Exploring Quantum Properties of Propagating Microwaves with Superconducting Circuits

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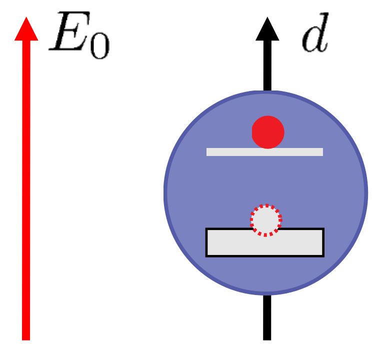
Collaborations:
A. Blais *(Sherbrooke, Canada)*
M. da Silva *(Raytheon, USA)*
K. Ensslin, F. Merkt, V. Wood *(ETH Zurich)*

SEVENTH FRAMEWORK PROGRAMME
(-)QED CIRCUIT AND CAVITY QUANTUM ELECTRODYNAMICS
SOLID
GEOMDISS
aqute
erc
QSIT Quantum Science and Technology
National Centre of Competence in Research
ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
FNSNF Swiss National Science Foundation

Controlling the Interaction of Photons and Qubits

challenging on the level of single particles



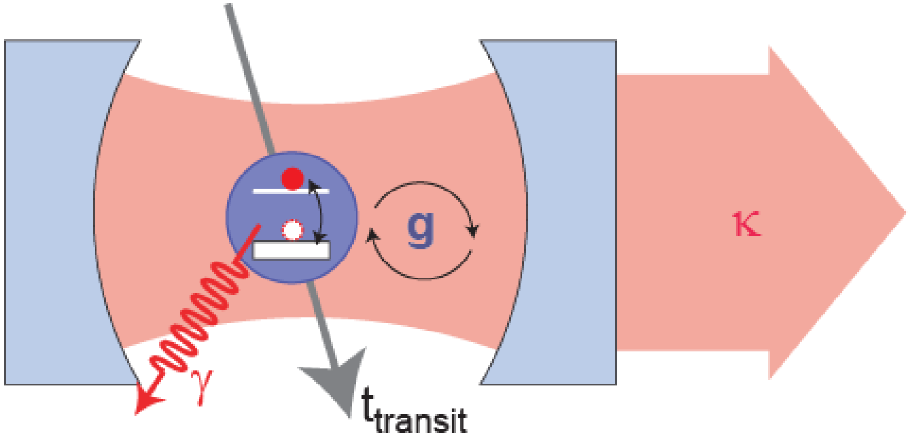
- dipole moment d in microscopic systems (usually small ~ ea_o)
- single photon fields E_o (small in 3D)
- photon/qubit interaction $\hbar g \sim dE_0$ (usually small)

What to do?

- confine qubit and photon in a cavity (cavity QED)
- engineer qubit/light interaction in solid state circuits

D. Walls, G. Milburn, Quantum Optics (Spinger-Verlag, Berlin, 1994)

Cavity QED with Superconducting Circuits

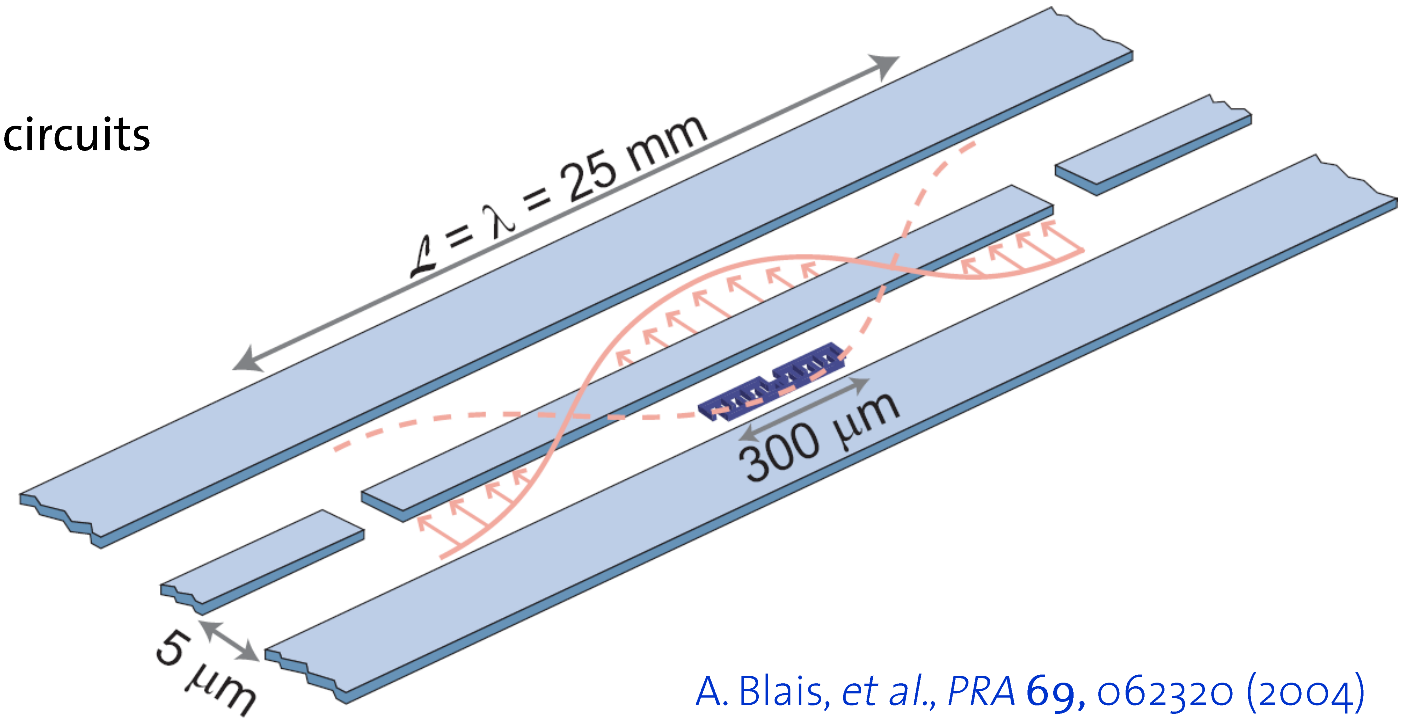


coherent interaction of photons with quantum two-level systems ...

J. M. Raimond *et al.*, *Rev. Mod. Phys.* **73**, 565 (2001)
S. Haroche & J. Raimond, *OUP Oxford* (2006)
J. Ye., H. J. Kimble, H. Katori, *Science* **320**, 1734 (2008)

... in superconducting circuits

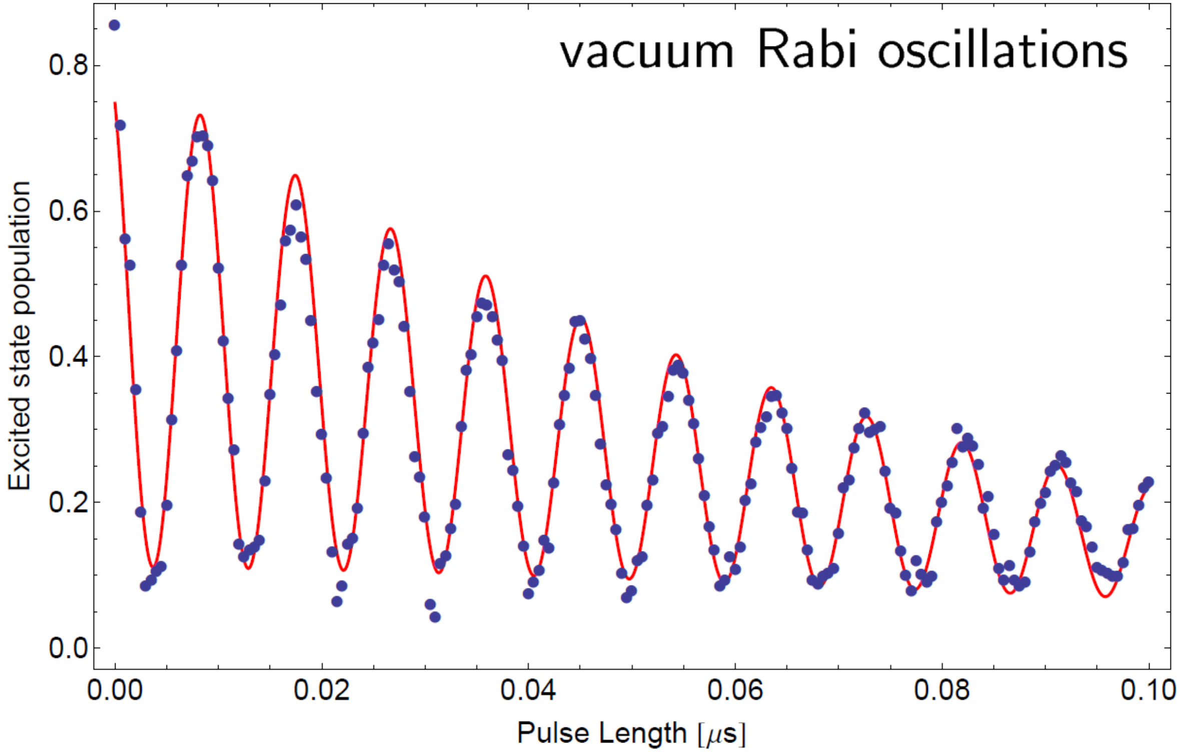
circuit quantum electrodynamics



A. Blais, *et al.*, *PRA* **69**, 062320 (2004)
A. Wallraff *et al.*, *Nature (London)* **431**, 162 (2004)
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* **451**, 664 (2008)

Resonant Vacuum Rabi Mode Splitting ...

... with one photon ($n = 1$):

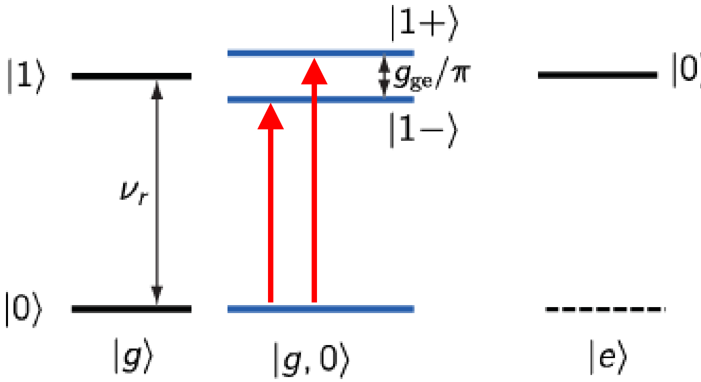


very strong coupling:

$$g_{ge}/\pi = 308\,\mathrm{MHz}$$

$$\kappa, \gamma < 1\ \mathrm{MHz}$$

$$g_{\mathrm{ge}} \gg \kappa, \gamma$$



forming a 'molecule' of a qubit and a photon

first demonstration in a solid: A. Wallraff *et al.*, *Nature (London)* **431**, 162 (2004)

this data: J. Fink et al., *Nature (London)* **454**, 315 (2008)

R. J. Schoelkopf, S. M. Girvin, *Nature (London)* **451**, 664 (2008)

Quantum Physics with Circuit QED ... some examples

Vacuum Rabi Mode Splitting
A. Wallraff *et al.*, *Nature* **431**, 162 (2004)

Coherent Flux-Qubit / SQUID Coupling
I. Chiorescu *et al.*, *Nature* **431**, 159 (2004)

Quantum AC-Stark Shift
D. Schuster *et al.*, *Nature* **445**, 515 (2007)

Lamb Shift
A. Fragner *et al.*, *Science* **322**, 1357 (2008)

Fock and Arbitrary Photon States
M. Hofheinz *et al.*, *Nature* **454**, 310 (2008)
M. Hofheinz *et al.*, *Nature* **459**, 546 (2009)

Root n Nonlinearity
J. Fink *et al.*, *Nature* **454**, 315 (2008)

Two Photon Nonlinearities
F. Deppe *et al.*, *Nat. Phys.* **4**, 686 (2008)

Parametric Amplification
Castellanos-Beltran *et al.*, *Nat. Phys.* **4**, 928 (2008)

Super Splitting and Root n Nonlinearity
L. Bishop *et al.*, *Nat. Phys.* **5**, 105 (2009)

Ultrastrong Coupling
T. Niemczyk *et al.*, *Nat. Phys.* **6**, 772 (2010)

Single Photon Source
A. Houck *et al.*, *Nature* **449**, 328 (2007)

Single Qubit MASER
O. Astafiev *et al.*, *Nature* **449**, 588 (2007)

Single Qubit Resonance Fluorescence
O. Astafiev *et al.*, *Science* **327**, 840 (2010)

QND Measurement of Single Photon
B. Johnson *et al.*, *Nat. Phys.* **6**, 663 (2010)

Correlation Function Measurements
D. Bozyigit *et al.*, *Nat. Phys.* **7**, 154 (2011)

Cooling and Amplification
M. Grajcar *et al.*, *Nat. Phys.* **4**, 612 (2008)

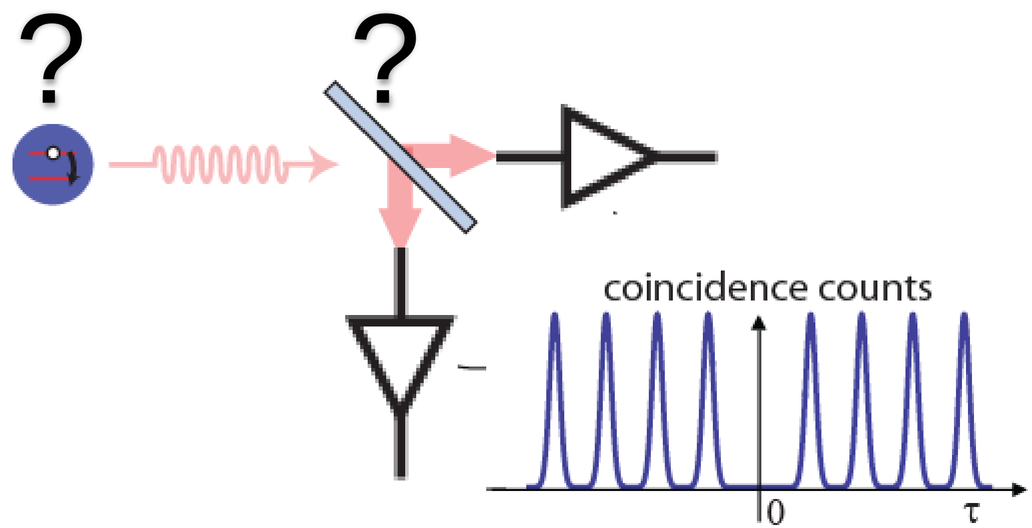
Quantum Algorithms & Entangled States
L. DiCarlo *et al.*, *Nature* **460**, 240 (2009)
L. DiCarlo *et al.*, *Nature* **467**, 574 (2010)
A. Fedorov *et al.*, *Nature* **481**, 170 (2012)
M. Reed *et al.*, *Nature* **481**, 382 (2012)

Quantum Bus
M. Sillanpaa *et al.*, *Nature* **449**, 438 (2007)
H. Majer *et al.*, *Nature* **449**, 443 (2007)
M. Mariantoni *et al.*, *Nat.Phys.* **7**, 287 (2011)
M. Mariantoni *et al.*, *Science* **334**, 61 (2011)

Quantum Optics with Propagating Microwaves

quantum optics in the **visible**:

- single photon sources
- beam splitters
- photon counters



o.k. at **optical frequencies**

But in the **microwave domain**?

- smaller photon energy ...

$$\frac{\nu_{\mathrm{opt}}}{\nu_{\mu\mathrm{w}}} = \frac{500\,\mathrm{THz}}{5\,\mathrm{GHz}} = 10^5$$

- ... requires lower operating temperature

$$\frac{h}{k_B} 5\,\mathrm{GHz} = 240\,\mathrm{mK}$$

instead:

- linear amplifiers
- signal processing

Here:

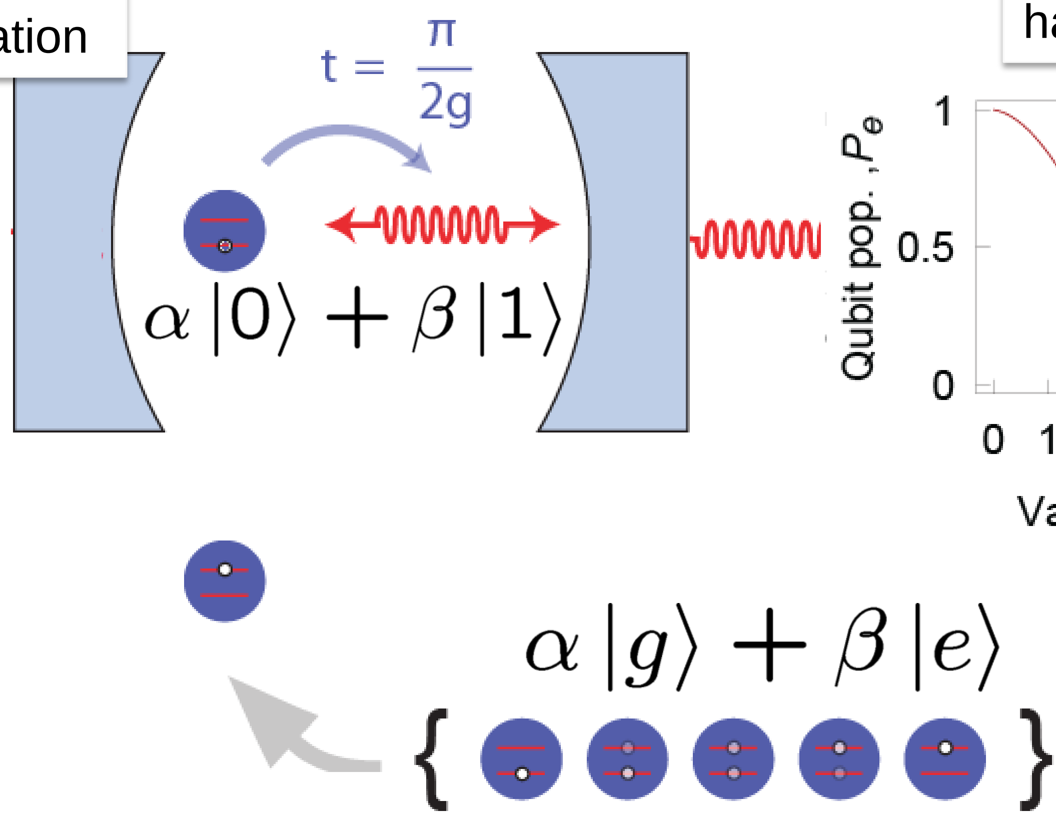
- correlation function msrmnts
- single photon tomography
- qubit/photon entanglement

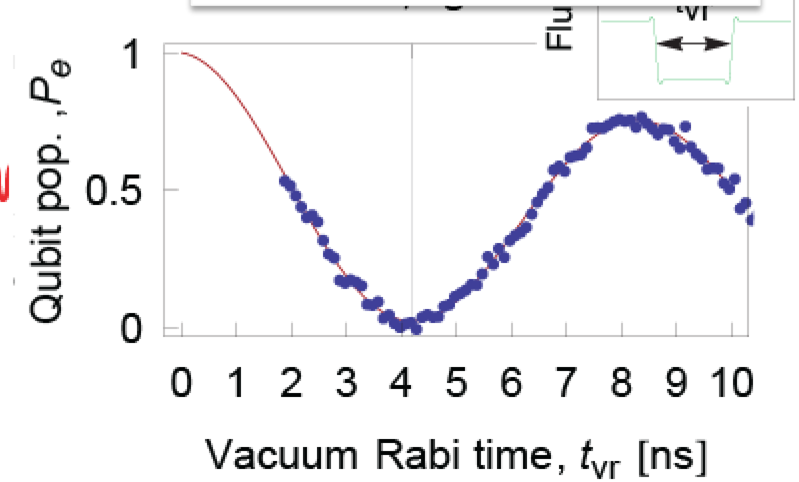
J. Gabelli et al., *Phys. Rev. Lett.* **93**, 056801 (2004)
E. P. Menzel et al., *Phys. Rev. Lett.* **105**, 100401 (2010)
M. P. da Silva et al.. Phys. *Rev. A* **82**, 043804 (2010)

On-Demand Pulsed Single Photon Source

Step 2:

Map qubit state to resonator by π/2 vacuum Rabi oscillation





Step 3:

Measure at the output using linear amplifier and signal processing hardware

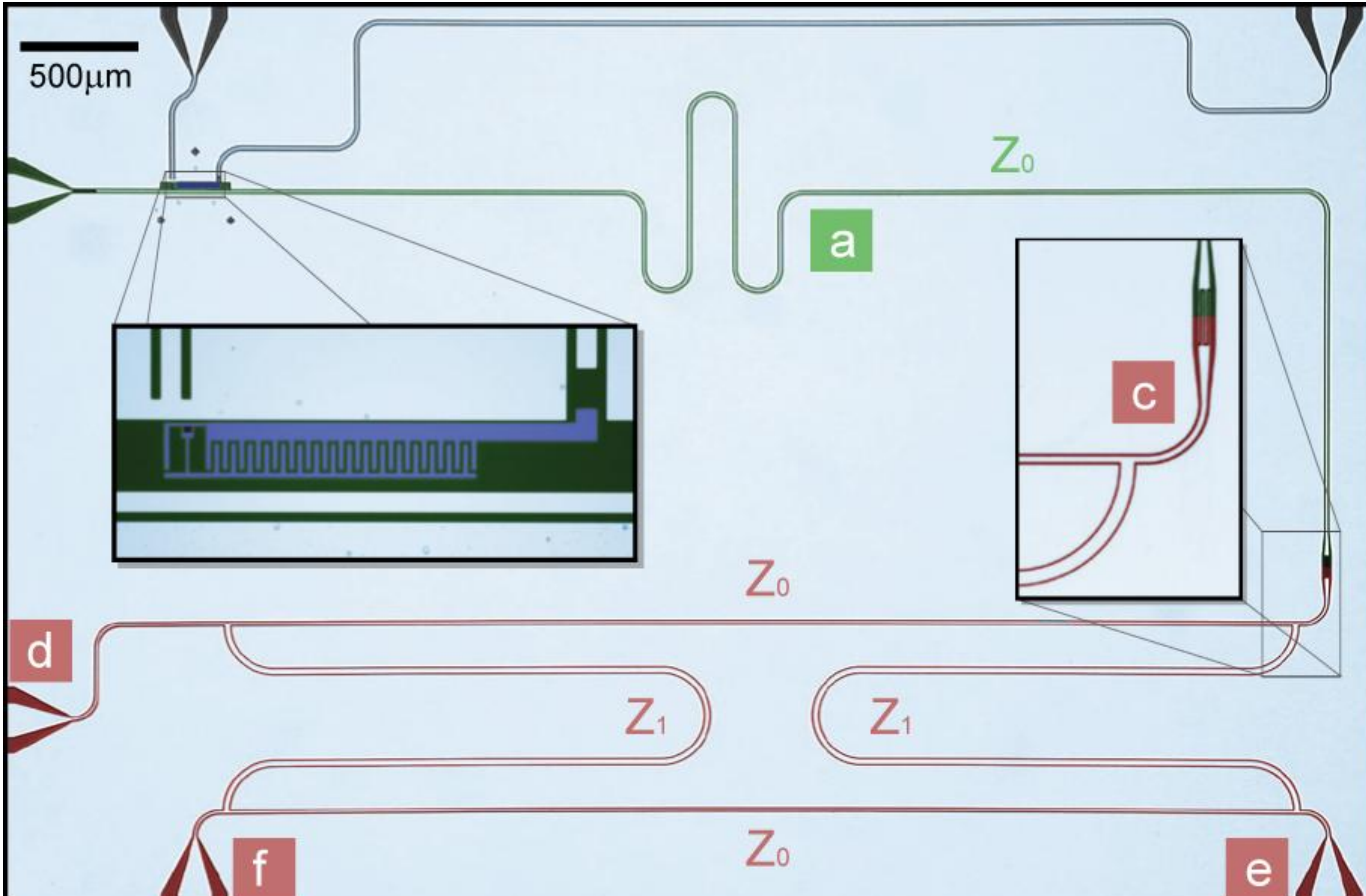
Step 1:

Prepare qubit state by Rabi oscillation

D. Bozyigit et al., *Nat. Phys.* **7**, 154 (2011)

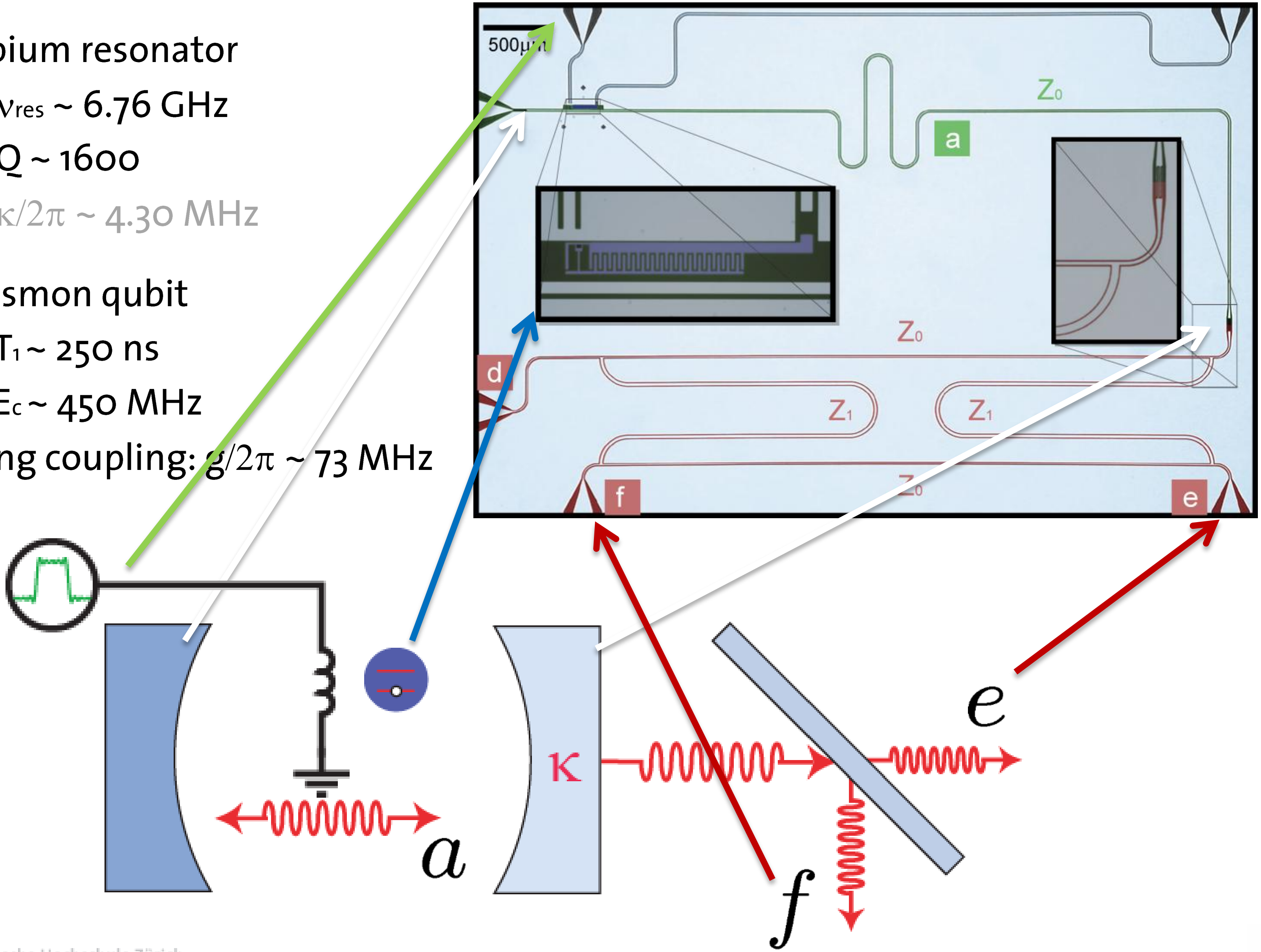
S. Deleglise et al. Nature **455**, 510514 (2008); M. Hofheinz *et al.*, *Nature* **454**, 310 (2008)

Single Sided Cavity and Beam Splitter

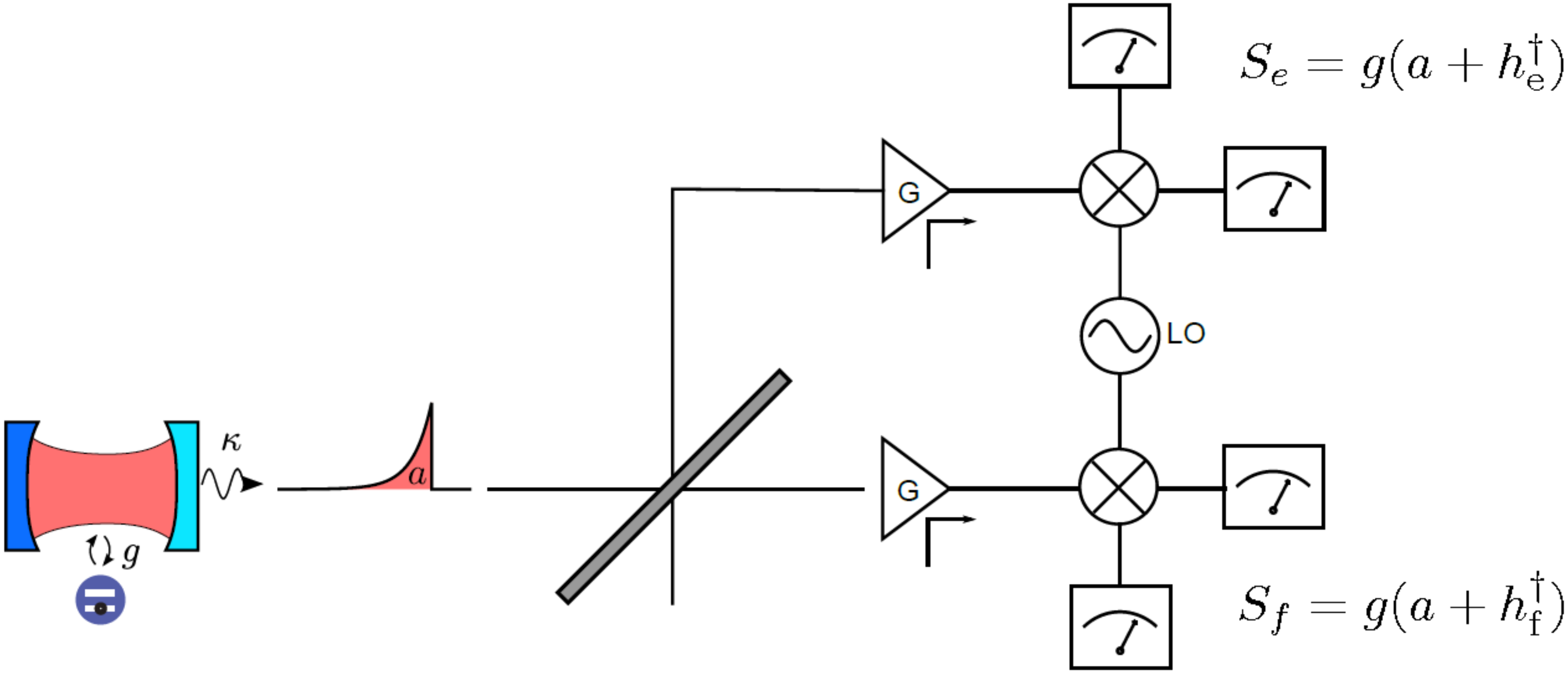


Single Sided Cavity and Beam Splitter

- Niobium resonator
  - ν_{res} ~ 6.76 GHz
  - Q ~ 1600
  - $\kappa/2\pi$ ~ 4.30 MHz
- Transmon qubit
  - T_1 ~ 250 ns
  - E_c ~ 450 MHz
- Strong coupling: $g/2\pi$ ~ 73 MHz



Schematic of Measurement Setup



$g \equiv \sqrt{G/2}$

$h_{\mathrm{e}}, h_{\mathrm{f}}$ effective noise modes

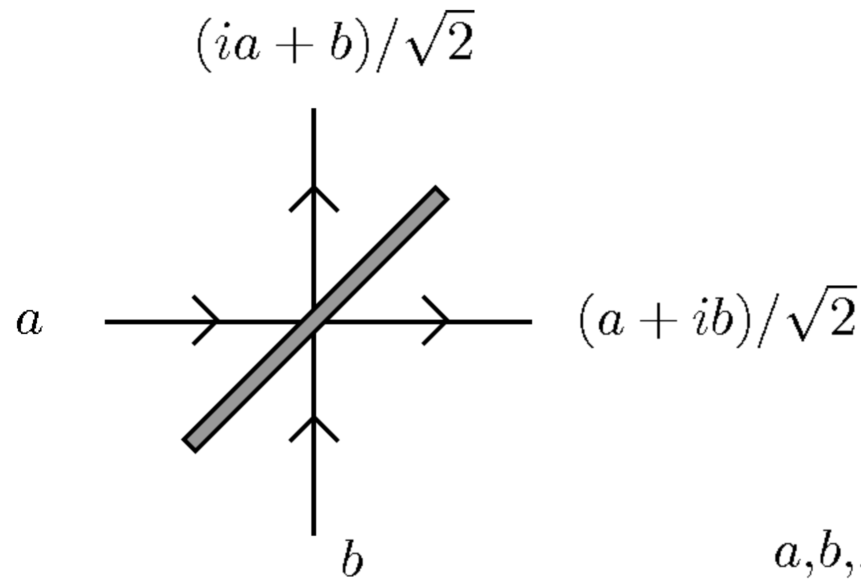
generalization of accessible expectation values:

$$\langle (S^\dagger)_{\mathrm{e}}^n S_{\mathrm{f}}^m \rangle = g^{n+m} \langle (a^\dagger)^n a^m \rangle$$

M. P. da Silva et al., *PRA* **82**, 043804 (2010)
D. Bozyigit et al., *Nat. Phys.* **7**, 154 (2011)
S. L. Braunstein et al., *PRA* **43**, 1153 (1991)
G. S. Argawal et al., *PRA* **49**, 2 (1994)

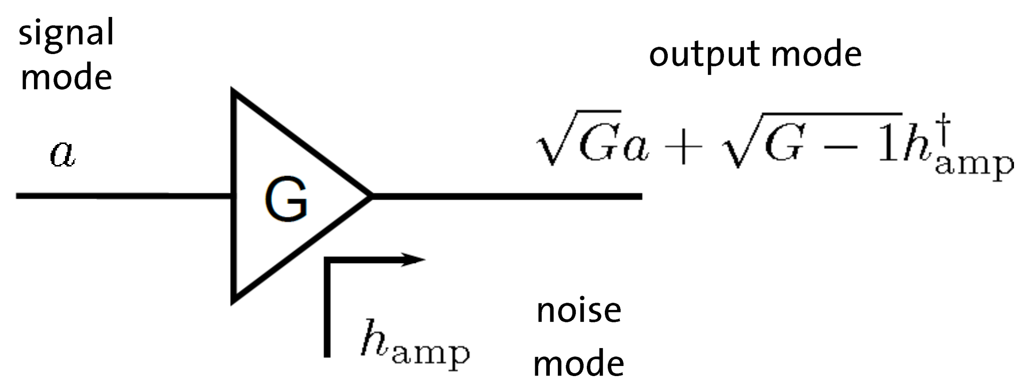
Detection Scheme using Beam Splitters, Amplifiers ...

beamsplitter:



$a, b, h, \ldots$ bosonic field operators

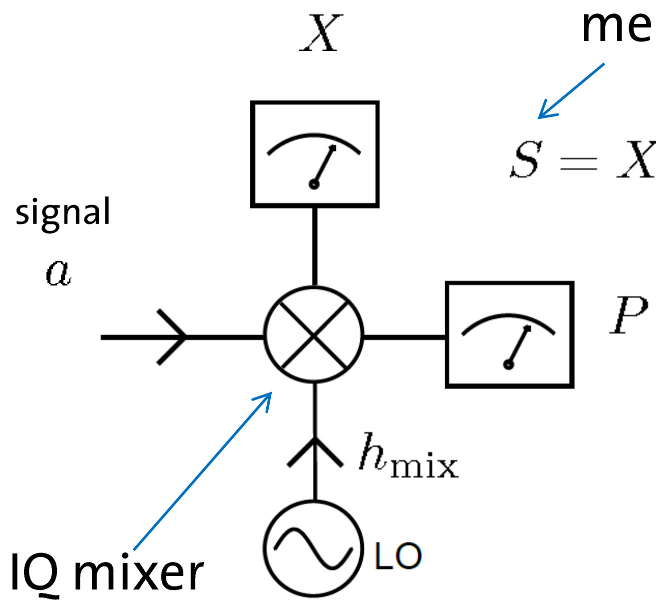
linear amplifier:



C. Caves, *PRD* **26**, 1817 (1982).

… and Quadrature Detectors

measuring field amplitude instead of photon number:



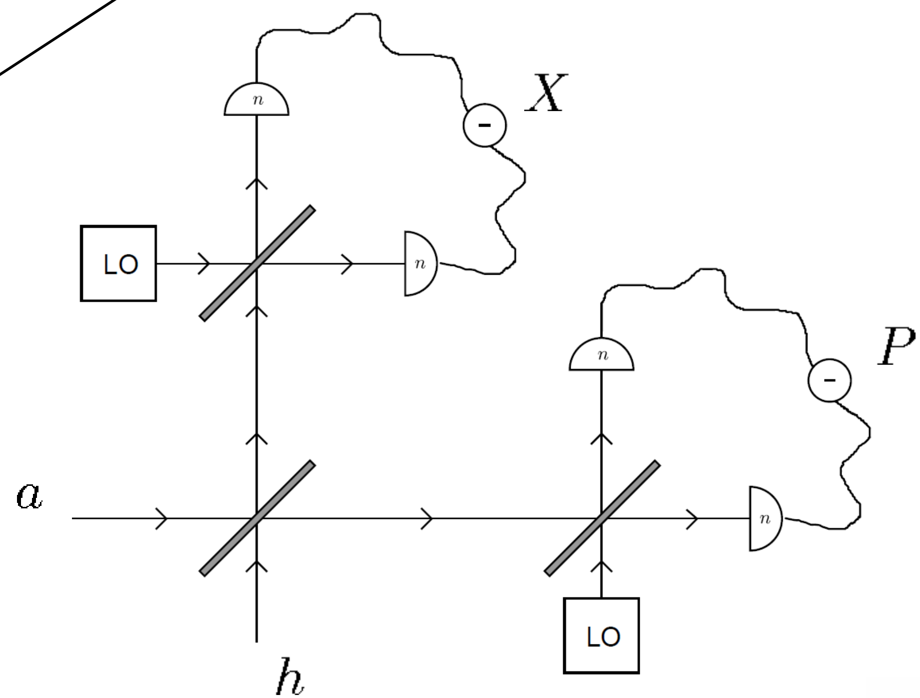
measured observable

$$S = X + iP = a + h^{\dagger}_{\mathrm{mix}}$$

M. P. da Silva et al., *PRA* **82**, 043804 (2010).

optical analogue

homodyne detection scheme



The Signal in One Channel of the Setup

signal mode a , vacuum mode v

$$\longrightarrow (a+iv)/\sqrt{2}$$

Beam splitter

$$\longrightarrow \sqrt{G/2}(a+iv)+\sqrt{G-1}h^\dagger_{\mathrm{amp}}$$

Linear amplifier

$$\longrightarrow \sqrt{G/2}(a+\underbrace{iv)+\sqrt{G-1}h^\dagger_{\mathrm{amp}}+h^\dagger_{\mathrm{mix}}}_{\propto h^\dagger}$$

Mixer

$$\equiv \sqrt{G/2}(a+h^\dagger)$$

$$\equiv S = X + iP$$

effective noise mode

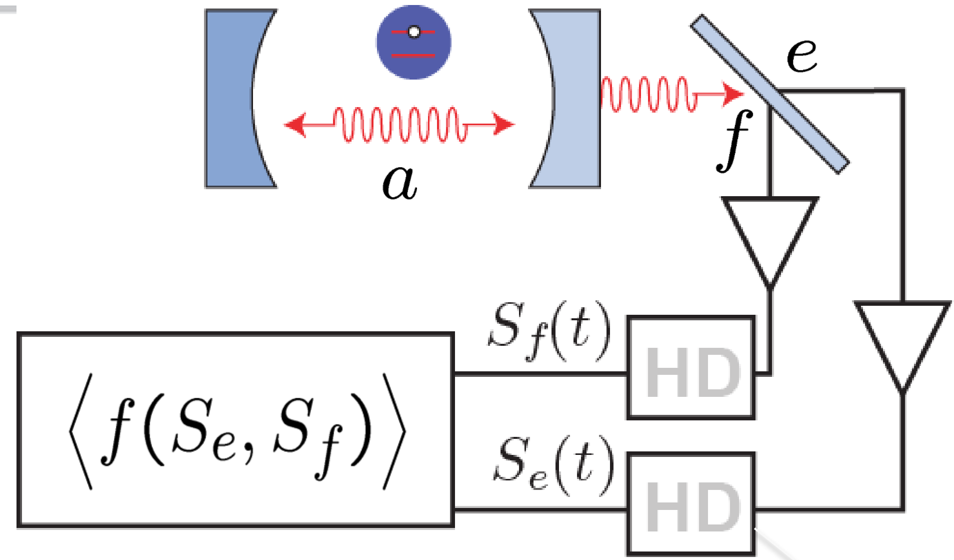
analogous for second channel!

Statistics of Full Measurement Record

Extract electric field quadratures:

$$S_e(t) = X_e(t) + iP_e(t)$$

$$S_f(t) = X_f(t) + iP_f(t)$$



Real-time statistics in digital-electronics

IQ-Mixer

Ensemble average finds:

- Quadratures $\langle S_e \rangle$ $\langle a \rangle$
- Crosspower $\langle S_e^* S_f \rangle$ $\langle a^\dagger a \rangle$
- Field correlation $\langle S_e^*(t) S_f(t+\tau) \rangle$ $\langle a^\dagger(t) a(t+\tau) \rangle$
- Intensity correlation $\langle S_e^*(t) S_e^* S_f(t+\tau) S_f(t) \rangle$ $\langle a^\dagger(t) n(t+\tau) a(t) \rangle$
- ... extract any correlation expressed in the cavity field operators

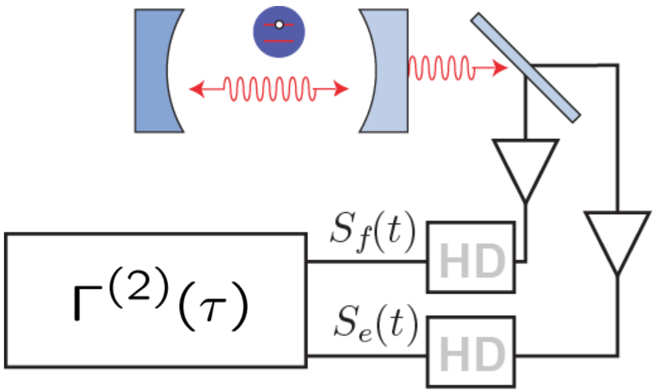
M. P. da Silva et al., *PRA* **82,** 043804 (2010)
D. Bozyigit et al., *Nat. Phys.* **7**, 154 (2011)
C. M. Caves, *Phys. Rev. D* **26**, 1817 (1982)
D. Walls and G. J. Milburn, Springer (2008)

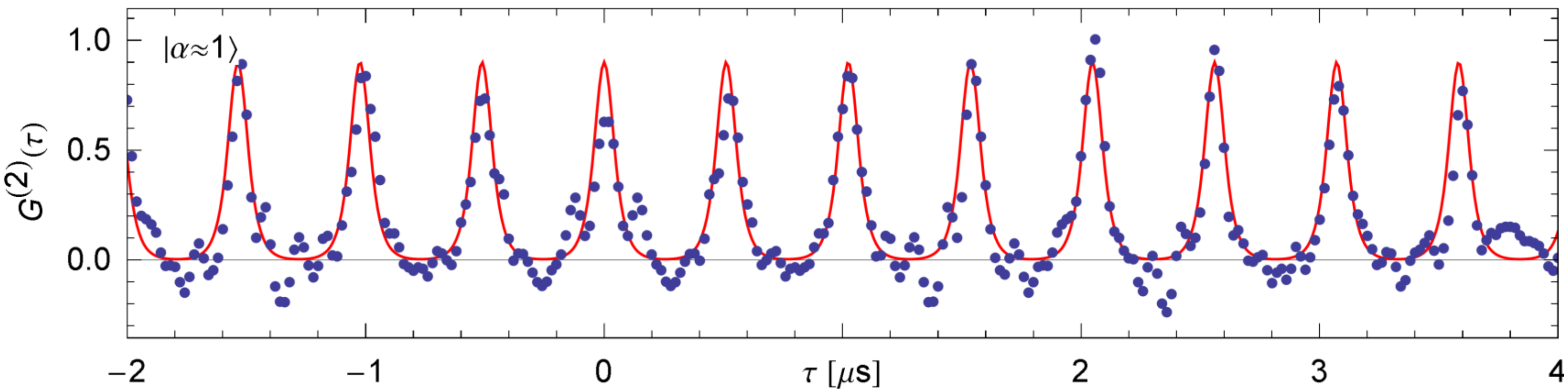
$G^{(2)}$ Measurement

Measure power correlation between channel e & f:

$$\Gamma^{(2)}(\tau) = \int \left\langle S_e^* S_f(t) S_e^* S_f(t+\tau) \right\rangle dt$$

$$G^{(2)}(\tau) = \Gamma^{(2)}_{prep}(\tau) - \Gamma^{(2)}_{ss}(\tau)$$

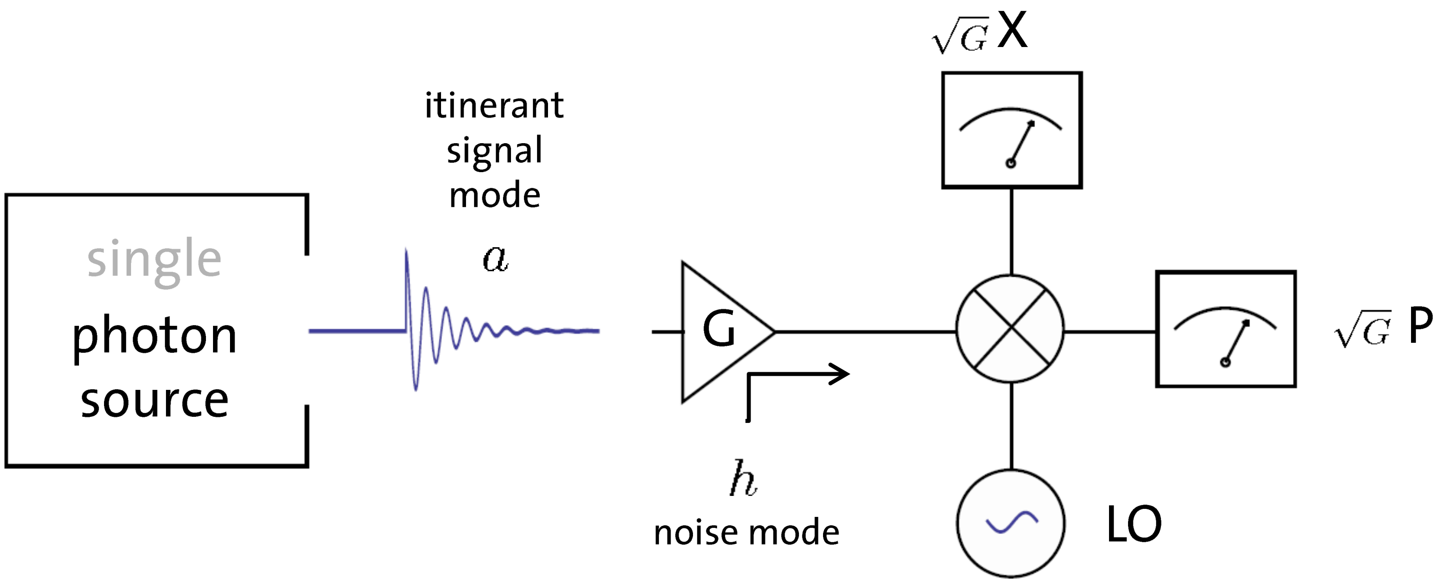




first $G^{(2)}$ measurement for a microwave frequency single photon source

D. Bozyigit et al., *Nat. Phys.* **7**, 154 (2011)

Scheme for Tomography of Itinerant Photons



measured observable: $X + iP = S = (a + h^\dagger)$

M. P. da Silva *et al.*, P*RA* **82**, 043804 (2010)

What is the quantum state of mode a ?

Goal: Reconstruct density matrix, **Wigner**-, Q-, or P-function!

Amplified Quadrature Histograms

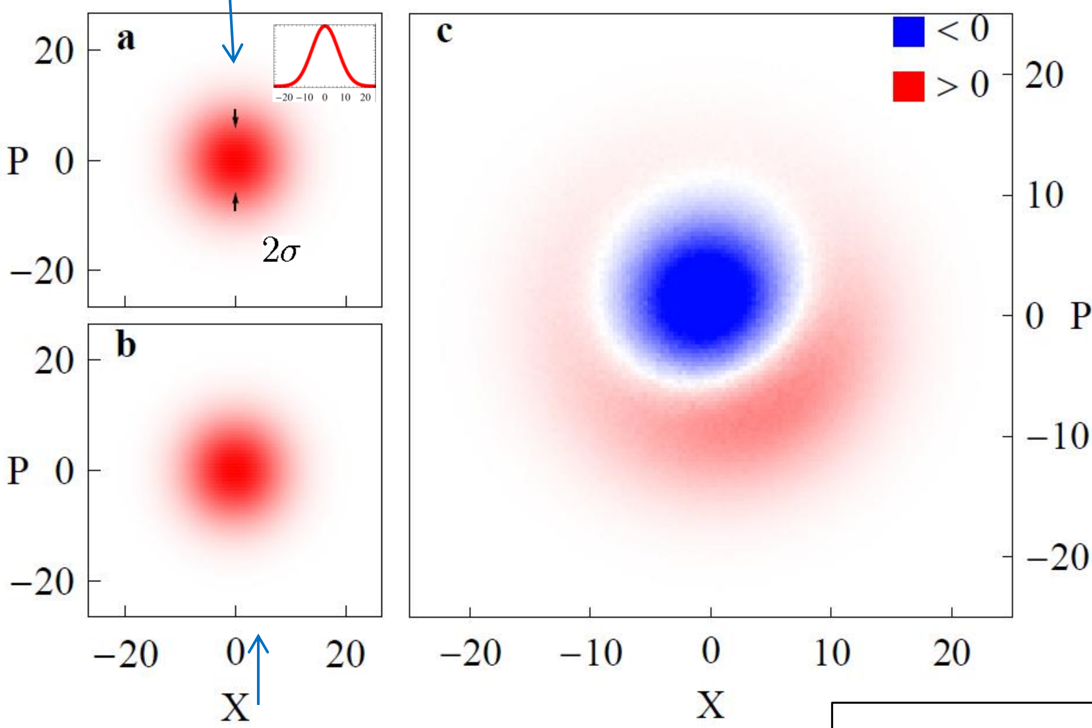
Store 2D histogram $V(S)$ from $S = X + iP$ measurement results:

corresponding phase space distribution

signal mode a in **vacuum**

Q - function of noise mode : Q_η

Convolution with **P** – function of signal $Q_\eta * P_a$



subtracted histograms to visualize difference

signal mode a in **single photon Fock state**

separate noise η from signal a systematically!

C. Eichler *et al.*, *PRL* **106**, 220503 (2011)

Statistical Analysis of Phase Space Histograms

Systematic mode separation:

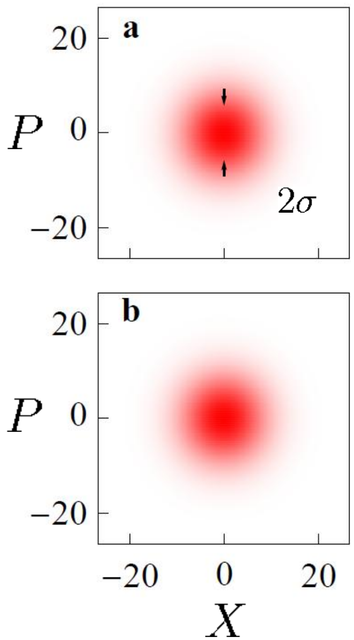
Histogram moments: $\langle (S^\dagger)^n S^m \rangle = \int d^2S \;\; D(S) \;\; (S^*)^n S^m$

1. calculate histogram moments

2. algebraic inversion

Source "OFF"

Source "ON"



→ $\langle (S^\dagger)^n S^m \rangle_{\mathrm{OFF}} = \langle h^n (h^\dagger)^m \rangle$

→ $\langle (S^\dagger)^n S^m \rangle_{\mathrm{ON}} = \langle (a^\dagger + h)^n (a + h^\dagger)^m \rangle$

} $\langle (a^\dagger)^n a^m \rangle$

reminder: $X + iP = S = (a + h^\dagger)$

State Dependent Moments of Probability Distribution

Moments $\langle (a^\dagger)^n a^m \rangle$ for different prepared states:

$\langle a^\dagger a \rangle$ "mean photon number"

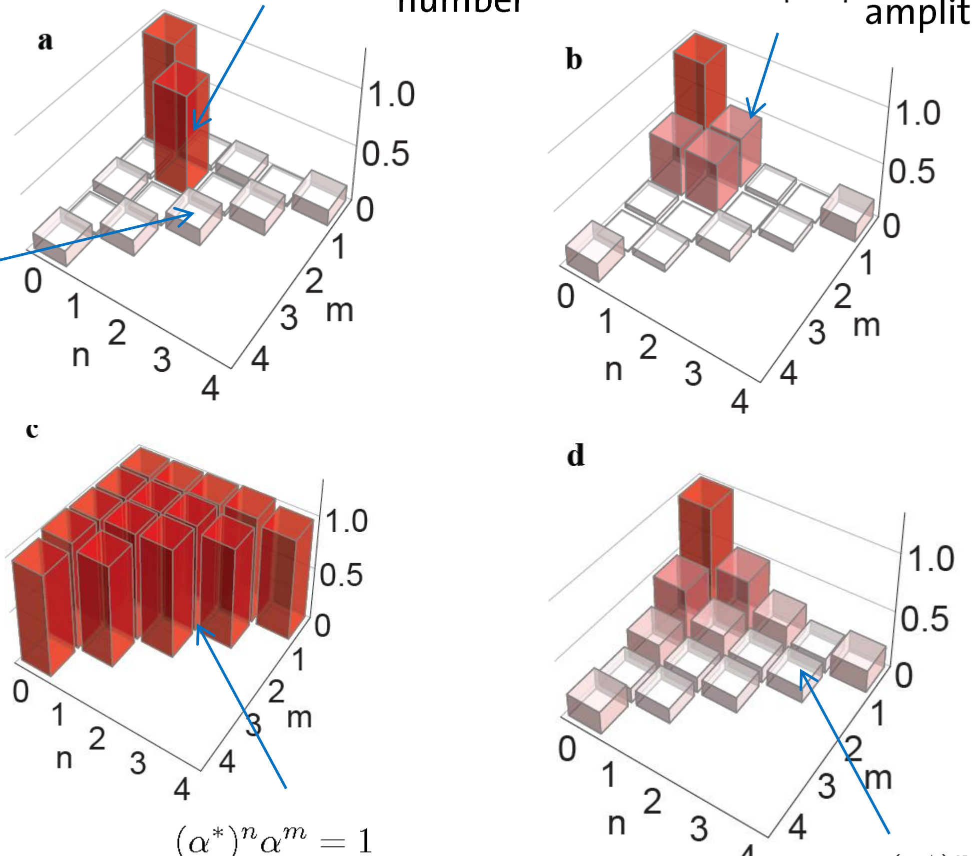
$\langle a^\dagger \rangle$ "mean amplitude"

Fock state

$|1\rangle$

$\langle (a^\dagger)^2 a^2 \rangle \sim 0$

"anti bunching"



superposition

$$\frac{1}{\sqrt{2}}(|0\rangle + e^{i\phi}|1\rangle)$$

coherent state

$|\alpha = 1\rangle$

$(\alpha^*)^n \alpha^m = 1$

coherent state

$|\alpha = 0.5\rangle$

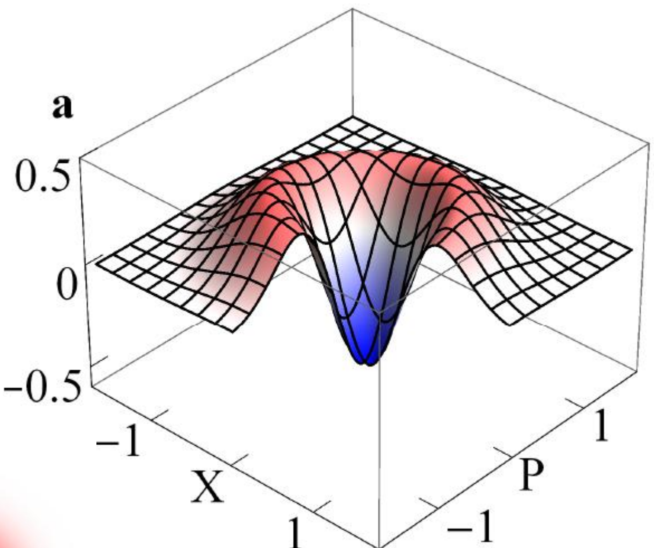
$(\alpha^*)^n \alpha^m = (1/2)^{n+m}$

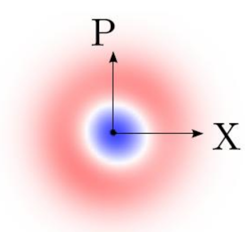
C. Eichler *et al.*, *PRL* **106**, 220503 (2011)

Reconstructed Wigner Function of Itinerant Photon

Wigner function reconstructed from statistical moments:

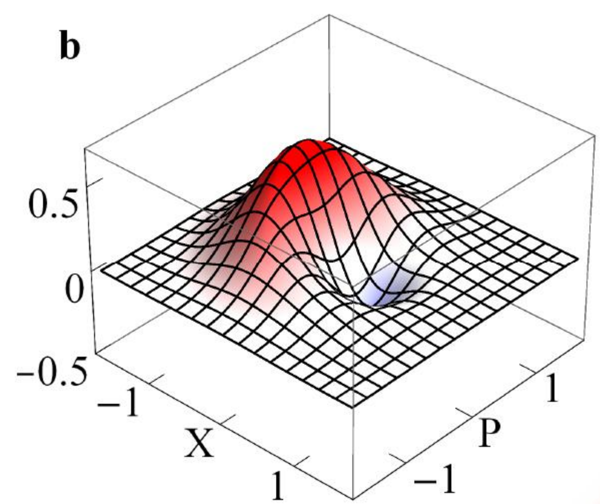
$$W(\alpha) = \frac{1}{\pi^2} \sum_{n,m} \int d^2\lambda \frac{\langle (a^\dagger)^m a^n \rangle (-\lambda^*)^n \lambda^m}{n!m!} e^{-\frac{1}{2}|\lambda|^2 + \alpha\lambda^* - \alpha^*\lambda} \quad \text{with} \quad n + m < 4$$

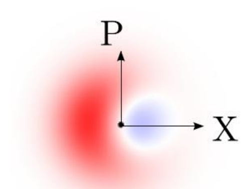




Fock state

$|1\rangle$





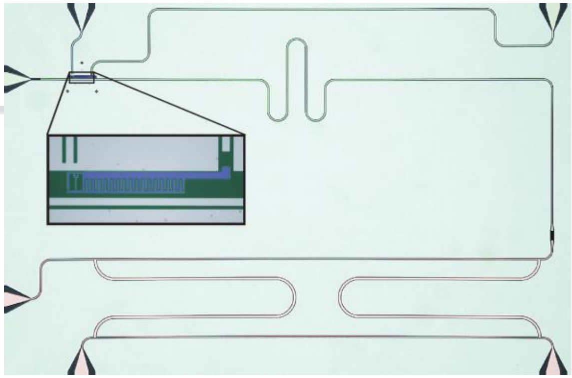
superposition

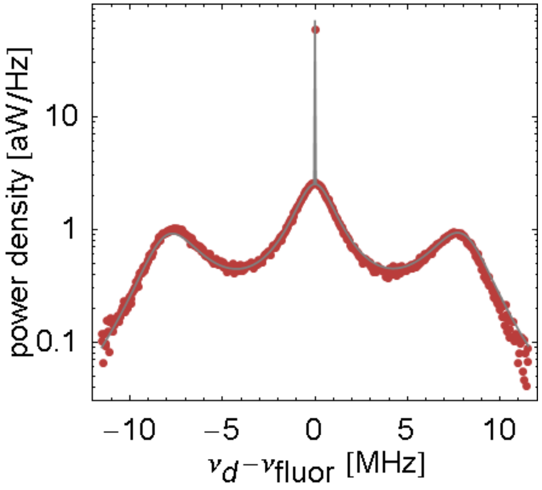
$\frac{1}{\sqrt{2}}(|0\rangle + e^{i\phi}|1\rangle)$

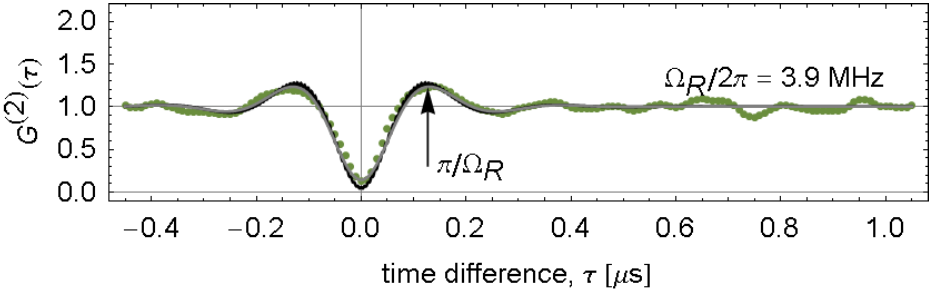
C. Eichler *et al.*, *PRL* **106**, 220503 (2011)

Summary Correlations & Tomography

- ✓ realization of pulsed and continuously pumped microwave frequency single photon source
- ✓ implementation of on-chip beam splitter for correlation analysis
- ✓ characterization of single photon sources by:
  - ✓ time-resolved cavity field quadrature measurements
  - ✓ power, cross-power and photon number measurements
  - ✓ 1st and 2nd order two-time correlation functions



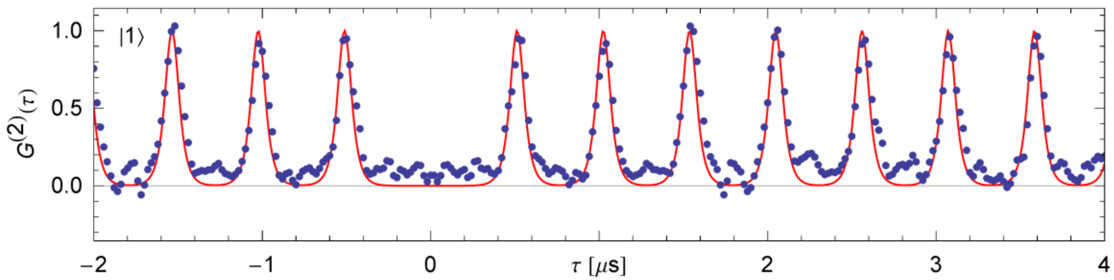




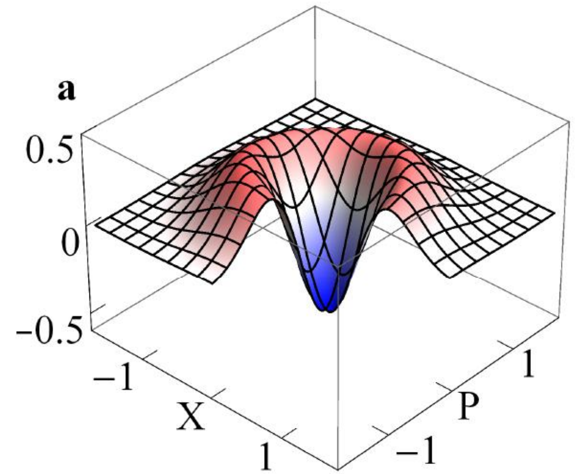
C. Lang *et al.*, *PRL* **106**, 243601 (2011)
M. P. da Silva et al., *PRA* **82**, 043804 (2010)

Summary Correlations & Tomography

- tomography of pulsed single photon sources ...
- ... and correlation function measurements



D. Bozyigit et al., *Nat. Phys.* **7**, 154(2011)



C. Eichler *et al., PRL* **106**, 220503 (2011)

- two mode squeezing generated using parametric amplifiers

  C. Eichler *et al., PRL* **107**, 113601 (2011)

- **in the future**: do linear/non-linear optics in the circuit QED framework (e.g. realize photon/photon logic gates & interferometers)
- explore correlations at microwave frequencies in other systems
  - e.g. electron transport in nanostructures
- Demonstrated a great set of tools ready to be used in other fields!

The ETH Zurich Quantum Device Lab

Postdoc and PhD positions available

FNSNF
Swiss National Science Foundation

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

QSIT Quantum Science and Technology
National Centre of Competence in Research

QED
CIRCUIT AND CAVITY
QUANTUM ELECTRODYNAMICS

aqute

SOLID

erc

GEOMDISS

Selected Circuit QED Publications

Circuit QED Proposal:

- Blais et al., *PRA* **69**, 062320 (2004)

Strong Coupling & Vacuum Rabi Mode Splitting:

- Wallraff et al., *Nature* **431**, 162 (2004)
- Fink et al., *Nature* **454**, 315 (2008)
- Fink et al., *PRL* **105**, 163601 (2010)

Tavis-Cummings Multi-Atom QED:

- Fink et al., *PRL* **103**, 083601 (2009)

AC-Stark & Lamb Shift, Autler-Townes and Mollow Transitions

- Schuster et al., *PRL* **94**, 123062 (2005)
- Gambetta et al., *PRA* **74**, 042318 (2006)
- Schuster et al., *Nature* **445**, 515 (2007)
- Fragner et al., *Science* **322**, 1357 (2008)
- Baur et al., *PRL* **102**, 243602 (2009)

Itinerant Photons, Tomography, Photon Blockade

- da Silva et al., *PRA* **82**, 043804 (2010)
- Bozyigit et al., *Nat. Phys.* **7**, 154(2011)
- Eichler et al., *PRL* **106**, 220503 (2011)
- Lang et al., *PRL* **106**, 243601 (2011)
- Eichler et al., *PRL* **107**, 113601 (2011)

One-, Two-, Three-Qubit Gates and Algorithms:

- Wallraff et al., *PRL* **95**, 060501 (2005)
- Blais et al., *PRA* **75**, 032329 (2007)
- Wallraff et al., *PRL* **99**, 050501 (2007)
- Majer et al., *Nature* **449**, 443 (2007)
- Leek et al., *Science* **318**, 1889 (2007)
- Leek et al., *PRB* **79**, 180511(R) (2009)
- Filipp et al., *PRL* **102**, 200402 (2009)
- Leek et al., *PRL* **104**, 100504 (2010)
- Bianchetti et al., *PRL* **105**, 223601 (2010)
- Fedorov et al., *Nature* **481**, 170 (2012)
- Baur et al., *PRL* **108**, 040502 (2012)

Hybrid Systems:

- Frey et al., *PRL* **108**, 046807 (2012)
- Hogan et al., *PRL* **108**, 063004 (2012)

Device Fabrication:

- Frunzio et al., *IEEE Trans. Appl. Sup.*. **15**, 860 (2005)
- Goeppl et al., *J. Appl. Phys.* **104**, 113904 (2008)

Review (gr.):

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Additional Information: www.qudev.ethz.ch