IQST Integrated Quantum Science and Technology

ulm university universität ulm

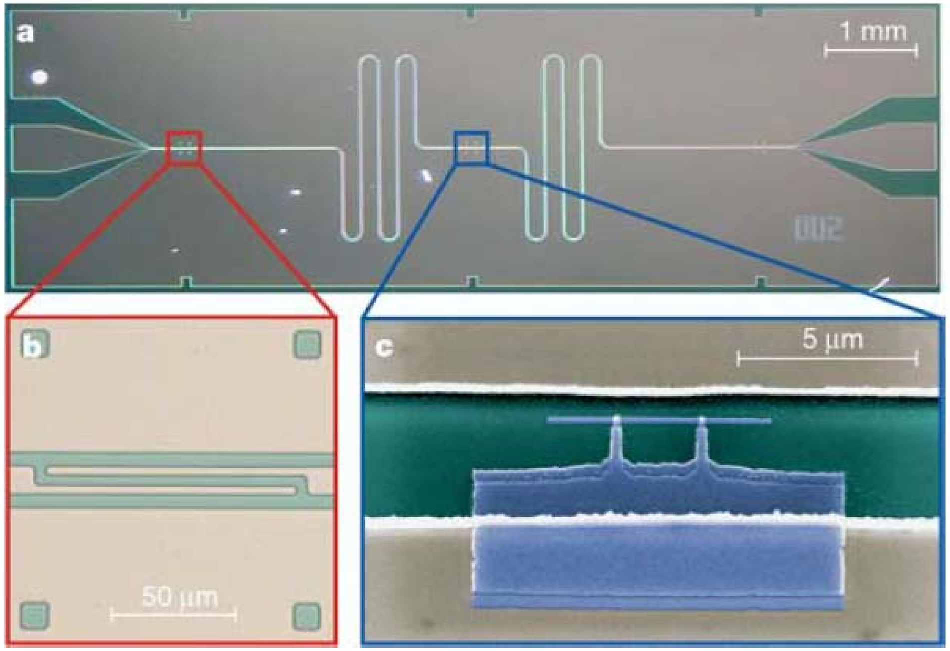
Superconducting Circuits as Testbeds for Quantum Optics and Atomic Physics

Joachim Ankerhold
Institute for Complex Quantum Systems & IQST
Ulm University, Germany

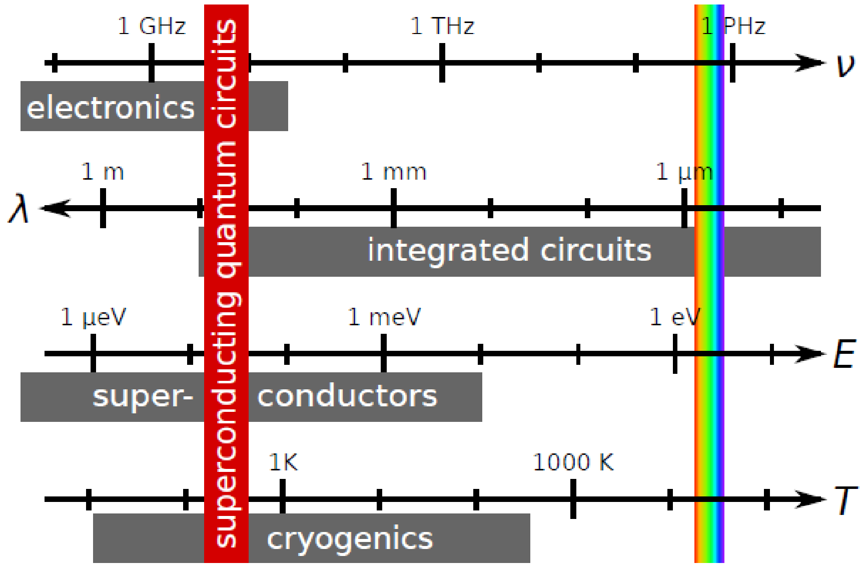
S. Dambach, V. Gramich, B. Kubala (Ulm)
F. Portier, D. Esteve (Saclay)
A. Armour (Nottingham)
M. Dykman (Michigan)
M. Hofheinz (Grenoble)
A. Rimberg, M. Blencowe (Dartmouth)
C. Ast, K. Kern (Stuttgart)

ECT* 01-10-19

Circuit QED – quantum optics/atomic physics on macro scales



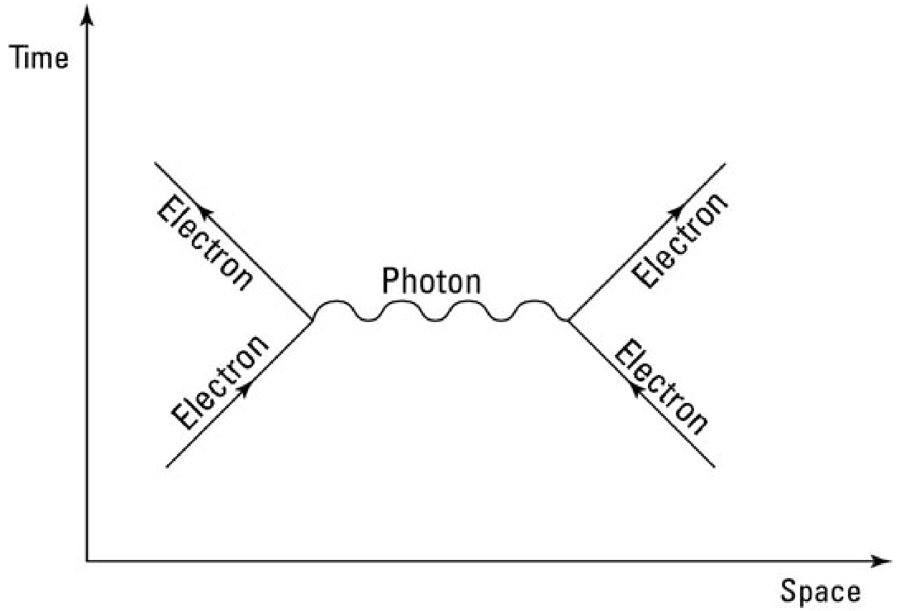
Schoelkopf et al, Nature 431, 162 (04)



Quantum Electrodynamics (QED)

Dirac

Bethe
Schwinger
Feynman
Lamb
……



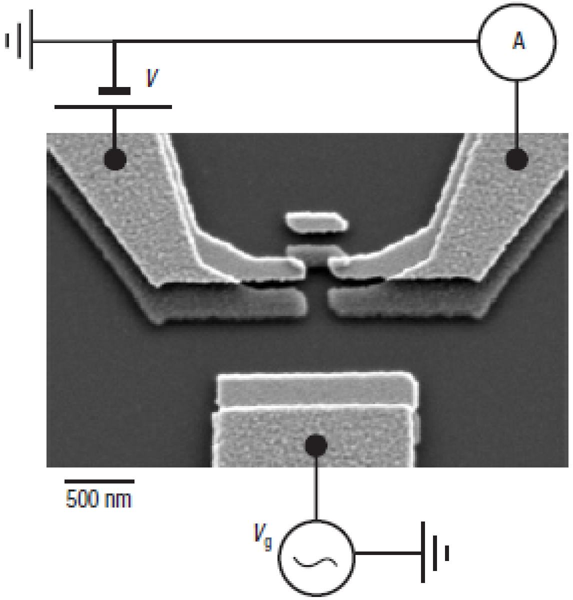
Fine structure constant $$\alpha_{\rm QED} = \frac{e^2}{4\pi\epsilon_0\,\hbar c} \approx \frac{1}{137}$$

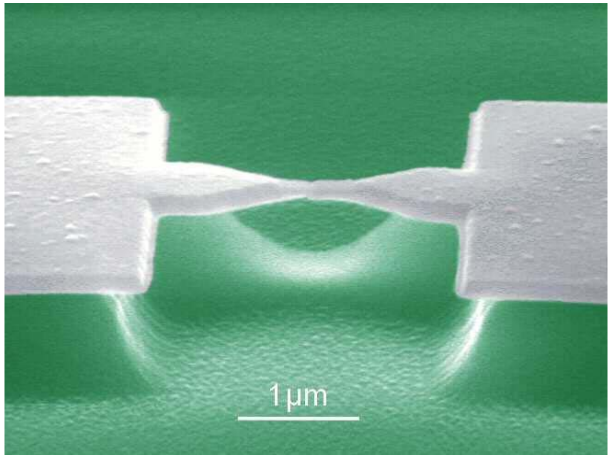
$$= \frac{Z_0}{2R_K}$$

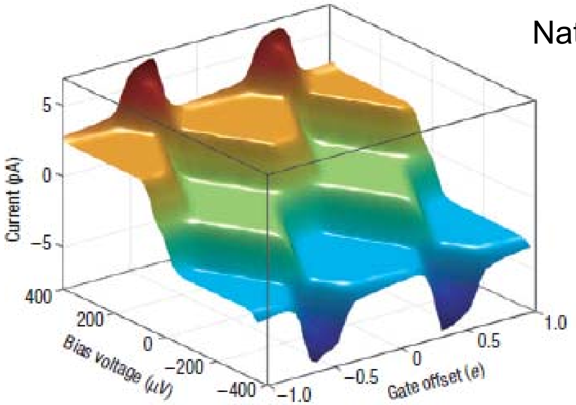
$$Z_0 = \mu_0 c\ ,\ \ R_K = \frac{h}{e^2}$$

Quantum electronics

Controlled transfer of single charge quanta (Coulomb blockade)







Nature Physics 4, 120 (2008)

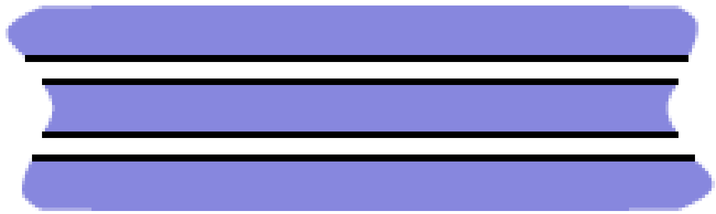
$$I = n\,e\,f$$

Nature 394, 154 (1998)
Science 349, 1199 (2015)

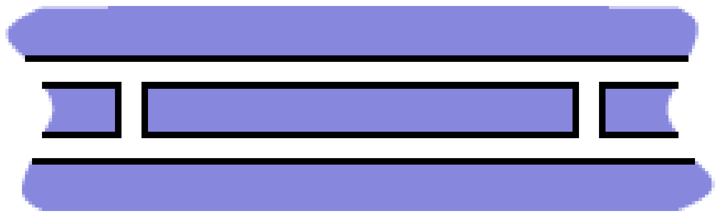
$$G_0 = \frac{e^2}{h}$$

Quantum circuits

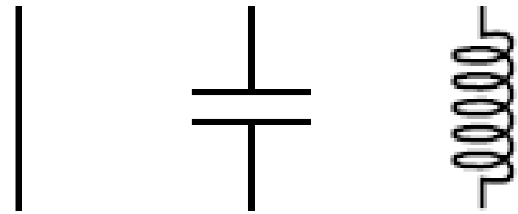
- Transmission lines



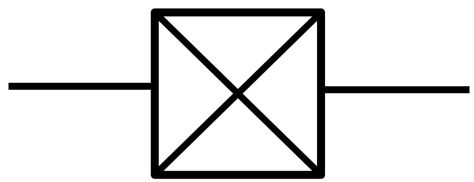
- Resonators



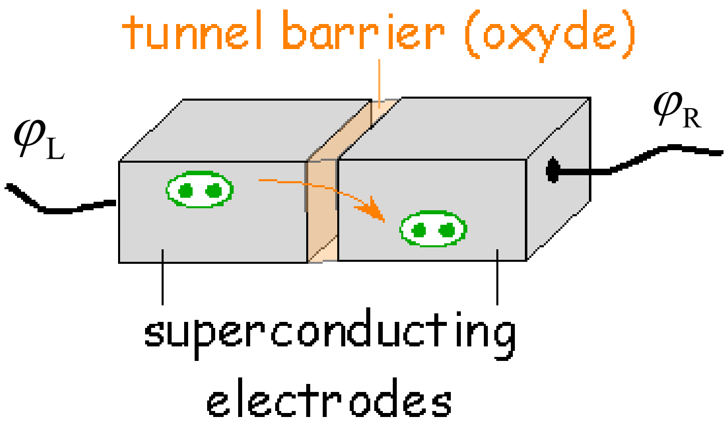
- Linear elements



- Nonlinear element: Josephson junction



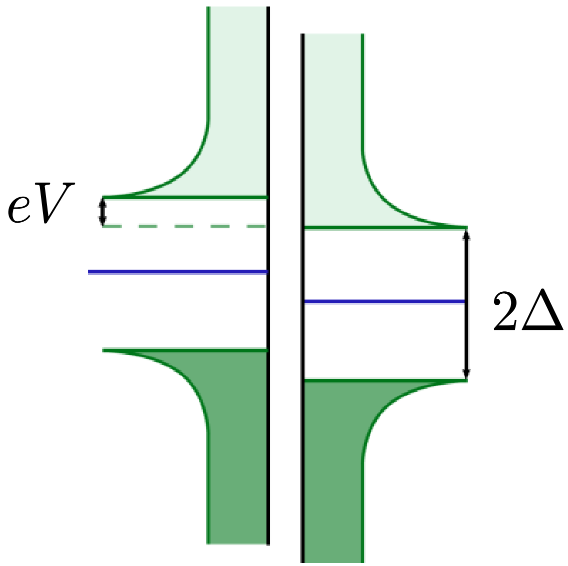
Josephson junction

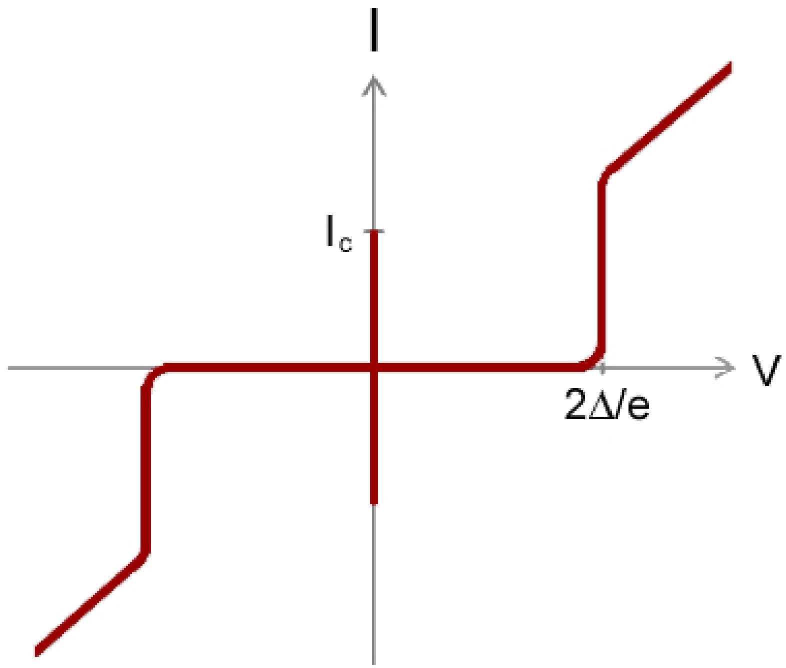


$$I_J = I_c \sin(\varphi)\ , \quad \varphi = \varphi_L - \varphi_R$$

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

(ac-Josephson)



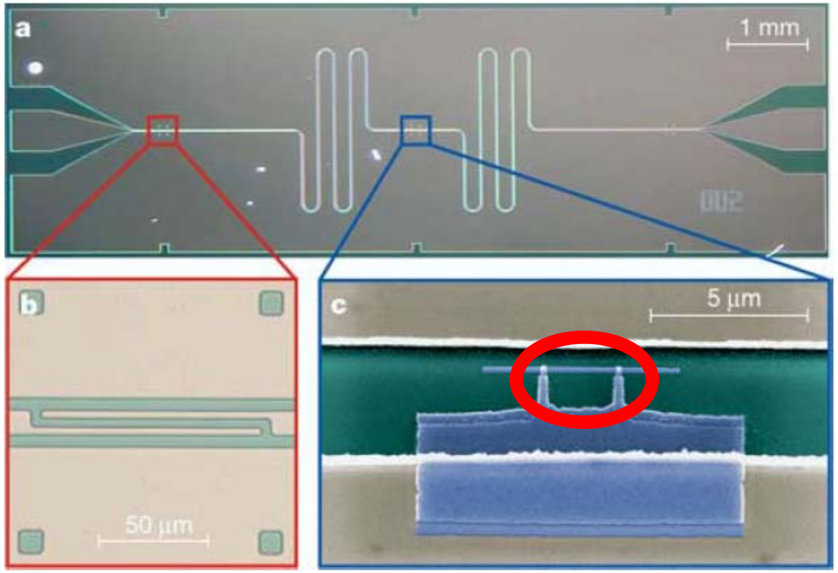


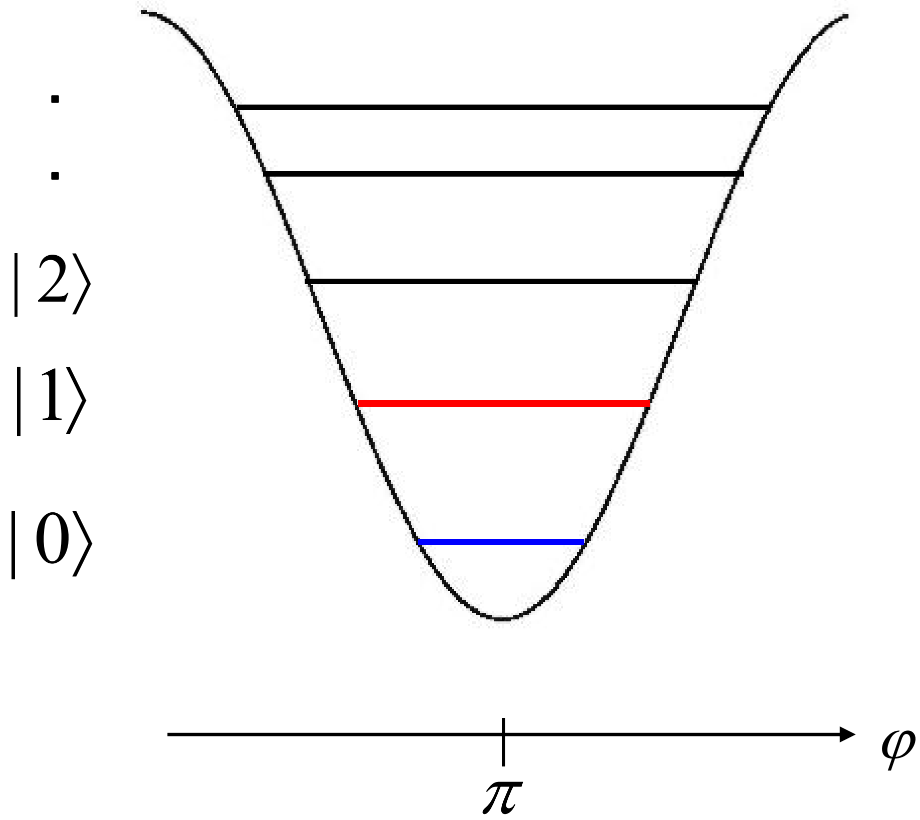
Josephson atom

Superconducting circuit:

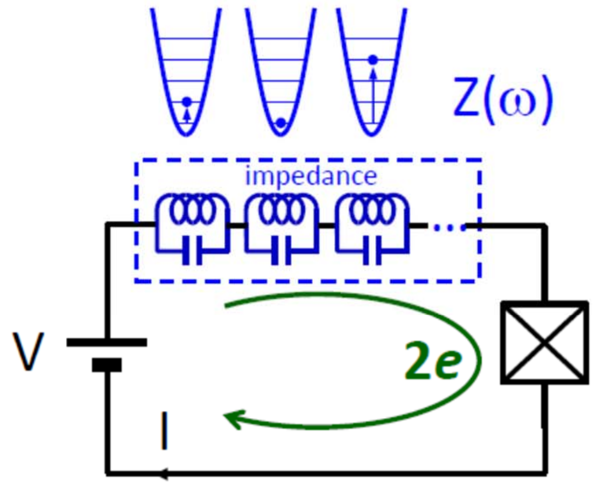
Decoupled from excitations

$$H_J = -E_J \cos(\varphi) \qquad E_J = I_c \frac{\hbar}{2e}$$





Quantum: embedded in circuit



Phase is a collective dof, embedded in electromagnetic environment

$$H = H_J + H_Z + H_{\text{int}}$$

$$V = 0: \quad H = E_C N^2 - E_J \cos(\varphi) + \sum_n \frac{4e^2 N_n^2}{2C_n} + \frac{\hbar^2}{4e^2} \frac{(\varphi_n - \varphi)^2}{2L_n}$$

$$E_C = \frac{2e^2}{C}$$

$$[N, \varphi] = -i \; , \; [N_n, \varphi_n] = -i$$

Number of transmitted Cooper pairs

$$H_J = \frac{E_J}{2} \left(\overrightarrow{T}_{2e} + \overleftarrow{T}_{2e} \right)$$

Quasi-continuum of modes:
open quantum system

Linear impedances (Gaussian fluctuations) characterized by $Z(\omega)$

Non-Markovian (memory),
weak to strong coupling

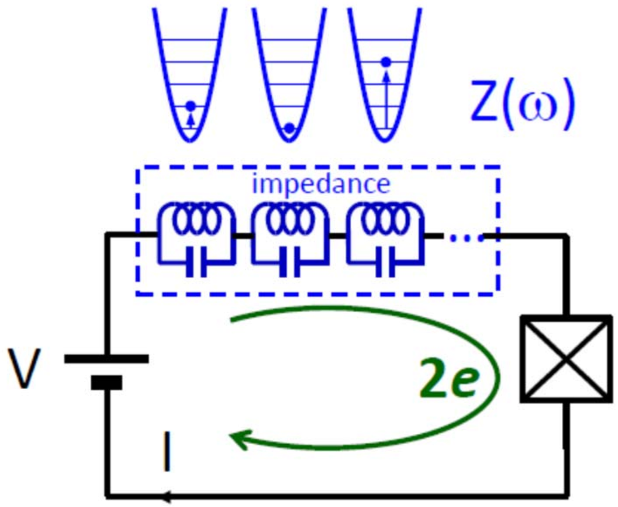
Low transmitting junction

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

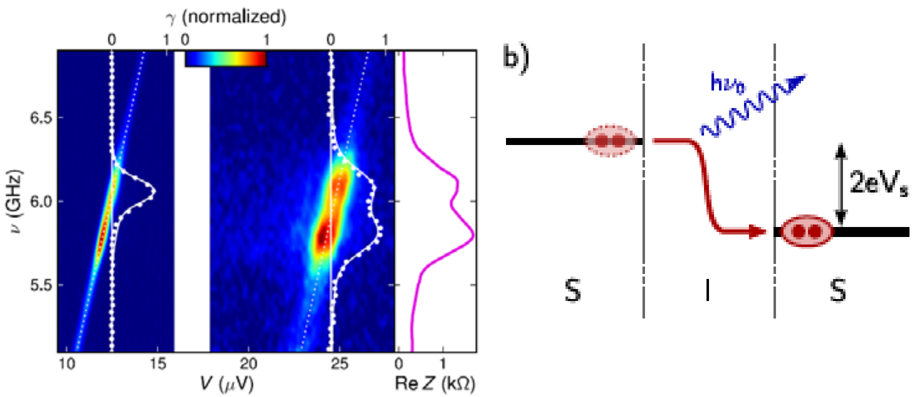
Fermi‘s golden rule (sequential charge transfer)

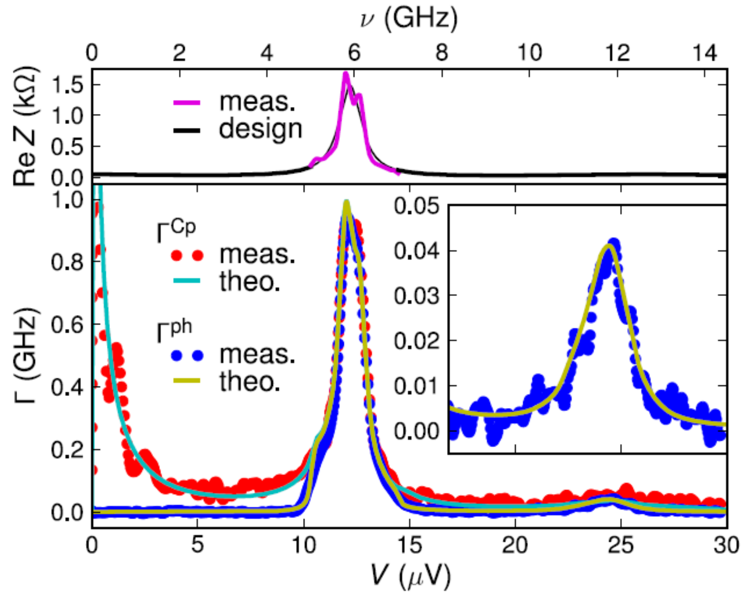
$$I_J = \frac{\pi e E_J^2}{\hbar} P(2eV) \quad , \quad T = 0$$

Probability of the environment
to absorb energy: phase-phase correlation



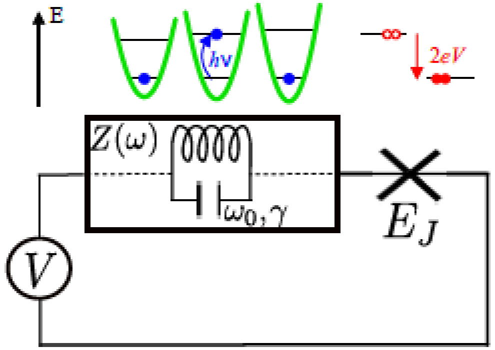
Limit: Single mode environment





Hofheinz et al, PRL 106, 217005 (2011)

Beyond low transmission: Josephson photonics



$$\omega_J = \frac{2eV}{\hbar}$$

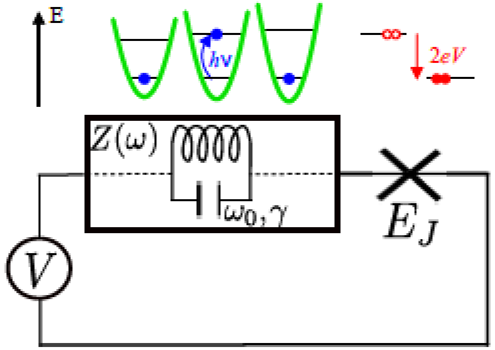
$$H = \hbar\omega_0\left(a^\dagger a + \frac{1}{2}\right) - E_J\cos(\varphi)$$

$$\varphi = \omega_J t + \sqrt{\alpha}(a^\dagger + a)$$

Effective fine structure constant $\alpha = \frac{Z_{LC}}{2R_K}$

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

Josephson photonics



p-photon resonance $\quad \omega_J \approx p\,\omega_0$

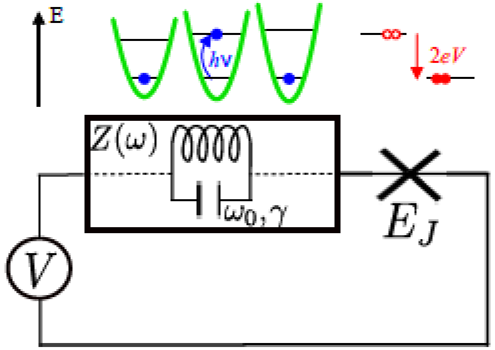
$$H^{(p)}_{\mathrm{RWA}} = \hbar\Delta\, a^\dagger a - (-i)^p \frac{E_J^*}{2} : \left[(a^\dagger)^p + (-1)^p a^p\right] \frac{J_p(2\sqrt{\alpha\, a^\dagger a})}{(a^\dagger a)^{p/2}} :$$

$$\alpha = \frac{Z_{LC}}{2R_K} \; (\approx\; 0.07 \ldots 1.5 \ldots) \qquad Z_{LC} = \sqrt{\frac{L}{C}}$$

Renormalized JJ-coupling $\quad E_J^* = E_J\, \mathrm{e}^{-\alpha/2}$

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

Josephson photonics



p-photon resonance $\omega_J \approx p\,\omega_0$

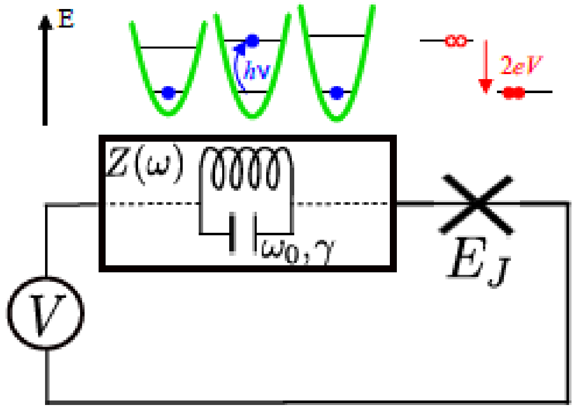
$$H^{(p)}_{\mathrm{RWA}} = \hbar\Delta\, a^\dagger a - (-i)^p \frac{E_J^*}{2} : \left[(a^\dagger)^p + (-1)^p a^p\right] \frac{J_p(2\sqrt{\alpha\, a^\dagger a})}{(a^\dagger a)^{p/2}} :$$

+ cavity damping (+ low frequency voltage noise)

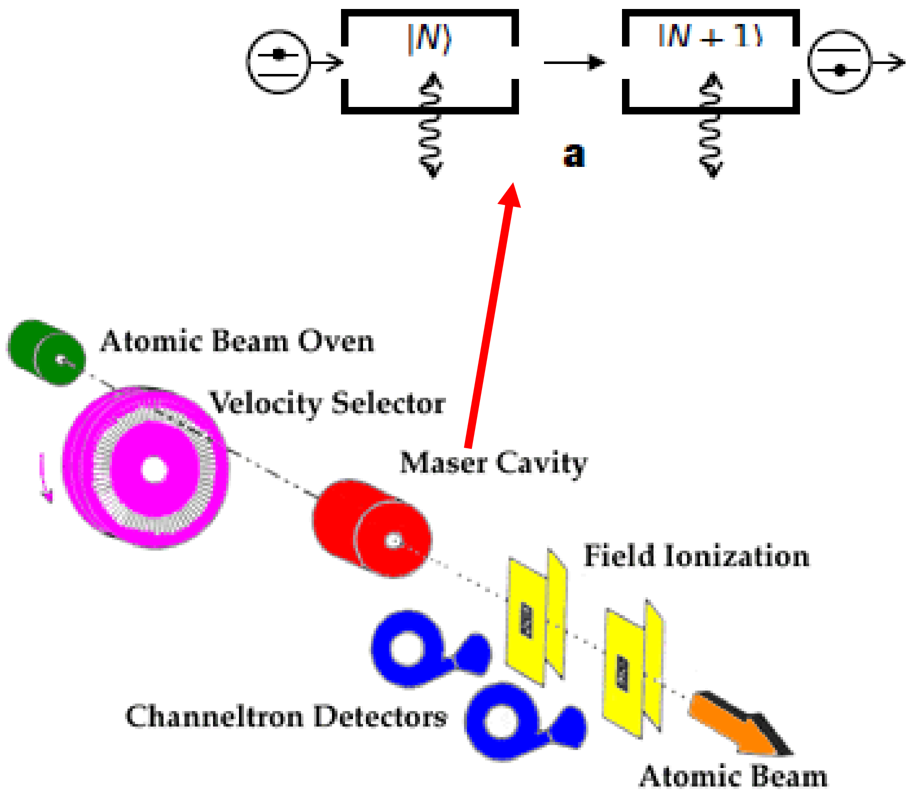
$$\dot\rho = \frac{1}{i\hbar}[H^{(p)}_{\mathrm{RWA}}, \rho] + \gamma\, \mathcal{L}_{\mathrm{res}}[\rho]$$

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

Josephson + cavity – micromaser (single atom maser)



$$\dot{\rho} = \frac{1}{i\hbar}[H^{(p)}_{\mathrm{RWA}}, \rho] + \gamma\, \mathcal{L}_{\mathrm{res}}[\rho]$$



$$\dot{\rho} = \mathcal{L}_{\mathrm{atom-field}}[\rho] + \gamma \mathcal{L}_{\mathrm{res}}[\rho]$$

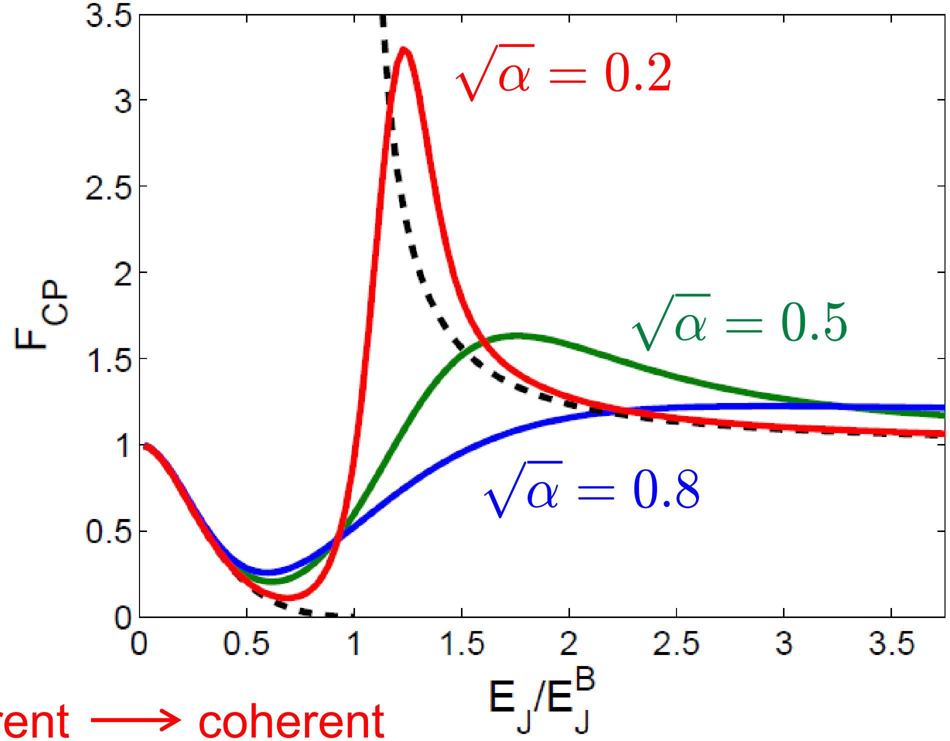
Dambach et al, Phys. Src. 94, 104001 (`19)

J. McKeever et al, Nature 425, 268 (2003)

Sequential to coherent charge flow: current noise

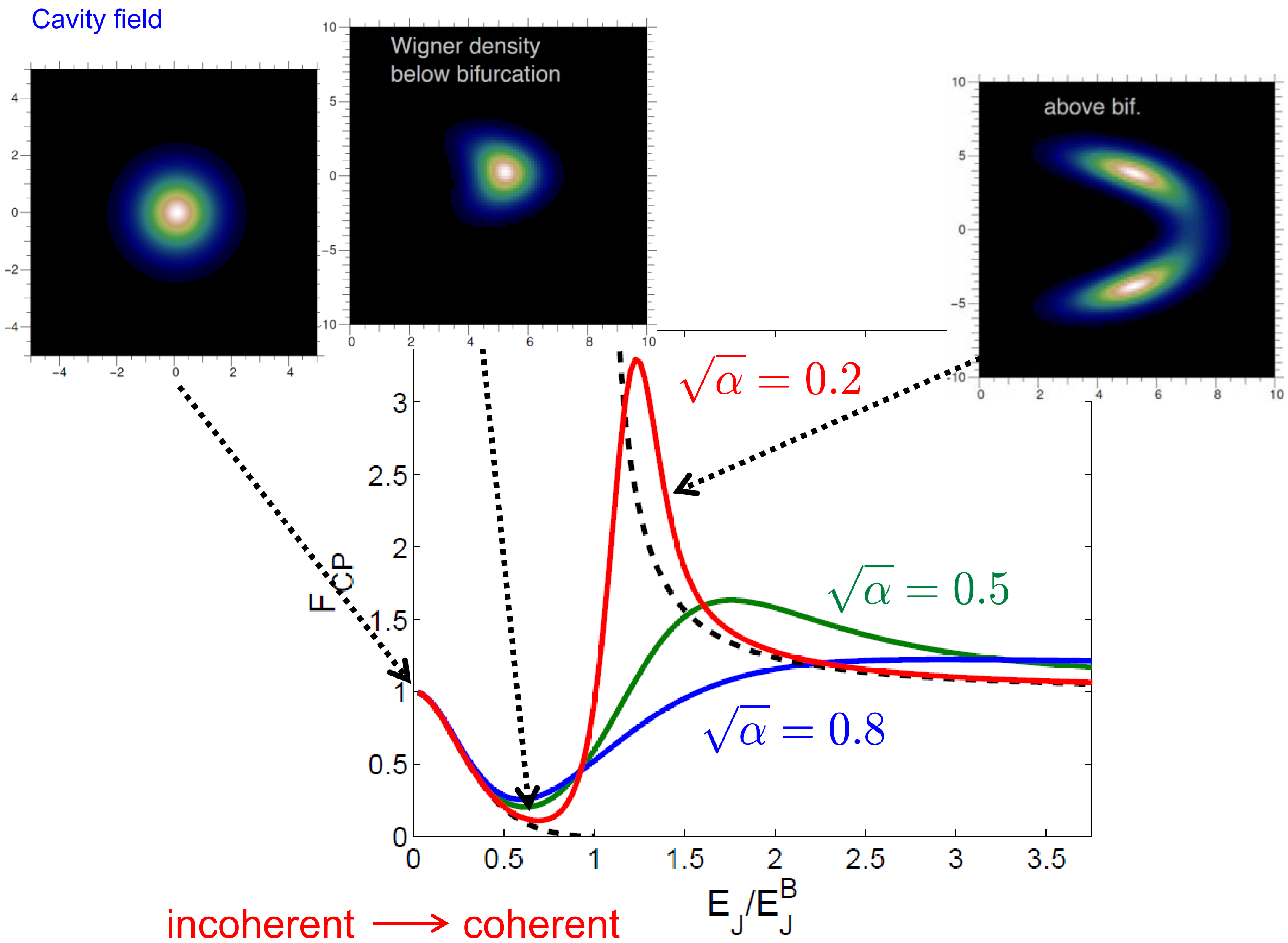
$$\delta I_{CP} = I_{CP} - \langle I_{CP} \rangle$$

Fano factor $$F_{CP} = \frac{1}{2eI_{CP}} \int d\tau \langle \delta I_{CP}(t+\tau)\delta I_{CP}(t) \rangle_{\mathrm{st}}$$



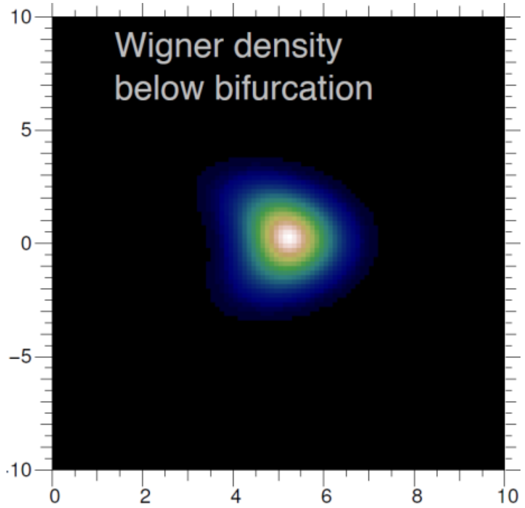
incoherent ⟶ coherent

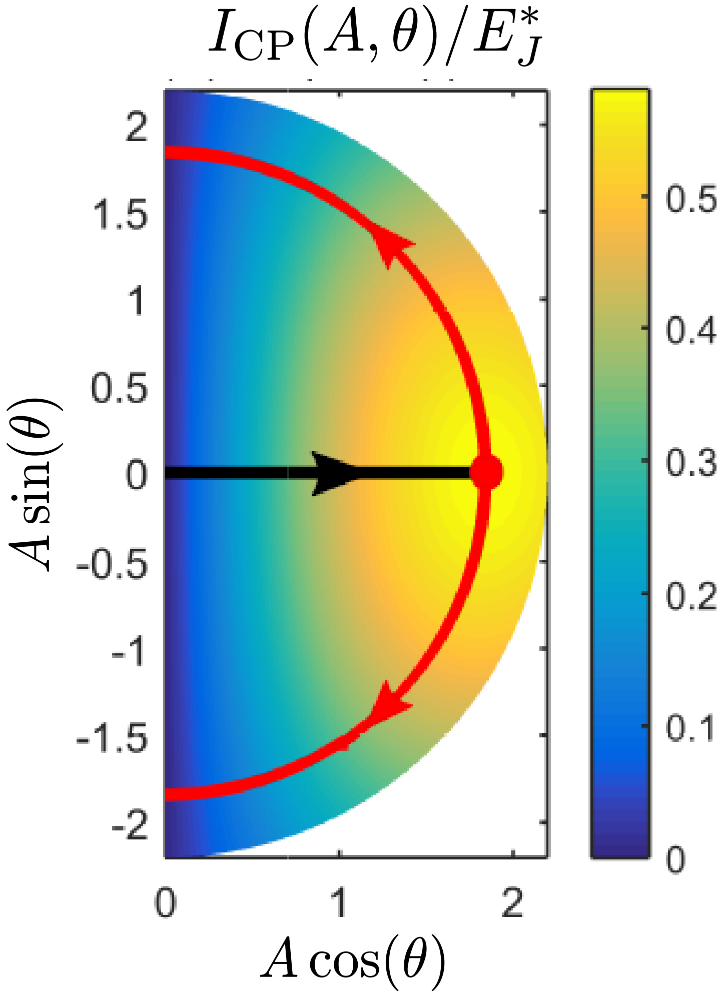
„Phase transition“-like behavior

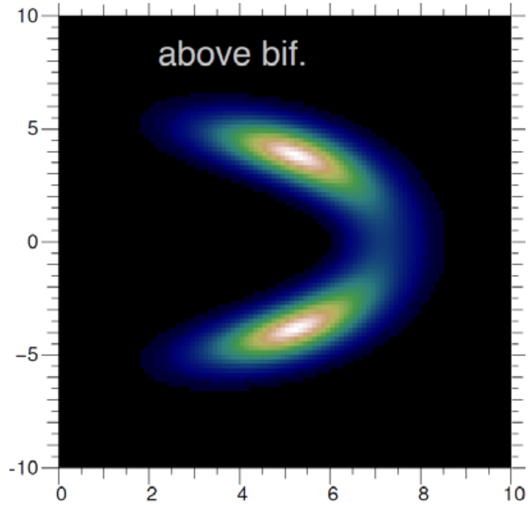


Semiclassics: critical behavior

$$\langle a \rangle = A\,e^{i\theta}$$







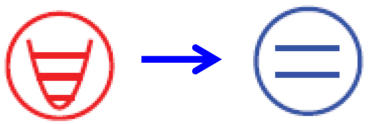
From phase locking to amplitude locking

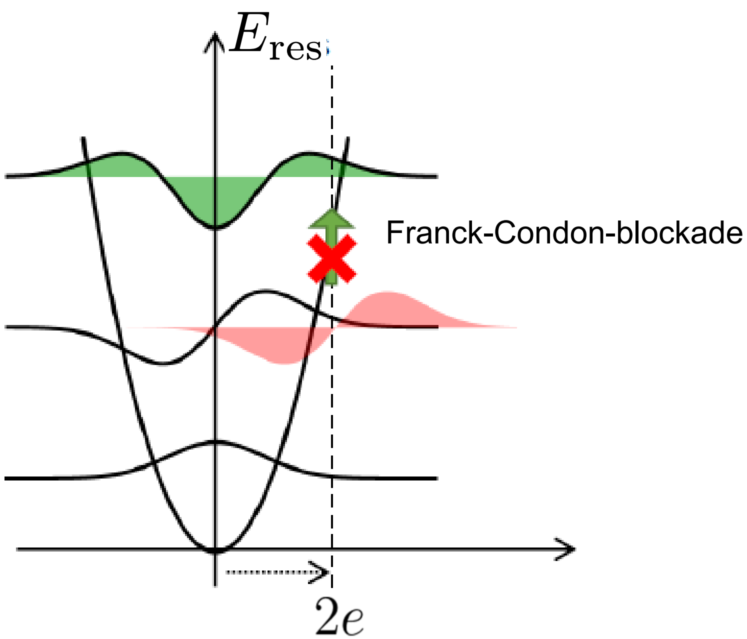
Towards single photon sources for microwaves

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

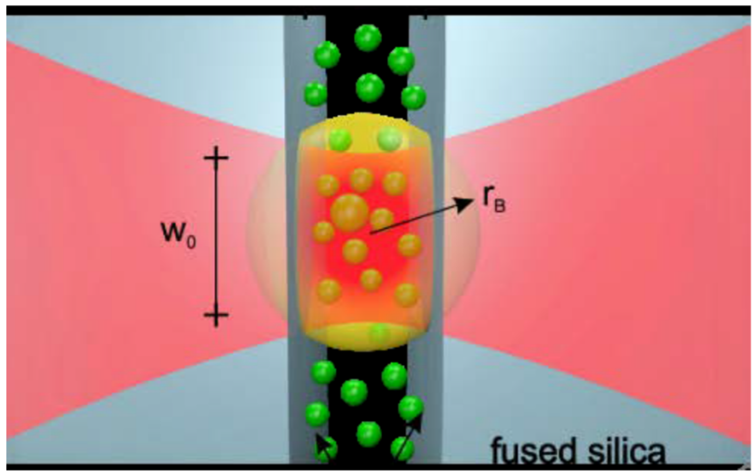
$$g^{(2)}(\tau) = \frac{\langle a^\dagger(\tau) a^\dagger a\, a(\tau)\rangle_{\rm st}}{\langle n\rangle_{\rm st}^2}$$

$$T_{12}(\alpha = 2) = \langle 2 | H^{(1)}_{\rm RWA} | 1 \rangle = 0$$





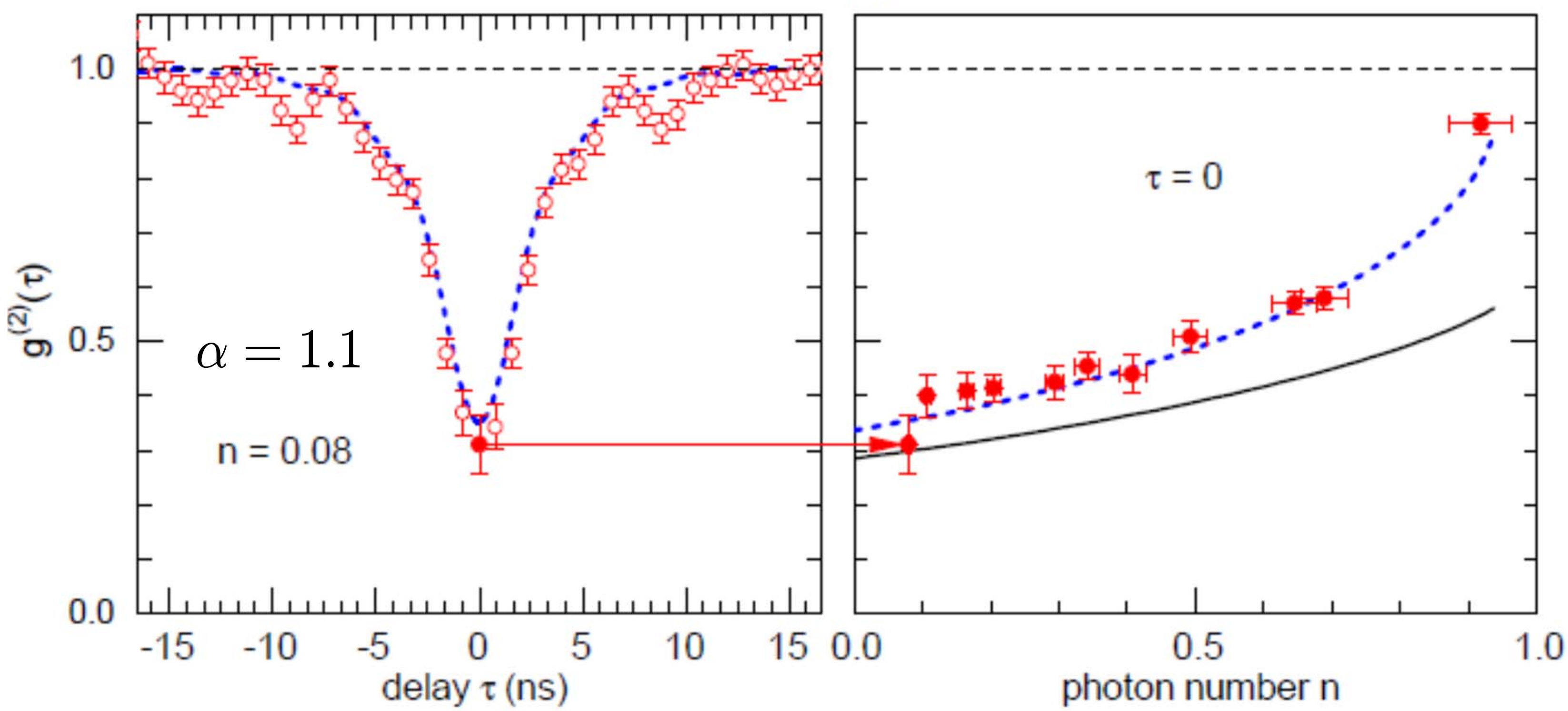
Atom physics: Rydberg blockade

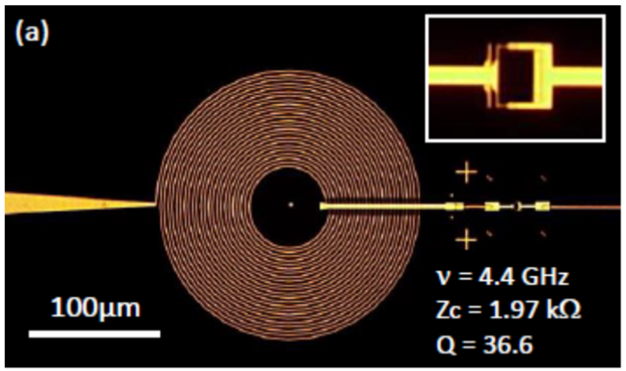


Gramich et al, PRL 113, 027001 (`14)
Dambach et al, PRB 92, 054508 ('15)

Ripka et al, Science 362, 446 (2018)

Ultra-large coupling regime: single photon sources

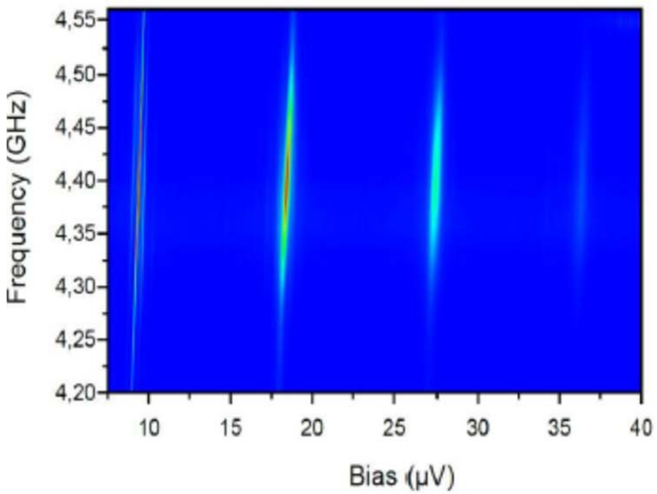


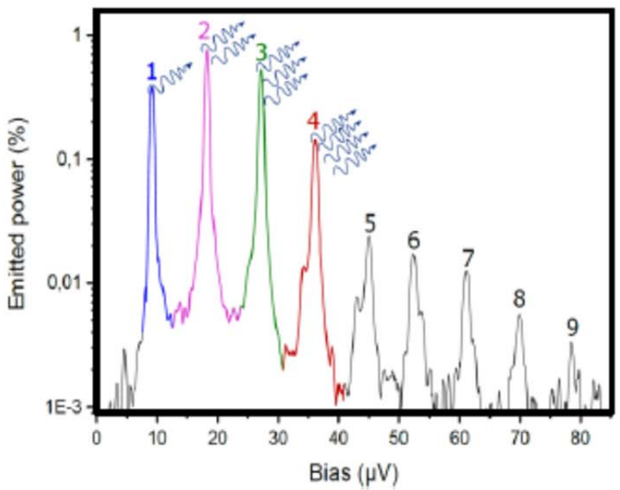


$\sim 10^8$ photons/s

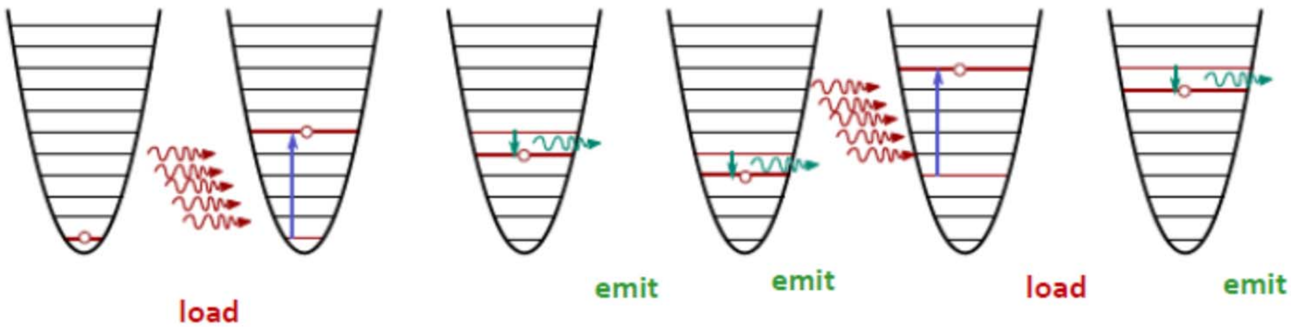
Saclay-Ulm, PRL 122, 186804 (`19)

Large coupling regime: multi-photon events



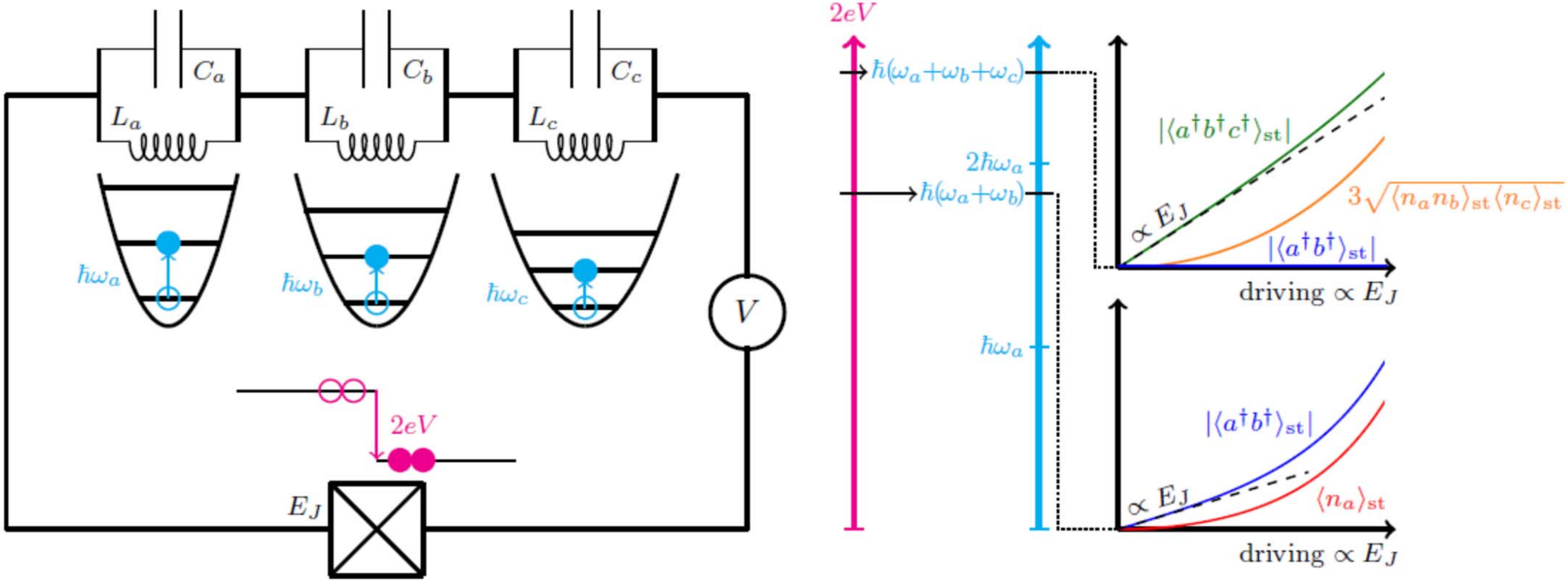


Out of equilibrium tunneling



Saclay-Ulm, in preparation

Multi-photon entanglement



$$H_N = \frac{E_J^*}{2} : \left(\prod_{k=1}^{N} a_k^\dagger + \prod_{k=1}^{N} a_k \right) \prod_{k=1}^{N} \frac{J_1(\sqrt{\alpha a_k^\dagger a})}{\sqrt{a_k^\dagger a_k}} :$$

Dambach et al, NJP 19, 023027 (2017)

Classical: Collective modes

REPORT

OPTOELECTRONICS

Kouwenhoven et al, Science 355, 939 (`17)

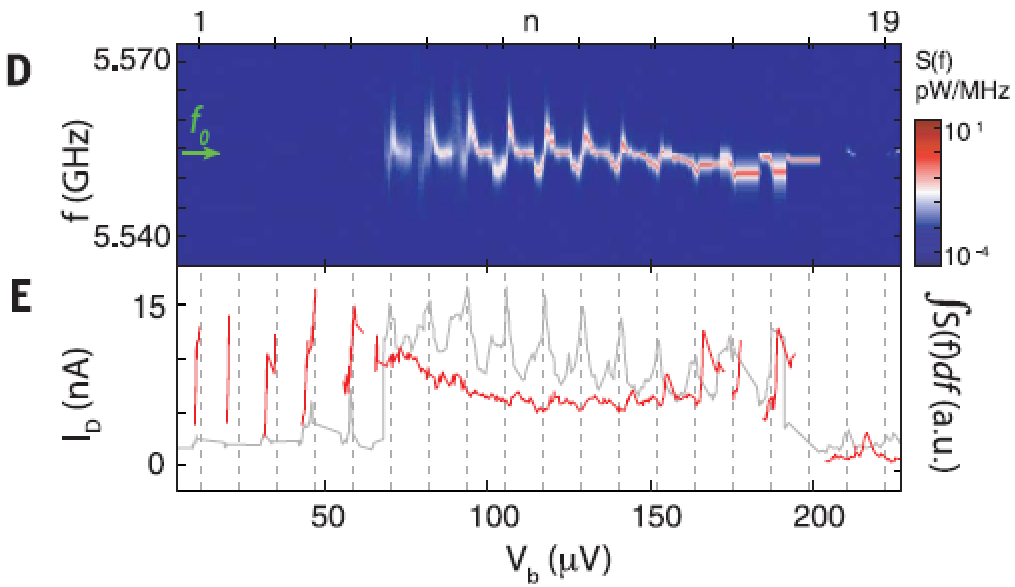
Demonstration of an ac Josephson junction laser

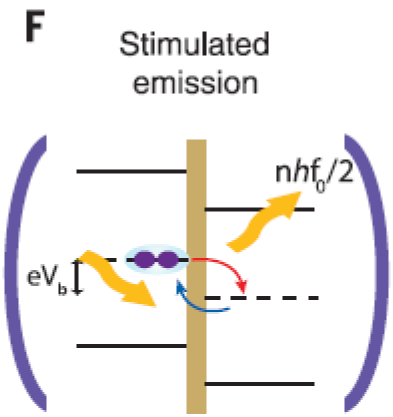
M. C. Cassidy,[1] A. Bruno,[1] S. Rubbert,[2] M. Irfan,[2] J. Kammhuber,[1] R. N. Schouten,[1,2] A. R. Akhmerov,[2] L. P. Kouwenhoven[1,2*]

Collective exitations

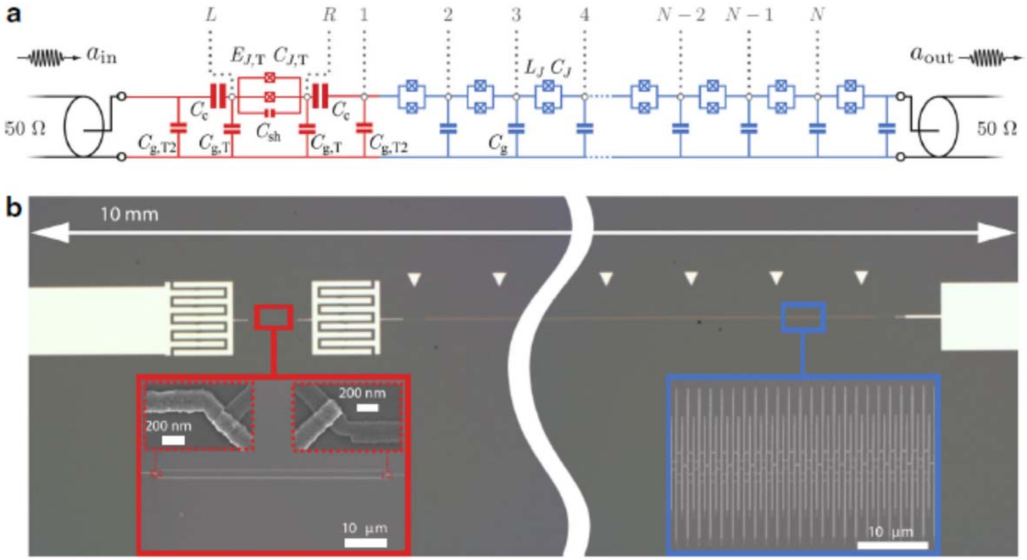
$$\psi = \sum_n a_n \varphi_n$$

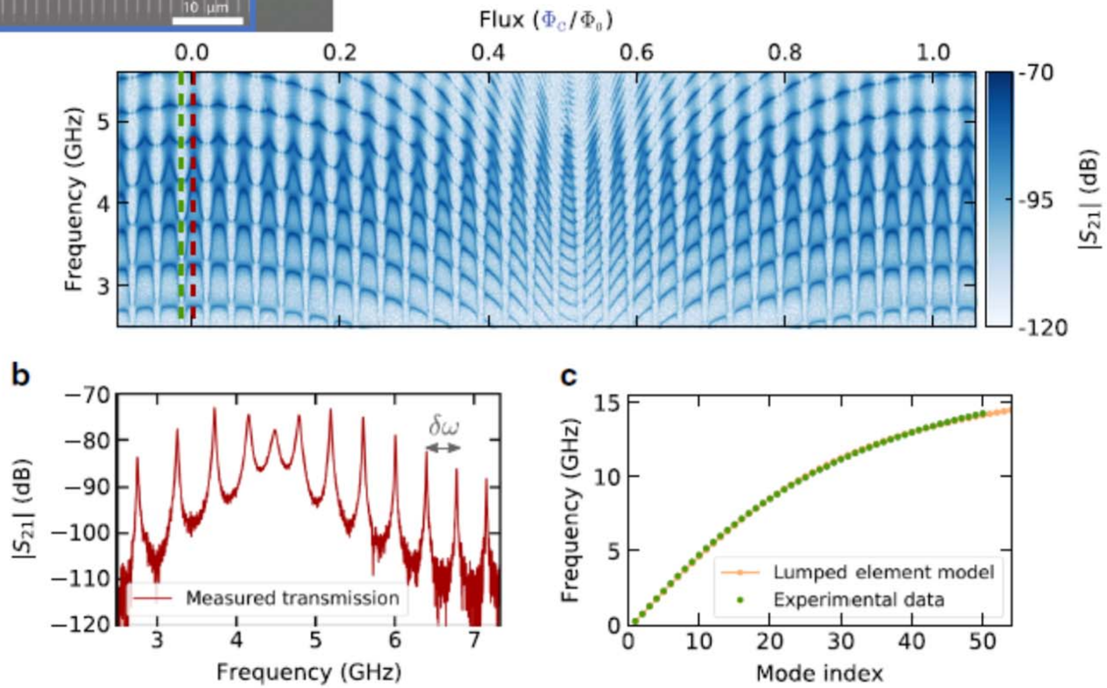
Classical: Simon et al, PRL 121, 027004 (`18)





Tunable N-mode environment

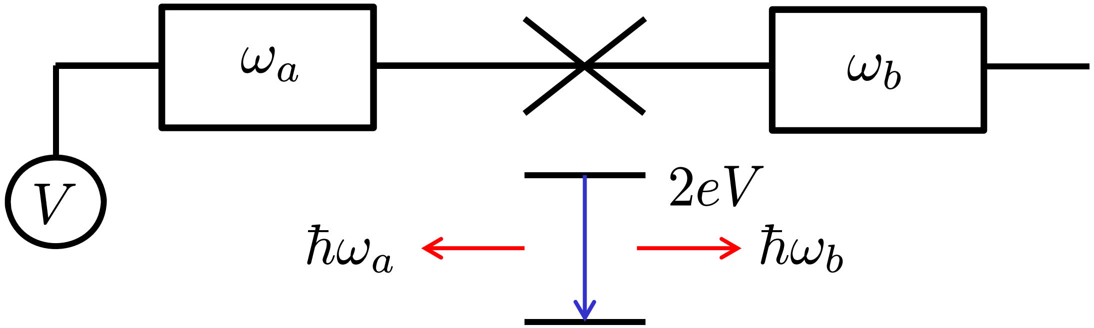




Martinez et al, npj QI 5, 19 (`19)

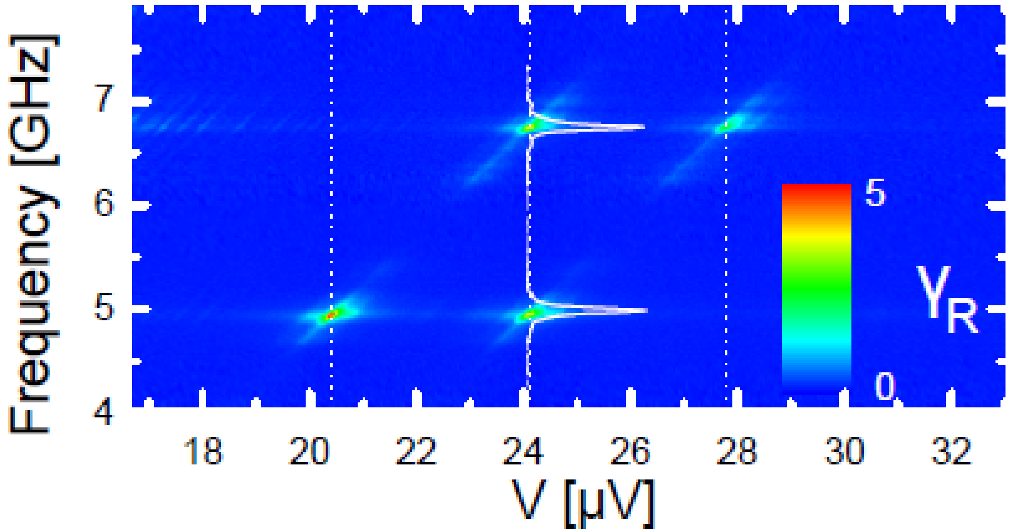
Towards entangled photon sources

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



Non-classical light:

$$g_{ab}^{(2)}(0) \not\leq \sqrt{g_{aa}^{(2)}(0)\, g_{bb}^{(2)}(0)}$$



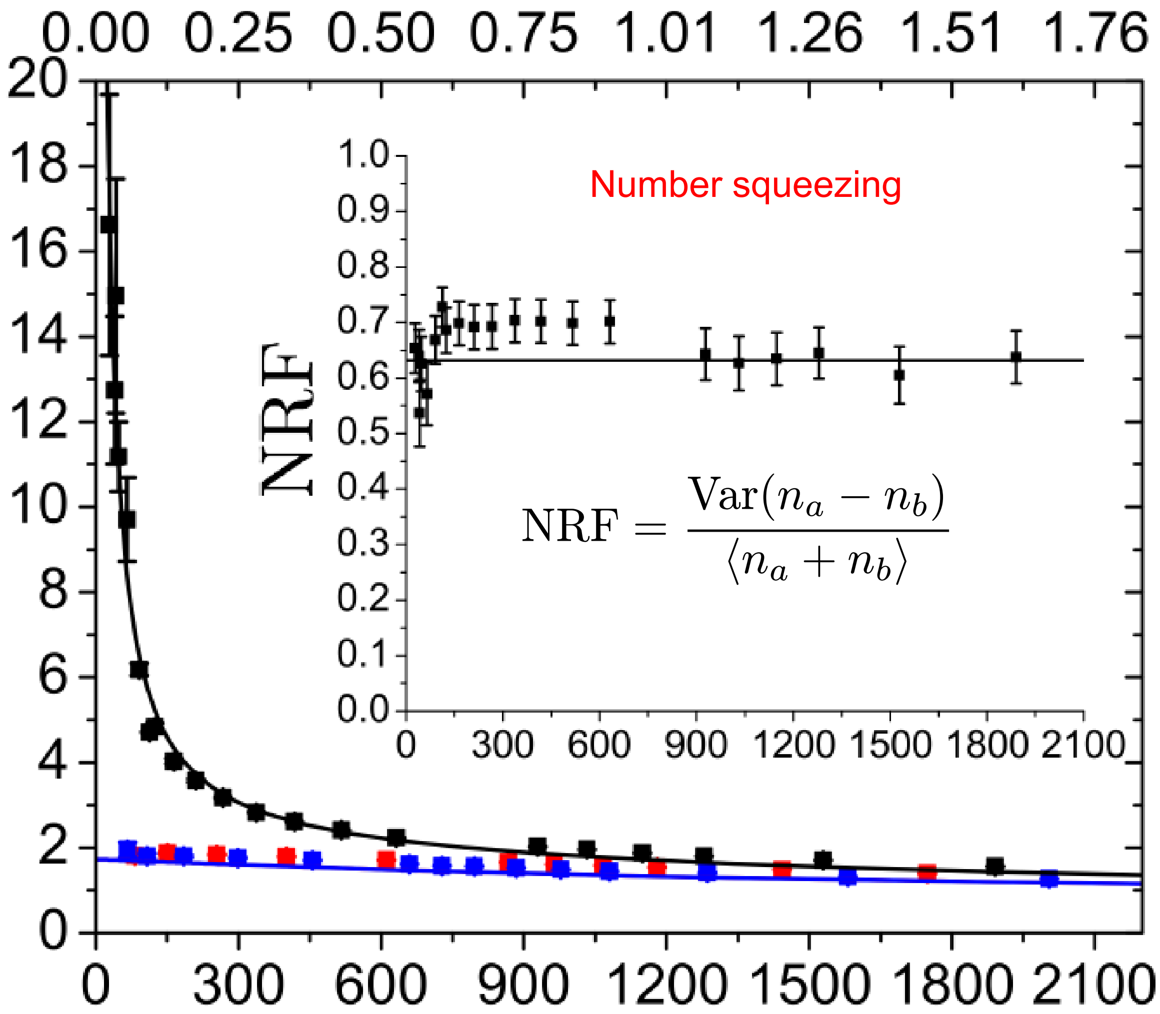
Saclay-Ulm, PRL 119, 137001 (2017)

Leppäkangas et al, NJP 2014
Armour, Kubala, JA, PRB (2015)

Two cavities: correlated photons

- $g_{ab}^{(2)}(0)$
- $g_{aa}^{(2)}(0)$
- $g_{bb}^{(2)}(0)$

$$g_{ab}^{(2)}(0) \not\leq \sqrt{g_{aa}^{(2)}(0)\, g_{bb}^{(2)}(0)}$$

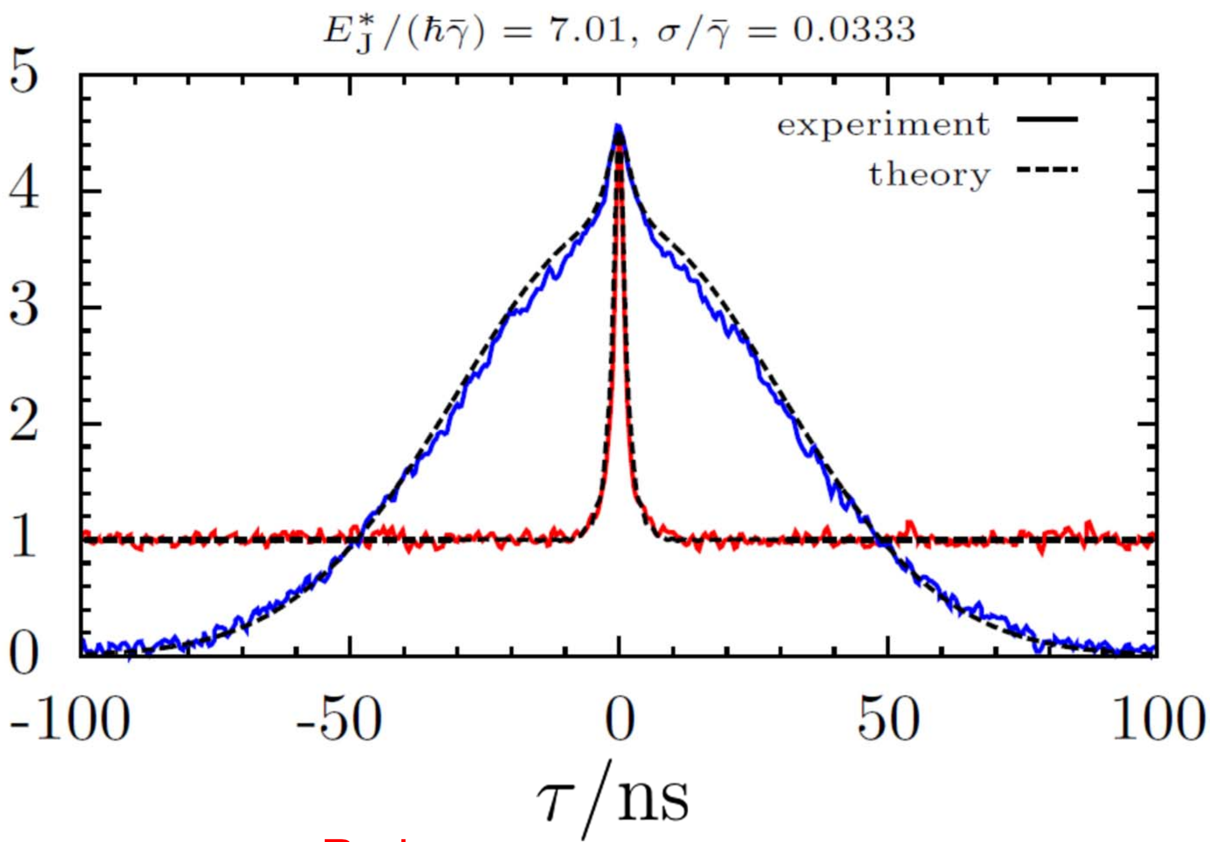


Saclay-Ulm, PRL 119, 137001 (2017)

Entangled photon pairs

Entanglement witness

$$g_\phi(\tau) > g_{ab}(\tau)$$



Blue

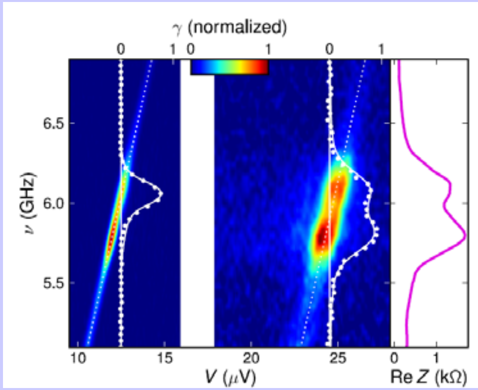
$$g_\phi(\tau) = \langle a^\dagger(\tau) b^\dagger(\tau) a(0) b(0) \rangle$$

Red

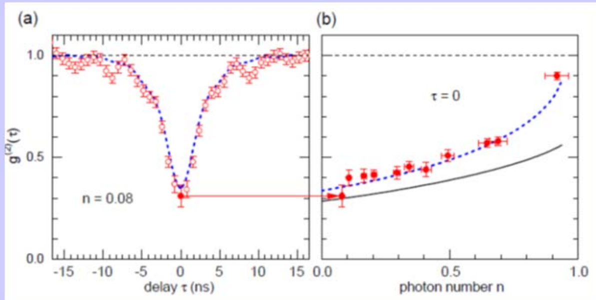
$$g_{ab}(\tau) = \langle b^\dagger(0) a^\dagger(\tau) a(\tau) b(0) \rangle$$

Wölk et al, PRA 90, 022315 (2014)
Saclay-Ulm, in preparation

Summary



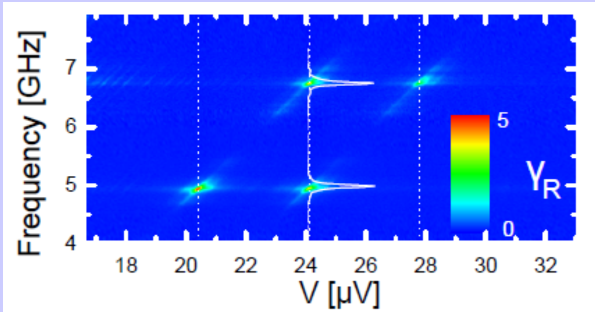
- Superconducting circuits as open quantum systems



- JJ-cavity devices: Weak to strong coupling

- Single to few-body quantum dynamics far from equilibrium

- Tailored light sources



DFG, ANR, BW-Foundation, EU