Electrostatic control of spin polarization in a quantum Hall ferromagnet: a platform to realize high order non-Abelian excitations

Aleksander Kazakov & Leonid Rokhinson

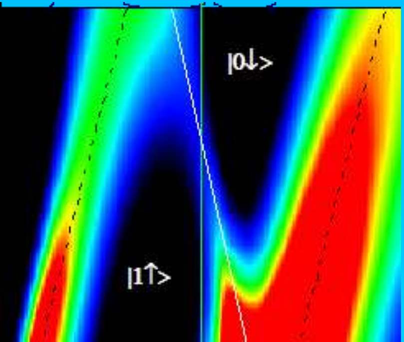
Department of Physics, Purdue University

V. Kolkovsky, Z. Adamus, & Tomasz Wojtowicz

Institute of Physics, Polish Academy of Science, Warsaw, Poland

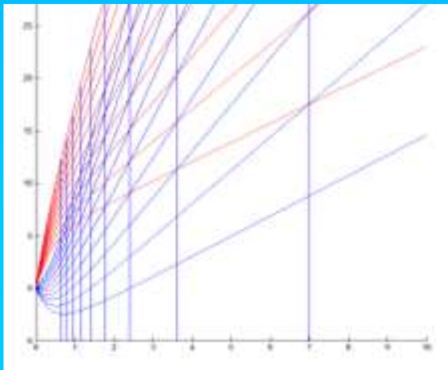
George Simion & Yuli Lyanda-Geller

Department of Physics, Purdue University



Luchon, France

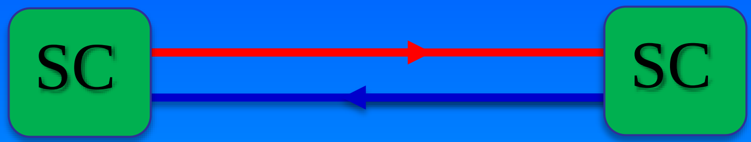
May 24 - 29, 2015

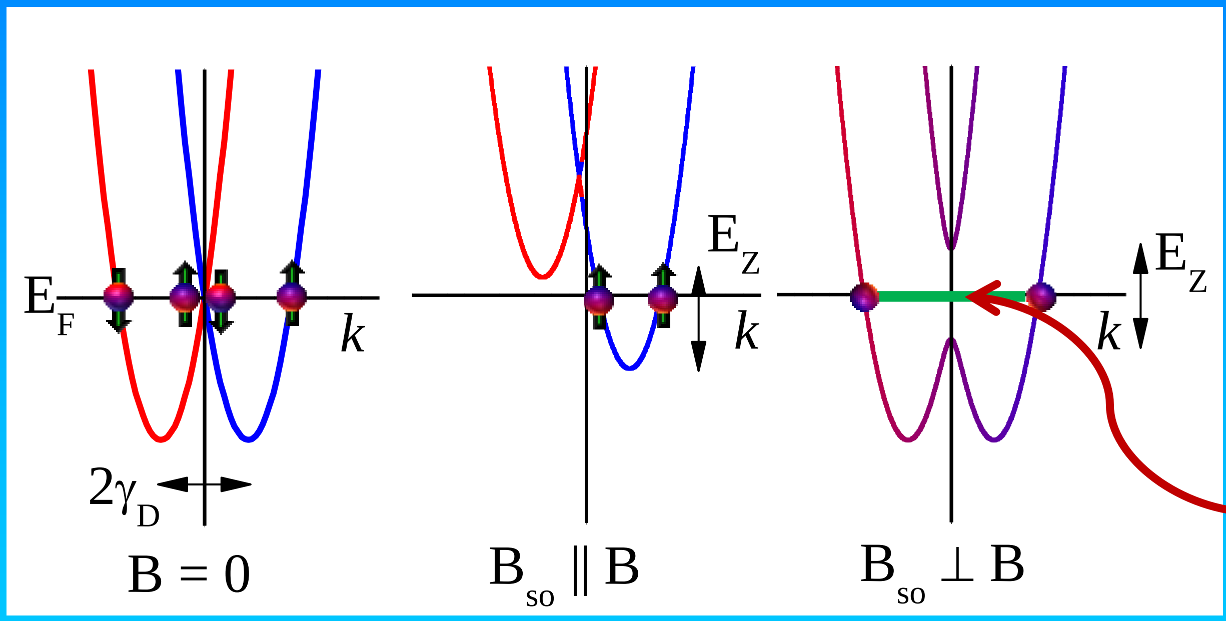


Engineering Majorana fermions

requirements:
- 1D
- spinless (one mode)
- superconductor

topological superconductor

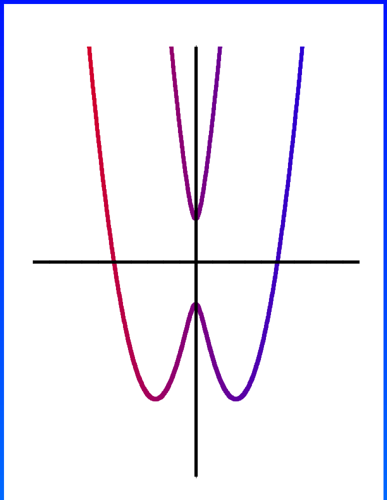




pairing possible

Sau, et al '10, Alicea, et al '10

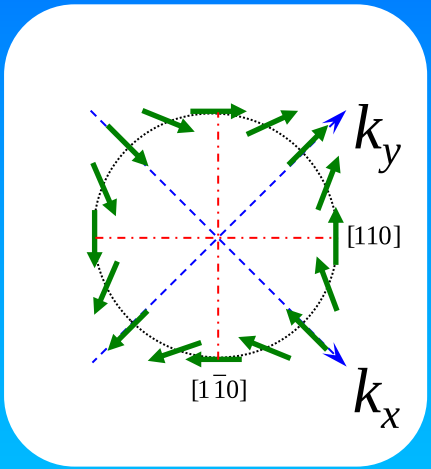
parameter space

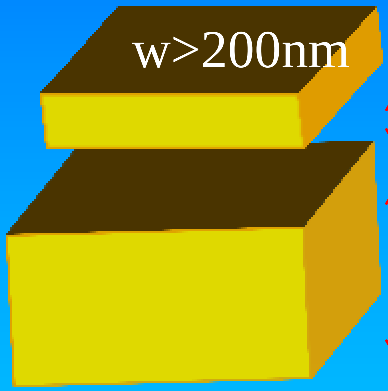


single-spin condition: $E_Z > \sqrt{\Delta^2 + E_F^2}$

to protect superconductivity: $E_Z \sim E_{SO}$

$$E_{SO} = \sqrt{2}\gamma_D \langle k_z^2 \rangle k = \sqrt{2}\gamma_D (\pi / d)^2 k$$





d=20nm $E_{SO} \approx 2.6 \cdot k$ [meV], $k[10^6 \mathrm{cm}^{-1}]$

d=100nm $E_{SO} \approx 0.1 \cdot k$ [meV], $k[10^6 \mathrm{cm}^{-1}]$

smallest dimension defines E_{so}:

small d ⇒ large E_{so} ⇒ large E_F ⇒ less localization

Characteristic 4π energy-flux relation

modification of the Josephson phase

trivial superconductor	2π	Cooper pairs,	$I \propto \sin(\phi)$
topological superconductor	4π	Majorana particles,	$I \propto \sin(\phi/2)$

$$b^\dagger = (\gamma_l - i\gamma_m)$$

Kitaev ‘01

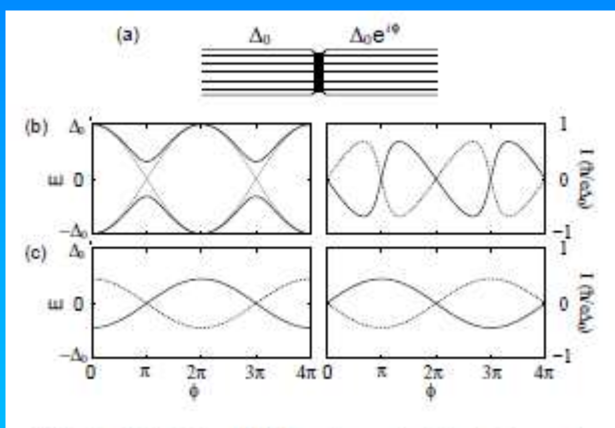
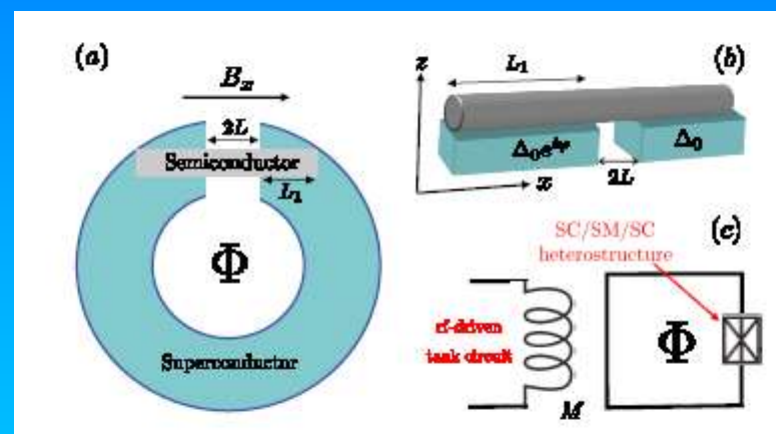


FIG. 1: (a) Butt-to-butt Josephson junction between two Q1D p_x-wave superconductors. (b) The energies (left panel)

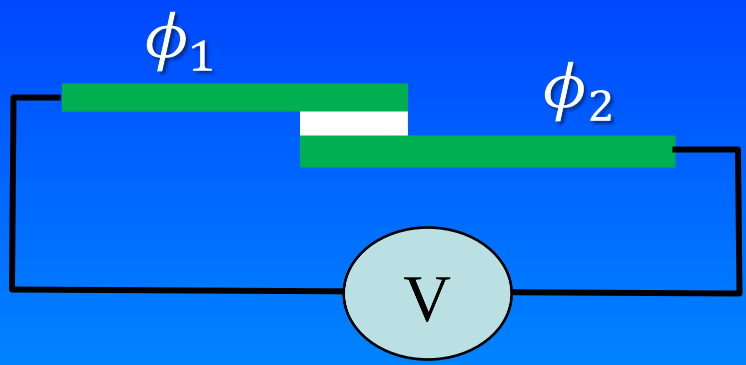
Kwon ’04



Lutchyn ‘10

ac Josephson effect

direct

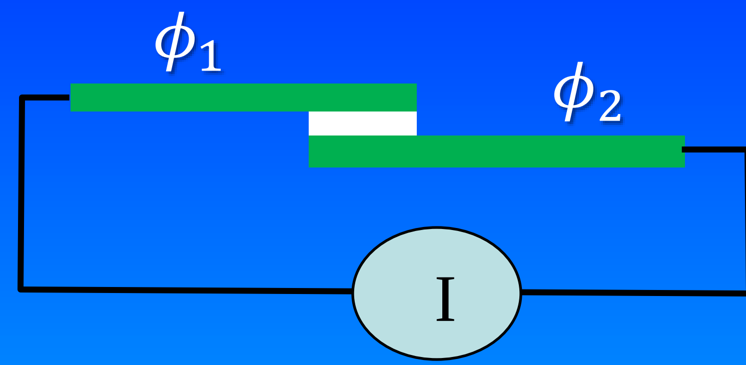


$$\frac{d(\Delta\phi)}{dt} = \frac{2eV}{\hbar}$$

$$I_s = Ic\sin(\omega_J t) = I_c \sin\left(\frac{2eV}{\hbar}t\right)$$

Current oscillates with frequency $\propto V$

inverse

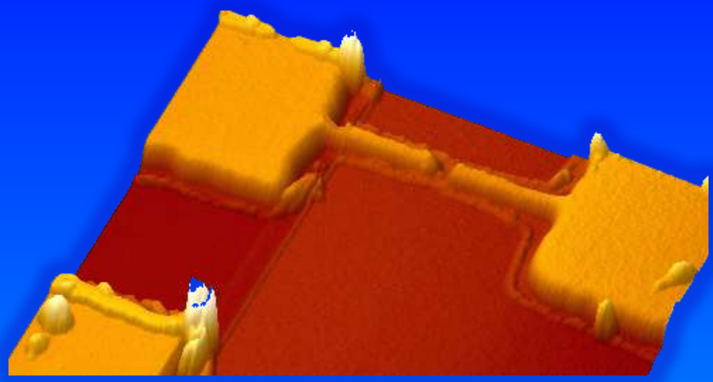


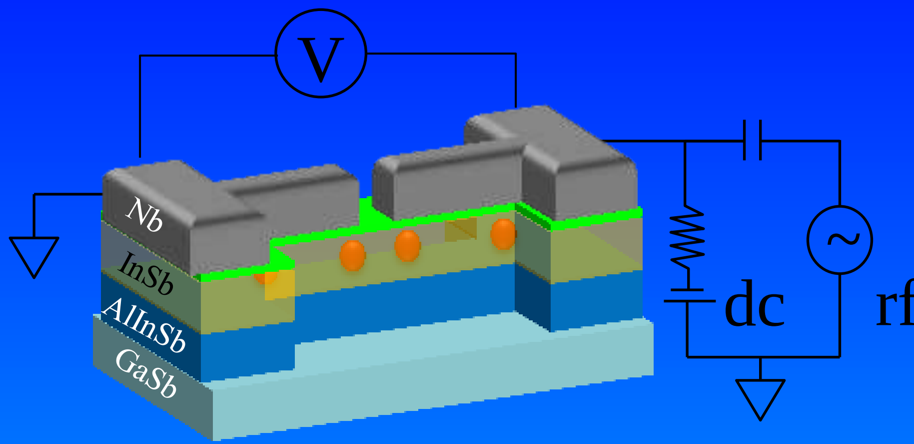
$$I = I_0 + I_\omega \sin(\omega t)$$

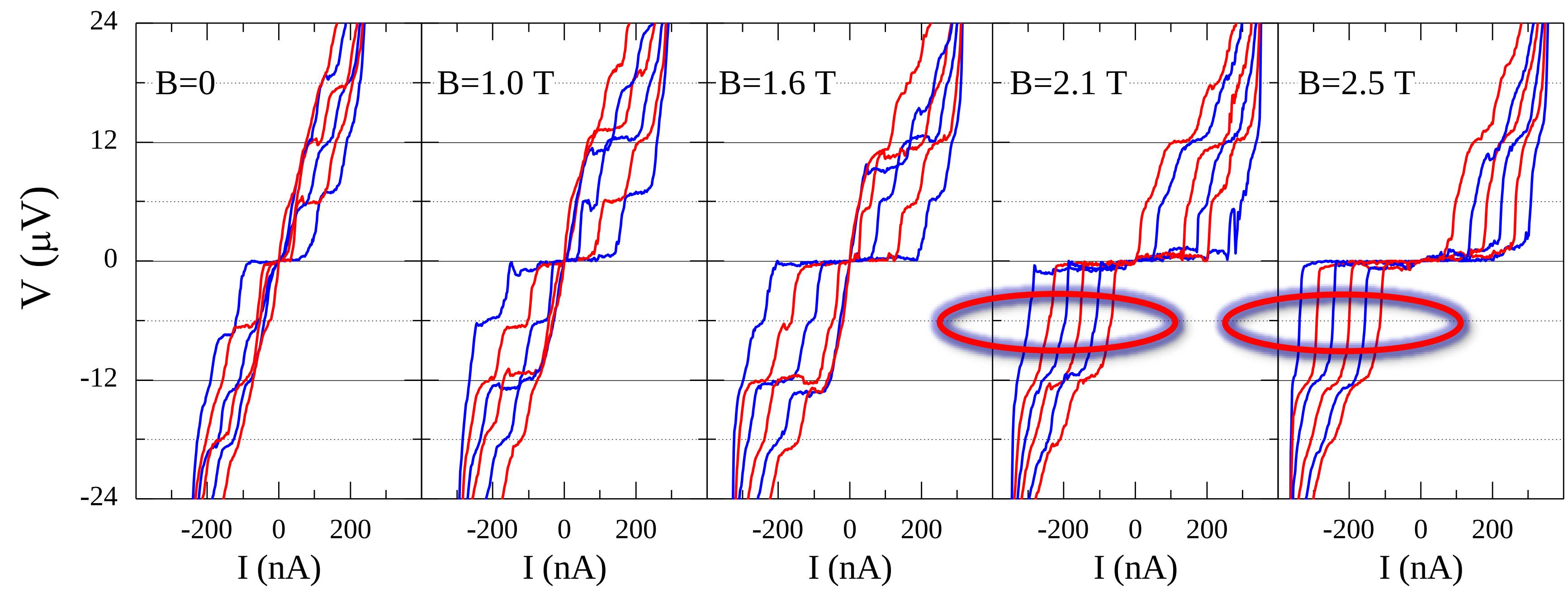
$$V = \left(\frac{h\omega}{2e}\right)$$

Constant voltage steps $\propto \omega$

Disappearance of the first Shapiro step



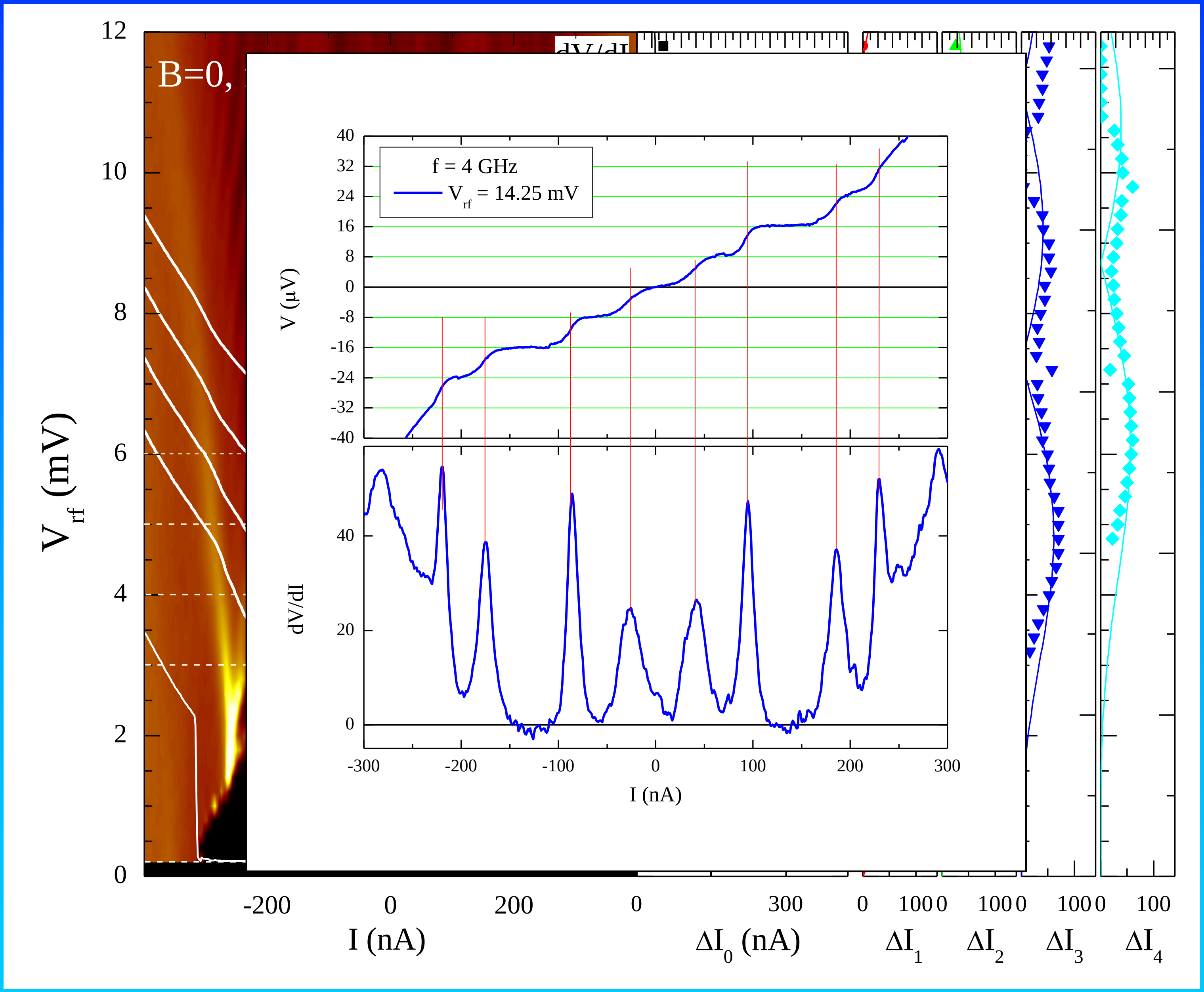




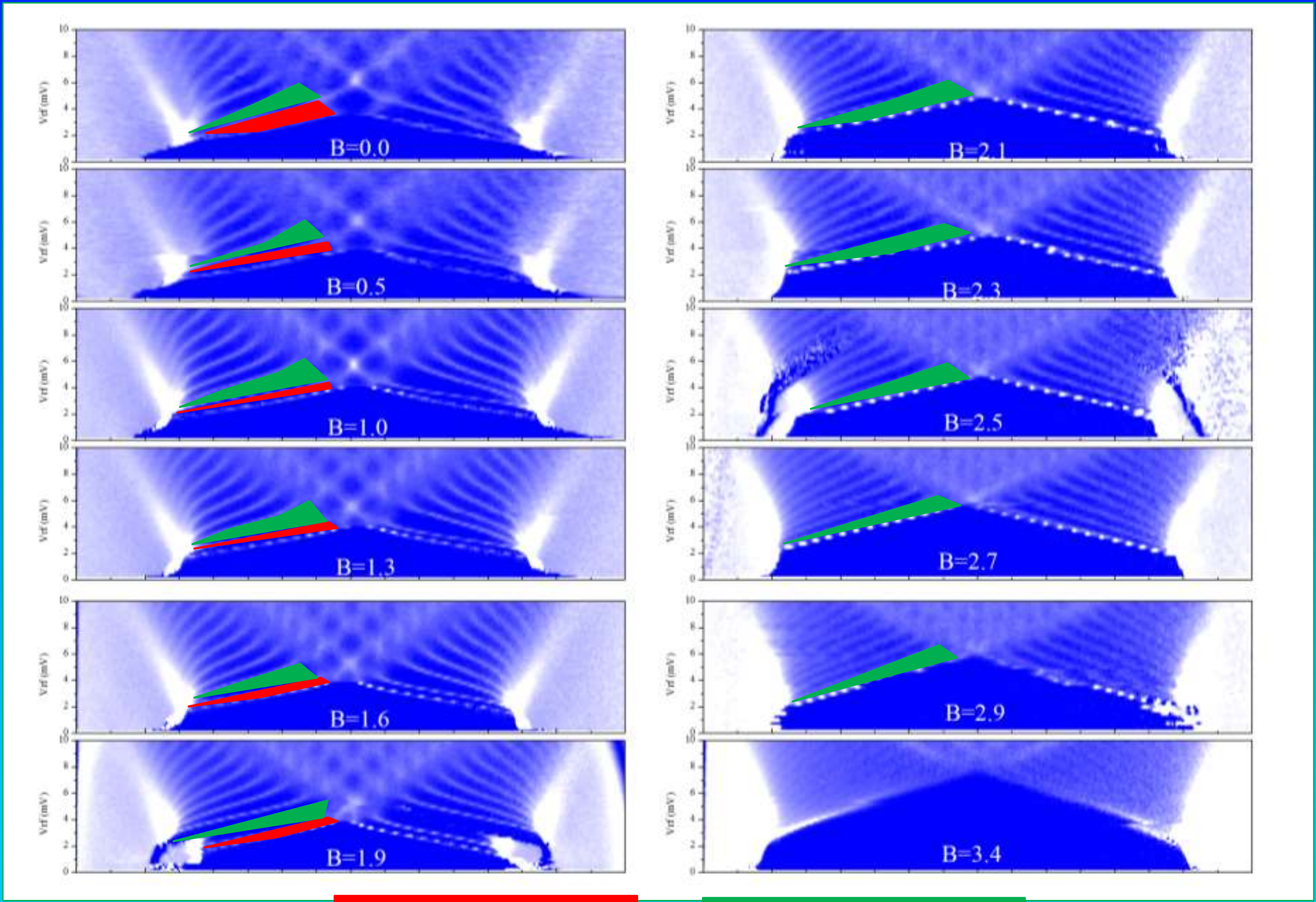
LR, X. Liu, J. Furdyna, Nature Physics **8**, 795 (2012)

Shapiro steps

$$\Delta I_n = A\left|J_n\left(\frac{2ev_{rf}}{\hbar\omega_{rf}}\right)\right|$$



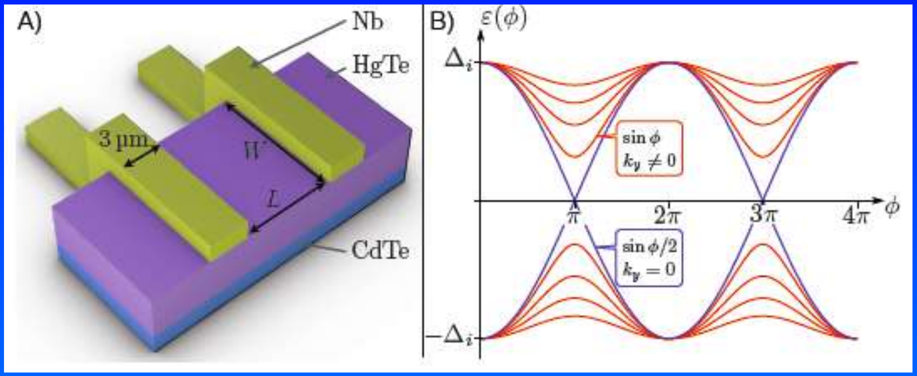
dV/dI vs B

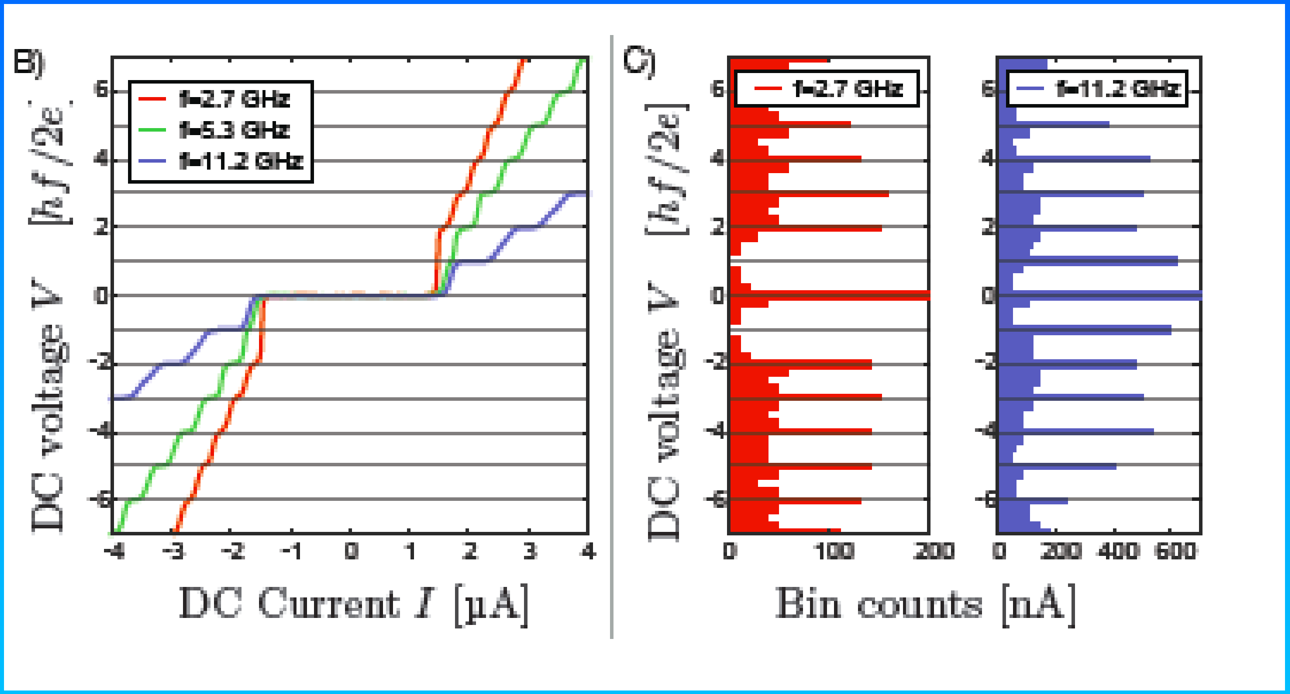


step @ 6 μV

step @ 12 μV

4-periodic Josephson supercurrent in HgTe-based *3D TI*





Wiedenmann, …M. Klapwijk, …, Seigo Tarucha, L. W. Molenkamp

arXiv:1503.05591

Advantage of 1D wires: Majorana modes are localized

easy to perform spectroscopy

Disadvantage of 1D wires: Majorana modes are localized

almost impossible to perform exchange

magnetic semiconductors

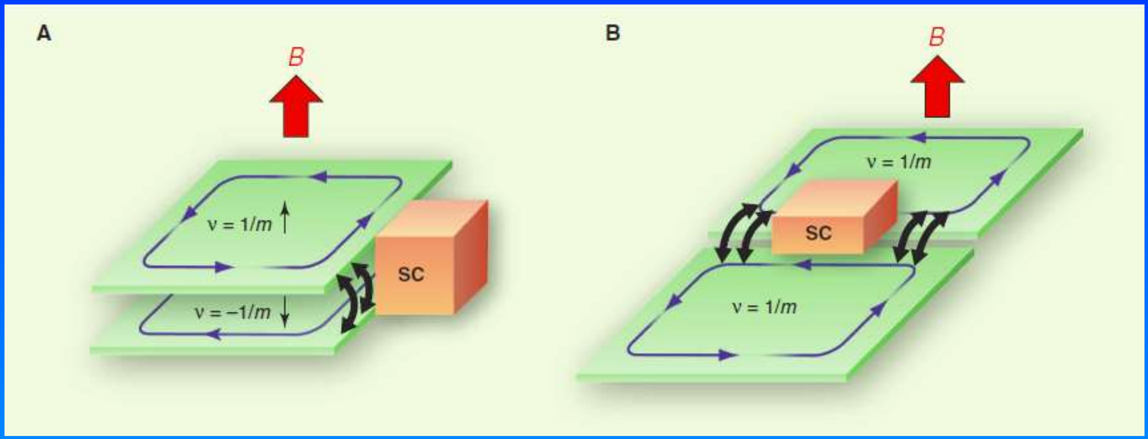
quantum Hall effect

superconductivity

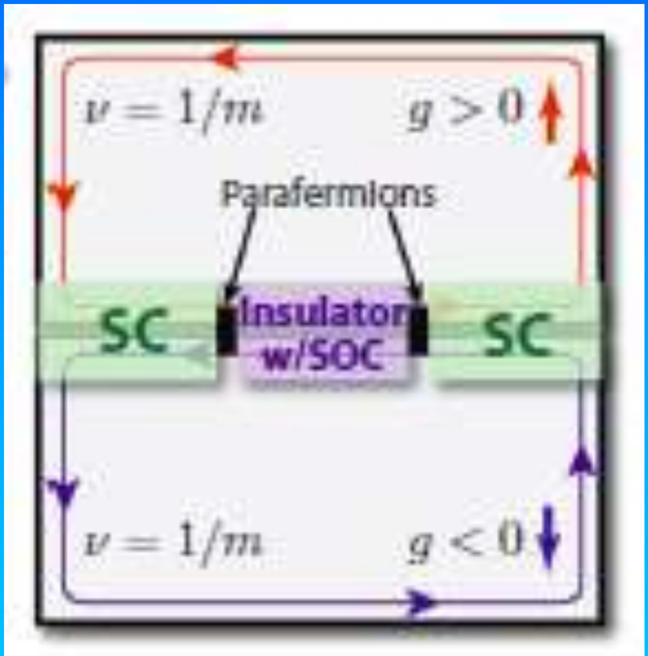
new materials to support exotic non-Abelian excitations

reconfigurable 1D topological superconductors in 2D systems

Motivation and inspiration

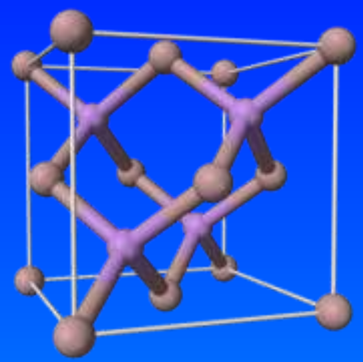


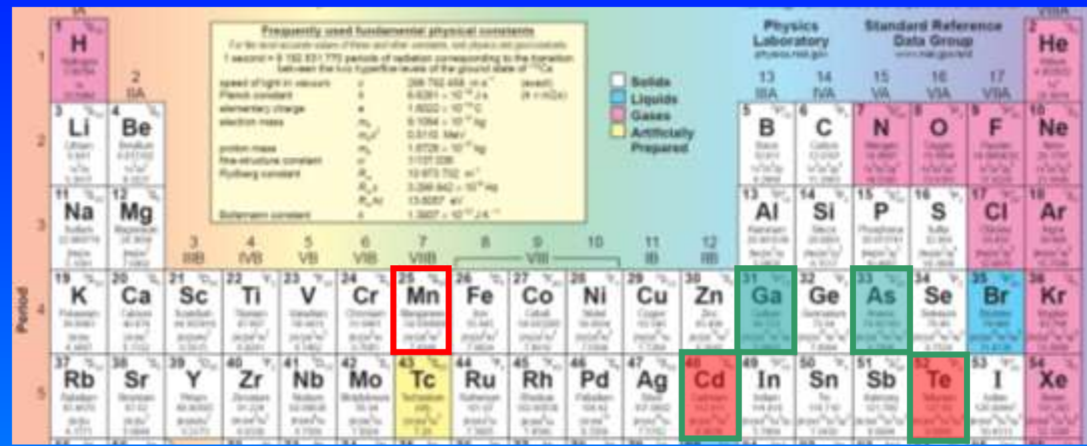
Topological Quantum Computation - From Basic Concepts to First Experiments
Ady Stern & Netanel Lindner
Science, **2013**, *339*, 1179



Exotic non-Abelian anyons from conventional fractional quantum Hall states
David J. Clarke, Jason Alicea, and Kirill Shtengel
Nature Commun., **2012**, *4*,, 1348

Development of a new system CdTe:Mn QW





GaAs:Mn   Ga [Ar]$3d^{10}4s^{2}4p^{1}$ As [Ar]$3d^{10}4s^{2}4p^{3}$

p-doping

large s-d exchange (ferromagnetic)

S=5/2

Mn [Ar]$3d^{5}4s^{2}$

exchange split ~3 eV (Hunds rule), ½ filled

CdTe:Mn   Cd [Kr]$4d^{10}5s^{2}$ Te [Kr]$4d^{10}5s^{2}5p^{4}$

neutral impurity, large s-d exchange

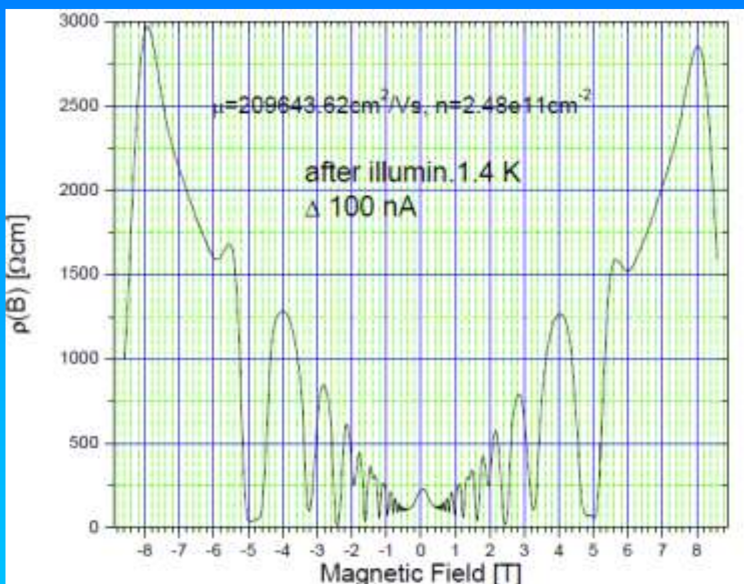
Development of a new system

High mobility 2D gas in CdTe/CdMgTe QW

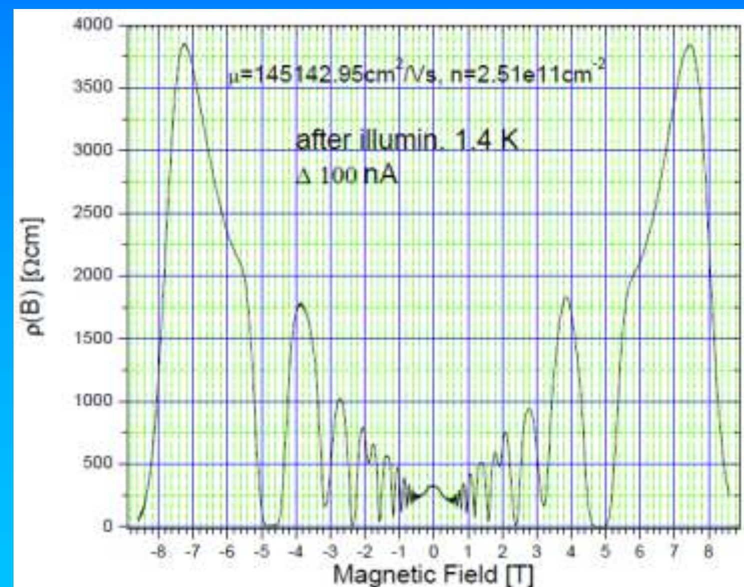
$m^*=0.11$, $E_g=1.44$ eV

add Mn into CdTe (neutral impurity with 5/2 spin)

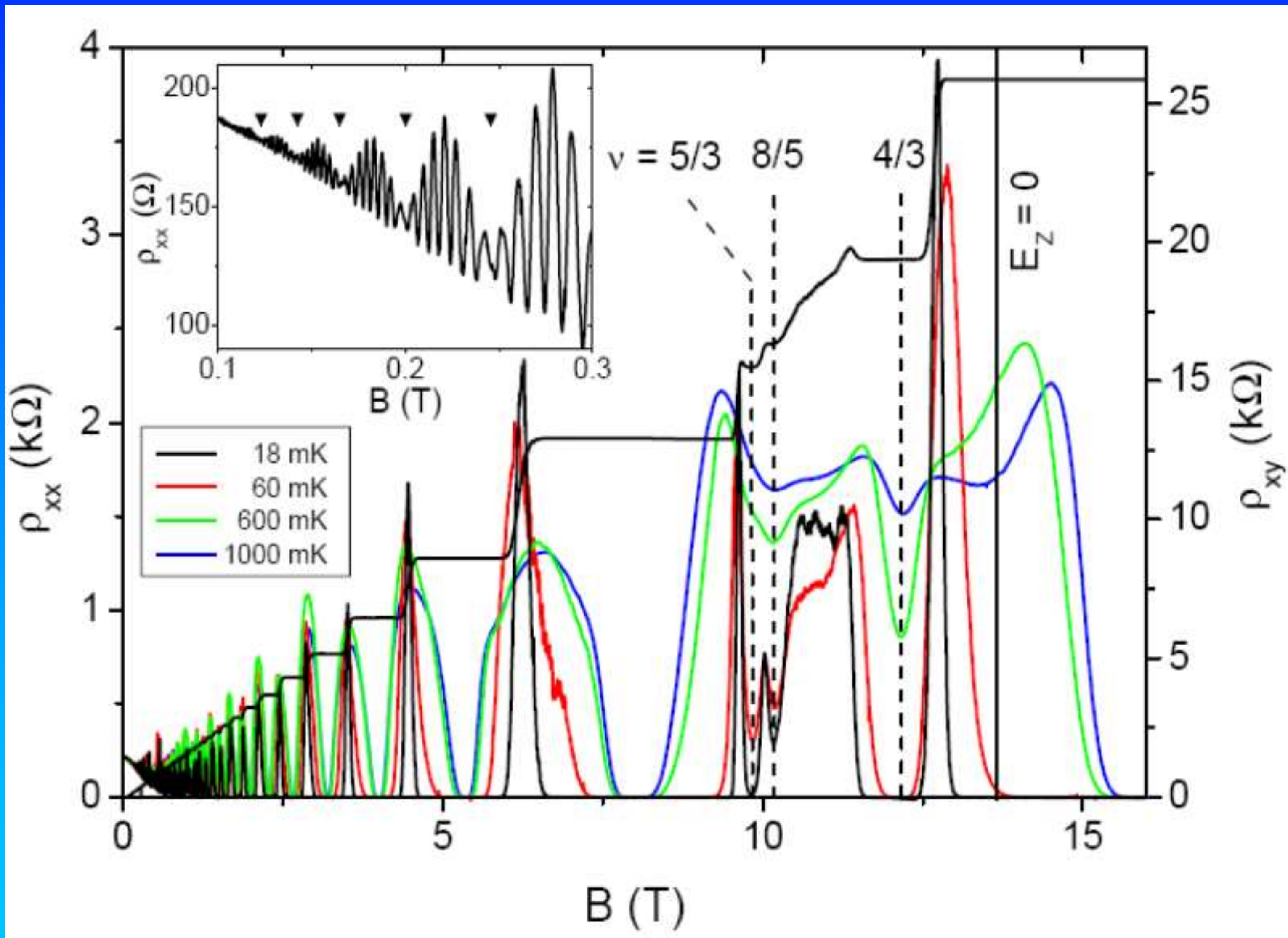
no Mn



~1% Mn



FQHE in CdTe:Mn



T. Wojtowicz

Betthausen, et al, Phys. Rev. B **90**, 115302 (2014)

Anomalous Zeeman splitting in CdTe:Mn

$$E_{n,\uparrow\downarrow} = (n + {}^1/_2)\hbar\omega_c \pm {}^1/_2 \left[g^* \mu_B B + x_{Mn} E_{sd} \mathfrak{B}_S \left(\frac{g\mu_B S B}{k_B T} \right) \right]$$

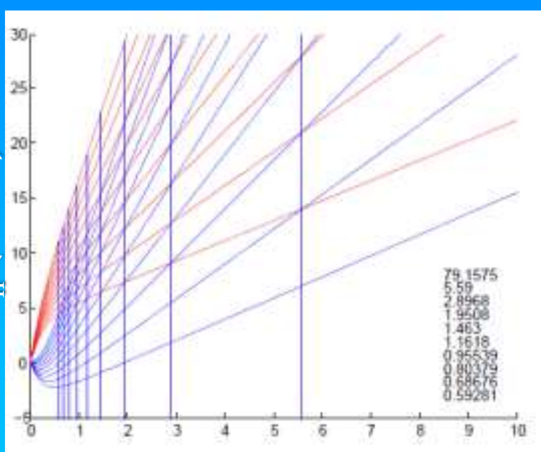
cyclotron

Zeeman
g^*=–1.6

s-d exchange (>0)

1.3% Mn

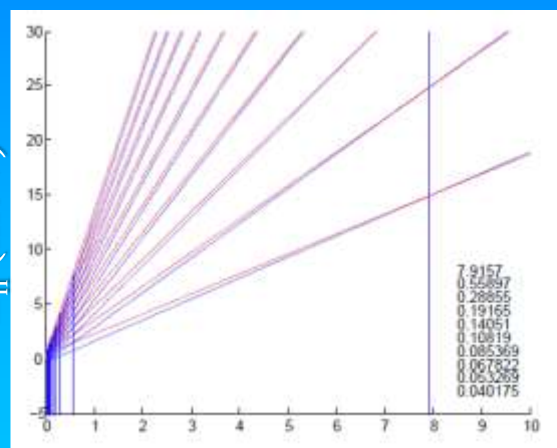
E_n (meV)



B (Tesla)

0.13% Mn

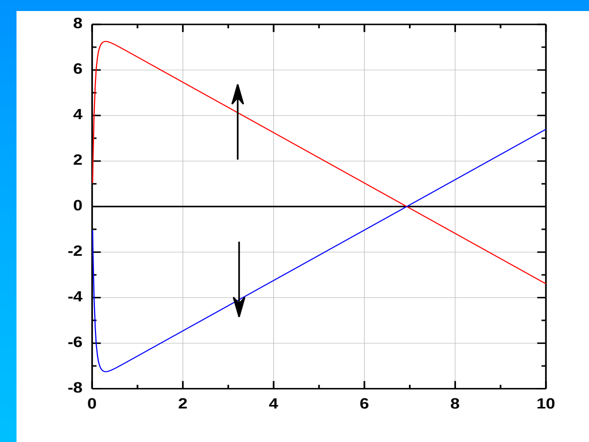
E_n (meV)



B (Tesla)

for n=1

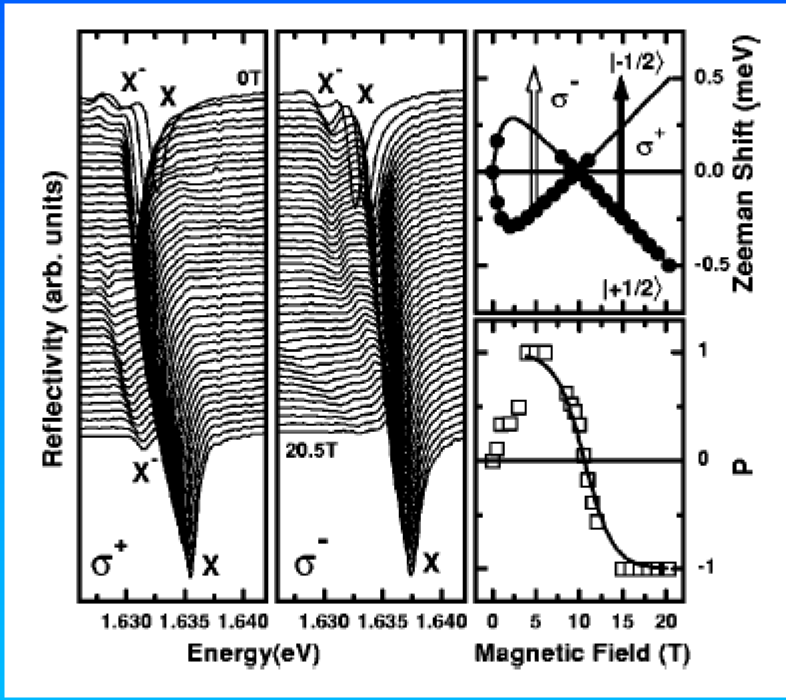
E_n (meV)

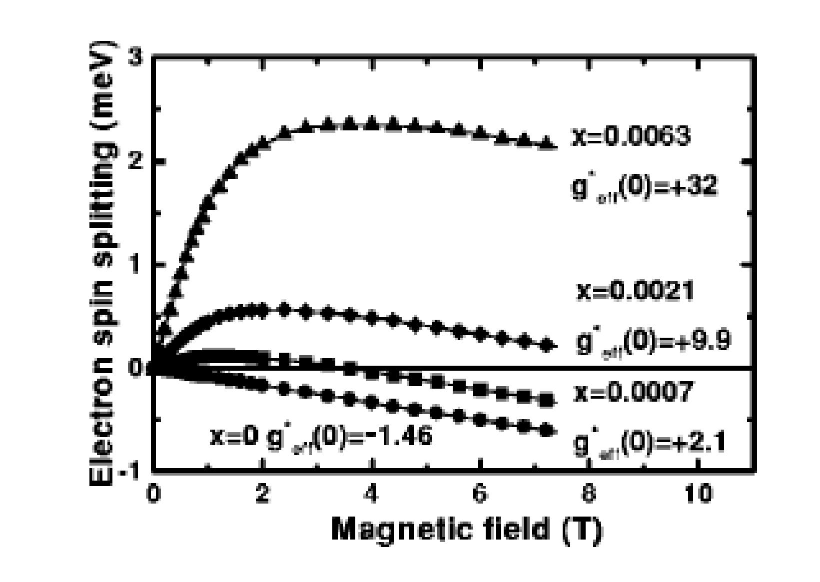


B (Tesla)

Magnetoreflectivity studies

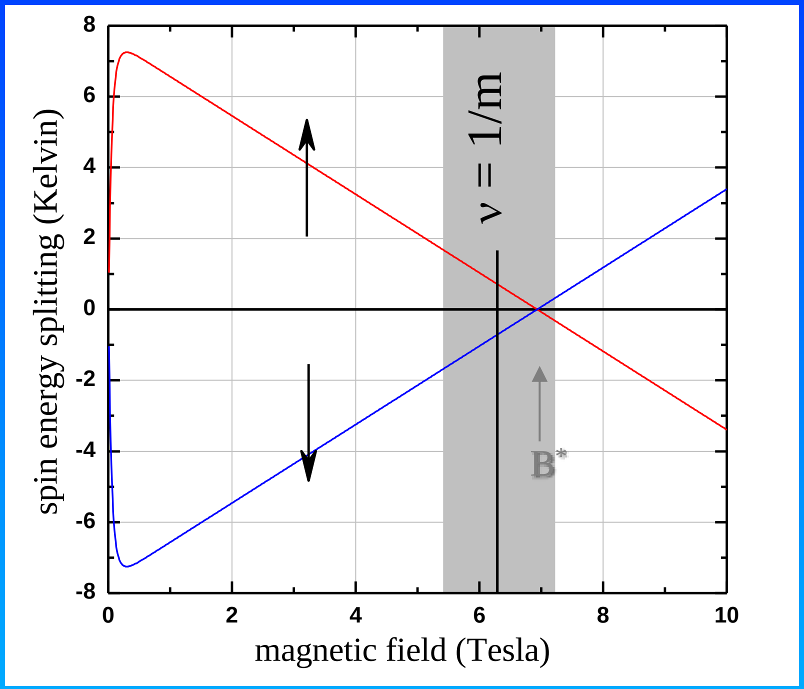
negatively charged exciton complex X^- (trion) to singlet X transition under polarized σ^+/σ^- light

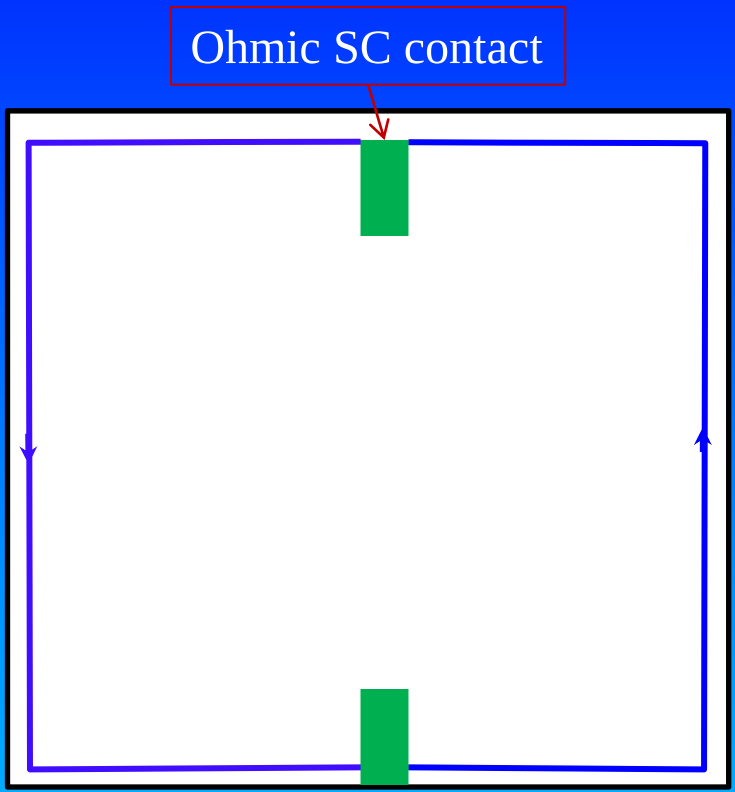




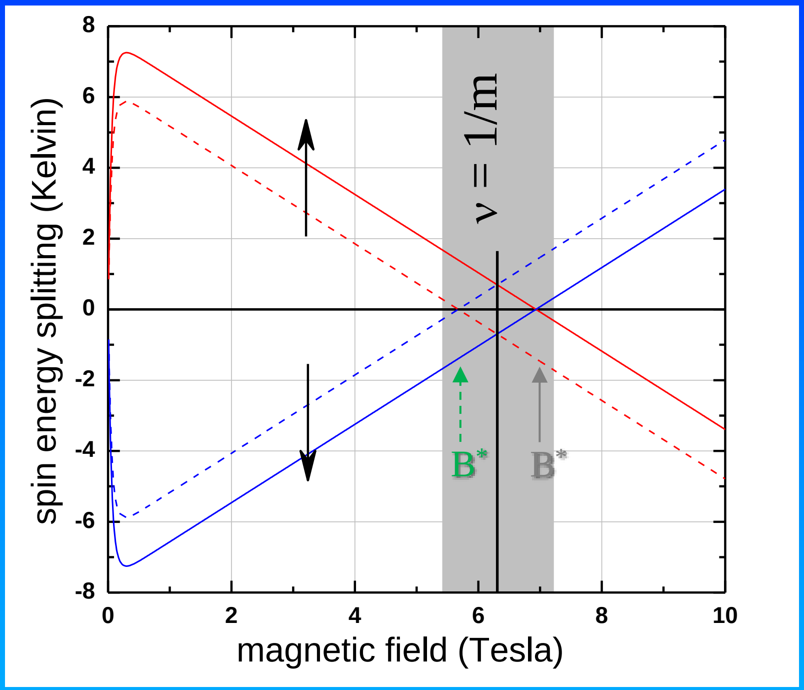
Wojtowicz, et al, PRB 59, R10437 (1999)

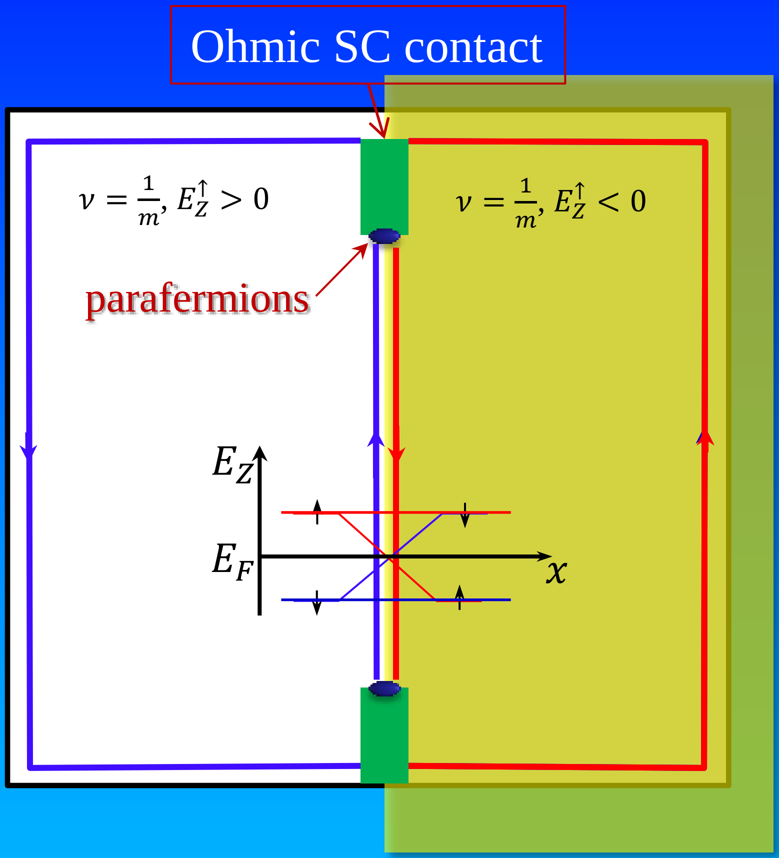
new platform for non-Abelian excitations

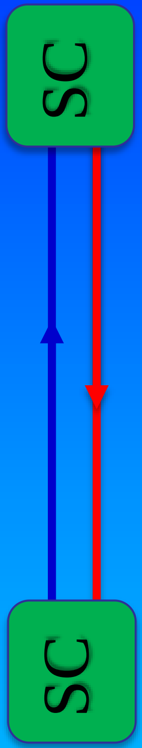




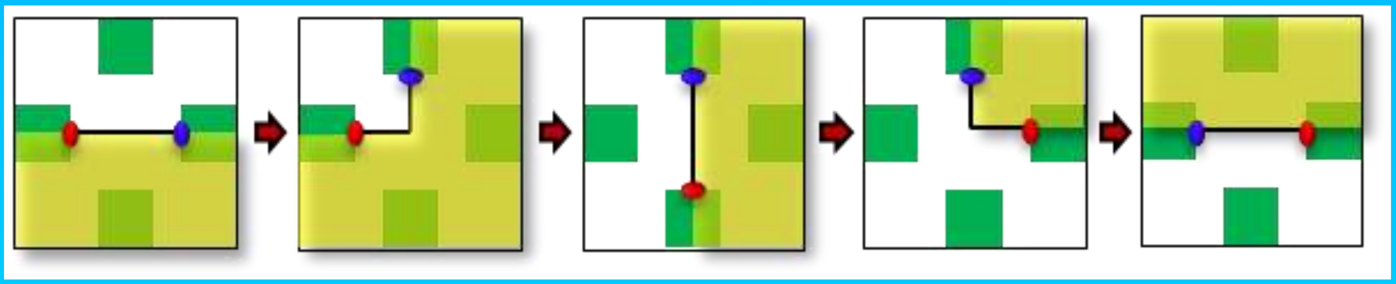
new platform for non-Abelian excitations



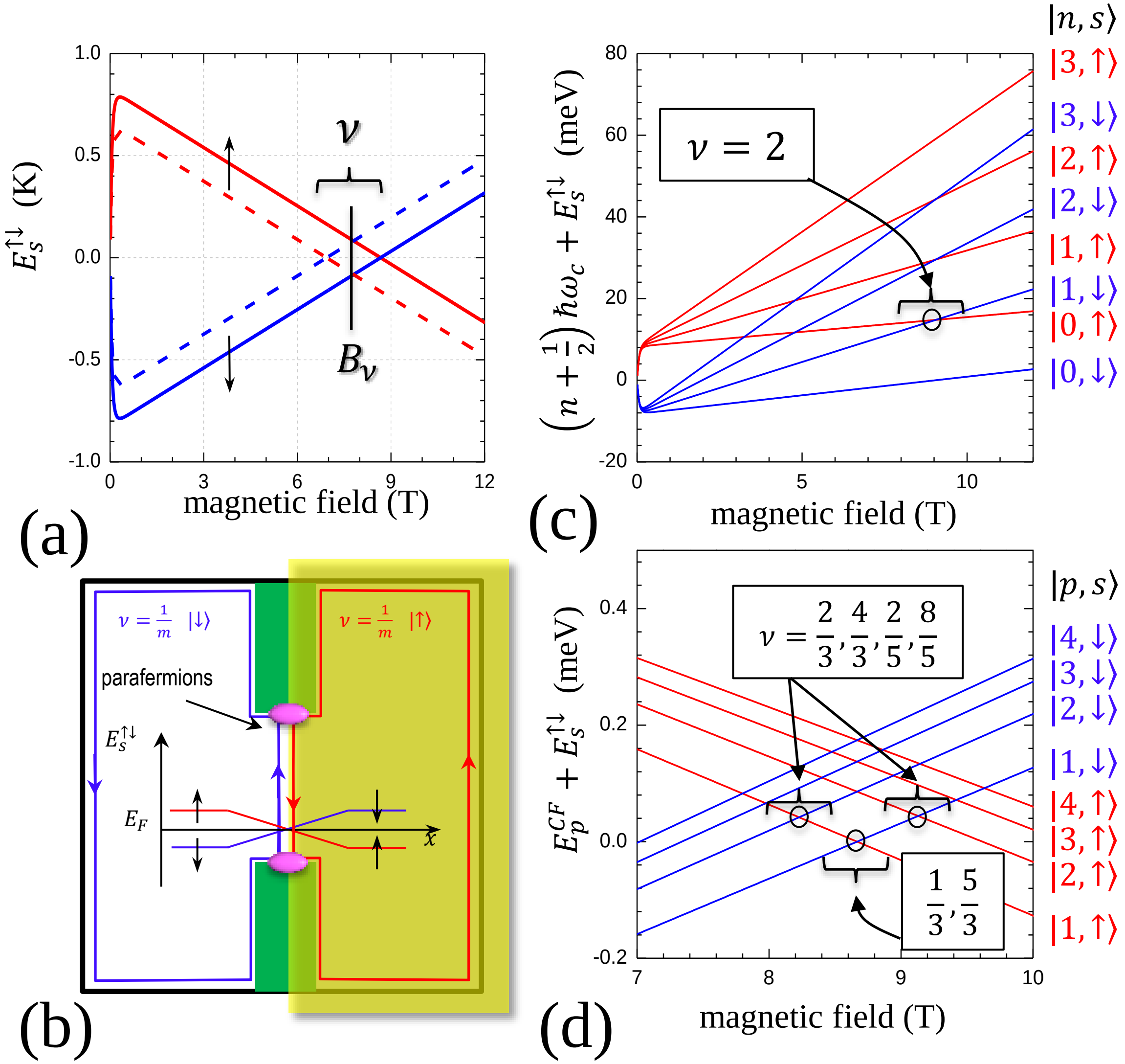




braiding sequence

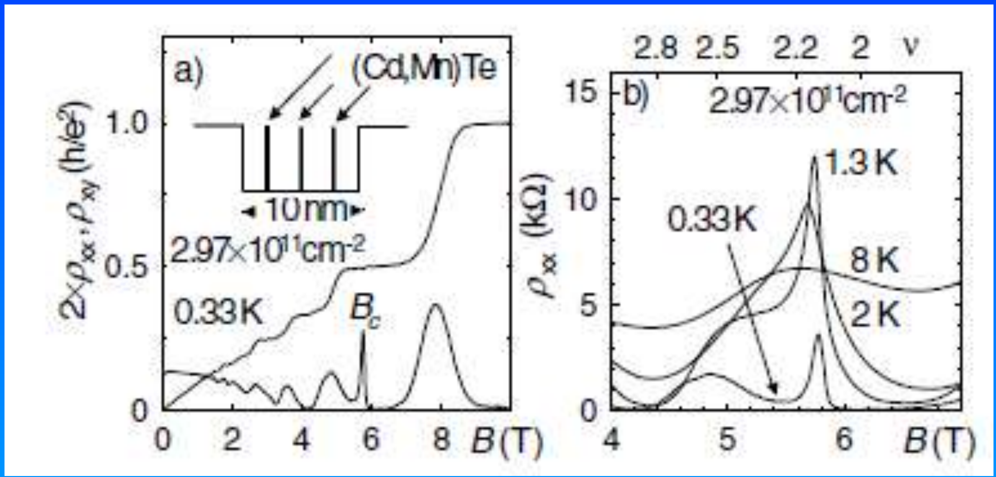


Crossing of neighboring LLs

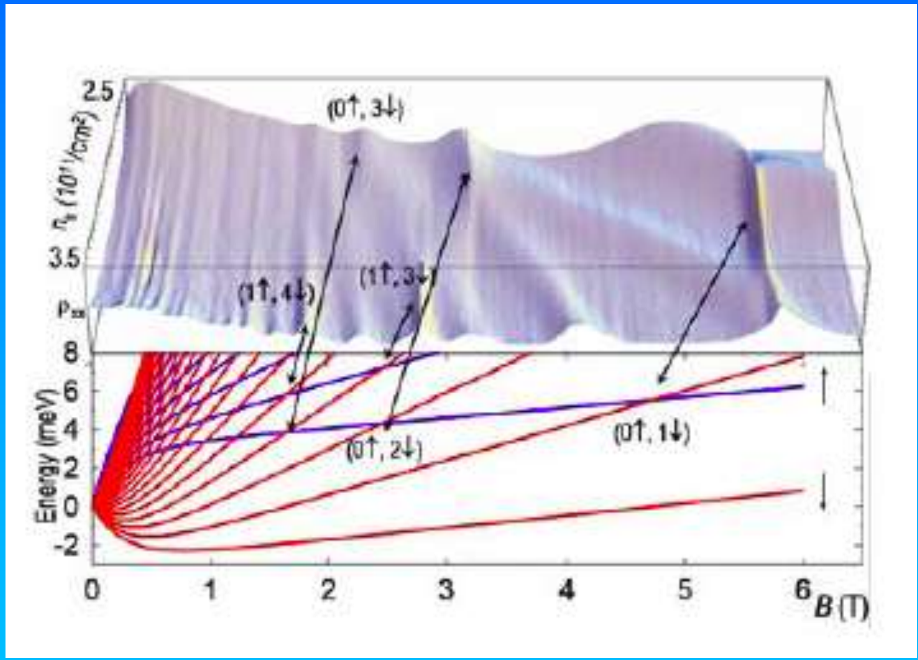


Quantum Hall ferromagnet & level crossing

uniformly Mn-doped quantum well



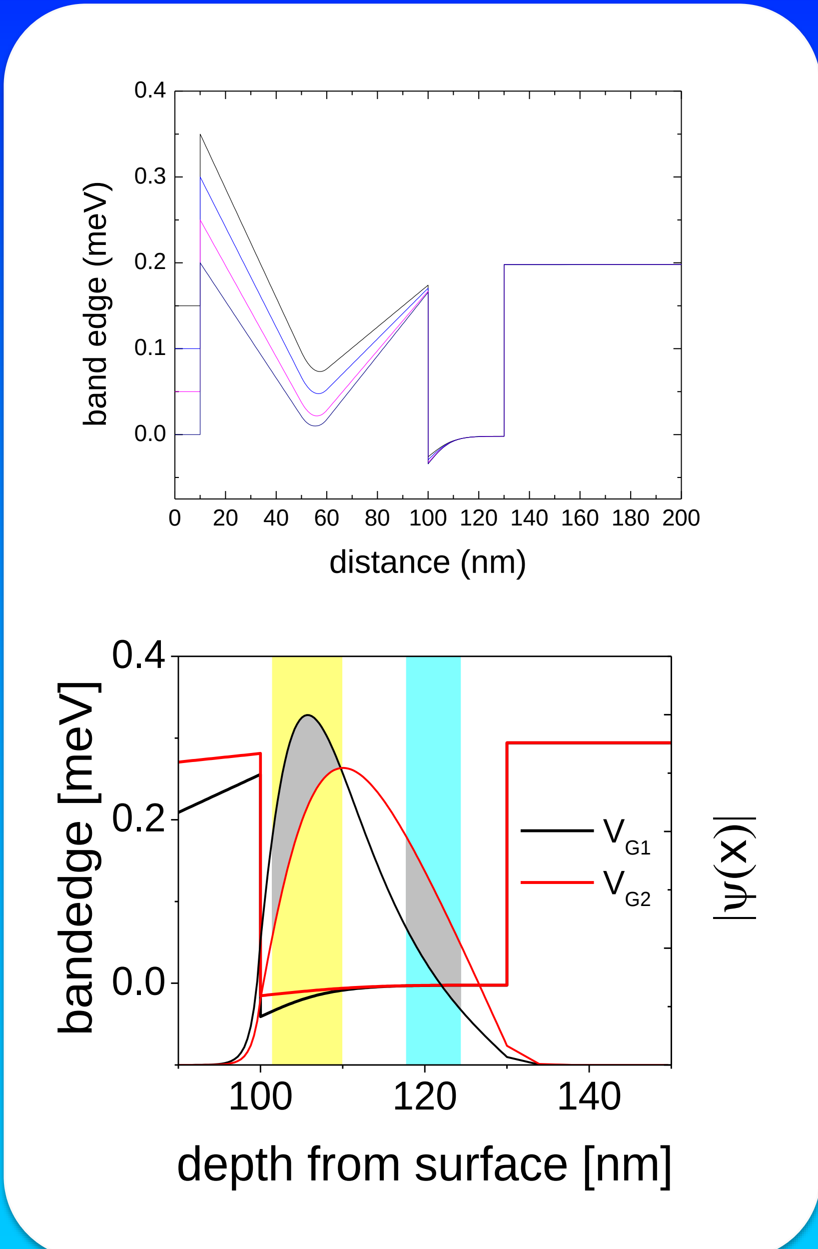
Jaroszynski, et al, PRL **89**, 266802 (2002)

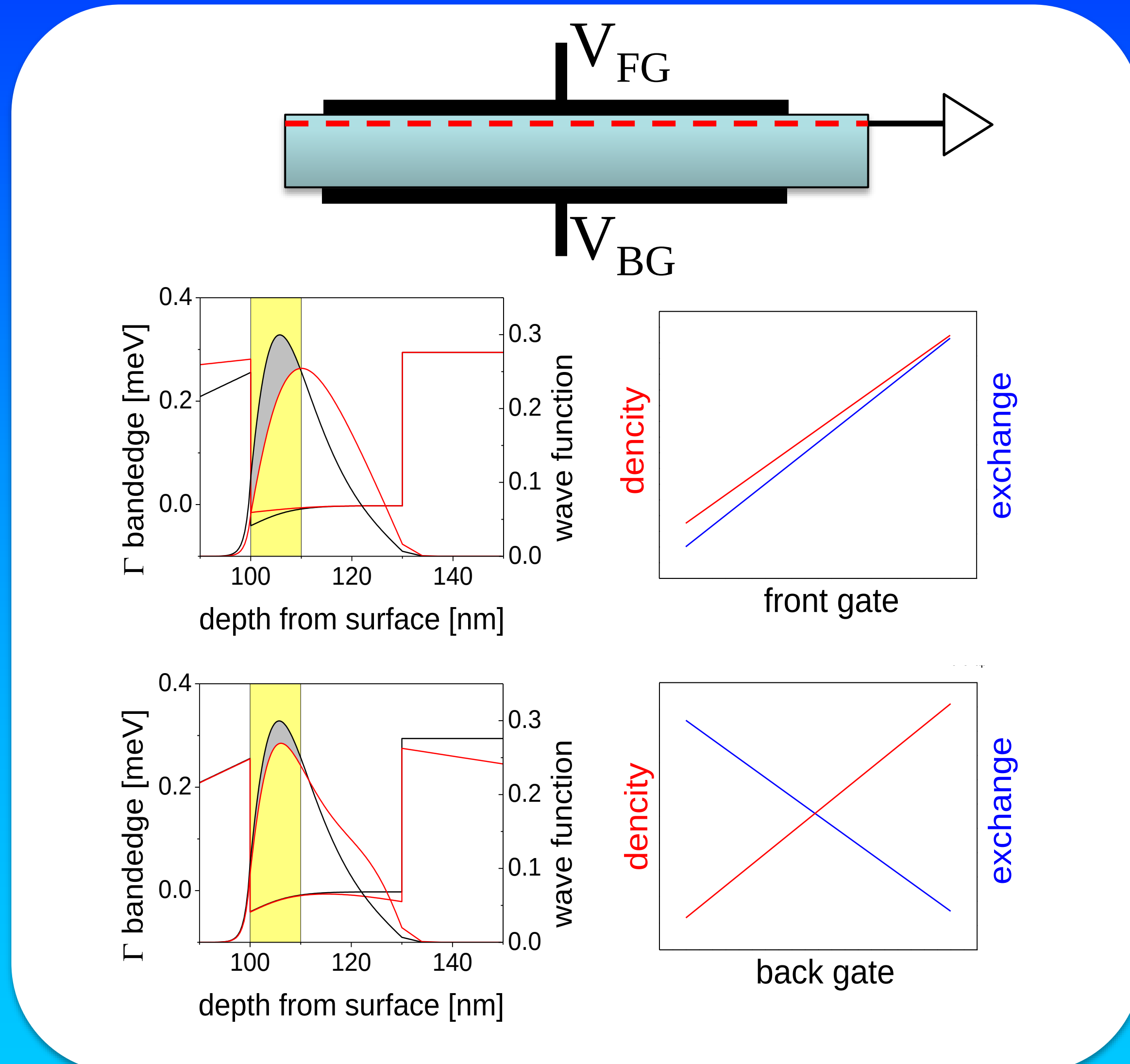


Jaroszynski, et al, AIP conference proceedings (2005)

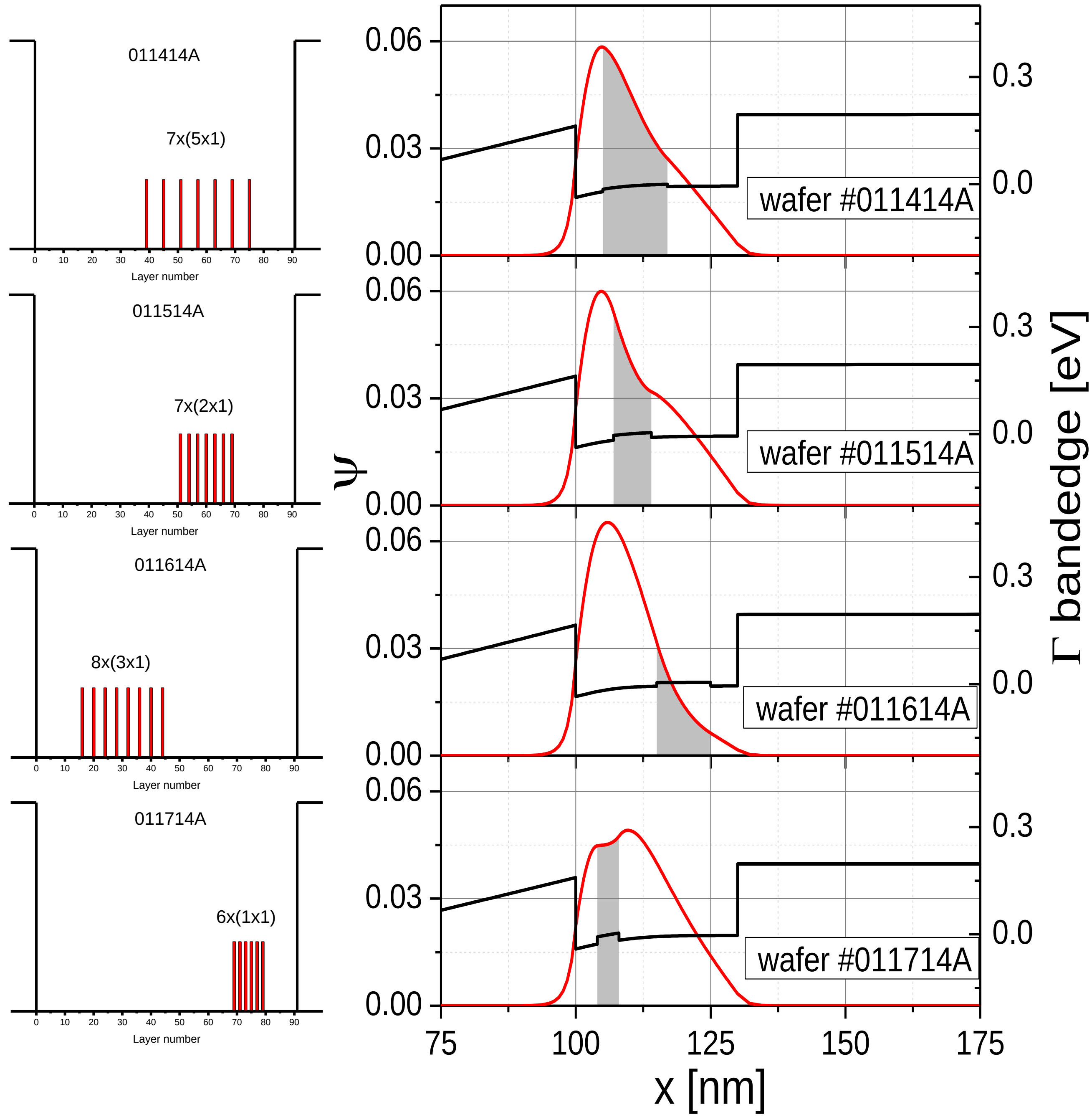
Gate control of exchange

$$E_{sd} \propto \int \psi_e(x)\chi_{Mn}(x)\,dx$$



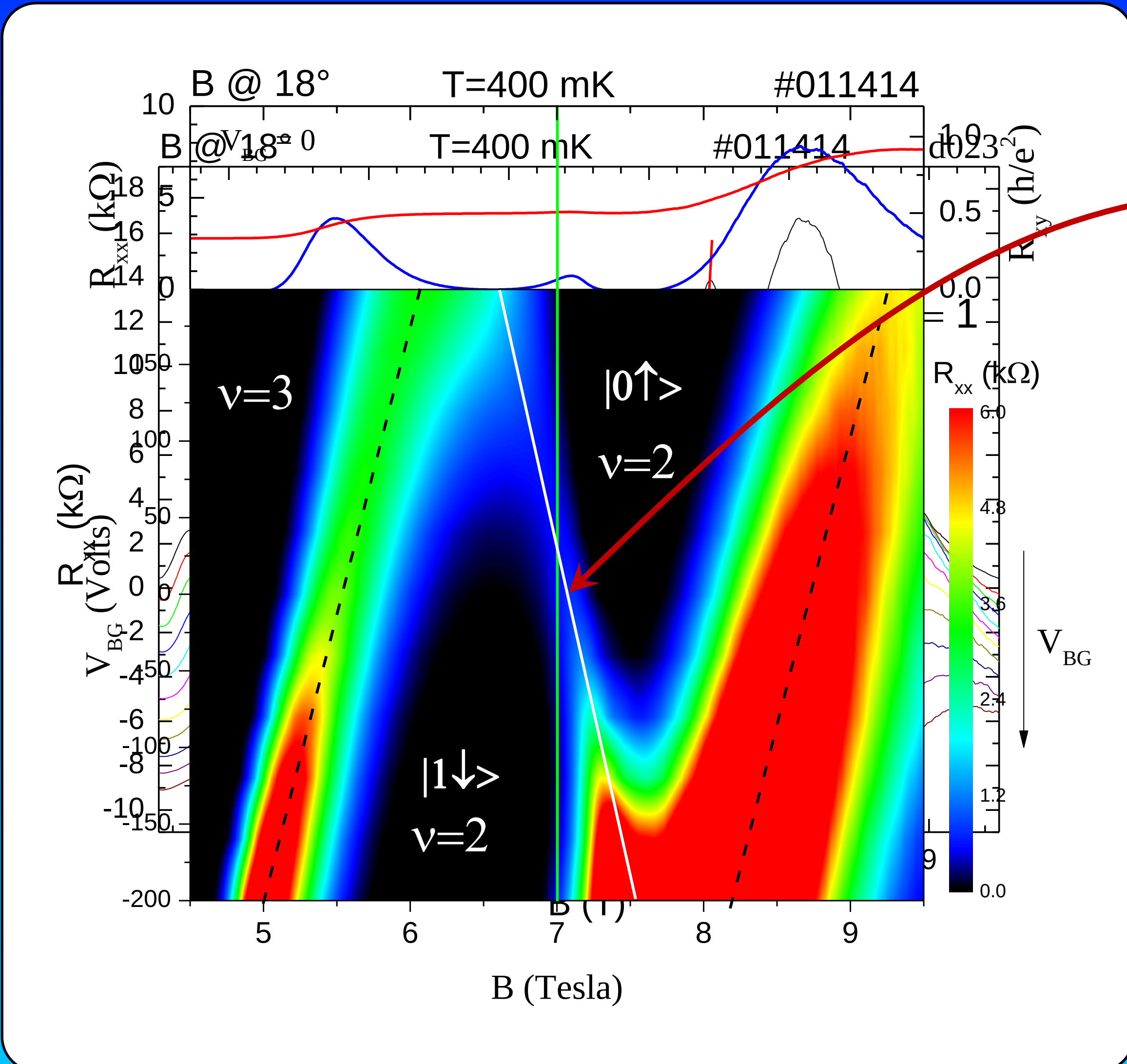


Structures with asymmetric doping

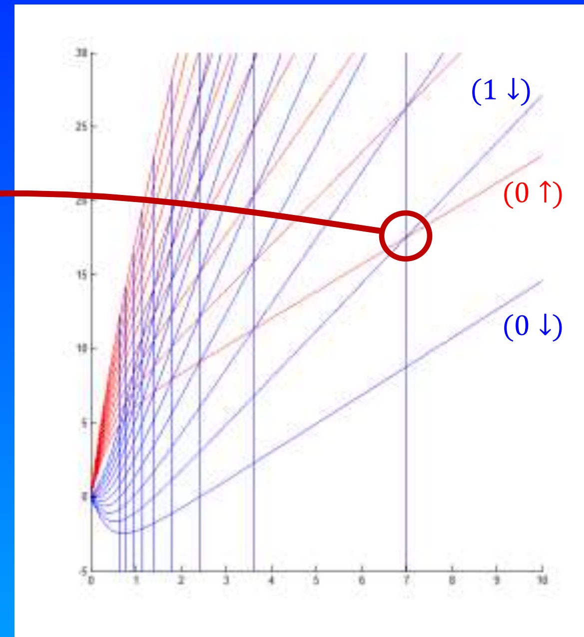


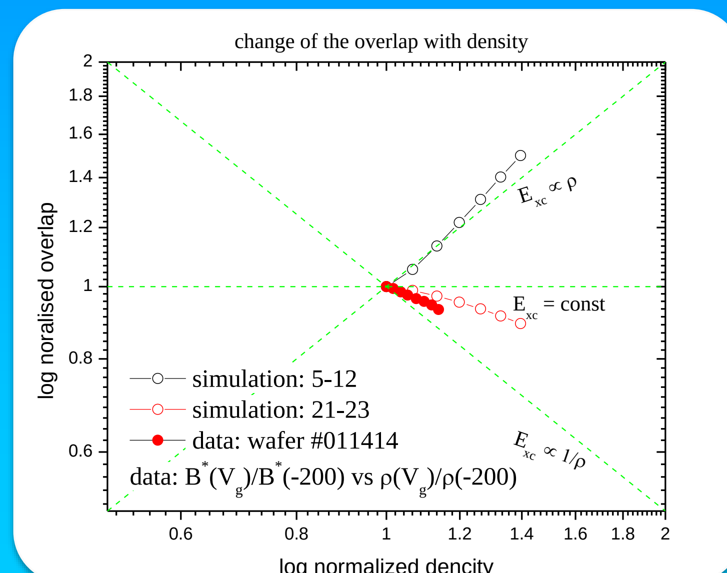
Gate control of s-d exchange

1.3% Mn

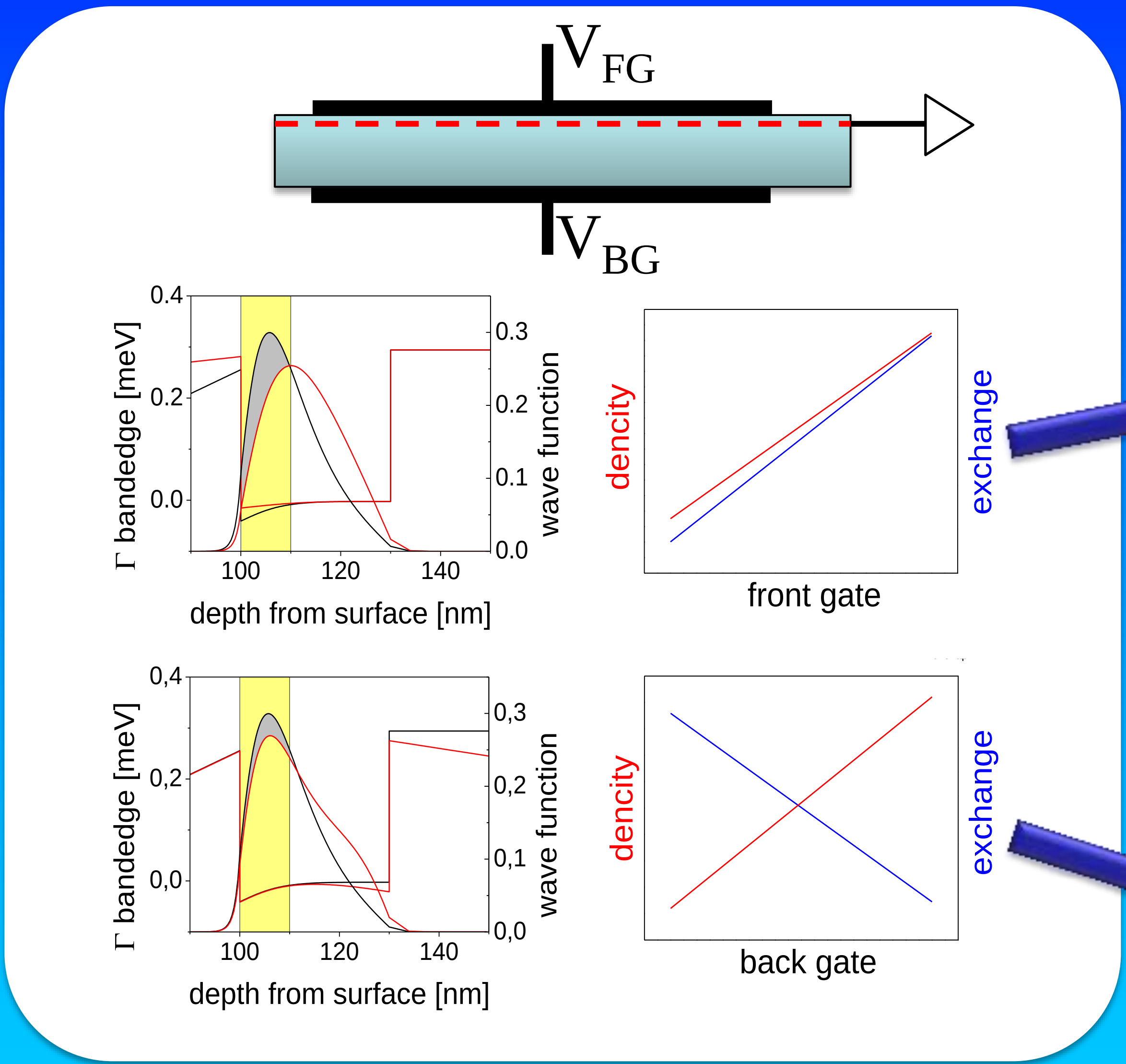


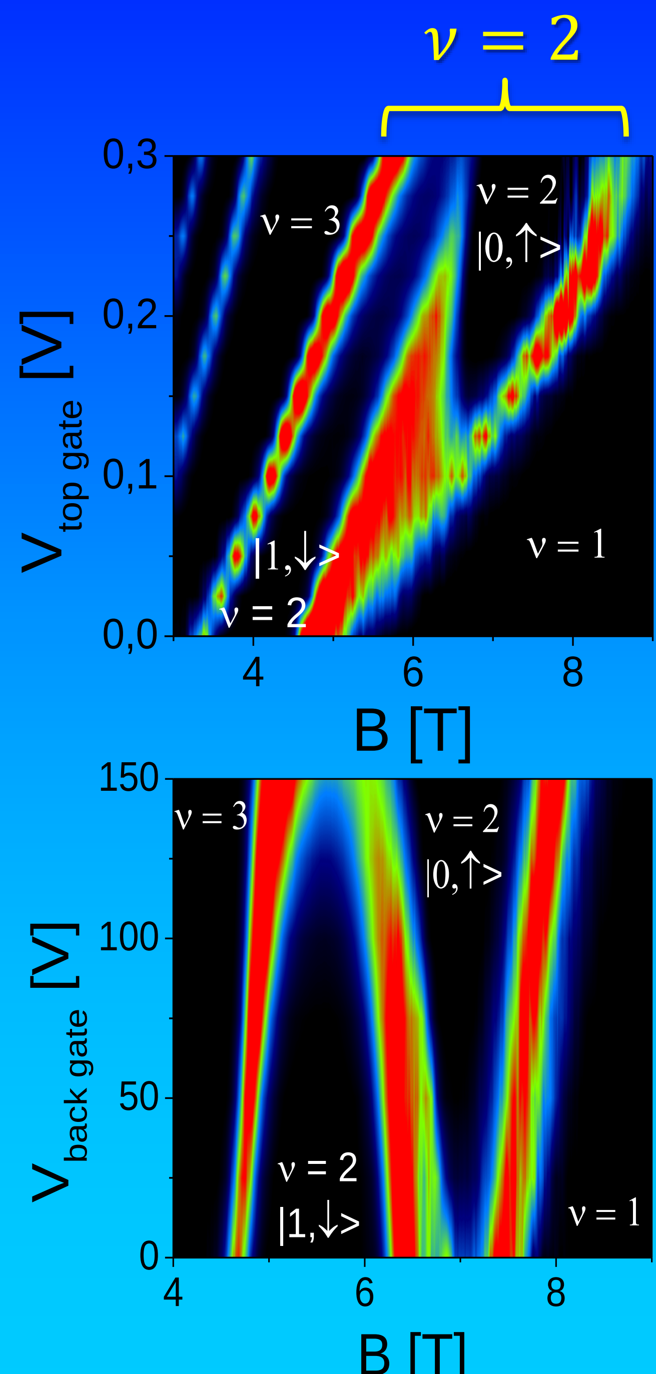
crossing $|1\downarrow>$ and $|0\uparrow>$





Gate control of the crossing

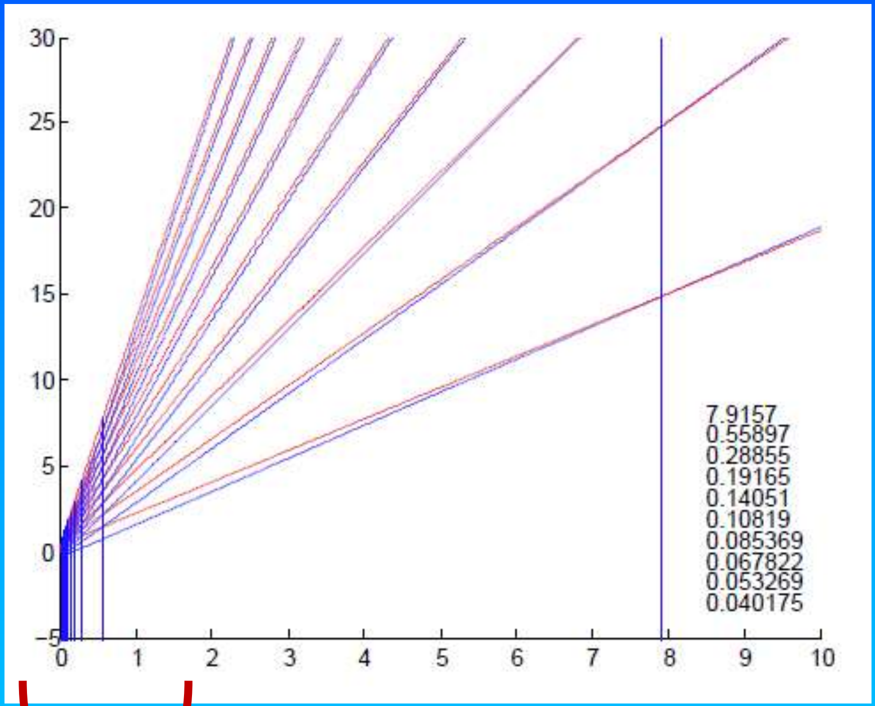




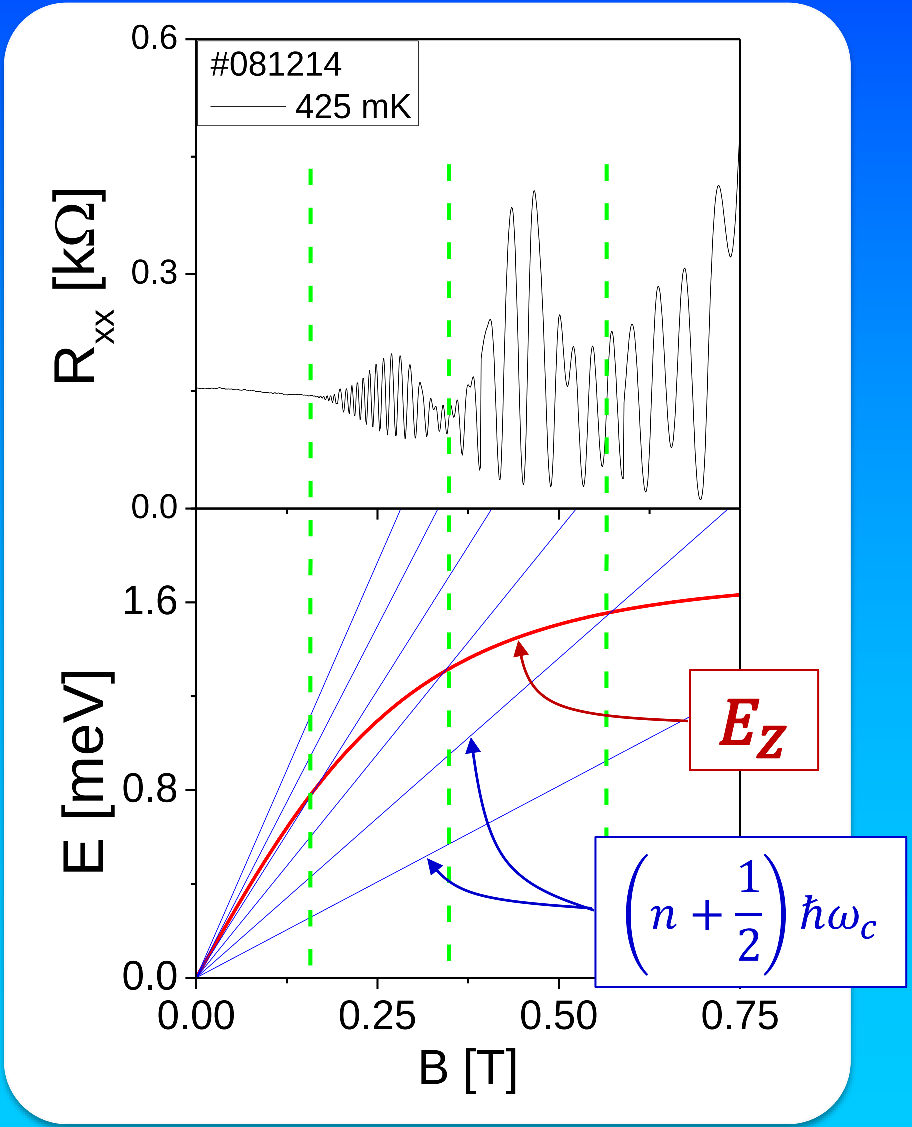
low Mn concentration

Node position:

$$E_Z = \left(N + \frac{1}{2}\right)\hbar\omega_C = g^*\mu_B B + \alpha x_{eff} S\mathcal{B}_S\left(\frac{g\mu_B SB}{k_B T_0}\right)$$

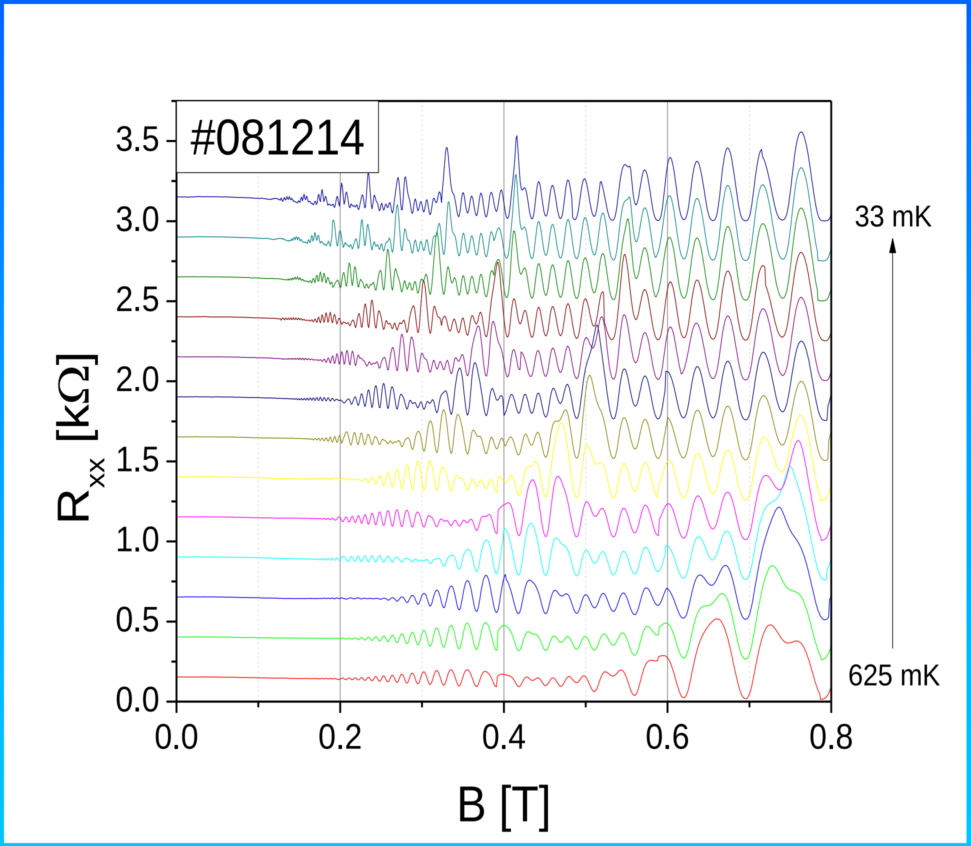


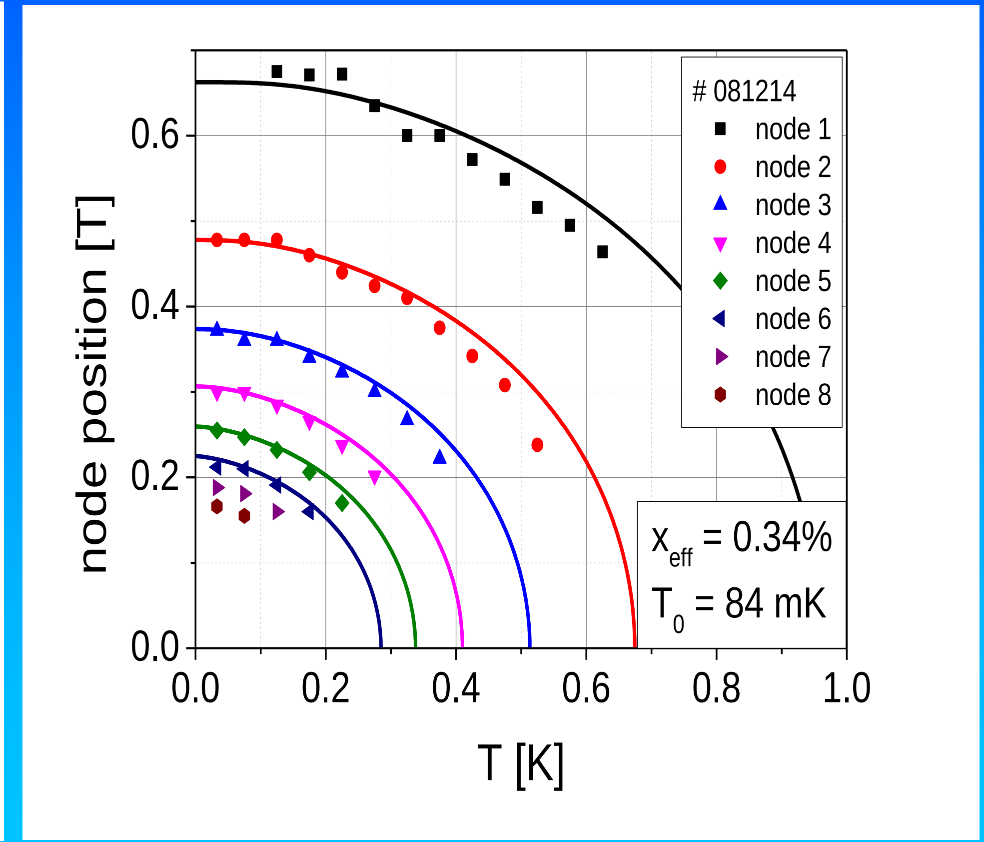
beating in SdH



SdH beating, x_{eff} and T_{FM}

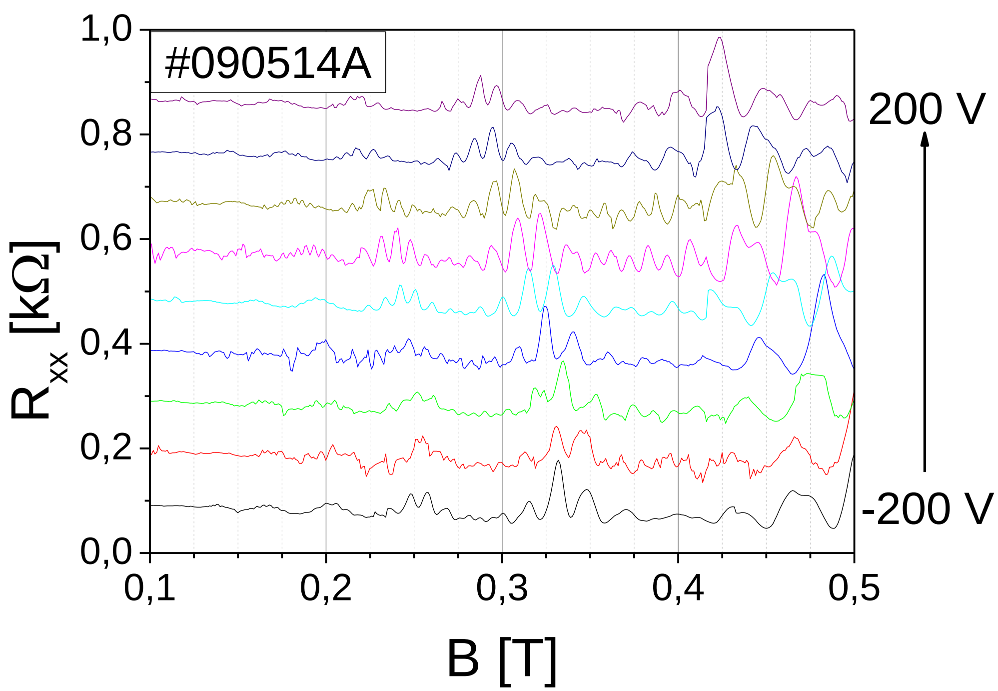
$$\left(N+\frac{1}{2}\right)\hbar\omega_C = g^*\mu_B B + \alpha x_{eff} S\mathcal{B}_S\left(\frac{g\mu_B SB}{k_B(T_{AF}+T)}\right)$$

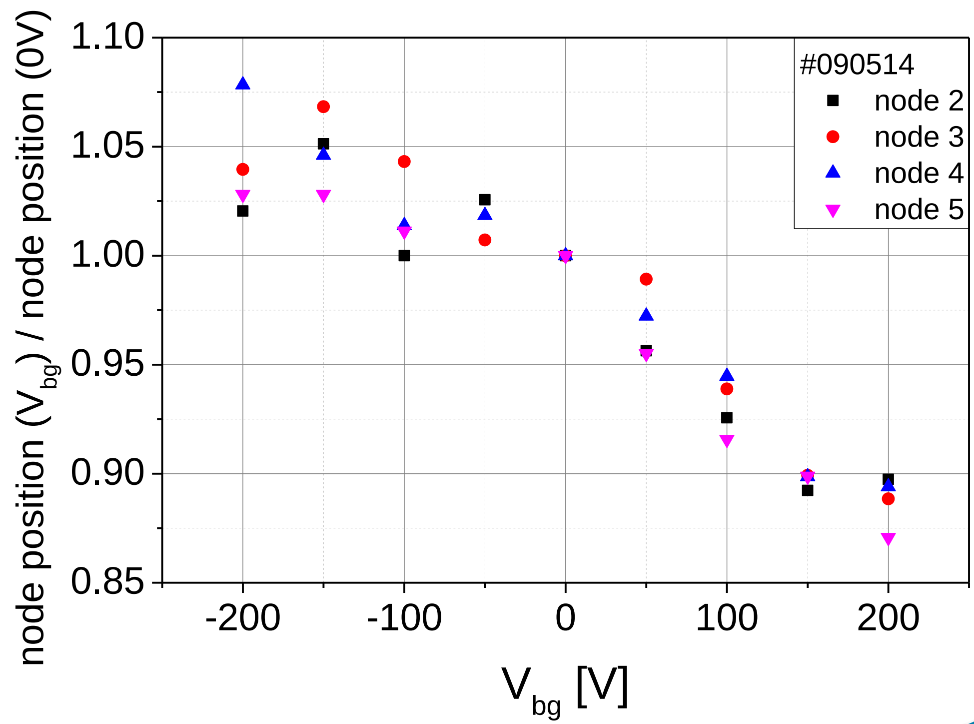




temperature dependence

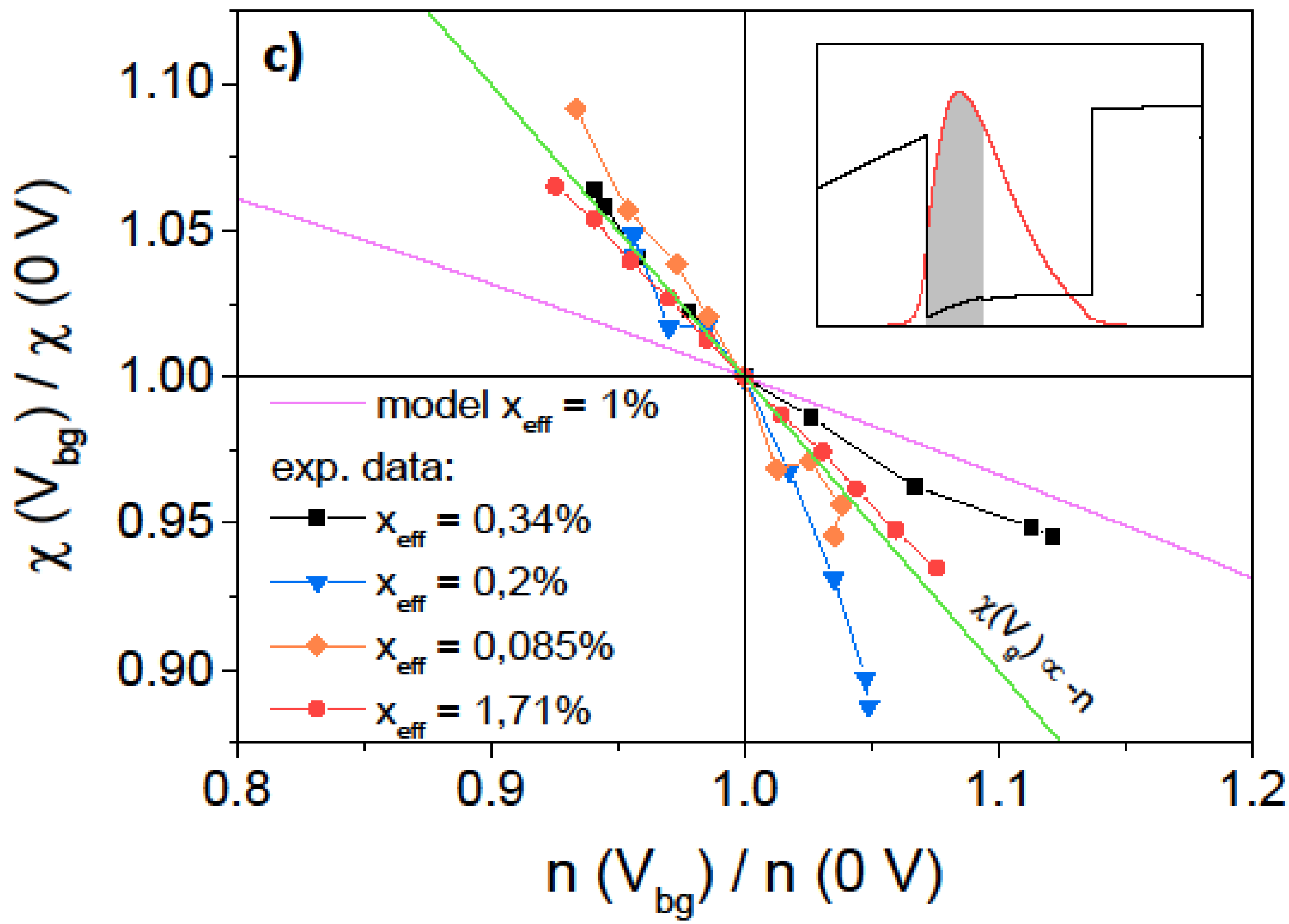
Gate control of SdH beating



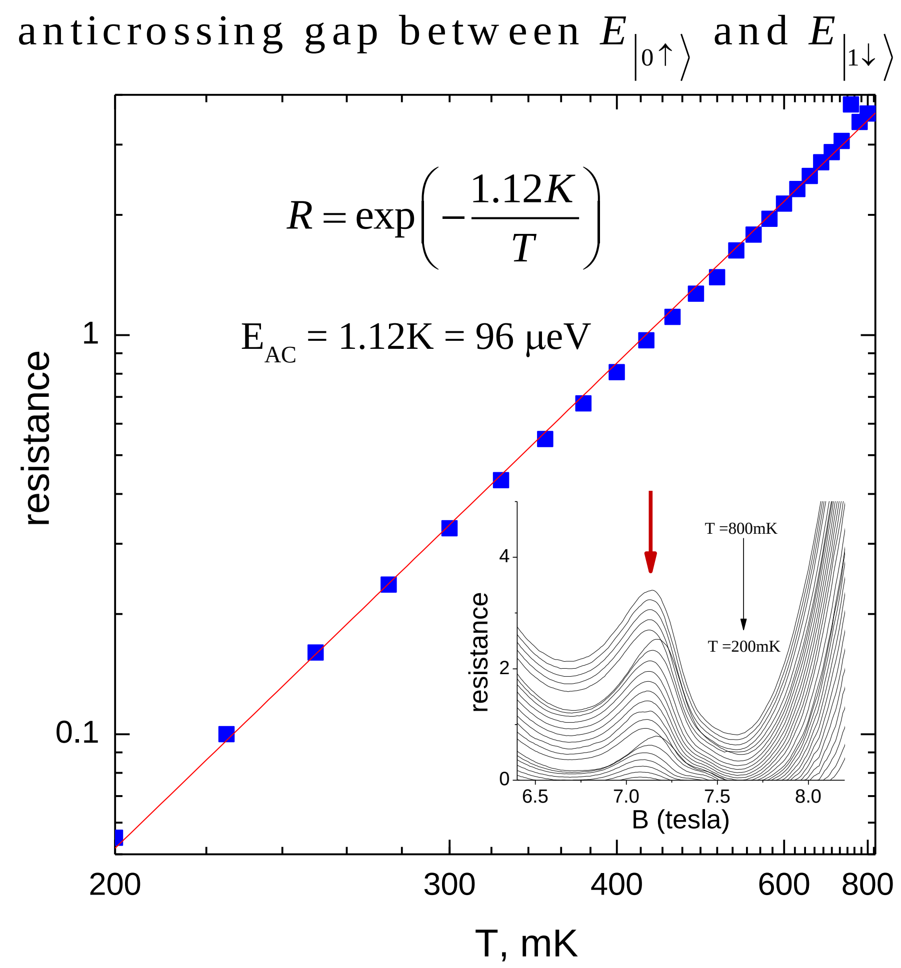


back gate dependence

Comparison of high and low Mn concentrations



Anticrossing between 1st and 2nd LLs



The role of SO interactions

$$H_{SO} = \gamma_D \boldsymbol{\sigma} \cdot \boldsymbol{\kappa} + \gamma_R (\boldsymbol{\sigma} \times \boldsymbol{k}) \cdot \boldsymbol{\mathcal{E}}$$

$$\kappa = (\{k_x, k_y^2 - k_z^2\}, \{k_y, k_z^2 - k_x^2\}, \{k_z, k_x^2 - k_y^2\})$$

$$\hat{a}^\dagger = \ell \frac{\hat{k}_x - i\hat{k}_y}{\sqrt{2}} \qquad \hat{a}^\dagger u_n = \sqrt{n+1}\, u_{n+1}$$

$$\hat{a} = \ell \frac{\hat{k}_x + i\hat{k}_y}{\sqrt{2}} \qquad \hat{a} u_n = \sqrt{n}\, u_{n-1}$$

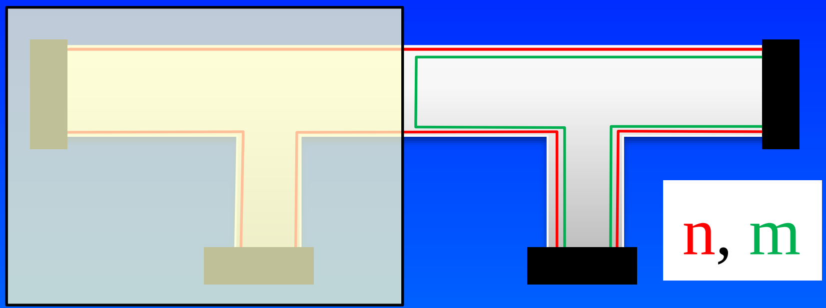
$$H_{SO} = \begin{pmatrix} \gamma_D k_z \left[(a^\dagger)^2 + a^2\right] & \frac{\gamma_D}{\sqrt{2}} \left[a a^\dagger a - \left(a^\dagger\right)^3 - 2k_z^2 a\right] + i\sqrt{2}\gamma_R \mathcal{E} a^\dagger \\ \frac{\gamma_D}{\sqrt{2}} \left[a^\dagger a a^\dagger - a^3 - 2k_z^2 a^\dagger\right] - i\sqrt{2}\gamma_R \mathcal{E} a & \gamma_D k_z \left[(a^\dagger)^2 + a^2\right] \end{pmatrix}$$

$$E_\pm = \frac{E^0_{1,\uparrow} + E^0_{0,\downarrow} \pm \sqrt{\left(E^0_{1,\uparrow} - E^0_{0,\downarrow}\right)^2 + 8\gamma_R^2 \mathcal{E}^2}}{2}$$

$$\delta = 2\sqrt{2}\gamma_R \mathcal{E} \approx 100 \mu eV$$

Only Rashba coupling contributes to N=1 and N+2 anticrossing

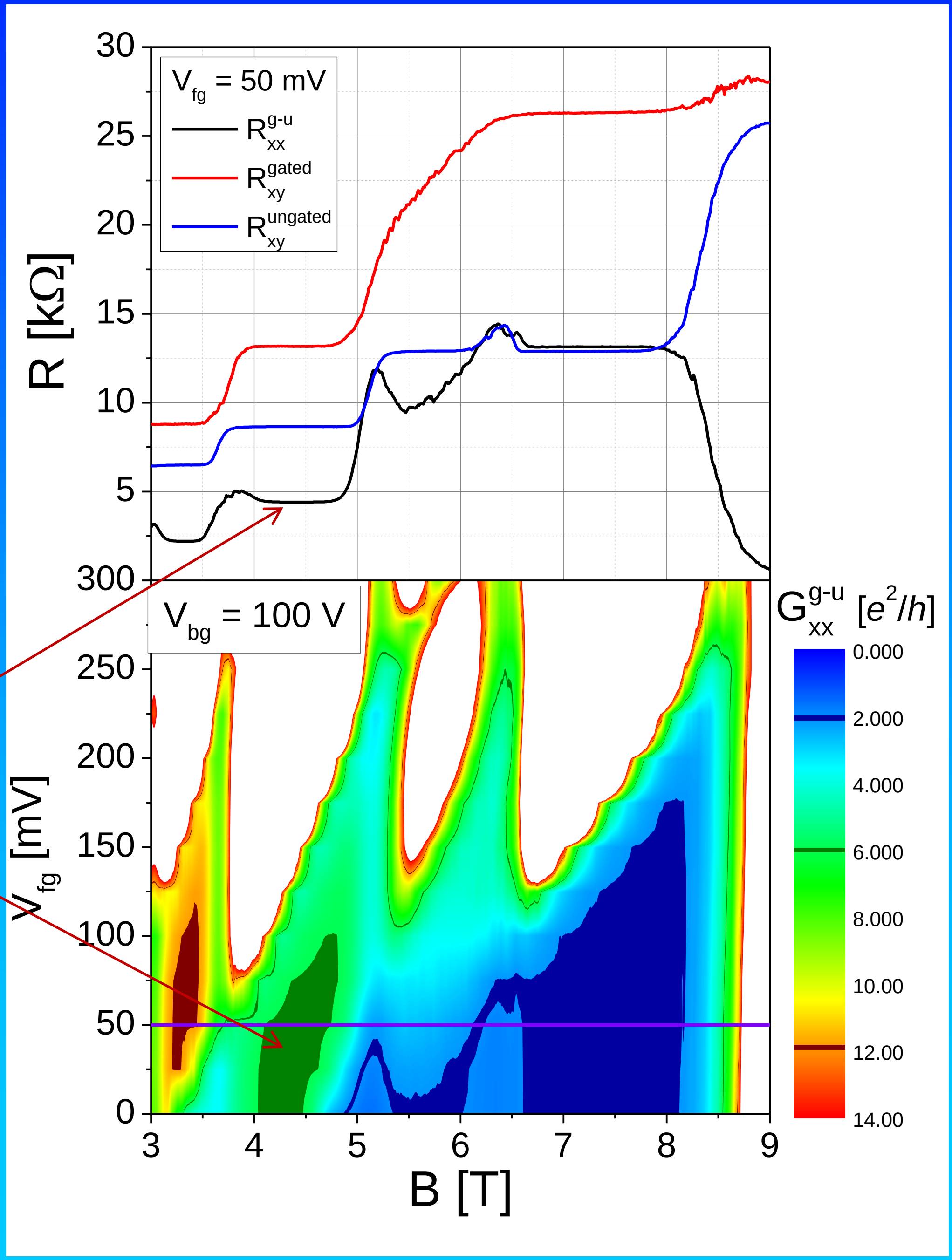
Transport across a gate



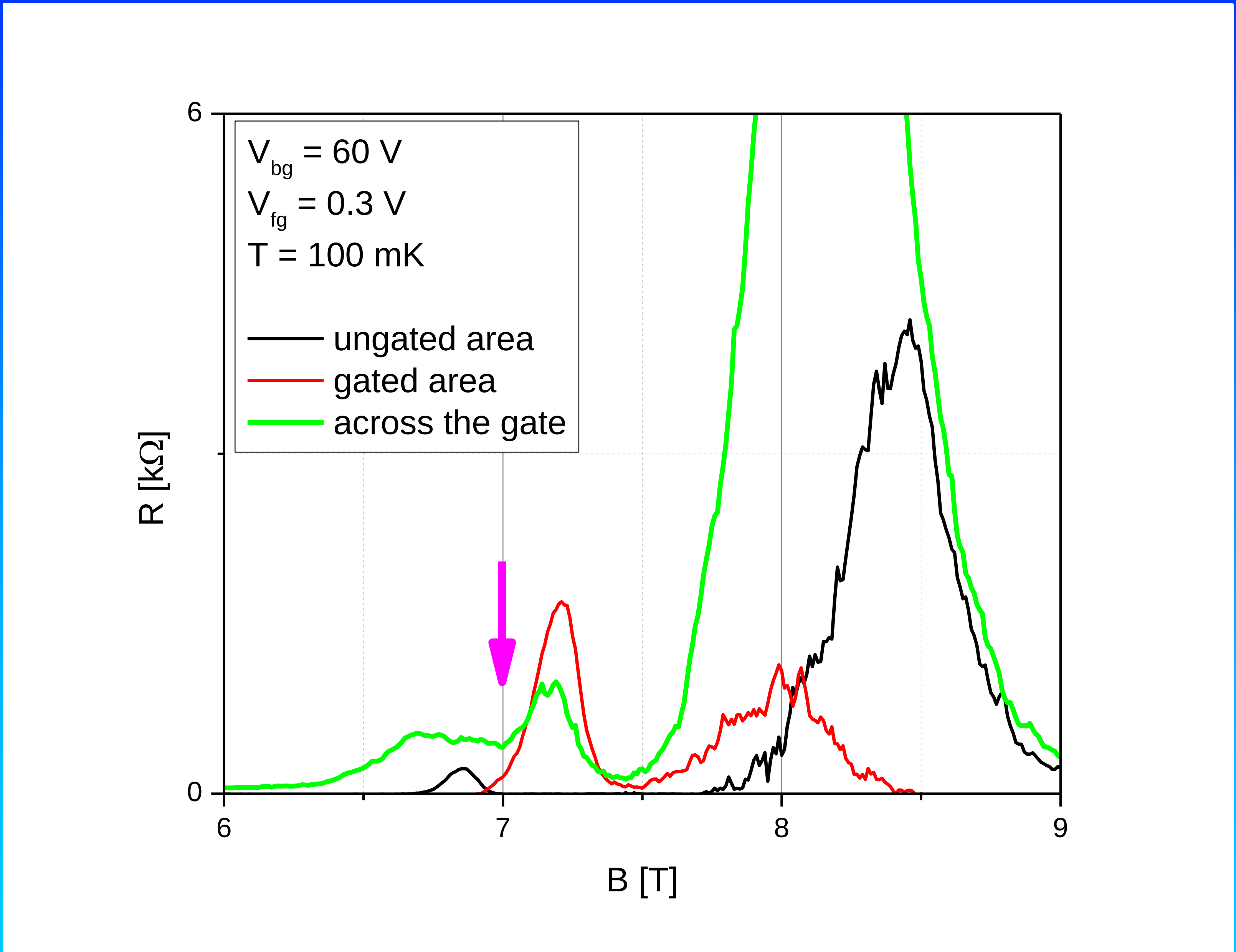
Landauer-Buttiker:

$$G = G_0 \frac{n(n+m)}{m}$$

$\nu = 2$ and $\nu = 3$
$(n = 2, m = 1)$
$G = 6G_0$



Transport across QHFm domain wall



people involved

Aleksander Kazakov, Purdue University

Tomasz Wojtowicz
Institute of Physics, Polish Academy of Sciences

Yuli Lyanda-Geller, Purdue University

V. Kolkovsky & Z. Adamus, Polish Academy of Science