Spin and charge dynamics in carbon nanotube circuits probed by transport and cQED

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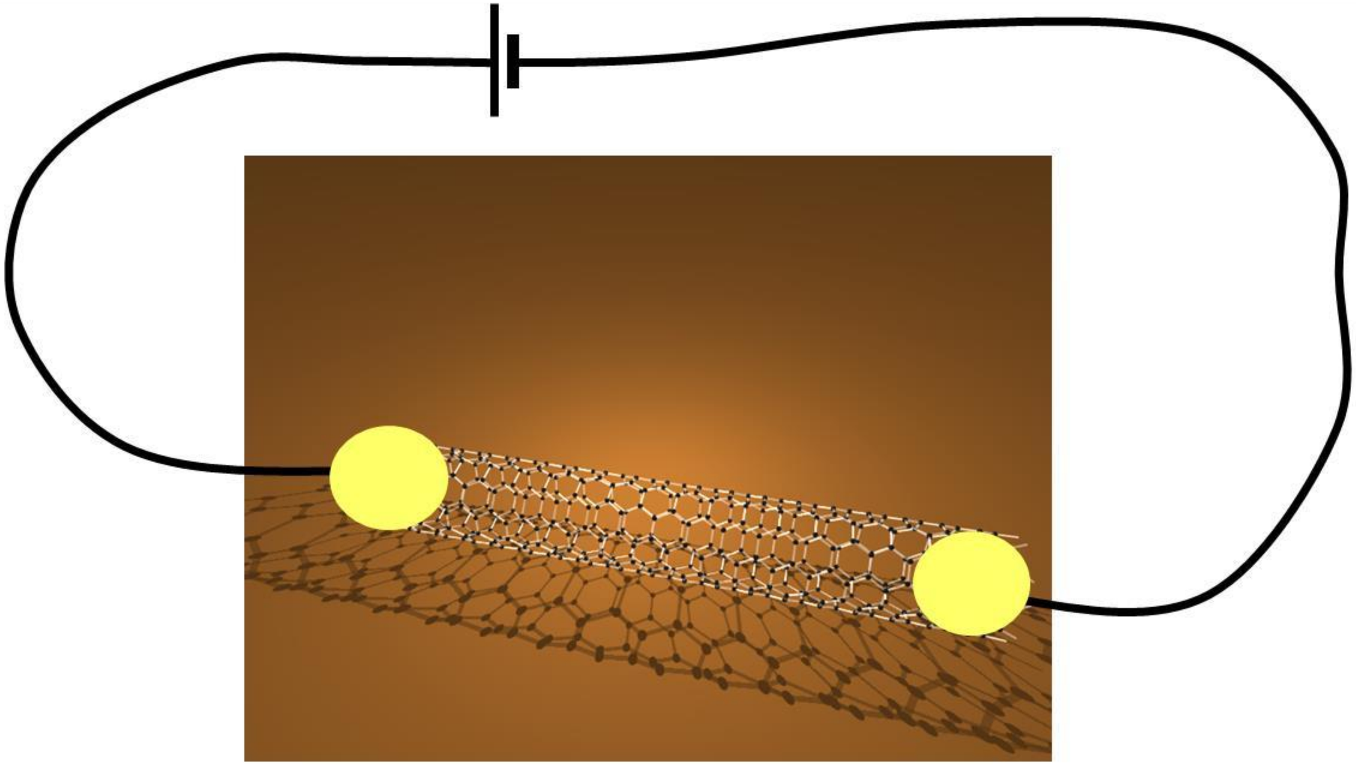
laboratoire pierre aigrain
électronique et photonique quantiques

Emergence of model systems for condensed matter

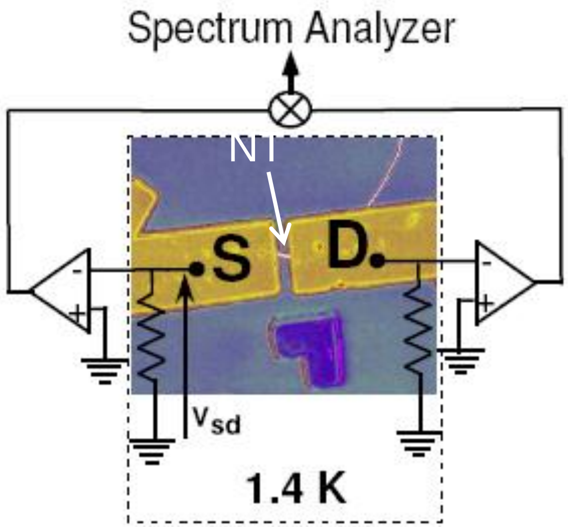


SWNT in a conventional transport experiment

- Experimental study of artificial atoms, molecules or wires
- Natural probe of electronic systems = transport
- Single Wall Nanotubes (and nanowires) as building block

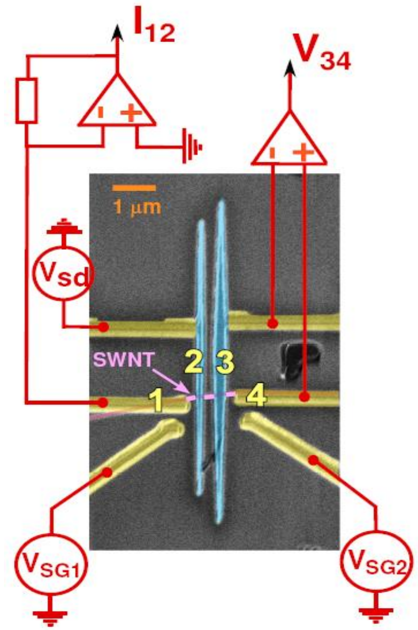
→ Model systems for 1D to 0D electrons : coherent manipulation of the quantum state of electrical circuits or strongly correlated electronic systems

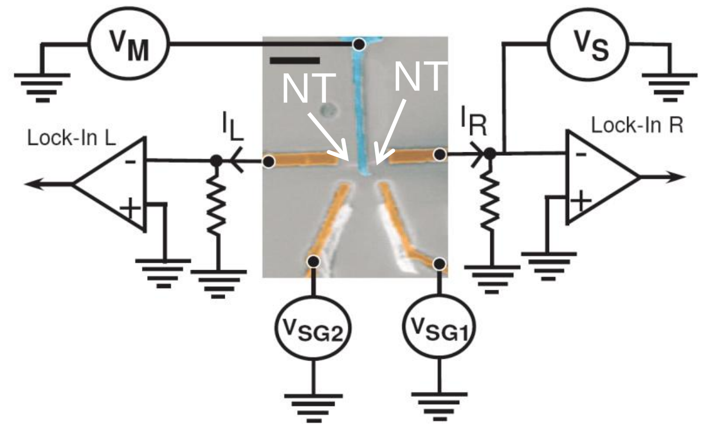
Nanotubes and hybrid structures



T. Delattre et al. Nature Phys. '09

Artificial magnetic impurity





L.G. Herrmann et al. PRL'10

Cooper pair splitter

C. Feuillet-Palma et al. PRB' 10

Non-local orbitally coherent spin valve

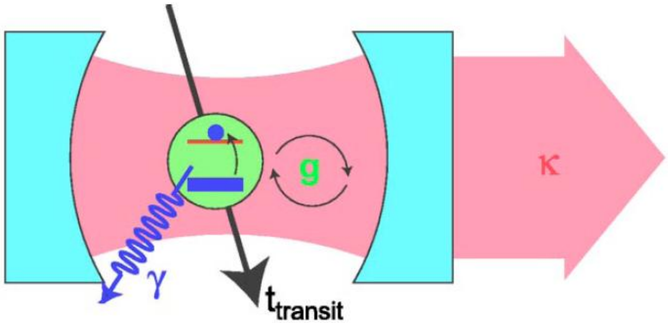
- Combining nanotubes with electrodes of very different nature

→ Depending on nature/regime/geometry of contacts, different fundamental physics can be probed.

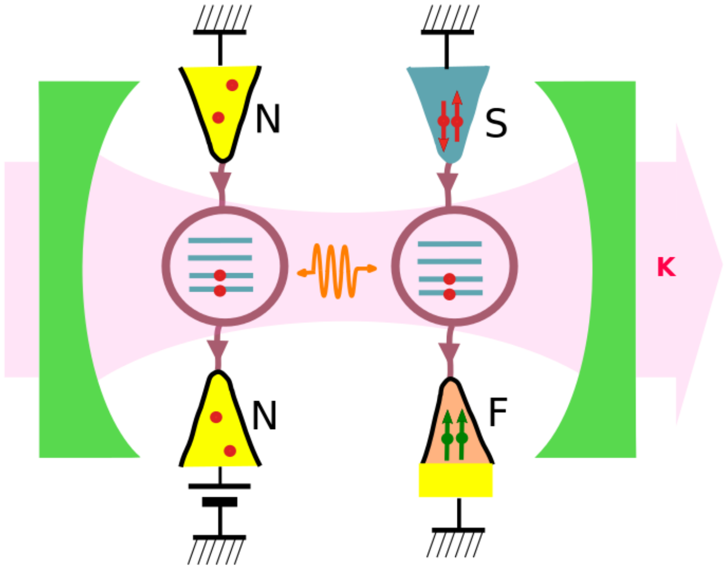
How to go beyond such transport experiments ?

Hybrid circuit Quantum Electro-Dynamics

From cavity QED … To circuit QED …



… To hybrid cQED with quantum dots



J.-M. Raimond, M. Brune, and S. Haroche, RMP 73, 565 (2001)
A. Blais et al. , PRA (2004)
A. Wallraff et al. , Nature 431, 162 (2004)

M.R. Delbecq et al. PRL (2011)
T. Frey et al. PRL (2012)
K.D. Peterson et al. Nature (2012)

➡ Light-matter interaction @ the most elementary level

➡ Probe/Manipulate micro- or macroscopic quantum states

➡ Spin-photon coupling

➡ Take advantage of the *versatility* of quantum dots (many-body physics…)

Outline

I. Out of equilibrium charge dynamics in a cQED architecture

II. Mesoscopic conductors in a cQED architecture

III. Non-collinear magnetoelectronics with a quantum dot

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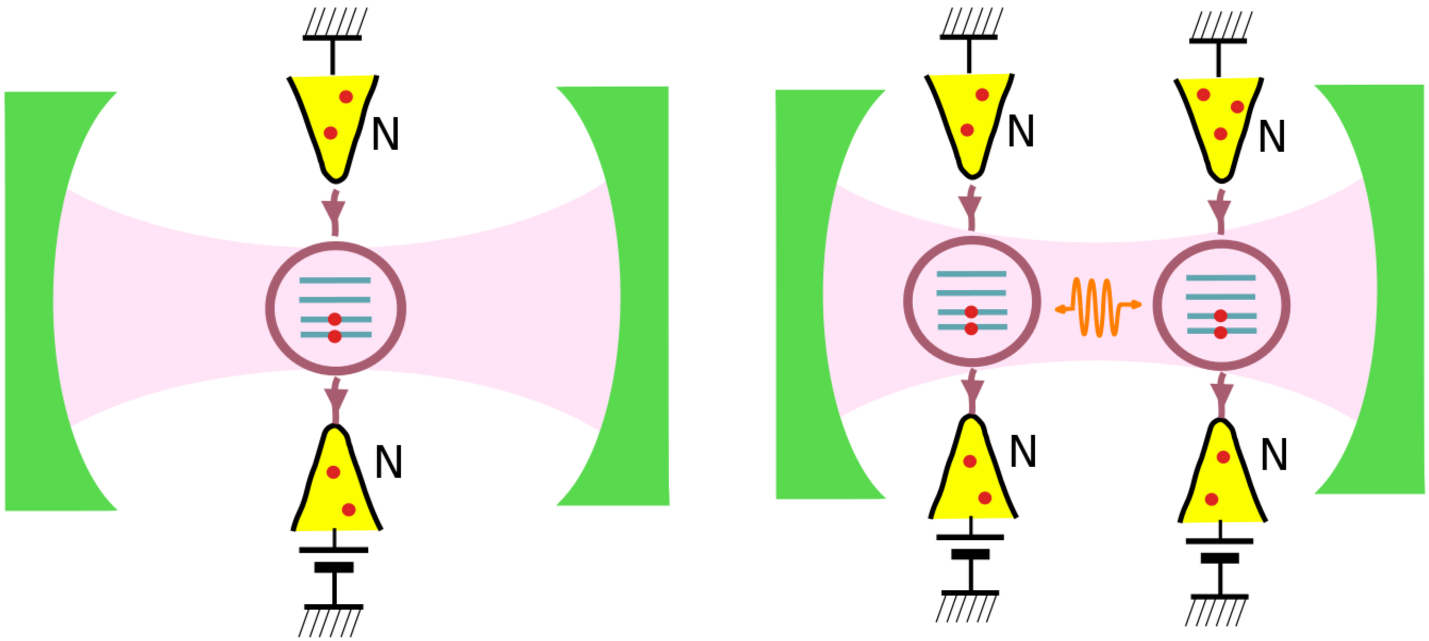
Coupling to single quantum dot circuits



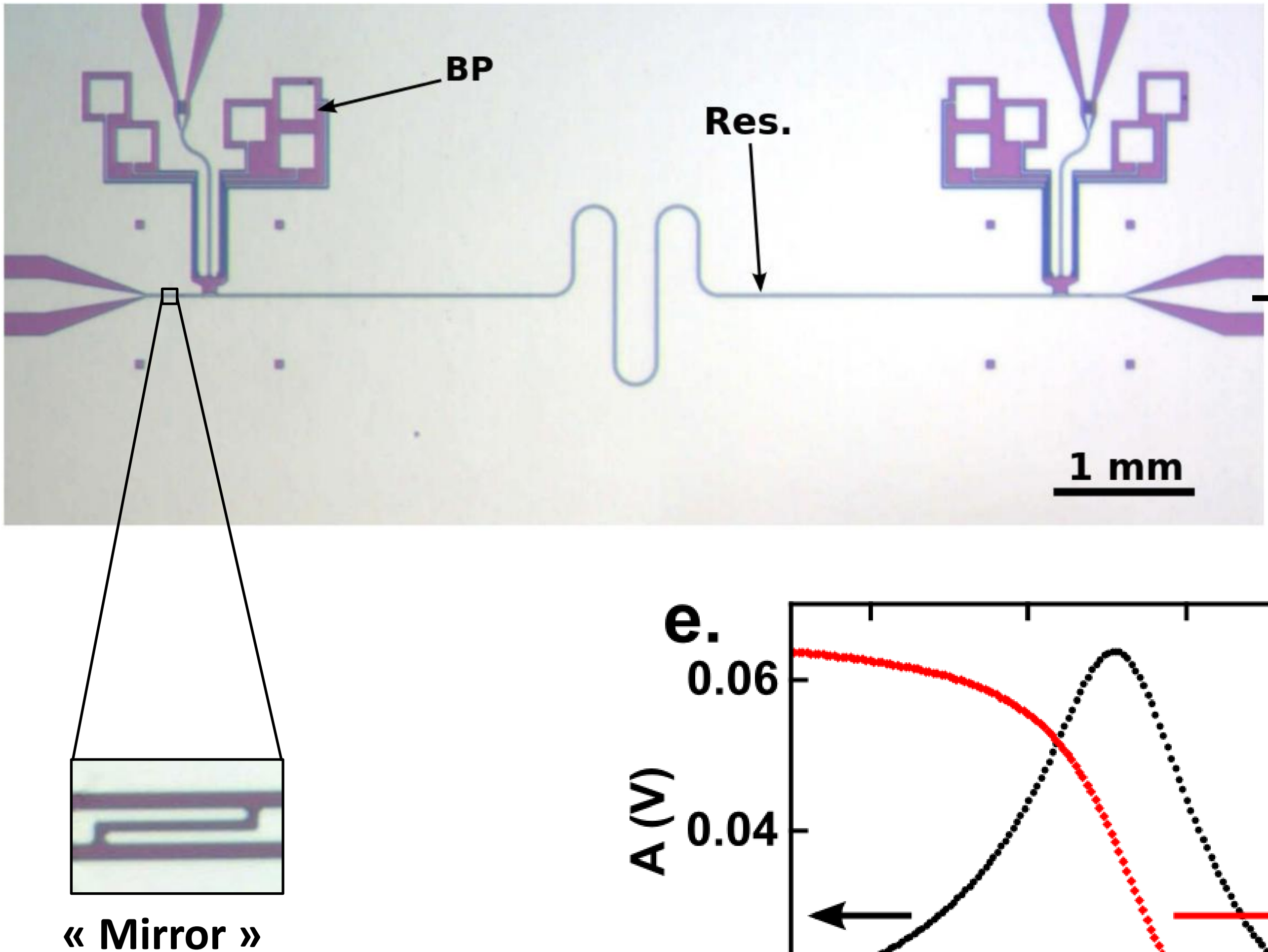
➡ Coupling to open quantum systems

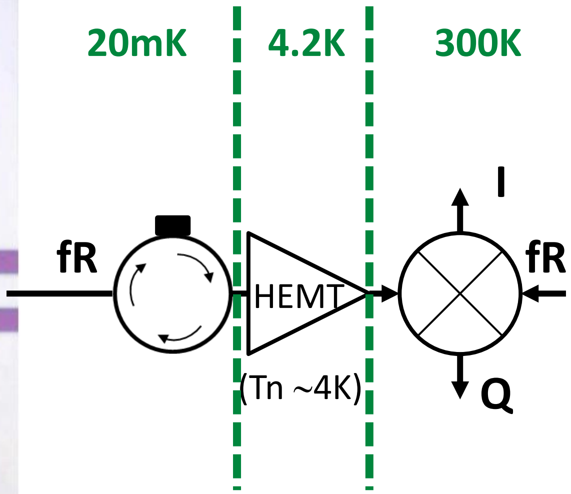
➡ Photon mediated polaronic interaction between distant quantum dots

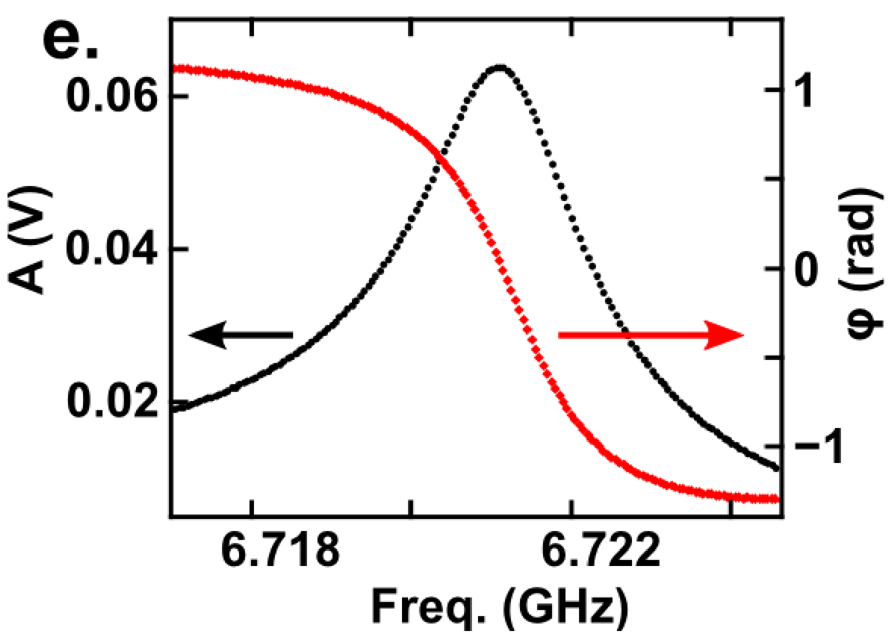
M.R. Delbecq et al. PRL (2011)
M.R. Delbecq et al. Nature Commun. 4, 1400 (2013)

Need to use double quantum dots for manipulating quantum information

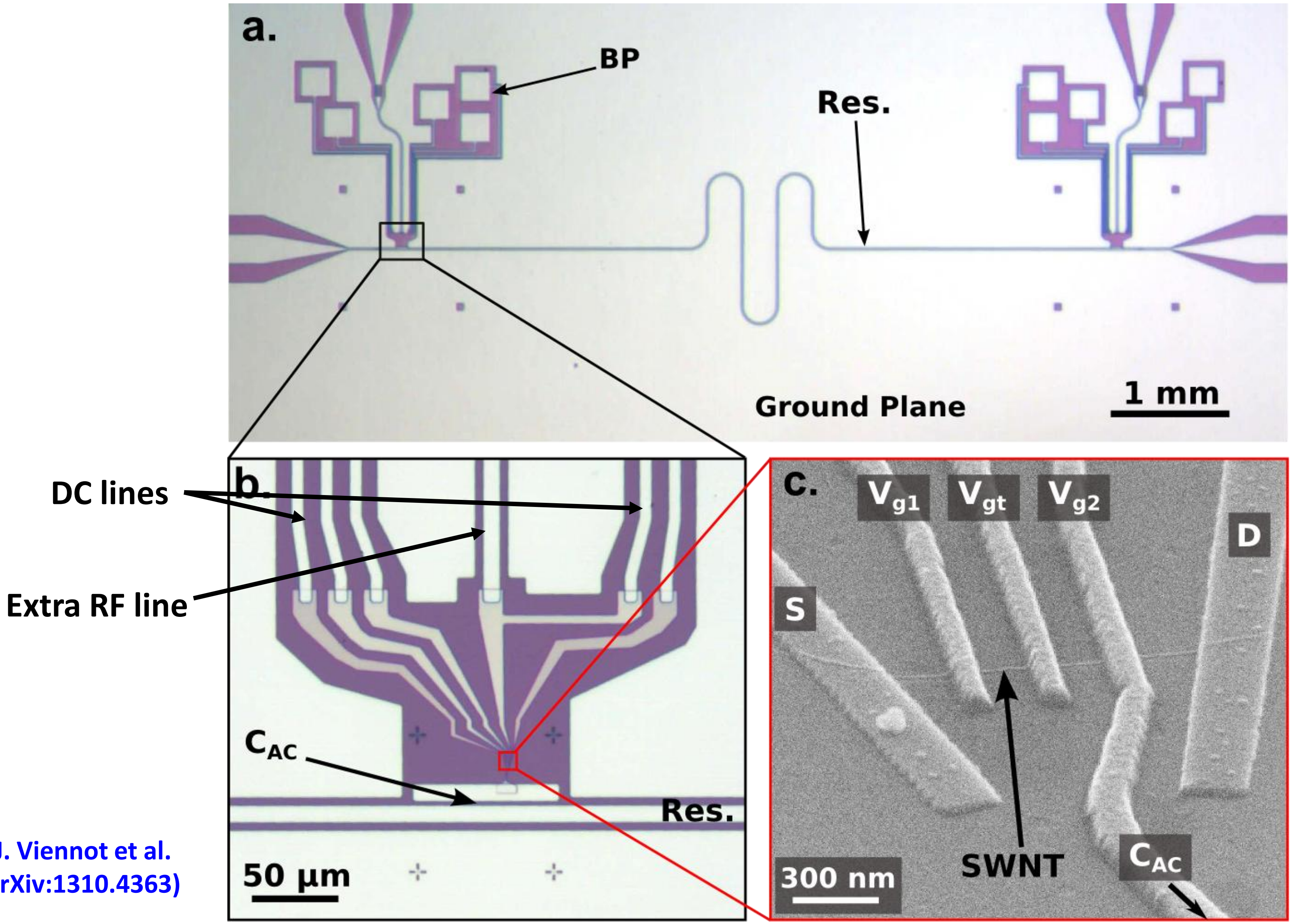
Our circuit QED architecture





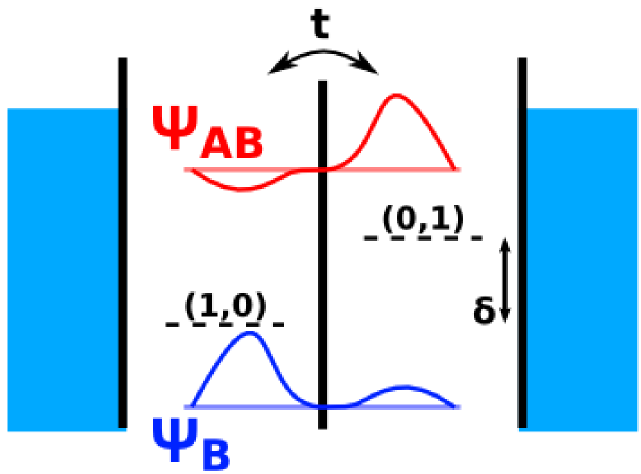


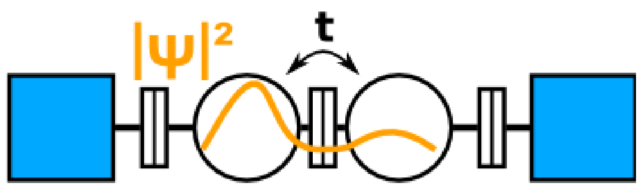
SWNT Double quantum dots for hybrid cQED



J.J. Viennot et al.
(arXiv:1310.4363)

Coupling mechanism of a Double QD





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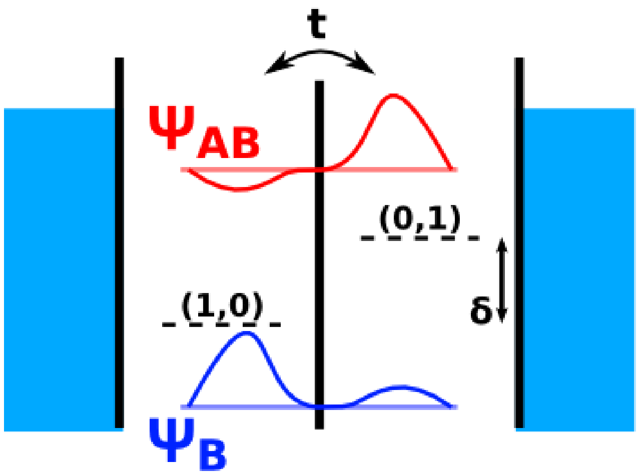

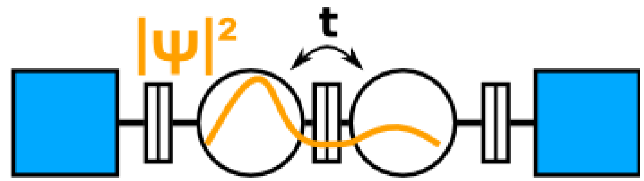

→ Asymmetric coupling particularly interesting (address intra-dot transitions)

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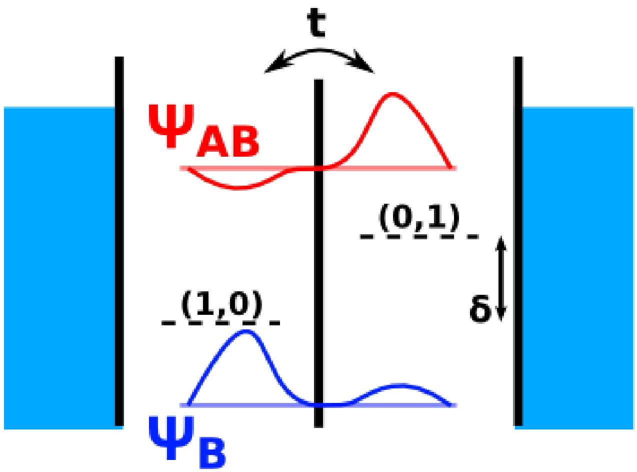

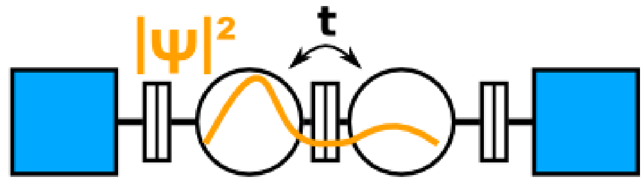

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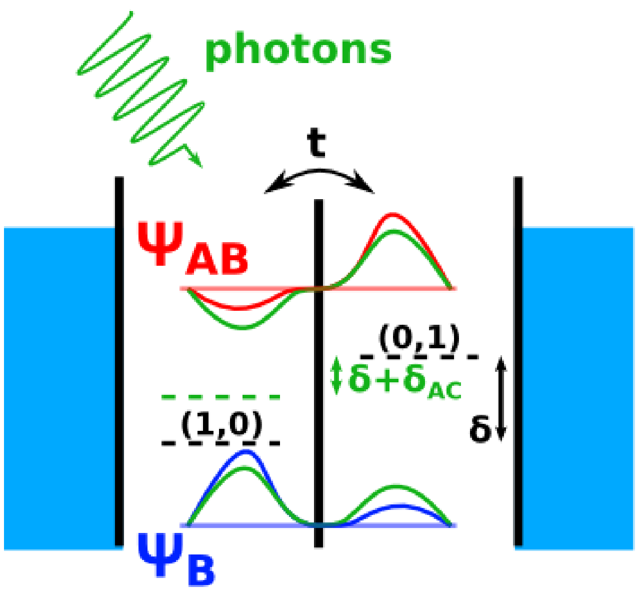

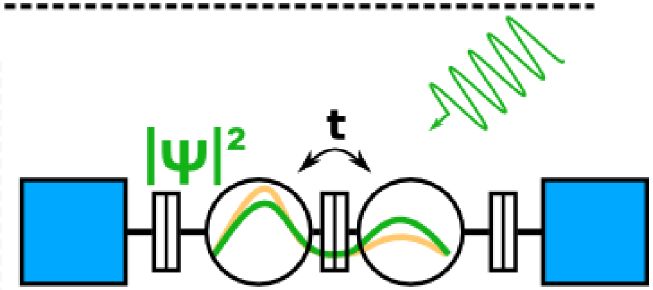

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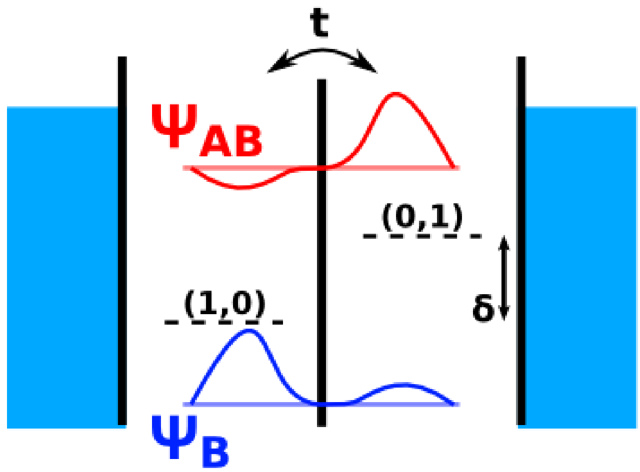

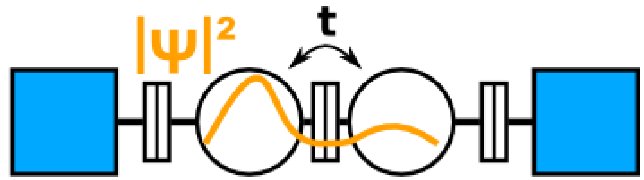

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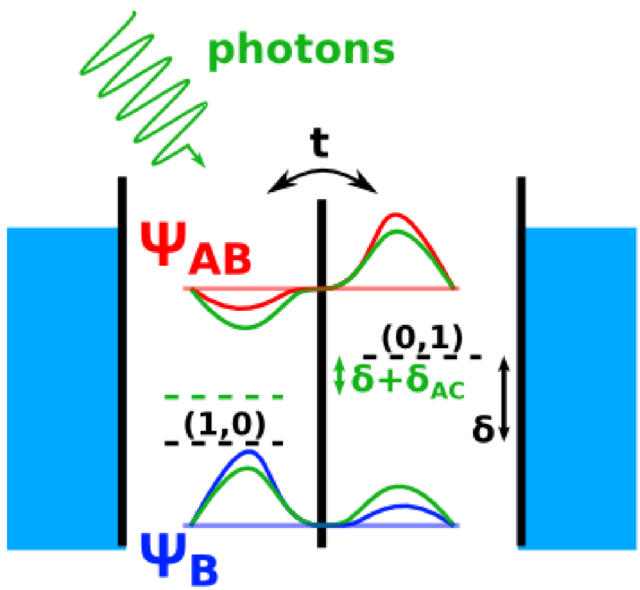
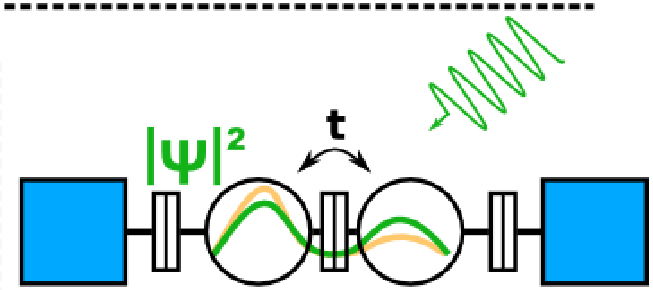




→ **What is the cavity detector exactly sensitive to?**

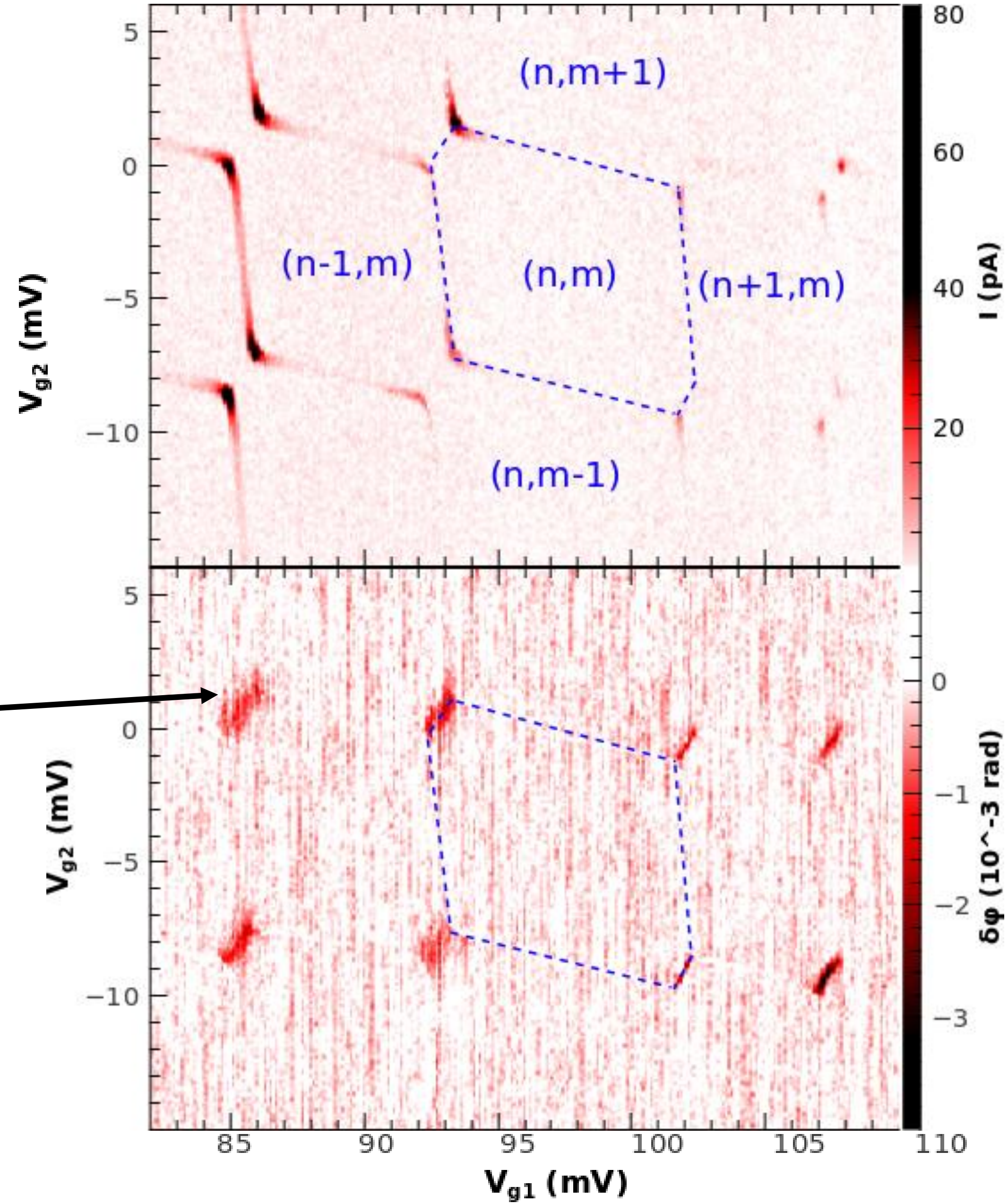
Towards CNT-based quantum information devices

- Preserve coherence (closed QD)
- Bring system to resonance with cavity

« Strong » confinement in SWNT

$$\Gamma_{lead} \approx 0.1 - 1\,\text{GHz}$$

Cavity mode couples to detuning of DQD



J.J. Viennot et al. (arXiv:1310.4363)
See also, in SC Nanowires and 2DEG :
T. Frey et al. PRL (2012)
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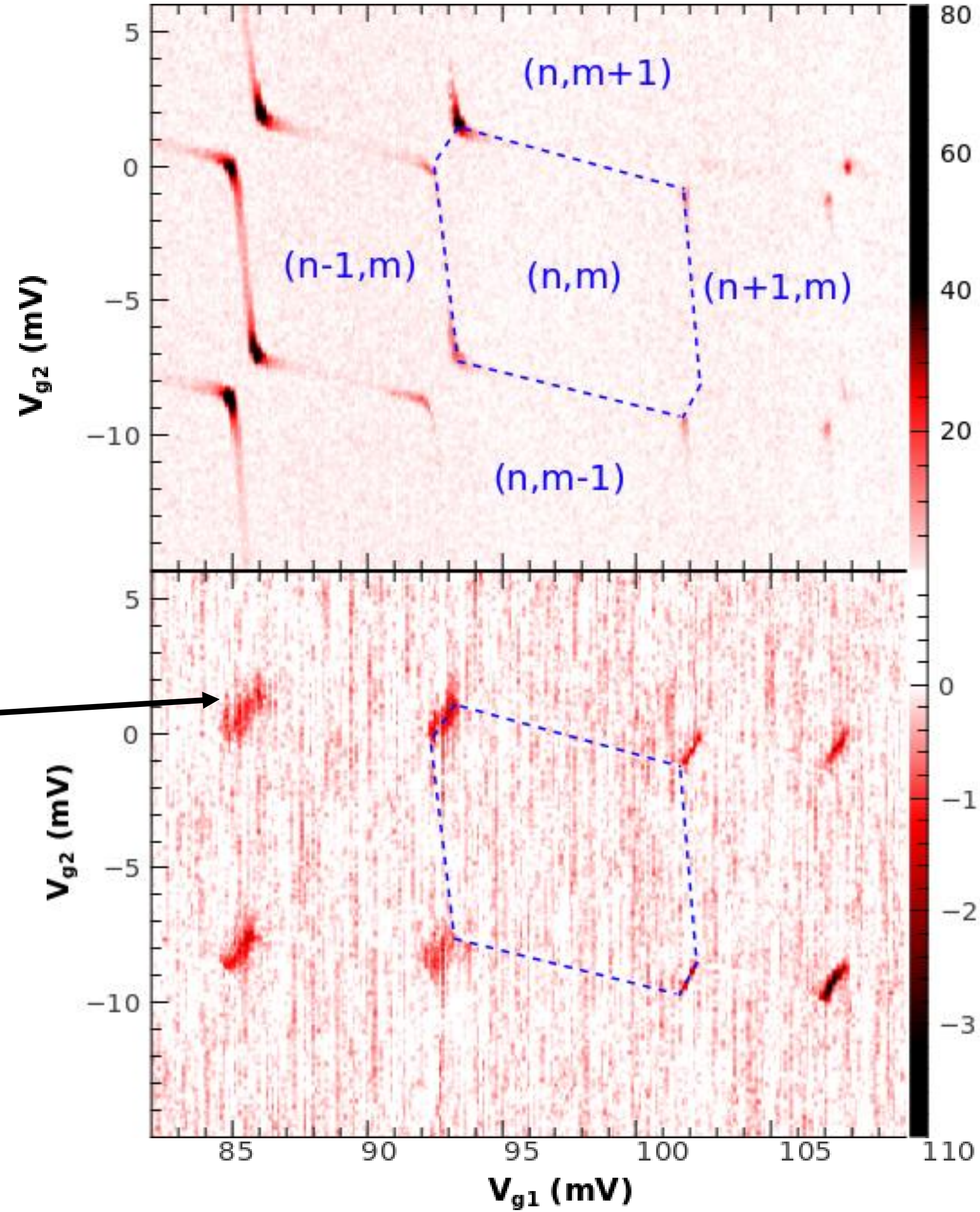

- Can we be quantitative ?

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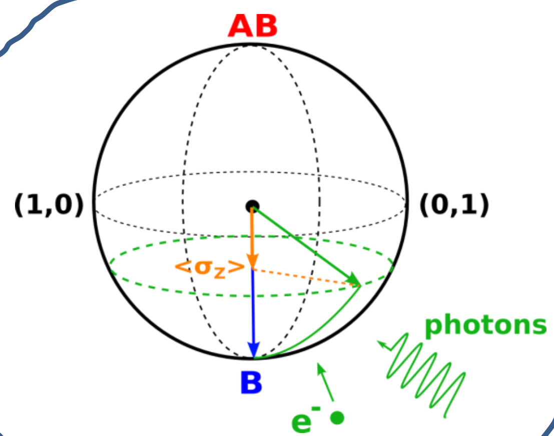
Driving the effective spin out of equilibrium

System hamiltonian: $\hbar\Omega = \sqrt{(2t)^2 + (\epsilon_L - \epsilon_R)^2}, \; g = g_0 \sin\theta, \; \theta = \arctan\frac{2t}{\epsilon_L - \epsilon_R},$

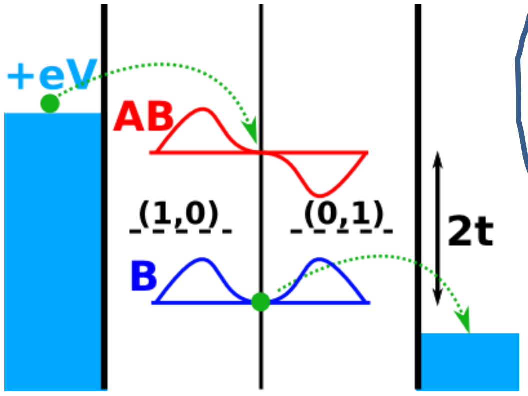
$$H = \hbar\frac{\Omega}{2}\sigma_z + E_0\sigma_0 + E_2\sigma_2 + \hbar\omega_0 a^\dagger a + \hbar g(\sigma_- a^\dagger + \sigma_+ a) + \hbar\epsilon_{in}(e^{-i\omega_d t}a^\dagger + e^{i\omega_d t}a) + H_{Bath}$$

Coupling term

Driving term



« Bosonic »+ fermionic (leads)



J.J. Viennot et al. (arXiv:1310.4363)

Driving the effective spin out of equilibrium

$$\Delta = \Omega - \omega_d \text{ and } \delta = \omega_0 - \omega_d$$

Effective spin-drive and cavity-drive detuning

$$\frac{d\langle a\rangle}{dt} = -(\kappa/2 + i\delta)\langle a\rangle - i\epsilon_{in} - ig\langle\sigma_-\rangle$$

$$\frac{d\langle\sigma_-\rangle}{dt} = -(\gamma/2 + \Gamma_\phi + i\Delta)\langle\sigma_-\rangle + ig\langle a(\sigma_p - \sigma_m)\rangle$$

$$\frac{d\langle\sigma_p\rangle}{dt} = -ig(\langle a\sigma_+\rangle - \langle a^\dagger\sigma_-\rangle) + \sum_{i\neq p}\Gamma_{pi}\langle\sigma_i\rangle - \sum_{i\neq p}\Gamma_{ip}\langle\sigma_p\rangle$$

$$\frac{d\langle\sigma_m\rangle}{dt} = ig(\langle a\sigma_+\rangle - \langle a^\dagger\sigma_-\rangle) + \sum_{i\neq m}\Gamma_{mi}\langle\sigma_i\rangle - \sum_{i\neq m}\Gamma_{im}\langle\sigma_m\rangle$$

$$\frac{d\langle\sigma_j\rangle}{dt} = \sum_{i\neq j}\Gamma_{ji}\langle\sigma_i\rangle - \sum_{i\neq j}\Gamma_{ij}\langle\sigma_j\rangle$$

- Coupled electron photon equation of motion (optical Bloch-Redfield type equation)
- Effective spin -> $\sigma_z = \sigma_p - \sigma_m$ if double dot occupied by *one* excess charge

J.J. Viennot et al. (arXiv:1310.4363)

Driving the effective spin out of equilibrium

Cavity drive

$\Delta = \Omega - \omega_d$ and $\delta = \omega_0 - \omega_d$

$$\frac{d\langle a\rangle}{dt} = -(\kappa/2 + i\delta)\langle a\rangle - i\epsilon_{in} - ig\langle\sigma_-\rangle$$

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Photon drive

$$\frac{d\langle\sigma_m\rangle}{dt} = ig(\langle a\sigma_+\rangle - \langle a^\dagger\sigma_-\rangle) + \sum_{i\neq m}\Gamma_{mi}\langle\sigma_i\rangle - \sum_{i\neq m}\Gamma_{im}\langle\sigma_m\rangle$$

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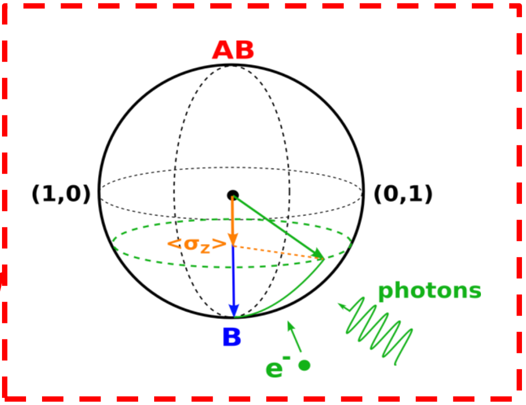

Torque on the effective spin

J.J. Viennot et al. (arXiv:1310.4363)

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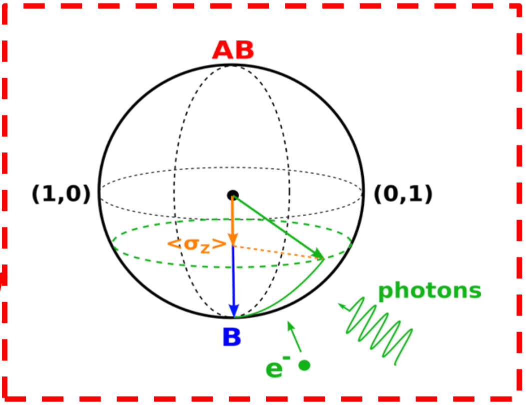

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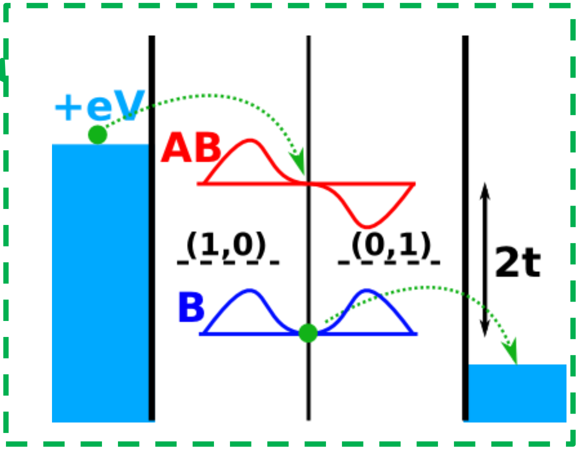

Change of projection of effective spin on z axis

J.J. Viennot et al. (arXiv:1310.4363)

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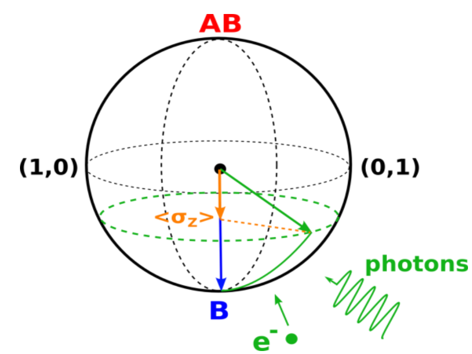

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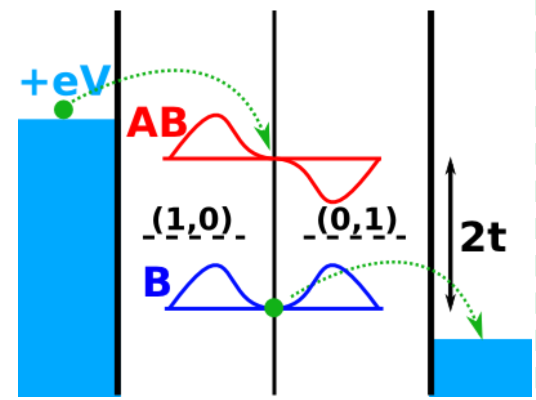


Change of projection of effective spin on z axis

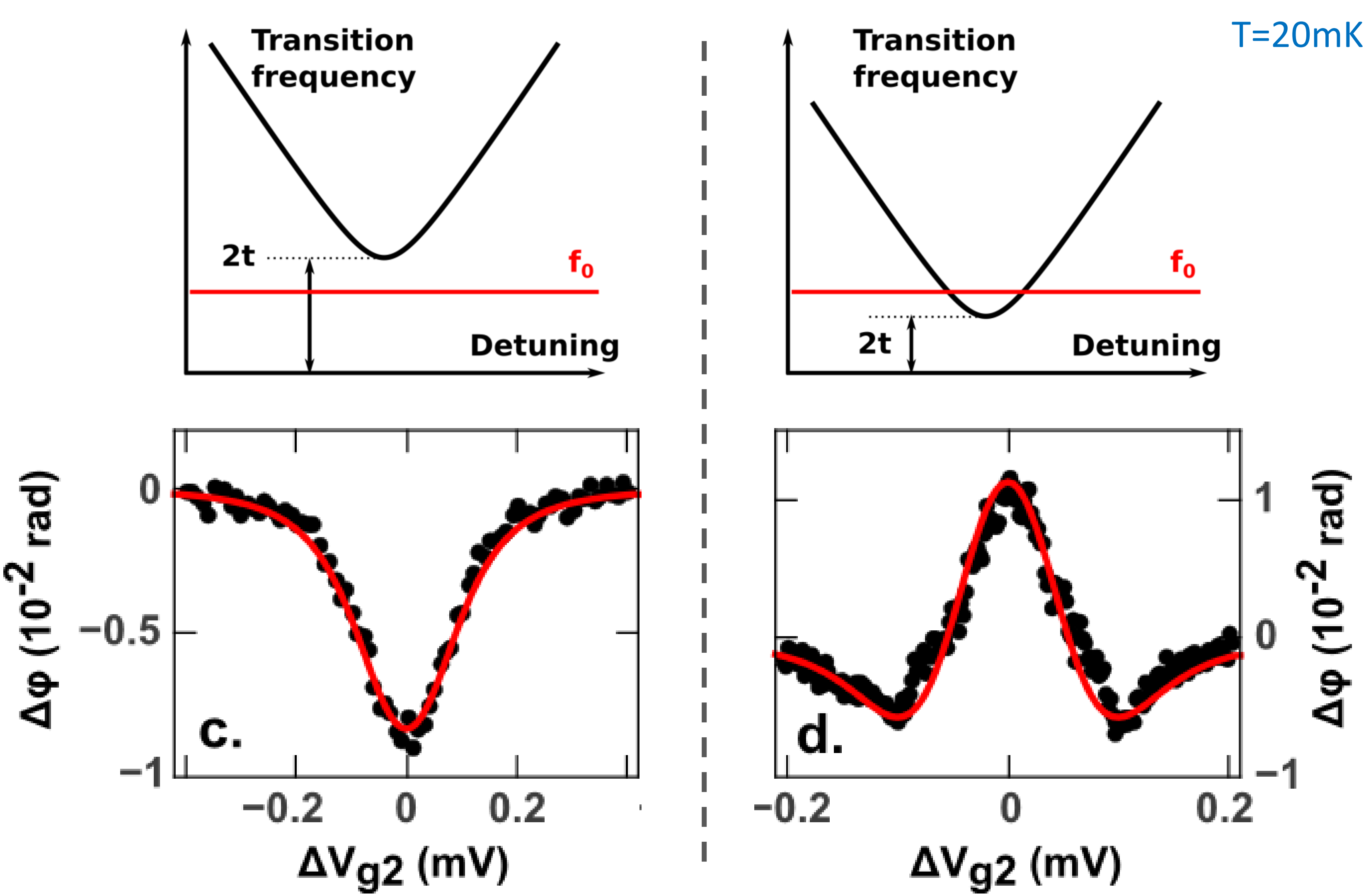
- Cavity frequency shift $\Delta f = \Re e[\chi]\langle\sigma_z\rangle$

$$\chi = \frac{(g_0 \sin\theta)}{-i(\gamma/2 + \Gamma_\phi) + \Delta}$$

- At equilibrium, $\langle\sigma_z\rangle = -1$

J.J. Viennot et al. (arXiv:1310.4363)

Towards CNT-based quantum information devices



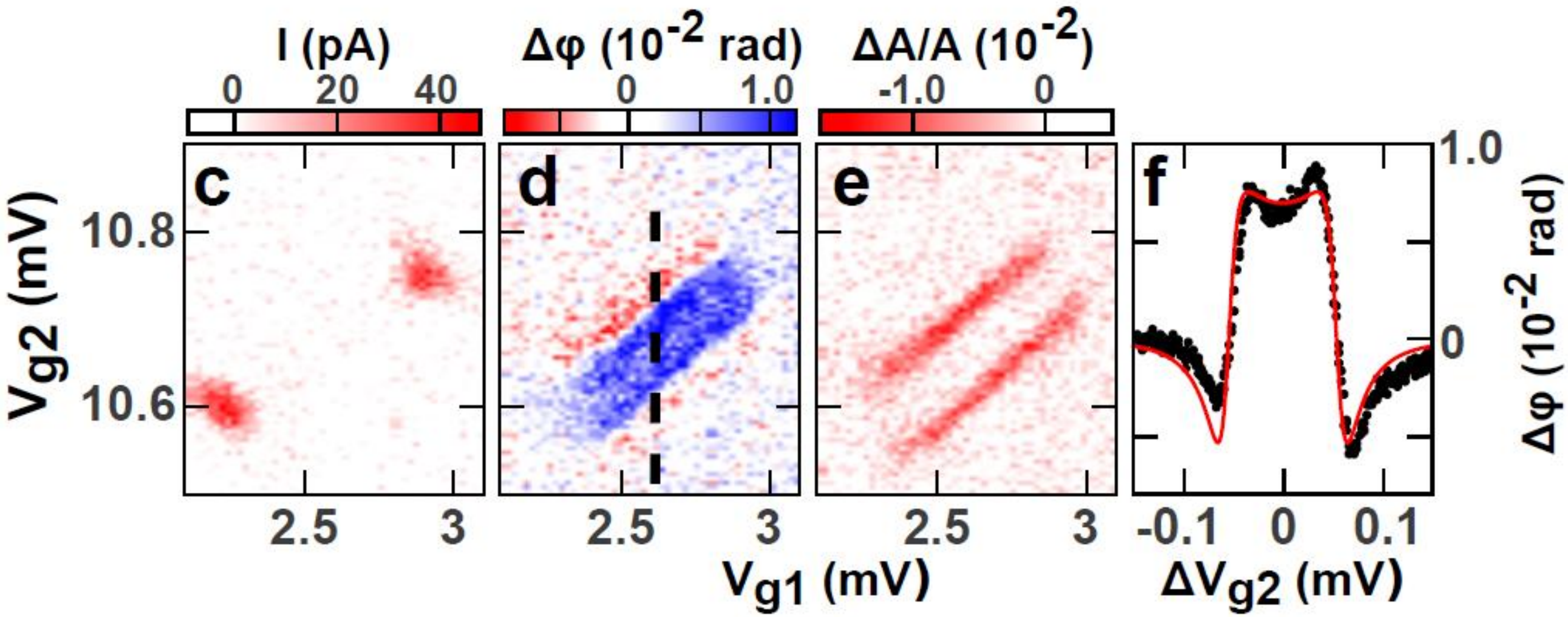
J.J. Viennot et al. (arXiv:1310.4363)

See also, in SC Nanowires and 2DEG :

T. Frey et al. PRL (2012); K.D. Peterson et al. Nature (2012); Toida et al. PRL (2013)

The effective spin picture

T=20mK



- Quantitative agreement with the theory for $\langle \sigma_z \rangle = -1$
- We extract g_0 from 3MHz to 12MHz
- We extract $\gamma/2+\Gamma_\phi$ from 450MHz to 3GHz

$\Omega \sim$ 6 GHz

$\omega_0 =$ 6.721 GHz

Q~3500

J.J. Viennot et al. (arXiv:1310.4363)

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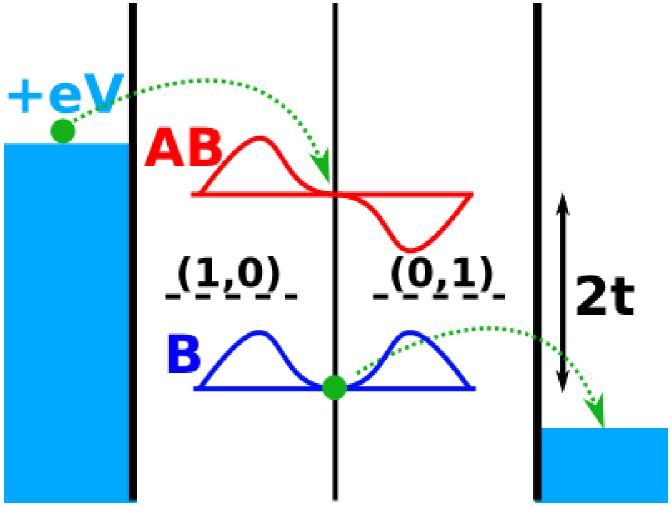
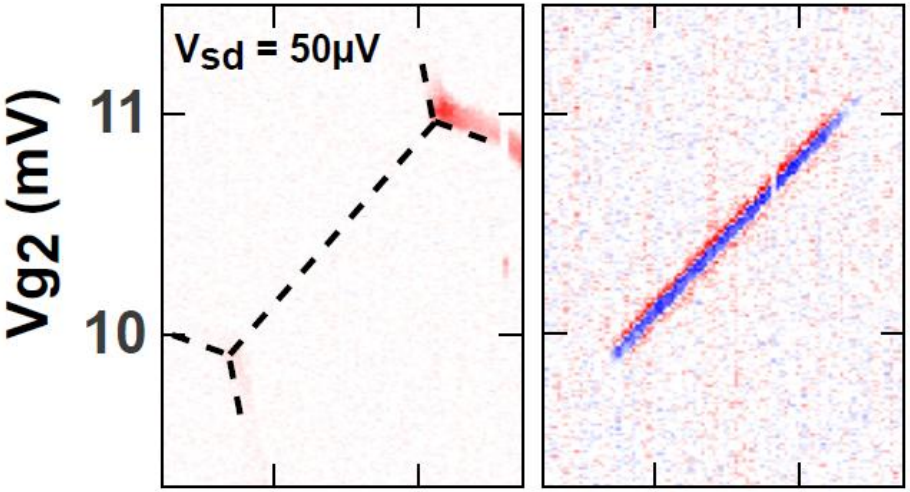
Out of equilibrium charge Qbit

Bias pumping:





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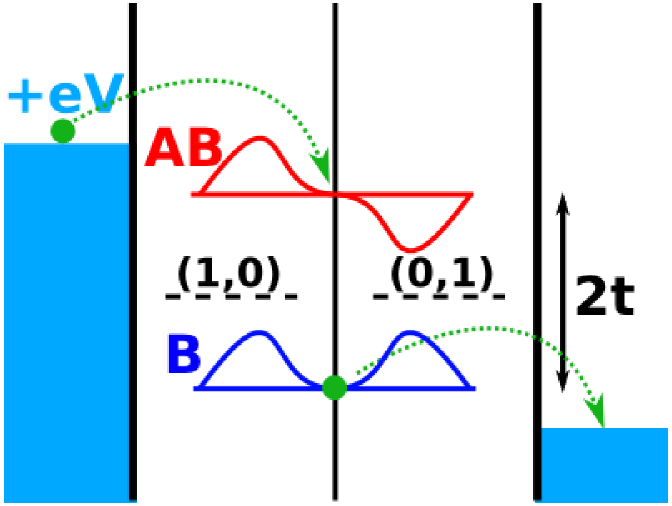
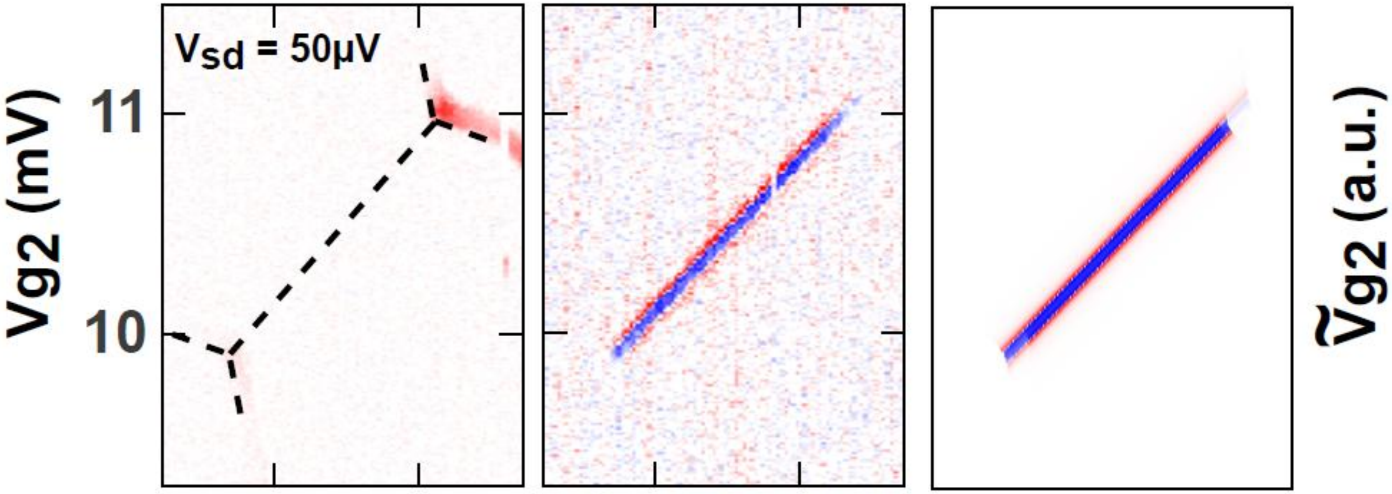


$$\Delta\varphi \sim \mathrm{Re}(\chi) < \sigma_Z >$$
$$< \sigma_Z > \approx -1$$



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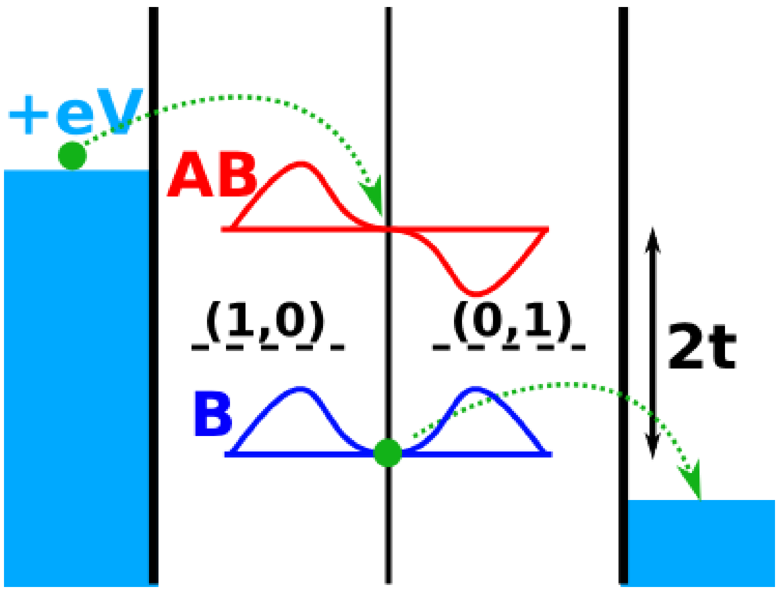
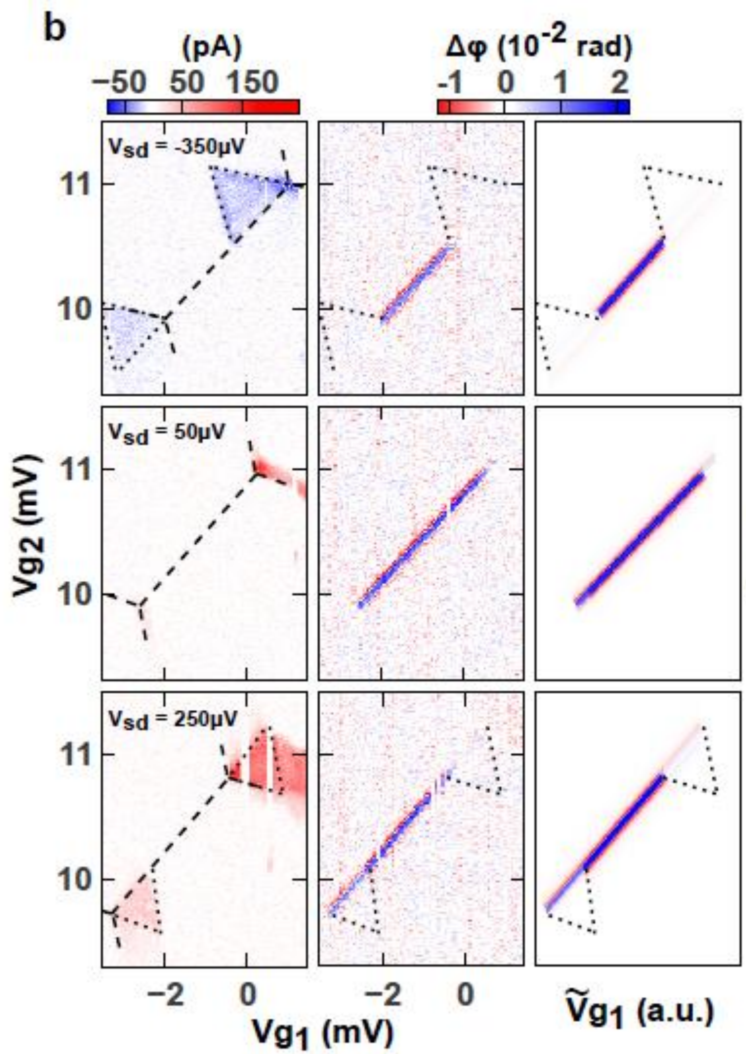


$$\Delta\varphi \sim \mathrm{Re}(\chi) < \sigma_Z >$$
$$< \sigma_Z > \neq -1$$



γ~300MHz
γ_R~10GHz
γ_L~10GHz

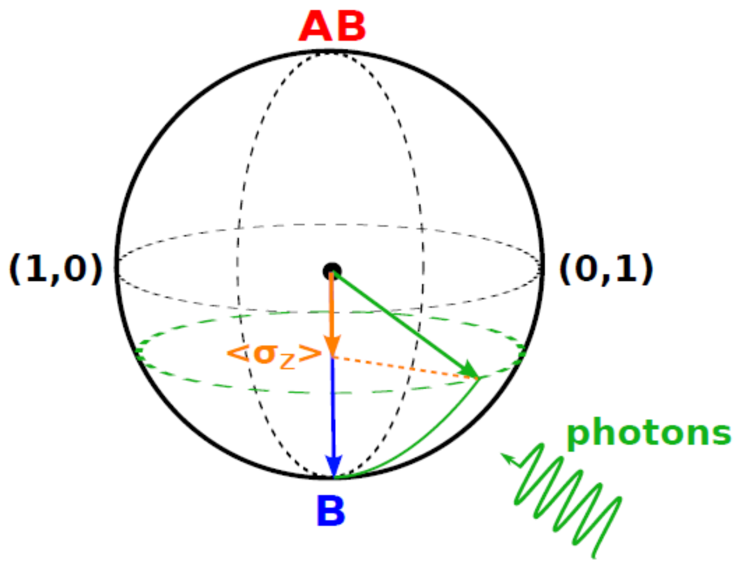
γ~300MHz
γ_R~1.6GHz
γ_L~300MHz

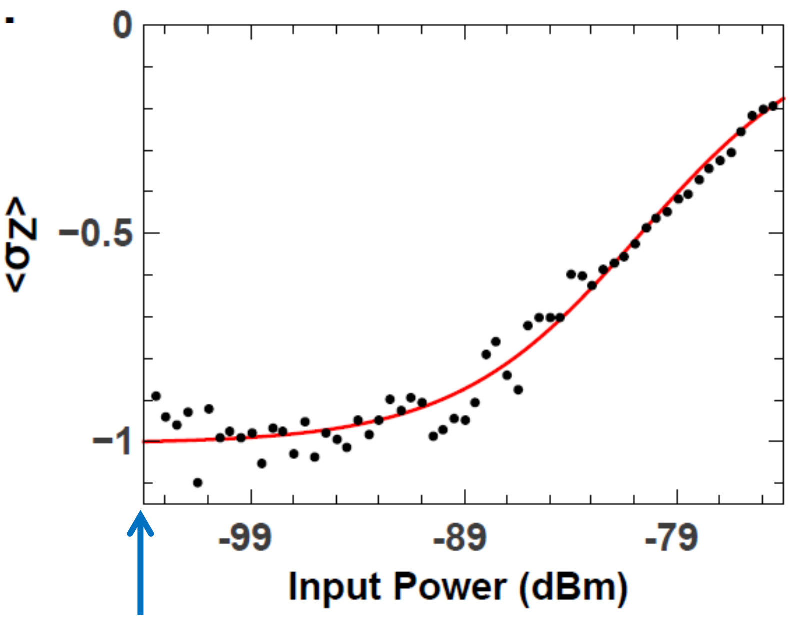
γ~300MHz
γ_R~1.6GHz
γ_L~300MHz

- Direct measurement of $< \sigma_Z >$ in a transport situation (not equivalent to current)
- Good agreement between theory and experimental data->extract relaxation rates

J.J. Viennot et al. (arXiv:1310.4363)

Out of equilibrium charge Qbit





n_{ph}~40 γ~300MHz

$$\langle \sigma_z \rangle = \frac{-1}{1 + 4\Im m[\chi] n_{ph}/\gamma}$$

Number of photons in the cavity

AB/B relaxation rate

- Photons reduce $< \sigma_Z >$ in a manner directly related to the internal relaxation rate and the number of photons in the cavity.
- Quantitative agreement with theory (red line)

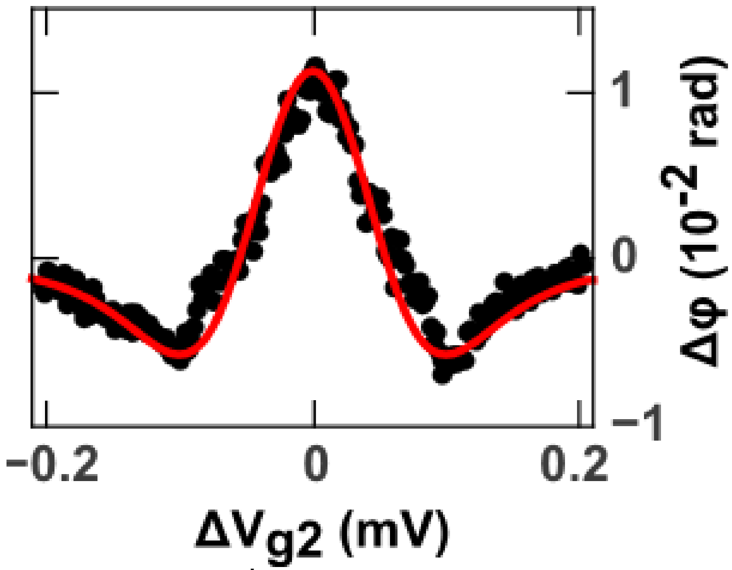
J.J. Viennot et al. (arXiv:1310.4363)

Towards spin-photon coupling?

Only charge coupling so far ➡ Weak coupling regime

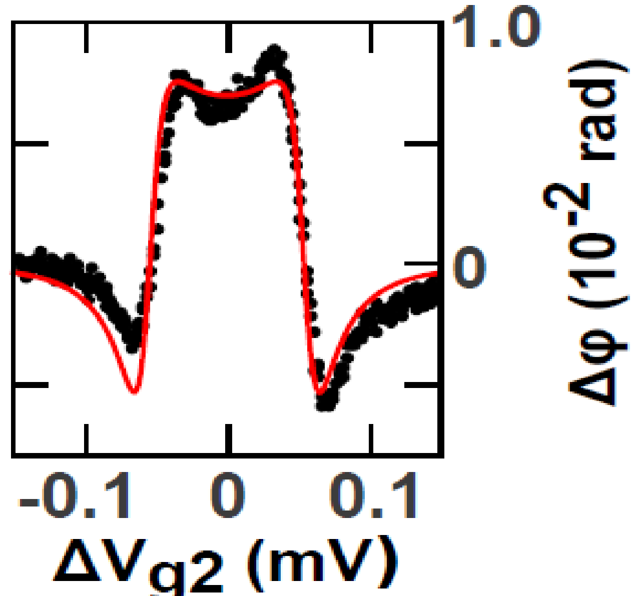
$g_{\text{charge}} \approx 3-12\,\text{MHz}$

$T_{2\,\text{charge}}^{*} \approx 0.3-3\,\text{ns}$



$\Gamma_2^{*} \approx 3\,\text{GHz}$

$<\sigma_e> \approx 15\mu V$



$\Gamma_2^{*} \approx 600\,\text{MHz}$

$<\sigma_e> \approx 6\mu V$

$$\Gamma_\phi \approx \frac{d^2\Omega}{d\epsilon^2}\langle\sigma_\epsilon\rangle^2 = \langle\sigma_\epsilon\rangle^2/2t$$

- Use of dephasing model at second order in detuning fluctuations (semiclassical)

Charge noise ~ $6-15\times 10^{-4} e/\sqrt{Hz}$ ➡ **Important for spin/valley quantum control !**

Towards spin-photon coupling?

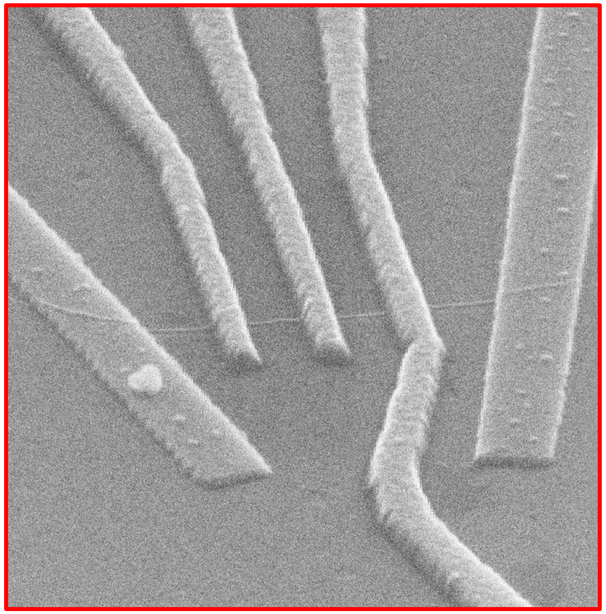
Only charge coupling so far ➡ Weak coupling regime

$$g_{\text{charge}} \approx 10 - 50\,\text{MHz}$$

$$T^*_{2\ \text{charge}} \approx 0.3 - 3\,\text{ns}$$

➡ Strong coupling? $g > \Delta f_{cavity}\ ,\ 1/T_2^*$

➡ Spin-Photon coupling mechanism?



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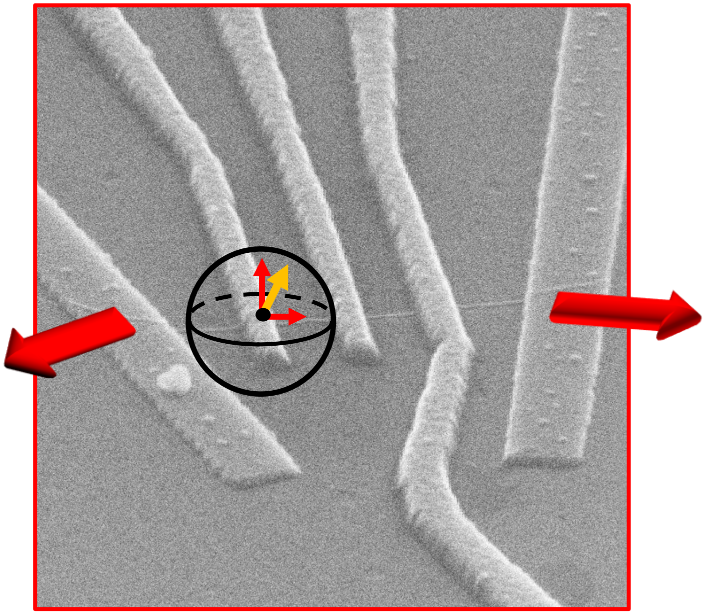
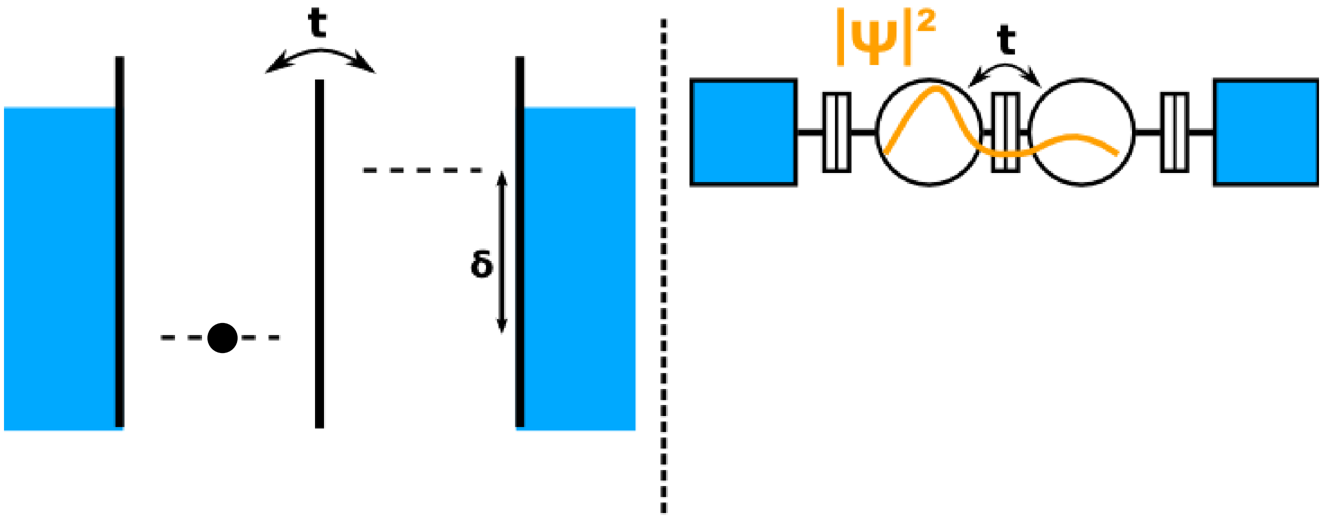
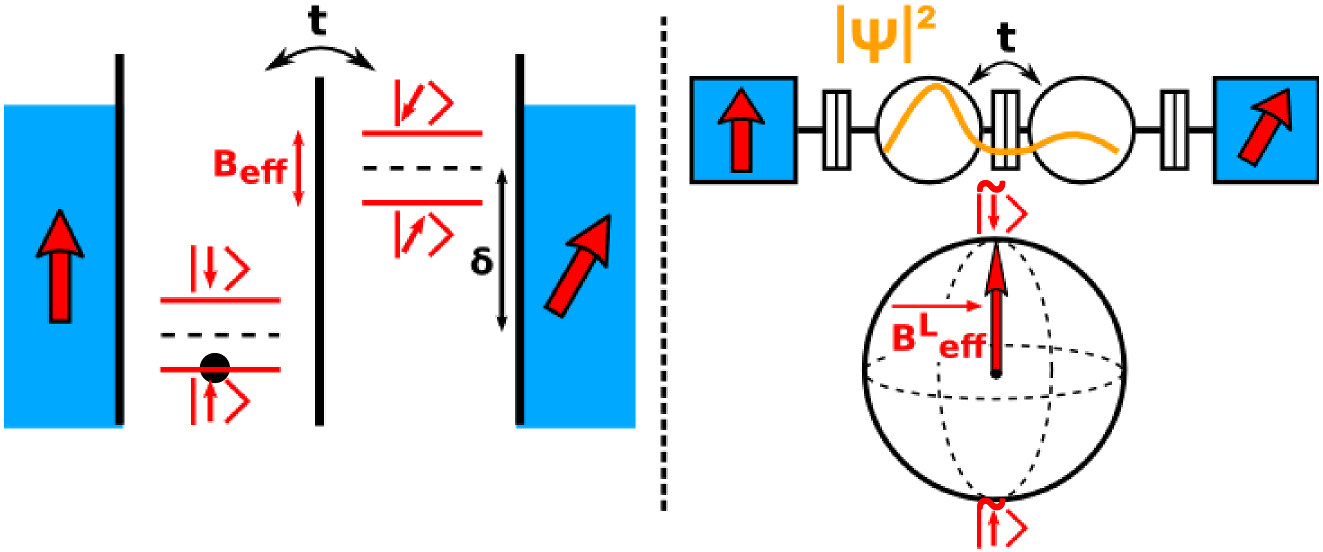


General principle of the ferromagnetic spin Qbit



A. Cottet et al. Phys Rev. Lett. (2010)

General principle of the ferromagnetic spin Qbit



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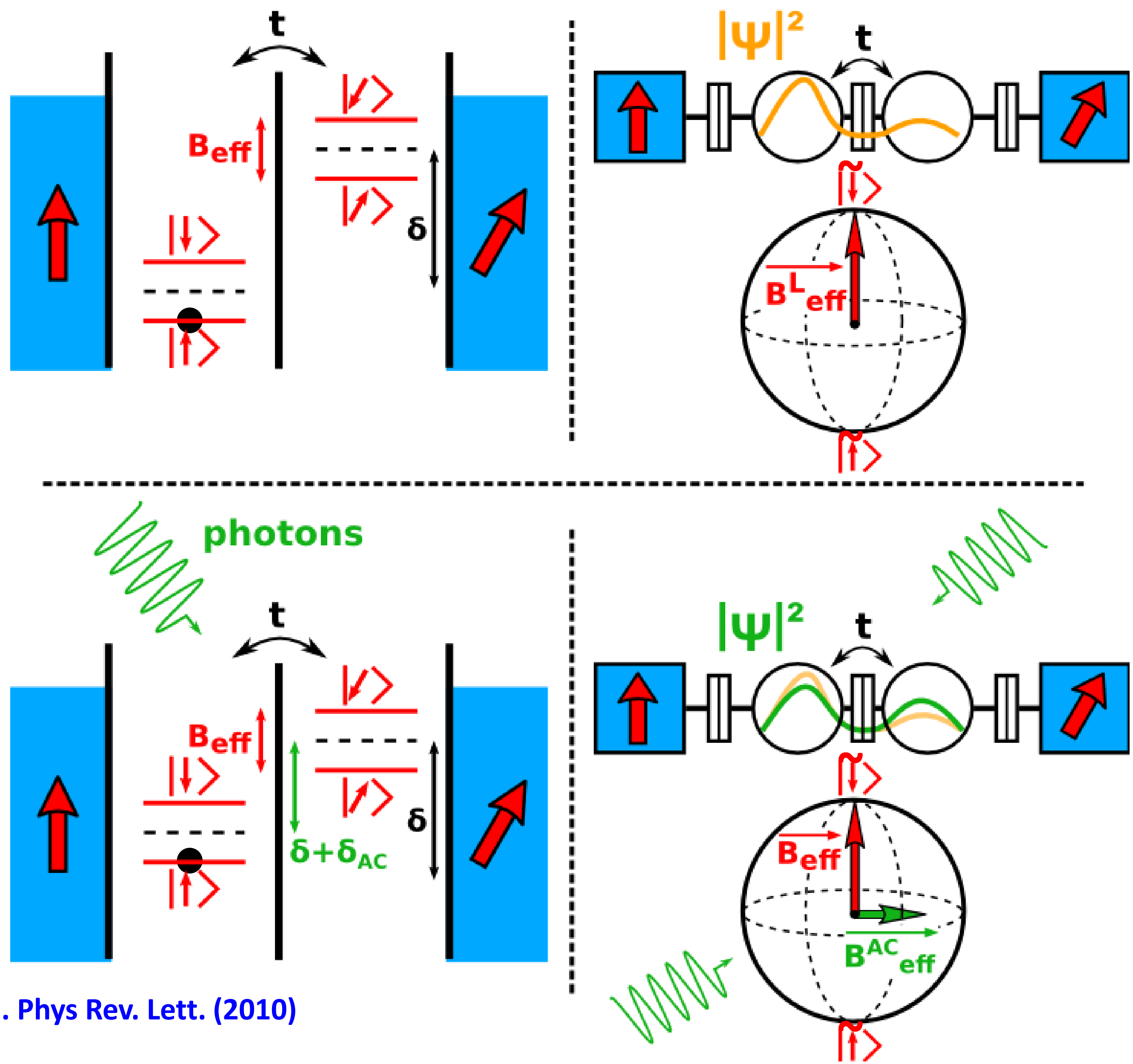
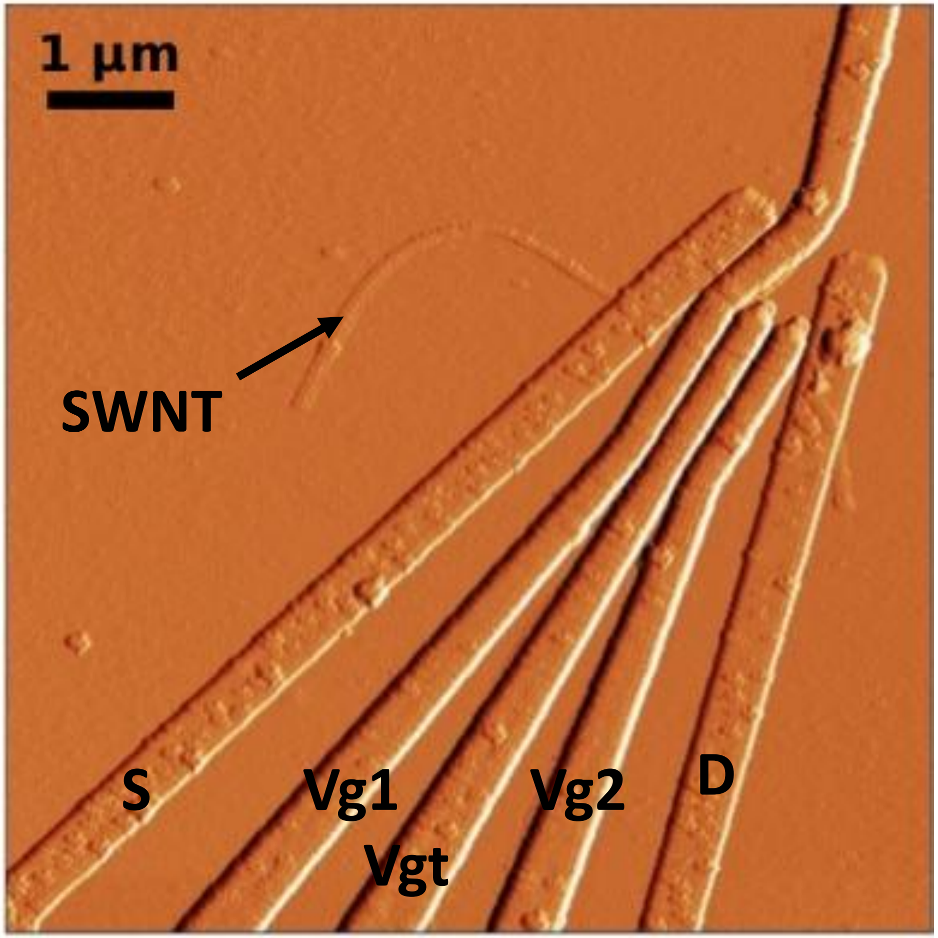
General principle of the ferromagnetic spin Qbit



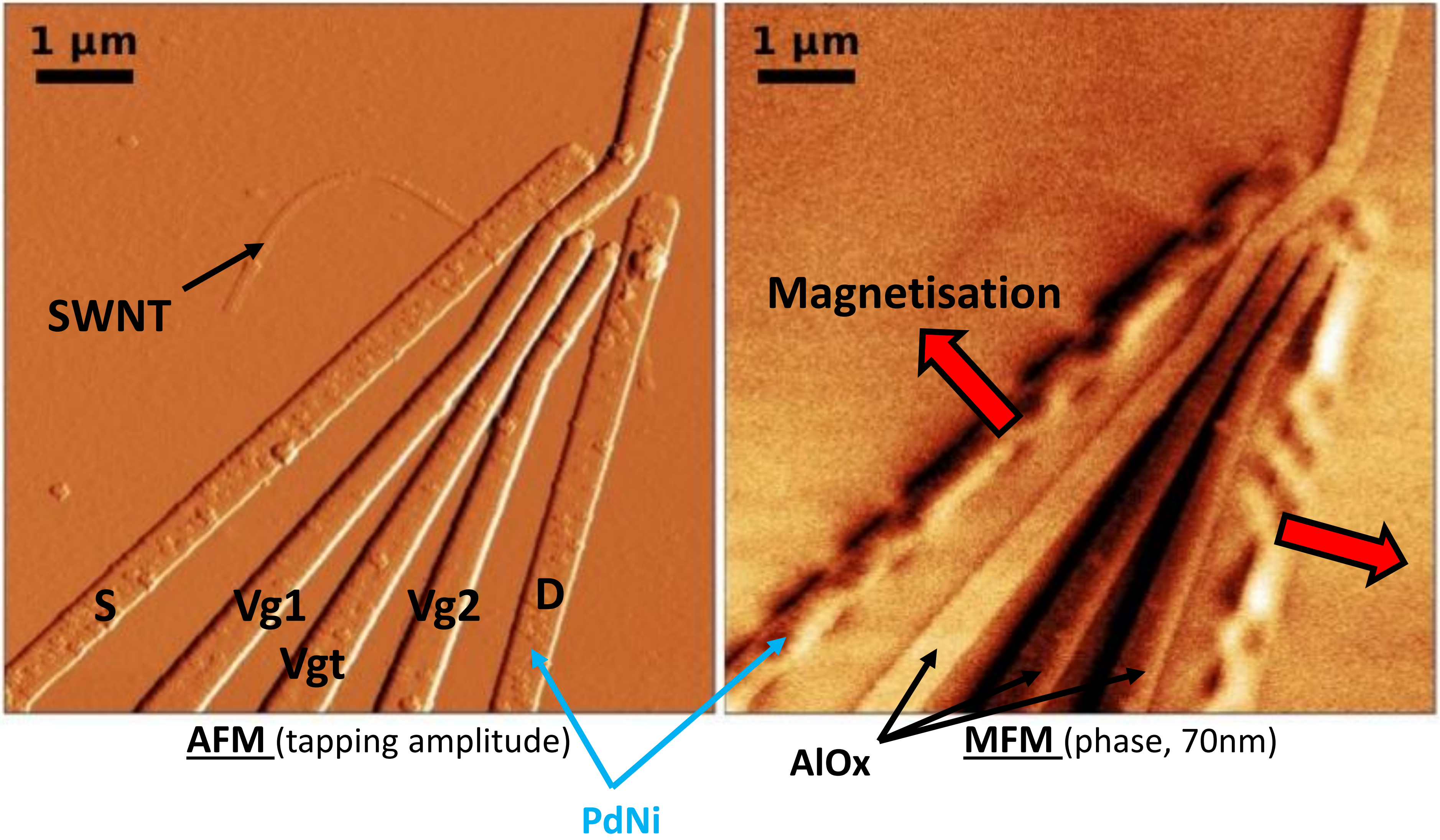
A. Cottet et al. Phys Rev. Lett. (2010)

Engineering non-collinear ferromagnets

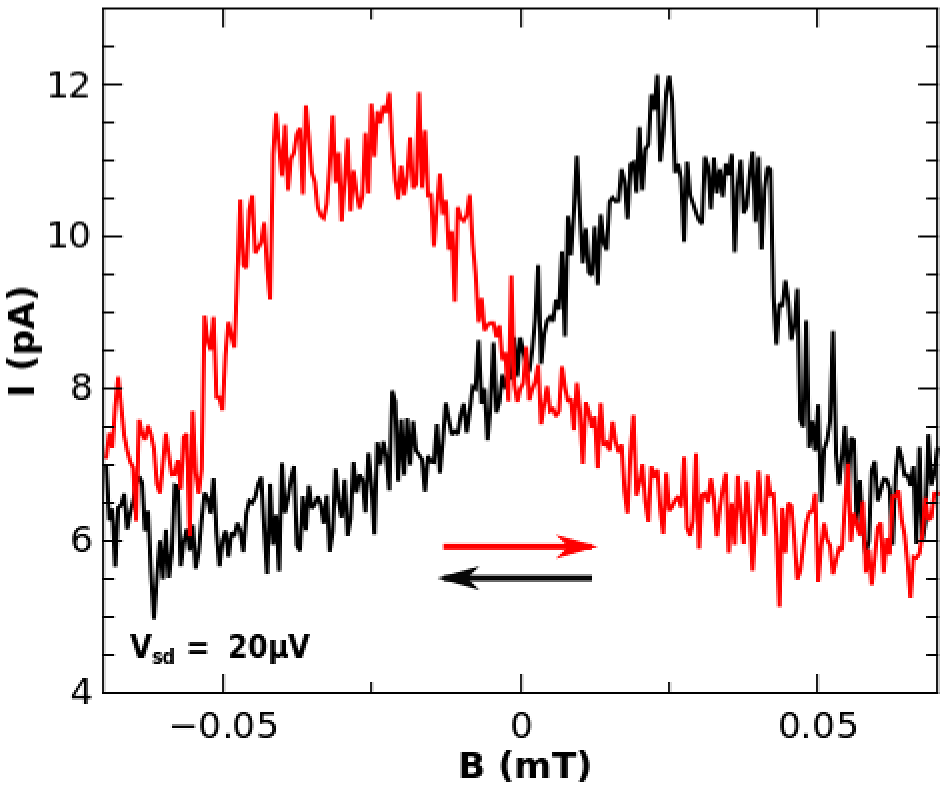


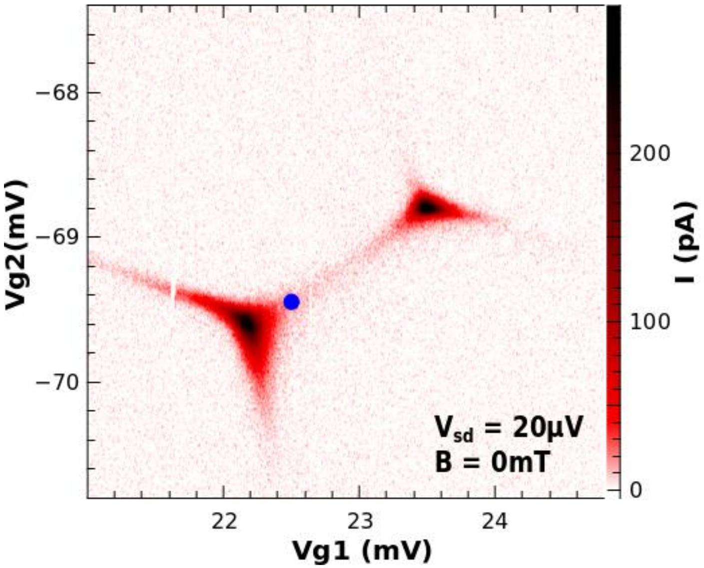
AFM (tapping amplitude)

Engineering non-collinear ferromagnets



Preliminary Results



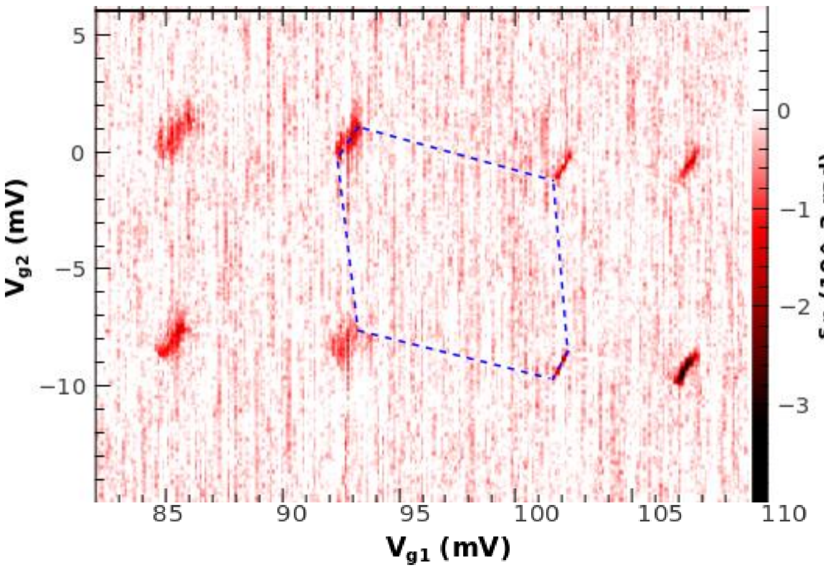


→ Signature of active ferromagnetic interfaces (MR~45%)

Conclusion part I

✓Coupling to charge Qbit, at resonance, in a *nuclear spin-free host material*

✓Out of equilibrium susceptibility measurement



Single Spin-Photon coupling in circuit-QED?

- Prediction of strong and switchable coupling for the ferromagnetic spinQbit

Other perspectives compatible with such an architechture:

- Decoherence study in strongly correlated systems
- Non-local effects in superconducting hybrid structures
- Quantum simulation of Anderson-Holstein physics
- …

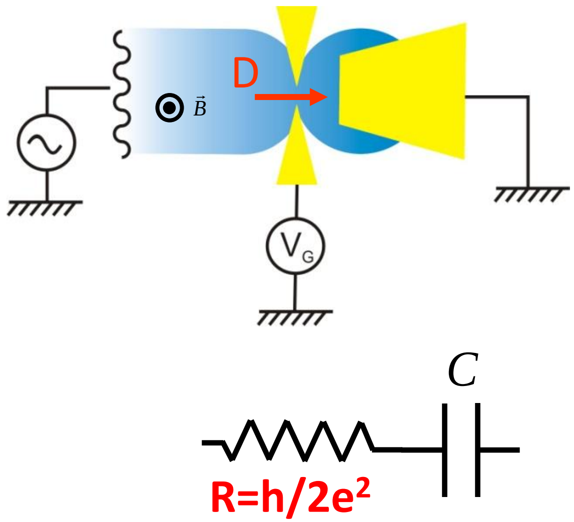
Outline

I. Out of equilibrium charge dynamics in a cQED architecture

II. Mesoscopic conductors in a cQED architecture

III. Non-collinear magnetoelectronics with a quantum dot

The quantum RC circuit



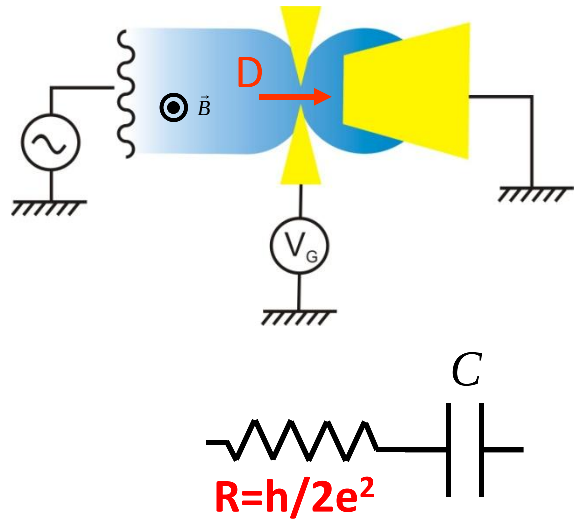
Universal relaxation resistance
(no interactions)

*J. Gabelli et al Science **313** 499 (2006)*

- Simplest paradigm for charge dynamics in a coherent conductor
- Universal relaxation resistance in a weakly interacting quantum dot in the coherent regime (Gamma's>>kT)

Nigg et al. Phys. Rev. Lett. 97, 206804 (2006), C. Mora and K. LeHur Nature Phys''08, M. Filippone et al. PRL'11, P. Dutt at al. arXiv:1301.3434

The quantum RC circuit



Universal relaxation resistance
(no interactions)

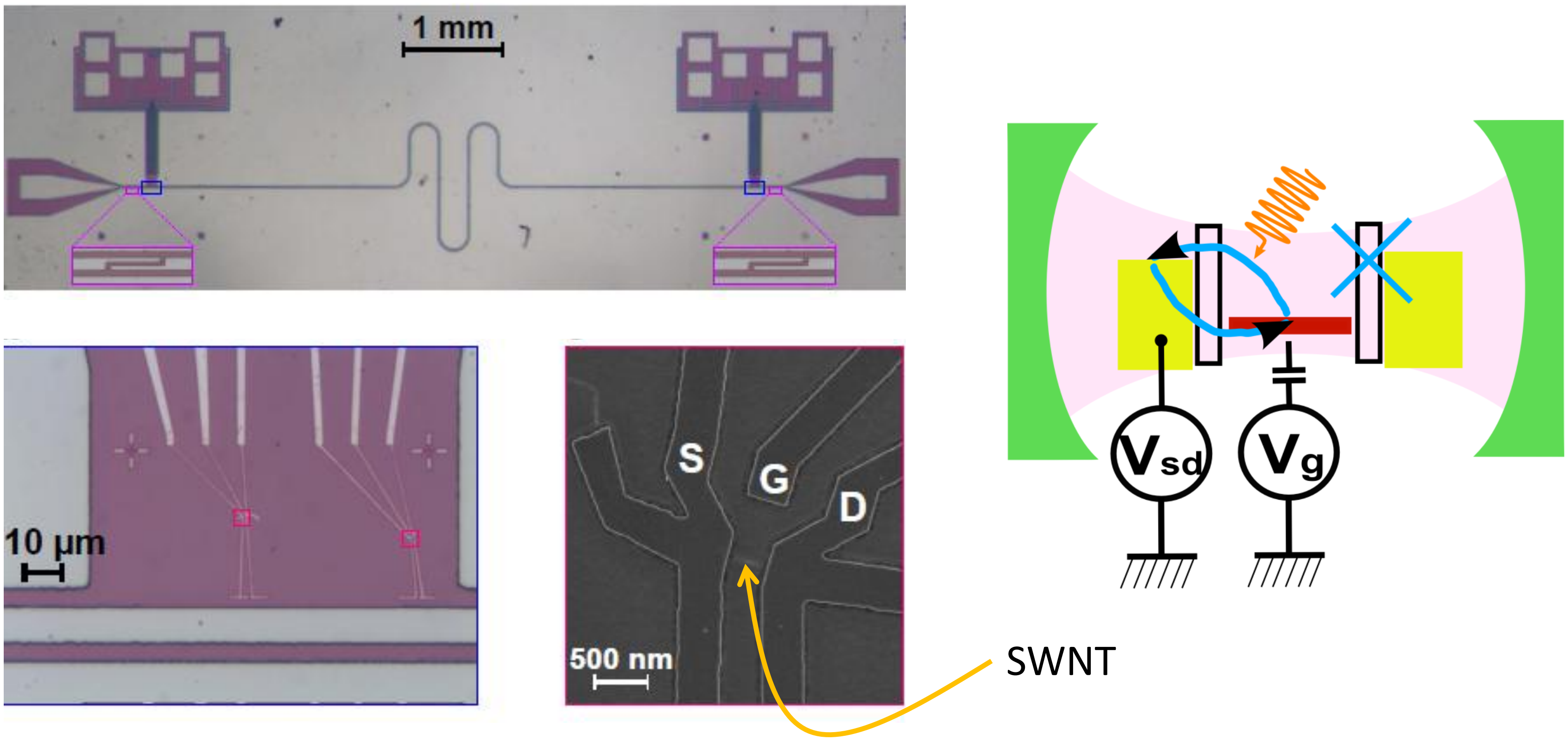
*J. Gabelli et al Science **313** 499 (2006)*

What happens if interactions are present ?

- Simplest paradigm for charge dynamics in a coherent conductor
- Universal relaxation resistance in a weakly interacting quantum dot in the coherent regime (Gamma's>>kT)

Nigg et al. Phys. Rev. Lett. 97, 206804 (2006), C. Mora and K. LeHur Nature Phys''08, M. Filippone et al. PRL'11, P. Dutt at al. arXiv:1301.3434

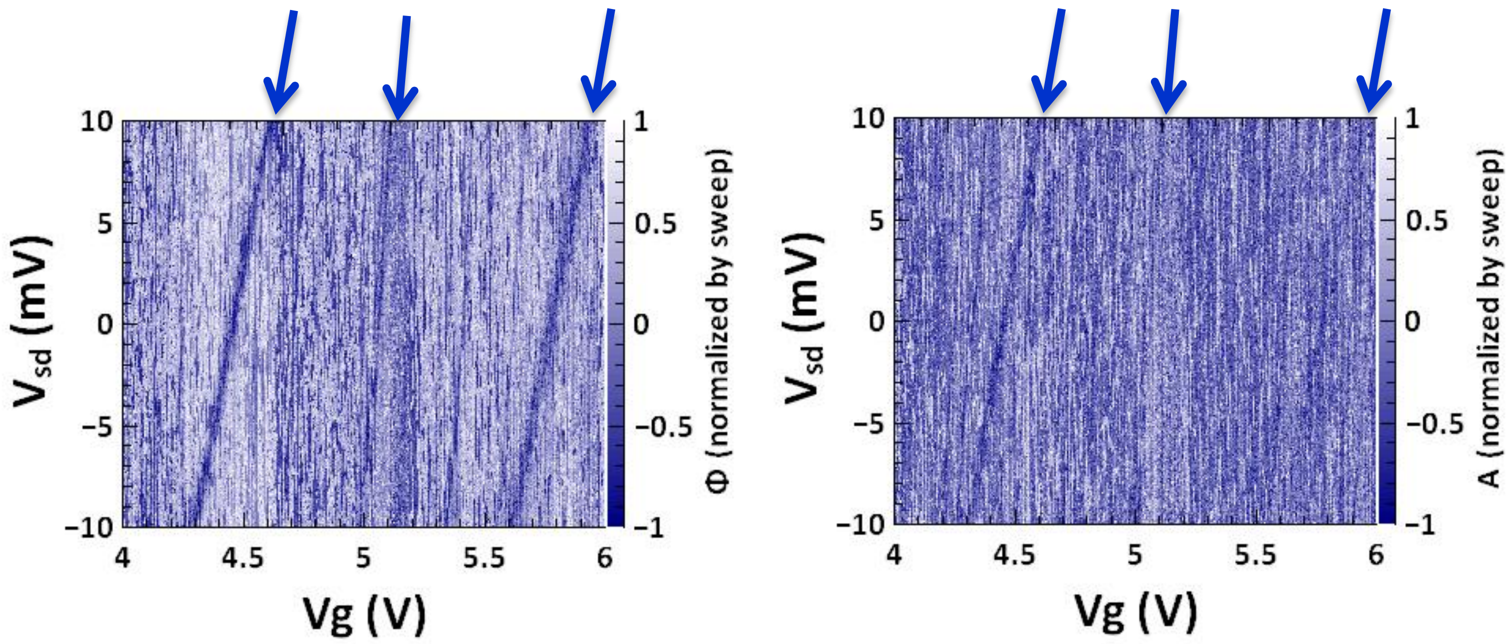
The quantum RC circuit



- Single wall carbon nanotube « connected » only to one metallic contact
- Use of cavity read-out only here (no DC current)

L.E. Bruhat et al. in preparation

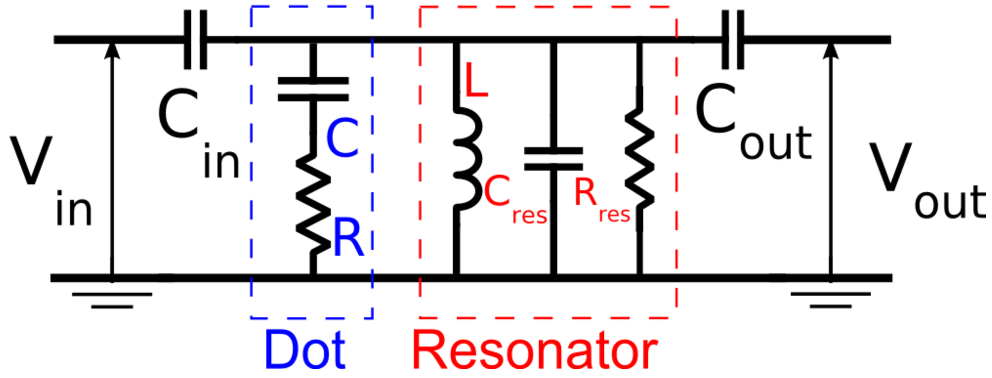
Phase and amplitude in the Vsd-Vg plane



- No DC current here (only one contact) but phase and amplitude contrast
- Resonant levels in the nanotube lead to peaks in phase and amplitude
- Positive slope show that one of the two metallic contact acts like a reservoir

L.E. Bruhat et al. in preparation

Classical circuit picture



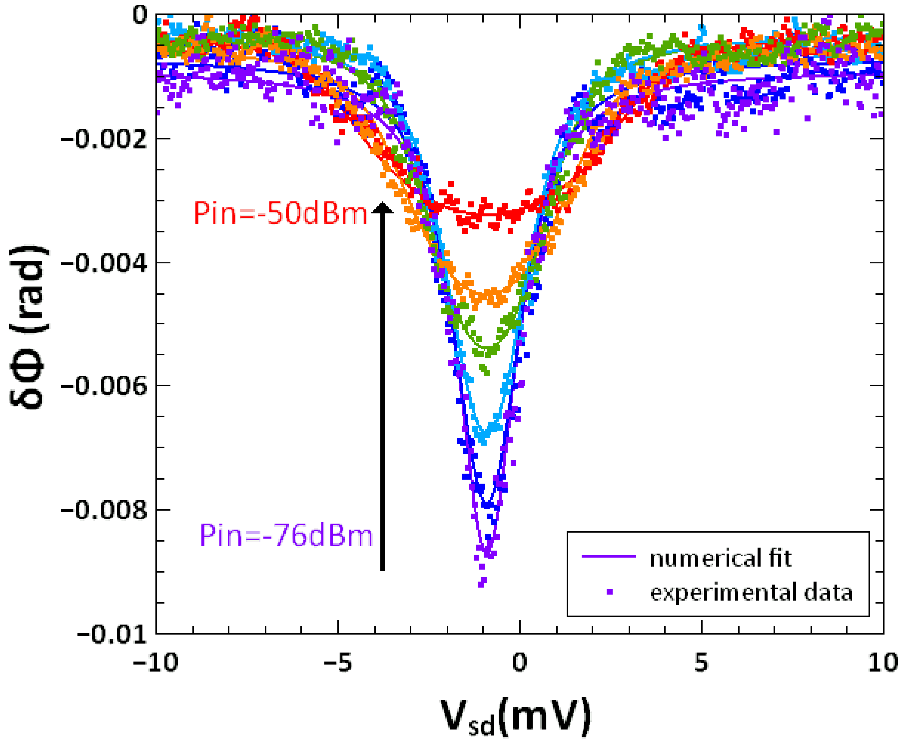
$$\delta f_R = \frac{f_0}{2Q}\delta\varphi = -f_0\frac{C}{2C_{res}}$$ → Dot capacitance

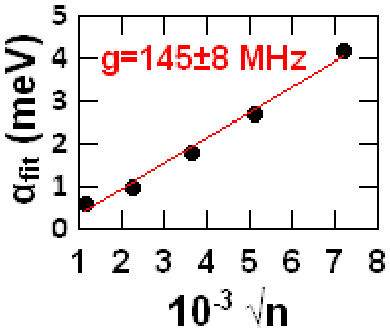
$$\delta f_D = -\frac{f_0}{2Q}\frac{\delta A}{A} = -\frac{1}{2\pi}\frac{RC^2\omega_0^2}{2C_{res}}$$ → Dot charge relaxation

- LC resonator and quantum RC circuit in parallel
- Cavity frequency shift is a direct measurement of dot's capacitance
- Amplitude change is a direct measurement of charge relaxation

L.E. Bruhat et al. in preparation

Electron-photon coupling calibration





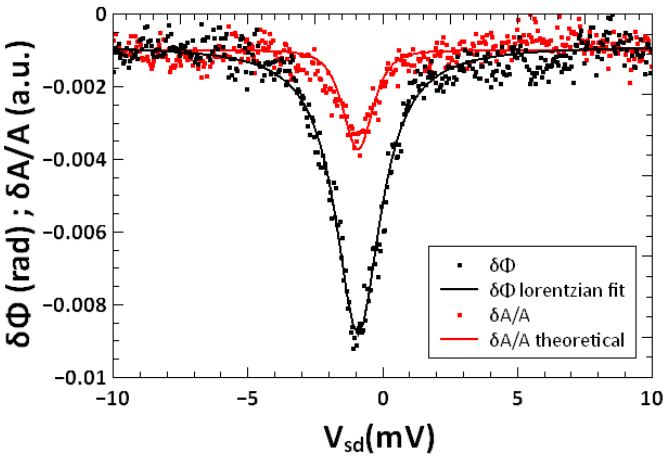
- Power evolution of phase peak allows to measure the electron-photon coupling
- Adiabatic peak modulation here (Gamma>>ω_0)
- Coupling strength consistent with previous measurements (about 100MHz)

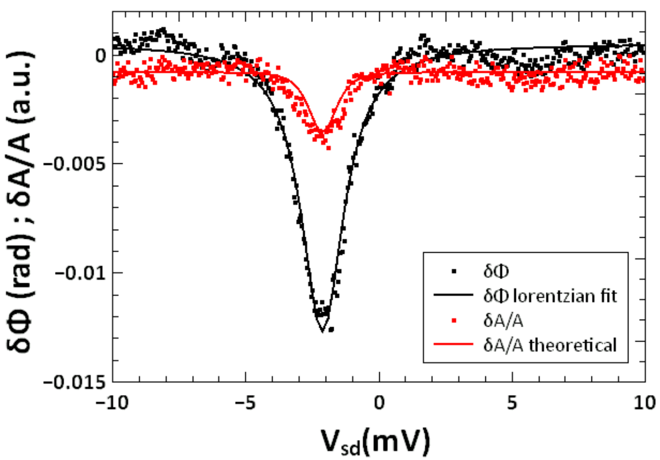
L.E. Bruhat et al. in preparation

Comparison with non-interacting theory !

Peak 1 g=145 MHz
<u>Cavity resonance fit</u> :
Q=6015   f0=6.41252 GHz
<u>Phase lorentzian fit :</u>
Γ=2.02 meV; **αint=0.077**

Peak 2 g=120 MHz
<u>Cavity resonance fit</u> :
Q=8100 ; f0=6.43629 GHz
<u>Phase lorentzian fit :</u>
Γ=1.94 meV ; **αint=0.13**





$$\delta\Phi = -\frac{2Q}{f_0}\frac{g^2}{h}\alpha_{int}\frac{4}{\pi}\frac{\Gamma}{4(eV_{sd}-\varepsilon_d)^2+\Gamma^2} \qquad \frac{\delta A}{A} = \frac{-g^2 Q}{\pi}\left(\frac{4\Gamma}{4(eV_{sd}-\varepsilon_d)^2+\Gamma^2}\right)^2$$

- Phase contrast corresponds to a strongly renormalized capacitance (OK if interactions)
- Relaxation account for by non-interacting theory with no adjustement parameter
- Non universal relaxation resistance (violation of Korringa-Shiba identity)

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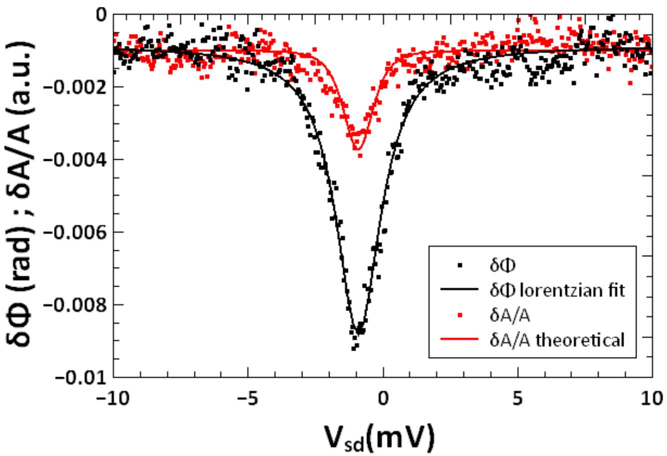

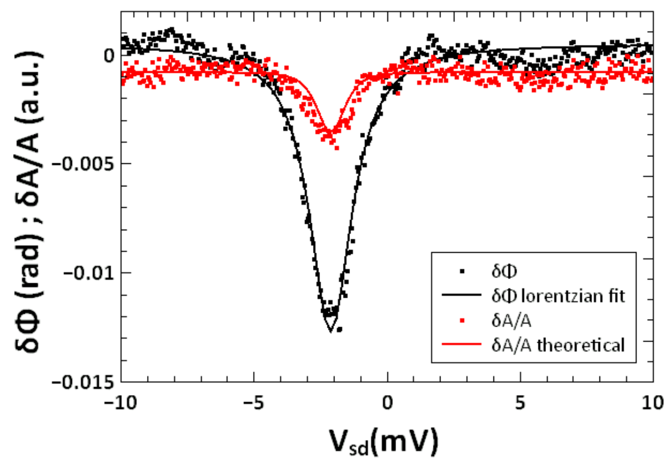

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- Phase contrast corresponds to a strongly renormalized capacitance (OK if interactions)
- Relaxation account for by non-interacting theory with no adjustement parameter
- Non universal relaxation resistance (violation of Korringa-Shiba identity)

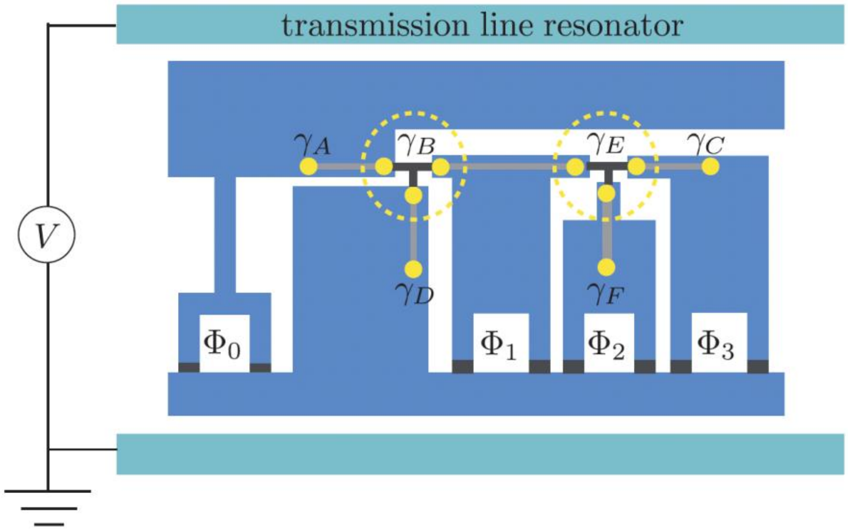
Can we expand this method to more exotic mesoscopic systems ?

Majorana systems in cavities

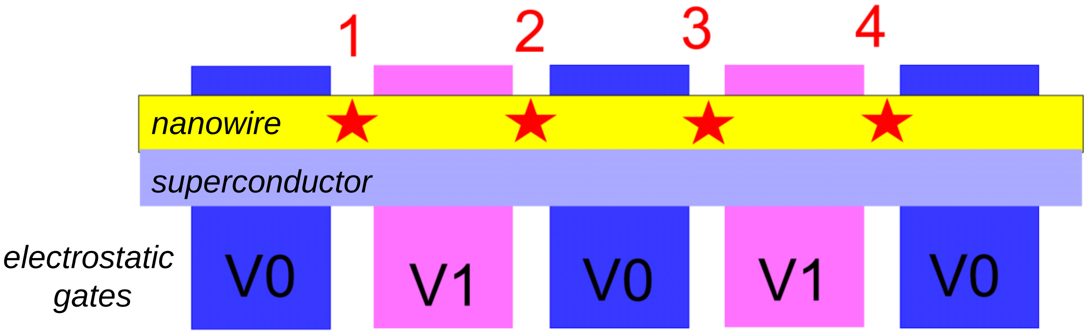
F. Hassler et al. New J. Phys. 13, 095004 (2011)
T. Hyart et al., PRB 88, 035121 (2013),
C. Müller, J. Bourassa and A. Blais, arXiv 1306.1539
E. Ginossar and E. Grosfeld, arXiv 1307.1159

Coupling to cavity mediated by a superconducting quantum bit

M. Trif, and Y. Tserkovnyak, Phys. Rev. Lett. 109, 257002 (2012).
T. L. Schmidt, A. Nunnenkamp, and C. Bruder, PRL110, 107006 (2013).



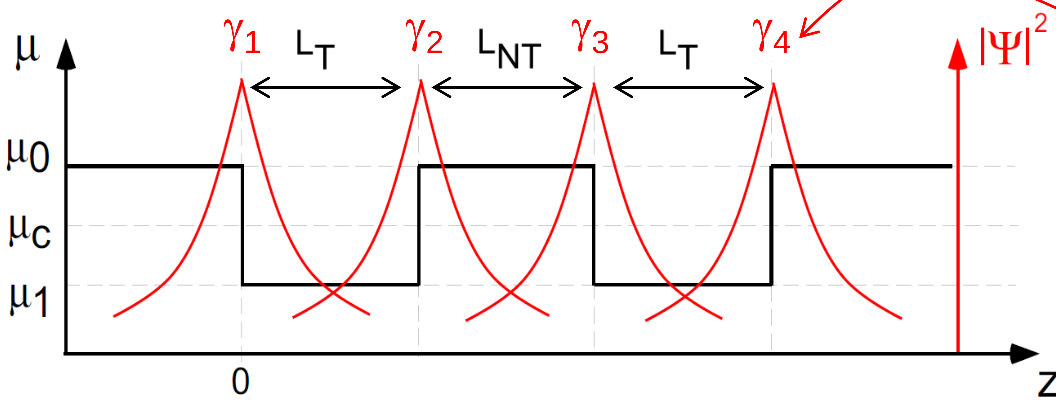
4-Majorana bound states system



$\mu_c/\Delta = 1.73$

Topological sections : $\mu_1 < \mu_c$

Non-topological sections : $\mu_0 > \mu_c$



Majorana operators:

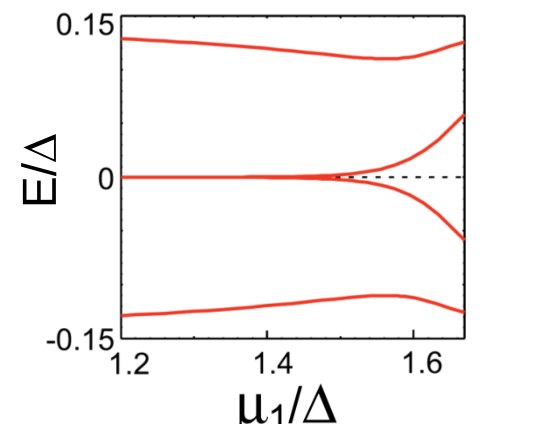
$\gamma_i^\dagger = \gamma_i \qquad \gamma_i^2 = 1/2$

$i \in \{1, 2, 3, 4\}$

$$H_{wire} = 2i\epsilon(\gamma_1\gamma_2 + \gamma_3\gamma_4) + 2i\tilde{\epsilon}\gamma_2\gamma_3$$

$$\begin{cases} \epsilon \simeq \lambda_\epsilon e^{-|k(\mu_1)|L_T} \\ \tilde{\epsilon} \simeq \lambda_{\tilde{\epsilon}} e^{-|k(\mu_0)|L_{NT}} \end{cases}$$

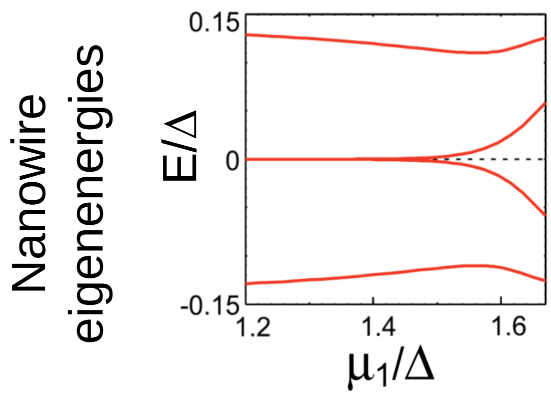
Nanowire eigenenergies:

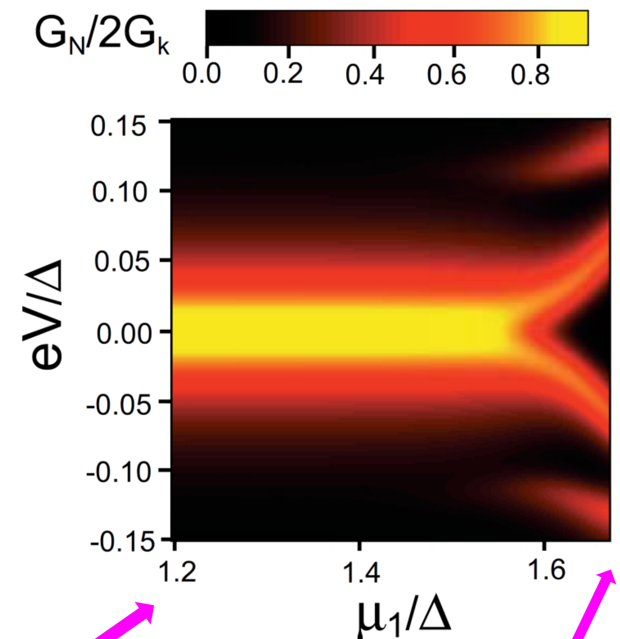


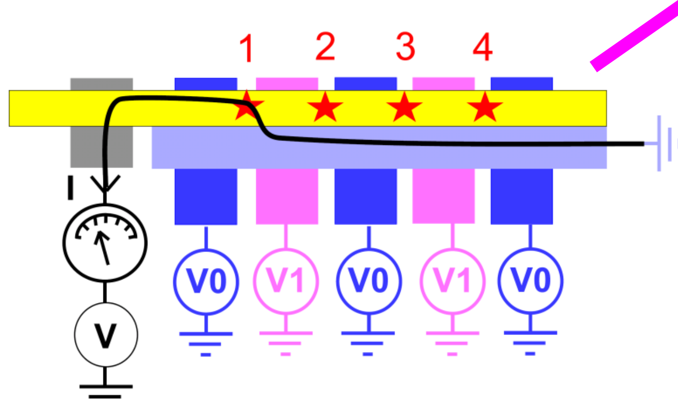
Conductance of the nanowire

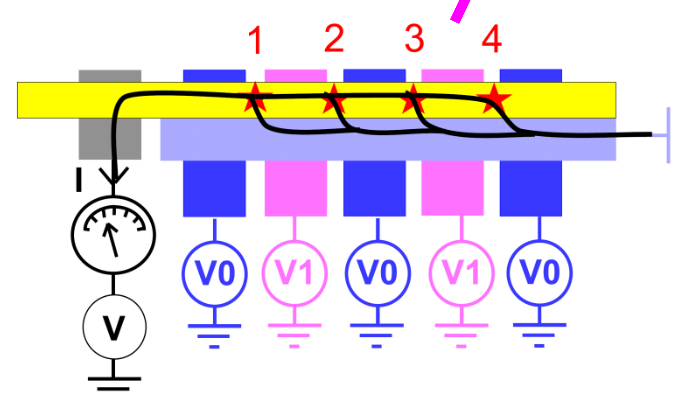
$$H_{wire} = 2i\epsilon(\gamma_1\gamma_2+\gamma_3\gamma_4)+2i\tilde{\epsilon}\gamma_2\gamma_3$$

$$H_c = \sum_p \varepsilon_p c_p^\dagger c_p + t(c_p^\dagger - c_p)\gamma_1$$





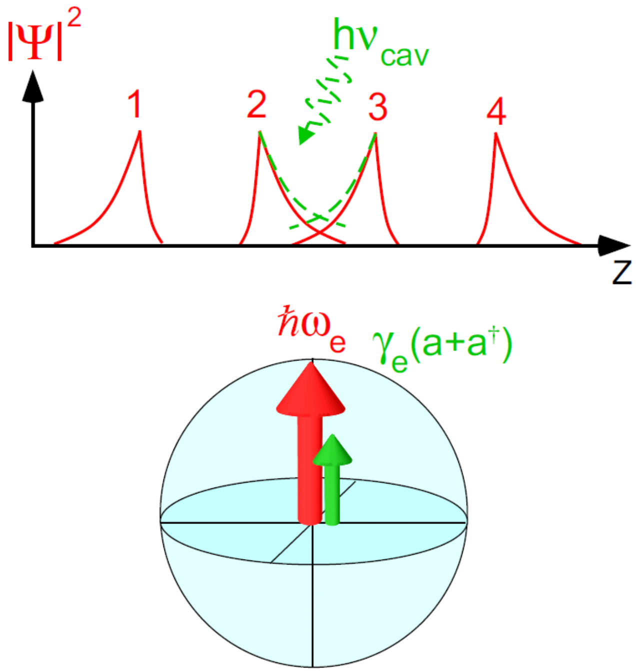




See for instance Flensberg, PRB (2010) for the conductance calculation

Effect of μ_1 on the transverse coupling

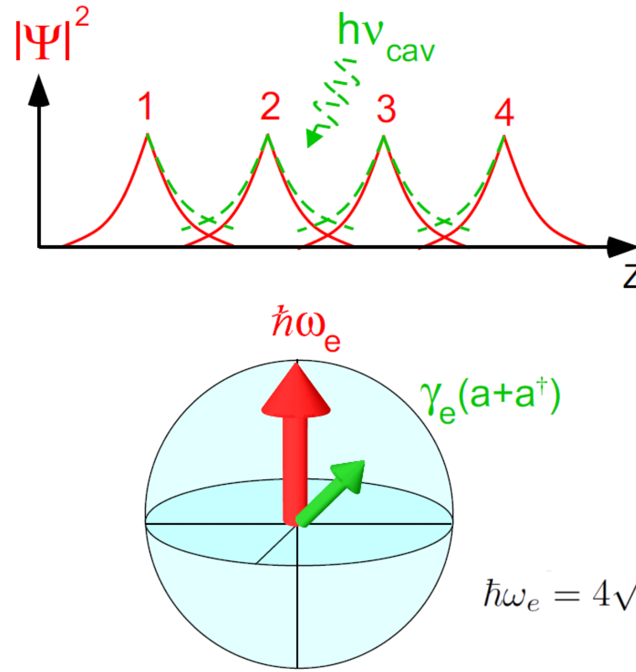
μ_1 far below μ_c



$$H_{wire} = 2i\tilde{\epsilon}\gamma_2\gamma_3$$

$$h_{int} = 2i\tilde{\beta}\gamma_2\gamma_3$$

μ_1 close to μ_c



$$\hbar\omega_e = 4\sqrt{4\epsilon^2 + \tilde{\epsilon}^2}$$

$$H_{wire} = 2i\epsilon(\gamma_1\gamma_2 + \gamma_3\gamma_4) + 2i\tilde{\epsilon}\gamma_2\gamma_3$$

$$h_{int} = 2i\beta(\gamma_1\gamma_2 + \gamma_3\gamma_4) + 2i\tilde{\beta}\gamma_2\gamma_3$$

The disappearance of the transverse coupling for μ_1 far below μ_c
is a direct consequence of the self-adjoint character of Majorana fermions

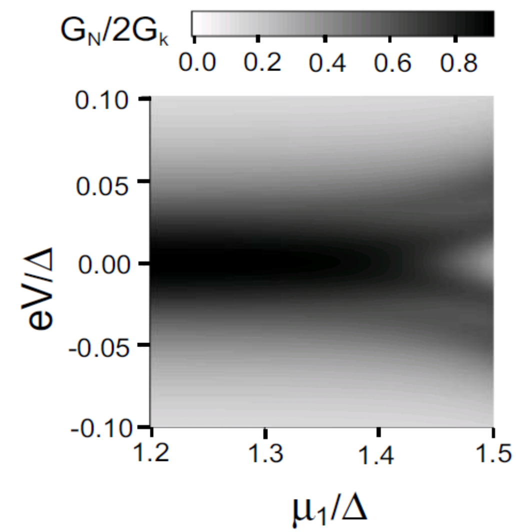
Experimental signatures of the Transverse coupling

Cottet, Kontos & Douçot, arXiv:1307.4185

Realistic parameters:

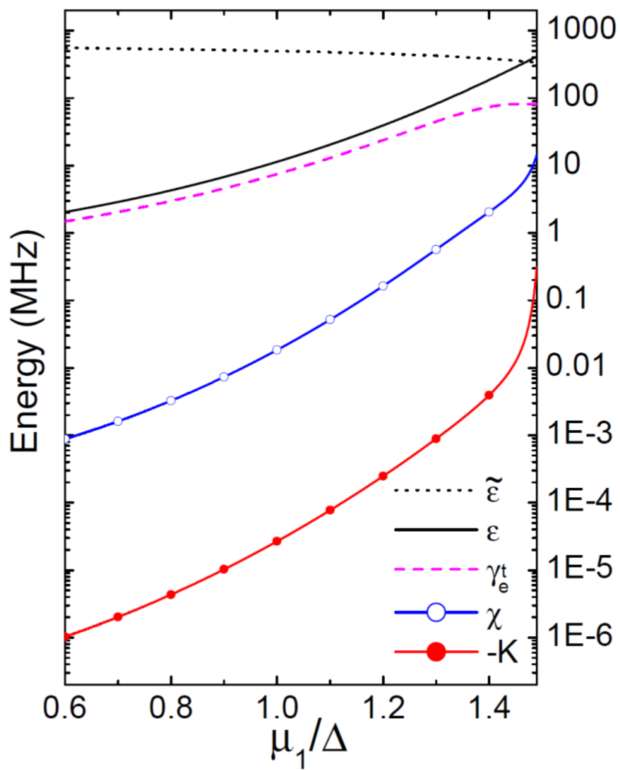
$$\Delta = 250\ \mu\text{eV}$$
$$E_z = 500\ \mu\text{eV}$$
$$\alpha_{so} = 4\ 10^4\ \text{m.s}^{-1}$$
$$L_{T(NT)} = 1\ \mu\text{m}$$
$$\alpha_c V_{rms} = 2\ \mu\text{V}$$
$$\omega_{cav}/2\pi = 4\ \text{GHz}$$

⇨ $\mu_c/\Delta = 1.73$



χ : cavity dispersive frequency shift

K: amplitude of nonlinear Kerr term



$\chi = 14$ MHz

$K = -0.31$ MHz

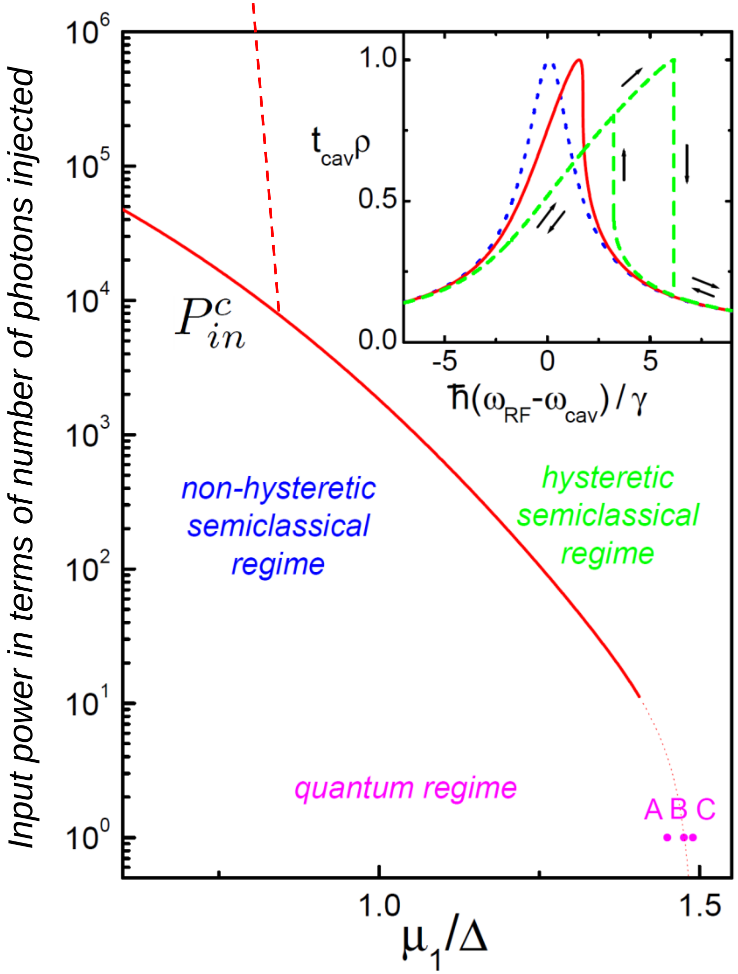
$\chi = 9\ 10^{-4}$ MHz

$K = -10^{-6}$ MHz

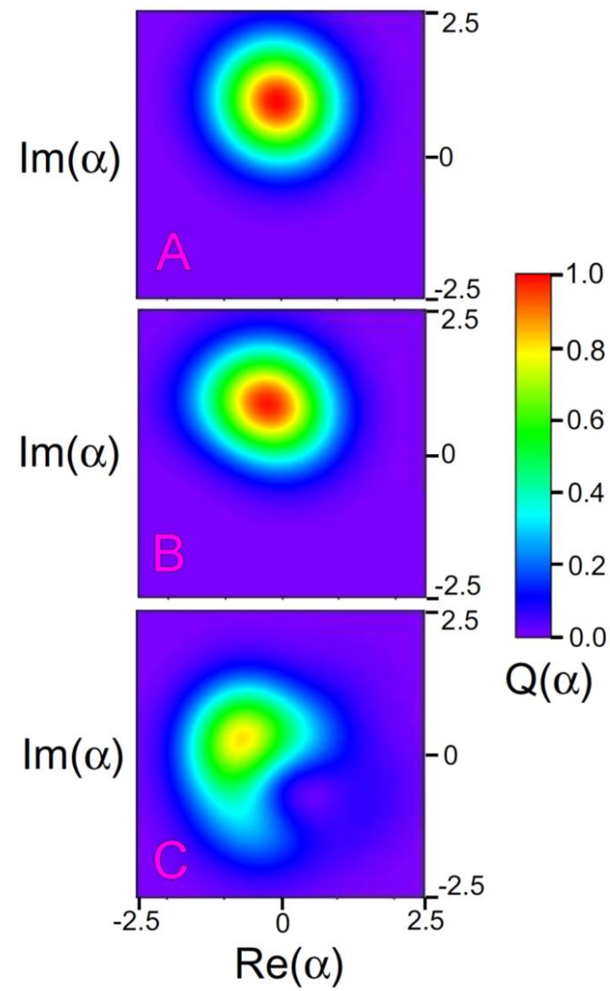
The evolutions of χ & K reveal $\gamma_i^\dagger = \gamma_i$ & the exponential confinement of MBSs

Measuring the cavity nonlinearity K

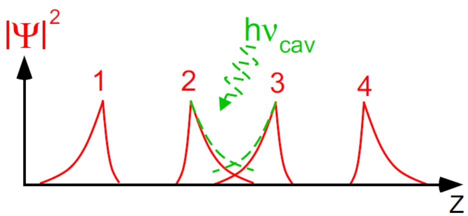
$$P_{in}^{c} \propto |K|^{-1} \propto e^{2|k_m(\mu_1)|L_T}$$

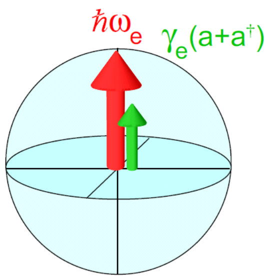


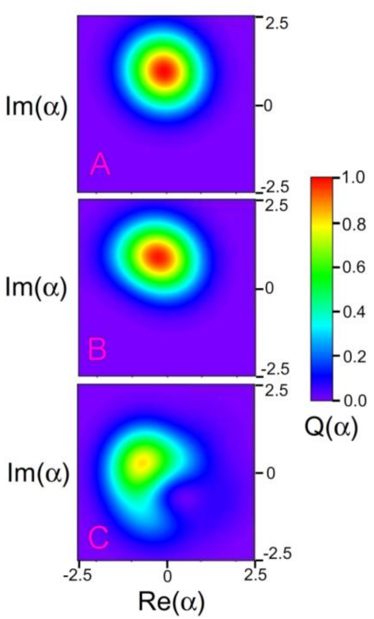
Cavity tomography at a time Δt after switching off the input power

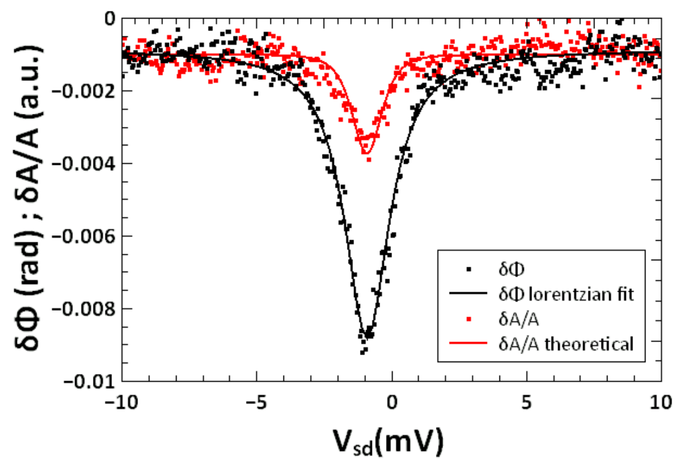


Conclusion part II









Study of the quantum RC circuit problem

- Non-interacting theory account with no adjustable parameter for relaxation… but capacitance renormalized by interaction (non-universal relaxation)

Generalization to more exotic electronic states

- Detection of self-adjoint character of Majorana's
- Squeezing of (microwave) light due to large Majorana-photon coupling

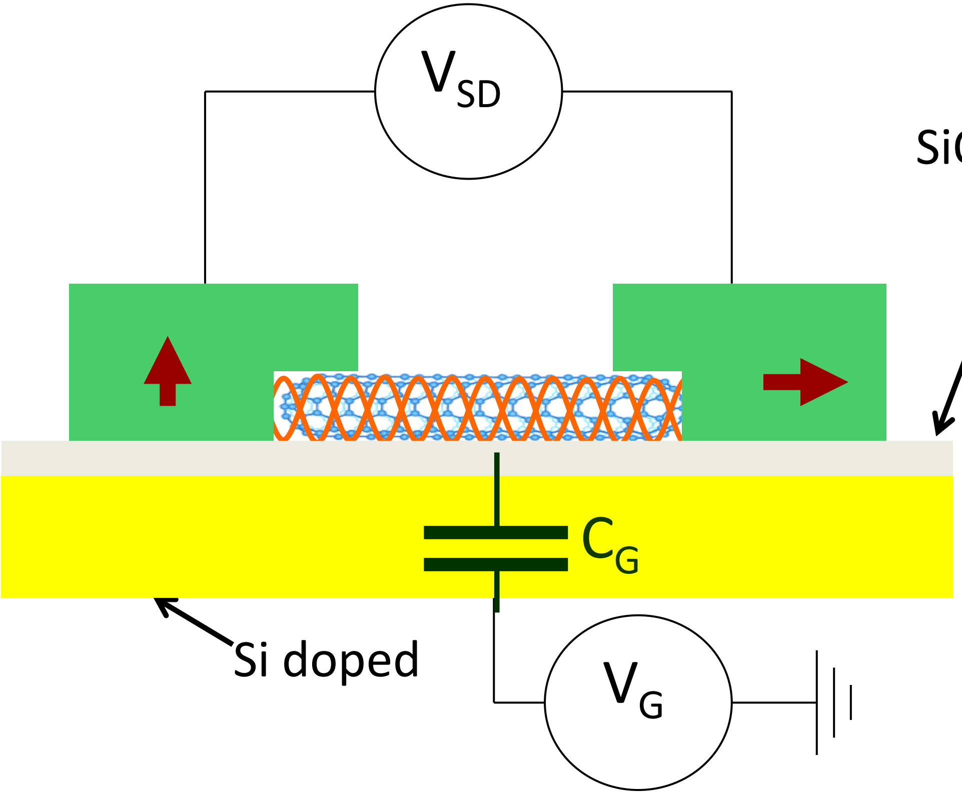
Outline

I. Out of equilibrium charge dynamics in a cQED architecture

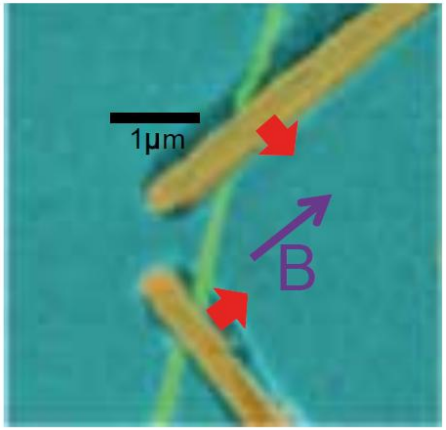
II. Mesoscopic conductors in a cQED architecture

III. Non-collinear magnetoelectronics with a quantum dot

A non-collinear spin valve with a nanotube

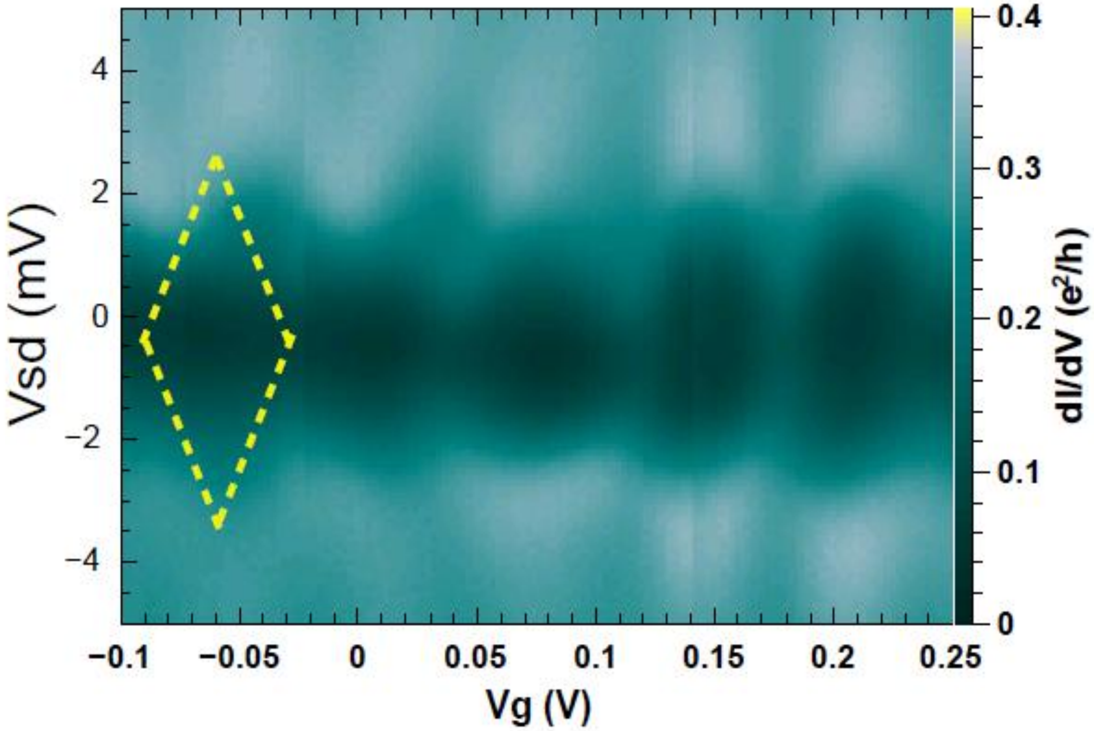


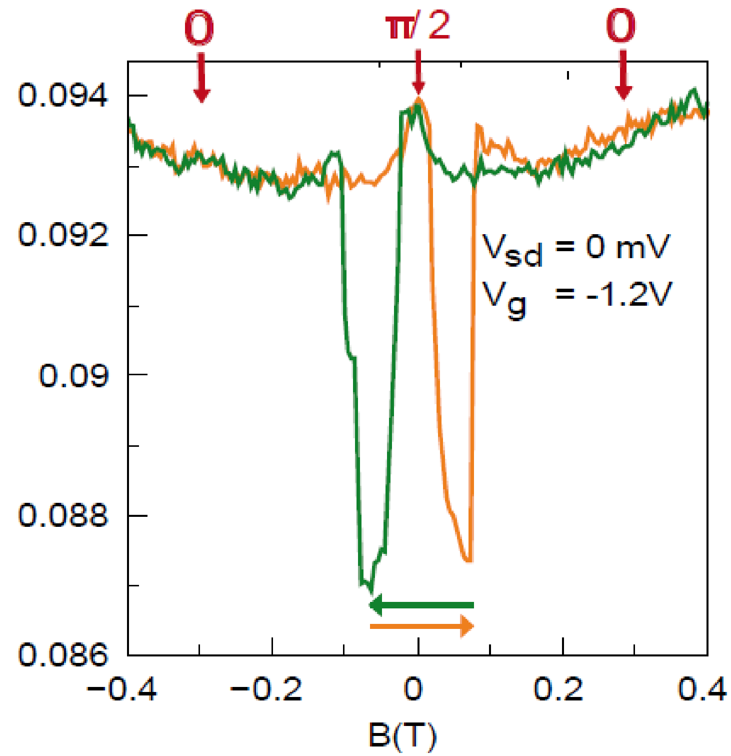
Spin valve geometry



- Electrical injection and detection of spins in the nanotube.
- Study as a function of V_{SD}, V_G and external B.
- Non-collinear magnetizations obtained geometrically (B along easy axis of one of the magnetizations

Characterization of the device

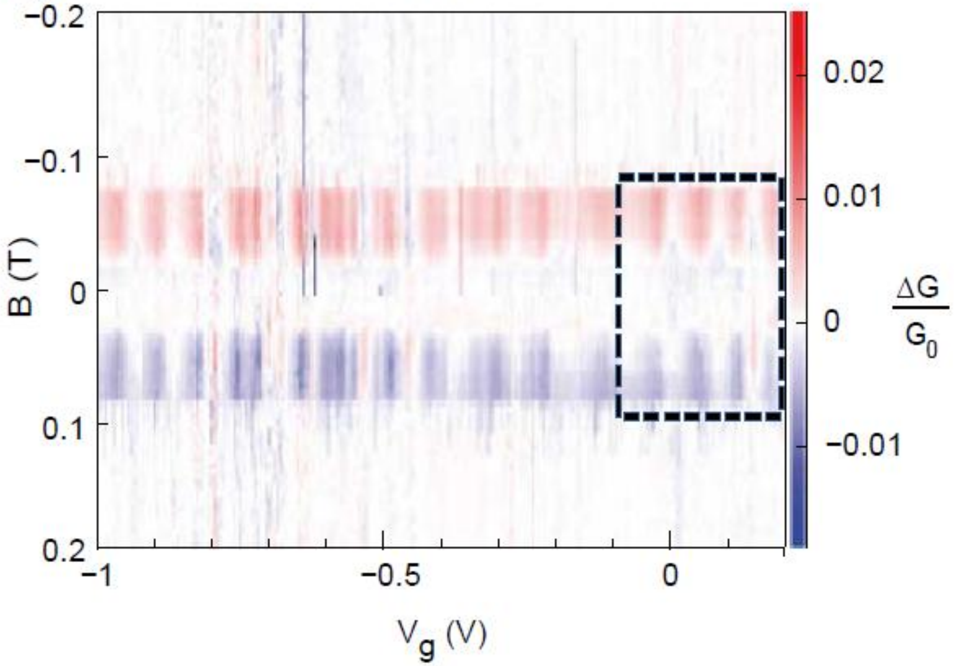


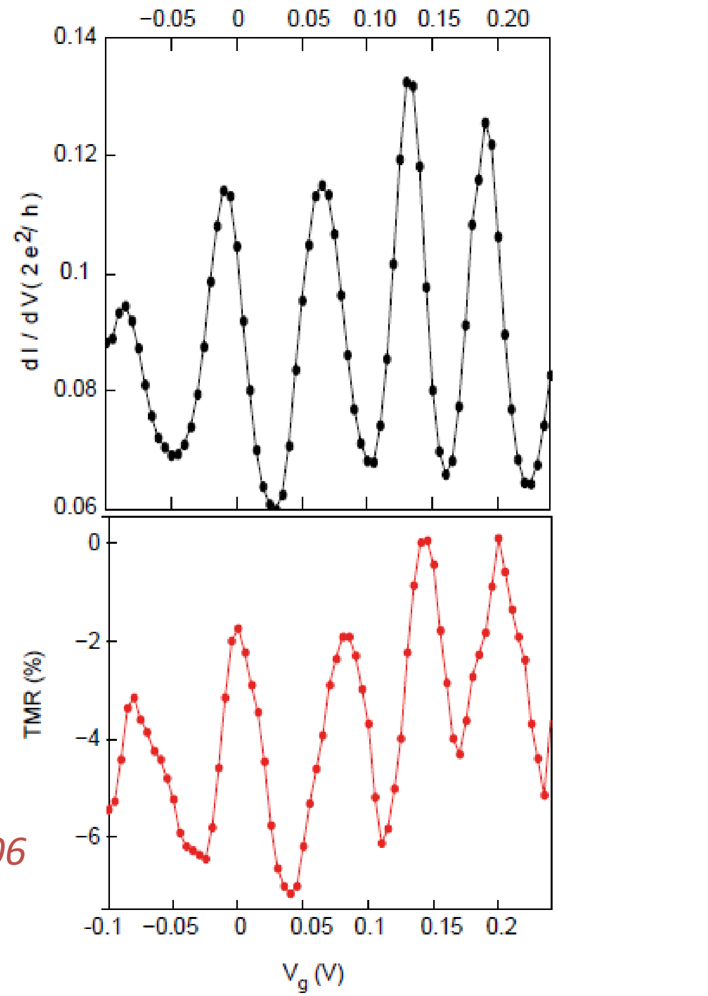


- Coulomb diamonds of a rather open and asymmetric Qdot
- Spin valve like signal of about 4%

A.D. Crisan et al. in preparation

Spin signal in the linear regime





See also: S. Sahoo et al. Nature Phys'05, H.T. Man et al PRB(R)'06
C. Feuillet-Palma et al. PRB'10

- Oscillations of TMR with the same period as G
- Standard behavior of a quantum dot spin valve (but no sign change)
- TMR and G slightly out of phase but TMR not derivative of G (no magnetocoulomb)

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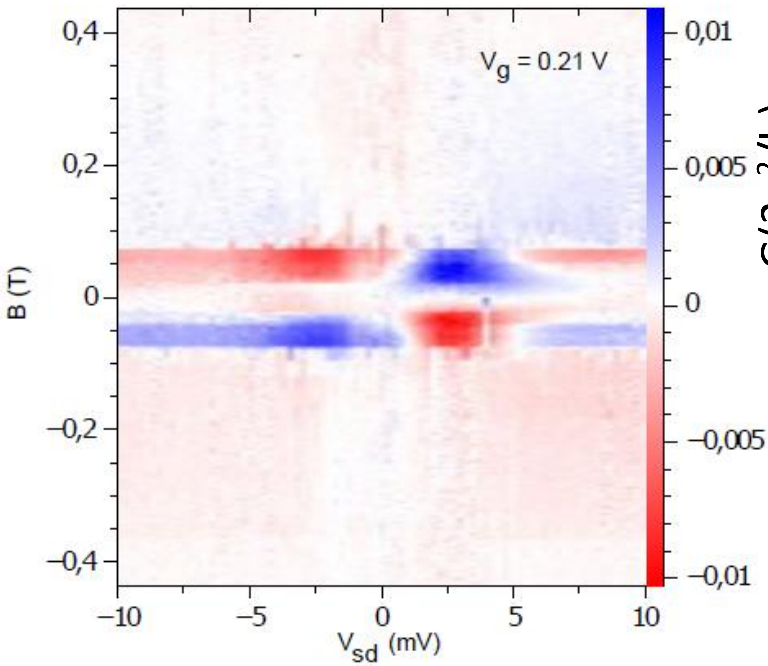
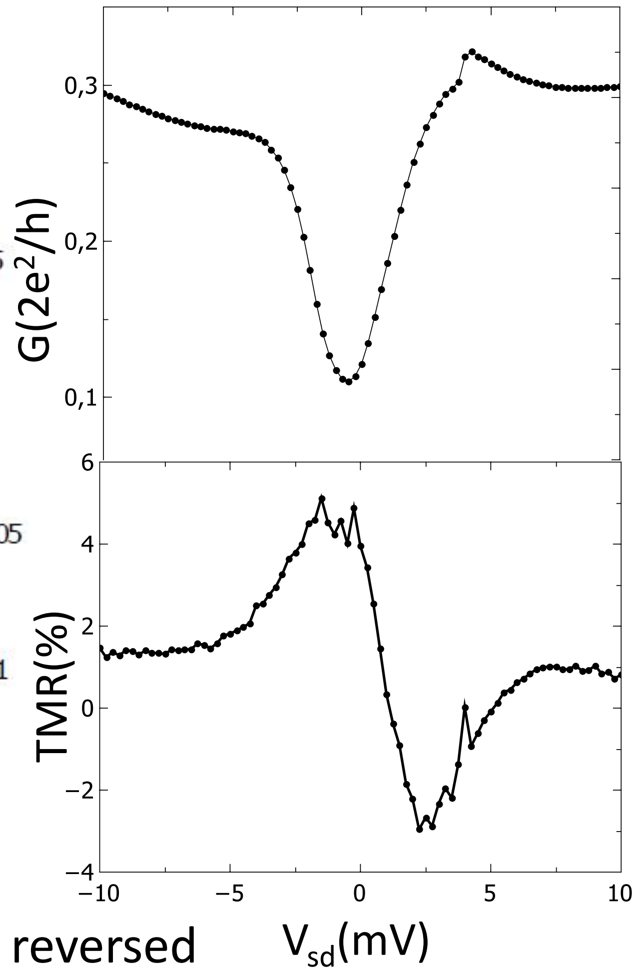
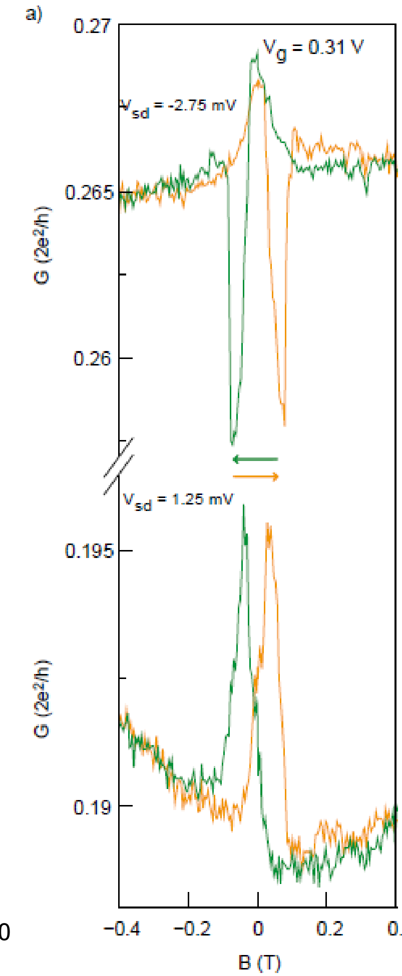
Spin signal in the nonlinear regime







- Sign change of TMR as bias is reversed
- Nearly antisymmetric TMR as a function of bias
- Same symmetry as current

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Spin signal in the nonlinear regime

$$\overrightarrow{B} = B_L \overrightarrow{n}_L + B_R \overrightarrow{n}_R$$

$$\frac{d\overrightarrow{S}}{dt} = \frac{h}{2e} p I (\overrightarrow{n}_L - \overrightarrow{n}_R) + \overrightarrow{S} \times \overrightarrow{B} - \frac{\overrightarrow{S}}{\tau_s}$$

$$S_{L(R)} = \frac{h}{2e} p (1 - \cos\phi) I \tau_s \times \frac{1}{1 + (\omega_L \tau_s)^2 (\sin\phi)^2}$$

Spin accumulation

Hanle term

See e.g. : W. Wetzels, M Grifoni and G.E.W Bauer PRB'06

- Phenomenological Bloch-Redfield type equation for the spin of the dot
- Competition between spin accumulation, spin precession and relaxation
- We assume that the interface fields are negligible

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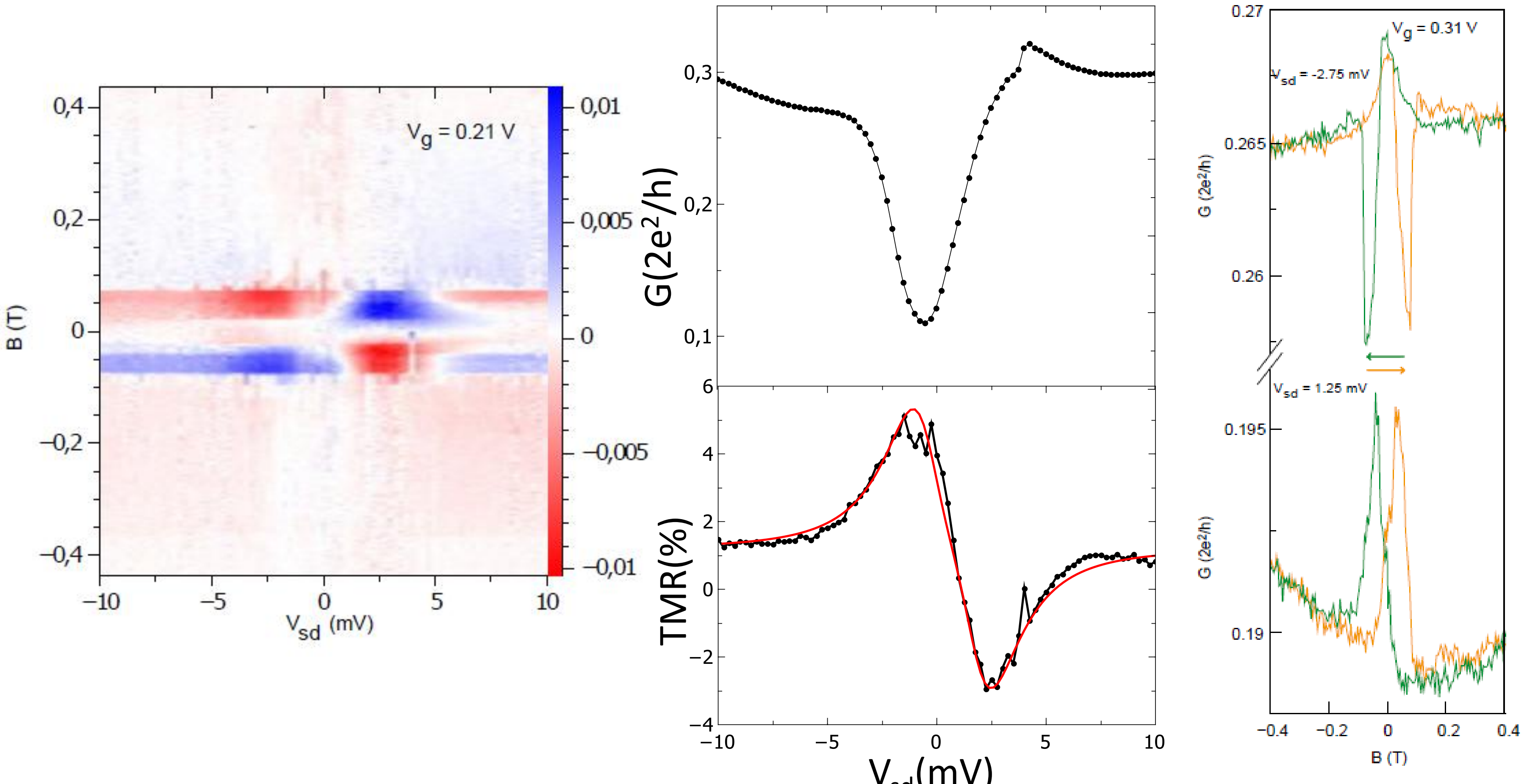
Spin signal in the nonlinear regime



- Quantitative agreement with simple spin accumulation/spin precession model
- Main ingredient is bias dependence of relaxation time $\tau_s \approx \tau_0/(1+(V_{sd}/V_0)^2)^2$
- Low bias proportional to current as expected from spin accumulation

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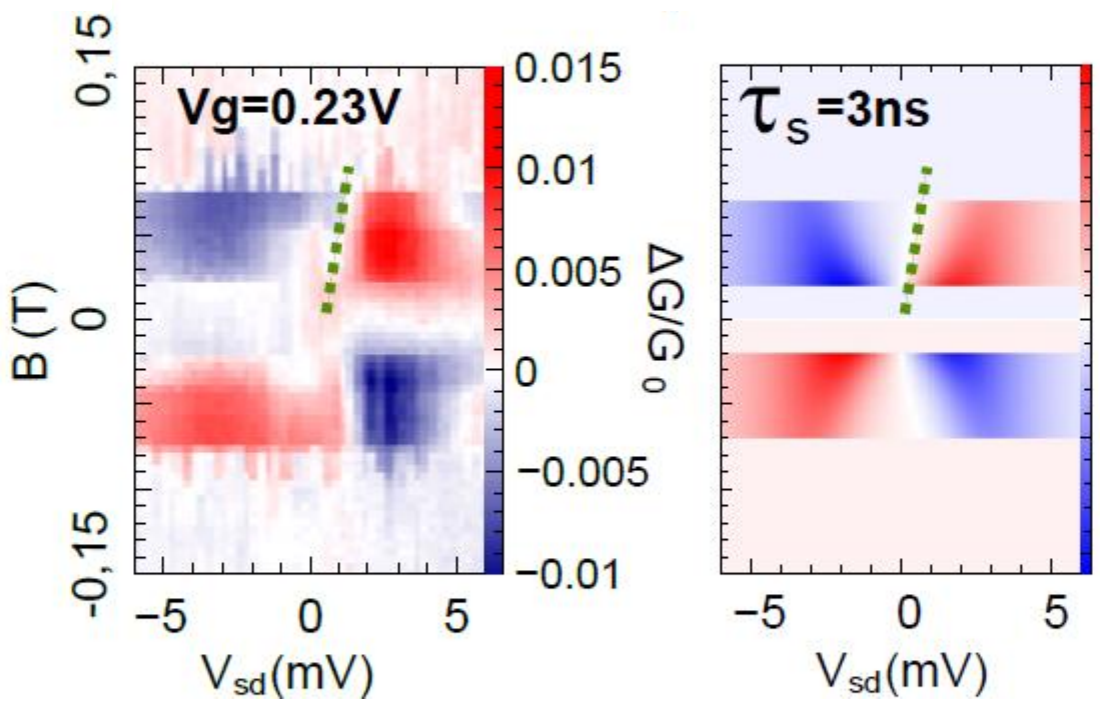
Spin signal in the nonlinear regime



- Slope of white line correspond to a «g» factor between 200 and 700 !
- Cannot be explained by Zeeman and/or orbital effect
- Spin precession model naturally explain it with reasonable spin relaxation time

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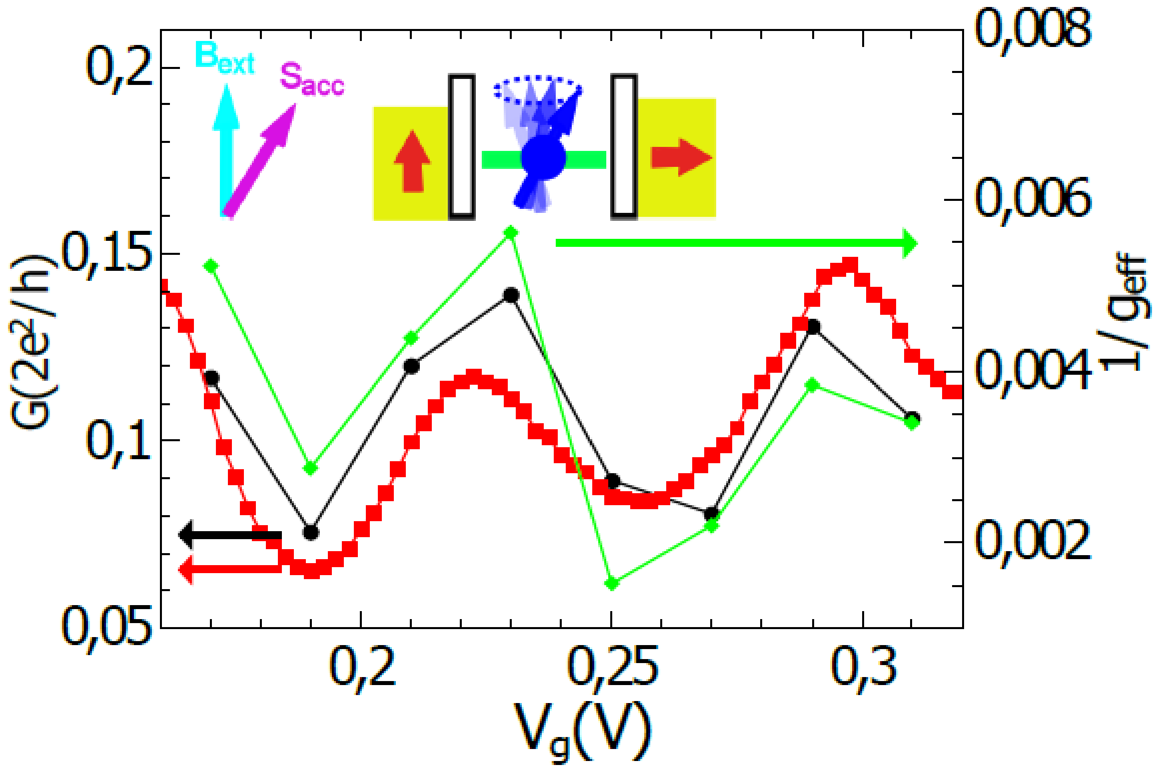
Spin signal in the nonlinear regime



- Effective «g» is strongly gate dependent
- Strong correlations between 1/g and dot's conductance
- Intuitively expected because higher conductance should give higher spin relaxation rate…

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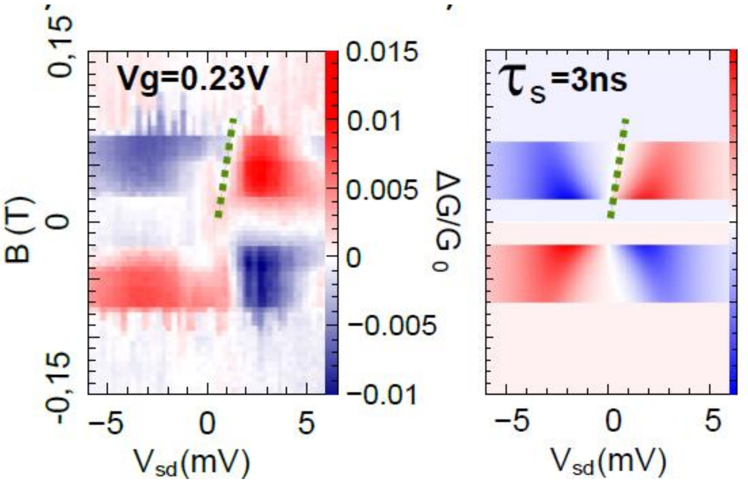
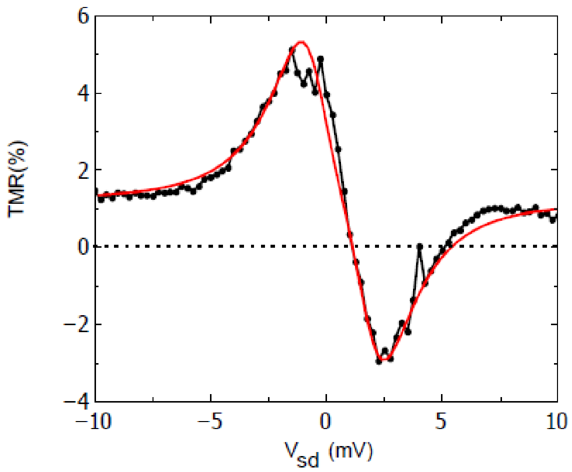
Conclusion part III

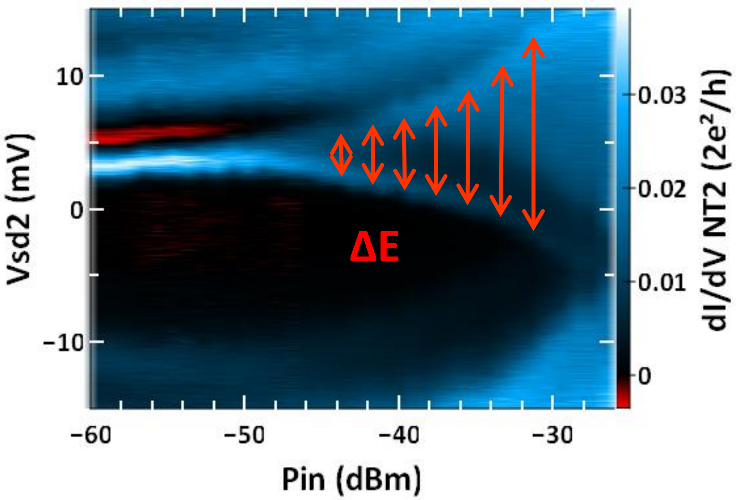




Study of spin transport in a quantum dot in non-collinear regime

- simple spin precession model explains the date
- consistent with reasonable spin relaxation time

Coupling a microwave cavity to an open system



$$\Gamma >> f_{cavity}$$

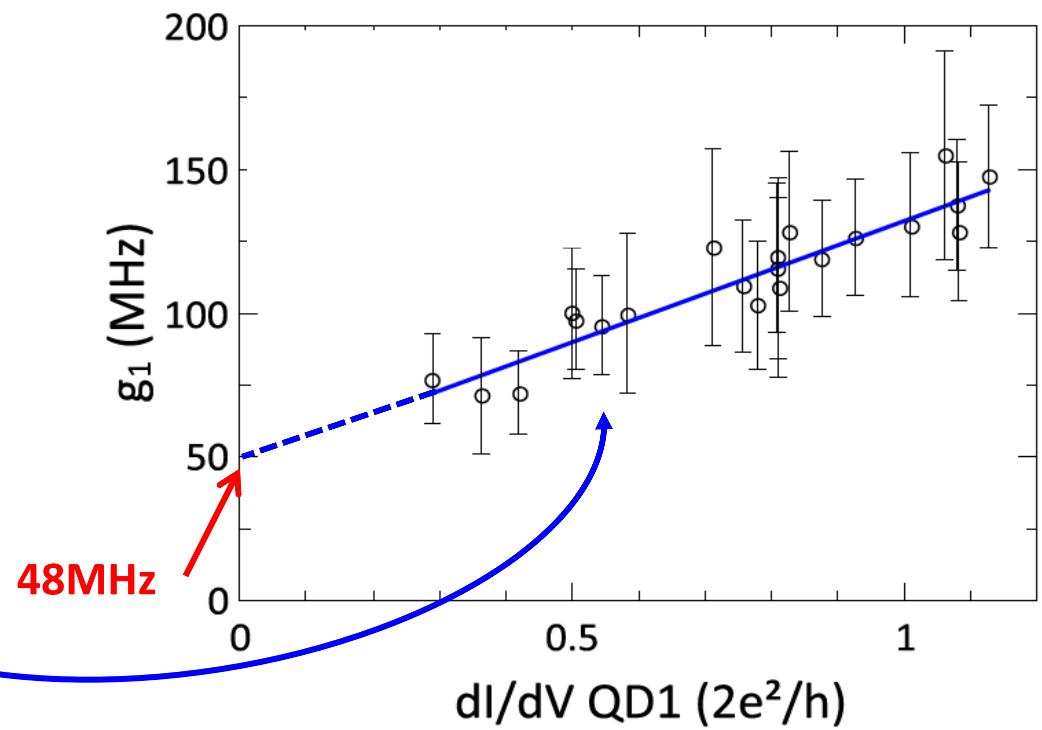
Adiabatic modulation of conductance peak

$$\Delta E = 2g\sqrt{\bar{n}}$$

- Coupling depends on **geometric and quantum capacitances**

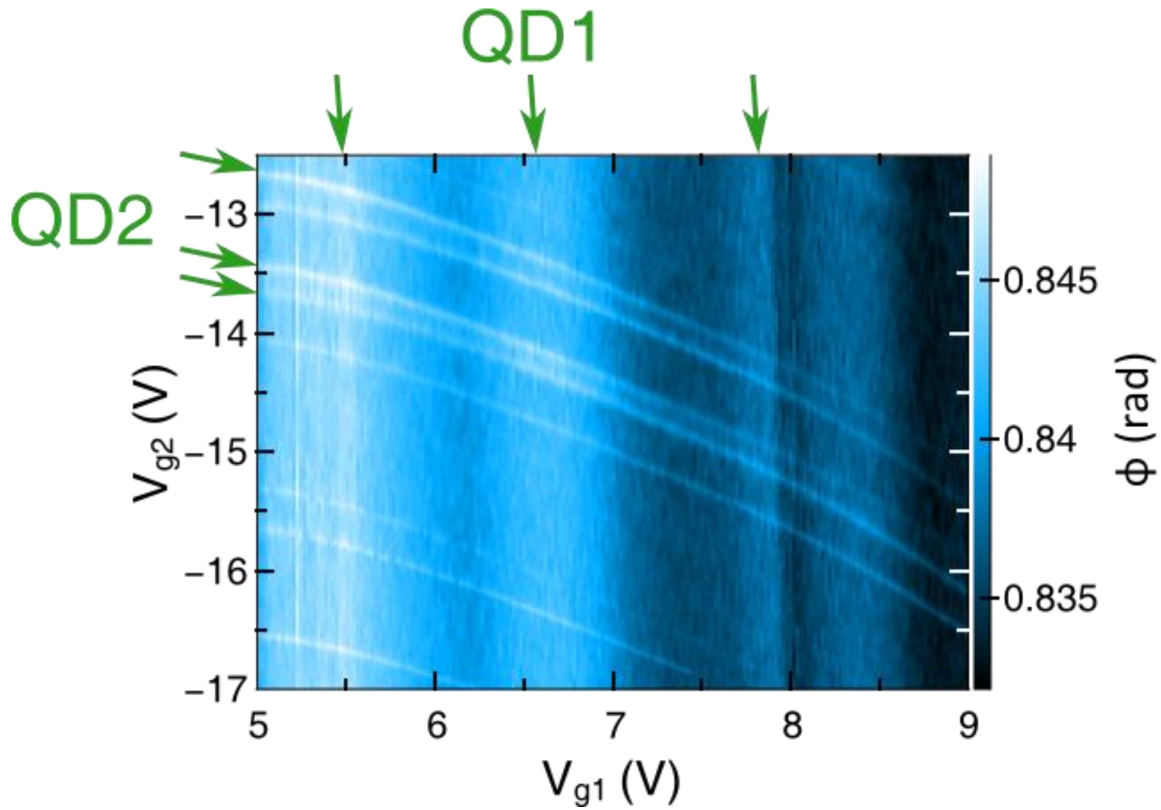
$$g = g_0 + f\left(\frac{\Gamma}{U}\right)$$

- Coupling **via the leads** is dominant



M.R. Delbecq et al. PRL (2011)
M.R. Delbecq et al. Nature Commun. 4, 1400 (2013)

Two single quantum dots in a microwave cavity



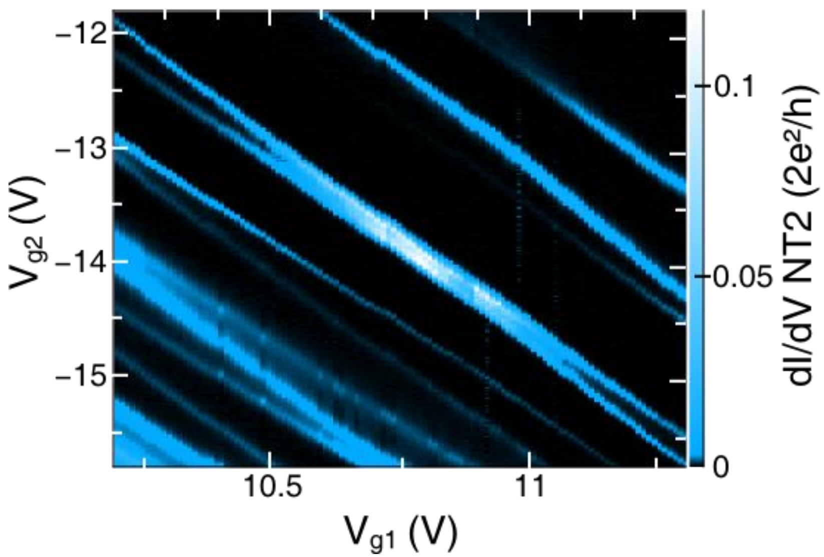
- QD1 and QD2 are read-out via the phase of the microwave signal
- Vertical lines slightly tilted (QD1)
- QD2 levels are controlled both by gate V_{g2} and distant gate V_{g1}

➡ **The slope of the closed dot levels is much larger than the slope of the open dot**

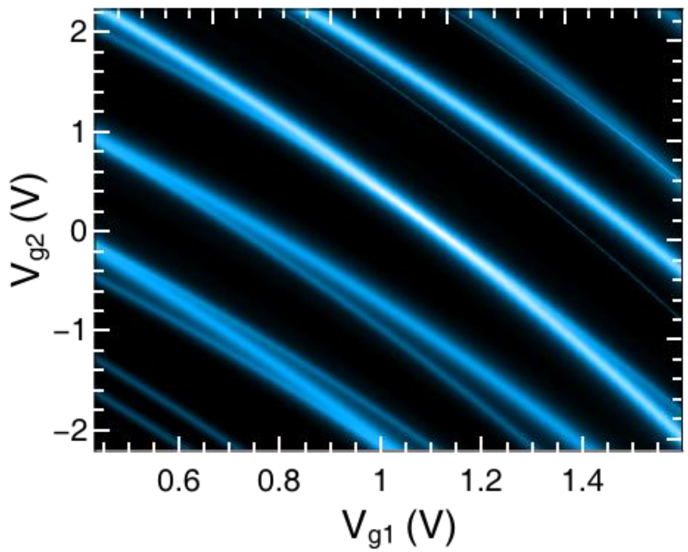
M.R. Delbecq et al. Nature Commun. 4, 1400 (2013)

Two single quantum dots in a microwave cavity

Experiment



Qualitative Model



Polaronic shift of energy levels :

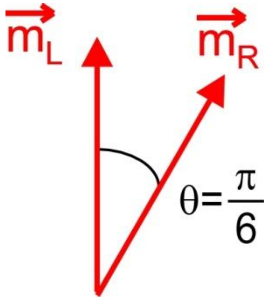
$$\delta\varepsilon_2 = -2\frac{g_1(V_{g1})g_2(V_{g2})}{\omega_0}N_{el,QD1} \approx 1meV$$

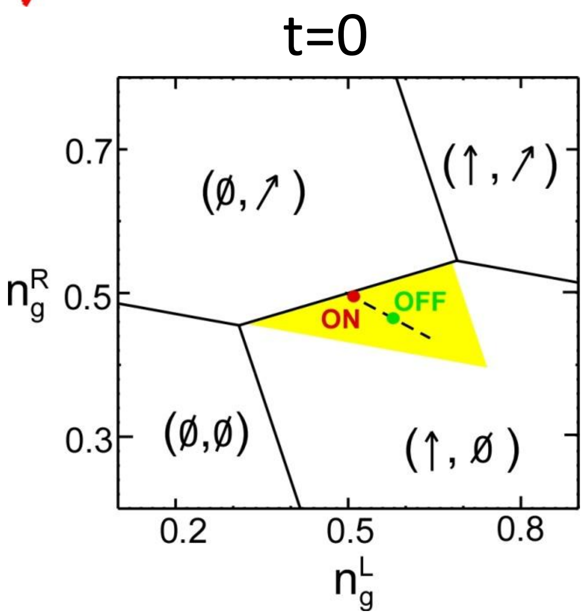
- N~10^4 on the open dot (QD1)
- All cavity modes up to Γ's matter (~100)

➡ **The gate dependence of the g's provide the mechanism for the dispersion of levels**

M.R. Delbecq et al. Nature Commun. 4, 1400 (2013)

Principle of the ferromagnetic spin Qubit

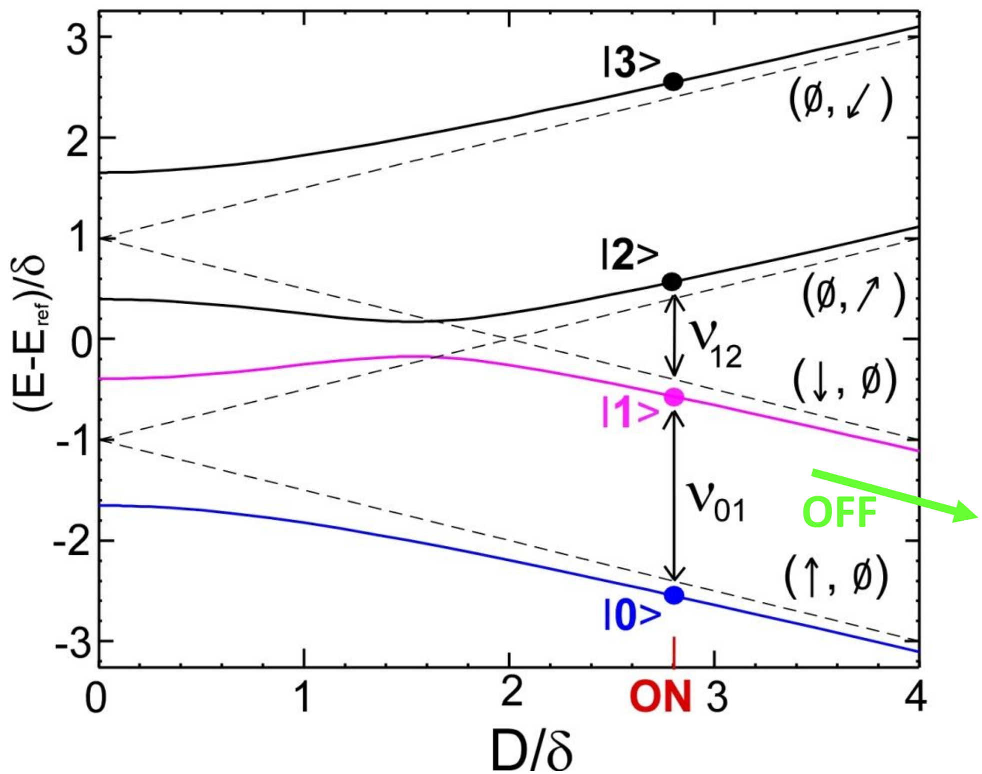




n_g^L: reduced gate voltages for dot L(R)

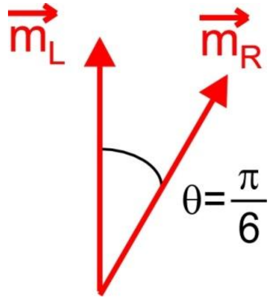
dashed lines: t=0

full lines: t=2δ/3



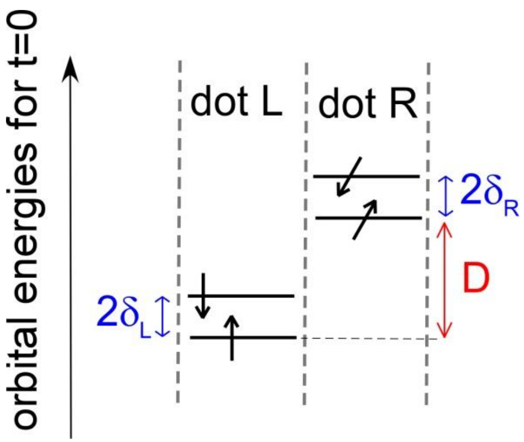
A. Cottet et al. Phys Rev. Lett. (2010)

Hamiltonian of the ferromagnetic spin Qbit



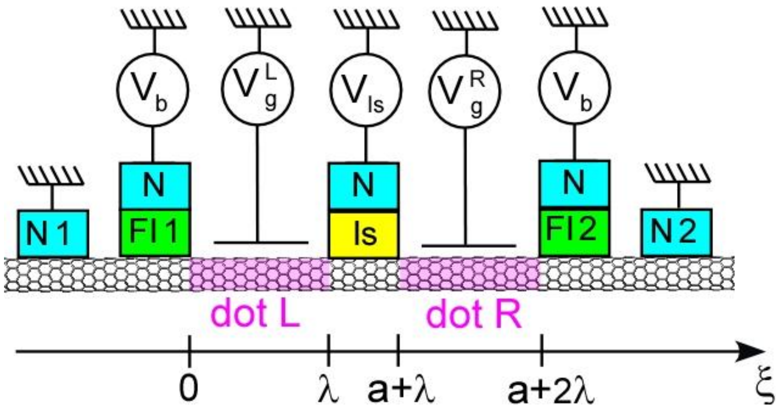
$$\begin{array}{cccc} |\uparrow,\emptyset\rangle & |\downarrow,\emptyset\rangle & |\emptyset,\nearrow\rangle & |\emptyset,\swarrow\rangle \end{array}$$

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



- D is controlled by V_g^L , V_g^R and possibly V_{ac}
- $2\delta_{L(R)}$: effective Zeeman splitting in dot L(R)
- t = hoping between left & right dot
- We assume $\delta_L = \delta_R = \delta$ for simplicity

Carbon nanotube as a good coherent conductor

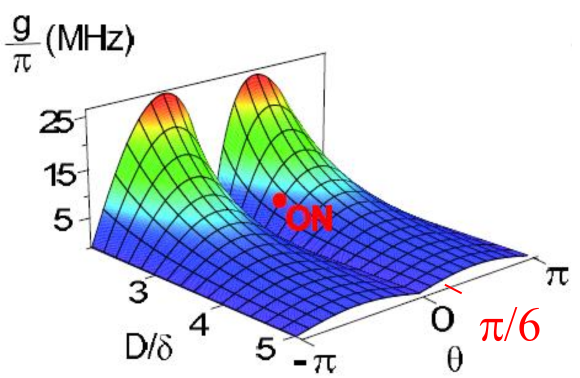


No nuclear spins

Dephasing only due to charge noise

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

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



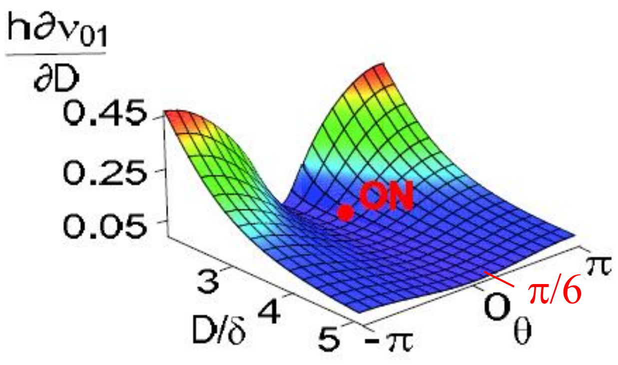
Strongly tunable Spin/Photon coupling

A. Cottet and T. Kontos, Phys Rev. Lett. 105, 160502 (2010)

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)

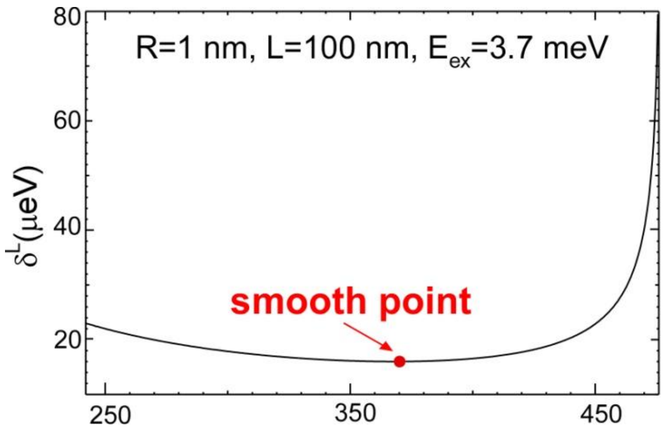
Charge noise mediated by fluctuations of D



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

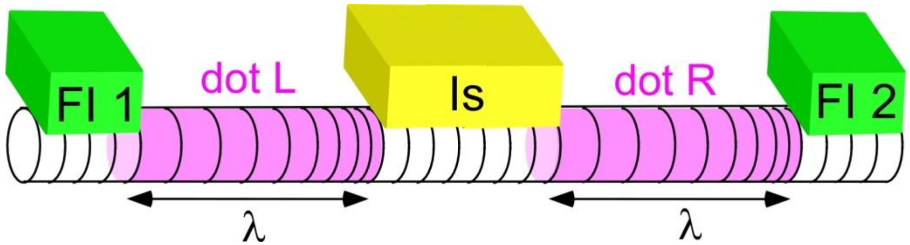
Charge noise mediated by fluctuations of δ_L

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



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

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

  $\tilde{g}_{l,p}$: 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 $Q_{ph} = 20$