Josephson photonics:
New sources for non-classical photon radiation

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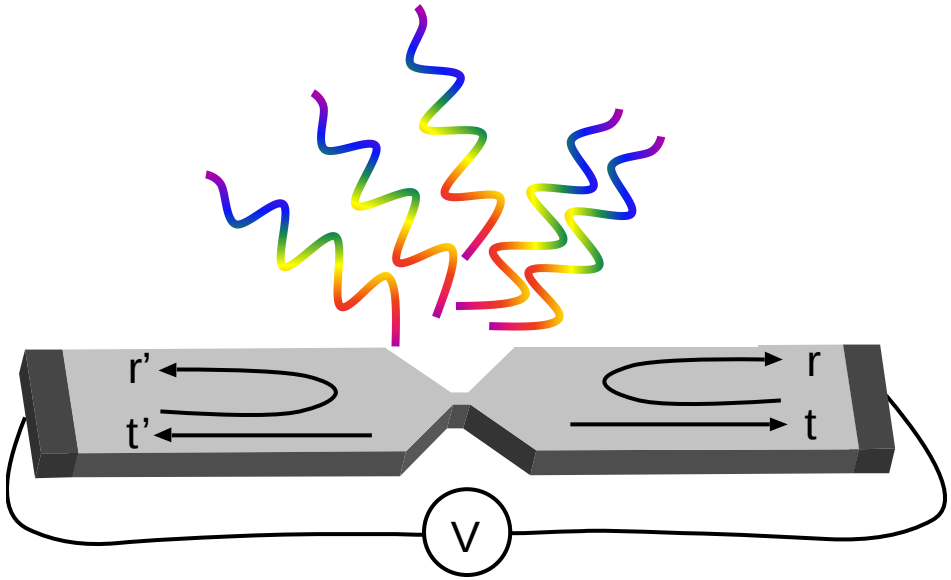
C. Ast, K. Kern (MPI-FKF)

NMP-2017

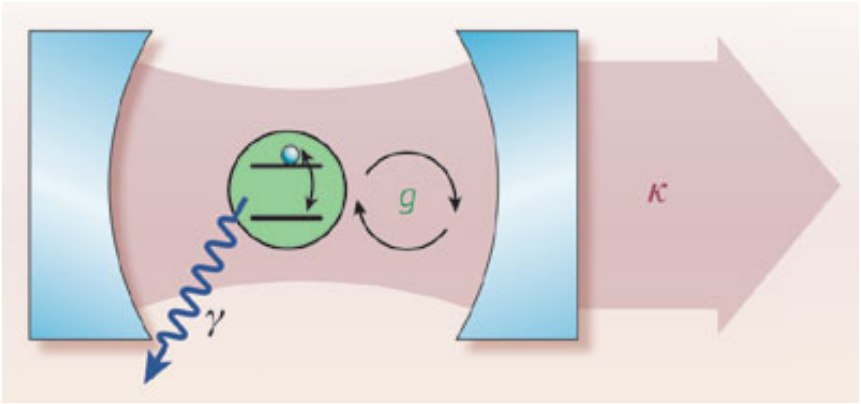
Quantum optics of quantum conductors



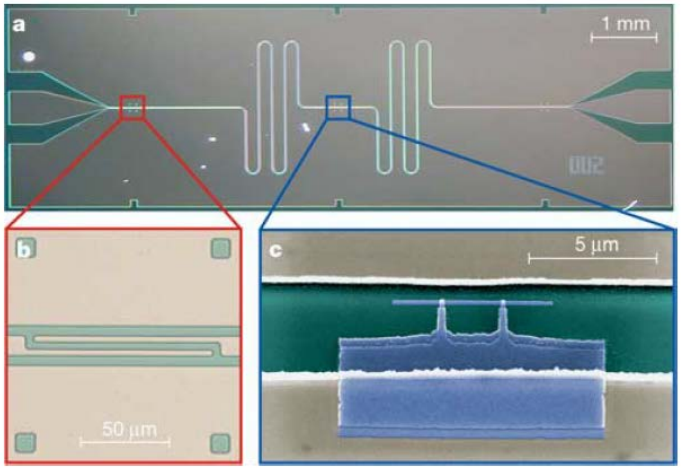
Glauber (1951):
Classical currents create classical light

Quantum optics: Light-matter interaction

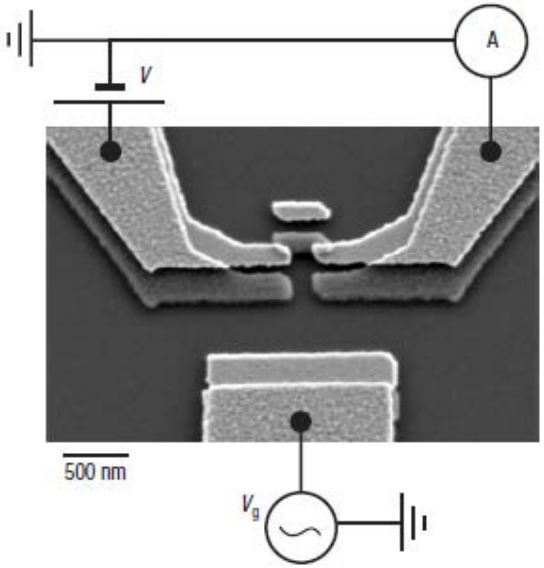
cavity QED

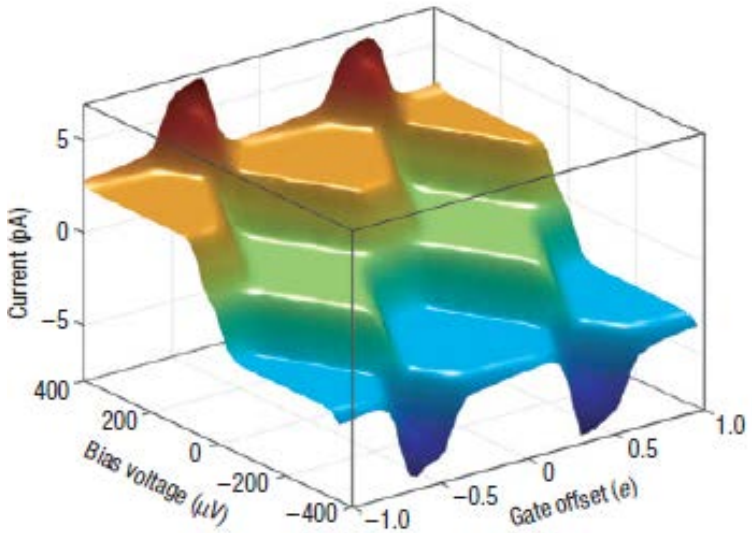


circuit QED: superconductors

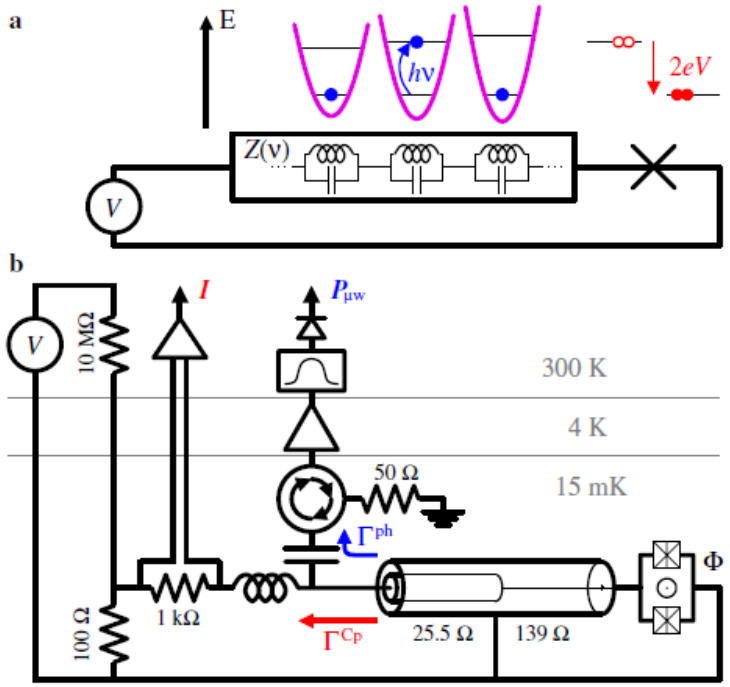


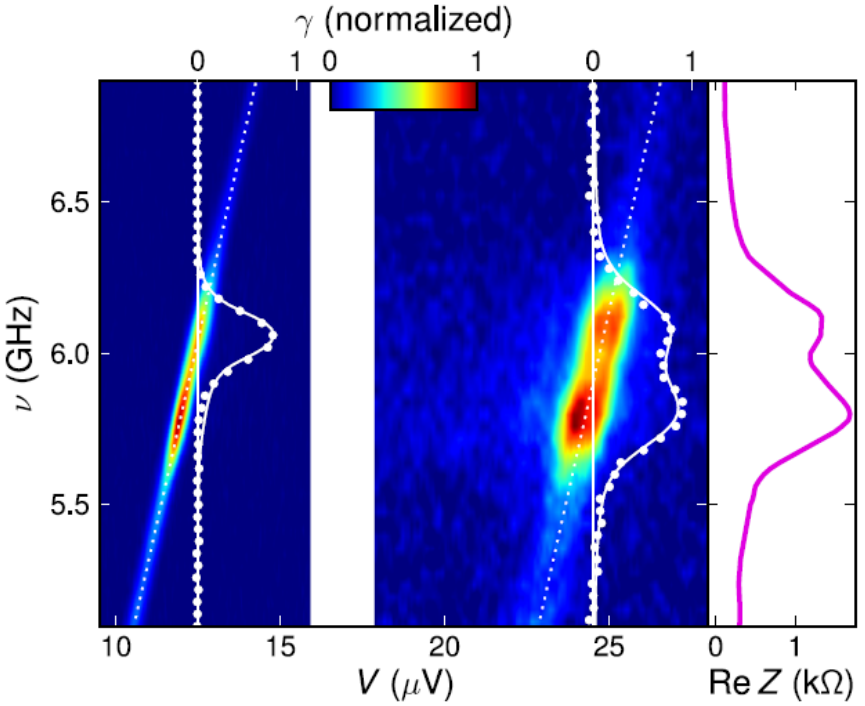
Quantum electronics: Single charge transfer





Charge transfer in Josephson junction – cavity devices





PRL **106,** 217005 (2011) PHYSICAL REVIEW LETTERS week ending 27 MAY 2011

Bright Side of the Coulomb Blockade

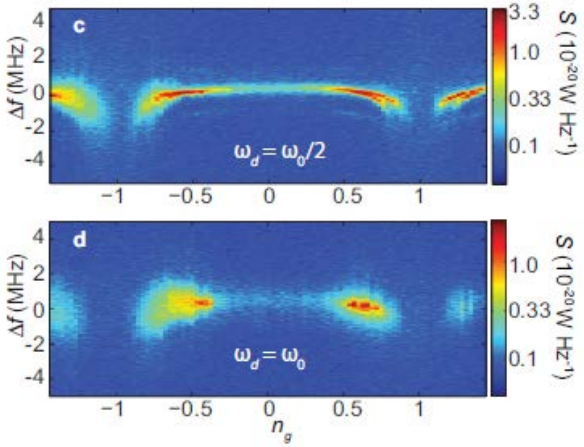
M. Hofheinz, F. Portier, Q. Baudouin, P. Joyez, D. Vion, P. Bertet, P. Roche, and D. Esteve

Service de Physique de l'Etat Condensé (CNRS URA 2464), IRAMIS, CEA Saclay, 91191 Gif-sur-Yvette, France

(Received 28 January 2011; published 27 May 2011)

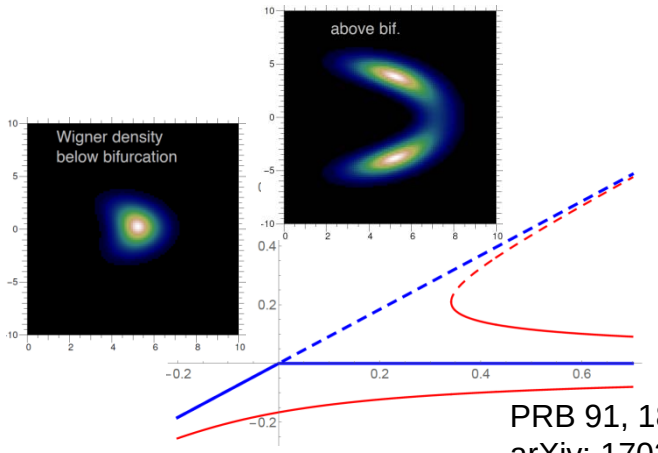
Josephson photonics

Josephson laser



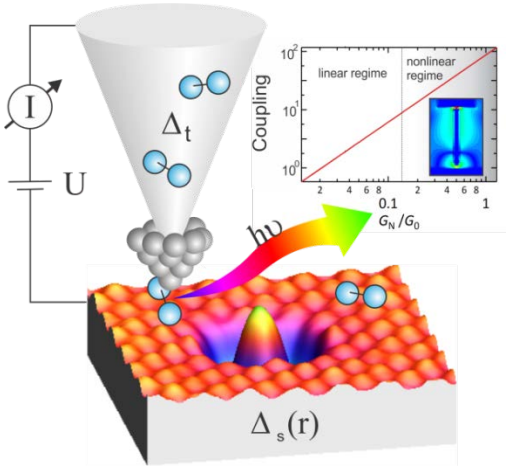
PRL 111 , 247001 (2013)

Nonlinear Quantum Oscillator



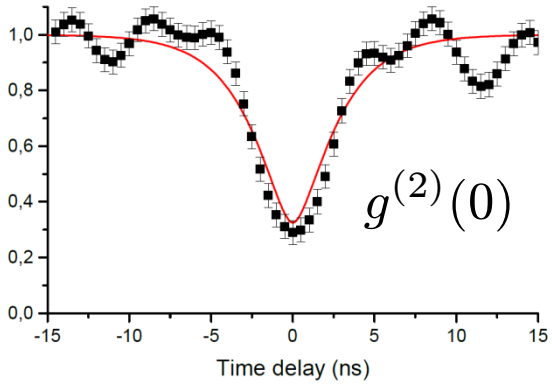
PRB 91, 184508 (2015)
arXiv: 1702.07931

Josephson-STM

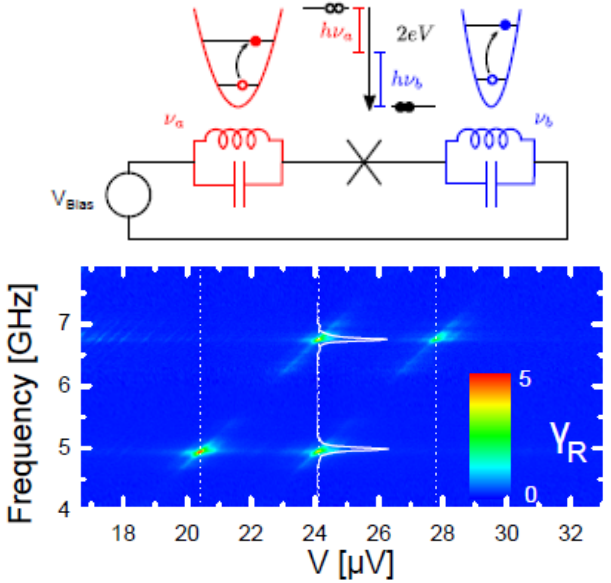


Nature Commun. 7, 13009 (2016)

Single photons



Correlated/Entangled photons



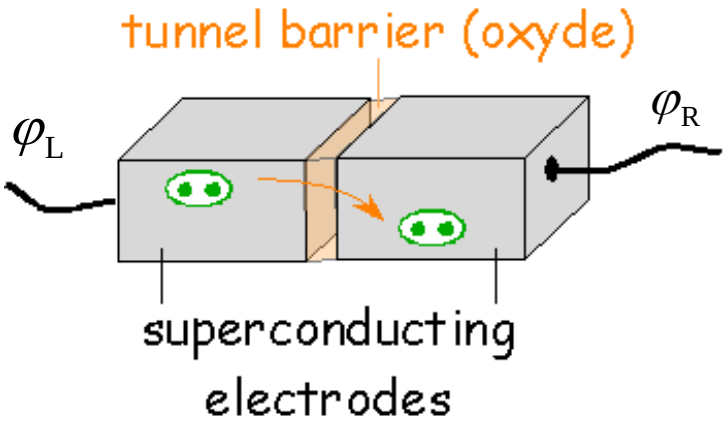
Agenda

Single charge transfer and quantum optics

Non-classical light sources

Full counting statistics of charge and light

Josephson junction

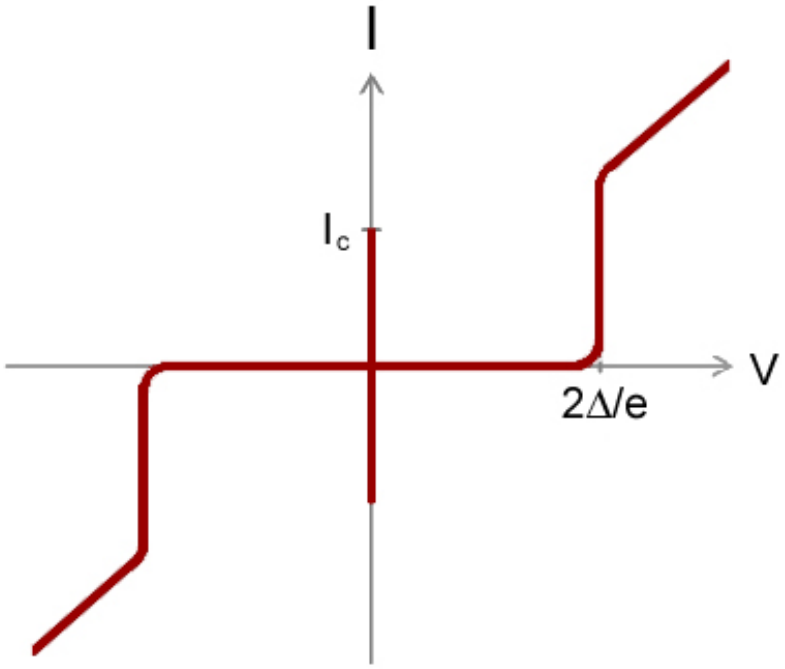


$$\varphi = \varphi_L - \varphi_R$$

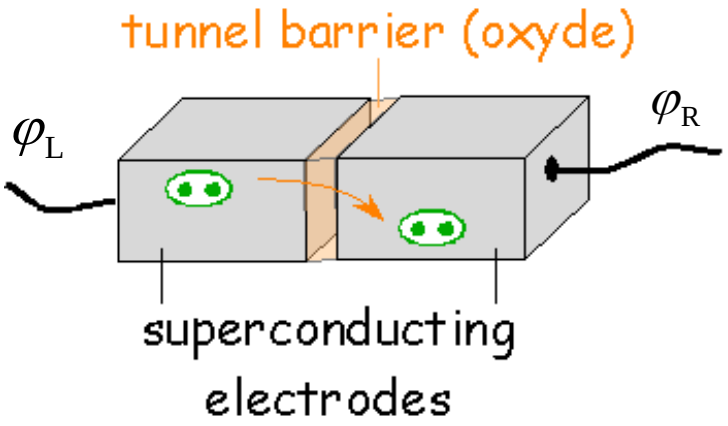
$$I_J = I_c \sin(\varphi)$$

$$V_J = \frac{\hbar}{2e}\dot{\varphi}$$

(ac-Josephson)



Josephson junction



$$\hat{H}_J = E_C \left(\frac{\hat{Q}}{2e}\right)^2 - E_J \cos(\hat{\varphi})$$

$$E_C = \frac{2e^2}{C} \qquad E_J = I_c \frac{\hbar}{2e}$$

Coherent Cooper pair transfer

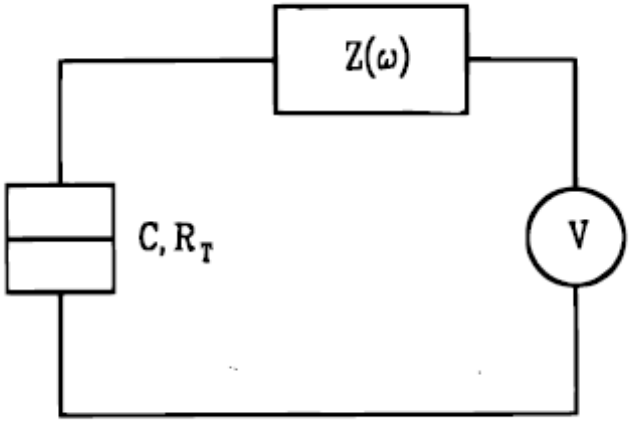
$$[\hat{Q}, \mathrm{e}^{i\hat{\varphi}}] = 2e \ \mathrm{e}^{i\hat{\varphi}}$$

$$\mathrm{var}[\hat{\varphi}] \ll \mathrm{var}[\hat{Q}]$$

Inelastic Cooper pair tunneling

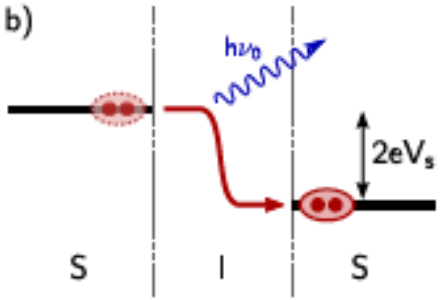
$$E_C \gg E_J, k_{\mathrm{B}}T$$

$$\mathrm{Re}Z \gg \frac{h}{4e^2}$$



Sequential charge transfer

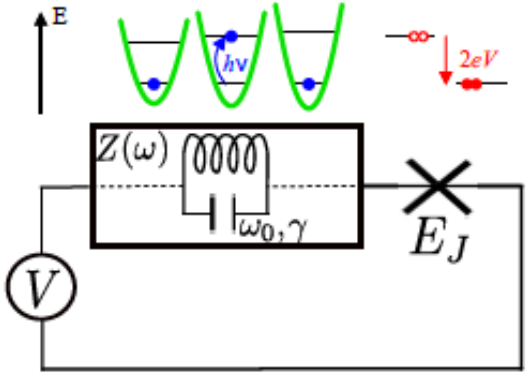
$$\mathrm{var}[\hat{\varphi}] \gg \mathrm{var}[\hat{Q}]$$



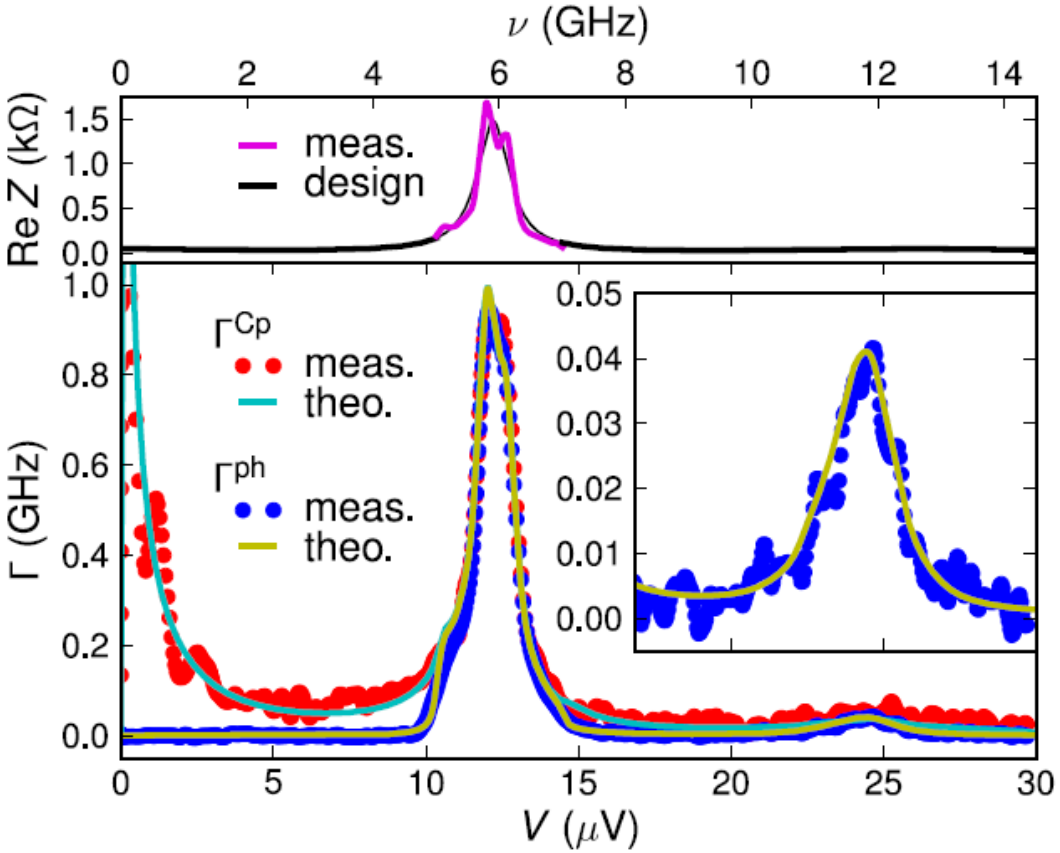
$$I_J = \frac{\pi E_J^2}{\hbar} P(2eV) \ , \quad T = 0$$

Grabert, Devoret,
Single Charge Tunneling, 1992

Bright-side of single charge transfer



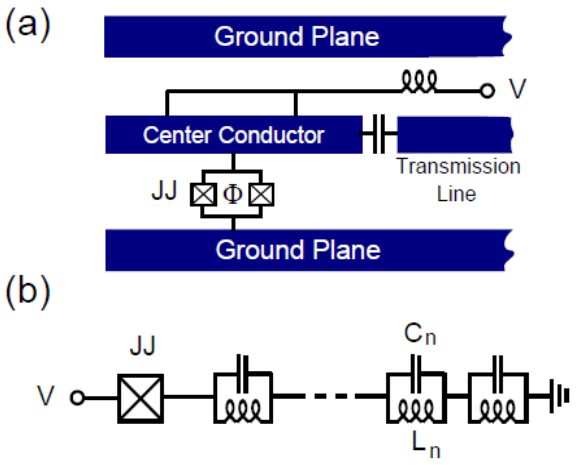
Sequential charge flow



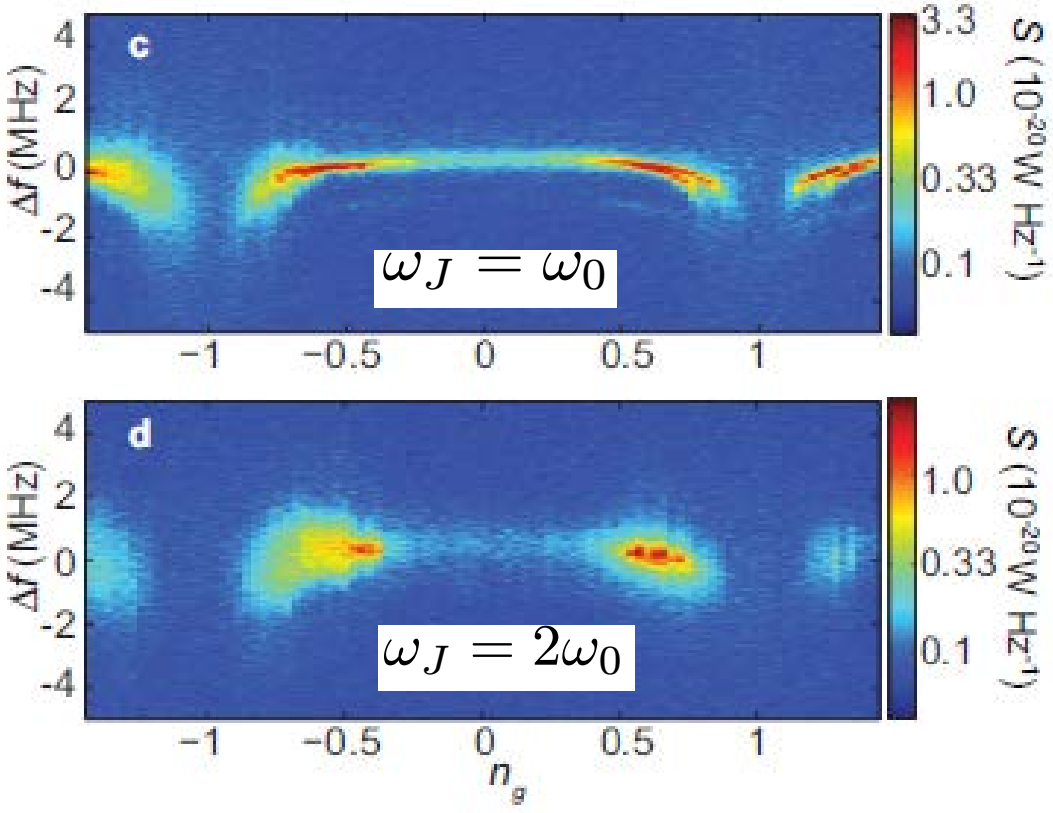
Hofheinz et al, PRL 106, 217005 (`11)
Altimiras et al, PRL 112, 236803 (`14)
Rimberg et al PRB 90, 020506(R) (`14)

Leppäkangas et al, PRL 110, 267004 (`13)
Armour et al, PRL 111, 247001 (`13)
Gramich et al, PRL 111, 247002 (`13)

Bright-side of coherent charge flow



Coherent charge flow



Hofheinz et al, PRL 106, 217005 (`11)
Altimiras et al, PRL 112, 236803 (`14)
Rimberg et al PRB 90, 020506(R) (`14)

Leppäkangas et al, PRL 110, 267004 (`13)
Armour et al, PRL 111, 247001 (`13)
Gramich et al, PRL 111, 247002 (`13)

Resonator mode

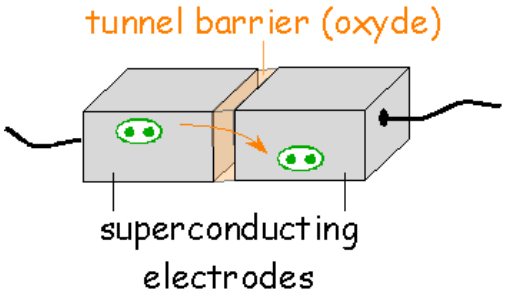
$$[a, a^\dagger] = 1$$

Photons

$$\hbar\omega_0, \gamma$$

$$\left(= \frac{1}{\sqrt{LC}}\right)$$

Josephson junction

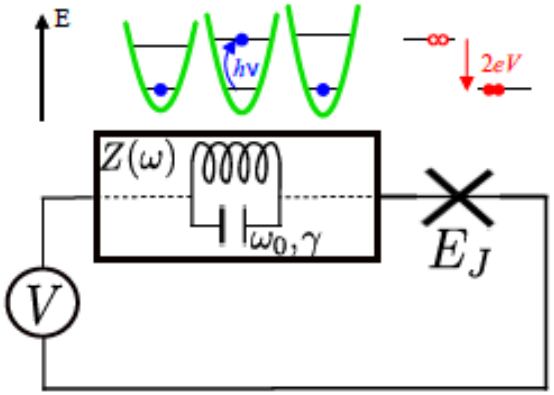


$$[\varphi, Q] = i\,2e$$

Cooper pairs

$$E_J, E_C$$

Quantum dynamics



$$H = \hbar\omega_0 a^\dagger a - E_J \cos[\omega_J t + \sqrt{\alpha}(a + a^\dagger)]$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad \omega_J = \frac{2eV}{\hbar}$$

$\omega_J \approx p\,\omega_0$:

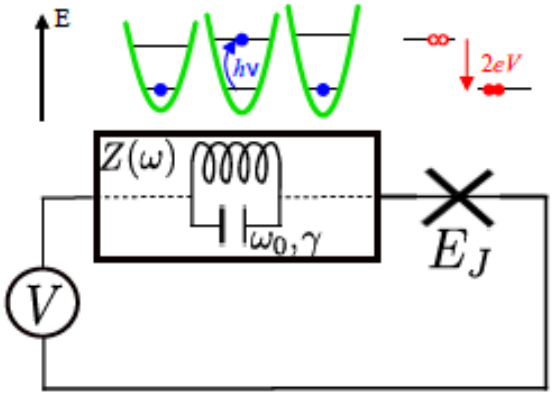
$$H_p = \hbar\Delta\, a^\dagger a - (-i)^p \frac{E_J^*}{2} : \left[(a^\dagger)^p + (-1)^p a^p\right] \frac{J_p(2\sqrt{\alpha\, a^\dagger a})}{(a^\dagger a)^{p/2}} :$$

$$E_J^* = E_J\, \mathrm{e}^{-\alpha/2}$$

„Fine structure constant“ $\alpha = \dfrac{Z_{LC}}{2R_K}$ $(\approx \ldots 0.07 \ldots 1.5 \ldots)$

Gramich, Kubala, JA et al, PRL 111, 247002 (`13)
Armour et al, PRL 111, 247001 (`13)

Quantum dynamics



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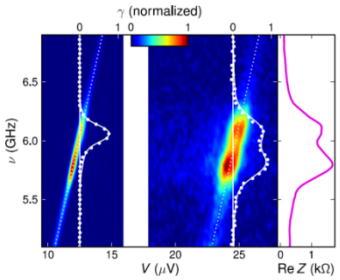
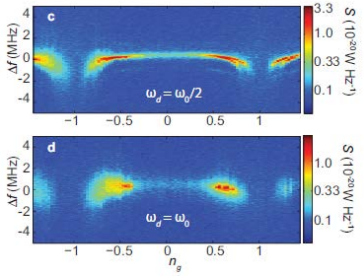
$$E_J^* = E_J\, \mathrm{e}^{-\alpha/2}$$

+ cavity damping and local voltage noise

$$\dot\rho = \frac{1}{i\hbar}[H_p, \rho] + \gamma\, \mathcal{L}_{\mathrm{cav}}[\rho] + \gamma_V\, \mathcal{L}_V[\rho] \qquad \gamma_V \ll \gamma$$

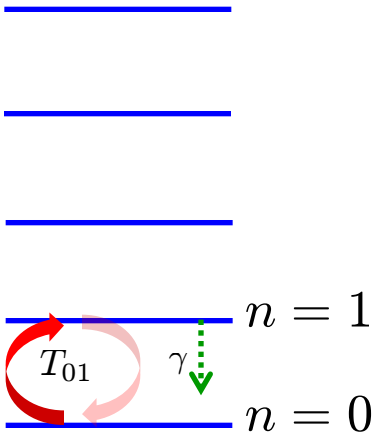
Gramich, Kubala, JA et al, PRL 111, 247002 (`13)

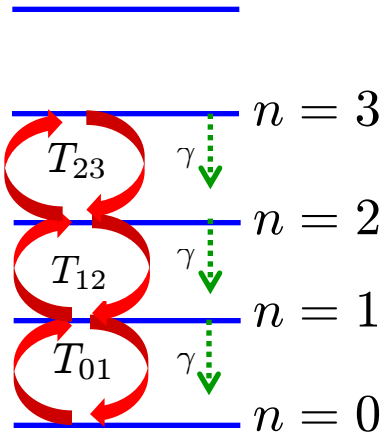




weak strong

$$T_{n,n+1}(E_J,\alpha) = \langle n+1|H^{(1)}_{\mathrm{RWA}}|n\rangle$$





$$|T_{0,1}(E_J,\alpha)| \ll \gamma \equiv \frac{1}{\tau_{\mathrm{cav}}}$$

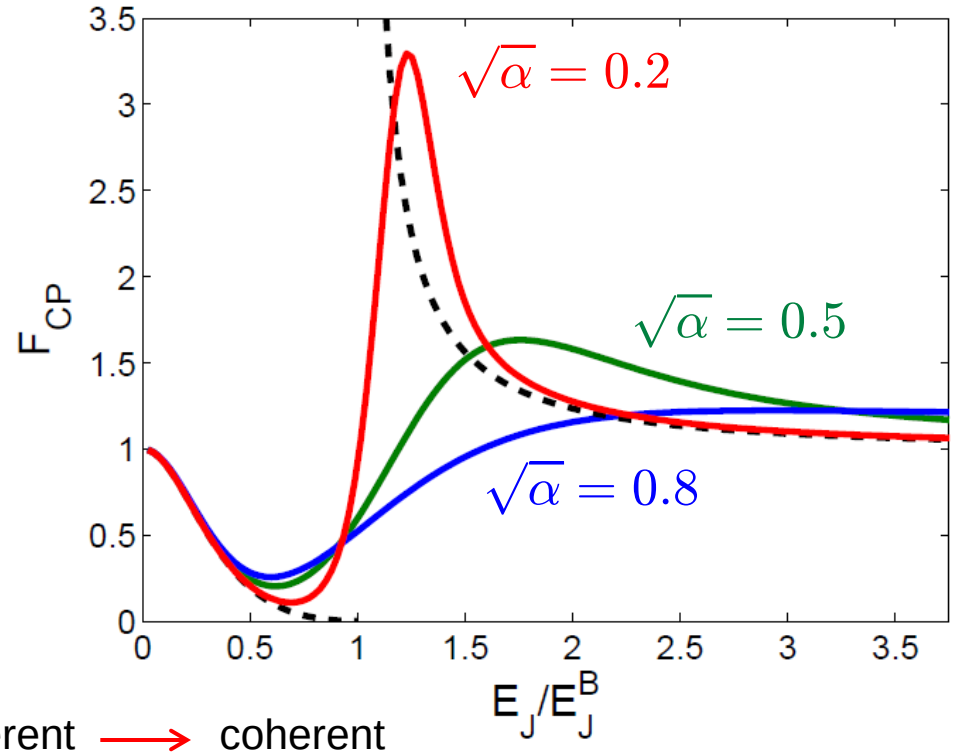
$$|T_{0,1}(E_J,\alpha)| > \gamma$$

No feedback onto JJ:
Charge well defined

Strong feedback onto JJ:
Large charge fluctuations

Current noise: Sequential and coherent charge flow

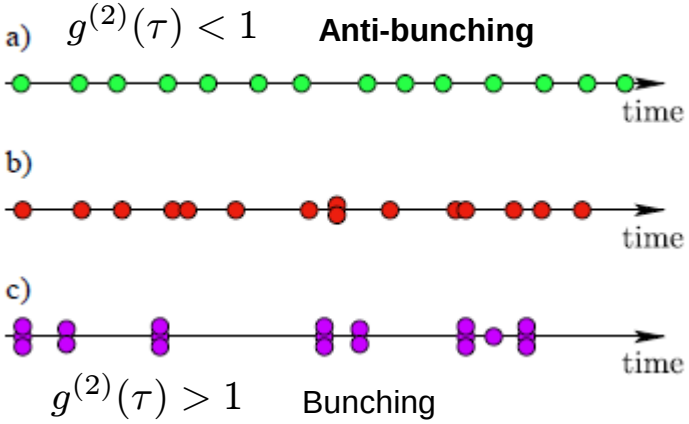
Fano factor $$F_{\rm CP} = \frac{1}{4eI_J}\int d\tau \langle \delta I_J(t+\tau)\,\delta I_J(t)\rangle_{\rm st}$$



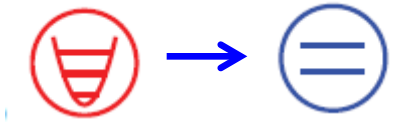
incoherent ⟶ coherent

CP transfer

Towards single photon sources for microwaves



$$g^{(2)}(\tau) = \frac{\langle a^\dagger(\tau) a^\dagger a\, a(\tau)\rangle_{\rm st}}{\langle n\rangle^2_{\rm st}}$$



$$T_{12}(\alpha = 2) = 0$$

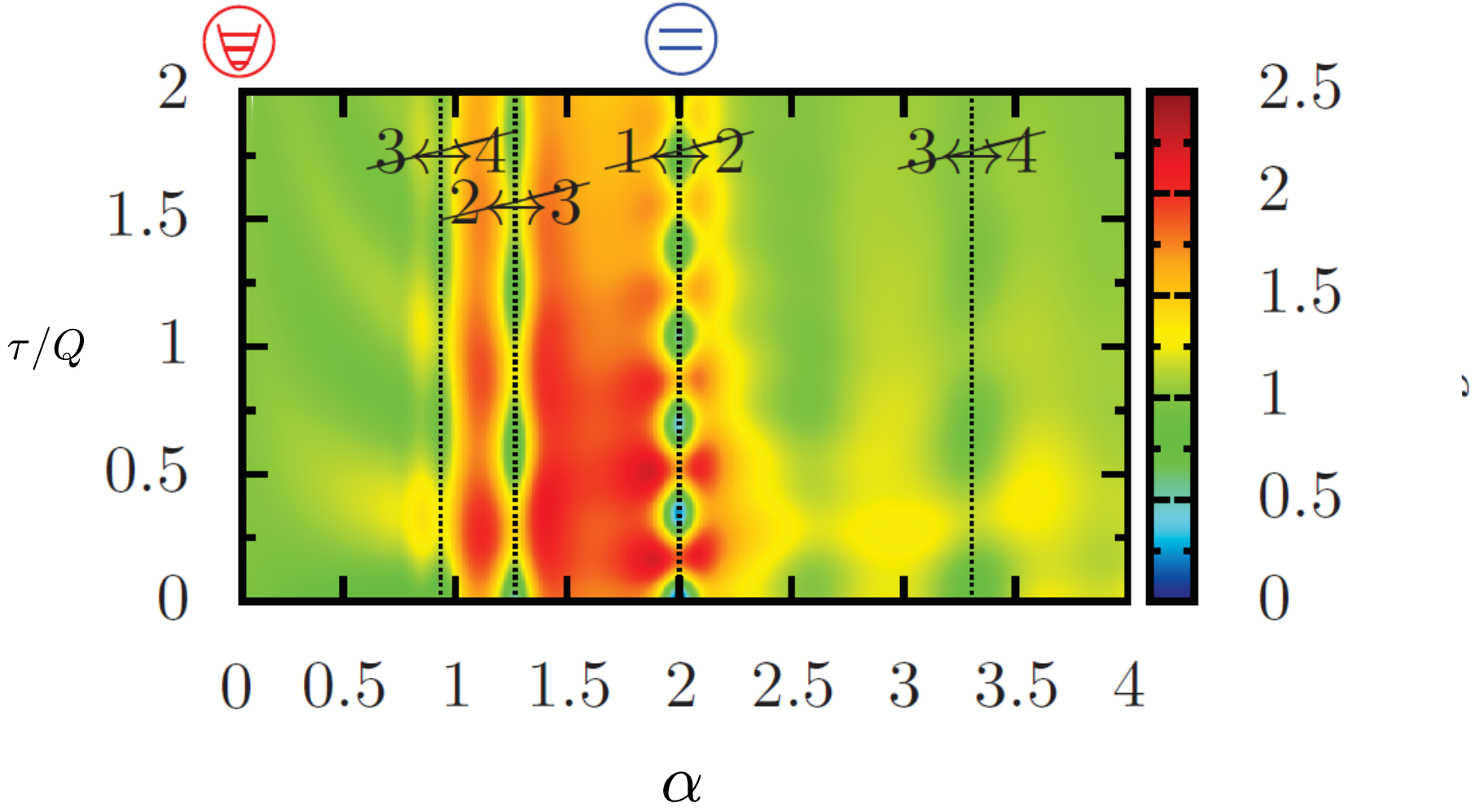
Weak driving $g^{(2)}(0) \approx \left(1 - \frac{\alpha}{2}\right)^2$

Gramich, JA et al, PRL 113, 027001 (`14)

Photon noise: anti-bunching

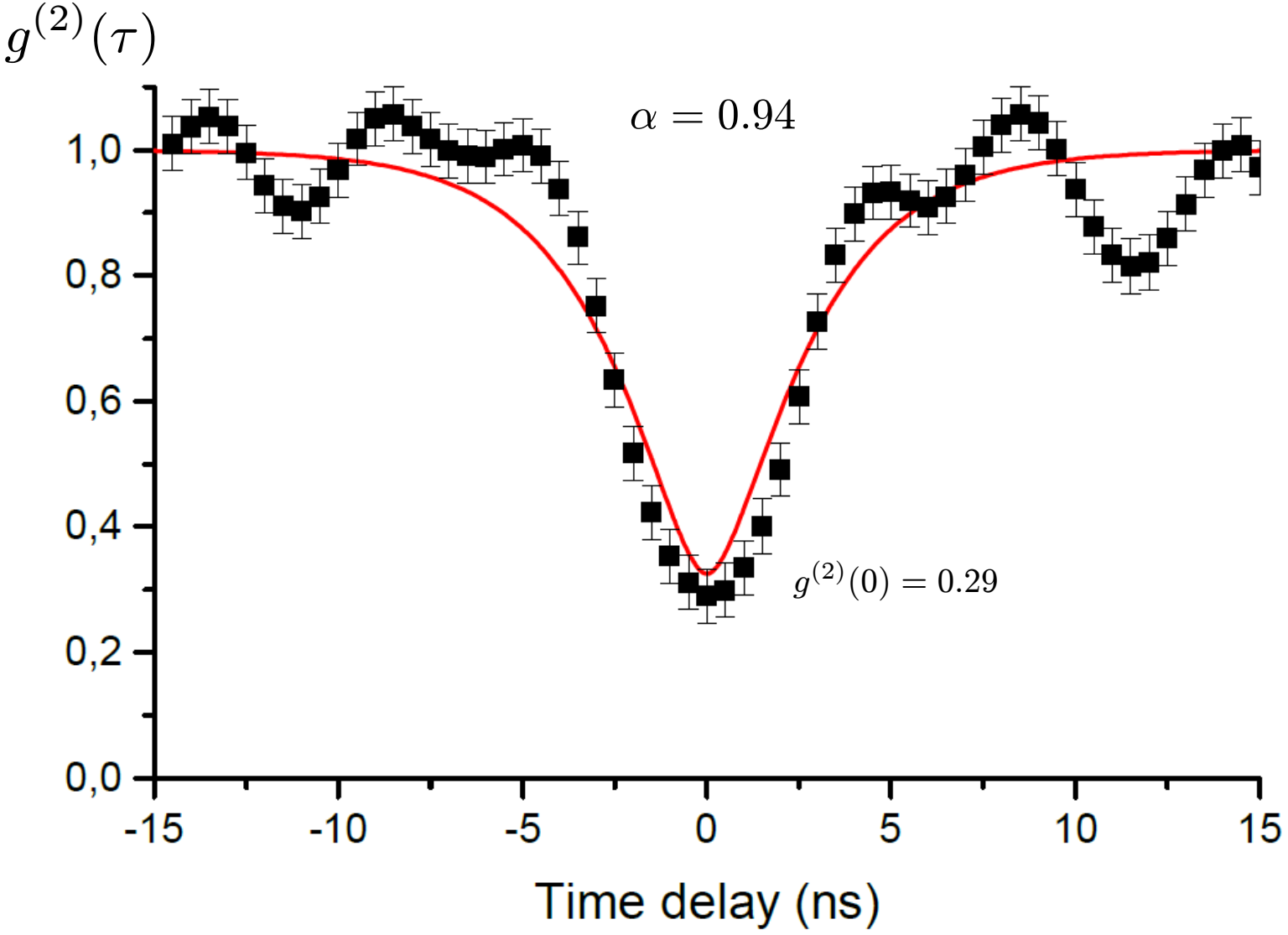
$g^{(2)}(\tau)$

$\langle n+1|H^{(1)}_{\mathrm{RWA}}|n\rangle = 0$



S. Dambach, JA et al, PRB 92, 054508 (`15)

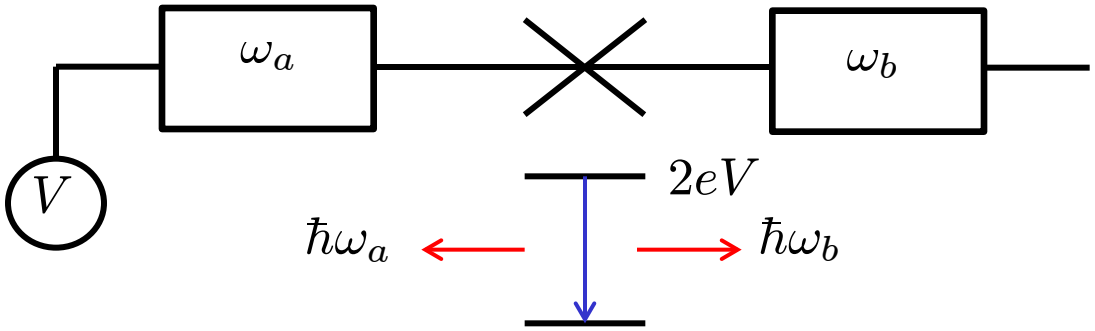
Towards single photon sources



Experiment: Saclay, December 2016

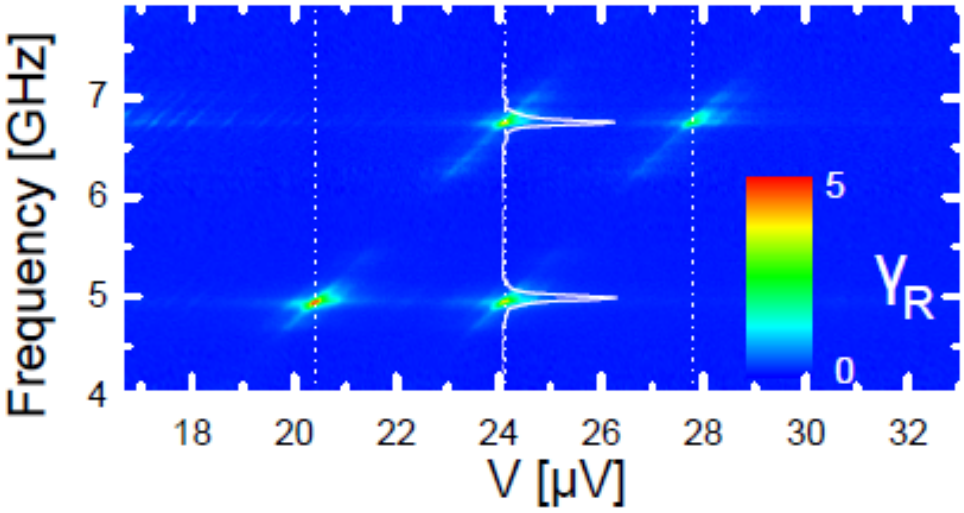
Correlated photon sources

$$2eV = \hbar(\omega_a + \omega_b)$$



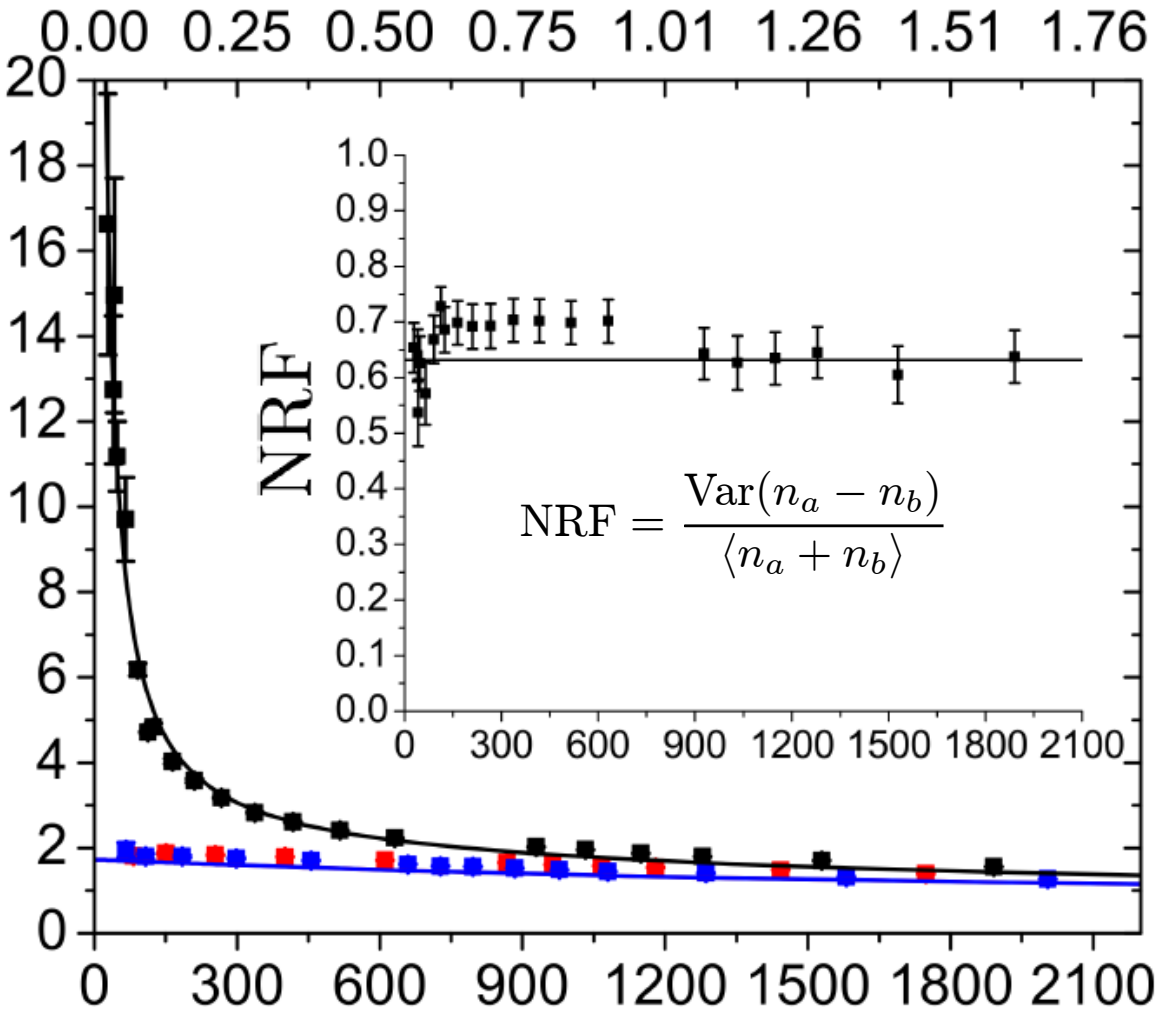
Non-classical light:
violation of Cauchy-Schwartz

$$g^{(2)}_{ab}(0) \leq \sqrt{g^{(2)}_{aa}(0)\, g^{(2)}_{bb}(0)}$$



Leppäkangas et al, NJP 2014
Armour, Kubala, JA, PRB (2015)
F. Portier, D. Esteve, JA et al, to be submitted

Two cavities: correlated photons



$g^{(2)}_{ab}(0)$

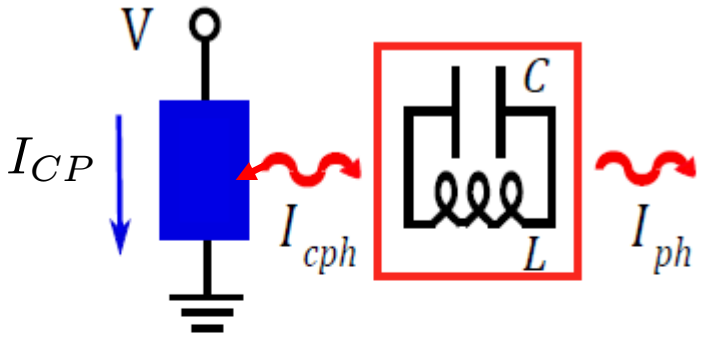
$g^{(2)}_{aa}(0)$

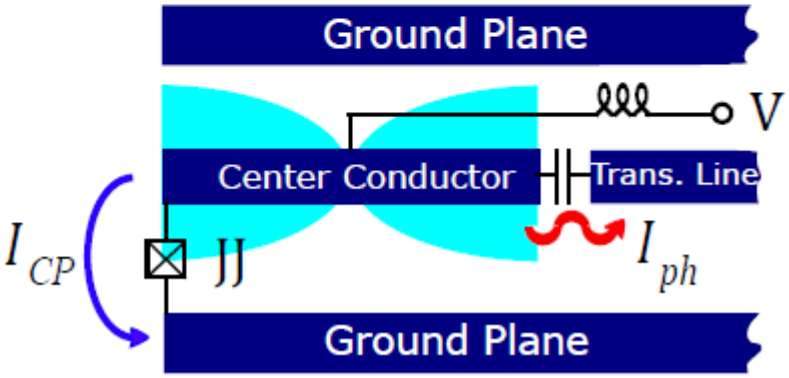
$g^{(2)}_{bb}(0)$

$g^{(2)}_{ab}(0) \not\sqsubseteq \sqrt{g^{(2)}_{aa}(0)\, g^{(2)}_{bb}(0)}$

Portier, Esteve, Kubala, JA, to be submitted

Full counting statistics for photons and charges



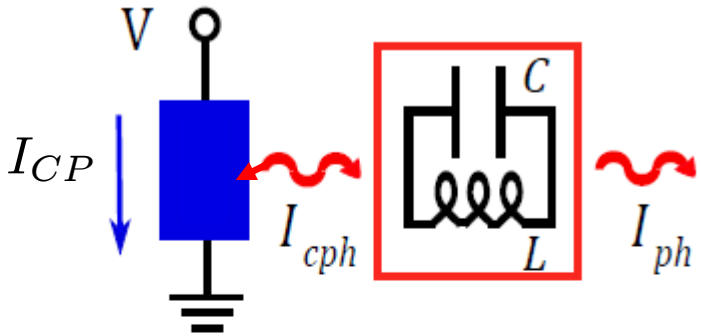


$$e^{\mathcal{F}_{CP}(p\chi,t)} = \sum_N \tilde{P}(N,t)\, e^{ip\chi N}$$

$$e^{\mathcal{F}_{ph}(\chi,t)} = \sum_N P(N,t)\, e^{i\chi N}$$

$$= \mathrm{Tr}\{e^{\mathcal{L}_\chi t}\, \rho(0)\}$$

Full counting statistics for photons and charges



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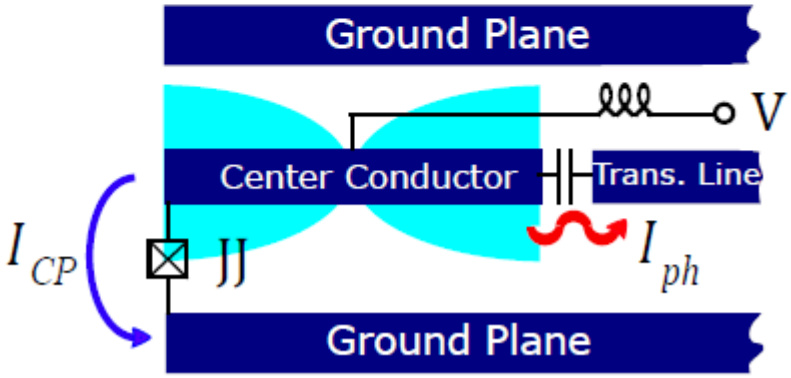
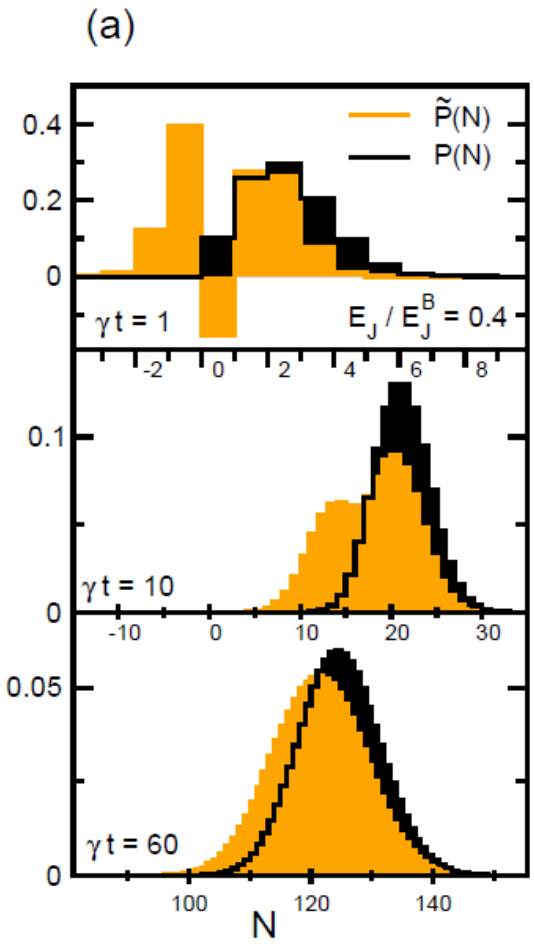


Long times $\gamma\, t \gg 1$

$$\mathcal{F}_{CP}(p\chi,t) \to \mathcal{F}_{ph}(\chi,t)$$

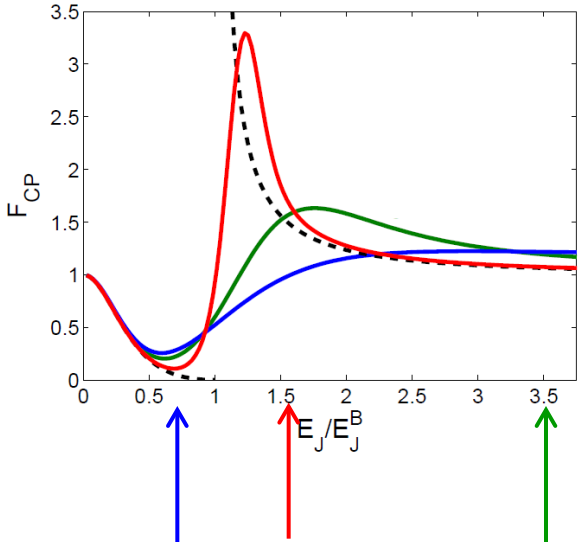
$$e^{\mathcal{F}_{CP}(p\chi,t)} = \sum_N \tilde{P}(N,t)\, e^{ip\chi N}$$

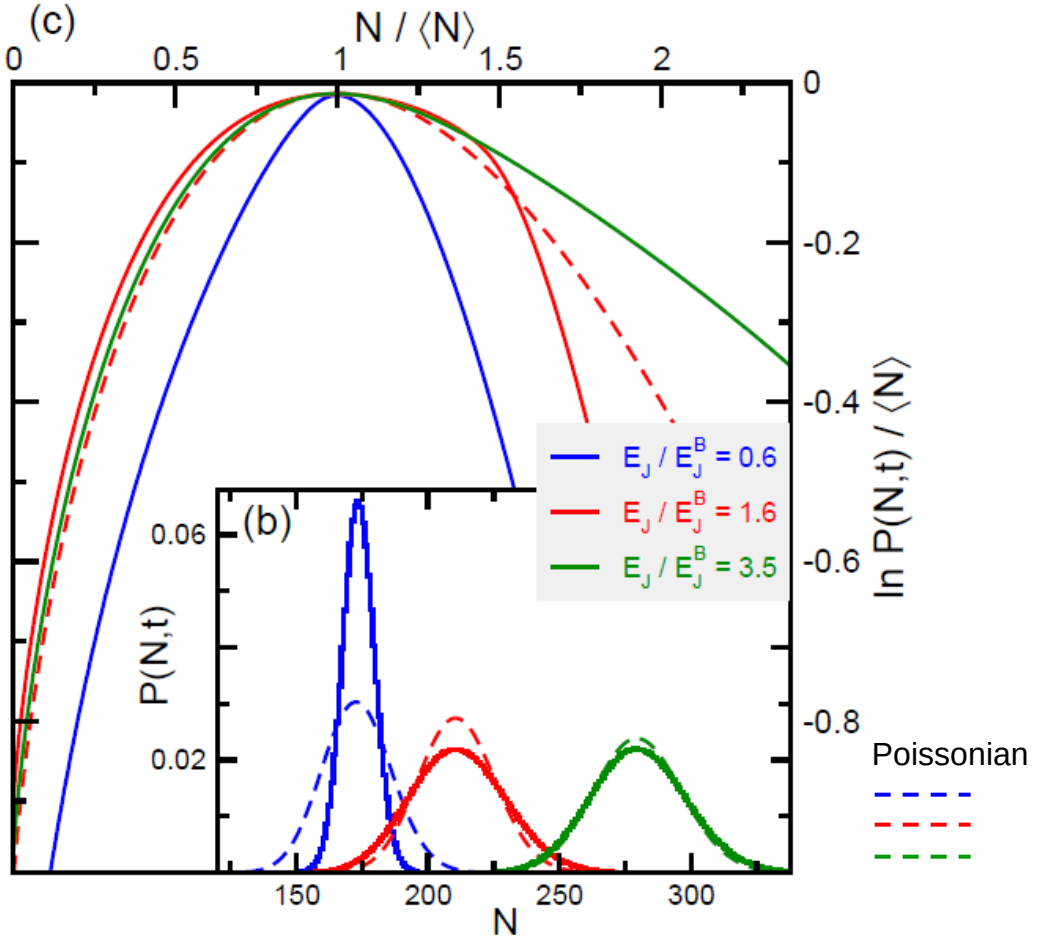
Full counting statistics for photons and charges



$$\mathcal{F}_{CP}(p\chi, t) \rightarrow \mathcal{F}_{ph}(\chi, t)$$

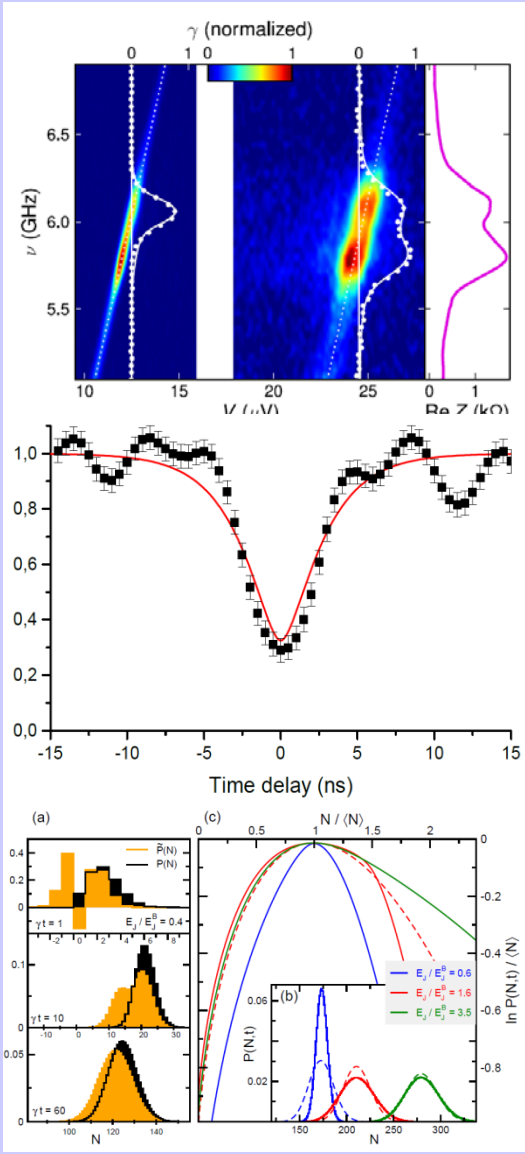
Large deviation distribution



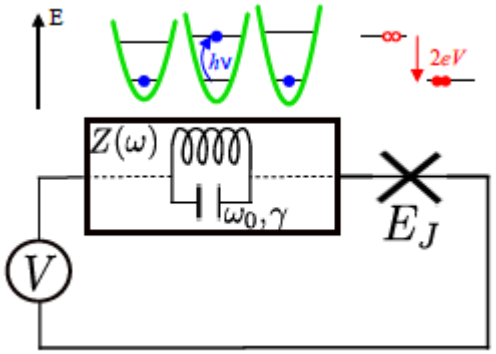


Summary

- Quantum optics of coherent conductors
- JJ-cavity devices: Weak to strong coupling
- Tailored photon sources
- Full counting statistics of photons and charges



Quantum dynamics



$$H = H_{\rm res} + H_J \quad @ \quad V = V_J + V_{\rm res}$$
$$\omega_J = \dot{\varphi} - \dot{\phi}$$

Fundamental resonance (1-photon resonance) $\omega_J \approx \omega_0$

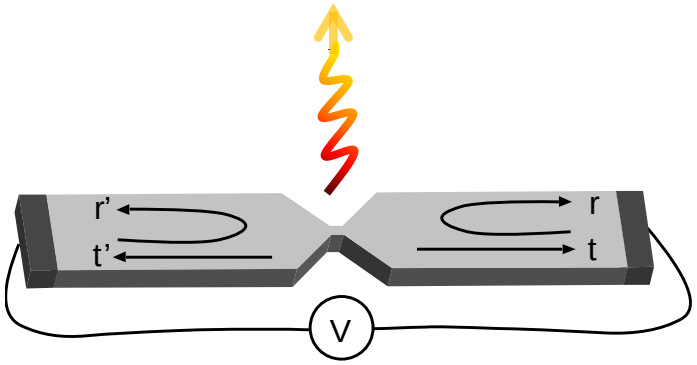
$$H^{(1)}_{\rm RWA} = \hbar\Delta\, a^\dagger a + i\frac{E_J^*}{2} : \left(a^\dagger\, {\rm e}^{i\eta} - a\, {\rm e}^{-i\eta}\right) \frac{J_1(2\sqrt{\alpha\, a^\dagger a})}{\sqrt{a^\dagger a}} :$$

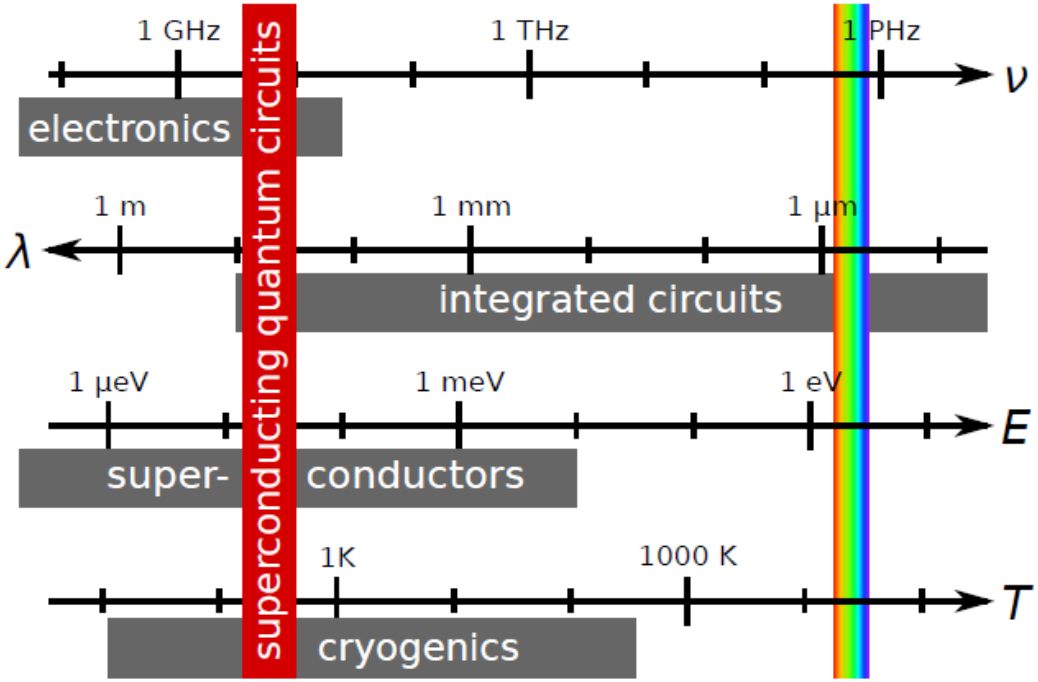
$$\Delta = \omega_0 - \omega_J$$
$$E_J^* = E_J\, {\rm e}^{-\alpha/2}$$

+ cavity damping and local voltage noise

Gramich, Kubala, JA et al, PRL 111, 247002 (`13)

Superconducting devices





No loss channel

High conversion rate

Highly tunable

Weak to strong coupling

Non-classical light sources

nature physics
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Antibunching of microwave-frequency photons observed in correlation measurements using linear detectors

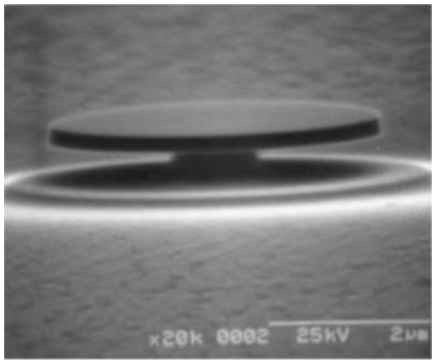
D. Bozyigit[1], C. Lang[1], L. Steffen[1], J. M. Fink[1], C. Eichler[1], M. Baur[1], R. Bianchetti[1], P. J. Leek[1], S. Filipp[1], M. P. da Silva[2], A. Blais[2] and A. Wallraff[1]*

Nature Phys 7, 154 (2011)

Science 290, 2282 (2000)

A Quantum Dot Single-Photon Turnstile Device

P. Michler,[1]* A. Kiraz,[1] C. Becher,[1] W. V. Schoenfeld,[2] P. M. Petroff,[1,2] Lidong Zhang,[1] E. Hu,[1,2] A. Imamoğlu[1,3,4]†



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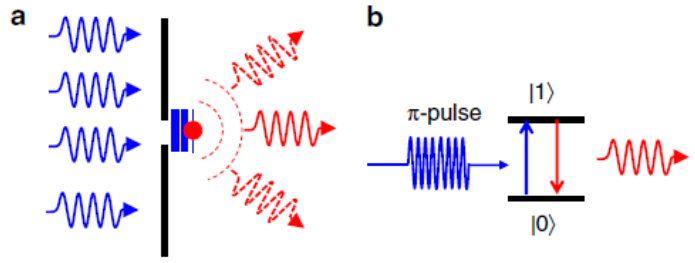
DOI: 10.1038/ncomms12588 OPEN

Tuneable on-demand single-photon source in the microwave range

Z.H. Peng[1,2], S.E. de Graaf[3], J.S. Tsai[2,4] & O.V. Astafiev[1,3,5]



- Quantum communication
- Quantum computing
- Quantum sensing