laboratoire pierre aigrain
électronique et photonique quantiques

Squeezing by a quantum conductor

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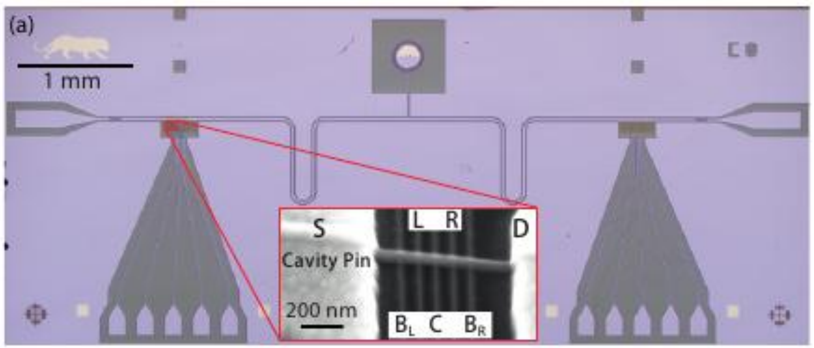
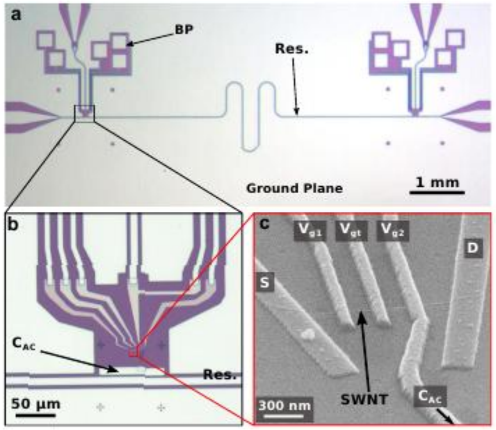
GDR Mesoscopic Quantum Physics, Aussois, 2016

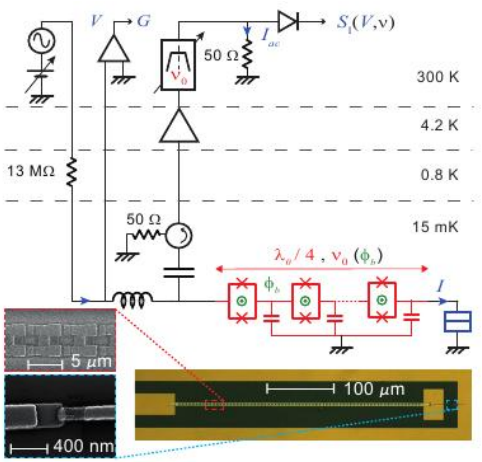
Mesoscopic QED



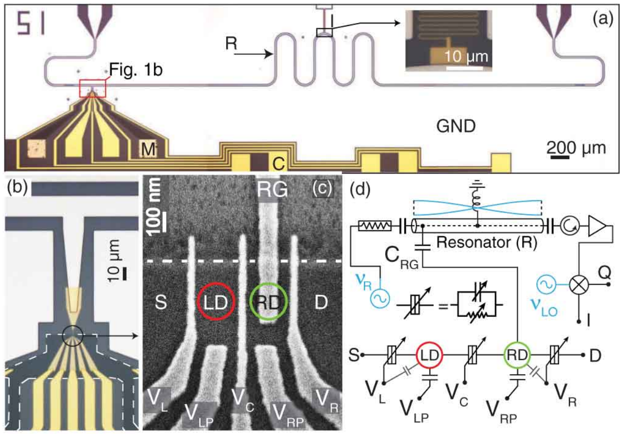
Princeton



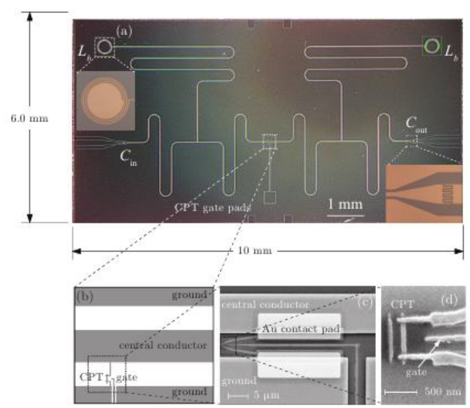
ENS, Paris



Saclay



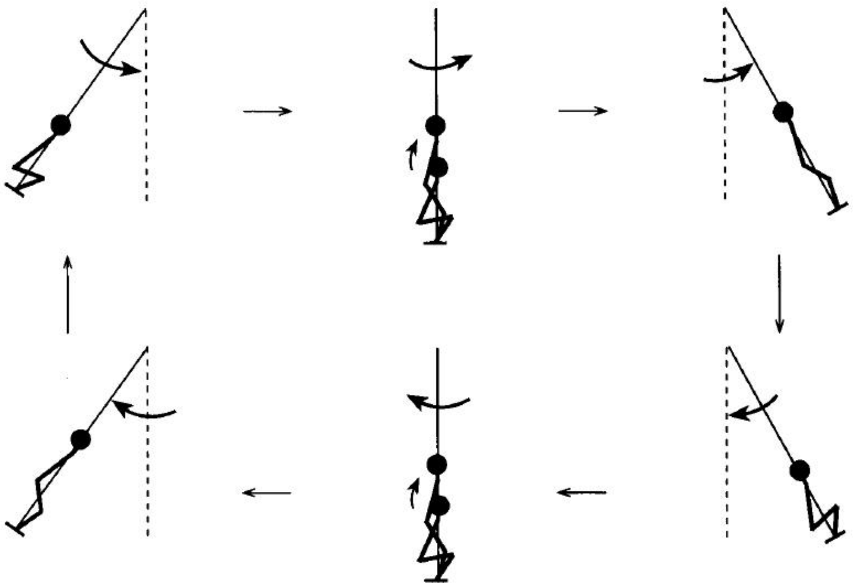
ETH Zurich



Darmouth college

Parametric excitation of a swing

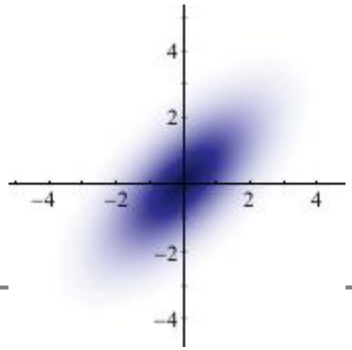
Parametric excitation



Strategy for Pumping a Swing while Standing

- Child stands up at zero angle and squats at maximum angle
- Frequency of pumping is twice the oscillator frequency $\omega_P = 2\omega_0$
- In-phase noise is amplified, out-of-phase noise is reduced

⇒ Squeezing of noise

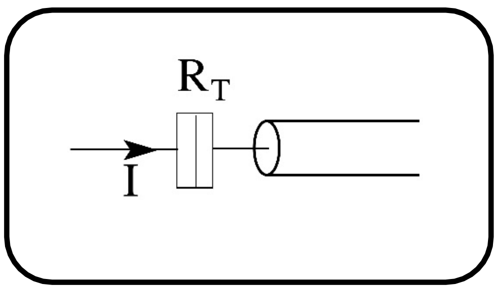


Squeezing experiment

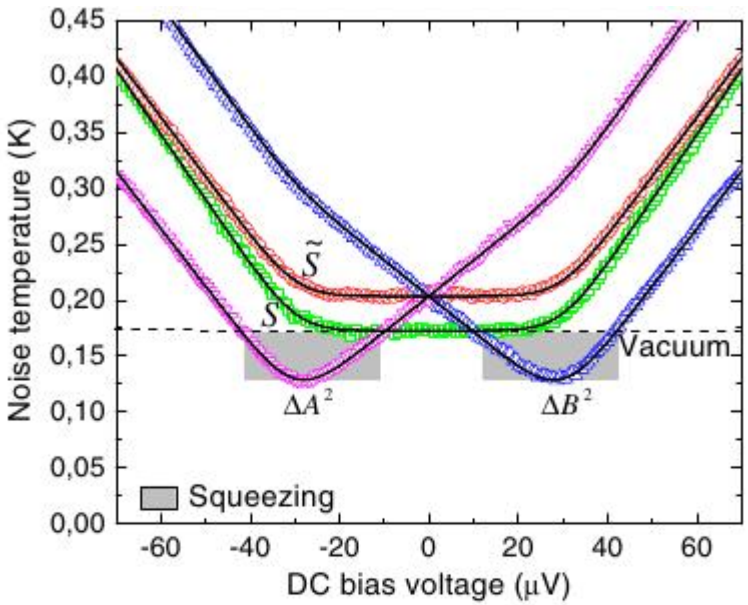
Observation of Squeezing in the Electron Quantum Shot Noise of a Tunnel Junction

Gabriel Gasse, Christian Lupien, and Bertrand Reulet
Département de Physique, Université de Sherbrooke, Sherbrooke, Québec, Canada J1K 2R1
(Received 3 July 2013; published 25 September 2013)

We report the measurement of the fluctuations of the two quadratures of the electromagnetic field generated by a quantum conductor, a dc- and ac-biased tunnel junction placed at very low temperature. We observe that the variance of the fluctuations on one quadrature can go below that of vacuum, i.e., that the radiated field is squeezed. This demonstrates the quantum nature of the radiated electromagnetic field.



Radiation of a tunnel junction



PRL 2013

Outline of the talk

I. Squeezed light with tunnel junction

II. Dynamical Coulomb Blockade

Squeezed light with tunnel junction

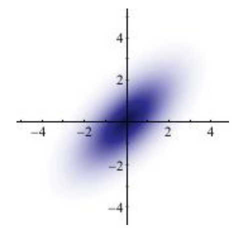
Hamiltonian vs dissipative squeezing

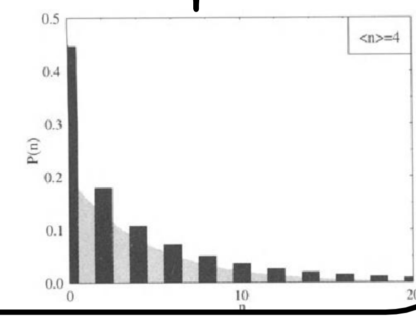
- Hamiltonian squeezing

$$\frac{H}{\hbar\omega}=\frac{X^2}{2}+\left[1+\varepsilon\sin(2\omega t)\right]\frac{P^2}{2}\approx a^+a-\underbrace{\frac{i\varepsilon}{4}\left(a^2e^{2i\omega t}-h.c.\right)}$$

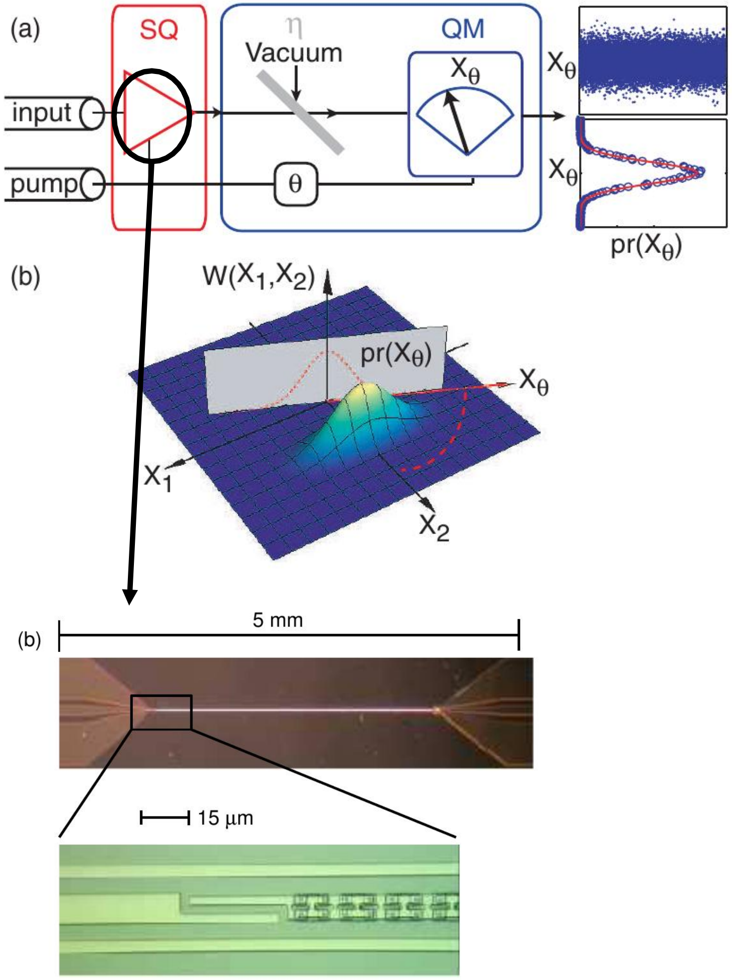
- Example: Josephson parametric Amplifier (JPA), limited to half-squeezing for cavity mode

$$\Delta X^2\geq 1/2$$

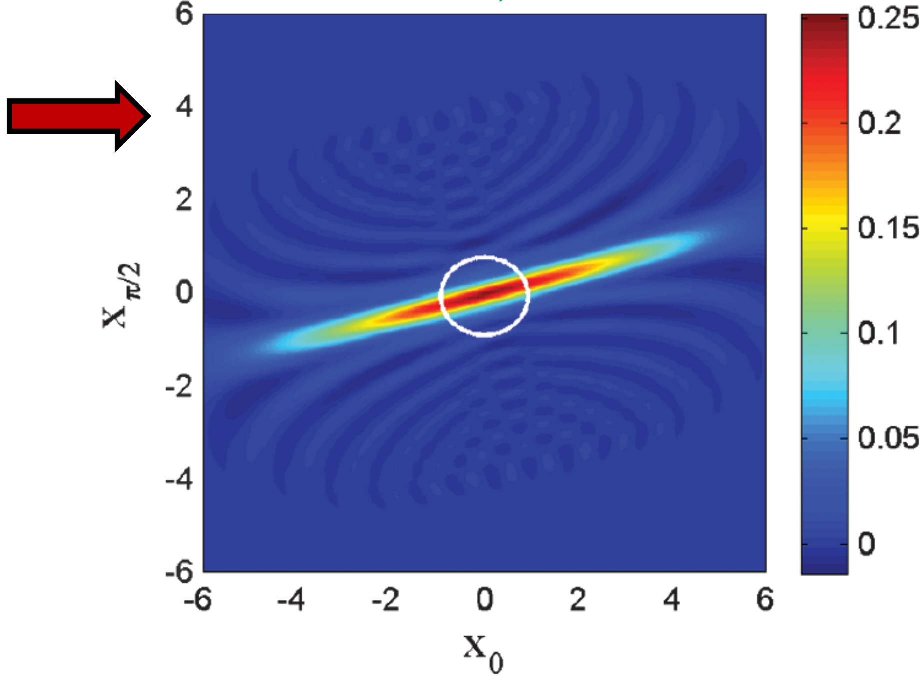




Josephson parametric amplifier (JPA)



Mallet et al., PRL 2011



Hamiltonian vs dissipative squeezing

- Hamiltonian squeezing

$$\frac{H}{\hbar\omega} = \frac{X^2}{2} + \left[1 + \varepsilon \sin(2\omega t)\right]\frac{P^2}{2} \approx a^+ a - \underbrace{\frac{i\,\varepsilon}{4}\left(a^2 e^{2i\omega t} - h.c.\right)}$$

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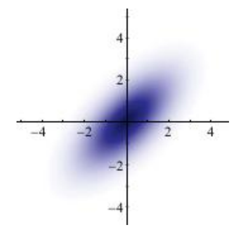
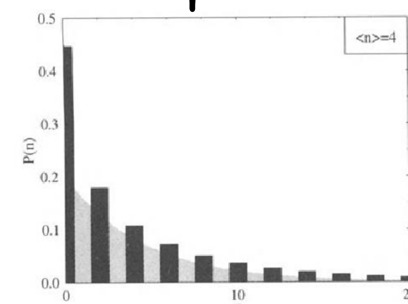




- Dissipative squeezing

Environment noise engineered to squeeze

Example: time-dependent damping rate

$$\Delta X^2 = \frac{1 - \lambda_1}{1 + \lambda_1}$$

$$\lambda(t) = \sqrt{\kappa_c}\left(1 + \lambda_1 e^{2i\omega t}\right)$$

Kronwald, Marquardt, Clerk, PRA 2014

Didier, Qassemi, Blais, PRA 2014

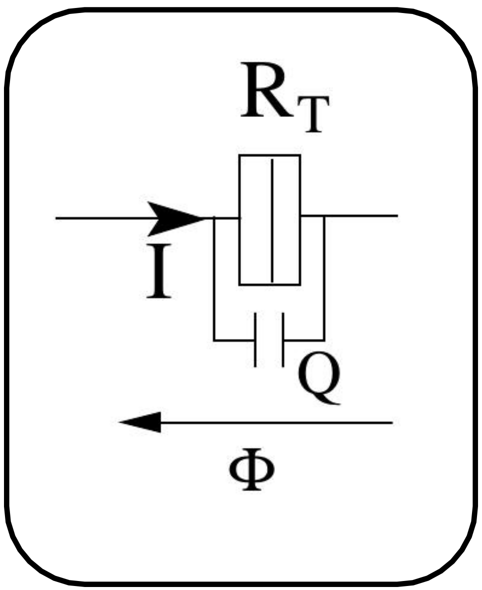
Coupling electrons and photons

- Hamiltonian for tunneling

$$\Lambda = e^{i\Phi} \quad [\Lambda, Q] = Q$$

$$H_T = \sum_{k,q} t\, c^{+}_{L,k} c_{R,q}\, \Lambda + h.c.$$

Λ transfers one electronic charge through the junction



- Gauge transform (cavity)

$$\Phi = i\lambda(a^{+} - a)$$

$$H_T = \sum_{k,q} t\, c^{+}_{L,k} c_{R,q} + h.c. + H_C$$

$$H_C = (a + a^{+})\left(\lambda_L \hat{N}_L + \lambda_R \hat{N}_R\right)$$

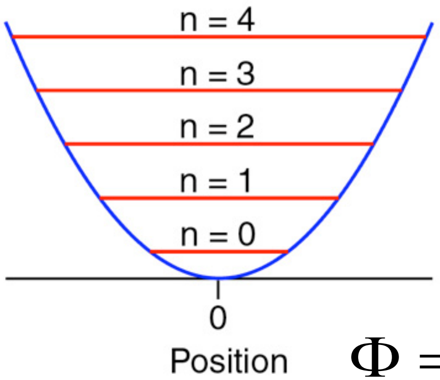
Gives a capacitive coupling

Udson, Mora PRB 2016

Dmytruk, Trif, Mora, Simon, PRB 2015

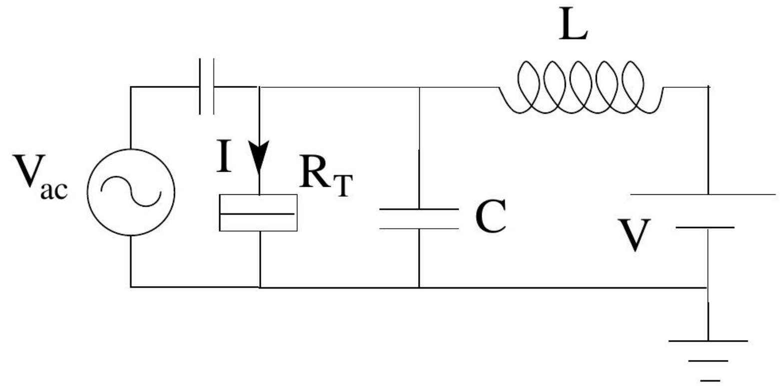
Tunnel junction feeding a LC resonant circuit

- (LC) Harmonic oscillator



$$[\Phi, Q] = i\hbar$$

$$\Phi = i\lambda(a^+ - a)$$



$$H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L} + H_T(\Lambda = e^{i\Phi})$$

- Derivation of a Quantum Langevin equation (a, I are quantum operators)

$$\dot{a} + i\,\omega_0 a + \frac{\kappa}{2} a = \lambda\, I \qquad \kappa = \lambda^2 \left[S_0(\omega_0) - S_0(-\omega_0) \right]$$

Fluctuation-dissipation theorem

- The noise of the current I both damps and excites the LC resonator

Equilibrium noise

$$\dot{a} + i\,\omega_0 a + \frac{\kappa}{2} a = \lambda\, I \qquad \langle I(\omega_1) I(\omega_2) \rangle = S_0(\omega_1)\, 2\pi\delta(\omega_1 + \omega_2)$$

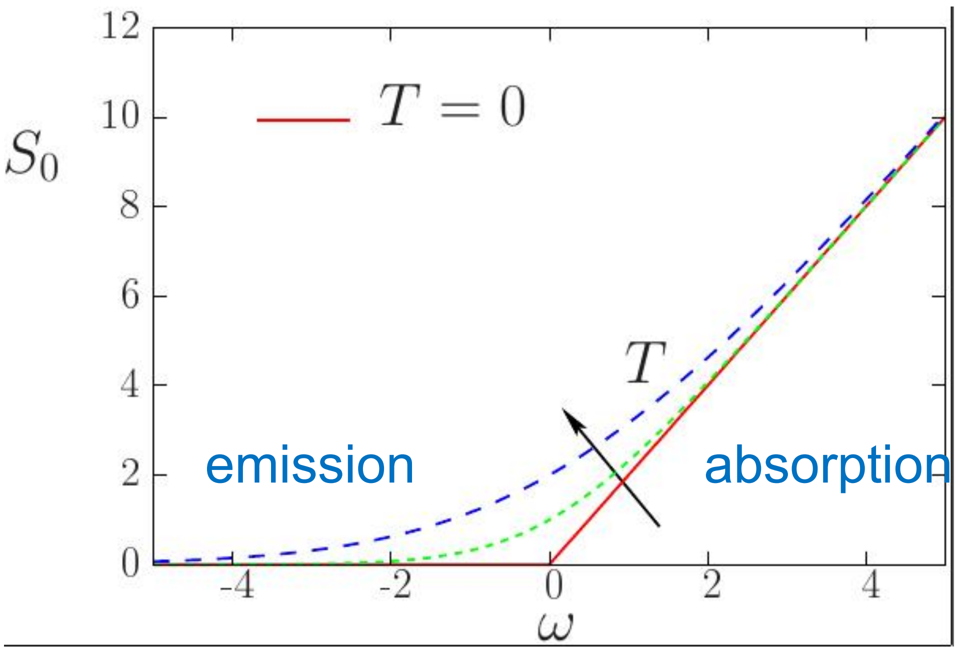
S_0 is absorption noise for positive frequency and emission noise for negative

At equilibrium (no voltage)

$$S_0^{eq}(\omega) = \frac{2}{R_T} \frac{\omega}{1 - e^{-\beta\hbar\omega}}$$

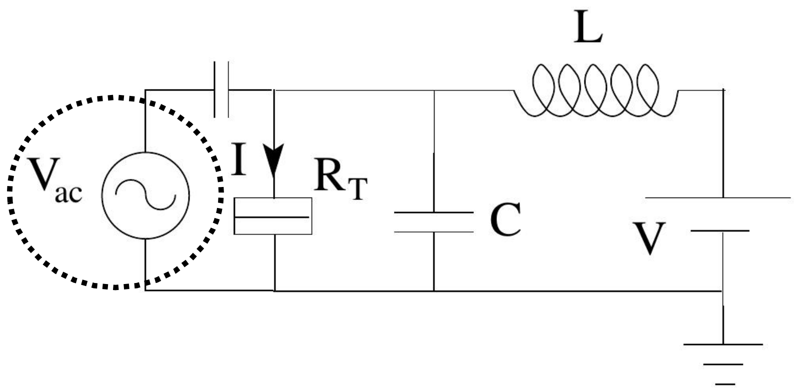
Solution of the Langevin equation

$$\langle a^+ a \rangle = \frac{\lambda^2 S_0(-\omega_0)}{\kappa}$$



Out-of-equilibrium noise

$$\dot{a} + i\,\omega_0 a + \frac{\kappa}{2} a = \lambda I$$

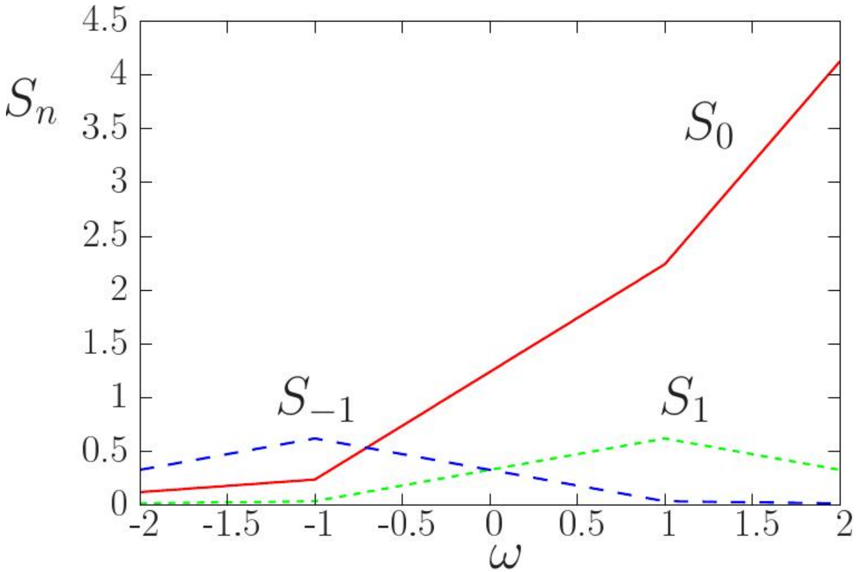


$$\langle I(\omega_1) I(\omega_2) \rangle = \sum_n S_n(\omega_1)\, 2\pi\delta(\omega_1 + \omega_2 - 2n\omega_0)$$

$n \neq 0$ Non-stationary terms

Quadrature Squeezing

$$\langle a\, a \rangle = \frac{\lambda^2 S_1(\omega_0)}{\kappa}$$



Optimizing squeezing

Squeezing depends on photo-assisted properties by the ac modulation or on emission/absorption probabilities c_n

$$X_1 = i(a^+ - a)$$

Single tone

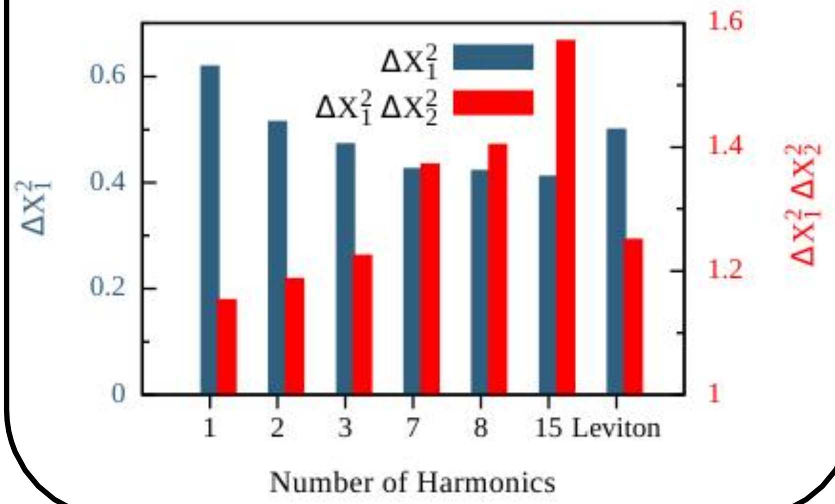
$$\Delta X_1^2 = 0.618$$

$$\frac{eV_{AC}}{2\hbar\omega_0} = 0.706$$

$$eV = \hbar\omega_0$$

Full agreement with Reulet's experiment

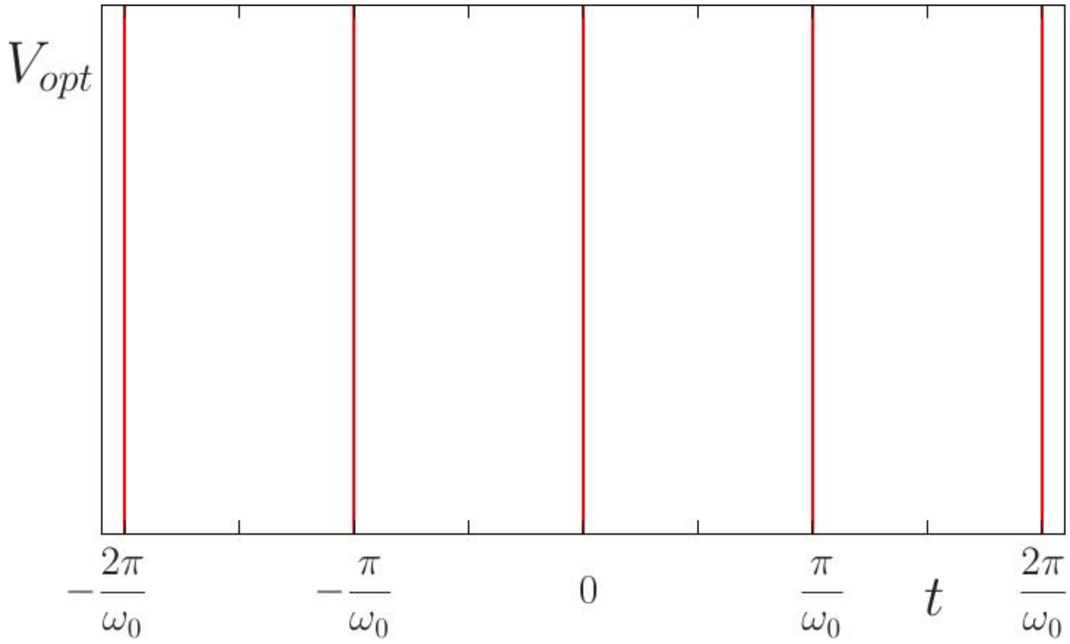
With harmonics



Optimal squeezing for a tunnel junction

Optimal squeezing is reached with the pulse shape

$$V_{opt}(t) = \frac{h}{2e} \sum_l \delta\left(t - \frac{l\pi}{\omega_0}\right)$$

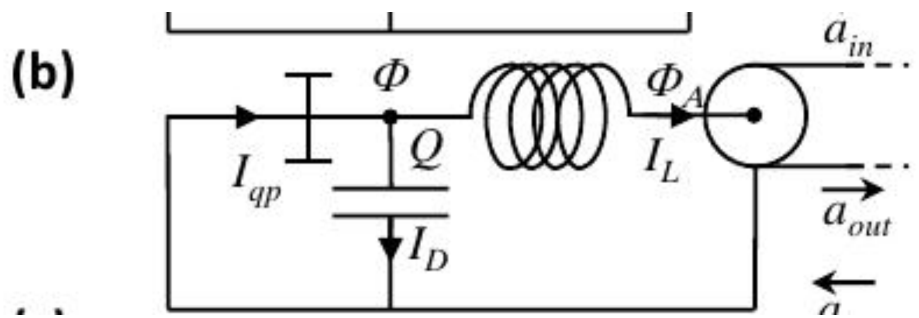


$$\Delta X_1^2 = \frac{4}{\pi^2} = 0.405$$

Dynamical Coulomb blockade

Input-output formalism, field emission

- Input-output formalism describes how the conductor interacts with its electromagnetic circuit environment



$a_{in}(\omega)$ incoming photon field (from coax line)

$a_{out}(\omega)$ outgoing photon field (to coax line)

$$\Phi_A(x) = \sqrt{\frac{\hbar Z_0}{8\pi^2}} \int_0^{+\infty} \frac{d\omega}{\sqrt{\omega}} \left[a_{\mathrm{in},\omega} e^{-ikx} + a_{\mathrm{out},\omega} e^{ikx} + \mathrm{h.c.}\right]$$

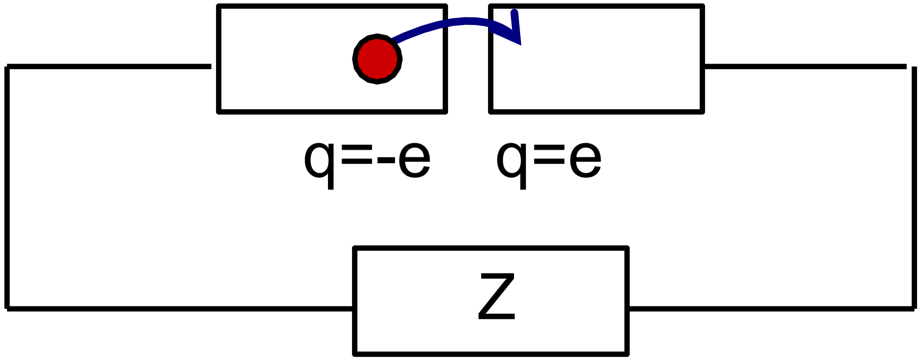
- Photon radiation in the transmission line (impedances are not matched)

$$P(t) = P_{out}(t) - P_{in}(t) = \frac{(1+n_B(\omega_0))S_I(\omega_0) - n_B(\omega_0)S_I(-\omega_0)}{2C}$$

Lesovik, Loosen, JETP 1997

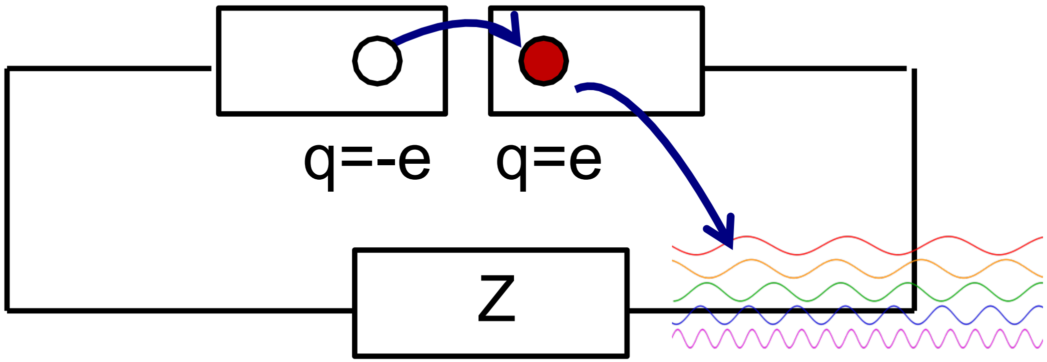
Dynamical Blockade for a tunnel junction

- Dynamical Coulomb blockade : transferred electric charge may excite environmental modes : reduction of current due to elastic processes



Dynamical Blockade for a tunnel junction

- Dynamical Coulomb blockade : transferred electric charge may excite environmental modes : reduction of current due to inelastic processes



$$\Lambda = e^{i\Phi} \quad [\Lambda, Q] = Q$$

$$\left|\langle 0|\Lambda|0\rangle\right|^2 \leq 1$$ Probability not to excite environment

$|0\rangle$ Ground state (electromagnetic circuit)

Dynamical Blockade for a tunnel junction

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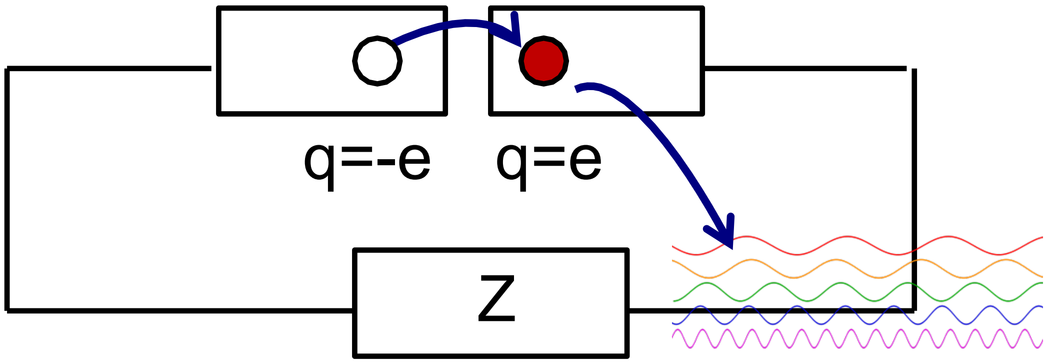

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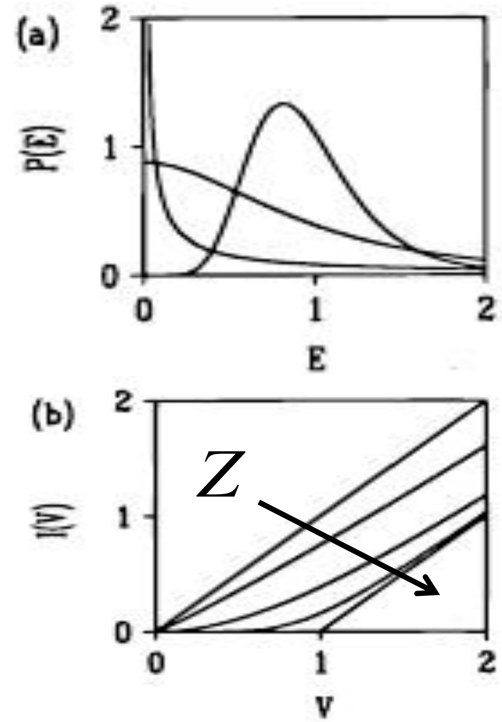
Inelastic transport encoded in P(E) function

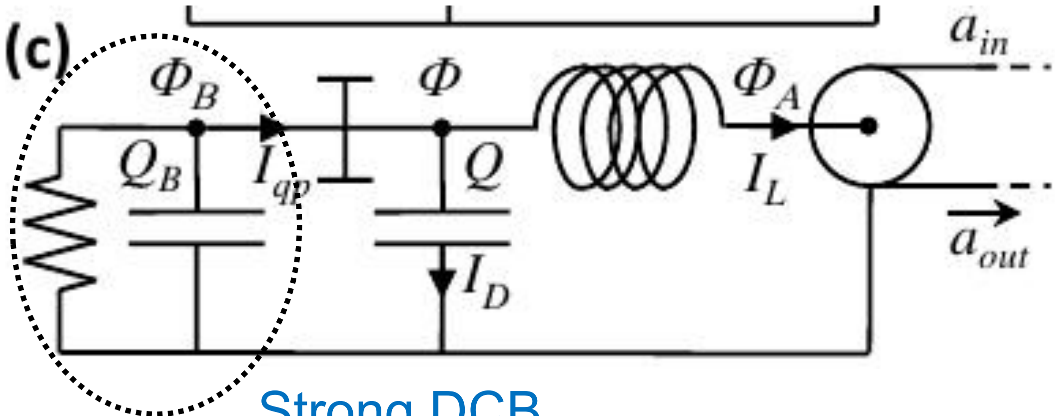
$$Z/\left(h/e^2\right)$$

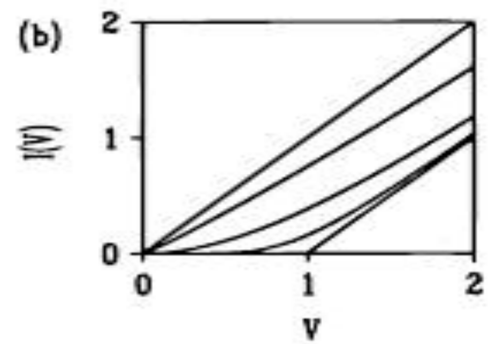
$$E_C = e^2/2C$$



Squeezed radiation

- We propose a circuit where dynamical Coulomb blockade and squeezed radiation readout are spatially separated



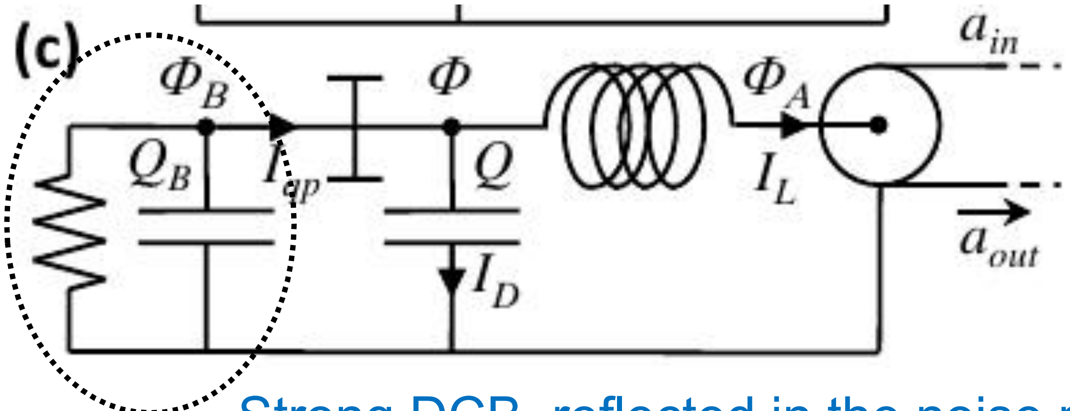


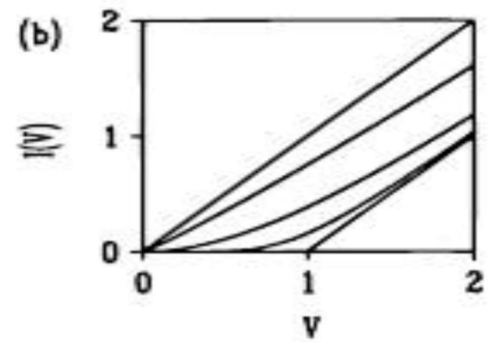
No DCB

Impedance matching $R_T Z_l = Z_{LC}^2$ $\delta\omega = \omega - \omega_0$

$$a_{out,\omega} = \frac{\delta\omega}{\delta\omega + i\kappa} a_{in,\omega} - \sqrt{\frac{R_T}{2\hbar\omega_0}} \frac{i\kappa}{\delta\omega + i\kappa} \hat{I}_\omega$$

Squeezed radiation from Dynamical Coulomb





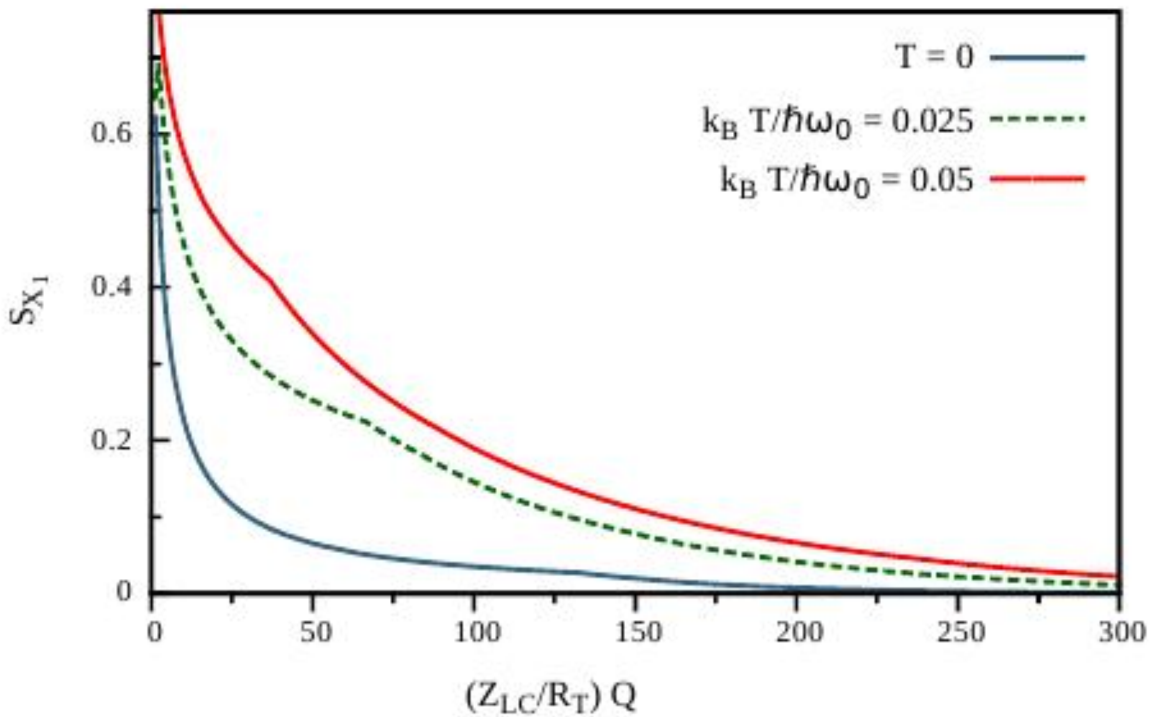
Strong DCB, reflected in the noise properties of the junction

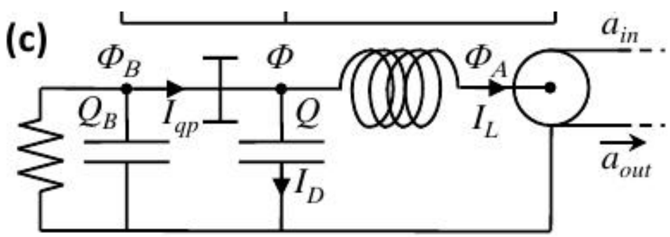
With DCB

$$(\omega + i\kappa_+) a_{out,\omega+\omega_0} = (\omega + i\kappa_-) a_{in,\omega+\omega_0} - i\sqrt{\frac{\omega_0 Z_l}{2\hbar}} \hat{I}_{\omega+\omega_0} - \frac{iY_1}{2C}\left(a^+_{out,\omega_0-\omega} - a^+_{in,\omega_0-\omega}\right)$$

$$2\kappa_{+/-} = Y_0 / C \pm Z_l / L \qquad Y_{0/1} \propto S_{0/1}(\omega_0) - S_{0/1}(-\omega_0)$$

Squeezed radiation from Dynamical Coulomb



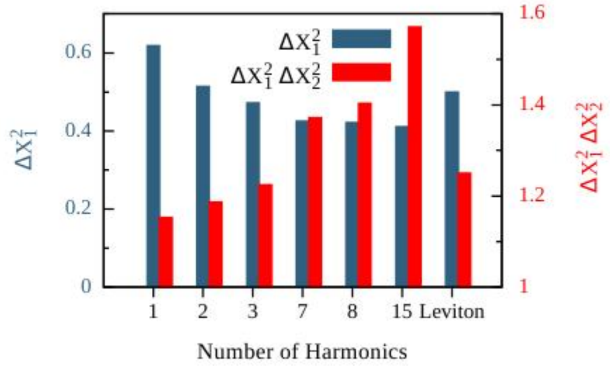


- Important temperature corrections
- Reflection coefficient is effectively strongly modulated

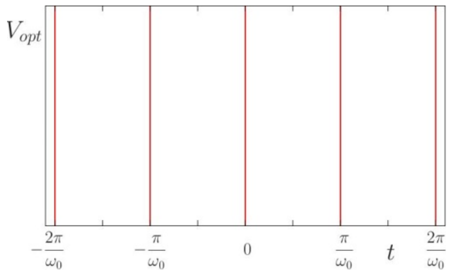
$$r = \frac{Z_l - Z_{sys}}{Z_l + Z_{sys}}$$

Conclusions

- A tunnel junction is in principle able to produce squeezed light in a resonator



- Squeezing is improved with concentrated pulses of voltage



- Non-linearities in a tunnel junction under strong Coulomb blockade could be used to achieve a competitive squeezed radiation

Udson, Mora, NJP 2015 *Mora, Altimiras, Joyez, Portier Arxiv 2015* *Udson, Mora, PRB 2016*