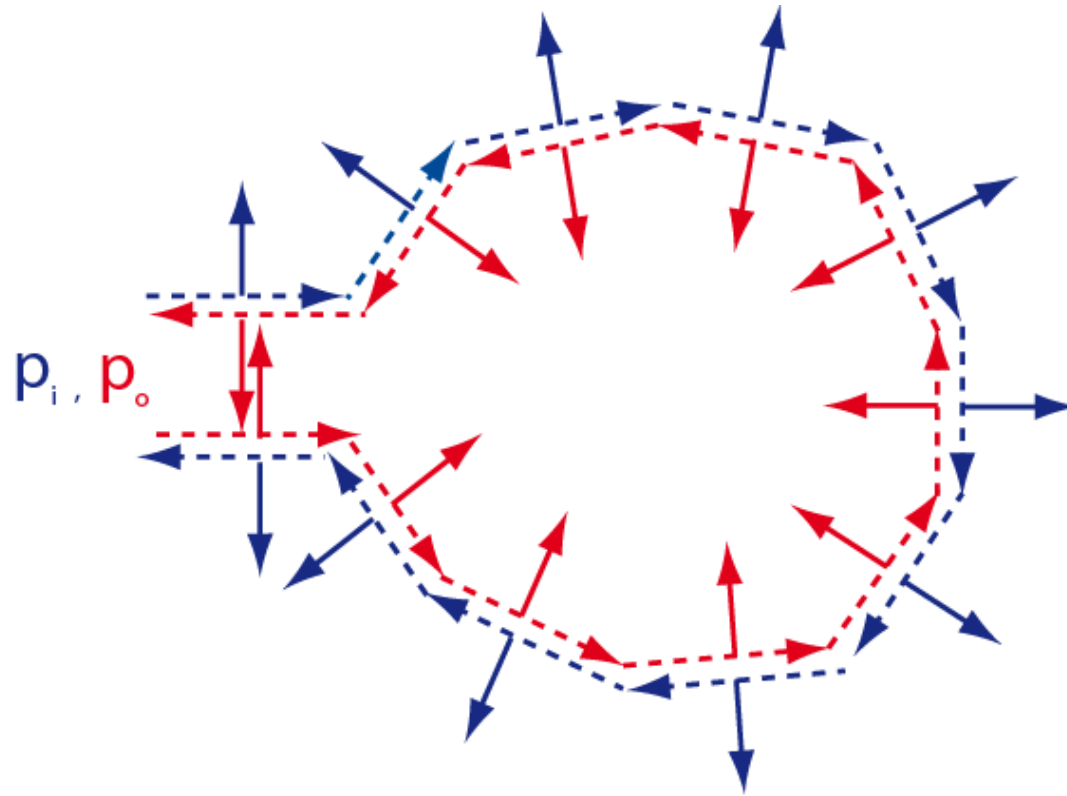


Also  
from SdH periods

$$\mu \propto \sqrt{V_g + V_{off}} \approx \sqrt{n}$$

→  $n = 1.6010^{11}(V_g - V_0)$

# Antilocalisation faible



2 sets of time-reversed paths

$$|u_i(p, \uparrow) + \Theta u_i(-p, \downarrow)|^2 + |u_o(-p, \downarrow) + \Theta u_o(p, \uparrow)|^2 = 0$$

Positive magnetoresistance

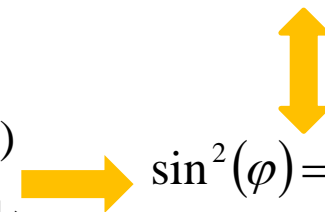
B=0

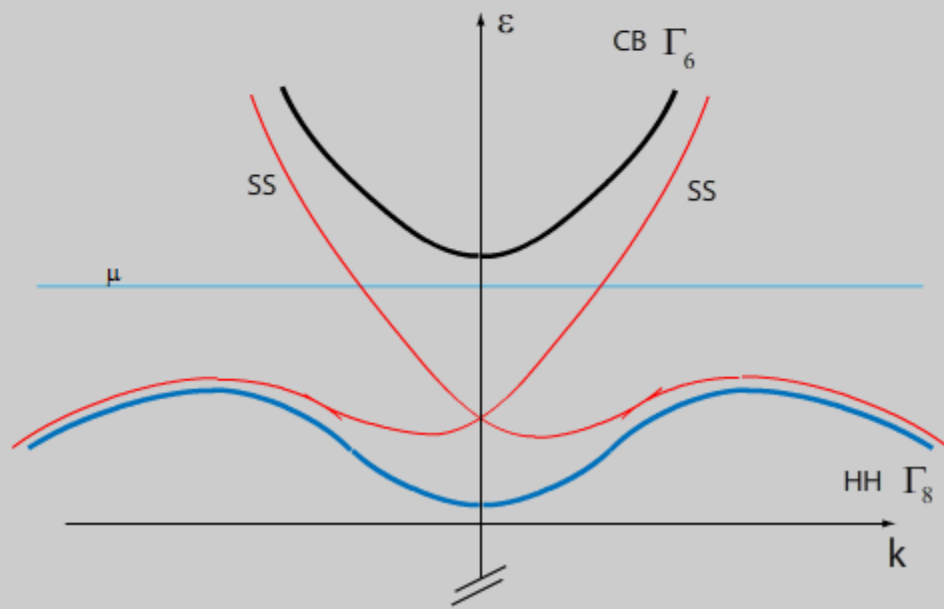
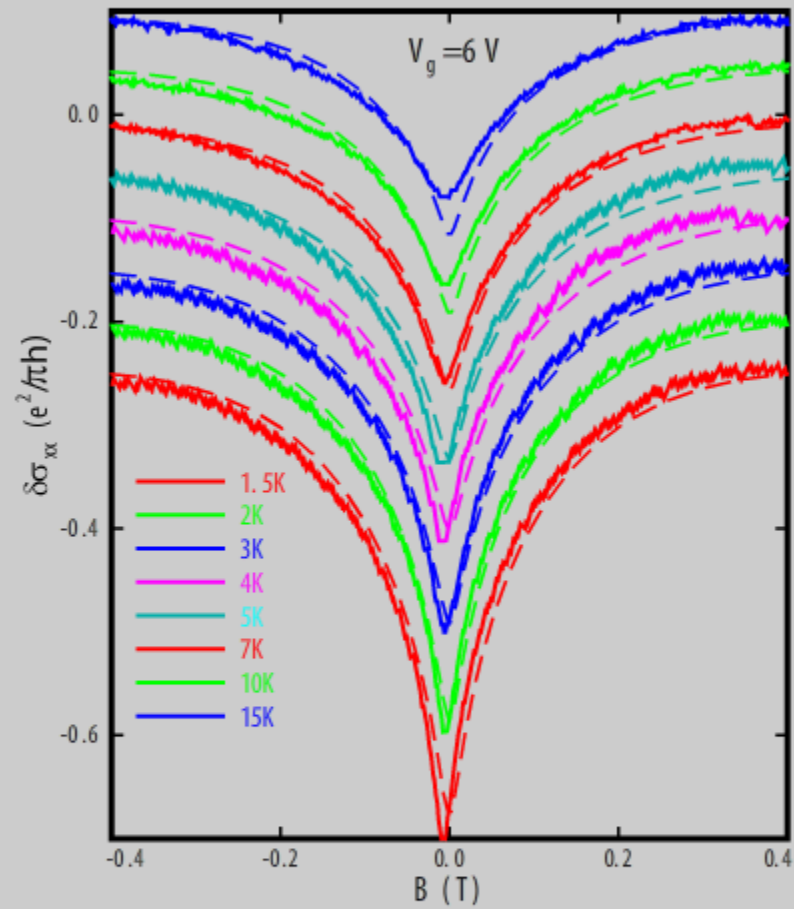
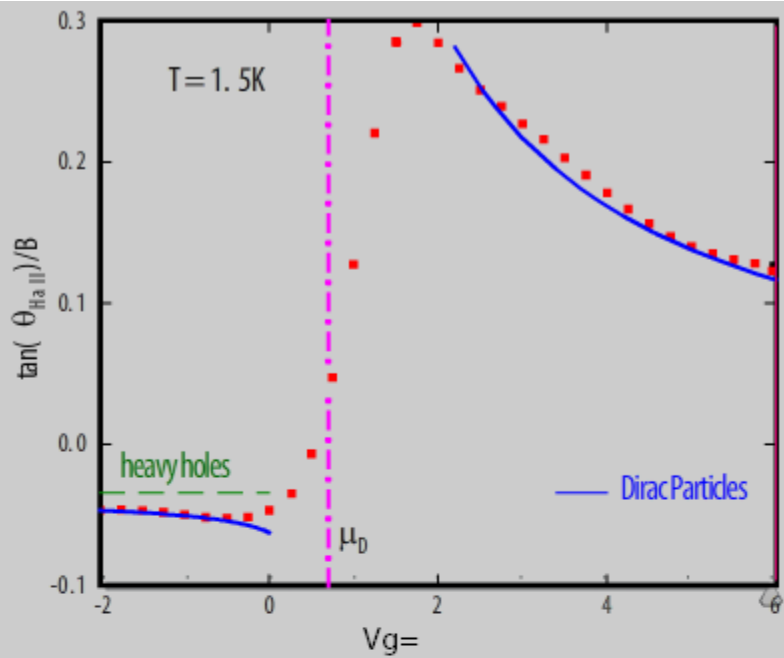
$$\Theta u_i(-p, \downarrow) = -u_i(p, \uparrow) \quad \Theta u_o(p, \uparrow) = -u_o(p, \downarrow)$$

B≠0

$$e^{i\varphi} u_i(p, \uparrow) \quad \Theta e^{i\varphi} u_i(p, \uparrow) = -e^{-i\varphi} u_i(-p, \downarrow)$$

$$\sin^2(\varphi) = 1 - 2 \cos(2\varphi)$$





# Regimes d'effet Hall quantique

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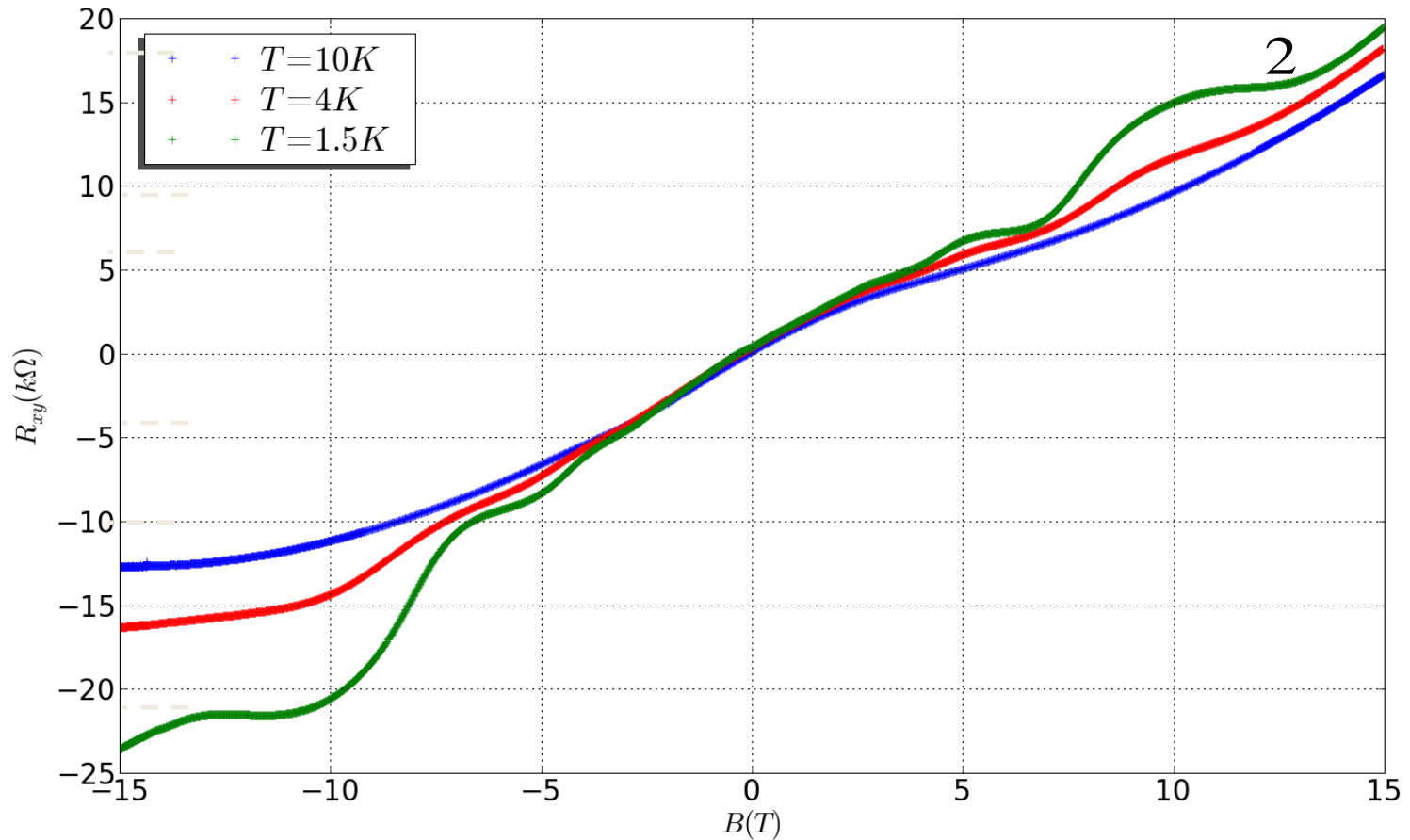
- Différents régimes observés
  - $V < 2.75$  V (coexistence avec les trous)
    - n=0 Dirac QH state
    - phase isolante above 15 T
  - $V > 2.75$  V
    - deux régimes de champ
    - faces découplées
    - Bicouches



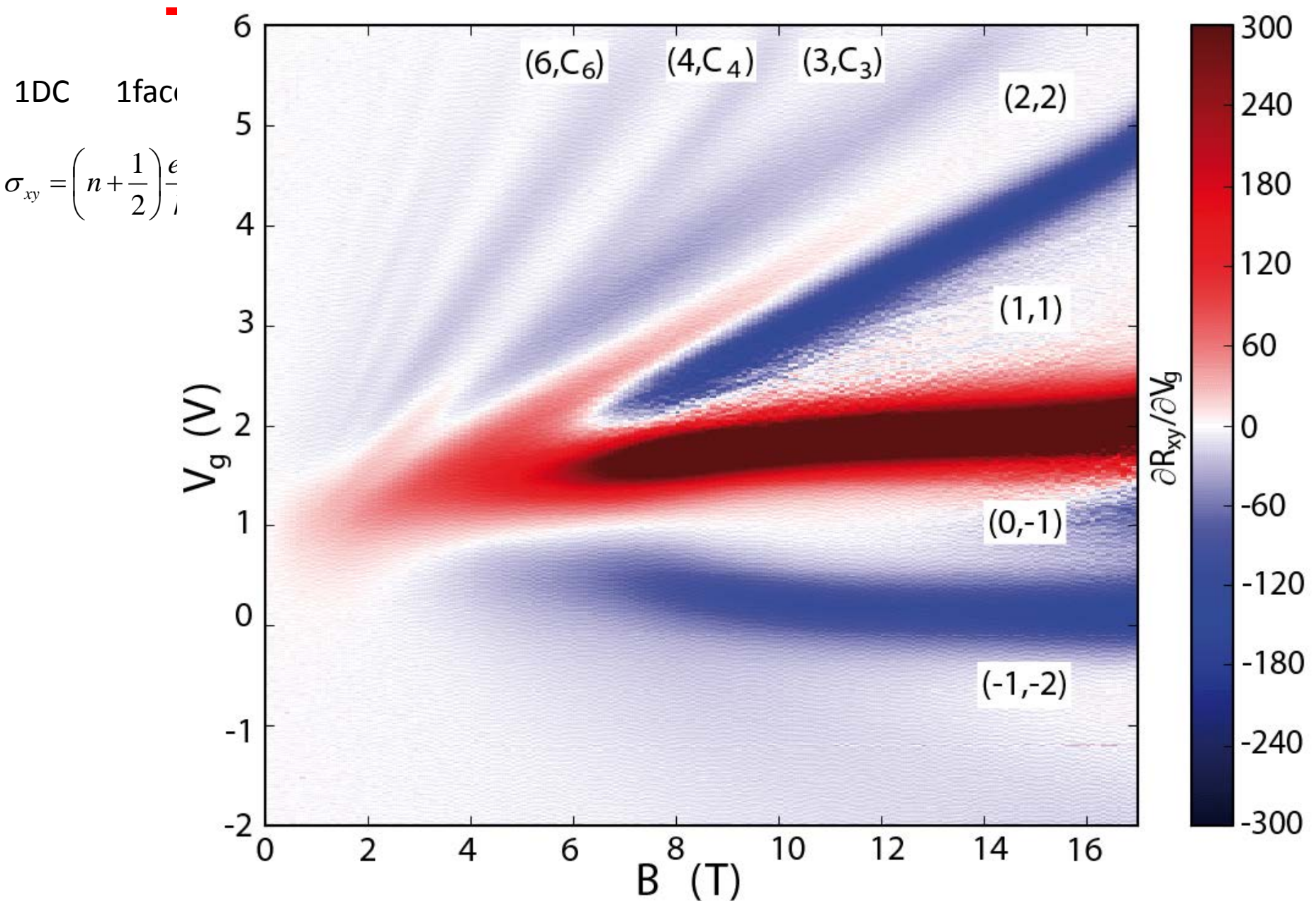
# Quantum Hall plateaus

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$$\sigma_{xy} = C \frac{e^2}{h}$$

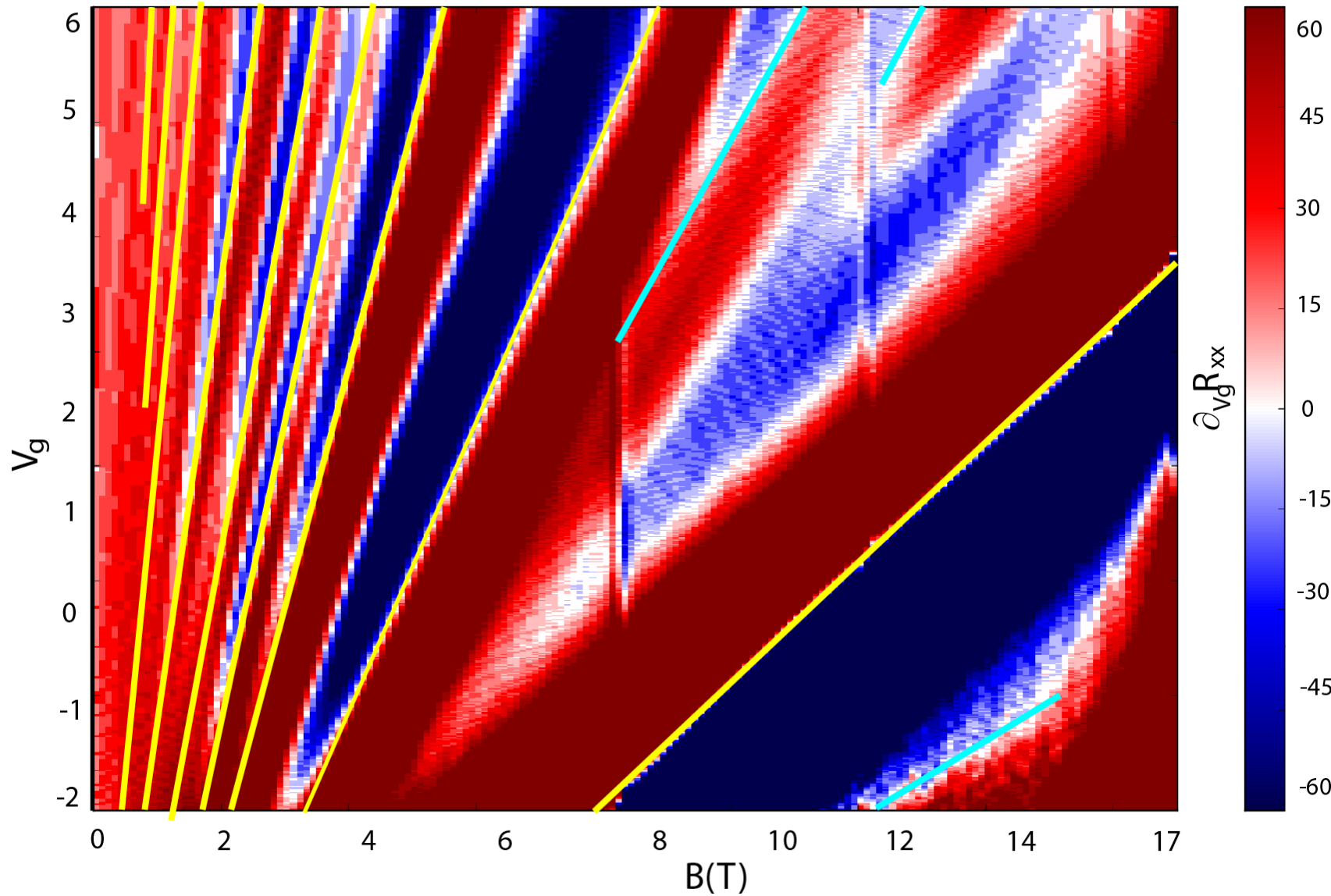


# Quantum Hall states



# Locating the Hall states

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# Determination of LL filling factor $\nu$

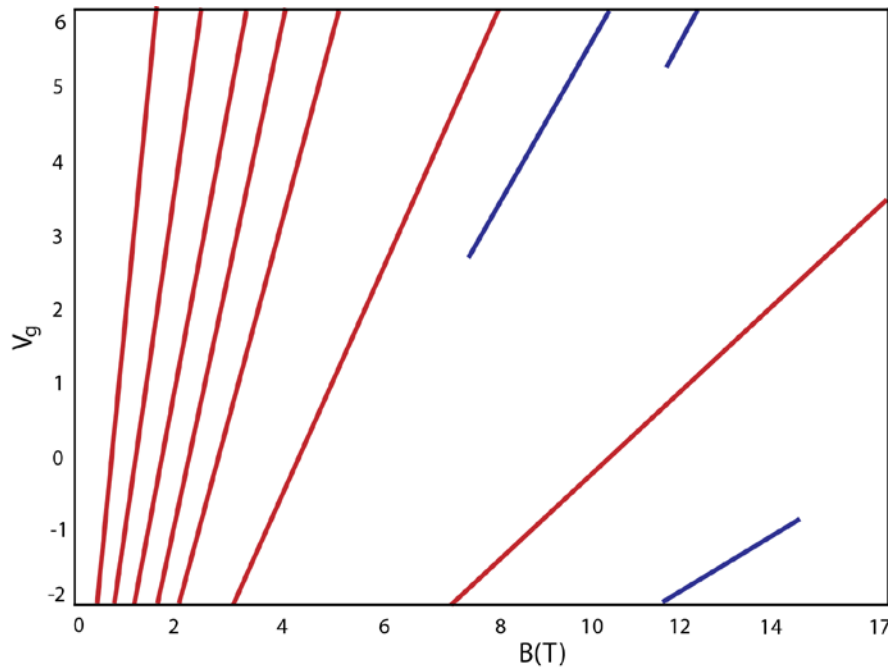
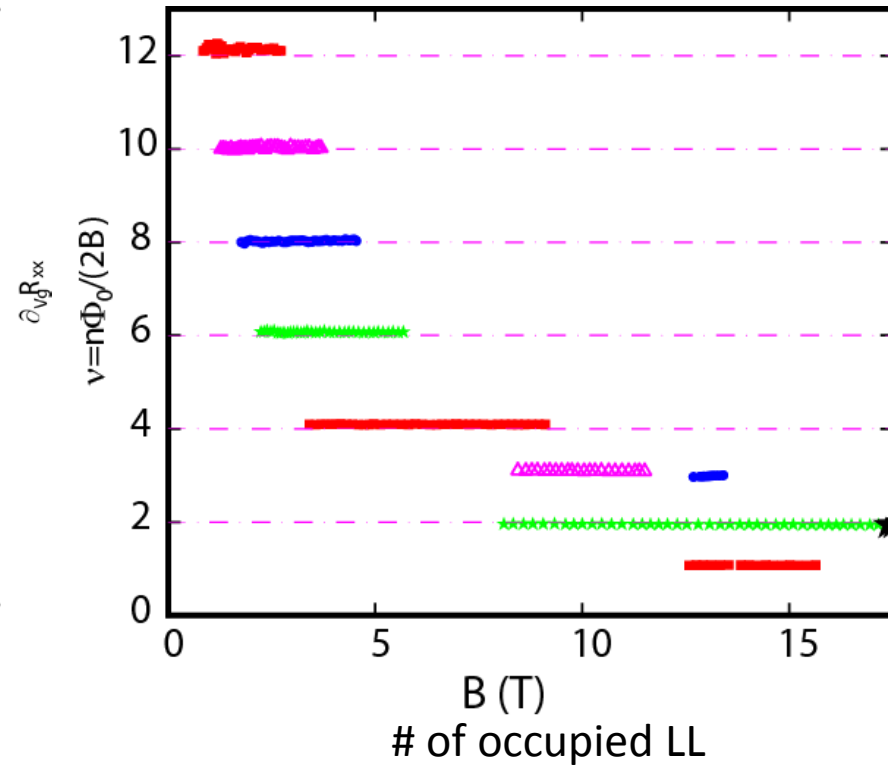


Diagram of QH states



# of occupied LL

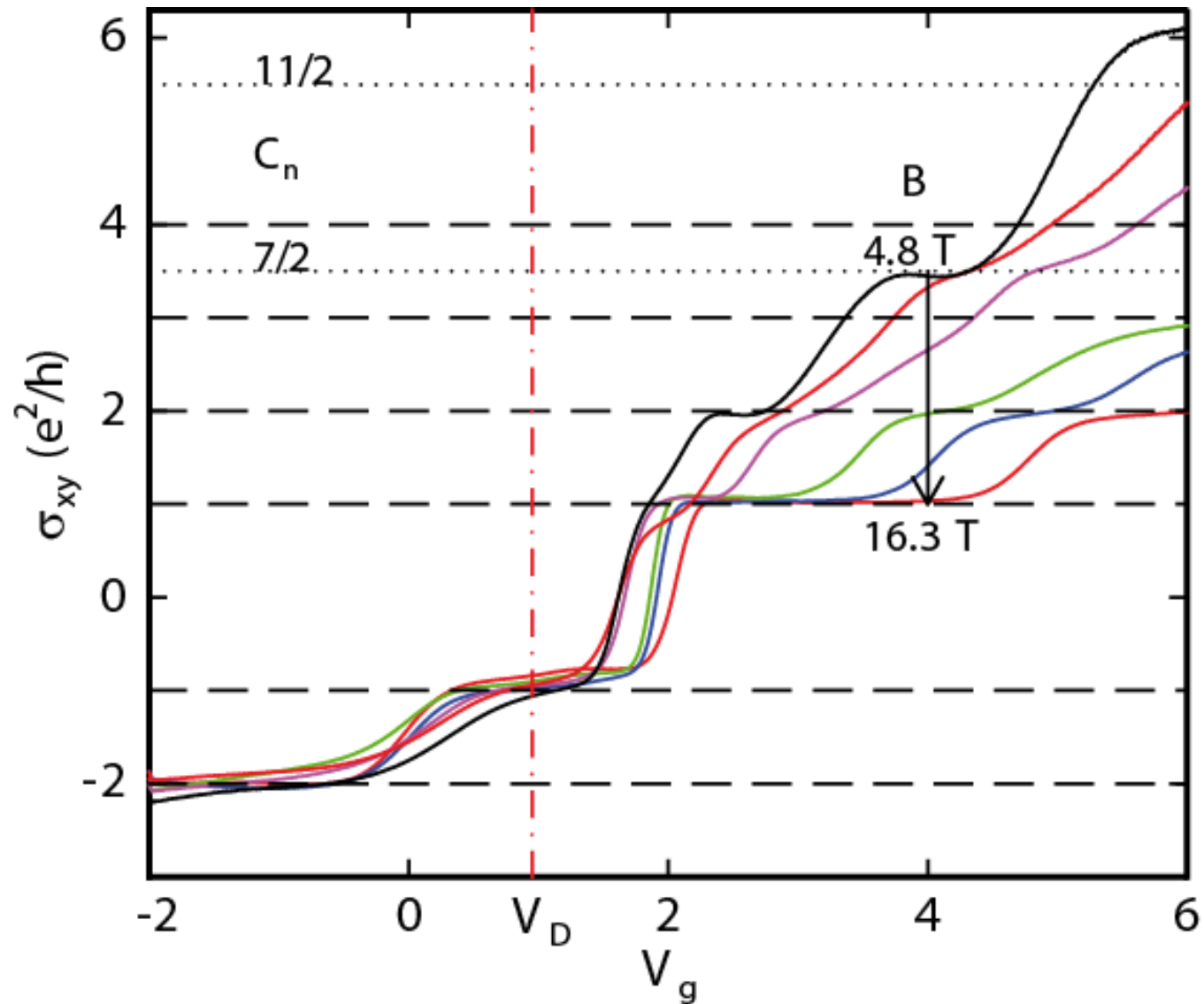
$$n = \frac{\partial n}{\partial V_g} (V_g - V_{g0})$$

$$n = \frac{B}{e\rho_{xy}}$$

← measured

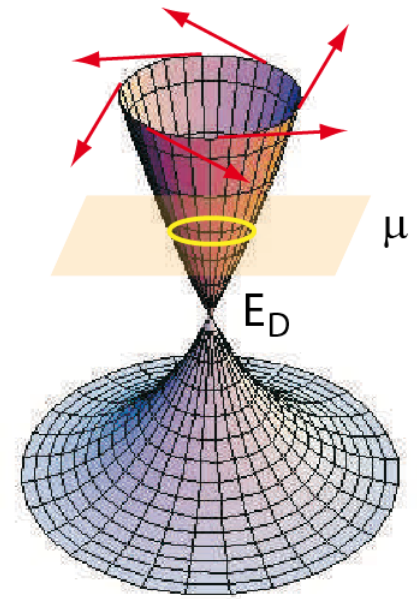


# Quantum Hall quantization



# Conclusions

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- Systèmes très riches!
- 2D: QSH permet de filtrer et détecter des spins
- Magneto-transport domine par des états de surface de Dirac
- Dirac SS: antilocalisation faible
- SdH  $\rightarrow \mu \sim v n \propto k$  (2D)  $\rightarrow$  Dirac SS
- Plusieurs régimes d'effet Hall
- Dispositifs de spintronique