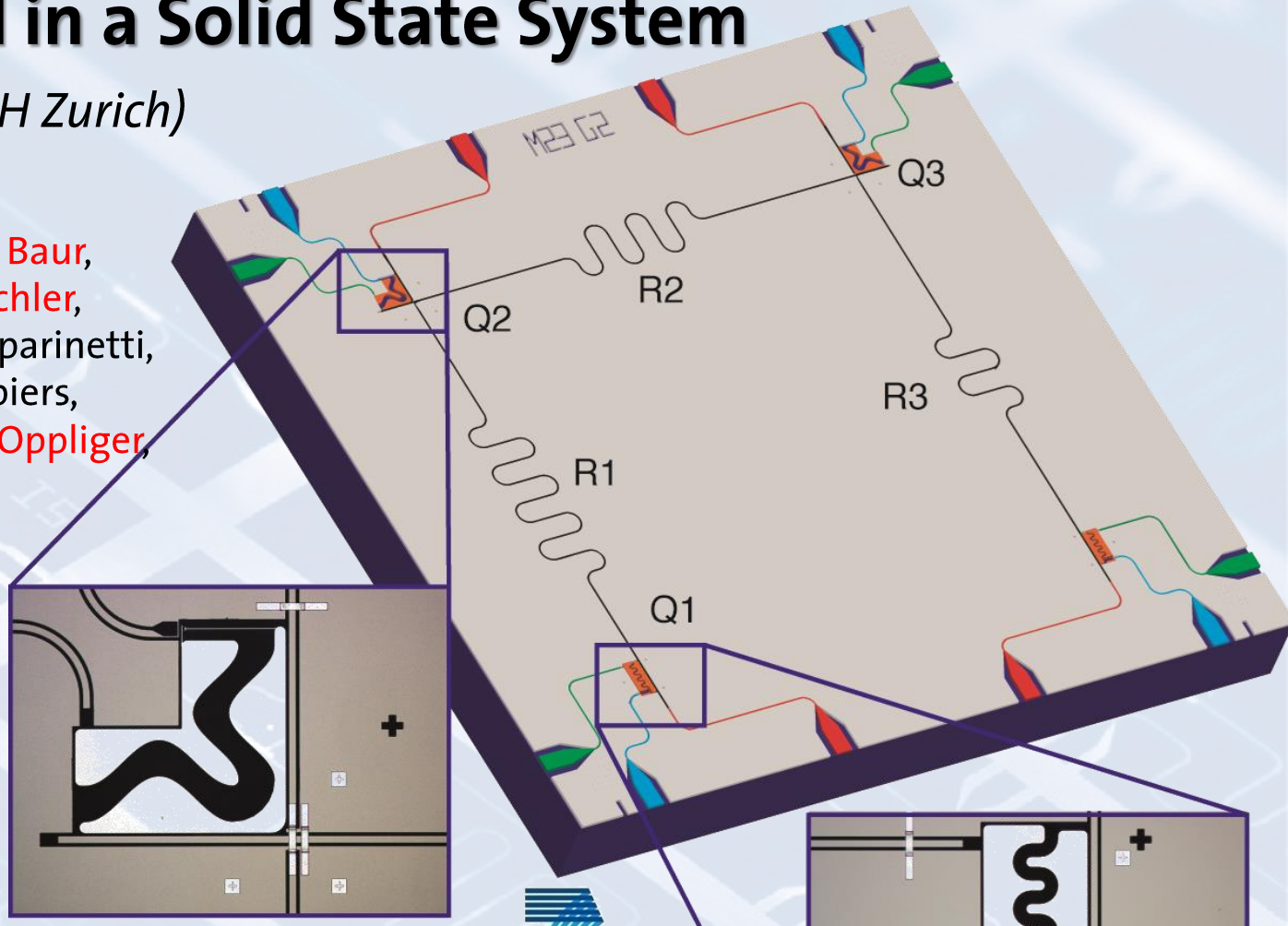
Deterministic Quantum Teleportation with Feed-Forward in a Solid State System

Andreas Wallraff *(ETH Zurich)*

www.qudev.ethz.ch

Team: A. Abdumalikov, M. Baur, S. Berger, M. Collodo, C. Eichler, A. Fedorov, S. Filipp, S. Gasparinetti, J. Heinsoo, C. Lang, P. Kurpiers, J. Mlynek, M. Mondal, M. Oppliger, M. Pechal, A. Potocnik Y. Salathe, M. Stammeier, L. Steffen, T. Thiele *(ETH Zurich)*

Collaborations with: A. Blais *(Sherbrooke)*



scaleQIT

SEVENTH FRAMEWORK PROGRAMME

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

erc

Acknowledgements

www.qudev.ethz.ch

Former group members now Faculty/PostDoc/PhD/Industry

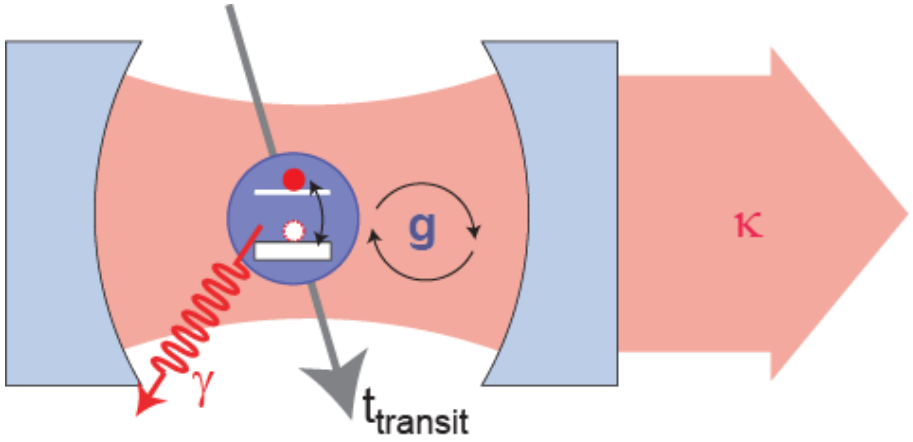
M. Baur (ABB)
J. Basset (U. Paris Sud)
R. Bianchetti (ABB)
D. Bozyigit (ETH Zurich)
C. Eichler (Princeton)
A. Fedorov (UQ Brisbane)
A. Fragner (Yale)
S. Filipp (IBM)
J. Fink (Caltech, IST Austria)
T. Frey (Bosch)
M. Goppl (Sensirion)
J. Govenius (Aalto)
L. Huthmacher (Cambridge)
D.-D. Jarausch (Cambridge)
K. Juliusson (CEA Saclay)
C. Lang (Radionor)
P. Leek (Oxford)
P. Maurer (Stanford)
J. Mlynek (Siemens)
G. Puebla (IBM)
L. Steffen (AWK Group)
A. van Loo (Oxford)
S. Zeytinoğlu (ETH Zurich)
L. Novotny (ETH Zurich)
B. Sanders (Calgary)
S. Schmidt (ETH Zurich)
R. Schoelkopf (Yale)
C. Schoenenberger (Basel)
E. Solano (UPV/EHU)
W. Wegscheider (ETH Zurich)

Collaborations with (groups of):

A. Blais (Sherbrooke)
C. Bruder (Basel)
M. da Silva (Raytheon)
L. DiCarlo (TU Delft)
K. Ensslin (ETH Zurich)
J. Faist (ETH Zurich)
J. Gambetta (IBM)
T. Ihn (ETH Zurich)
F. Merkt (ETH Zurich)

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
erc Seventh Framework Programme
SOLID
GEOMDISS
aqute
scaleQIT

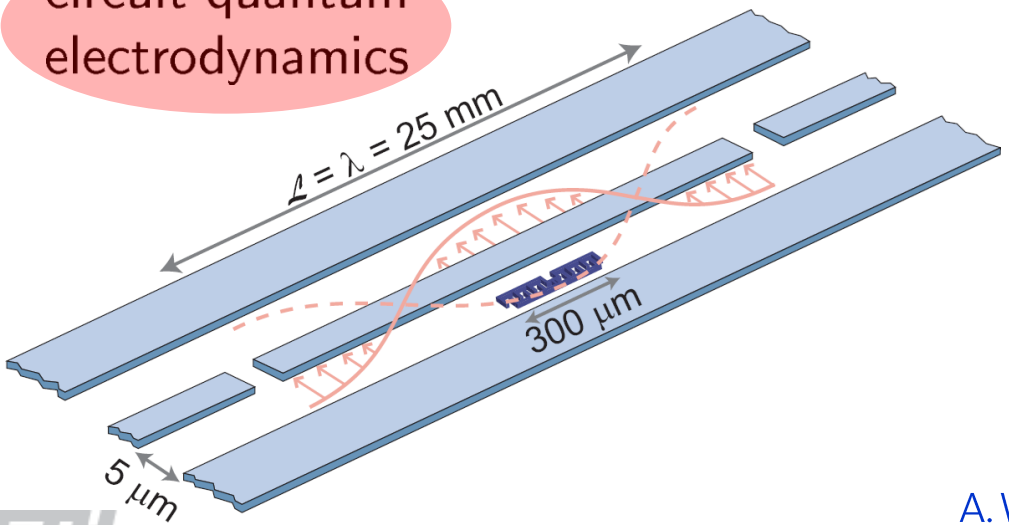
Cavity QED with Superconducting Circuits



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:

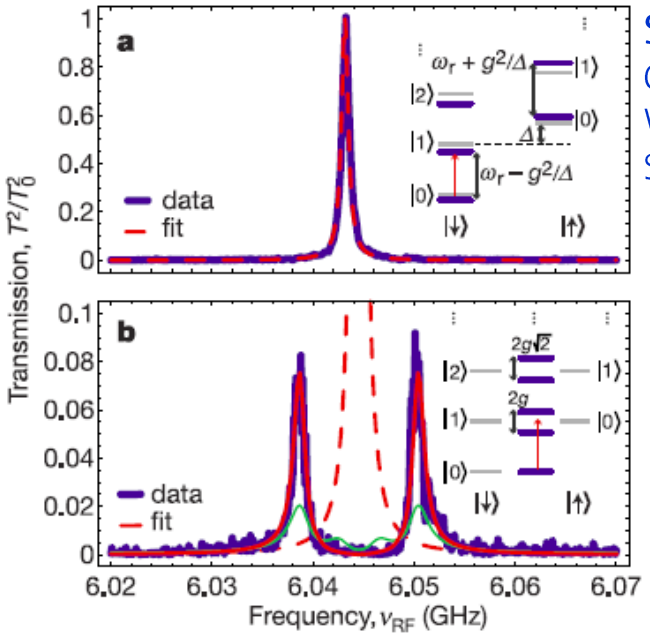
- strong coupling in solid state sys.
- 'easy' to fabricate and integrate

Research directions:

- quantum optics
- hybrid quantum systems
- quantum information

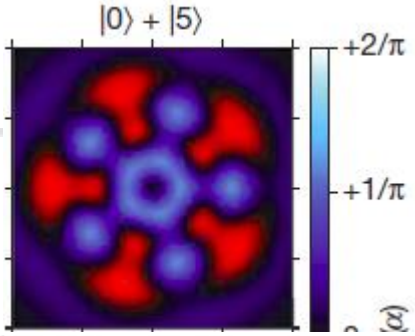
A. Blais, *et al., PRA* **69**, 062320 (2004)
A. Wallraff *et al., Nature (London)* **431**, 162 (2004)
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* **451**, 664 (2008)

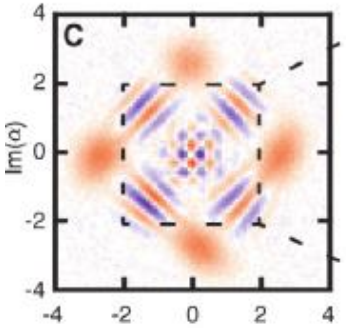
Quantum Optics with Supercond. Circuits



Strong Coherent Coupling

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



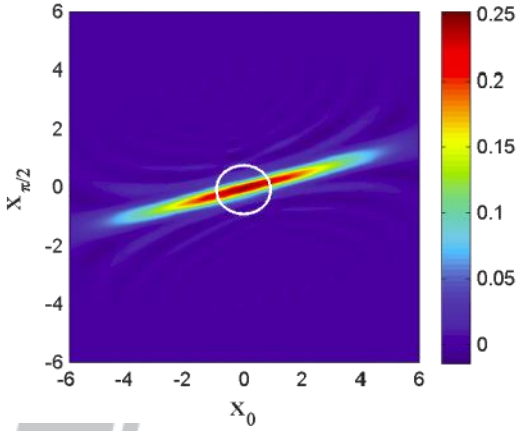


Root n Nonlinearities

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

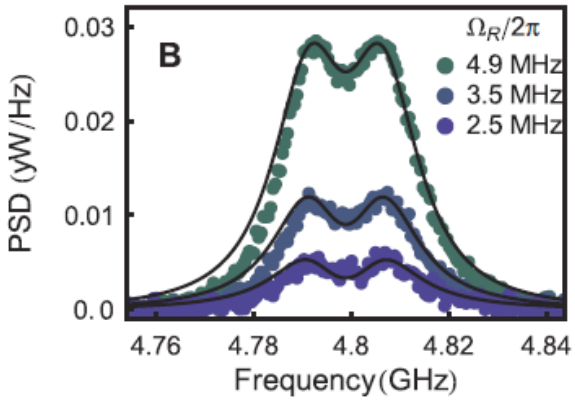
Microwave Fock and Cat States

Hofheinz *et al.*, *Nature* **454**, 310 (2008)
Hofheinz *et al.*, *Nature* **459**, 546 (2009)
Kirchmair *et al.*, *Nature* **495**, 205 (2013)
Vlastakis *et al.*, *Science* **342**, 607 (2013)



Parametric Amplification & Squeezing

Castellanos-Beltran *et al.*, *Nat. Phys.* **4**, 928 (2008)
Abdo *et al.*, *PRX* **3**, 031001 (2013)

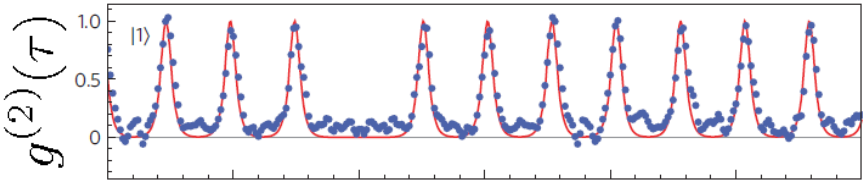


Waveguide QED – Qubit Interactions in Free Space

Astafiev *et al.*, *Science* **327**, 840 (2010)
van Loo *et al.*, *Science* **342**, 1494 (2013)

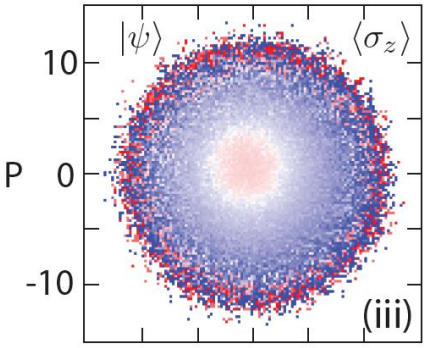
Experiments with Propagating Quantum Microwaves

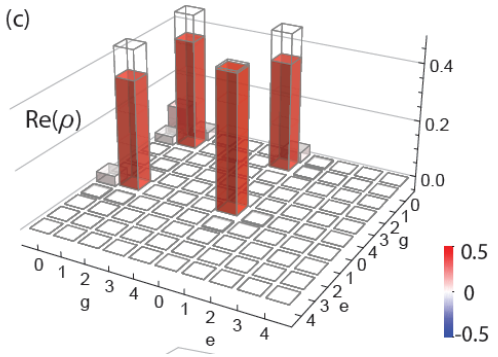
Single photon sources and their anti-bunching



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

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

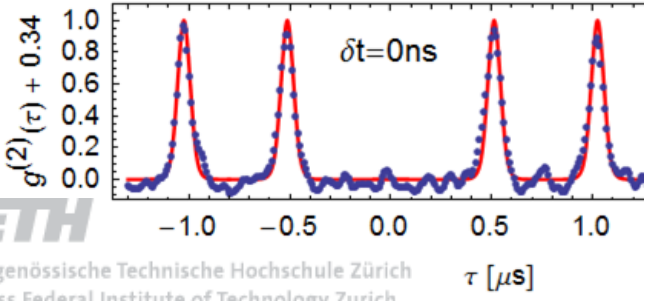


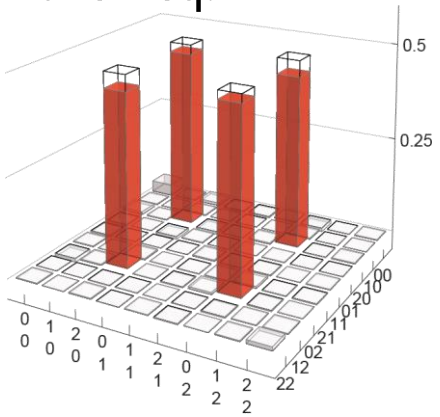


Eichler *et al.*, *PRL* **109**, *240501* (2012)
Eichler *et al.*, *PRA* **86**, 032106 (2012)

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

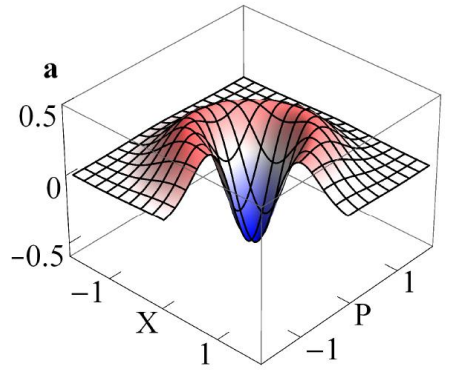
Lang *et al.*, *Nat. Phys.* **9**, 345 (2013)





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

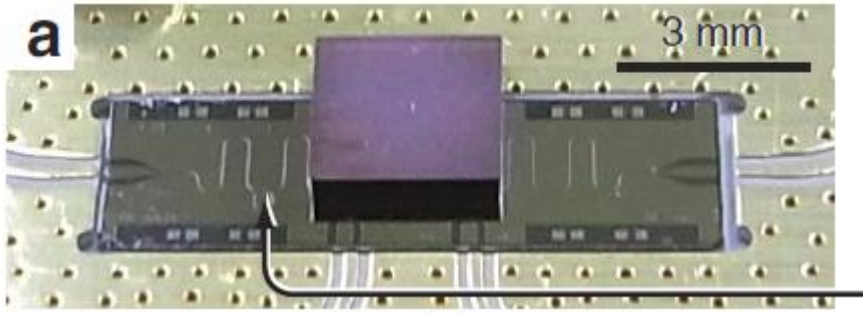
Eichler *et al.*, *PRL* **106**, 220503 (2011)



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)

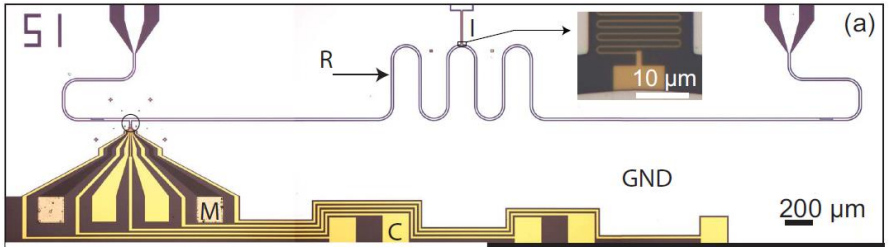


Polar Molecules, Rydberg, BEC

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)

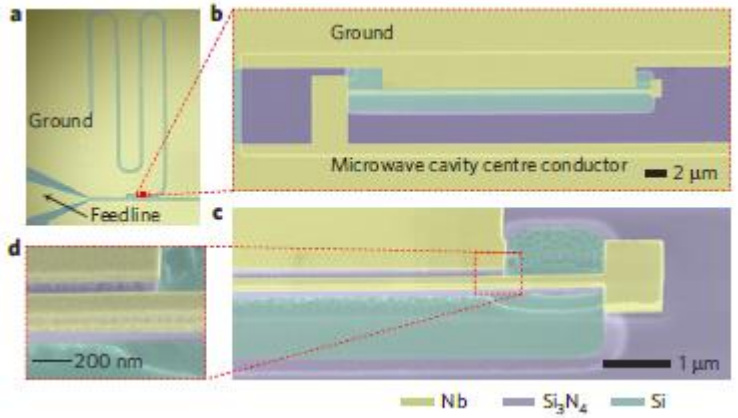
CNT, Gate Defined 2DEG, or nanowire Quantum Dots

M. Delbecq *et al.*, *PRL* **107**, 256804 (2011)
T. Frey *et al.*, *PRL* **108**, 046807 (2012)
K. Petersson *et al.*, *Nature* **490**, 380 (2013)



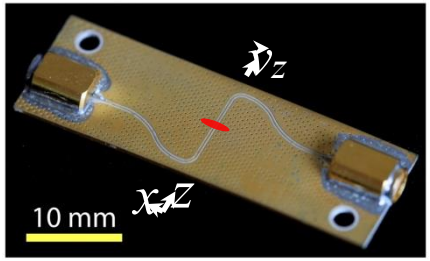
Nano-Mechanics

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



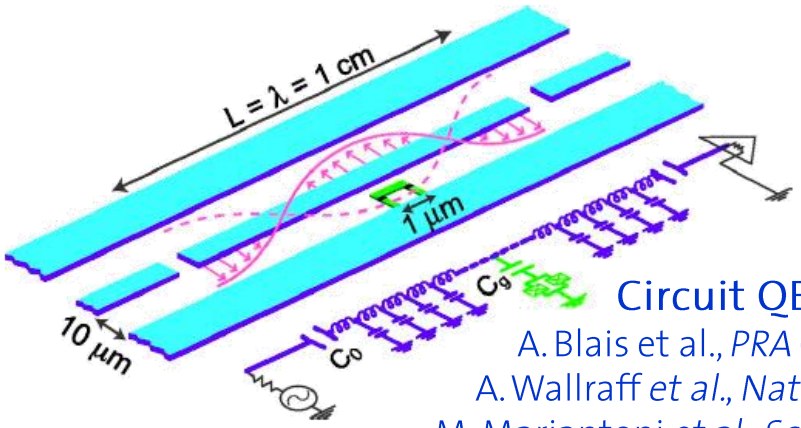
Rydberg Atoms

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



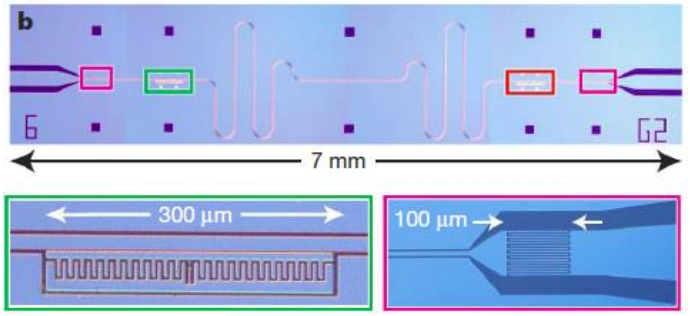
... and many more

Quantum Computing with Superconducting Circuits



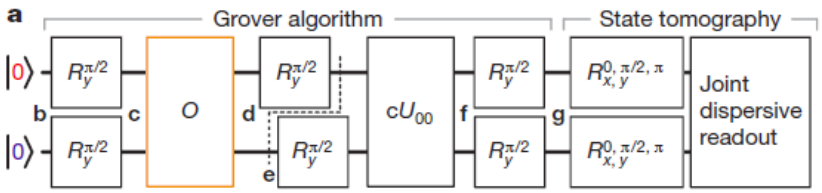
Circuit QED Architecture

A. Blais et al., *PRA* **69**, 062320 (2004)
A. Wallraff *et al.*, *Nature* **431**, 162 (2004)
M. Mariantoni *et al.*, *Science* **334**, 61 (2011)
R. Barends *et al.*, *Nature* **508**, 500 (2014)



Resonator as a Coupling Bus

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

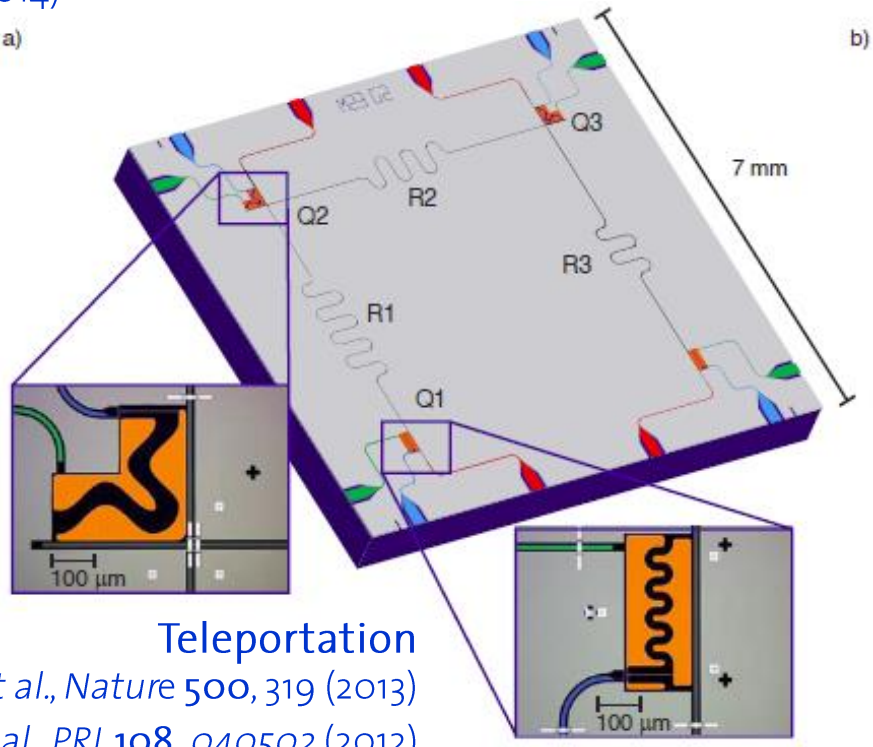


Deutsch, Grover Algorithms

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* **500**, 319 (2013)
M.. Baur *et al.*, *PRL* **108**, 040502 (2012)

Teleportation ... what one may wish for !?

Teleportation in the Quantum World

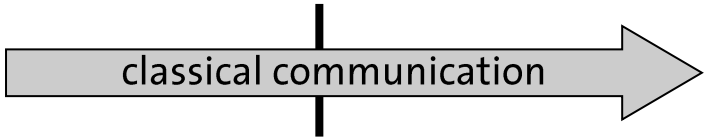
Objective:

- transfer information stored in an quantum bit from a sender to receiver

Resources:

- a pair of entangled qubits shared between the sender and receiver
- a small quantum computer at the sender and at the receiver
- a classical communication channel

Alice



Bob

Features:

- exploits non-local quantum correlations
- uses all essential ingredients required for realizing a universal quantum computer
- full protocol demonstrates use of real-time feed-forward

Applications:

- universal quantum computation
- simplification of quantum circuits
- repeaters for quantum comm.

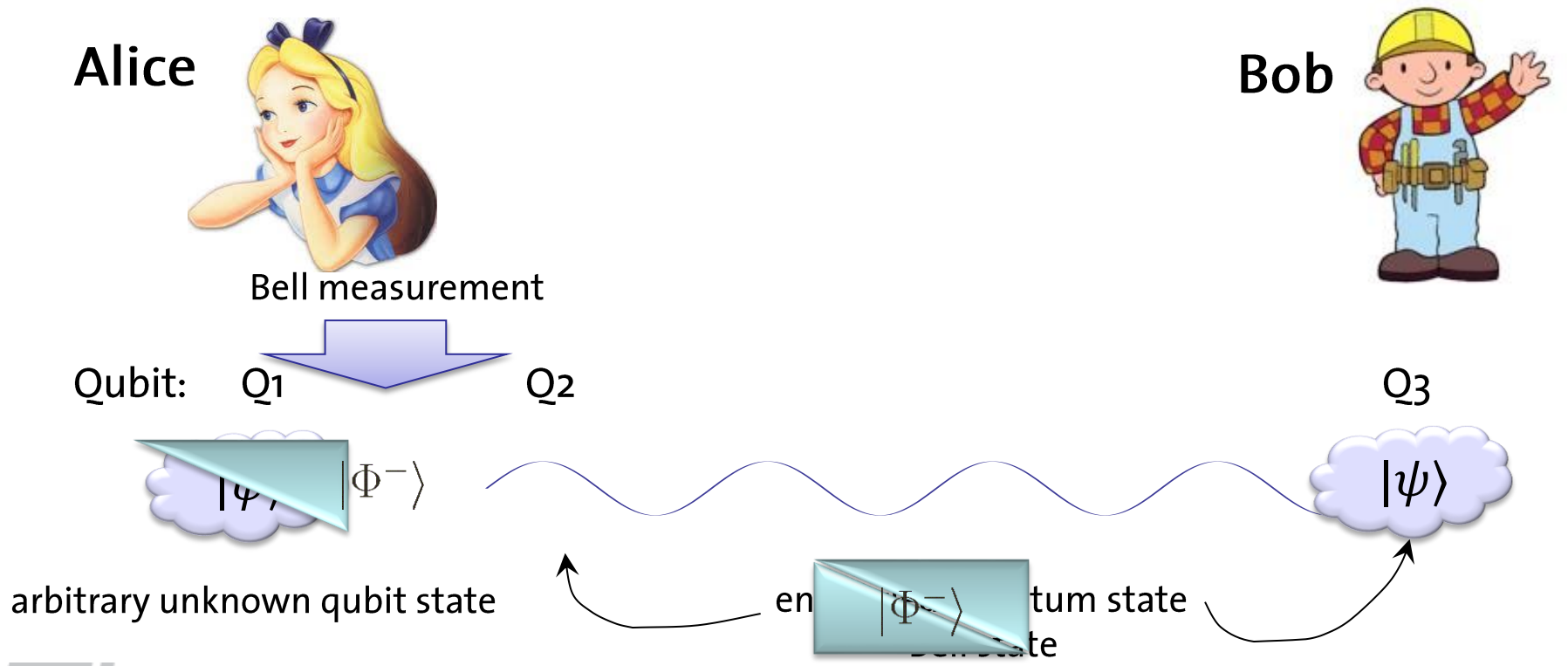
Has been demonstrated for photons, ions and recently also in solid state systems.

proposal: Bennett *et al.*, *Phys. Rev. Lett.* **70**, 1895 (1993)

Teleportation Protocol

Task:
- transfer unknown quantum state from Alice to Bob

Resources:
- a pair of entangled qubits (Q1 + Q2)

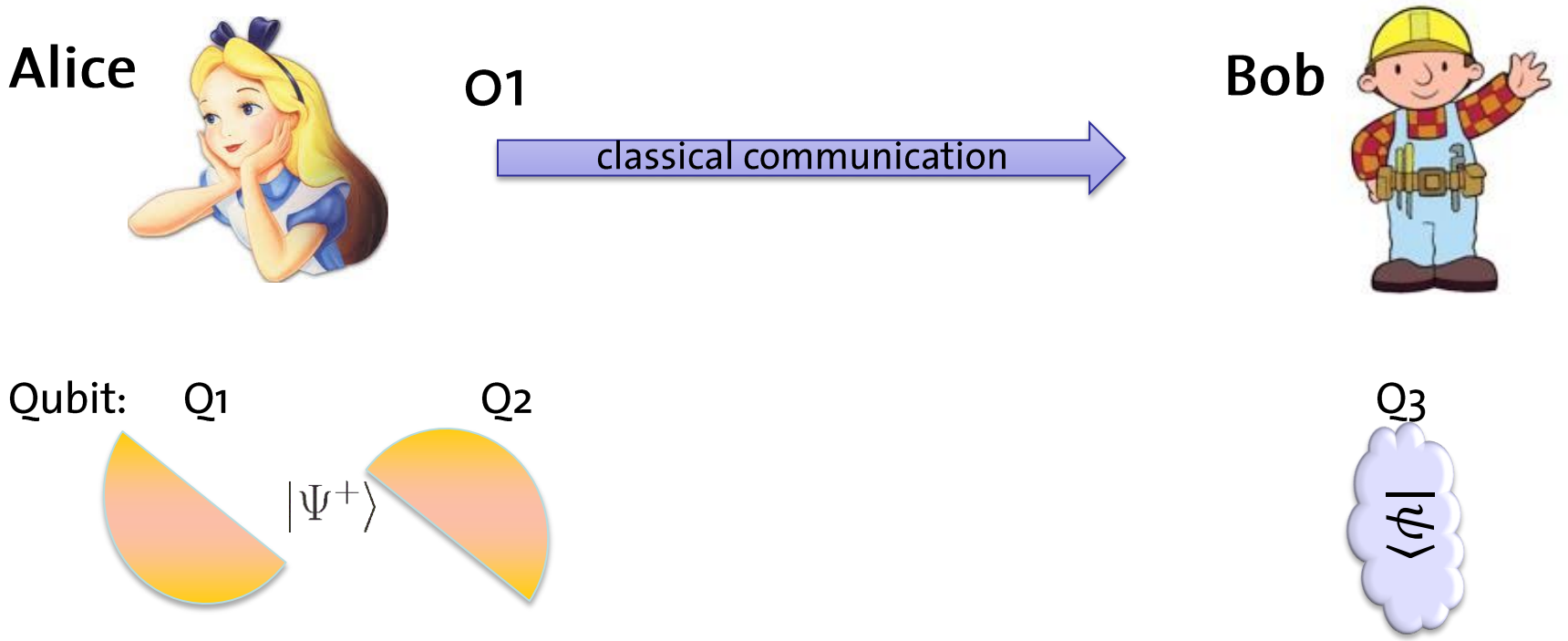


proposal: Bennett *et al.*, *Phys. Rev. Lett.* **70**, 1895 (1993)

Teleportation Protocol

Task:
- transfer unknown quantum state from Alice to Bob

Resources:
- a pair of entangled qubits (Q1 + Q2)
- classical communication



proposal: Bennett *et al.*, *Phys. Rev. Lett.* **70**, 1895 (1993)

Teleportation in other Systems

Single photons

D. Bouwmeester, *et al., Nature*, **390**, 575–579 (1997)
I. Marcikic, *et al., Nature*, **421**, 509–513 (2003)
J. Yin, *et al., Nature*, **488**, 185–188 (2012)
X.-S. Ma, *et al., Nature*, **489**, 269–273 (2012)

Ion traps

M. Riebe *et al., Nature*, **429**, 734–737 (2004)
M. Barrett, *et al., Nature*, **429**, 737–739 (2004)
S. Olmschenk, *et al., Science*, **323**, 486–489 (2009)

Atomic ensembles

X.-H. Bao, *et al., PNAS*, **109**, 20347 (2012)

Single atoms

C. Nölleke, *et al., Phys. Rev. Lett.*, **110**, 140403 (2013)

NMR

M. A. Nielsen, *et al., Nature*, **396**, 52–55 (1998)

Continuous variables

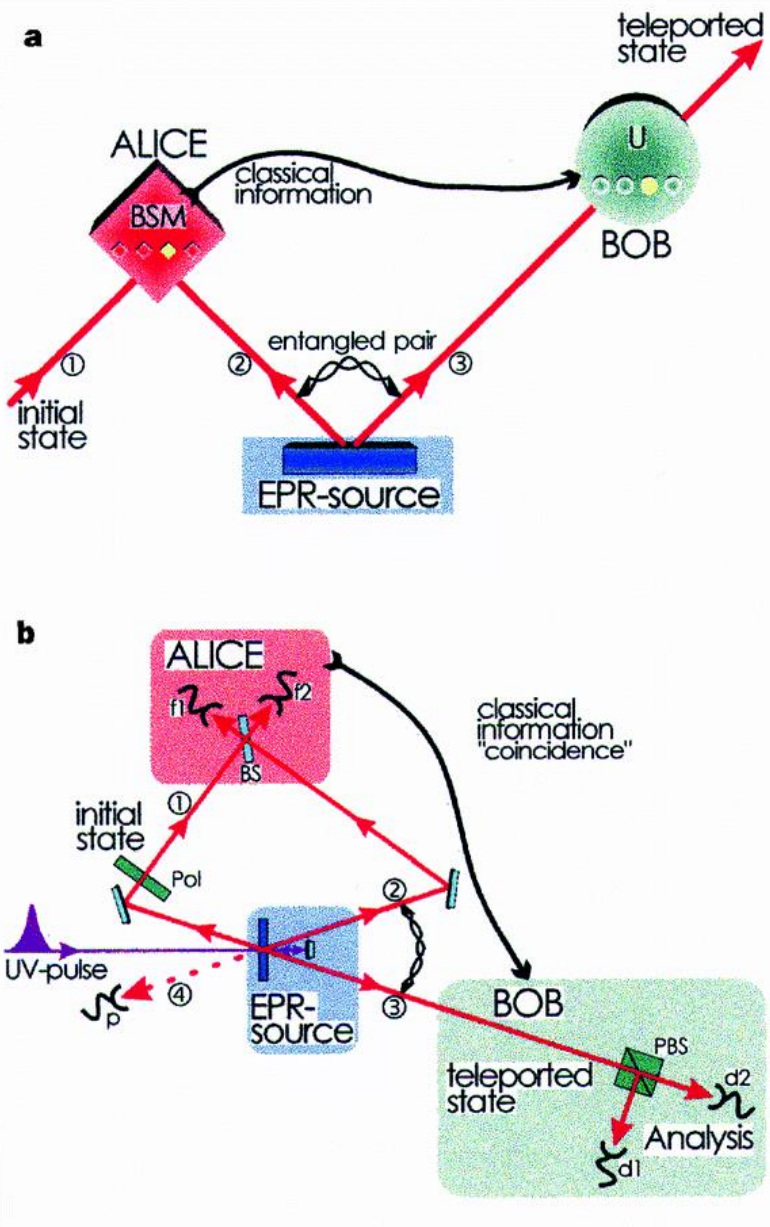
A. Furusawa, *et al., Science*, **282**, 706–709 (1998)
N. Lee, *et al., Science*, **332**, 330–333 (2011)
S. Takeda, *et al., Nature*, **500**, 315–318 (2013)

Semiconductor Quantum Dots

W.B. Gao, et al., *Nat. Comm* **4**, 2744 (2013)

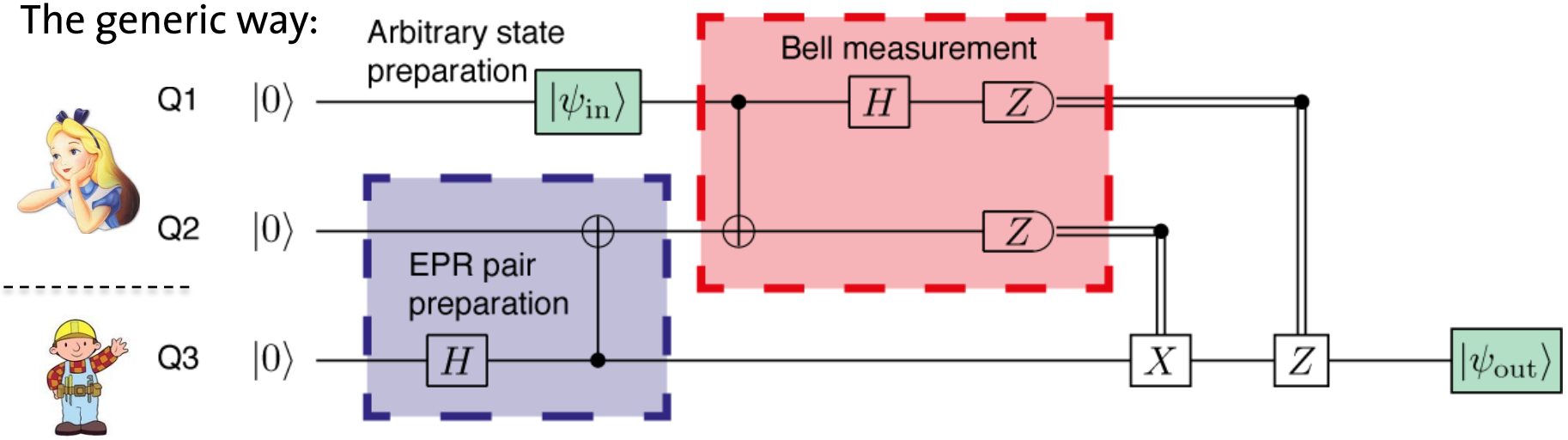
NV Centers

W. Pfaff, et al., *Science* **345**, 532 (2014)



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

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

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

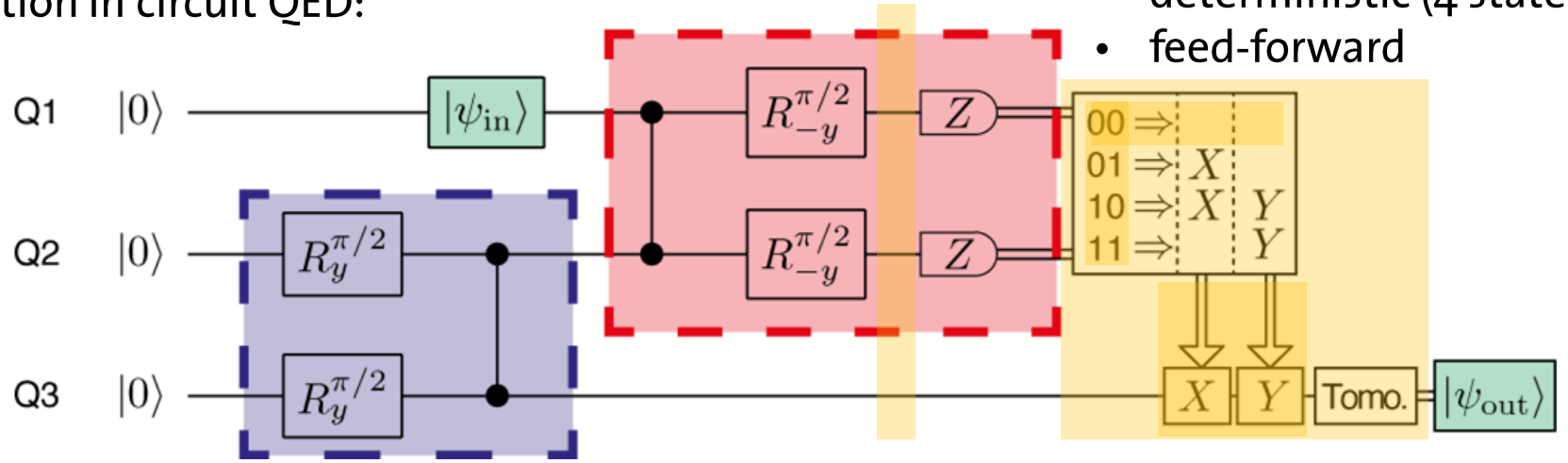
Implementation of the Teleportation Protocol

The generic way:

verification

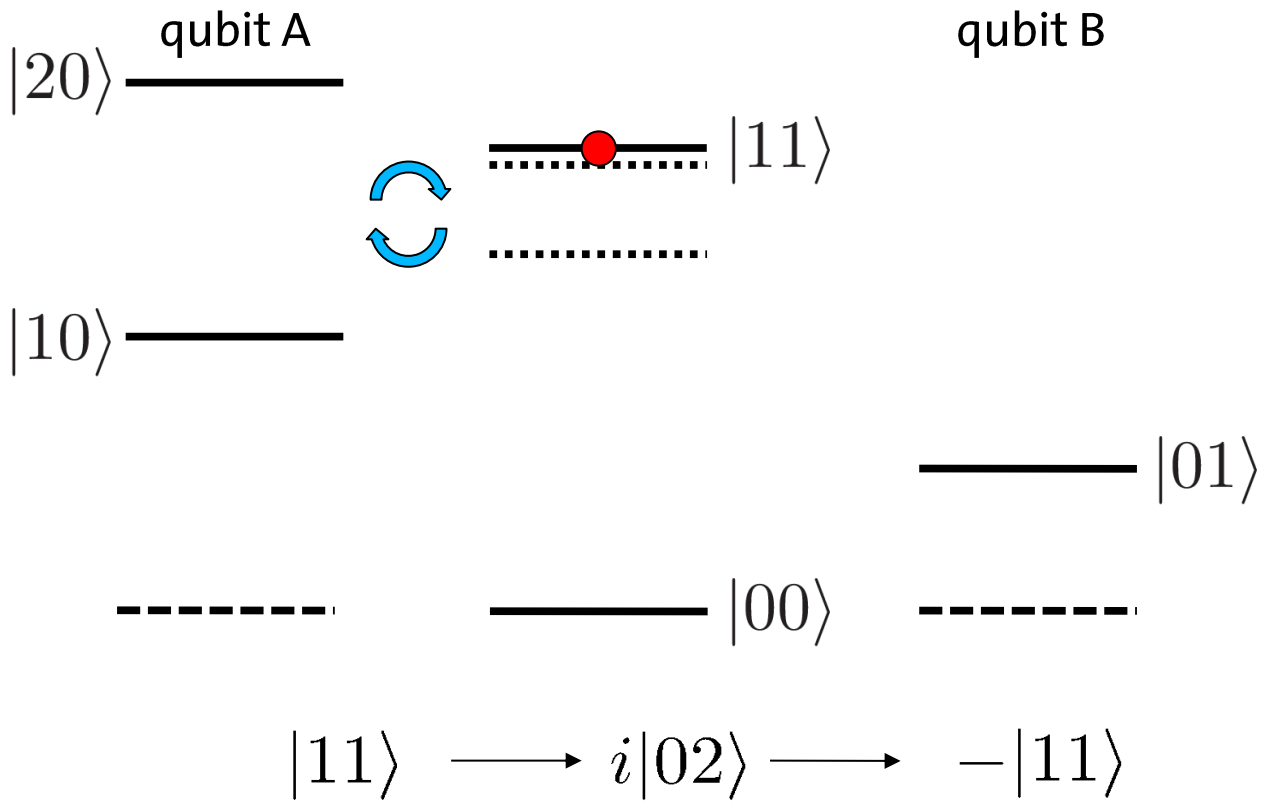
- 3-qubit tomography
- post selection (1 state)
- deterministic (4 states)
- feed-forward

Realization in circuit QED:



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

Controlled phase gate

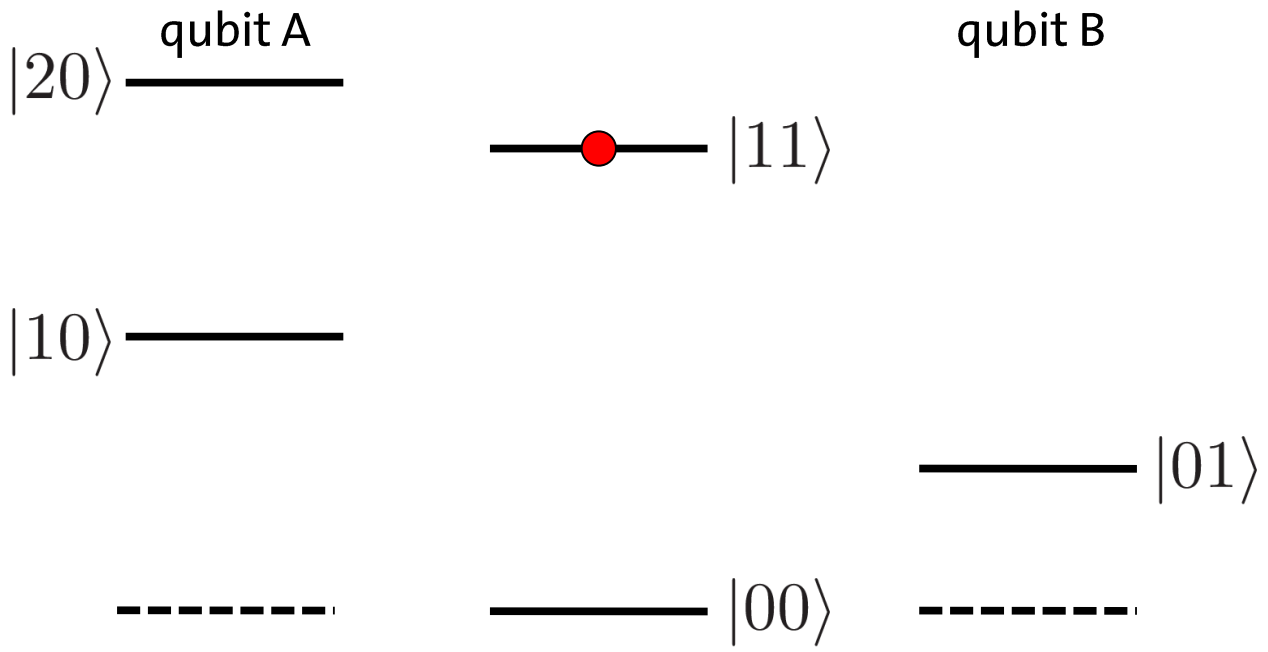


Tune levels into resonance using magnetic field

Interaction mediated by virtual photon exchange through resonator

proposal: F. W. Strauch *et al*, *PRL* **91**, 167005 (2003)
first implementation: L. DiCarlo *et al.*, *Nature* **467**, 467 (2010)

Controlled phase gate



Tune levels into resonance using magnetic field

Interaction mediated by virtual photon exchange through resonator

This experiment:
Universal two-qubit gates: F ~ 90%.
Single-qubit gates: F ~ 98%.
.. to realize needed quantum operations.

$$|11\rangle \longrightarrow i|02\rangle \longrightarrow -|11\rangle$$
$$|01\rangle \longrightarrow |01\rangle$$
$$|10\rangle \longrightarrow |10\rangle$$
$$|00\rangle \longrightarrow |00\rangle$$

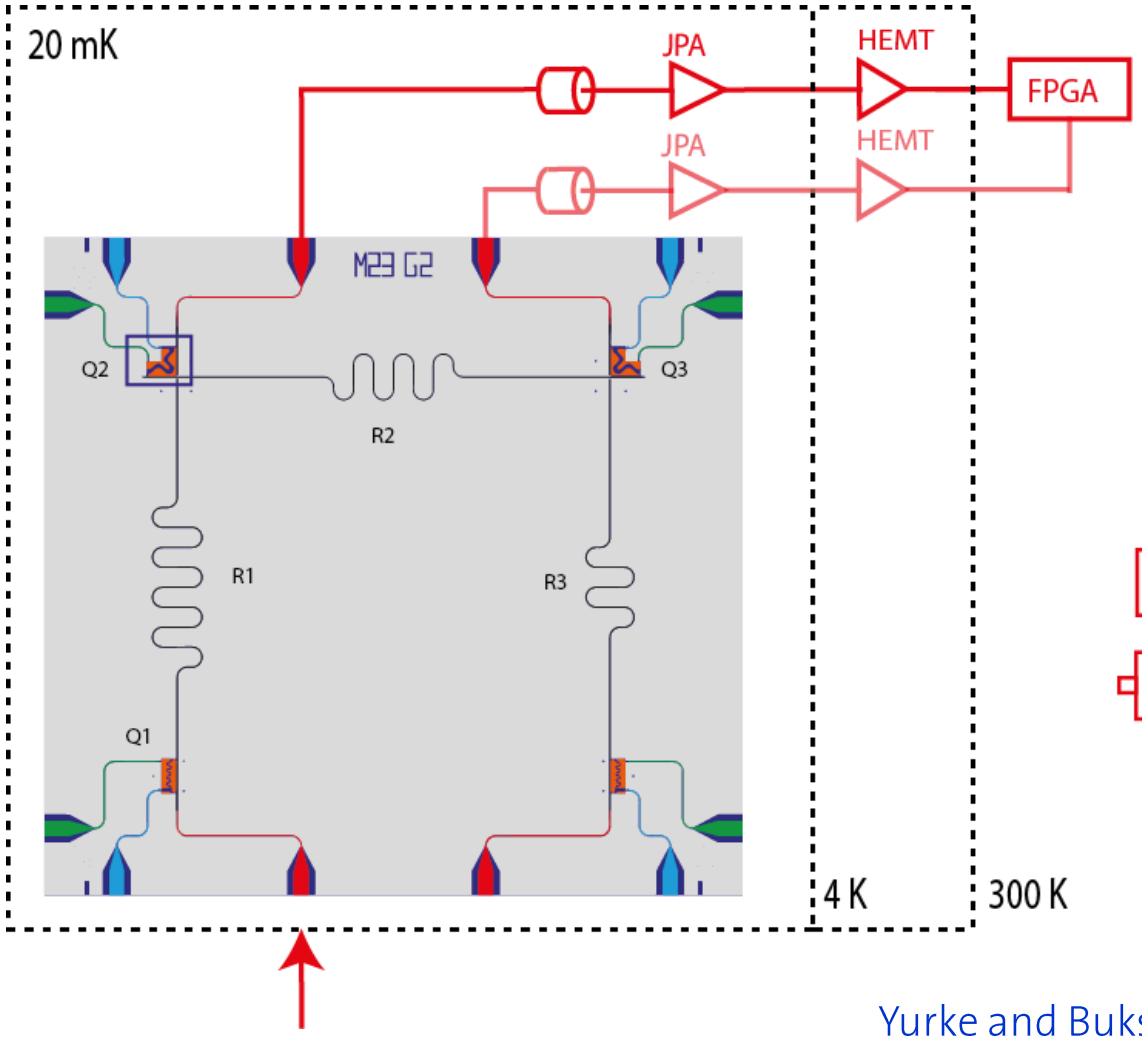
C-Phase gate:

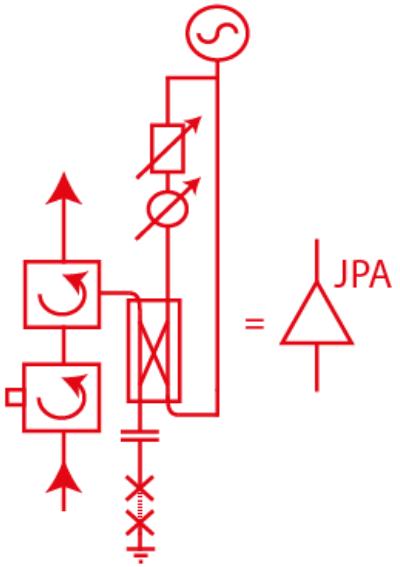
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

proposal: F. W. Strauch *et al*, *PRL* **91**, 167005 (2003)

first implementation: L. DiCarlo *et al.*, *Nature* **467**, 467 (2010)

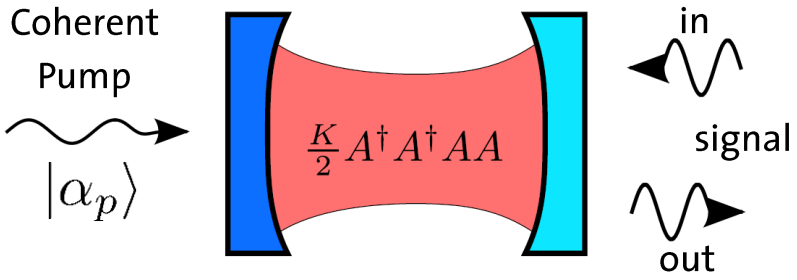
Dispersive Qubit Readout with Parametric Amplifiers

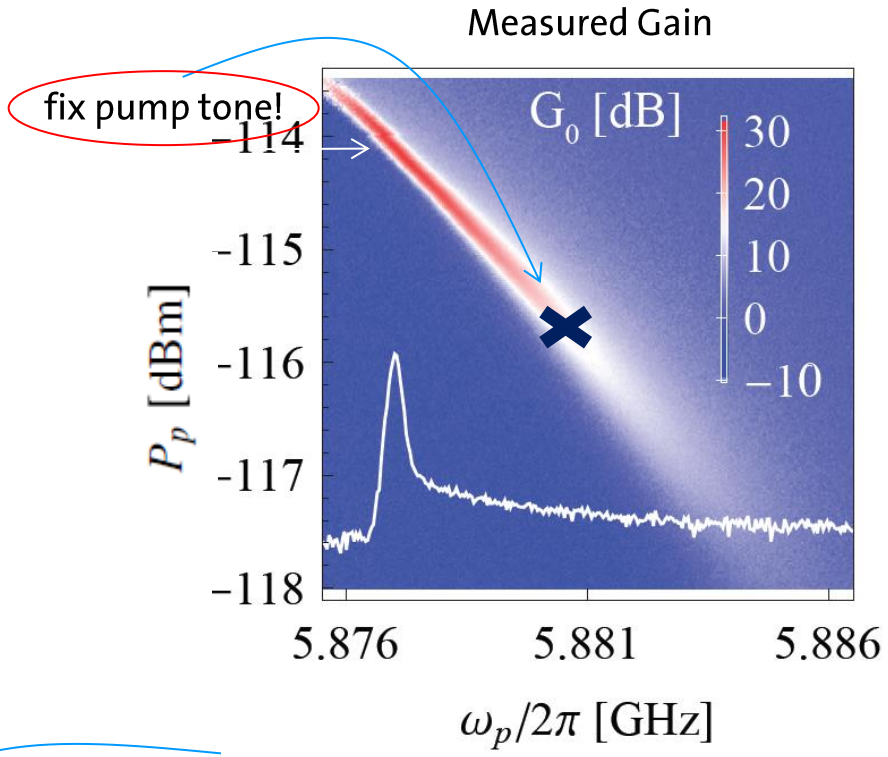




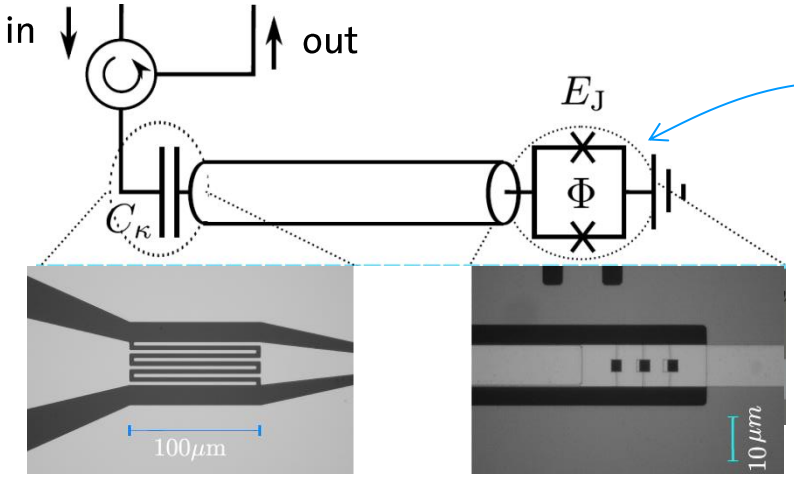
Yurke and Buks, *J. Lightwave Tech.* **24**, 5054 (2006)
Castellanos-Beltran et al., *Nat. Phys.* **4**, 929 (2008)
Eichler *et al.*, *PRL* **107**, 113601 (2011)
R. Vijay *et al*, *PRL* **106**, 110502 (2011)

Near Quantum-Limited Parametric Amplifier





Circuit QED implementation:



SQUID(-array) provides required nonlinearity

Eichler *et al.*, EPJ Quantum Technology **1**, 2 (2014)

Eichler *et al.*, *Phys. Rev. Lett.* **107**, 113601 (2011)

Eichler et al., *Phys. Rev. Lett.* **113**, 110502 (2014)

Caves, *Phys. Rev. D* **26**, 1817 (1982)

Yurke and Buks, *J. Lightwave Tech.* **24**, 5054 (2006)

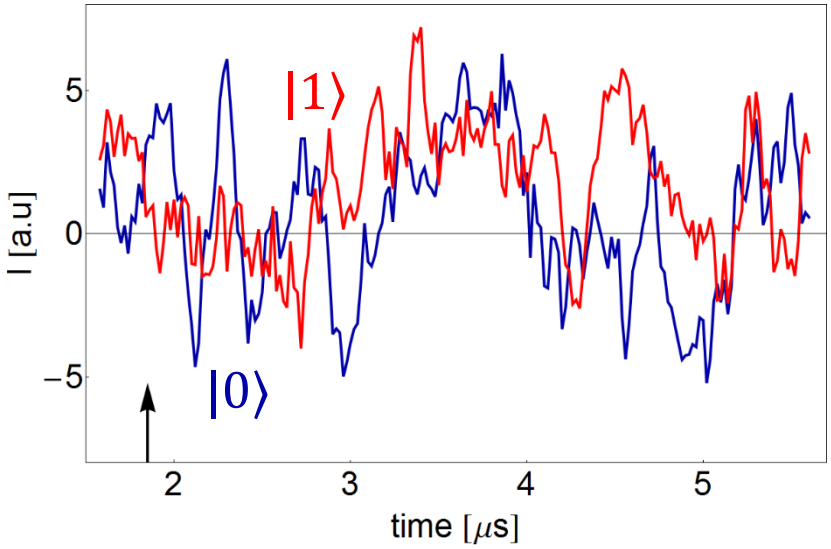
Castellanos-Beltran *et al.*, *Nat. Phys.* **4**, 929 (2008)

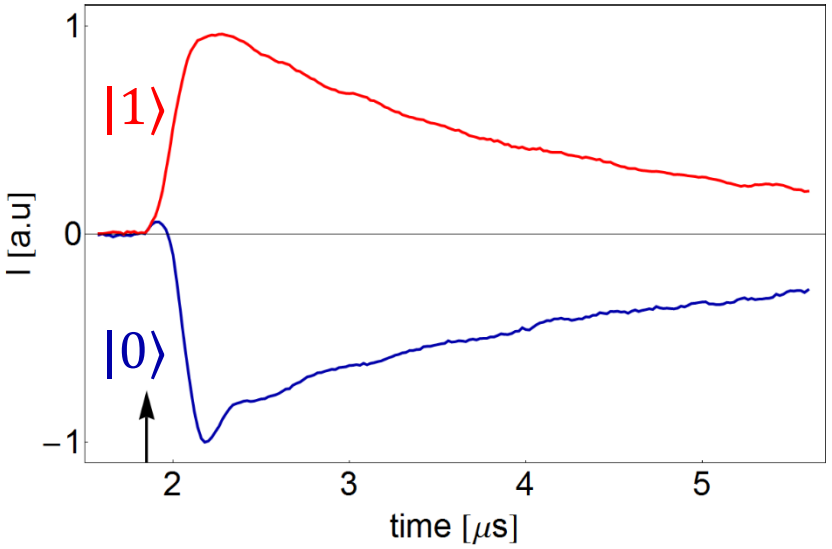
Single-Shot Single-Qubit Readout

single-shot measurements:

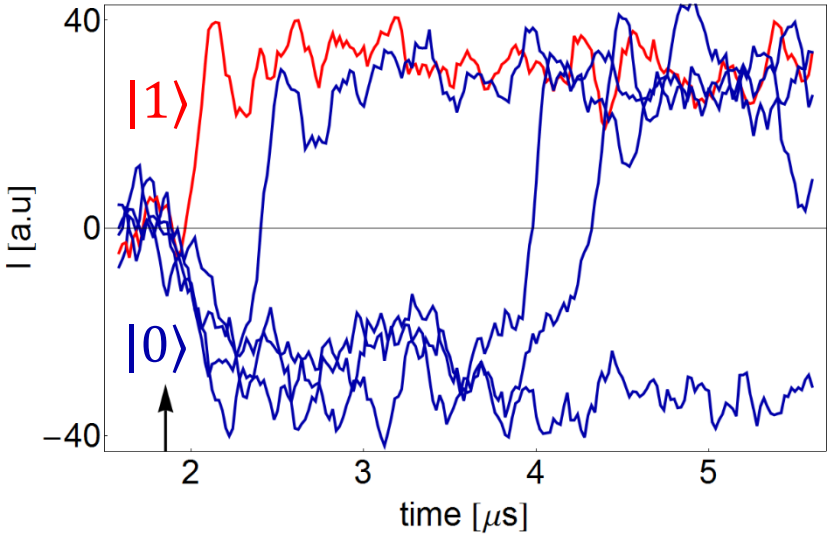
averaged measurements ($8\ 10^4$):

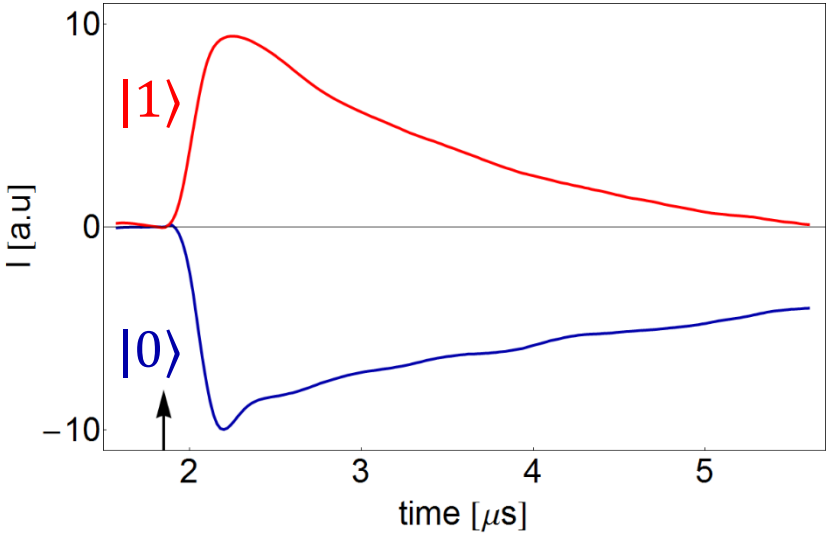
Conventional HEMT





Parametric Amplifier

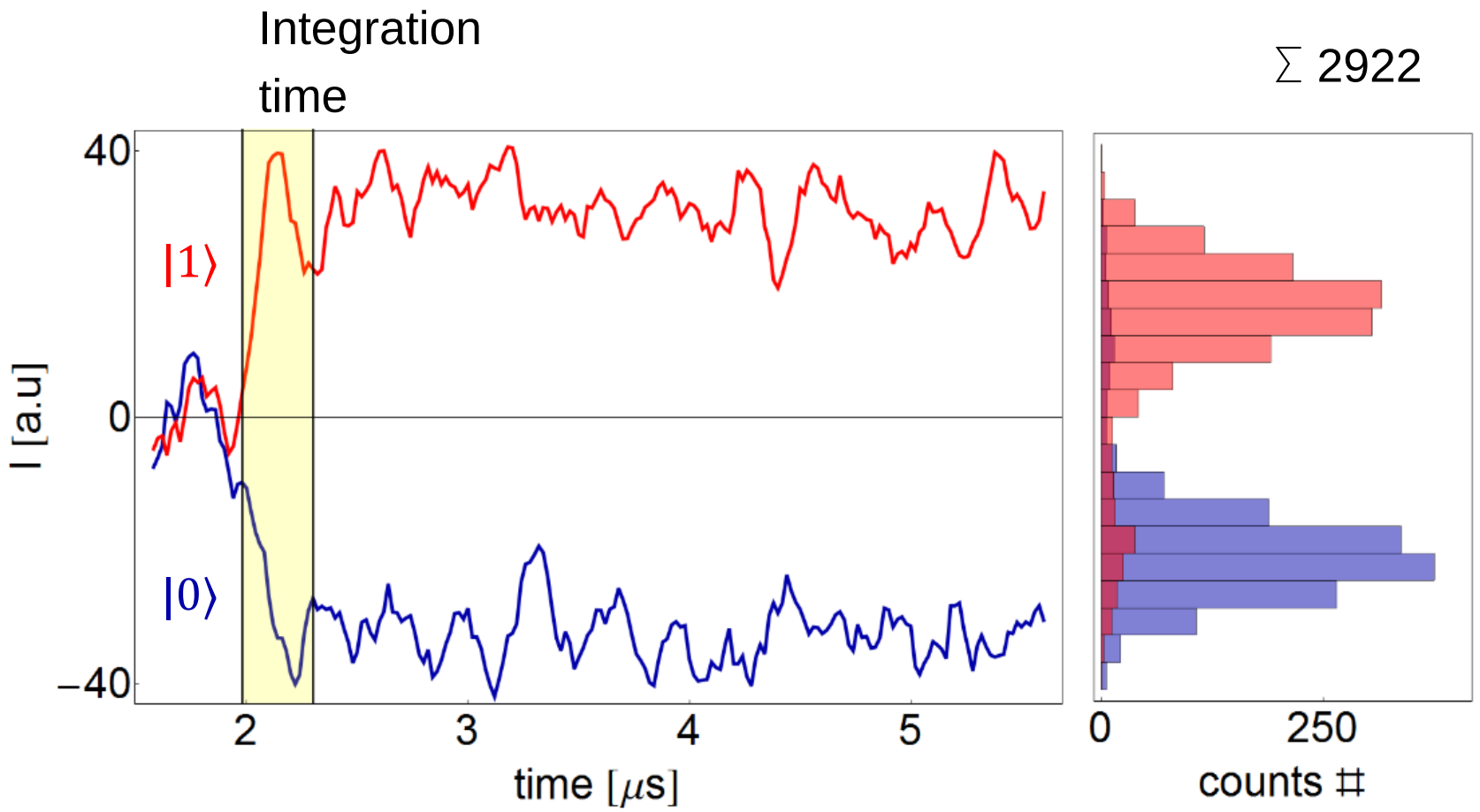




P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)

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

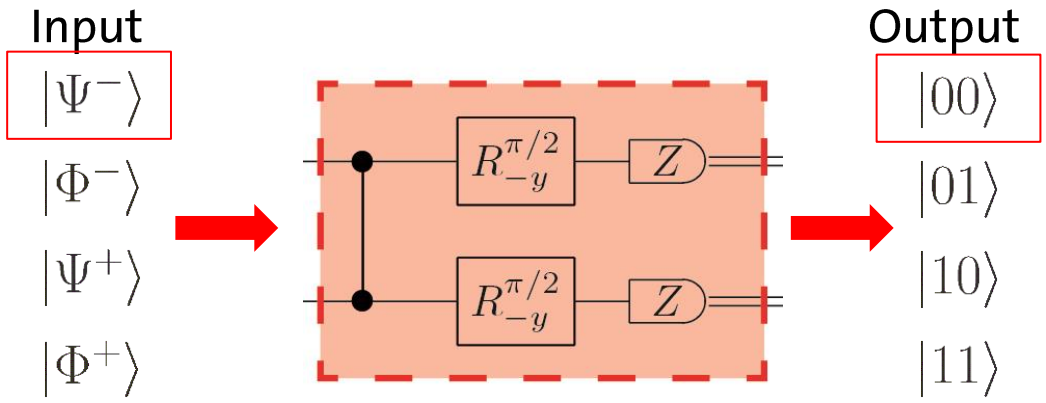
Statistics of Integrated Single-Shot Readout



P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)

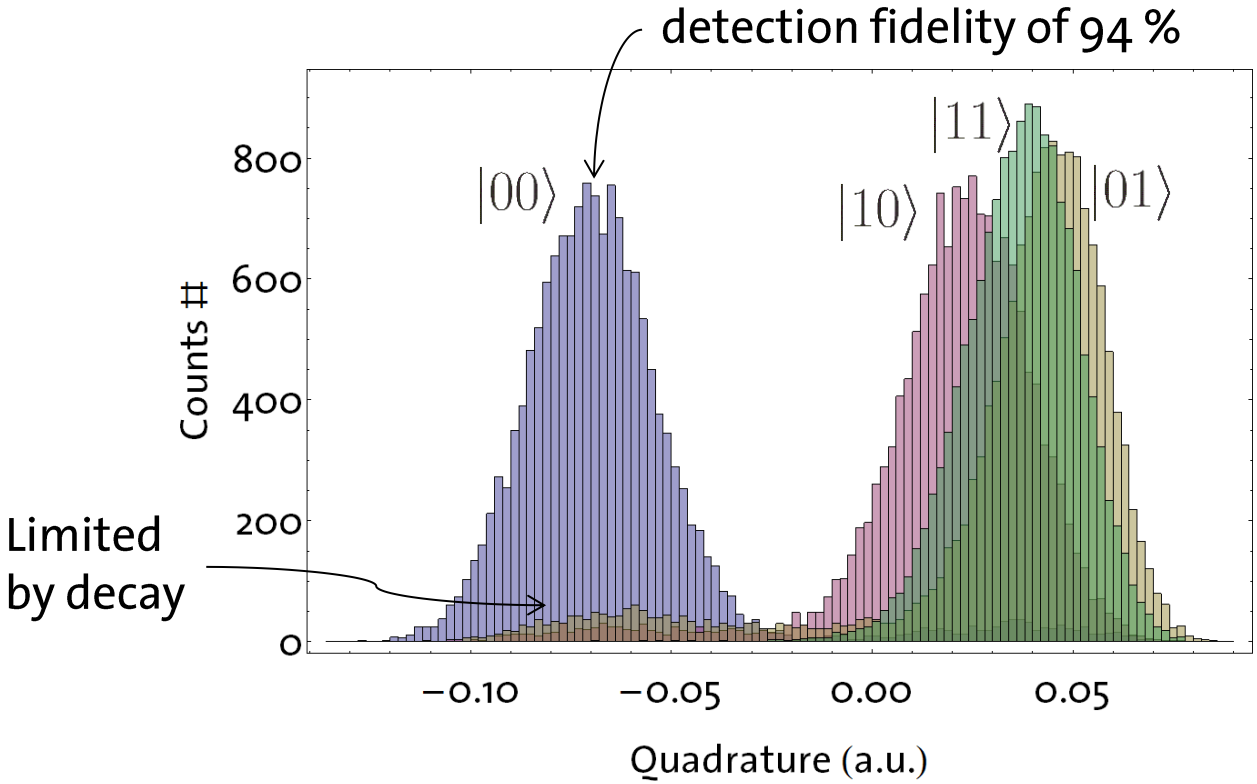

Quantum Teleportation with Superconducting Circuits
DELL
DELL

Post-Selected Teleportation: Bell Measurement



Operate parametric amplifier in phase sensitive mode

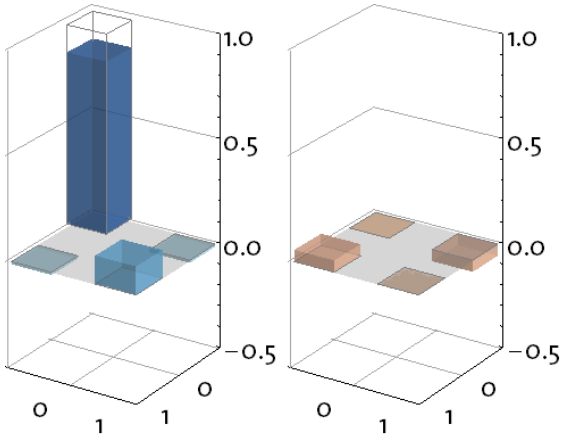
Maximize contrast of $|00\rangle$ to other states



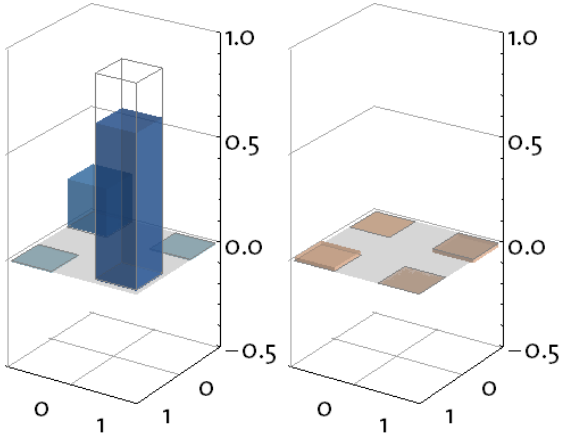
Steffen *et al.*, *Nature* 500, 319 (2013)

Tomography of Teleported States with Post-Selection

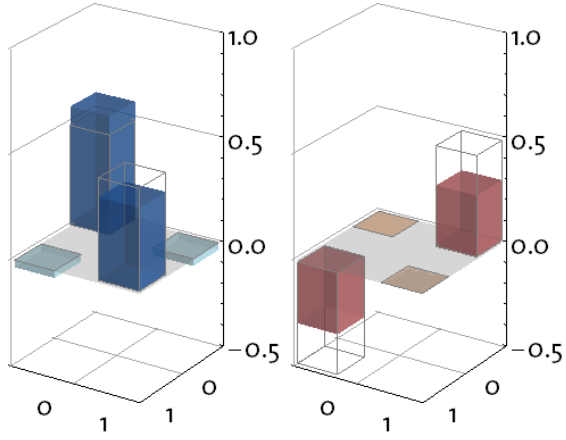
$\psi_{in} = |0\rangle$ 82.2 %



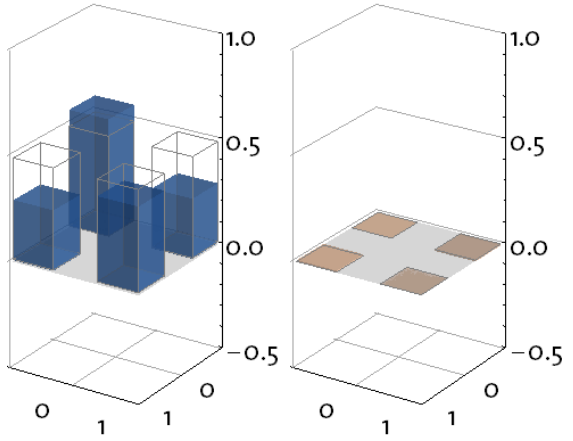
$\psi_{in} = |1\rangle$ 80.5 %



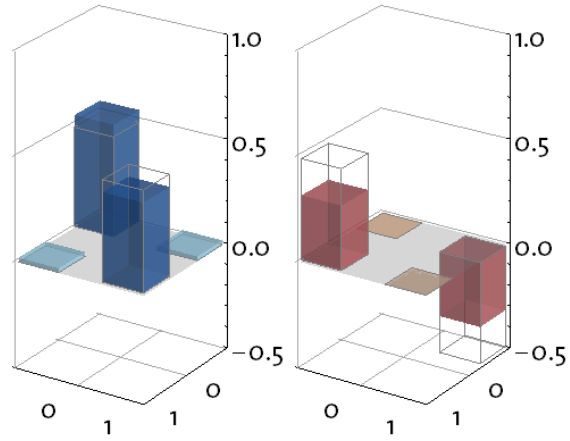
$\psi_{in} = |0\rangle - i\,|1\rangle$ 79.4 %



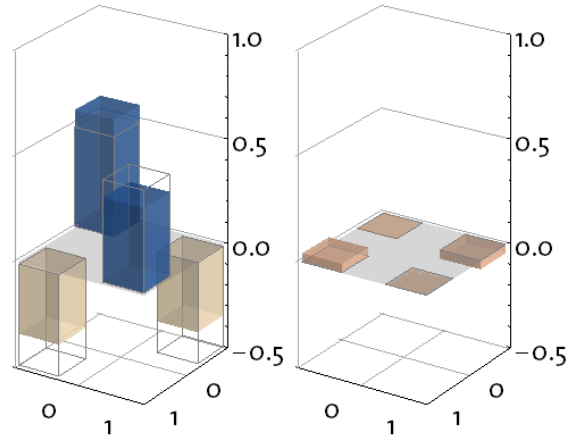
$\psi_{in} = |0\rangle + |1\rangle$ 84.2 %



$\psi_{in} = |0\rangle + i\,|1\rangle$ 79.5 %



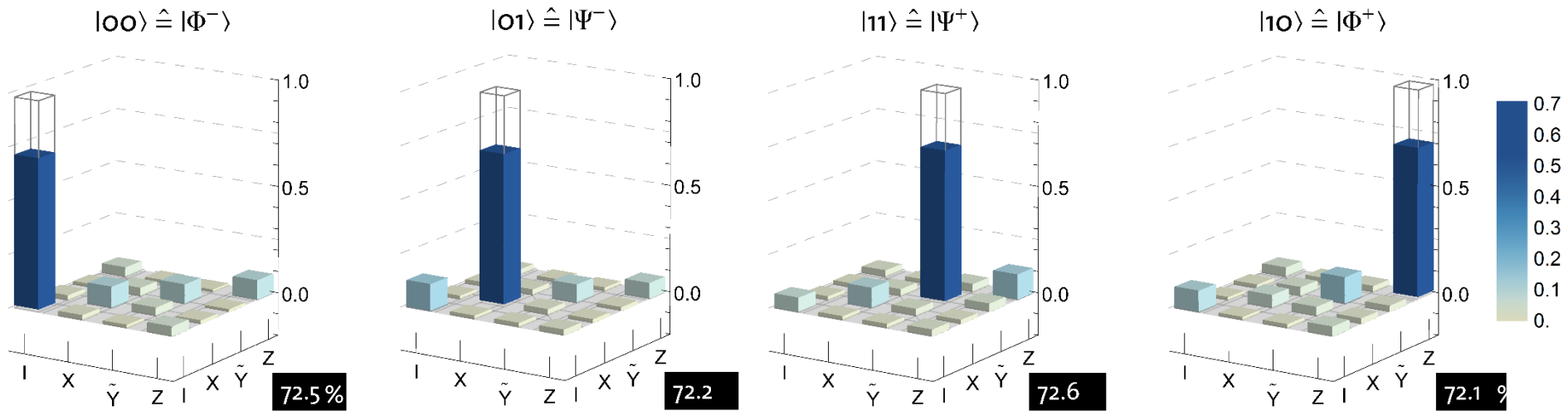
$\psi_{in} = |0\rangle - |1\rangle$ 83.6 %



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

Process Tomography: Teleportation with Post-Selection

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



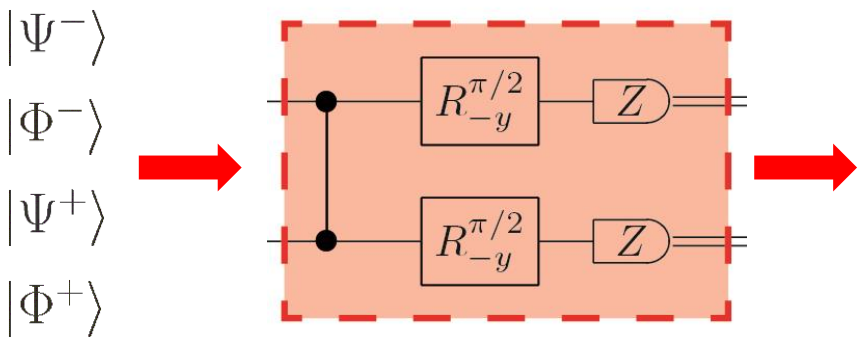
$$|\psi_{\text{out}}\rangle = |\psi_{\text{in}}\rangle \qquad |\psi_{\text{out}}\rangle = X\,|\psi_{\text{in}}\rangle \qquad |\psi_{\text{out}}\rangle = \tilde{Y}\,|\psi_{\text{in}}\rangle \qquad |\psi_{\text{out}}\rangle = Z\,|\psi_{\text{in}}\rangle$$

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

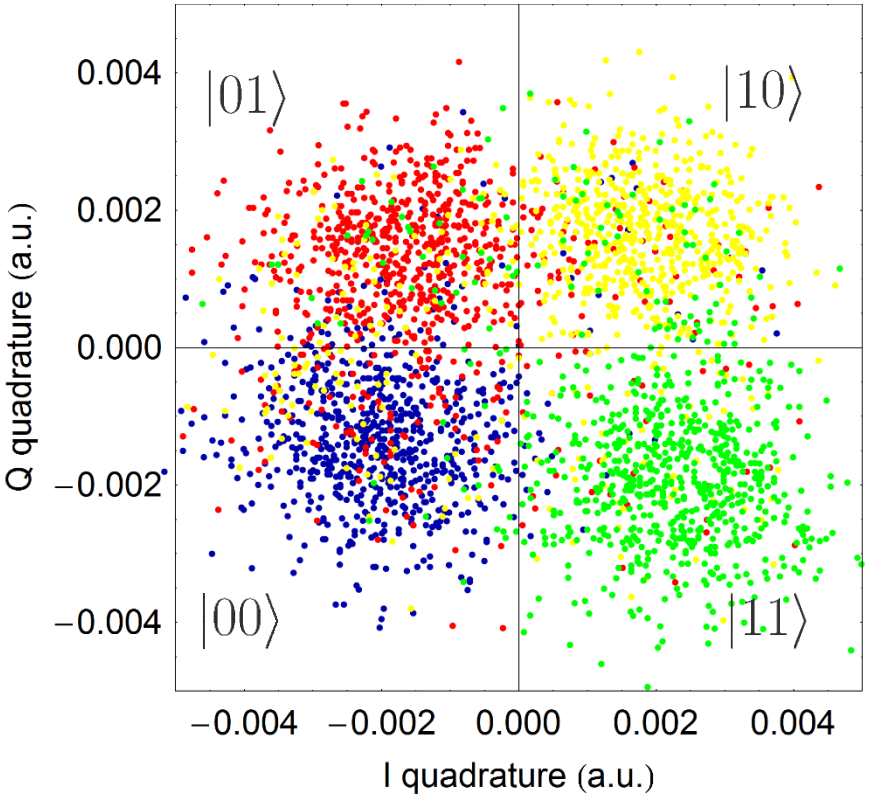
Average process fidelity **72.3 ± 0.7 %**

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

Deterministic Bell-Measurement of all 4 States



- map Bell states on basis states
- perform joint two-qubit read-out
- paramp operated in the phase preserving mode to amplify both quadratures



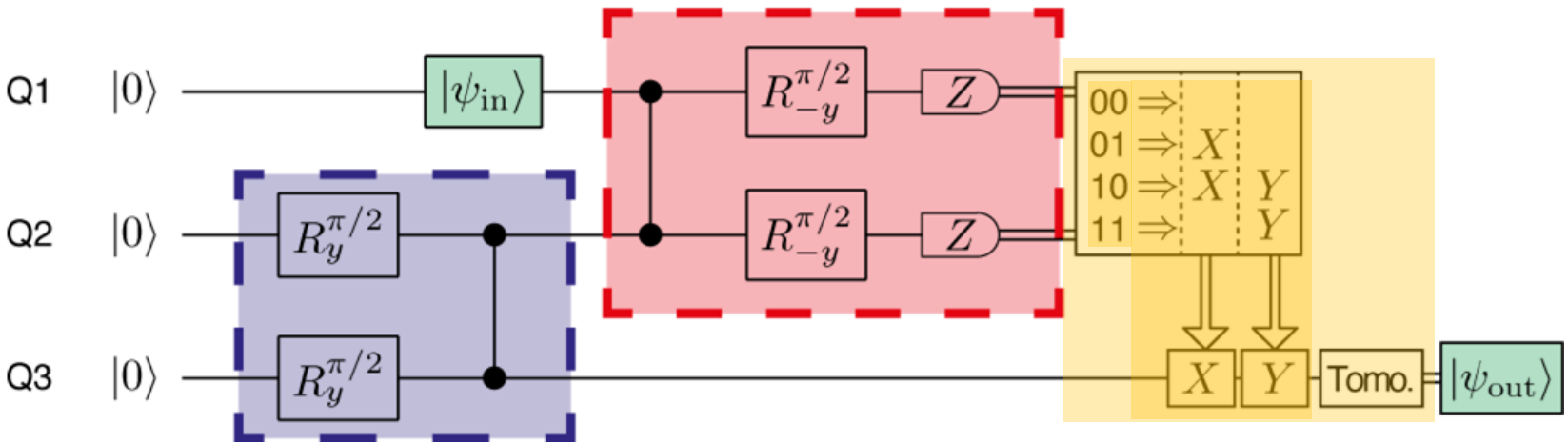
States are identified correctly with ~80% probability

identified as

Prepared as	$\|00\rangle$	$\|01\rangle$	$\|10\rangle$	$\|11\rangle$
$\|00\rangle$	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

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

Feed-Forward in the Teleportation Protocol

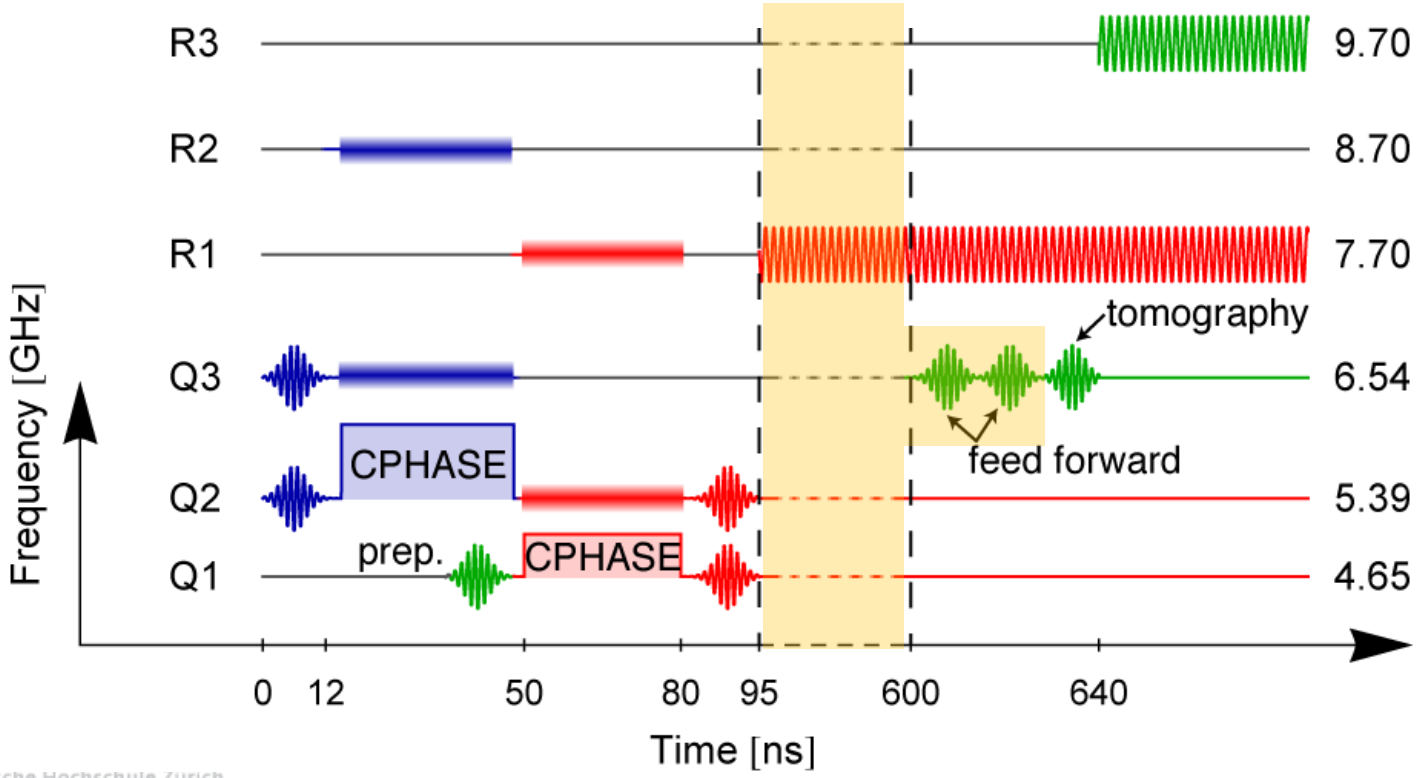


render protocol deterministic:

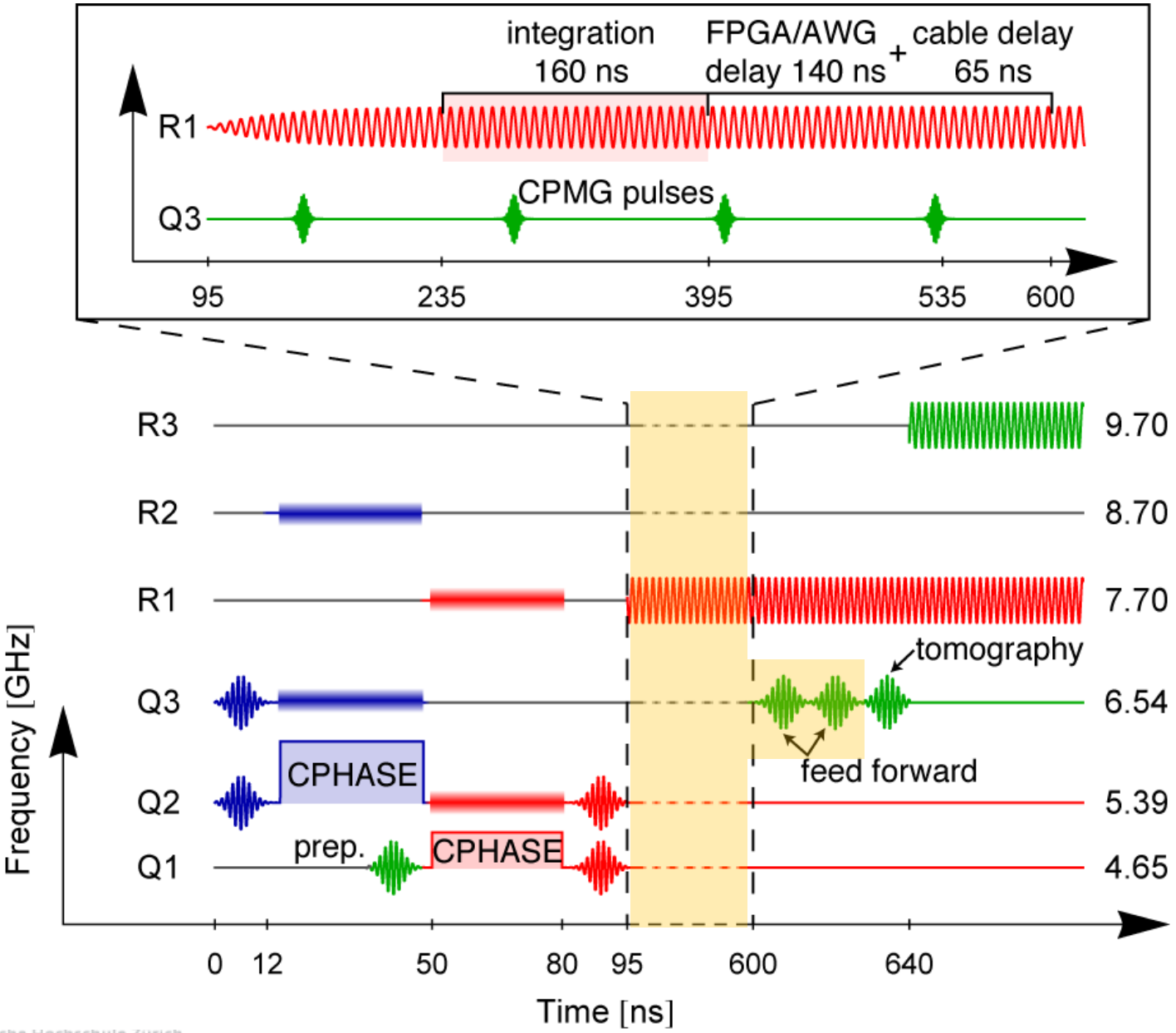
- Bell measurement (4 states)
- feed-forward
- completed in ~ 500 ns with FPGA based electronics

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

Pulse Scheme

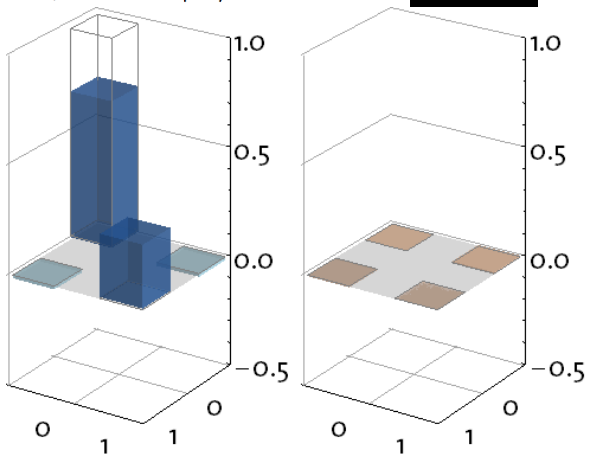


Pulse Scheme

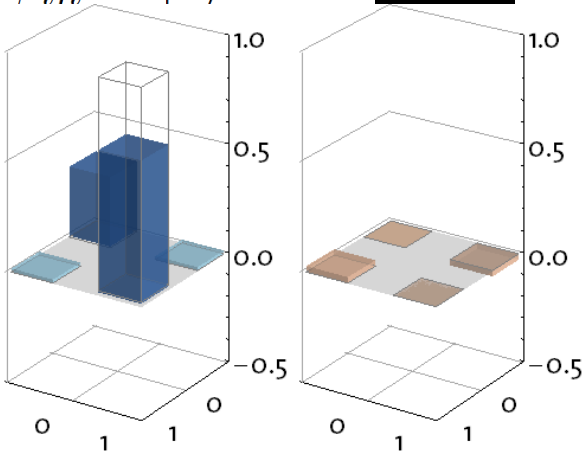


Tomography of Teleported States with Feed-Forward

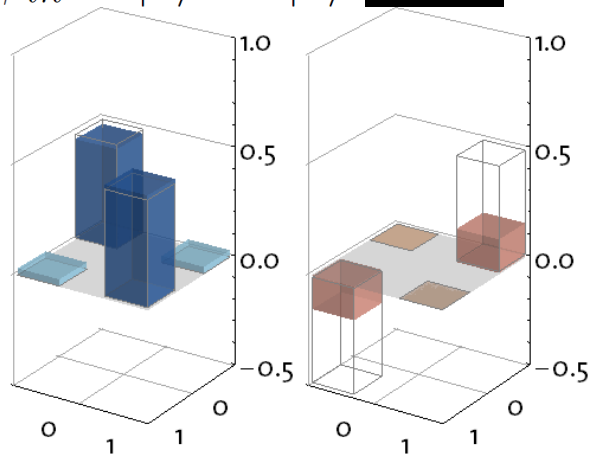
$\psi_{in} = |0\rangle$ 70.3 %



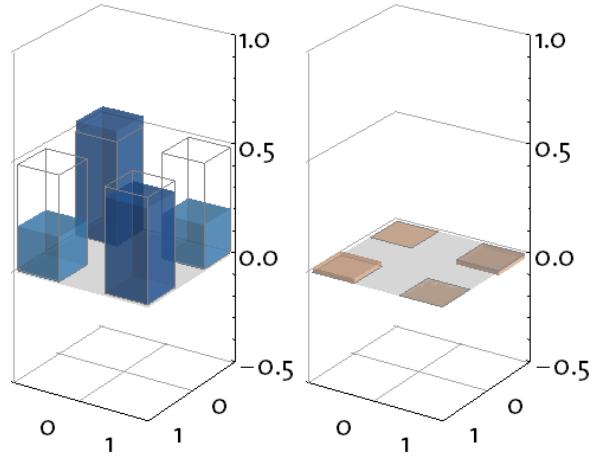
$\psi_{in} = |1\rangle$ 66.6 %



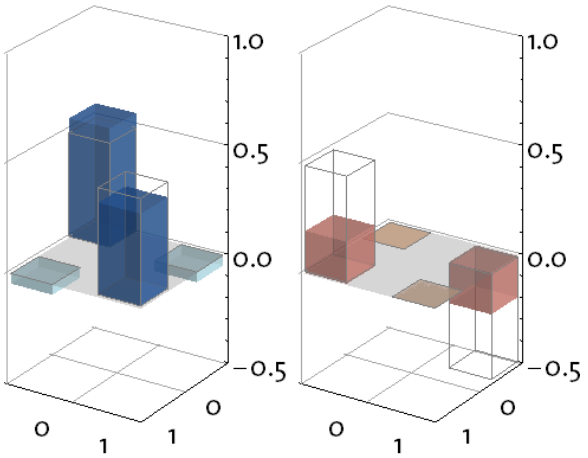
$\psi_{in} = |0\rangle - i\,|1\rangle$ 65.78%



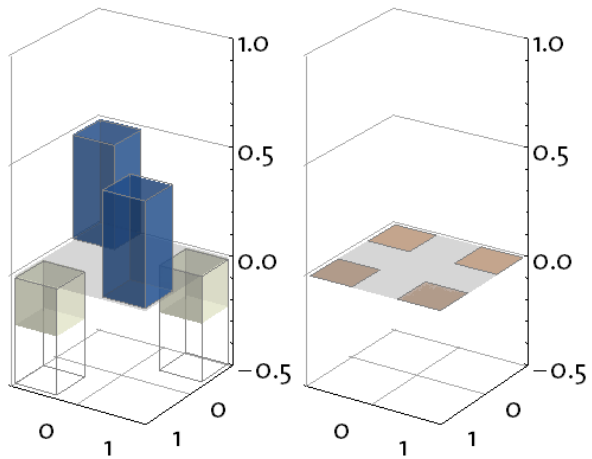
$\psi_{in} = |0\rangle + |1\rangle$ 71.3 %



$\psi_{in} = |0\rangle + i\,|1\rangle$ 69.7 %



$\psi_{in} = |0\rangle - |1\rangle$ 72.8 %



Average state fidelity of 69.5±0.1 %

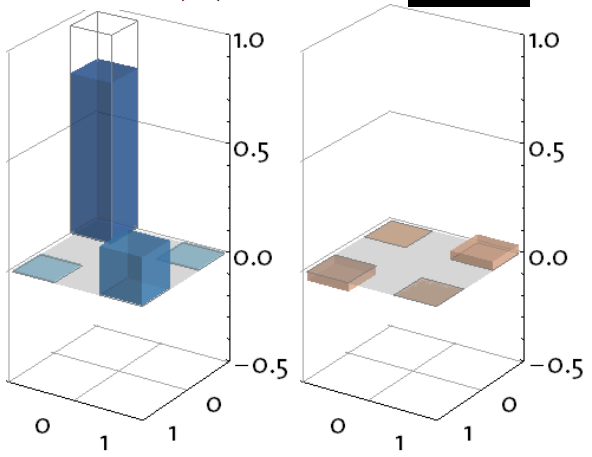
classical limit: 66.7 %

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

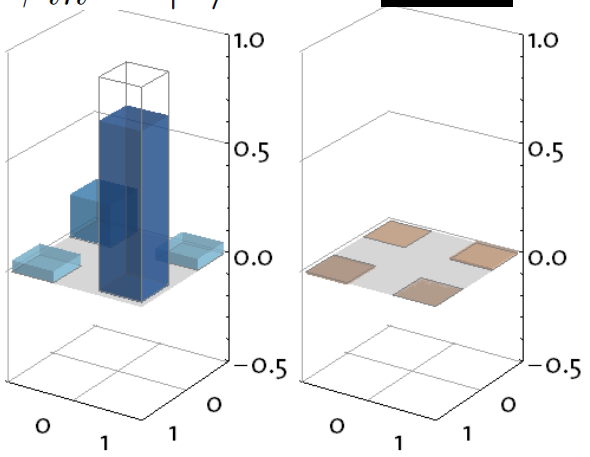
Tomography of Teleported States with Feed-Forward

averaged readout of qubit 3

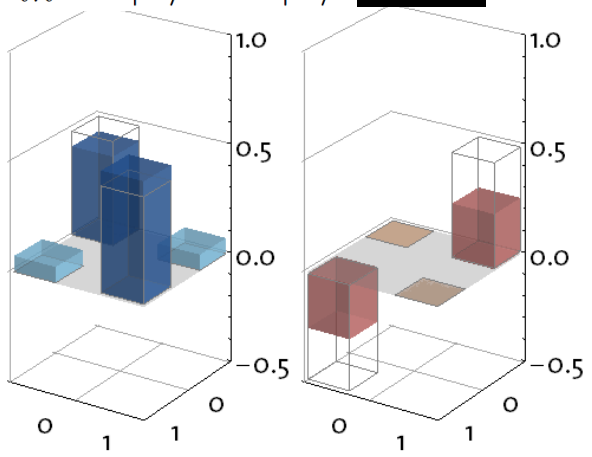
$\psi_{in} = |0\rangle$ 77.5 %



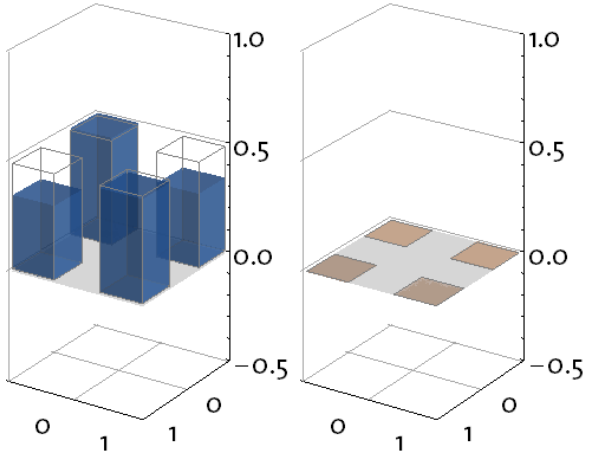
$\psi_{in} = |1\rangle$ 79.9 %



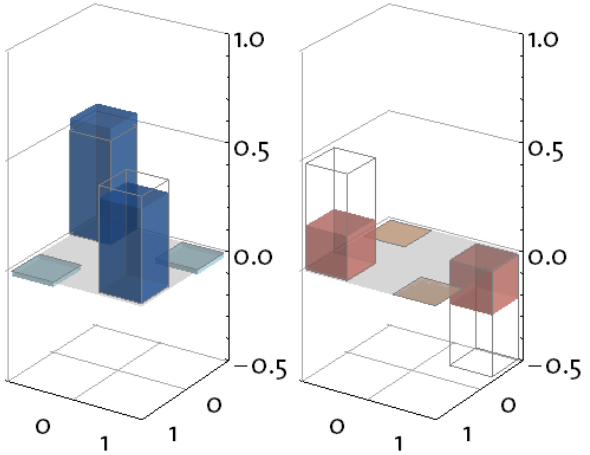
$\psi_{in} = |0\rangle - i\,|1\rangle$ 76.2 %



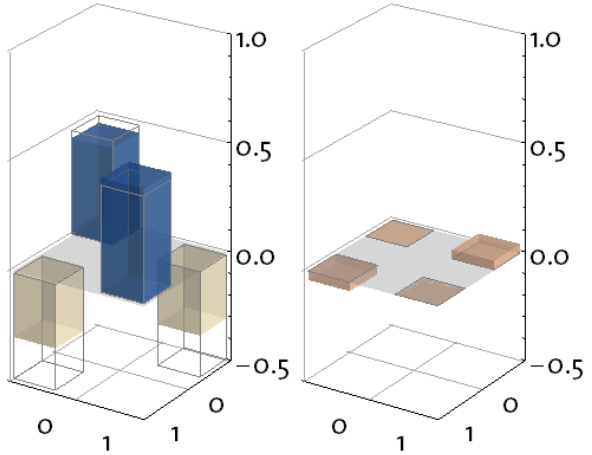
$\psi_{in} = |0\rangle + |1\rangle$ 85.3 %



$\psi_{in} = |0\rangle + i\,|1\rangle$ 71.2 %



$\psi_{in} = |0\rangle - |1\rangle$ 80.7 %

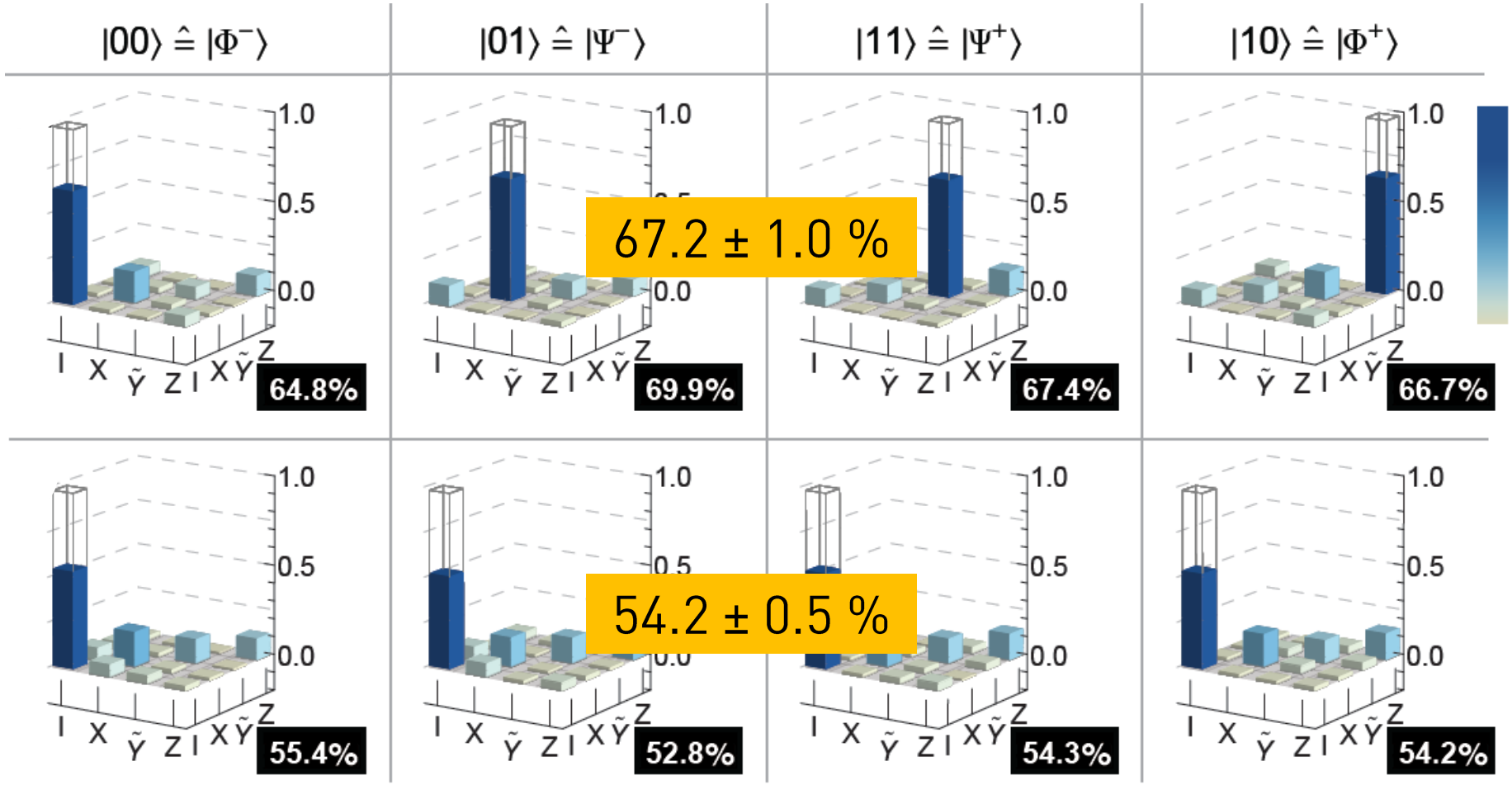


Average state fidelity of 78.5± 0.9%

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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

Process Tomography – w/o and with Feed-Forward



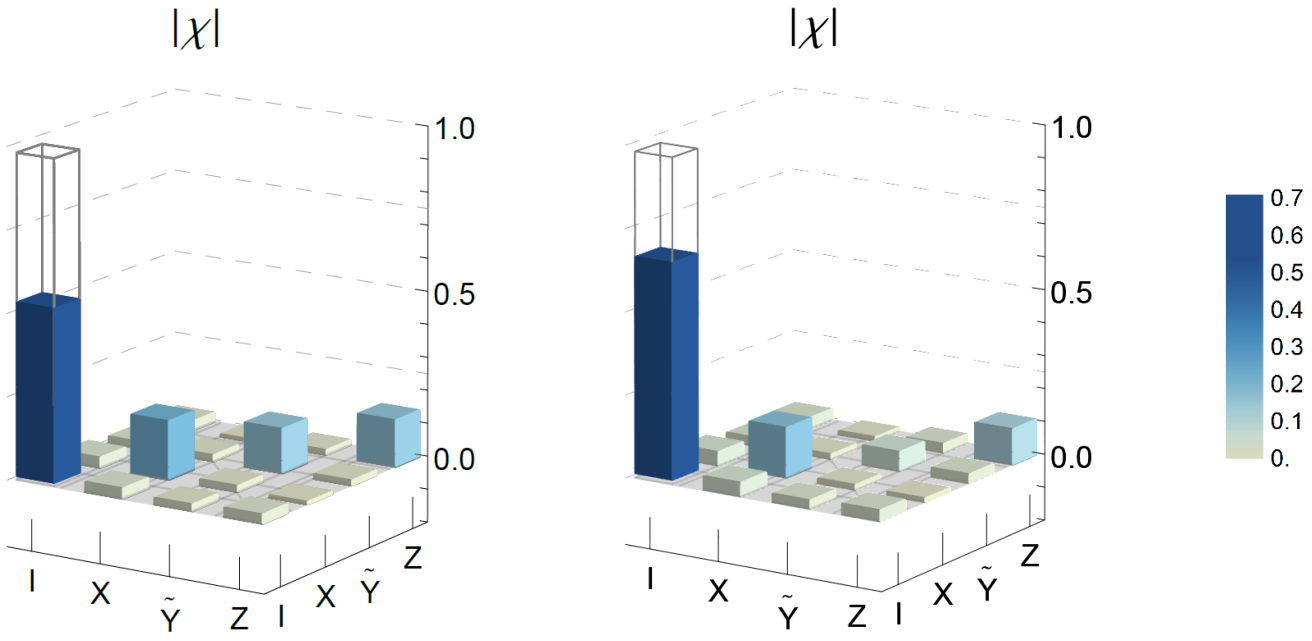
$|\psi_{\text{out}}\rangle = |\psi_{\text{in}}\rangle$ $|\psi_{\text{out}}\rangle = |\psi_{\text{in}}\rangle$ $|\psi_{\text{out}}\rangle = |\psi_{\text{in}}\rangle$ $|\psi_{\text{out}}\rangle = |\psi_{\text{in}}\rangle$

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

Classical limit: 50 %

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

Teleportation Process with Feed-Forward



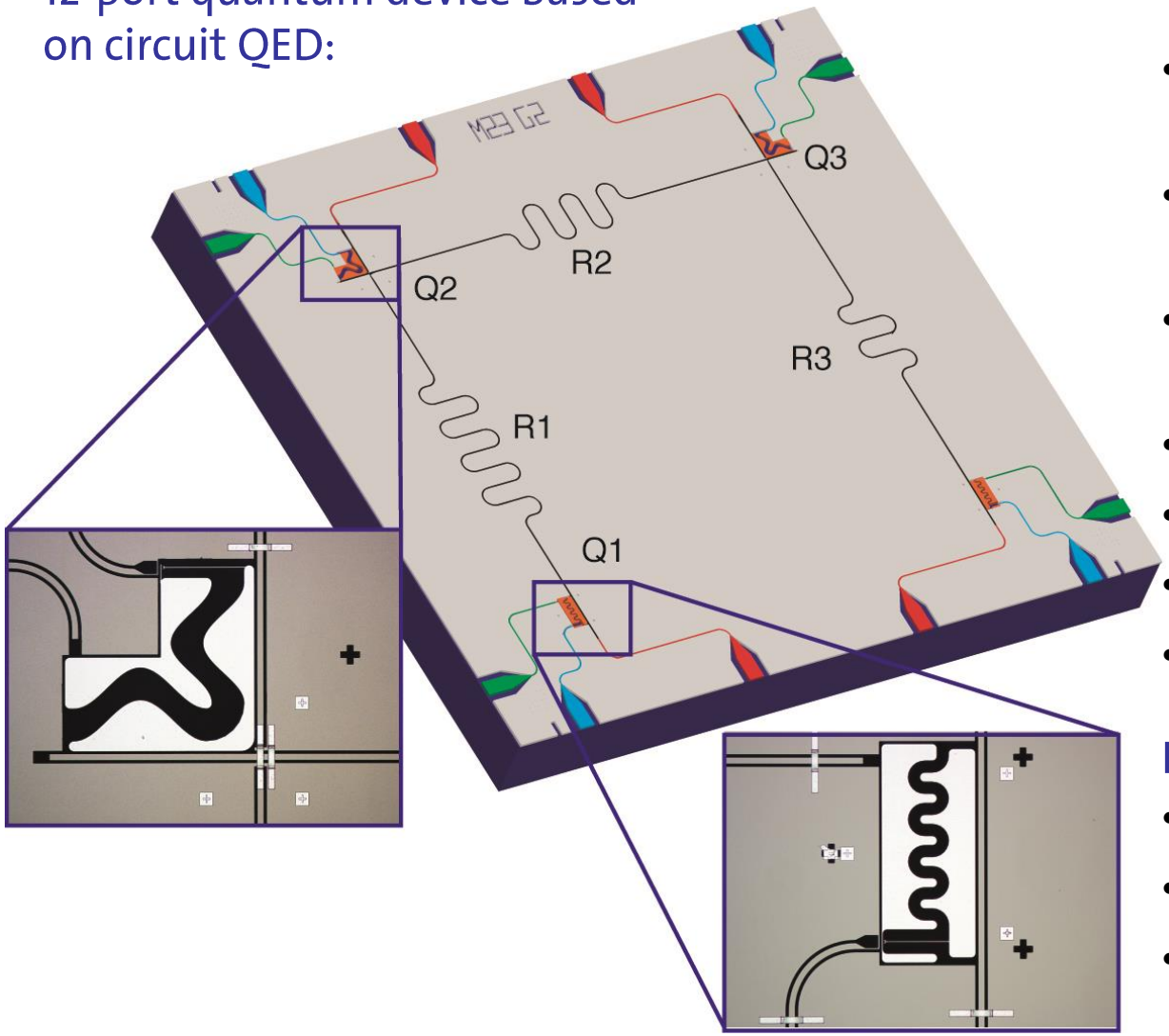
Average process fidelity with single shot readout: 54.2 ± 0.1 %

Average process fidelity with averaged readout: 67.7 ± 1.1 %

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

Teleportation

12-port quantum device based on circuit QED:



Experimental highlights:

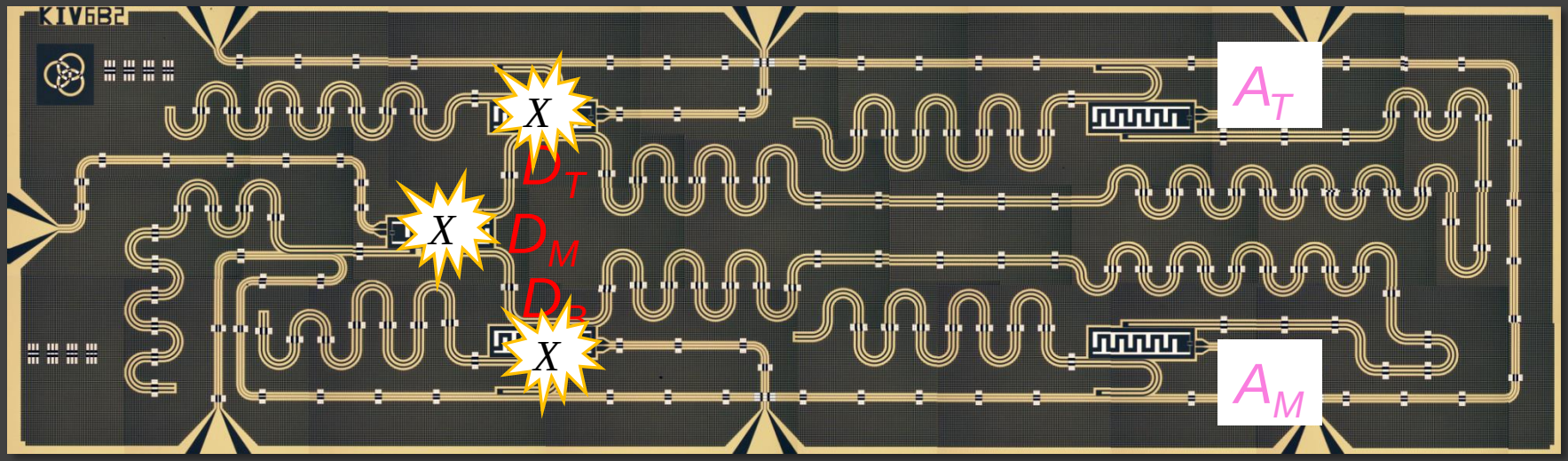
- teleportation in a (macroscopic) solid state system
- post-selection on either of 4 Bell states individually
- Simultaneous deterministic Bell measurement of all states
- implementation of feed-forward
- fidelities > classical threshold
- O(Unity) success probability
- teleportation rate > 10 kHz
- distance ~ 6 mm

Next steps:

- use teleportation in alg.
- improve fidelities
- increase distances for quantum communication

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

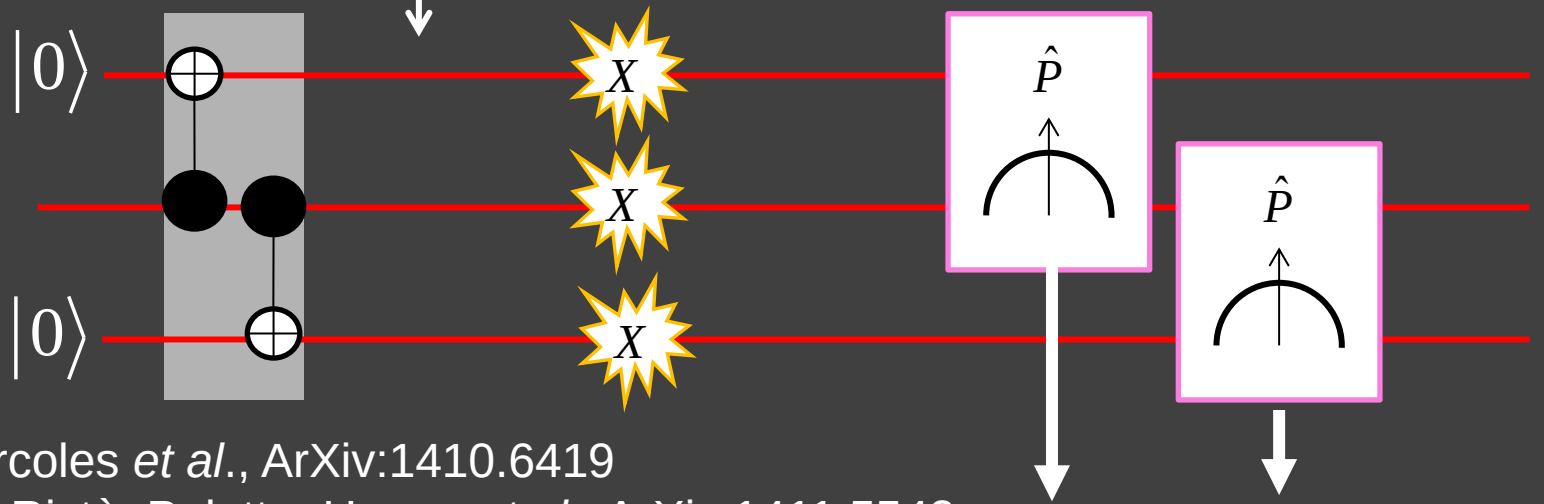
Recent Developments in Quantum Error Correction



$\alpha|000\rangle + \beta|111\rangle$

encode

Discretize, signal errors using quantum parity checks



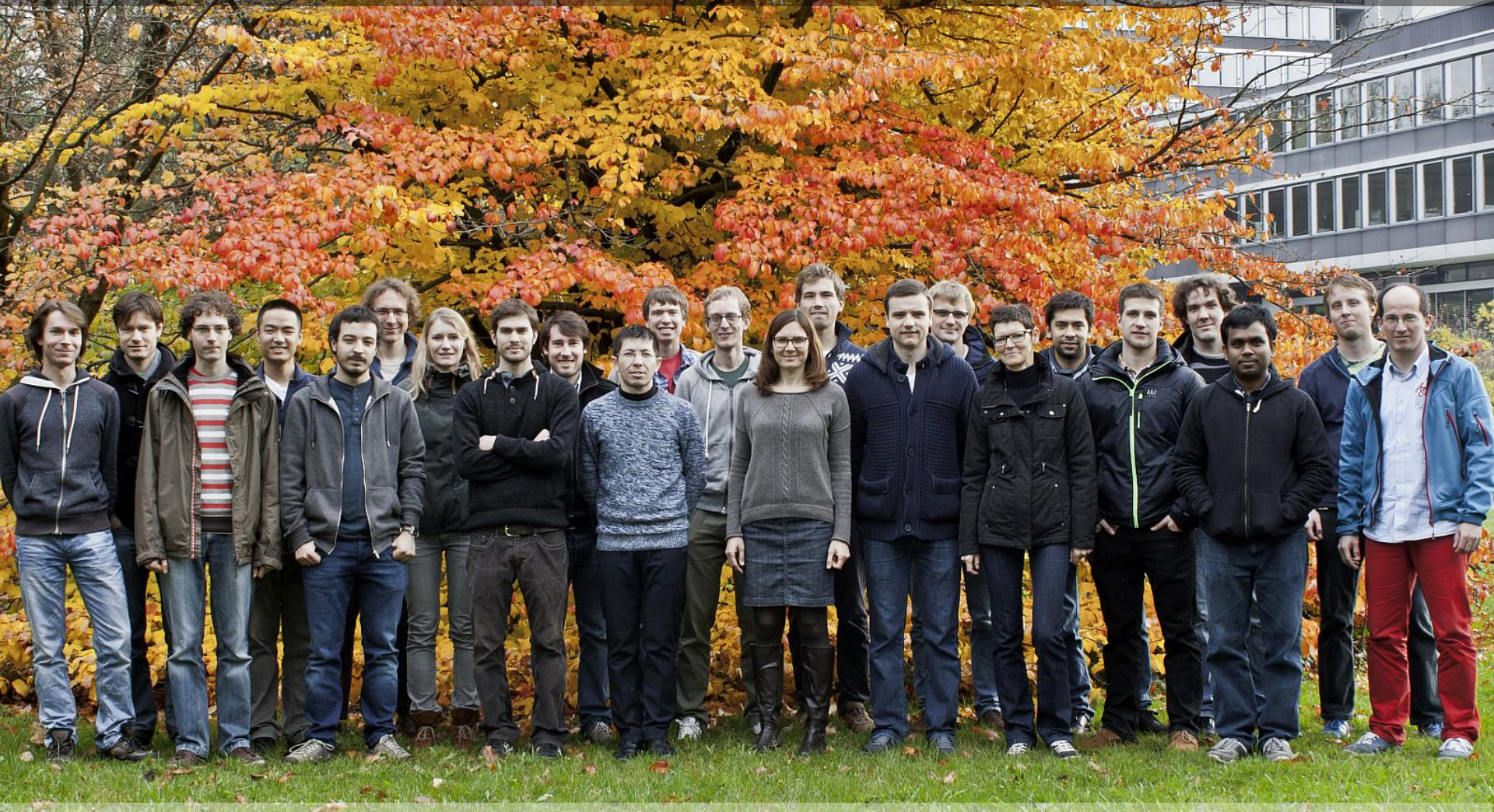
IBM: Corcoles *et al*., ArXiv:1410.6419

QuTech: Ristè, Poletto, Huang *et al*., ArXiv:1411.5542

UCSB/Google: Kelly *et al.*, ArXiv:1411.7403

The ETH Zurich Quantum Device Lab

incl. undergrad and summer students



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

QSIT Quantum Science and Technology
National Centre of Competence in Research

CIRCUIT AND CAVITY QUANTUM ELECTRODYNAMICS

FNSNF
Swiss National Science Foundation

scaleQIT

erc

Want to work with us?
Postdoc and PhD positions are available!

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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)

Device Fabrication:

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

Geometric Phases:

- Leek et al., *Science* **318**, 1889 (2007)
- Pechal et al., *PRL* **108**, 170401 (2012)
- Abdumalikov et al., *Nature* **496**, 482 (2013)

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

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

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, Qubit-Photon Entanglement, Hong-Ou-Mandel Effect:

- 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., *PRL* **109**, 240501 (2012)
- Lang et al., *Nat. Phys.* **9**, 345 (2013)

Interaction in 1D free space

- van Loo et al., *Science* **342**, 1494 (2013)

Hybrid Systems: Quantum Dots

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

Hybrid Systems: Rydberg Atoms

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

Additional Information: www.qudev.ethz.ch