V. Exploring Propagating Microwaves with Linear Detectors

- Correlation Function Measurements
- Quantum State Tomography
- Qubit Photon Entanglement
- Two-Mode Entanglement

Exploring the Properties of Propagating Photons

quantum optics in the **visible**:

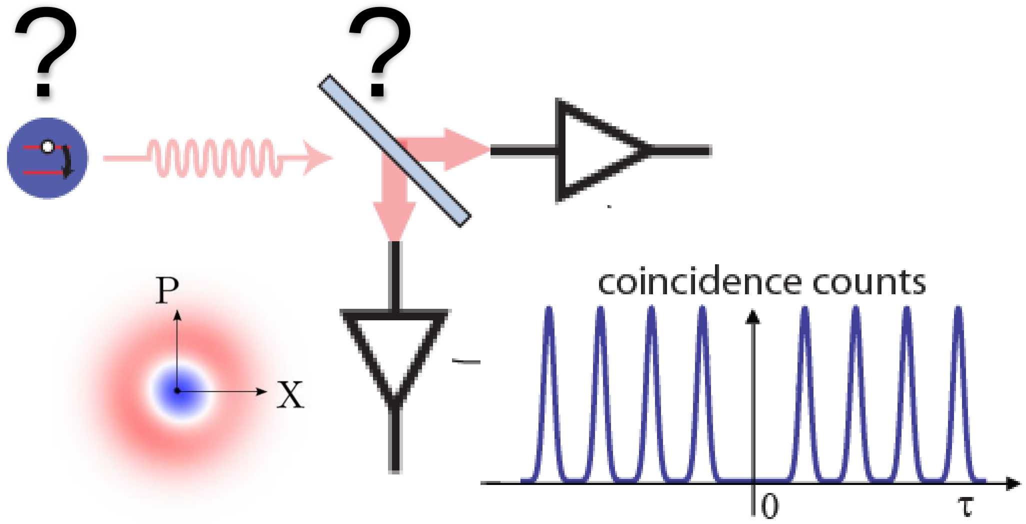
- single photon sources
- beam splitters
- photon counters

o.k. at **optical frequencies**

But in the **microwave domain**?

- smaller photon energy ...

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



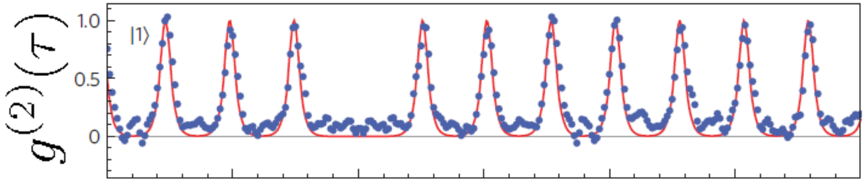
instead:

- linear amplifiers
- signal processing

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)
C. Eichler et al., *Phys. Rev. A* **86**, 032106 (2012)

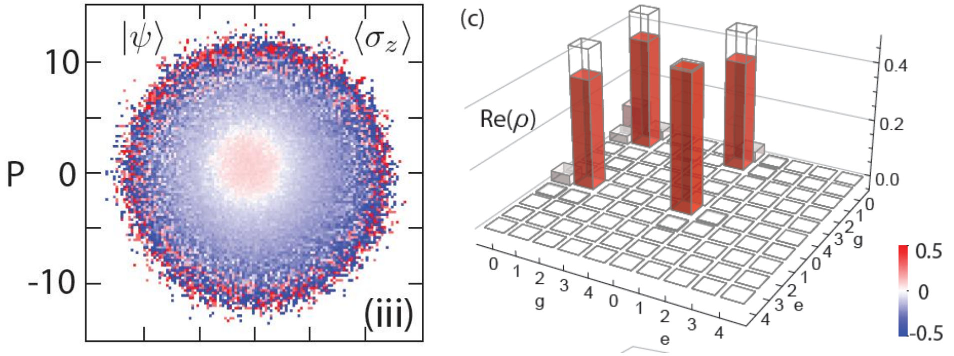
Experiments with Propagating Quantum Microwaves

Single photon sources and their anti-bunching



Bozyigit *et al.*, Nat. Phys **7**, 154 (2011)
Lang *et al.*, *PRL* **107**, 073601 (2011)

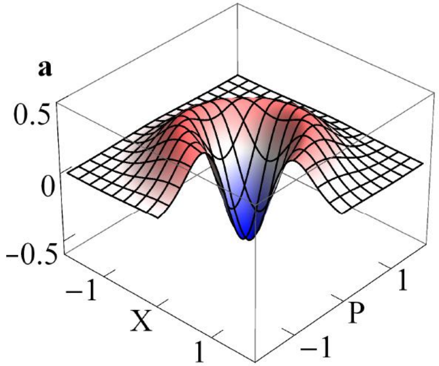
Preparation and characterization of qubit-**propagating** photon entanglement



Eichler *et al., arXiv:1209.0441* (2012)
Eichler *et al., Phys. Rev. A* **86**, 032106 (2012)

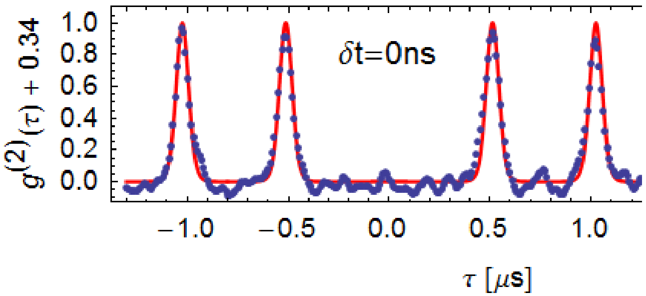
Wigner functions and full state tomography of **propagating** photons

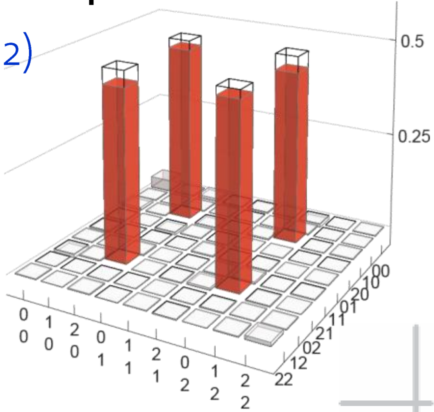
Eichler *et al., PRL* **106**, 220503 (2011)



Hong-Ou-Mandel: Two-photon interference with coherences at microwave frequencies

Lang, Eichler *et al., ETH Zurich* (2012)





Single Pulsed Photon Source and Beam-Splitter

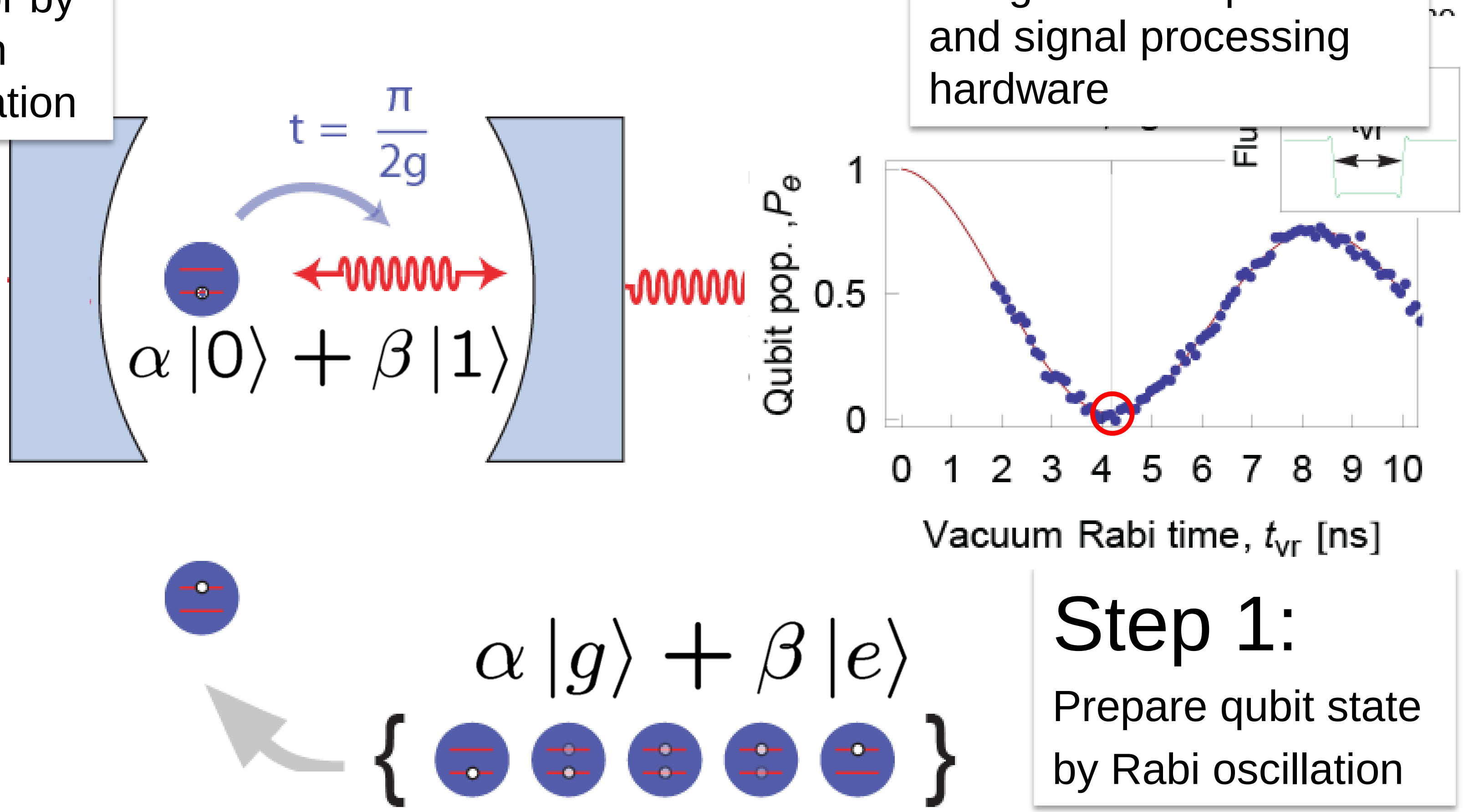
On-Demand Pulsed Single Photon Source

Step 2:

Map qubit state to resonator by 1/2 vacuum Rabi oscillation

Step 3:

Measure at the output using linear amplifier and signal processing hardware

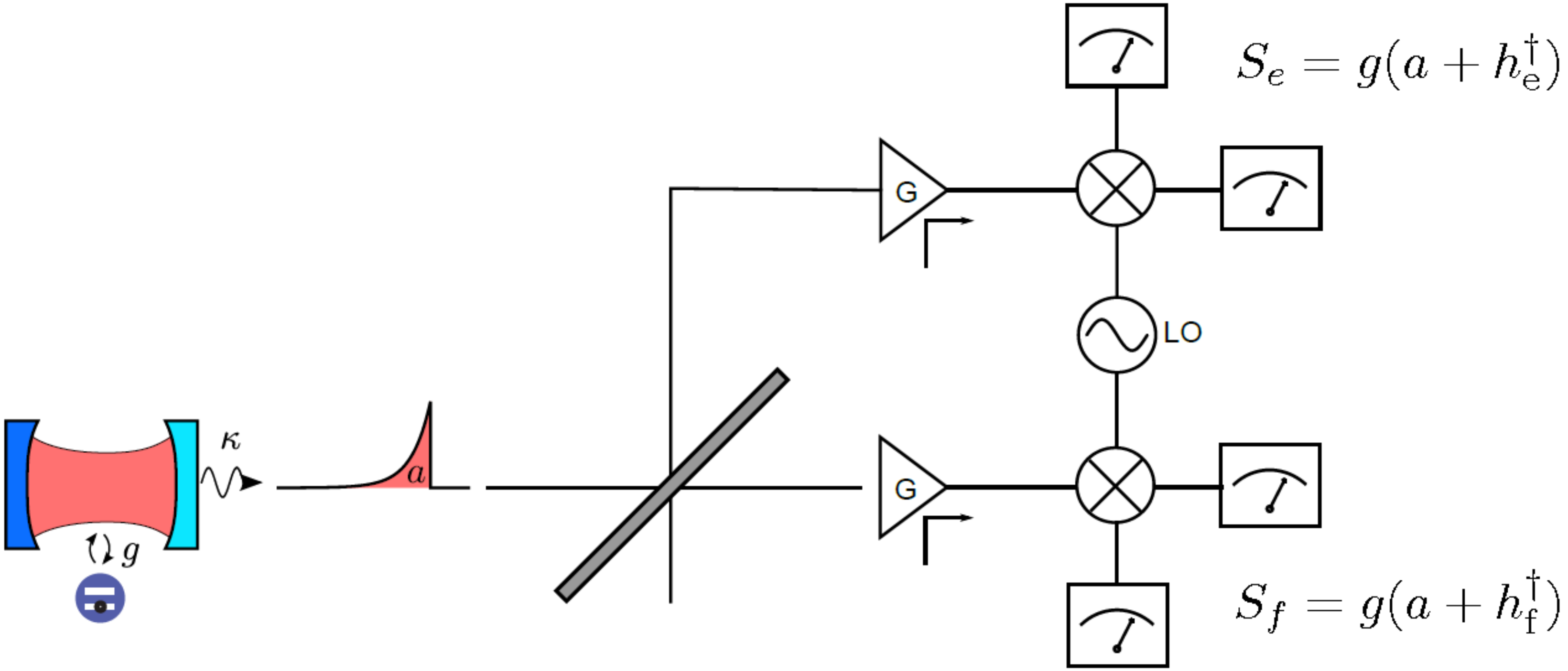


Step 1:

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

Schematic of Measurement Setup



$$S_e = g(a + h_\mathrm{e}^\dagger)$$

$$S_f = g(a + h_\mathrm{f}^\dagger)$$

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

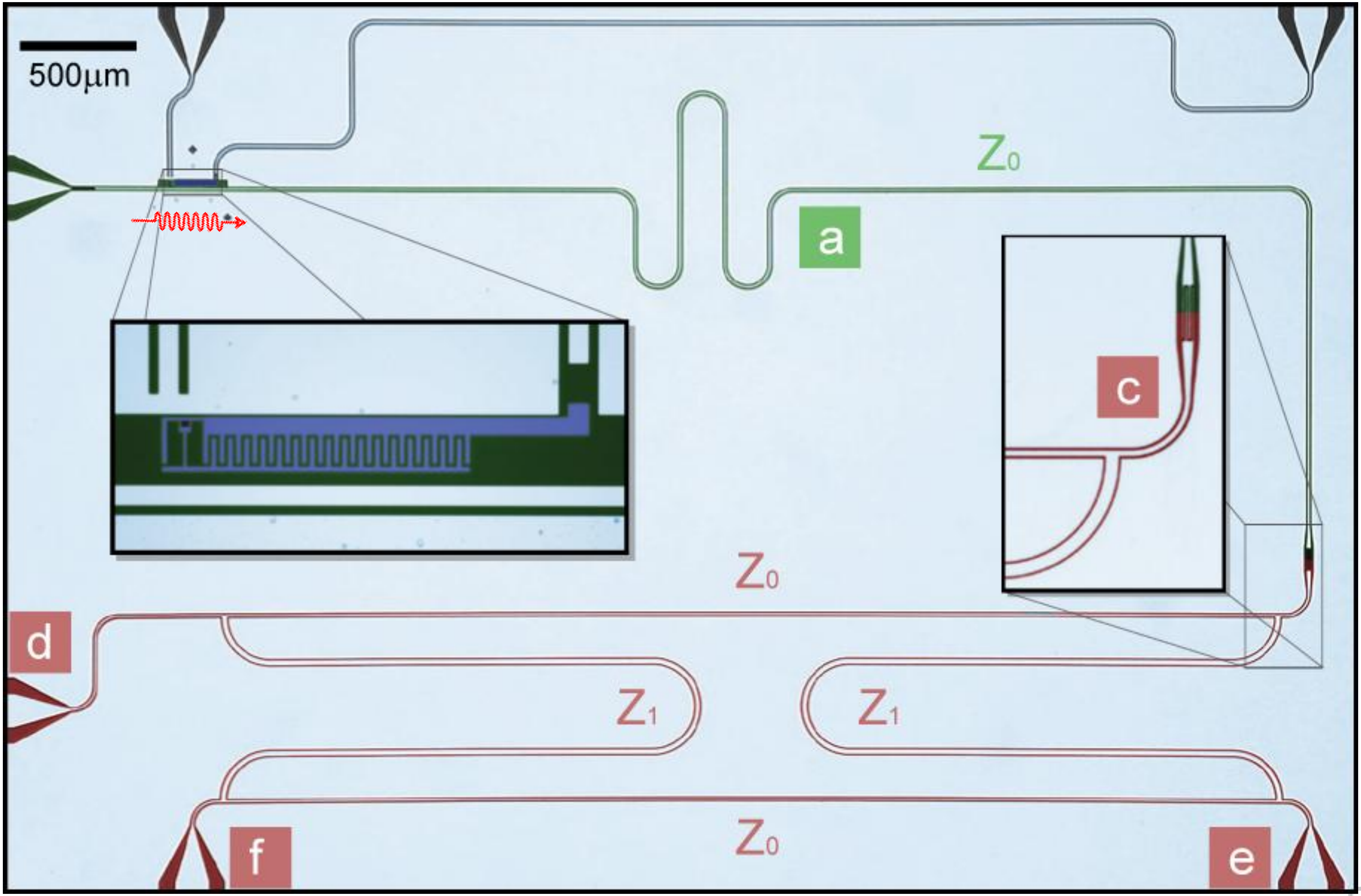
$h_\mathrm{e}, h_\mathrm{f}$ effective noise modes

generalization of accessible expectation values:

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

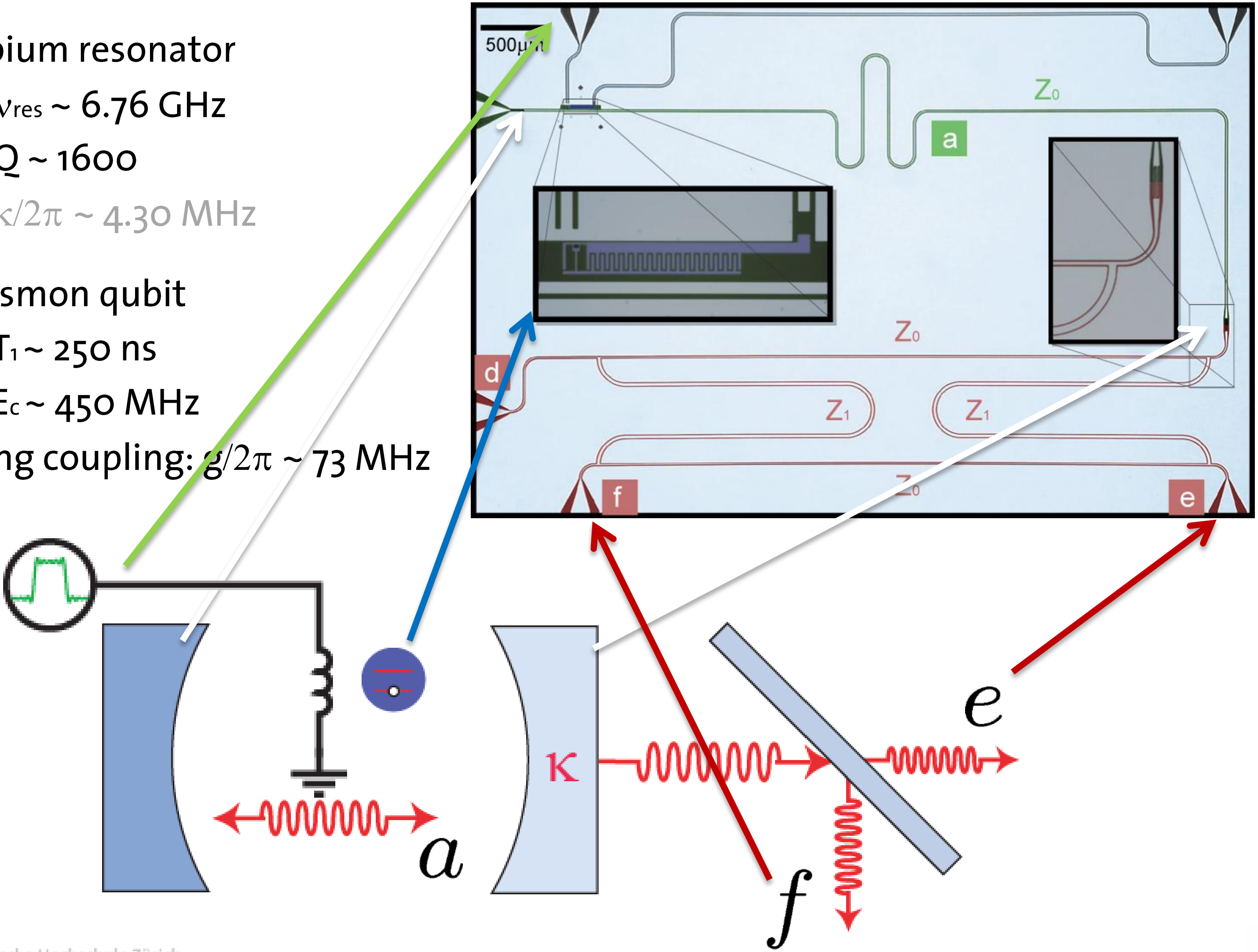
C. Eichler et al., *PRA* **86**, 032106 (2012)
M. P. da Silva et al., *PRA* **82**, 043804 (2010)
D. Bozyigit et al., *Nat. Phys.* **7**, 154 (2011)
G. S. Argawal et al., *PRA* **49**, 2 (1994). S. L. Braunstein et al., *PRA* **43**, 1153 (1991)

Single Sided Cavity and Beam Splitter



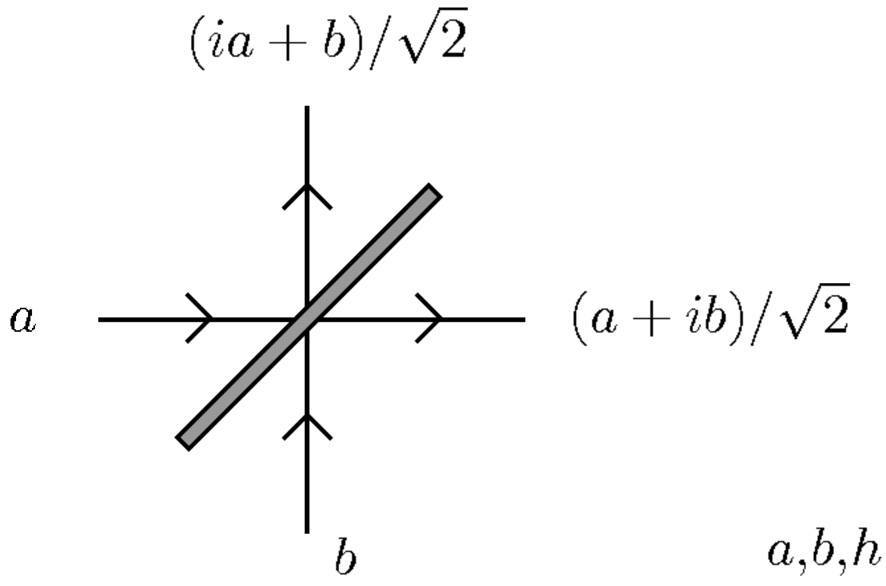
Single Sided Cavity and Beam Splitter

- 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



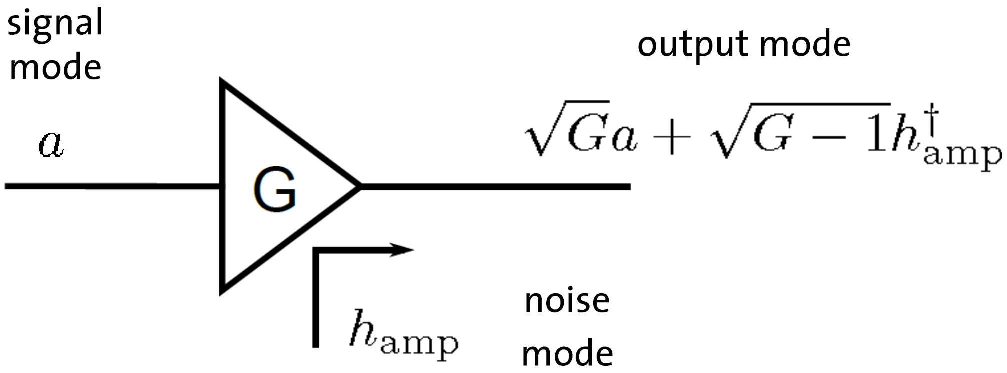
Detection Scheme using Beam Splitters, Amplifiers ...

beamsplitter:



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

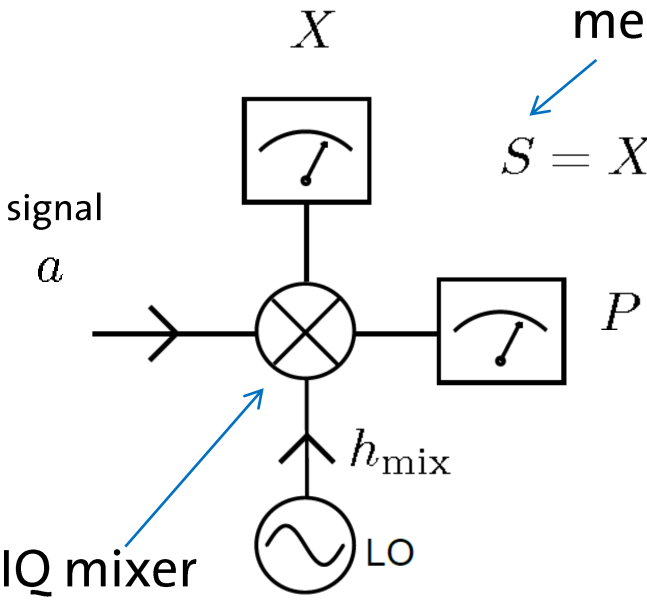
linear amplifier:



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

… and Quadrature Detectors

measuring field amplitude instead of photon number:



measured observable

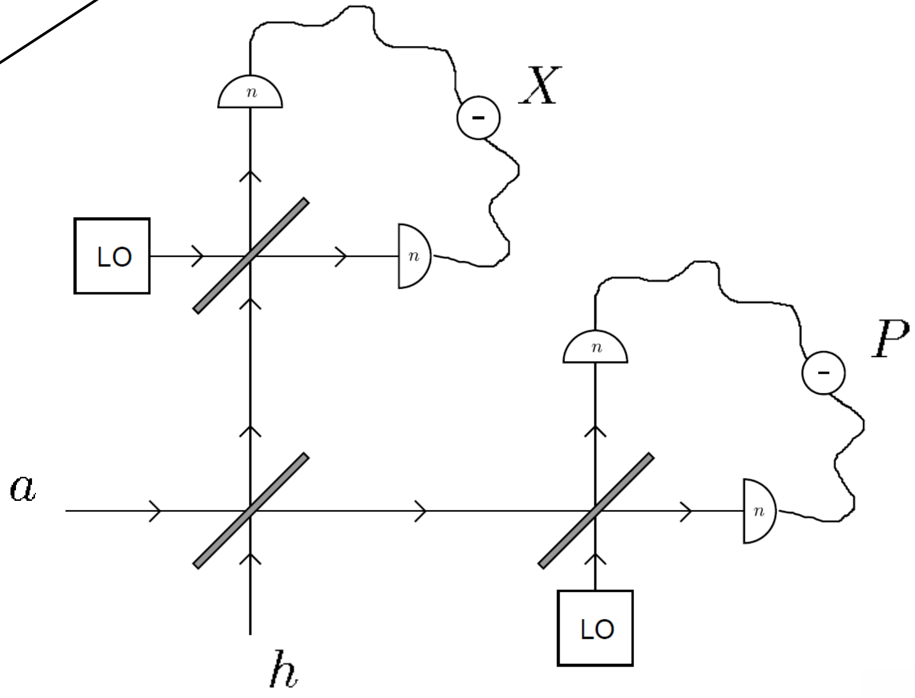
$$S = X + iP = a + h_{\mathrm{mix}}^{\dagger}$$

IQ mixer

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

Beam splitter

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

Linear amplifier

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

Mixer

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

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

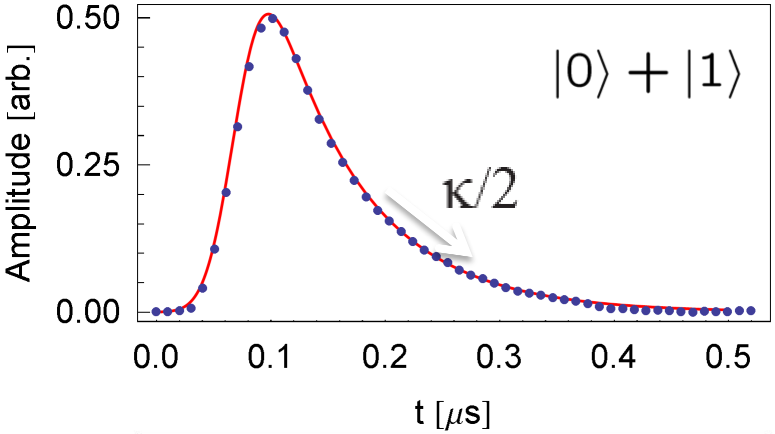
$$\equiv S = X + iP$$

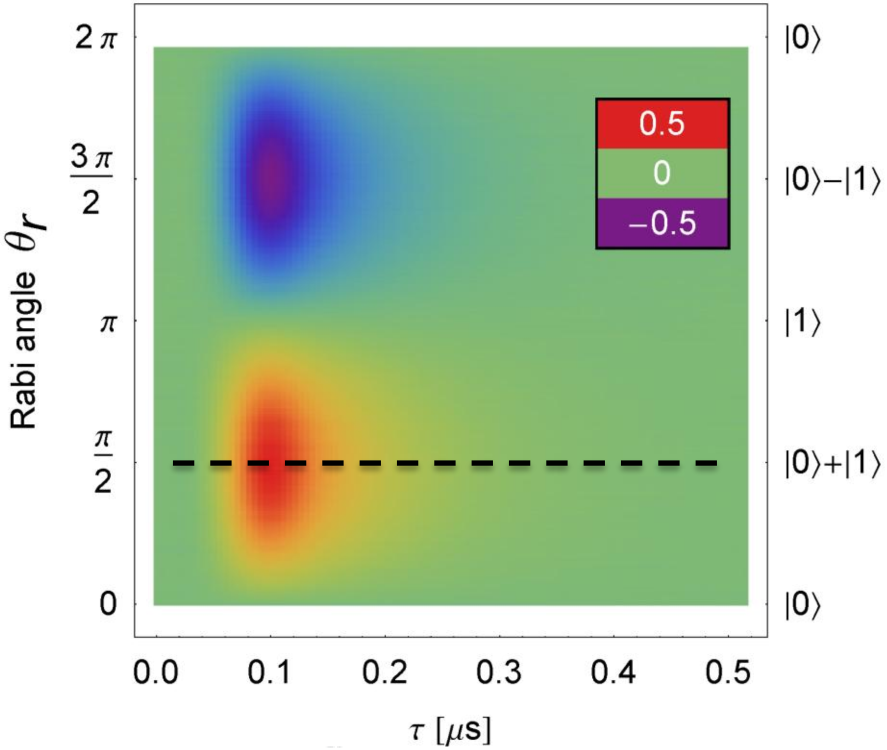
effective noise mode

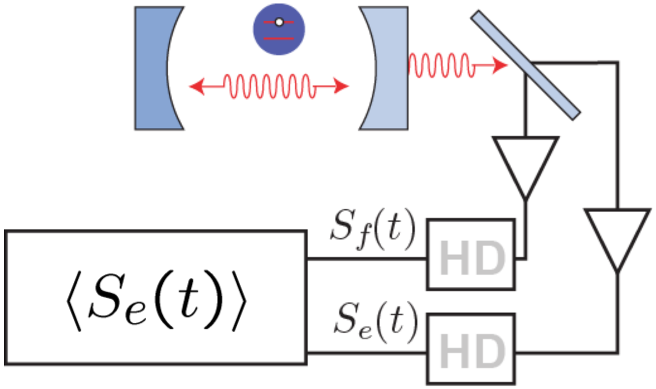
analogous for second channel!

Cavity Field Quadrature Measurement

Measure quadratures at channel b:







$$\langle S_e(t)\rangle \propto \langle a(t)\rangle \propto \sin(\theta_r)/2$$

Time-dependence:

- Falling edge: cavity decay
- Rising edge: detection bandwidth

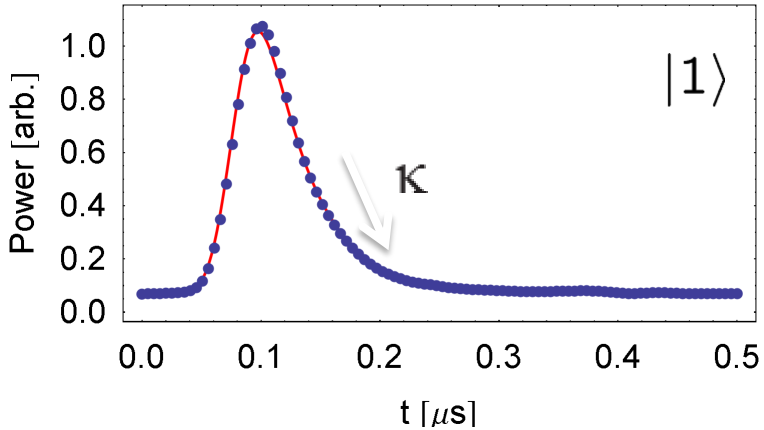
Rabi angle dependence:

- Maximum signal for $|0\rangle + |1\rangle$
- No signal for $|1\rangle$
- Excellent agreement with theory

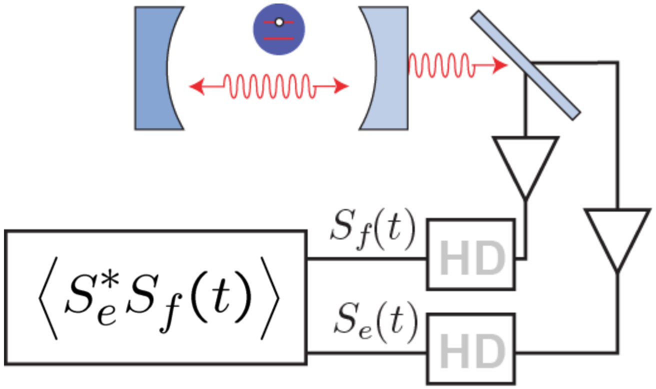
D. Bozyigit *et al.*, *Nat. Phys.* **7**, 154 (2011)
A. Houck *et al.*, *Nature* **449**, 328 (2007)

Cavity Photon Number Measurement

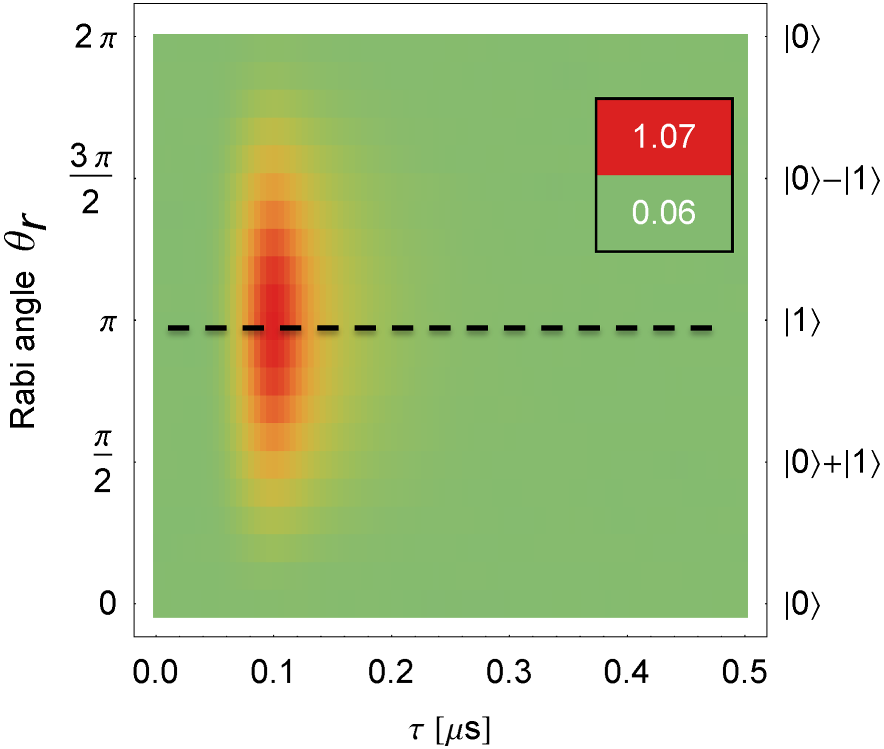
Measure crosspower between channel e&f:



~ 80 mK



$$\left\langle S_e^*(t) S_f(t)\right\rangle \propto \left\langle a^\dagger(t) a(t)\right\rangle + N_{ef}$$
$$\propto \sin^2(\theta_r/2)$$



Time-dependence:

- Falling edge: cavity decay
- Rising edge: detection bandwidth

Rabi angle dependence:

- **Maximum signal for** $|1\rangle$
- Excellent agreement with theory

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

Single-Channel Power vs. Two-Channel Cross Power

Single channel power:

system noise uncorrelated from signal $\langle a h_e^\dagger \rangle = \langle a \rangle \langle h_e^\dagger \rangle$

$$\langle S_e^\dagger S_e \rangle / g^2 = \langle a^\dagger a \rangle + \langle h_e h_e^\dagger \rangle + \cancel{\underbrace{\langle a \rangle \langle h_e^\dagger \rangle + \langle a^\dagger \rangle \langle h_e \rangle}_{=0}}$$

signal photons

added noise photons

system noise is Gaussian with vanishing mean

… vs. cross power:

$$\langle S_e^\dagger S_f \rangle / g^2 = \langle a^\dagger a \rangle + \underbrace{\langle h_e h_f^\dagger \rangle}_{=0} + \underbrace{\langle a \rangle \langle h_e^\dagger \rangle + \langle a^\dagger \rangle \langle h_e \rangle}_{=0} = \langle a^\dagger a \rangle$$

v in vacuum

Noise in 2 detection channels uncorrelated

… similar for higher order moments:

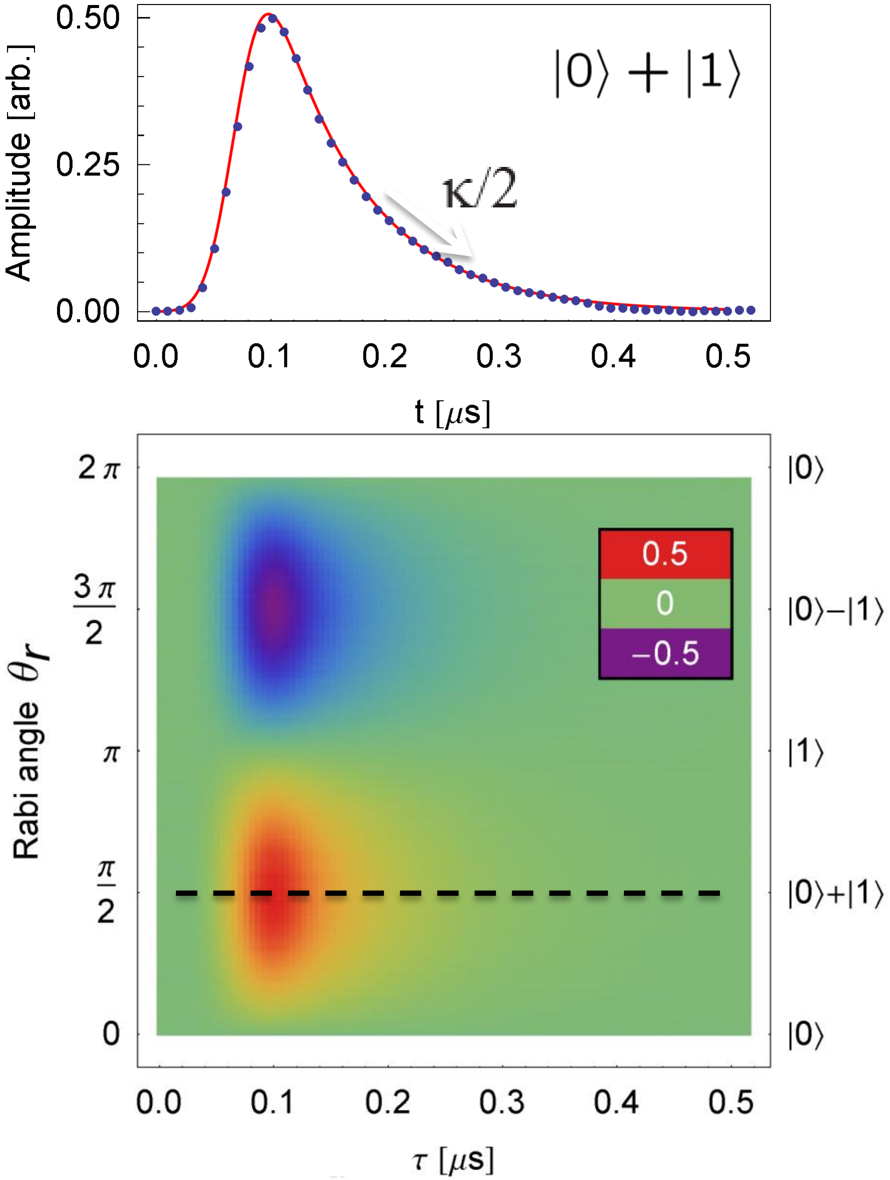
$$\langle (S_e^\dagger)^2 S_f^2 \rangle = \langle (a^\dagger)^2 a^2 \rangle$$

whereas

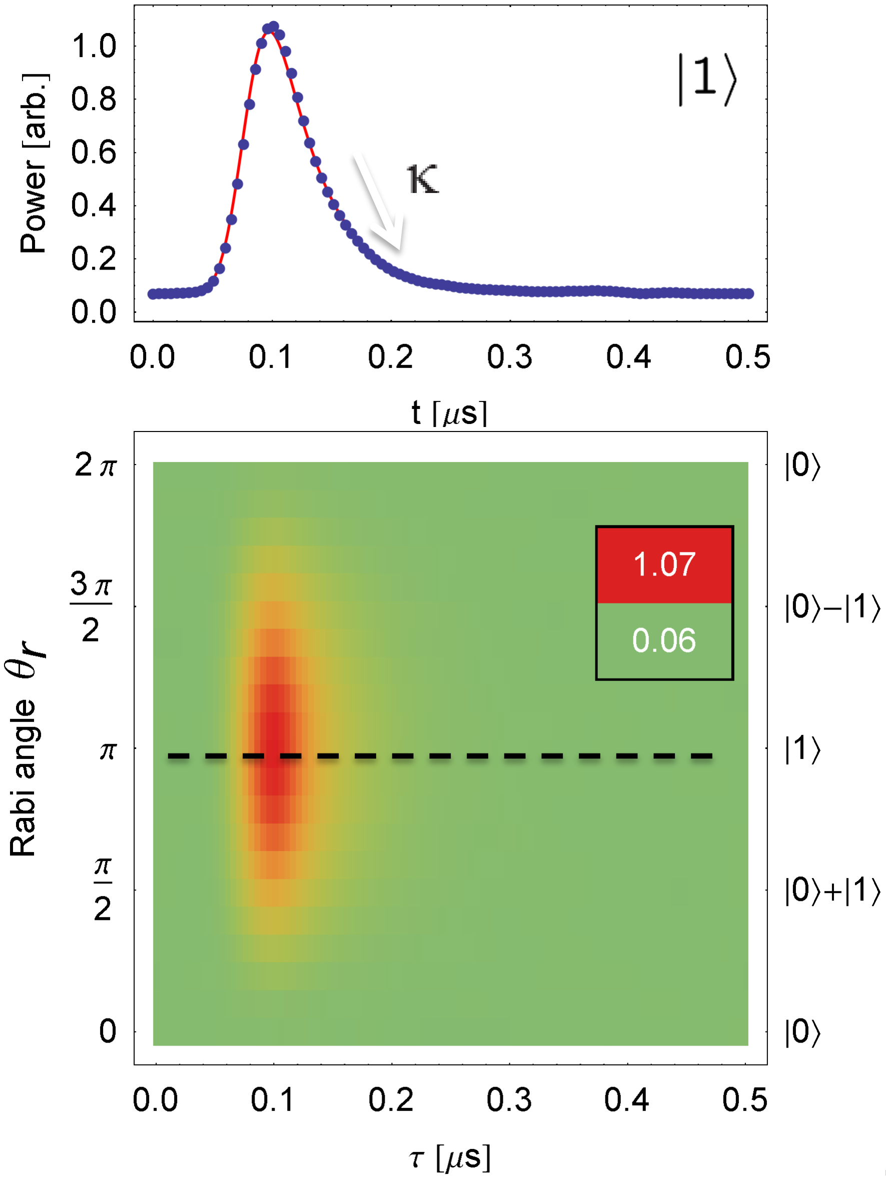
$$\langle S_e^\dagger S_e S_f^\dagger S_f \rangle = \langle (a^\dagger)^2 a^2 \rangle + \langle a^\dagger a \rangle \langle h_e h_e^\dagger \rangle + \ldots$$

Field Quadrature and Photon Number Measurements

Measure quadratures at channel b:



Measure cross-power between channel e&f:

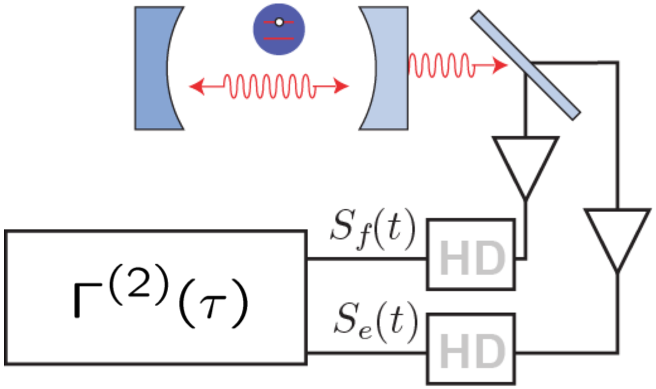


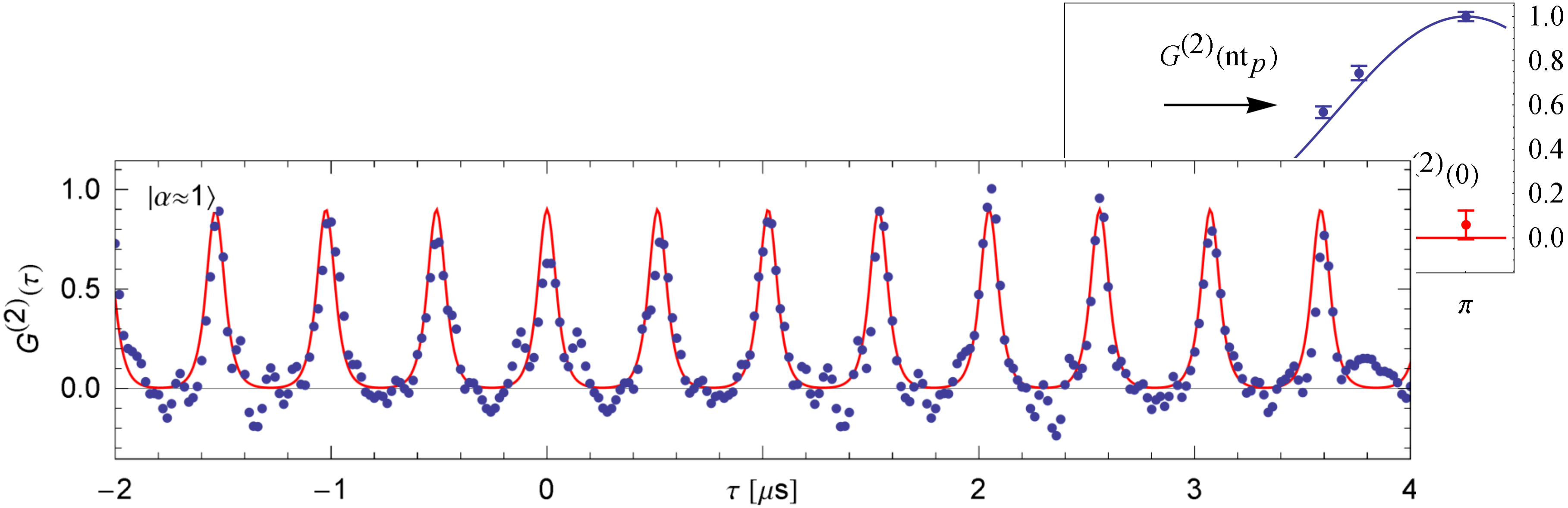
$G^{(2)}$ Measurement

Measure power correlation between channel e & f:

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

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





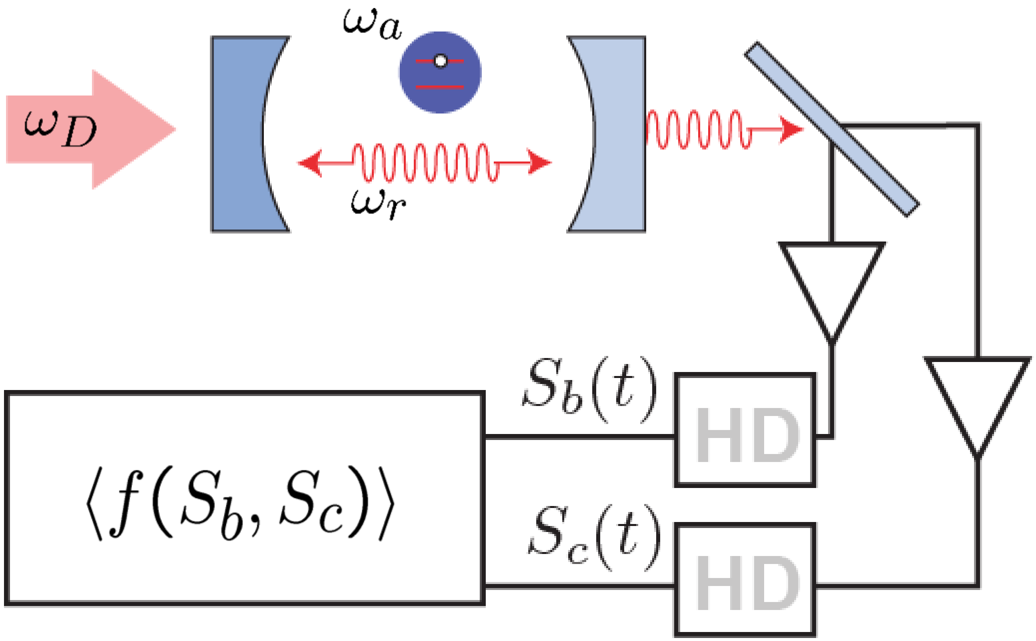
$G^{(2)}$ measurement for a microwave frequency single photon source

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

Continuously Pumped Single Photon Source and Beam-Splitter

Continuously Pumped Microwave Single Photon Source

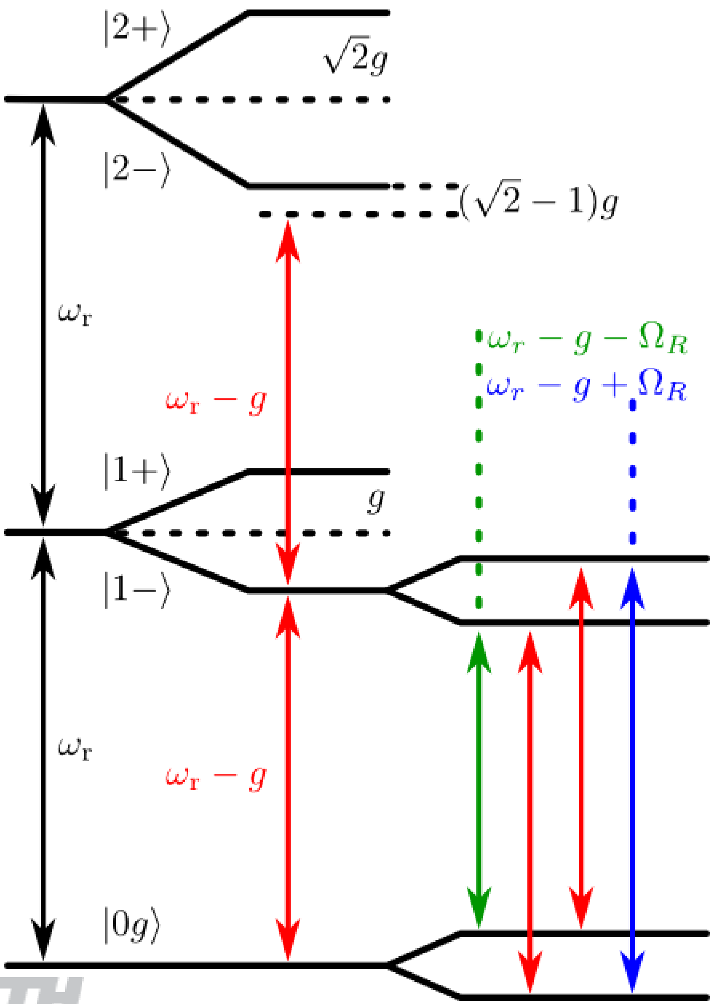
- Based on photon blockade (c.f. Coulomb blockade)
  Imamoglu et al., PRL **79**, 1467 (1997)
- mediated photon/photon interactions
- Characterization by field amplitude measurements
- FPGA based correlation analysis



M. P. da Silva et al., *PRA* **82,** 043804 (2010)
D. Bozyigit et al., *Nat. Phys.* **7**, 154 (2011)
C. Lang *et al., PRL* **106**, 243601 (2011)

Photon Blockade: A Single Photon Turnstile

Level diagram:



- Vacuum Rabi mode splitting:

$$|n, \mp\rangle = 1/\sqrt{2} \cdot (|n, g\rangle \mp |n-1, e\rangle)$$

- Drive:

$$\omega_p = \omega_r - g$$

- Photon blockade: first photon enters cavity second is blocked
- mediated photon/photon interactions
- Effective two-level system (polariton)

$$|\downarrow\rangle = |0, g\rangle \qquad |\uparrow\rangle = |1, -\rangle$$

  - Mollow-type triplet:

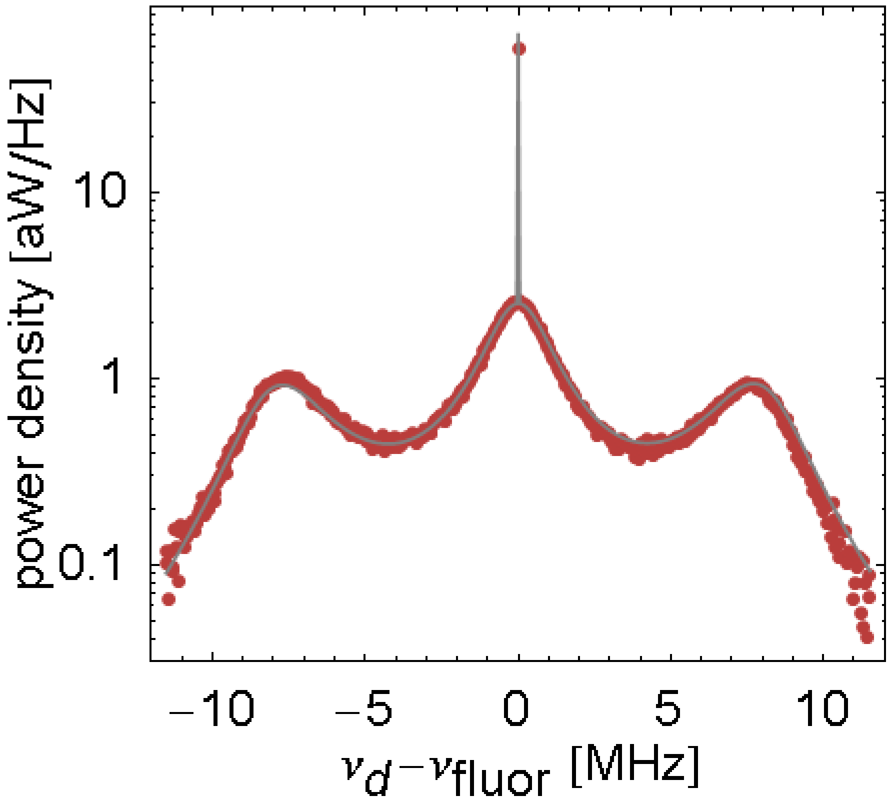
$$\omega_{1,2,3} = \omega_p \begin{cases} +0 \\ \pm\Omega_R \end{cases}$$

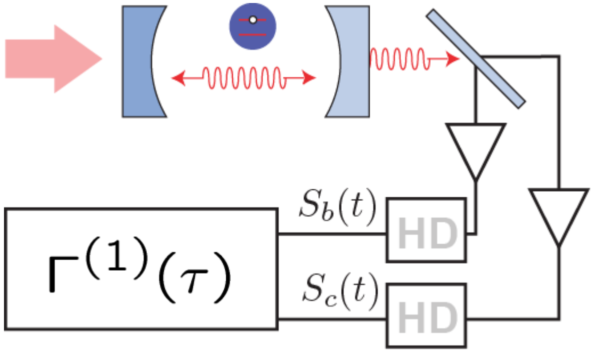
C. Lang *et al.*, *PRL* **107**, 243601 (2011)

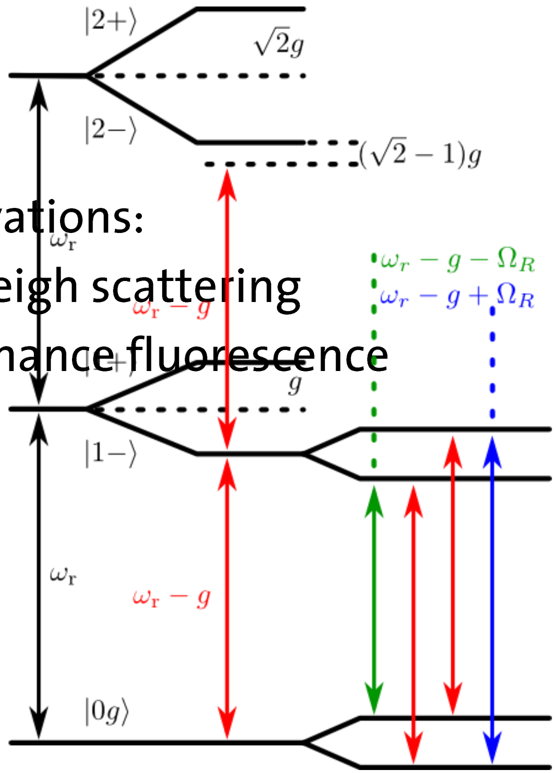
Polariton Mollow Triplet Measurement

(cross-)power spectrum:

$$\mathcal{F}\{\Gamma^{(1)}(\tau)\} = \langle \mathcal{F}\{S_b(t)\} \cdot \mathcal{F}\{S_c(t)\}^* \rangle$$





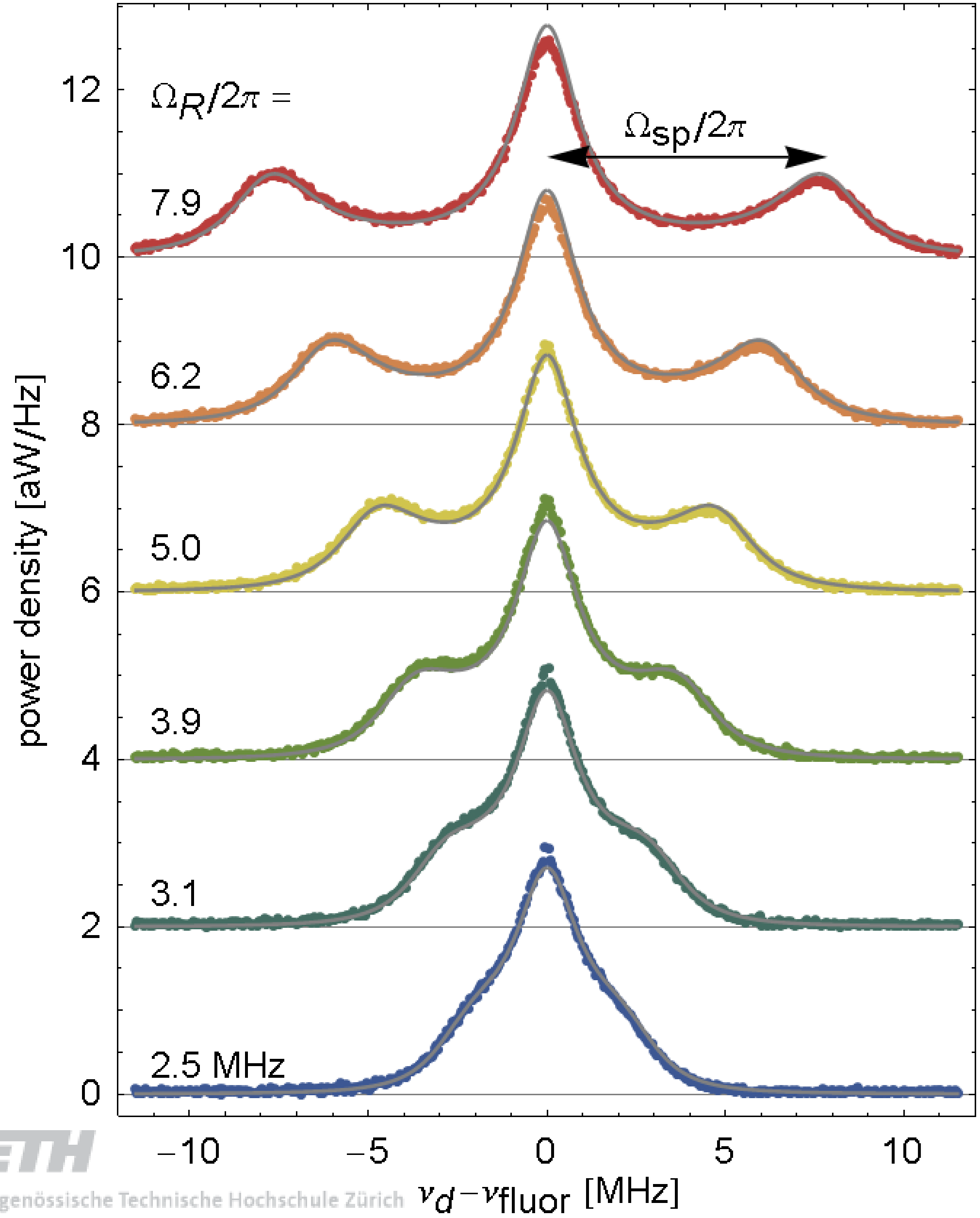


observations:

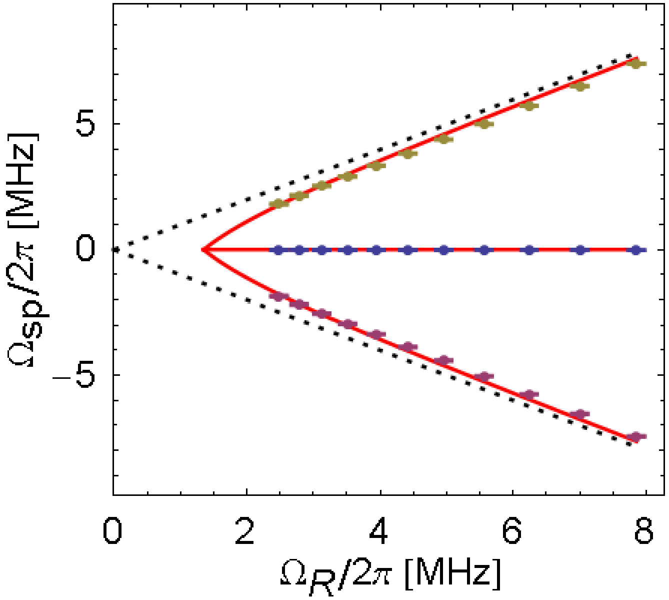
- Rayleigh scattering
- resonance fluorescence

C. Lang *et al.*, *PRL* **106**, 243601 (2011)

Dependence on Drive Amplitude



- 'Mollow' fluorescence sidebands at Rabi frequency Ω_{sp}



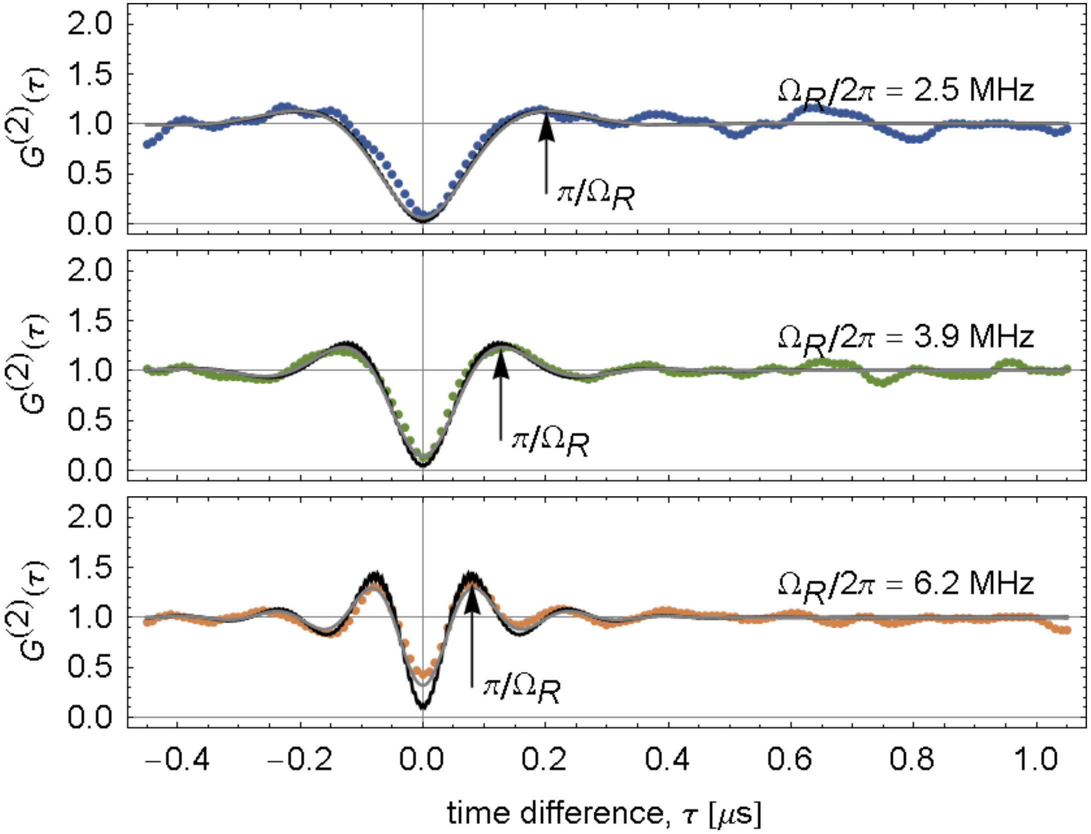
- analytical expression explains nonlinear drive scaling

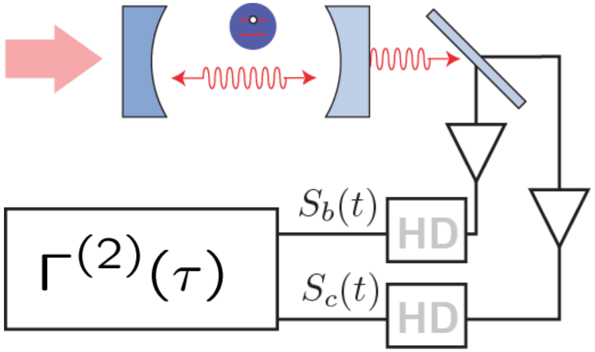
C. Lang *et al.*, *PRL* **106**, 243601 (2011)

Antibunching and Subpoissonian Statistics

- intensity/intensity correlation function (dots)

$$\Gamma^{(2)}(\tau) = \int \langle S_b^* S_b(t) S_c^* S_c(t+\tau)\rangle \, dt$$





observations:

- sub-Possionian statistics
- anti-correlation at τ = 0
- Rabi oscillations visible

solid lines are master equation simulations

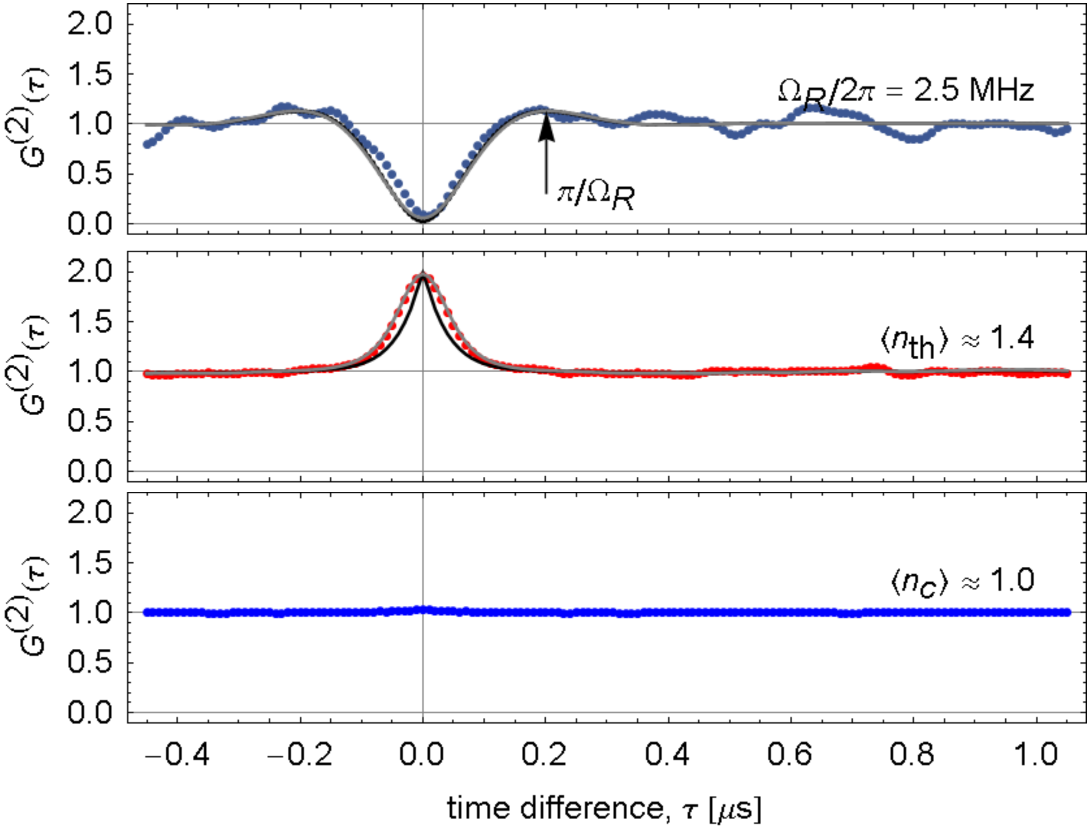
C. Lang *et al., PRL* **106**, 243601 (2011)

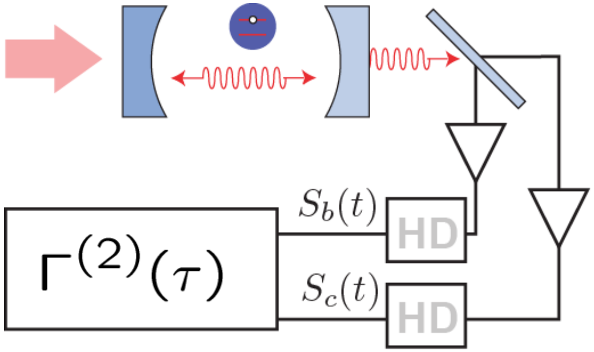
also dispersive photon blockade: A. J. Hoffman *et al., PRL* **107**, 053602 (2011)

Compare to Thermal and Coherent Fields

- intensity/intensity correlation function (dots)

$$\Gamma^{(2)}(\tau) = \int \langle S_b^* S_b(t) S_c^* S_c(t+\tau)\rangle \, dt$$





thermal field:

- $G^{(2)}(0) = 2$
- $G^{(2)}(\tau) = 1$ for large τ

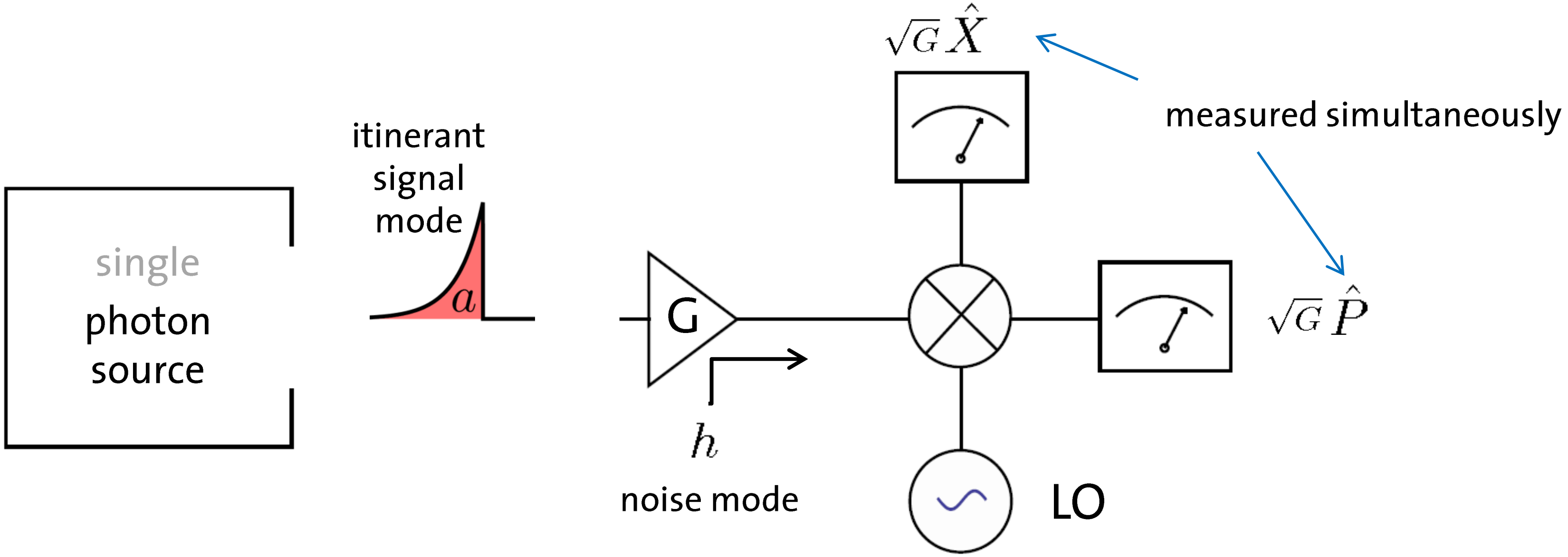
coherent field:

- $G^{(2)} = 1$

C. Lang *et al.*, *PRL* **106**, 243601 (2011)

Tomography of Pulsed Single Photon Source

Tomography using Microwave Quadrature Detection



complex amplitude: $\boxed{\sqrt{G}(a+h^\dagger) \equiv \hat{S} \equiv \sqrt{G}(\hat{X}+i\hat{P})}$

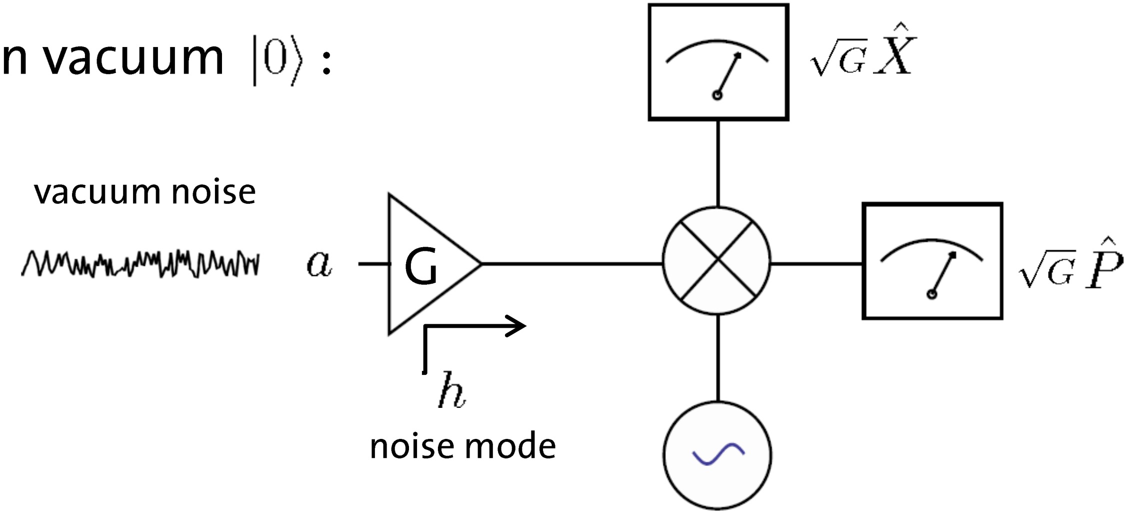
ideal (quantum limited) case: h in vacuum state $|0\rangle$

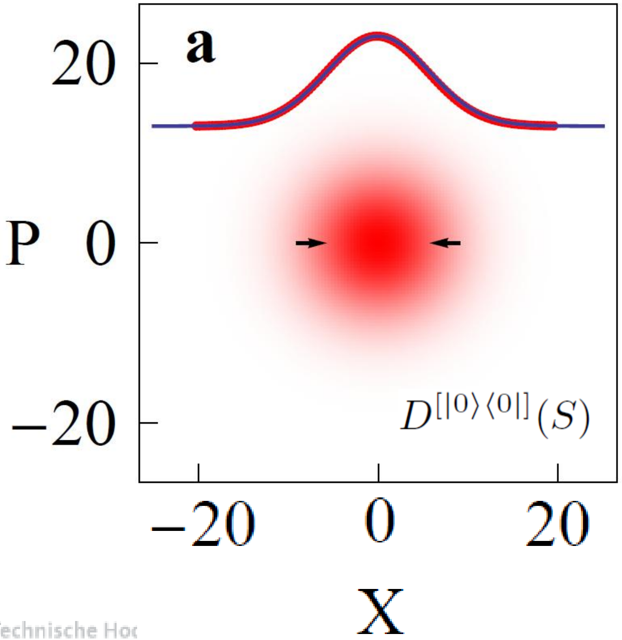
real (commercial amplifier) case: h in thermal state with N_{noise} photons

C. Eichler et al., *PRA* **86**, 032106 (2012)
M. P. da Silva et al., *PRA* **82**, 043804 (2010)
C. M. Caves, *PRD* **26**, 1817 (1982)

Full Tomography of a Single Propagating Mode

1) prepare a in vacuum $|0\rangle$:





record histogram $D^{[|0\rangle\langle 0|]}(S)$

of measurement results $S/\sqrt{G} = X + iP$

normal distribution with variance

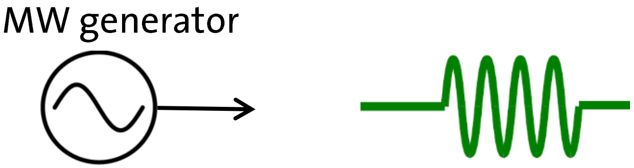
$$2\sigma^2 = \langle \hat{S}^\dagger \hat{S} \rangle / G = \frac{1}{G} \int \mathrm{d}^2 S \, D^{[|0\rangle\langle 0|]}(S) \, S^* S = 67$$

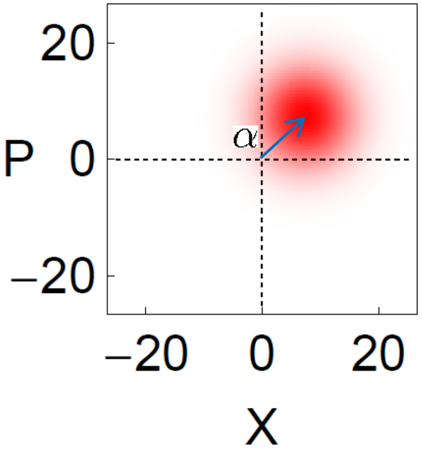
h introduces thermal noise

with mean photon number N_{noise}

Coherent State Histograms

2) prepare a in coherent state $|\alpha\rangle$:



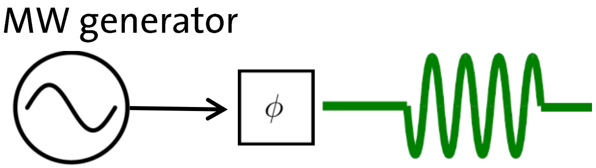


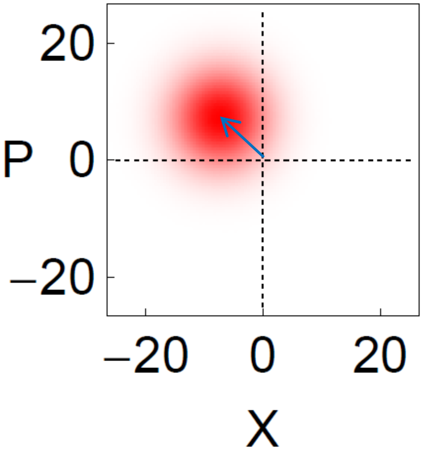
$$|\alpha| \approx 6.3$$

$$\Leftrightarrow$$

$$\langle a^\dagger a\rangle \approx 41 \sim N_{\text{noise}}$$

3) rotate phase $|e^{i\phi}\alpha\rangle$:





Question: What can we learn about state when $\langle a^\dagger a\rangle \leq 1$?

Single Photon Source Histogram

store 2D histogram $D^{[\rho]}(S)$ from $S/\sqrt{G} = X + iP$ measurement results:

corresponding
phase space
distribution

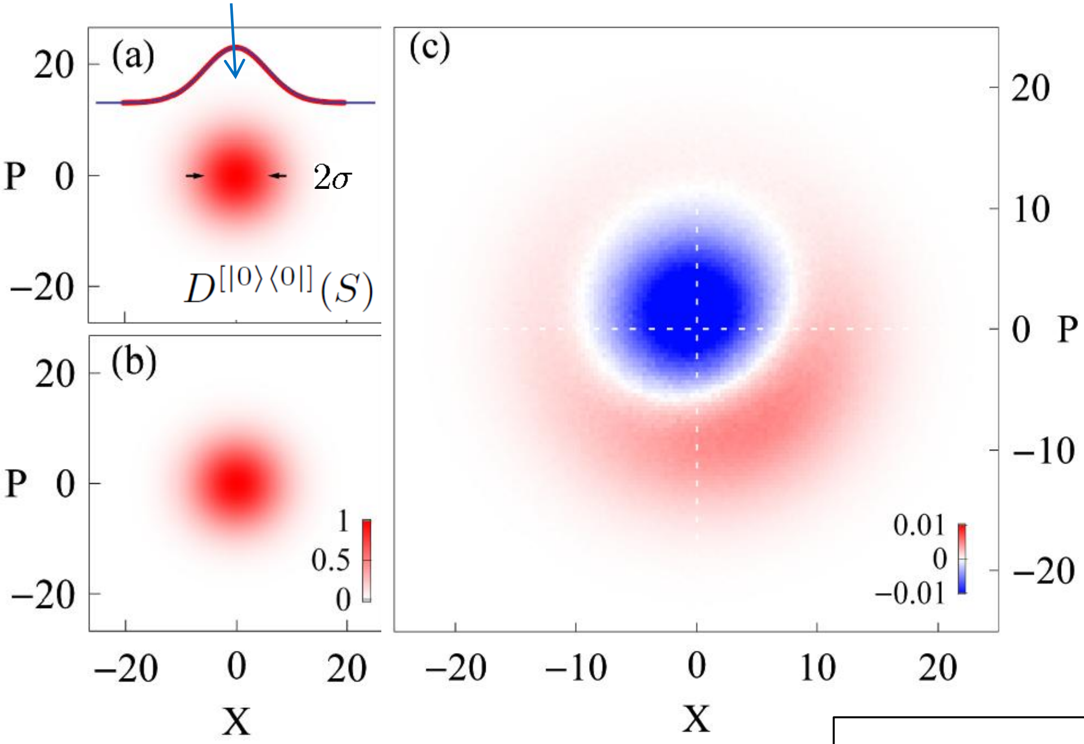
Q - function
of noise mode :

Q_h

convolution
with **P** – function
of signal

$Q_h * P_a$

signal mode a
in **vacuum**



subtracted
histograms
to visualize
difference

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

separate noise h from
signal a systematically!

C. Eichler, et al., *PRL* **106**, 220503 (2011), *PRA* **86**, 032106 (2012)

Statistical Analysis of Histograms

systematic mode separation:

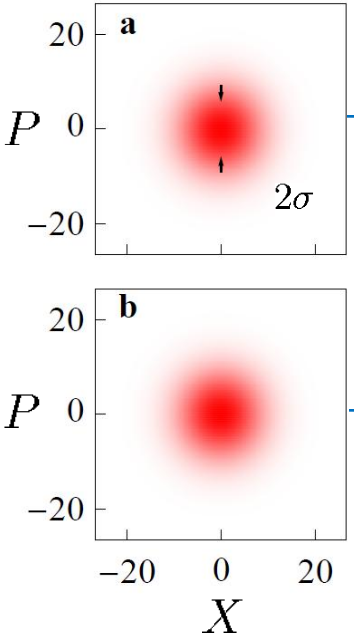
histogram moments: $\langle (\hat{S}^\dagger)^n \hat{S}^m \rangle_\rho = \int \mathrm{d}^2 S \; (S^*)^n S^m \; D^{[\rho]}(S)$

1. calculate histogram moments

2. algebraic inversion

vacuum $|0\rangle$

Fock state $|1\rangle$



$$\left.\begin{aligned} \frac{\langle (\hat{S}^\dagger)^n \hat{S}^m \rangle_{|0\rangle\langle 0|}}{G^{(n+m)/2}} &= \langle h^n (h^\dagger)^m \rangle \\ \frac{\langle (\hat{S}^\dagger)^n \hat{S}^m \rangle_{|1\rangle\langle 1|}}{G^{(n+m)/2}} &= \langle (h + a^\dagger)^n (h^\dagger + a)^m \rangle \end{aligned}\right\} \langle (a^\dagger)^n a^m \rangle$$

reminder: $X + iP = S/\sqrt{G} = (a + h^\dagger)$

C. Eichler, et al., *PRL* **106**, 220503 (2011), *PRA* **86**, 032106 (2012)

State Dependent Moments of Probability Distribution

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

Fock state

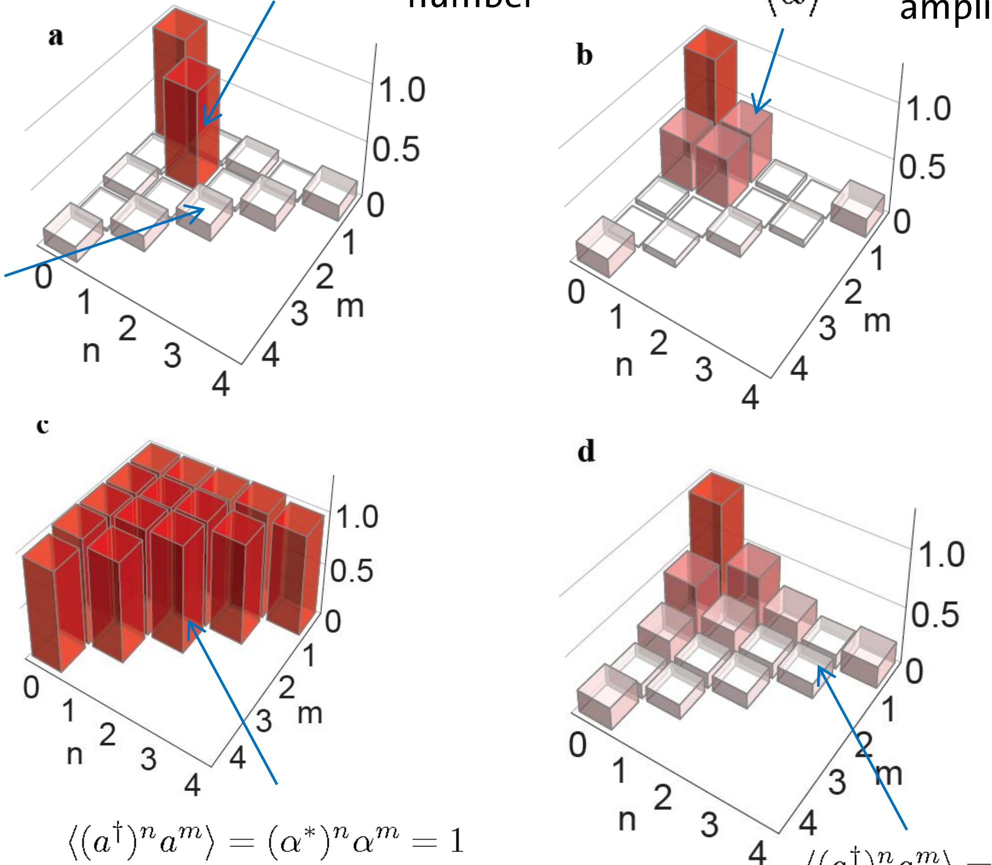
$|1\rangle$

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

“anti bunching”

$\langle a^\dagger a \rangle =$ “mean photon number”

$\langle a \rangle =$ “mean amplitude”



superposition

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

coherent state

$|\alpha = 1\rangle$

$\langle (a^\dagger)^n a^m \rangle = (\alpha^*)^n \alpha^m = 1$

coherent state

$|\alpha = 0.5\rangle$

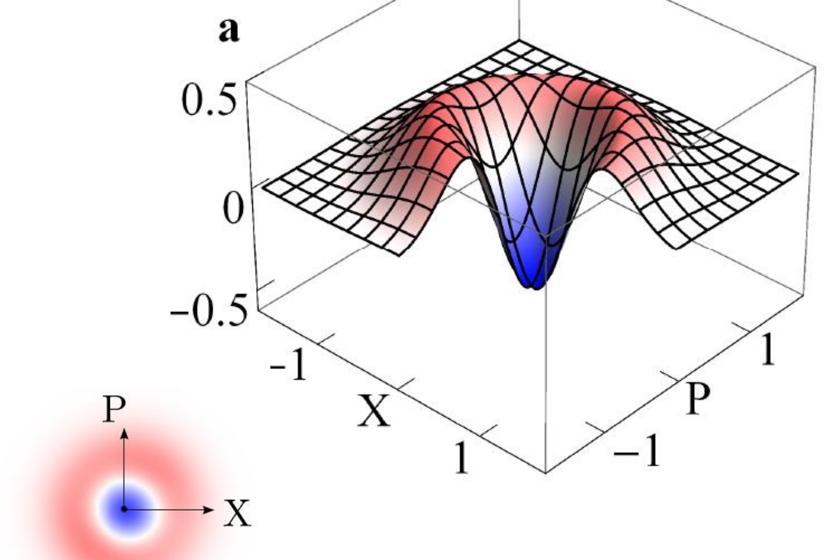
$\langle (a^\dagger)^n a^m \rangle = (1/2)^{n+m}$

C. Eichler, et al., *PRL* **106**, 220503 (2011), *PRA* **86**, 032106 (2012)

Reconstructed Wigner Function of Itinerant Photon

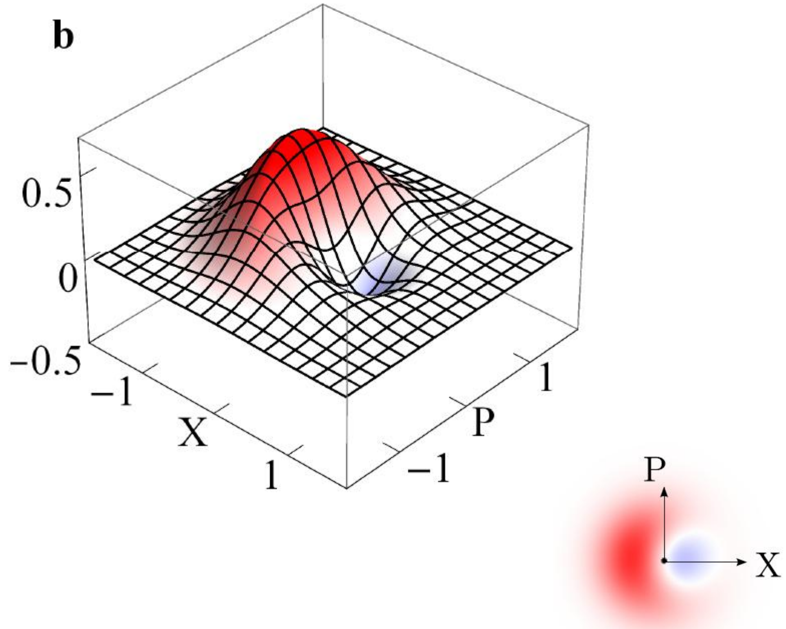
Wigner function reconstructed from measured moments:

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



Fock state

$|1\rangle$



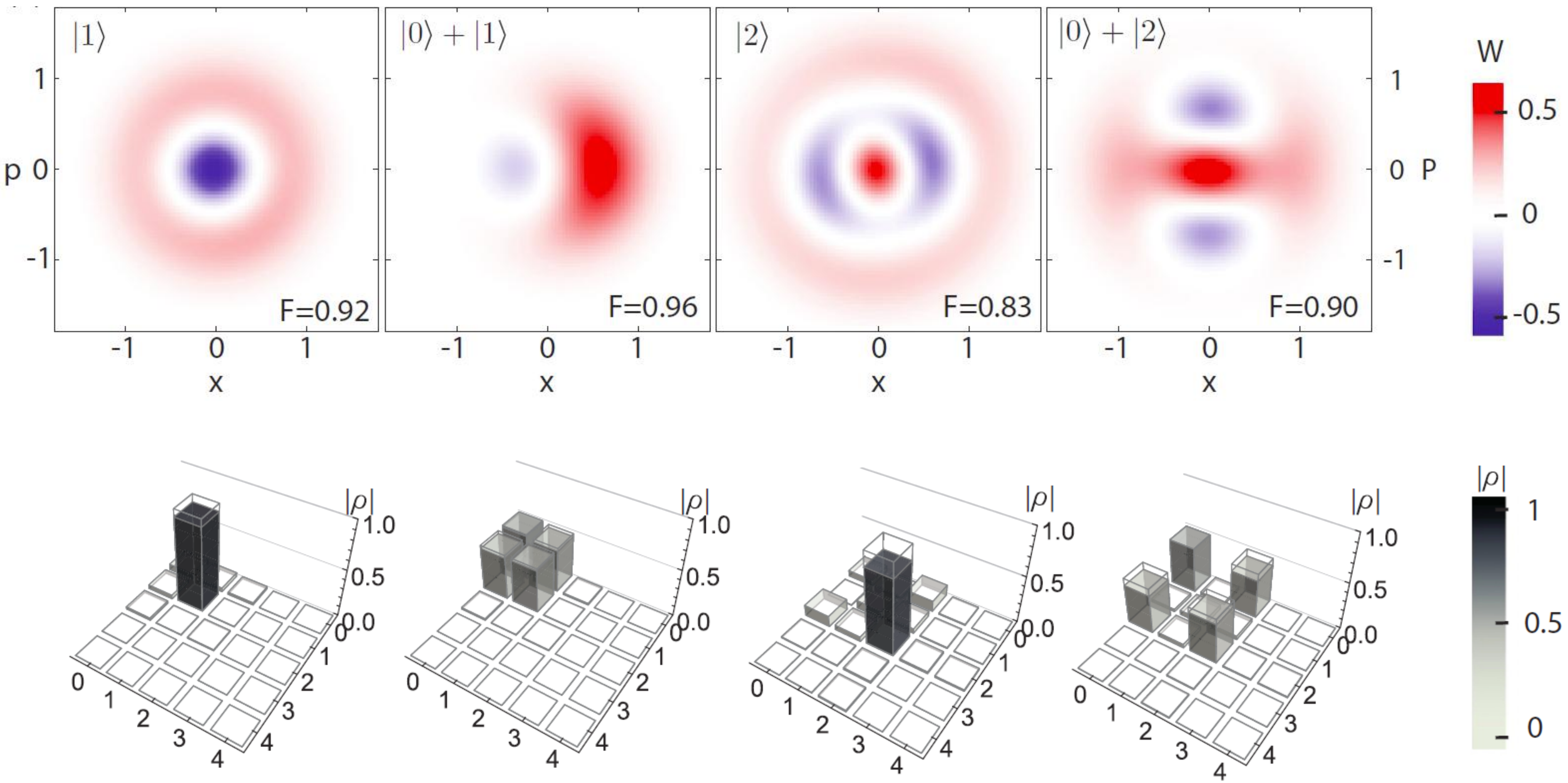
superposition

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

C. Eichler, et al., *PRL* **106**, 220503 (2011), *PRA* **86**, 032106 (2012)

Wigner Function and Density Matrices ...

... for **propagating multi-photon** Fock states and their superpositions:



measured using near-quantum-limited parametric amplifier

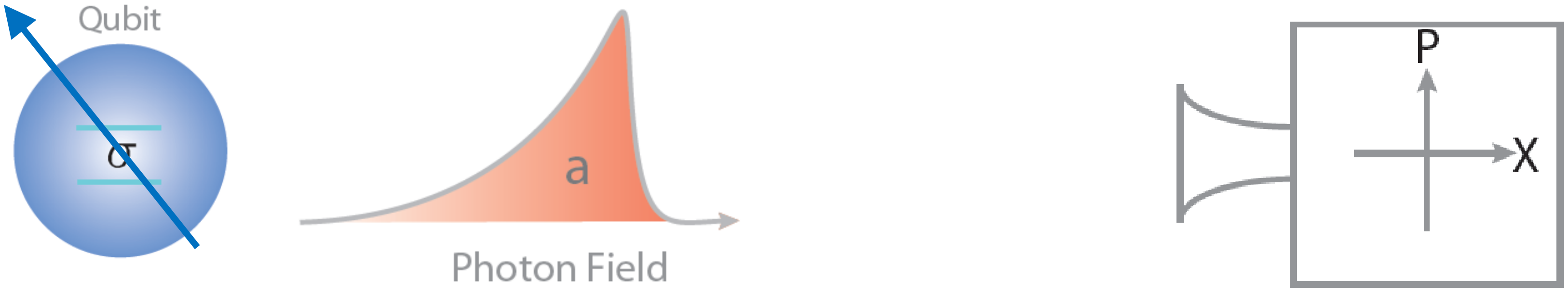
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

C. Eichler et al., *PRA* **86**, 032106 (2012)

Two-Mode Squeezing with Parametric Amplifier

Entanglement between Propagating Photon and Stationary Qubit

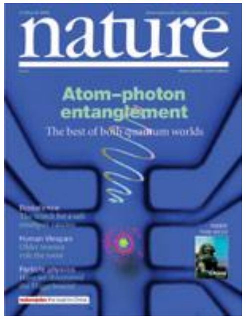
Entanglement of Localized and Propagating Modes



- test of correlations between propagating photon and qubit
- probe non-local aspects of quantum mechanics in circuits

- interfacing stationary and flying qubits
- entanglement distribution in a quantum network

Photon/Qubit Entanglement at Optical Frequencies


nature

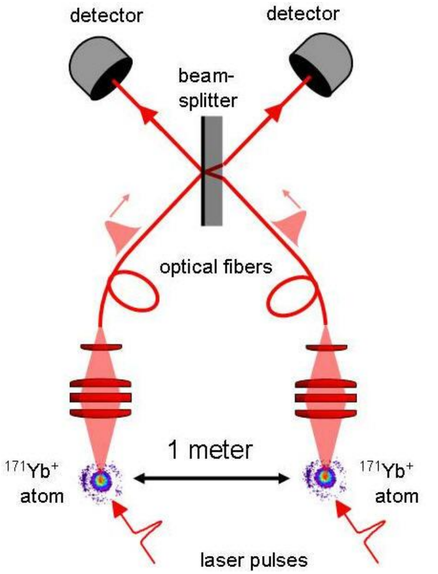
Atom–photon entanglement

The best of both quantum worlds

Atom–Photon Entanglement

Blinov *et al.*, *Nature* **428**, 153 (2004)

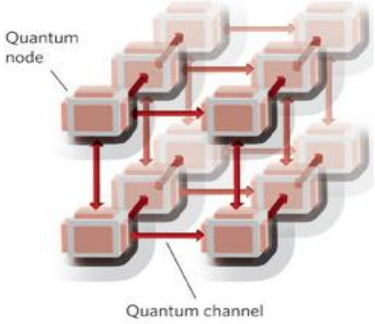
Volz *et al.*, *PRL* **96**, 030404 (2006)



Atom–Atom Entanglement

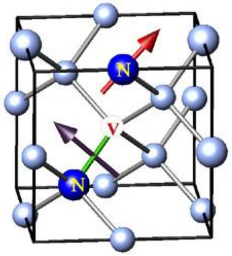
Moehring *et al.*, *Nature* **449**, 68 (2007)

Ritter *et al.*, *Nature* **484**, 195 (2012)



The quantum internet

Kimble, *Nature* **453**, 1023 (2008)



Spin–Photon Entanglement

Togan *et al.*, *Nature* **466**, 730 (2010)

What about superconducting circuits?

Experiments at Microwave Frequencies

On-chip entanglement:

- Three Qubits (GHZ, W, Teleportation)
  - DiCarlo *et al., Nature* **467**, 574 (2010)
  - Neely *et al., Nature* **467**, 570 (2010)
  - Baur *et al., PRL* **108**, 040502 (2012)
  - Mlynek *et al.*, arXiv:1202.5191 (2012)
- Qubit- Resonator (arb. Res. states)
  - Haroche /Raimond, *Expl. the Quantum*
  - Hofheinz *et al., Nature* **454**, 310 (2008)
- Res–Res (Noon States)
  - Wang *et al., PRL* **106**, 060401 (2011)
  - Mariantoni *et al., Nat. Phys.* **7**, 287 (2011)

...

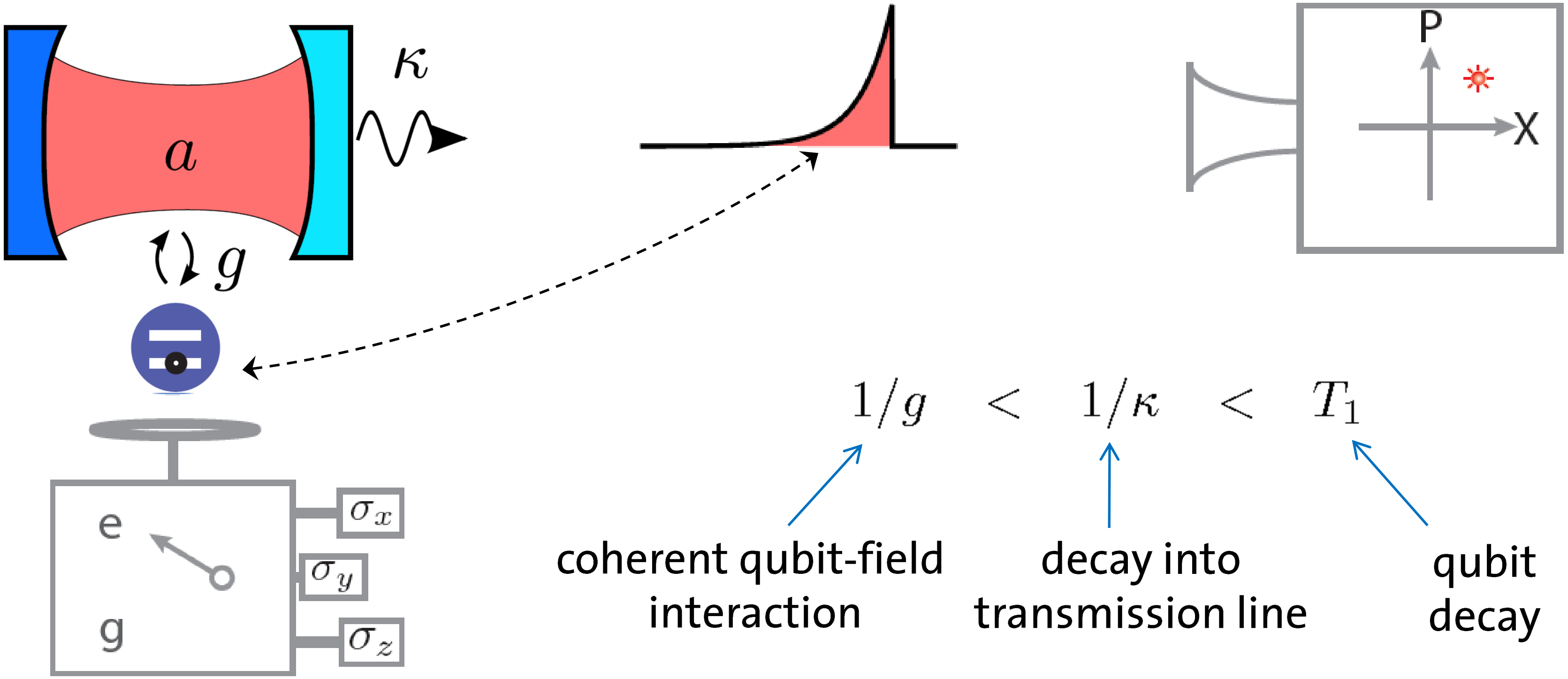
Itinerant microwave fields:

- Single Photons
  - Houck *et al., Nature* **449**, 328 (2007)
  - Bozyigit *et al., Nat. Phys.* **7**, 154 (2011)
  - Eichler *et al., PRL* **106**, 220503 (2011)
  - Lang *et al., PRL* **107**, 073601 (2011)
- Squeezed States/EPR states
  - Castellanos *et al., Nat. Phys.* **4**, 929 (2008)
  - Mallet *et al., PRL* **106**, 220502 (2011)
  - Eichler *et al., PRL* **107**, 113601 (2011)
  - Bergeal *et al., PRL* **108**, 123902 (2012)
  - Flurin *et al.*, arXiv:1204.0732 (2012)

...

Here: Entanglement of stationary qubit with itinerant microwave field.

Concept of Photon/Qubit Entanglement Experiment



$$1/g \;<\; 1/\kappa \;<\; T_1$$

coherent qubit-field interaction

decay into transmission line

qubit decay

Conditions for generation and detection of qubit/photon entanglement

Experimental Setup

- Transmon qubit

$$T_1 = 1.1\,\mu s$$
$$T_2 = 550\,ns$$
$$T_2^* = 220\,ns$$

- Single sided resonator

$$1/\kappa = 25\,ns$$

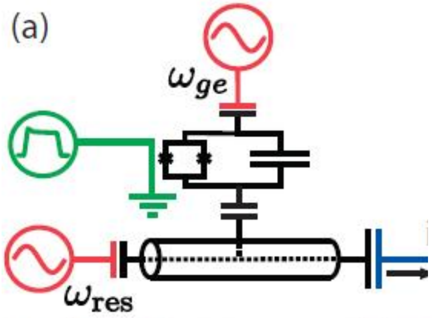
- Coupling strength

$$\pi/g = 7.7\,ns$$

- Parametric amplifier

$$\sqrt{G}B = 178\,\mathrm{MHz}$$
$$P_{1dB}\,@\sim 16\,\mathrm{photons}$$

Castellanos-Beltran *et al.*, *Nat. Phys.* **4**, 929 (2008)



Detector = Paramp + ...

Eichler *et al.*, *arXiv:1209.0441* (2012)

Prepare and Measure Qubit/Photon Entanglement

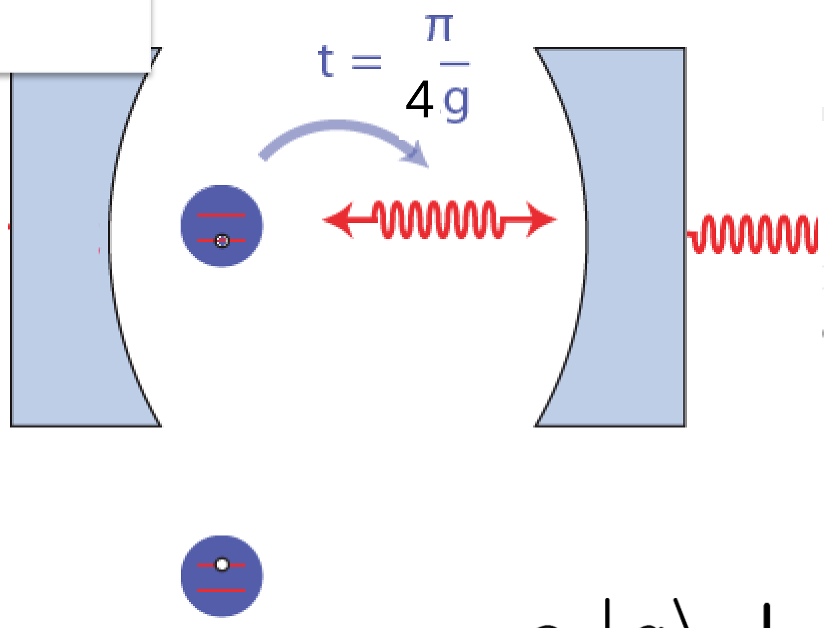
Step 2:

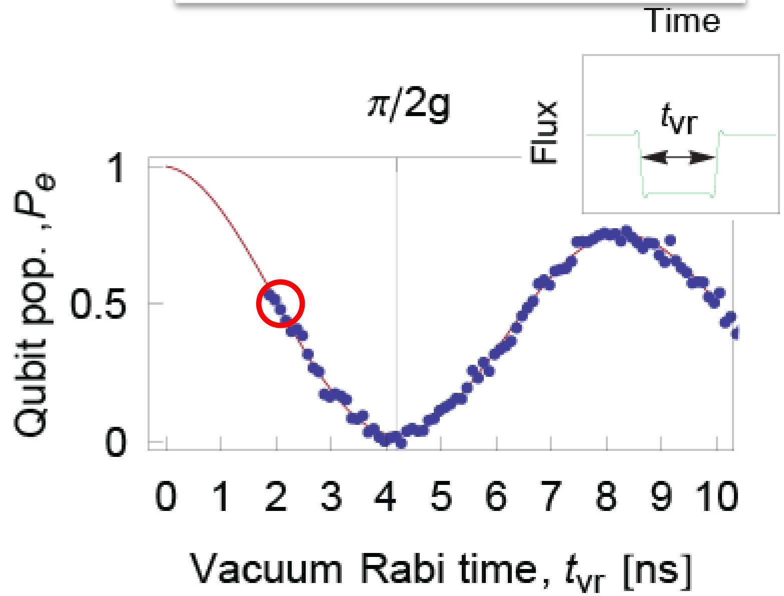
Entangle qubit with resonator by 1/4 vacuum Rabi oscillation

$$\frac{1}{\sqrt{2}}(|0e\rangle + |1g\rangle)$$

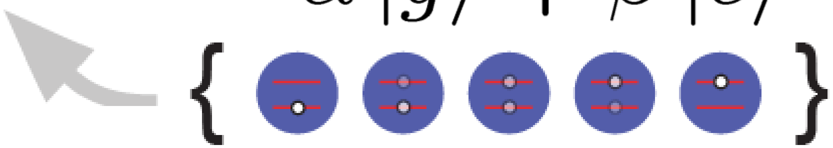
Step 3:

Measure qubit and photon state.





$$\alpha\,|g\rangle + \beta\,|e\rangle$$

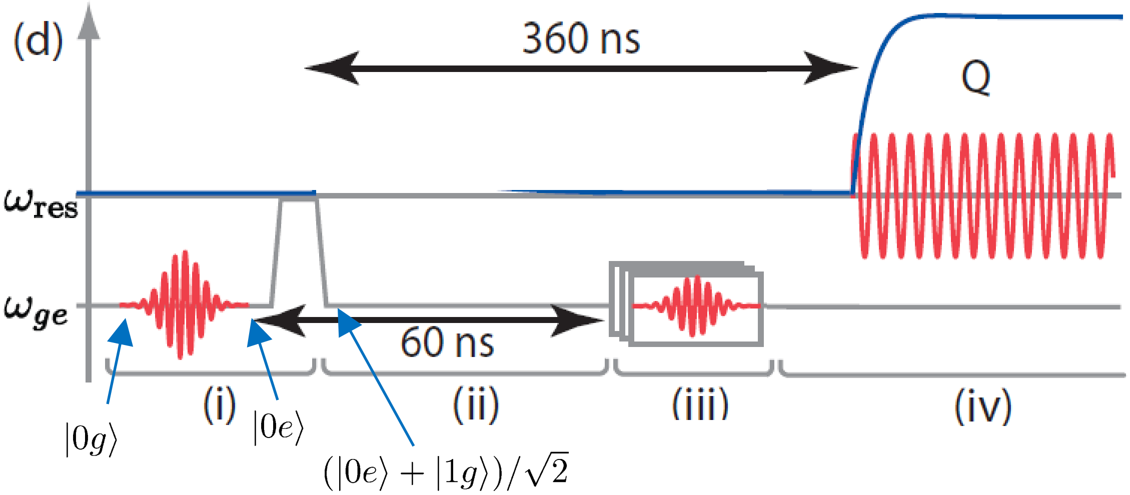


Step 1:

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

Exp. Entanglement Generation and Detection Sequence



(i) preparation of Bell state

$$\frac{1}{\sqrt{2}}(|0e\rangle + |1g\rangle)$$

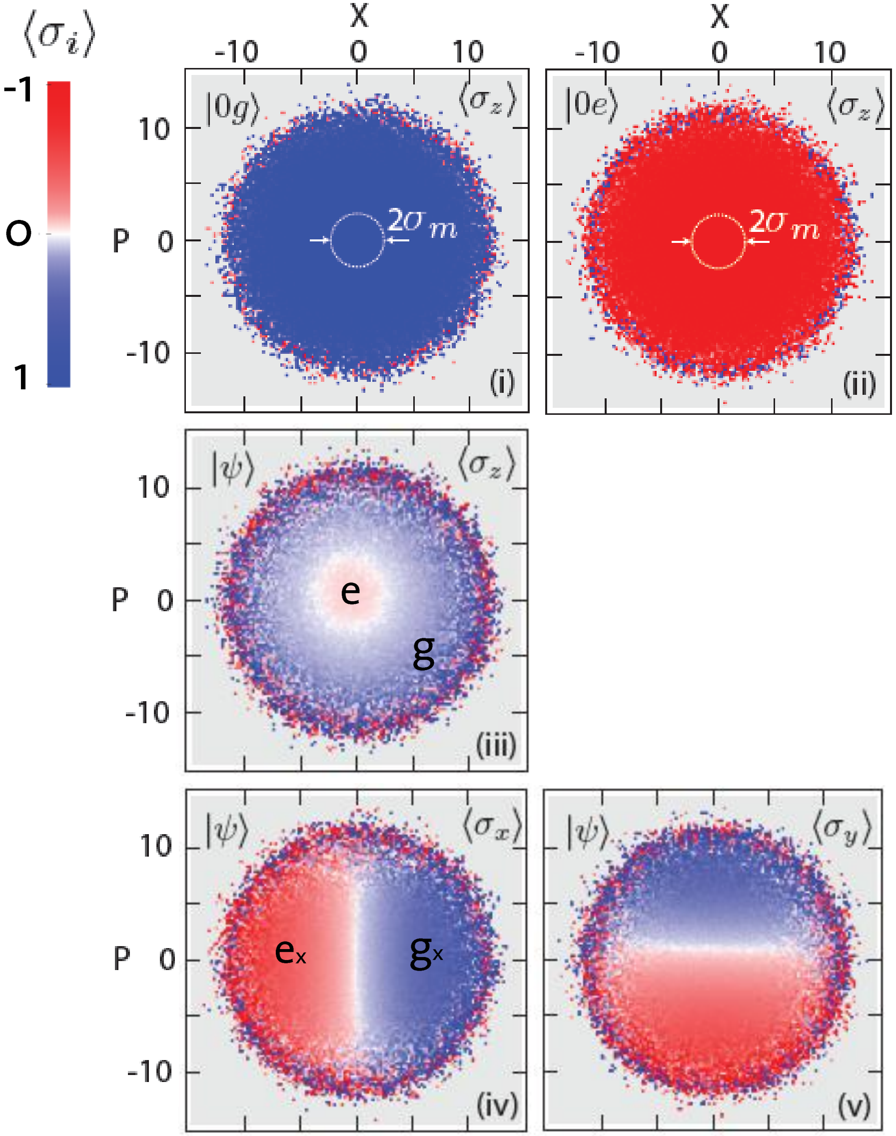
(ii) field decay into transmission line and measurement of X and P

(iii) qubit tomography pulses

(iv) dispersive qubit read-out

Eichler *et al.*, *arXiv:1209.0441* (2012)

Measurement Results



und state

e

ation vs.

$+ iP$

→ as expected $\langle\sigma_z\rangle_\alpha$ independent of α

Analyzing the Bell state

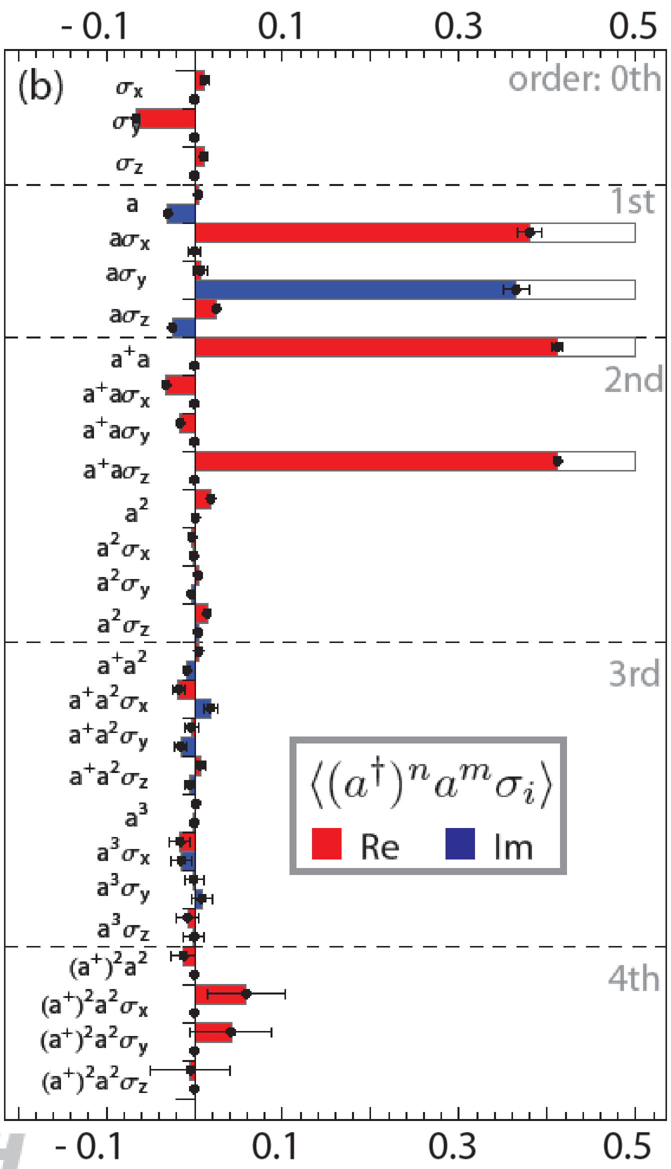
$$|\psi\rangle = |0e\rangle + |1g\rangle$$

Probing coherences:

$$= |e_x\rangle\underbrace{(|1\rangle - |0\rangle)}_{\langle\hat{X}\rangle < 0} + |g_x\rangle\underbrace{(|1\rangle + |0\rangle)}_{\langle\hat{X}\rangle > 0}$$

exp: C. Eichler *et al.*, *arXiv:1209.0441* (2012)
theo: C. Eichler *et al.*, *Phys. Rev. A* **86**, 032106 (2012)

Extract Expectation Values of Moments of Distribution



0^{th} : qubit state with **photon** traced out

1^{st} : **phase correlations** between qubit and photon field

2^{nd} : **number** correlations!

e <-> no photon

g <-> one photon

3^{rd}, 4^{th} : no higher photon number states!

exp: C. Eichler *et al., arXiv:1209.0441* (2012)

theo: C. Eichler *et al., Phys. Rev. A* **86**, 032106 (2012)

Photon/Qubit Joint State Density Matrix

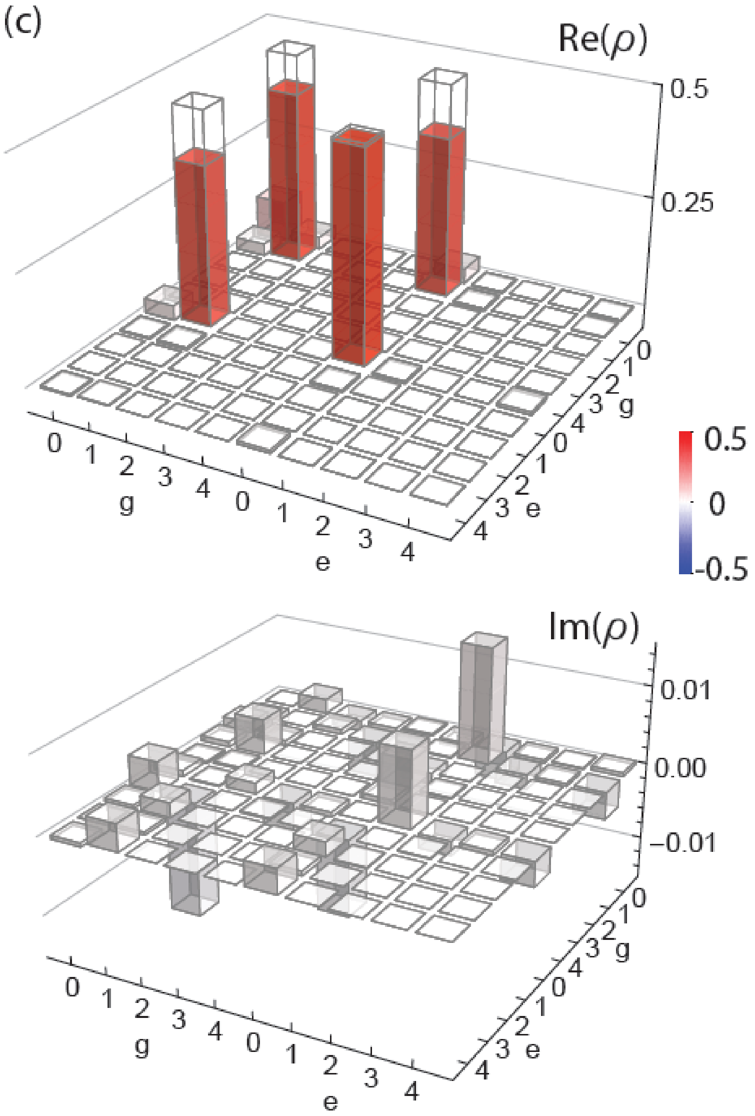
Reconstruction from measured moments

Fidelity: $\langle\psi|\rho|\psi\rangle = 0.83$

Limited by qubit decay during time required for photon detection in same mode.

Extension to states with more than a single photon possible, e.g.:

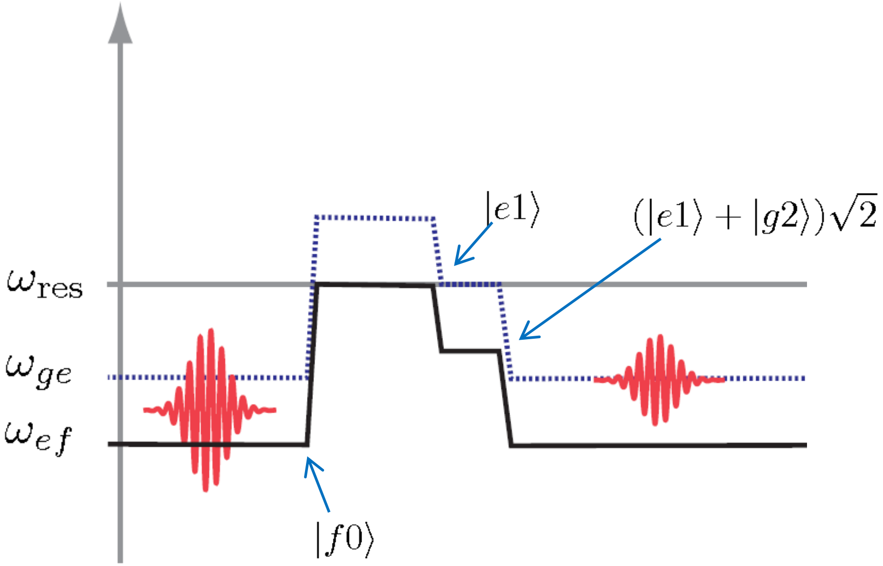
$$\frac{1}{2}[|g\rangle(|1\rangle + |2\rangle) + |e\rangle(|1\rangle - |2\rangle)]$$



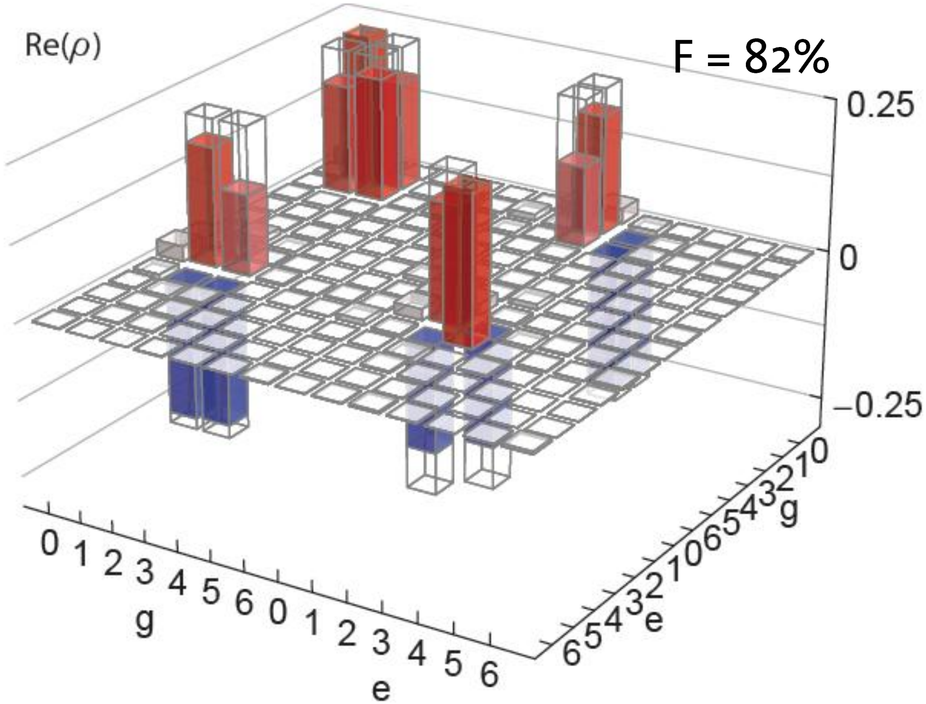
exp: C. Eichler *et al.*, *arXiv:1209.0441* (2012)
theo: C. Eichler *et al.*, *Phys. Rev. A* **86**, 032106 (2012)

Qubit Entangled with Two Propagating Photons

state: $\frac{1}{2}[|g\rangle(|1\rangle+|2\rangle)+|e\rangle(|1\rangle-|2\rangle)]$ → use second excited state of qubit for preparation



joint state tomography

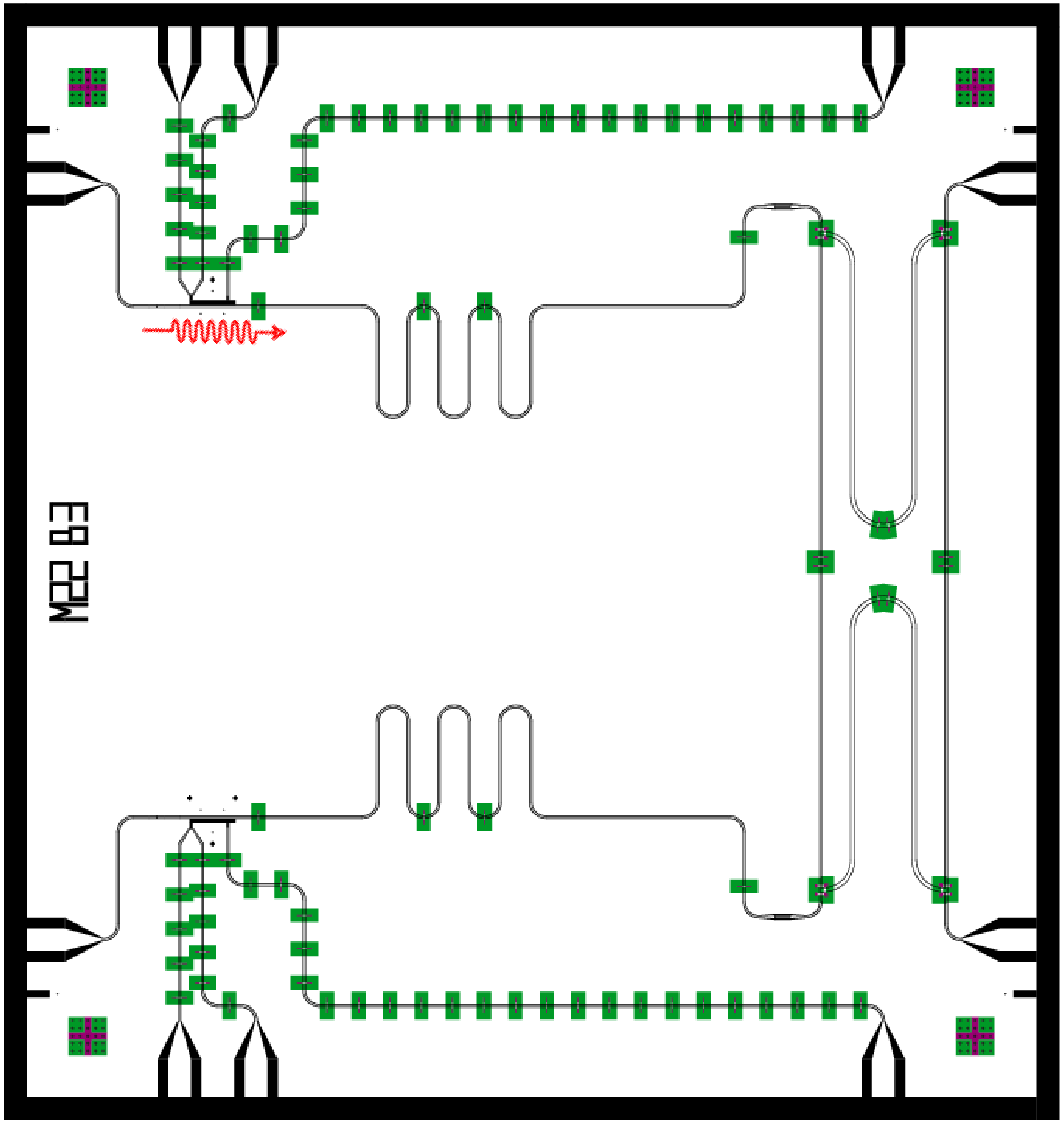


F = 82%

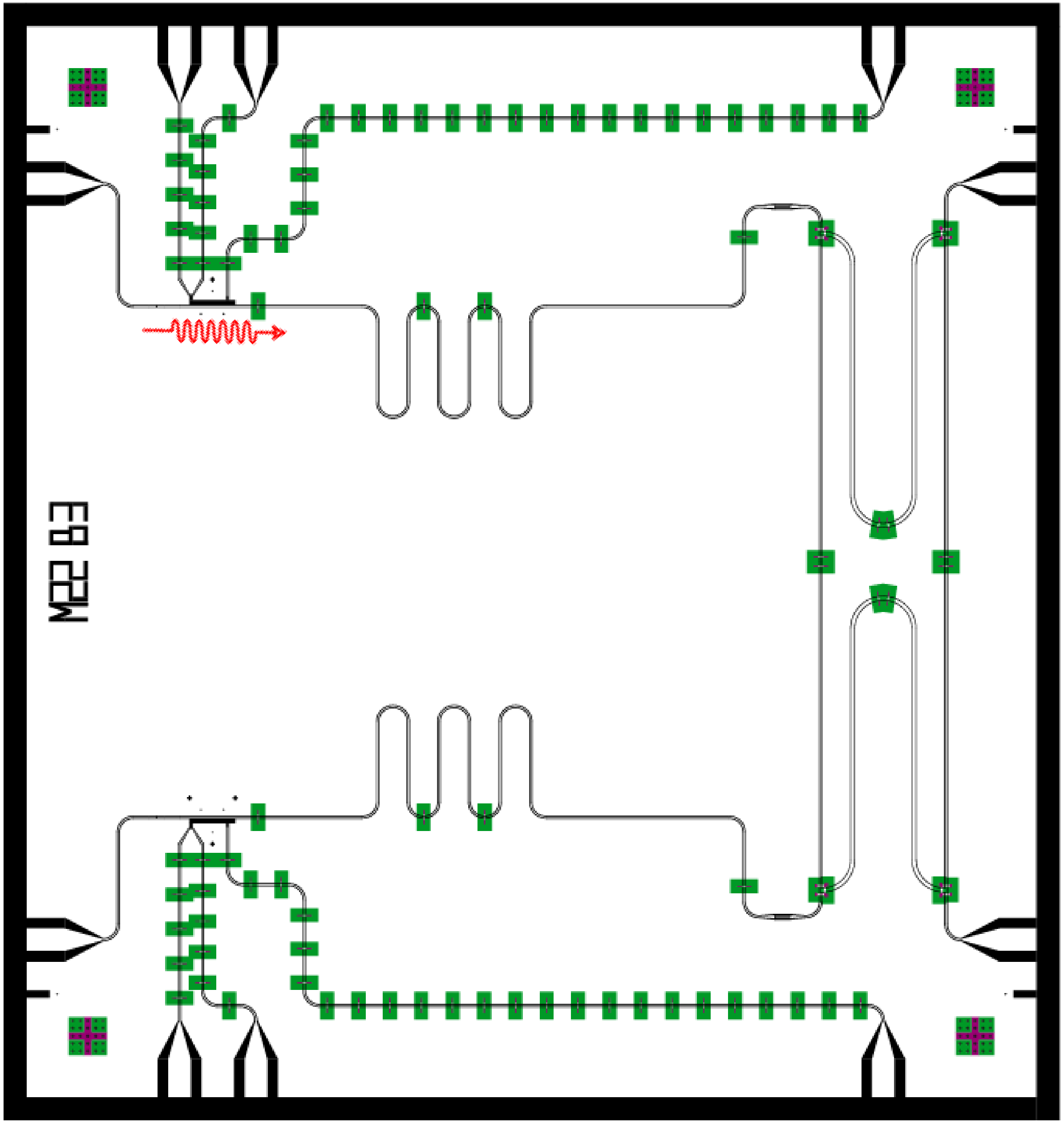
exp: C. Eichler *et al., arXiv:1209.0441* (2012)
theo: C. Eichler *et al., Phys. Rev. A* **86**, 032106 (2012)

Two-Photon Interference:
The Hong-Ou-Mandel Experiment with Microwaves

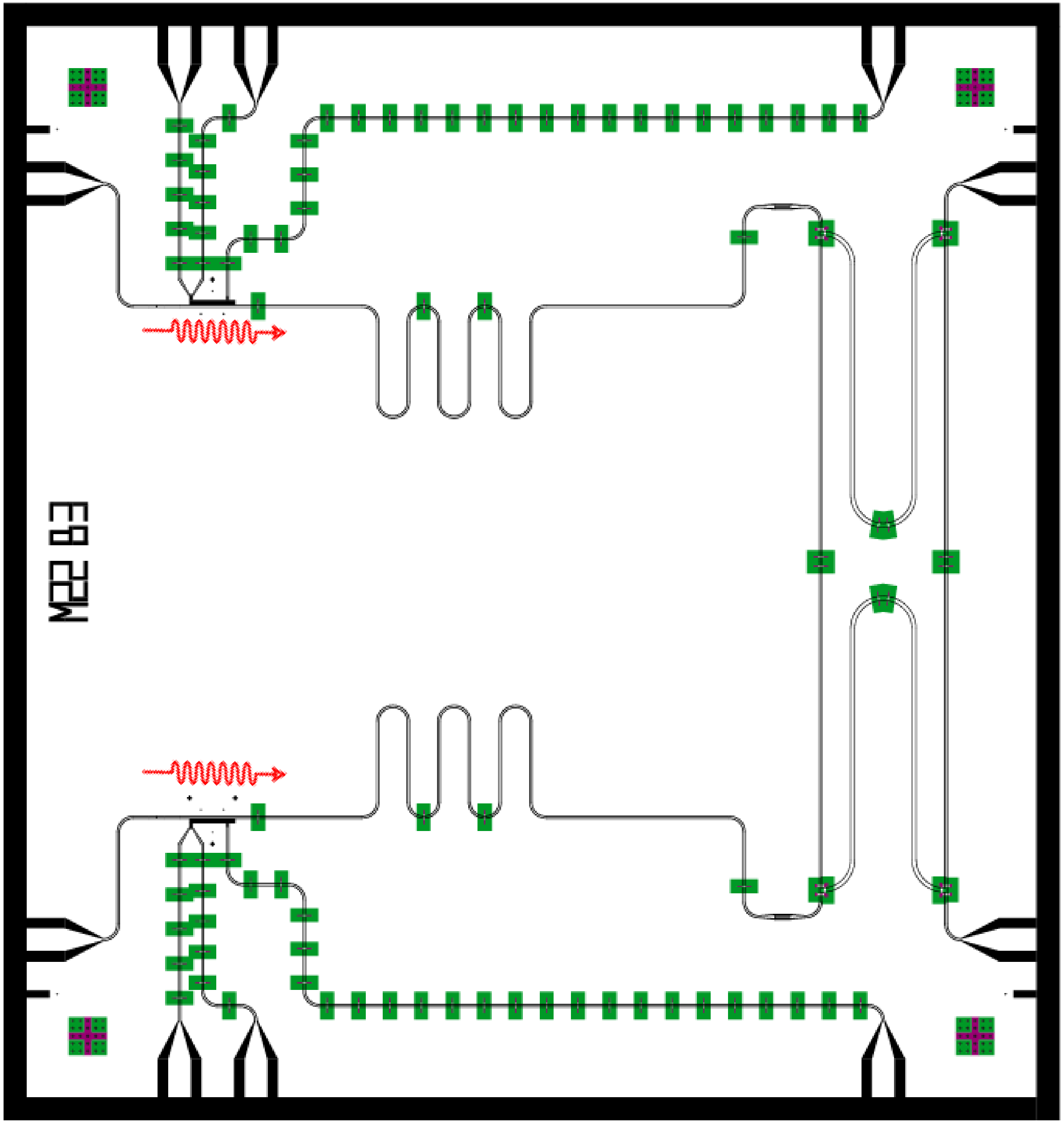
Design: Two Single Photon Sources and Beam Splitter



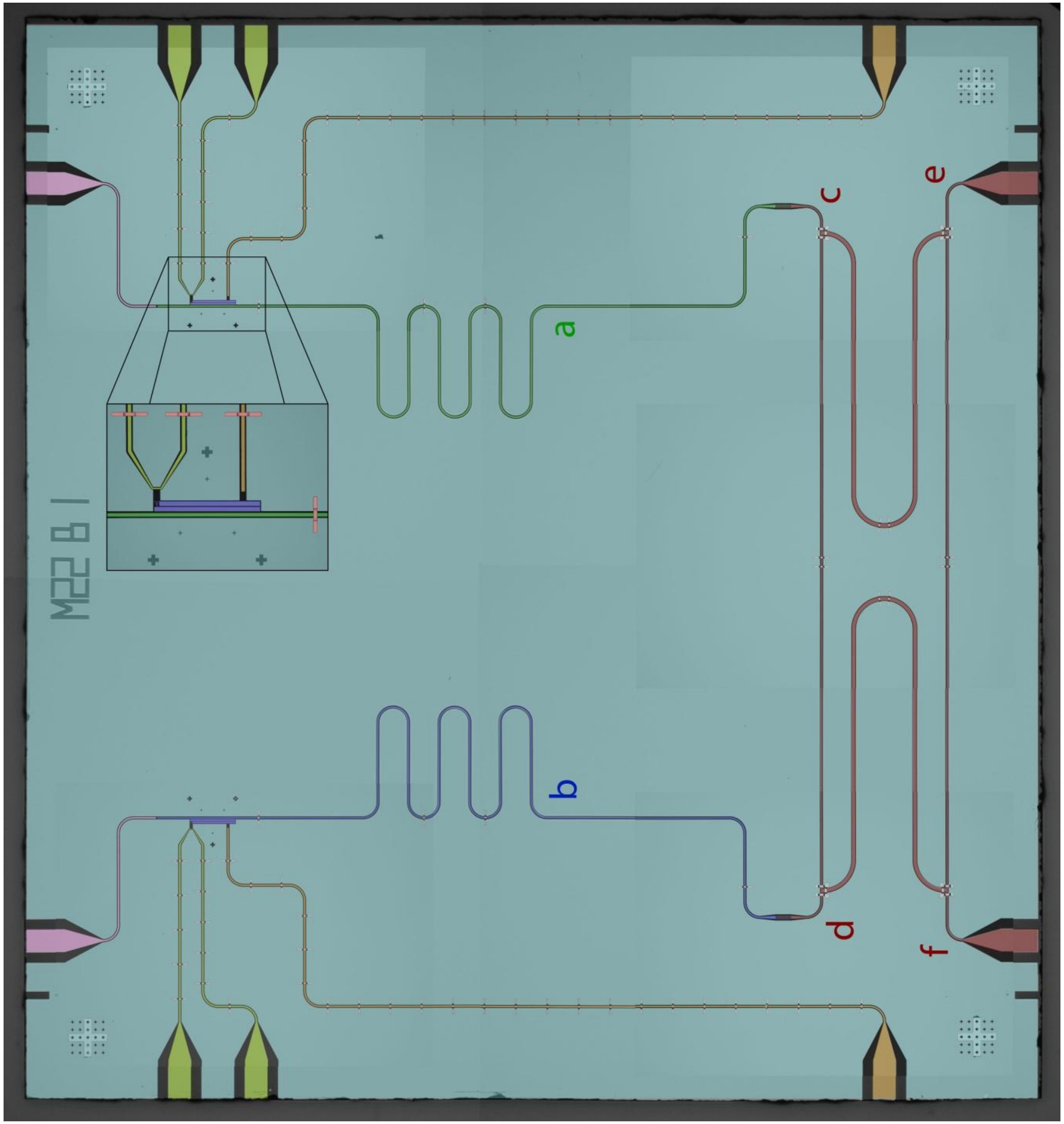
Design: Two Single Photon Sources and Beam Splitter



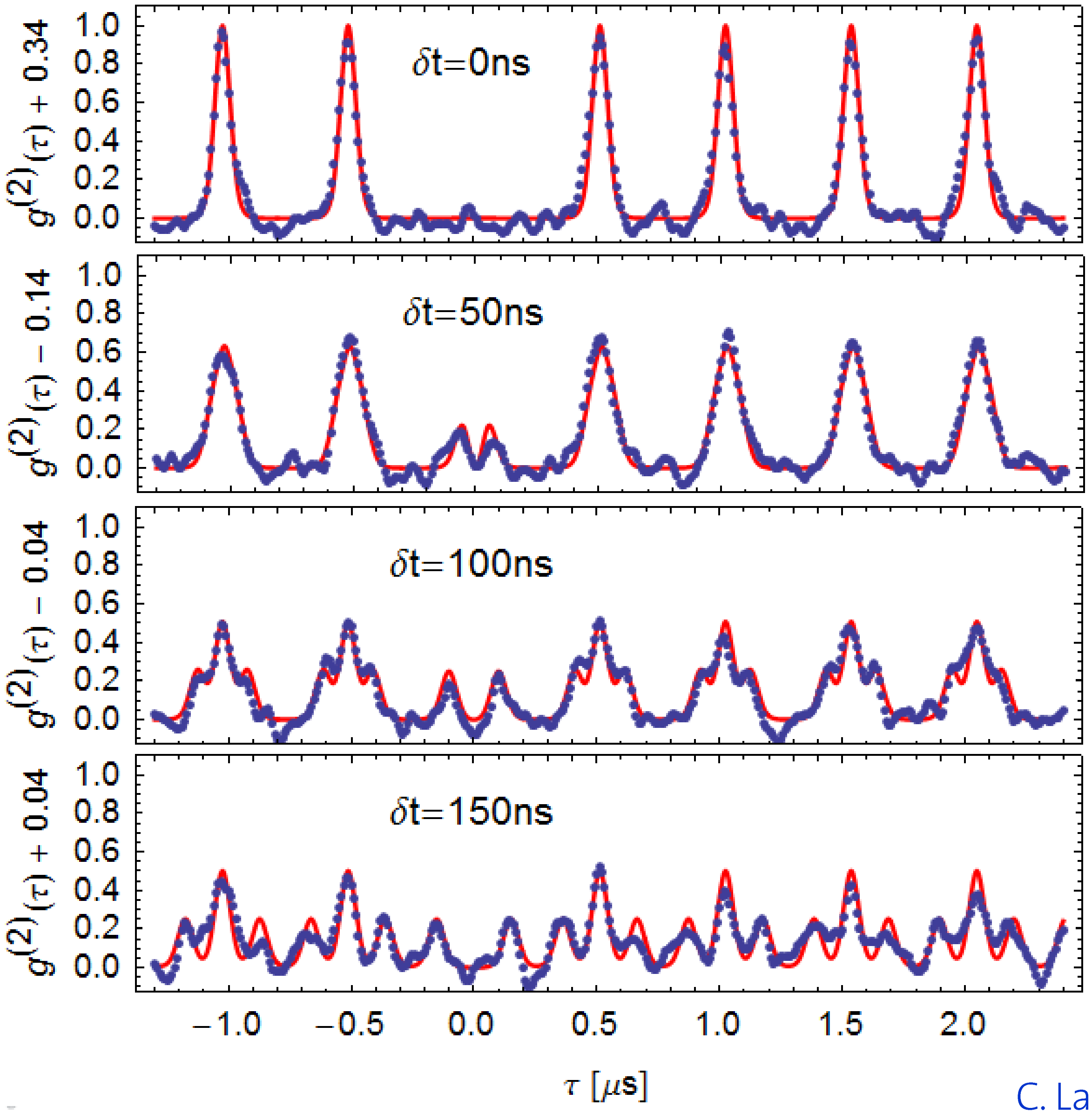
Design: Two Single Photon Sources and Beam Splitter



Design: Two Single Photon Sources and Beam Splitter



Hong-Ou-Mandel $g^{(2)}(\tau)$ for Microwave Photons



Observations:

- Photon-Pair anti-bunching

For $\tau > 0$:

- Broadening of satellite peaks
- Triple-peak structure of satellite peaks
- Full recovery of double-peak at $\tau \approx 0$

C. Lang, C Eichler *et al.*, ETH Zurich (2012)

Learning More: Two-Channel Tomography

Idea: Measure 4D histogram and evaluate relevant photon statistics

$$D_{\mathrm{ON}}(X_a, P_a, X_b, P_b)$$

$$D_{\mathrm{OFF}}(X_a, P_a, X_b, P_b)$$

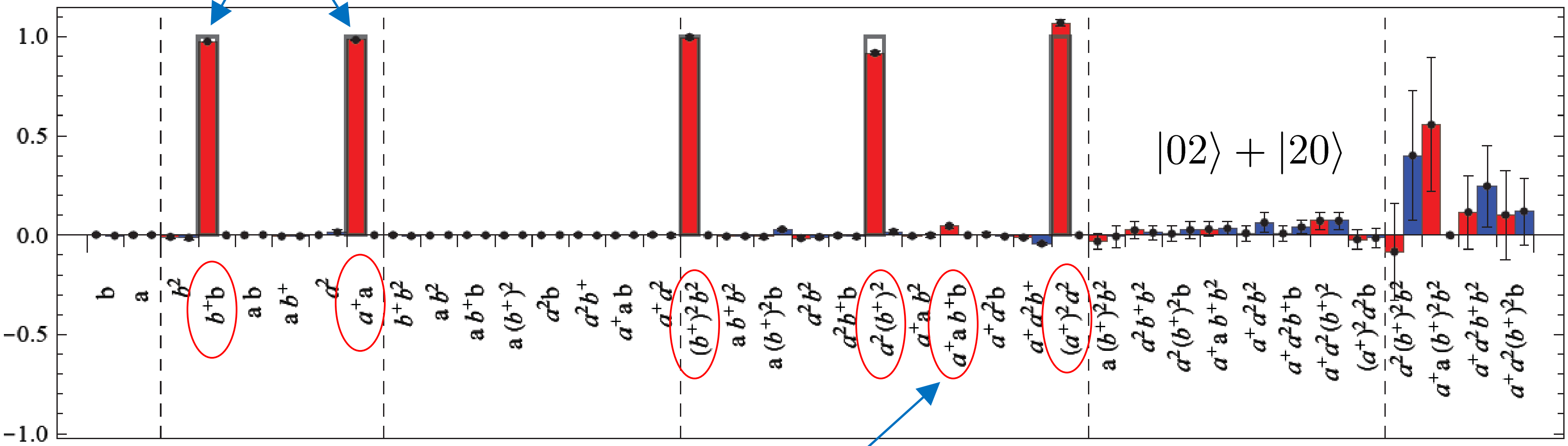
analogous to
1-channel case

$$\langle (a^\dagger)^n a^m (b^\dagger)^k b^l \rangle$$

1 average photon
in each channel

2-photon
bunching

Quantum
superposition!



never simultaneous
“click” in both channels

C. Lang, C Eichler *et al.*, ETH Zurich (2012)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Density Matrix Displaying Two-Mode Entanglement

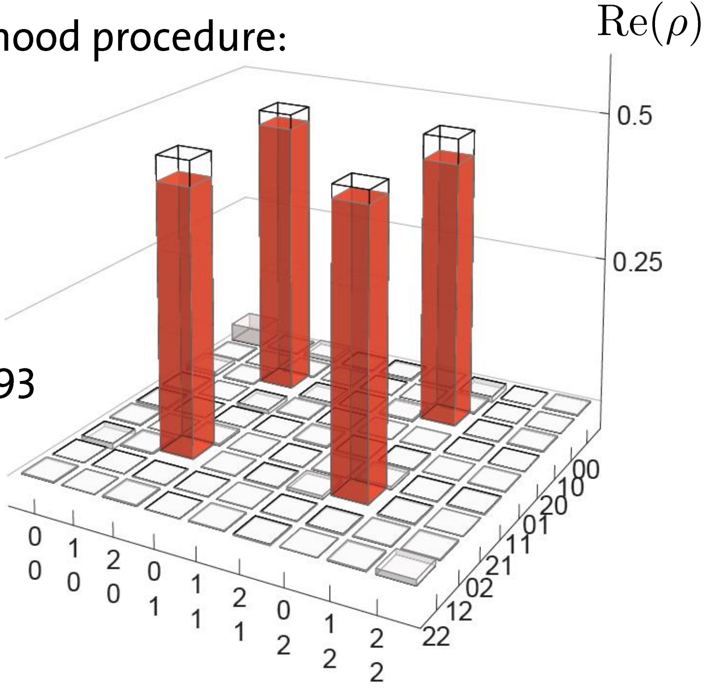
Density matrix reconstruction:

$\langle (a^\dagger)^n a^m (b^\dagger)^k b^l \rangle$ $\xrightarrow{\text{linear map}}$ $\langle nm|\rho|kl \rangle$

moments

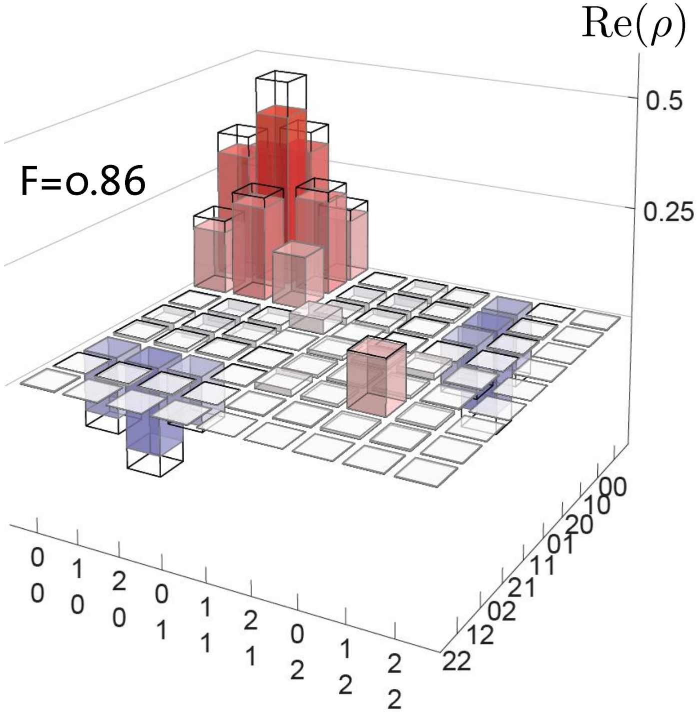
Fock space
density matrix

Apply maximum
likelihood procedure:



F=0.93

$|02\rangle + |20\rangle$

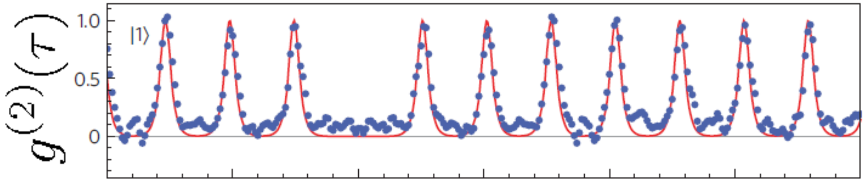


$|00\rangle + \sqrt{2}|10\rangle + (|20\rangle - |02\rangle)\sqrt{2}$

C. Lang, C Eichler *et al.*, ETH Zurich (2012)

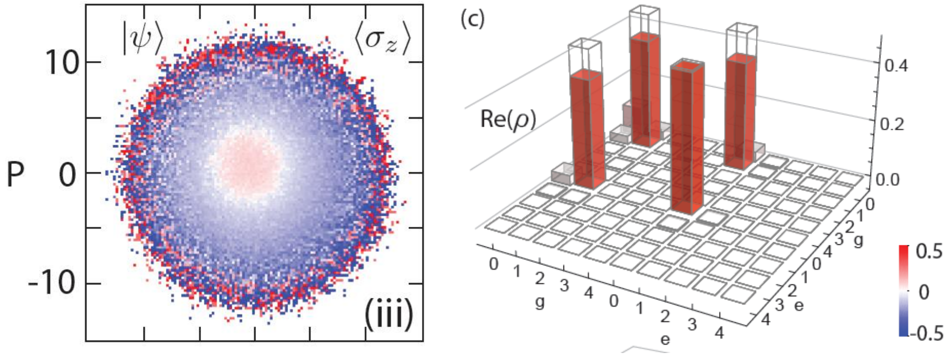
Experiments with Propagating Quantum Microwaves

Single photon sources and their anti-bunching



Bozyigit *et al.*, Nat. Phys **7**, 154 (2011)
Lang *et al.*, *PRL* **107**, 073601 (2011)

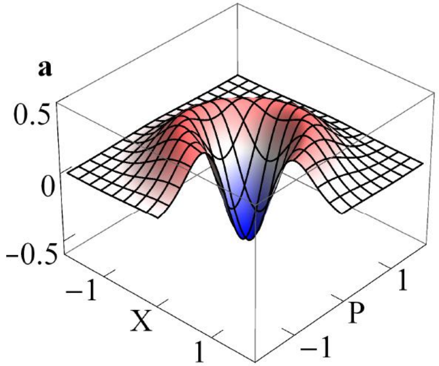
Preparation and characterization of qubit-**propagating** photon entanglement



Eichler *et al., arXiv:1209.0441* (2012)
Eichler *et al., Phys. Rev. A* **86**, 032106 (2012)

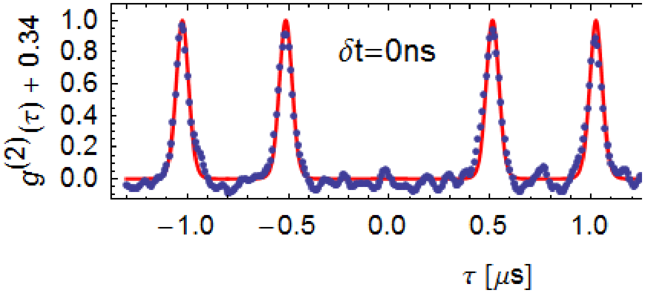
Wigner functions and full state tomography of propagating photons:

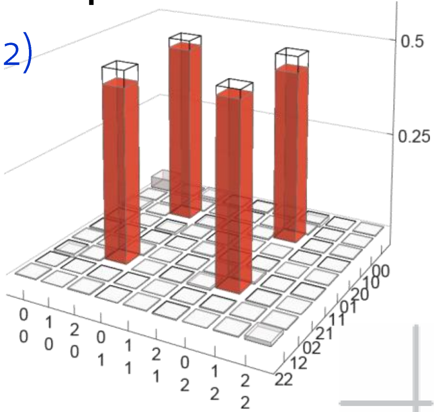
Eichler *et al., PRL* **106**, 220503 (2011)



Hong-Ou-Mandel: Two-photon interference with coherences at microwave frequencies

Lang, Eichler *et al., ETH Zurich* (2012)





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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)

Geometric Phases:

- Leek et al., *Science* **318**, 1889 (2007)
- Pechal et al., *PRL* **108**, 170401 (2012)

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., *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)
- Steffen et al., *PRL* **108**, 260506 (2012)

Device Fabrication:

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

Review (gr.):

- Wallraff, *Physik Journal* **7 (12)**, 39 (Dez. 2008)

Additional Information: www.qudev.ethz.ch

Selected Circuit QED Publications (cont'd)

Itinerant Photons, Tomography, Photon Blockade, Correlation Functions:

- 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)
- Eichler et al., *PRA* **86**, 032106 (2012)
- Eichler et al., arXiv:1209.0441 (2012)

Hybrid Systems:

- Frey et al., *PRL* **108**, 046807 (2012)
- Frey et al., *PRB* **86**, 115303 (2012)
- Hogan et al., *PRL* **108**, 063004 (2012)

Additional Information: www.qudev.ethz.ch