QUANTUM ELECTRONICS GROUP

Service de Physique de l'Etat Condensé

In contact with Frank since the early 1990s

THESE DE DOCTORAT DE L'UNIVERSITE PARIS 6

Spécialité :
Physique des Solides

Présentée par Anne ANTHORE
Pour obtenir le grade de DOCTEUR DE L'UNIVERSITE PARIS 6

Sujet de la thèse :

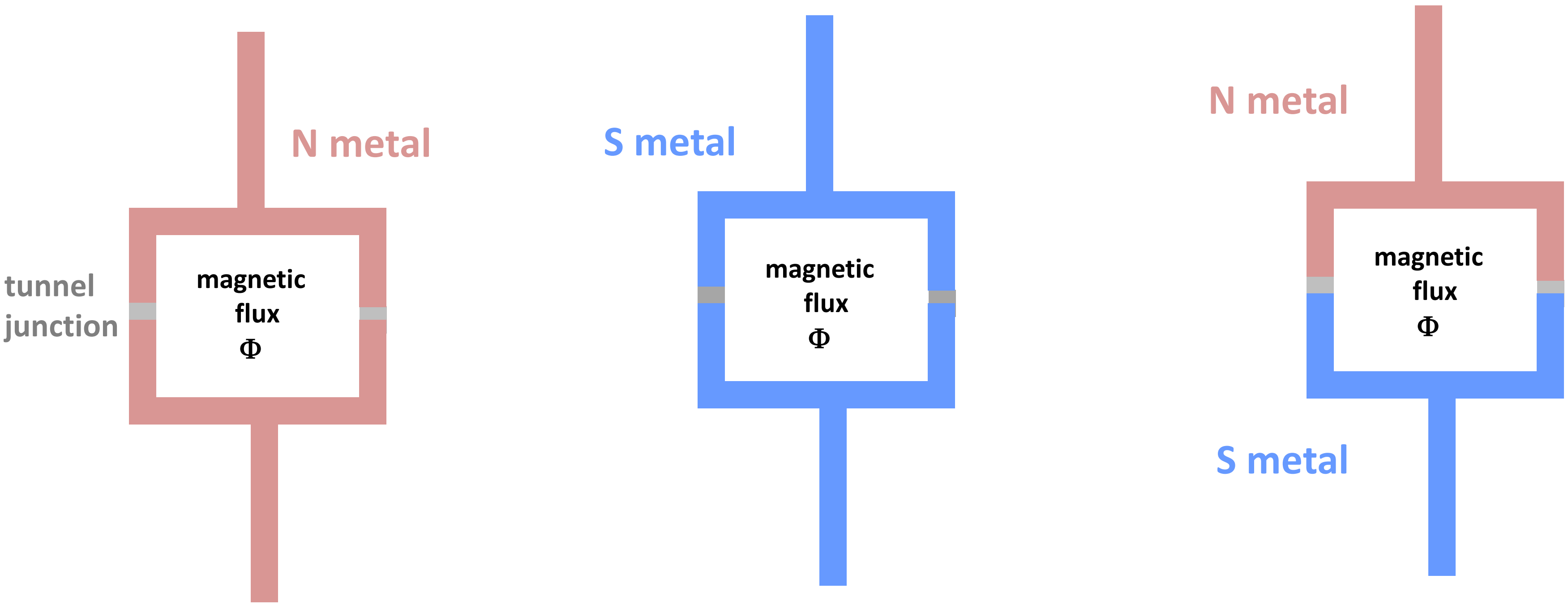
MECANISMES DE DECOHERENCE DANS LES

CONDUCTEURS MESOSCOPIQUES

soutenue le 26 septembre 2003
devant le jury composé de:

R. Combescot
H. Courtois (rapporteur)
D. Estève (directeur de thèse)
F. Hekking
G. Montambaux
C. Van Haesendonck (rapporteur)

A discussion in Quantronics on transport in coherent diffusive nanostructures (early 1990s)



normal tunnel junctions:
G=G1+G2

SQUID: supercurrent modulation

Andreev conductance modulation ?
→ experiment

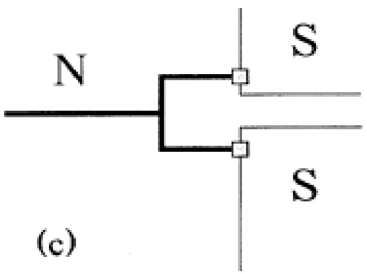
later continued with Frank and Yuli

A fruitful interaction

VOLUME 71, NUMBER 10 PHYSICAL REVIEW LETTERS 6 SEPTEMBER 1993

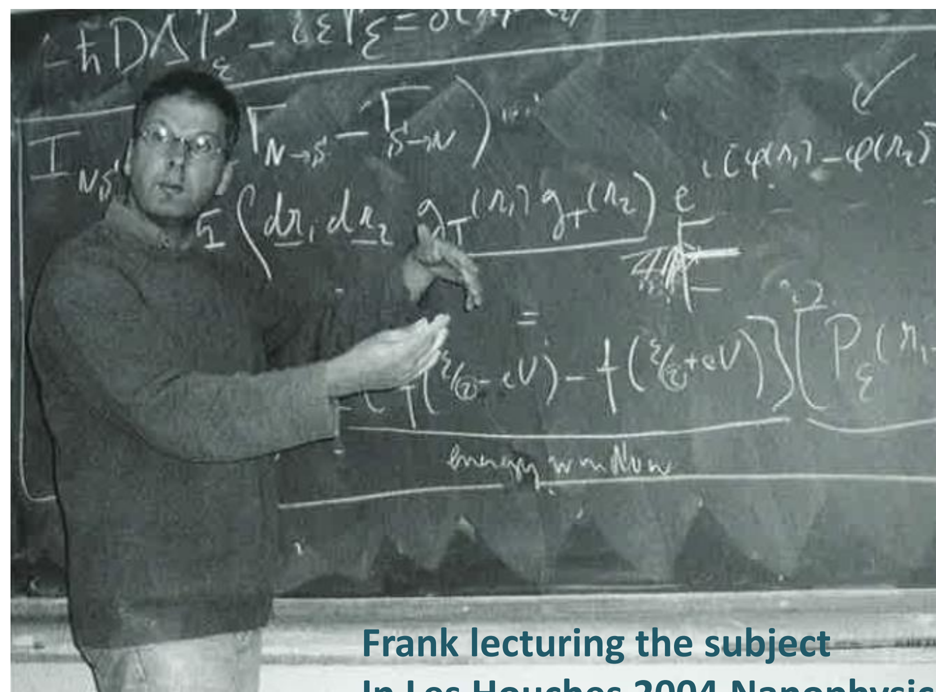
Interference of Two Electrons Entering a Superconductor

F. W. J. Hekking and Yu. V. Nazarov*
Institut für Theoretische Festkörperphysik, Universität Karlsruhe, Postfach 6980, 76128 Karlsruhe, Federal Republic of Germany
(Received 23 February 1993)



$$I(V) = \frac{\pi^2\hbar}{e^3\nu_N}\int d^2r_1 d^2r_2\, g(r_1)g(r_2)\exp i[\phi(r_1)-\phi(r_2)]\int d\omega[f(\omega/2-eV)-f(\omega/2+eV)][P^C_\omega(r_1,r_2)+P^C_{-\omega}(r_1,r_2)]\,. \quad (4)$$

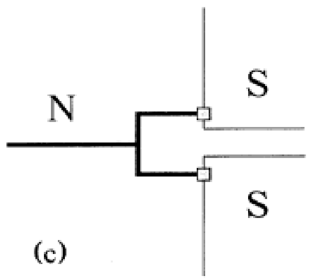
$$G_J = 53.8R_{\rm cor}\left[G_1^2+G_2^2+2G_1G_2\cos(eV_St/\hbar)\right]\,. \quad (11)$$



Frank lecturing the subject
In Les Houches 2004 Nanophysics: coherence and transport

The authors are indebted to D. Estève for a very useful discussion which initiated this work. We furthermore want to thank C. Bruder, M. Büttiker, H. Schoeller, and G. Schön for discussions.

The experiment :



VOLUME 73, NUMBER 18 PHYSICAL REVIEW LETTERS 31 OCTOBER 1994

Flux-Modulated Andreev Current Caused by Electronic Interference

H. Pothier, S. Guéron, D. Esteve, and M. H. Devoret
Service de Physique de l'Etat Condensé, Commissariat á l'Energie Atomique, Saclay, F-91191 Gif-sur-Yvette, France
(Received 26 April 1994)

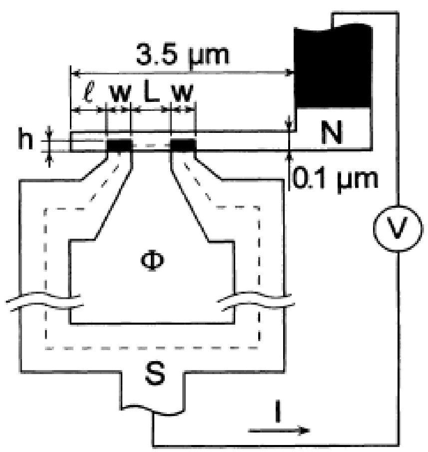


FIG. 2. NS-QUID layout: a normal metal wire overlaps an oxidized superconducting fork electrode to form a split tunnel junction.

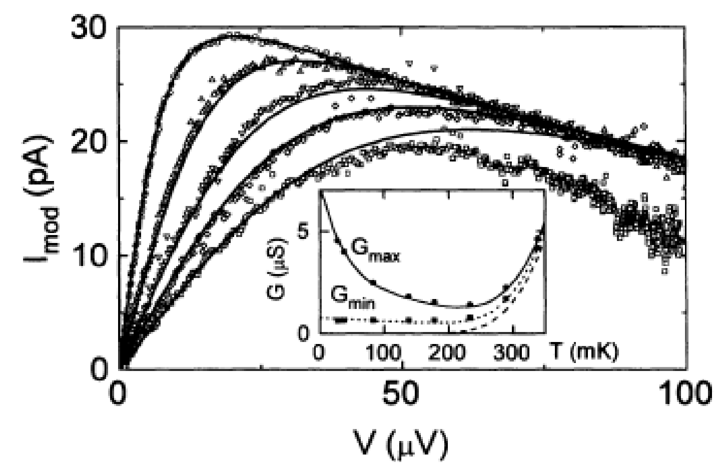


FIG. 4. Comparison between the measured (open symbols) and predicted (solid lines) bias voltage dependence of the peak to peak modulation I_{mod} of the current with the magnetic field

Last but not least:

We have benefited from many discussions with F. Hekking and Yu. Nazarov.

A story which started a solid friendship with Quantronics

A simple implementation of an open system strongly coupled to radiation

Chloé Rolland, Olivier Parlavecchio, Ambroise Peugeot, Marc Westig, Iouri Moukharski, Carles Altimiras, Max Hofheinz, Patrice Roche, Philippe Joyez, Patrice Bertet, Denis Vion, Fabien Portier, & Daniel Estève

Nanoelectronics & Quantronics, SPEC, CEA-Saclay

with

Mircea Trif, Pascal Simon
LPS, Paris-Sud University

Perola Milman
LMPQ, Paris-Diderot University

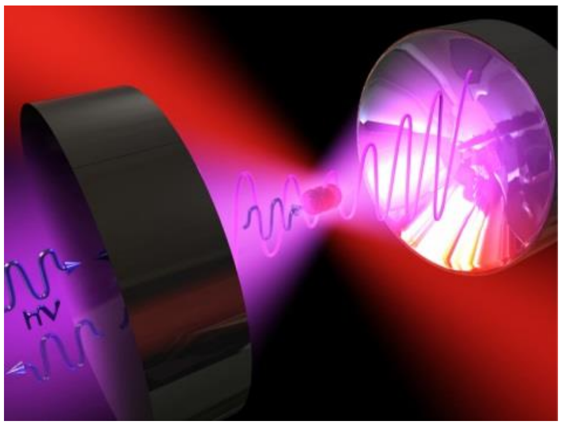
Bjorn Kubala, Vera Gramich, Joachim Ankerhold
University of Ulm, Germany

Juha Leppäkangas, Göran Johansson
Chalmers University, Sweden

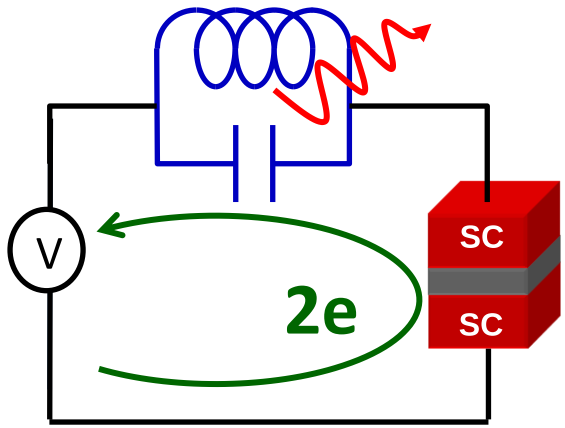
For the thy supply chain

Strong coupling QED :
a Josephson junction coupled to a resonator

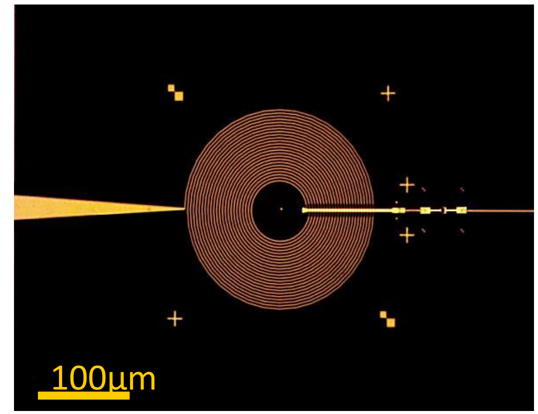
cavity QED

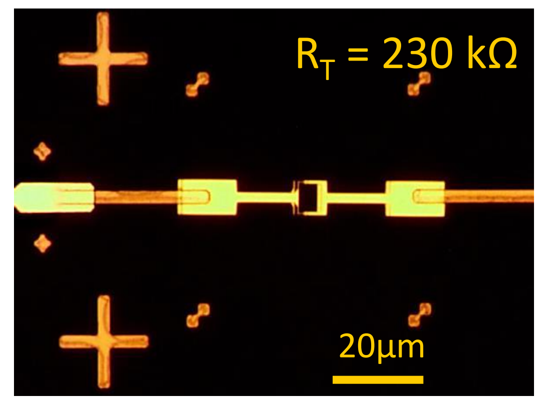


circuit QED



tunable Josephson junction





Established field

Strong coupling regime reached

hard, because starting from :

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} = \frac{1}{8}\frac{Z_V}{R_Q} \simeq 1/137$$

$R_Q = h/(2e)^2 \cong 6.4\ \text{k}\Omega$

dimensionless coupling constant:

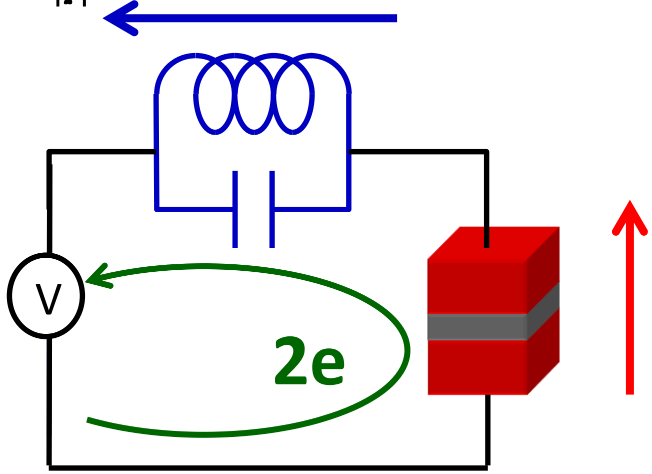
$g = \pi\, Z/R_Q \quad Z = \sqrt{L/C}$

g=1 achieved

A simple but rich open quantum system

$$2eV_{env} = \hbar \dot{j}_{env}$$

$$j_{env} = \sqrt{r}\,(a^{\dagger} + a) \qquad r = \frac{\pi}{R_Q}\sqrt{L/C}$$



$$\varphi_J = \frac{2eV}{\hbar}t + \sqrt{r}\,(a^{\dagger} + a)$$

$$H = h\nu_0(a^{\dagger}a + 1/2) - \frac{E_J}{2}\left(e^{i\varphi_J} + e^{-i\varphi_J}\right)$$

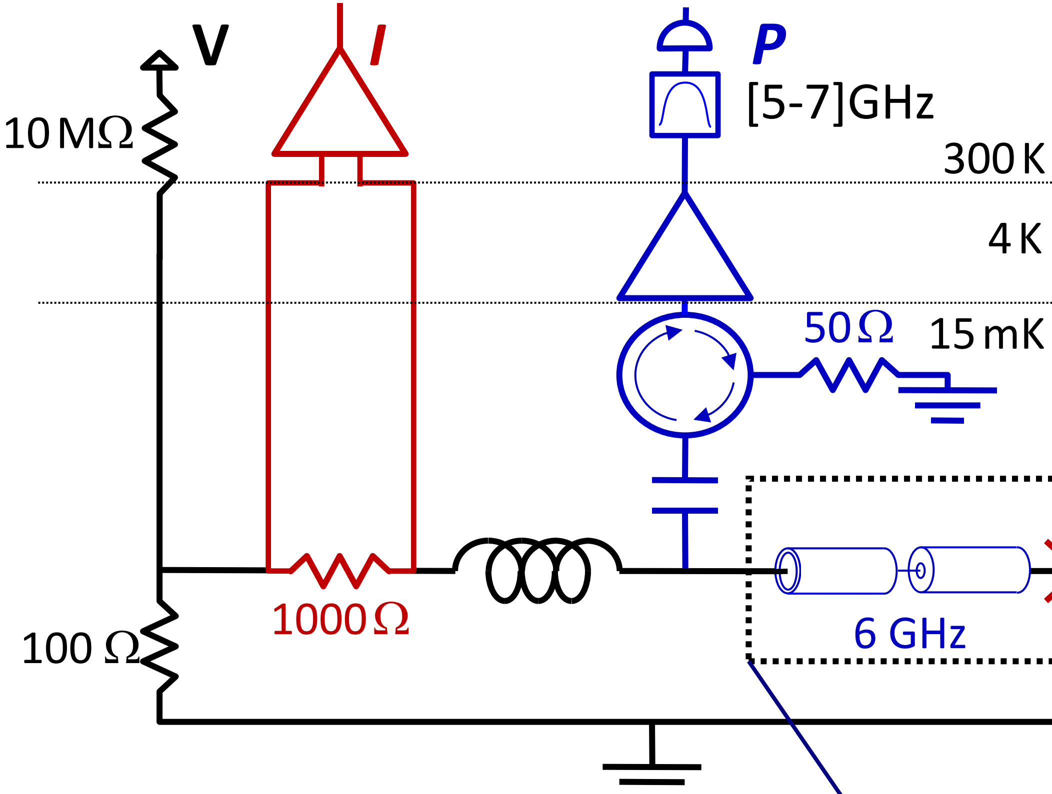
At subgap voltage, no qps can be created!

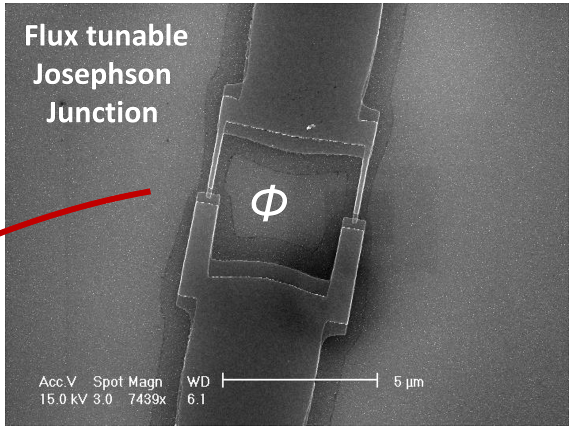
Cooper pair transfer : electrostatic energy transferred to resonator $2eV = n\,h\nu_a$

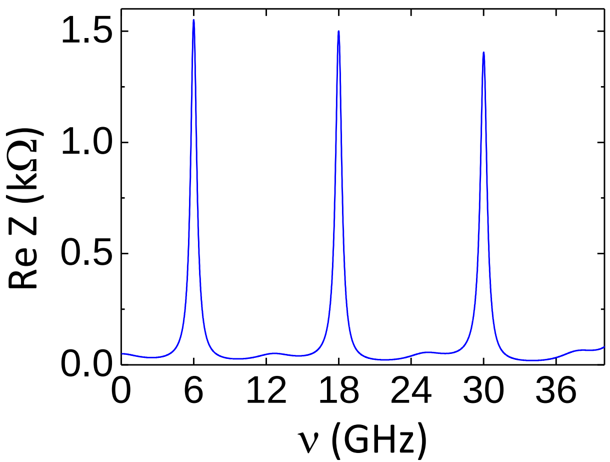
Detecting Cooper pairs and photons

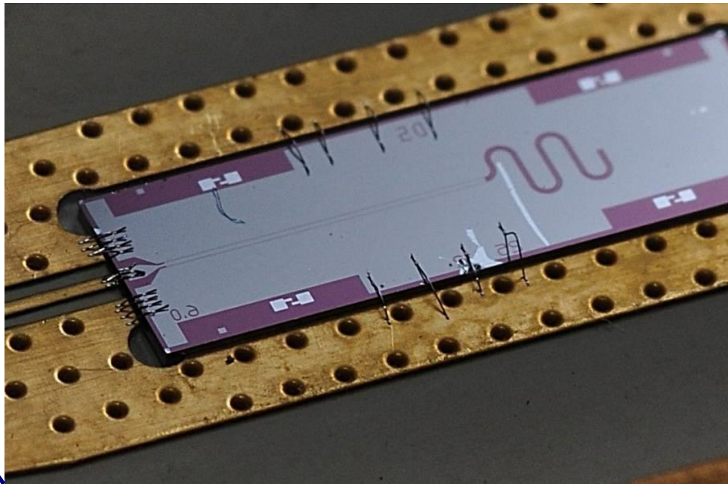
Hofheinz *et al.*,
PRL **106**, 217005 (2011)

$$E_J(\Phi) = E_J^0 \left|\cos(\pi\, \Phi/\Phi_0)\right|$$









Detecting Cooper pairs and photons

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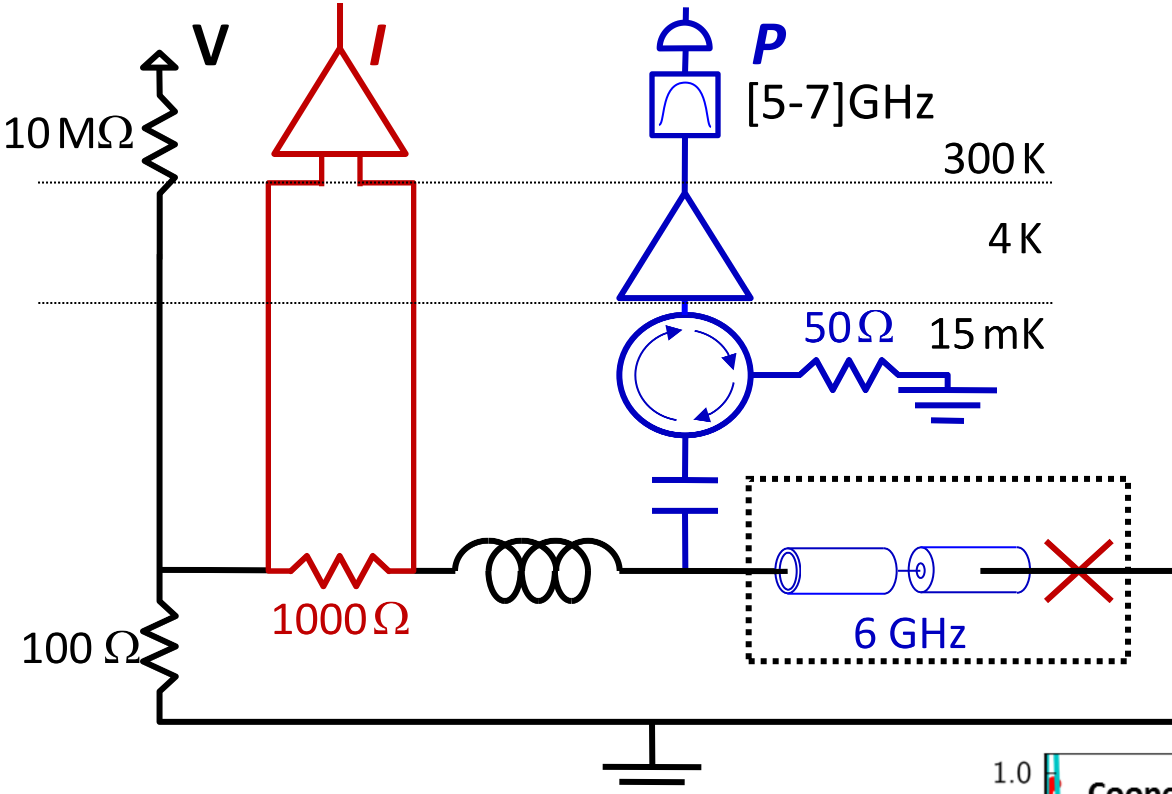
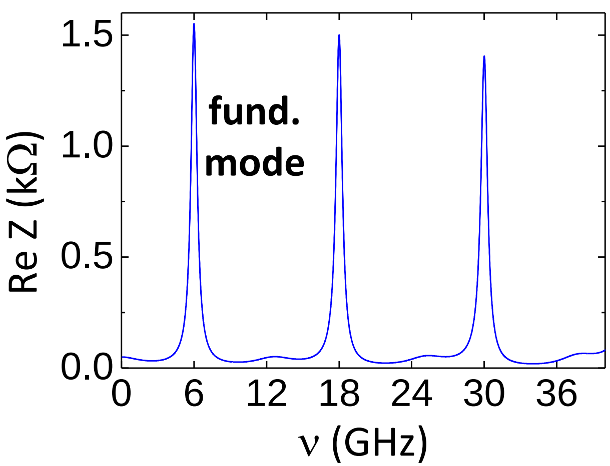
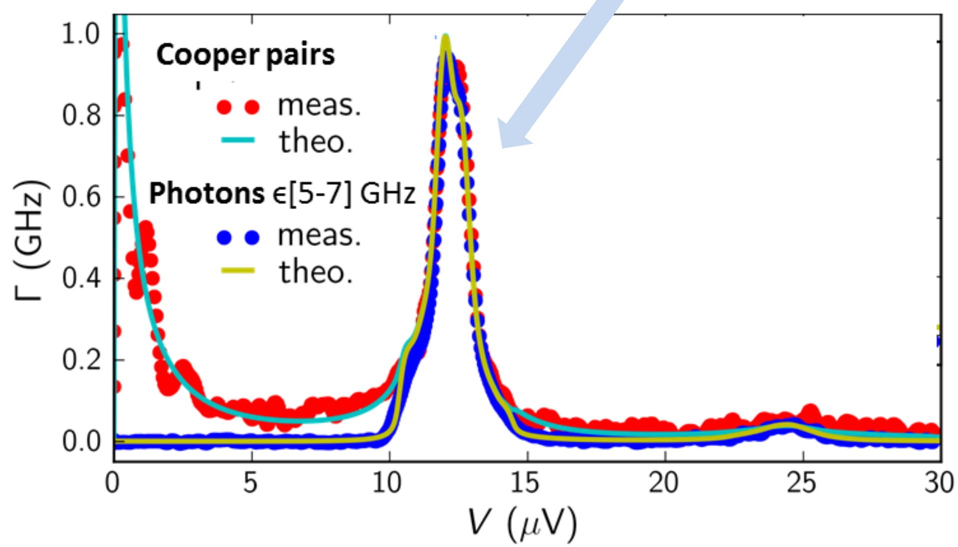


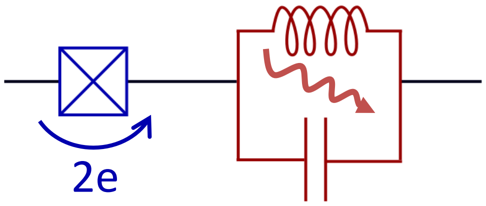
P : Total power in
Resonator 1st mode
bandwidth

the 1 photon-1 Cooper pair regime

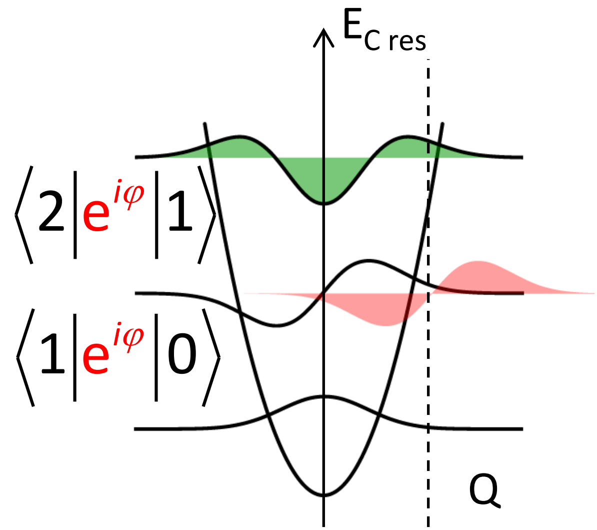




emitting single photons ?



Stop at
1 photon !



Γ^{ph} = 42 Mphoton /s

r = 1.1

g$^{(2)}$ function

Probe:
statistics of photon emission

$$g^{(2)}(\tau) = \frac{\langle a^\dagger(t) a^\dagger(t+\tau) a(t+\tau) a(t)\rangle}{\langle a^\dagger a\rangle^2}$$

V. Gramich *et al*,
Phys.Rev.B. **92(5)**:54508, 2015

$$g^{(2)}(\tau) = 1 + \frac{\langle \delta PA(t)\delta PB(t+\tau)\rangle}{P_A P_B}$$

$$\left\langle 2 \middle| e^{i\varphi} \middle| 1 \right\rangle$$

1 CP transfer matrix element
vanishes at r=2

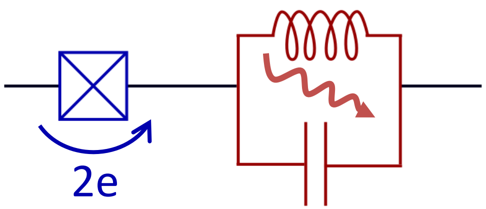
$$g^{(2)}(0) = \left(1 - \frac{r}{2}\right)^2$$

emitting single photons ?

PROBE: HBT setup

Block successive resonator loadings !

Stop at 1 photon



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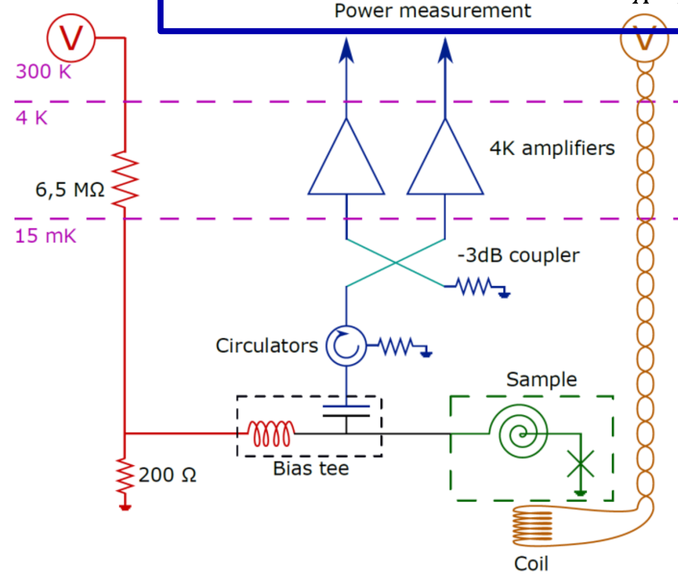
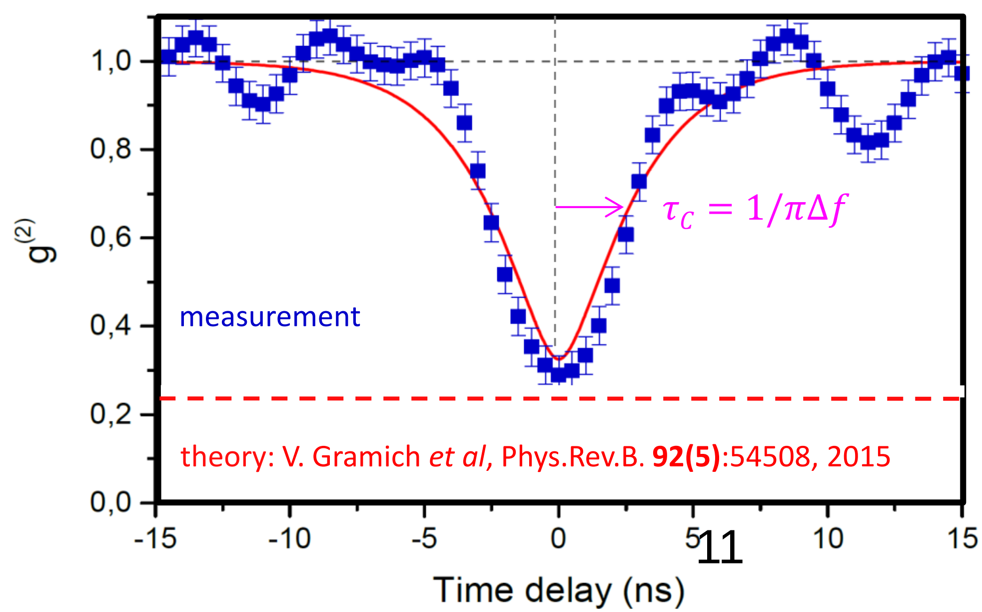
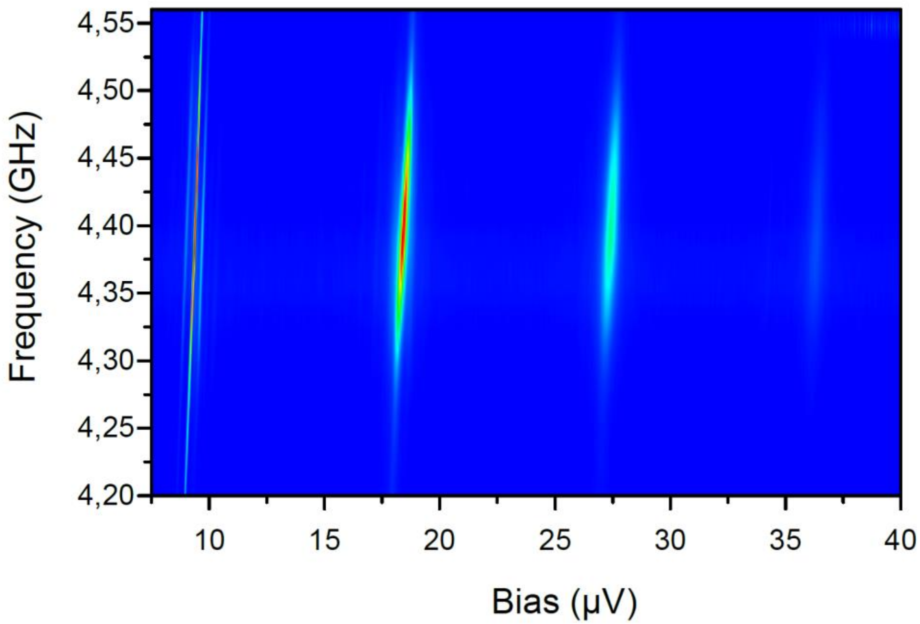
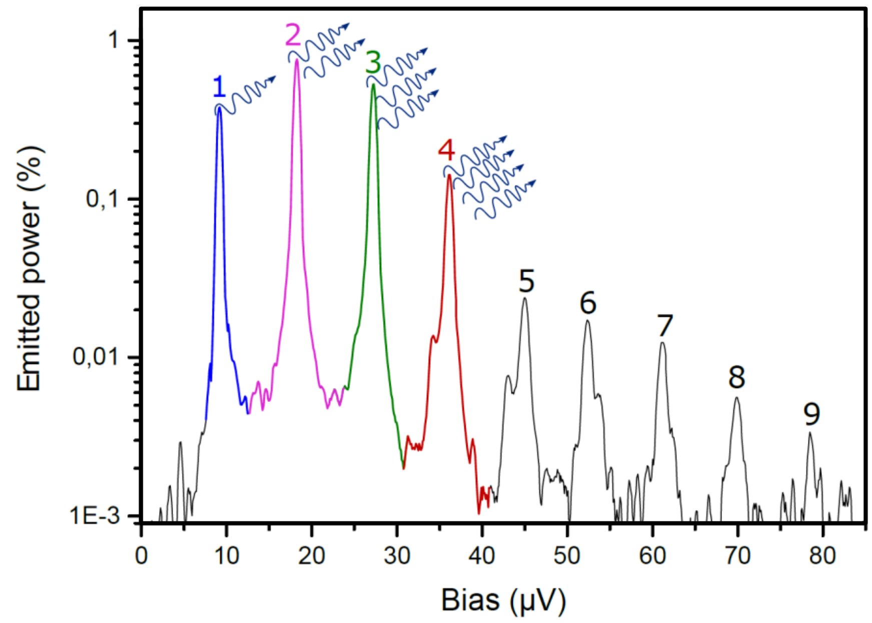


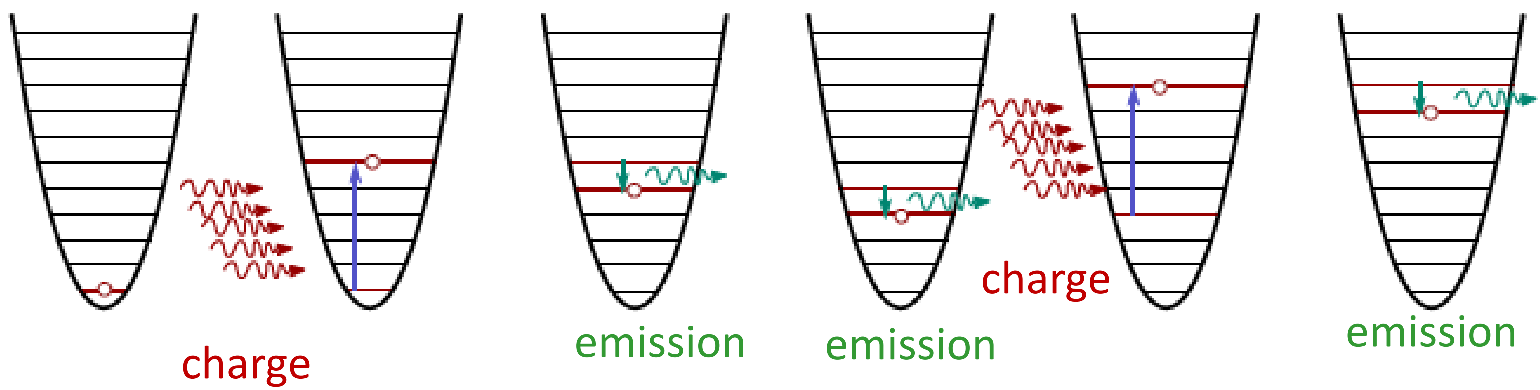


Rolland et al., in preparation
(with new data)

A consequence of strong coupling: multiple photon processes



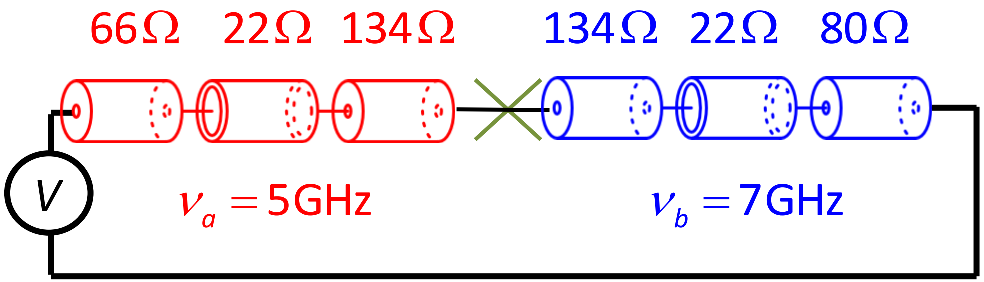


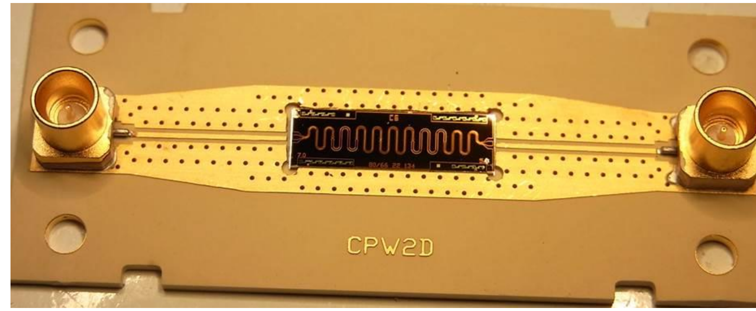


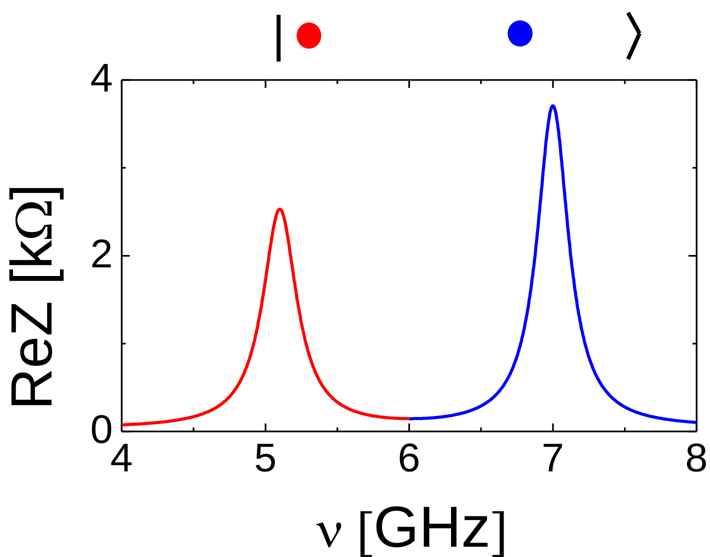
Out of equilibrium tunneling

An engineered two mode environment

Westig et al.
PRL 119, 137001, 2017



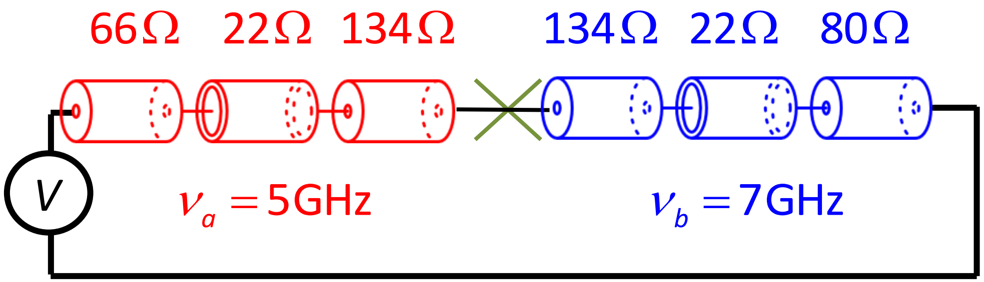


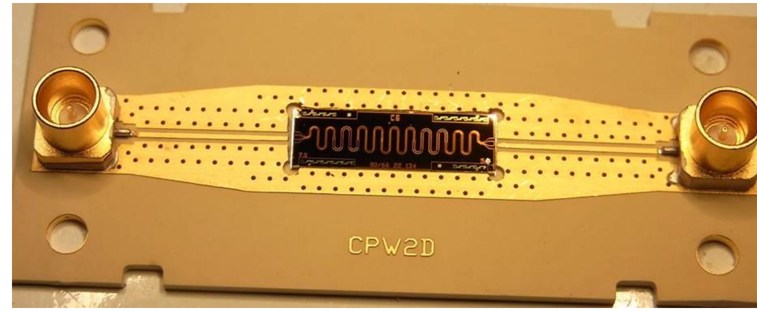


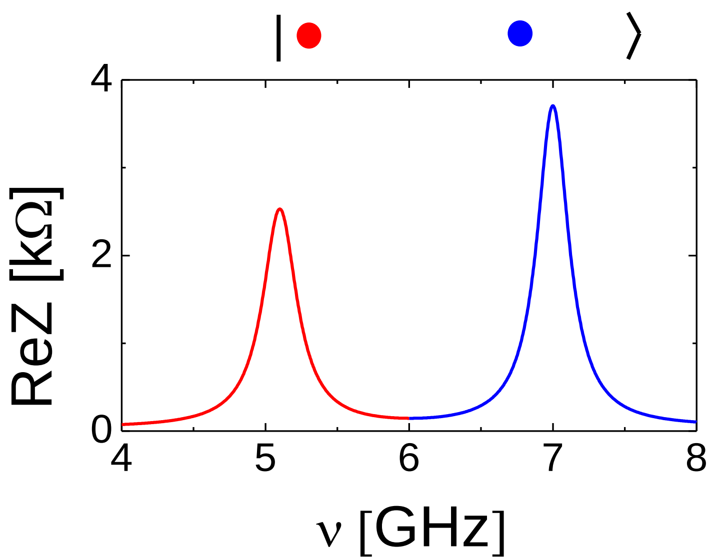
Emission at $2eV = h\nu_a + h\nu_b$ **?**

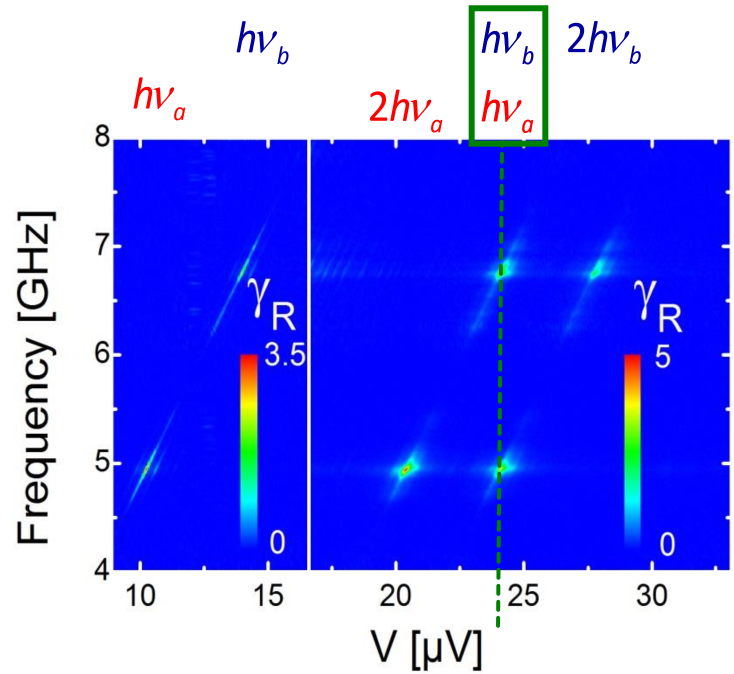
An engineered two mode environment

Westig et al.
PRL 119, 137001, 2017









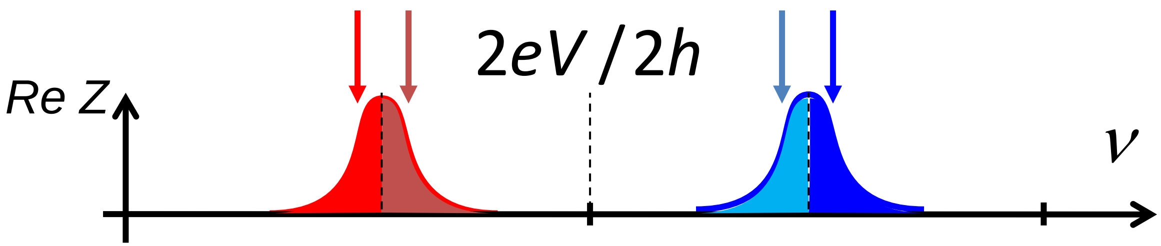
Emission of photons pairs at $2eV = h\nu_a + h\nu_b$

Classical radiation ?

Entanglement probed with a phase sensitive correlator

$2eV = h\nu_a + h\nu_b$ ⇒ $\alpha|00\rangle + \beta|11\rangle + \gamma|22\rangle + \ldots$ **in Fock bases**

$|red\, blue\rangle + |orange\, cyan\rangle$ **in frequency**



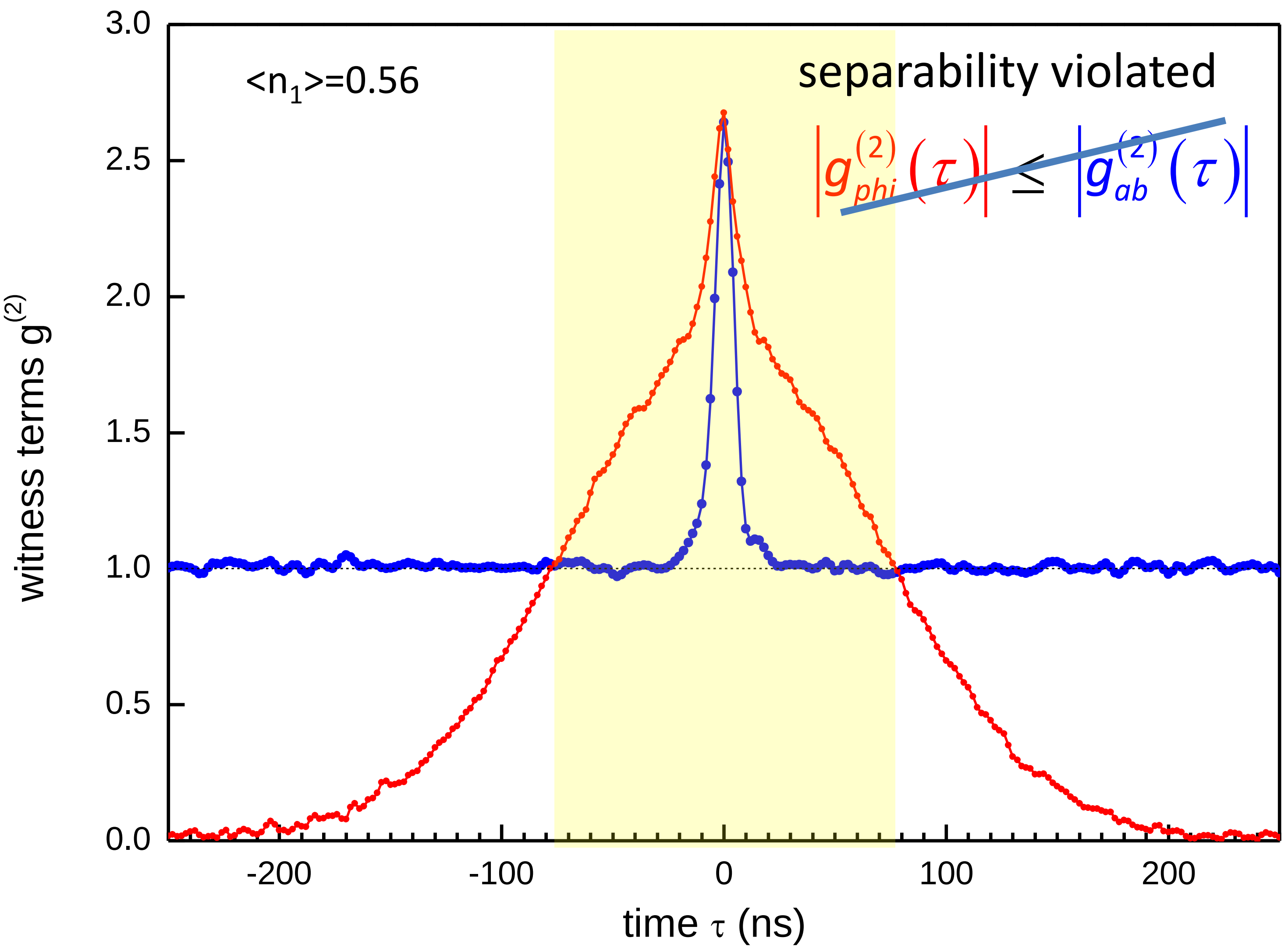
Entanglement ⇒ Phase phase cross-correlation in a(t) b(t) **in time**

S. Wolk et al, Phys Rev. A 90 (2014): inequality for any separable state of a and b:

$$\left|\left\langle a^\dagger(t+\tau)a(t)b^\dagger(t+\tau)b(t)\right\rangle\right| \leq \left|\left\langle a^\dagger(t)a(t)b^\dagger(t+\tau)b(t+\tau)\right\rangle\right|$$

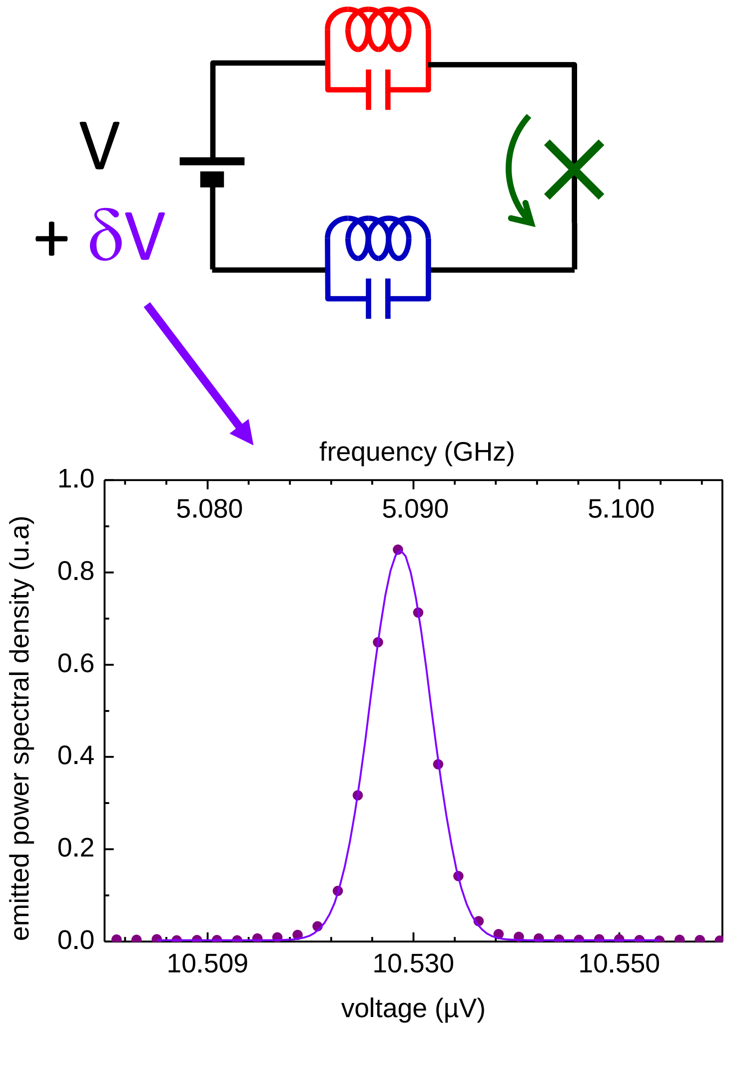
$$\left|g^{(2)}_{phi}(\tau)\right| \qquad \left|g^{(2)}_{ab}(\tau)\right|$$

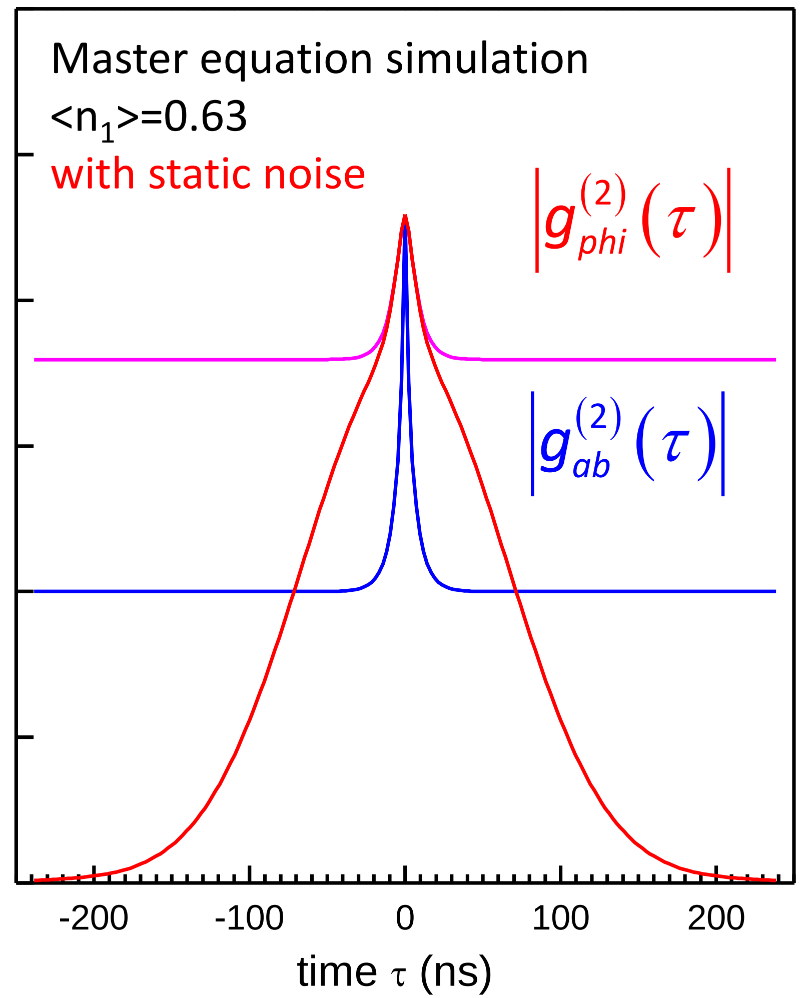
Entanglement probed with a phase sensitive correlator



Qutip simulation with experimental noise

(D. Vion, B. Kubala, work in progress)





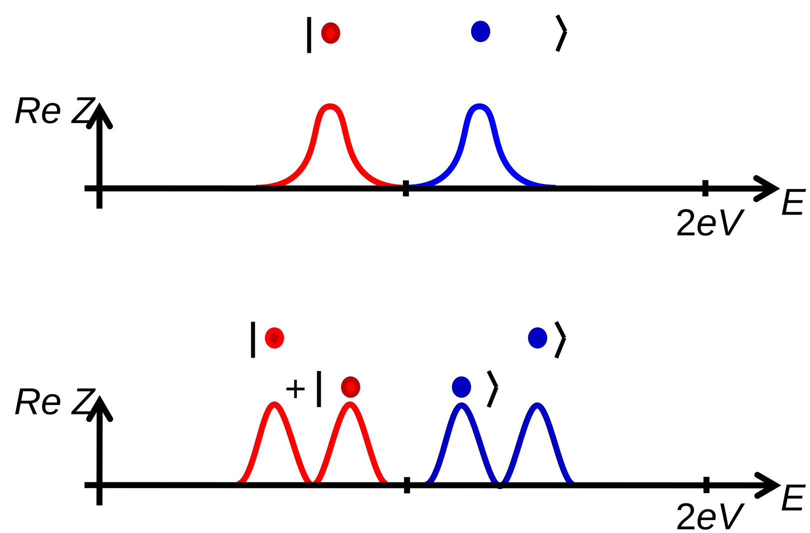
Summing up:

DC biased Josephson junction:
simple, compact and bright source of radiation
for a **quantum microwave toolbox**

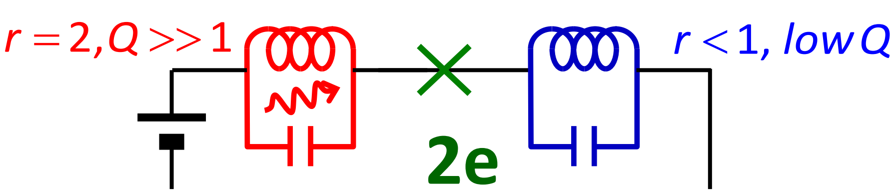
What's next ?

- bridging the gap with quantum optics: towards THz sources ?
- applications ?
- understand Cross-over from incoherent transfer of Cooper pairs to "classical" AC Josephson effect
- large Josephson coupling: Transition to parametric resonance
- current-photon correlations …
- -entangling pairs, stabilizing a Fock state, …

Entangling pairs ?



How to stabilize a Fock state



The people ☺

QUANTUM ELECTRONICS GROUP

NANOELECTRONICS GROUP

Collaborators: **Ulm**: V. Gramich, B. Kubala, J. Ankerhold

KIT: J. Leppäkangas