Quantum Optics with Microwave Photons

Andreas Wallraff *(ETH Zurich)*

www.qudev.ethz.ch

Team: A. Abdumalikov, M. Allan, J. Basset, M. Baur, S. Berger, C. Eichler, A. Fedorov, S. Filipp, T. Frey, P. Kurpiers, C. Lang, J. Mlynek, M. Mondal, M. Oppliger, M. Pechal, G. Puebla-Hellmann, Y. Salathe, M. Stammeier, L. Steffen, A. Stockklauser, T. Thiele, A. van Loo *(ETH Zurich)*

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

SEVENTH FRAMEWORK PROGRAMME

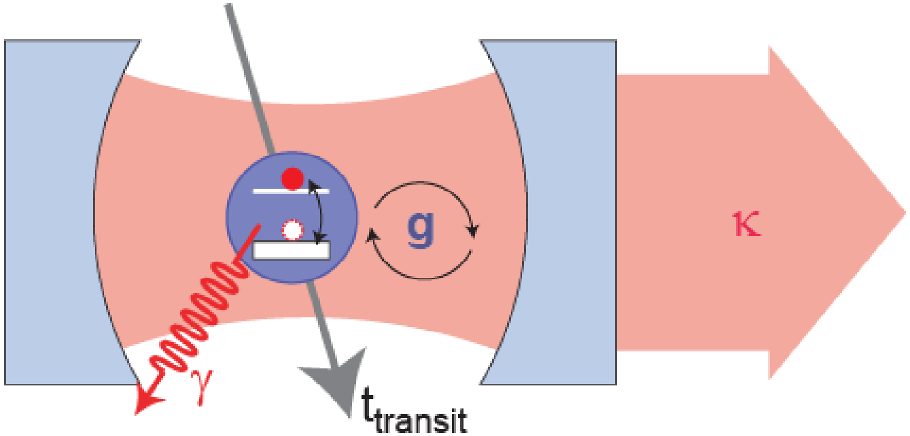
CIRCUIT AND CAVITY QUANTUM ELECTRODYNAMICS

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

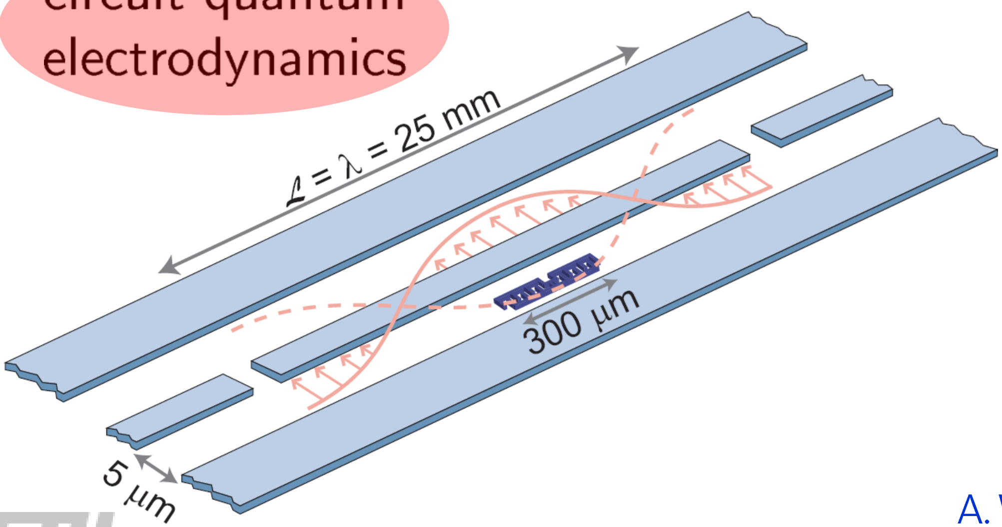
Cavity QED with Superconducting Circuits



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)

circuit quantum electrodynamics



Properties:

- strong coupling in solid state sys.
- ‘easy’ to fabricate and integrate

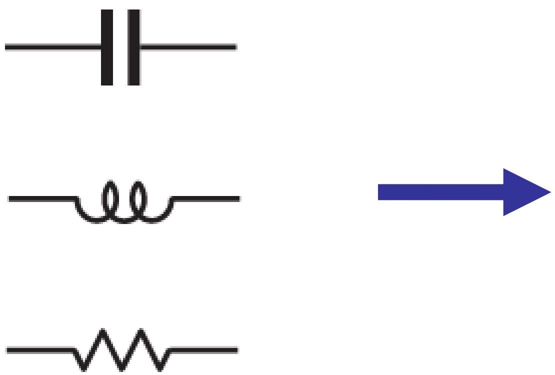
Research directions:

- quantum optics
- quantum information
- hybrid quantum systems

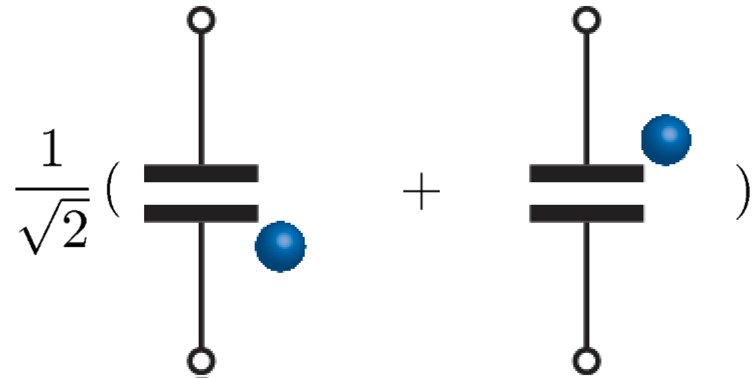
A. Blais, *et al.*, *PRA* **69**, 062320 (2004)
A. Wallraff *et al.*, *Nature (London)* **431**, 162 (2004)
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* **451**, 664 (2008)

Classical and Quantum Electronic Circuit Elements

basic circuit elements:



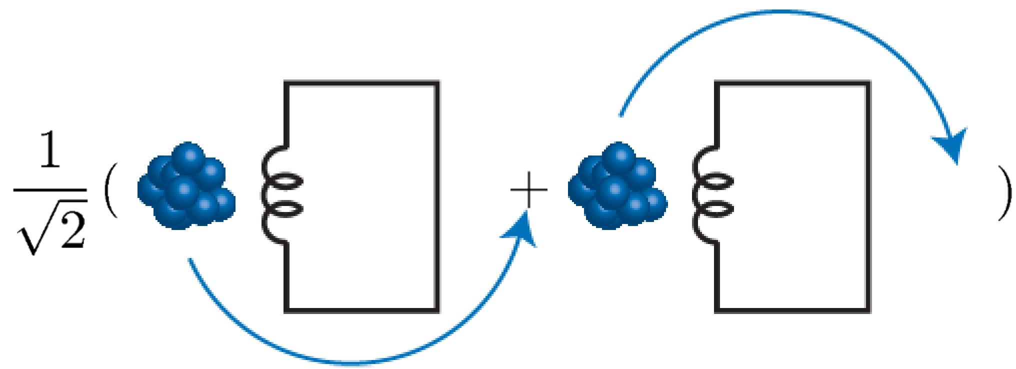
charge on a capacitor:



quantum superposition states of:

- charge q
- flux ϕ

current or magnetic flux in an inductor:

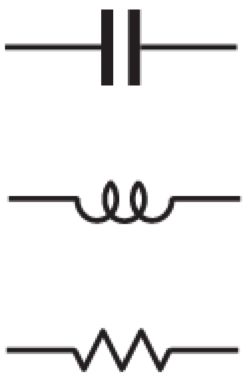


commutation relation (c.f. *x*, *p*):

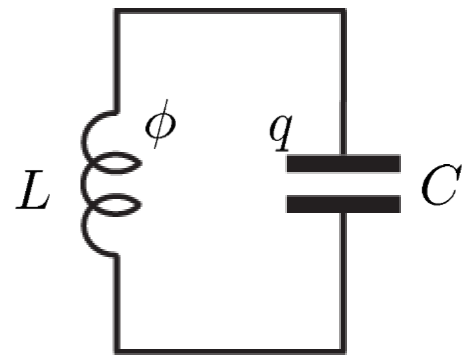
$$\left[\hat{\phi}, \hat{q}\right] = i\hbar$$

Constructing Linear Quantum Electronic Circuits

basic circuit elements:



harmonic LC oscillator:



$$\omega = \frac{1}{\sqrt{LC}} \sim 5\,\mathrm{GHz}$$

classical physics:

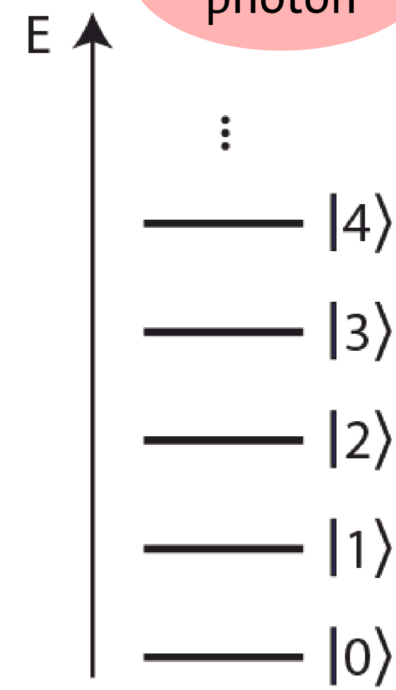
$$H = \frac{\phi^2}{2L} + \frac{q^2}{2C}$$

quantum mechanics:

$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{\hat{q}^2}{2C} = \hbar\omega(\hat{a}^\dagger\hat{a} + \frac{1}{2}) \qquad \left[\hat{\phi}, \hat{q}\right] = i\hbar$$

energy:

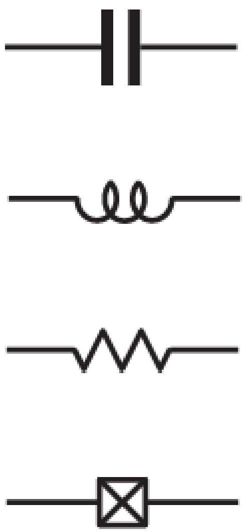
electronic photon



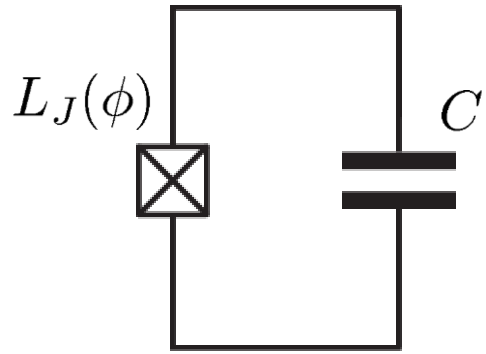
Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)

Constructing Non-Linear Quantum Electronic Circuits

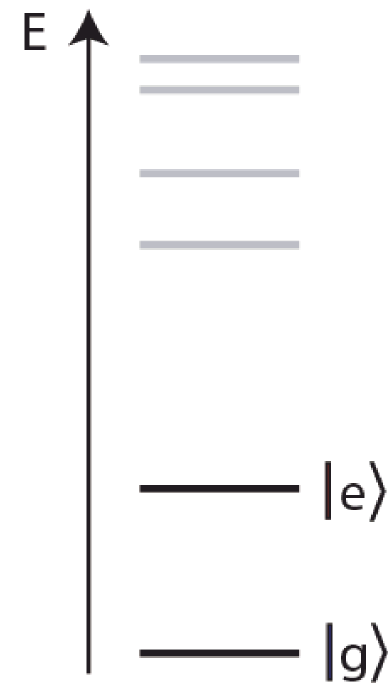
circuit elements:



anharmonic oscillator:



non-linear energy level spectrum:



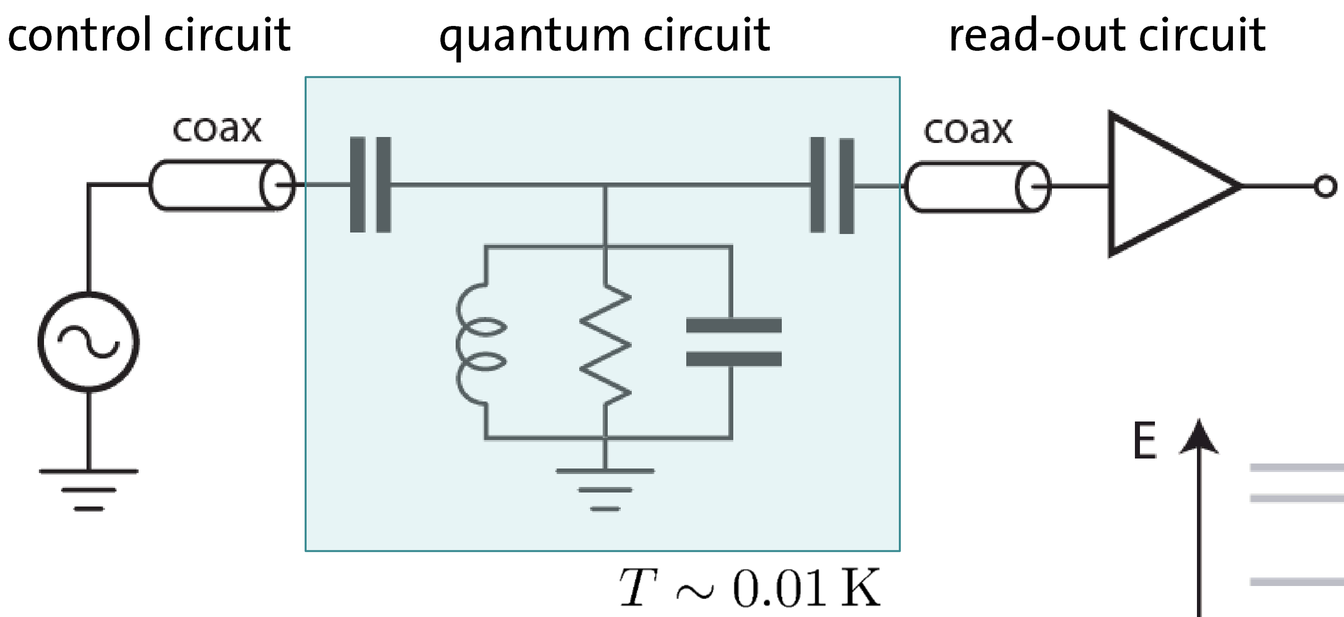
Josephson junction:
a non-dissipative nonlinear element (inductor)

$$L_J(\phi) = \left(\frac{\partial I}{\partial \phi}\right)^{-1} = \frac{\phi_0}{2\pi I_c}\frac{1}{\cos(2\pi\phi/\phi_0)}$$

electronic artificial atom

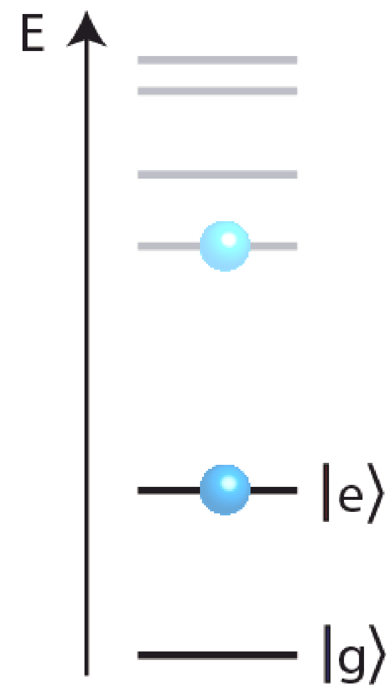
Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)

How to Operate Circuits in the Quantum Regime?



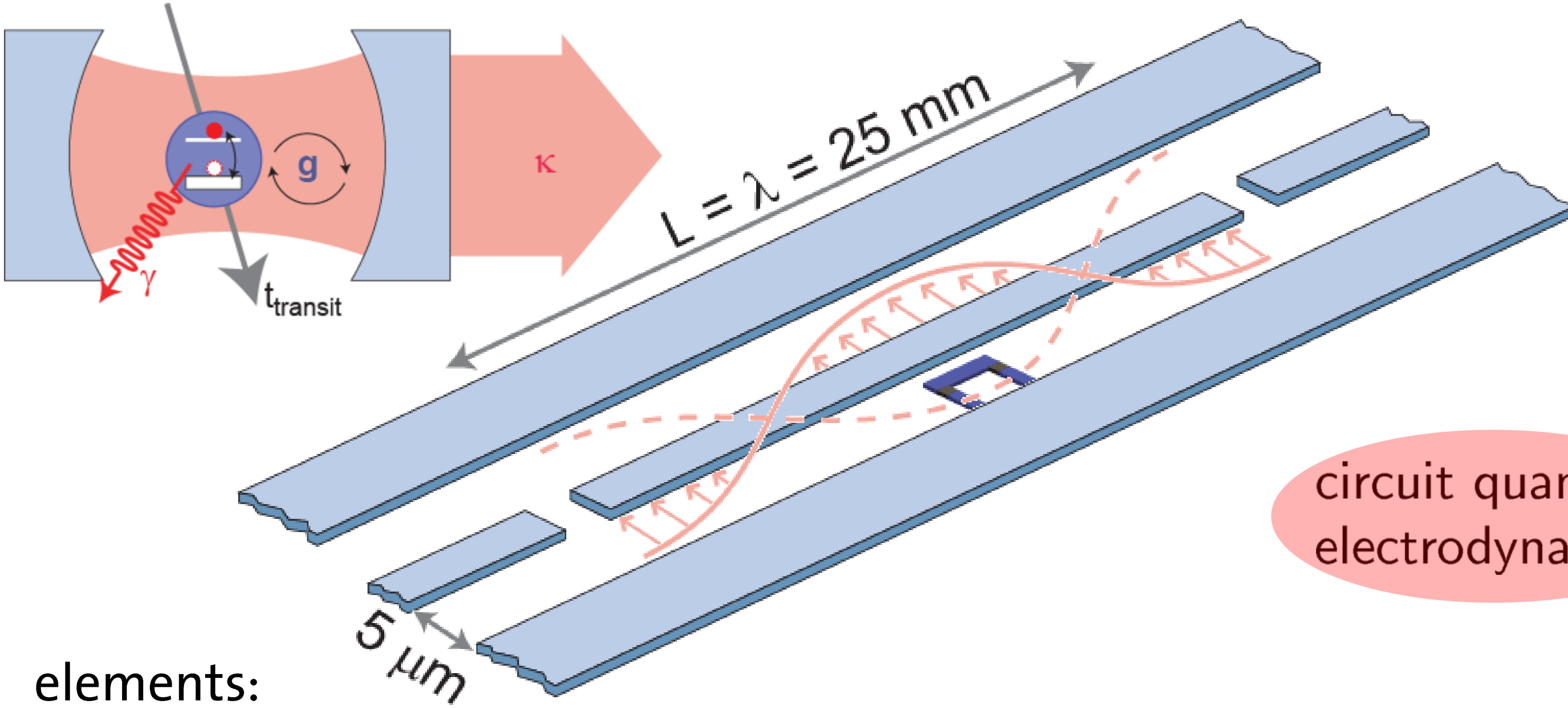
recipe:

- avoid dissipation
- work at low temperatures
- isolate quantum circuit from environment



Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)

Cavity QED with Superconducting Circuits



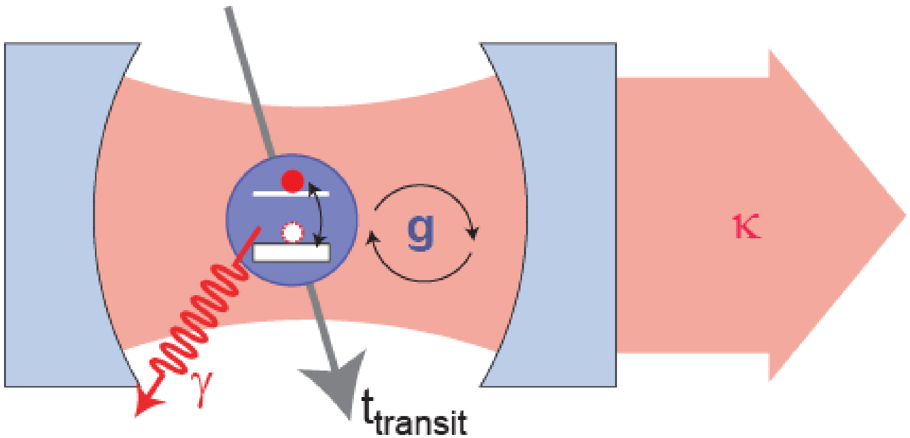
circuit quantum electrodynamics

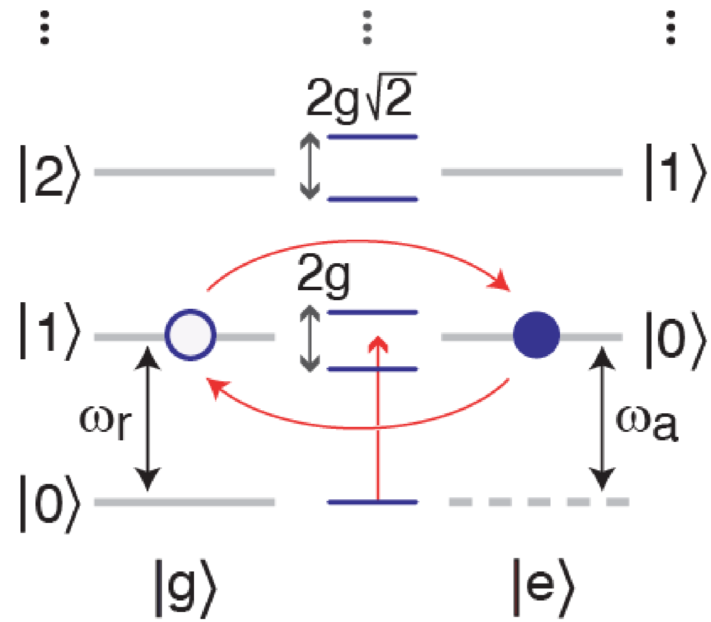
elements:

- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_o and long photon life time $1/\kappa$
- the atom: a superconducting qubit with large dipole moment d and long coherence time $1/\gamma$ and fixed position ...
- ... or any microscopic/macroscopic quantum element or ensemble thereof with an appreciable dipole moment

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)

Cavity Quantum Electrodynamics





Jaynes-Cummings Hamiltonian

Jaynes-Cummings Ladder

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+) + H_\kappa + H_\gamma$$

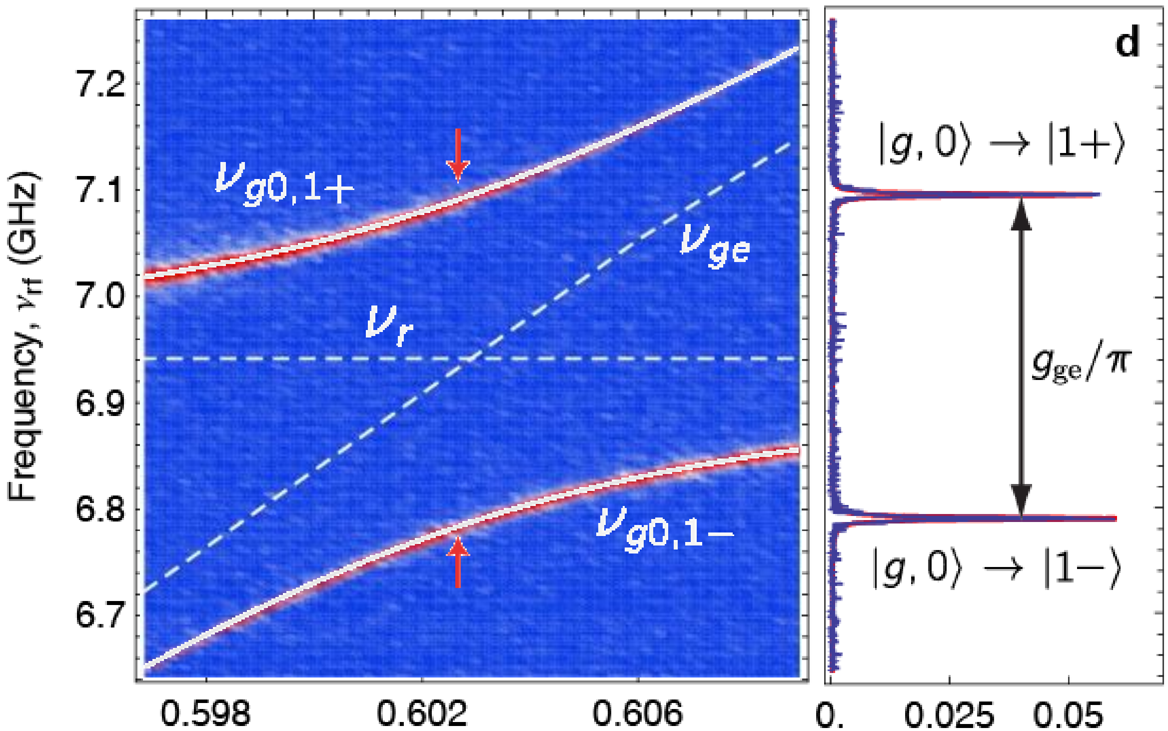
strong coupling limit $(g = dE_0/\hbar > \gamma,\ \kappa\,,1/t_{\mathrm{transit}})$

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

Resonant Vacuum Rabi Mode Splitting ...

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

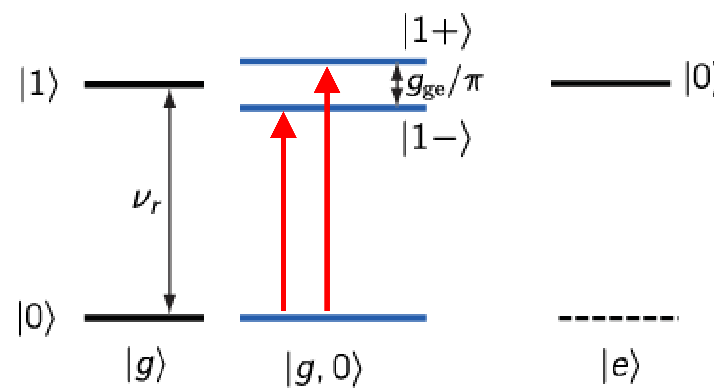
very strong coupling:



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

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

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



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)

Resonant Vacuum Rabi Mode Splitting …

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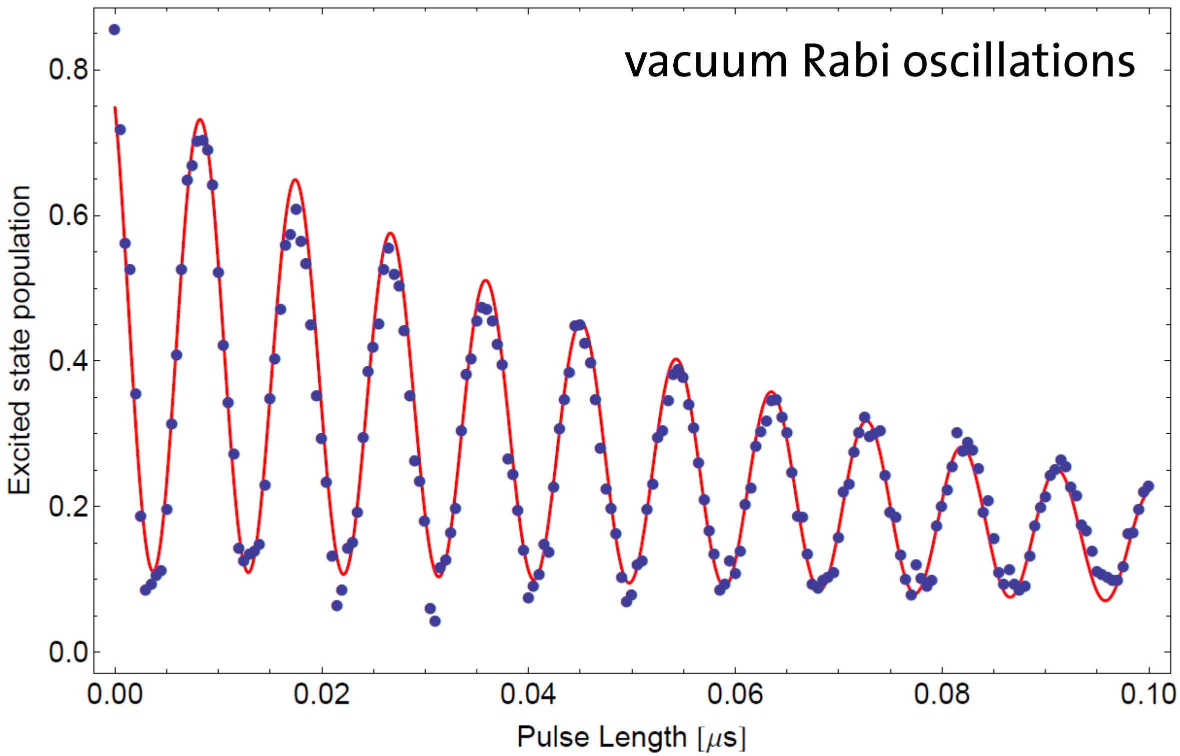

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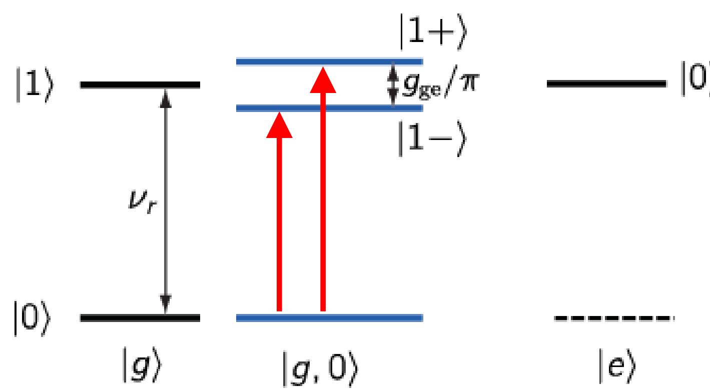

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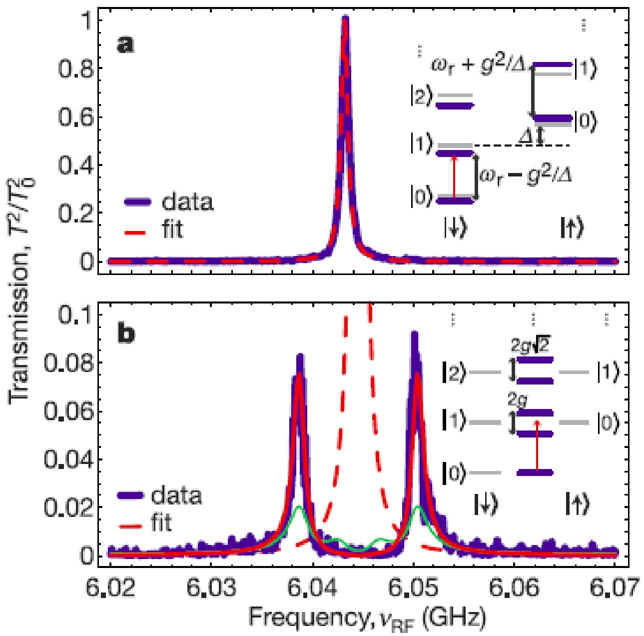
this data: J. Fink et al., *Nature (London)* **454**, 315 (2008)

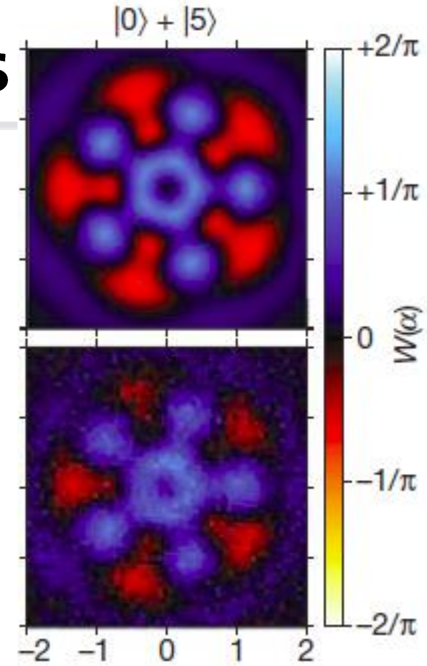
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* **451**, 664 (2008)

Quantum Optics with Supercond. Circuits



Strong Coherent Coupling

Chiorescu *et al.*, *Nature* **431**, 159 (2004)
Wallraff *et al.*, *Nature* **431**, 162 (2004)
Schuster *et al.*, *Nature* **445**, 515 (2007)

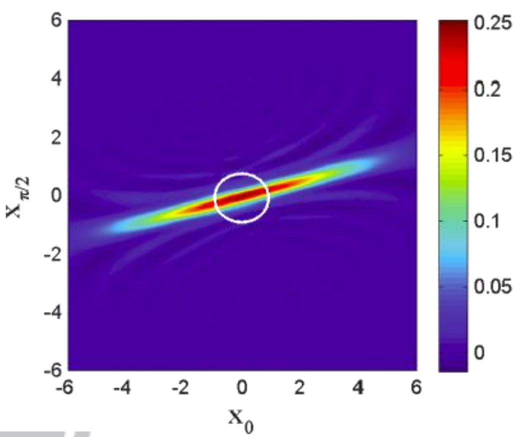


Root n Nonlinearities

Fink *et al.*, *Nature* **454**, 315 (2008)
Deppe *et al.*, *Nat. Phys.* **4**, 686 (2008)
Bishop *et al.*, *Nat. Phys.* **5**, 105 (2009)

Microwave Fock and Cat States

Hofheinz *et al.*, *Nature* **454**, 310 (2008)
Hofheinz *et al.*, *Nature* **459**, 546 (2009)
Kirchmair *et al.*, *Nature* **495**, 205 (2013)

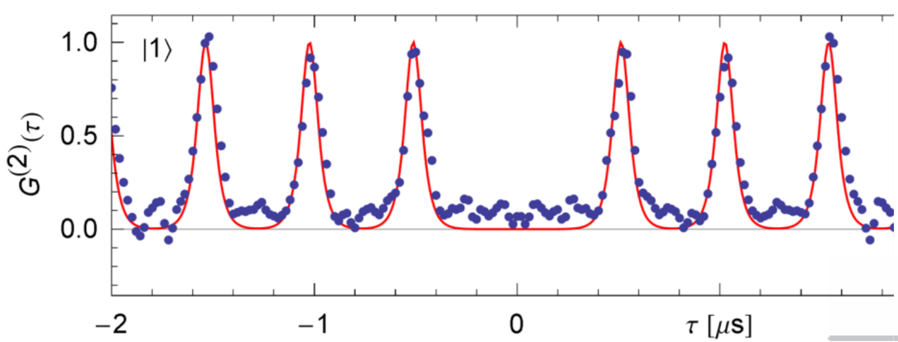


Parametric Amplification & Squeezing

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

Single Photons & Correlations

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

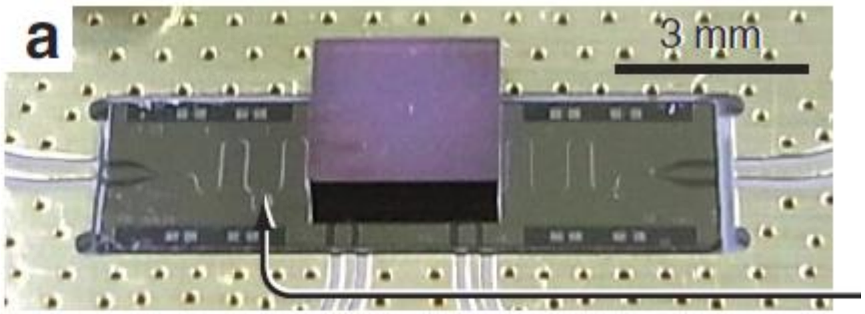


Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Hybrid Systems with Superconducting Circuits

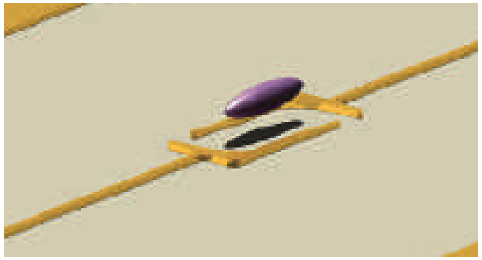
Spin Ensembles: e.g. NV centers

D. Schuster *et al.*, *PRL* **105**, 140501 (2010)
Y. Kubo *et al.*, *PRL* **105**, 140502 (2010)



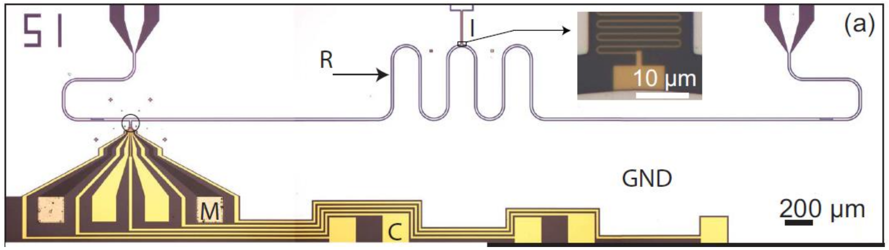
Polar Molecules, Rydberg, BEC

P. Rabl *et al*, *PRL* **97**, 033003 (2006)
A. Andre *et al*, *Nat. Phys.* **2**, 636 (2006)
D. Petrosyan *et al*, *PRL* **100**, 170501 (2008)
J. Verdu *et al*, *PRL* **103**, 043603 (2009)



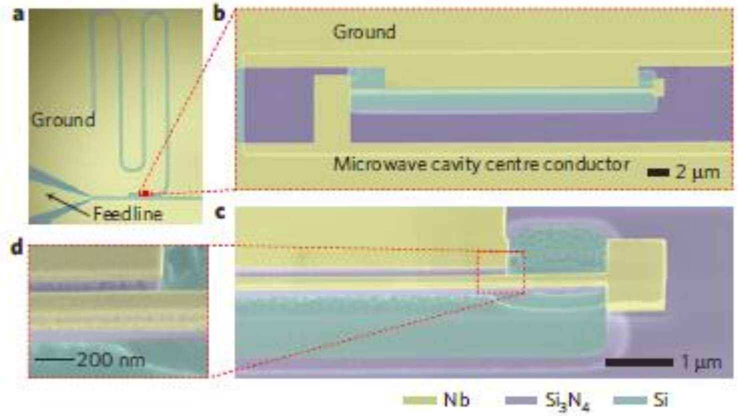
CNT, Gate Defined 2DEG, or nanowire Quantum Dots

M. Delbecq *et al.*, *PRL* **107**, 256804 (2011)
T. Frey *et al.*, *PRL* **108**, 046807 (2012)
K. Petersson *et al.*, *arXiv*:1205.6767 (2012)



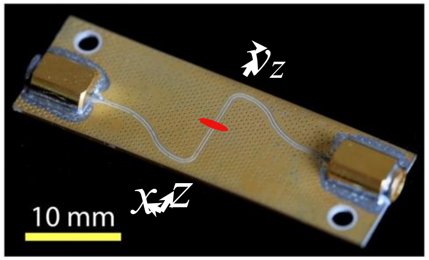
Nano-Mechanics

J. Teufel *et al.*, *Nature* **475**, 359 (2011)
X. Zhou *et al.*, *Nat. Phys.* **9**, 179(2013)



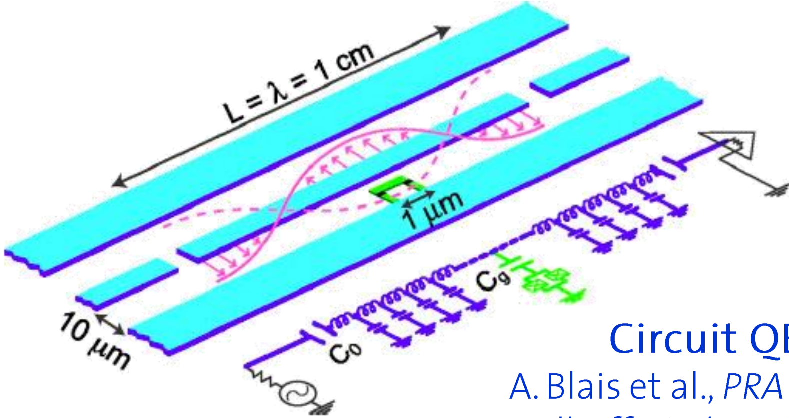
Rydberg Atoms

S. Hogan*et al.*, *PRL* **108**, 063004 (2012)



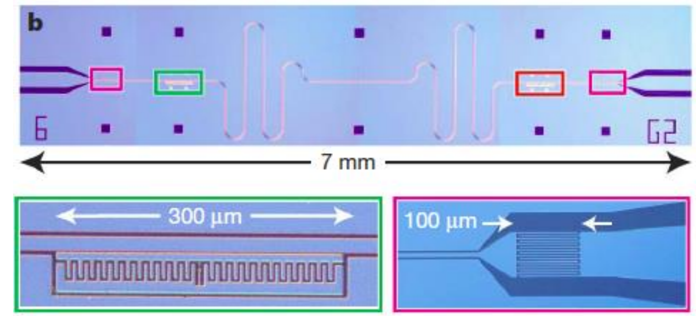
... and many more

Quantum Computing with Superconducting Circuits



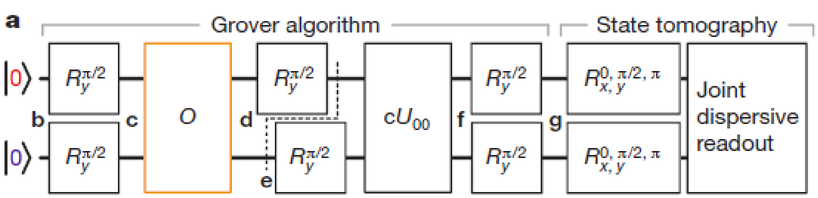
Circuit QED Architecture

A. Blais et al., *PRA* **69**, 062320 (2004)
A. Wallraff *et al.*, *Nature* **431**, 162 (2004)
M. Mariantoni *et al.*, *Science* **334**, 61 (2011)



Resonator as a Coupling Bus

M. Sillanpaa *et al.*, *Nature* **449**, 438 (2007)
H. Majer *et al.*, *Nature* **449**, 443 (2007)

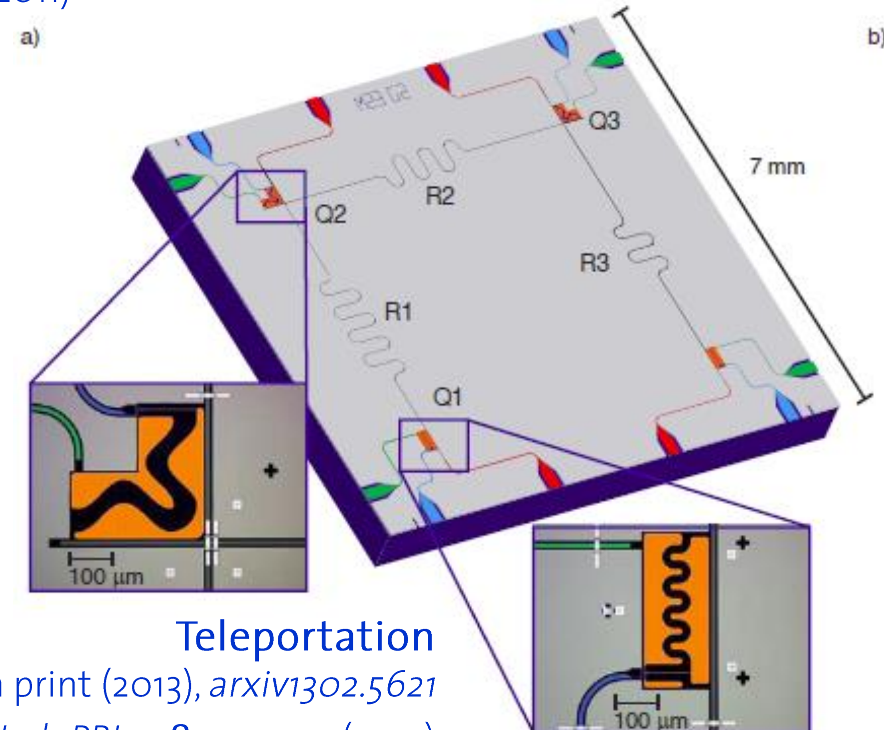


Deutsch, Grover Algorithms

L. DiCarlo *et al.*, *Nature* **460**, 240 (2009)
L. DiCarlo *et al.*, *Nature* **467**, 574 (2010)

Toffoli Gates & Error Correction

A. Fedorov *et al.*, *Nature* **481**, 170 (2012)
M. Reed *et al.*, *Nature* **481**, 382 (2012)



Teleportation

L. Steffen *et al.*, *Nature*, in print (2013), *arxiv1302.5621*
M.. Baur *et al.*, *PRL* **108**, *040502* (2012)

Exploring the Properties of Propagating Photons

quantum optics in the **visible**:

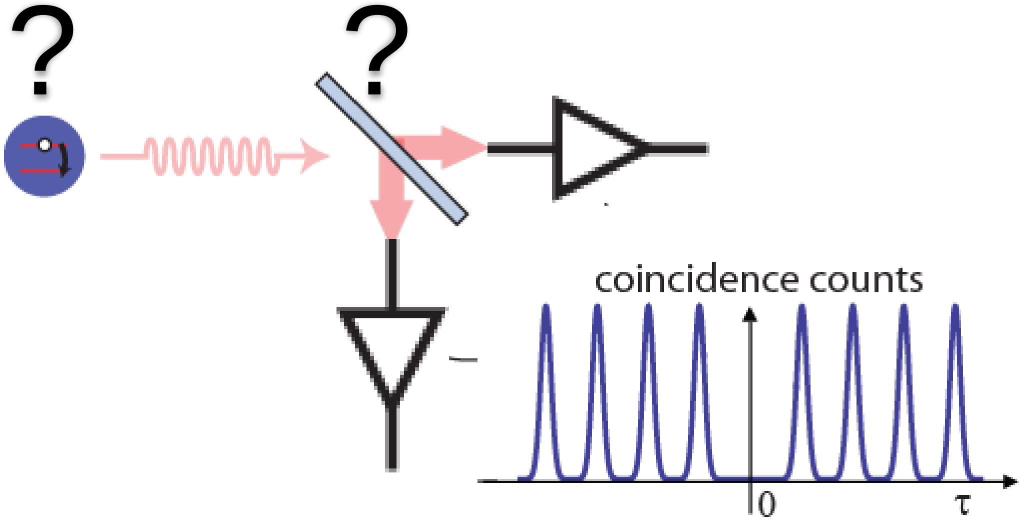
- single photon sources
- beam splitters
- photon counters

o.k. at **optical frequencies**

But in the **microwave domain**?

- smaller photon energy ...

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



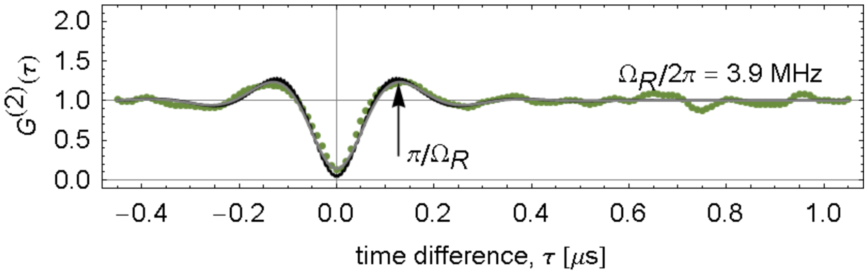
instead:

- 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

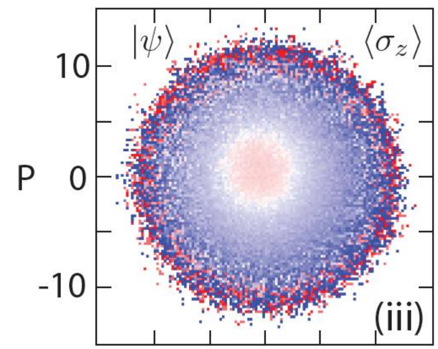
Single photon sources and their anti-bunching

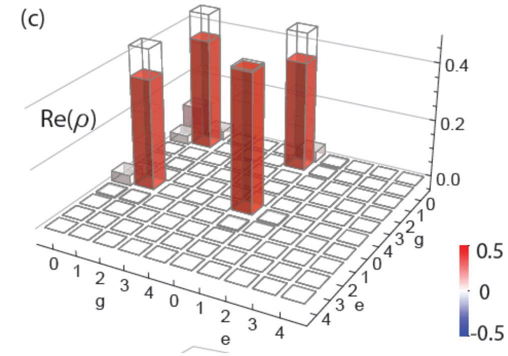


Lang *et al.*, *PRL* **107**, 073601 (2011)

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

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



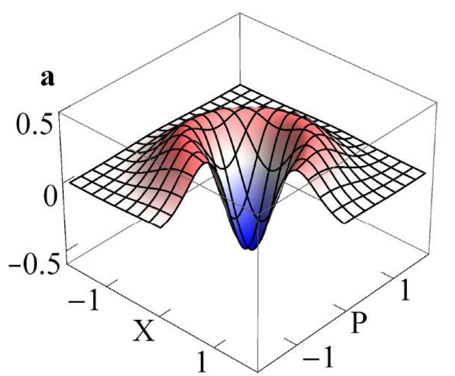


Eichler *et al.*, *PRL* **109**, *240501* (2012)

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

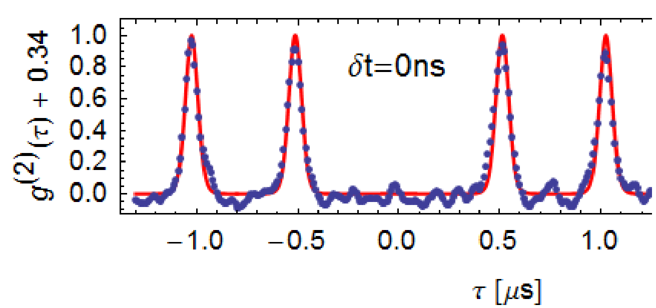
Wigner functions and full state tomography of propagating photons:

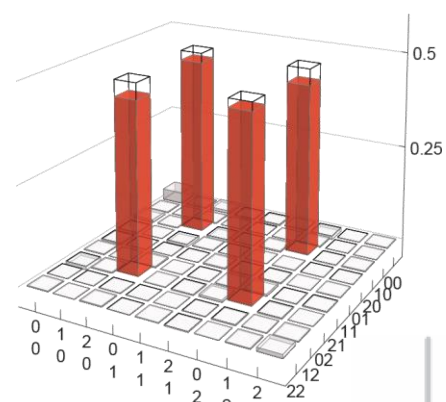
Eichler *et al.*, *PRL* **106**, 220503 (2011)



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

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





Propagating Quantum Microwaves

Correlation Function Measurements of Single Photons

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

Quantum State Tomography

Mallet *et al.*, *PRL* **106**, 220502 (2011)

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

Photon Routers

Hoi *et al.*, *PRL*, **107**, 073601 (2011)

Single Photon Detectors

Chen *et al.*, *PRL* **107**, 217401 (2011)

Positive P-Function/Dual Path Detection

Menzel *et al.* PRL **105**, 100401 (2010)
Eichler *et al.*, *PRA* **86**, 032106 (2012)

Photon/Qubit Entanglement

Eichler *et al.*, *PRL* **109**, *240501* (2012)

Hong-Ou-Mandel N-Photon Interference

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

Thermal and Vacuum Noise

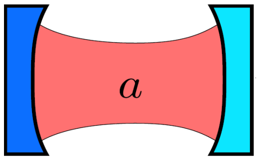
Mariantoni *et al.*, *PRL* **105**, 133601 (2010)

Squeezing & Two Mode Correlations

Castellanos *et al.*, *Nat. Phys.* **4**, 929 (2008)
Eichler *et al.*, *PRL* **107**, 113601 (2011)
Bergeal *et al.*, *PRL* **108**, 123902 (2012)
Flurin *et al.*, *PRL* **109**, 183901 (2012)
Menzel *et al.*, *PRL* **109**, 250502 (2012)

Circuit QED components

cavity



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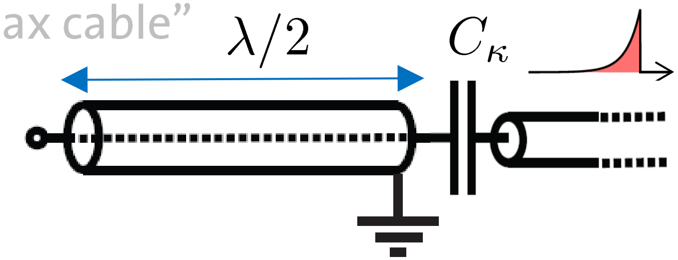
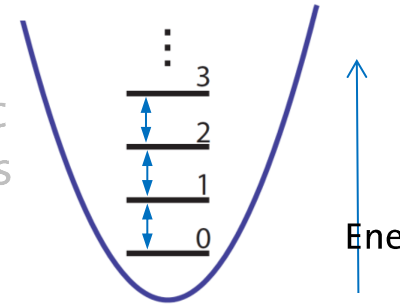
"piece of a coax cable"



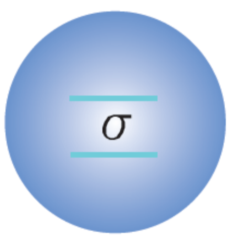
Radiation field stored inside:

$$H = \hbar\omega \; a^\dagger a$$

harmonic oscillators

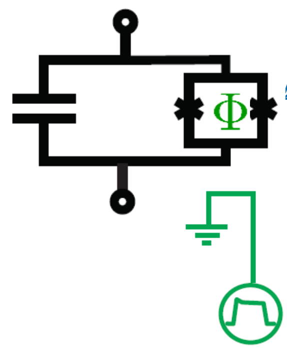


atom



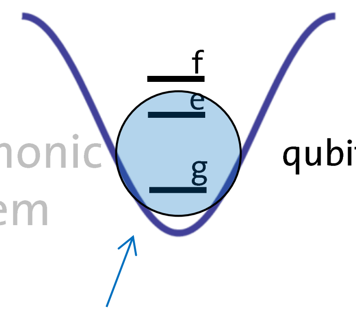
=

transmon



Josephson Junction = "Nonlinear Inductor"

anharmonic system



Change transition energy on **ns** timescales!

Strong coupling regime

- Transmon qubit

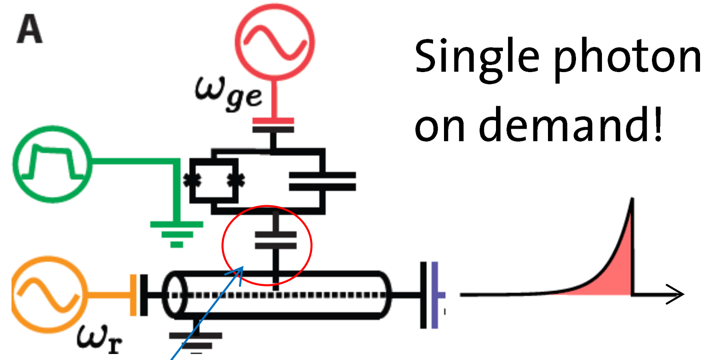
$$T_1 = 1.1\,\mu s$$
$$T_2 = 550\,ns$$
$$T_2^* = 220\,ns$$

- Single sided resonator

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

- Coupling strength

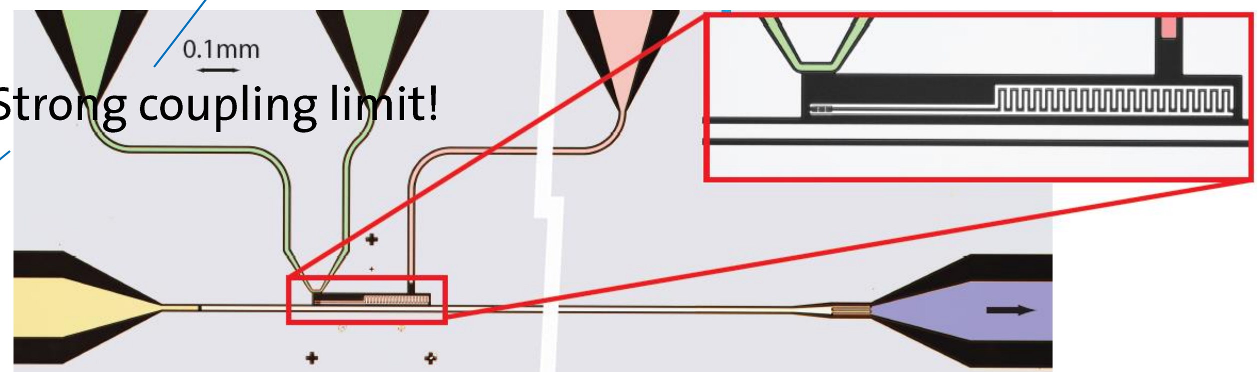
$$\pi/g = 7.7\,ns$$



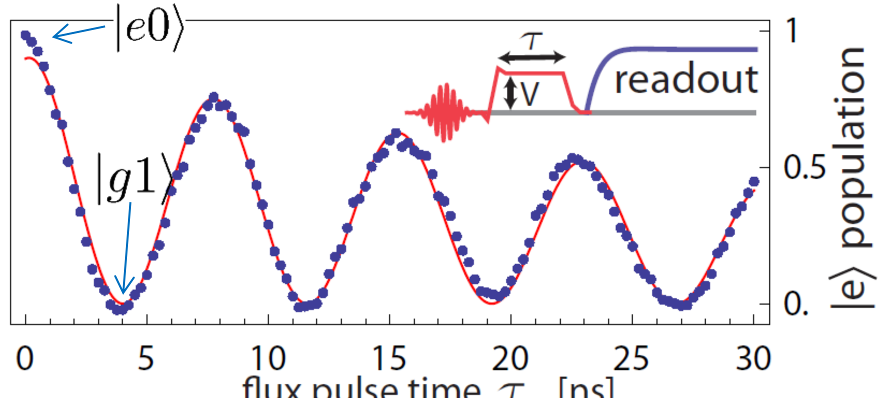
Single photons on demand!

Detection ?

Strong coupling limit!

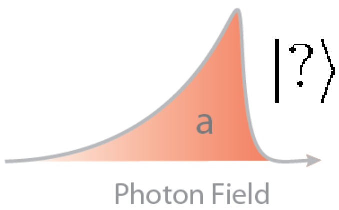


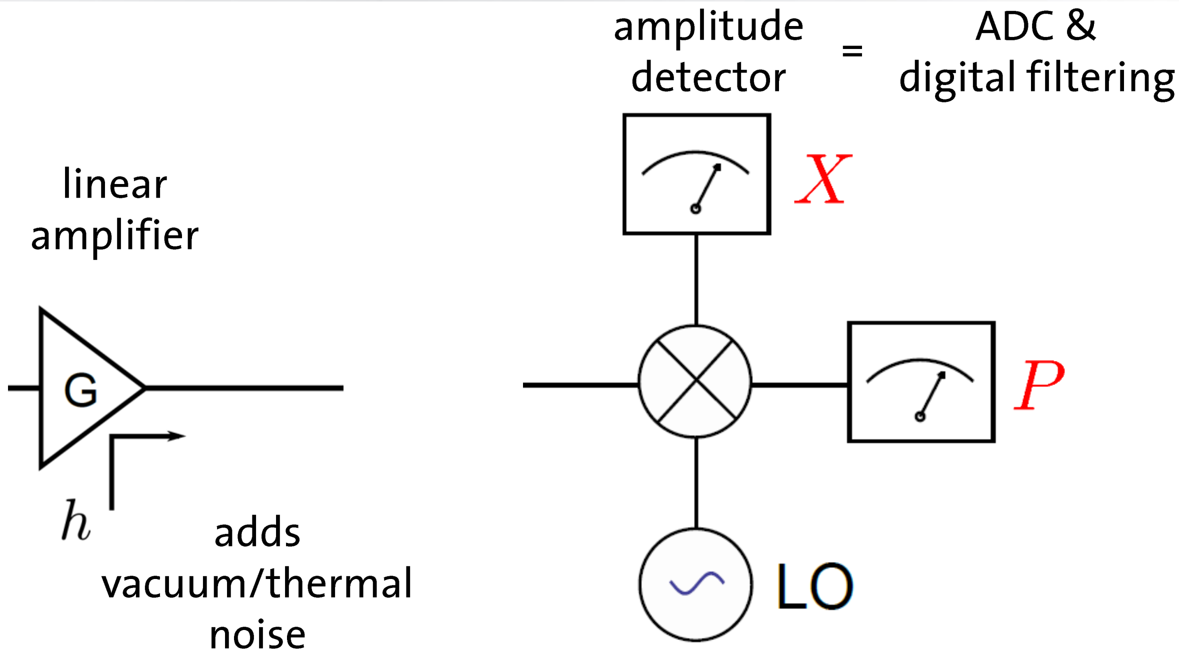
Vacuum Rabi oscillations



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

Microwave Photon Field Detection



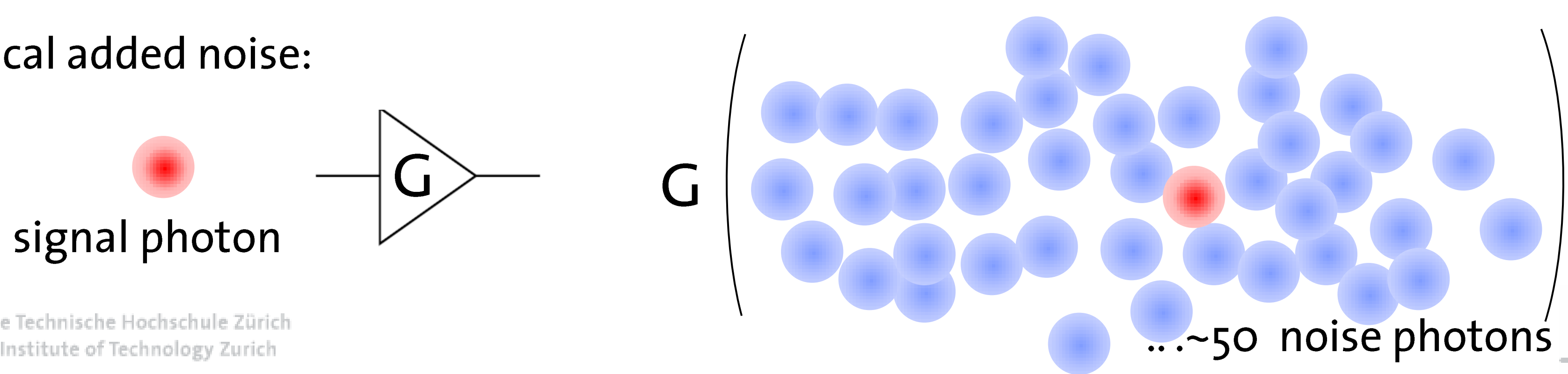


complex amplitude: $$S = X + iP = a + h^\dagger$$

"signal" "noise"

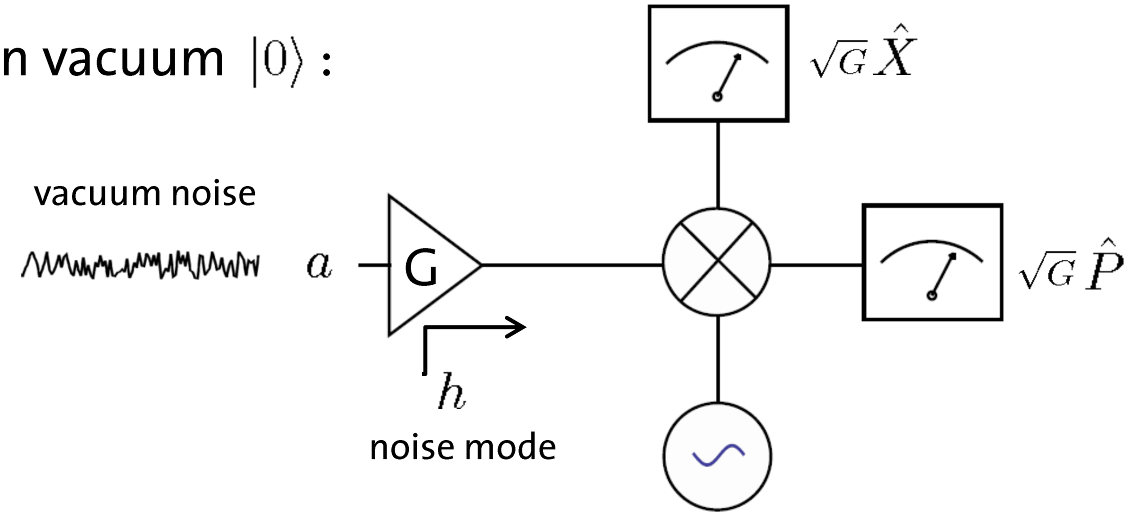
Eichler *et al.*, *PRA* **86**, 032106 (2012)
M. P. da Silva et al., *PRA* **82**, 043804 (2010).
C. M. Caves, *PRD* **26**, 1817 (1982).

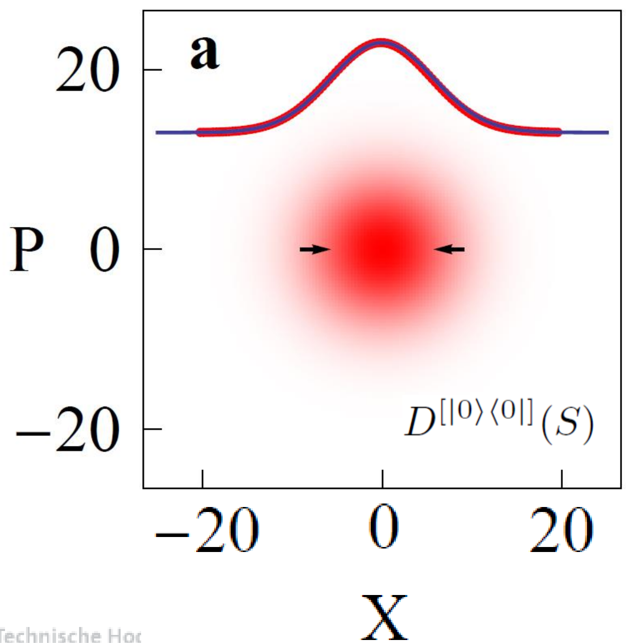
typical added noise:



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

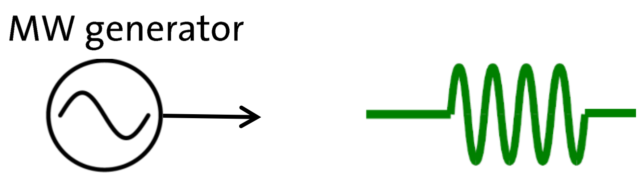
normal distribution with variance

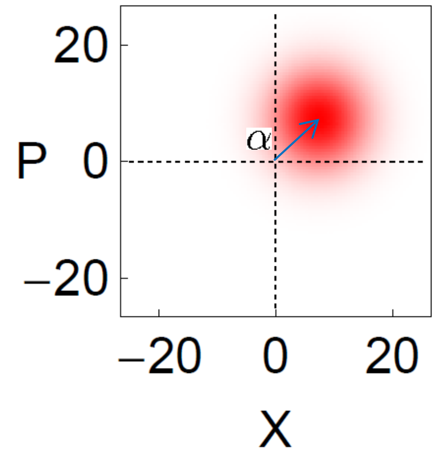
$$2\sigma^2 = \langle \hat{S}^\dagger \hat{S}\rangle / G = \frac{1}{G}\int \mathrm{d}^2 S\, D^{[|0\rangle\langle 0|]}(S)\, S^* S = 67$$

h introduces thermal noise
with mean photon number N_{noise}

Coherent State Histograms

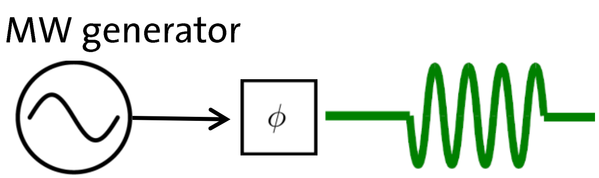
2) prepare a in coherent state $|\alpha\rangle$:

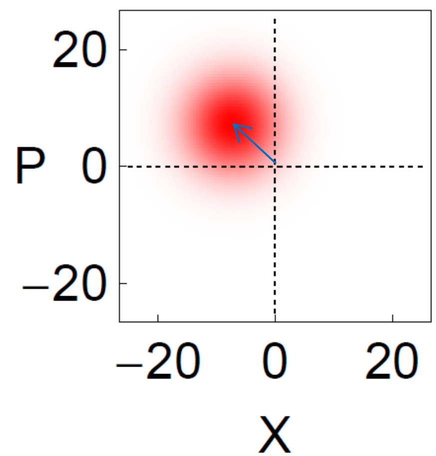




$$|\alpha| \approx 6.3$$
$$\Leftrightarrow$$
$$\langle a^\dagger a\rangle \approx 41 \sim N_{\mathrm{noise}}$$

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

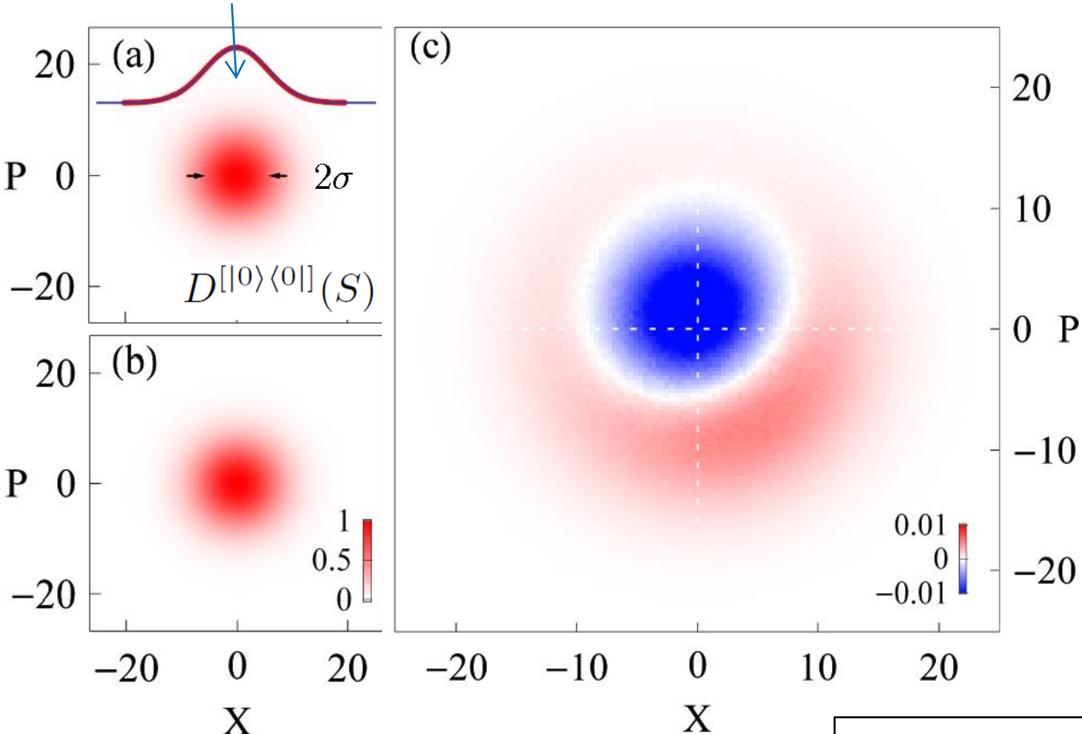
store 2D histogram $D^{[\rho]}(S)$ from $S/\sqrt{G} = X + iP$ measurement results:

corresponding phase space distribution

signal mode a in **vacuum**

Q - function of noise mode : Q_h

convolution with **P** – function of signal $Q_h * P_a$



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:

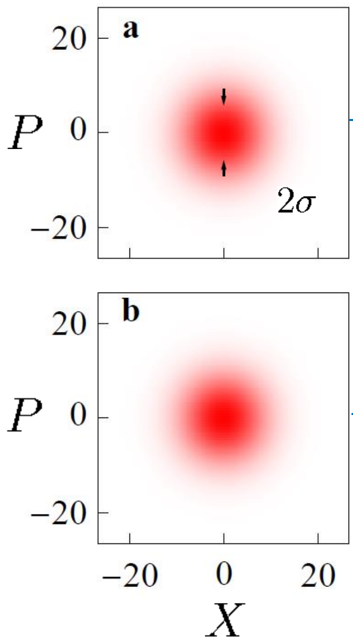
histogram moments: $\langle (\hat{S}^\dagger)^n \hat{S}^m \rangle_\rho = \int \mathrm{d}^2 S \; (S^*)^n S^m \; D^{[\rho]}(S)$

1. calculate histogram moments

2. algebraic inversion

vacuum $|0\rangle$

Fock state $|1\rangle$



$$\frac{\langle (\hat{S}^\dagger)^n \hat{S}^m \rangle_{|0\rangle\langle 0|}}{G^{(n+m)/2}} = \langle h^n (h^\dagger)^m \rangle$$

$$\frac{\langle (\hat{S}^\dagger)^n \hat{S}^m \rangle_{|1\rangle\langle 1|}}{G^{(n+m)/2}} = \langle (h + a^\dagger)^n (h^\dagger + a)^m \rangle$$

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

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

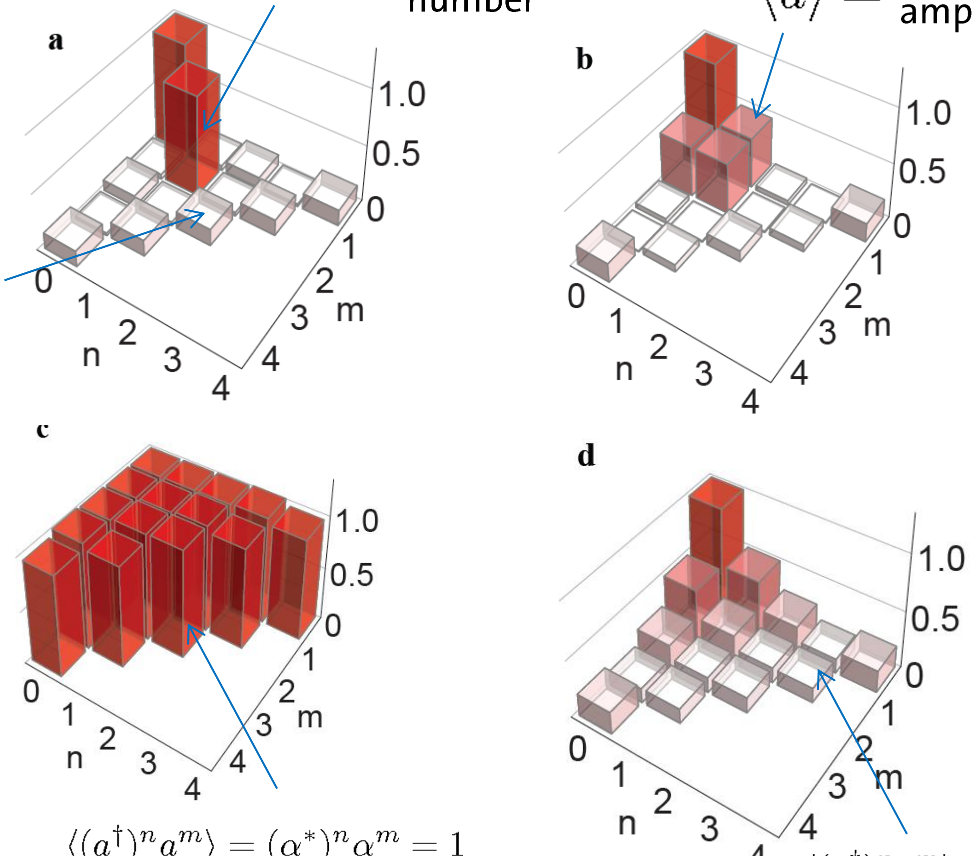
$|1\rangle$

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

$\langle a \rangle =$ "mean amplitude"

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

"anti bunching"



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

$|\alpha = 0.5\rangle$

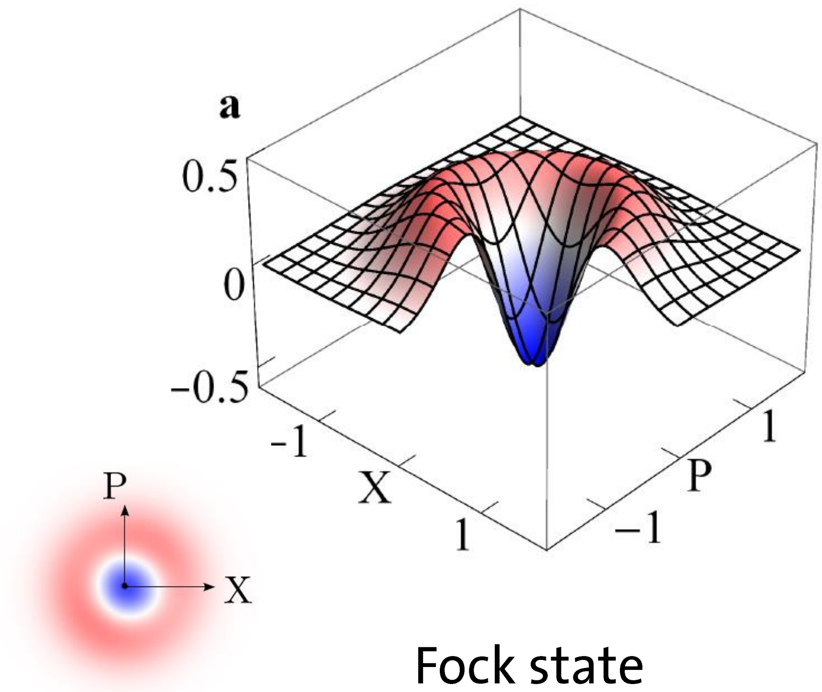
$\langle (a^\dagger)^n a^m \rangle = (1/2)^{n+m}$

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

Reconstructed Wigner Function of Itinerant Photon

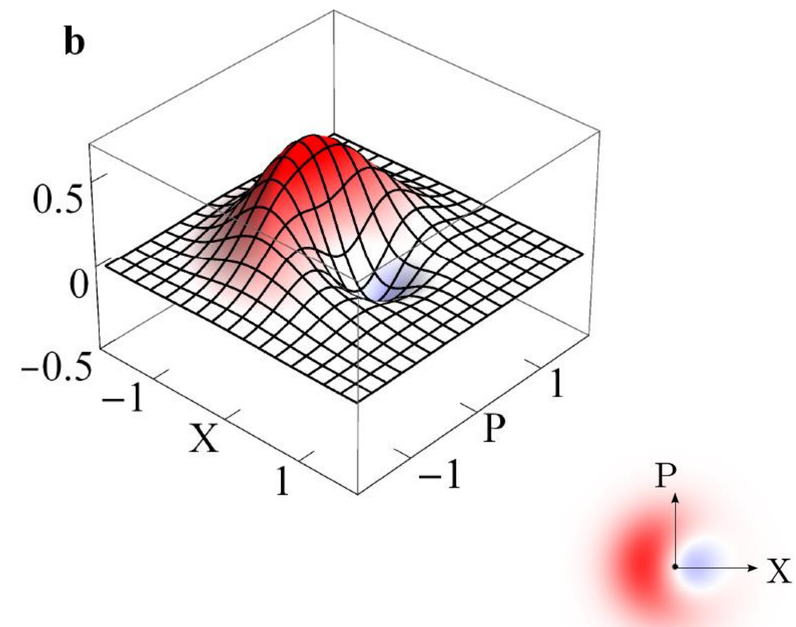
Wigner function reconstructed from measured moments:

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



Fock state

$|1\rangle$



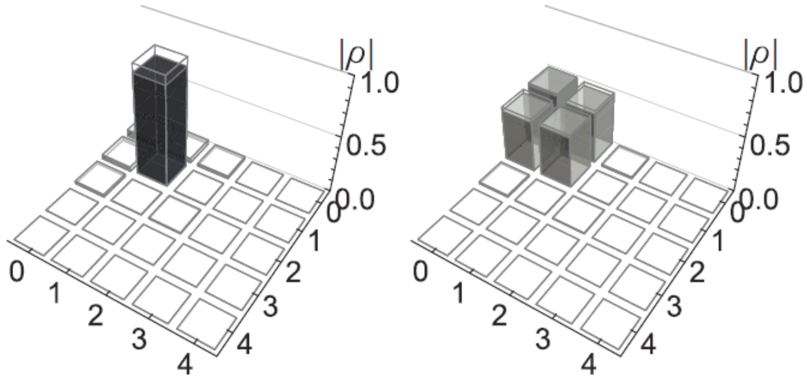
superposition

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

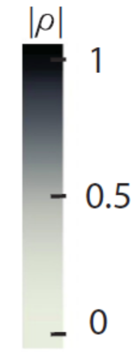
C. Eichler, et al., *PRL* **106**, 220503 (2011), *PRA* **86**, 032106 (2012)

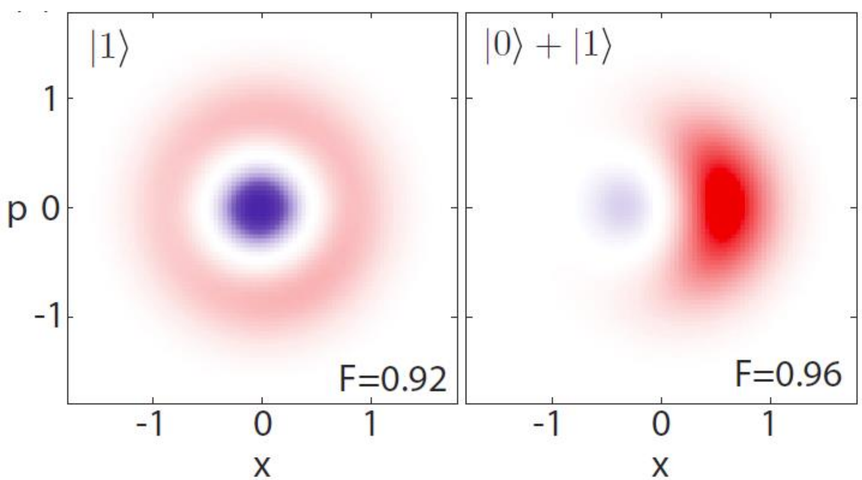
Reconstruct Density Matrices and Wigner functions...

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

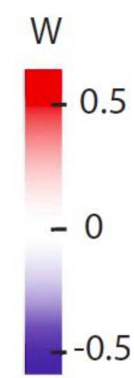


Density matrices





Wigner functions

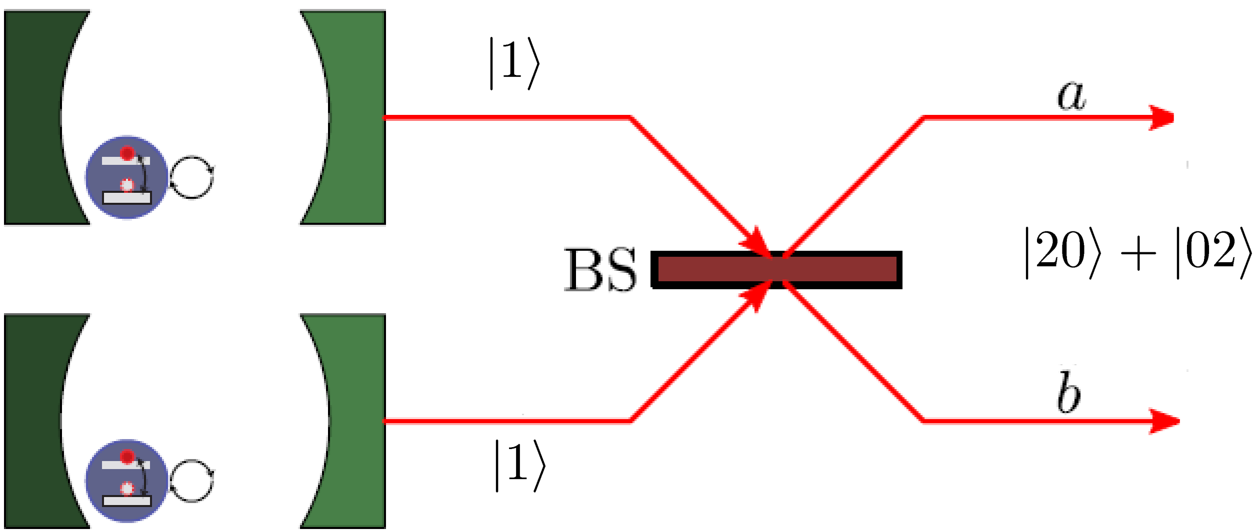


measured using near-quantum-limited parametric amplifier

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

Hong-Ou-Mandel Experiments with Microwaves

Measure field – field correlations in two spatial modes:



Measure

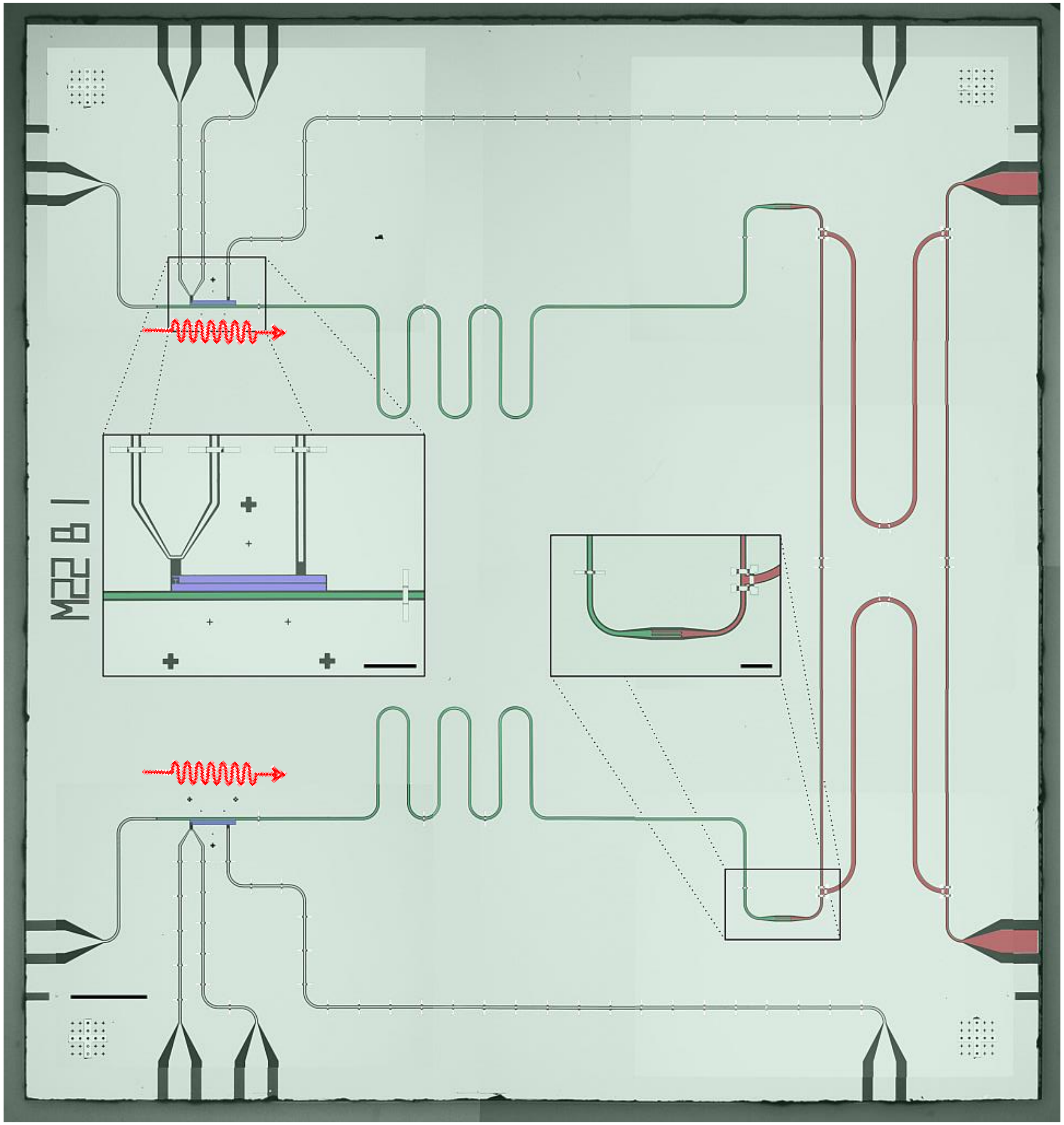
$$\langle (a^\dagger)^n a^m (b^\dagger)^k b^l \rangle$$

... from recorded **4D histograms:** $D(X_a, P_a, X_b, P_b)$

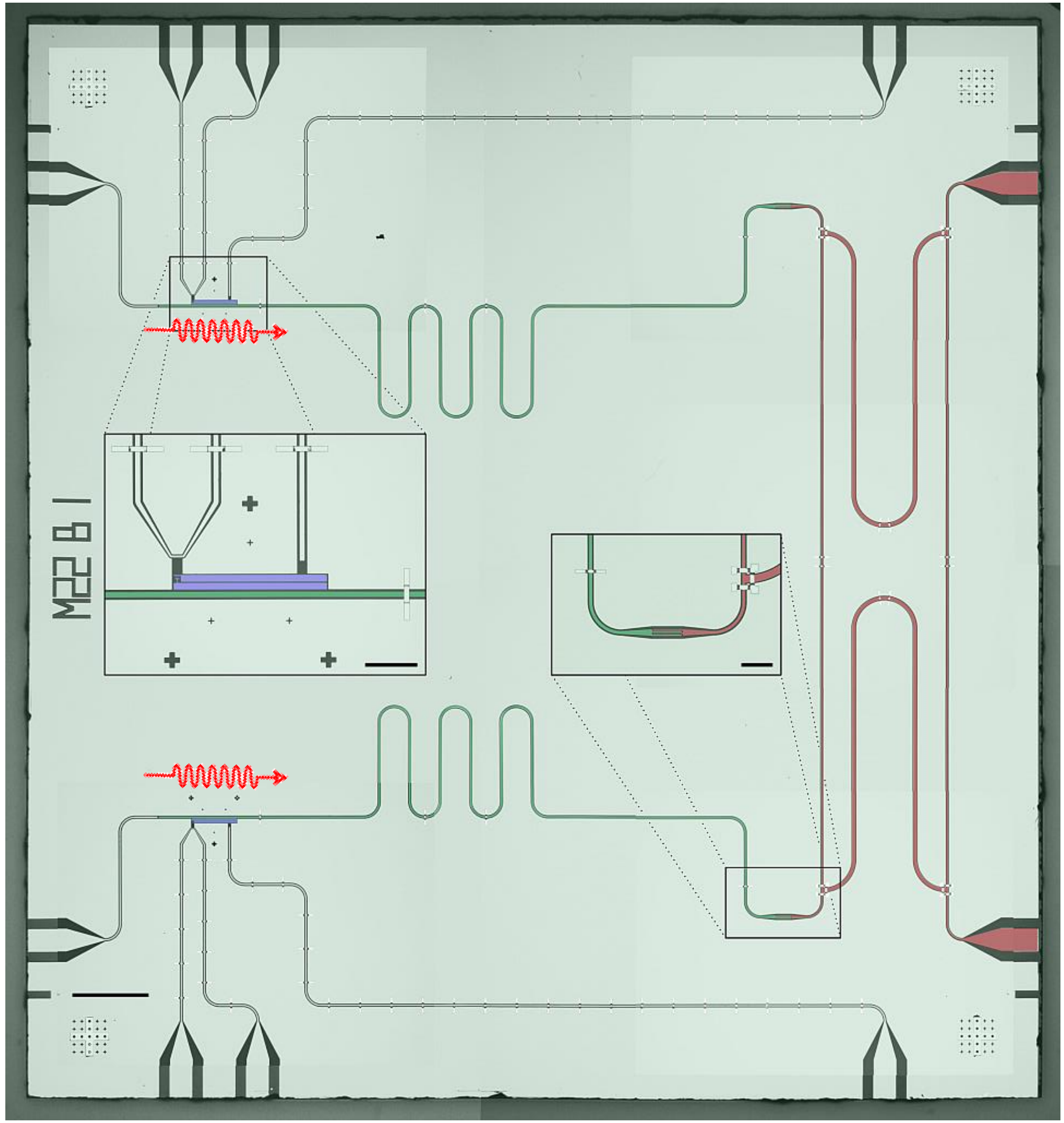
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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

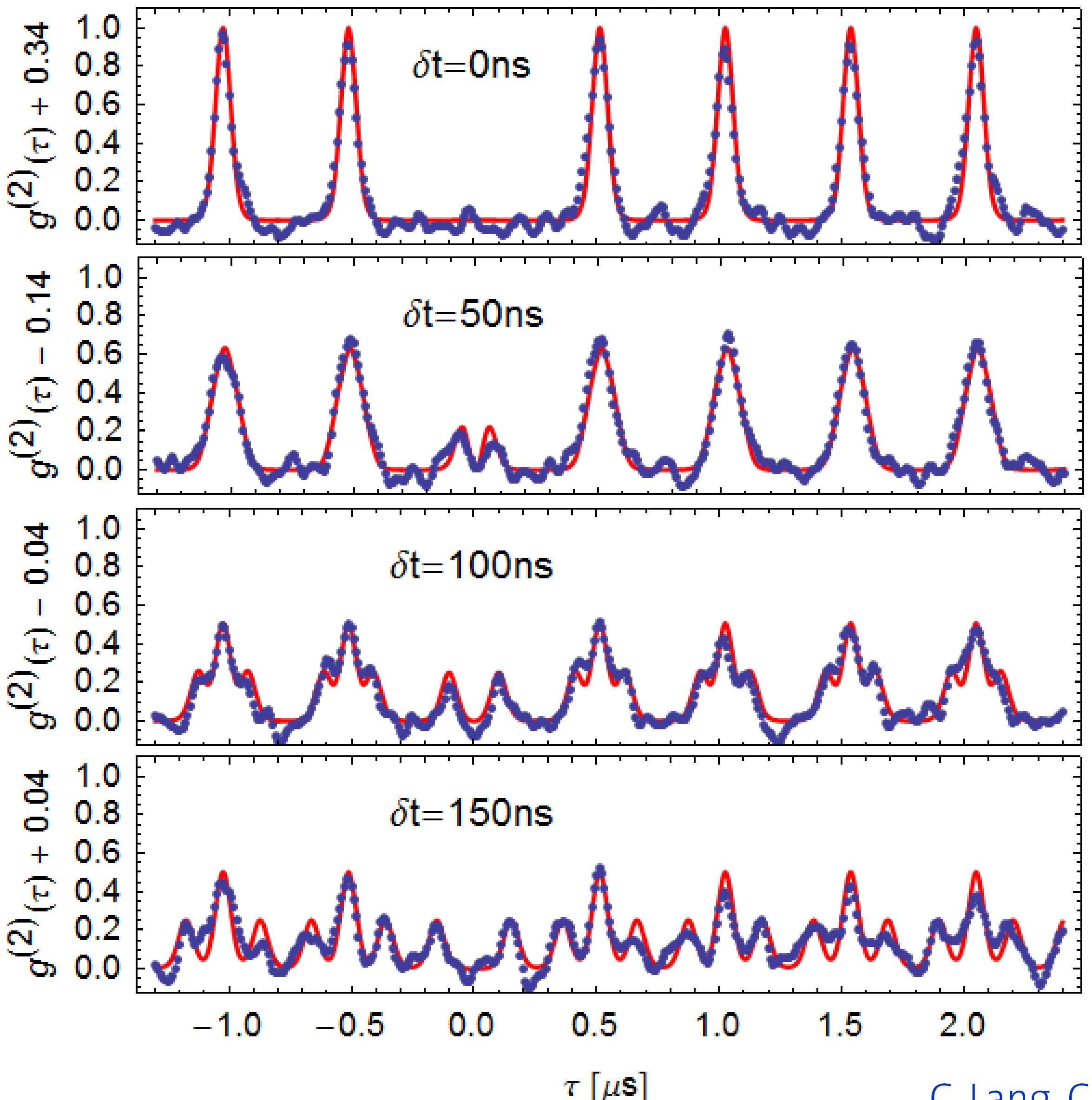
Two Single Photon Sources and Beam Splitter



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.*, *Nat. Phys.* **9**, 345 (2013)

Learning More: Two-Channel Tomography

Idea: Measure 4D histogram and evaluate relevant photon statistics

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

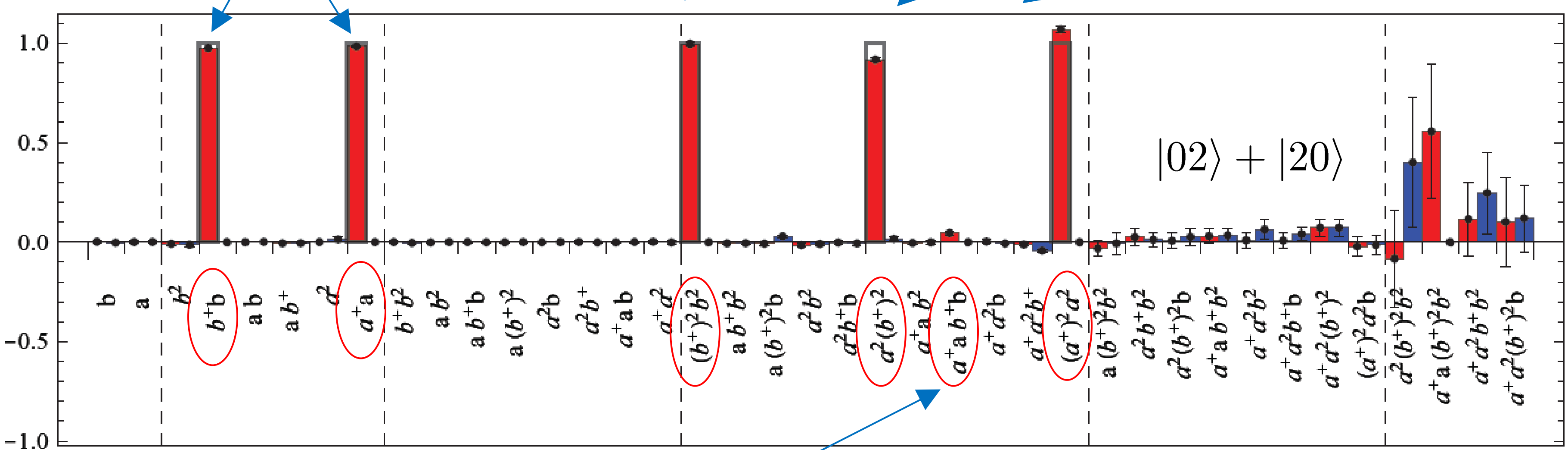
$$D_{\mathrm{OFF}}(X_a, P_a, X_b, P_b)$$

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.*, *Nat. Phys.* **9**, 345 (2013)

Density Matrix Displaying Two-Mode Entanglement

Density matrix reconstruction:

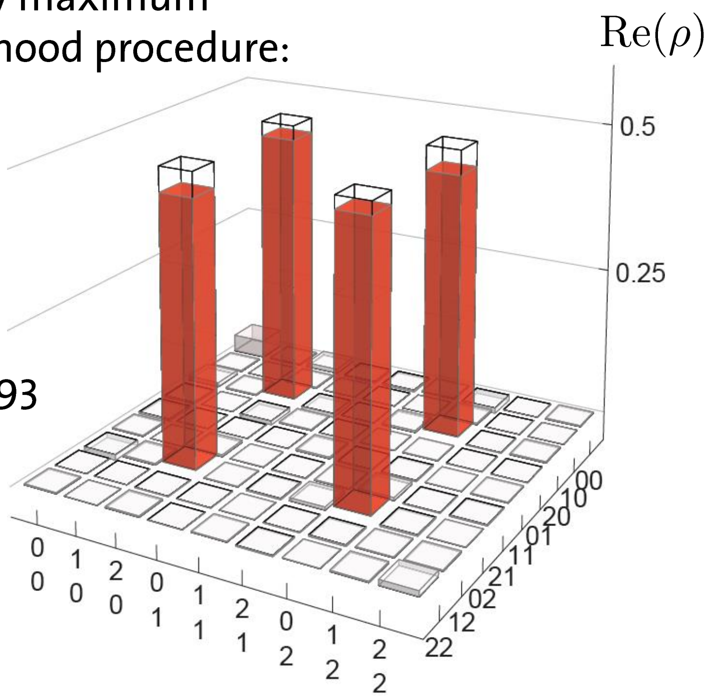
$\langle (a^\dagger)^n a^m (b^\dagger)^k b^l \rangle$ → linear map → $\langle nm|\rho|kl\rangle$

moments

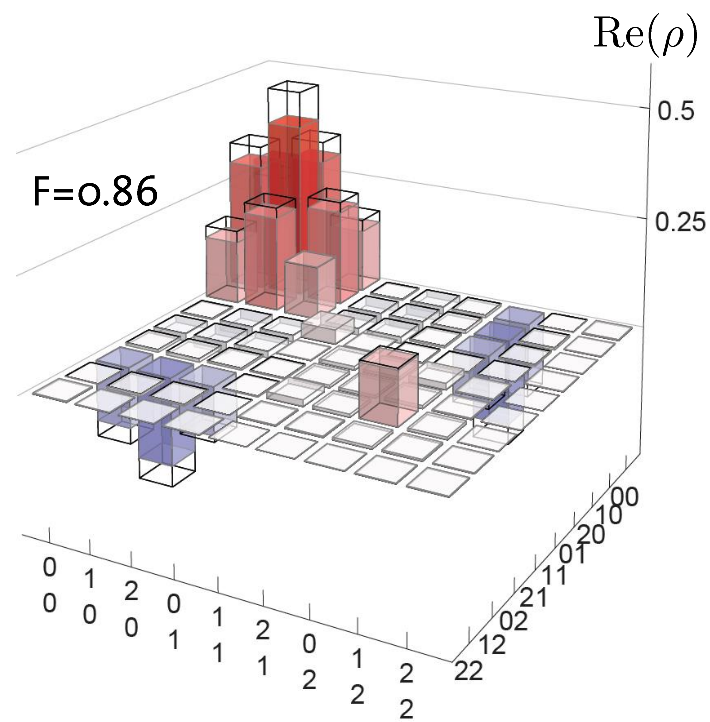
Fock space density matrix

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.*, *Nat. Phys.* **9**, 345 (2013)

Photon/Qubit Entanglement

Atom–Photon Entanglement

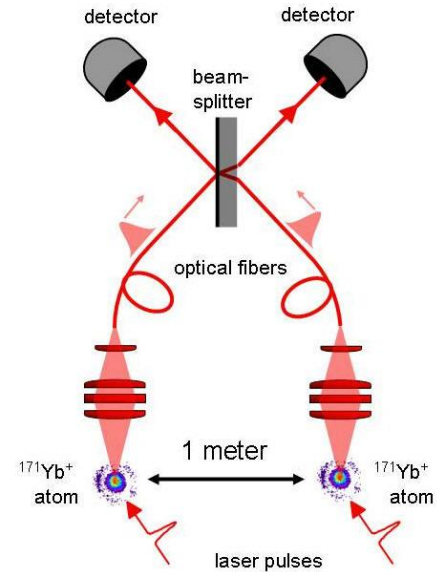
Blinov *et al.*, *Nature* **428**, 153 (2004)

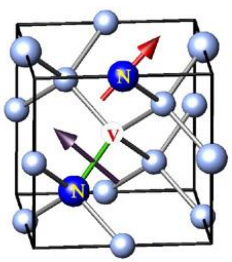
Volz *et al.*, *PRL* **96**, 030404 (2006)

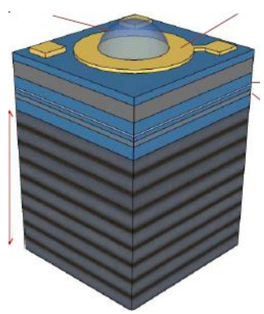
Atom–Atom Entanglement

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

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



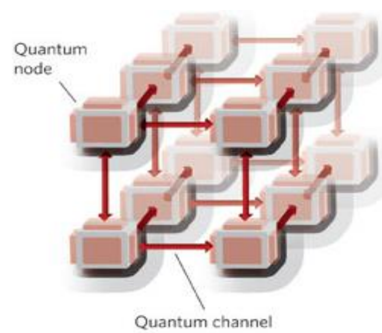




Spin–Photon Entanglement

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

Gao *et al.*, *Nature* **491**, 426 (2012)

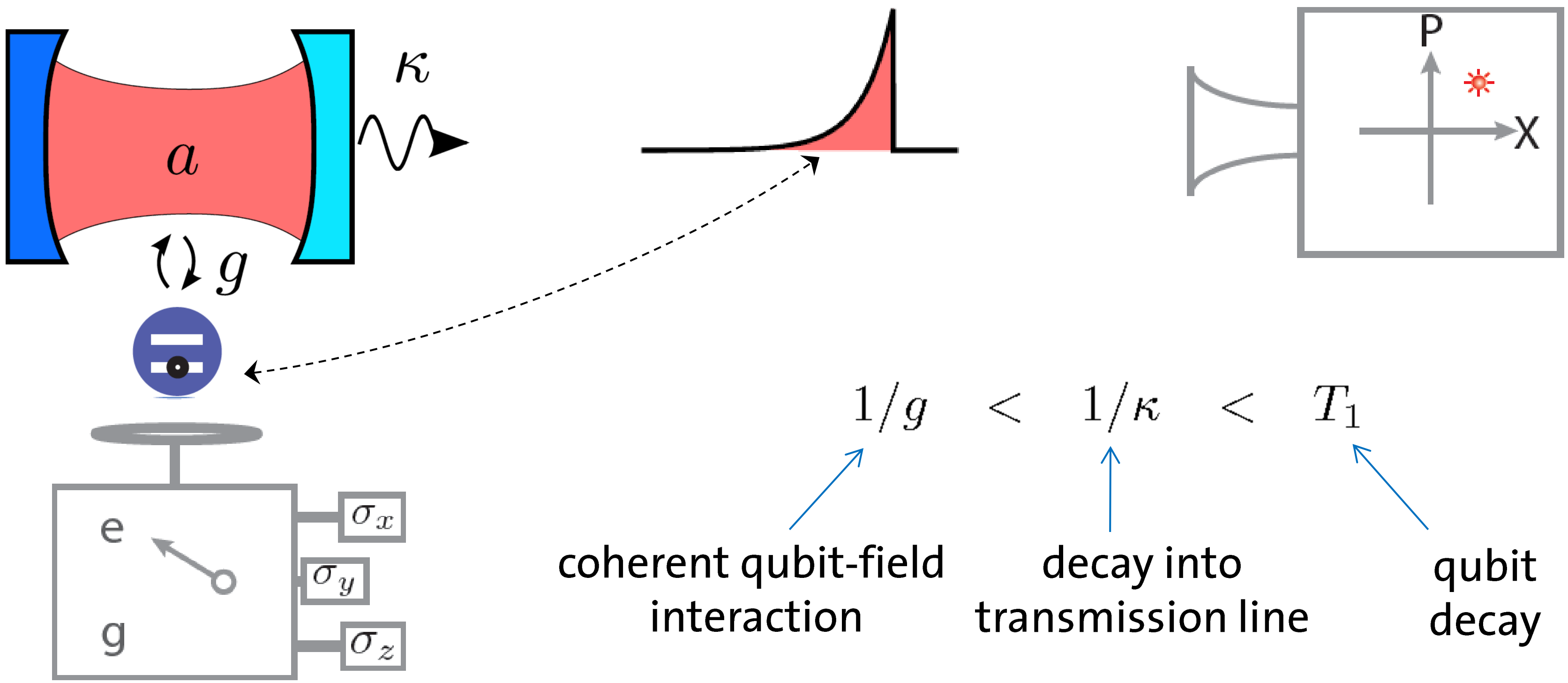


Quantum networks

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

What about superconducting circuits?

Concept of Photon/Qubit Entanglement Experiment



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

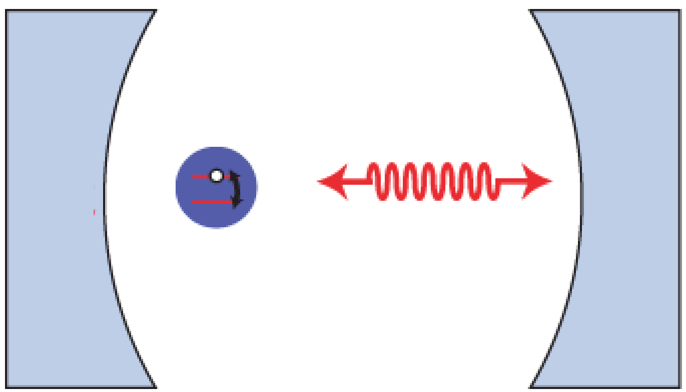
coherent qubit-field interaction

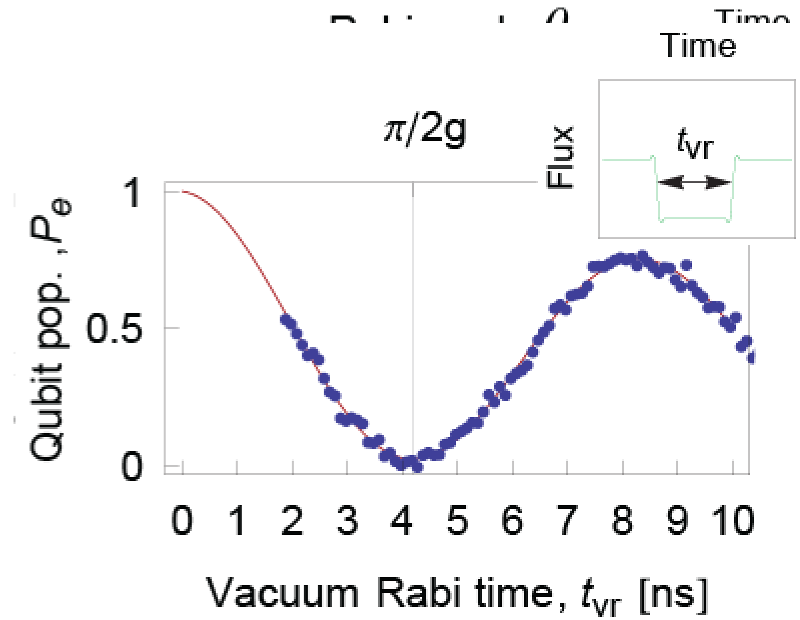
decay into transmission line

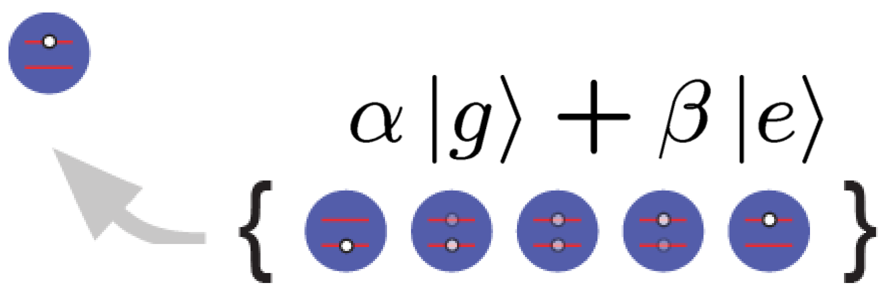
qubit decay

Conditions for generation and detection of qubit/photon entanglement

Create Qubit/Photon Entanglement







Step 1:

Prepare qubit state by Rabi oscillation

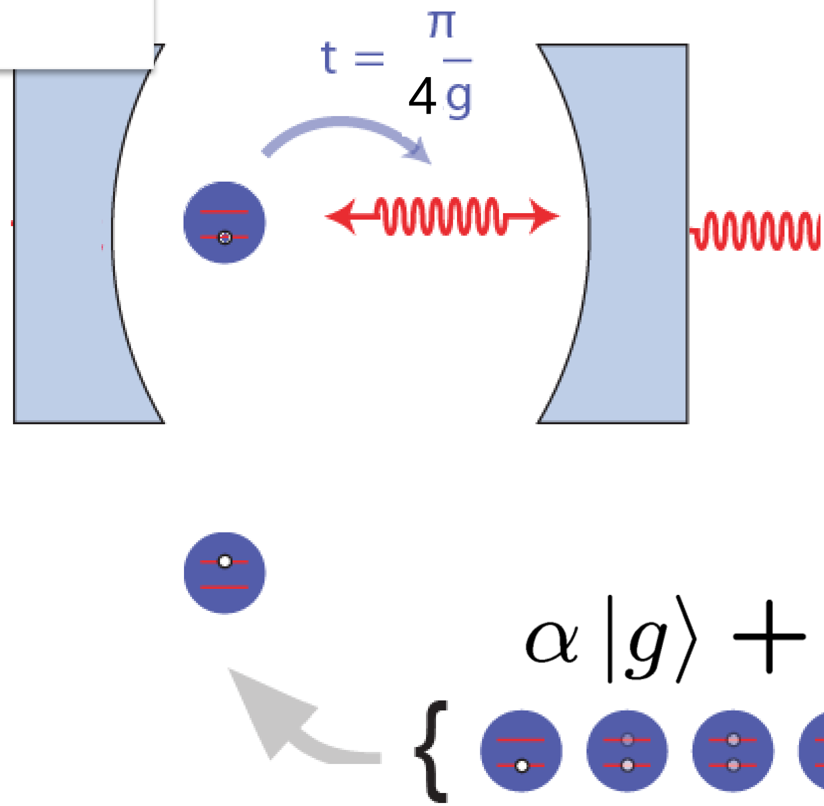
D. Bozyigit et al., *Nat. Phys.* **7**, 154 (2011)
S. Deleglise et al. Nature **455**, 510514 (2008); M. Hofheinz *et al.*, *Nature* **454**, 310 (2008)

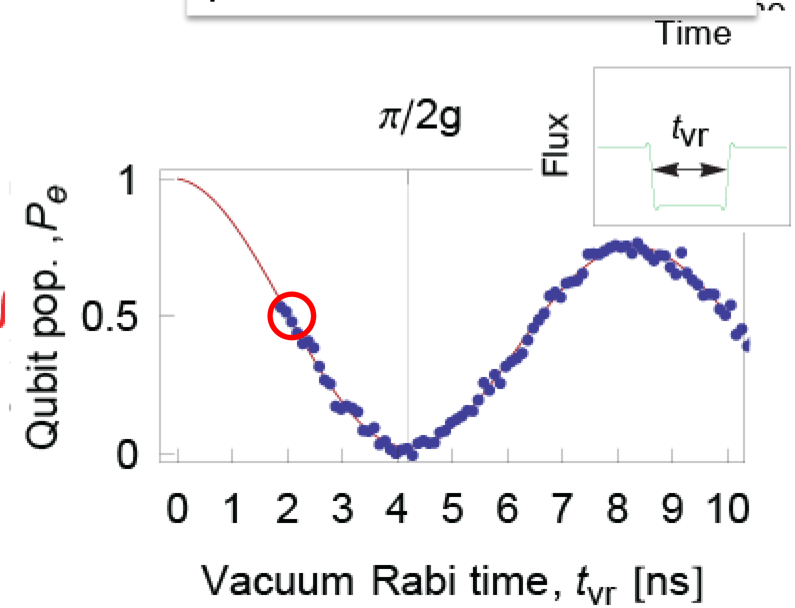
Create Qubit/Photon Entanglement

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.



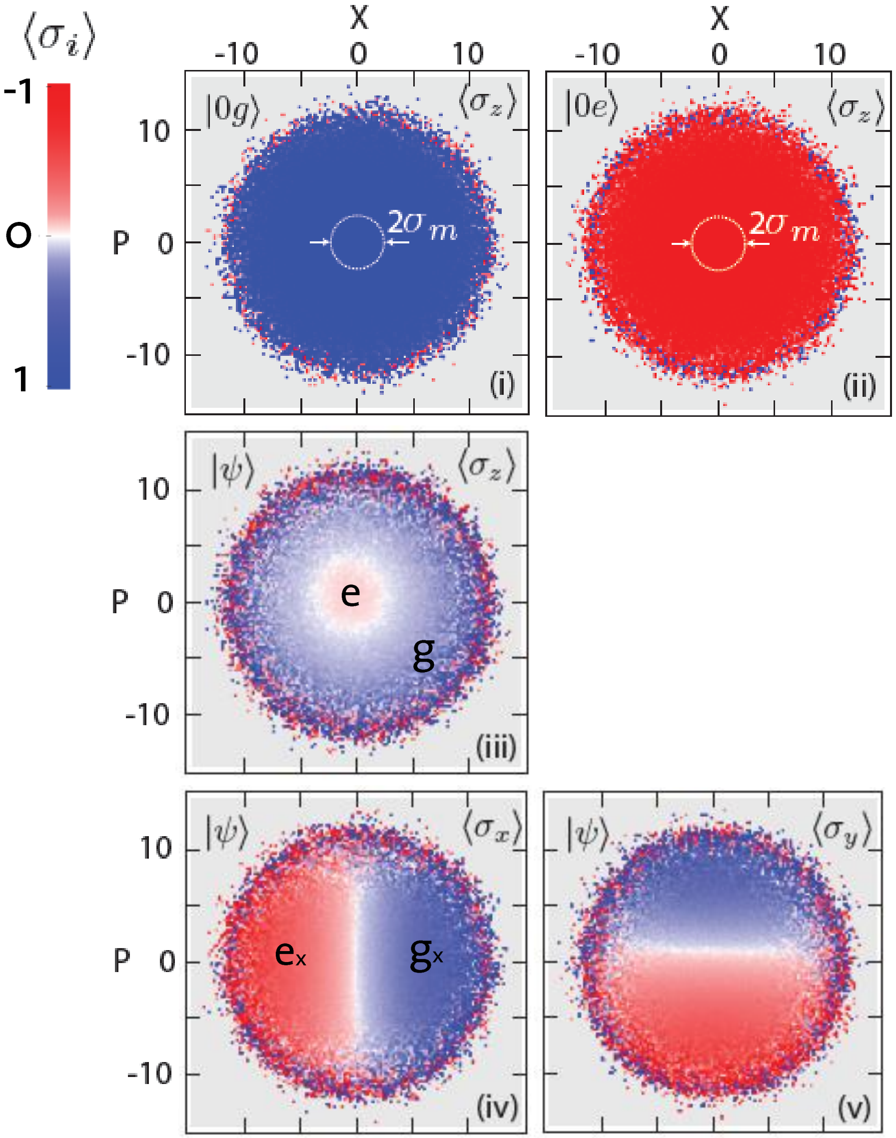


$$\alpha\,|g\rangle + \beta\,|e\rangle$$

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)

Measurement Results



und state
e
ation vs.
$+ iP$

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

Analyzing the Bell state

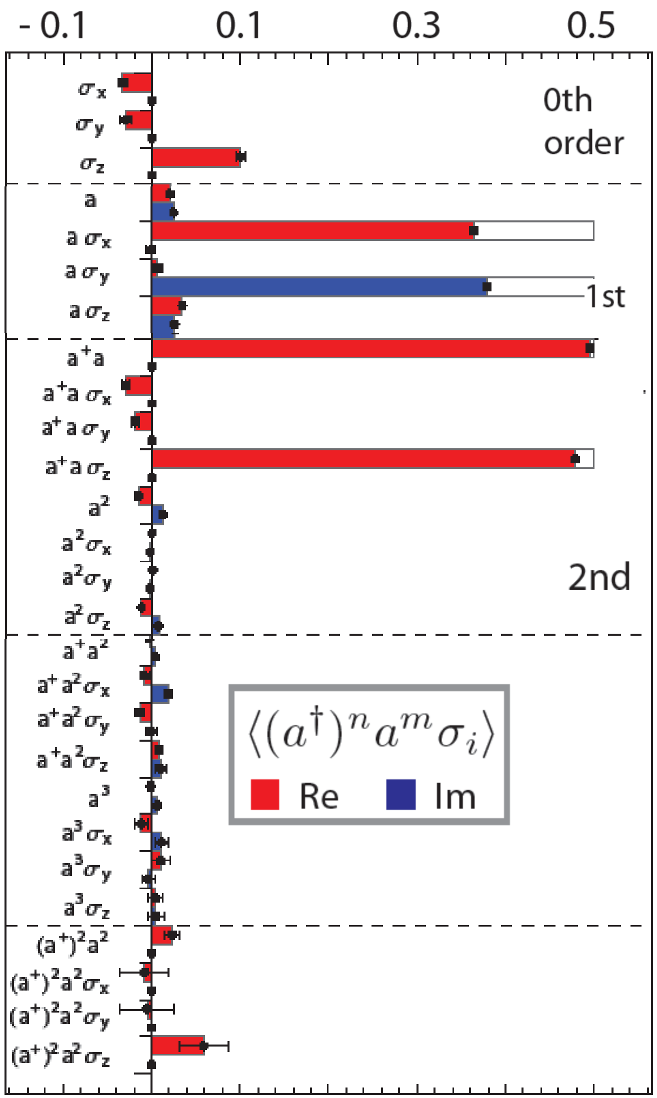
$$|\psi\rangle = |0e\rangle + |1g\rangle$$

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.*, *PRL* **109**, 240501 (2012)
theo: C. Eichler *et al.*, *PRA* **86**, 032106 (2012)

Measured Moments for Bell state



0th : qubit state with **photon discarded**/traced out

1st : **phase correlations** between qubit and photon field

2nd : **number** correlations!

e <-> no photon

g <-> one photon

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

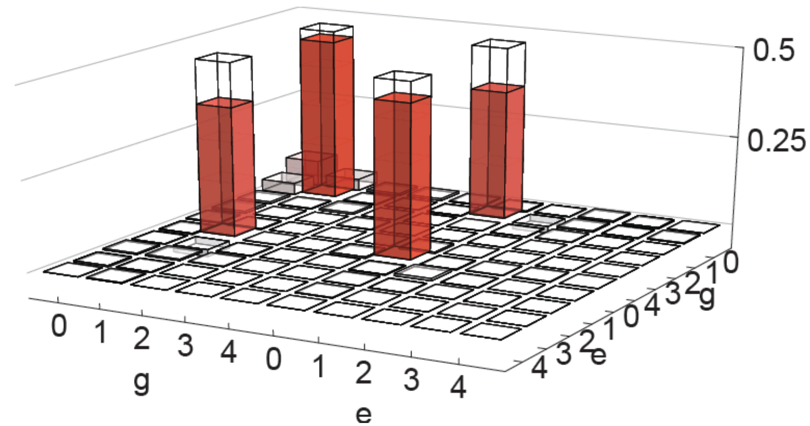
exp: C. Eichler *et al., PRL* **109**, *240501* (2012)
theo: C. Eichler *et al., PRA* **86**, 032106 (2012)

Photon/Qubit Joint State Density Matrix

Reconstruction from measured moments

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

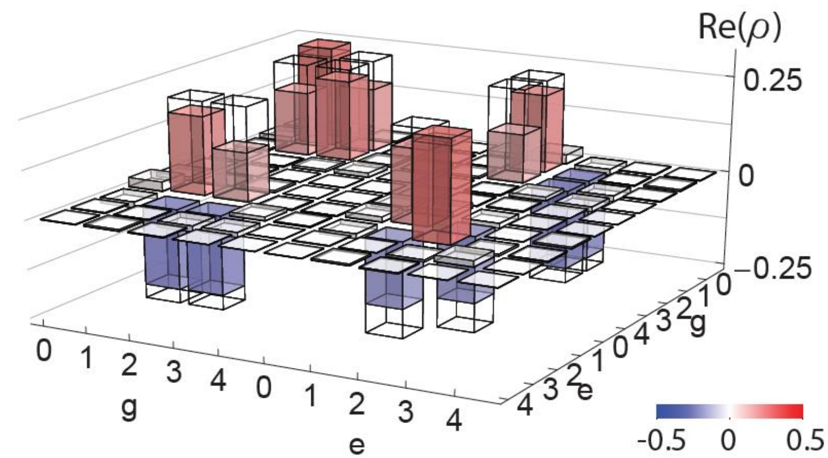
Limited by qubit decay during time required for photon detection in same mode.



Extension to states with more than a single photon:

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

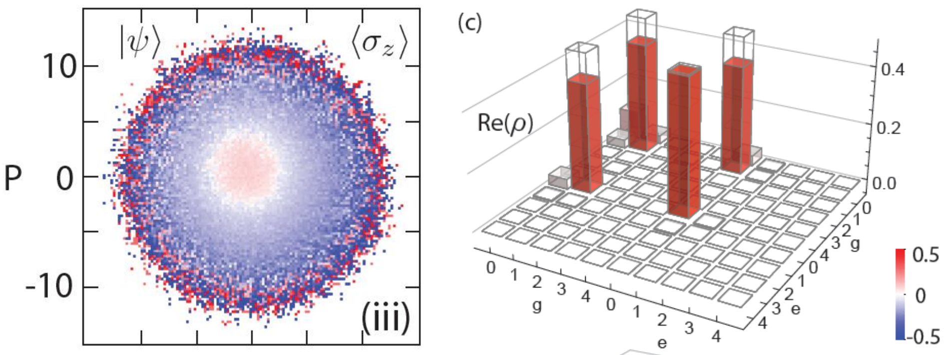
F = 0.80



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

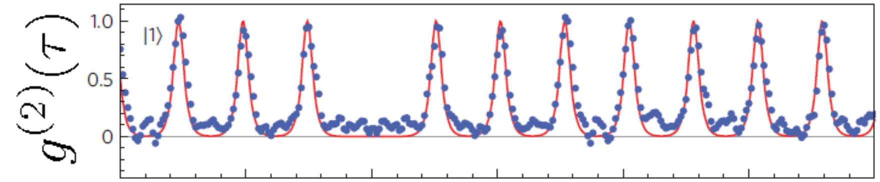
Experiments with Propagating Quantum Microwaves

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



Eichler *et al., PRL* **109**, *240501* (2012)
Eichler *et al., PRA* **86**, 032106 (2012)

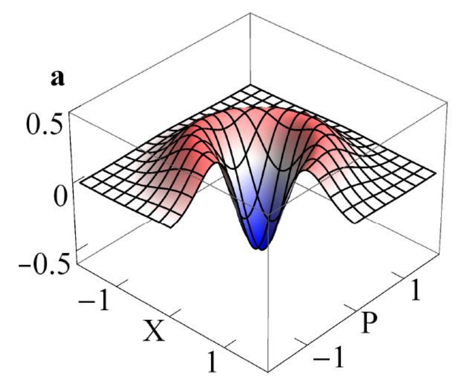
Single photon sources and their anti-bunching



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

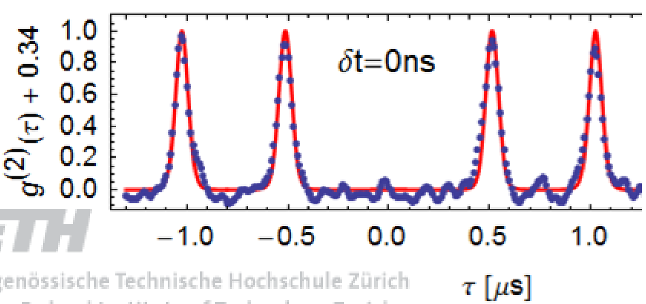
Full state tomography and Wigner functions of **propagating** photons

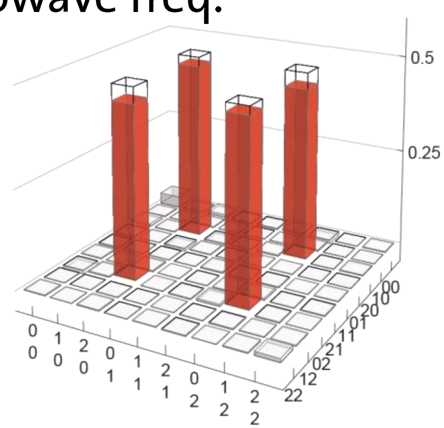
Eichler *et al., PRL* **106**, 220503 (2011)



Hong-Ou-Mandel: Two-photon interference incl. msrmnt of coherences at microwave freq.

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





Teleportation

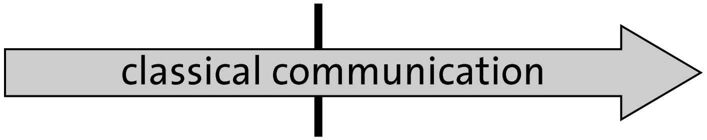
Task:

- transfer unknown state of qubit (A) from Alice to Bob

Resources:

- a pair of entangled qubits (B+C)
- a small quantum computer
- classical communication

Alice



Bob

Features:

- exploits non-local quantum correlations
- uses many essential ingredients required for realizing a quantum computer: important benchmark to pass!

Applications:

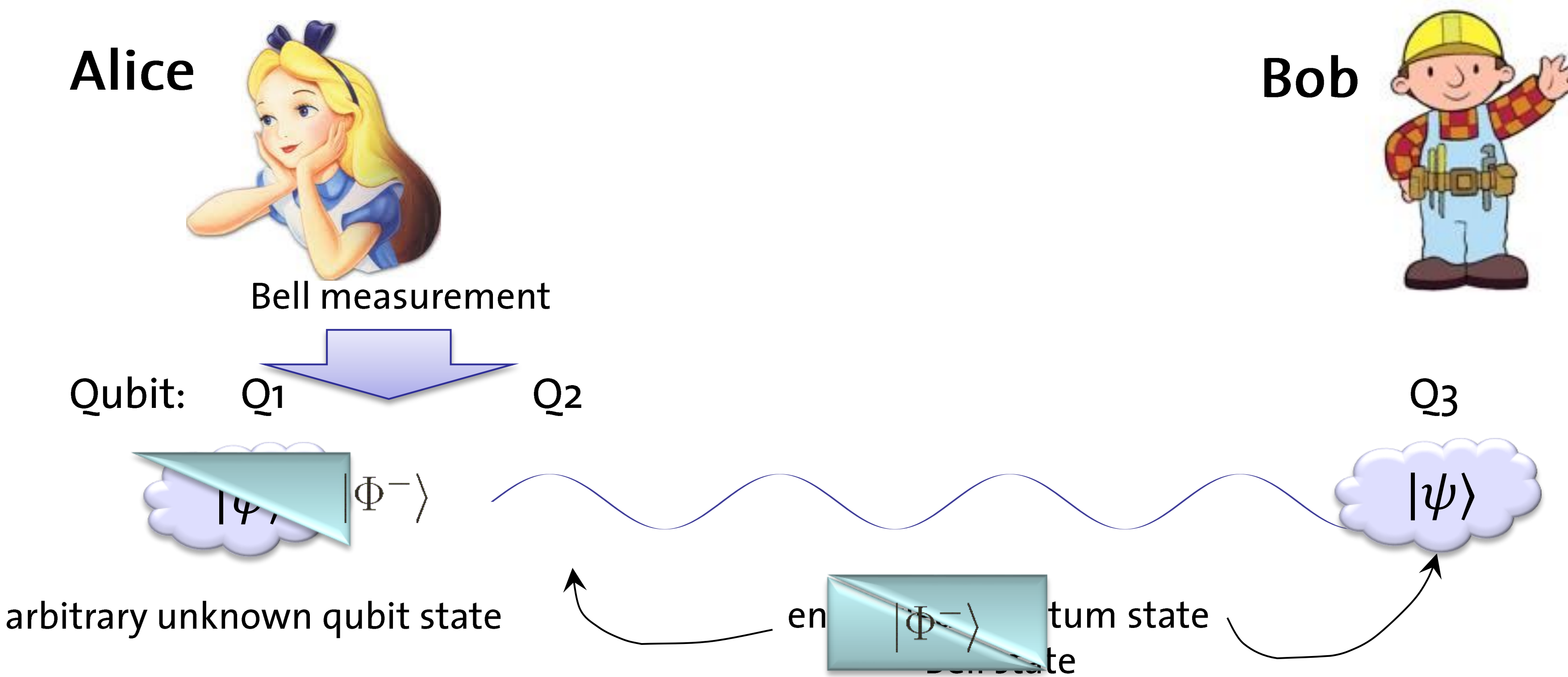
- quantum repeaters
- simplification of quantum circuits
- universal computation

Has only been demonstrated for photons and ions. But work on solid state realizations is progressing!

Teleportation Protocol

Task:
- transfer unknown quantum state from Alice to Bob

Resources:
- a pair of entangled qubits (B+C)



Teleportation Protocol

Task:

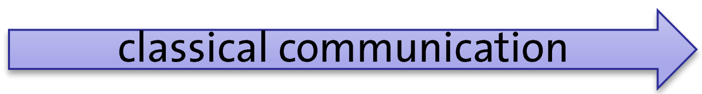
- transfer unknown quantum state from Alice to Bob

Resources:

- a pair of entangled qubits (B+C)
- classical communication

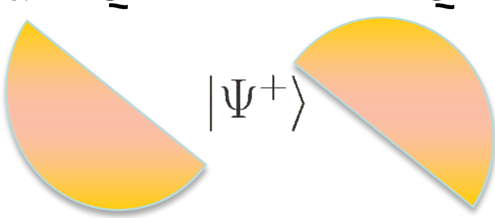
Alice

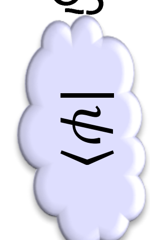
O1



Bob

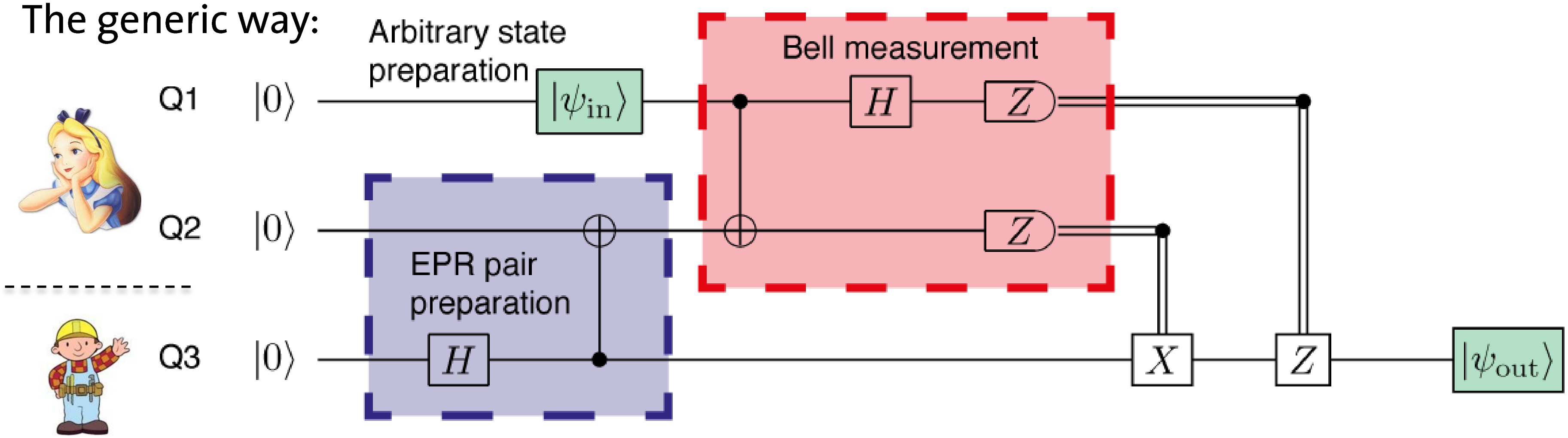
Qubit: Q1 Q2 Q3

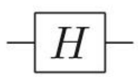




Implementation of the Teleportation Protocol

The generic way:





Hadamard

Rotation around Y-axis

Controlled NOT

Controlled phase gate

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

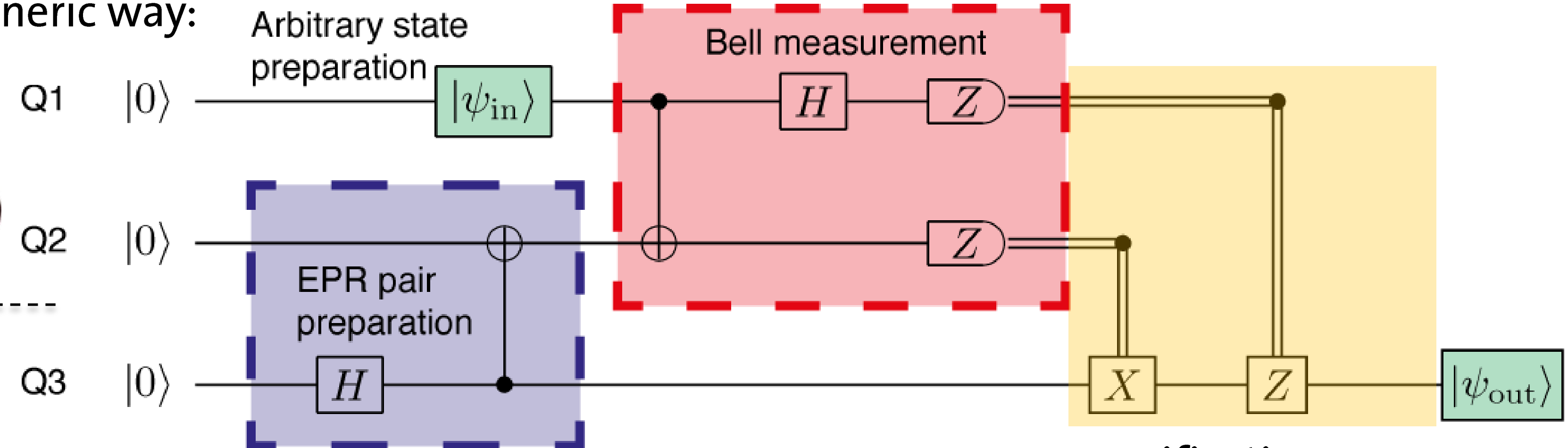
Measurement along Z-axis

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

proposal: F. W. Strauch, *Phys. Rev. Lett.* **91**, 167005 (2003).
implementation: L. DiCarlo, *Nature* **460**, 240 (2010).

Implementation of the Teleportation Protocol

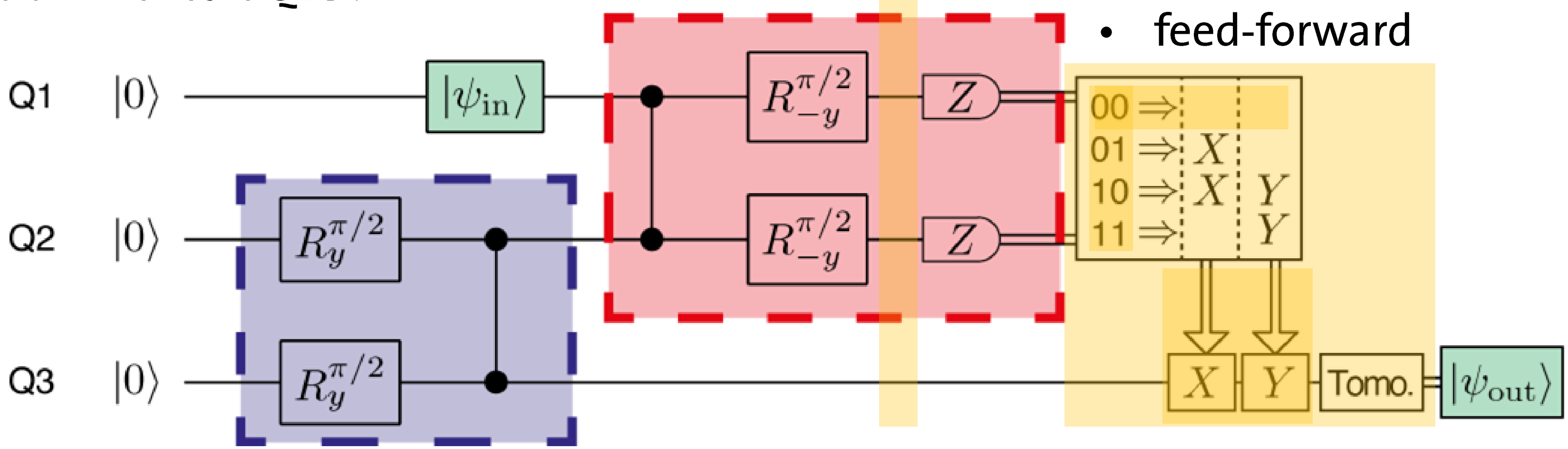
The generic way:

verification

- 3-qubit tomography
- post selection (1 state)
- deterministic (4 states)
- feed-forward

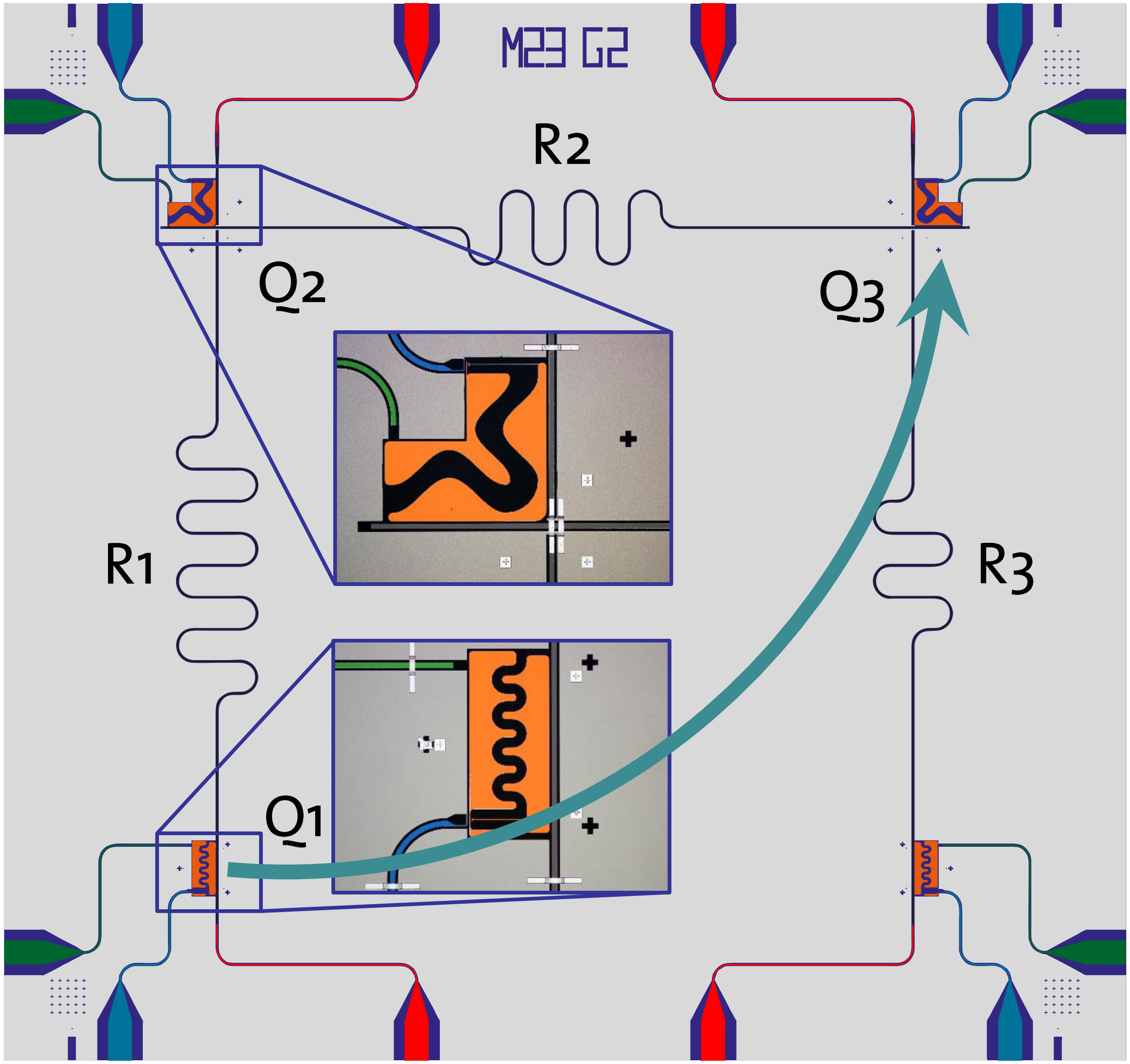
Realization in circuit QED:



The Sample

- 3 Resonators
- 3 Qubits
- single-qubit gates
- two-qubit gates (qubits in the same resonator)
- joint single-shot readout of qubits 1 & 2
- single-shot readout of qubit 3
- with two parametric amplifiers

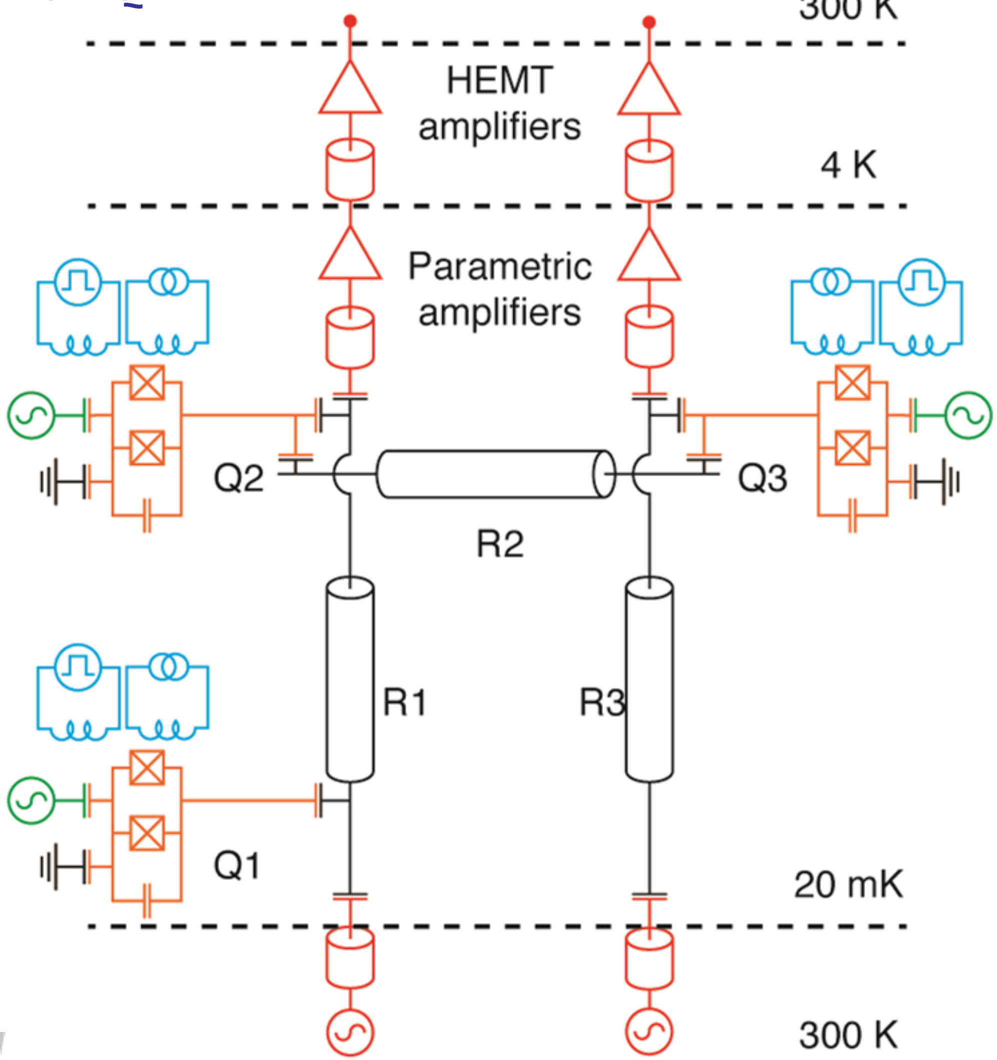
Yurke and Buks, *J. Lightwave Tech.* **24**, 5054 (2006).
Castellanos-Beltran et al., *Nat. Phys.* **4**, 929 (2008).
Eichler *et al.*, *PRL* **107**, 113601 (2011).



Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*

The Circuit

12-port quantum device based on circuit QED:



Device highlights:

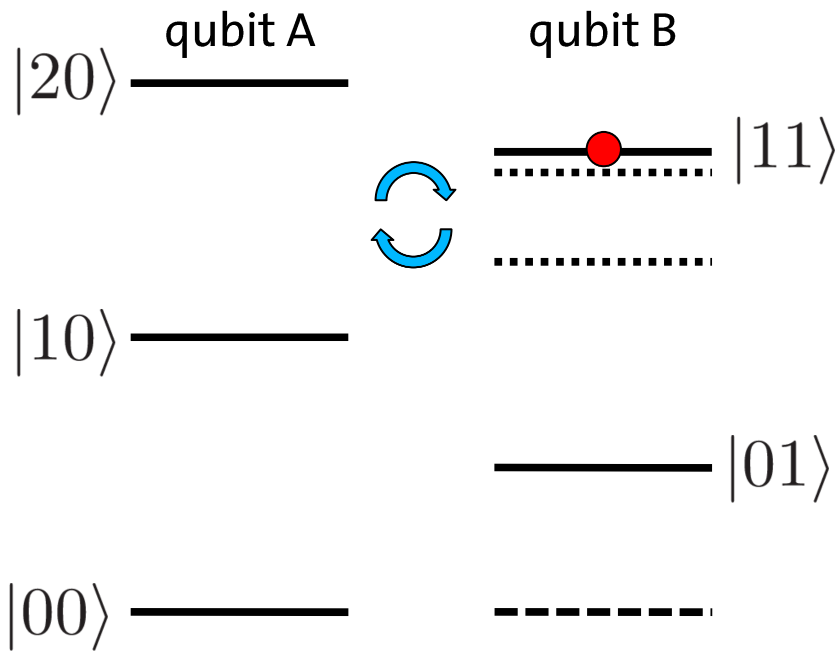
- 3 high-Q resonators
- 4 transmon qubits
- individual control of all qubits
- nearest neighbor interaction via quantum bus
- individual read-out for pairs of qubits 1-2 and 3-4 through resonators
- single-shot read-out using parametric amplifiers
- qubit separation ~ 10 mm
- cross-overs for resonators

Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*


Quantum Teleportation with
Superconducting Circuits
1 μeV ≙ 240 MHz
10 μeV ≙ 2.4 GHz
100 μeV ≙ 24 GHz
1 meV ≙ 240 GHz
10 meV ≙ 2.4 THz
DELL
QUDEV Phonelist

Universal Two-Qubit Phase Gate

Tune levels into resonance using magnetic field

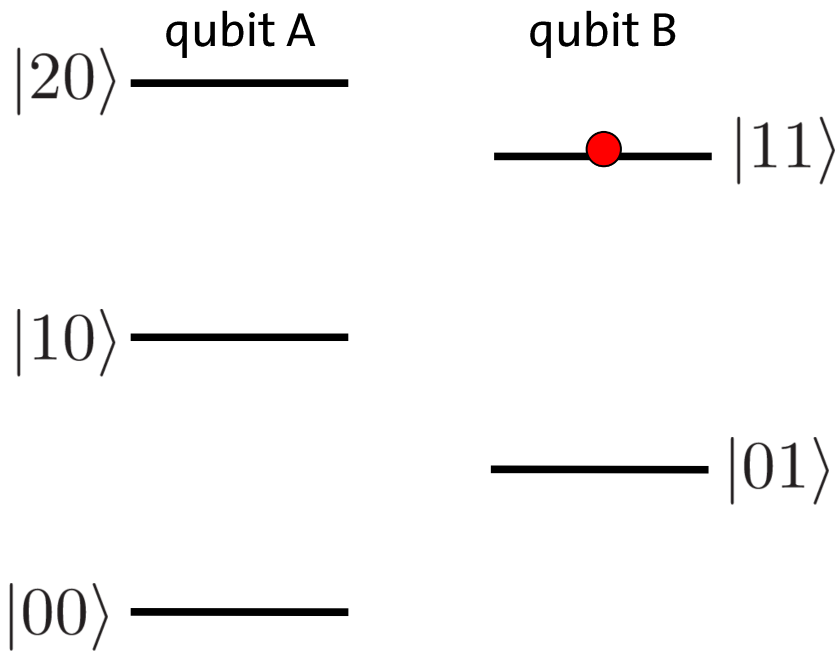


Interaction mediated by virtual photon exchange through resonator

$$|11\rangle \longrightarrow i|20\rangle \longrightarrow -|11\rangle$$

proposal: F. W. Strauch, *Phys. Rev. Lett.* **91**, 167005 (2003).
first implementation: L. DiCarlo, *Nature* **460**, 240 (2010).

Controlled Phase Gate



How to verify the operation of this gate?

$$|11\rangle \longrightarrow i|20\rangle \longrightarrow -|11\rangle$$

$$|01\rangle \longrightarrow |01\rangle$$

$$|10\rangle \longrightarrow |10\rangle$$

$$|00\rangle \longrightarrow |00\rangle$$

Universal two-qubit gate. Used together with single-qubit gates to create any quantum operation.

C-Phase gate:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

proposal: F. W. Strauch, *Phys. Rev. Lett.* **91**, 167005 (2003).

first implementation: L. DiCarlo, *Nature* **460**, 240 (2010).

Process Tomography: C-Phase Gate

arbitrary quantum process

$$\rho' = \mathcal{E}(\rho)$$

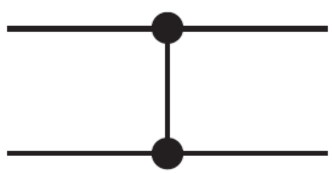
decomposed into

$$\mathcal{E}(\rho) = \sum_{mn} \tilde{E}_m \rho \tilde{E}_n^\dagger \chi_{mn}$$

$\{\tilde{E}_k\}$ is an operator basis

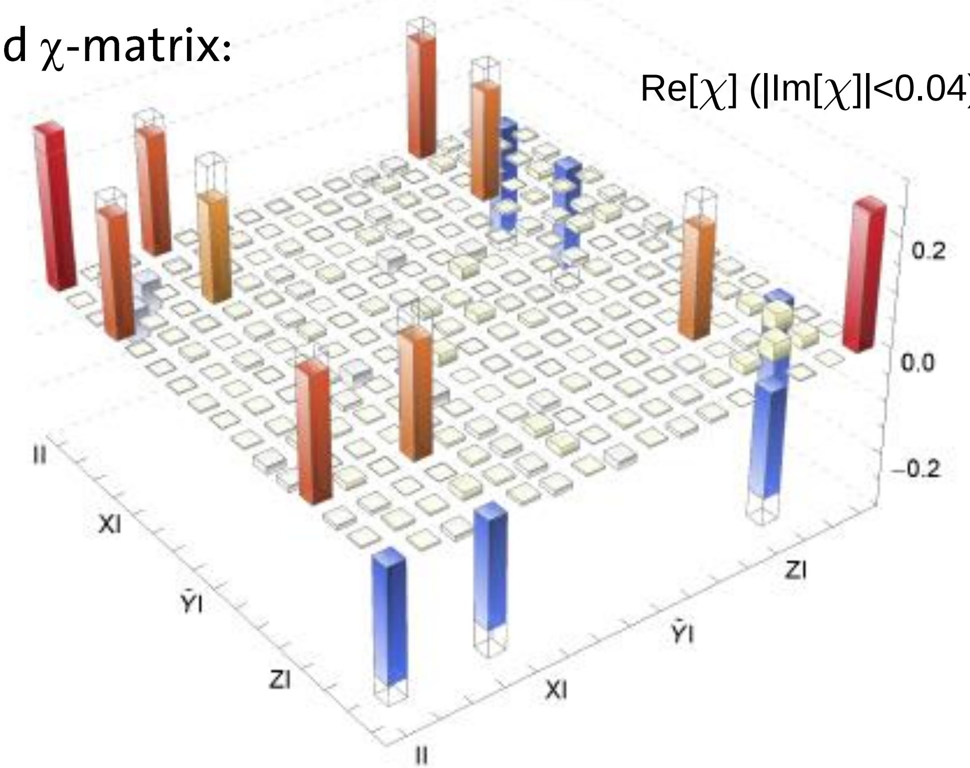
χ is a positive semi definite Hermitian matrix characteristic for the process

Controlled phase gate



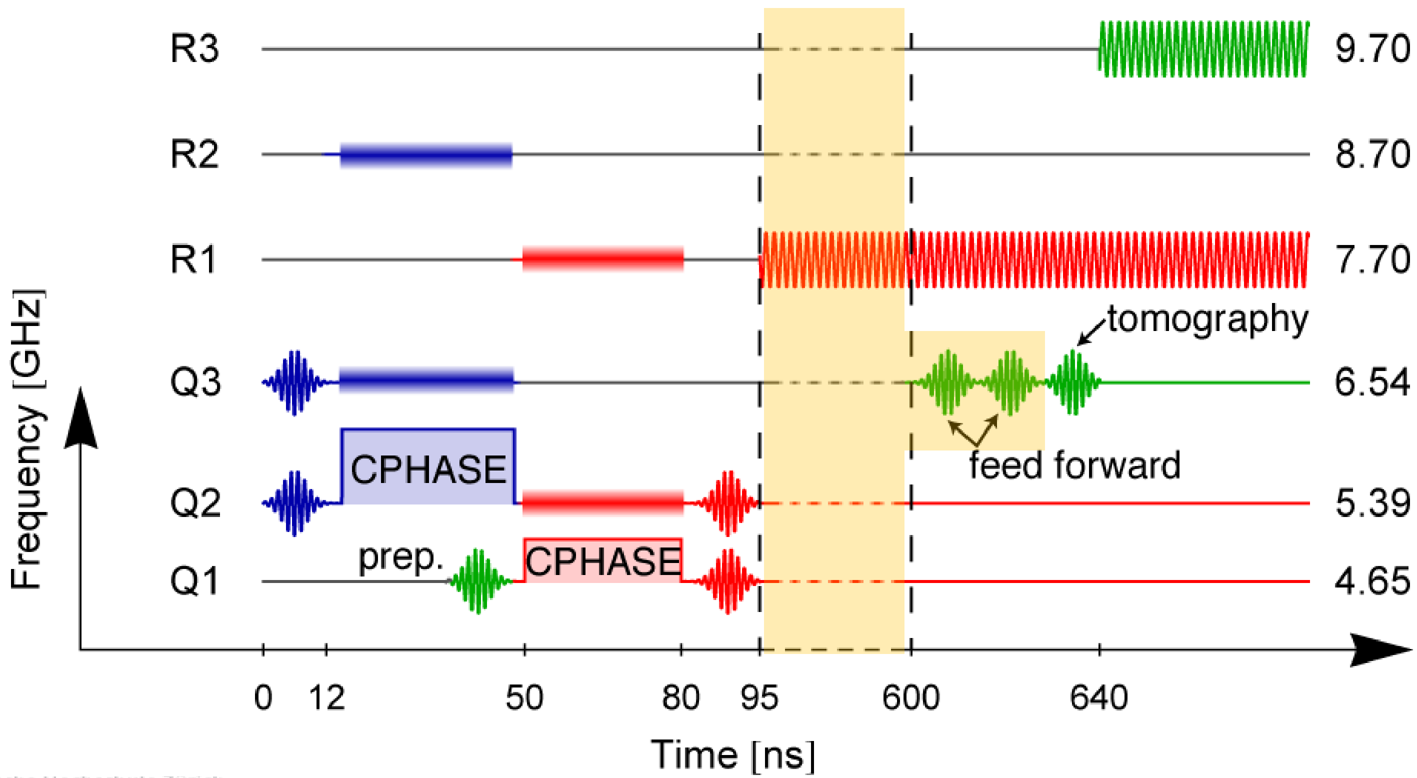
$$cZ_{00} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Measured χ-matrix:

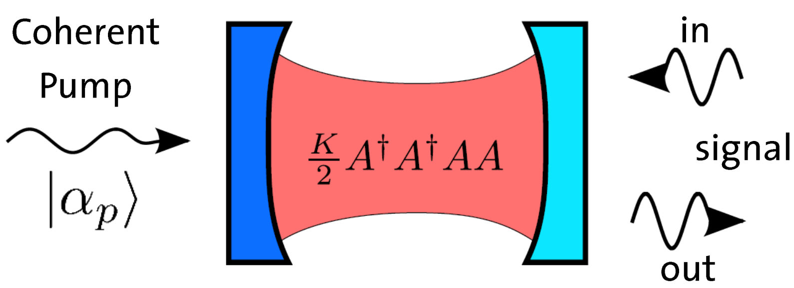


$$F = \mathrm{Tr}[\chi_{\mathrm{meas}}\chi_{\mathrm{ideal}}] = 0.86$$

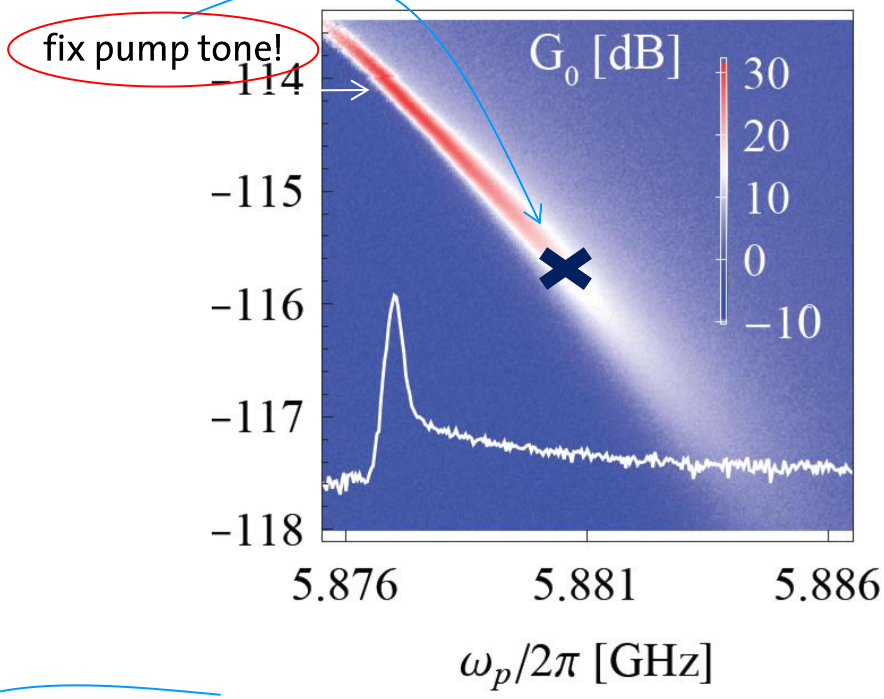
Pulse scheme



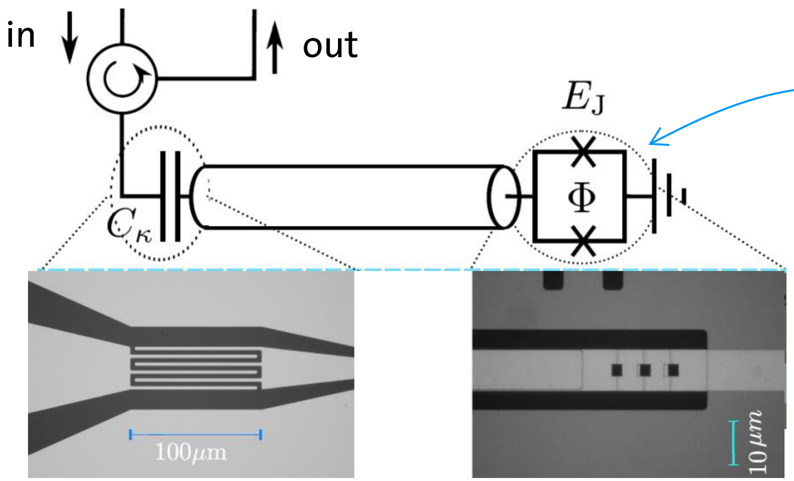
Near Quantum-Limited Parametric Amplifier



Measured Gain



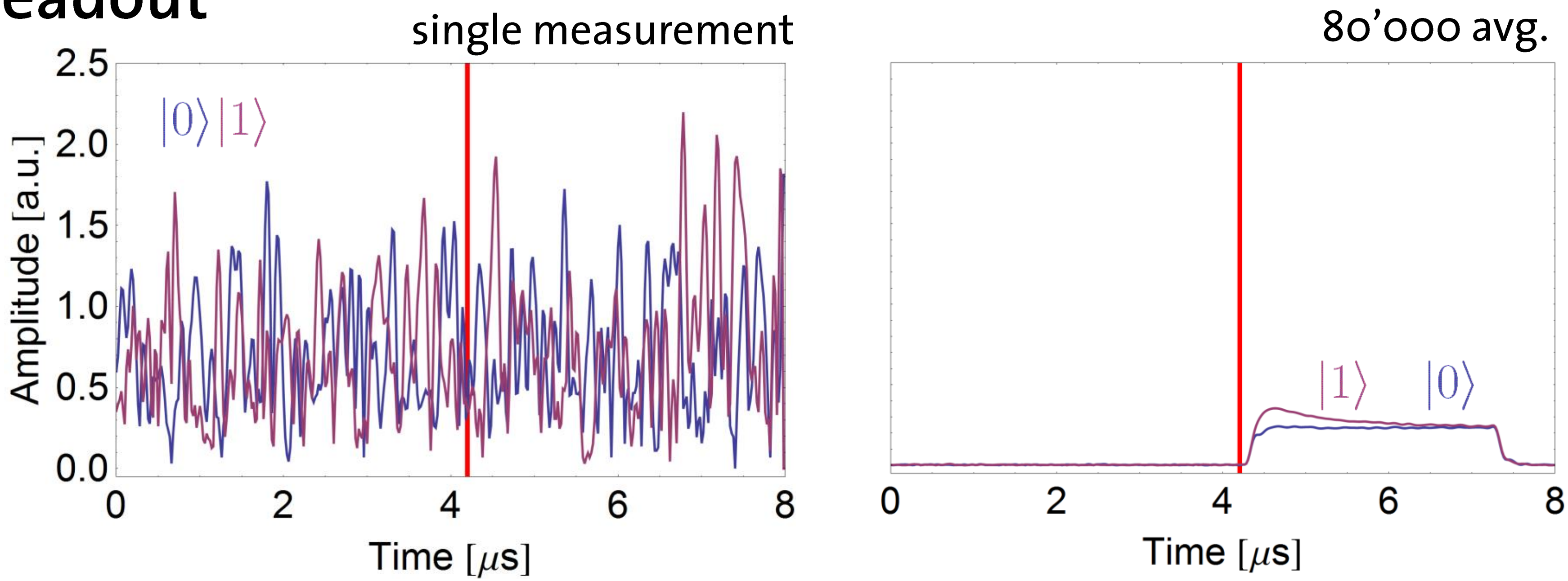
Circuit QED implementation:

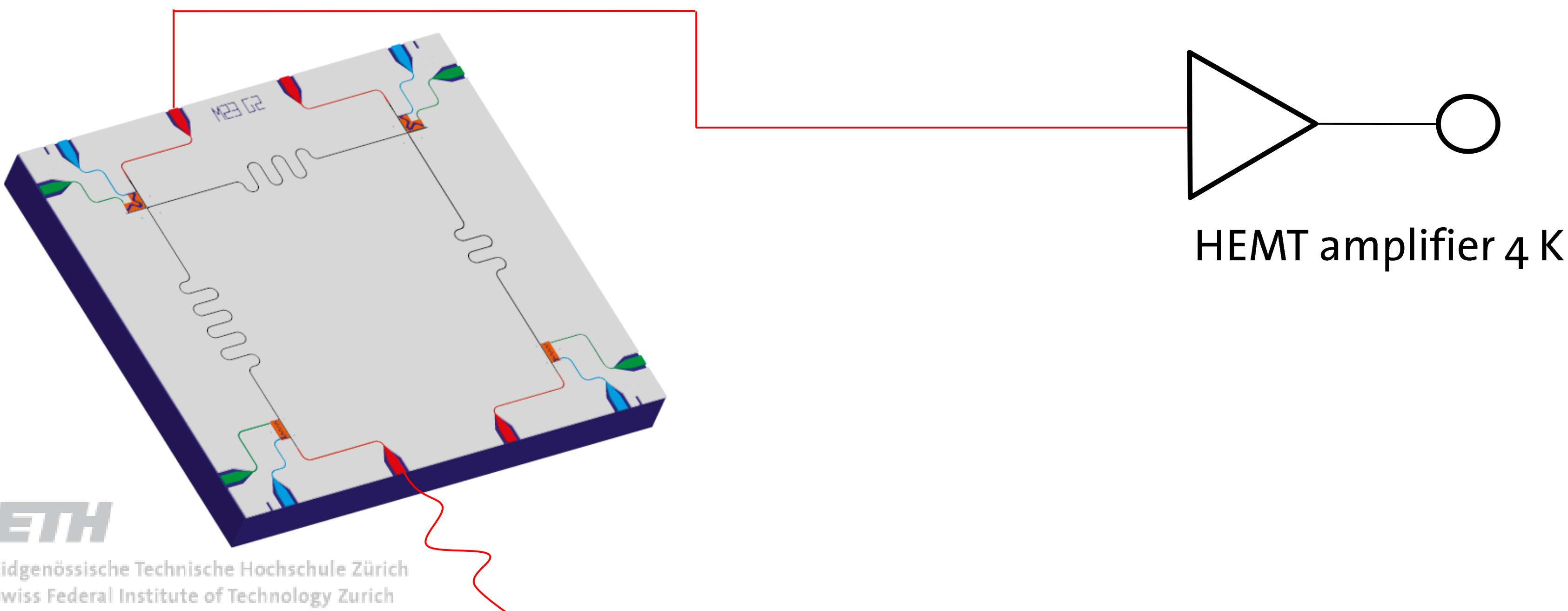


SQUID provides nonlinearity!

Caves, *Phys. Rev. D* **26**, 1817 (1982)
Yurke and Buks, *J. Lightwave Tech.* **24**, 5054 (2006)
Castellanos-Beltran et al., *Nat. Phys.* **4**, 929 (2008)
Eichler et al., *Phys. Rev. Lett.* **107**, 113601 (2011)

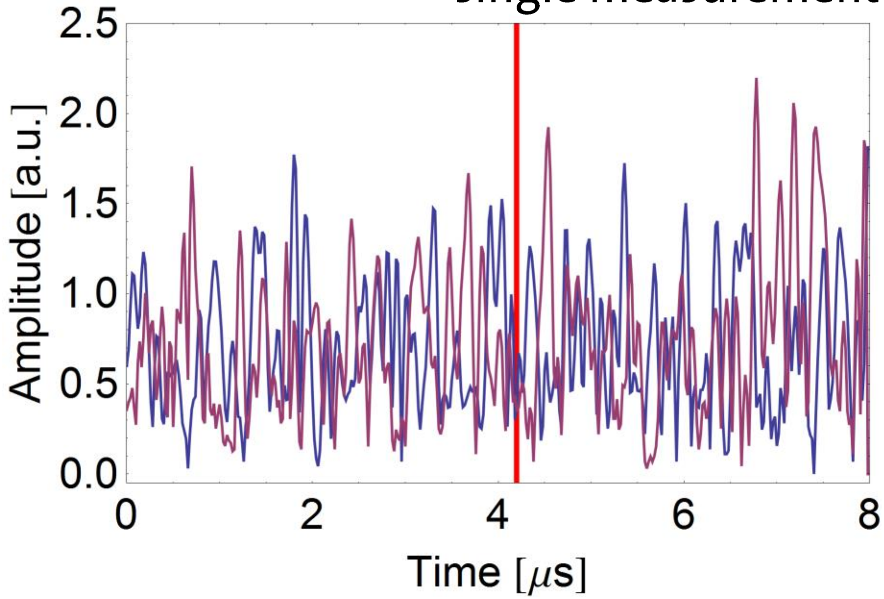
Readout


single measurement
80’000 avg.
Amplitude [a.u.]
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
Time [μs]
|0⟩ |1⟩
|1⟩
|0⟩
0
2
4
6
8
Time [μs]

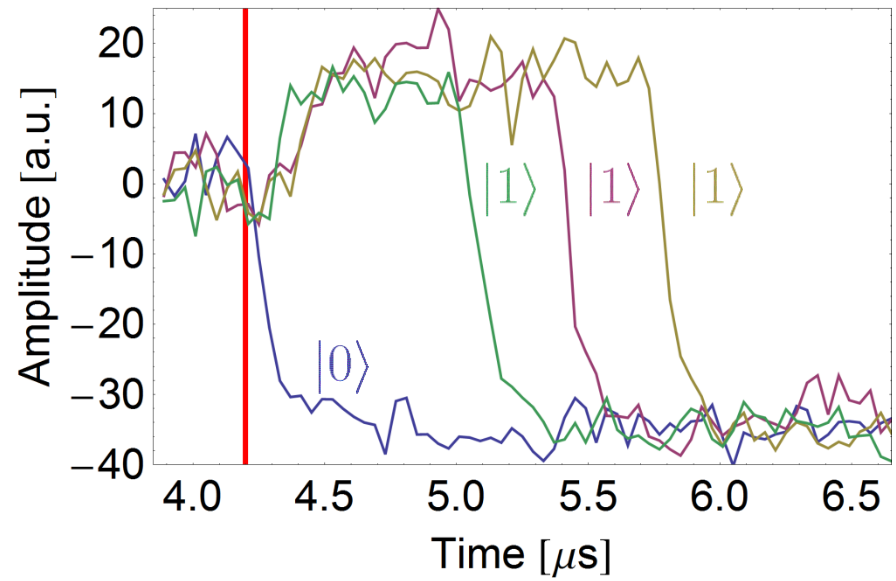

HEMT amplifier 4 K

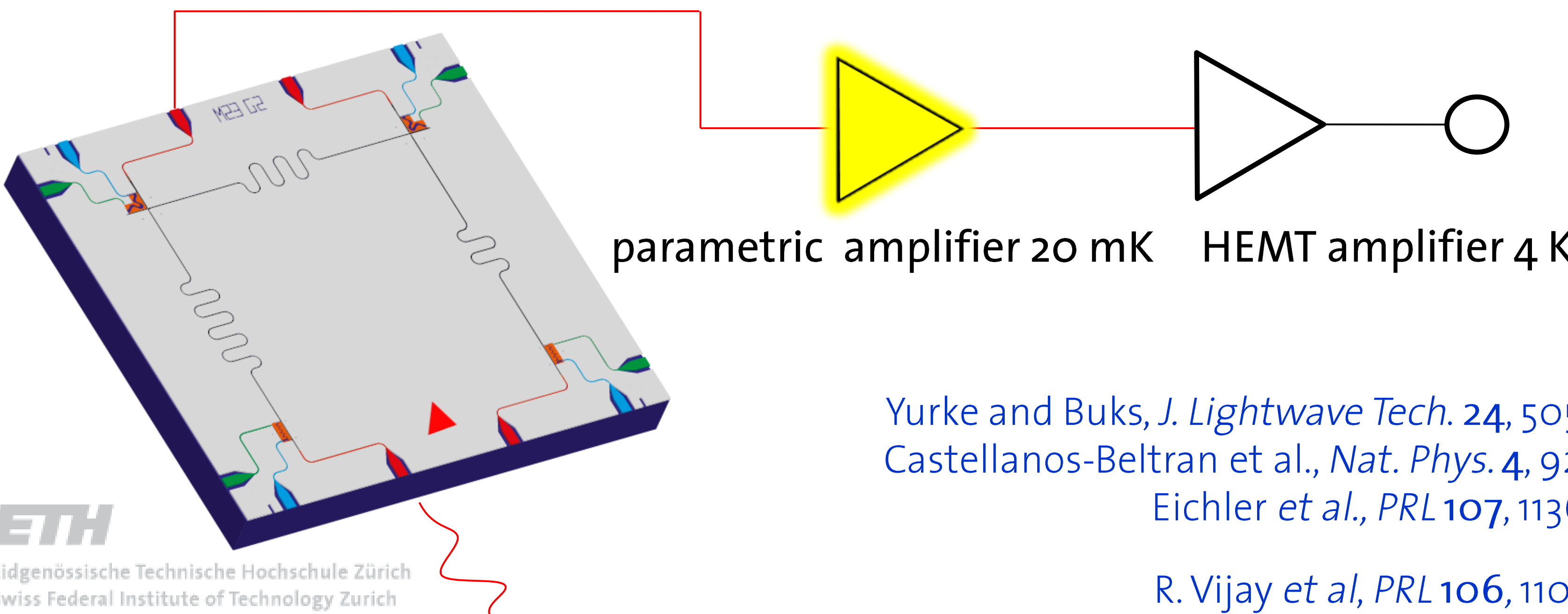
Readout

single measurement



single measurement with paramp

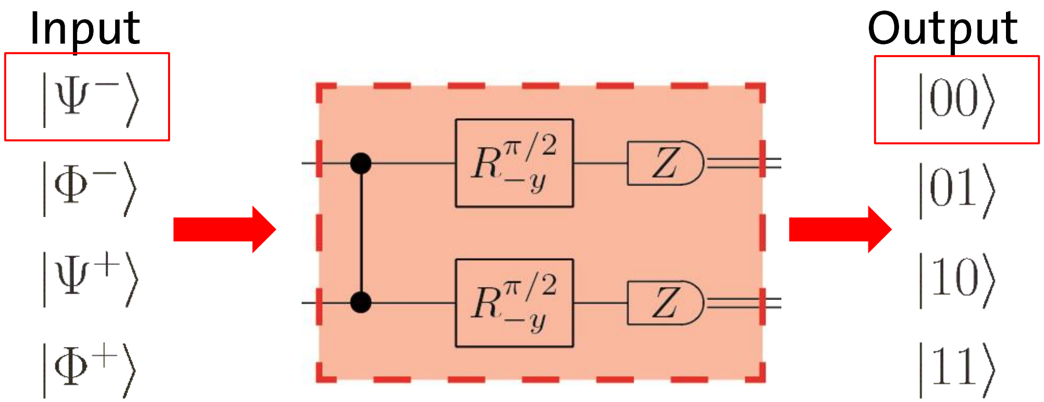




Yurke and Buks, *J. Lightwave Tech.* **24**, 5054 (2006)
Castellanos-Beltran et al., *Nat. Phys.* **4**, 929 (2008)
Eichler *et al.*, *PRL* **107**, 113601 (2011)

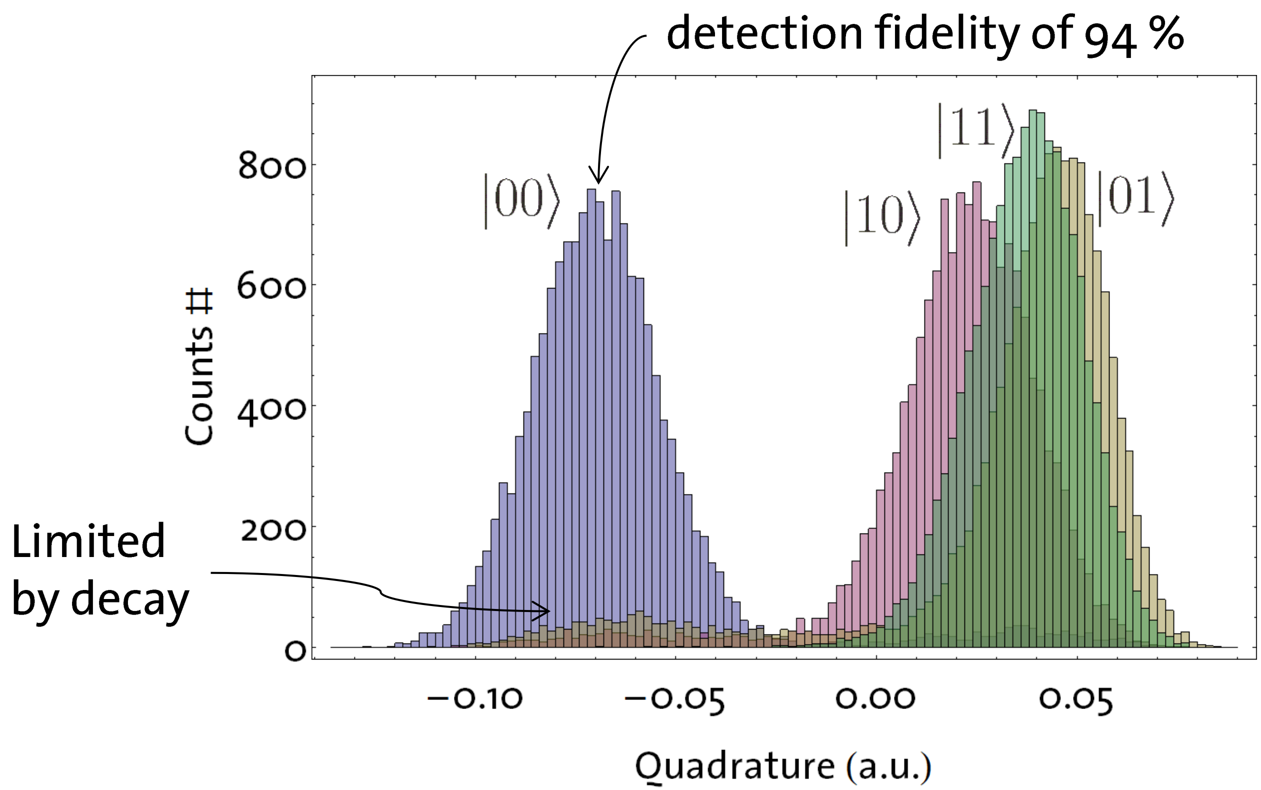
R. Vijay *et al*, *PRL* **106**, 110502 (2011)

Post-Selected Teleportation: Bell Measurement



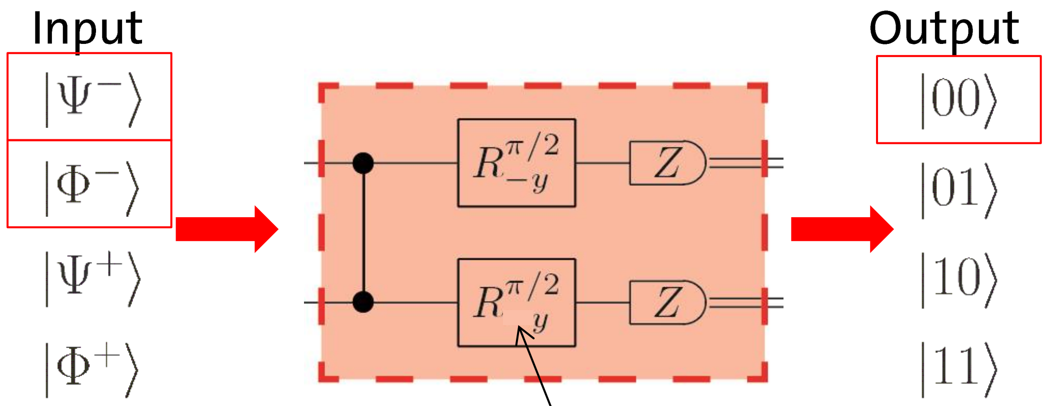
Operate parametric amplifier in phase sensitive mode

Maximize contrast of $|00\rangle$ to other states



Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*

Post-Selecting Every State Individually

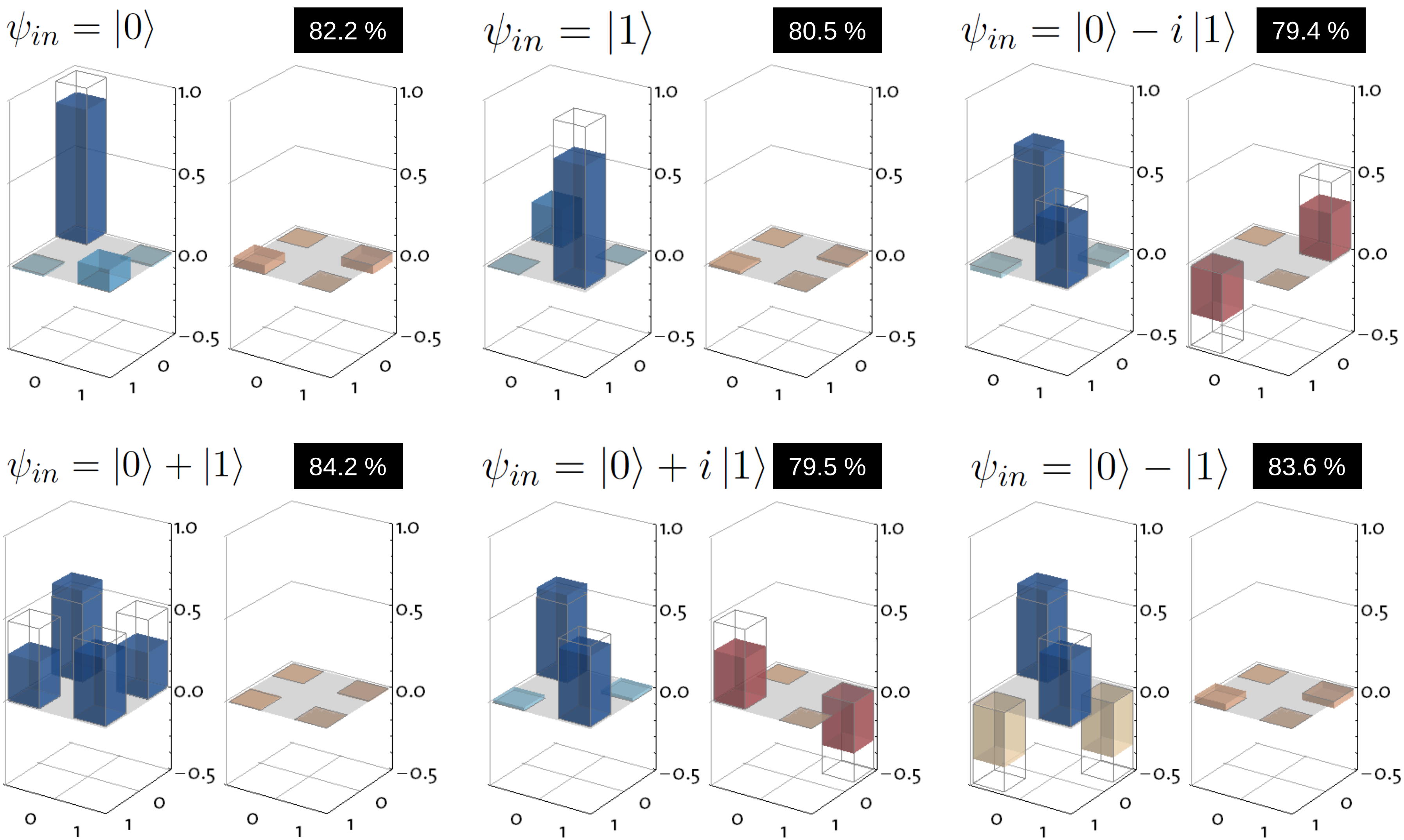


How to post-select on the other Bell states:

- Change the phases of the $\pi/2$ pulses
- Another Bell state is transformed to the $|00\rangle$ state
- Possibility to post-select on all four Bell states

Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*

Tomography of Teleported States with Post-Selection

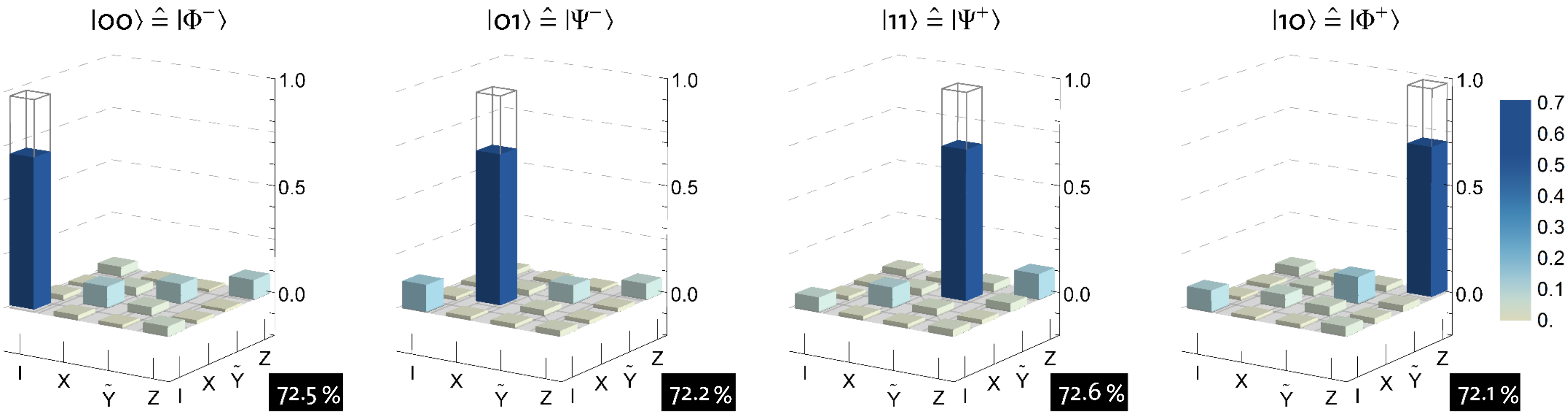


Average state fidelity **78.1 ± 0.9 %**

Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*

Process Tomography: Teleportation with Post-Selection

absolute value of process matrices $|\chi|$ for state transfer from qubit 1 to qubit 3:



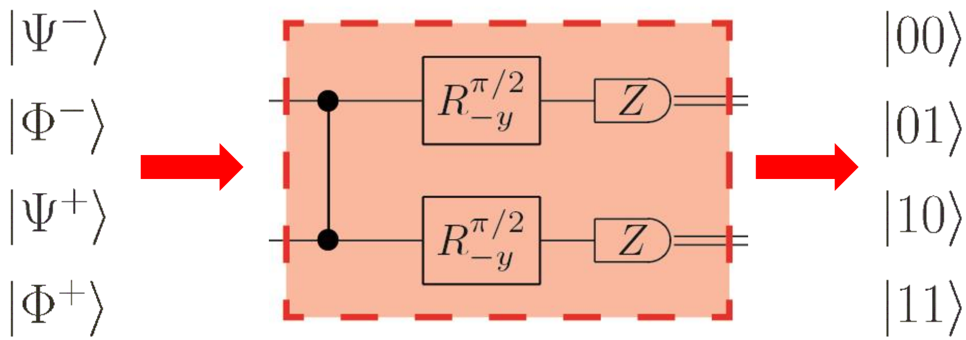
$$|\psi_{\text{out}}\rangle = |\psi_{\text{in}}\rangle \qquad |\psi_{\text{out}}\rangle = X\,|\psi_{\text{in}}\rangle \qquad |\psi_{\text{out}}\rangle = \tilde{Y}\,|\psi_{\text{in}}\rangle \qquad |\psi_{\text{out}}\rangle = Z\,|\psi_{\text{in}}\rangle$$

$$X = \hat{\sigma}_x, \tilde{Y} = i\hat{\sigma}_y, Z = \hat{\sigma}_z$$

Average process fidelity **72.3 ± 0.7 %**

Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*

Deterministic Measurement of all 4 Bell States



- operate paramp in the phase preserving mode
- both quadratures are amplified equally

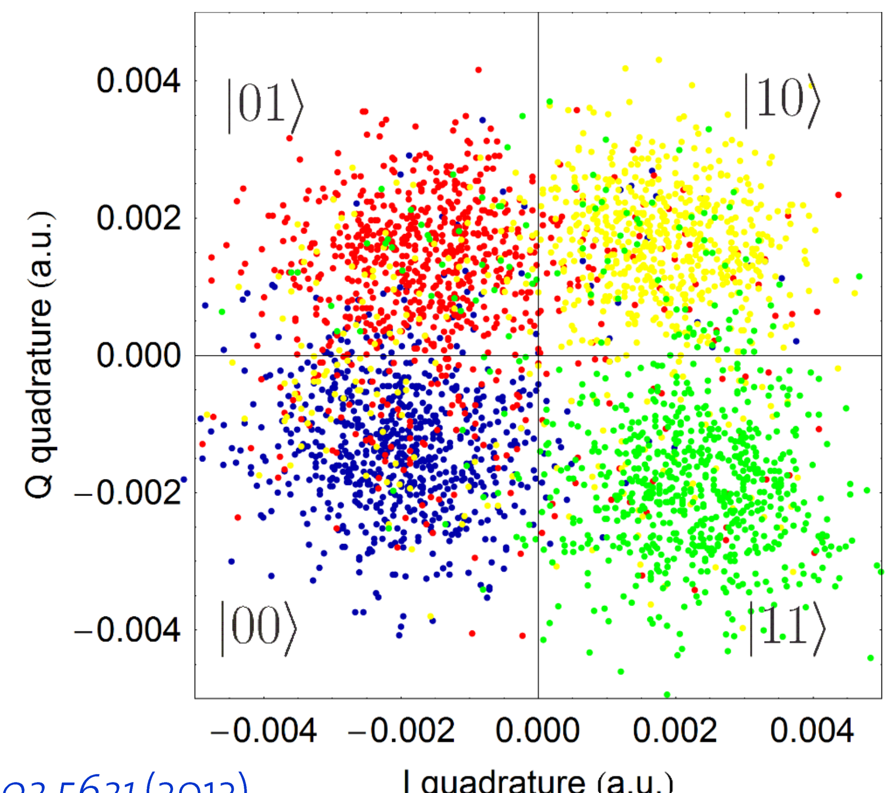
States are identified correctly with ~80% probability

upper left   upper right

identified as

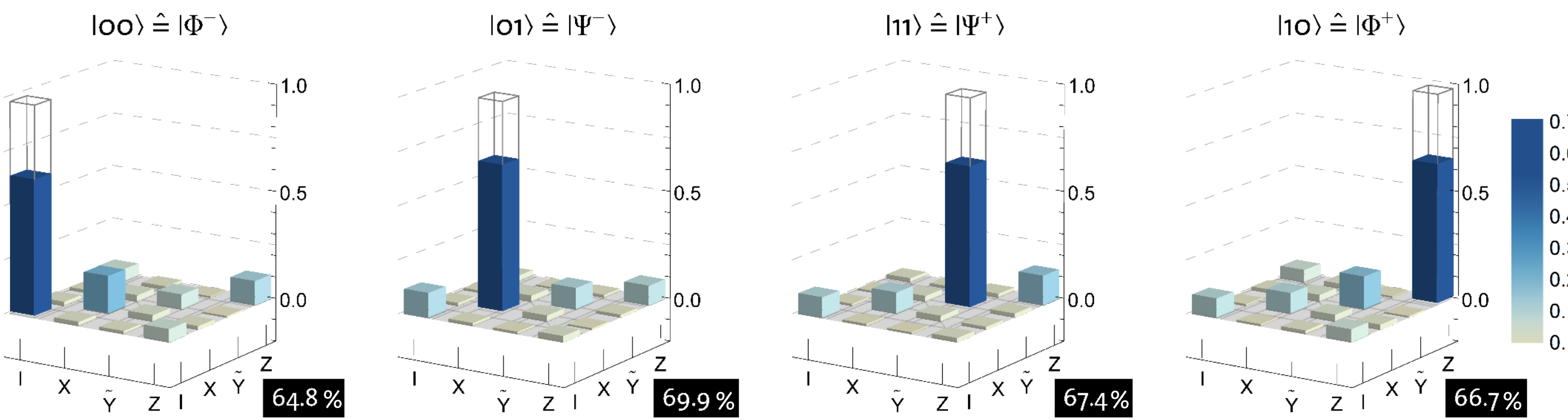
lower left   lower right

	$\|00\rangle$	$\|01\rangle$	$\|10\rangle$	$\|11\rangle$
$\|00\rangle$	0.86	0.09	0.02	0.02
$\|01\rangle$	0.14	0.73	0.04	0.09
$\|10\rangle$	0.03	0.05	0.84	0.09
$\|11\rangle$	0.08	0.10	0.09	0.73



Lars Steffen *et al., arxiv1302.5621* (2013)

Teleportation with Deterministic Bell Measurement



$$|\psi_{\text{out}}\rangle = |\psi_{\text{in}}\rangle \qquad |\psi_{\text{out}}\rangle = X\,|\psi_{\text{in}}\rangle \qquad |\psi_{\text{out}}\rangle = \tilde{Y}\,|\psi_{\text{in}}\rangle \qquad |\psi_{\text{out}}\rangle = Z\,|\psi_{\text{in}}\rangle$$

Average process fidelity **67.1 ± 0.5 %**

Average state fidelity **78.1 ± 0.9 %**

$$\mathcal{F}_p = (\mathcal{F}_s(d+1) - 1)/d$$

Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*

Feed-Forward Characterization

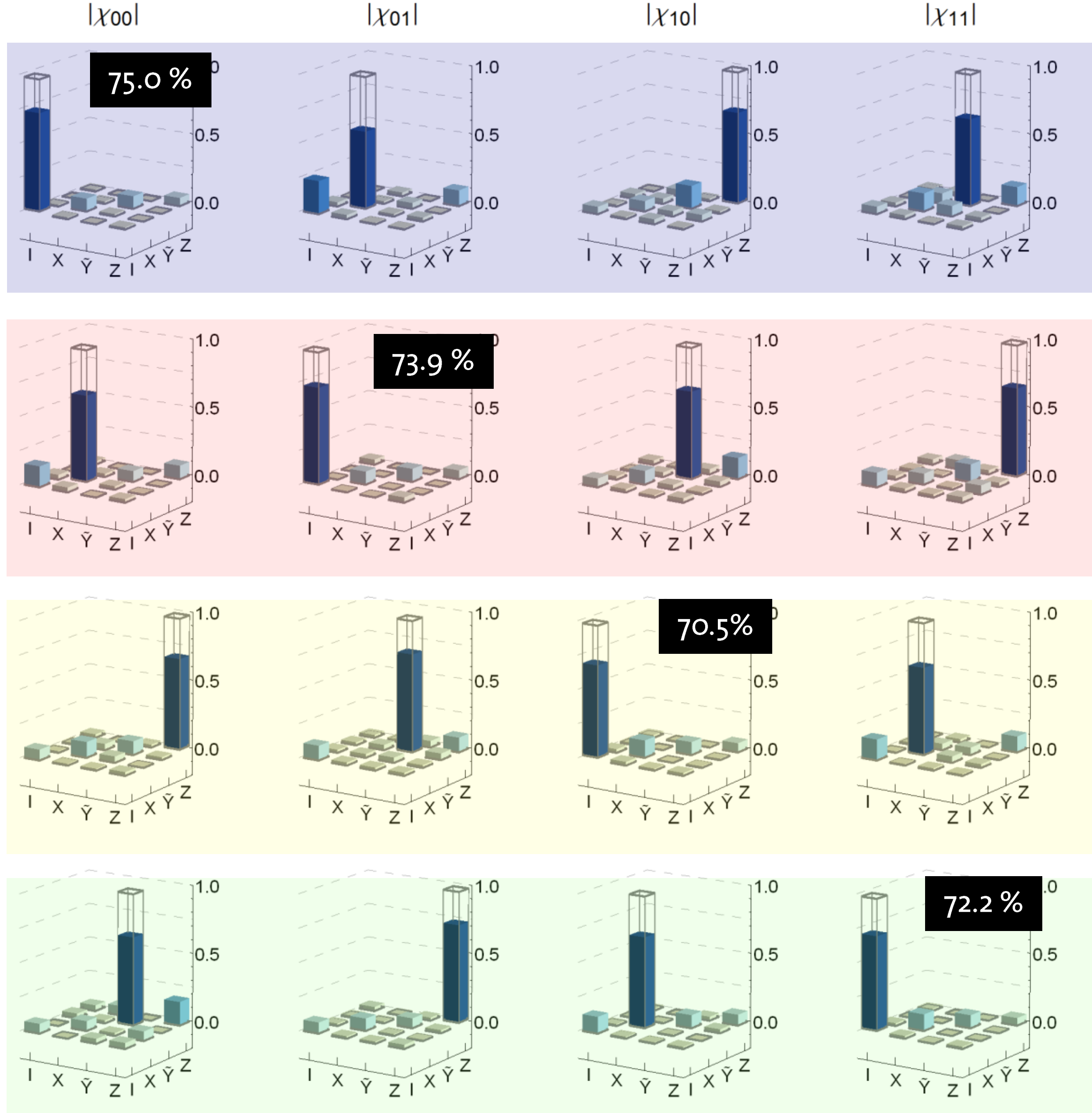
preparation:

- $|00\rangle \otimes |\psi\rangle$
- $|01\rangle \otimes \sigma_x |\psi\rangle$
- $|10\rangle \otimes \sigma_z |\psi\rangle$
- $|11\rangle \otimes i\sigma_y |\psi\rangle$

readout of qubit 1 and 2

	$|00\rangle$	$|01\rangle$	$|10\rangle$	$|11\rangle$
$|00\rangle$	0.91	0.05	0.02	0.02
$|01\rangle$	0.1	0.81	0.03	0.05
$|10\rangle$	0.04	0.04	0.8	0.12
$|11\rangle$	0.06	0.03	0.11	0.8

process tomography for qubit 3 assuming input = $|\psi\rangle$



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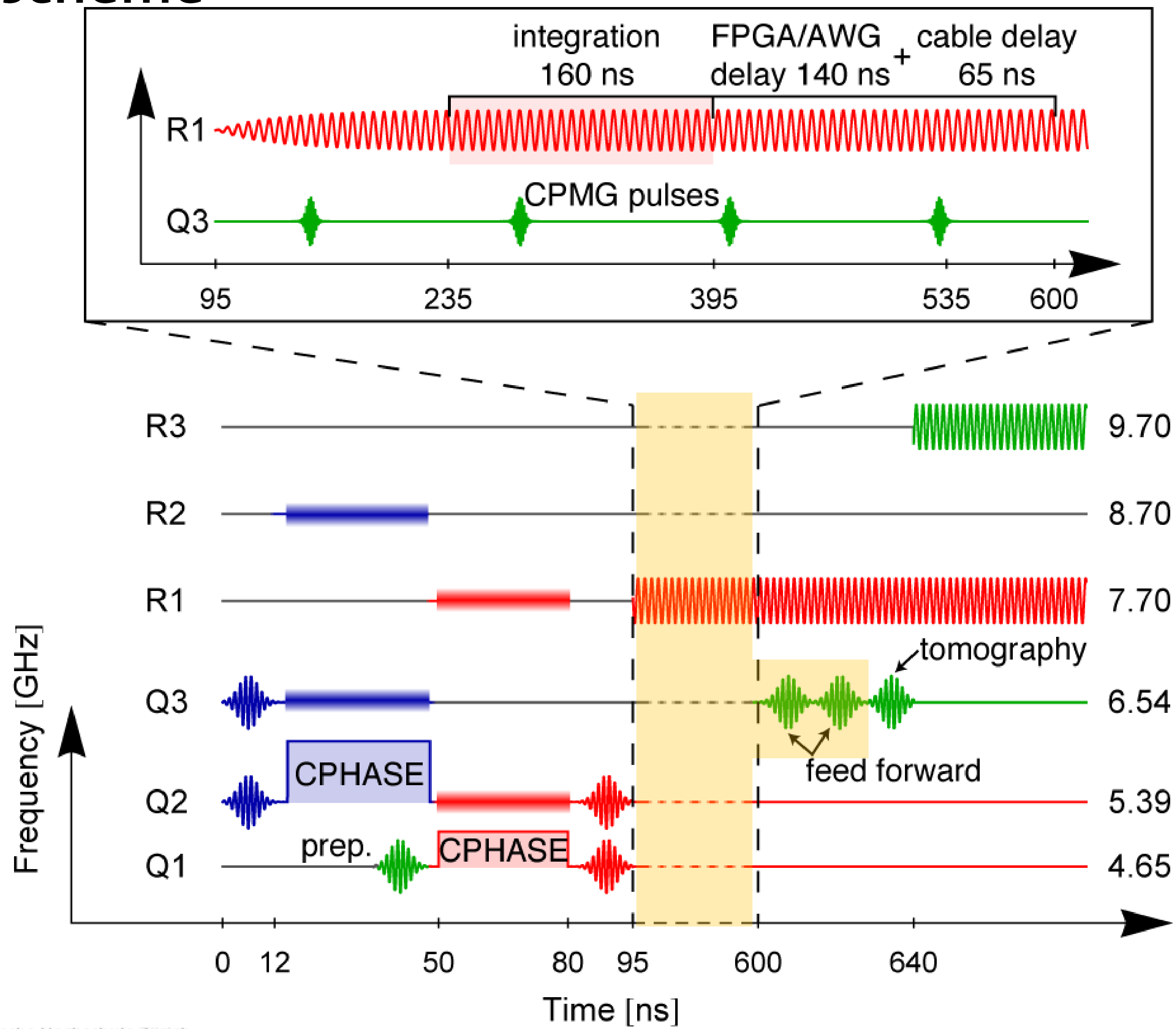
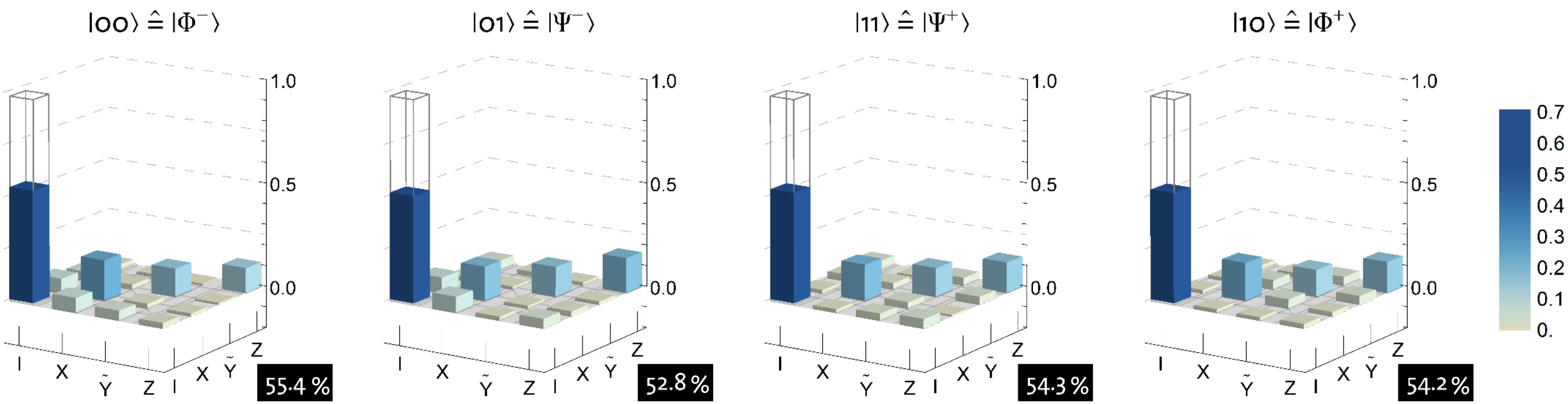
Pulse scheme

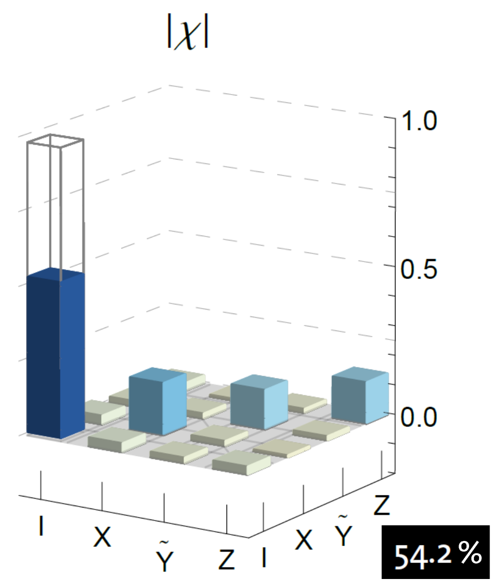


Teleportation Process with Feed-Forward



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

Average process fidelity **54.2 ± 0.1 %**



ETH
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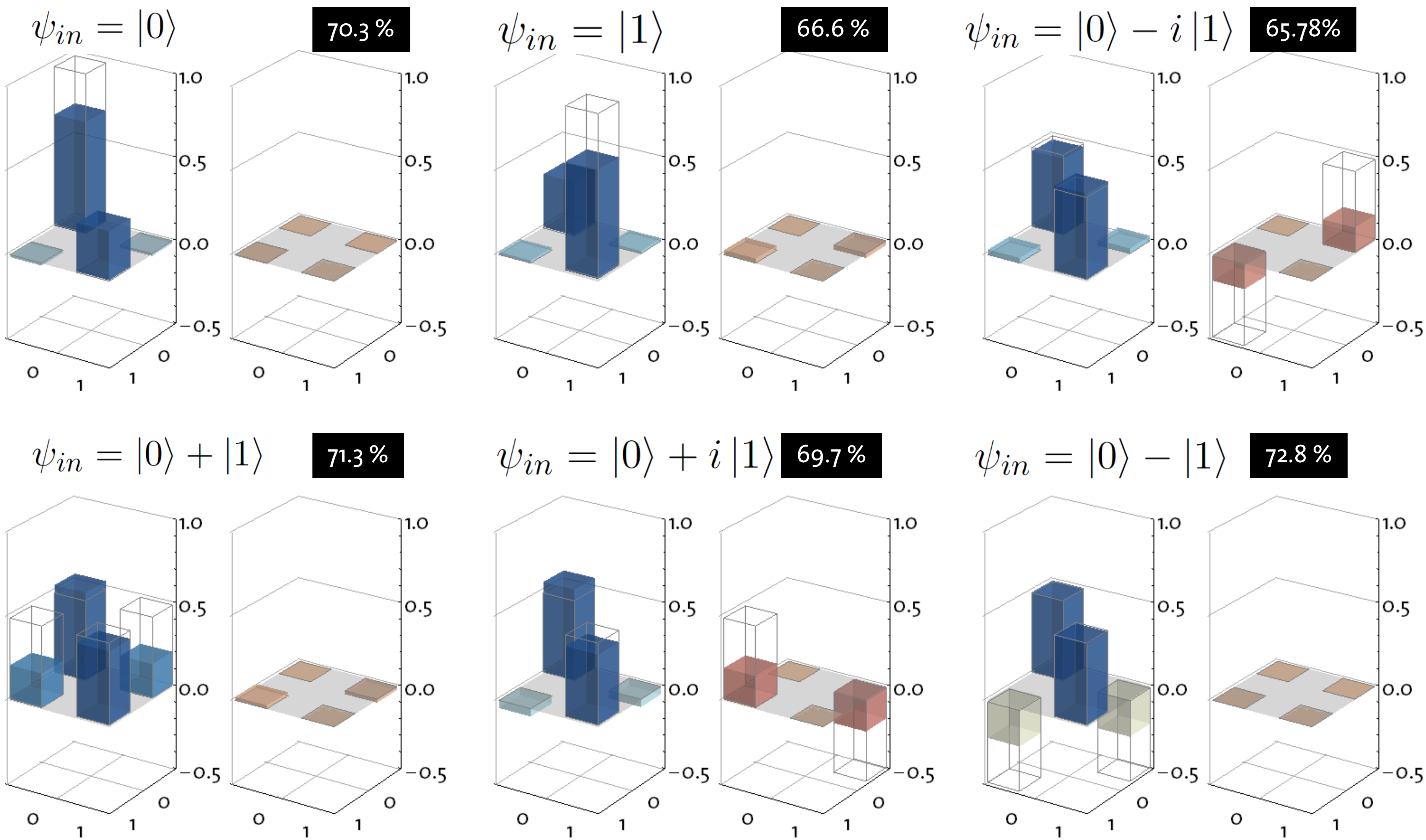
Swiss Federal Institute of Technology Zurich

Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*

Tomography of Teleported States with Feed-Forward



ETH
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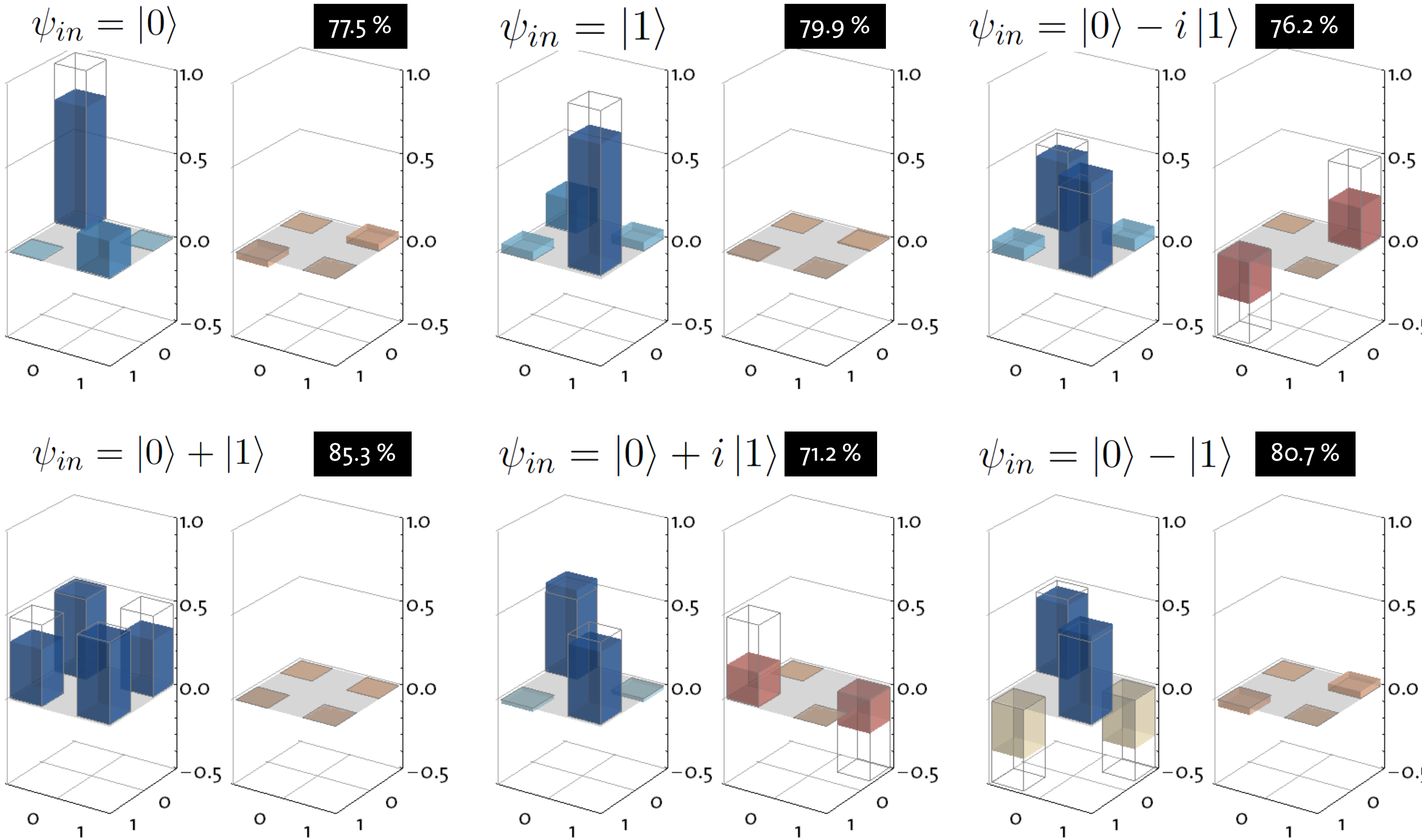
Average state fidelity of 69.5±0.1 %

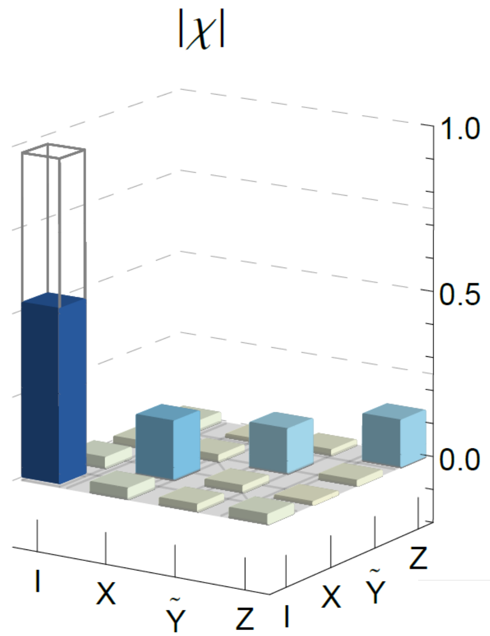
Tomography of Teleported States with Feed-Forward

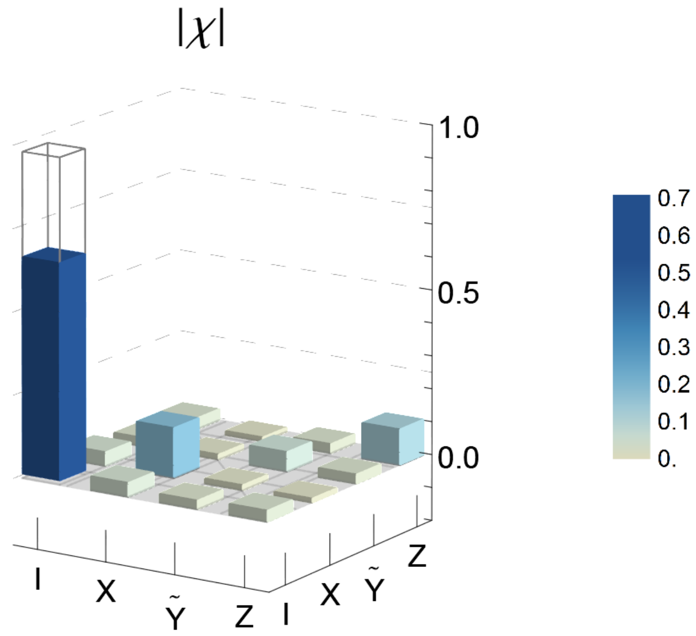
averaged readout of qubit 3



Average state fidelity of 78.5± 0.9%

Teleportation Process with Feed-Forward





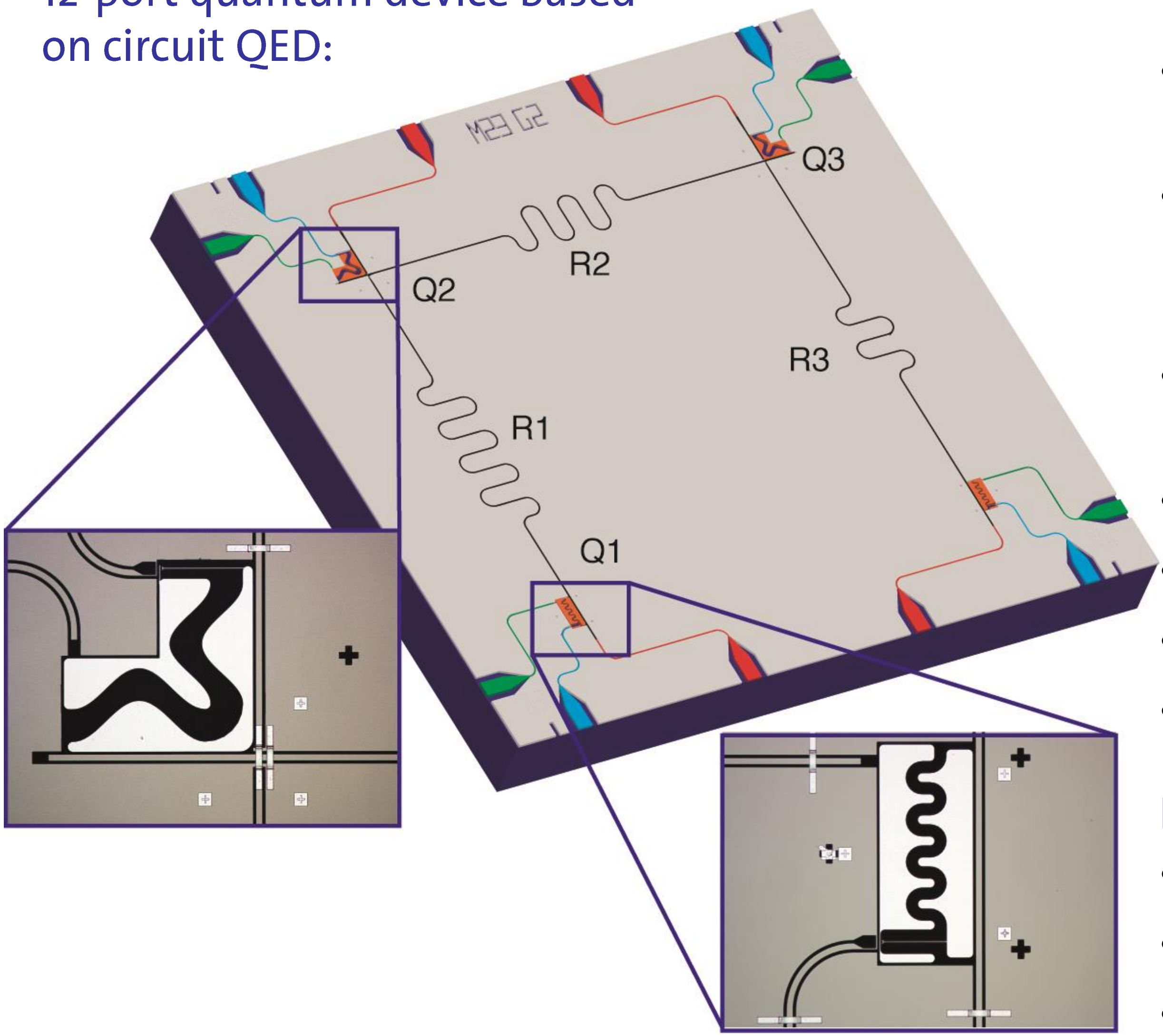
Average process fidelity with single shot readout: **54.2 ± 0.1 %**

Average process fidelity with averaged readout: **67.7 ± 1.1 %**

Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*

Teleportation

12-port quantum device based on circuit QED:



Experimental highlights:

- teleportation in a (macroscopic) solid state system
- post-selection on either of 4 Bell states individually
- simultaneous and det. measurement of all 4 Bell states
- implementation of feed-forward
- fidelities > classical threshold
- O(Unity) success probability
- teleportation rate > 10 kHz
- distance ~ 10 mm

Next steps:

- improve fidelities
- increase distances
- apply teleportation

Steffen *et al.*, *Nature* in print (2013), *arxiv1302.5621*

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)
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