Lecture 12

Last week(s)

- Basics concepts of superconducting circuits covered

Today:

- Quantum Optics and Information processing with SC circuits: a few examples

Next two weeks:

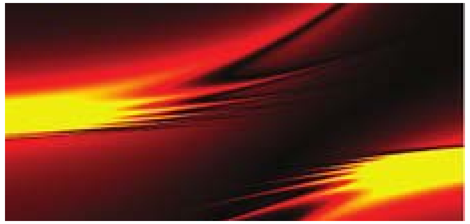
- Quantum error correction and near-term applications

Superconducting circuits ... a few examples

Cavity QED/Radiation-Matter-Interaction

Vacuum Rabi splitting
Stark/Lamb shifts
Root N nonlinearity
Two Photon nonlinearity

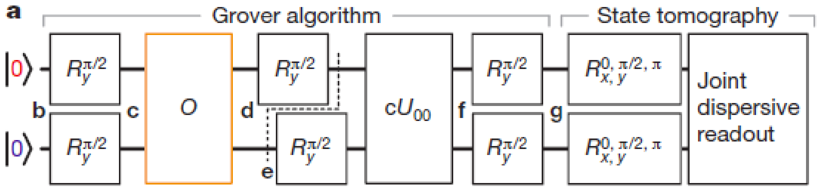
Collective effects
Ultrastrong coupling
Quantum-to-classical



Quantum Computation

Single qubit operations
Quantum bus
Multi-qubit gates
Toffoli gate

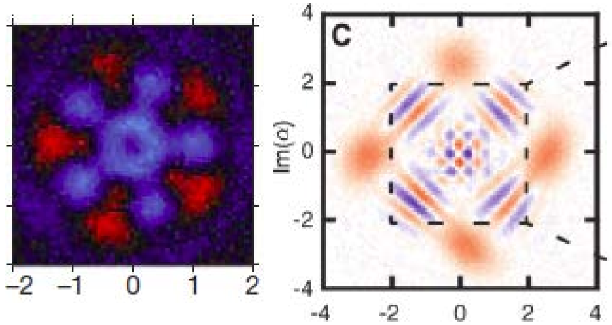
Error correction
Quantum feedback
Single shot readout
Teleportation



Quantum state engineering/tomography

Dispersive readout
Cavity-qubit interactions
Fock states and arbitrary superpositions

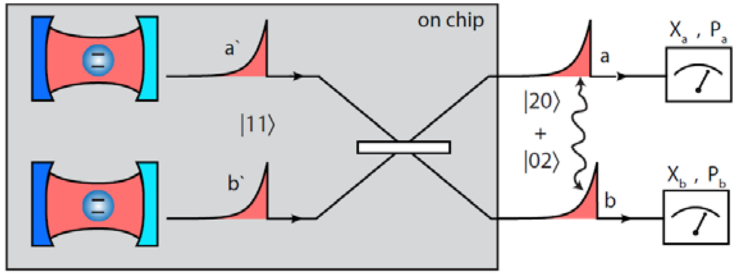
Multi-qubit readout
NOON states, cat states
W and GHZ states
Wigner tomography



Quantum Optics with propagating microwaves

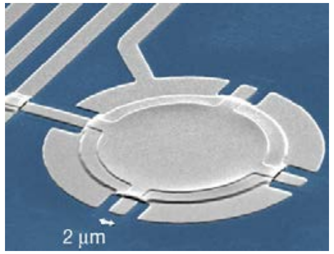
Single photon sources
State Tomography
Squeezing/DCE
Time-correlations
Photon Shaping

Qubit-photon entanglement
Hong-Ou-Mandel
Photon routing
Single photon detectors
Quantum simulations
Remote entanglement



Hybrid systems

Cavity electromechanics Cavity QED with semiconductor Qdots
Measurement and control of electron spins
Coupling to magnons



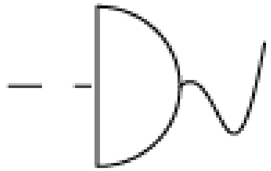
Outline

1) Deterministic quantum teleportation

2) Quantum Optics with Propagating Microwaves

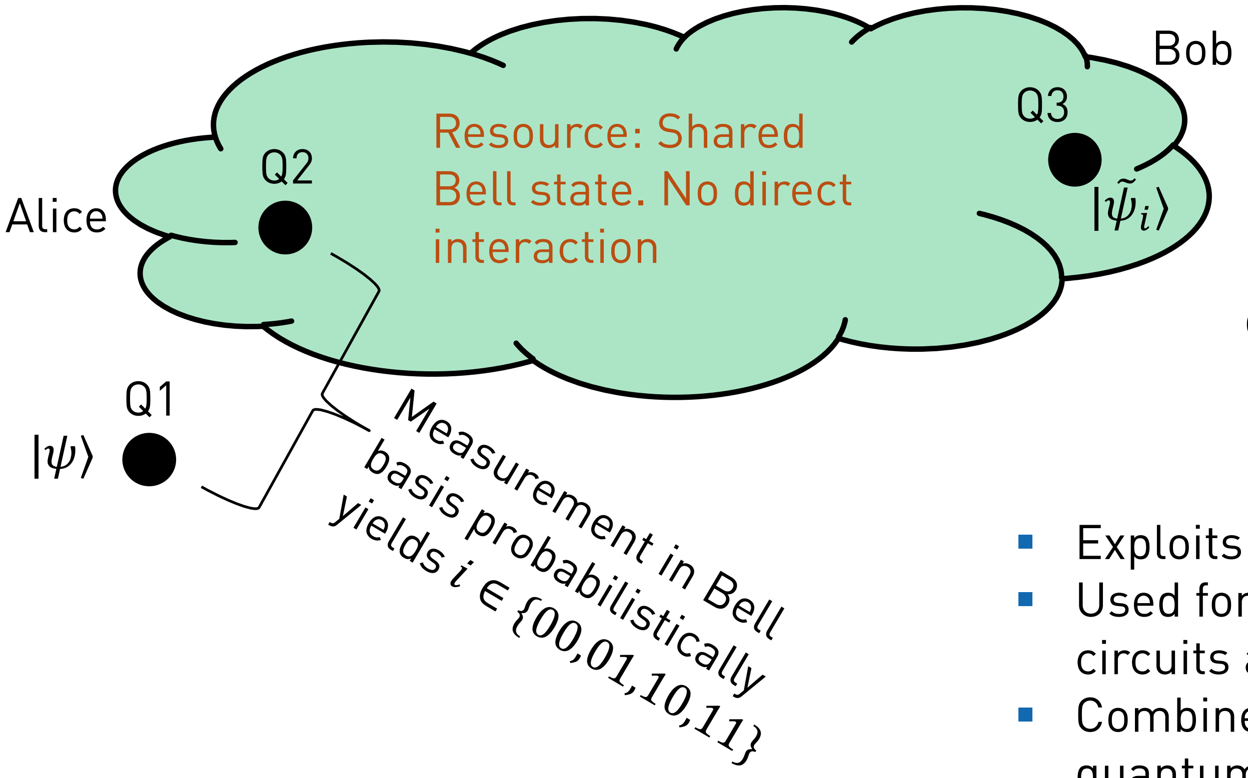
a) Measuring Photon Correlations with Linear Detectors
- Anti-bunching of single photons
- Qubit-photon entanglement
- Two-photon (Hong-Ou-Mandel) interference

b) Single photon detection
- Parity detection
- Creation of itinerant cat states by measurement
- Direct Wigner function measurement



The teleportation protocol

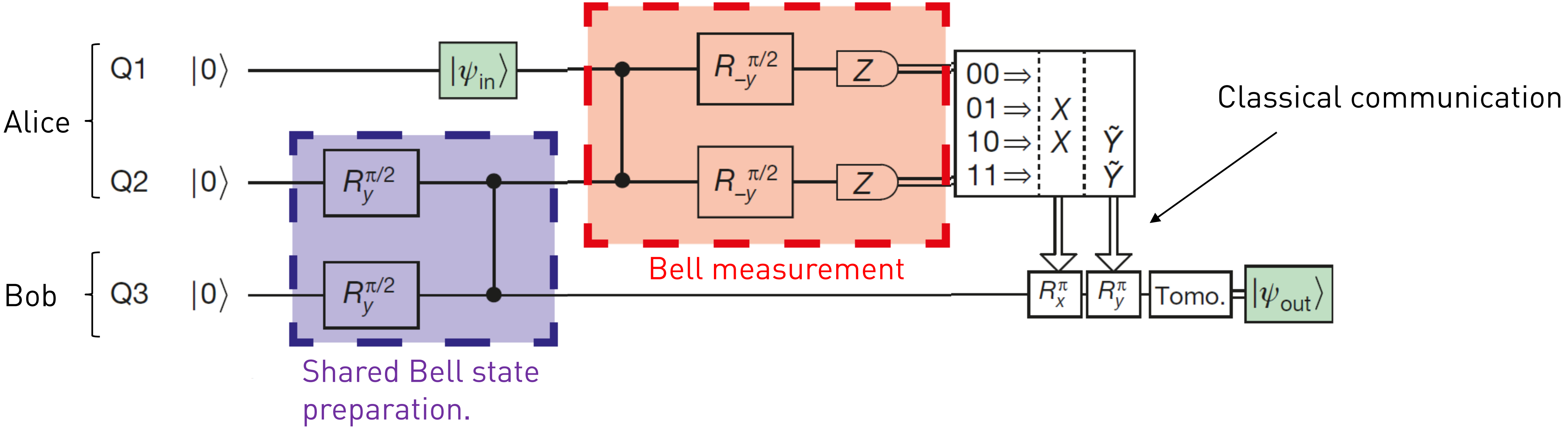
Teleportation: Transmission of a quantum state from Alice to Bob using previously shared entanglement.



... asks Alice about measurement outcome i and $\longrightarrow$ performs conditional operation to deterministically get $|\psi\rangle$.

- Exploits (non-local) quantum correlations
- Used for quantum repeaters, to simplify quantum circuits and for universal quantum computing.
- Combines essential ingredients required for building a quantum computer: Unitary gates, multi-qubit entanglement, high fidelity readout, real-time feedback.

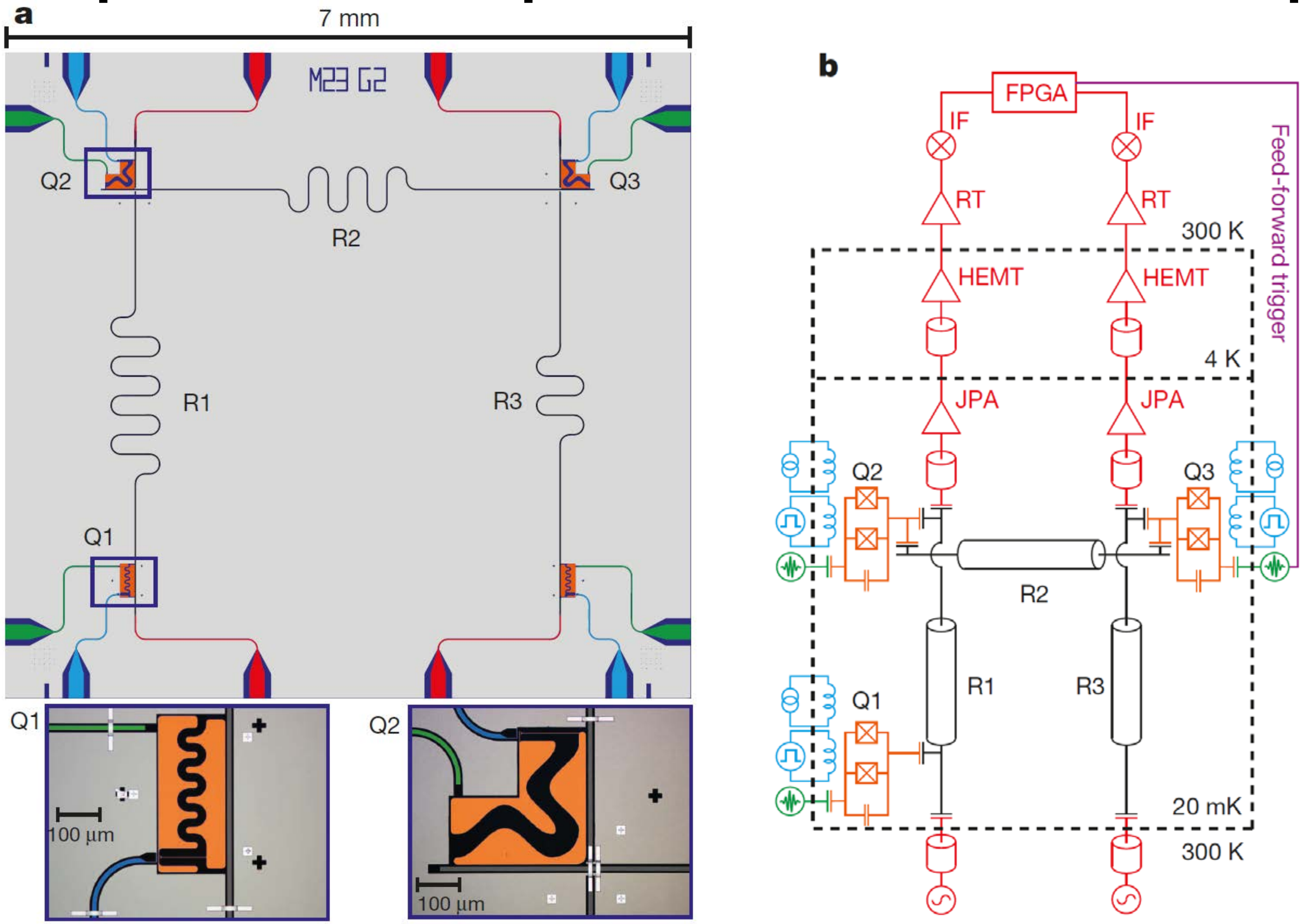
Teleportation: Gate sequence



Ideally: $|\psi_{\text{in}}\rangle = |\psi_{\text{out}}\rangle$

Steffen et al., Nature 500, 319 (2013)

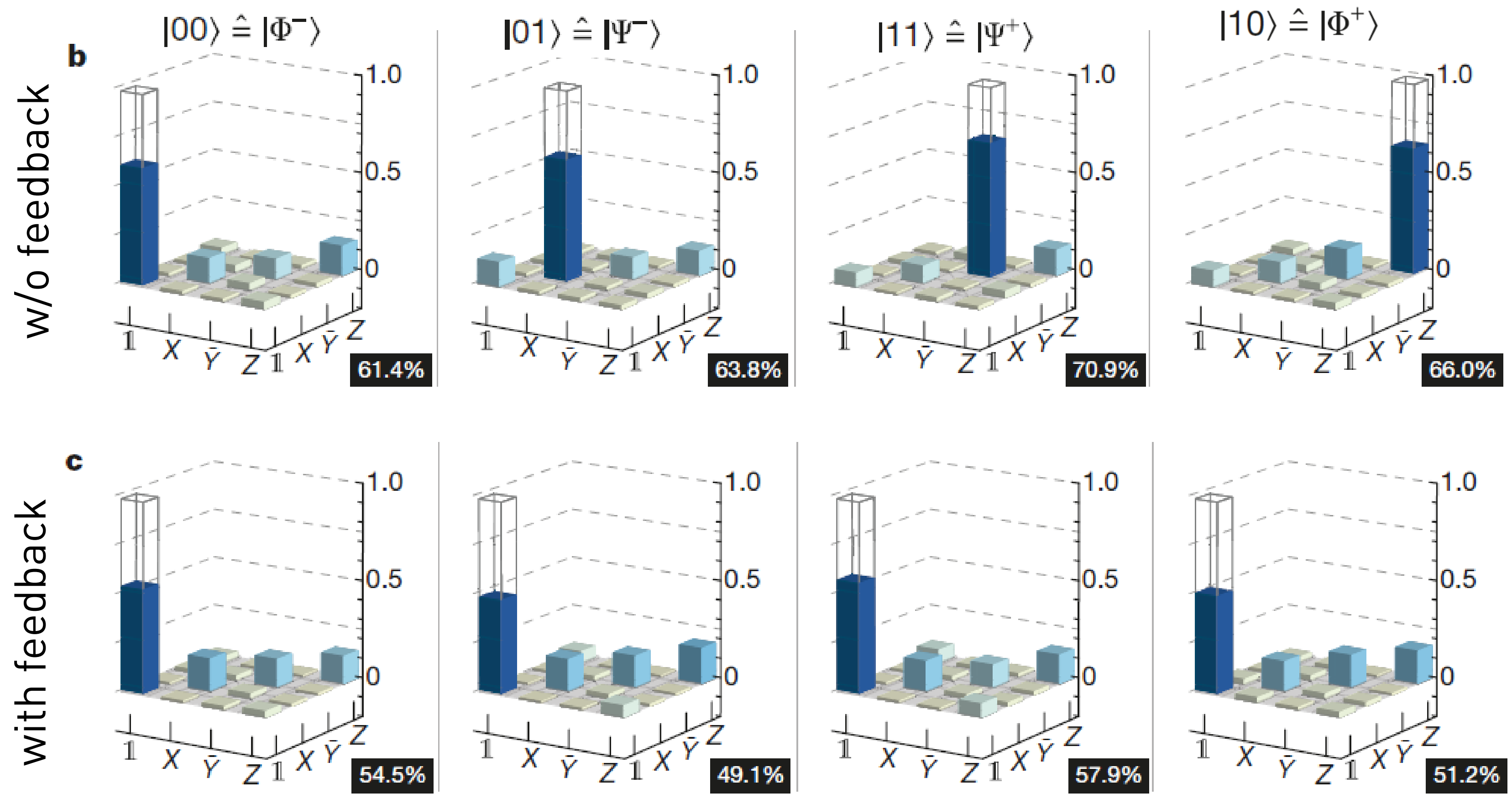
Teleportation: Sample and measurement setup



- Use three qubits on a 4Q chip.
- Use joint dispersive readout (see Filipp et al., Rev. Lett. 102, 200402 (2009)) to measure Q1 and Q2 with a single resonator.
- Second readout line for Q3.
- Josephson parametric amplifiers allow for high fidelity single shot readout.
- Signal processing and real-time feedback triggered by FPGA electronics.

Steffen et al., Nature 500, 319 (2013)

Teleportation: Process tomography



- Perform process tomography post-selected on any of the four possible measurement outcomes

$$\rho_{out} = \mathcal{E}(\rho) = \sum_i E_i \rho_{in} E_j^+ \chi_{ij}$$

- Without feedback, the process depends on the outcome of the Bell measurement.
- Recover initial state by applying conditional feedback pulse.
- Fidelity reduced due to feedback delay time.

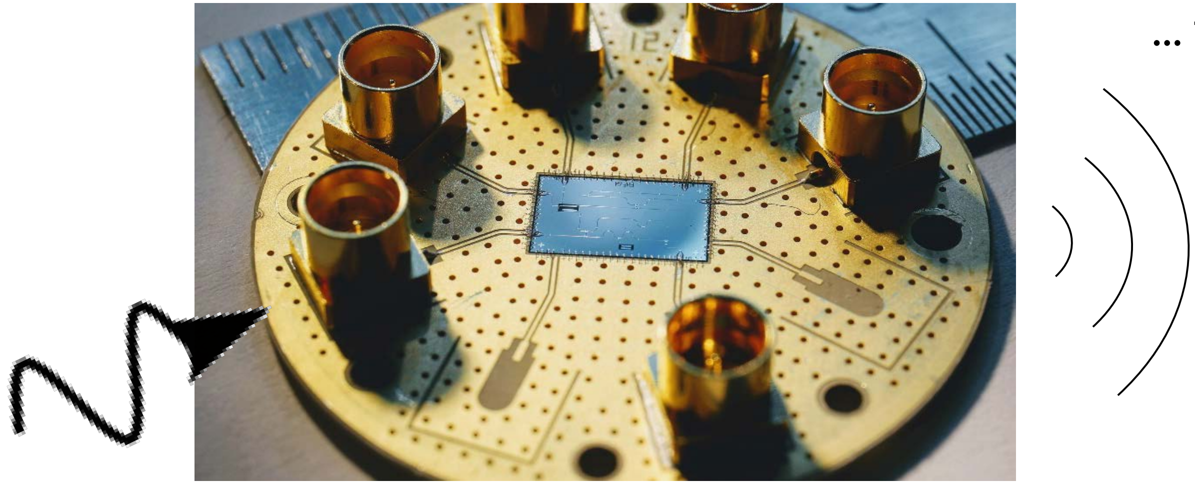
Steffen et al., Nature 500, 319 (2013)

Quantum Optics **with Propagating Microwaves**

Exploring propagating microwave radiation

Emitted radiation exhibits quantum correlations

Superconducting circuit



Control with electromagnetic (EM) radiation at GHz frequencies.

How to characterize?

... typically measured:
- amplitude $\langle a \rangle$
- intensity $\langle a^\dagger a \rangle$

$\Big|$  $\Big\rangle$

- Single photons
- Quantum superposition states
- Entanglement with the emitter
- Squeezed states

... NEED: higher order correlations

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

Example: Single-photon source

Transmon qubit

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

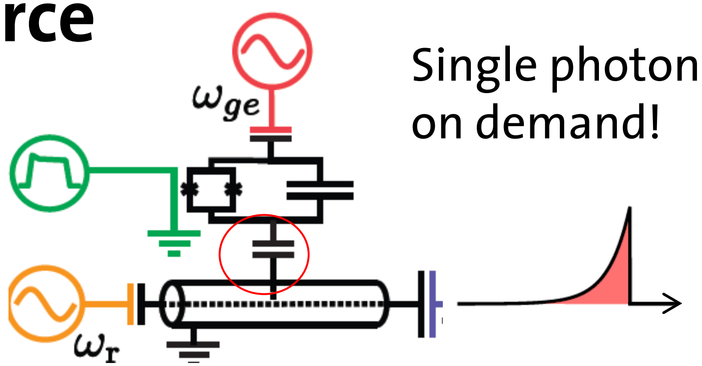
Single sided resonator

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

Coupling strength

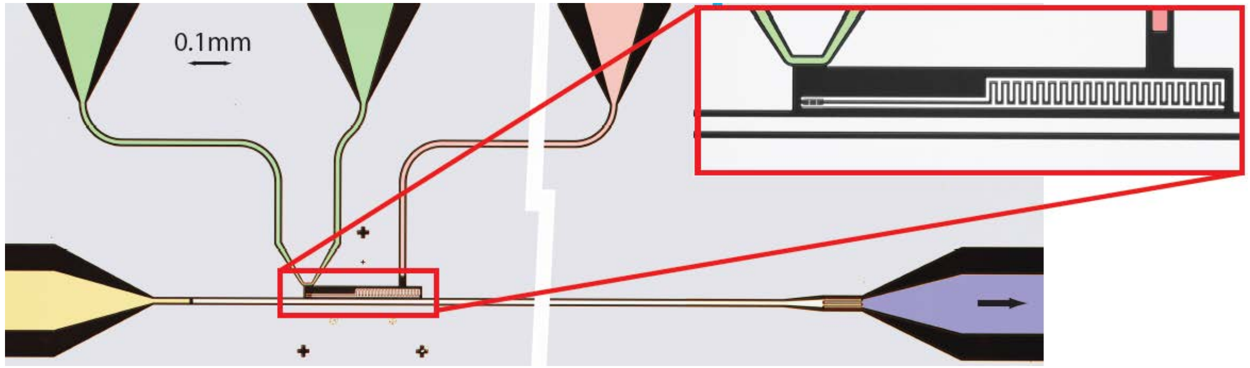
$$\pi/g = 7.7\,ns$$

Strong coupling limit

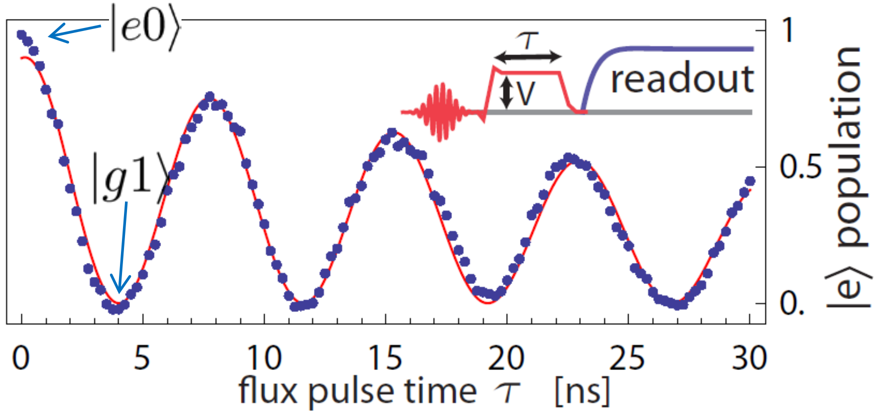


Single photons on demand!

Detection ?

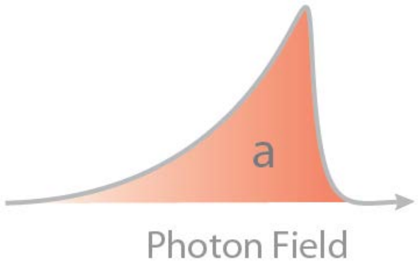


Vacuum Rabi oscillations

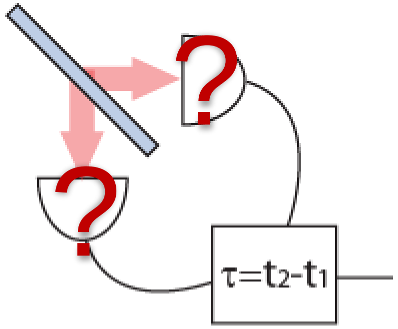


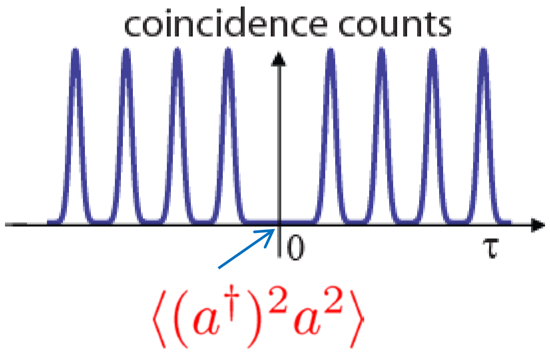
Houck *et al., Nature* 449, 328 (2007), Bozyigit *et al., Nat. Phys.* 7, 154 (2011)

Microwave Photon Field Detection



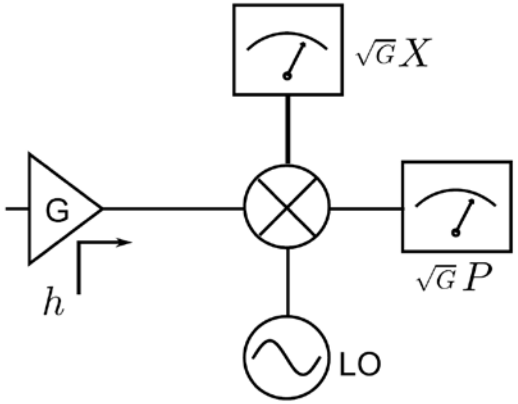
In the visible





At microwave frequencies:

- Typical detection scheme based on linear amplifiers, equivalent to optical homodyne detection.
- Measurement of higher order photon correlation by signal processing and averaging.



Complex amplitude:
$S = X + i\,P$

How to measure $\langle (a^+)^n a^m \rangle$?

$$\langle (\hat{S}^\dagger)^n \hat{S}^m \rangle_\rho = \sum_{i,j=0}^{n,m} \binom{m}{j} \binom{n}{i} \langle (a^\dagger)^i a^j \rangle \langle h^{n-i} (h^\dagger)^{m-j} \rangle \quad (*)$$

- Measure noise correlations in a reference measurements …

$$\langle (\hat{S}^\dagger)^n \hat{S}^m \rangle_{|0\rangle\langle 0|} = \langle h^n (h^\dagger)^m \rangle$$

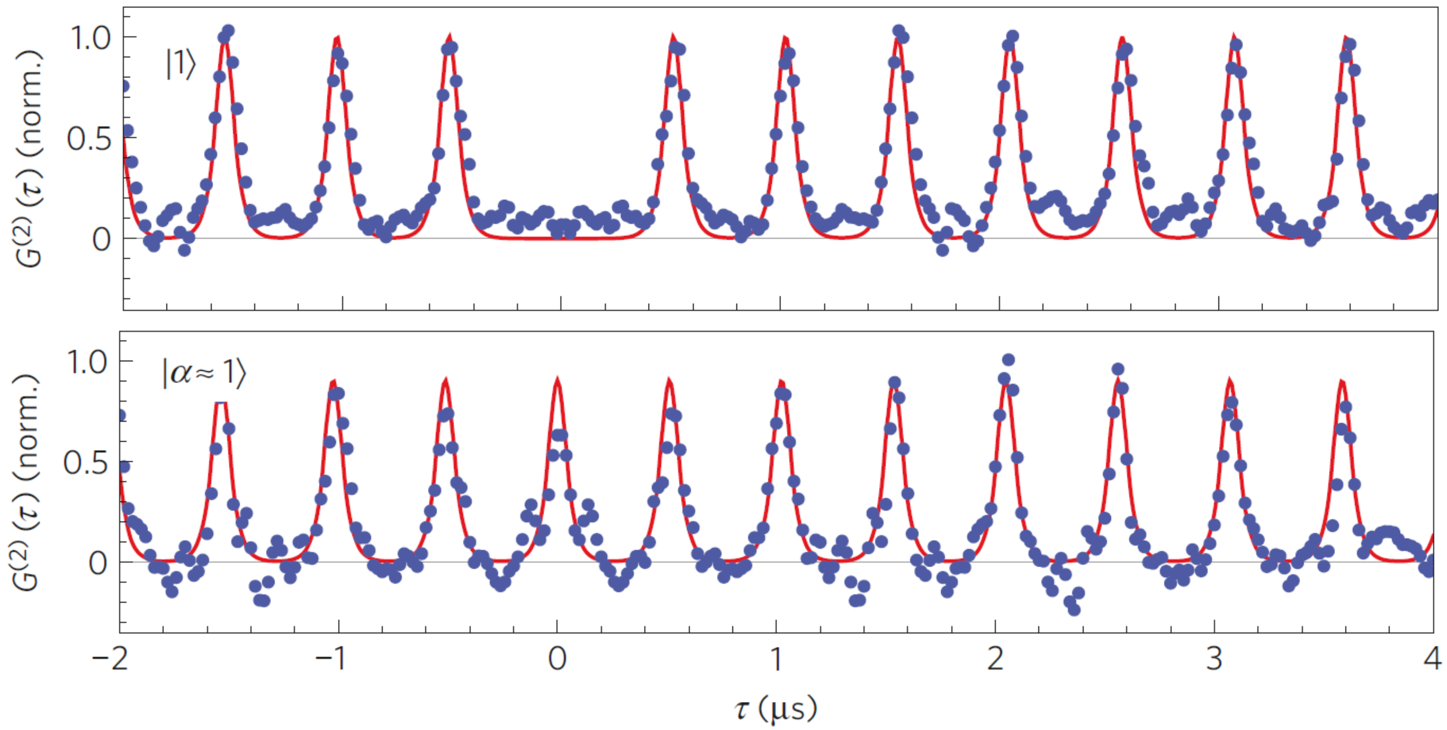
- … and solve set of linear Eqs. (*).

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., *PRA 82, 043804 (2010)*
C. Eichler, et al., *PRL* 106, 220503 (2011)

Demonstration of anti-bunching using linear detection

- Generate train of single photon pulses.
- Measure intensity-intensity correlations as a function of time-delay τ
- Use method discussed on previous slide to account for amplifier noise.

$$G^{(2)}(\tau) = \langle a^\dagger(0)a^\dagger(\tau)a(\tau)a(0)\rangle$$



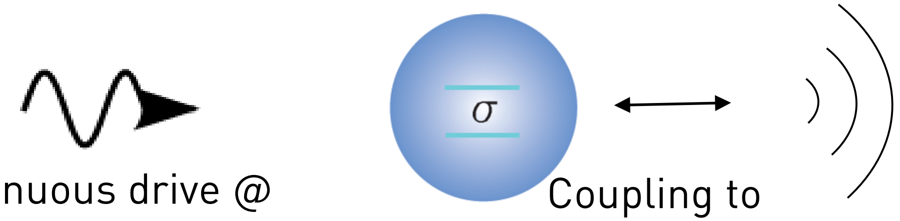
D. Bozyigit et al., Nat. Phys. 7, 154 (2011)

Observations:

- Intensity-intensity vanishes at $\tau = 0$ as expected for single photons.
- Measurements (back in 2011) done **w/o** parametric amplifier $\rightarrow \eta \sim 3\%$
- Prepare and measure reference coherent state $|\alpha\rangle$ for comparison:
- $\rightarrow G^{(2)}(0) \approx 1$, as expected.

Measurement scheme also applicable to continuously driven systems ...

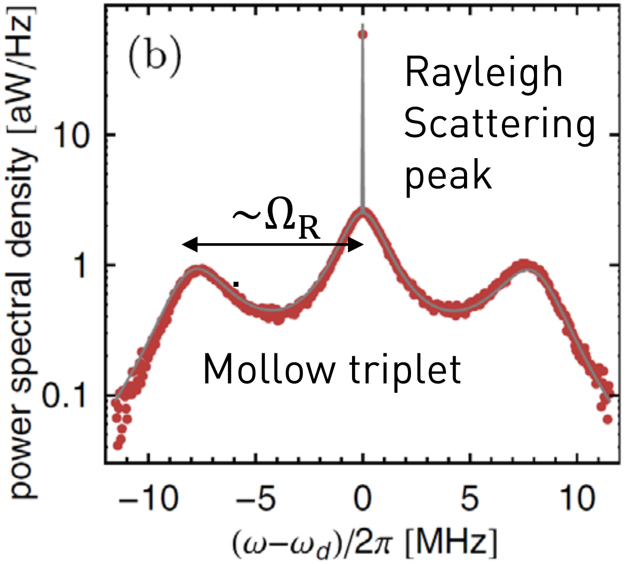
Quantum Optics textbook scenario:



Continuous drive @ frequency ω_d and amplitude Ω_R.

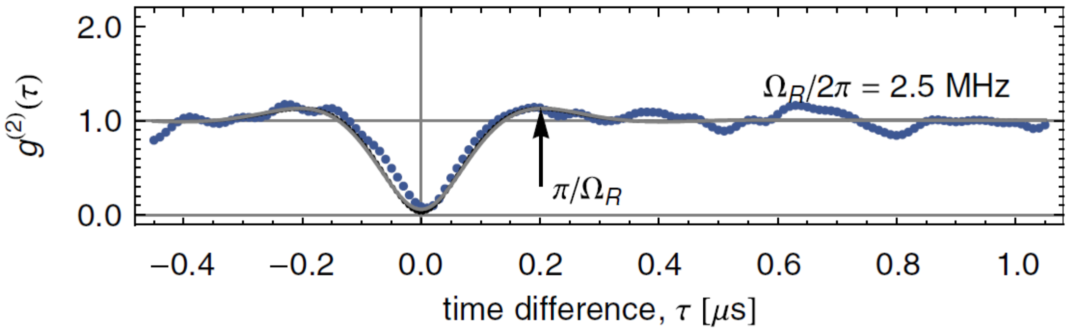
Coupling to EM env. with rate κ

Properties of emitted radiation?



- Elastically scattered radiation at $\omega = \omega_d$ (Rayleigh scattering)
- In addition: incoherent emission with triplet structure.
- ! Two-level system can only emit one photon at a time !

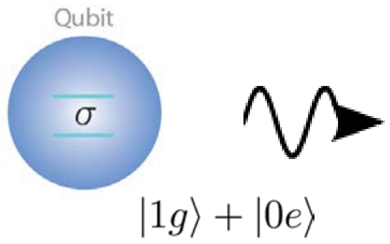
- $\rightarrow$ anti-bunching $g^{(2)}(\tau = 0)$
- Onset of Rabi oscillations when $\Omega_R \approx \kappa \rightarrow$ enhanced emission probability at delay $\tau = \pi/\Omega_R$.



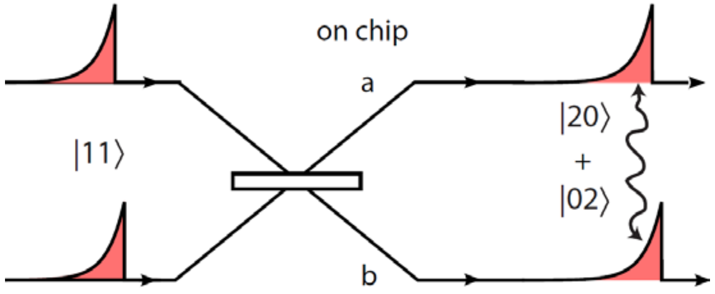
C. Lang et al., PRL 106, 243601 (2011)

Experiments with Propagating Photons: Two examples

1) Entanglement between the emitter qubit and photons



2) Hong-Ou-Mandel interference of single photons at a beamsplitter



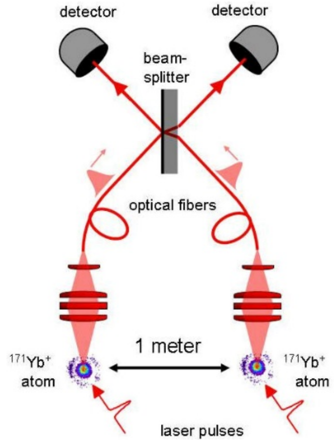
Why interesting?

- Test of correlations between propagating and stationary modes
- Probe non-local aspects of quantum mechanics in circuits

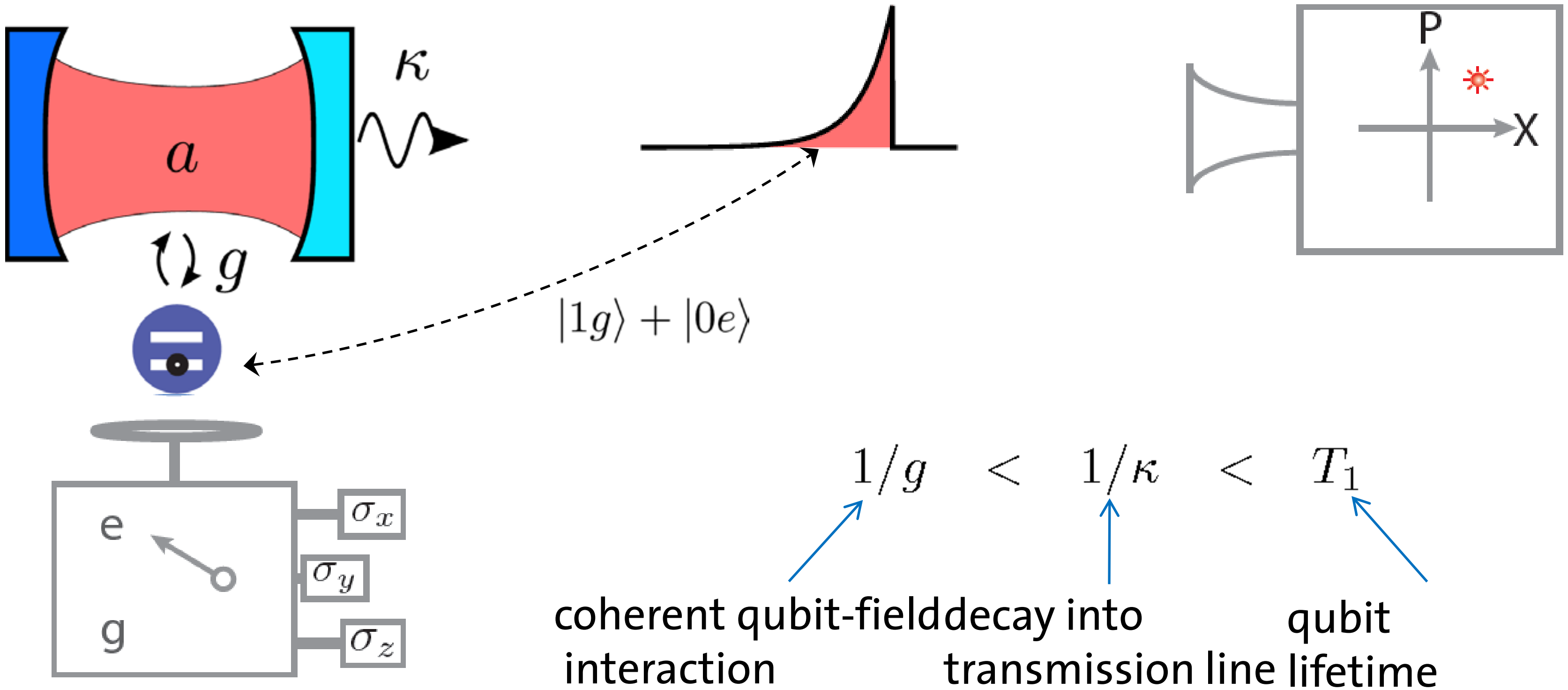
- Interfacing stationary and flying qubits
- Entanglement distribution in a quantum network

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

Atom–Atom Entanglement
Moehring *et al.*, *Nature* **449**, 68 (2007)
Ritter *et al.*, *Nature* **484**, 195 (2012)
Kurpiers et al., *Nature* 558, 263 (2018)



Concept of Photon/Qubit Entanglement Experiment

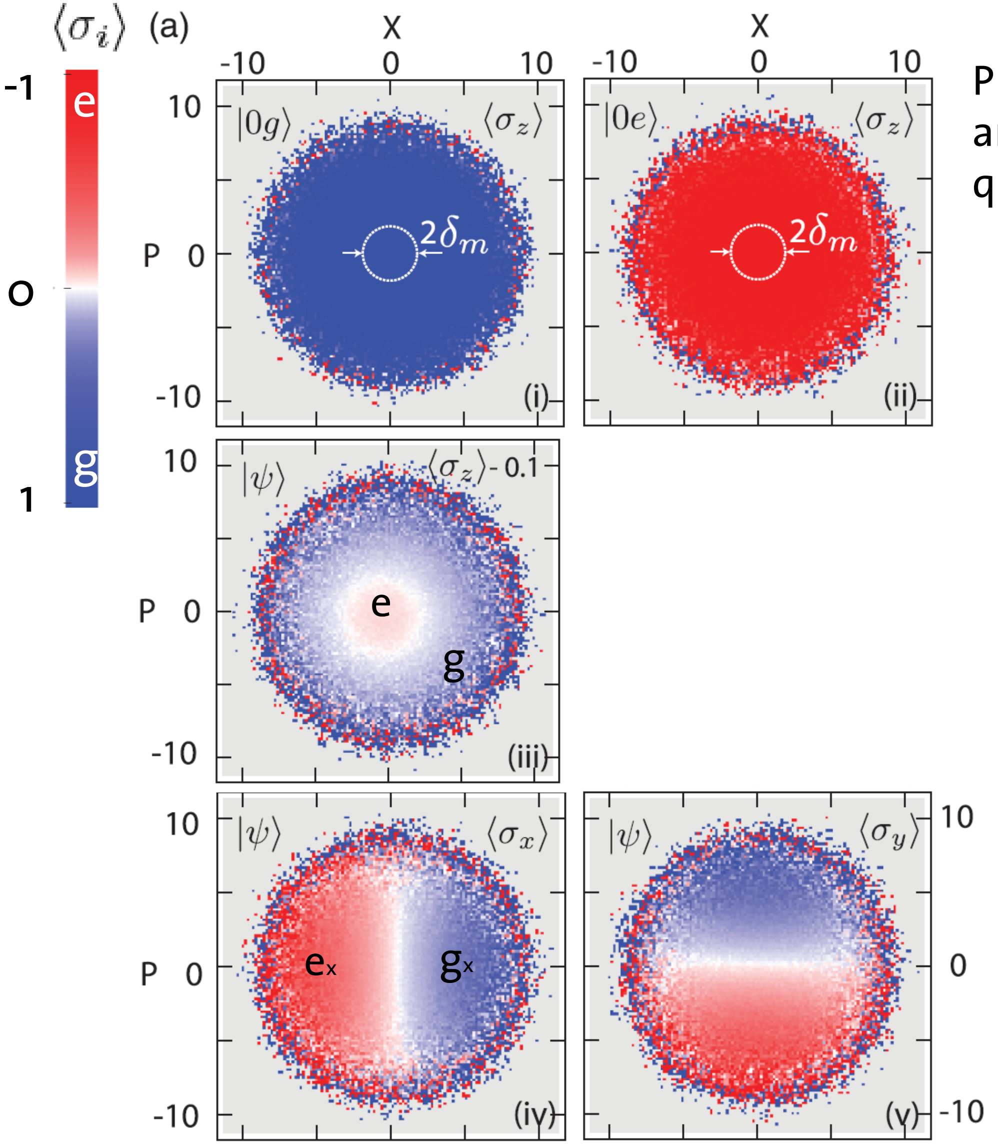


$$1/g \quad < \quad 1/\kappa \quad < \quad T_1$$

coherent qubit-field interaction | decay into transmission line | qubit lifetime

Challenge: Generation and detection of qubit/photon entanglement

Photon/Qubit Entanglement Experiment



Prepare ground state and measure qubit population vs. X, P → as expected $\langle\sigma_z\rangle_\alpha$ independent of X, P

What about the Bell state?

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

What about coherences?

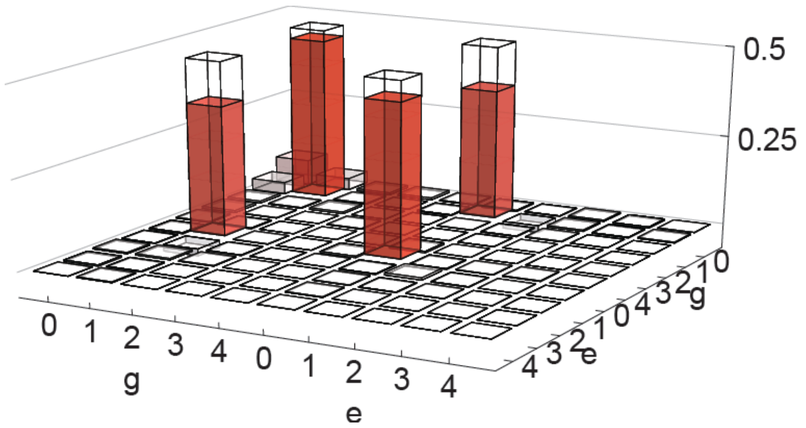
$$= |e_x\rangle\underbrace{(|1\rangle - |0\rangle)}_{\langle\hat{X}\rangle < 0} + |g_x\rangle\underbrace{(|1\rangle + |0\rangle)}_{\langle\hat{X}\rangle > 0}$$

Photon/Qubit Joint State Density Matrix

Reconstruction from measured moments

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

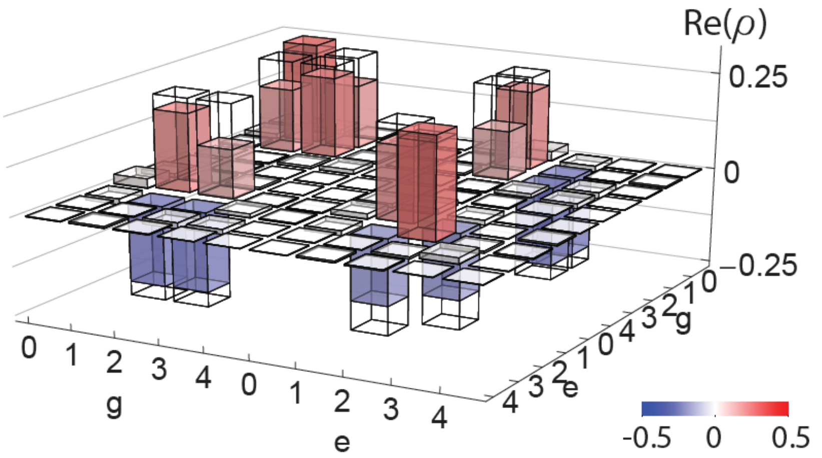
Limited by qubit decay during time required for photon detection in same mode.



Extension to states with more than a single photon:

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

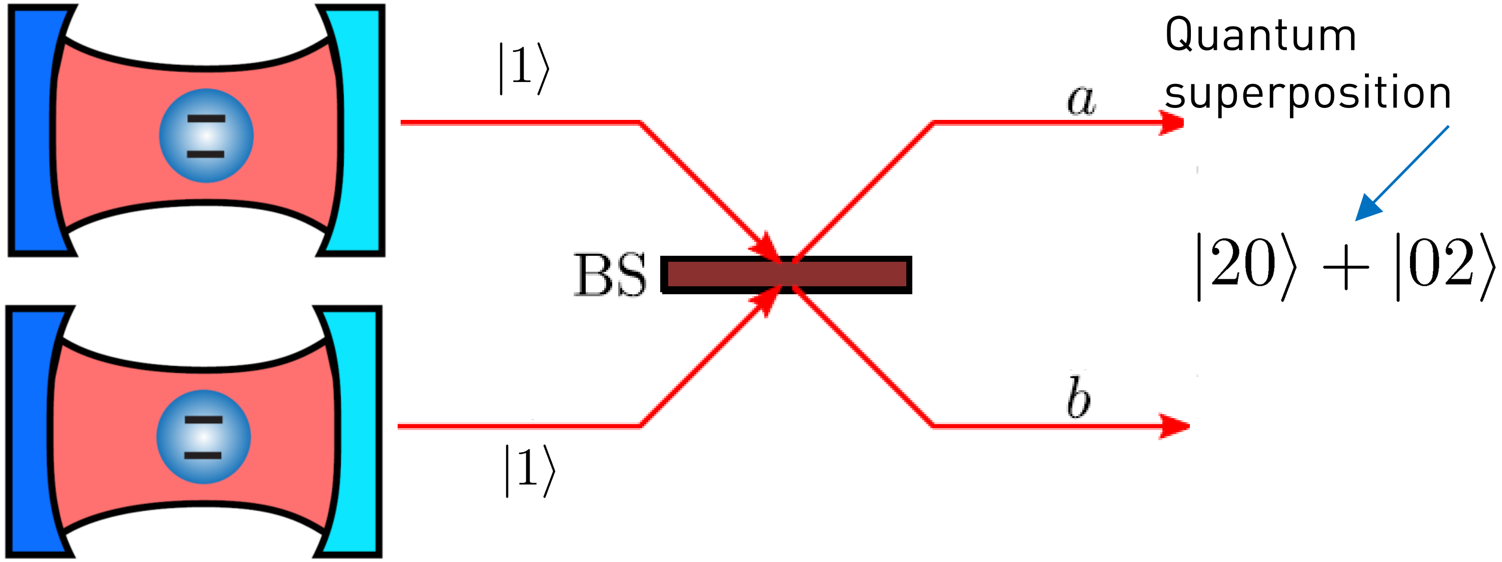
$$F = 0.80$$



exp: C. Eichler *et al., PRL* 109, *240501* (2012)
theo: C. Eichler *et al., Phys. Rev. A* 86, 032106 (2012)

Two-photon interference of microwaves

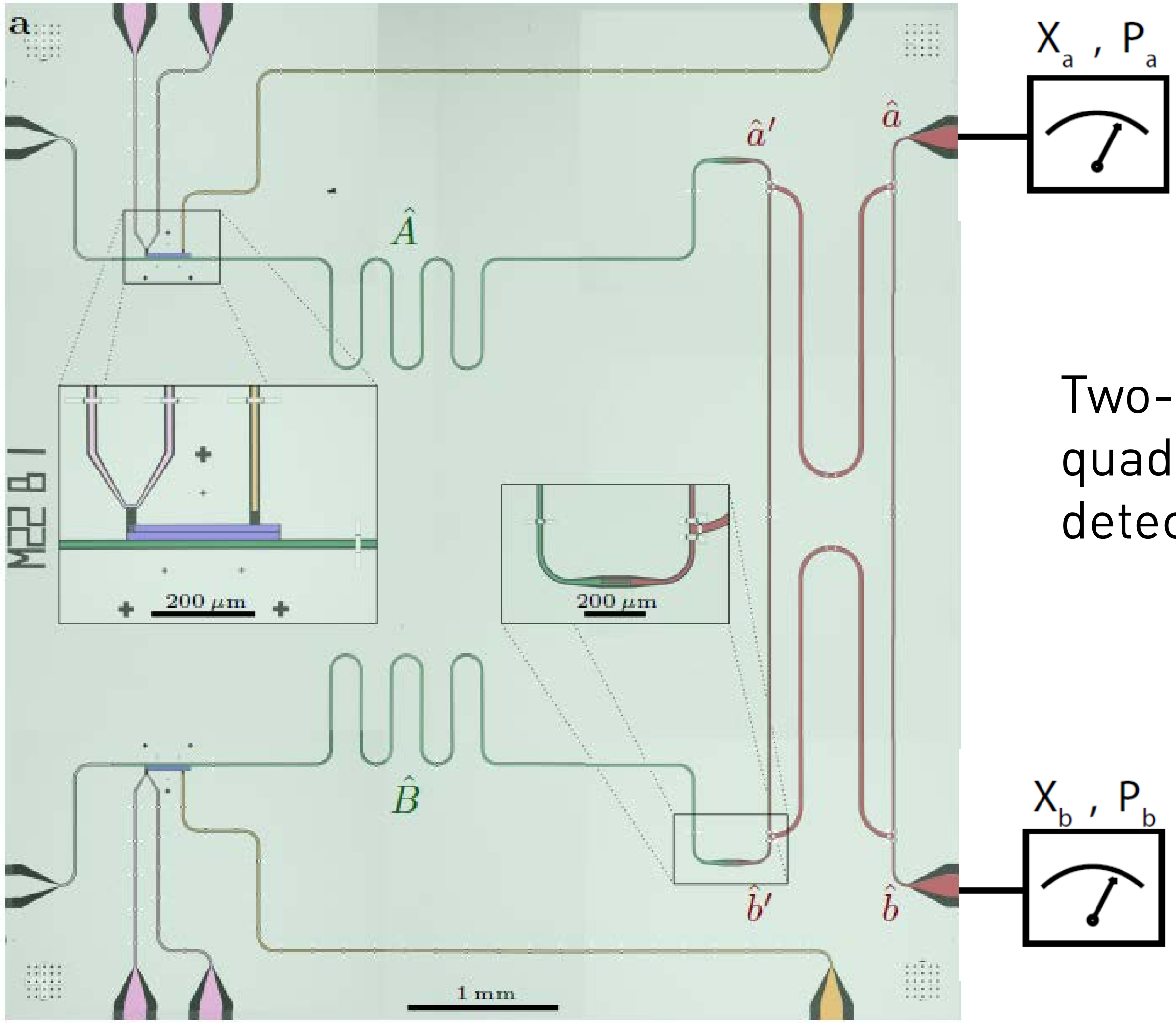
Hong–Ou–Mandel experiment:



Interesting for …

- Testing indistiguishability of single photons
- Entanglement swapping and quantum repeaters
- Optical quantum computation and quantum walks

Hong–Ou–Mandel experiment:



Two-channel quadrature detection

C. Lang, *et al.* Nat. Phys. 9, 345 (2013)

Two-photon interference of microwaves

Approach: Measure 4D histogram and evaluate field correlations.

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

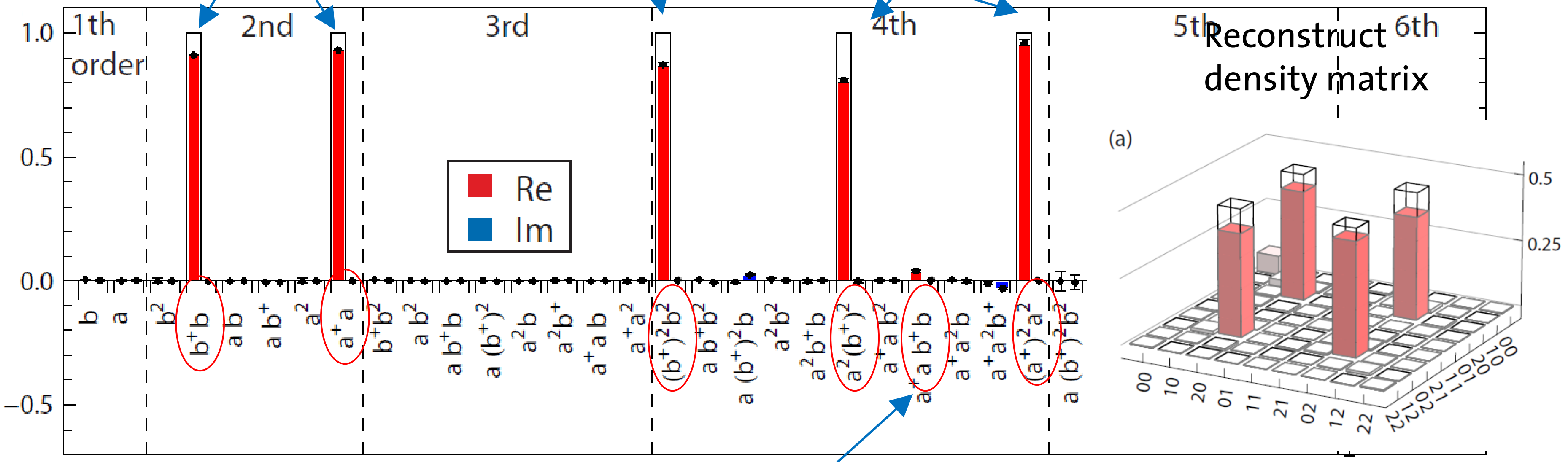
analogous to 1-channel case → $\langle (a^\dagger)^n a^m (b^\dagger)^k b^l \rangle$

1 average photon in each channel

2-photon bunching

Quantum superposition!

Reconstruct density matrix

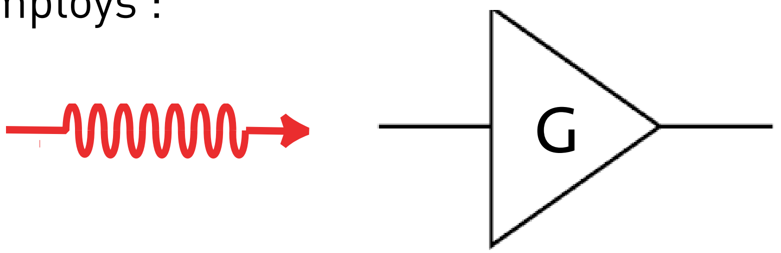


never simultaneous "click" in both channels

C. Lang, *et al.* Nat. Phys. 9, 345 (2013)

Linear amplification vs. Single photon detection

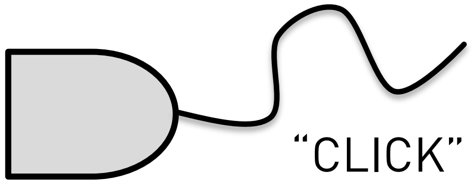
Standard microwave detection chain employs :



Linear (quantum limited) amplifier

- Quantum efficiency approaching unity
- Well suited for dispersive readout
- Established at MW frequencies
- Unable to resolve single photons with high efficiency

Most common detector at optical frequencies:



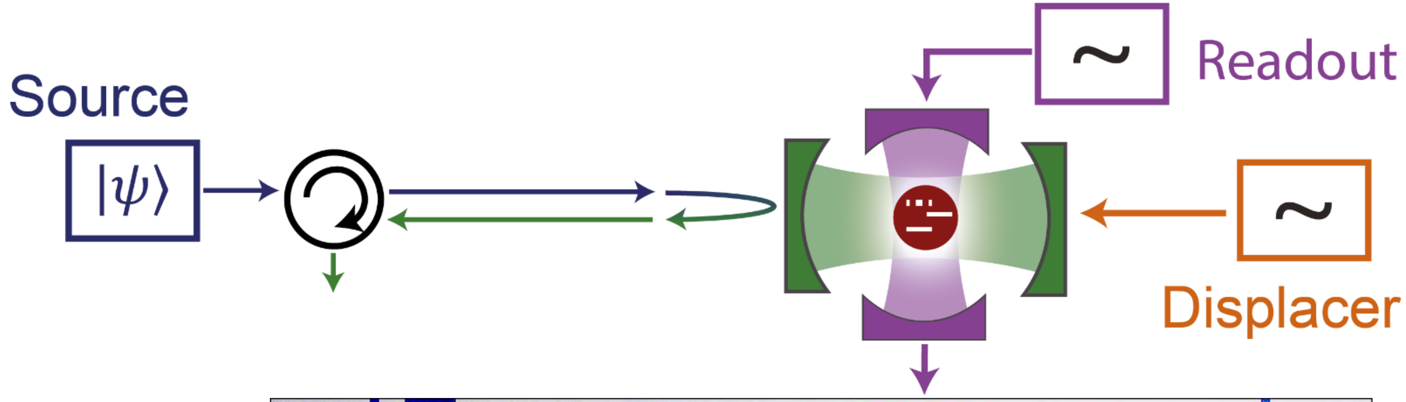
Single photon detector, interesting for

- Non-demolishing detection of single photon
- Heralding schemes for remote entanglement
- Essential requirement for photonic quantum computing
- Photon statistics measurements
- Under development at MW frequencies

Concept of Single Photon Detector

Want:

- Projection into photon number basis …
- … instead of quadrature basis



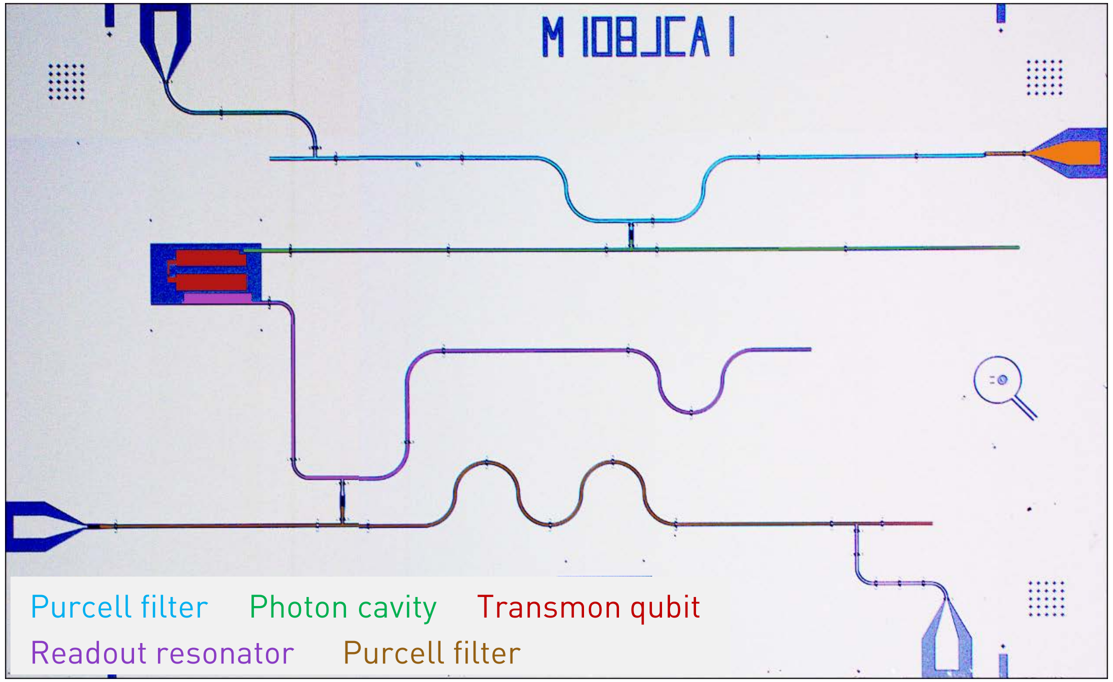
Approach:

Photon-Qubit interaction induced C-PHASE gate in a cavity QED system*

- **Transmon** coupled to **resonator**

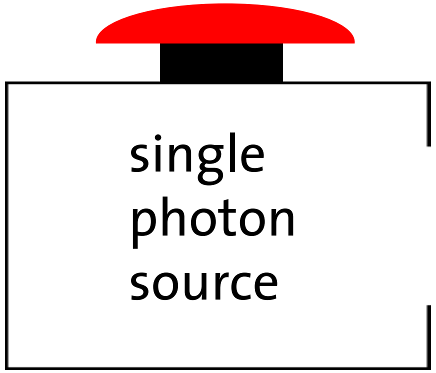
  $$\omega_c = \omega_{ef} \neq \omega_{ge}$$

- Input: **single photon source** or coherent source
- Dedicated qubit **readout** for **photon** and **parity** detection
- **Displacement** field for direct Wigner tomography

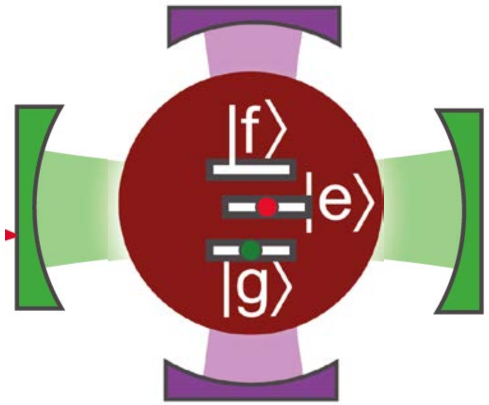


*Duan and Kimble, PRL **92** 12 (2004),
Optical implementation: Reiserer et al. Science **342** 1349 (2013),

Non-demolition detection of single photons



Detector =



Qutrit-Cavity system:

- $\omega_c = \omega_{ef} \neq \omega_{ge}$
- $\kappa/2\pi$ = 19 MHz
- $g/2\pi$ = 40 MHz
- T1 = 3 us
- T2 = 1.8 us

Qubit initialized in $|g\rangle + |e\rangle$ $\xrightarrow{\text{No photon}}$ $|g\rangle + |e\rangle$

Single Photon reflected off the cavity → $|g\rangle - |e\rangle$

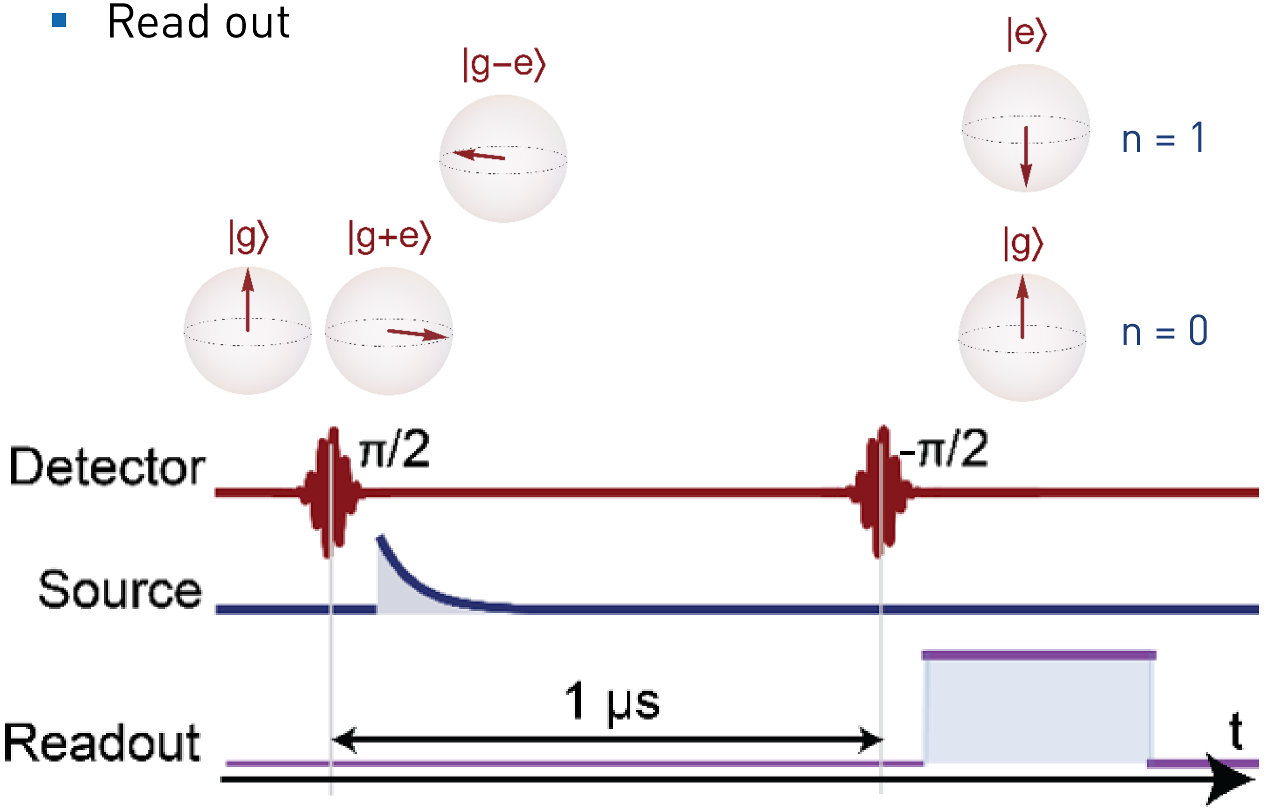
Distinguishable in single shot using:

- $\pi/2$ – pulse
- Single-shot qubit readout with 92% fidelity

Protocol: Duan and Kimble, PRL **92** 12 (2004),
Optical implementation: Reiserer et al. Science **342** 1349 (2013),
cQED @ETH: Besse et al., Phys. Rev. X **8**, 021003 (2018)
Kono et al., Nat. Phys. (2018)

Qubit Perspective of Interaction: Single Photon Detection

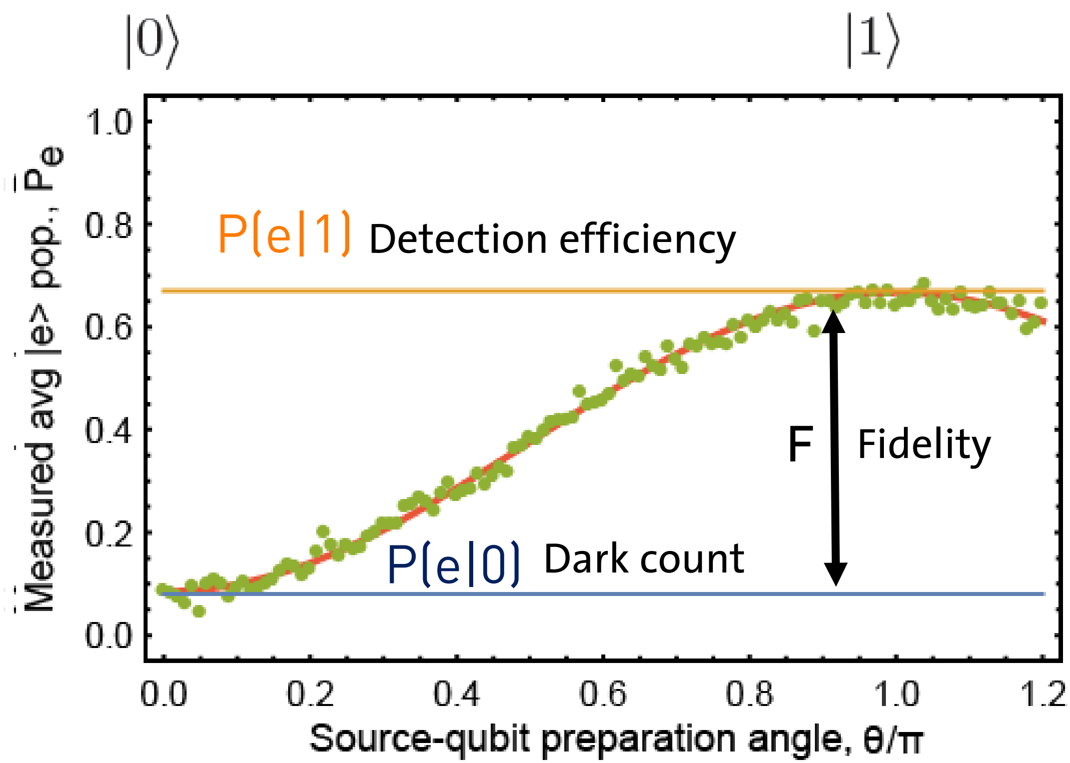
- Prepare qubit in superposition state
- Presence of photon induces π −phase shift
- Map qubit state back to measurement basis
- Read out



- Preparation of photonic state

$$|\gamma\rangle = \cos(\theta/2)\,|0\rangle + \sin(\theta/2)\,|1\rangle$$

- Measurement of qubit excited state population P_e



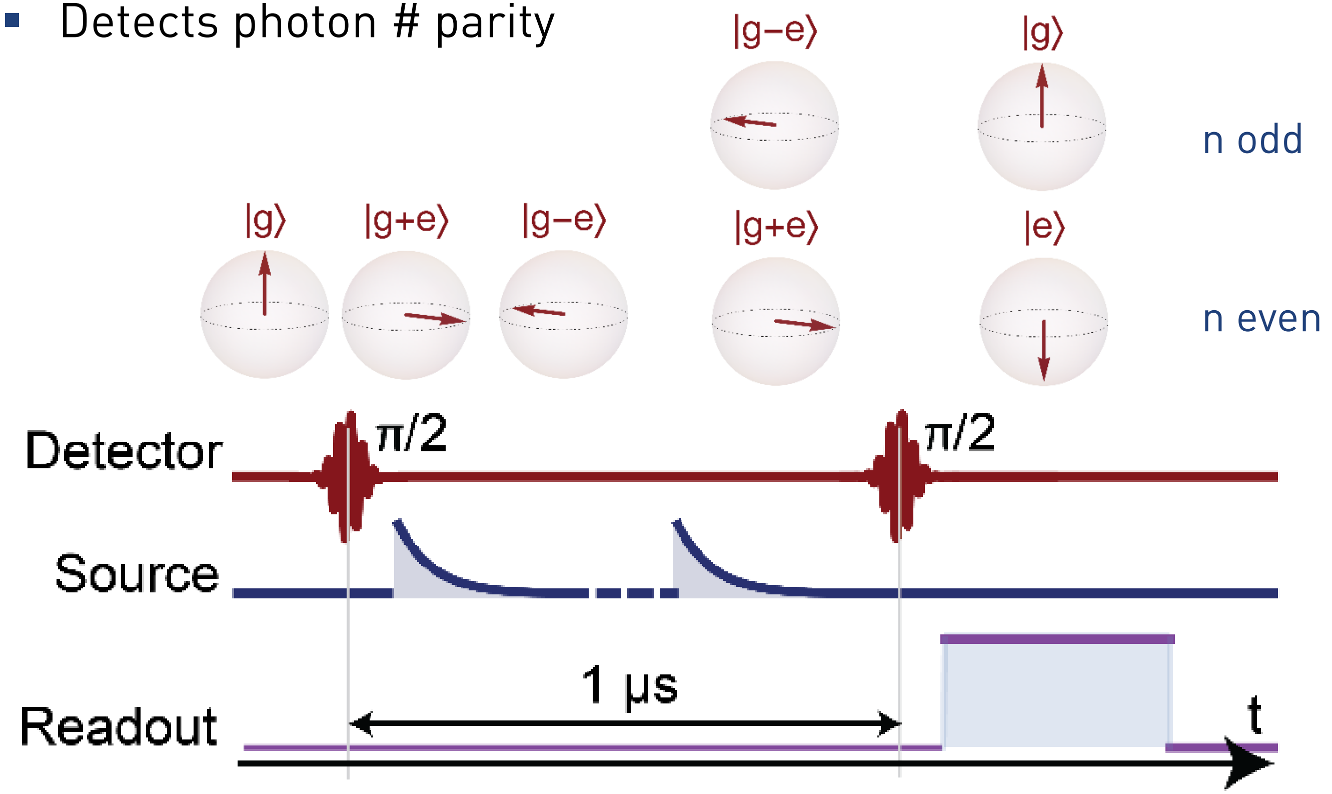
Single photon source: Pechal, **Besse** et al., PRApplied **6** 024009 (2016)

Single photon detection: Besse et al., PRX **8** 021003 (2018), Kono et al., Nat.Phys. **14**, 546 (2018)

Photon Number Parity Detection for Microwave Fields

Operation of detector:

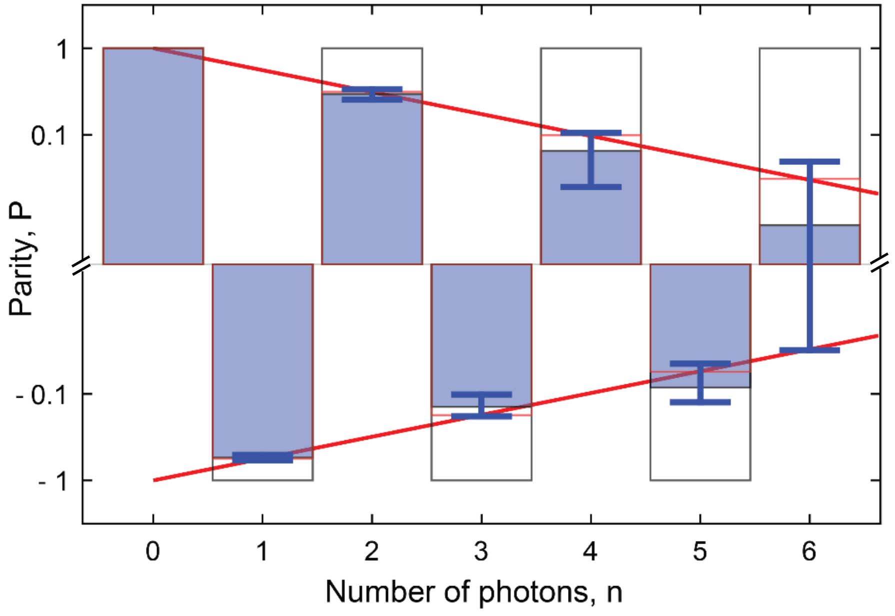
- Perform Ramsey sequence
- Sensitive to field-induced qubit-phase shift
- Single-shot qubit readout capability
- Detects photon # parity



J.C. Besse et al., Quantum Device Lab (2019)

Observations:

- Alternating parity signal (log-scale)
- Reduction in contrast due to finite transmission efficiency $\eta = 0.78$ between source and detector.



Conclusion

- Superconducting circuits provide versatile platform to study quantum optics phenomena.
- Deterministic generation of quantum light: single photons, multi-mode entanglement.
- Measurement schemes: Quadrature, single photon, parity detection
- Access to field correlations: Density matrix reconstruction, time-dependent correlations, direct Wigner tomography.

Outlook

- Realization of photon/photon interactions for QIP.
- Generation of cluster states for measurement-based quantum computing.
- Quantum networks based on microwave radiation.