Mesoscopic Quantum electrodynamics: from atomic-like physics to quantum transport

Audrey COTTET - LPA – Ecole Normale Supérieure – Paris

Theory:

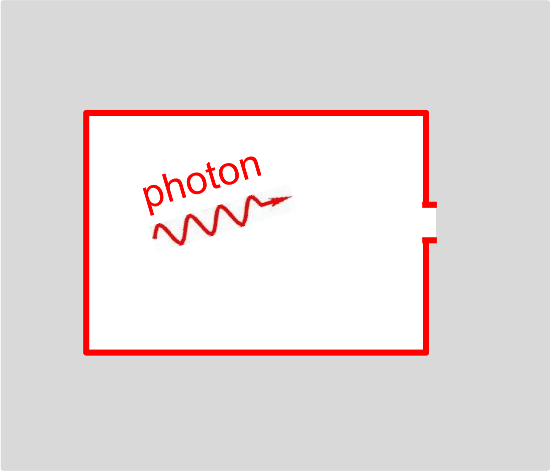
M. C. Dartiailh[1]
B. Douçot
T. Kontos
Z. Legthas

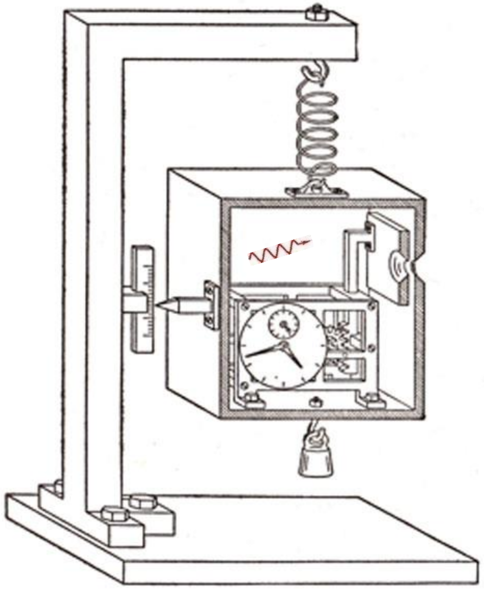
Experiments:

L.E Bruhat
T. Cubaynes[2]
M. C. Dartiailh
M. Delbecq
M.M. Desjardins
T. Kontos
J.J. Viennot[3]

[1] *now in New York*
[2] *now in Karlsruhe*
[3] *now in Grenoble*

Photons and atoms in a box





Einstein's photon box, Solvay 1930
(scheme by Bohr, 1949)

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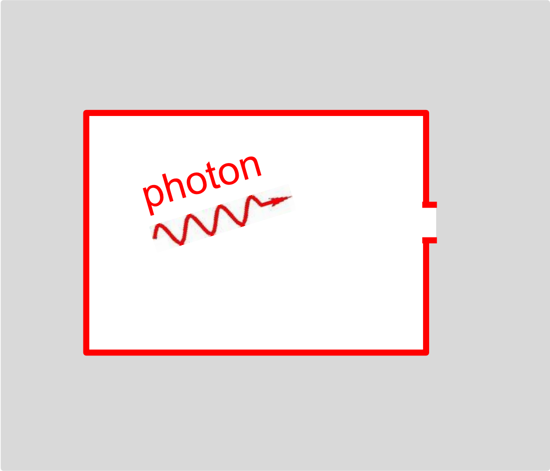
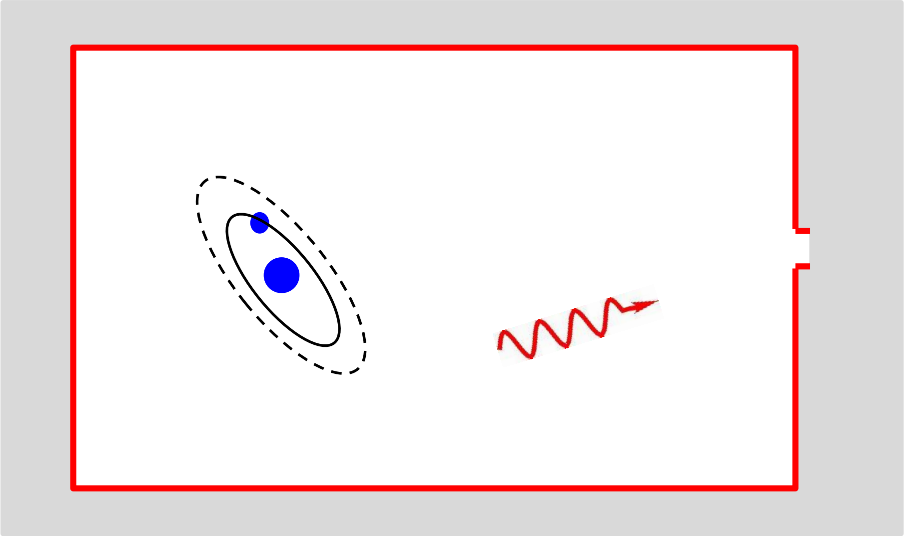
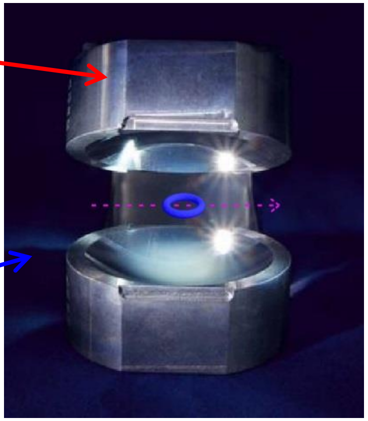




Cavity Quantum ElectroDynamics (QED)

<u>Atomic cavity QED</u>



M. Brune et al. PRL (1996)

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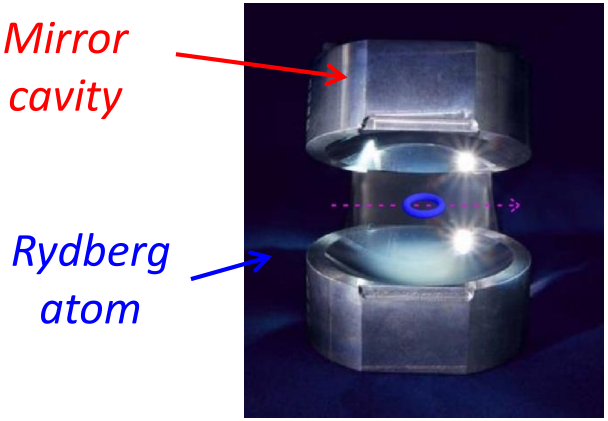
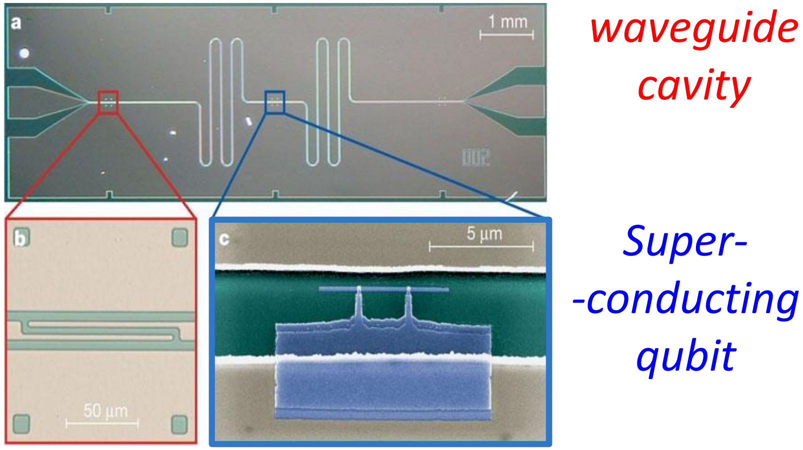

Mirror cavity
Rydberg atom

M. Brune et al. PRL (1996)

<u>Circuit QED</u>

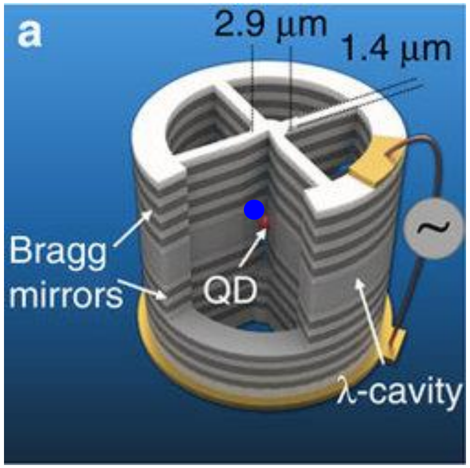


Coplanar waveguide cavity

Super--conducting qubit

A. Wallraff et al, Nature (2004)

<u>Optical cavity QED</u>



Optical cavity

Self-assembled Quantum dot

Giesz et al., Nature Comm. (2016)

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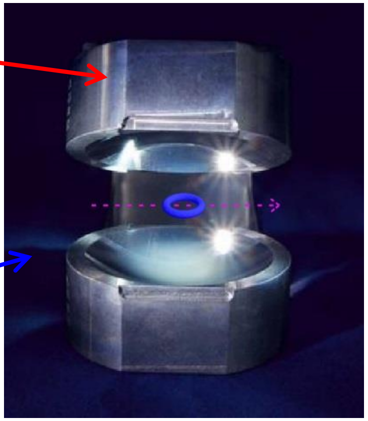

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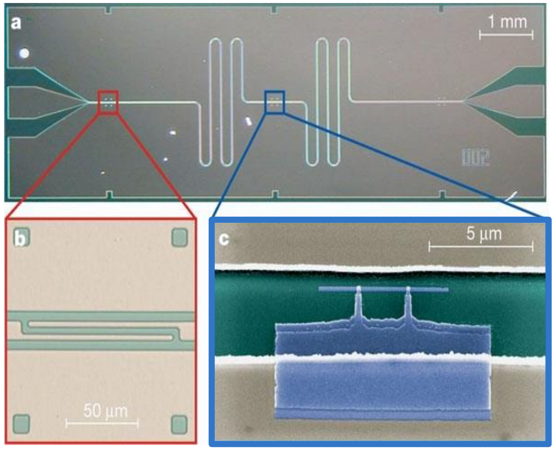


Super--conducting qubit

A. Wallraff et al, Nature (2004)

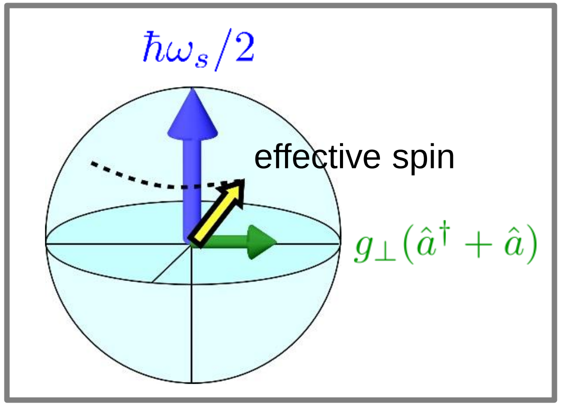
Jaynes-Cummings Hamiltonian

$$\hat{H} = -\frac{\hbar\omega_s}{2}\hat{\sigma}_z + \hbar\omega_0 \hat{a}^\dagger\hat{a} + g_\perp\hat{\sigma}_x(\hat{a}^\dagger + \hat{a})$$

Two level system

Cavity photons

Transverse coupling



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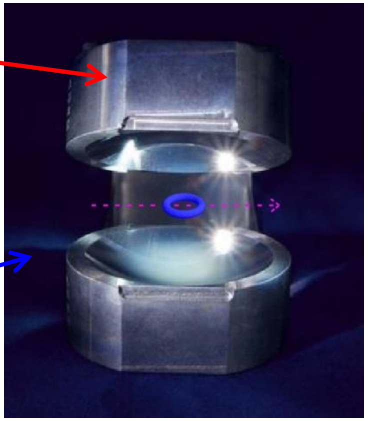

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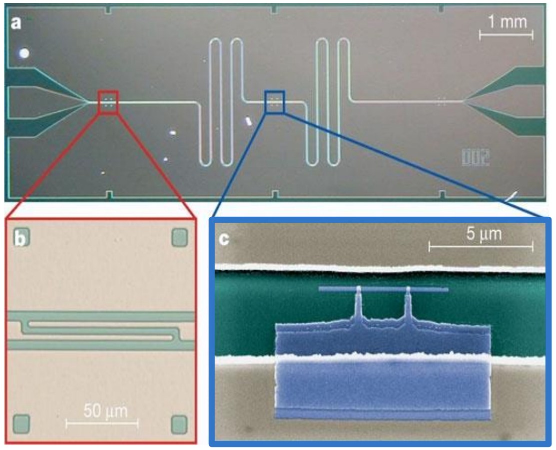

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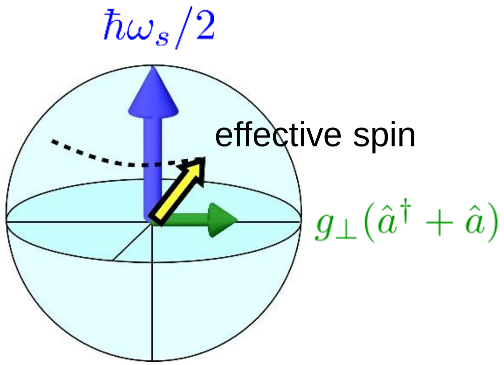
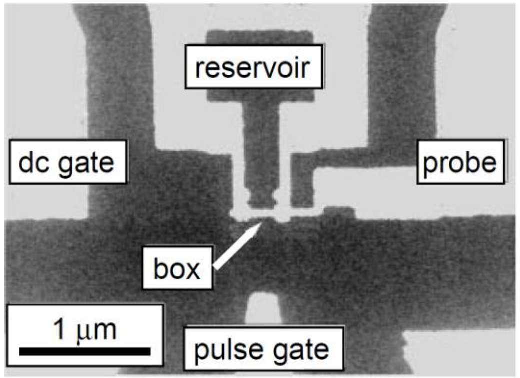
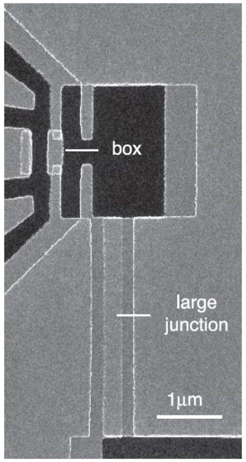


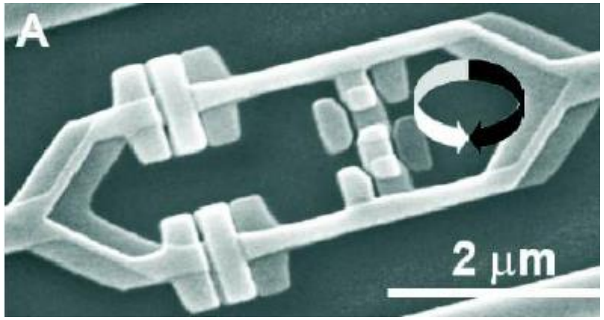
Different superconducting qubit designs



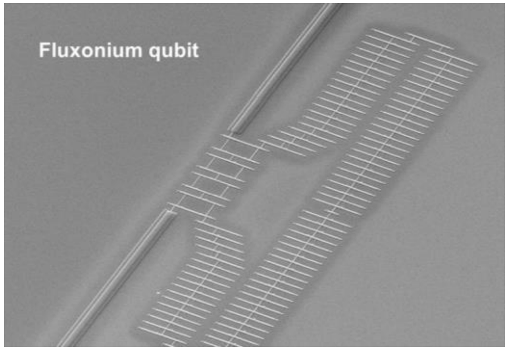
Cooper pair box
Nakamura et al., Science 1999



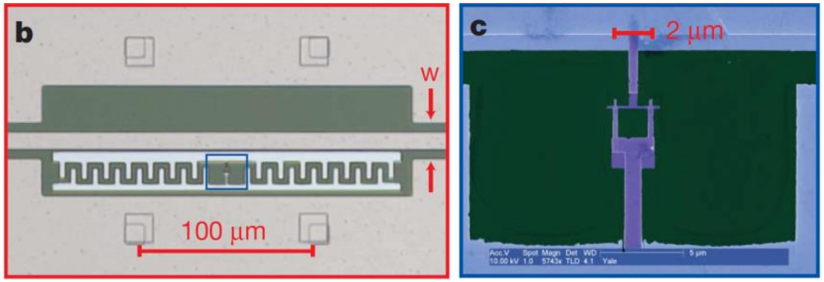
Quantronium
Vion et al., Science 2002



Flux qubit, Chioresku et al., Science 2003



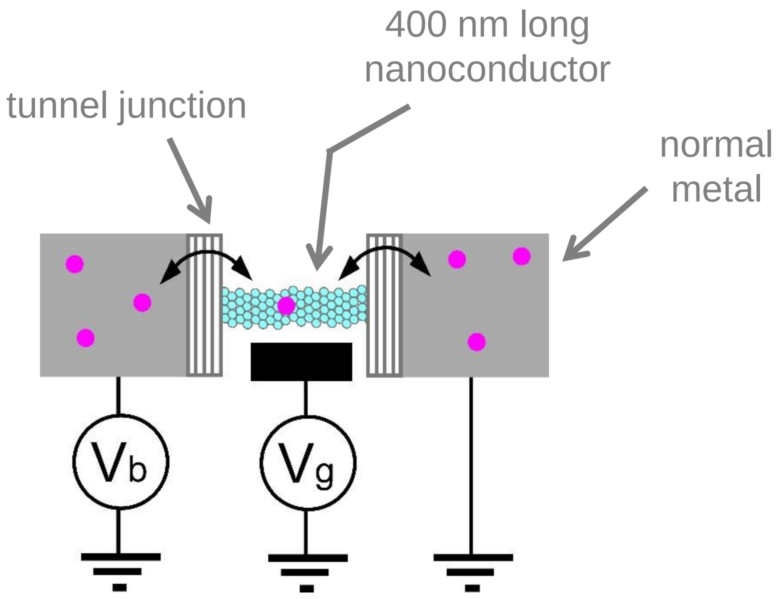
Fluxonium, Manucharyan et al., Science 2009
Photo: Pop et al., Nature 2014



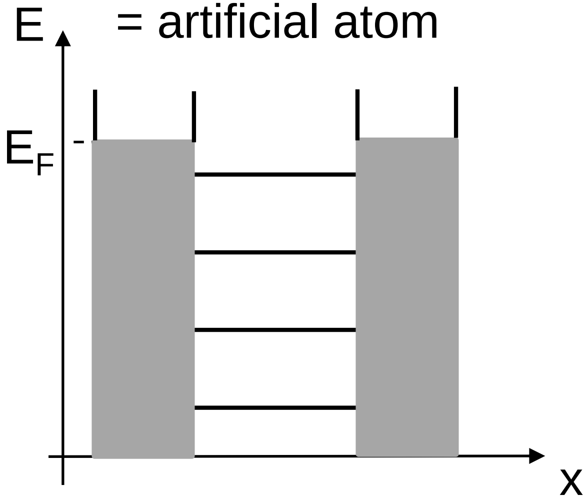
Transmon, Schuster et al., Nature 2007

Can we push further the versatility of Circuit QED ?

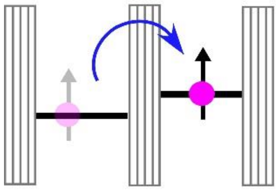
Hybrid nanocircuits as artificial atoms



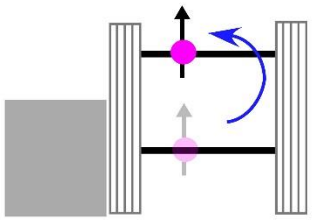
discrete spectrum
= artificial atom



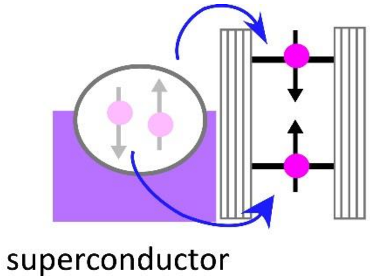
Various degrees of freedom available:



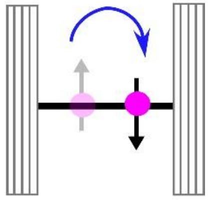
charge



electron/hole

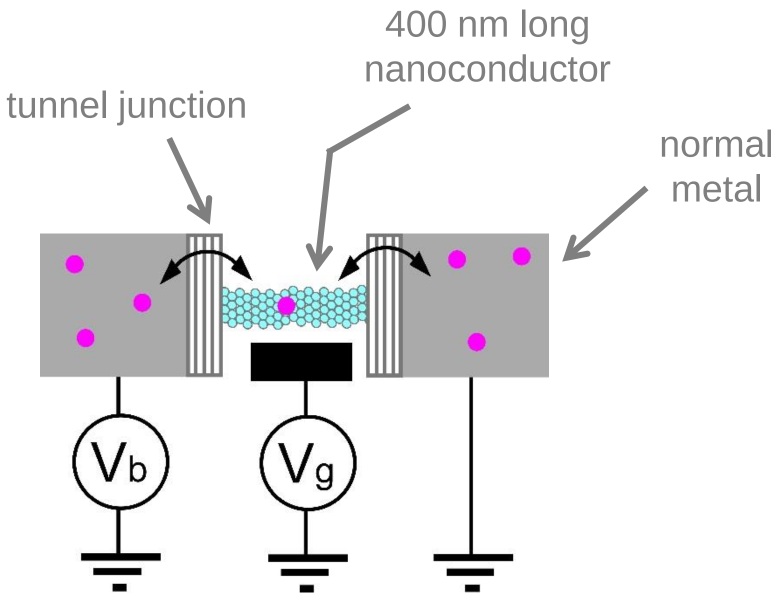


Andreev process



spin

Hybrid nanocircuits as artificial atoms



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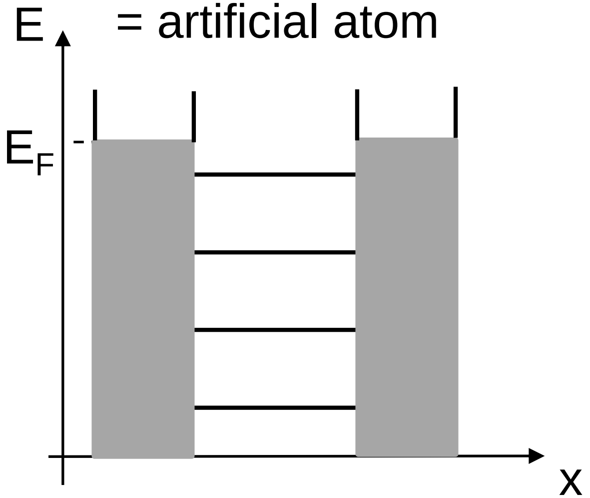

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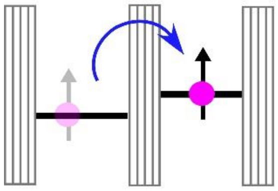
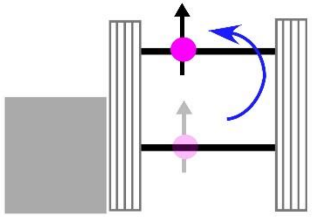


charge



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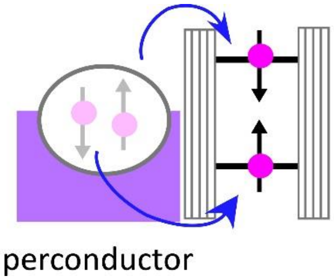

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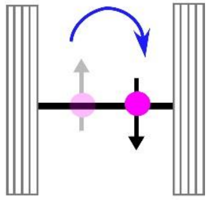


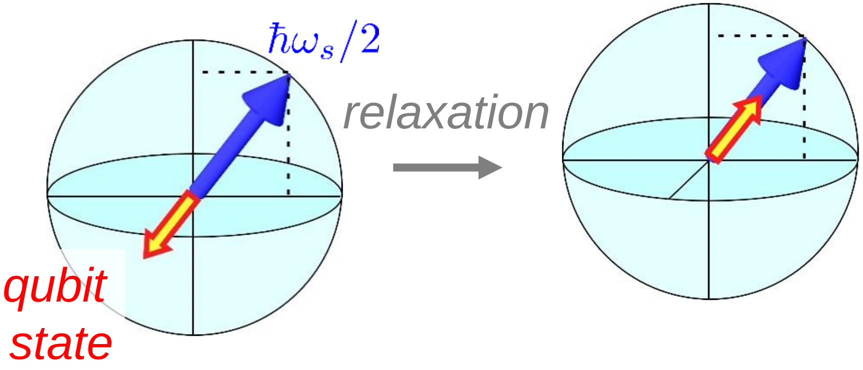
spin

Quantum dot circuits potentialities?

Superconducting qubits :

Coherence limited by relaxation $T_1 < 100\ \mu s$

Review: Devoret and Schoelkopf, Science (2013)

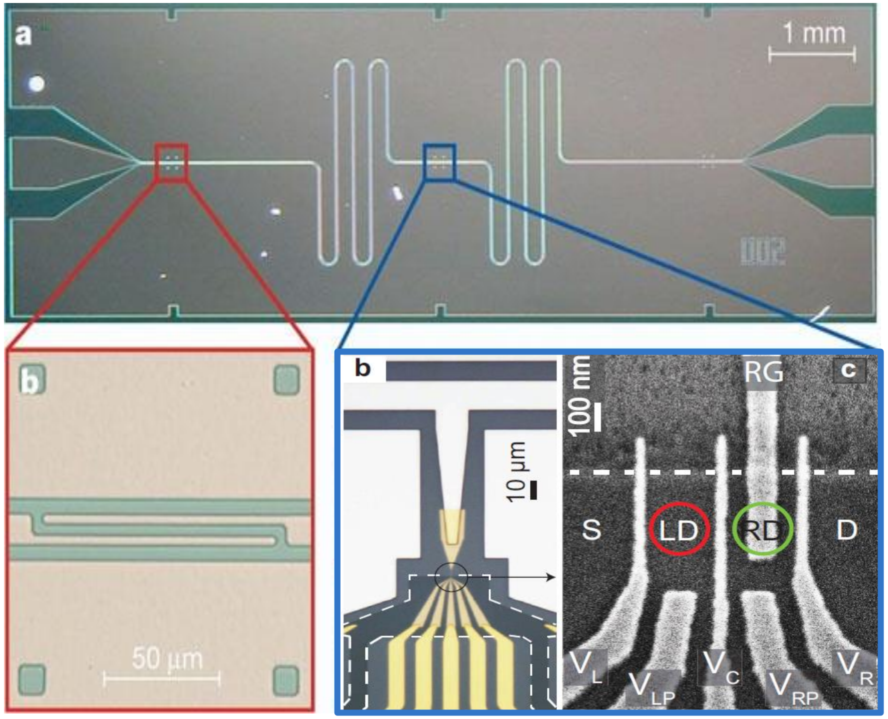


Spin in a quantum dot :

- GaAs (single dot) @ 130mK: $T_1 \sim 80$ ms *Scarlino et al., PRL 2014*
- Si/SiGe (double dot) @ 15mK: $T_1 \sim 3$ s *Prance et al., PRL 2012*
- Carbon nanotube (bulk) @ 4K: T1~170 μs *Rice et al. PRB 2013*

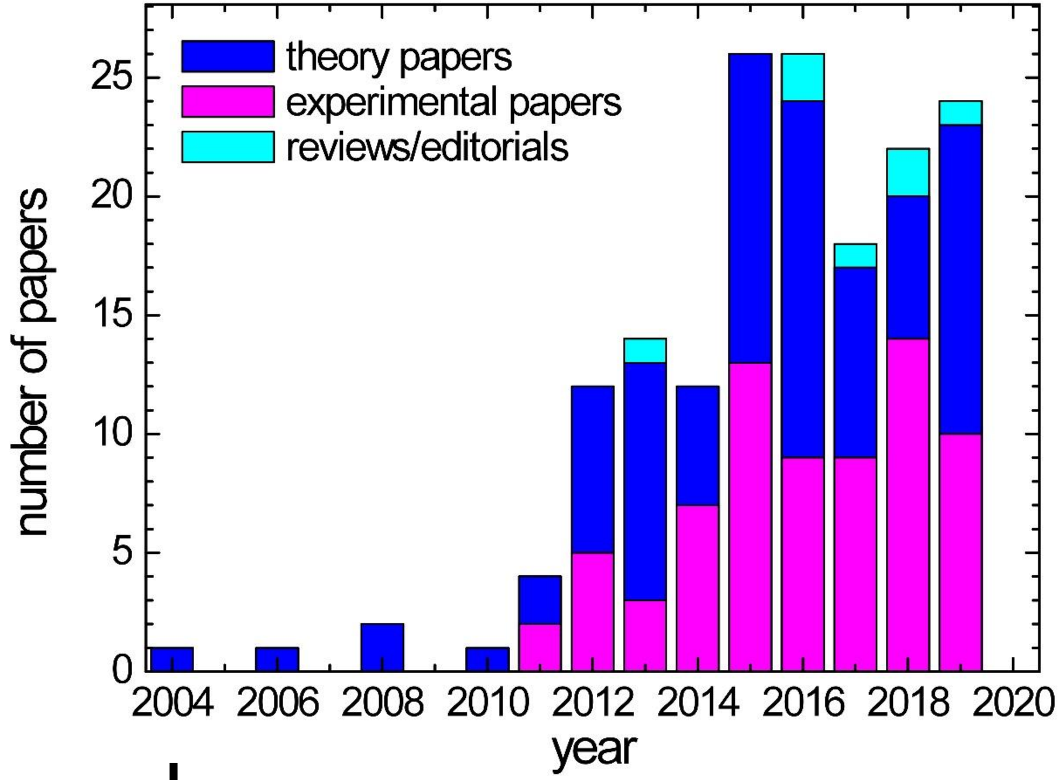
⇨ quantum dot circuit or a hybrid nanocircuit in a microwave cavity?

The Mesoscopic QED architecture



- Nanoconductors: Carbon nanotubes, 2DEGs, semiconducting nanowires, graphene, atomic contacts…
- Different types fermionic reservoirs (normal, superconducting, ferromagnetic)
- Many circuit geometries possible

Mesoscopic QED : research activity



Experiments:

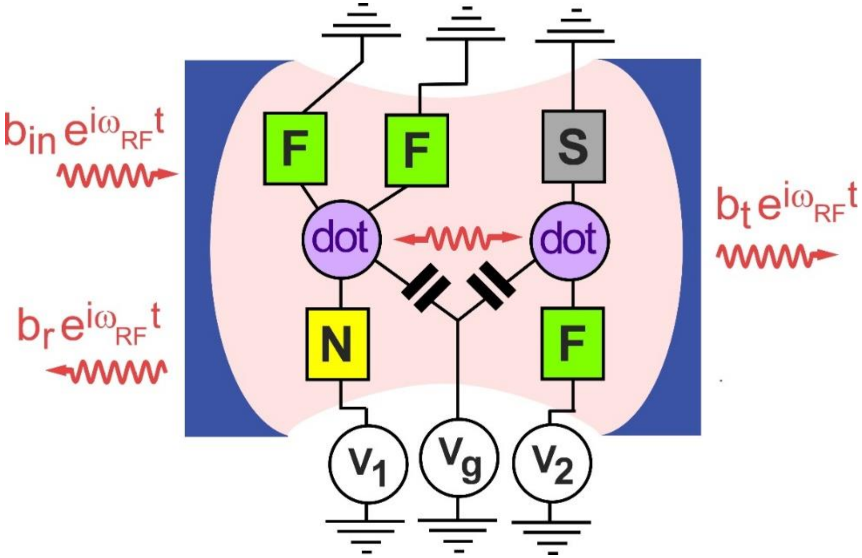
Delft
Heifei
Paris
Princeton
Yale
Zurich
….

Pionneering theory paper:
Childress et al., PRA (2004)

Single dot with N contacts:
Delbecq et al., PRL (2011)
Frey et al., APL (2011)

Double dot with N contacts:
Frey et al., PRL (2012)
Petersson et al. , Nature (2012)

Interests of Mesoscopic QED

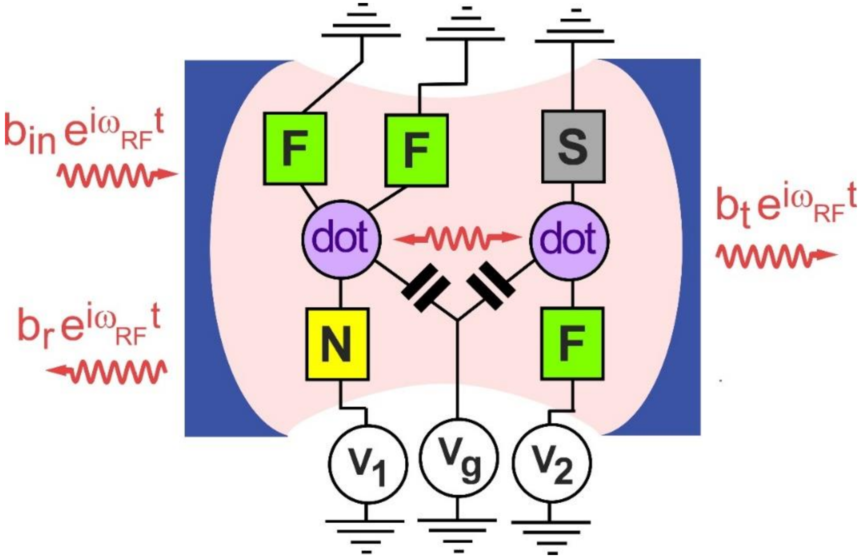


⇨ Artificial atom limit:

Transfer ideas of circuit QED to probe/couple/manipulate *new degrees of freedom*

Dot orbitals, electronic spins...

Interests of Mesoscopic QED



Artificial atom limit:

Transfer ideas of circuit QED to probe/couple/manipulate *new degrees of freedom*

Dot orbitals, electronic spins...

Open system limit:

Study electronic transport and condensed matter problems

DC currents and cavity response provide different information

New ways to manipulate cavity state?

OUTLINE

I. Description of a microwave cavity coupled to a nanocircuit

II. A nanocircuit as an artifical atom in a cavity

- Strong charge/photon coupling
- Strong spin/photon coupling

III. Condensed matter problems and electron transport probed with cavity photons

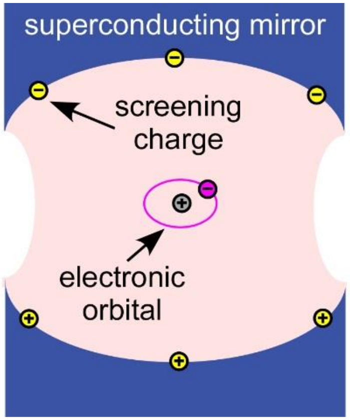
- Semiclassical cavity response modified by a dissipative nanocircuit
- Photon emission by a dot/superconductor jonction
- Majorana bound states in a cavity

III. Using a dissipative nanocircuit to prepare non-classical cavity states

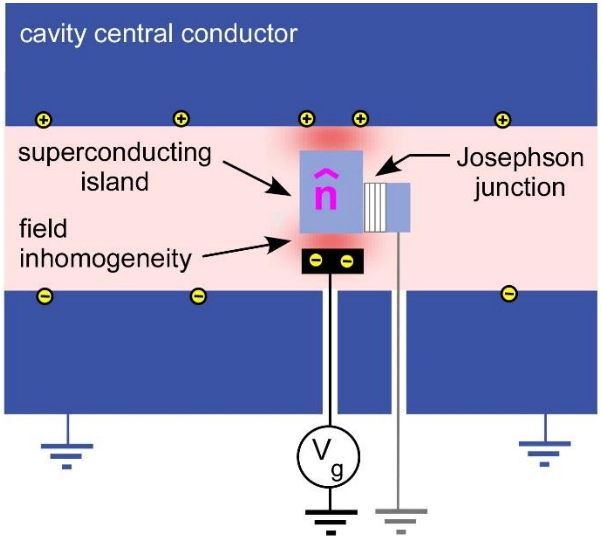
- Quantum non-linear description of Mesoscopic QED
- Preparation of a photonic Schrödinger cat using dissipative tunneling

Comparison between different cavity QED setups

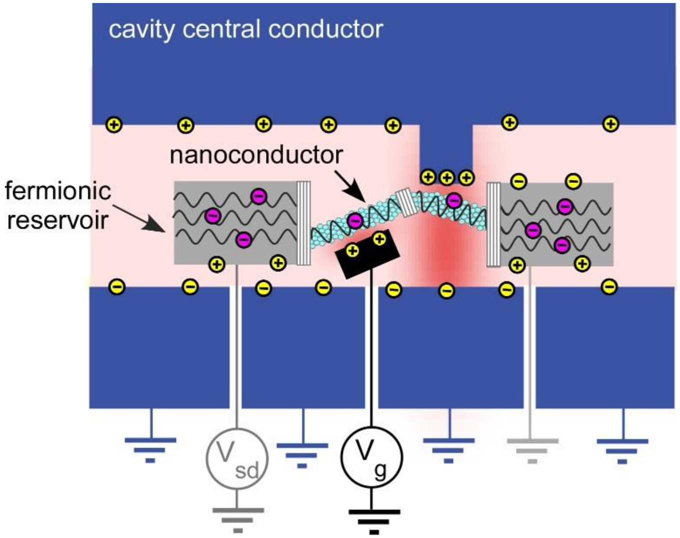
Cavity QED:
with atoms



Circuit QED:
with superconducting quantum bits



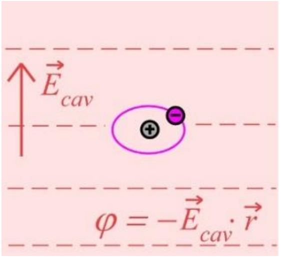
Mesoscopic QED:
with hybrid nanocircuits



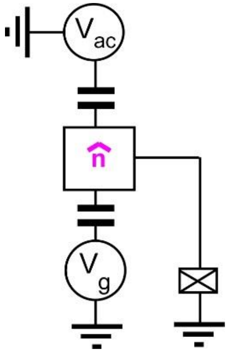
Models

Electric-dipole approximation

$H_{int} = -\vec{d}.\vec{E}_{cav}$



Circuit model (electrical nodes)

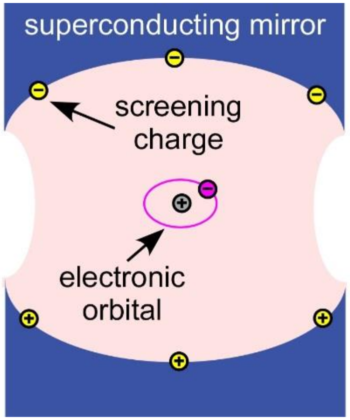


- Orbital fermionic degrees of freedom
- Inhomogeneous cavity field
- Tunneling physics

?

Comparison between different cavity QED setups

Cavity QED:
with atoms



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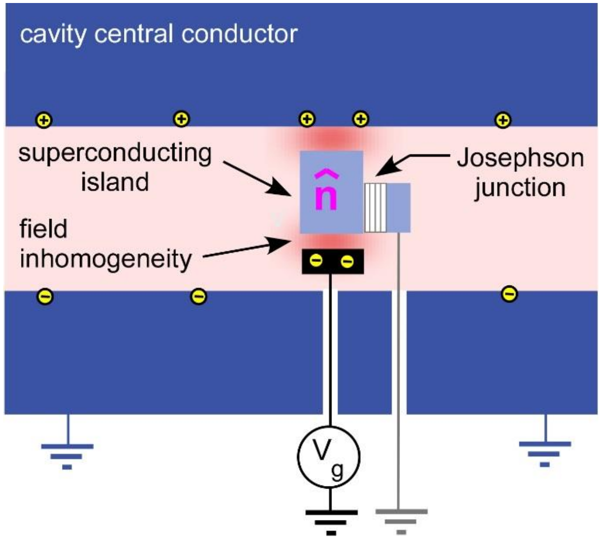

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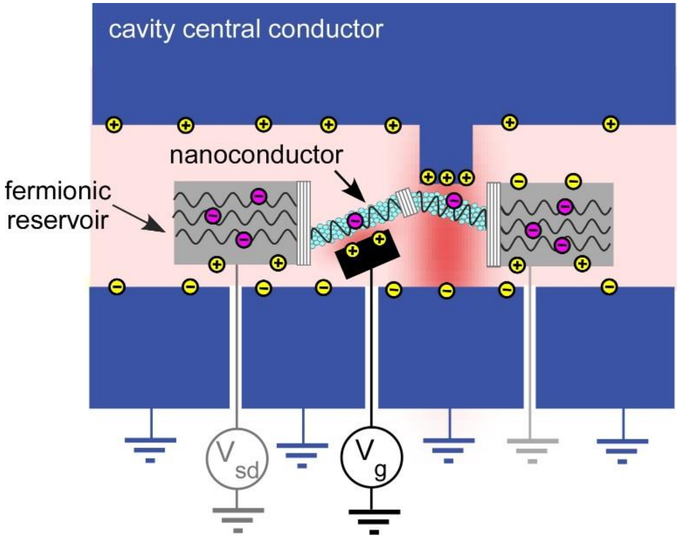

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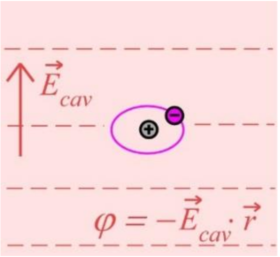

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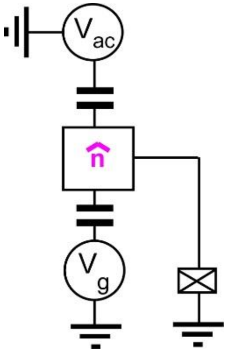

- Orbital fermionic degrees of freedom
- Inhomogeneous cavity field
- Tunneling physics

Approximations:
- plasmonic dynamics ultra-fast
- cavity magnetic field disregarded

Electron/photon electric coupling scheme

Cottet, Kontos and Douçot, Phys. Rev. B 91, 205417 (2015)

$$\begin{aligned}\widetilde{\hat{H}_{tot}} = & \int d^3r\,\hat{\psi}^\dagger(r)\hat{h}_{\mathcal{T}}(\vec{r})\hat{\psi}(r) + \hat{H}_{Coul} + \hbar\omega_0\hat{a}^\dagger\hat{a} \\ & + \boxed{\hat{\mathcal{V}}(\hat{a}+\hat{a}^\dagger)} + (\hat{\mathcal{V}}^2/\hbar\omega_0) \; + \int d^3r\left(\Delta(\vec{r})\hat{\psi}_\uparrow^\dagger(\vec{r})\hat{\psi}_\downarrow^\dagger(\vec{r}) + H.c.\right)\end{aligned}$$

linear electron/photon coupling (scalar photonic potential)

$$\begin{cases} \hat{h}_{\mathcal{T}}(\vec{r}) = -\hbar^2\Delta_{\vec{r}}/2m - e\Phi_{harm}(\vec{r}) - eV_{conf}(\vec{r}) \\ \hat{\mathcal{V}} = -e\int d^3r\,V_\perp(\vec{r})\hat{\psi}^\dagger(r)\hat{\psi}(r) \end{cases}$$

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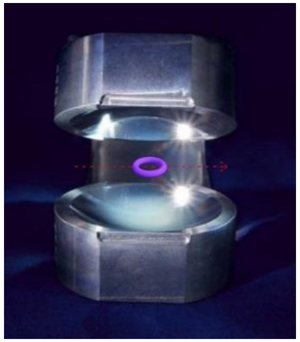
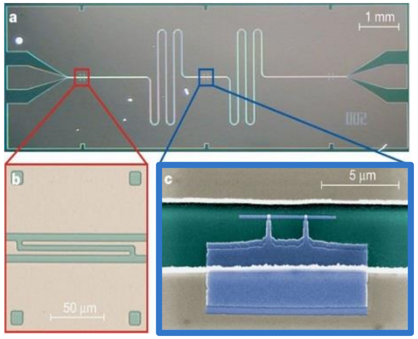
This description bridges between cavity QED and circuit QED (two limit cases)

dipolar approximation ←





→ *electrical circuit model*

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Cottet, Kontos and Douçot, Phys. Rev. B 91, 205417 (2015)

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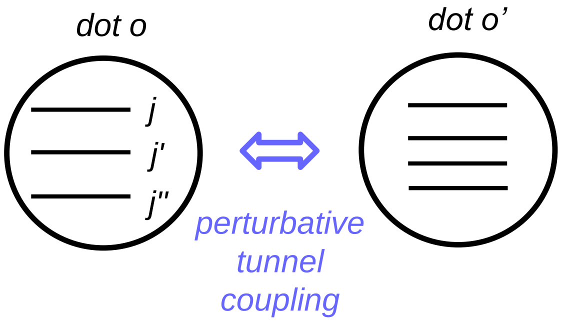
<u>Tunnel model:</u>

$$\hat{\psi}^\dagger(\vec{r}) = \sum_{o,j}\underbrace{\varphi^*_{oj}(\vec{r})}\hat{c}^\dagger_{oj}$$

wavefunction for orbital j in dot/reservoir o

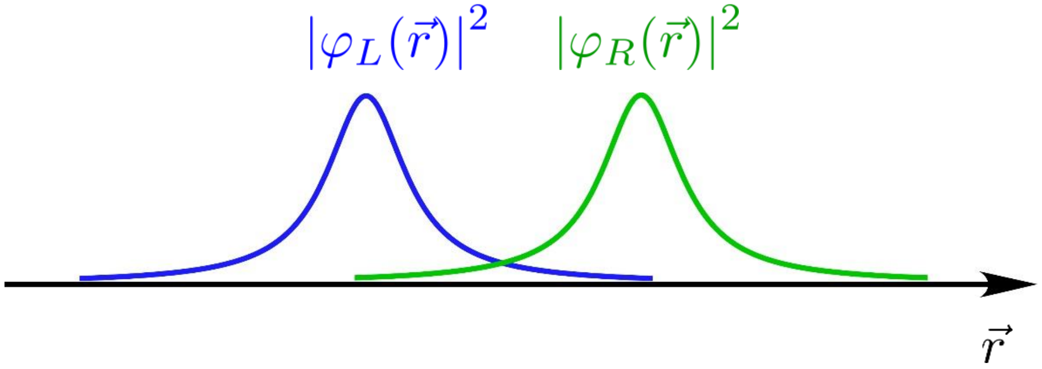


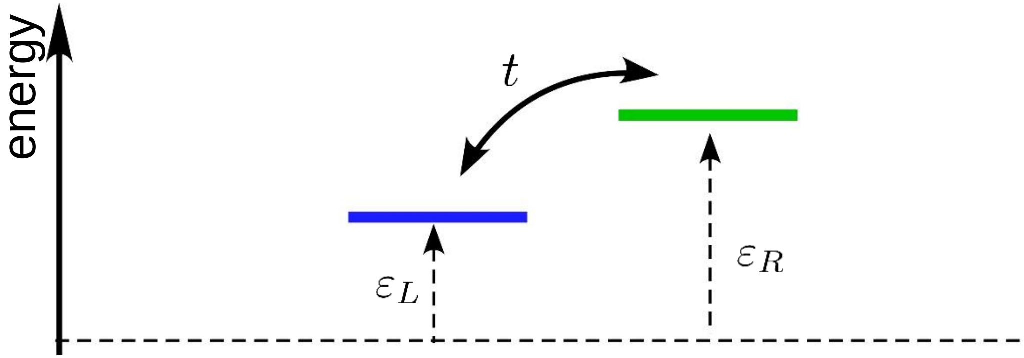
Prange, Phys. Rev. 131, 1083 (1963)

Tunnel model of Mesoscopic QED

Cottet, Kontos and Douçot, Phys. Rev. B 91, 205417 (2015)

$$\hat{H}_{DC} = \varepsilon_L \hat{c}_L^\dagger \hat{c}_L + \varepsilon_R \hat{c}_R^\dagger \hat{c}_R + t \hat{c}_L^\dagger \hat{c}_R + t^* \hat{c}_R^\dagger \hat{c}_L$$

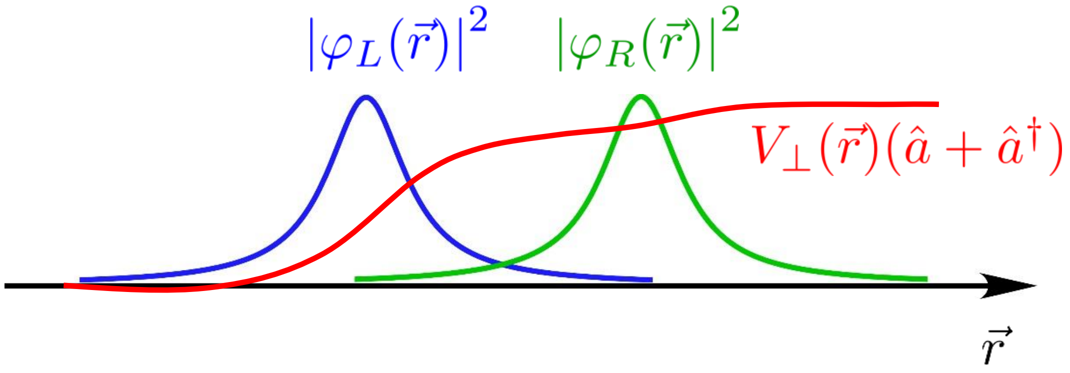




Tunnel model of Mesoscopic QED

Cottet, Kontos and Douçot, Phys. Rev. B 91, 205417 (2015)

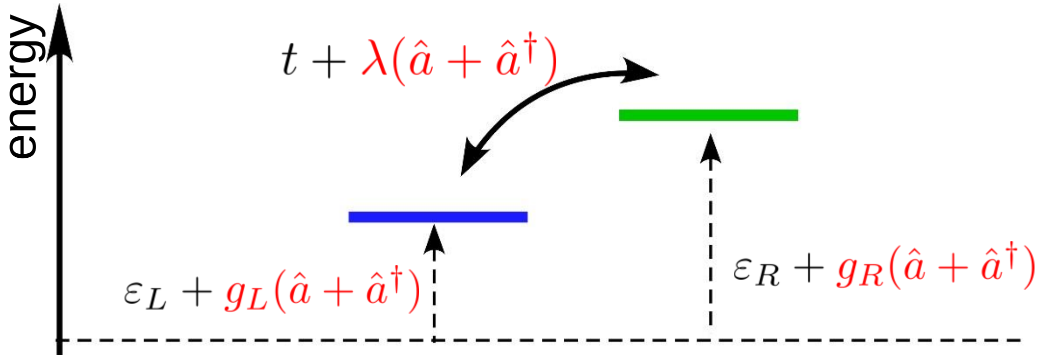
$$\boxed{\hat{H}_{DC} = \varepsilon_L \hat{c}_L^\dagger \hat{c}_L + \varepsilon_R \hat{c}_R^\dagger \hat{c}_R + t \hat{c}_L^\dagger \hat{c}_R + t^* \hat{c}_R^\dagger \hat{c}_L}$$



$$g_L = -e \int d^3r\, |\varphi_L(\vec{r})|^2\, V_\perp(\vec{r})$$

$$g_R = -e \int d^3r\, |\varphi_R(\vec{r})|^2\, V_\perp(\vec{r})$$

$$\lambda = -e \int d^3r \varphi_L^*(\vec{r}) \varphi_R(\vec{r}) V_\perp(\vec{r})$$



$$\begin{aligned}\hat{H}_{AC} = {} & g_L(\hat{a}+\hat{a}^\dagger)\hat{c}_L^\dagger \hat{c}_L \\ & + g_R(\hat{a}+\hat{a}^\dagger)\hat{c}_R^\dagger \hat{c}_R \\ & + \lambda(\hat{a}+\hat{a}^\dagger)\hat{c}_L^\dagger \hat{c}_R + H.c.\end{aligned}$$

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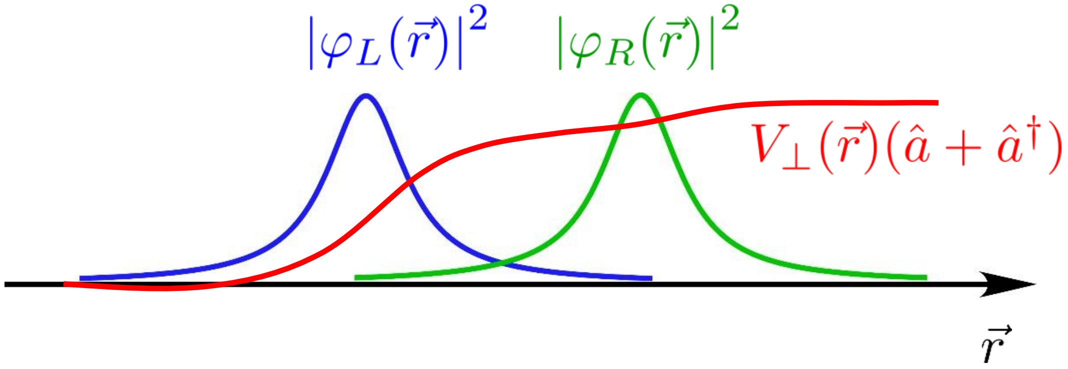

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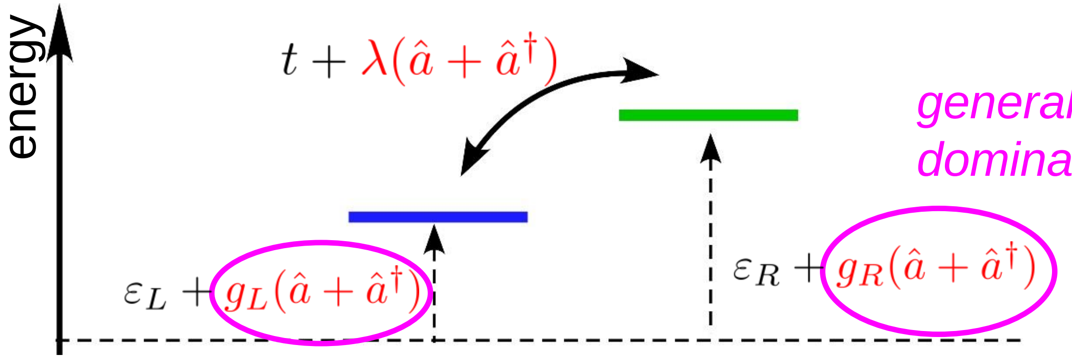

generally dominant

$$\begin{aligned}\hat{H}_{AC} = {} & g_L(\hat{a}+\hat{a}^\dagger)\hat{c}_L^\dagger \hat{c}_L \\ & + g_R(\hat{a}+\hat{a}^\dagger)\hat{c}_R^\dagger \hat{c}_R \\ & \xcancel{+\lambda(\hat{a}+\hat{a}^\dagger)\hat{c}_L^\dagger \hat{c}_R + H.c.}\end{aligned}$$

OUTLINE

I. Description of a microwave cavity coupled to a nanocircuit

➡ **II. A nanocircuit as an artifical atom in a cavity**

- Strong charge/photon coupling
- Strong spin/photon coupling

III. Condensed matter problems and electron transport probed with cavity photons

- Semiclassical cavity response modified by a dissipative nanocircuit
- Photon emission by a dot/superconductor jonction
- Majorana bound states in a cavity

III. Using a dissipative nanocircuit to prepare non-classical cavity states

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III. C

Artificial atom limit: designs to reach the **strong coupling limit** ?

$g_{\perp} \gg \Gamma_s, \Lambda_0$

Non-destructive readout of the qubit state

Distant coupling of two qubits via photons

it

- Majorana bound states in a cavity

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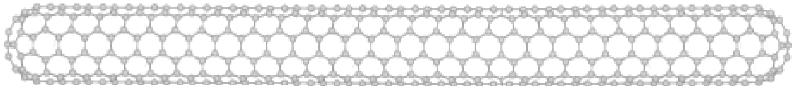
Double quantum dot (DQD) in a carbon nanotube



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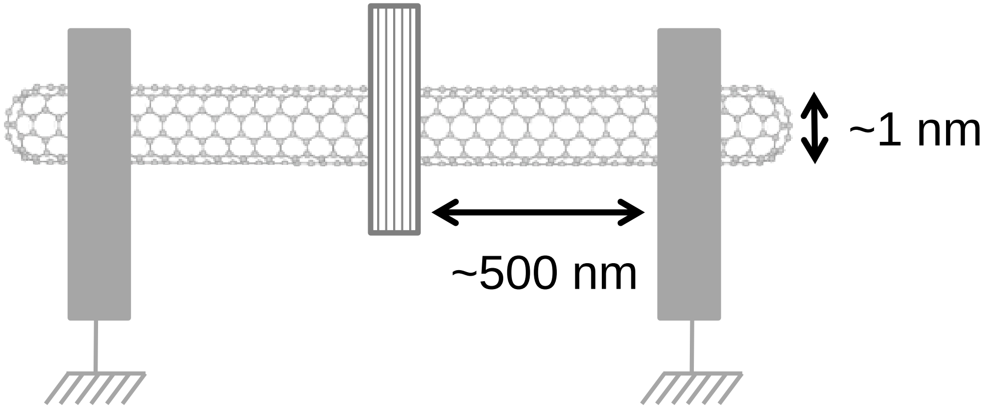

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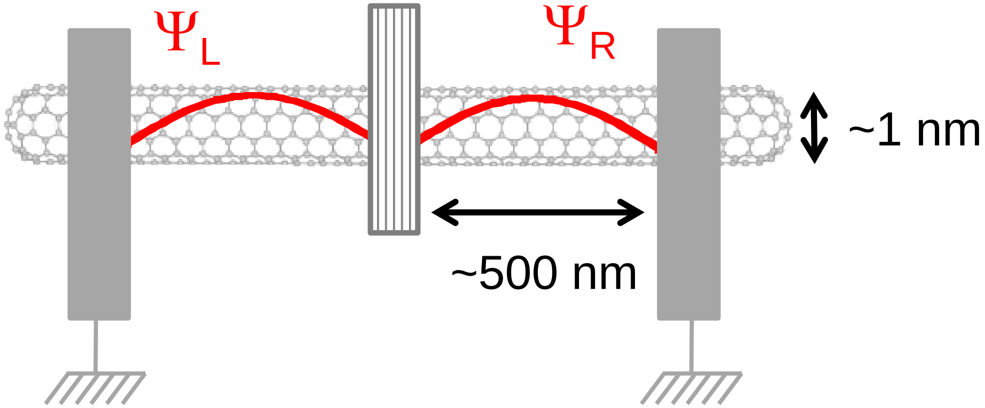

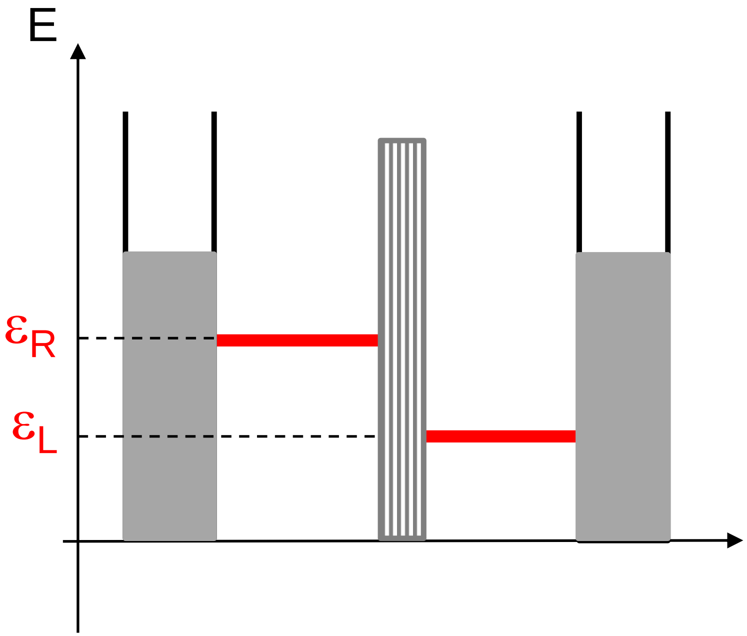

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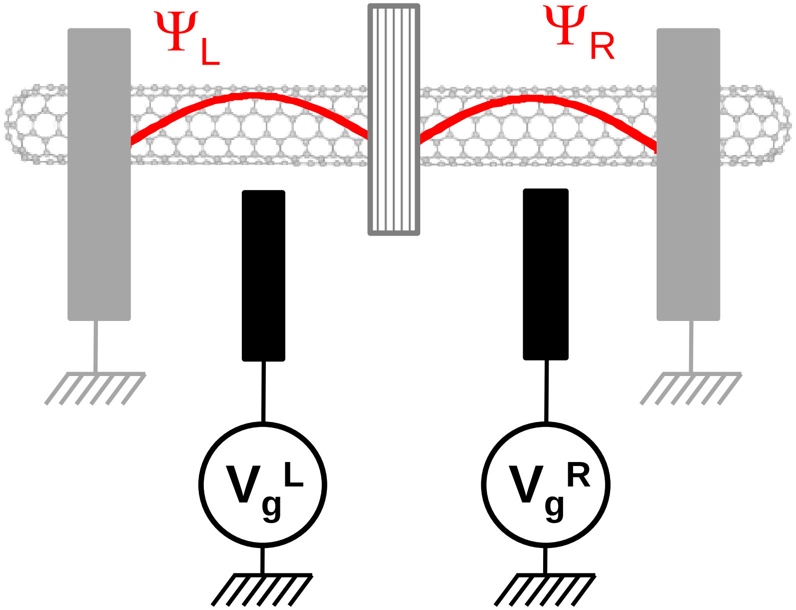

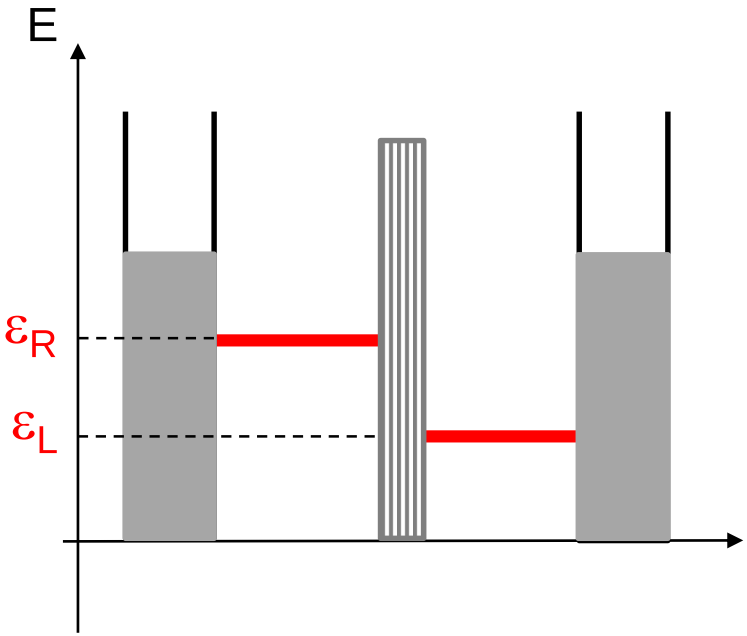

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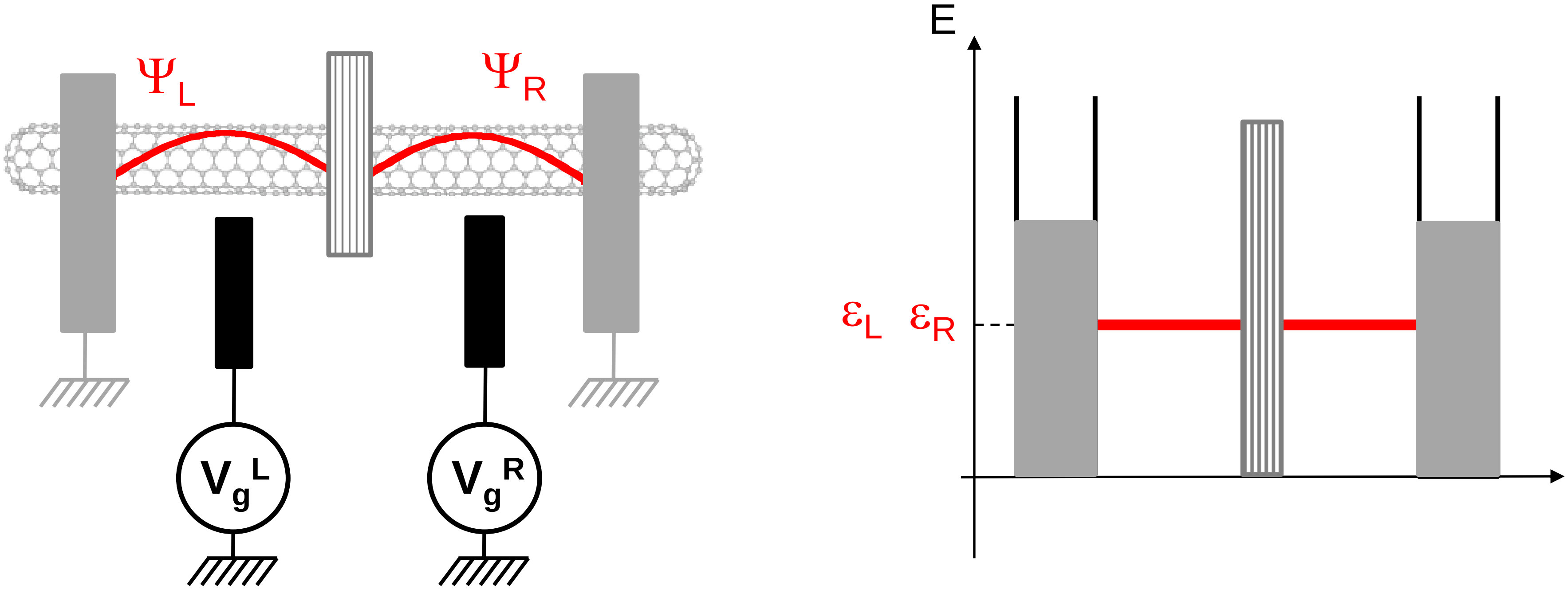

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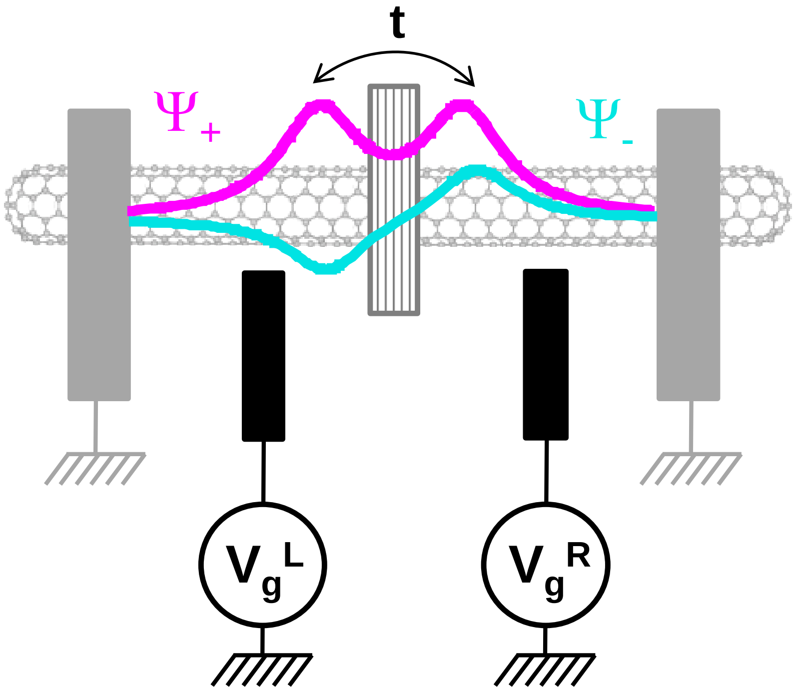
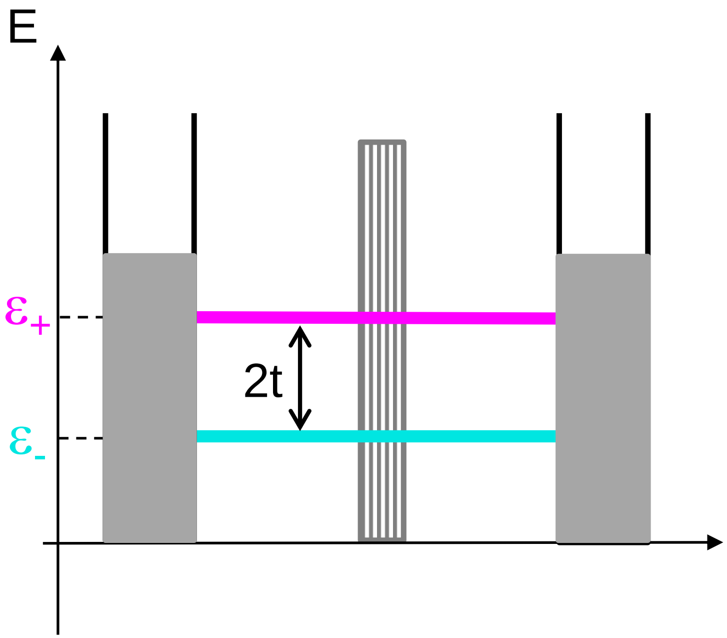
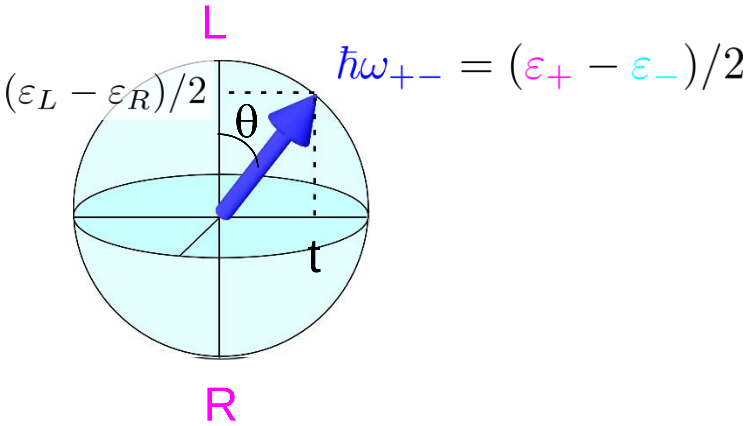
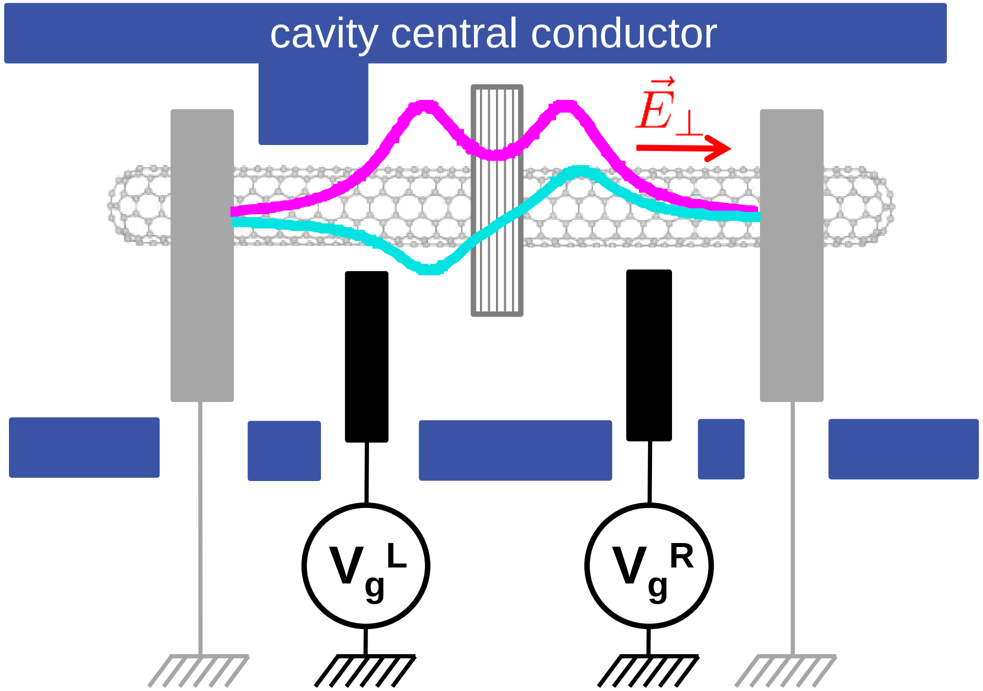






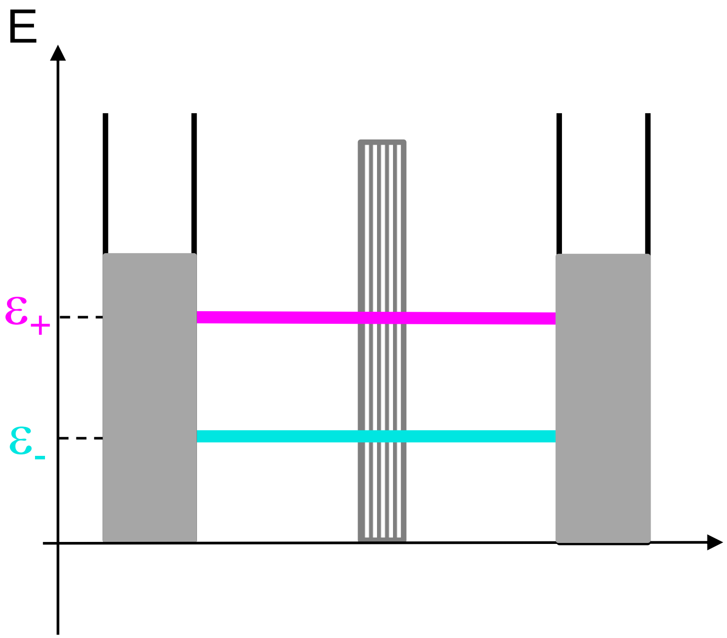
DQD coupled to a microwave cavity

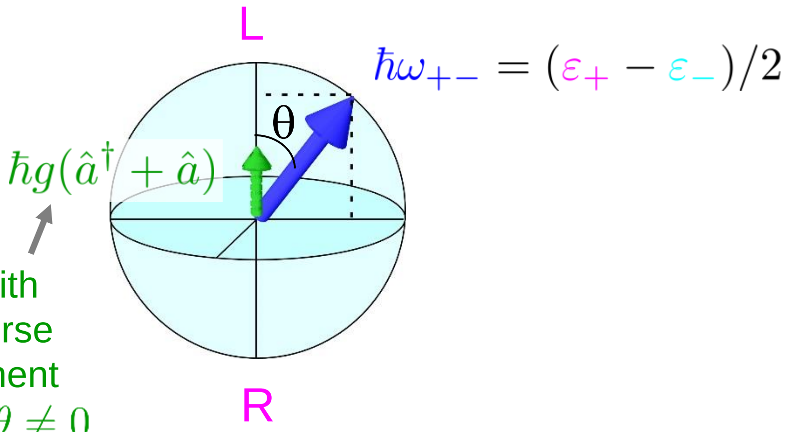


$$E \sim (\hat{a} + \hat{a}^\dagger) \times 1\,\mathrm{V.m^{-1}}$$

$$g_\perp = \frac{g_R - g_L}{2} \frac{2t}{\sqrt{4t^2 + (\varepsilon_L - \varepsilon_R)^2}}$$

~ 100 MHz

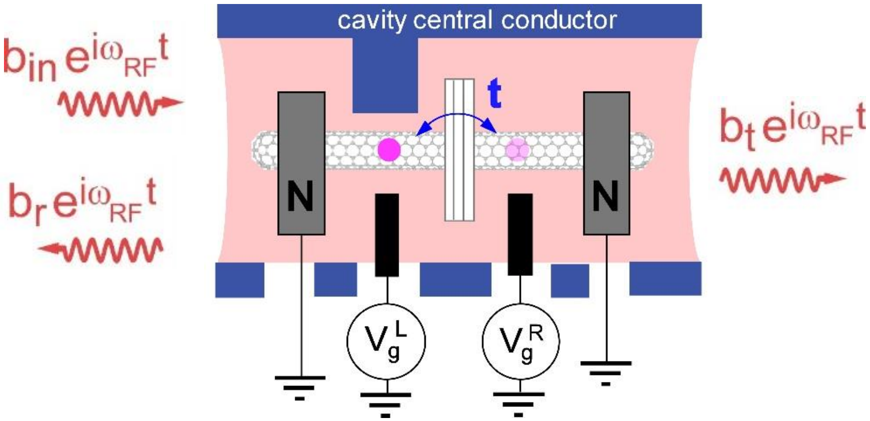




field with transverse component $g_\perp$ if $\theta \neq 0$

Cavity response in presence of the DQD

Bruhat, Cubaynes, *Viennot, Dartiailh, Desjardins, Cottet, and Kontos, PRB 2018*



$$\frac{b_t}{b_{in}} = ?$$

Cavity+DQD, semiclassical linear response model

$$\boxed{\begin{aligned} \hat{H}_{tot} &= \omega_0 \hat{a}^\dagger \hat{a} + \hat{H}_{DD} + (g_L \hat{c}_L^\dagger \hat{c}_L + g_R \hat{c}_R^\dagger \hat{c}_R)(\hat{a} + \hat{a}^\dagger) \\ &\quad + \hat{H}_{bath} + (\hat{a} \varepsilon_{in} e^{-i\omega_{RF} t} + H.c.) \end{aligned}}$$

$$\Rightarrow \quad \frac{d\hat{a}}{dt} = -i\omega_0 \hat{a} - \Lambda_0 \hat{a} - i(g_L \hat{c}_L^\dagger \hat{c}_L + g_R \hat{c}_R^\dagger \hat{c}_R) - i\varepsilon_{in} e^{-i\omega_{RF} t}$$

Semi-classical approximation: $\hat{a} = \langle \hat{a} \rangle \simeq \bar{a} e^{-i\omega_{RF} t}$

Linear response: $\hat{c}_j^\dagger \hat{c}_j = \cancel{a_0} + \sum_j \chi_{j,j'}(\omega_{RF}) e^{-i\omega_{RF} t} + \cancel{\sum_j \chi_{j,j'}(-\omega_{RF}) e^{i\omega_{RF} t}}$ for $j \in \{L, R\}$

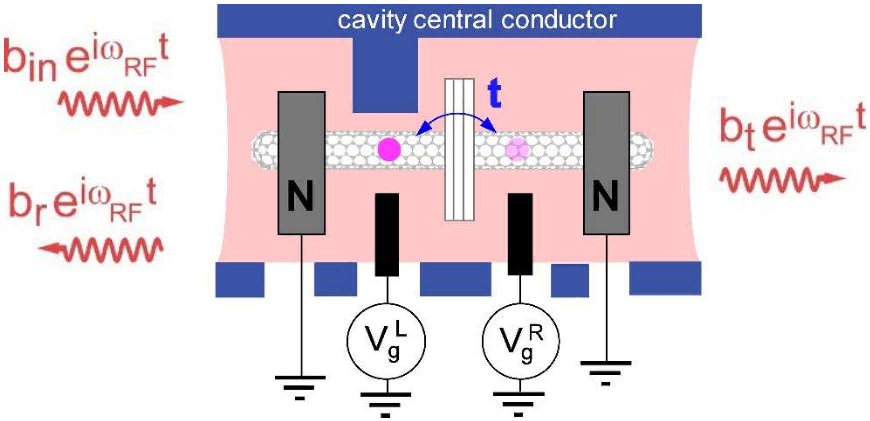
resonant approximation

$$\Rightarrow \quad \boxed{\bar{a} = \frac{a_0}{\omega_{RF} - \omega_0 - i\Lambda_0 - \chi(\omega_{RF})}}$$

Second order in g

Cavity response in presence of the DQD

__Bruhat, Cubaynes__, Viennot, Dartiailh, Desjardins, Cottet, and Kontos, PRB 2018



semiclassical cavity transmission
linear response treatment

$$\boxed{\frac{b_t}{b_{in}} = (A_0 + \Delta A)\, e^{i(\varphi_0 + \Delta\varphi)} = \frac{t_0}{\omega_{RF} - \omega_0 - i\Lambda_0 - \chi_2(\omega_{RF})}}$$

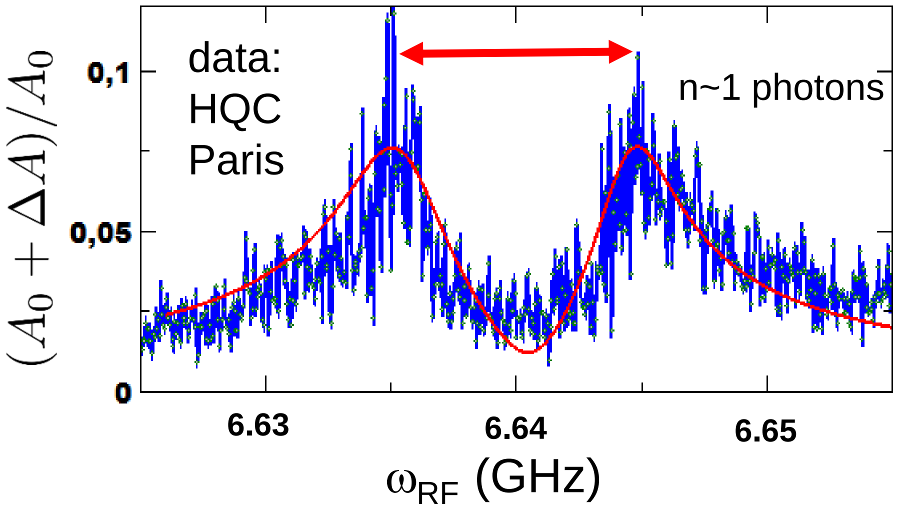
Nanocircuit charge susceptibility:

$$\boxed{\chi_2(\omega_{RF}) = \frac{(g_\perp)^2}{\omega_{RF} - \omega_{+-} + i\Gamma_2}}$$

transverse coupling crucial!

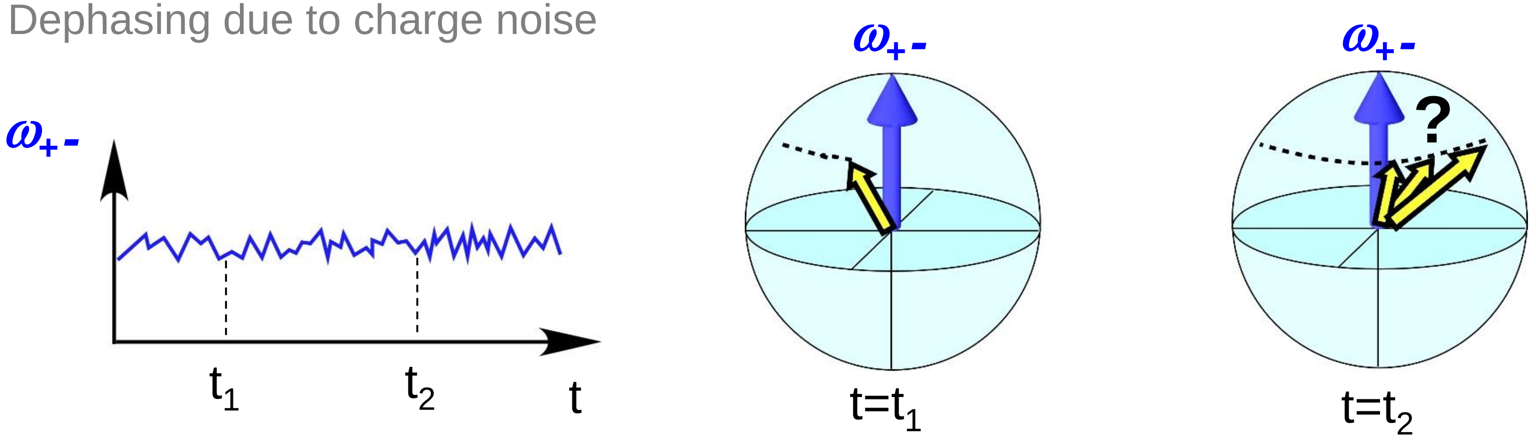
$$g_\perp \gg \Gamma_2, \Lambda_0$$

$2\tilde{g}_\perp$ ~10 MHz



Reaching the strong coupling regime

Dephasing due to charge noise



Ideas:

$$g_\perp \gg \Gamma_s, \Lambda_0$$

increase $g_\perp$

$$\Gamma_s \sim \frac{1}{\pi}\frac{\partial^2\omega_{+-}}{\partial\varepsilon^2}E_c^2(\delta n)^2$$

decrease

$$E_c = \frac{e^2}{2C_{dot}}$$

decrease intrinsic charge noise

Charge transition strongly coupled to cavity

	charge decoherence rate:	reduced charge/photon coupling:
● ***Carbon nanotube:*** *Bruhat et al., PRB 2018 (Paris)*	$\Gamma_2 = 5\ \mathrm{MHz}$	$\tilde{g}_\perp/(\Lambda_0+\Gamma_2) = 2.3$
● **2DEG: GaAs/AlGaAs** *Scarlino et al., PRL 2019 (Zurich)*	$\Gamma_2 = 3{,}3\ \mathrm{MHz}$	$g_\perp/(\Lambda_0+\Gamma_2) = 3.1$
● **2DEG Si/SiGe** *Mi et al., Science 2017 (Princeton)*	$\Gamma_2 = 6.7\ \mathrm{MHz}$	$g_\perp/(\Lambda_0+\Gamma_2) = 2.2$

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Coupling spins to photons

Readout of a single spin and distant spin/spin coupling by using circuit QED techniques?

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⇨ **Boost weak natural magnetic coupling** *Haikka et al. PRA 95 022306 (2017)*

Coupling spins to photons

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⇨ **Electric coupling?**

- Inhomogeneous nuclear fields: *Burkard et al., PRB (2006)*
- Spin-orbit interaction: *Trif et al., PRB (2008)*

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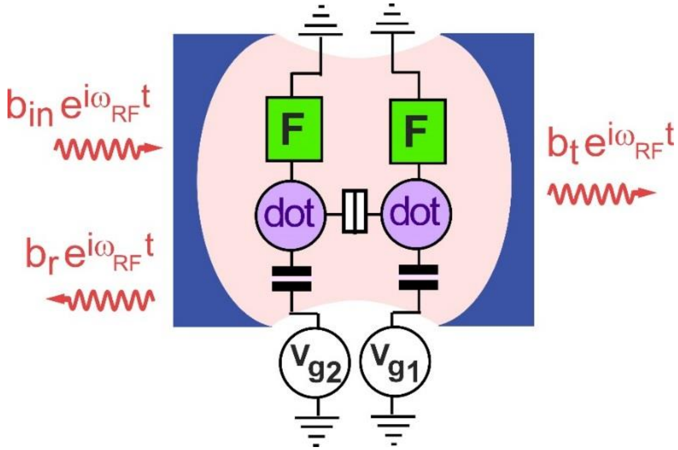
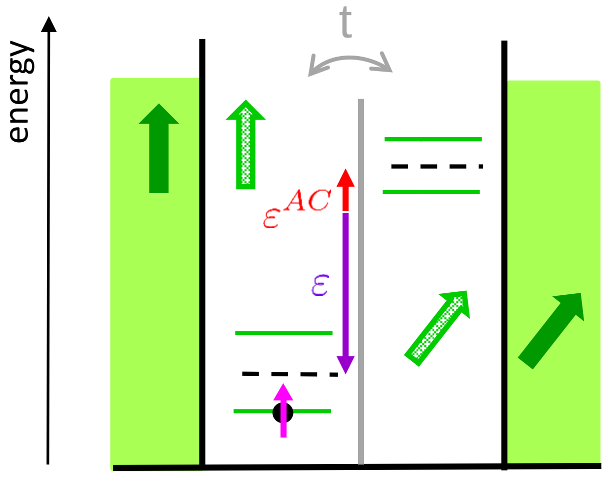
- Inhomogeneous nuclear fields: *Burkard et al., PRB (2006)*
- Spin-orbit interaction: *Trif et al., PRB (2008)*
- Articial spin-orbit coupling from ferromagnetic contacts: *Cottet/Kontos, PRL (2010)*

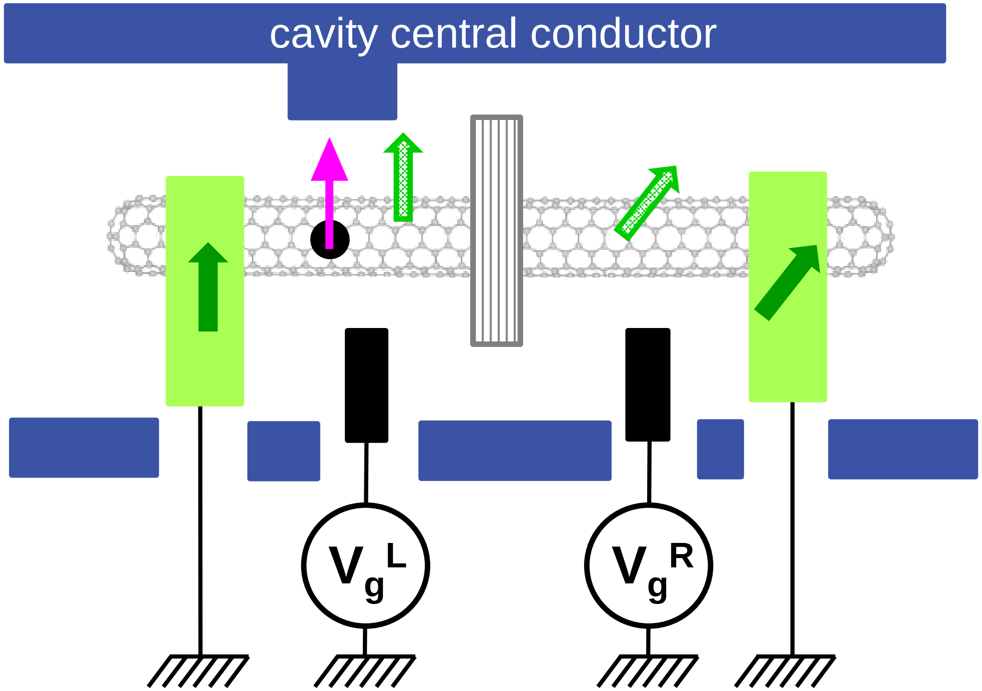


DQD with non-collinear ferromagnetic contacts

*Theory proposal: Cottet & Kontos, PRL **105**, 160502 (2010)*



$$\varepsilon^{AC} = \hbar(g_L - g_R)(\hat{a} + \hat{a}^\dagger)$$



- Coupled orbital and spin variables ⟹ « artificial spin-orbit interaction »
- Photons couple to orbital part and therefore to spin $\hat{h}_{int}(\hat{a} + \hat{a}^\dagger) \simeq \hbar g(\hat{a}^\dagger \hat{c}_\uparrow^\dagger \hat{c}_\downarrow + \hat{a}\hat{c}_\downarrow^\dagger \hat{c}_\uparrow)$

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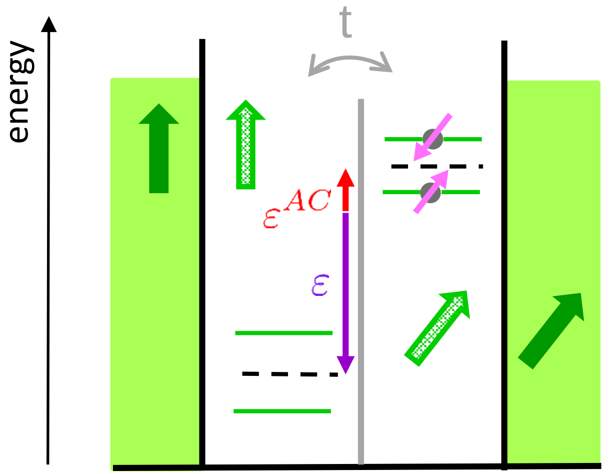

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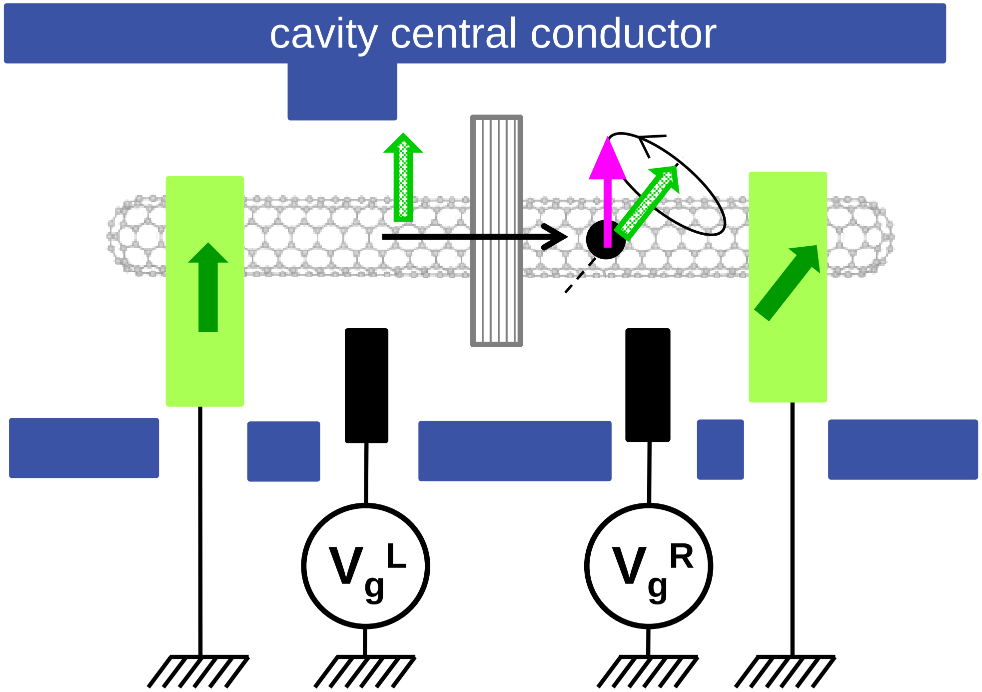

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Optimization of the spin/photon coupling

Theory proposal:
Cottet & Kontos,
*PRL **105**, 160502 (2010)*

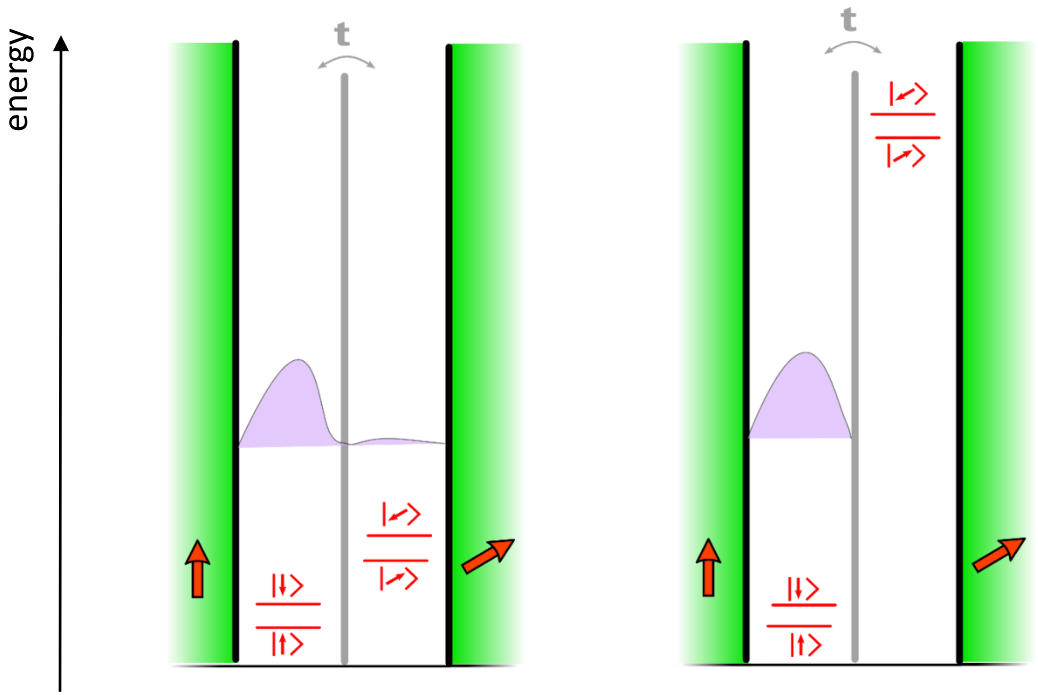
<u>Main sources of decoherence</u>:

- charge noise => dephasing

- phonons => relaxation

$\varepsilon = 2.8\delta$

$\varepsilon = 20\delta$



ON POINT
(theory proposal)

$g_\perp = 5.6$ MHz

$\Gamma_2^* = 1$ MHz

Strong coupling limit

OFF POINT
(theory proposal)

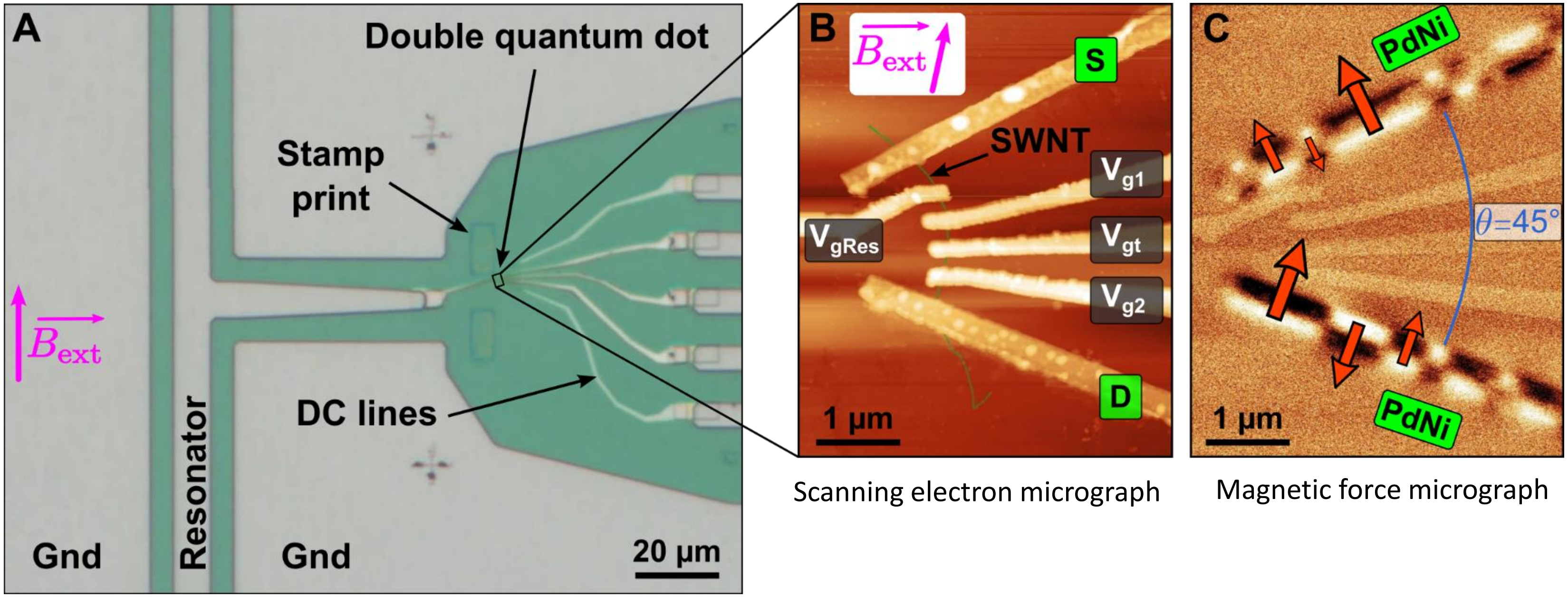
$g_\perp = 13$ kHz

$\Gamma_2^* = 0.5$ kHz

pure spin limit
= quantum memory?

Experiment: carbon nanotube and PdNi contacts

Viennot, Dartiailh, Cottet, & Kontos, Science ***349****, 6246 (2015)*



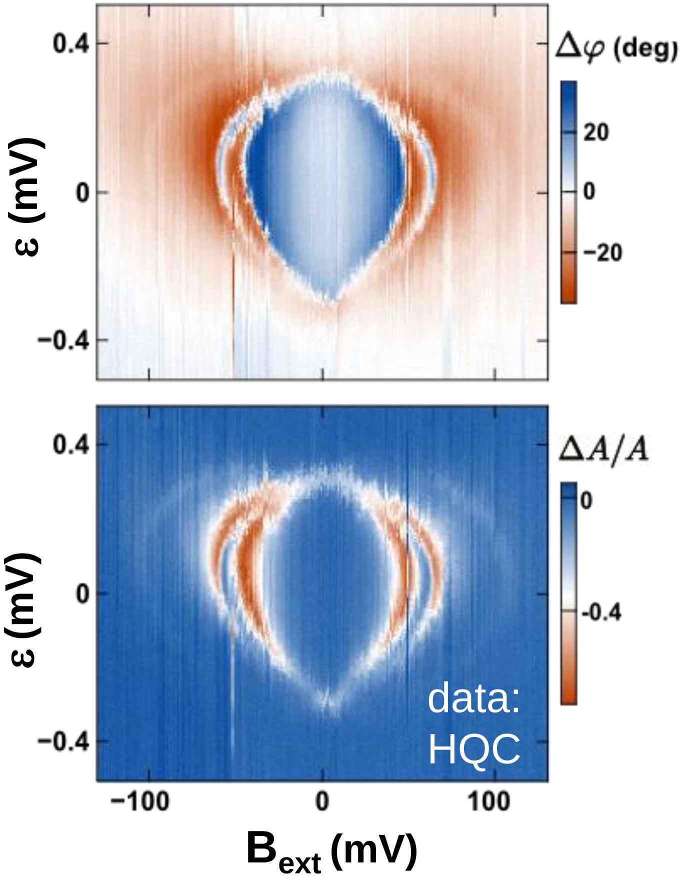
Scanning electron micrograph

Magnetic force micrograph

- **V_{g1}, V_{g2}** are DC electrostatic gates controlling ε^{DC}
- Selective coupling of the right dot to the cavity by the gate **V_{gRes}**
- Non-colinear magnetizations imposed by contacts shape
- Resonator $\omega_0/2\pi = 6.72GHZ$, quality factor $Q \simeq 10^4$ up to $B_{ext} = 100mT$

Magneto-spectroscopy

__Viennot, Dartiailh__, Cottet, & Kontos, Science __349__, 6246 (2015)

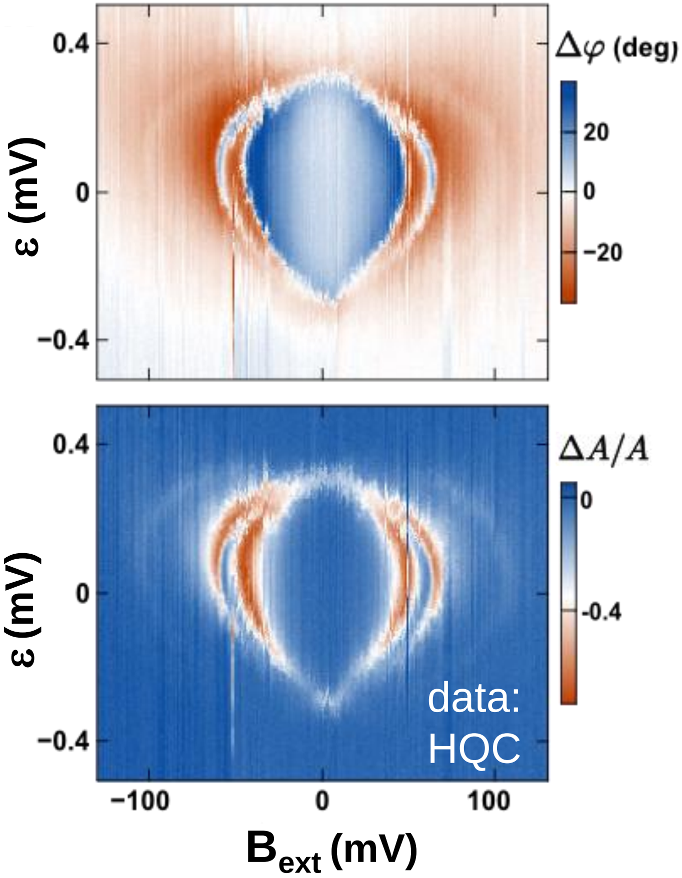


These resonances strongly move with B_{ext} !

⇨ Spin degree of freedom involved

Magneto-spectroscopy

__Viennot, Dartiailh__, Cottet, & Kontos, Science __349__, 6246 (2015)



Cavity transmission at $\omega_{RF} = \omega_0$

$$\frac{b_t}{b_{in}} = (A_0 + \Delta A)\, e^{i(\varphi_0 + \Delta\varphi)}$$

$$= \frac{t_0}{i\Lambda_0 - \chi_2(\omega_0)}$$

Nanocircuit charge susceptibility:

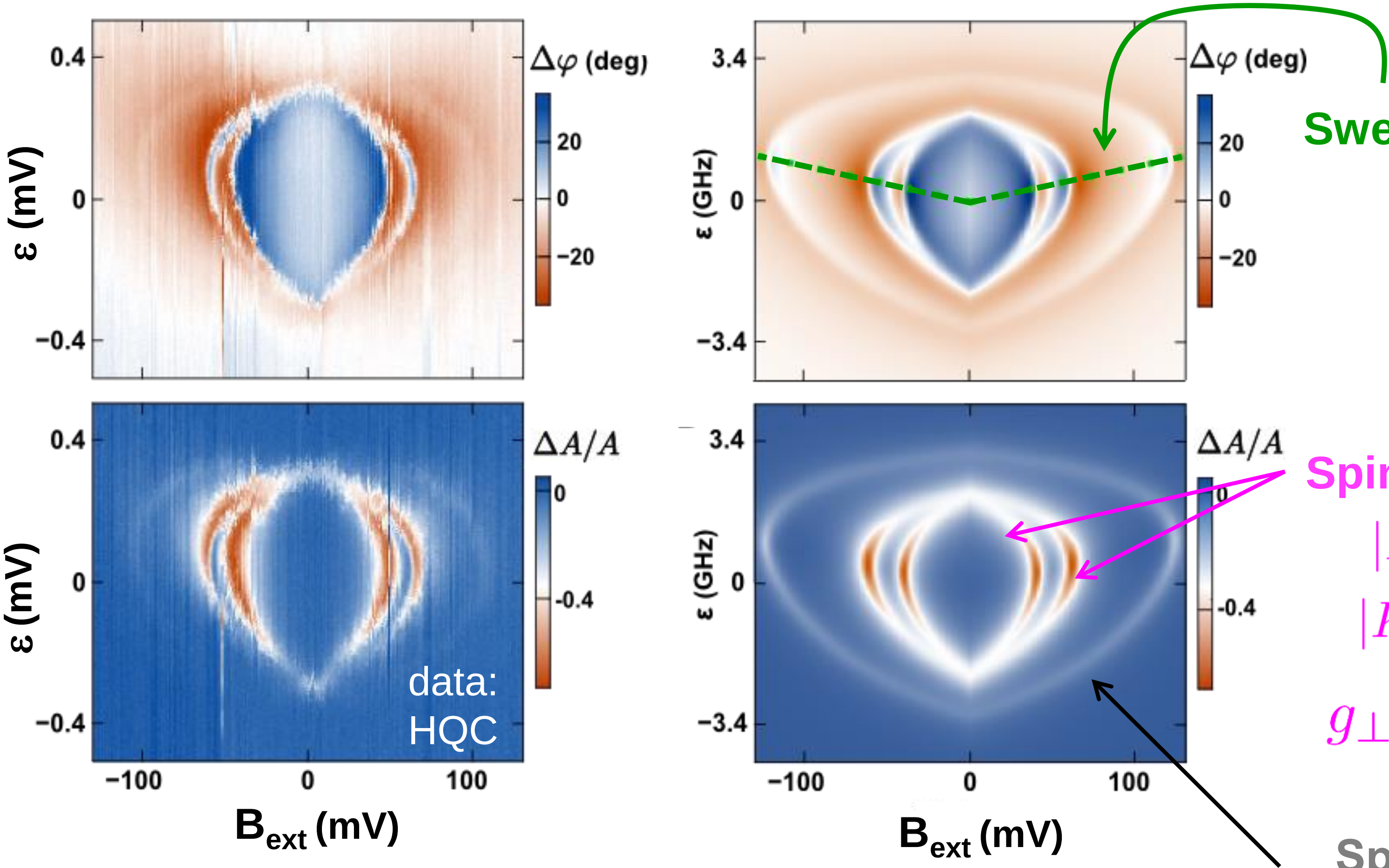
$$\chi_2(\omega_0) = \sum_{ij} \frac{g_{ij}^2}{\omega_0 - \omega_{ij} + i\Gamma_{ij}}$$

Multiple transitions due to
L/R, spin and K/K' degrees of freedom

The cavity provides a cut of the DQD spectrum at frequency ω_0

Magneto-spectroscopy

***Viennot, Dartiailh**, Cottet, & Kontos, Science **349**, 6246 (2015)*



Sweet line $\frac{\partial \omega_{ij}}{\partial \varepsilon} = 0$

Spin-flip transitions

$|K,\uparrow\rangle \leftrightarrow |K,\downarrow\rangle$

$|K',\uparrow\rangle \leftrightarrow |K',\downarrow\rangle$

$g_\perp/(\Lambda_0+\Gamma_s) \sim 0.5$

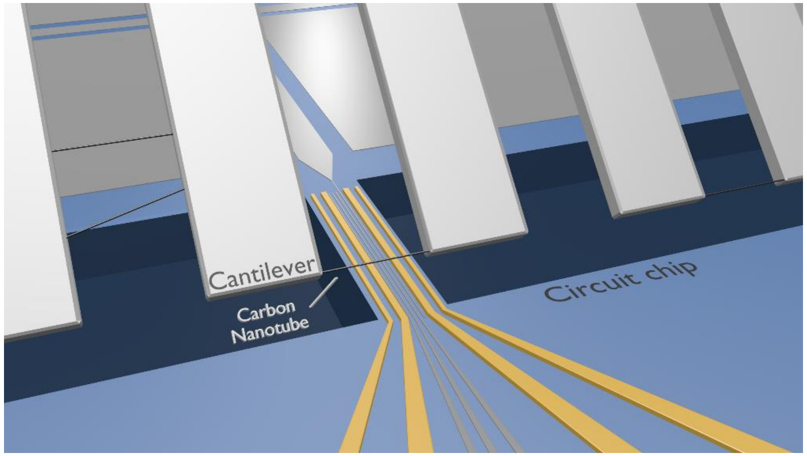
Spin and K/K' flip

$|K',\uparrow\rangle \leftrightarrow |K,\downarrow\rangle$

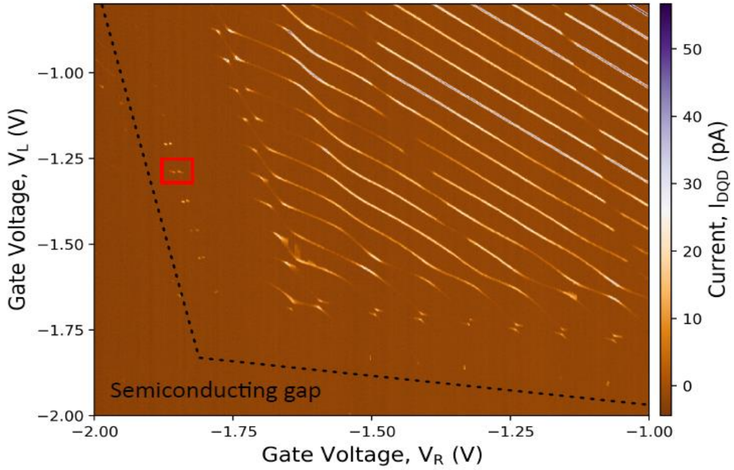
Charge noise gives an important contribution to decoherence!

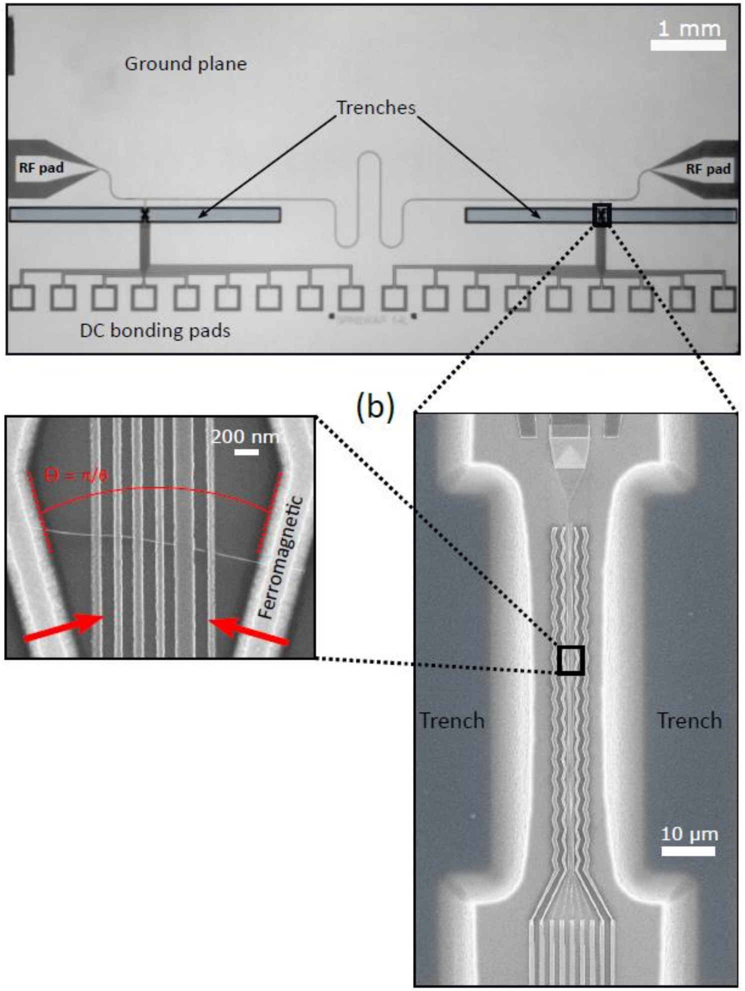
Towards the strong spin/photon coupling with carbon nanotubes

T. Cubaynes et al., NPJQI 2019



Stapling technique, see also Pei et al. Nature Nano'12, Waissman et al. Nature Nano'13, Ranjan et al. Nature Comm. '15





Reaching the strong spin/photon coupling with carbon nanotubes

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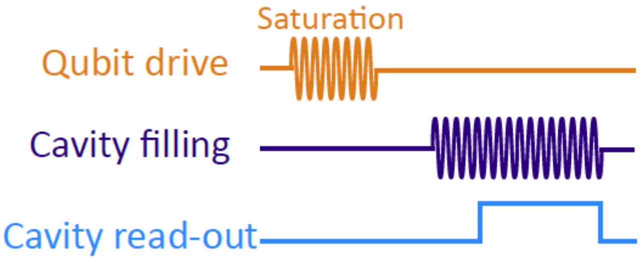
NPJQI 2019

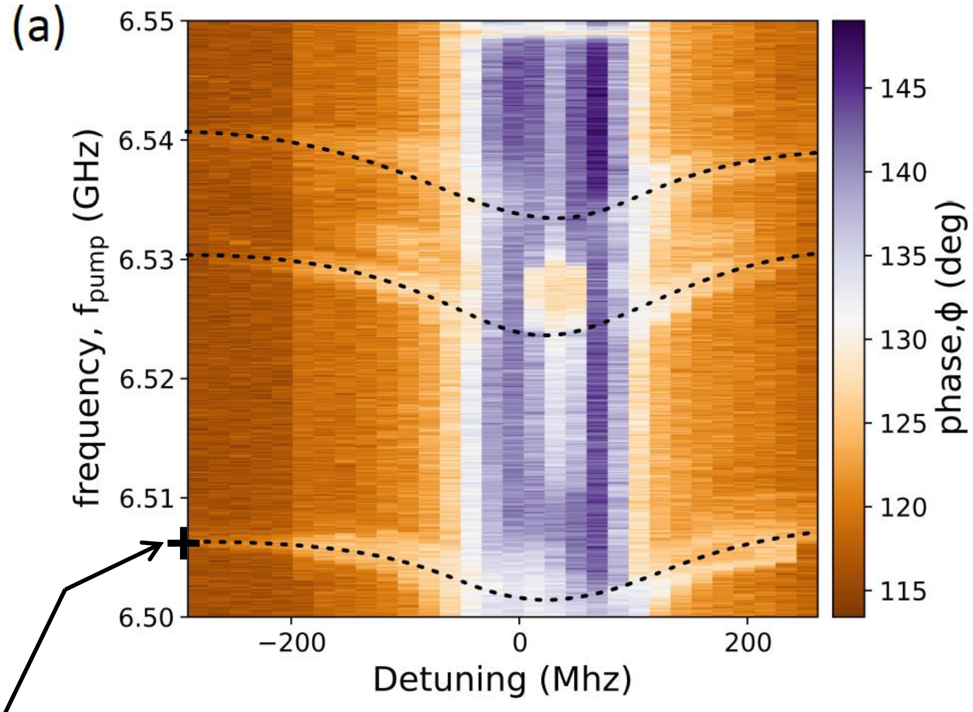


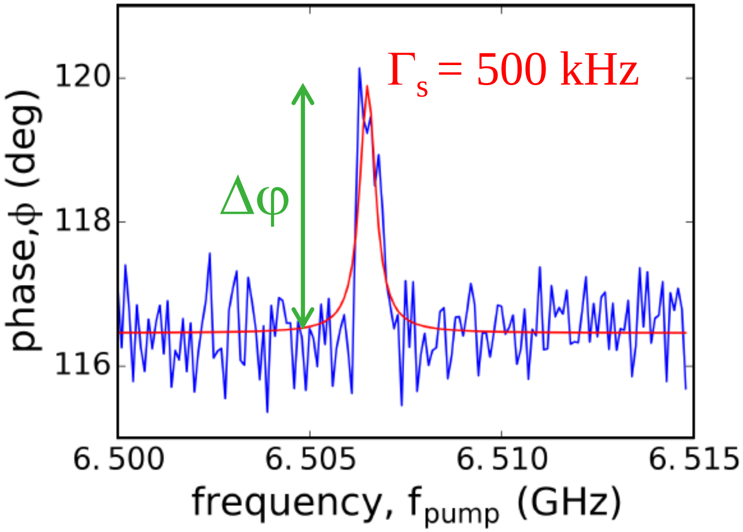
Saturation

Qubit drive

Cavity filling

Cavity read-out





Γ_s = 500 kHz

$$\Delta\varphi \sim \frac{g_\perp^2}{\Lambda_0(\omega_s-\omega_0)}$$

$$\Rightarrow g_\perp/(\Lambda_0+\Gamma_s) = 2$$

Strong spin/photon coupling

- ***Carbon nanotube:***

  Viennot, et al. Science (2015) (Paris) $\Gamma_s = 2.5\ \mathrm{MHz}$ $g_\perp/(\Lambda_0+\Gamma_s) = 0.46$

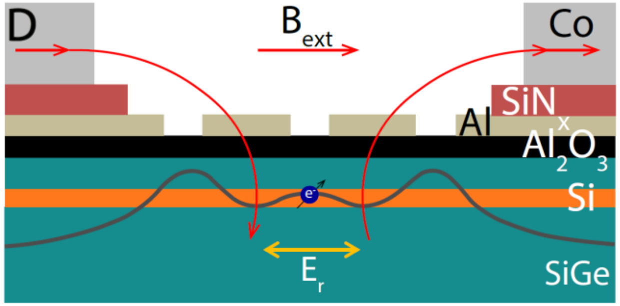
- ***Suspended carbon nanotube:***

  Cubaynes, et al. NPJQI (2019) (Paris) $\Gamma_s = 0.25\ \mathrm{MHz}$ $g_\perp/(\Lambda_0+\Gamma_s) = 2$

- **2DEG Si/SiGe:** anticrossing observed

  Samkharadze et al., Science (2018) (Delft) $\Gamma_s = 1.8\ \mathrm{MHz}$ $g_\perp/(\Lambda_0+\Gamma_s) = 2.6$

  Mi et al. Nature (2018) (Princeton) $\Gamma_s = 2.4\ \mathrm{MHz}$ $g_\perp/(\Lambda_0+\Gamma_s) = 1.7$



See also: Landig et al.,
Nature (2018) (Zurich)
[different principle]

Strong spin/photon coupling

- ***Carbon nanotube:***

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  Mi et al. Nature (2018) (Princeton) $\Gamma_s = 2.4\ \mathrm{MHz}$ $g_\perp/(\Lambda_0+\Gamma_s) = 1.7$

Possible improvements:

⇨ A better control of spin/charge hybridization

⇨ Use nanotubes with pure C12

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III. Using a dissipative nanocircuit to prepare non-classical cavity states

- Quantum non-linear description of Mesoscopic QED
- Preparation of a photonic Schrödinger cat using dissipative tunneling

Keldysh theory for quantum dot circuits

Bruhat, Viennot, Dartiailh, Desjardins, Kontos and Cottet, Phys. Rev. X, ***6****, 021014 (2016)*

$$\boxed{\frac{b_t}{b_{in}} = \frac{t_0}{\omega_{RF}-\omega_0-i\Lambda_0-\chi_2(\omega_{RF})}}$$

semiclassical cavity transmission
linear response treatment

electron/photon
coupling matrix

Nanocircuit charge susceptibility (non interacting multi-dot case) :

$$\boxed{\chi_2 = -\frac{i}{2}\int_{\omega} \mathrm{Tr}\left[\tilde{G}_K(\omega)\tilde{g}\left(\tilde{G}_a(\omega-\omega_0)+\tilde{G}_r(\omega+\omega_0)\right)\tilde{g}\right]}$$

Keldysh Green's functions:

$$G_r^{j,j'}(t,t') = -i\theta(t)\left\langle\{\hat{c}_j(t),\hat{c}^\dagger_{j'}(t')\}\right\rangle$$

$$G_a^{j,j'}(t,t') = i\theta(-t)\left\langle\{\hat{c}_j(t),\hat{c}^\dagger_{j'}(t')\}\right\rangle$$

$$G_K^{j,j'}(t,t') = -i\left\langle[\hat{c}_j(t),\hat{c}^\dagger_{j'}(t')]\right\rangle$$

j,j': dot, orbital, and spin indices

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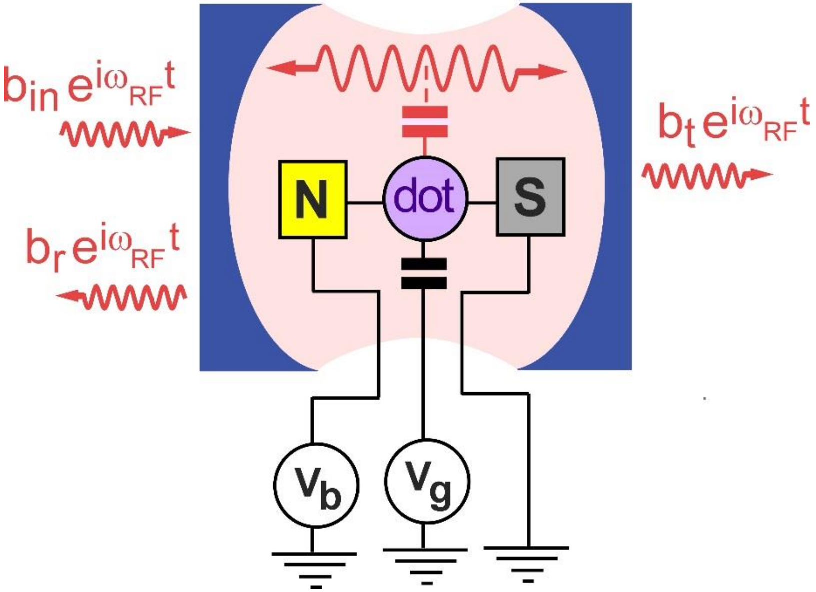
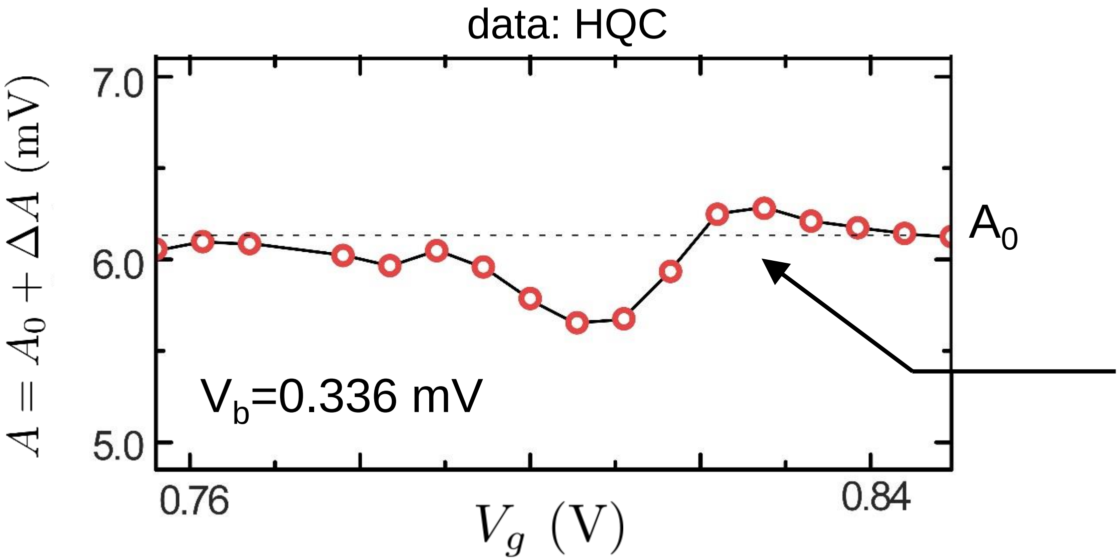
S/dot/N bijunction at finite V_b

***Bruhat**, Viennot, Dartiailh, Desjardins, Kontos & Cottet,*
Phys. Rev. X 6, 021014 (2016)

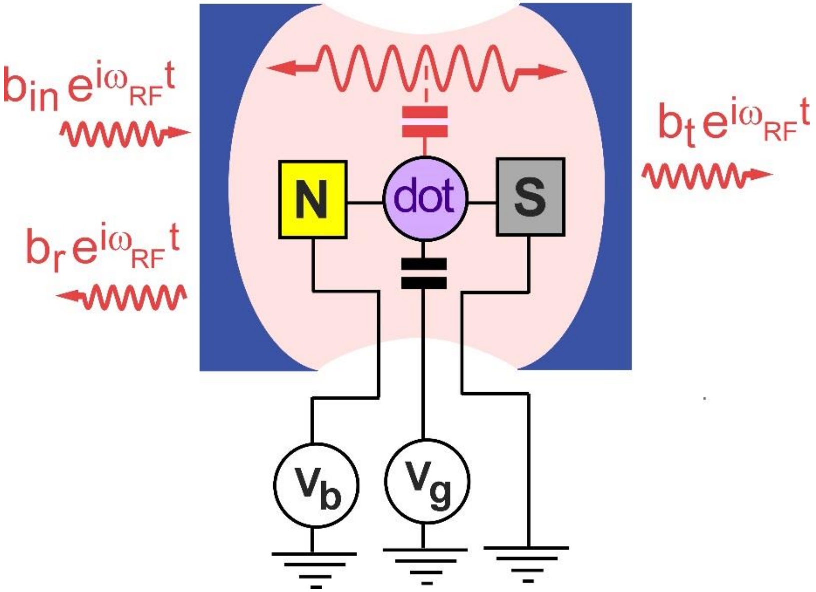


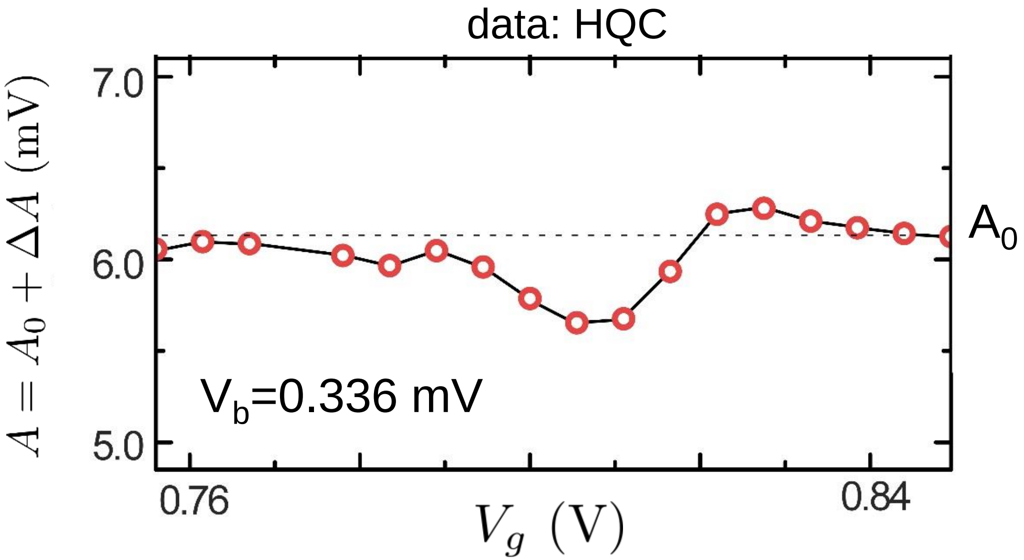


Microwave amplification $\Delta A>0$

S/dot/N bijunction at finite V_b

***Bruhat**, Viennot, Dartiailh, Desjardins, Kontos & Cottet, Phys. Rev. X 6, 021014 (2016)*





No relevant
dot internal degree of freedom
to explain photon-emission

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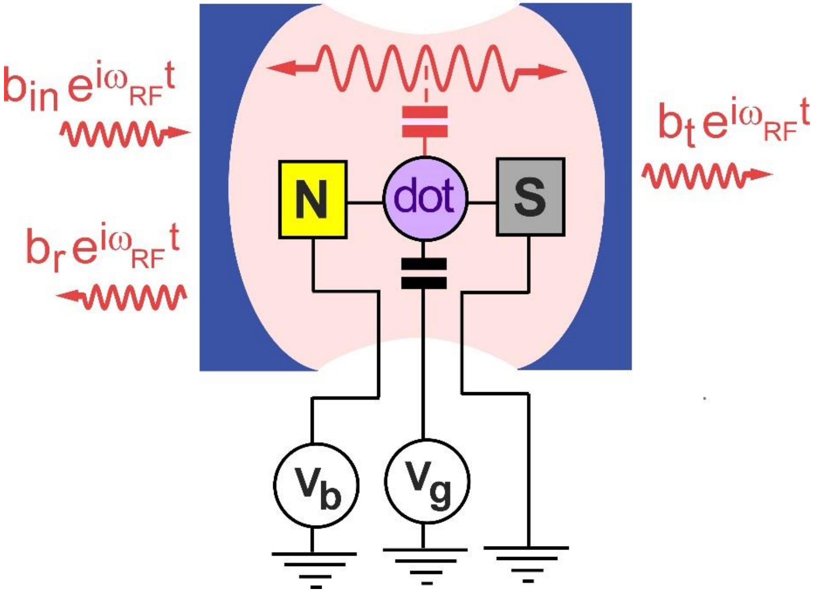
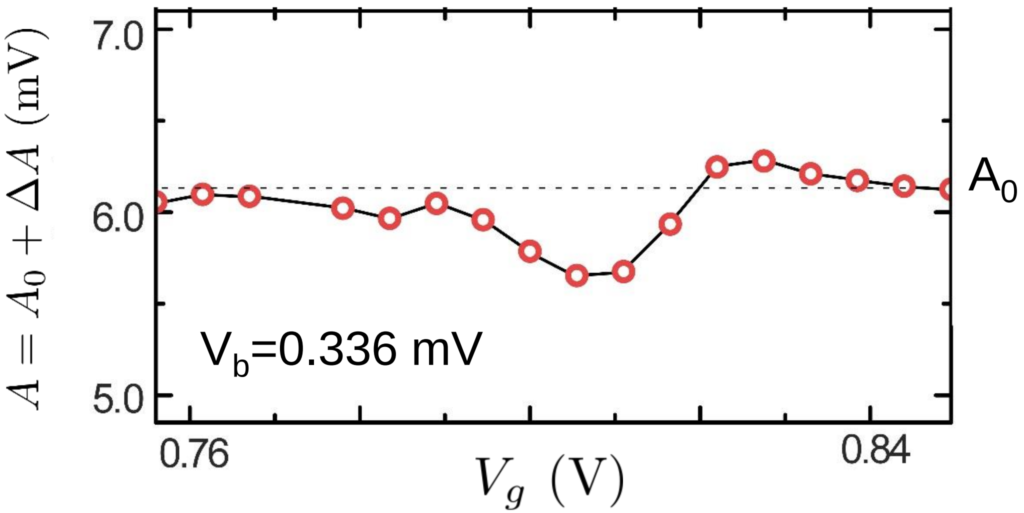


data: HQC



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Look at theory?

Keldysh theory for quantum dot circuits

Bruhat, Viennot, Dartiailh, Desjardins, Kontos and Cottet, Phys. Rev. X, ***6****, 021014 (2016)*

$$\boxed{\frac{b_t}{b_{in}} = \frac{t_0}{-i\Lambda_0 - g^2\chi_2(\omega_0)}}$$

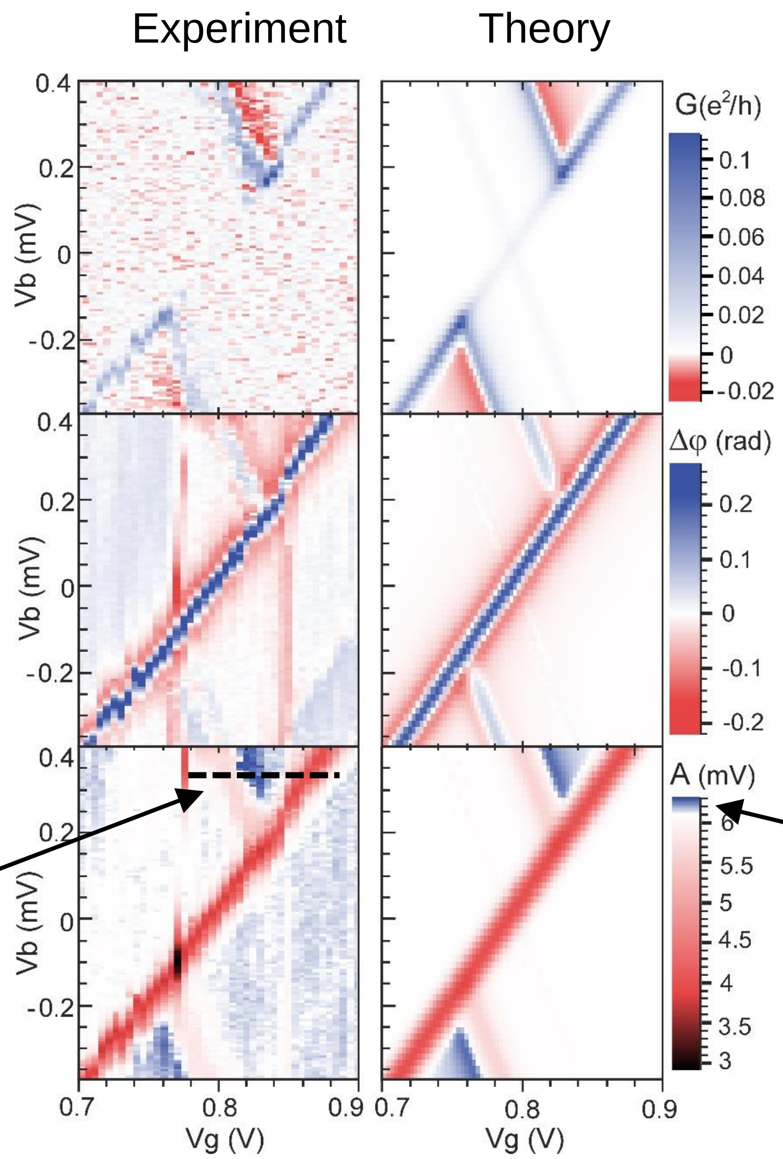
$$\boxed{\chi_2 = -\frac{i}{2}\int_\omega \operatorname*{Tr}_d \left[\tilde{G}_K(\omega)\tilde{g}\left(\tilde{G}_a(\omega-\omega_0)+\tilde{G}_r(\omega+\omega_0)\right)\tilde{g}\right]}$$

<u>Fitting parameters:</u>

- gap of S: Δ
- temperature: T
- dot/cavity coupling: g
- dot/N tunnel rate: Γ_N
- dot/S tunnel rate: Γ_S
- BCS peaks broadening: Γ_b

Test of theory at finite bias voltages

Quantitative agreement with the data



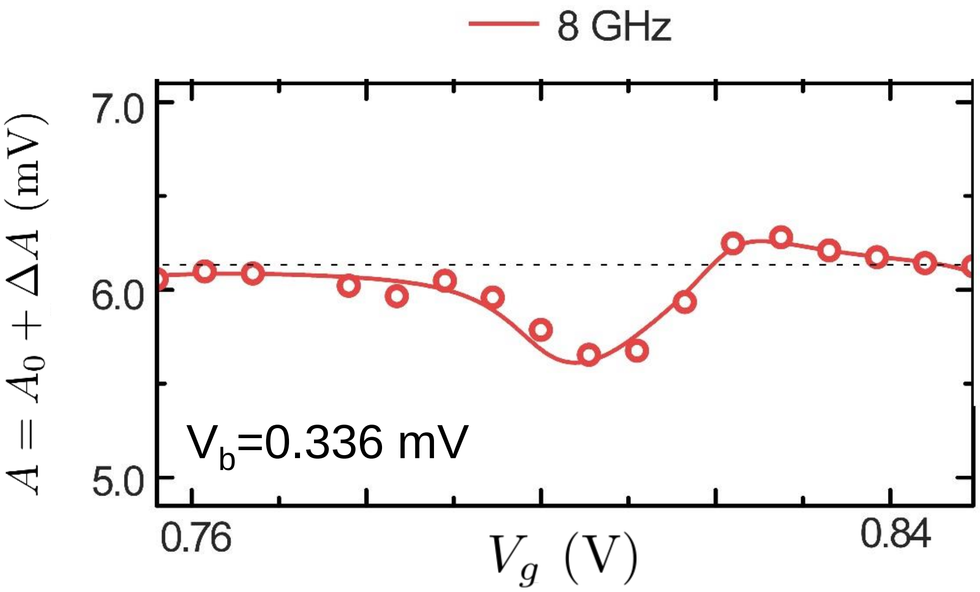
CUT

Microwave amplification ΔA>0

Inelastic tunneling between dot and S

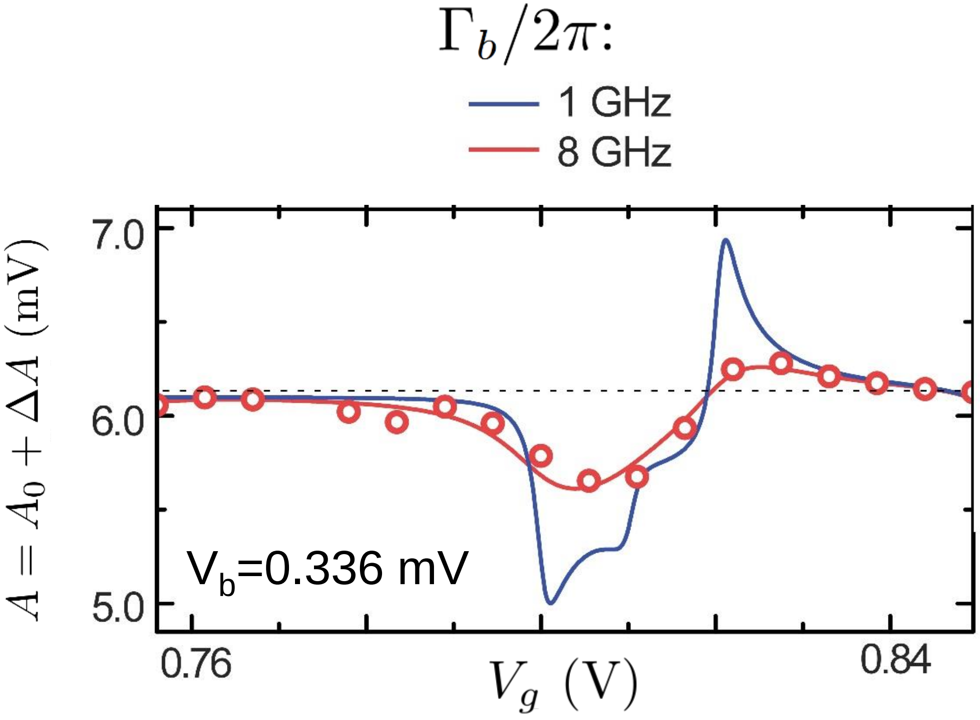
Bruhat et al., Phys. Rev. X (2016)

$\Gamma_b/2\pi$:



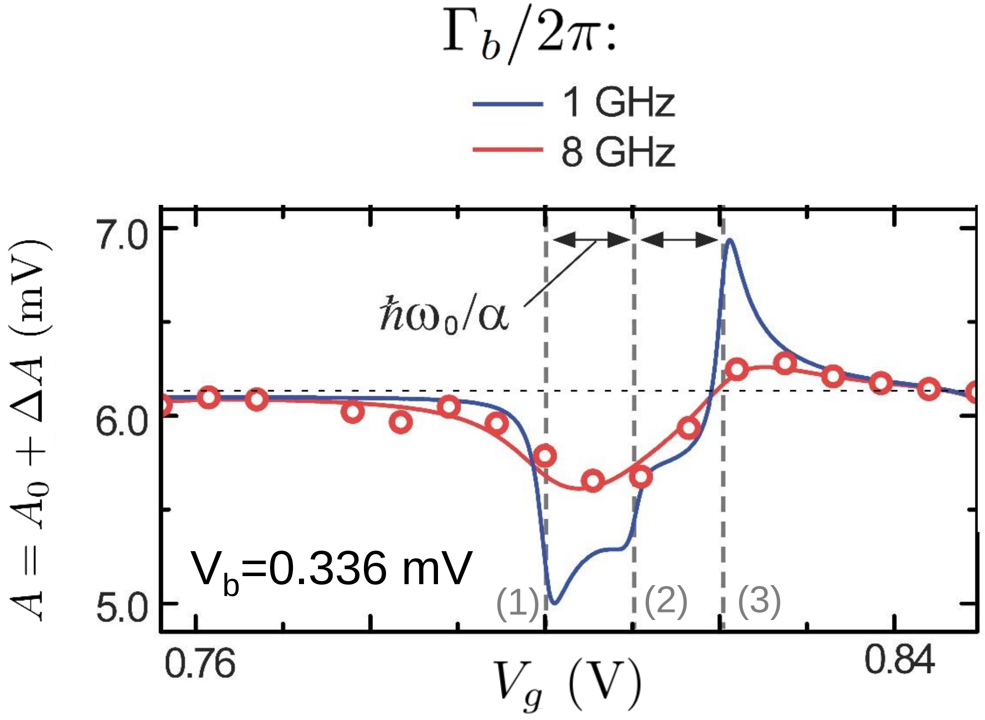
Inelastic tunneling between dot and S

Bruhat et al., Phys. Rev. X (2016)



Inelastic tunneling between dot and S

ω_0 : cavity frequency
α : DC-gate lever arm



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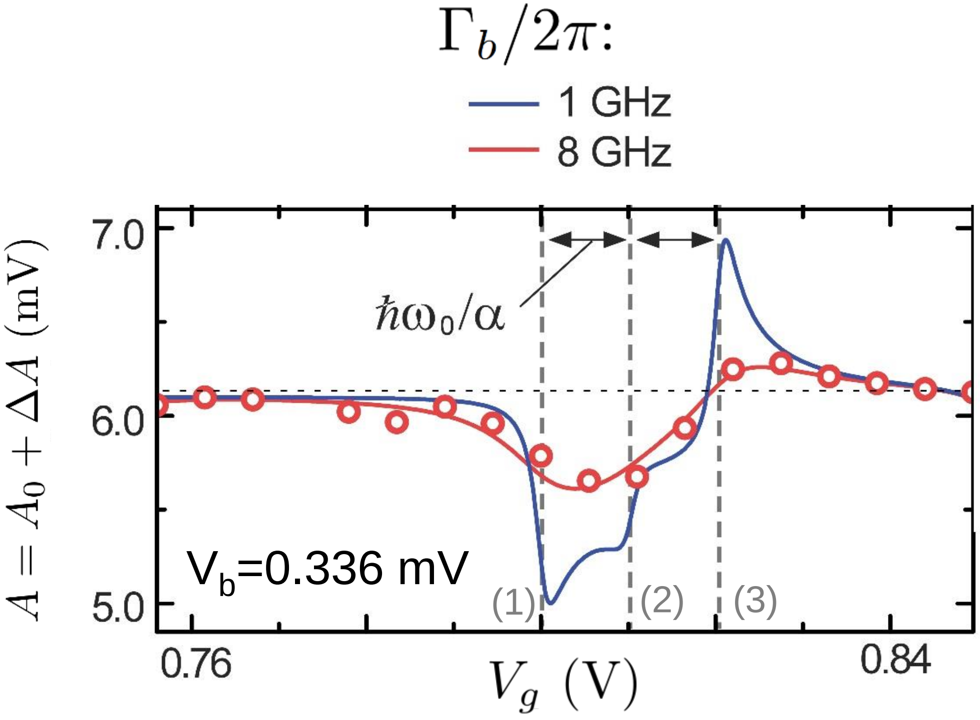
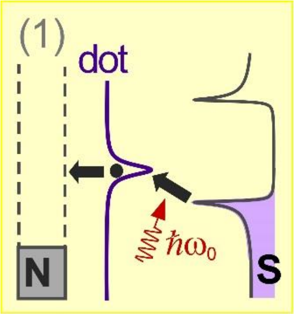
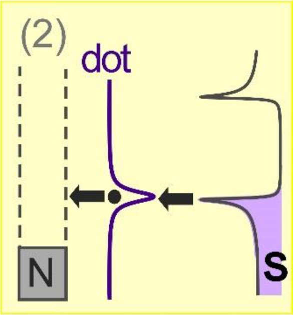


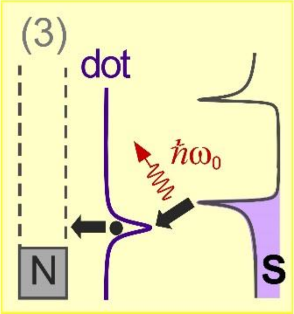
Photon-emission visible only through cavity!



Photon-absorption



Elastic transport



Photon-emission

$$\text{rate} \sim 2MHz$$
$$\sim 0.3 \text{ pA}$$

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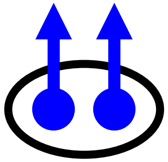
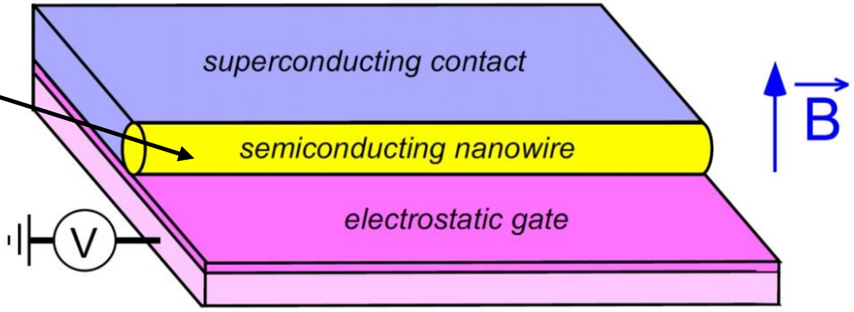
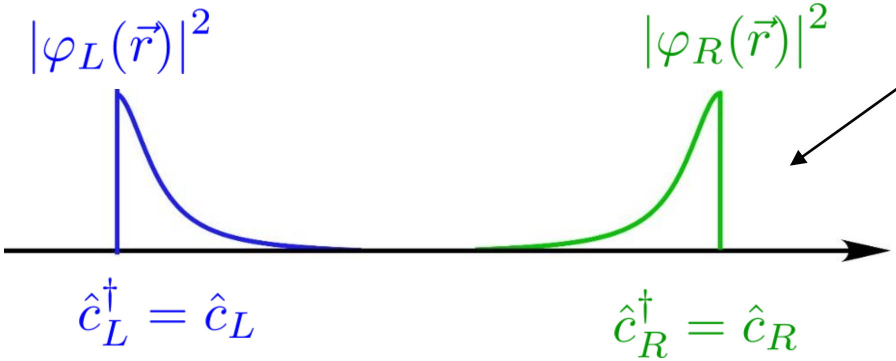
Majorana fermions in a nanowire

Synthetic
topological
superconductivity







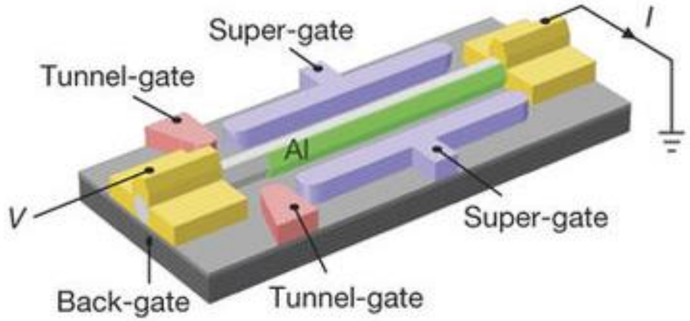
low-energy
self-adjoint
quasiparticle state

Possible application = **topologically protected quantum computation**

Review: Leijnse and Flensberg, Semicond. Sci. Technol.(2012)

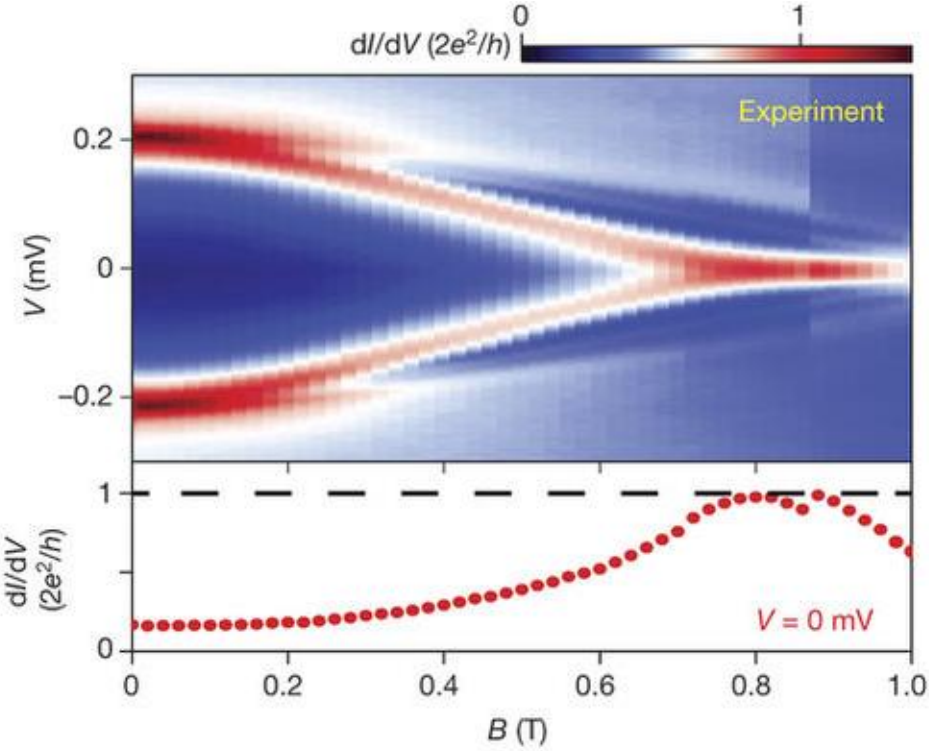
Observation of zero bias conductance peaks in semiconducting nanowires

Zhang et al., Nature (2018)



See also:
Mourik, et al., Science 336, 1003 (2012)
Williams, et al., PRL (2012)
Das, et al., Nature Phys. (2012).
Deng, et al., Nano Lett. (2012),
Rokhinson et al., Nature Phys. (2012)
Albrecht et al., Nature (2016)
Deng et al, Science (2016)
etc…

Density of states measurement:

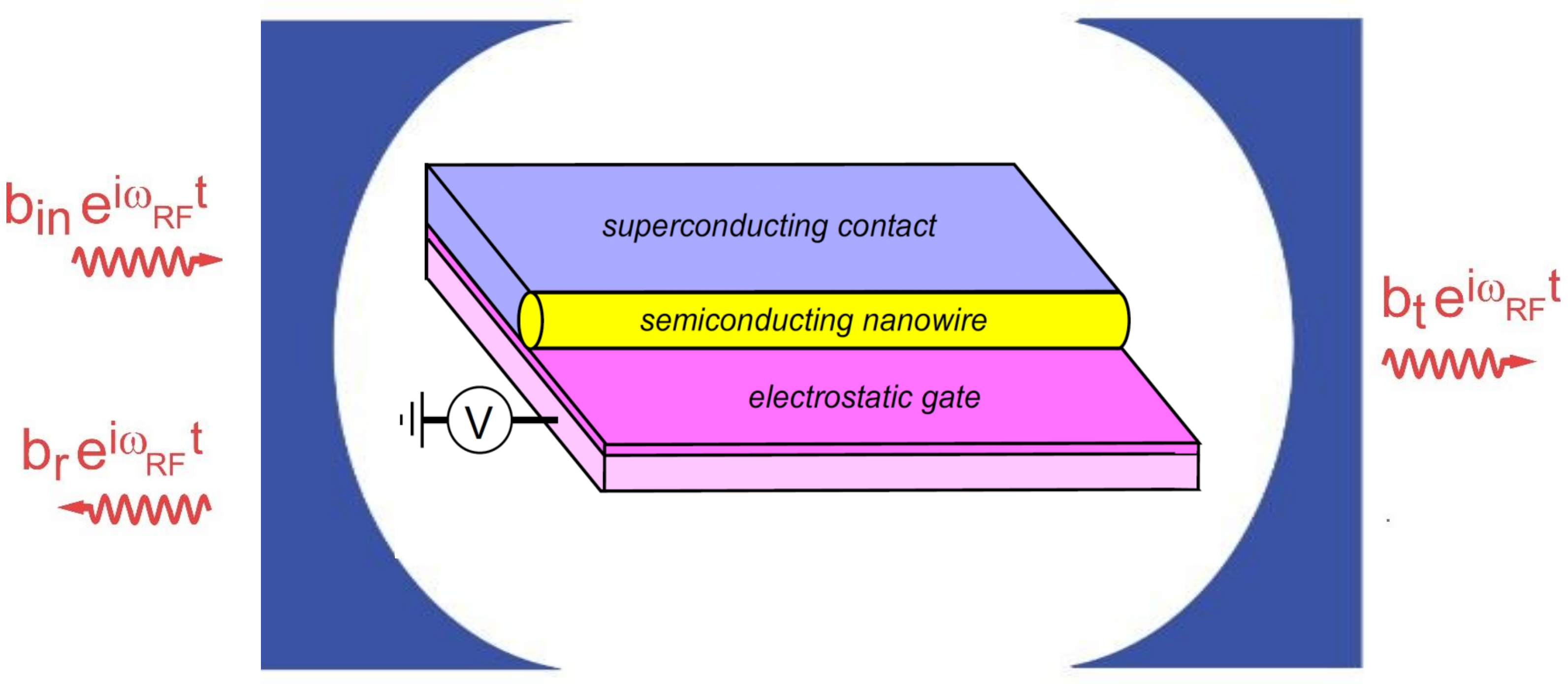


⇨

Majorana bound state

$$\hat{c}^\dagger = \hat{c} \ ?$$

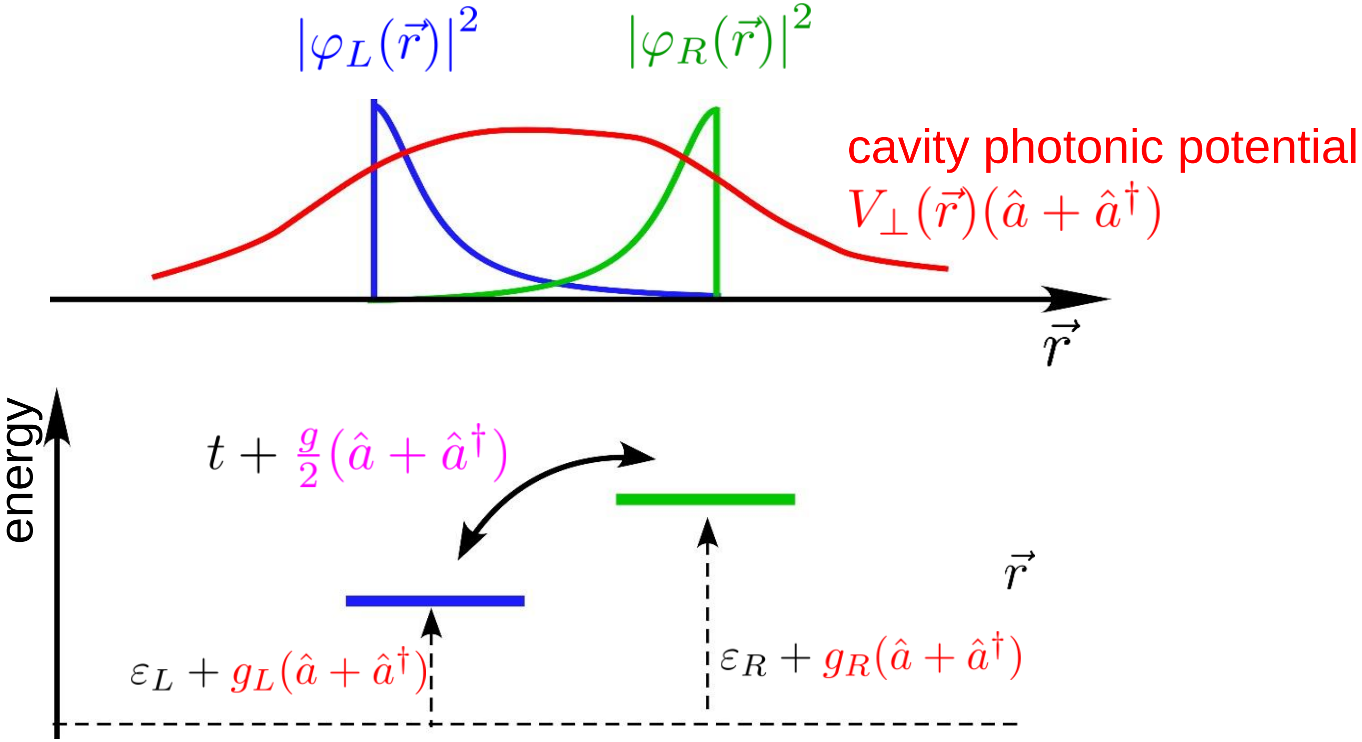
Majorana nanocircuit in a microwave cavity



What can we learn from a Majorana nanocircuit with a cavity?

Majorana + cavities, see also:
Hassler et al. New J. Phys. (2011), Hyart et al., PRB (2013), Müller et al. PRB (2013), Ginossar and Grosfeld, arXiv 1307.1159, Trif and Tserkovnyak, PRL (2012), Schmidt et al. PRL (2013). Dmytruk et al. PRB (2015), Trif et al. PRL (2019)

Majorana pair in a cavity



$|\varphi_L(\vec{r})|^2$

$|\varphi_R(\vec{r})|^2$

cavity photonic potential

$V_\perp(\vec{r})(\hat{a}+\hat{a}^\dagger)$

$\vec{r}$

energy

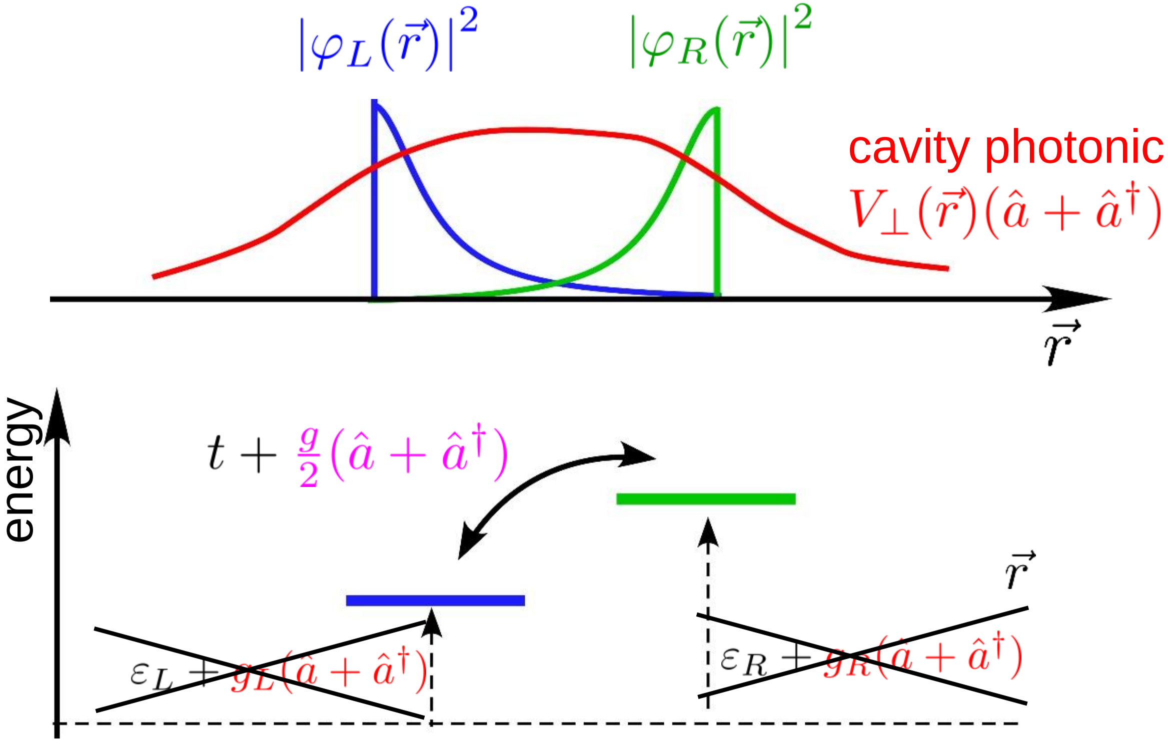
$t+\frac{g}{2}(\hat{a}+\hat{a}^\dagger)$

$\vec{r}$

$\varepsilon_L+g_L(\hat{a}+\hat{a}^\dagger)$

$\varepsilon_R+g_R(\hat{a}+\hat{a}^\dagger)$

Majorana pair in a cavity

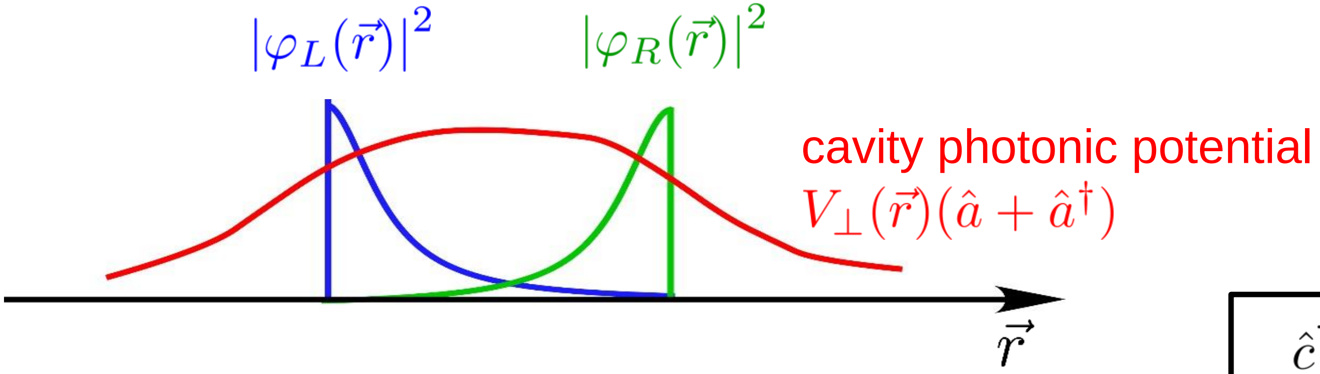


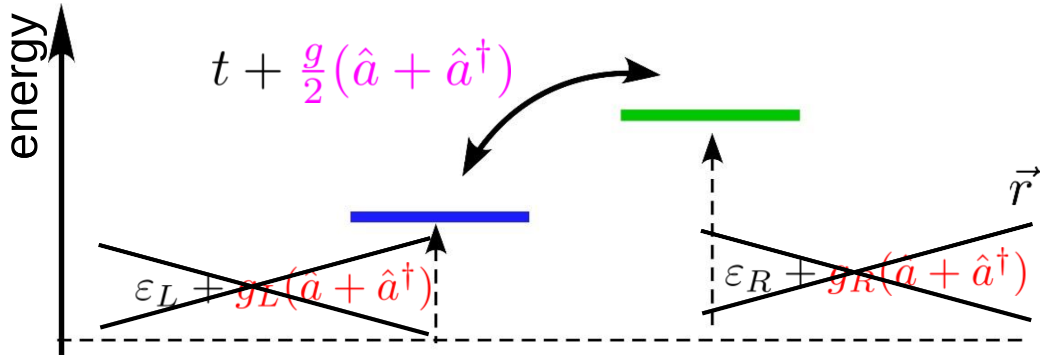
$$\hat{c}^\dagger_{L(R)} = \hat{c}_{L(R)}$$

$$\Rightarrow$$

$$\hat{c}^\dagger_L \hat{c}_L = \hat{c}^\dagger_R \hat{c}_R = 1$$

Majorana pair in a cavity





$$\hat c^\dagger_{L(R)} = \hat c_{L(R)}$$

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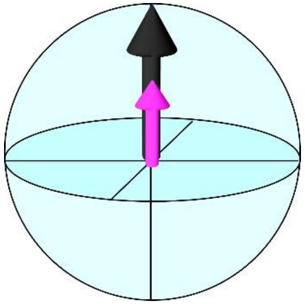


no cavity signal?

$$\hat H = 2it\hat c_L \hat c_R + ig(\hat a + \hat a^\dagger)\hat c_L \hat c_R + \hbar\omega_0 \hat a^\dagger \hat a$$

Dissipative response of the cavity (theory)

***Dartiailh**, Kontos, Douçot & Cottet, PRL 118, 126803 (2017)*

Theory

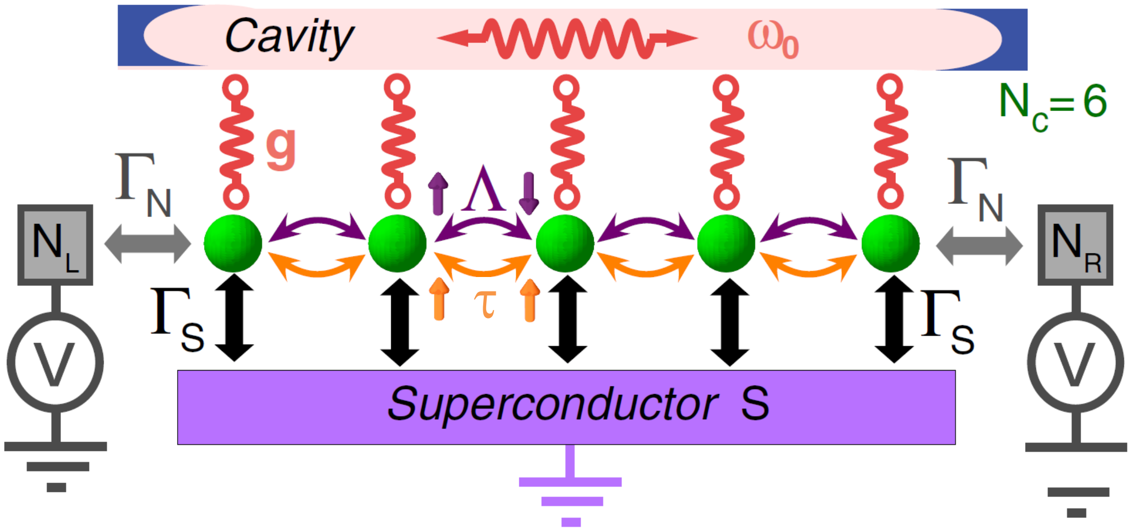
$$\boxed{\frac{b_t}{b_{in}} = \frac{t_0}{\omega_{RF} - \omega_0 - i\Lambda_0 - \chi(\omega_{RF})}}$$

semiclassical cavity transmission
linear response treatment

Nanocircuit charge susceptibility calculated with Keldysh Green's functions

Bruhat et al.,
*PRX **6**, 021014 (2016)*

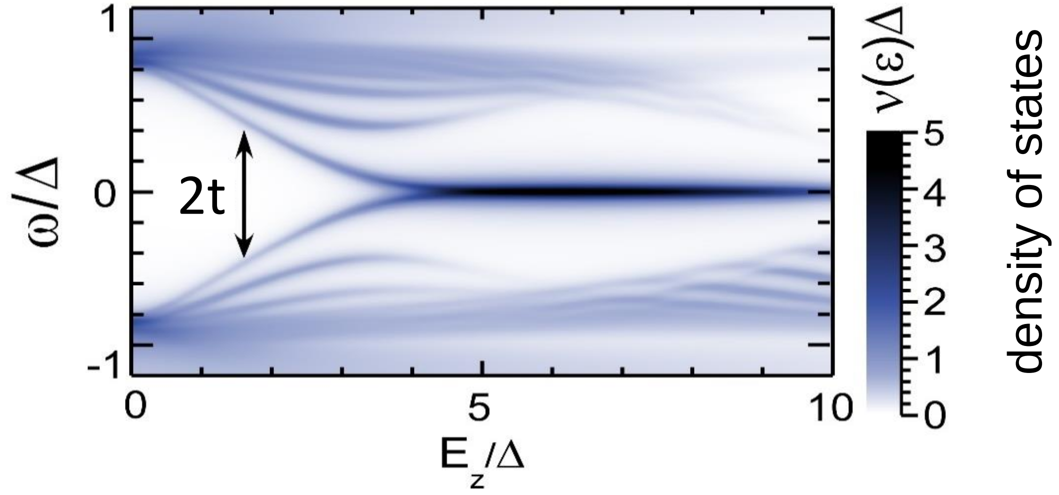
Spin-dependent Kitaev chain (tight binding model)



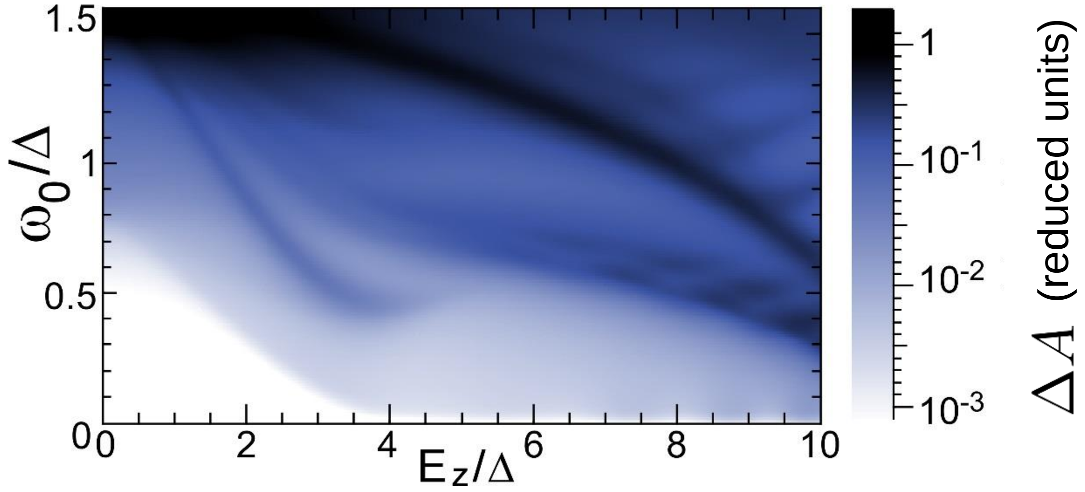
Dissipative response of the cavity (theory)

***Dartiailh**, Kontos, Douçot & Cottet, PRL 118, 126803 (2017)*

DOS measurable
With DC current



Cavity signal



Dissipative response of the cavity (theory)

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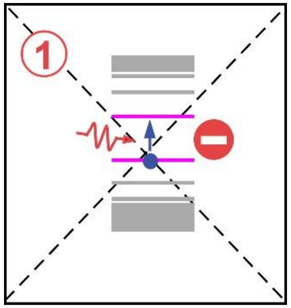

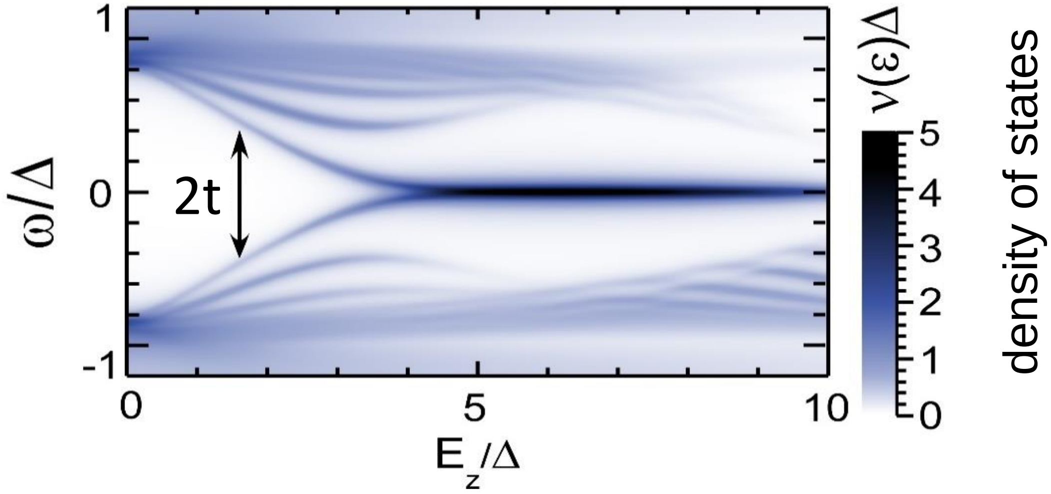

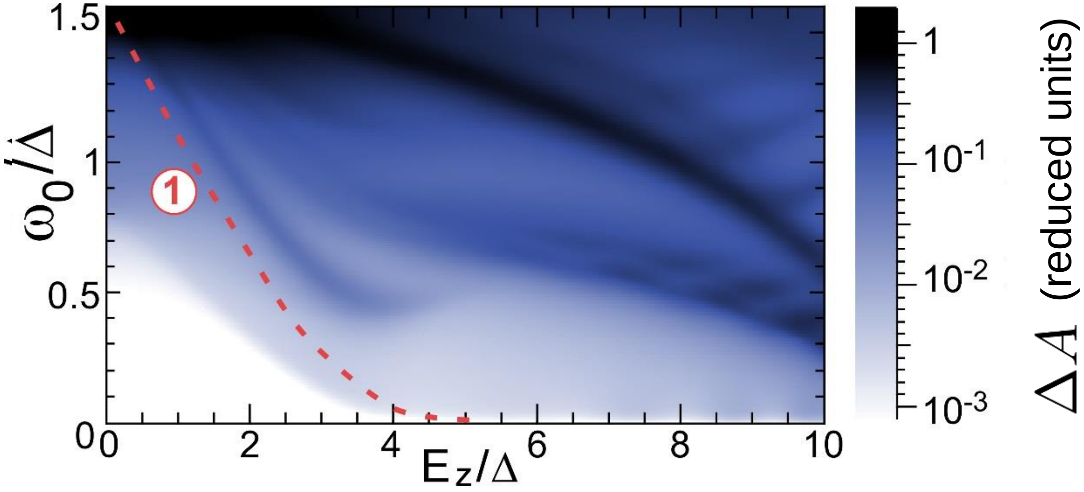

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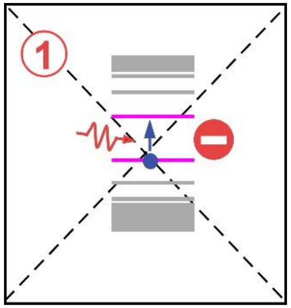
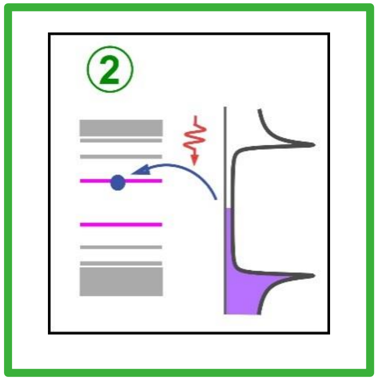
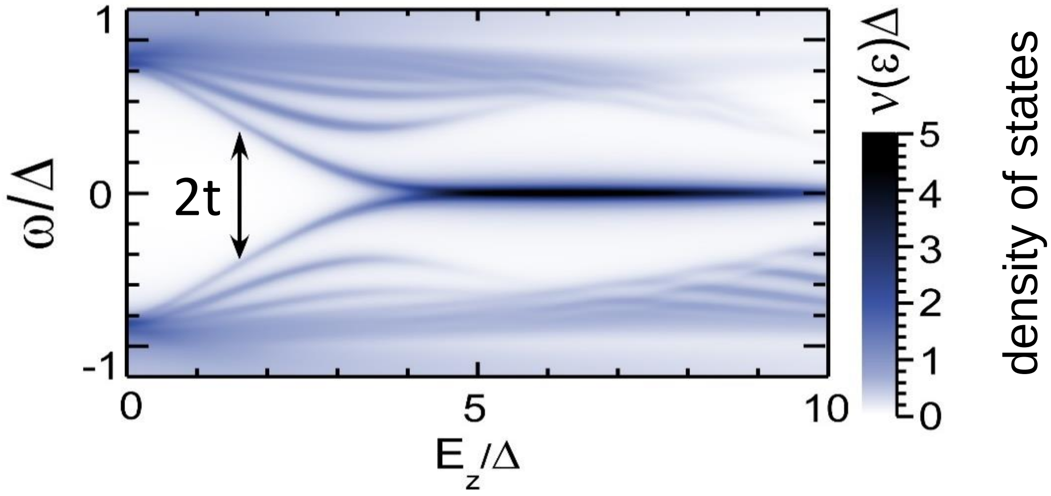
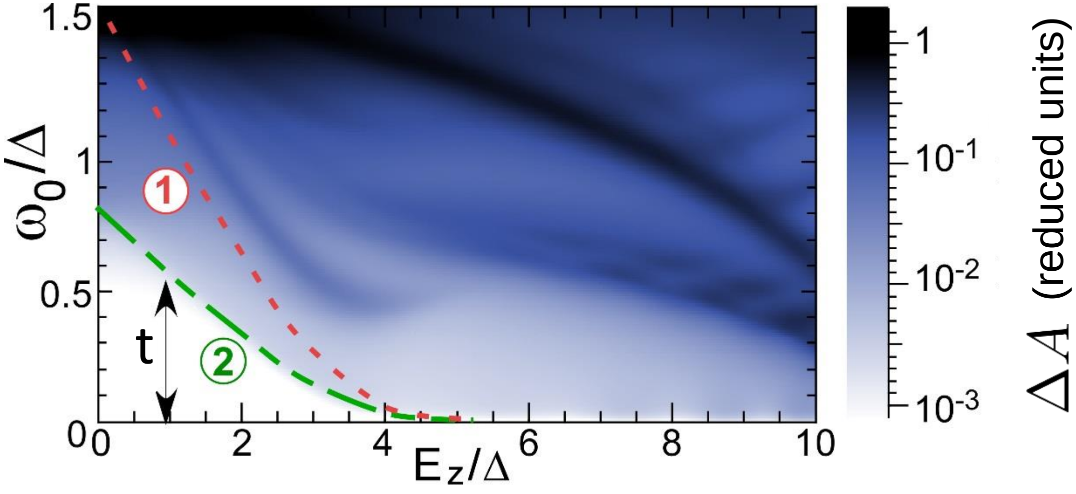




$g \neq 0$

$$\hat{H} = 2it\hat{c}_L\hat{c}_R + ig(\hat{a}+\hat{a}^\dagger)\hat{c}_L\hat{c}_R$$
$$+\hbar\omega_0\hat{a}^\dagger\hat{a}$$





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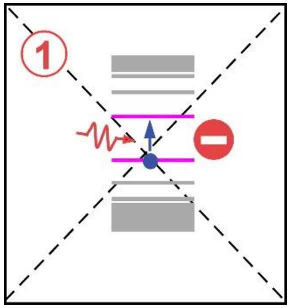
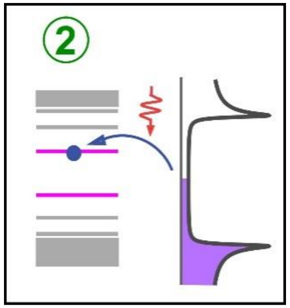
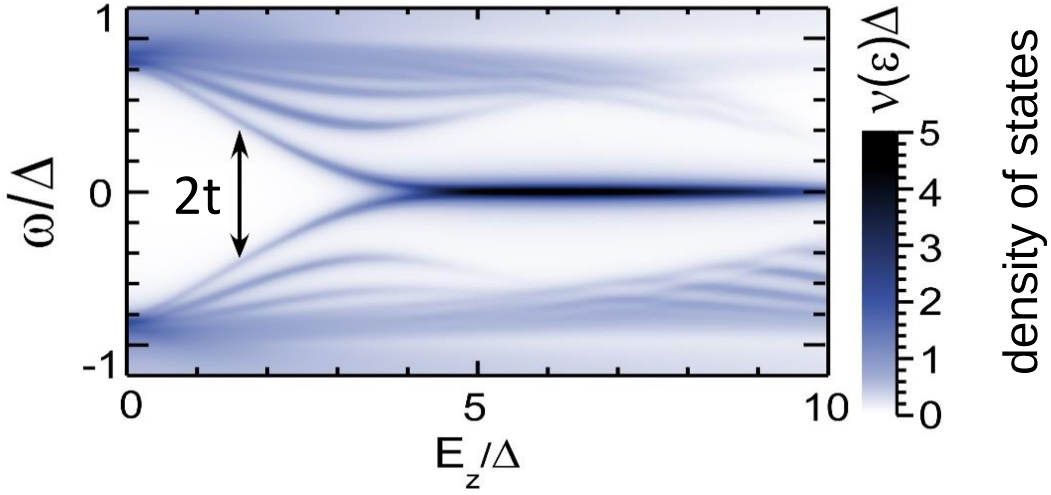


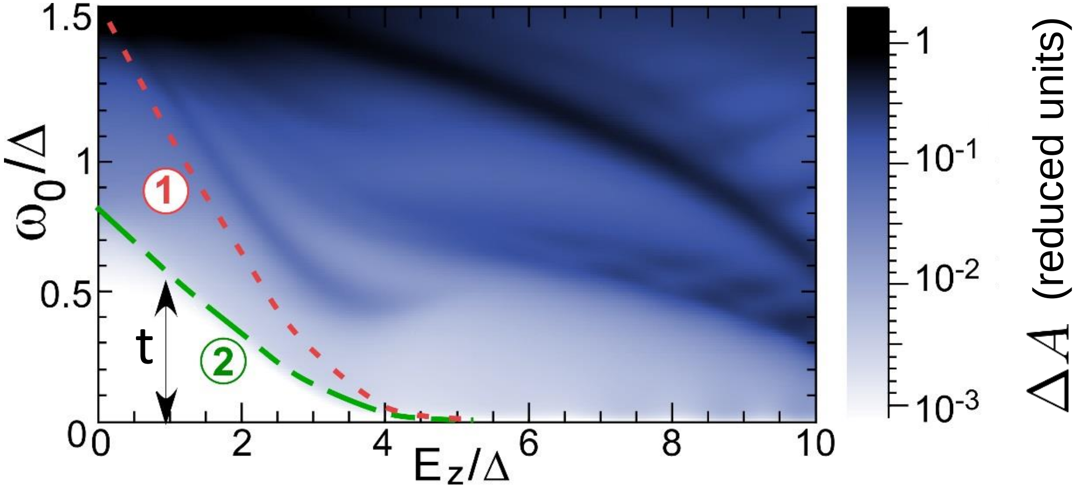
dark transition due to self-adjoint property



$g \neq 0$

$$\hat{H} = 2it\hat{c}_L\hat{c}_R + ig(\hat{a}+\hat{a}^\dagger)\hat{c}_L\hat{c}_R + \hbar\omega_0\hat{a}^\dagger\hat{a}$$





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Quantum non-linear description of Mesoscopic QED

See preprint, to appear on ArXiv in September 2019…

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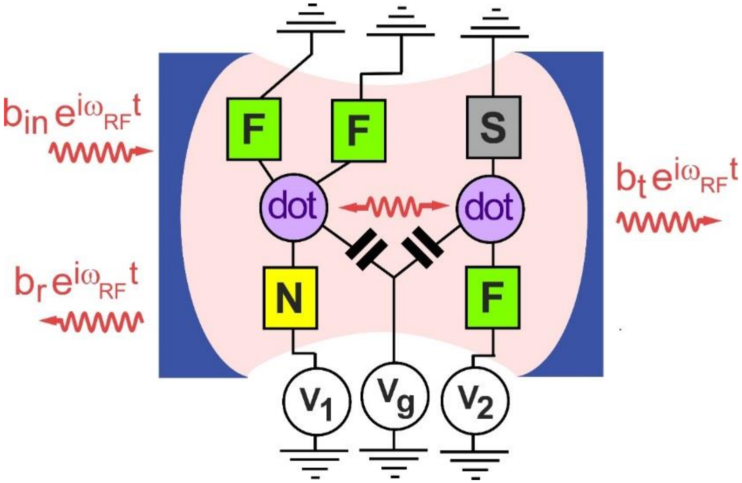
Preparation of a photonic Schrödinger cat using dissipative tunneling

See preprint, to appear on ArXiv in September 2019…

Summary of results presented

- Microwave cavities are a powerful tool to study/control mesoscopic circuits

- Mesoscopic circuits can be used to prepare non-classical cavity states



Other cases studied so far in Paris:

- Prediction: Cooper pair splitting in a cavity: *A. Cottet et al. PRB (2012) & (2014)*
- Experiment+Theory: Kondo effect in a cavity: *M. Desjardins et al., Nature 545, 71 (2017)*

REVIEWS: A. Cottet, et al. J. Phys.: Condens. Matter 29 433002 (2017)

The end