Points quantiques et ferromagnétisme

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Theory: **A. Cottet**

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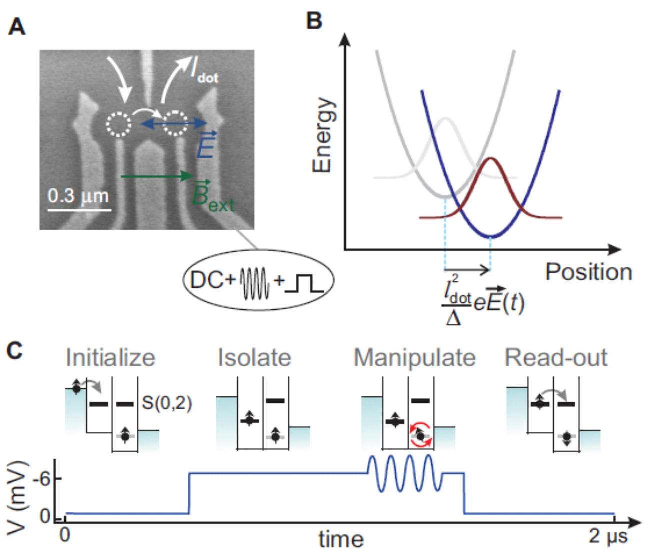
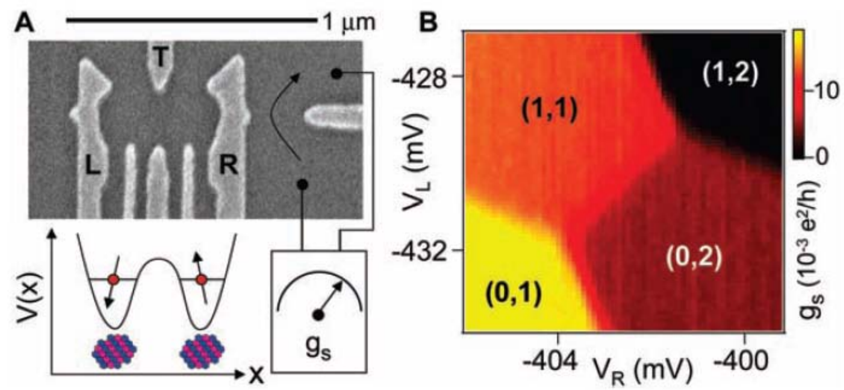
Electron spin manipulation in nanocircuits

K.C. Nowack et al. Science '07



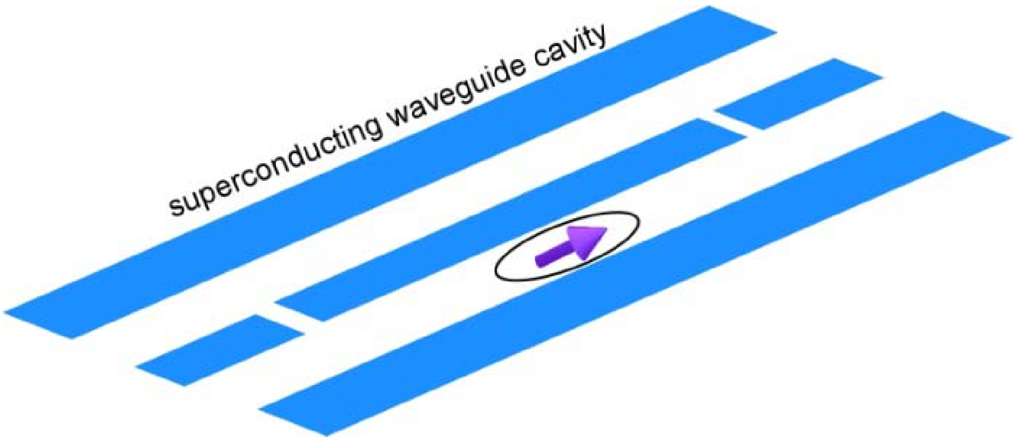
J. Petta et al. Science '05



- Spin manipulation in confined conductors
- Orthogonal (real or effective) magnetic fields needed to perform coherent manipulations
- Detection via transport measurement
- Use of specific material properties (spin-orbit, nuclear spins…)

Can one use ferromagnetic hybrid nanostructures to implement spin manipulation/detection setups?

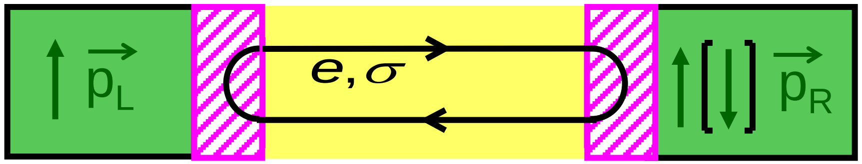
Circuit Quantum Electrodynamics with electronic spins confined in nanoconductors?



- Inclusion of electronic spins in superconducting coplanar waveguide cavities (similar to superconducting Qbits)
- Detection via dispersive shift of cavity resonance (not transport)
- Manipulation and coupling using cavity QED techniques

Use of intrinsic nanoconductor properties possible (spin-orbit, hyperfine interaction)
But ferromagnetic contacts can be used to "engineer" spin/photon coupling

Phase coherent spin dependent phenomena in nanoscale conductors



Resonance condition for θ=0 [θ= π] :

$$2\delta_0 + \varphi^{WW}_{\sigma,L} + \varphi^{WW}_{[-]\sigma,R} = 2\pi j,\ j \in Z$$

$$+\ \delta_0 = k_e L$$

Directly coupled to local electric field

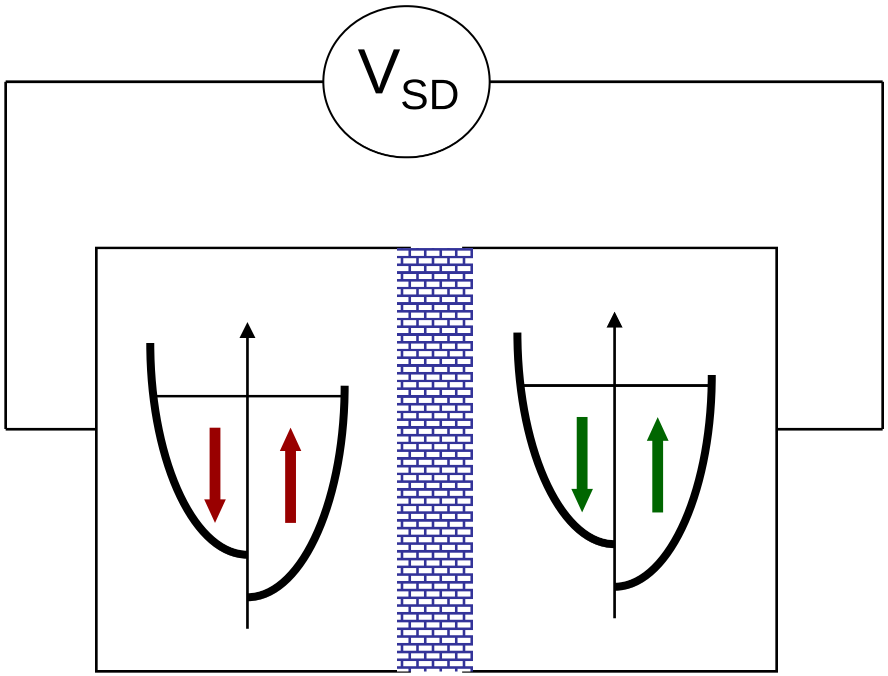
- Spin dependent quantum interference expected + electronic phase directly coupled to local electric field

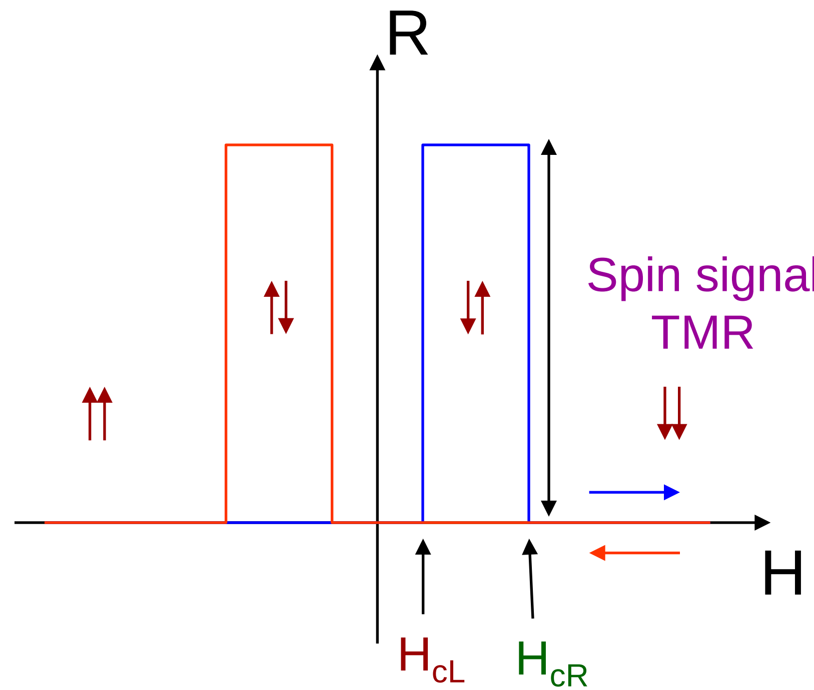
OUTLINE

1. Direct (first) experimental demonstration of orbitally phase coherent spintronics (multiterminal spin transport experiment)

2. Use of this coupling for spin quantum bit with ferromagnetic contacts for circuit QED

A magnetic tunnel junction…





H_{cL} < H_{cR}

Jullière's model

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

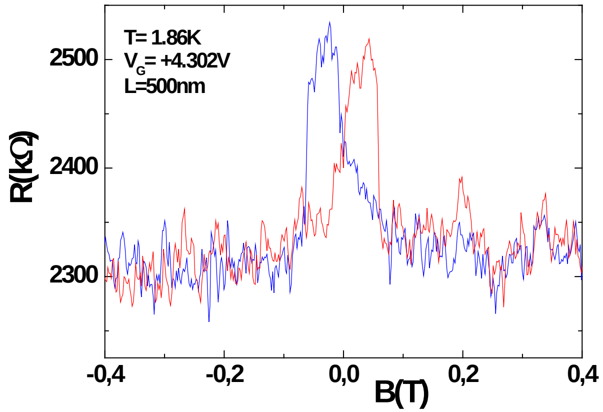
$$G_{AP} \propto |T|^2 2N_\uparrow N_\downarrow$$

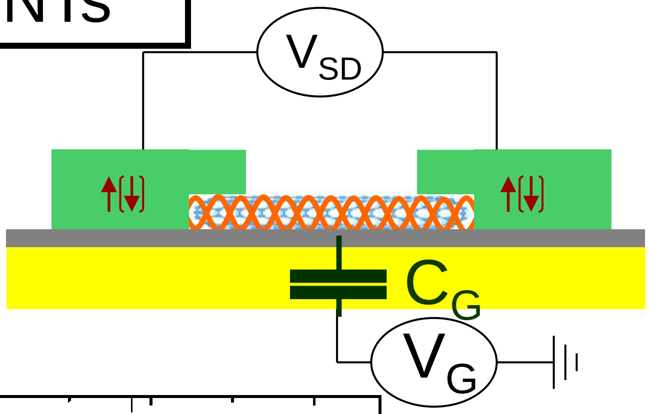
$$G_P \propto |T|^2 (N_\uparrow{}^2 + N_\downarrow{}^2)$$

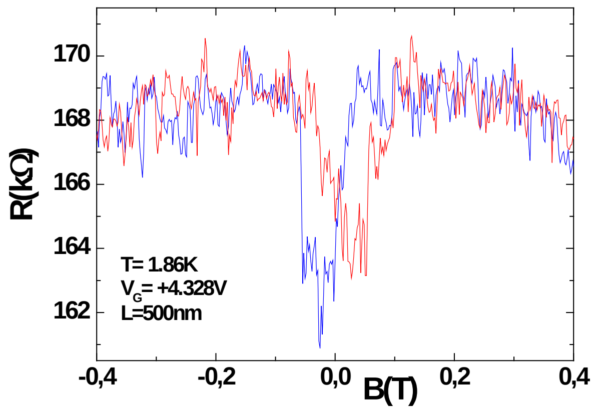
$$TMR = \frac{R_{AP} - R_P}{R_P} = \frac{2P^2}{1 - P^2}$$

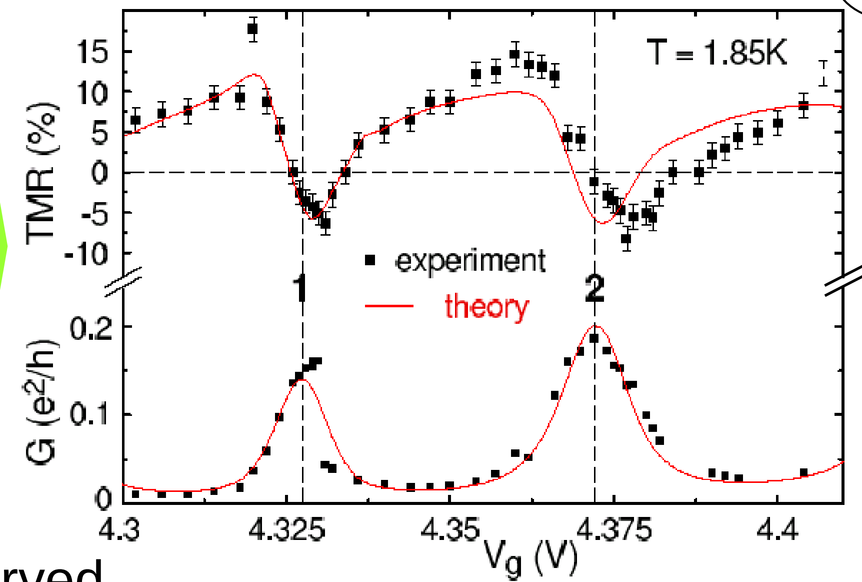
Phase of carriers completely ignored

Spin FET behavior in SWNTs









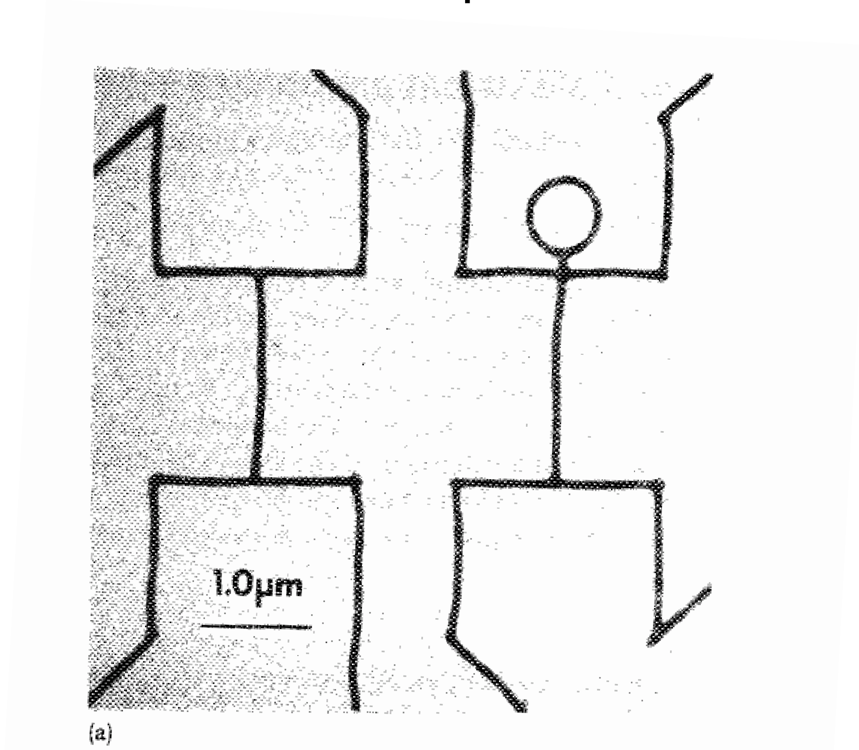
- Both signs of TMR can be observed.
- Oscillations of TMR as a function of gate voltage.
- Spin dependent resonant tunneling mechanism (quantitative theory A. Cottet et al.)

Phase-coherent phenomena particularly visible in multi-terminal devices (non-local effects)

S. Sahoo, TK et al., Nature Phys., **1,** 99 (2005), H.T. Man et al., Phys. Rev. B R 73, 241401 (2006), A. Cottet, TK et al. Semicond. Sci. Tech. 21, S78 (2006), A. Cottet and M.-S. Choi PRB '06

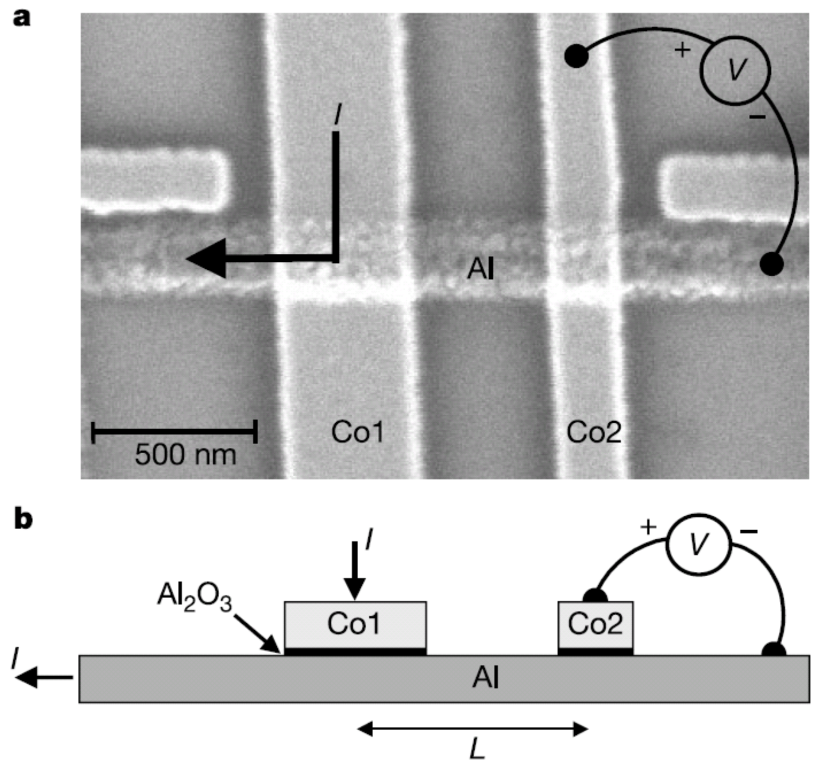
Quantum coherent transport vs spintronics

« Theorist's blob » experiment



C.P. Umbach et al., APL, **50,** 1289 (1987)

« Non-local » spin injection



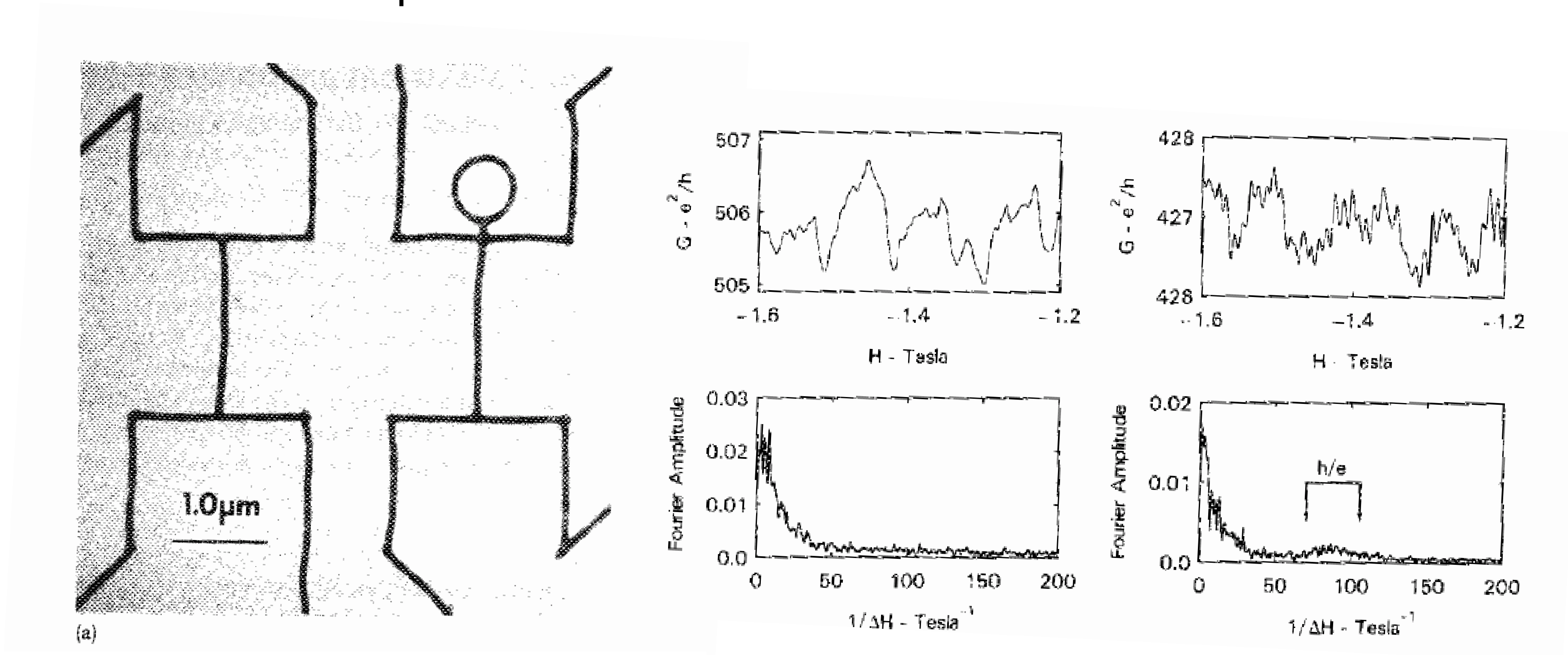
F.D. Jedema et al., Nature, **416,** 713 (2002)
See also M. Johnson and R. H. Silsbee, PRL 55, 1790 (1985)

- Coherent non-local effects in disordered mesoscopic devices and non-local spin dependent voltages in disordered incoherent conductors

→ Nanotubes ideally suited for the study of the interplay of orbital coherence and spin transport

Quantum coherent transport vs spintronics

« Theorist's blob » experiment

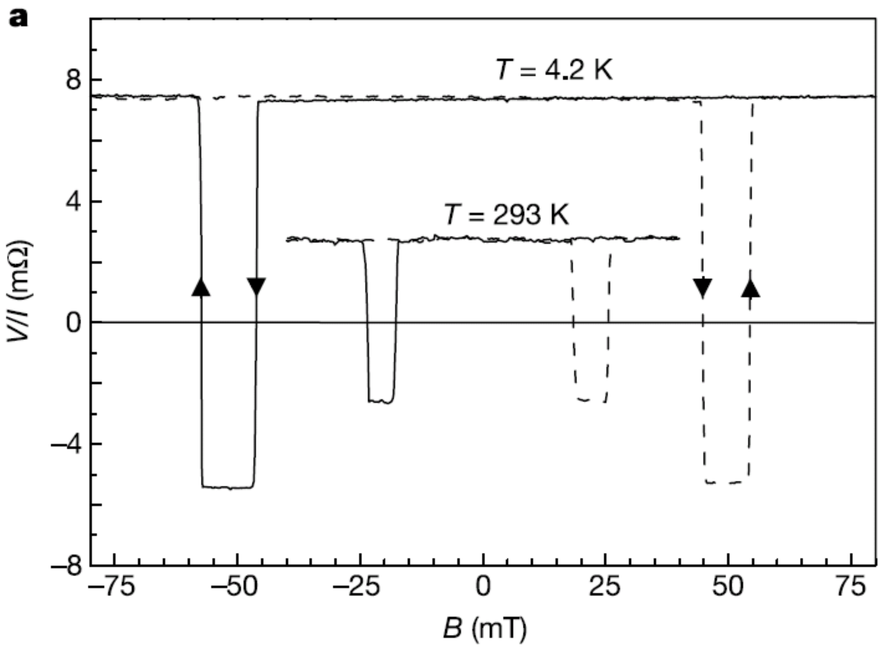


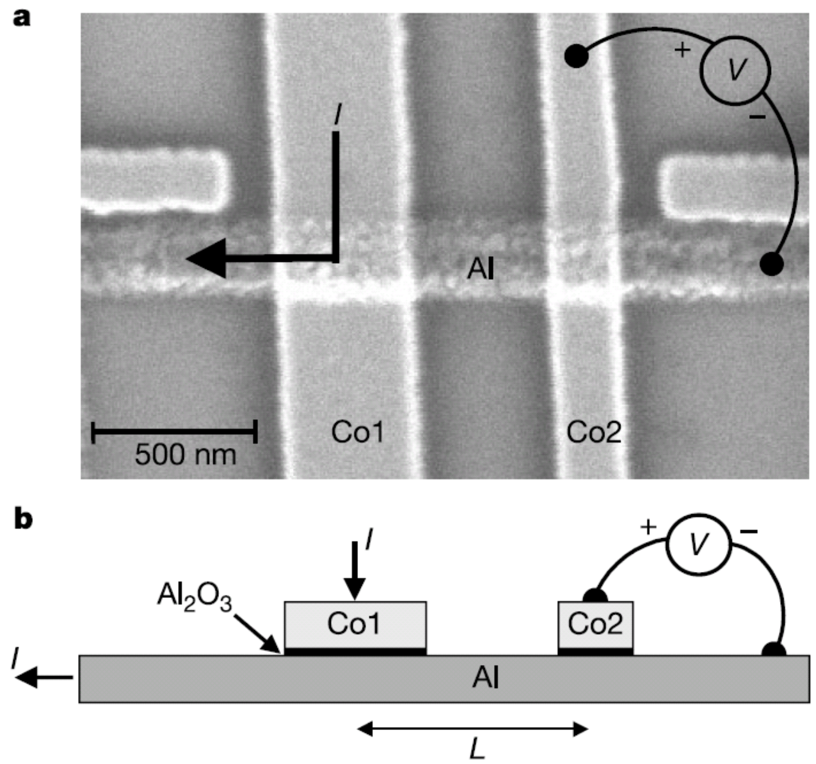
C.P. Umbach et al., APL, **50,** 1289 (1987)

- h/e modulations due to Aharonov-Bohm effect in the outer loop (not in the classical path)
- Small effect here (1 e^2/h over 500 e^2/h)

Quantum coherent transport vs spintronics

« Non-local » spin injection



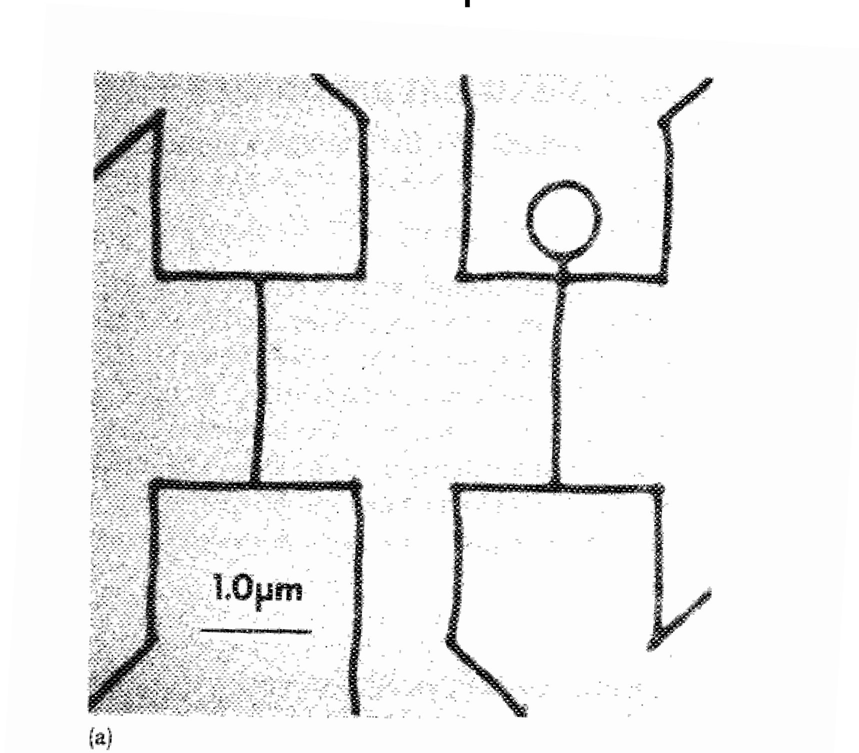


F.D. Jedema et al., Nature, **416,** 713 (2002)
See also M. Johnson and R. H. Silsbee, PRL 55, 1790 (1985)

- Hysteretic switching of non-local voltage as a function of magnetic field

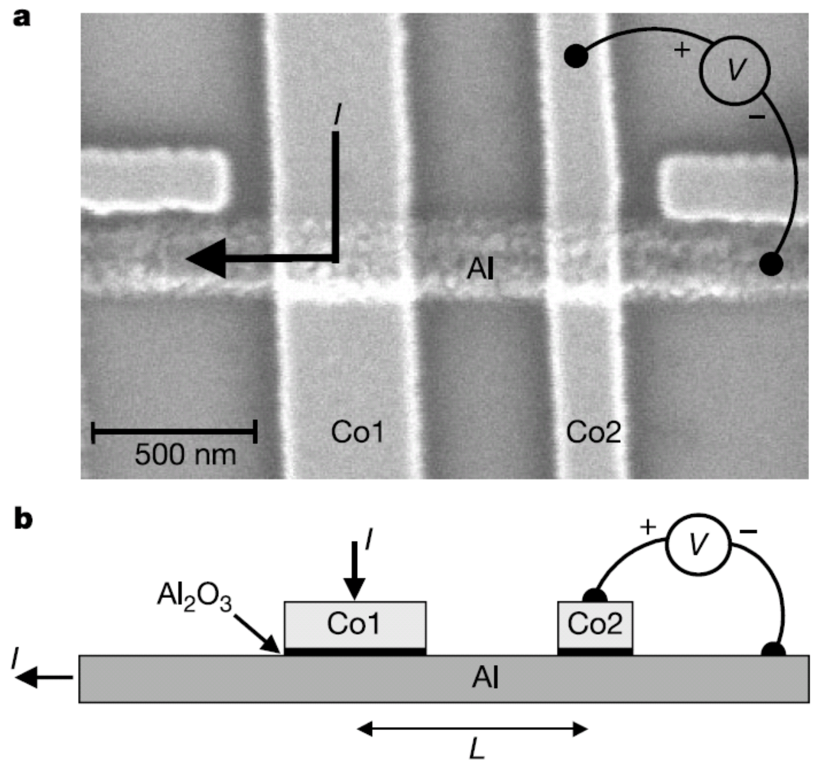
Quantum coherent transport vs spintronics

« Theorist's blob » experiment



C.P. Umbach et al., APL, **50,** 1289 (1987)

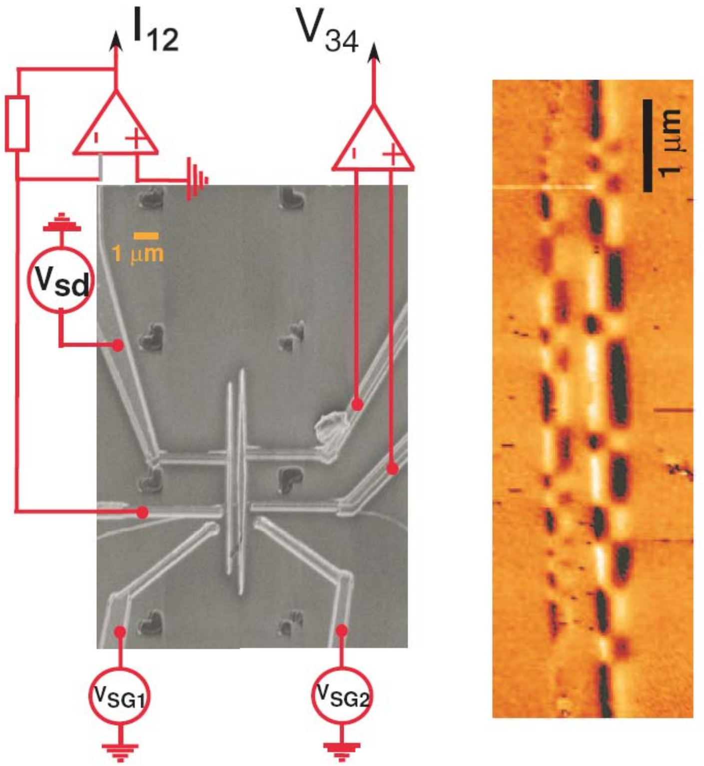
« Non-local » spin injection



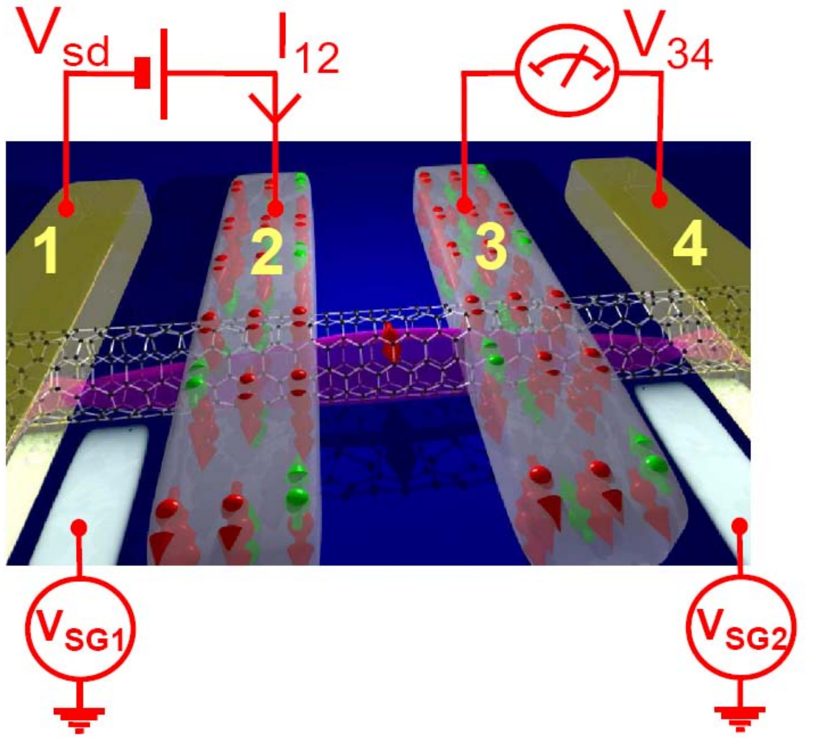
F.D. Jedema et al., Nature, **416,** 713 (2002)
See also M. Johnson and R. H. Silsbee, PRL 55, 1790 (1985)

- Few channel regime in NTs make quantum effect a priori prominent.

Device geometry



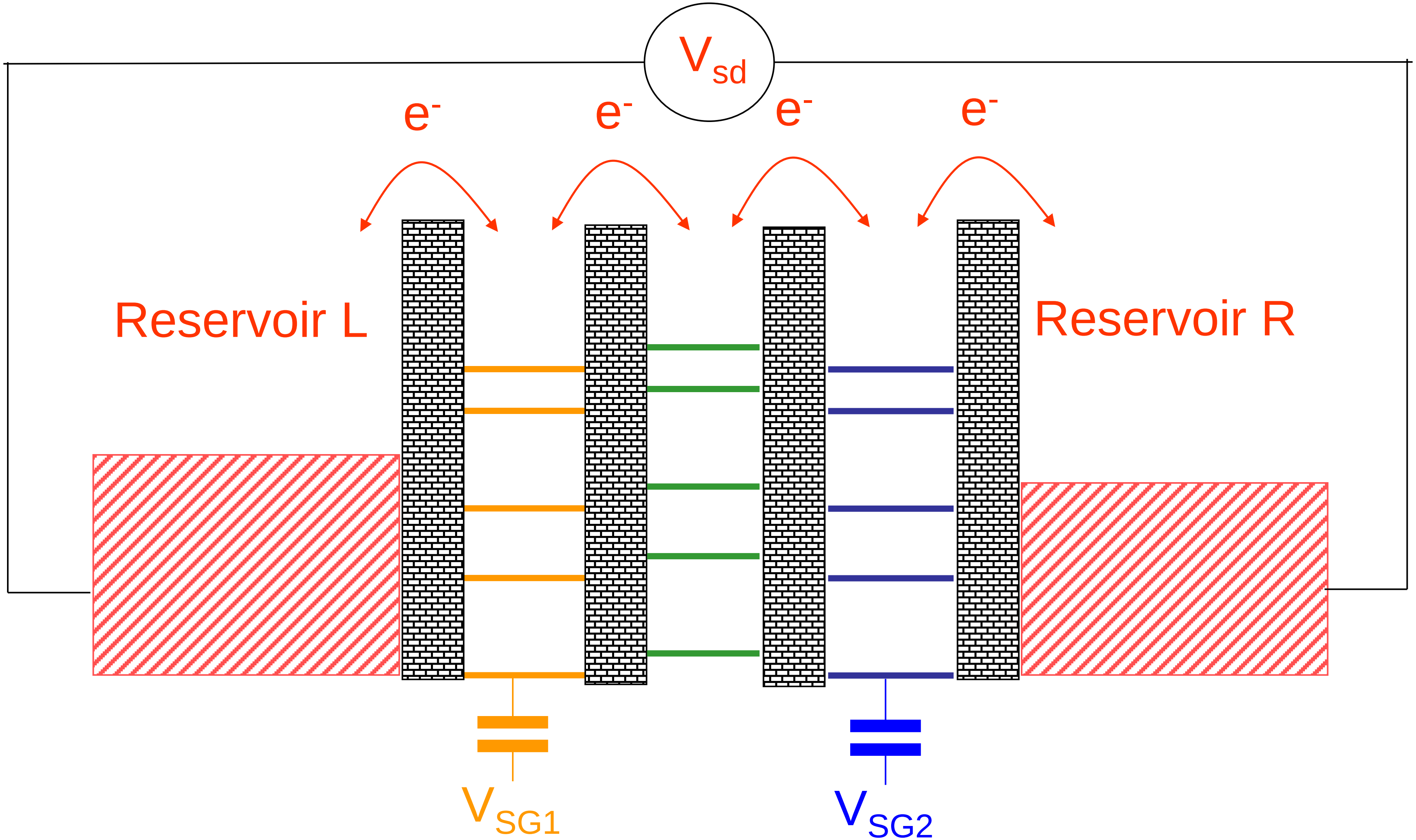
MFM, S. Rohart, A. Thiaville (LPS,Orsay)



- Transverse anisotropy for magnetization of NiPd stripes
- Non-local geometry for charge and spin transport
- Side gates in addition to back gate to control locally the sections of NT

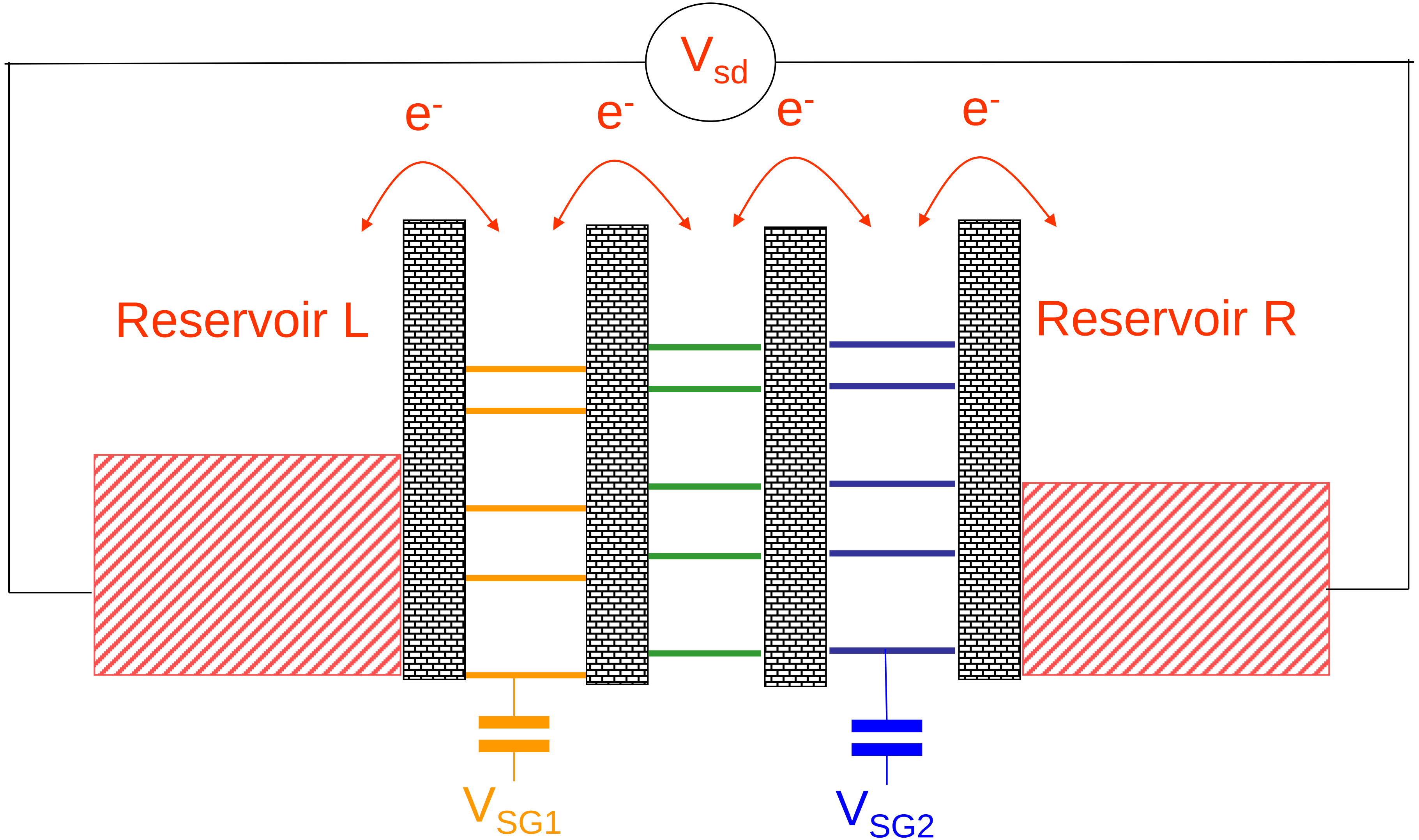
C. Feuillet-Palma et al. PRB **81**, 115414 (2010).

Nanotubes based multi quantum dots



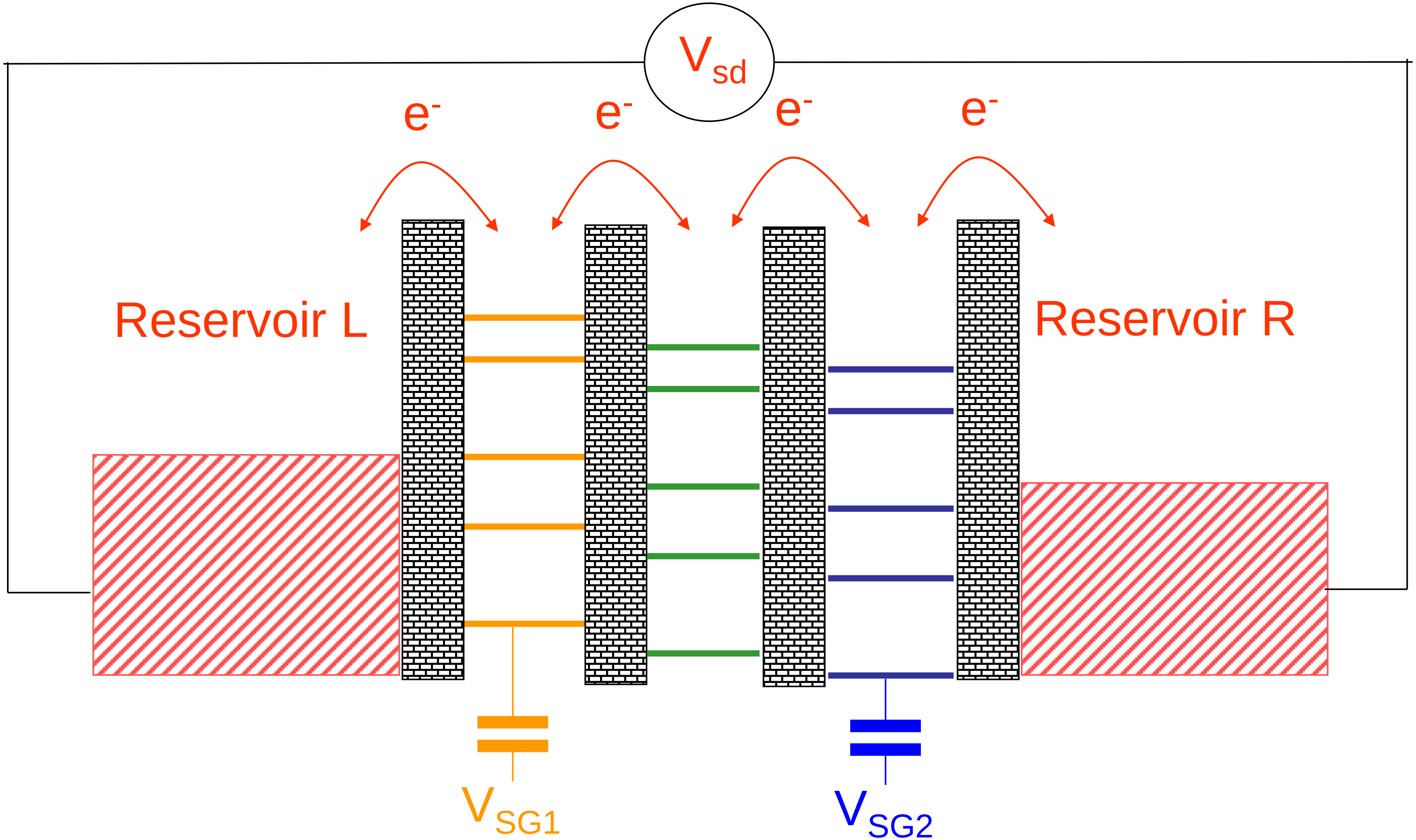
- $V_{SG1}=0$ and $V_{SG2}=0$

Nanotubes based multi quantum dots



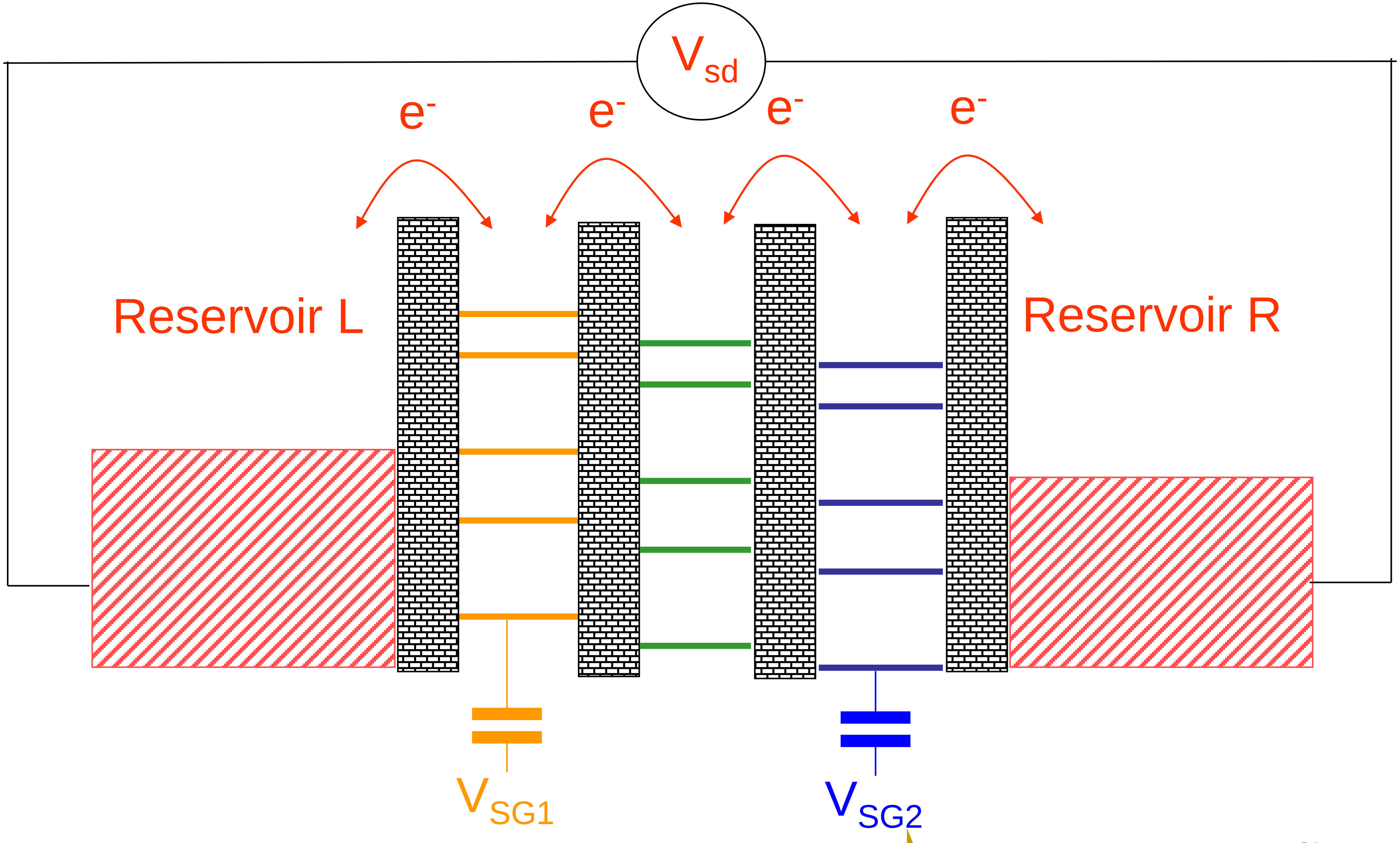
- $V_{SG1}=0$ and V_{SG2} non zero

Nanotubes based multi quantum dots



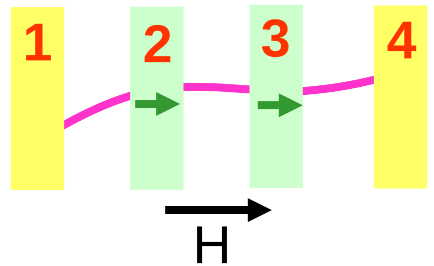
- V_{SG1} non zero and $V_{SG2}=0$

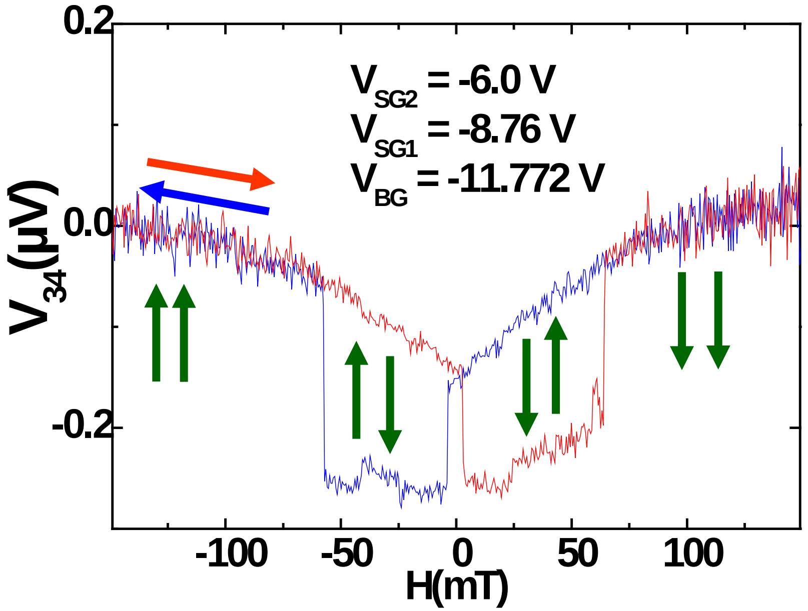
Nanotubes based multi quantum dots

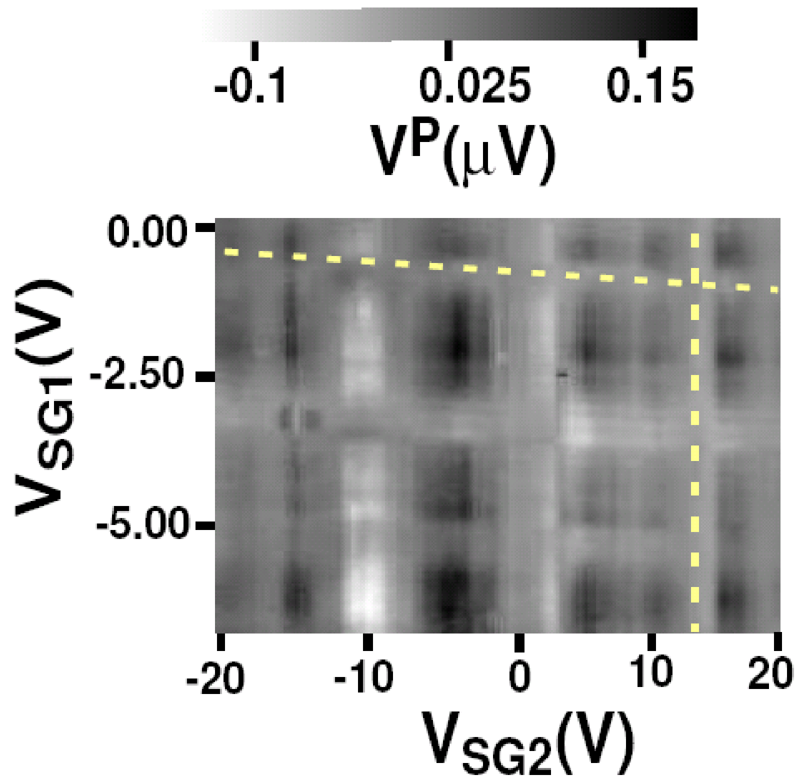


- V_{SG1} non zero and V_{SG2} non zero ⇒ Resonances on lignes $V_{SG1} + \alpha\, V_{SG2} = cste$

Non-local voltage signal







- Tartan pattern for non-local voltage as a function of side gates

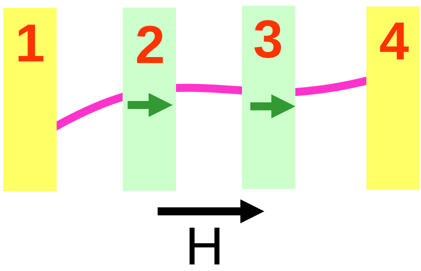
→ Leads to oscillations of non-local voltage in P config as a function of back gate

see also G. Gunnarsson, J. Trbovic, C. Schönenberger PRB 77, 201405(R) (2008)

- Characteristic hysteretic switching of non-local voltage

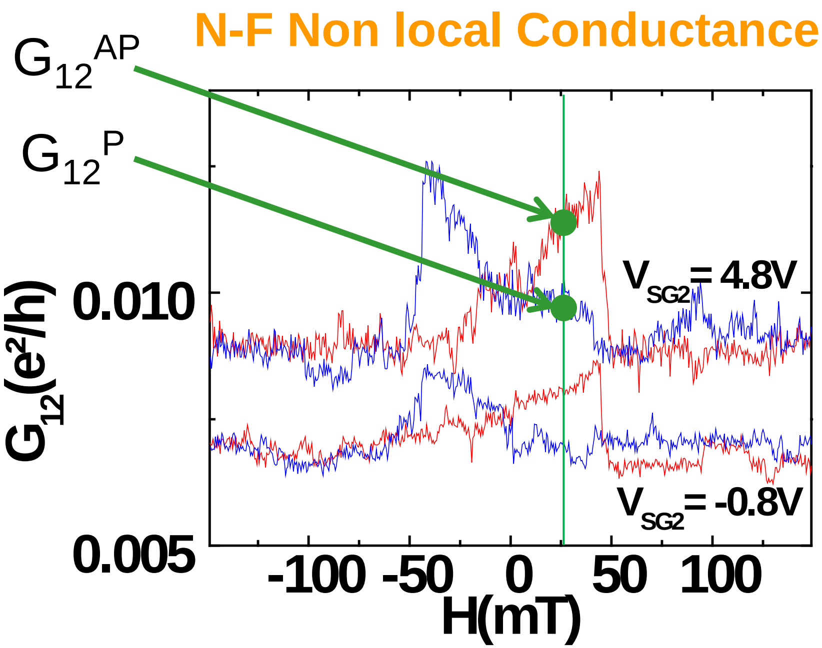
➡ A priori interplay between non local spin transport and orbital coherence

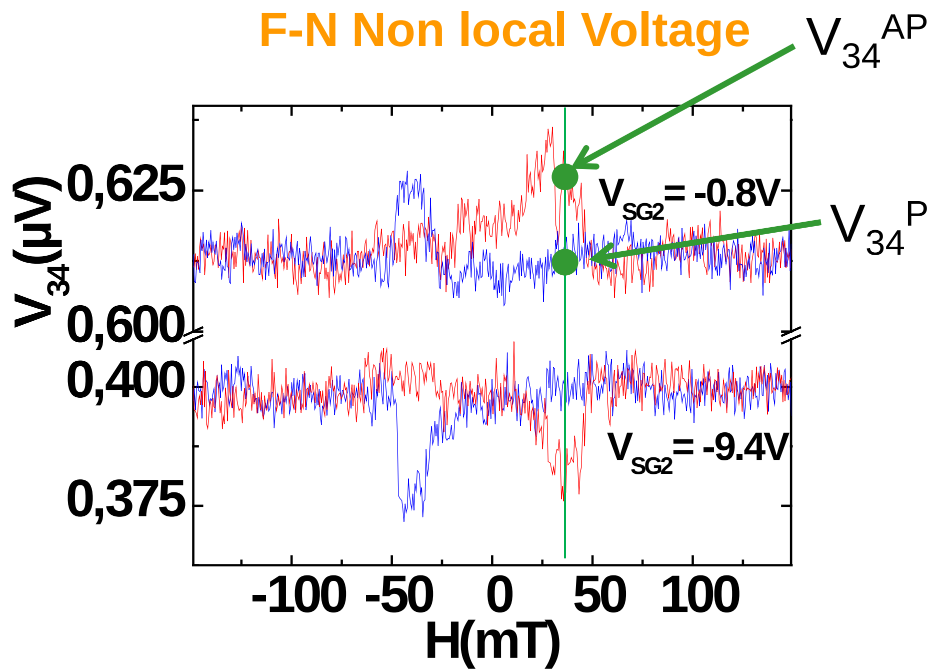
Anomalous hysteresis in the current



$MG=1-G_{12}^{AP}/G_{12}^{P}$

$MV=V_{34}^{P}-V_{34}^{AP}$

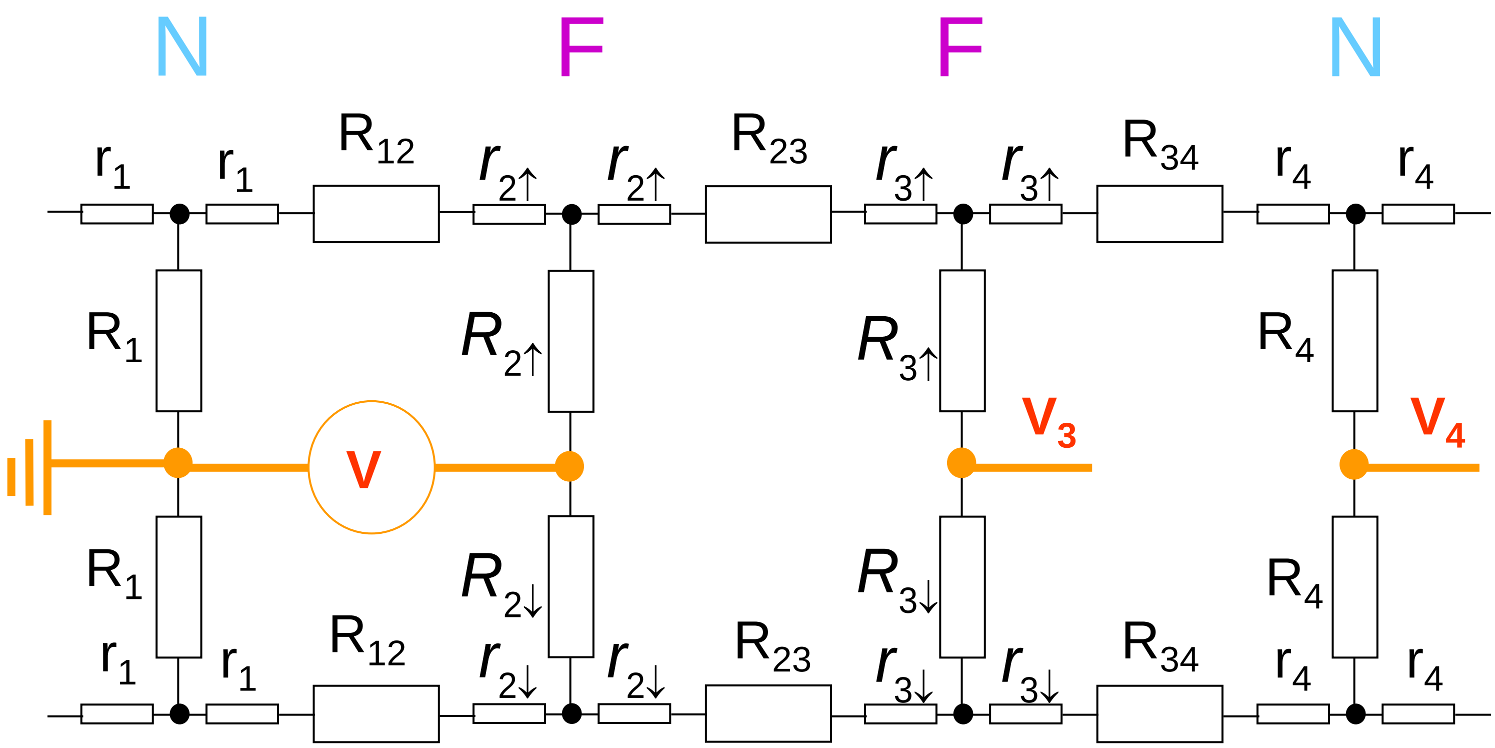




- MG controlled by remote side gate
- Sign change in MV specific to coherent case

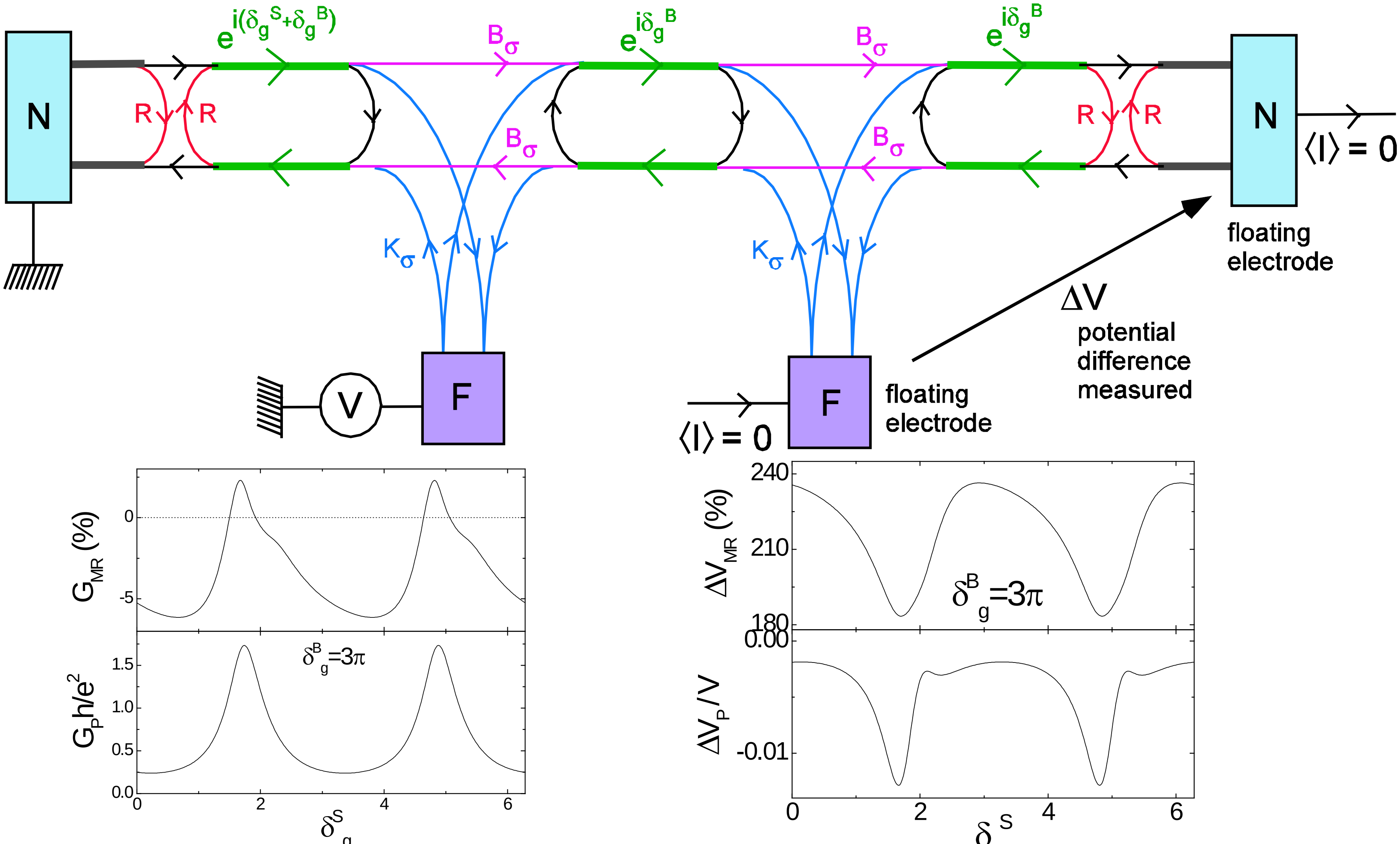
→ Non local spin transitor action in G and V

Resistor network model ?



- Model conventionally used in incoherent spin transport
- Non-local spin signal obtained because spin asymmetry
- N-F current independent of magnetization relative orientations (also found In more sophisticated models e.g. Takahashi & Maekawa).

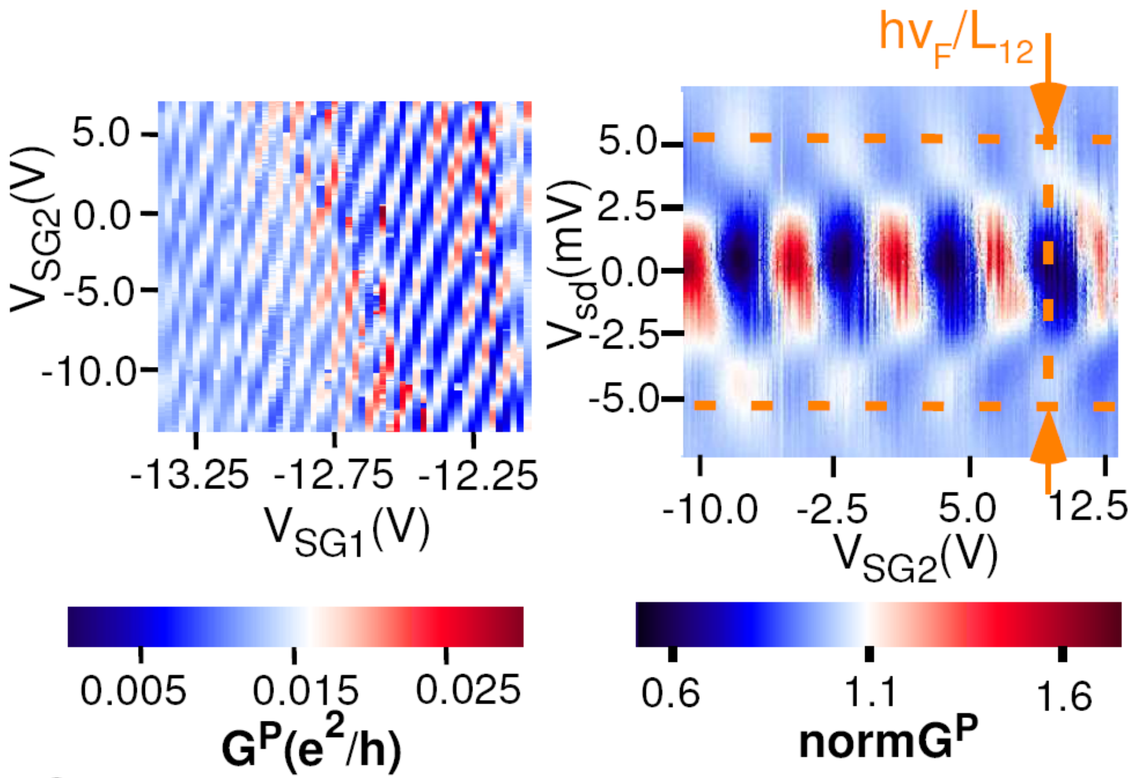
Multi-terminal scattering appoach



- The scattering approach provides an explanation for both non local signals in V and G.
- Difficult to obtain N-F current magnetic configuration dependent in the diffusive Incoherent regime

A. Cottet, C. Feuillet-Palma and TK Phys. Rev. B 79, 125422 (2009)

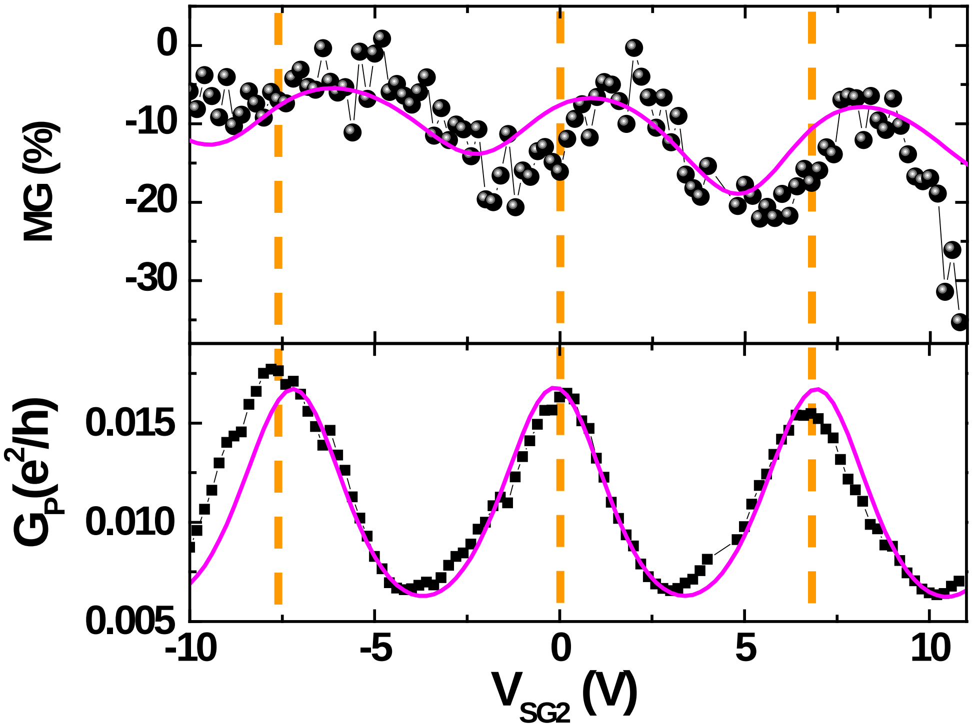
Spectroscopy of conductance



- Interference fringes observed in the conductance
- Multiple Fabry-Perot electronic interferometers physics
- Energy scale correspond to one NT section here

C. Feuillet-Palma et al. PRB **81**, 115414 (2010).

Magnetic configuration dependent phase shift



- Modulations of G_P due to Fabry-Perot physics
- Gate modulations of MG phase shifted
- Quantitative agreement with scattering theory

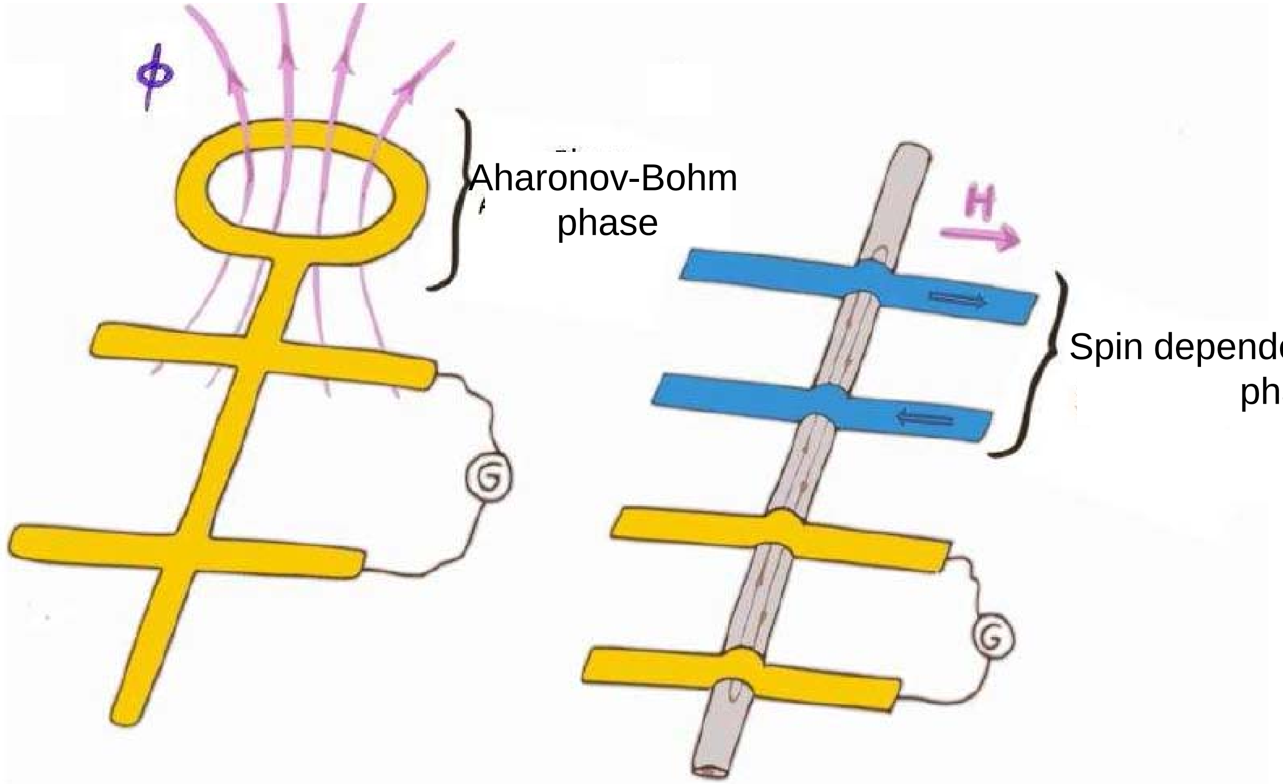
➡ The orbital phase depends on magnetic configuration !

➡ Orbitally coherent spintronics

C. Feuillet-Palma et al. PRB **81**, 115414 (2010).

Theory : A. Cottet, C. Feuillet-Palma and TK Phys. Rev. B 79, 125422 (2009)

The theorist's blob experiment for spintronics

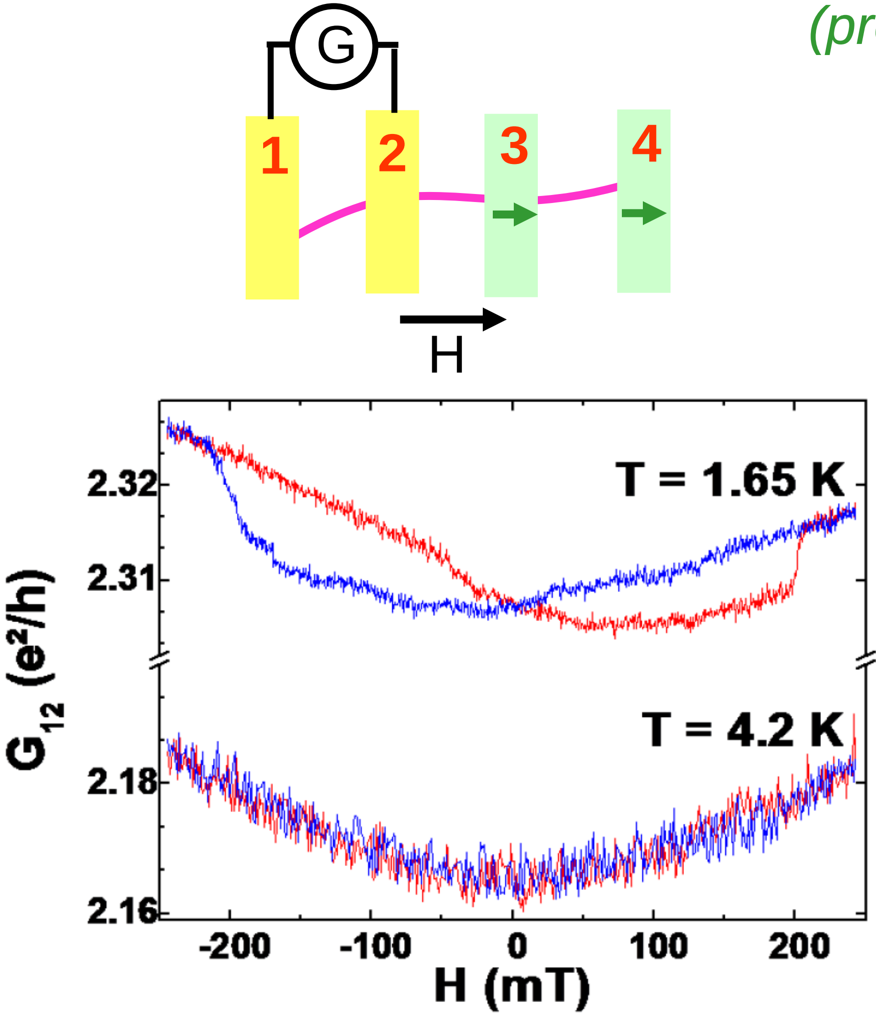


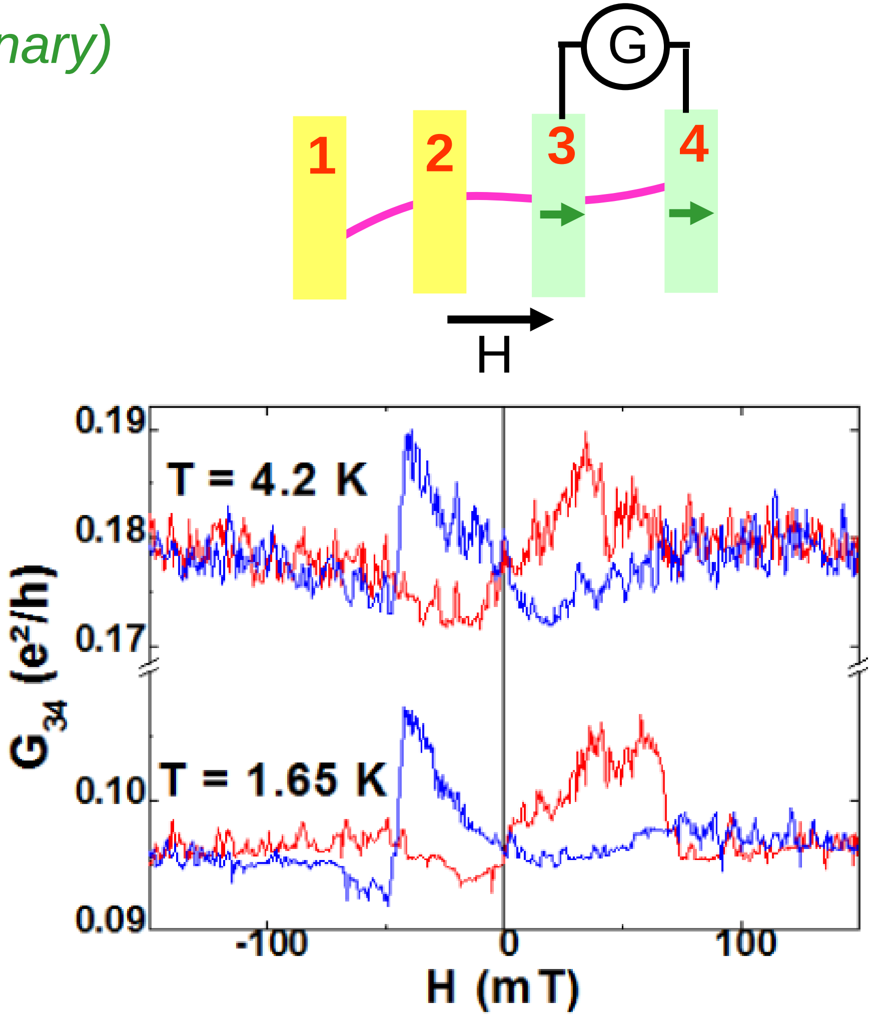
- No classical analog of such a spintronic device (no classical signal)
- Exact analog of Aharonov-Bohm loop outside classical path

→ We should observe a « spin signal » between the two N's

The theorist's blob experiment for spintronics

(preliminary)



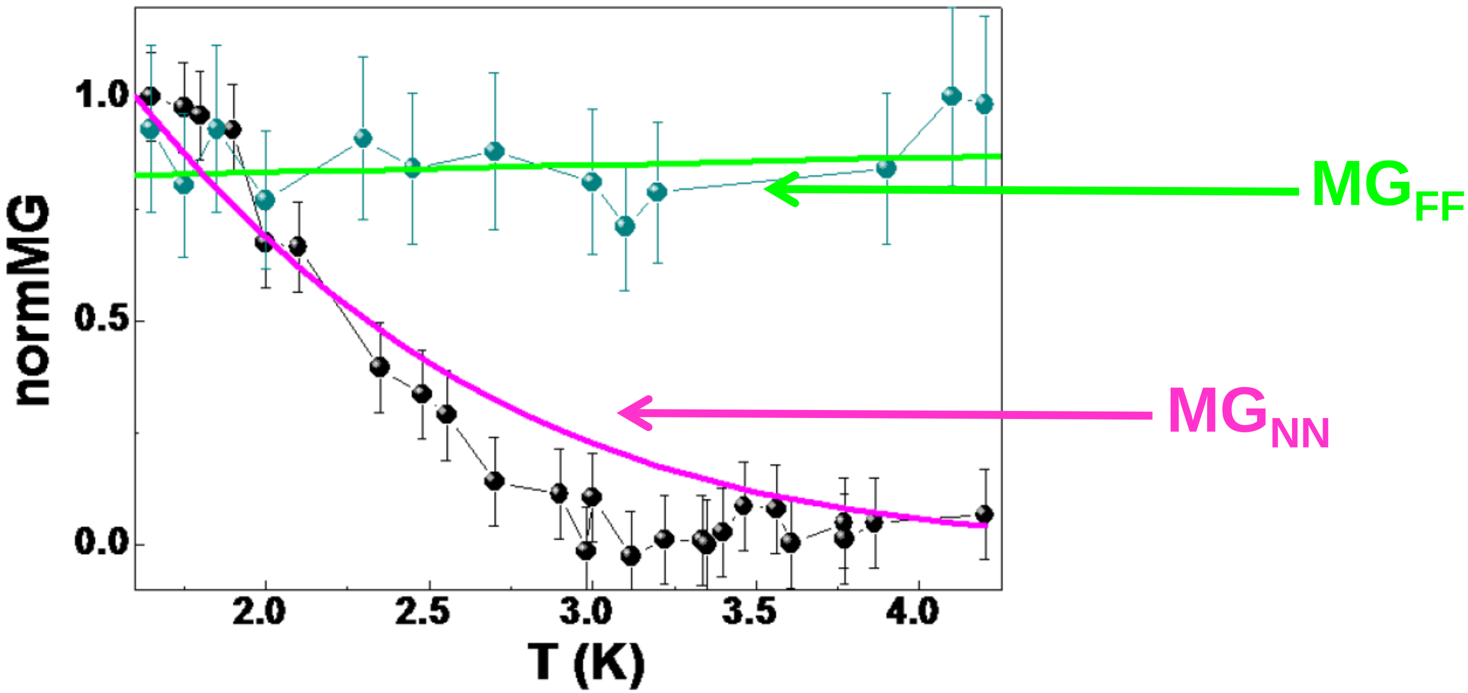


- No signal at 4.2 K for G12 but signal at 1.65K !
- Signal both at 4.2K and 1.65K (same amplitude) between the two F's

C. Feuillet-Palma et al. in preparation

Temperature dependence of spin signal

(preliminary)



- MR between the two ferromagnets essentially constant
- Sharp decrease of MR between normal electrodes
- Accounted by theory with no adjustment parameters essentially

C. Feuillet-Palma et al. in preparation

Conclusion part I

- Observation of local gate controlled “non local” magnetoresistance in mutli-terminal SWNT devices

- Multi-terminal devices are multi-electronic interferometers

- Anomalous magnetoresistance between a N contact and a F contact in conductance due to delocalization of electronic waves

- Behaviour qualitatively and quantitatively reproduced within the scattering approach

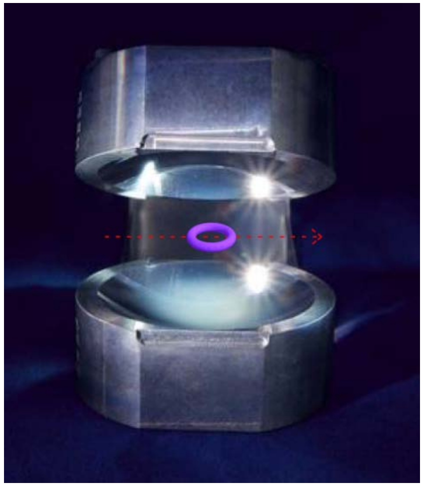
⇒ Observation of spin signals with no classical analog

⇒ Orbitally phase coherent spintronics

⇒ A new way to couple the orbital and spin degree of freedom

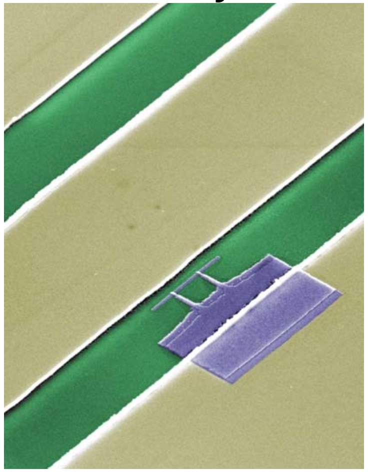
Cavity Quantum Electrodynamics: from optical systems to superconducting chips

Rydberg atom coupled to a superconducting mirror cavity



M. Brune et al., Phys. Rev. Lett. 76, 1800 (1996).

Superconducting quantum bit coupled to a superconducting coplanar waveguide cavity



A. Wallraff et, Nature 431, 162 (2004).

Jaynes-Cummings Hamiltonian

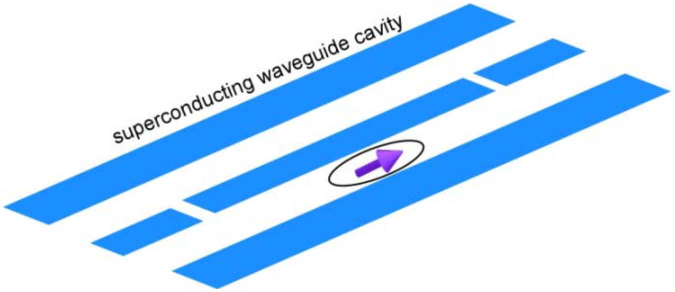
$$\hat{H}_{eff} = -h\nu_{01}\hat{S}_z/2 + \hbar\omega_r a^\dagger a + \hbar g(a^\dagger \hat{S}_- + a\hat{S}_+)$$

$\hat{S}_z, \hat{S}_+, \hat{S}_+$: two-level (true or artificial) atom

$a, a^\dagger$: cavity photons

g: atom/photon coupling $>$ decoherence time of atom and photons

Circuit Quantum Electrodynamics with spins confined in nanoconductors?



Basic requirements:

- Strong spin/photon coupling g
- Local spin manipulation

There exists schemes based on spin-orbit coupling or hyperfine interaction

Nowack et al. (2007), Trif et al. PRL 101, 217201 (2008), Burkard et al. (2006), etc…

Our motivation:

-A scheme free from external magnetic fields

-A strongly tunable g

$$\Delta_{1(2)} = \hbar\omega_{01}^{1(2)} - \hbar\omega_r$$

$$J = \frac{g_1 g_2}{2}\left(\frac{1}{\Delta_1} + \frac{1}{\Delta_2}\right)$$

First observation with superconducting qubits: J. Majer et al., Nature 449, 443 (2007)

Effective Zeeman fields in nanoconductors with ferromagnetic contacts

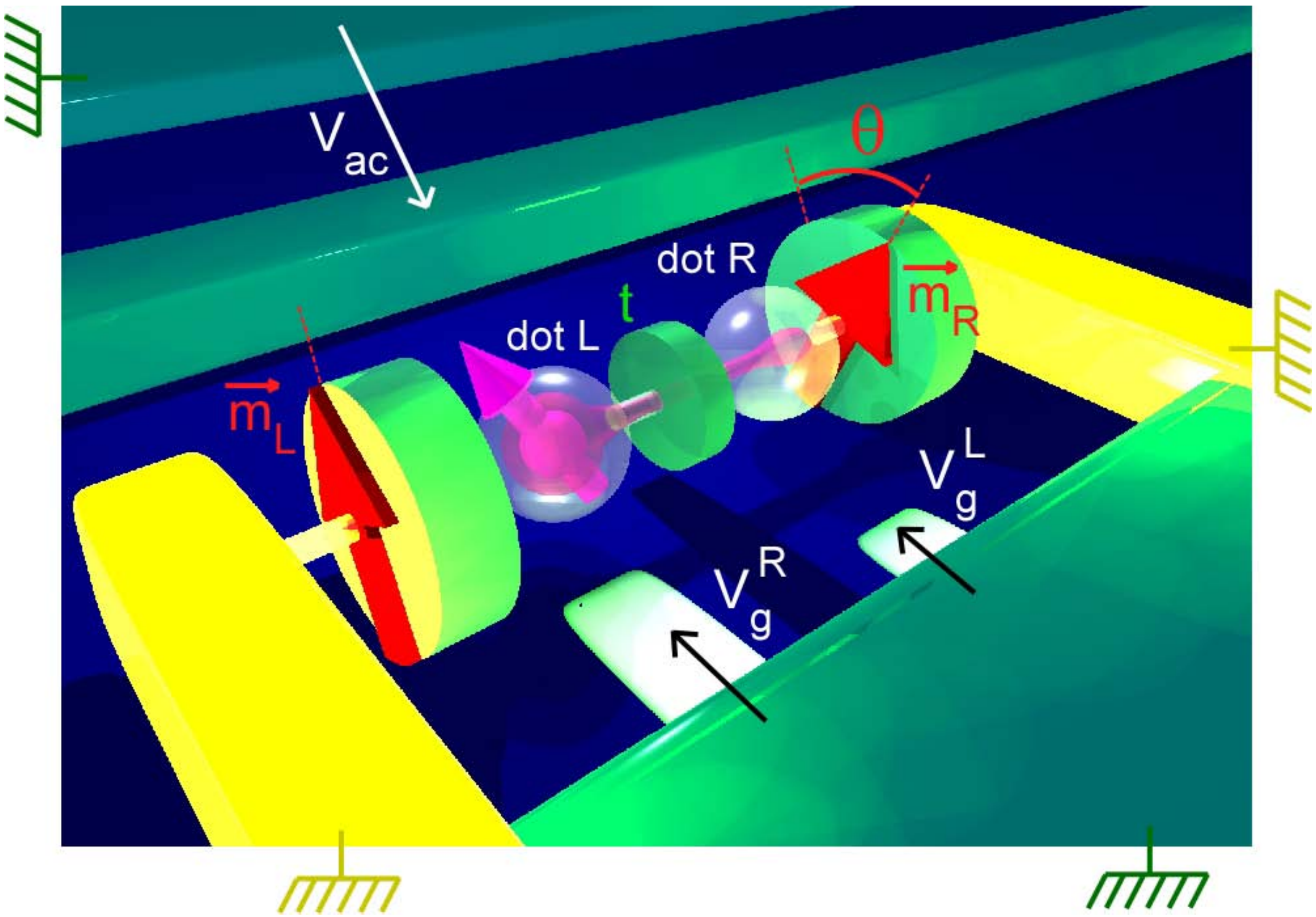
A very general effect seen in:

- Thin superconducting layers *Tedrow et al., Phys. Rev. Lett. 56, 1746 (1986)*
- InAs quantum dots and nanowires *Hamaya et al, APL 91, 022107 (2007)*
  L. Hofstetter et al., arXiv:0910.3237
- Single Wall Carbon nanotubes *Sahoo et al, Nature Phys. 1, 99 (2005).*
  Hauptmann et al, Nature Phys. 4, 373 (2008).

Here: quantum dots contacted to thick ferromagnetic insulators (FIs)

⇨ hybridization of the dot orbitals with the first atomic layers of the FIs

General principle of the ferromagnetic spin qubit

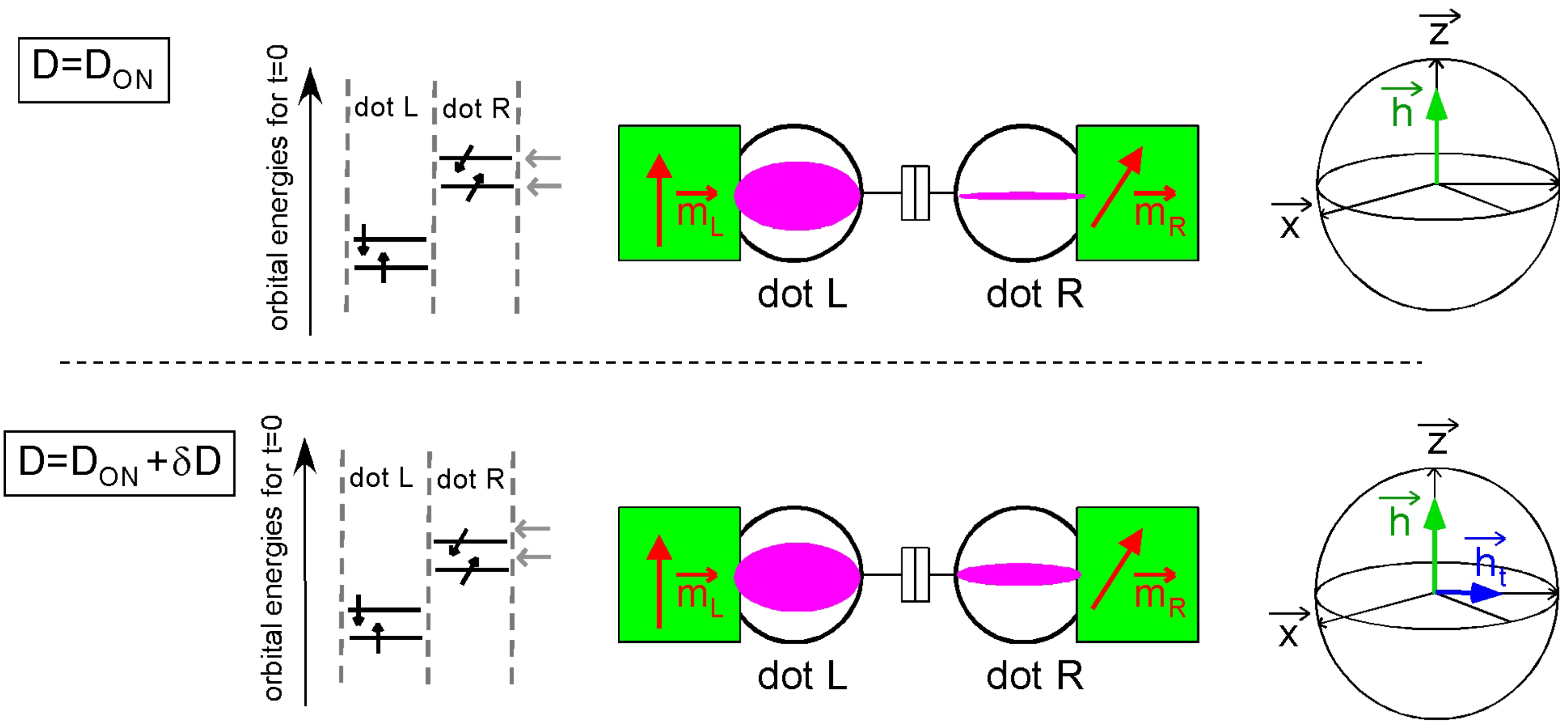


2δ: effective spin splittings in dot $L(R)$

A. Cottet and TK, arXiv:1005.1901

Spin/photon coupling

(1) $D = D_{ON} + \delta D \text{ and } \theta \neq 0[\pi] \implies \langle \mathbf{0} | \; \hat{H}_{double\ dot} \; | \mathbf{1} \rangle = \mathcal{C} \delta D$

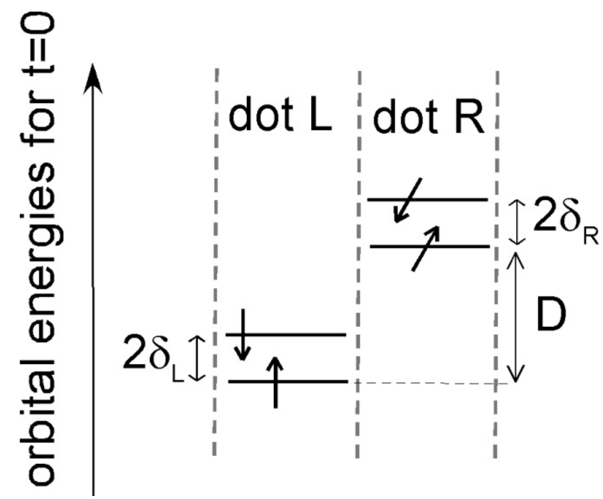


- Dots L and R controlled by local gates
- Transverse effective field due to the (gate controlled) spatial modification of the double dot eigenstates

Hamiltonian of the ferromagnetic spin qubit

$$|\uparrow,\varnothing\rangle \quad |\downarrow,\varnothing\rangle \quad |\varnothing,\nearrow\rangle \quad |\varnothing,\swarrow\rangle$$

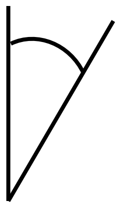
$$\hat{H} = \begin{bmatrix} -\delta_L & 0 & t\cos[\theta/2] & -t\sin[\theta/2] \\ 0 & +\delta_L & t\sin[\theta/2] & t\cos[\theta/2] \\ t\cos[\theta/2] & t\sin[\theta/2] & -\delta_R + D & 0 \\ -t\sin[\theta/2] & t\cos[\theta/2] & 0 & +\delta_R + D \end{bmatrix}$$



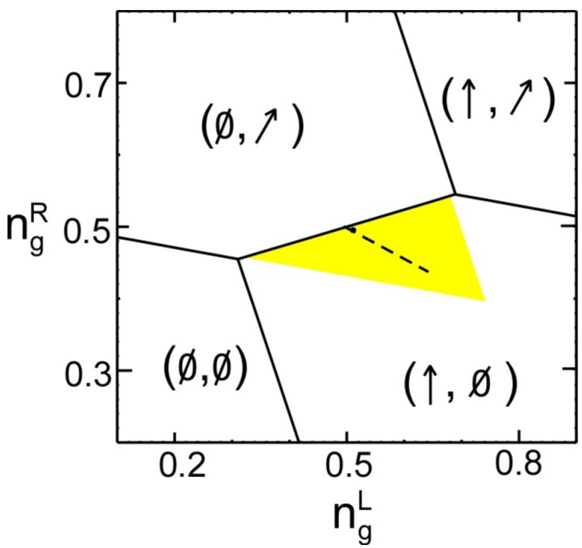
- D is a function of V_g^L and V_g^R and also possibly V_{ac}
- $2\delta_{L(R)}$: effective Zeeman splitting in dot L(R)
- We assume $\delta_L = \delta_R = \delta$ for simplicity

Stability diagram and energy levels of the circuit

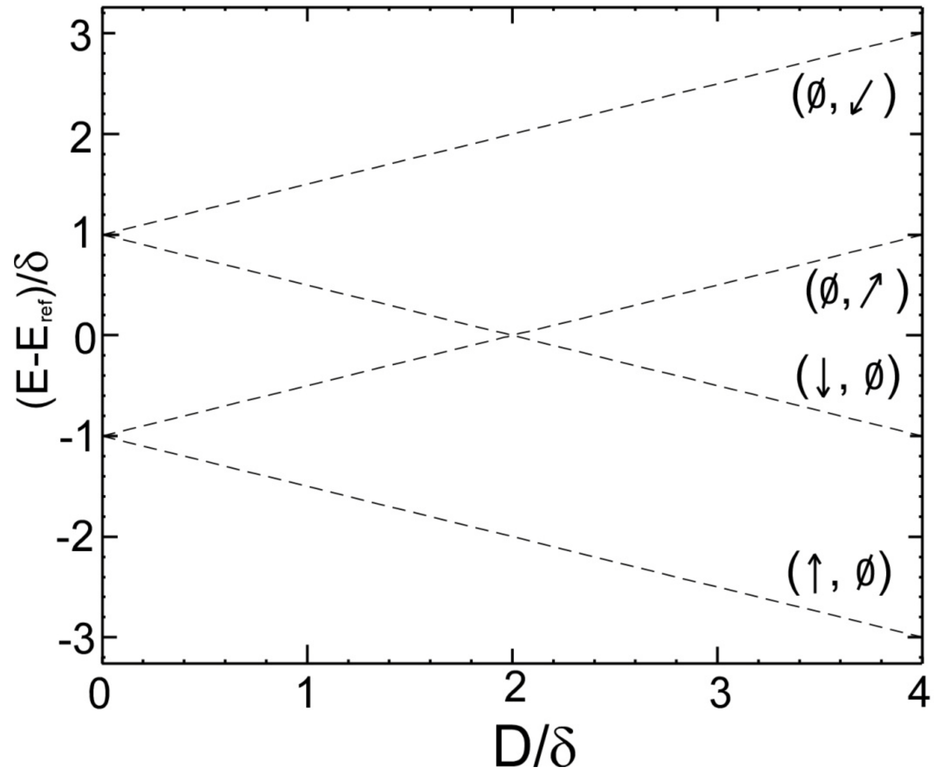
θ=π/6



t=0



dashed lines: t=0



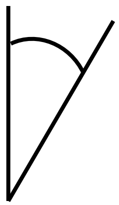
D : energy shift between (↑, ø) and (ø, ↗)

n_g^L: reduced gate voltages for dot L(R)

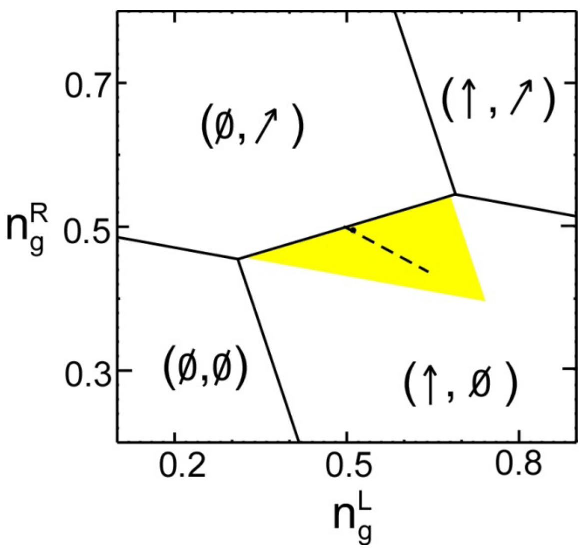
A. Cottet and TK, arXiv:1005.1901

Stability diagram and energy levels of the circuit

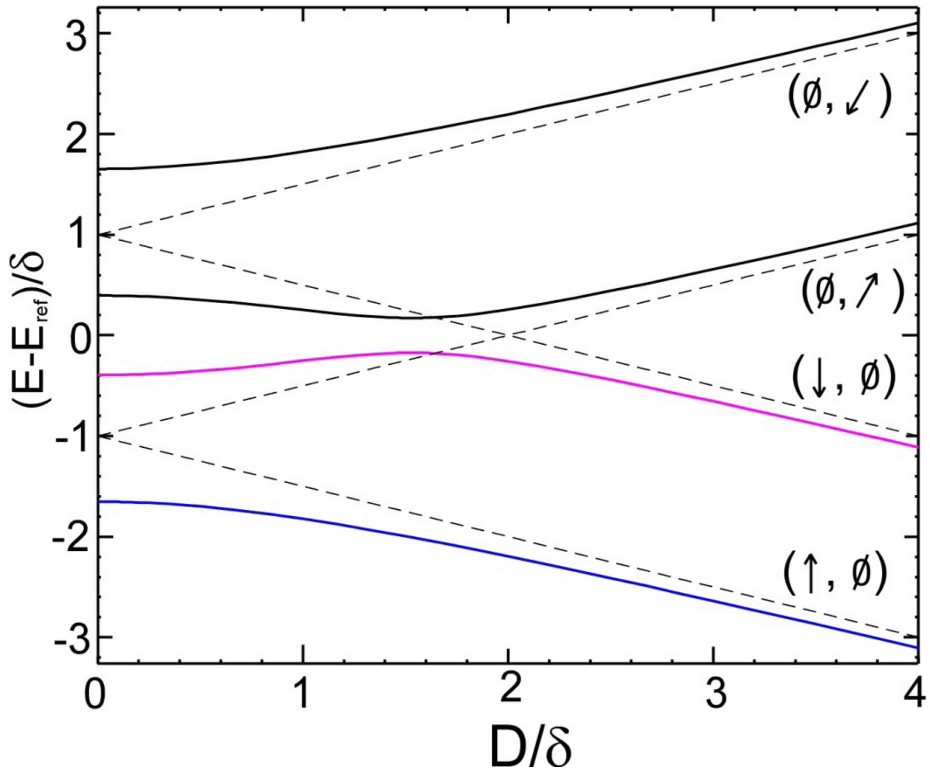
$\theta=\pi/6$



t=0



dashed lines: t=0, full lines: t=2δ/3



D : energy shift between (↑, ø) and (ø, ↗)

n_g^L: reduced gate voltages for dot L(R)

A. Cottet and TK, arXiv:1005.1901

Stability diagram and energy levels of the circuit

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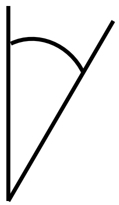

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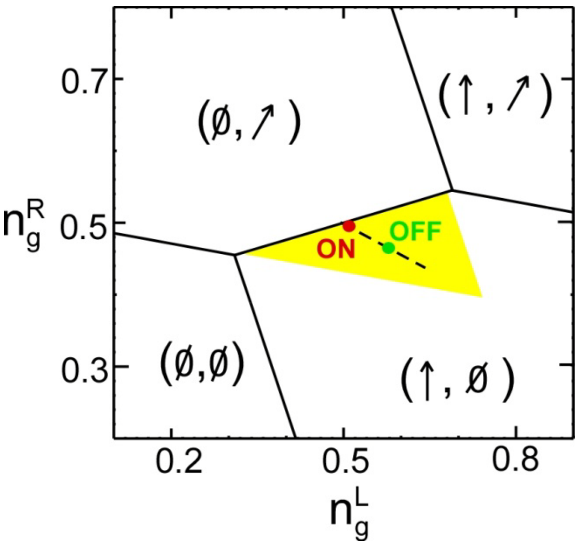
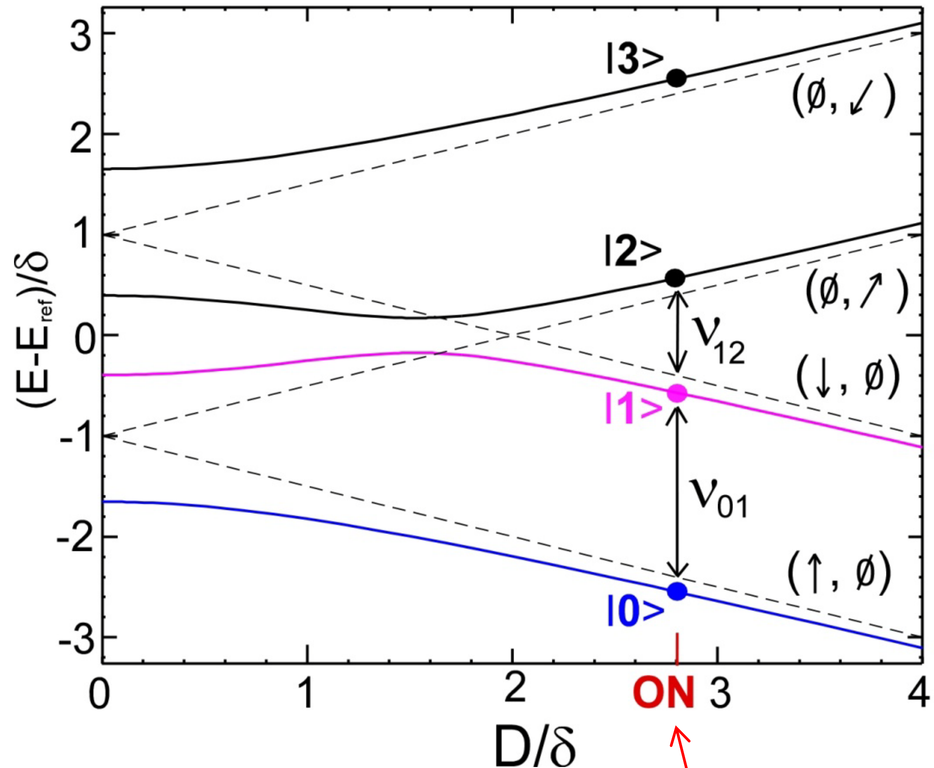


dashed lines: t=0, full lines: t=2δ/3



D : energy shift between (↑, ø) and (ø, ↗)

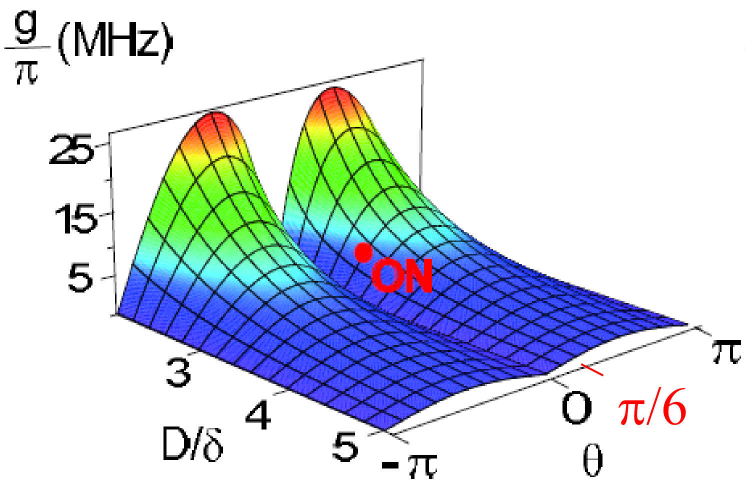
n_g^L: reduced gate voltages for dot L(R)

$2\delta=32\mu eV$

$D_{ON}=2.8\delta$
$\nu_{01}=7.7$ GHz
$\nu_{12}=4.4$ GHz

A. Cottet and TK, arXiv:1005.1901

Spin/photon coupling



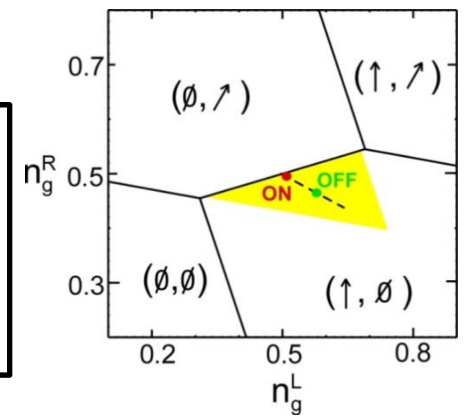
θ=π/6, 2δ=32μeV, V_{rms}=2μeV

realistic capacitances

D_{ON}=2.8δ, g_{ON}=5.6 MHz

D_{OFF}=20δ, g_{OFF}=13 kHz

g_{ON}/g_{OFF}=450



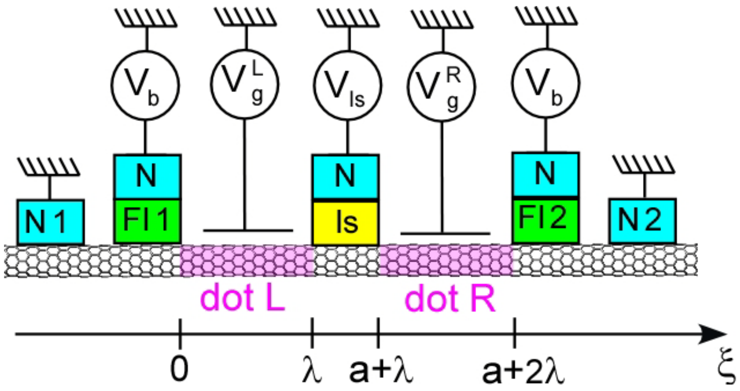
- $D = D_{ON} + \delta D$ and $\theta \neq 0[\pi] \implies \langle \mathbf{0}| \; \hat{H}_{double\ dot} \; |\mathbf{1}\rangle = \mathcal{C}\delta D$
- $\partial D/\partial V_{ac} \neq 0$ using asymmetric capacitive couplings to the two dots

$$\hbar g = \mathcal{C} V_{rms} \partial D/\partial V_{ac}$$

- Rabi oscillation possible using an oscillating V_{ac}
- Spin/photon coupling g tunable with D and θ

Evaluation of decoherence processes

Example of a Single Wall Carbon Nanotube Based Setup



Description with a Dirac-like hamiltonian with realistic parameters

$\Delta_{K\text{-}K'}$ ~3meV [Liang (2002), Sapmaz (2005)]

<u>Several decoherence sources</u>:

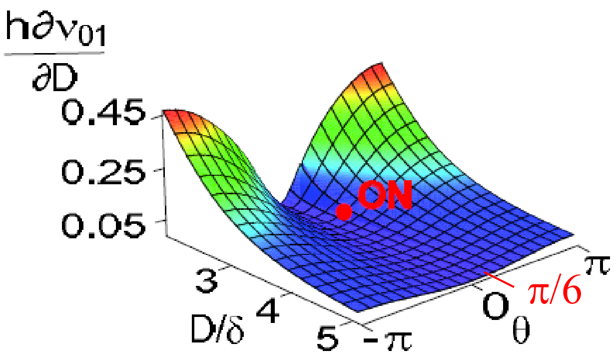
- Spin orbit coupling T_1~ ms *[Bulaev et al., PRB 77, 235301 (2008)]*
- Low frequency charge noise
- Phonons

} *Specific to our setup*

Dephasing due to low-frequency charge noise

Estimates using a semiclassical approximation and extrapolating the charge noise amplitude given in Herrman et al., Phys. Rev. Lett. 99, 156804 (2007)

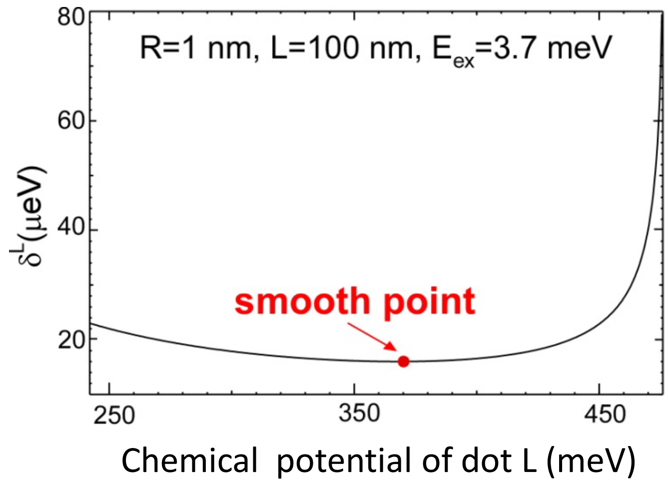
Charge noise mediated by fluctuations of D



ON point: $T_\varphi^D \sim 2.9\ \mu s$
OFF point: $T_\varphi^D \simeq 2$ ms

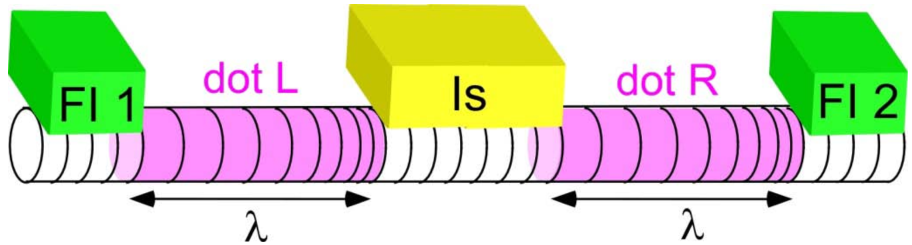
Charge noise mediated by fluctuations of δ_L

$\nu_{01} \sim 2\delta_L$



ON and OFF points: $T_\varphi^{\delta_L} = 15$ ms

Relaxation due to phonons



λ=100 nm

- Stretching vibrons confined in dots L and R

- vibron frequencies $\nu_p = p * 100$ GHz, $p \in \mathbb{N}$

  vibron damping $Q_{ph} = \frac{h\nu_{ph}}{\Gamma} \Longrightarrow$ analogy with Purcell effect

- $$\frac{1}{T_1} = \sum_{\substack{l \in \{L,R\} \\ p \in \mathbb{N}}} \hbar \tilde{g}^2_{l,p} \frac{\Gamma}{\left(\frac{\Gamma}{2}\right)^2 + (h\nu_p - h\nu_{01})^2}$$

  $\tilde{g}_{l,p}$: electron/vibron coupling

Non-suspended carbon nanotube:

$T_1^{ON} \simeq 1.0\ \mu$s and $T_1^{OFF} \simeq 0.21$ s for $Q_{ph} = 1.5$

Suspended carbon nanotube:

$T_1^{ON} \simeq 14\ \mu$s and $T_1^{OFF} \simeq 2.8$ s for $Q_{ph} = 20$

Expected performances

Non-suspended carbon nanotube setup:

$D_{ON}=2.8\delta$, $g_{ON}=5.6$ MHz, $T2=1.2\,\mu s$ $\Rightarrow$ strong coupling regime reached

$D_{ON}=20\delta$, $g_{OFF}=13$ kHz, $T2=2$ ms $\Rightarrow$ quantum register at the OFF point

These performances may be further enhanced with suspended nanoconductors

- A *generic* setup

  Our setup does not require spin-orbit coupling or hyperfine interaction

- A relatively *robust* setup

  δ can be adjusted by choosing the dot size and the active dot orbital, regardless of the FI contact properties

A. Cottet and TK, arXiv:1005.1901

Conclusion part II

- New scheme for manipulating single electronic spins in nanocircuits
- Theoretical proposal based on orbitally phase coherent spintronics
- Prediction of observation of strong coupling regime for realistic parameters
- Strongly tunable coupling g + quantum register behavior

⇒ Possibility to explore cavity QED with electronic spins

⇒ Maybe a new platform to study decoherence in strongly correlated systems ?

C. Feuillet-Palma et al. PRB **81**, 115414 (2010)

A. Cottet and TK, arXiv:1005.1901

A. Cottet, C. Feuillet-Palma and TK Phys. Rev. B 79, 125422 (2009)