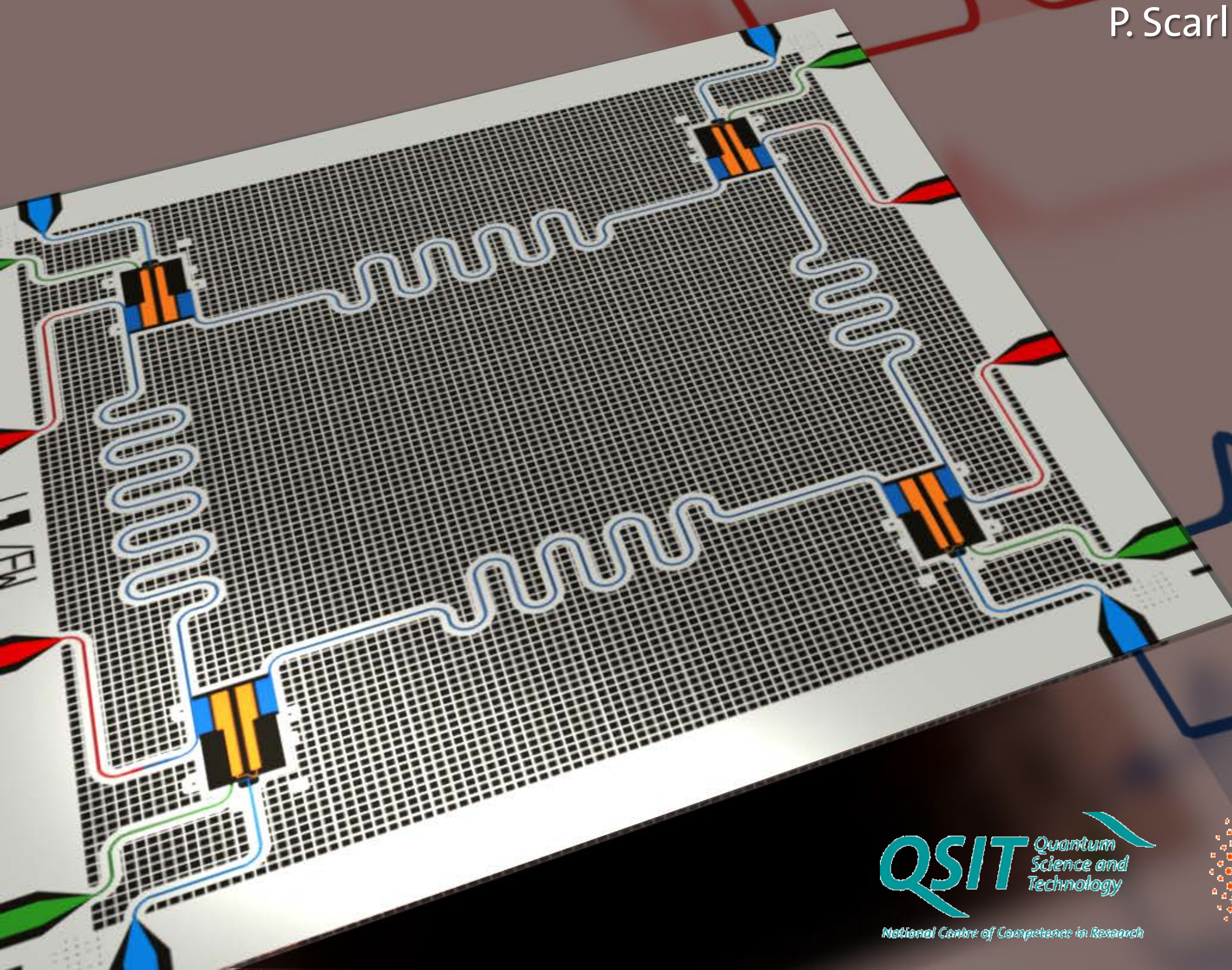
Exploring Quantum Physics with Superconducting Circuits

Andreas Wallraff *(ETH Zurich)*
www.qudev.ethz.ch

Team: J.-C. Besse, M. Collodo, S. Garcia, S. Gasparinetti, J. Heinsoo, S. Krinner, P. Kurpiers, P. Magnard M. Oppliger, M. Pechal, A. Potocnik, Y. Salathe, P. Scarlino, M. Stammeier, A. Stockklauser, T. Thiele, T. Walter *(ETH Zurich)*



FNSNF Swiss National Science Foundation
QSIT Quantum Science and Technology
National Centre of Competence in Research
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Swiss Federal Institute of Technology Zurich

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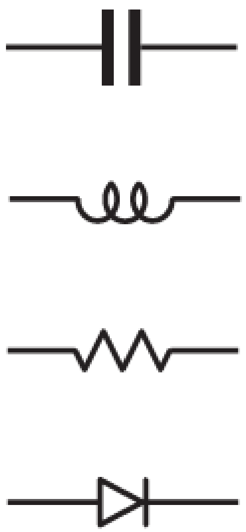
scaleQIT

Conventional Electronic Circuits

basic circuit elements:

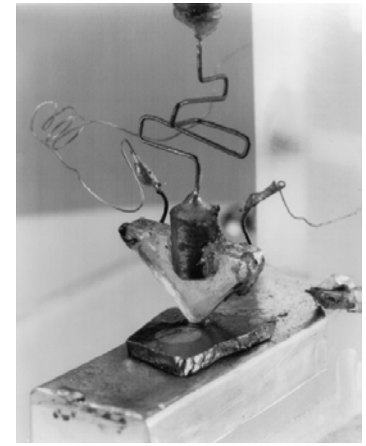


basis of modern information and communication technology

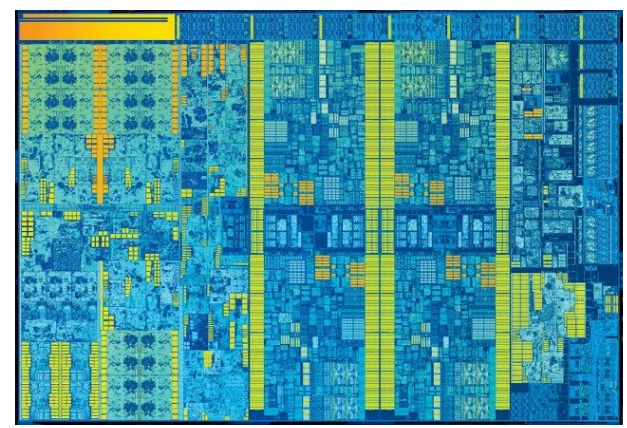
properties :

- classical physics
- no quantum mechanics
- no superposition or entanglement
- no quantization of fields

first transistor at Bell Labs (1947)



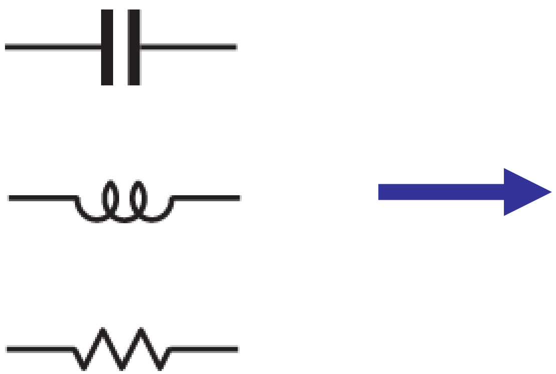
Intel Core i7-6700K Processor



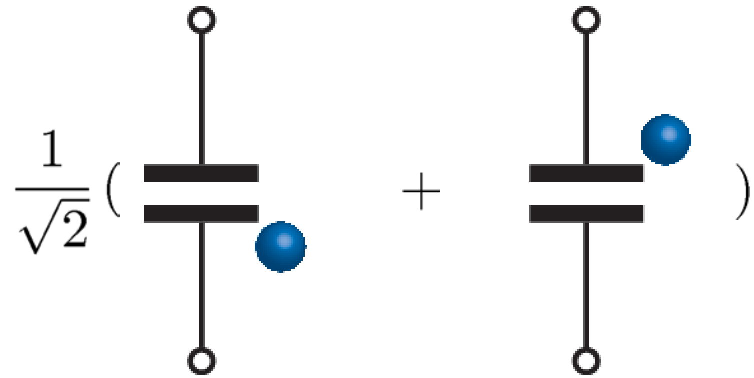
smallest feature size 14 nm
clock speed ~ 4.2 GHz
> $3 \cdot 10^9$ transistors
power consumption > 10 W

Classical and Quantum Electronic Circuit Elements

basic circuit elements:



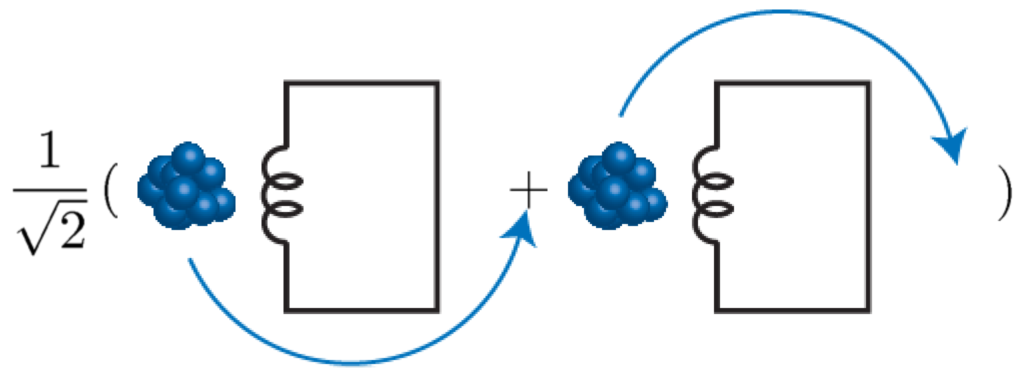
charge on a capacitor:



quantum superposition states of:

- charge q
- flux ϕ

current or magnetic flux in an inductor:

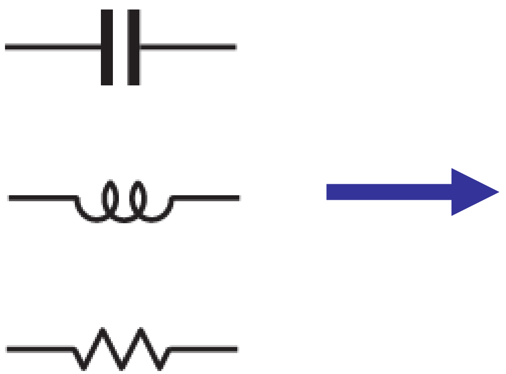


commutation relation (c.f. *x*, *p*):

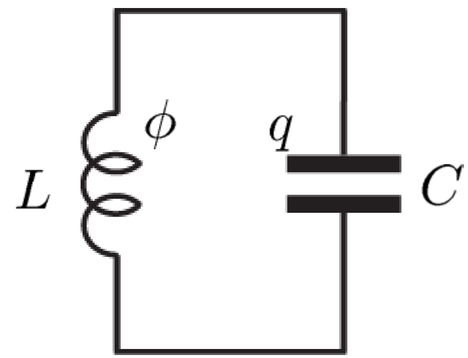
$$\left[\hat{\phi}, \hat{q}\right] = i\hbar$$

Constructing Linear Quantum Electronic Circuits

basic circuit elements:



harmonic LC oscillator:



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

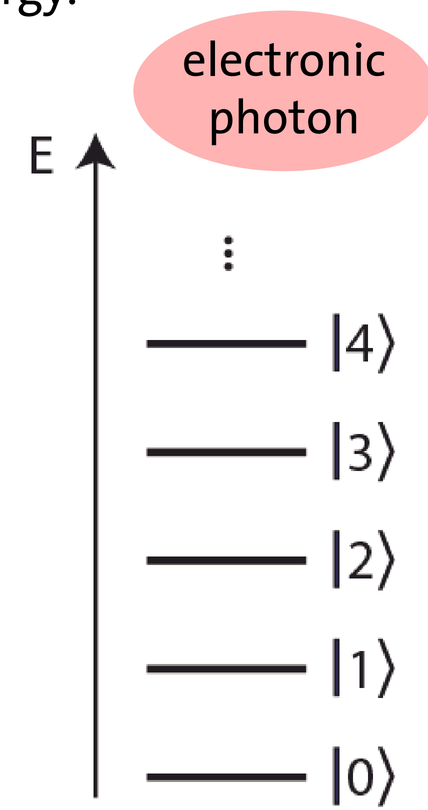
classical physics:

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

quantum mechanics:

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

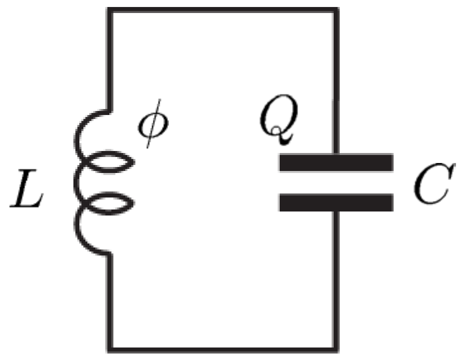
energy:



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

Quantization of an Electronic Harmonic Oscillator

Harmonic LC oscillator:



$$\begin{aligned} Q &= CV \\ \phi &= LI \\ V &= -L\dot{I} = -\dot{\phi} \end{aligned}$$

Charge on capacitor

Flux in inductor

Voltage across inductor

Classical Hamiltonian:

$$H = \frac{CV^2}{2} + \frac{LI^2}{2} = \frac{Q^2}{2C} + \frac{\phi^2}{2L}$$

Conjugate variables:

$$\begin{aligned} \frac{\partial H}{\partial \phi} &= \frac{\phi}{L} = I = \dot{Q} \\ \frac{\partial H}{\partial Q} &= \frac{Q}{C} = V = -L\dot{I} = -\dot{\phi} \end{aligned}$$

Hamilton operator:

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

Flux and charge operator:

$$\begin{aligned} \hat{\phi} &= \phi \\ \hat{Q} &= -i\hbar \frac{\partial}{\partial \phi} \end{aligned}$$

Commutation relation:

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

Creation and Annihilation Operators for Circuits

Hamilton operator of harmonic oscillator in second quantization:

$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{\hat{Q}^2}{2C} = \hbar\omega(\hat{a}^\dagger\hat{a} + 1/2)$$

$\hat{a}^\dagger \lvert n\rangle = \sqrt{n+1}\,\lvert n+1\rangle$	Creation operator
$\hat{a} \lvert n\rangle = \sqrt{n}\,\lvert n-1\rangle$	Annihilation operator
$\hat{a}^\dagger\hat{a} \lvert n\rangle = n\,\lvert n\rangle$	Number operator

$$\hat{Q} = \sqrt{\frac{\hbar}{2Z_C}}(\hat{a}^\dagger + \hat{a})$$

Charge/voltage operator $\hat{V} = \frac{\hat{Q}}{C}$

$$\hat{\phi} = i\sqrt{\frac{\hbar Z_C}{2}}(\hat{a}^\dagger - \hat{a})$$

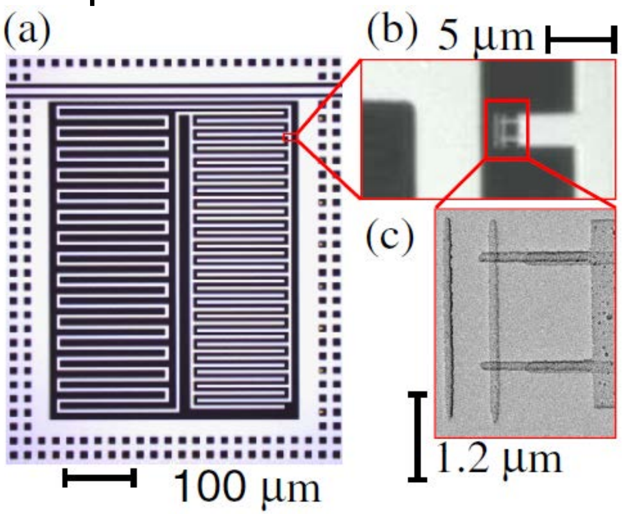
Flux/current operator $\hat{I} = \frac{\hat{\phi}}{L}$

With characteristic impedance:

$$Z_C = \sqrt{\frac{L}{C}}$$

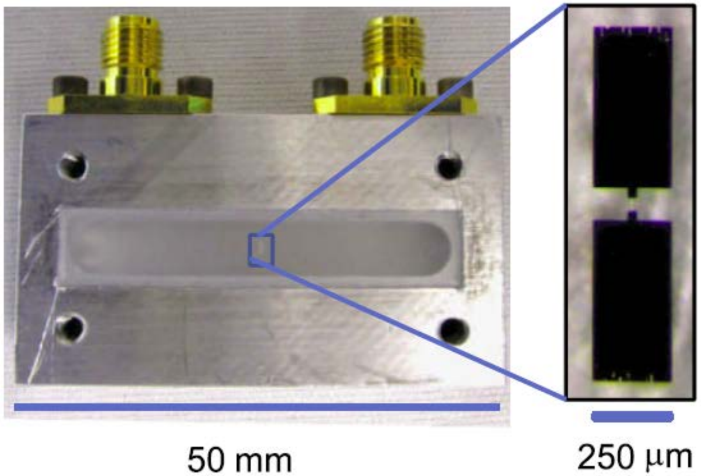
Flavors of Superconducting Harmonic Oscillators

lumped element resonator:



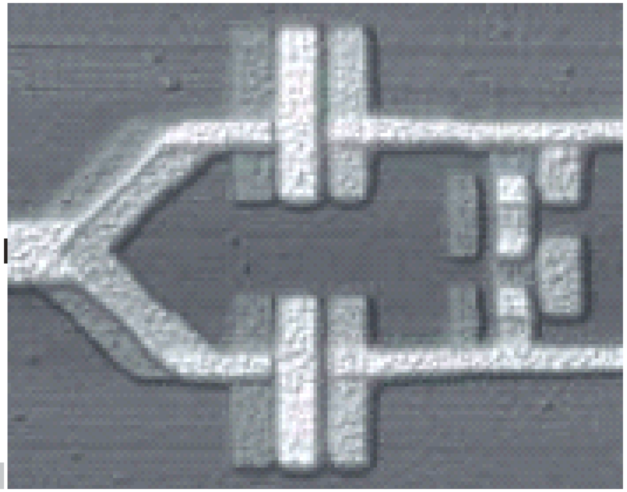
Z. Kim *et al.*, *PRL* 106, 120501 (2011)

3D cavity:



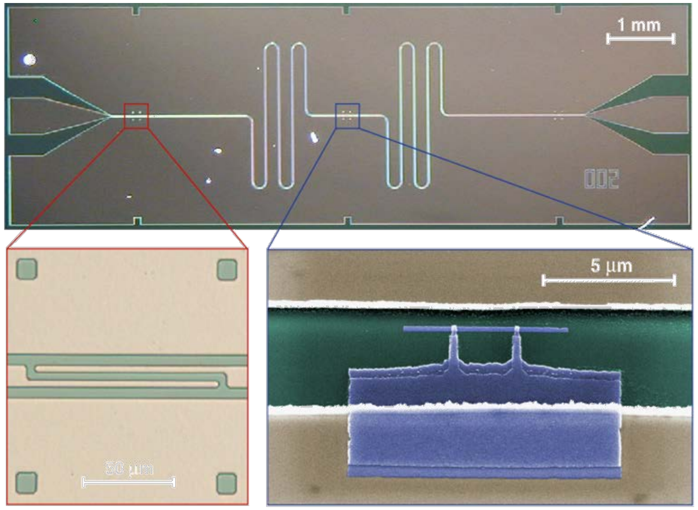
H. Paik *et al.*, *PRL* 107, 240501 (2011)

weakly nonlinear junction:



I. Chiorescu *et al.*, *Nature* 431, 159 (2004)

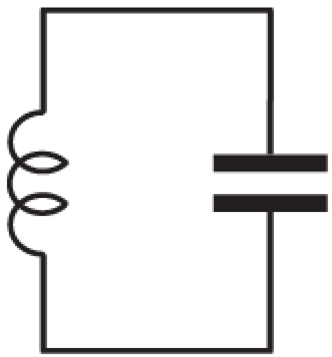
planar transmission line resonator:



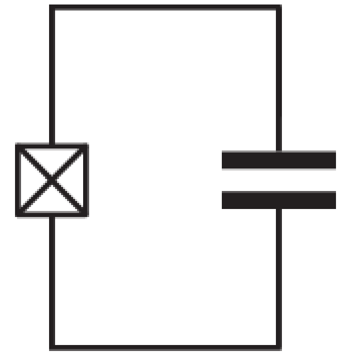
A. Wallraff *et al.*, *Nature* 431, 162 (2004)

Linear vs. Nonlinear Superconducting Oscillators

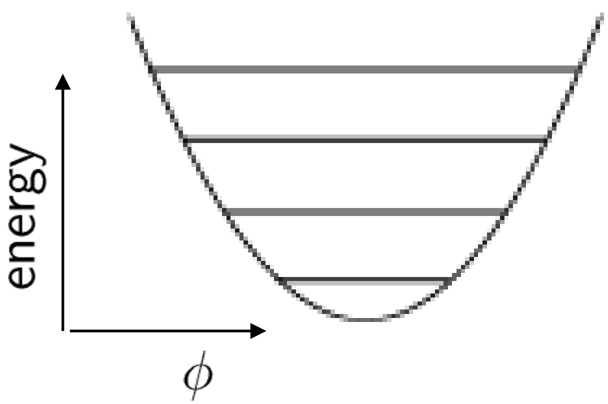
LC resonator:

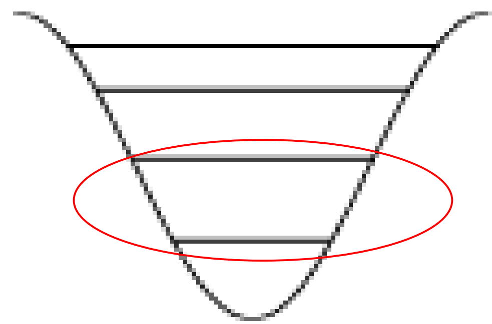


Josephson junction resonator:
Josephson junction = nonlinear inductor



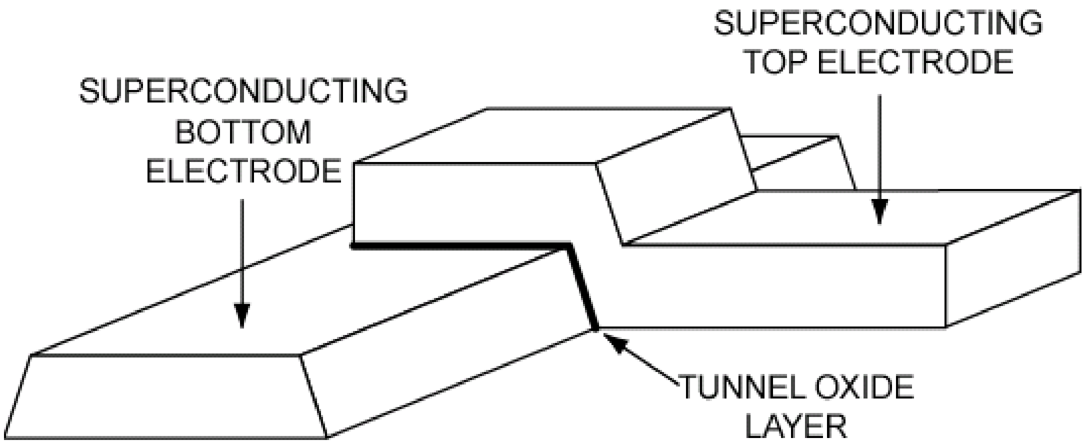
anharmonicity defines effective two-level system





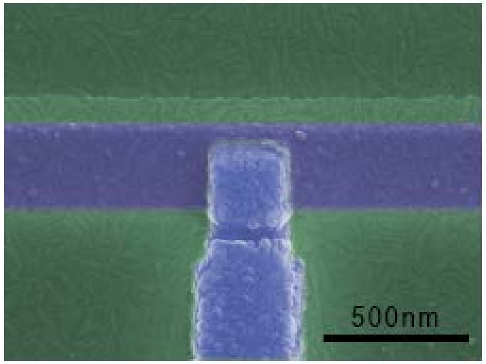
A Low-Loss Nonlinear Element

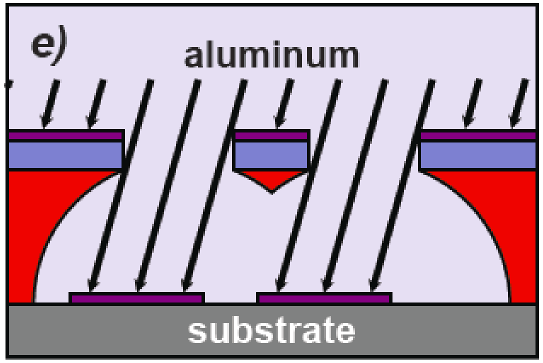
a (superconducting) Josephson junction:

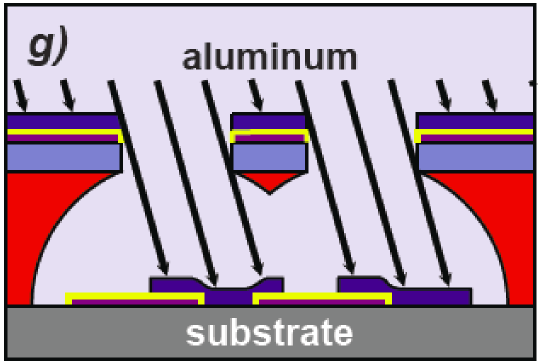


- superconductors: Nb, Al
- tunnel barrier: AlO_x

Josephson junction fabricated by shadow evaporation:



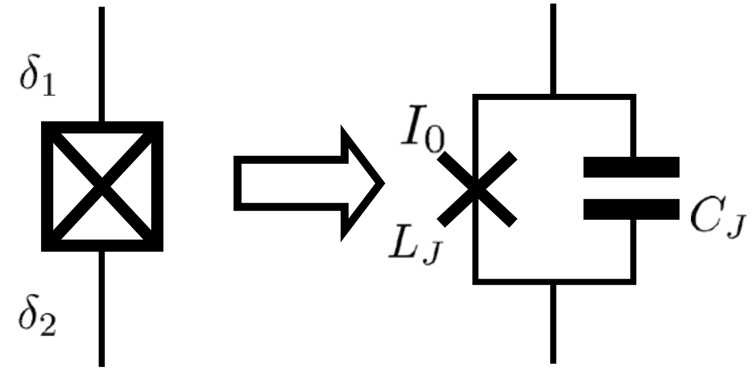




M. Tinkham, *Introduction to Superconductivity* (Krieger, Malabar, 1985).

The Josephson Junction as an ideal Non-Linear Inductor

a nonlinear inductor without dissipation



Josephson relations:

$$I = I_0 \sin\delta = I_0 \sin\left[2\pi\phi(t)/\phi_0\right]$$

$$V = \frac{\phi_0}{2\pi}\dot{\delta} = \dot{\phi}$$

nonlinear current/phase relation

gauge inv. phase difference:

$$\delta = \delta_2 - \delta_1 = 2\pi\phi(t)/\phi_0$$

specific Josephson inductance L_{J0}

Josephson inductance:

$$V = -L_J \dot{I} = \frac{\phi_0}{2\pi I_0}\frac{1}{\cos\delta}\dot{I}$$

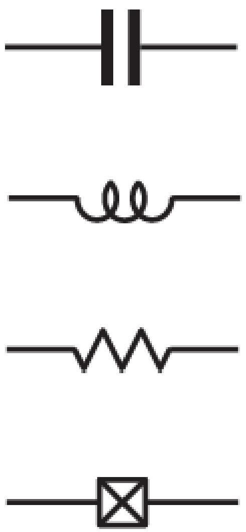
specific Josephson energy E_{J0}

Josephson energy:

$$E_J = \int V I dt = \frac{I_0 \phi_0}{2\pi}\cos\delta$$

Constructing Non-Linear Quantum Electronic Circuits

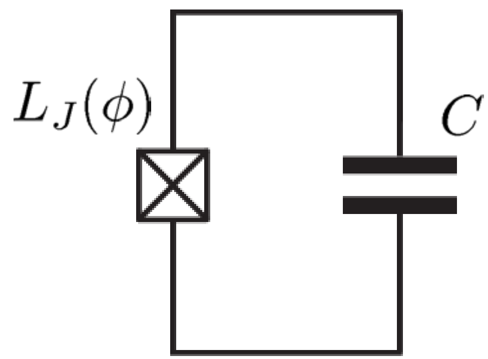
circuit elements:



Josephson junction:

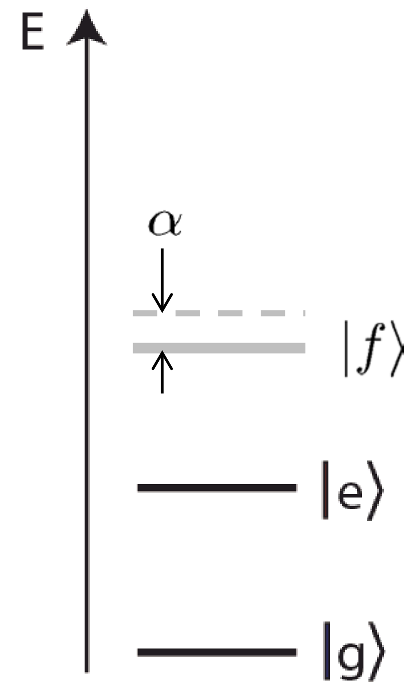
a non-dissipative nonlinear element (inductor)

anharmonic oscillator:



$$H \approx \hbar(\omega_{ge}\,\hat{b}^\dagger\hat{b} - \frac{\alpha}{2}\,\hat{b}^{\dagger 2}\hat{b}^2)$$

non-linear energy level spectrum:

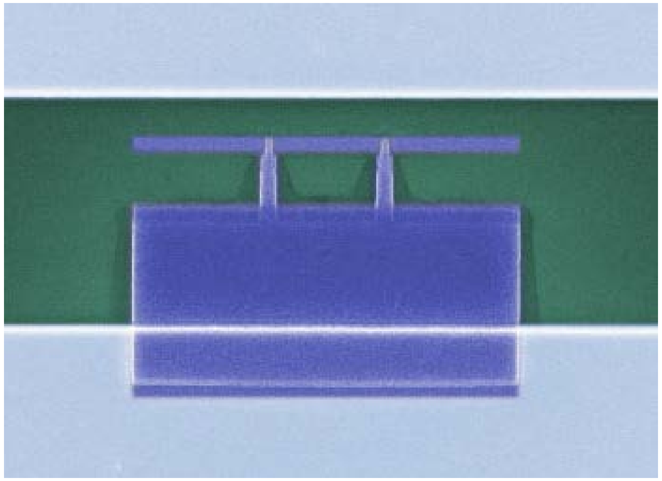


electronic artificial atom

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

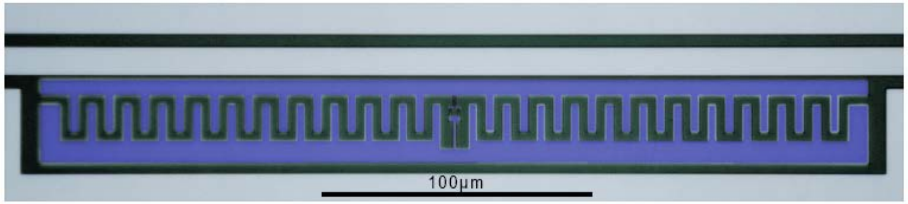
Flavors of Superconducting Artificial Atoms

Cooper pair box:



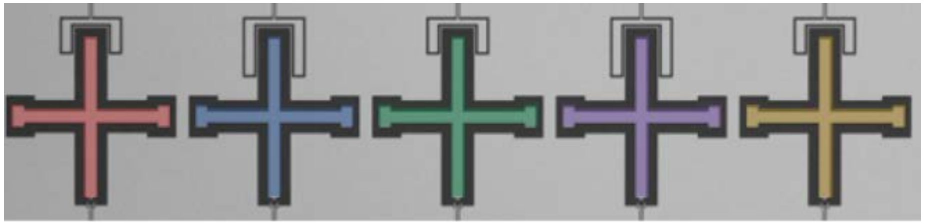
Bouchiat et al., *Physica Scripta* T76, 165 (1998).

Transmon:



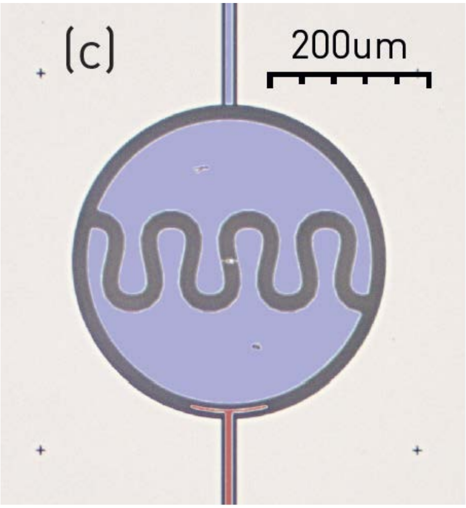
J. Koch *et al.*, PRA 76, 042319 (2007)

Xmons:



Barends *et al.*, *Phys. Rev. Lett.* 111, 080502 (2013)

(Jellymon):

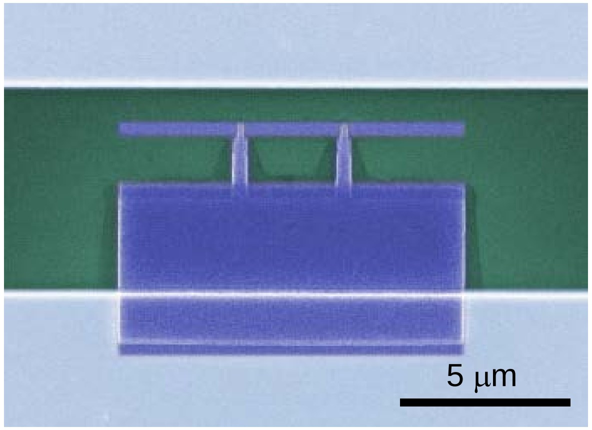


Pechal *et al.*, *arXiv*:1606.01031 (2004)

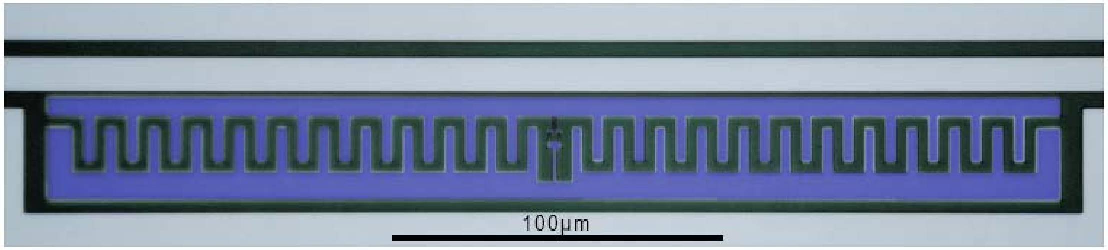
A Variant of the Cooper Pair Box

a Cooper pair box with a small charging energy

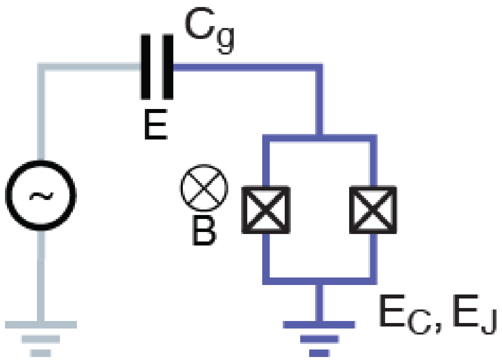
standard CPB:

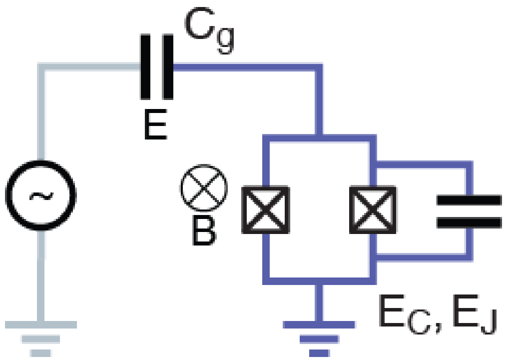


Transmon qubit:



circuit diagram:

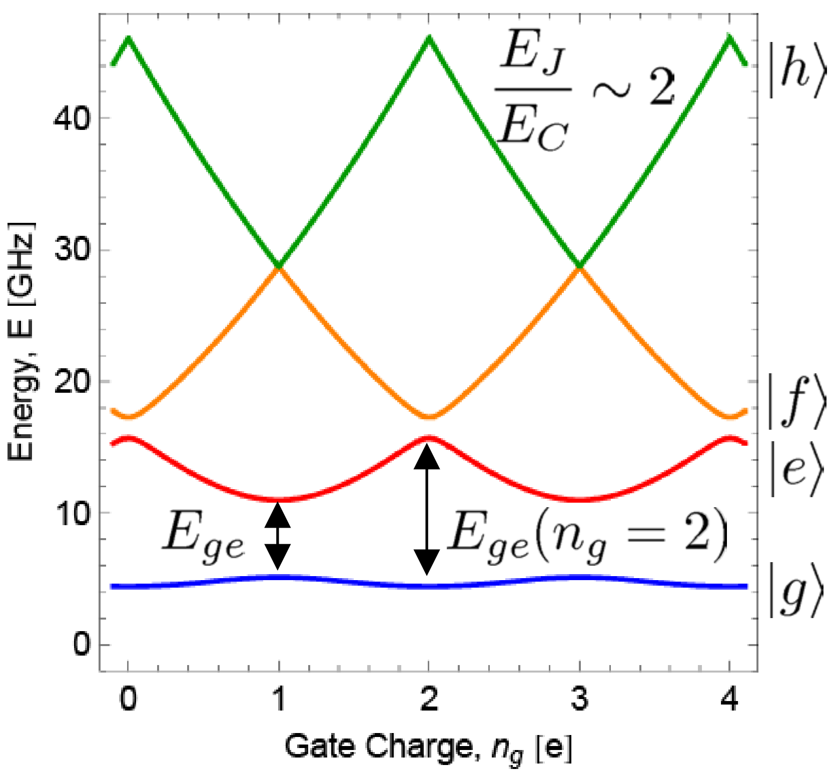




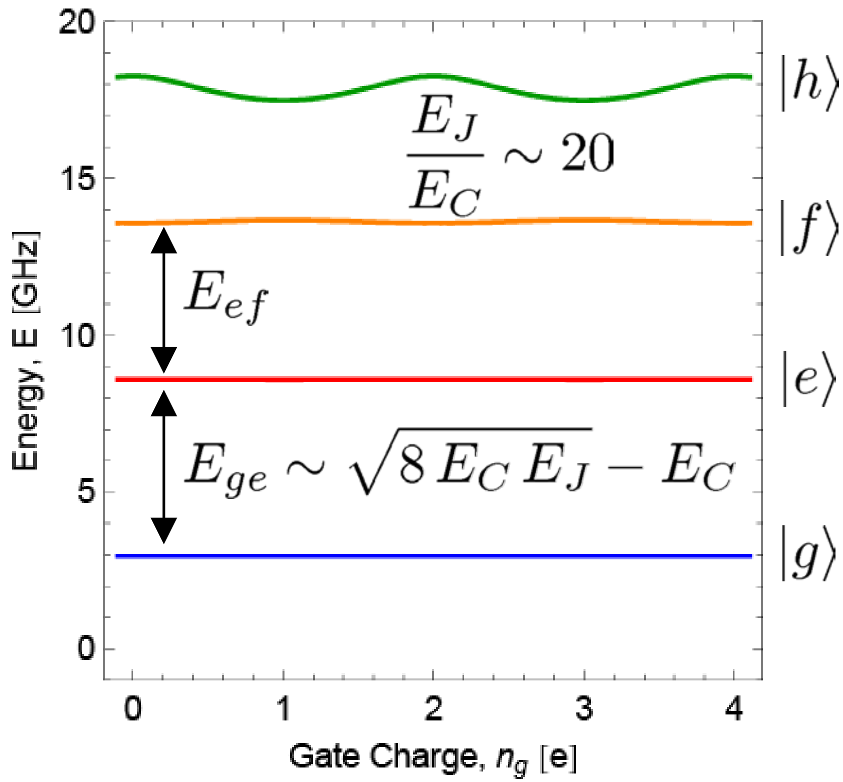
J. Koch *et al.*, Phys. Rev. A 76, 042319 (2007)
J. Schreier *et al.*, Phys. Rev. B 77, 180502 (2008)

The Transmon: A Charge Noise Insensitive Qubit

Cooper pair box energy levels:



Transmon energy levels:



dispersion:

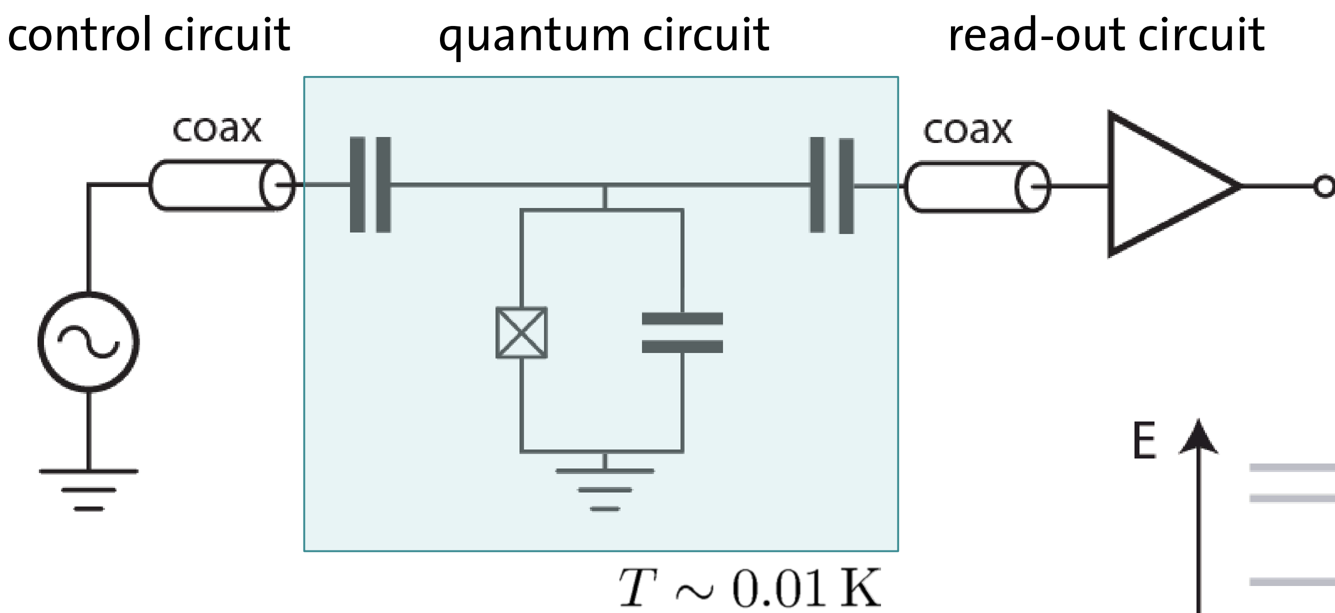
$$\epsilon = E_{ge}(n_g = 1) - E_{ge}(n_g = 2)$$

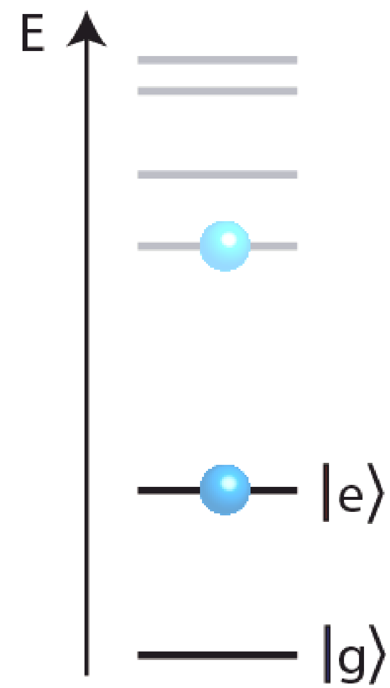
relative anharmonicity:

$$\alpha_r = \frac{E_{ef} - E_{ge}}{E_{ge}}$$

J. Koch *et al.*, Phys. Rev. A 76, 042319 (2007)

How to Operate Circuits in the Quantum Regime?



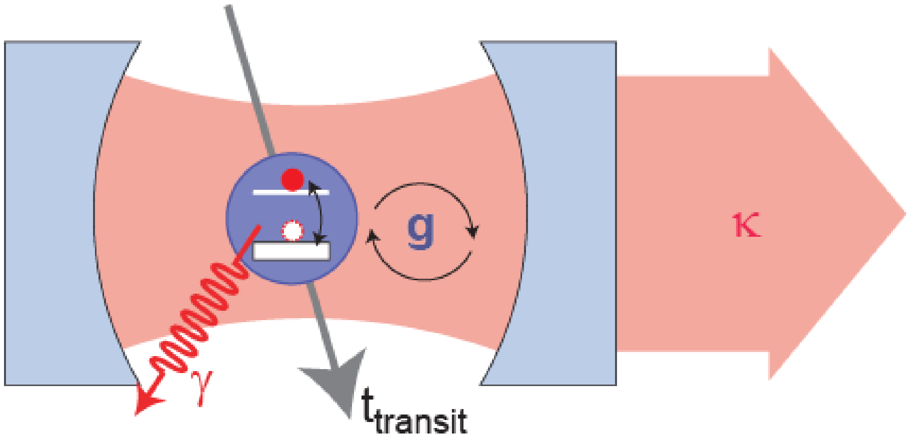


recipe:

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

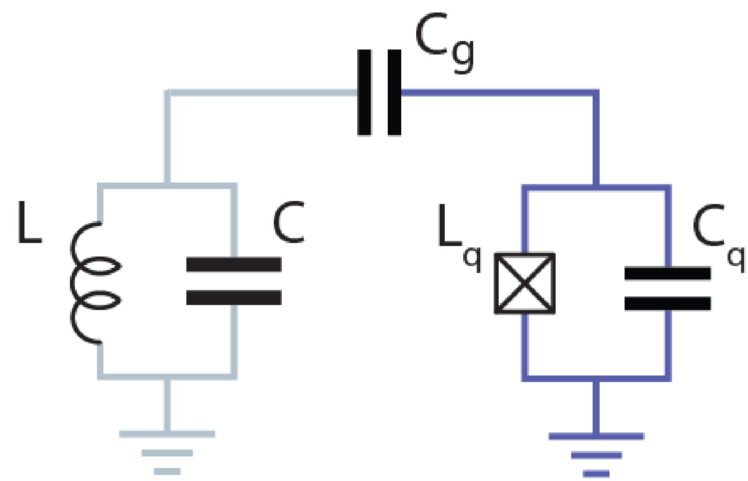
Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411174* (2004)

Cavity QED with Superconducting Circuits



coherent quantum mechanics
with individual photons and qubits ...

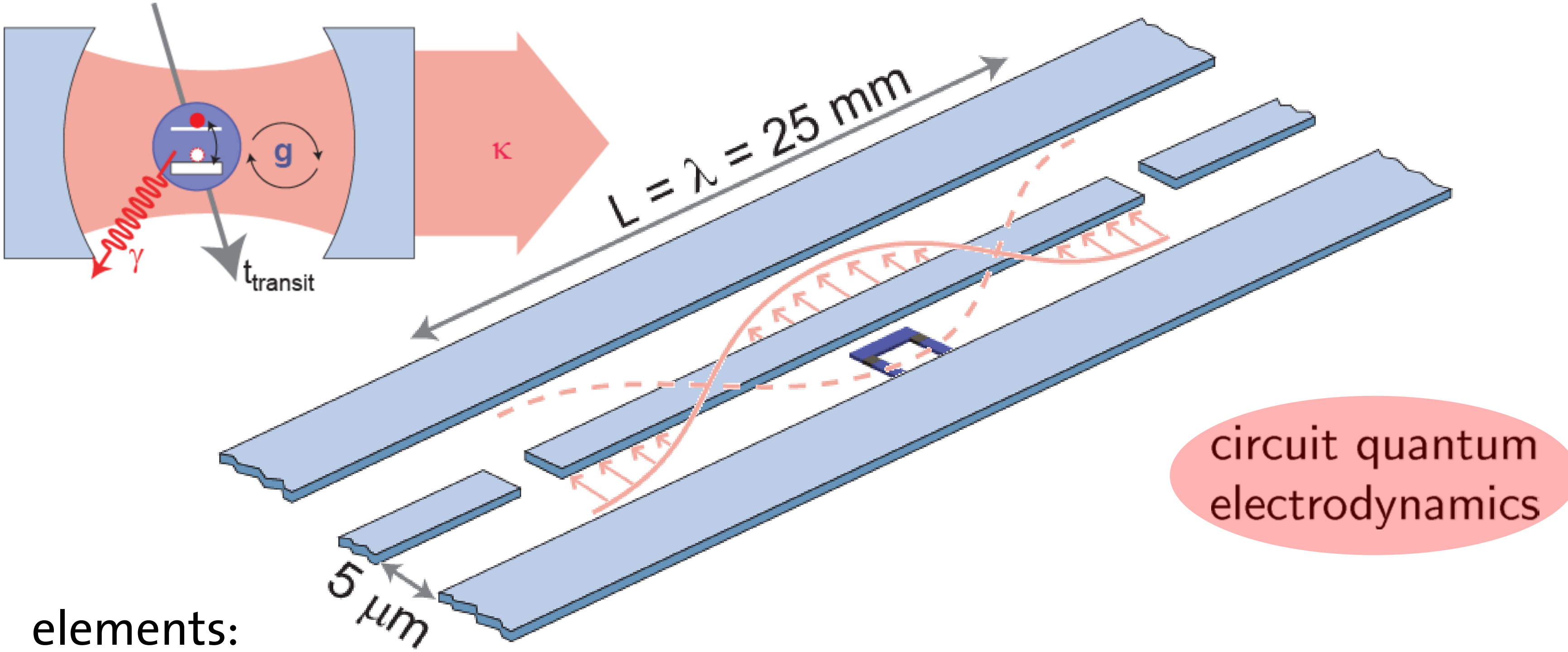
... basic approach:



What is this good for?

- Isolating qubits from their environment
- Maintain addressability of qubits
- Reading out the state of qubits
- Coupling qubits to each other
- Converting stationary qubits to flying qubits

Cavity QED with Superconducting Circuits

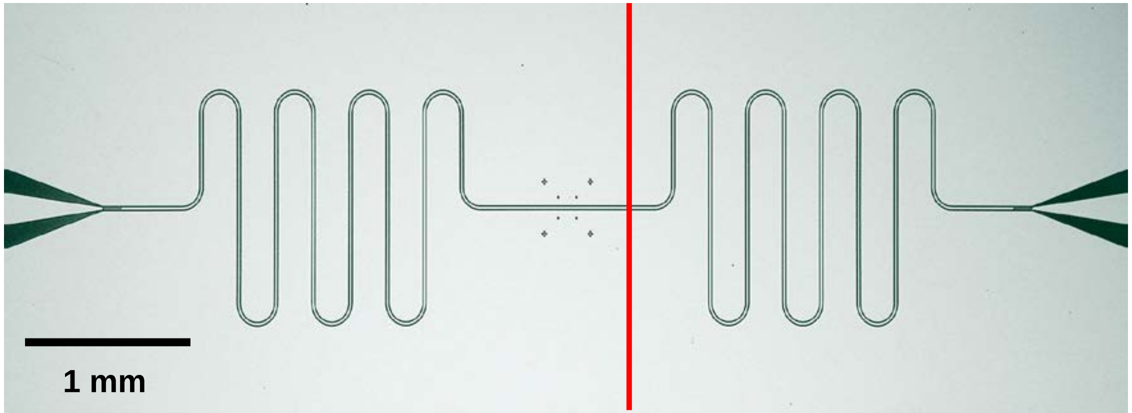


elements:

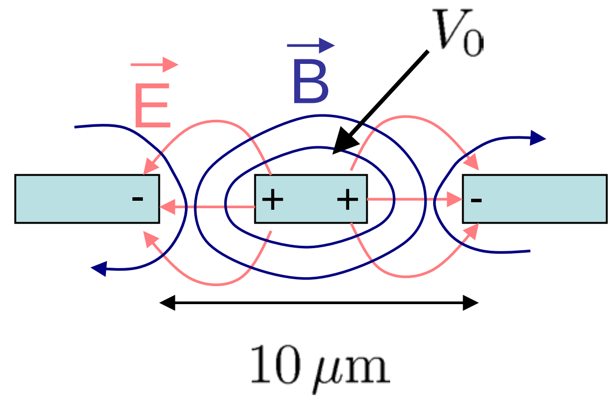
- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_o and long photon life time $1/\kappa$
- the atom: a superconducting qubit with large dipole moment d and long coherence time $1/\gamma$ and fixed position ...
- ... or any microscopic/macroscopic quantum element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

Large Vacuum Field in 1D Cavity



optical microscope image of strip line resonator



electric field across resonator in vacuum state (*n=0*):

$$\int \epsilon_0 E_{0,\mathrm{rms}}^2 \, dV_{\mathrm{mod}} = \frac{\hbar\omega_r}{2}$$

harmonic oscillator

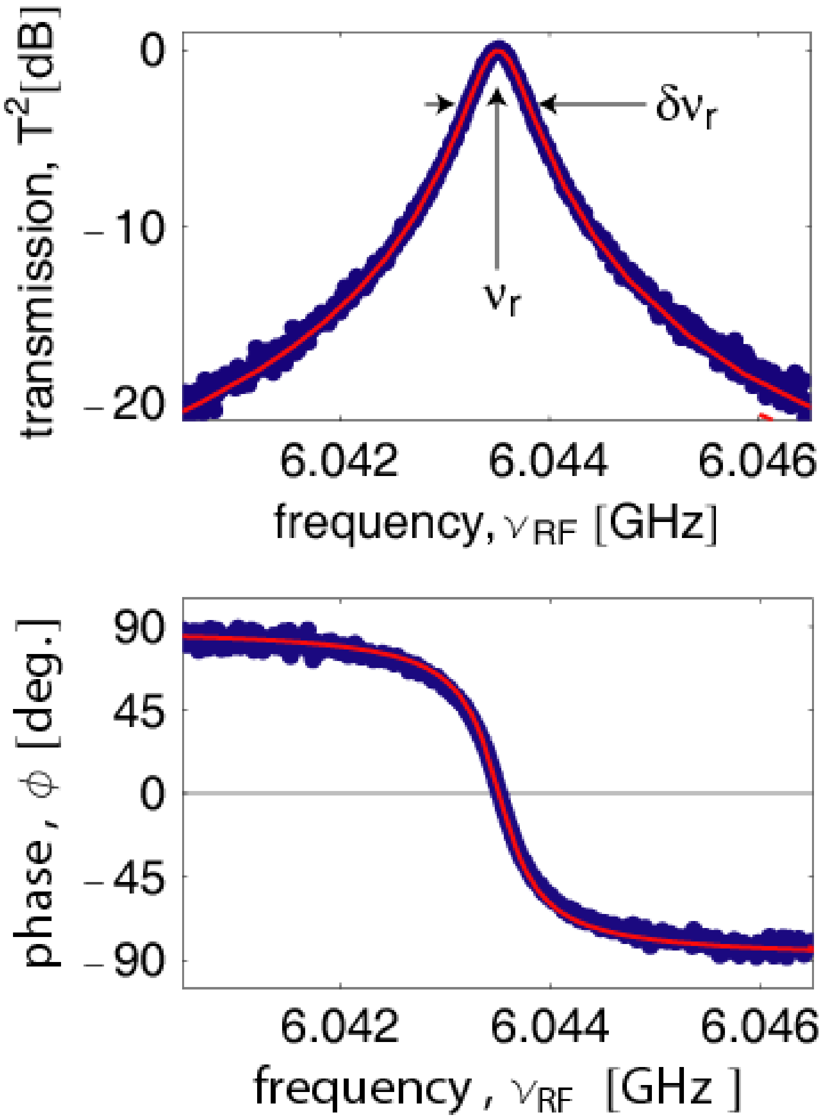
$$H_r = \hbar\omega_r \left(a^\dagger a + \frac{1}{2} \right)$$

$$E_{0,\mathrm{rms}} \approx 0.2\,\mathrm{V/m}$$

for $\omega_r/2\pi \approx 6\,\mathrm{GHz}$

$\times 10^6$ larger than E_0
in 3D microwave cavity

Resonator Quality Factor and Photon Lifetime



resonance frequency:

$$\nu_r = 6.04\,\mathrm{GHz}$$

quality factor:

$$Q = \frac{\nu_r}{\delta\nu_r} \approx 10^4$$

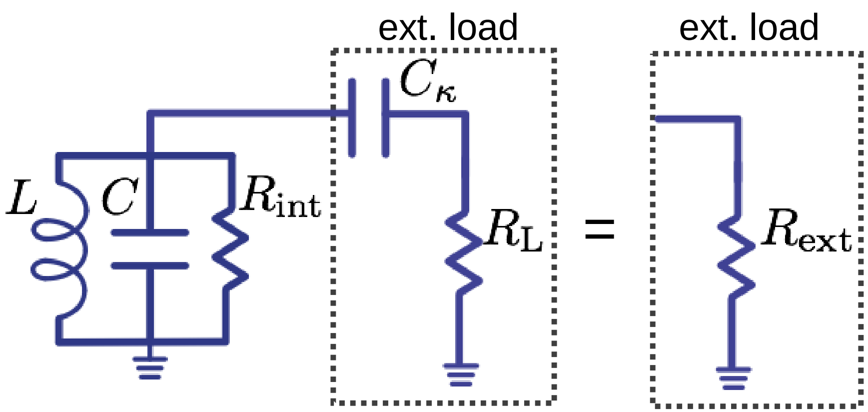
photon decay rate:

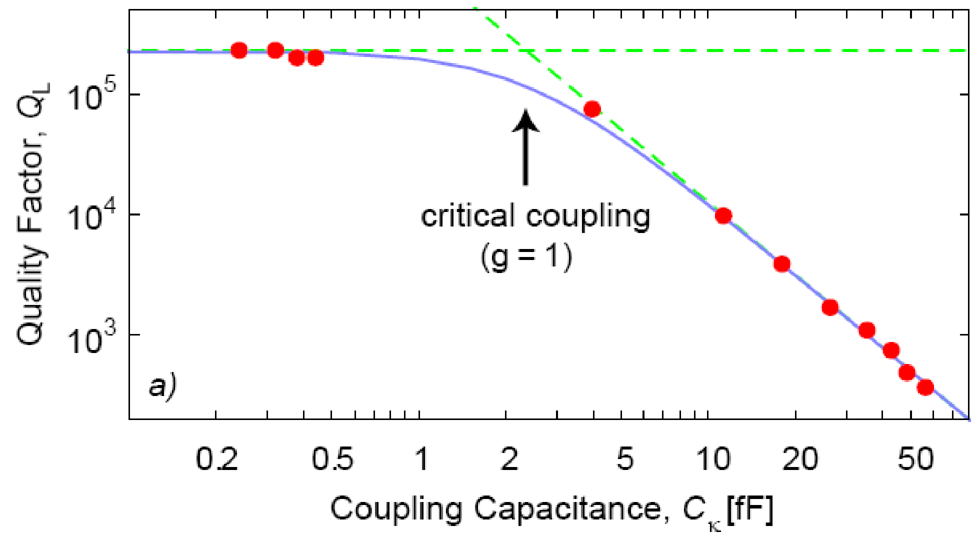
$$\frac{\kappa}{2\pi} = \frac{\nu_r}{Q} \approx 0.8\,\mathrm{MHz}$$

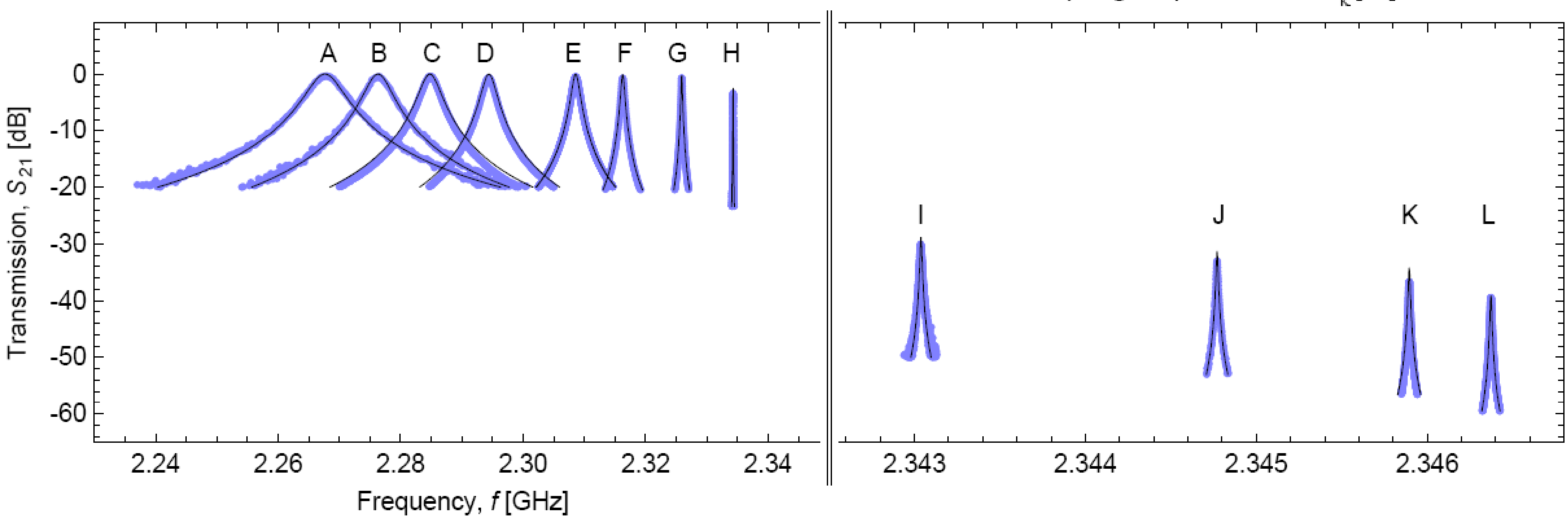
photon lifetime:

$$T_\kappa = 1/\kappa \approx 200\,\mathrm{ns}$$

The Quality Factor

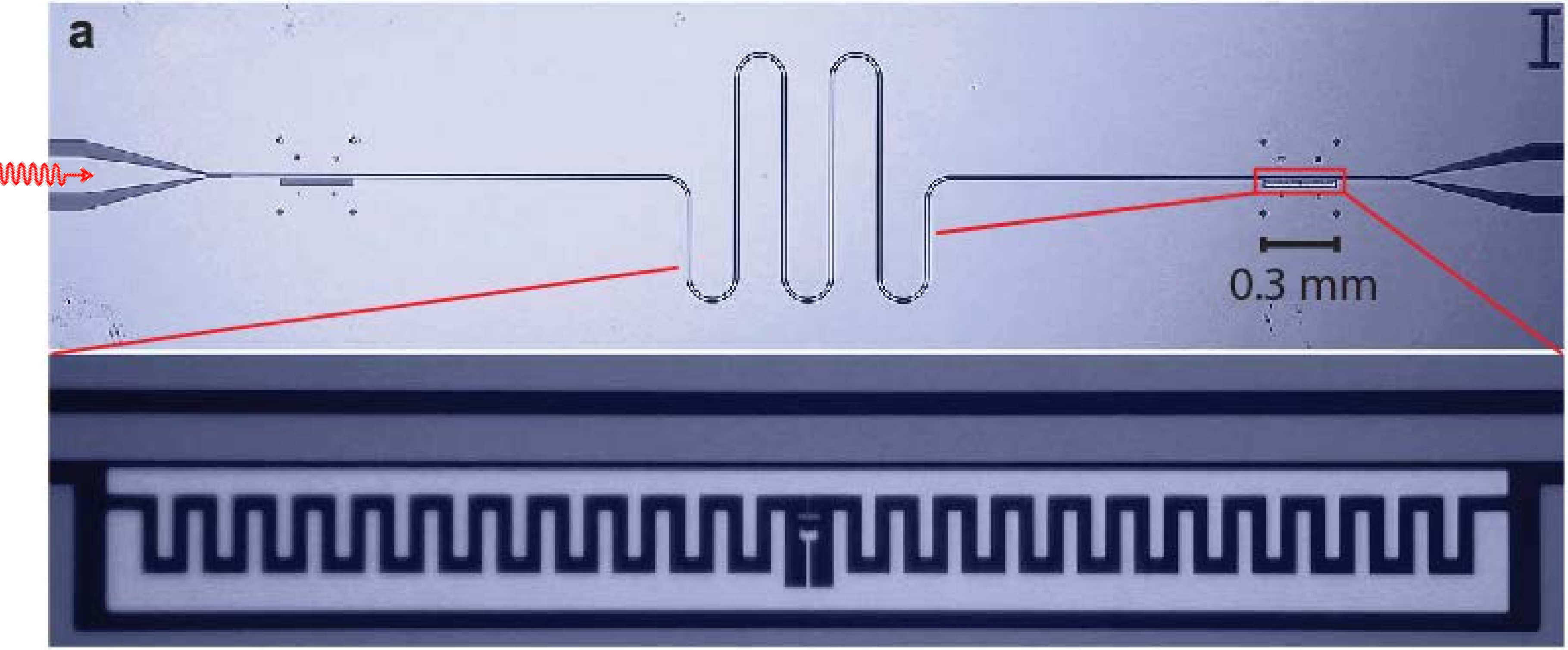




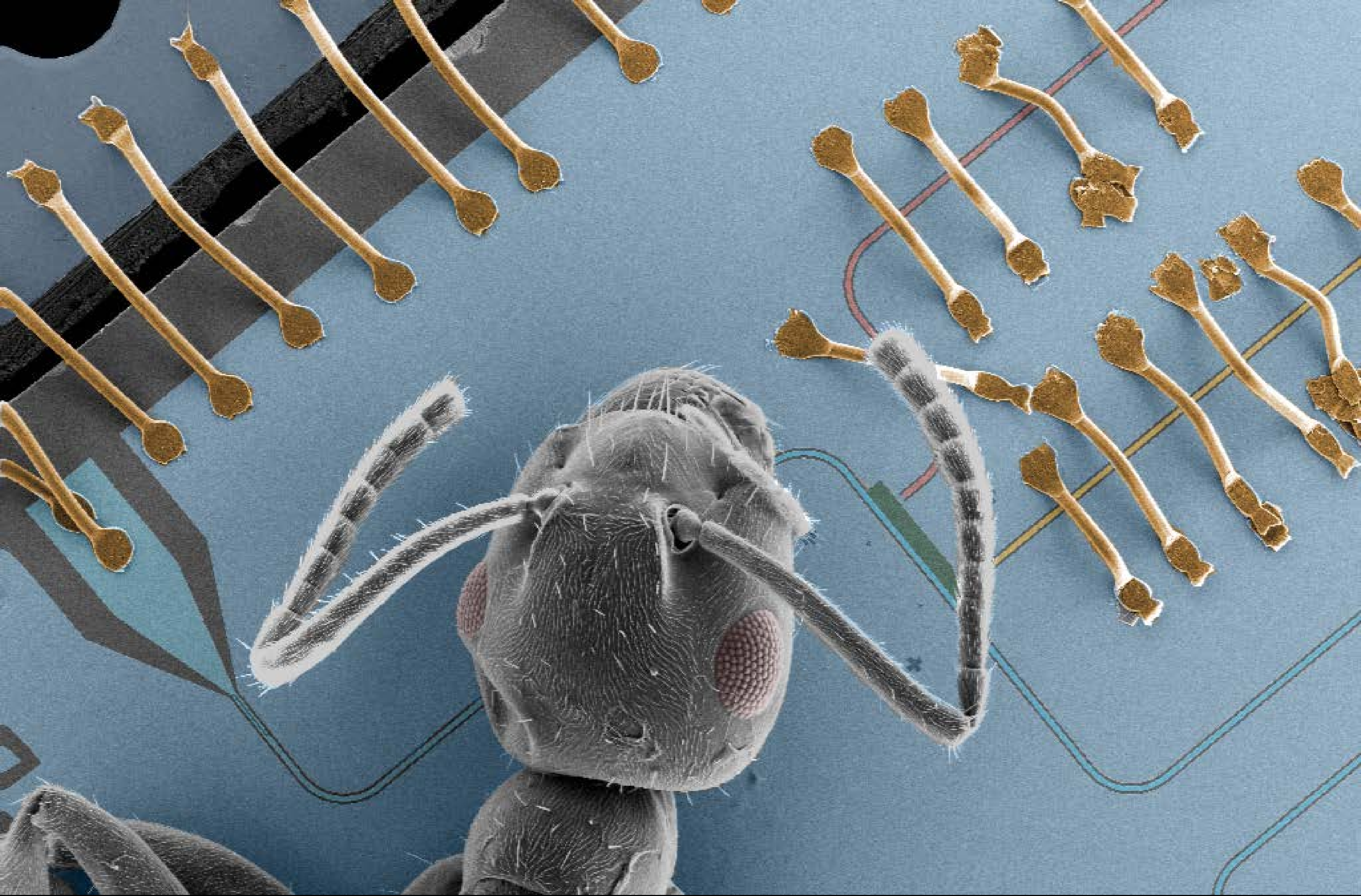


M. Goeppl, *et al. J. Appl. Phys.* 104, 113904 (2008)

Realization



device fabrication: L. Frunzio et al., IEEE Trans. on Appl. Supercon. 15, 860 (2005)



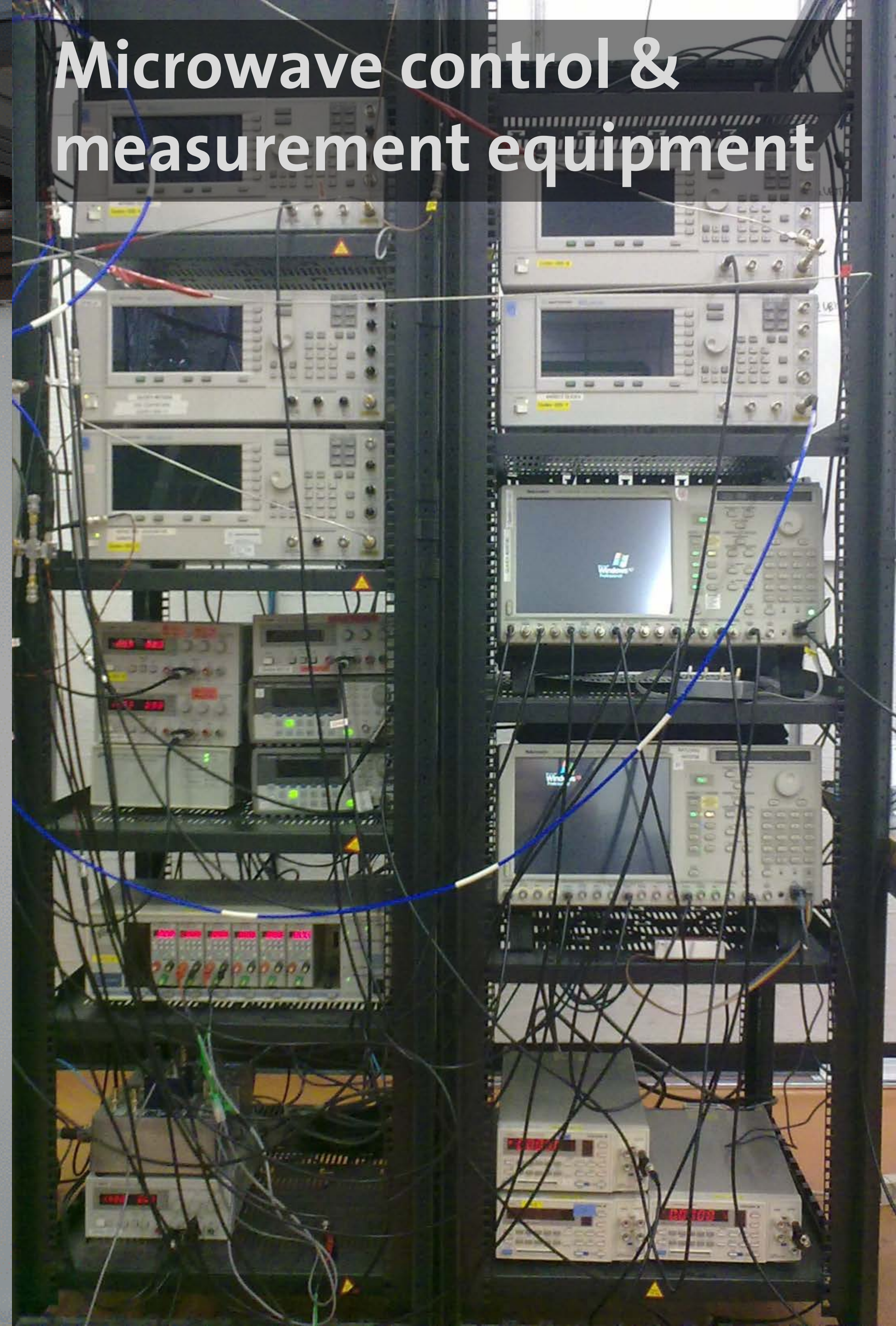
J. Mlynek *et al.,* Quantum Device Lab, ETH Zurich (2012)

Sample Mount

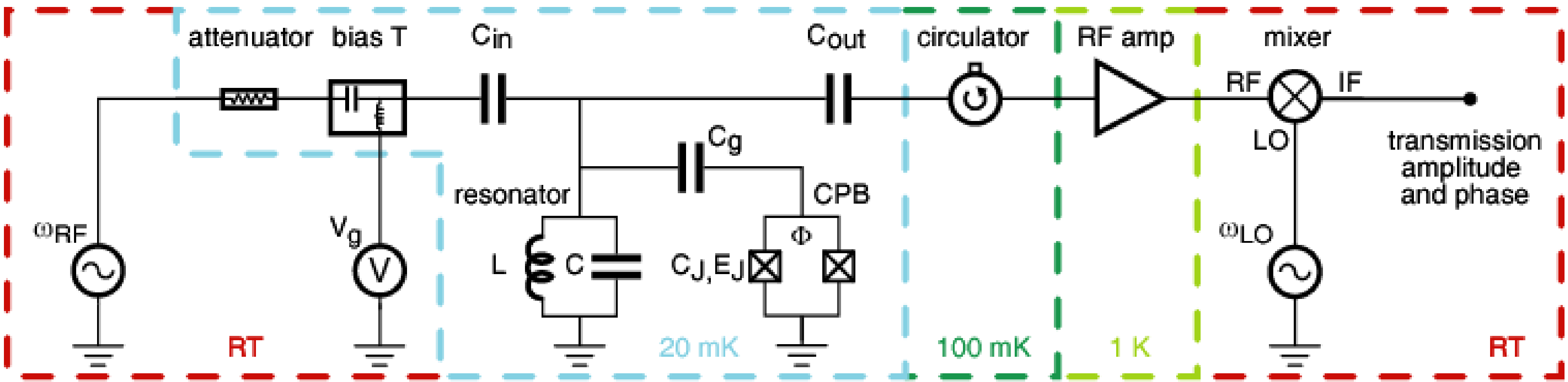
M. Peterer *et al.,* Quantum Device Lab, ETH Zurich (2012)

Cryostate for temperatures down to 0.02 K

Microwave control & measurement equipment



How to do the Measurement



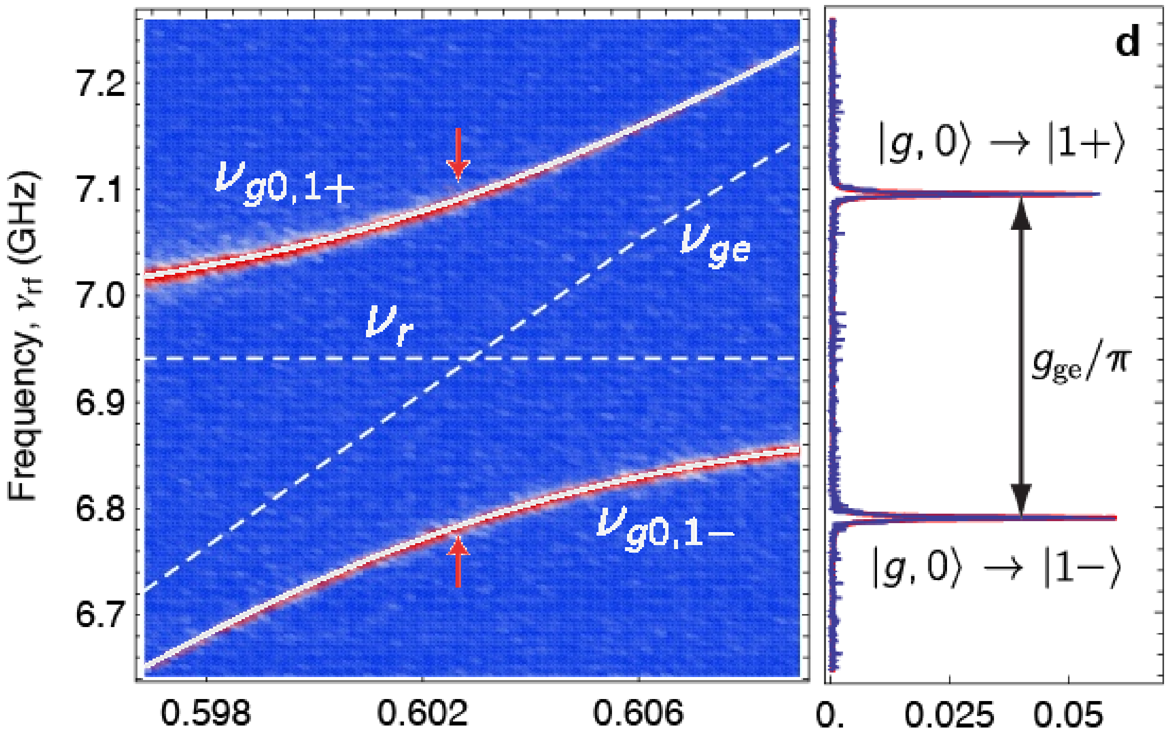
- prevent leakage of thermal photons (cold attenuators and circulators)
- average power to be detected ($\omega_r/2\pi$ = 6 GHz, $\kappa/2\pi$ = 1 MHz)

$$\langle n = 1 \rangle \hbar\omega_r\kappa/2 \approx P_{RF} = -140\,\mathrm{dBm} = 10^{-17}\,\mathrm{W}$$

- efficient with cryogenic low noise HEMT amplifier $T_N = 6$ K

Resonant Vacuum Rabi Mode Splitting ...

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

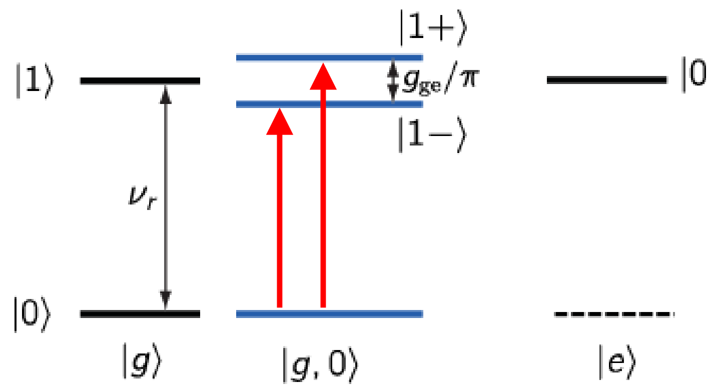


very strong coupling:

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

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

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



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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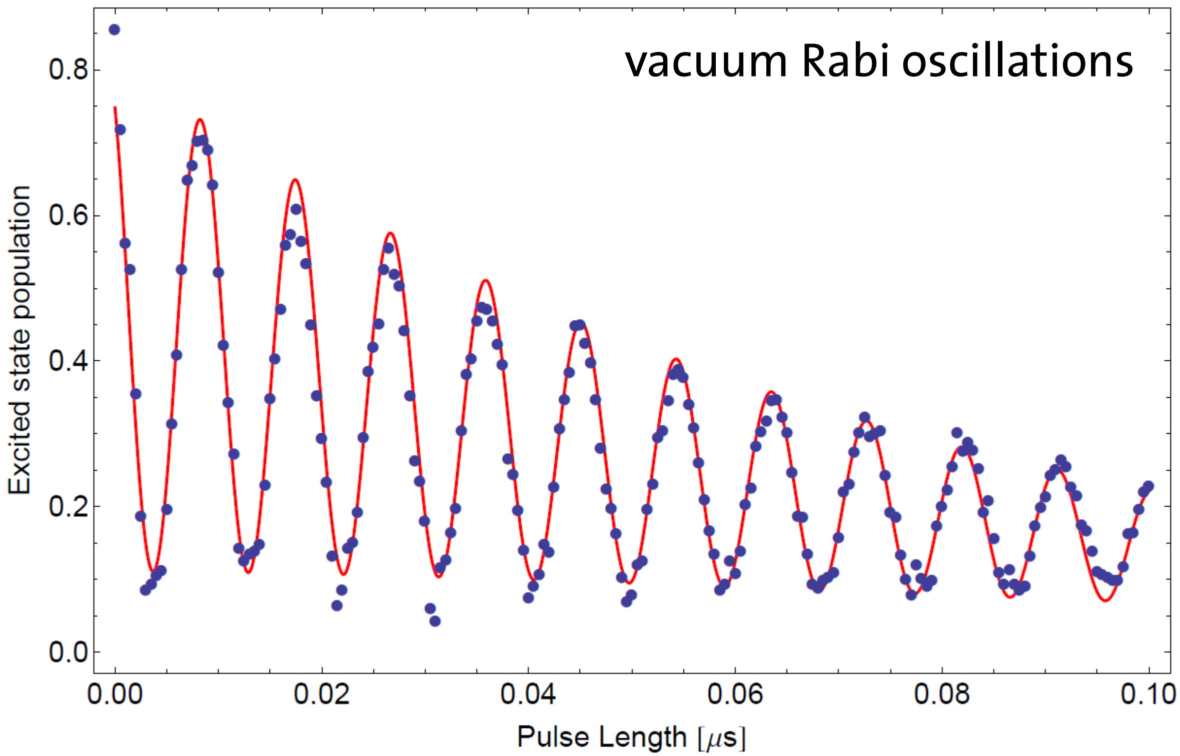

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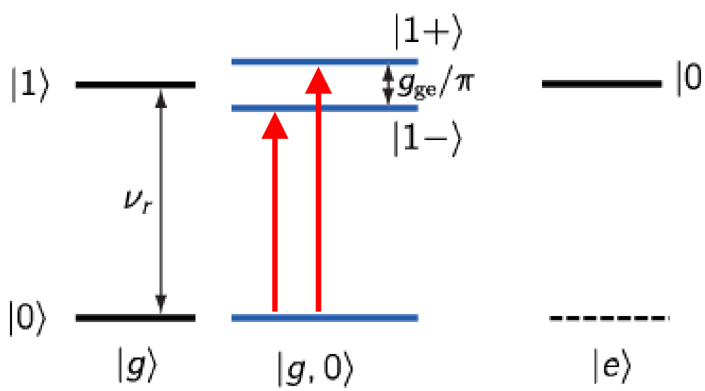

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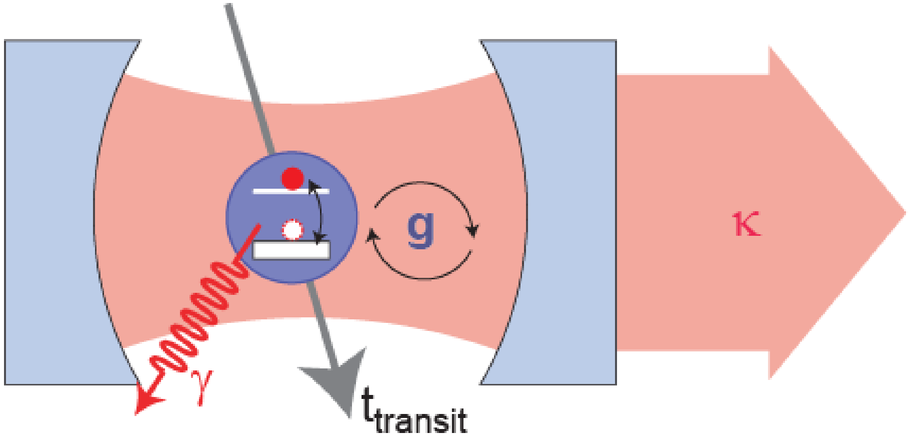
first demonstration in a solid: A. Wallraff e*t al.*, *Nature (London)* 431, 162 (2004)

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

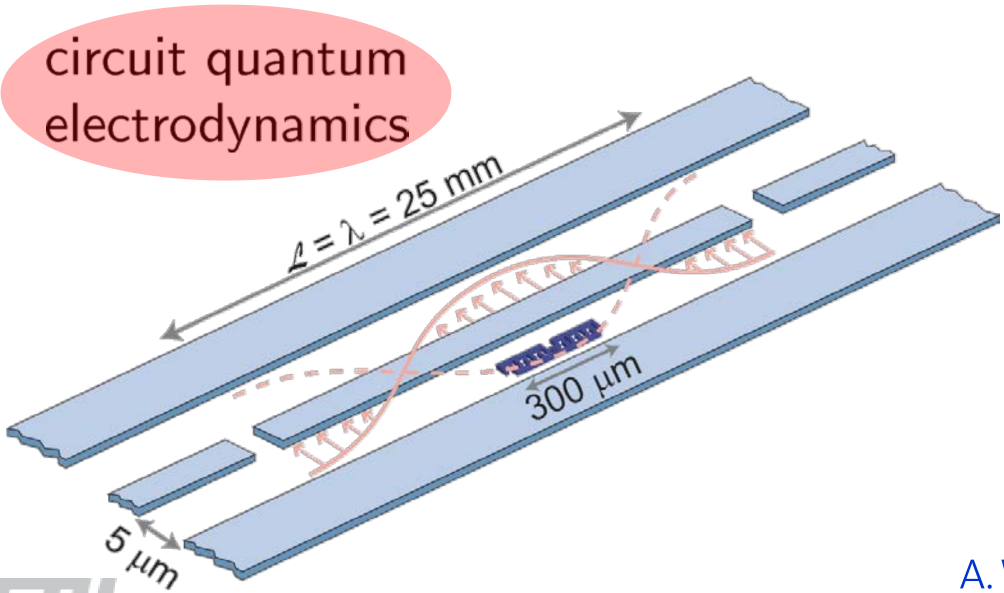
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* 451, 664 (2008)

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)



Properties:

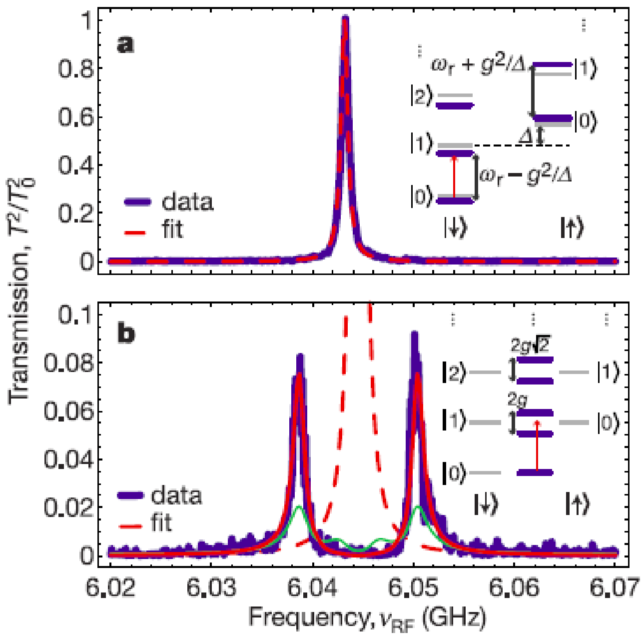
- strong coupling in solid state sys.
- 'easy' to fabricate and integrate

Research directions:

- quantum optics
- quantum information
- hybrid quantum systems

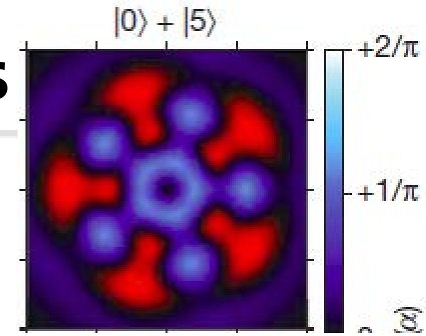
A. Blais, *et al., PRA* 69, 062320 (2004)
A. Wallraff *et al., Nature (London)* 431, 162 (2004)
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* 451, 664 (2008)

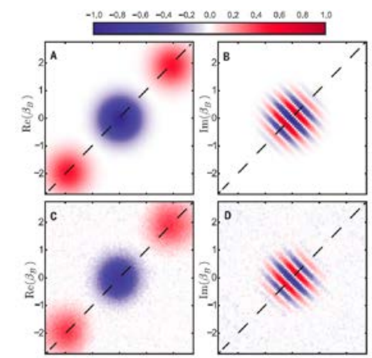
Quantum Optics with Supercond. Circuits



Strong Coherent Coupling

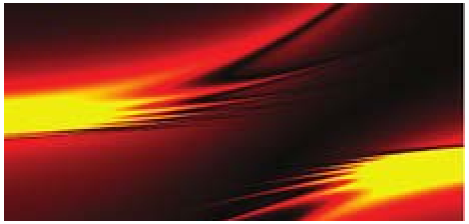
Chiorescu *et al.*, *Nature* 431, 159 (2004)
Wallraff *et al.*, *Nature* 431, 162 (2004)
Schuster *et al.*, *Nature* 445, 515 (2007)





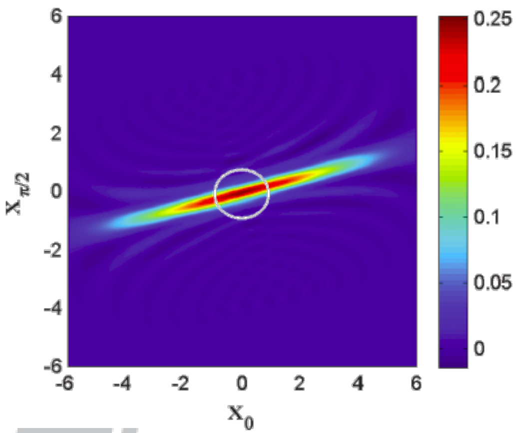
Root n Nonlinearities

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



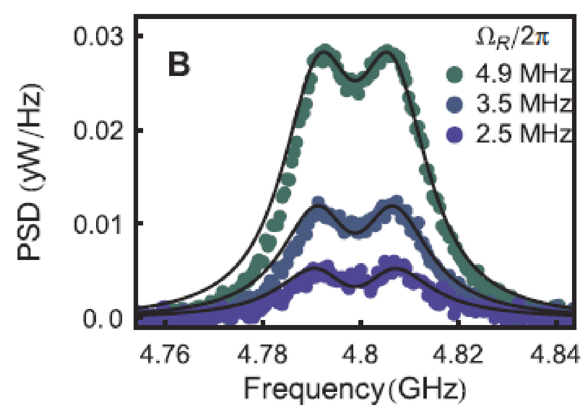
Microwave Fock and Cat States

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)
Wang *et al.*, Science 352, 1087 (2016)



Parametric Amplification & Squeezing

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

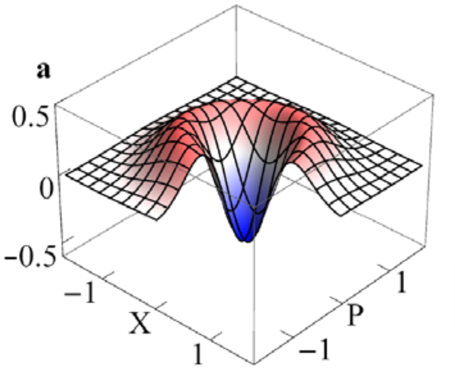


Waveguide QED – Qubit Interactions in Free Space

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

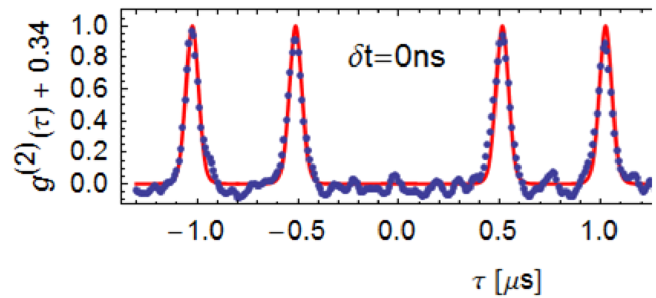
Experiments with Propagating Microwaves

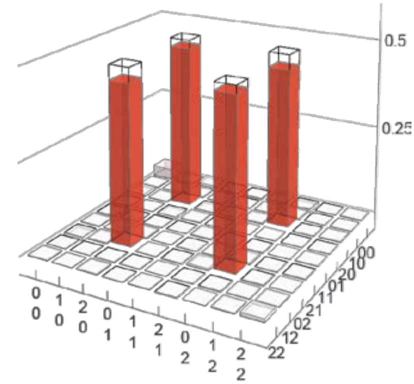
Full state tomography and Wigner functions of propagating photons



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

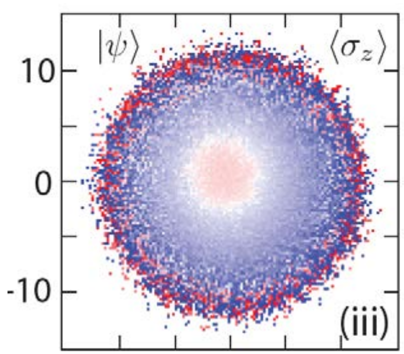
Hong-Ou-Mandel: Two-photon interference incl. msrmnt of coherences at microwave freq.

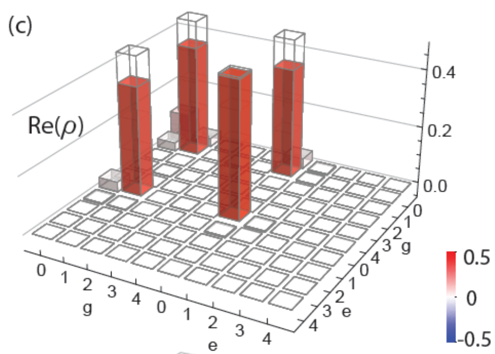




Lang *et al.*, *Nat. Phys.* 9, 345 (2013)

Preparation and characterization of qubit-propagating photon entanglement

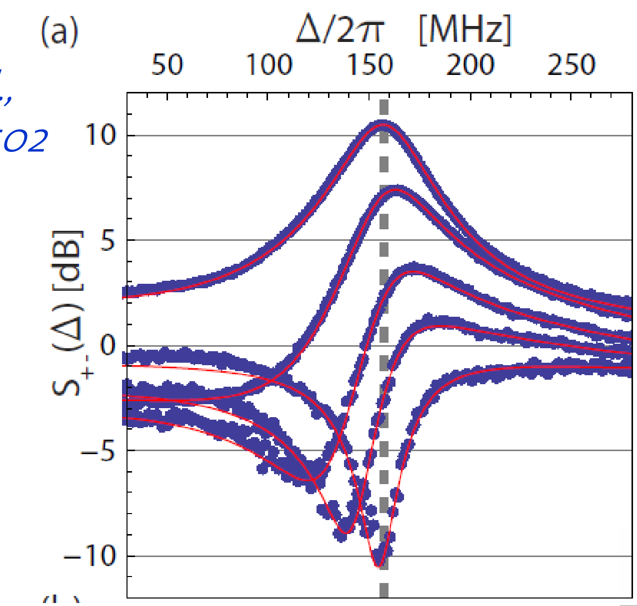




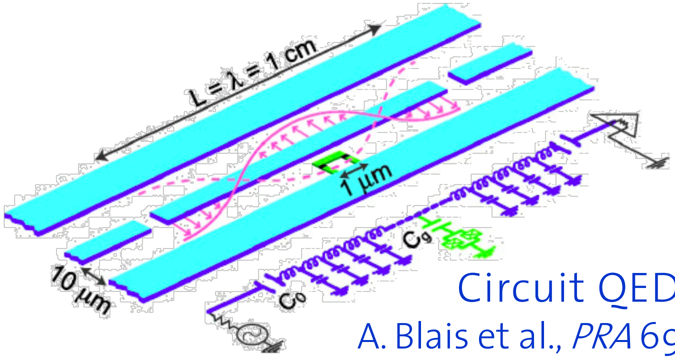
Eichler *et al., PRL* 109, *240501* (2012)
Eichler *et al., PRA* 86, 032106 (2012)

Squeezing in a Josephson parametric dimer

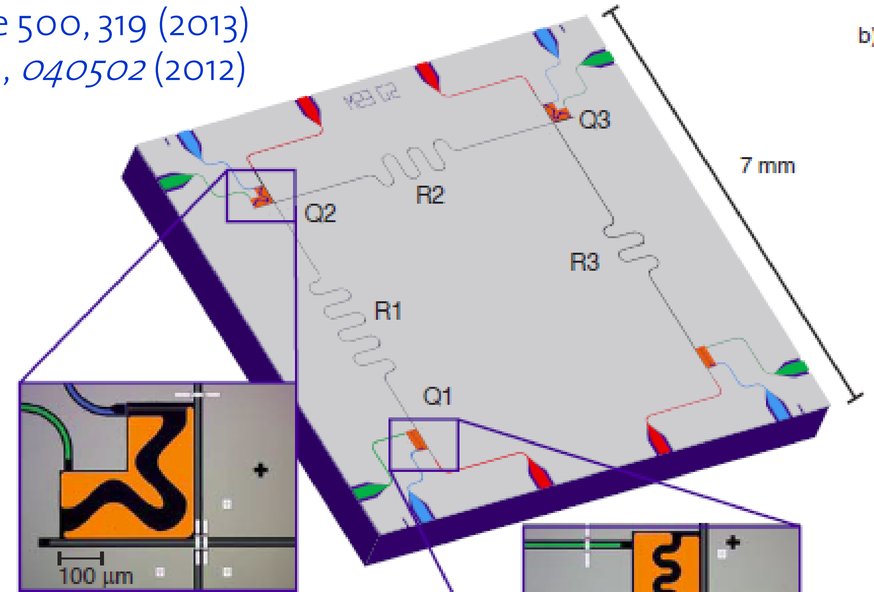
Eichler *et al., PRL* 113, *110502* (2014)



Quantum Computing with Superconducting Circuits



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



Circuit QED Architecture
A. Blais et al., *PRA* 69, 062320 (2004)
A. Wallraff *et al.*, *Nature* 431, 162 (2004)
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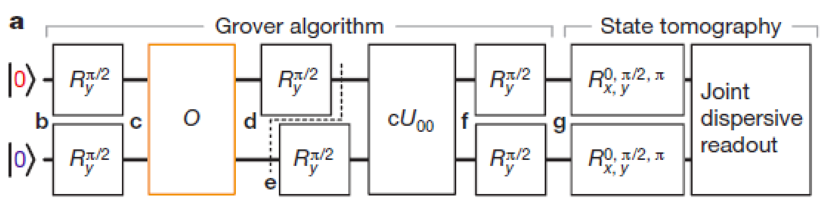
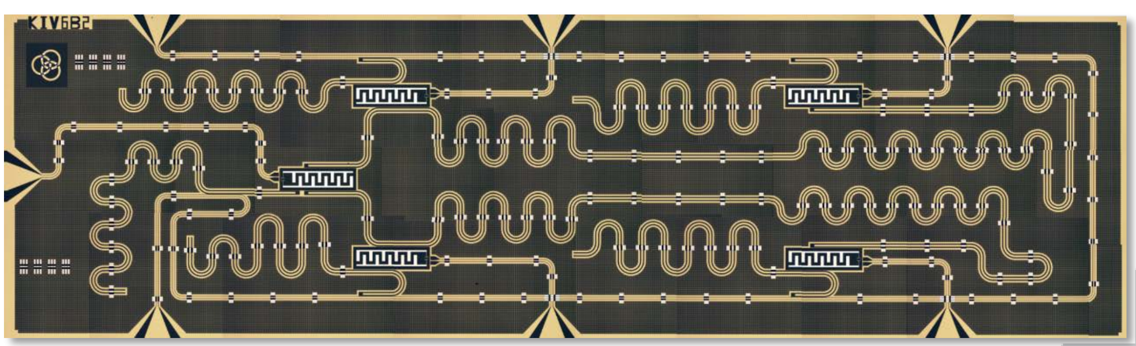
H. Majer *et al.*, *Nature* 449, 443 (2007)
M. Mariantoni *et al.*, *Science* 334, 61 (2011)
R. Barends *et al.*, *Nature* 508, 500 (2014)

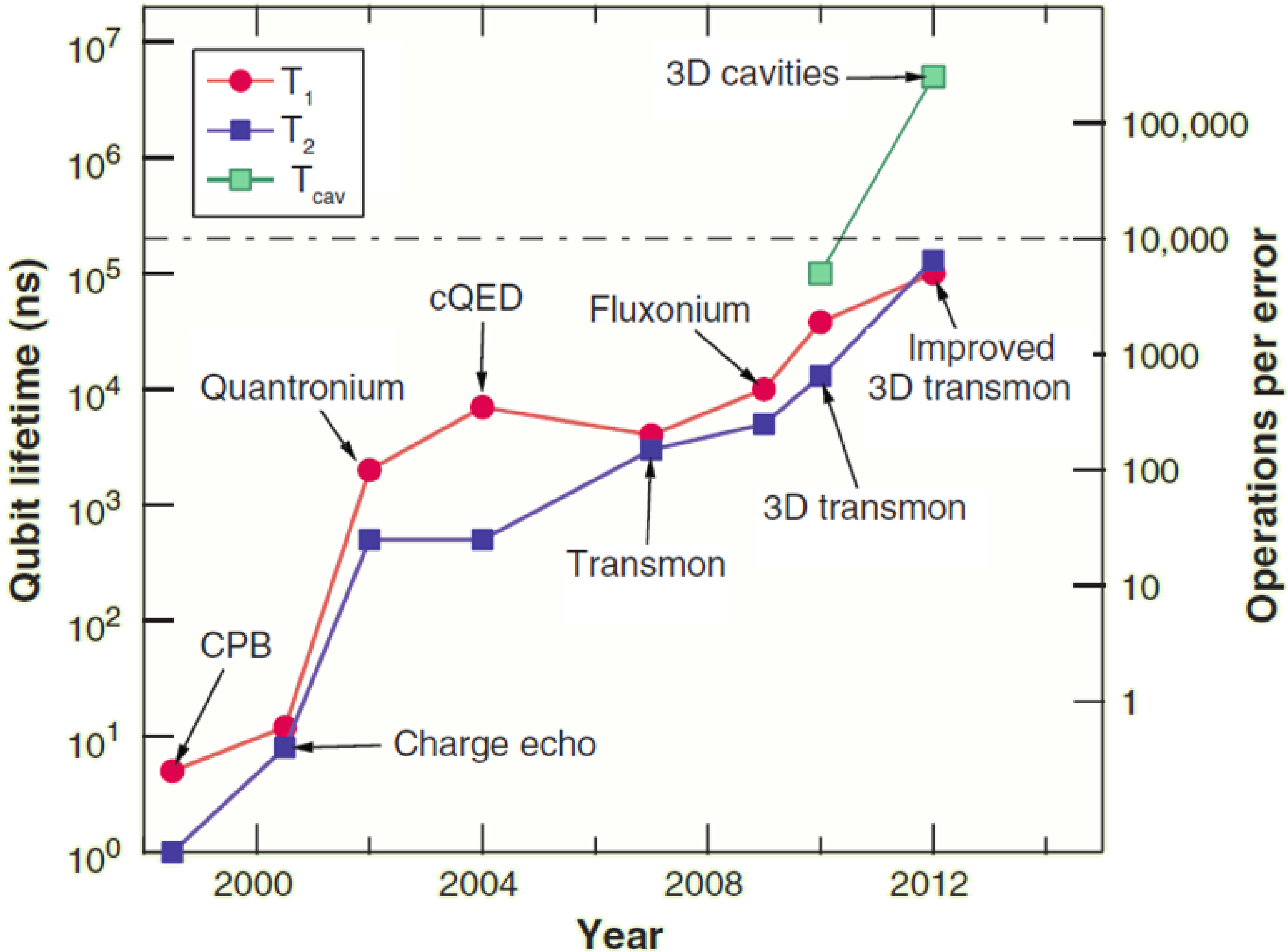


Deutsch & Grover Algorithm, Toffoli Gate
L. DiCarlo *et al.*, *Nature* 460, 240 (2009)
L. DiCarlo *et al.*, *Nature* 467, 574 (2010)
A. Fedorov *et al.*, *Nature* 481, 170 (2012)

Error Correction
M. Reed *et al.*, *Nature* 481, 382 (2012)
Corcoles et al., *Nat. Com.* 6, 6979 (2015)
Ristè et al., *Nat. Com.* 6, 6983 (2015)
Kelly et al., *Nature* 519, 66-69 (2015)

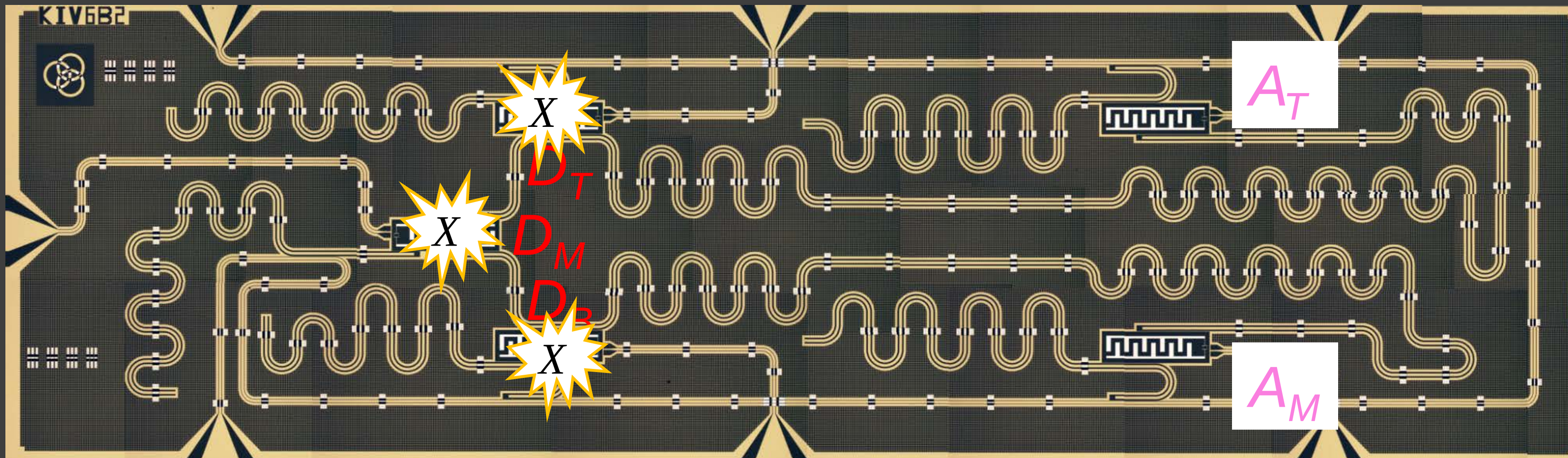


10^5 Improvement in Coherence Time in 13 Years



M. Devoret, R. Schoelkopf *Science* 339, 1169 (2013)

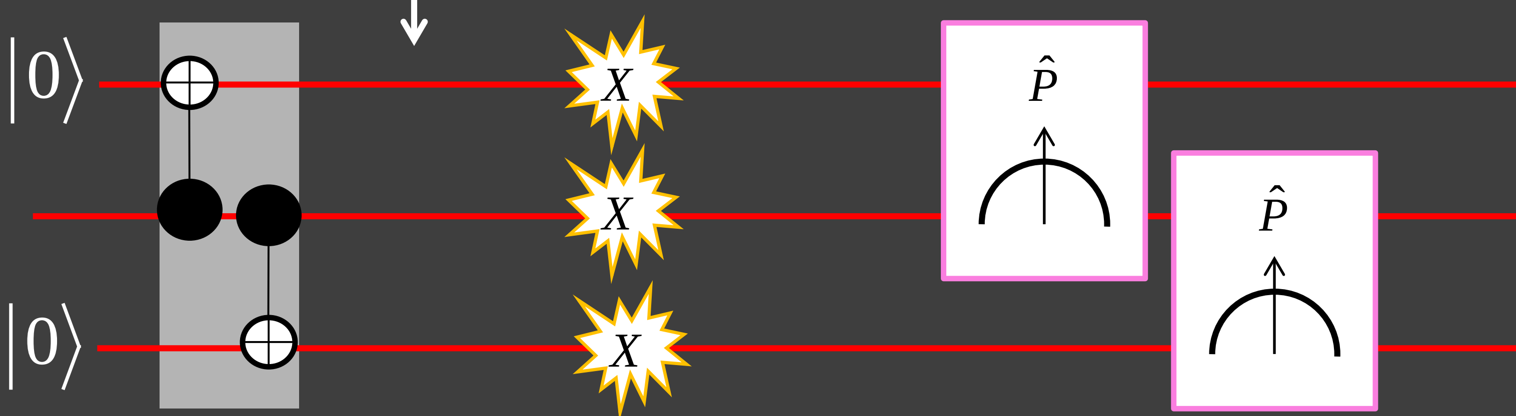
Recent Progress in Quantum Error Correction



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

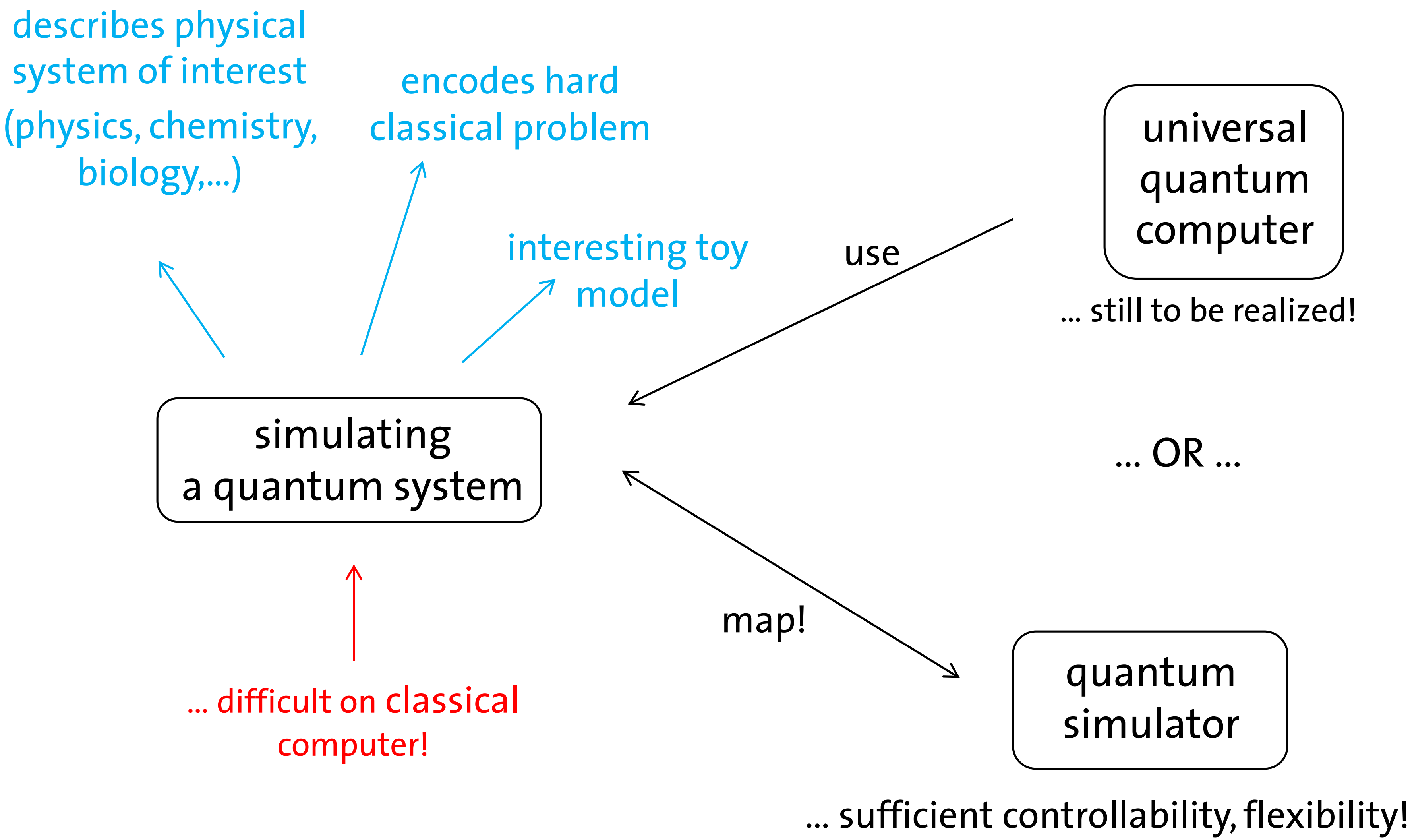
Discretize, signal errors using quantum parity checks

encode



IBM: Corcoles *et al.*, *Nat. Com.* **6**, 6979 (2015), ArXiv:1410.6419
QuTech: Ristè, Poletto, Huang *et al.*, *Nat. Com.* **6**, 6983 (2015), ArXiv:1411.5542
UCSB/Google: Kelly *et al.*, *Nature* **519**, 66-69 (2015), ArXiv:1411.7403

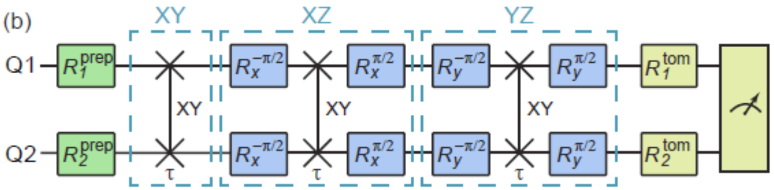
Quantum Simulation



Feynman, *Int. Journal of Th. Phys.* 21, 467 (1982)
Llloyd, *Science* 273, 5278 (1996)

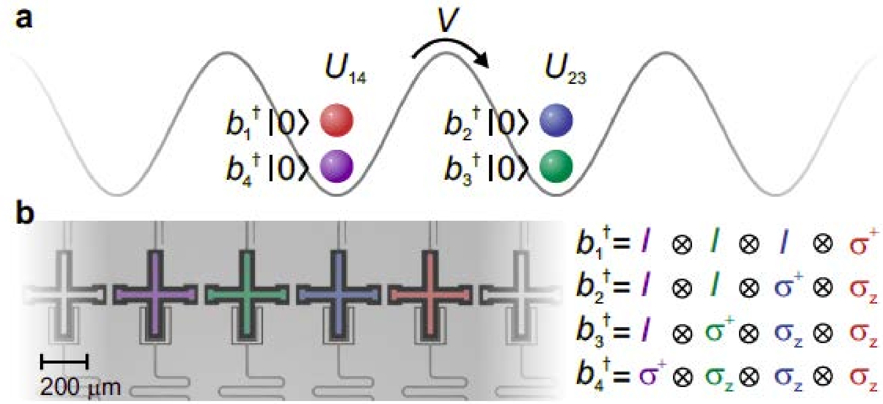
Quantum Simulation with Superconducting Circuits

Digital simulation of exchange, Heisenberg, Ising spin models



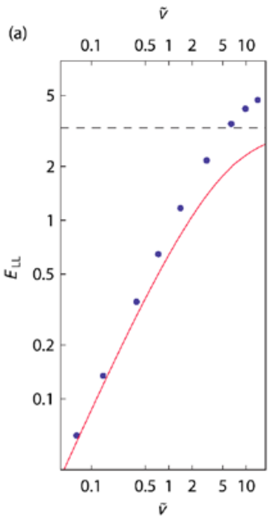
Salathe *et al.*, *PRX* 5, 021027 (2015)

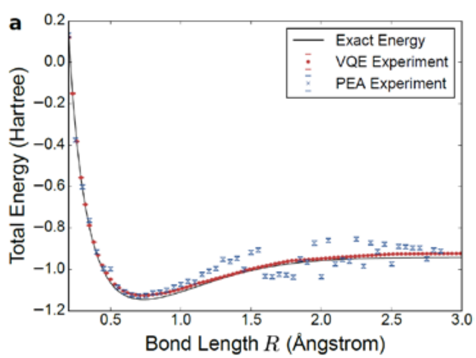
... two-mode fermionic Hubbard models



Barends *et al.*, *Nat. Com.* 6, 7654 (2015)

Quantum simulation of correlated systems with variational Ansatz



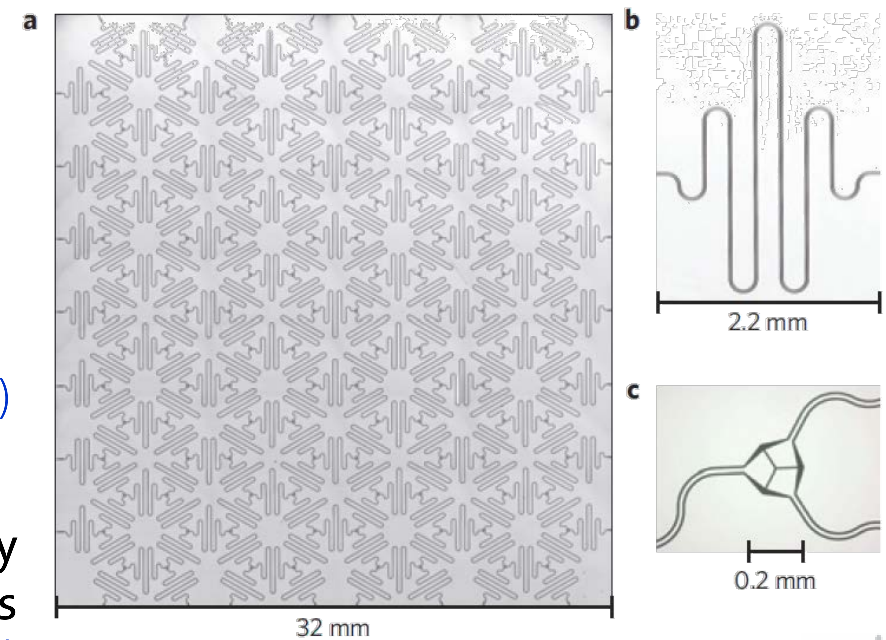


Eichler *et al.*, *Phys. Rev. X* 5, 041044 (2015)

O'Malley *et al.*, *arXiv*:1512.06860 (2015)

Analog simulations with cavity and/or qubit arrays

Houck *et al.*, *Nat Phys.* 8, 292 (2012)

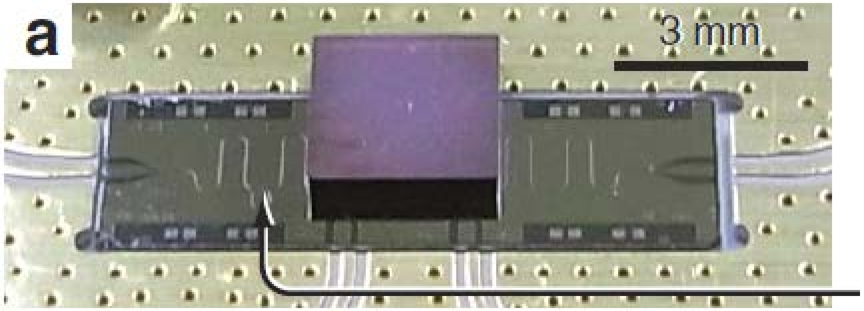


Raftery *et al.*, *Phys. Rev. X* 4, 031043 (2014)

Hybrid Systems with Superconducting Circuits

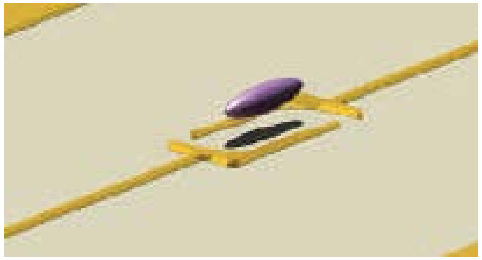
Spin Ensembles: e.g. NV centers

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



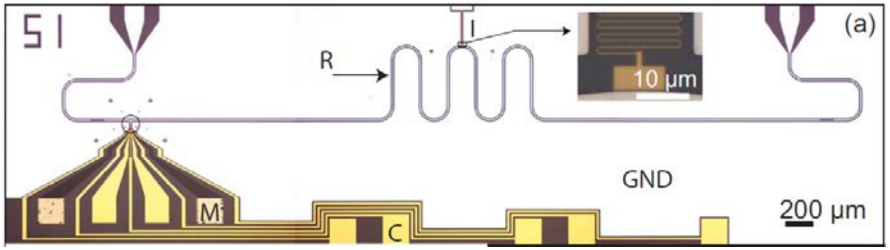
Polar Molecules, Rydberg, BEC

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



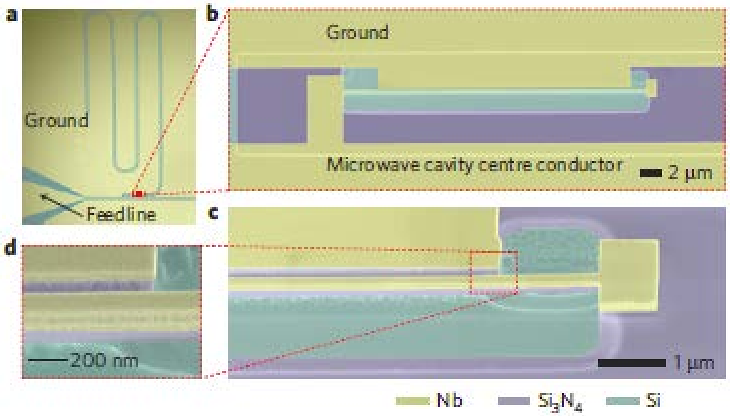
CNT, Gate Defined 2DEG, or nanowire Quantum Dots

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



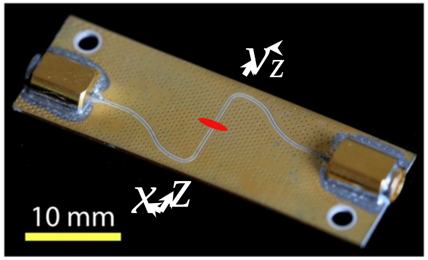
Nano-Mechanics

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



Rydberg Atoms

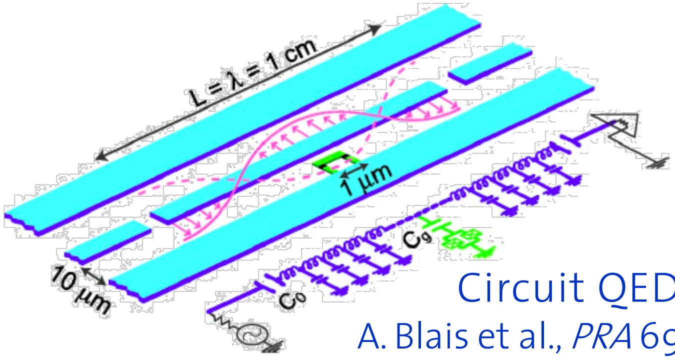
S. Hogan *et al.*, *PRL* 108, 063004 (2012)



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

... and many more

Quantum Computing with Superconducting Circuits



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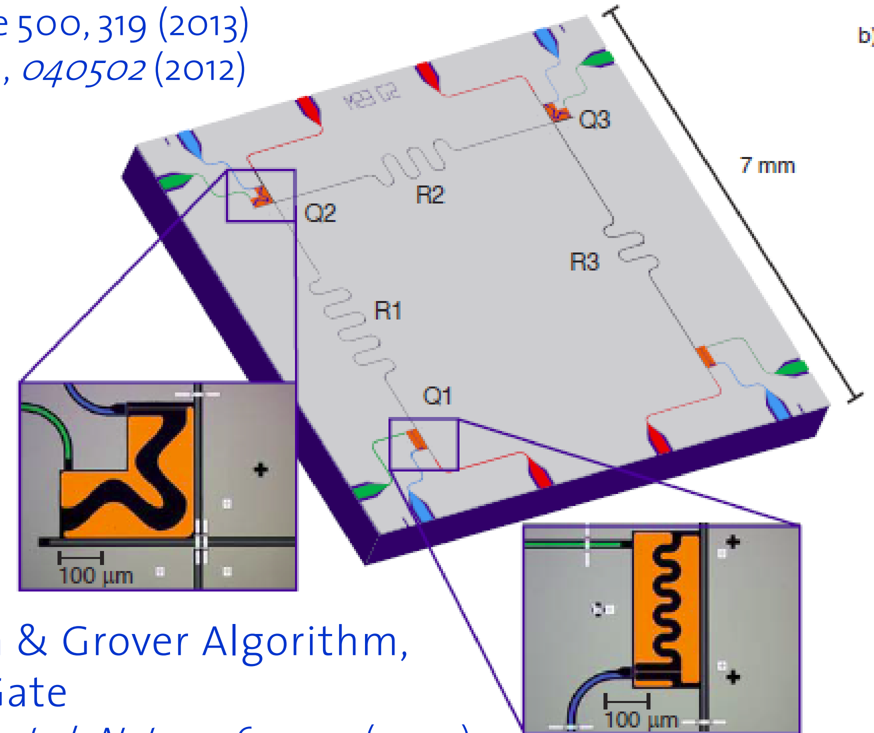
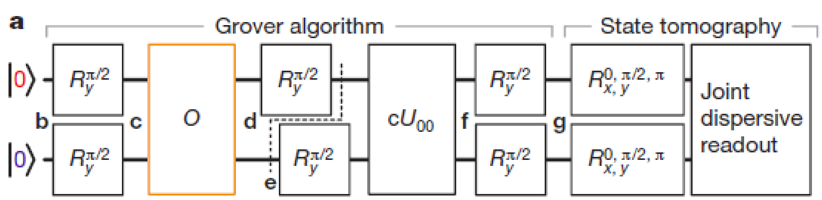
R. Barends *et al.*, *Nature* 508, 500 (2014)





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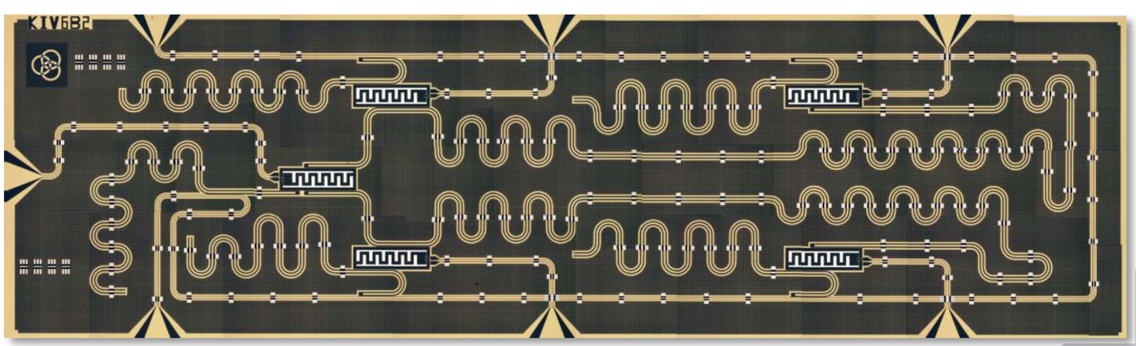
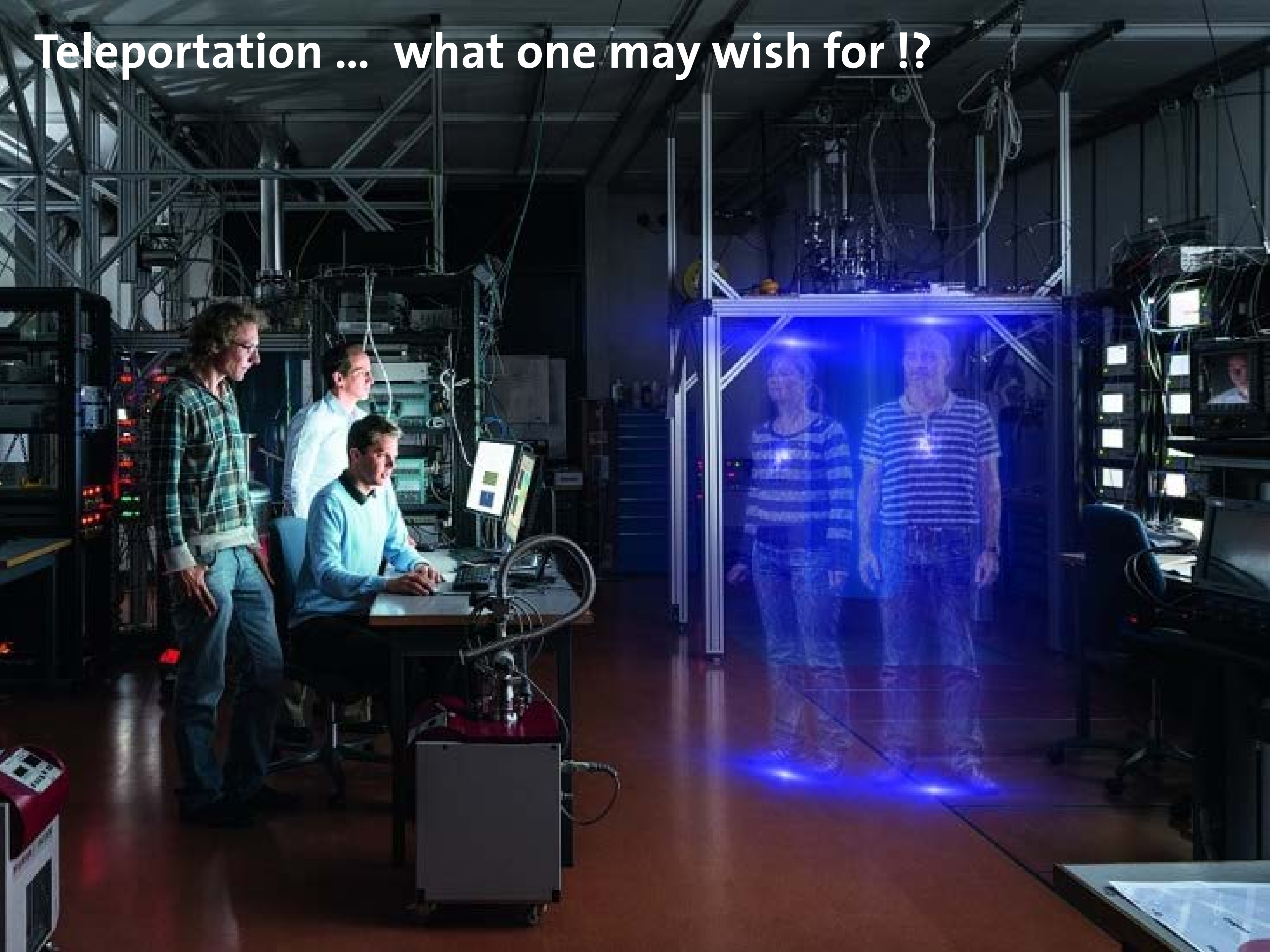
A. Fedorov *et al.*, *Nature* 481, 170 (2012)

Error Correction
M. Reed *et al.*, *Nature* 481, 382 (2012)
Corcoles et al., *Nat. Com.* 6, 6979 (2015)
Ristè et al., *Nat. Com.* 6, 6983 (2015)
Kelly et al., *Nature* 519, 66-69 (2015)



Teleportation ... what one may wish for !?



Teleportation in the Quantum World

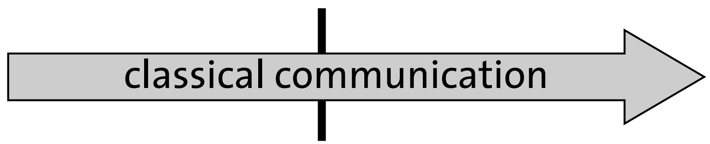
Objective:

- 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 now 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

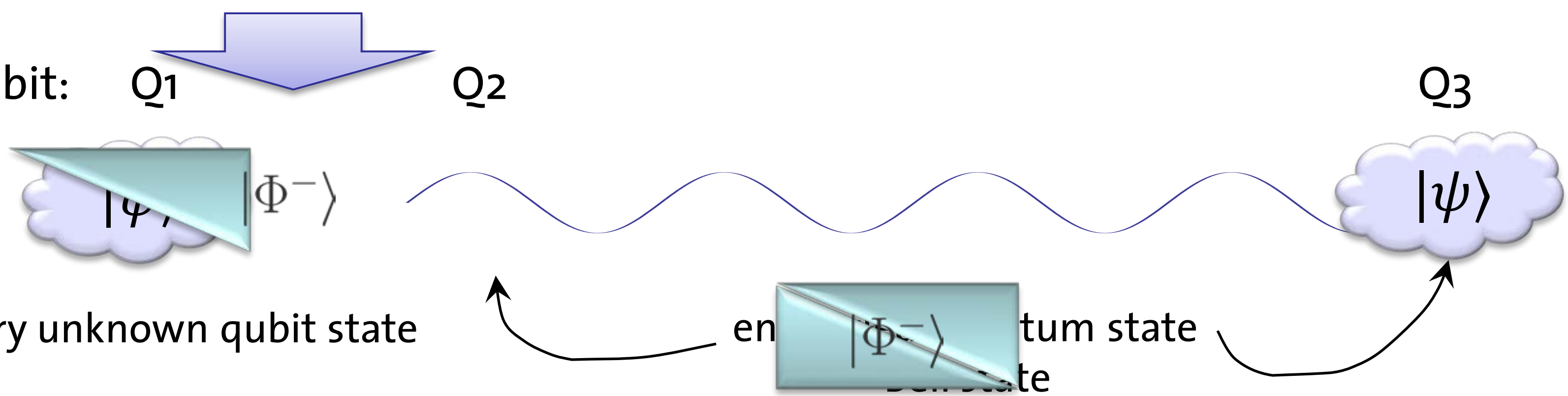
Resources:

- a pair of entangled qubits (Q1 + Q2)

Alice

Bob

Bell measurement



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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

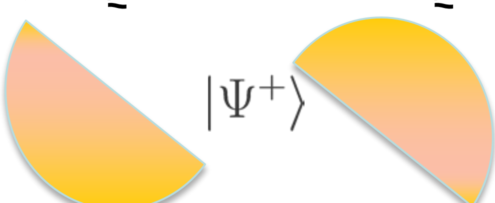
Alice

O1

classical communication

Bob

Qubit: Q1 Q2



Q3

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

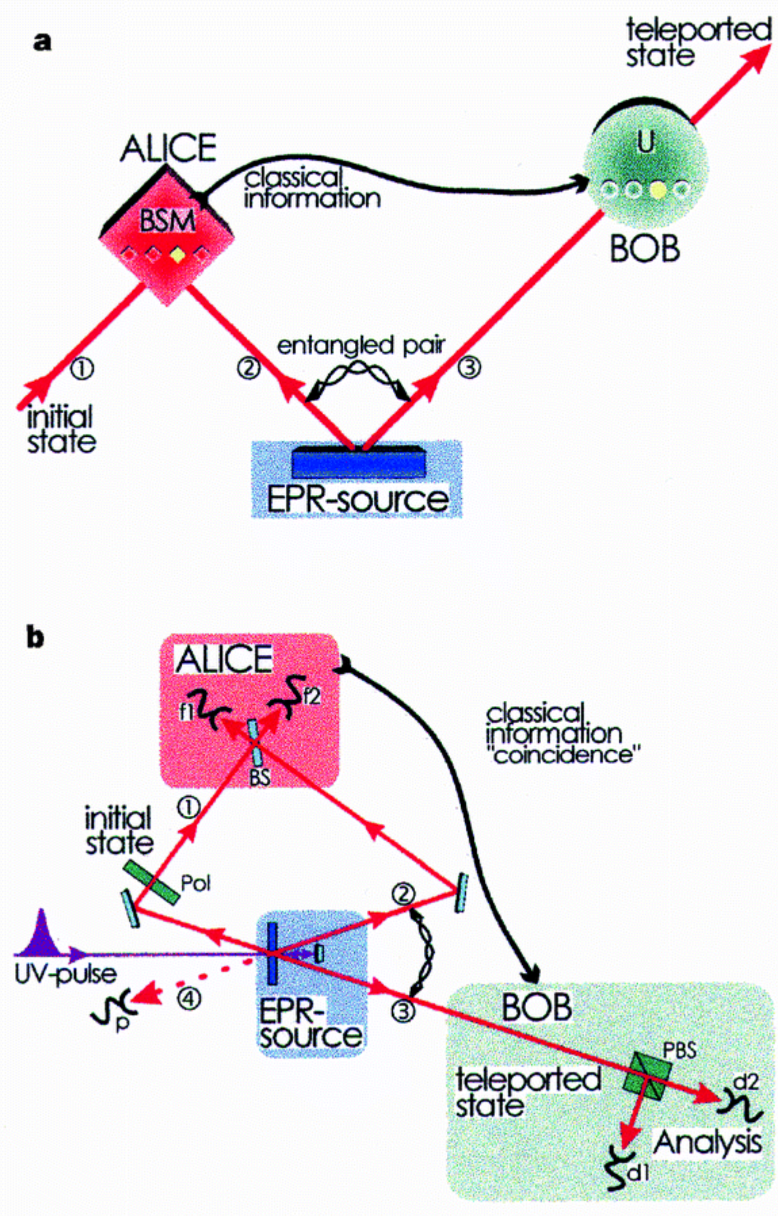
A. Furusawa, *et al., Science*, 282, 706–709 (1998)
N. Lee, *et al., Science*, 332, 330–333 (2011)
S. Takeda, *et al., Nature*, 500, 315–318 (2013)

Semiconductor Quantum Dots

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

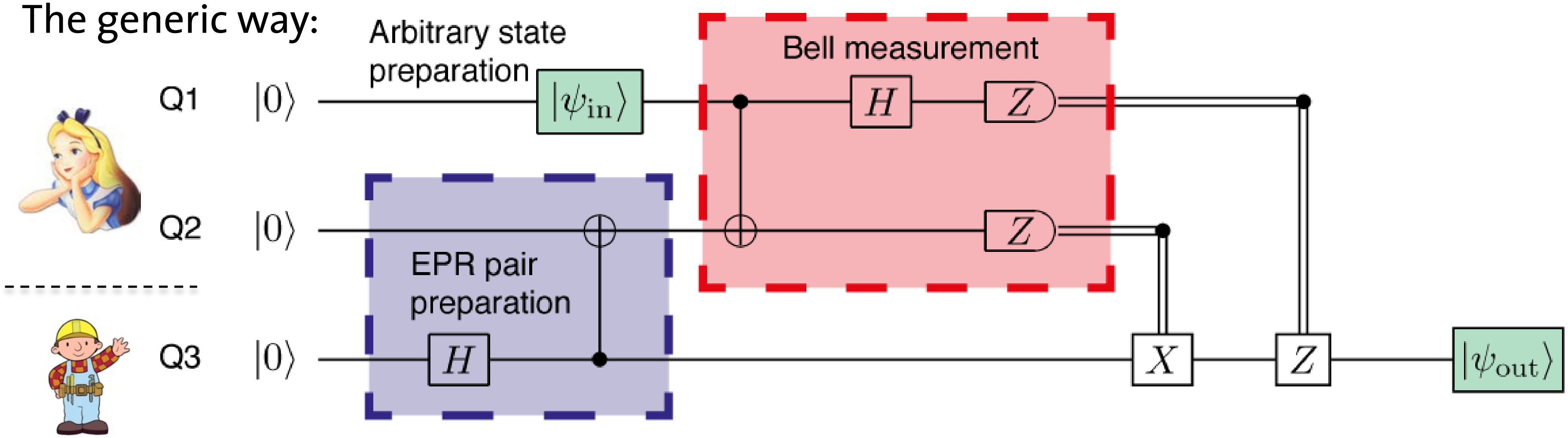
NV Centers

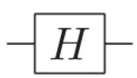
W. Pfaff, et al., *Science* 345, 532 (2014)



Implementation of the Teleportation Protocol

The generic way:





Hadamard

Rotation around Y-axis

Controlled NOT

Controlled phase gate

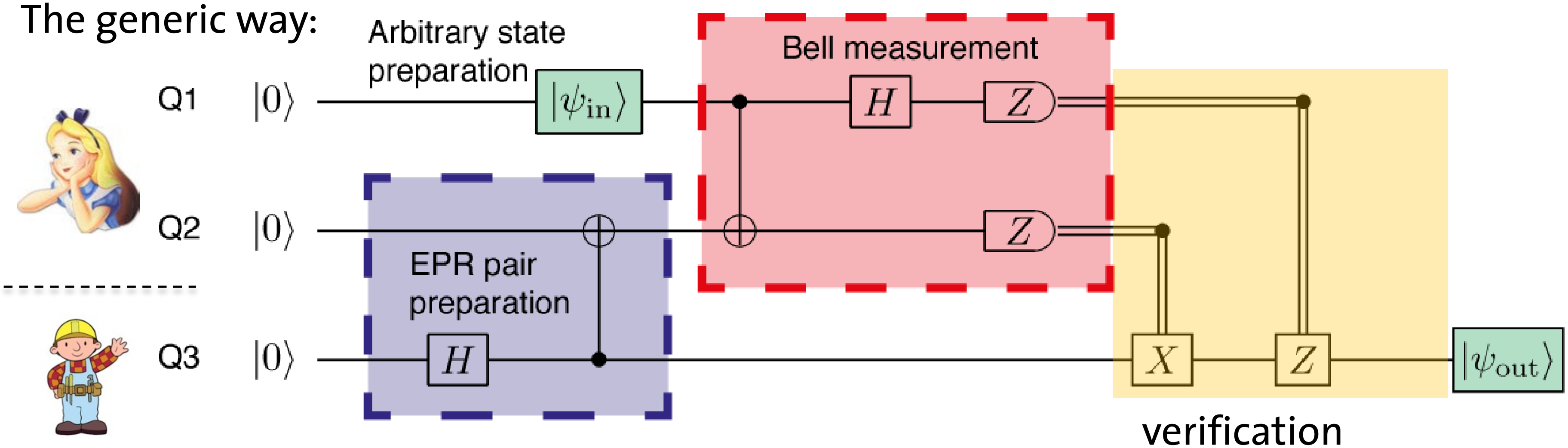
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

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

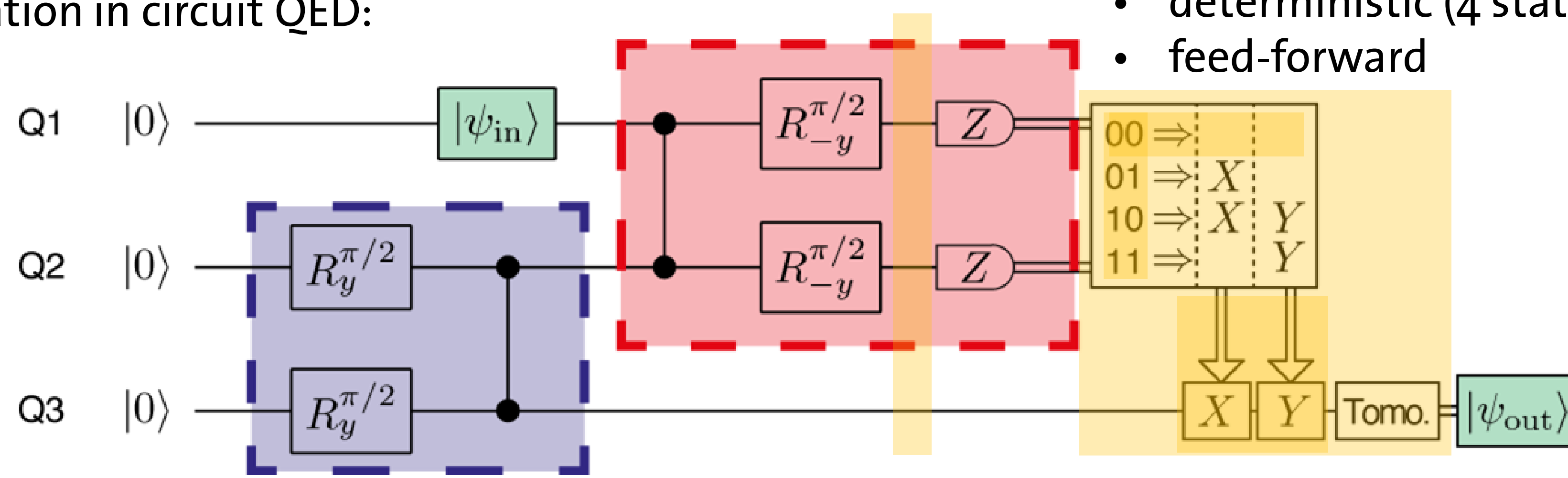
The generic way:



verification

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

Realization in circuit QED:

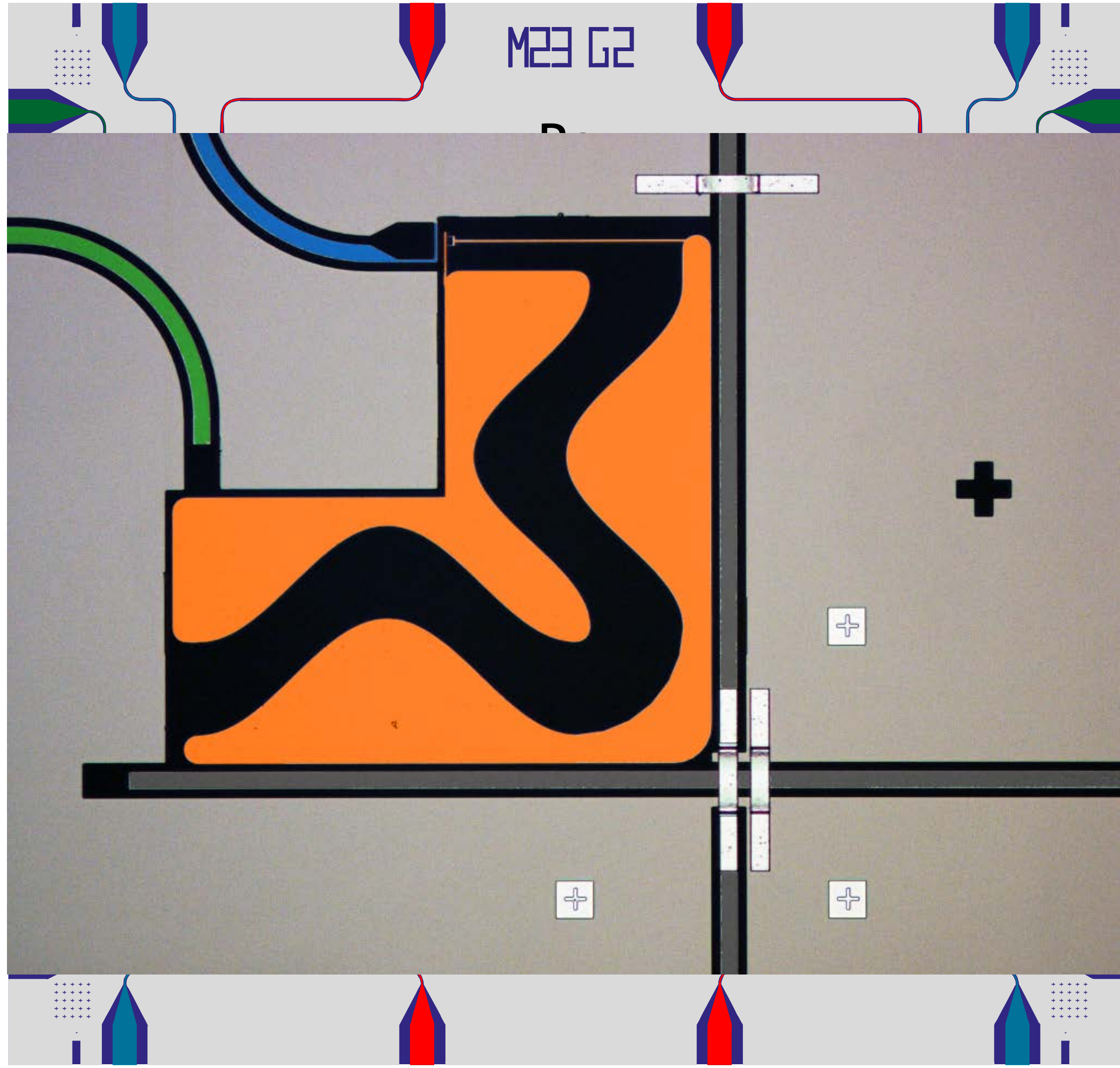


Steffen *et al.*, *Nature* 500, 319 (2013)

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

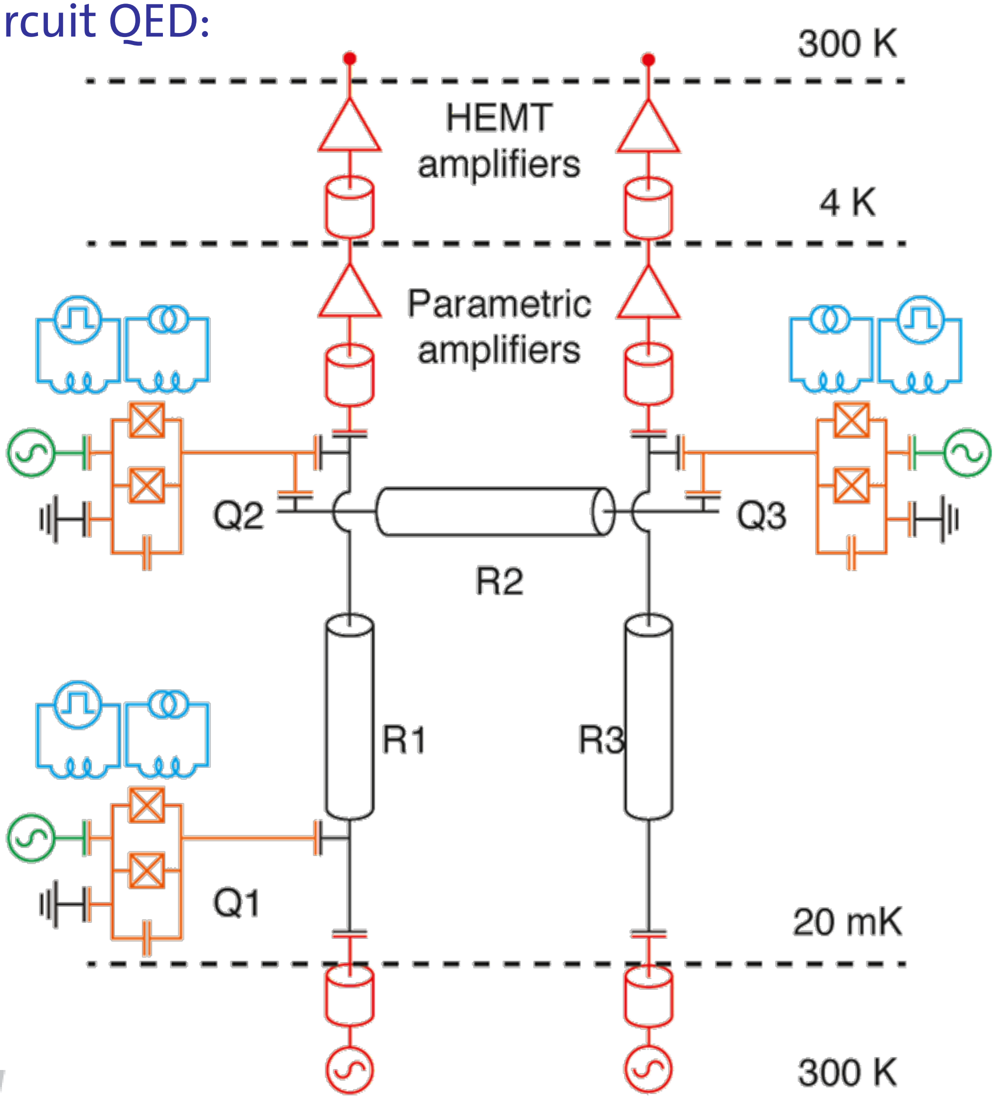
Yurke and Buks, *J. Lightwave Tech*. 24, 5054 (2006).
Castellanos-Beltran et al., *Nat. Phys.* 4, 929 (2008).
Eichler *et al., PRL* 107, 113601 (2011).



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

The Circuit

12-port quantum device based on circuit QED:



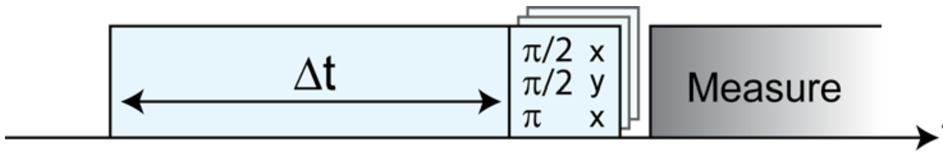
Device highlights:

- 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

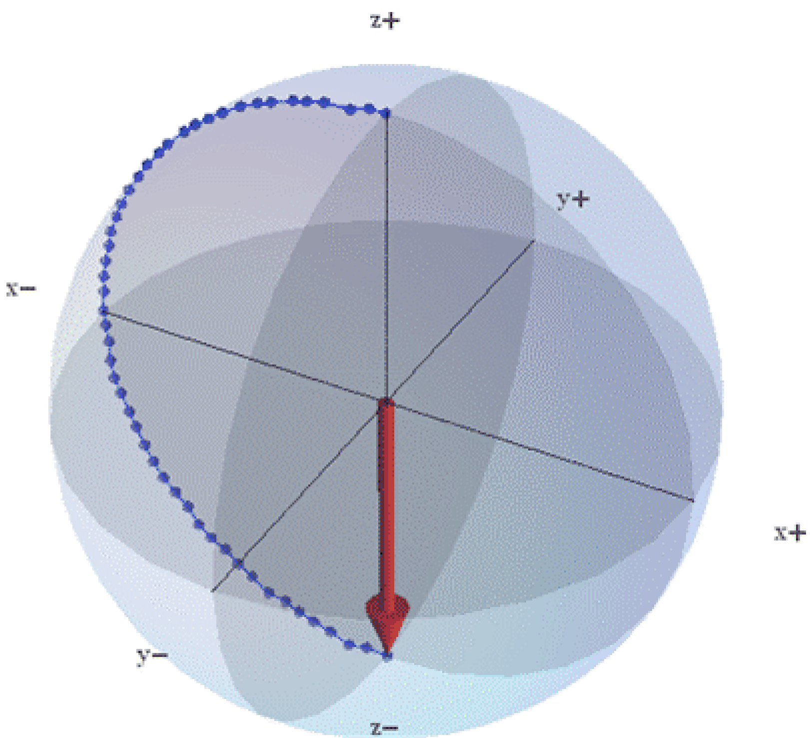
Steffen *et al.*, *Nature* 500, 319 (2013)

Single Qubit Gates

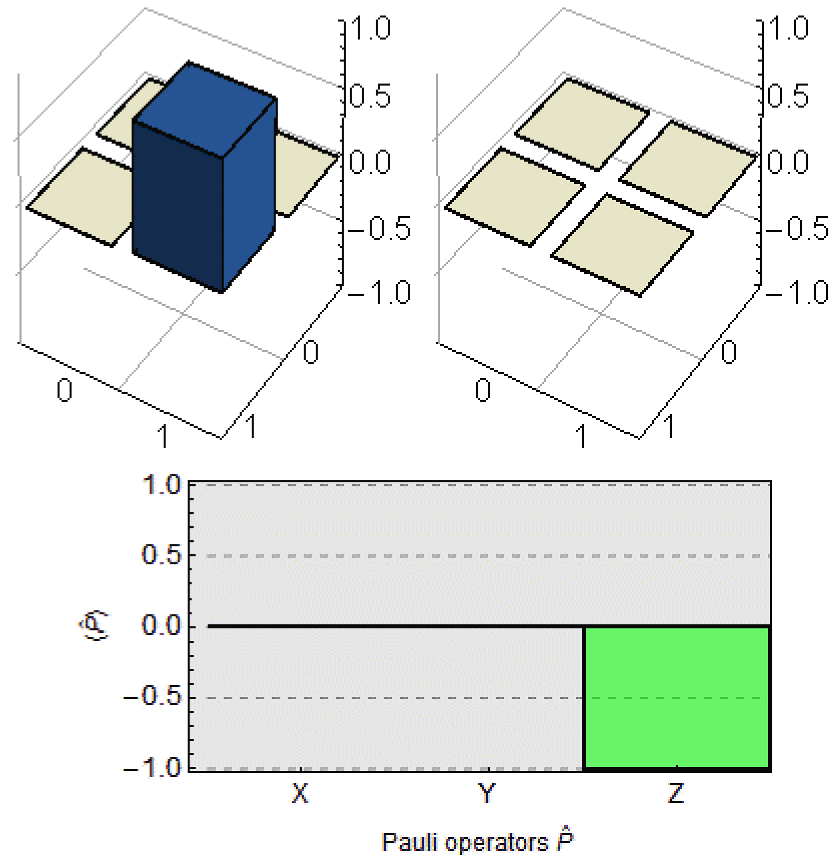
Pulse sequence for qubit rotation and readout:



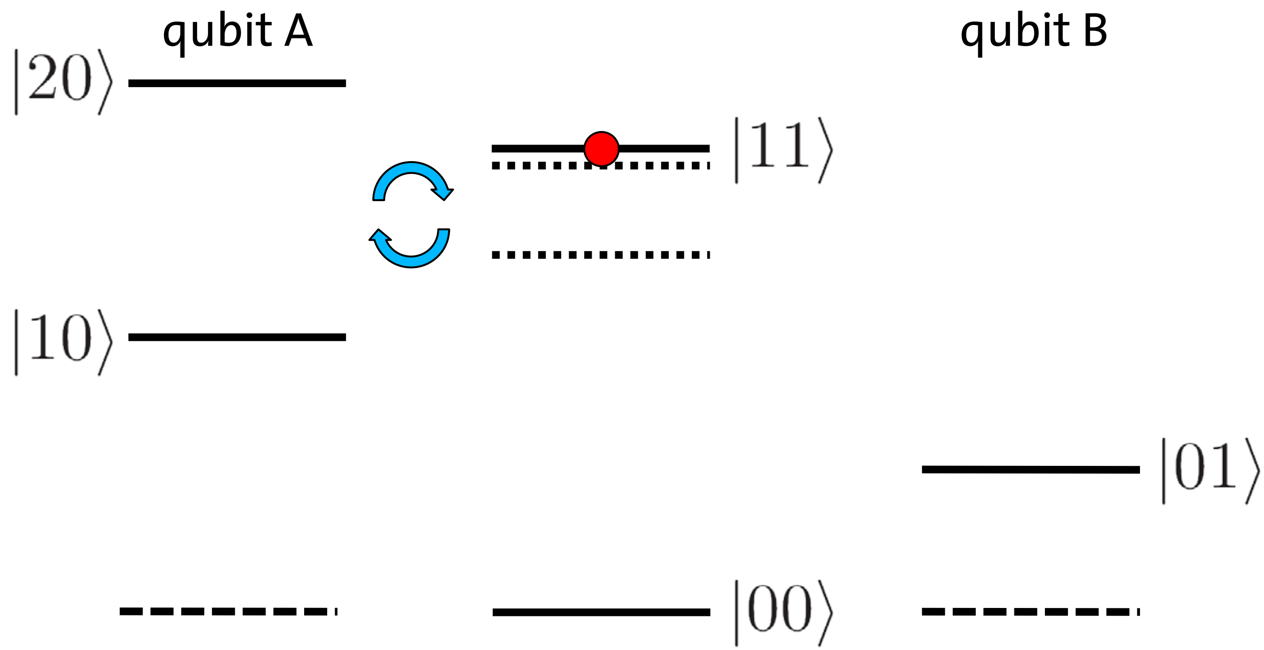
experimental Bloch vector:



experimental density matrix and Pauli set:



Controlled Phase Gate



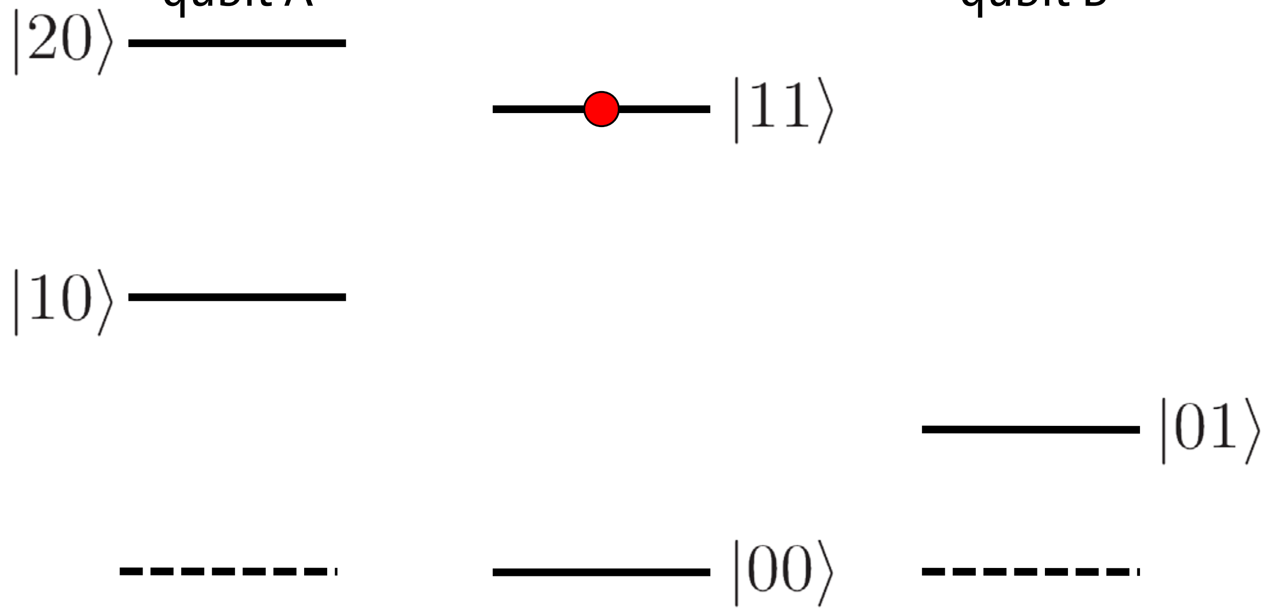
$$|11\rangle \longrightarrow i|02\rangle \longrightarrow -|11\rangle$$

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



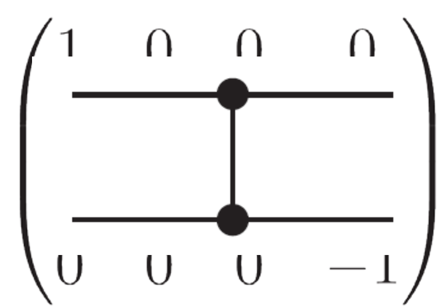
Tune levels into resonance using magnetic field

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.

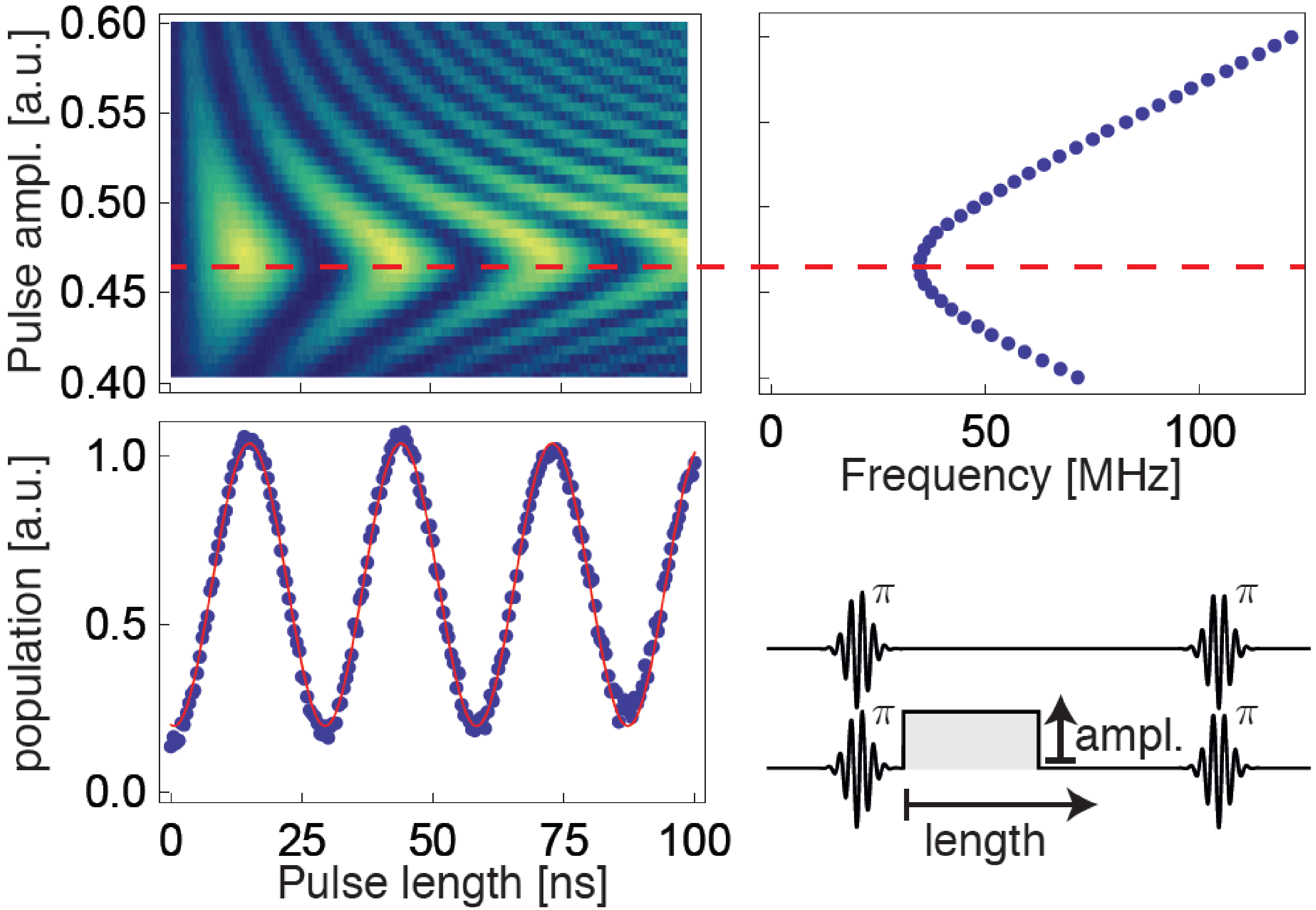
$$|11\rangle \longrightarrow i|02\rangle \longrightarrow -|11\rangle$$
$$|01\rangle \longrightarrow |01\rangle$$
$$|10\rangle \longrightarrow |10\rangle$$
$$|00\rangle \longrightarrow |00\rangle$$

C-Phase gate:



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

Experimental C-PHASE Gate



Process Tomography: C-Phase Gate

arbitrary quantum process

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

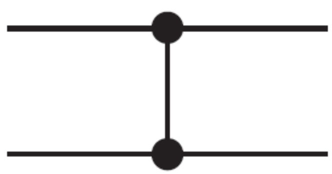
decomposed into

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

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

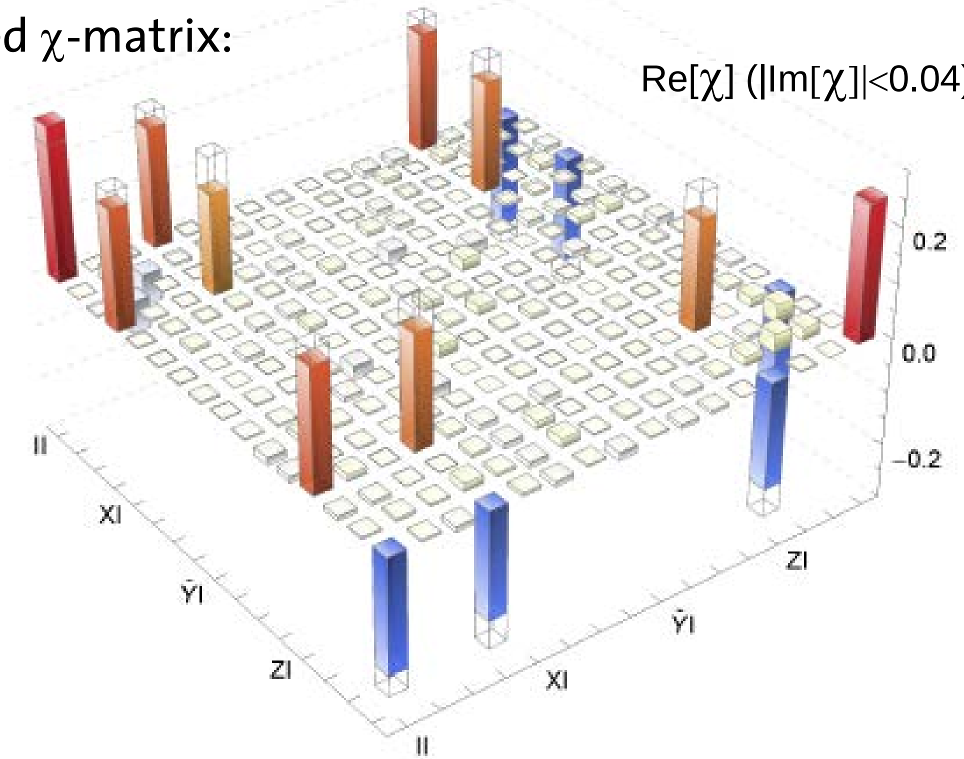
χ is a positive semi definite Hermitian matrix characteristic for the process

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:



$$F = \mathrm{Tr}[\chi_{\mathrm{meas}}\chi_{\mathrm{ideal}}] > 0.90$$

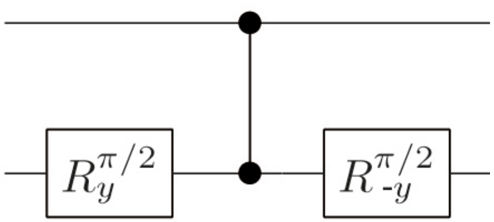
Process Tomography: C-NOT Gate

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

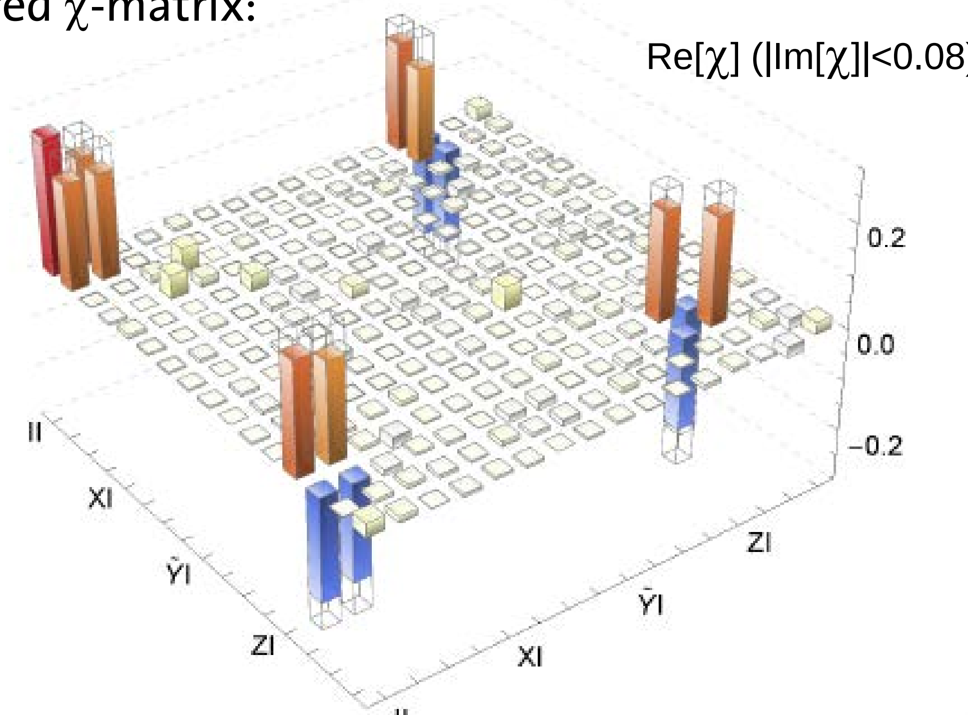
χ is a positive semi definite Hermitian matrix characteristic for the process

Controlled-NOT gate



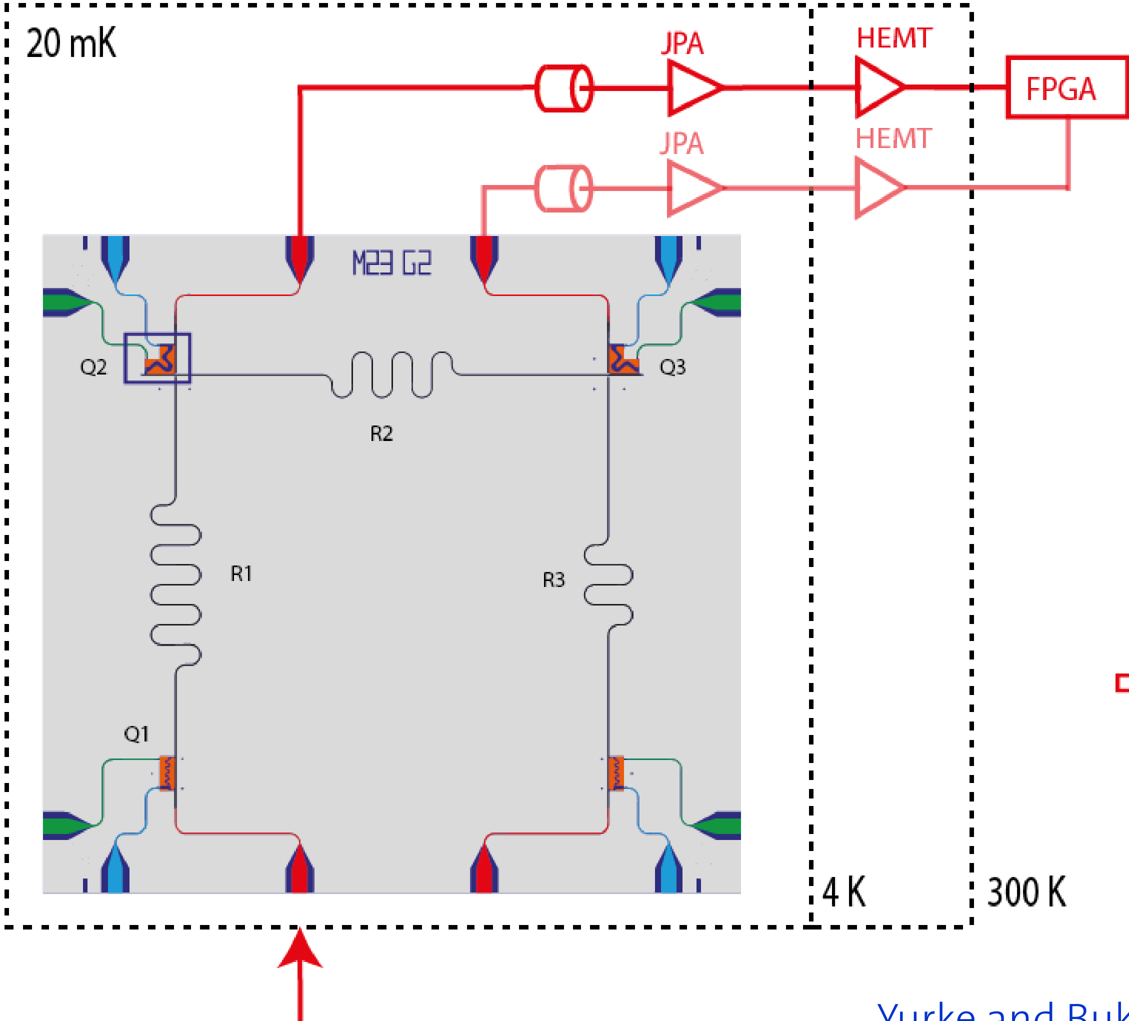
$$\mathrm{C-NOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

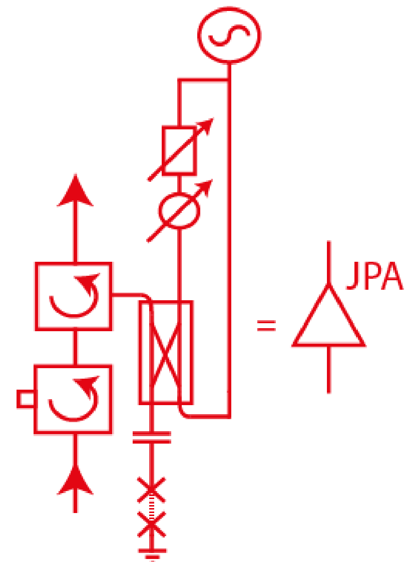
Measured χ-matrix:



$$F = \mathrm{Tr}[\chi_{\mathrm{meas}}\chi_{\mathrm{ideal}}] = 0.81$$

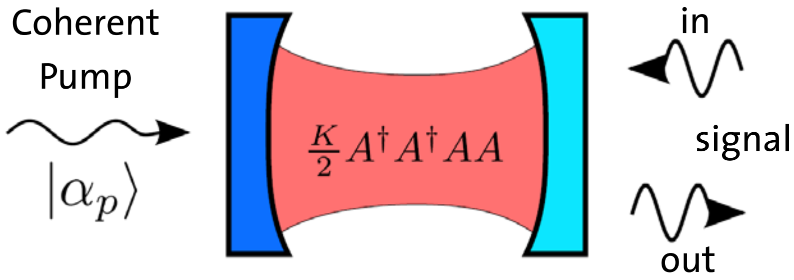
Dispersive Qubit Readout with Parametric Amplifiers



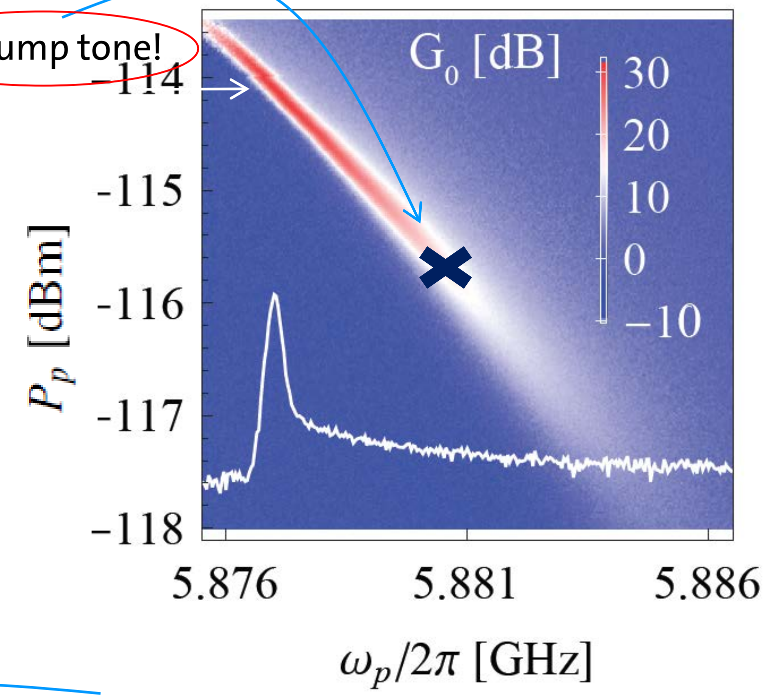


Yurke and Buks, *J. Lightwave Tech.* 24, 5054 (2006)
Castellanos-Beltran et al., *Nat. Phys.* 4, 929 (2008)
Eichler *et al., PRL* 107, 113601 (2011)
R. Vijay *et al, PRL* 106, 110502 (2011)

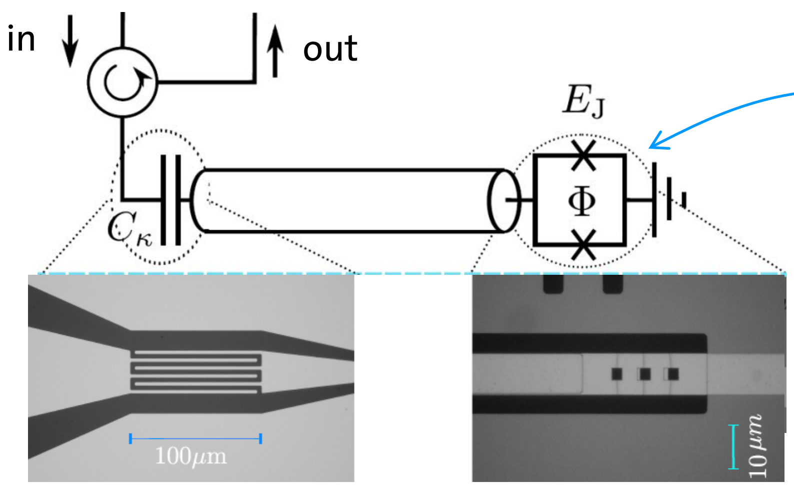
Near Quantum-Limited Parametric Amplifier



Measured Gain



Circuit QED implementation:



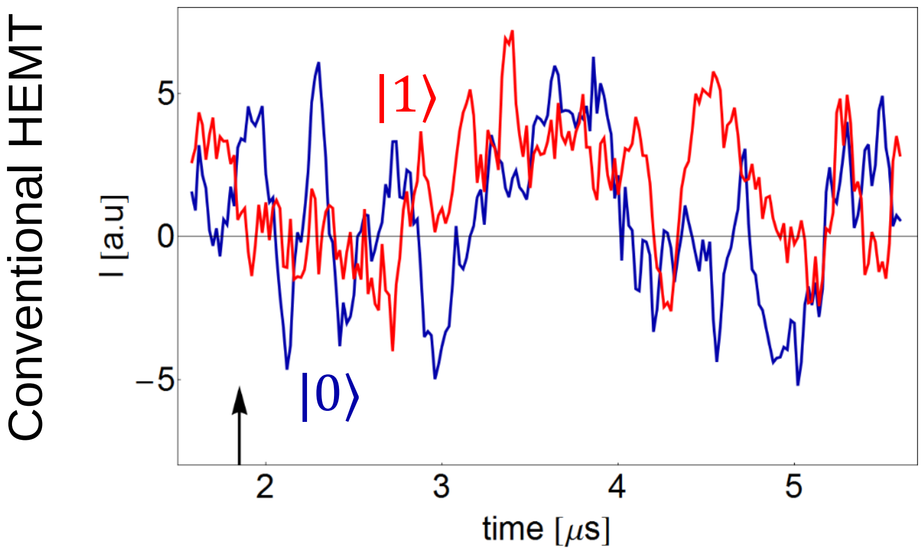
SQUID(-array) provides required nonlinearity

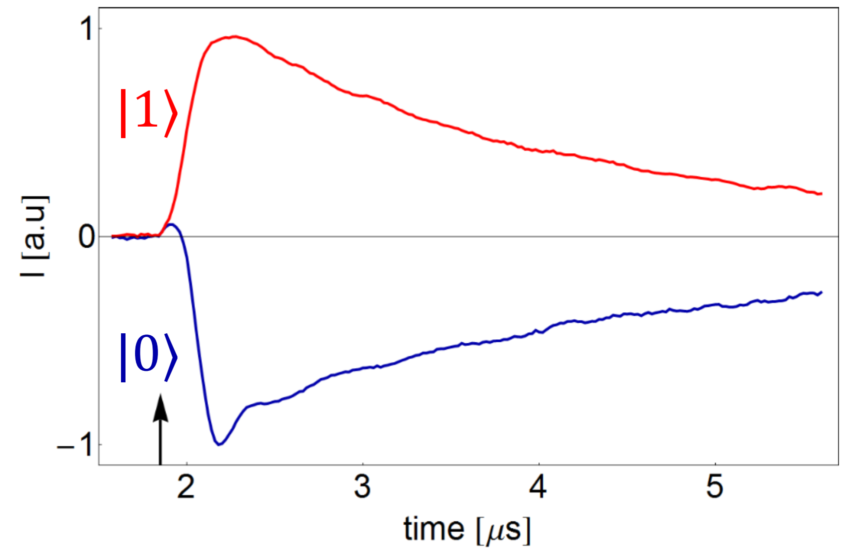
Eichler *et al.*, EPJ Quantum Technology 1, 2 (2014)
Eichler *et al.*, *Phys. Rev. Lett.* 107, 113601 (2011)
Eichler et al., *Phys. Rev. Lett.* 113, 110502 (2014)
Caves, *Phys. Rev. D* 26, 1817 (1982)
Yurke and Buks, *J. Lightwave Tech.* 24, 5054 (2006)
Castellanos-Beltran *et al.*, *Nat. Phys.* 4, 929 (2008)

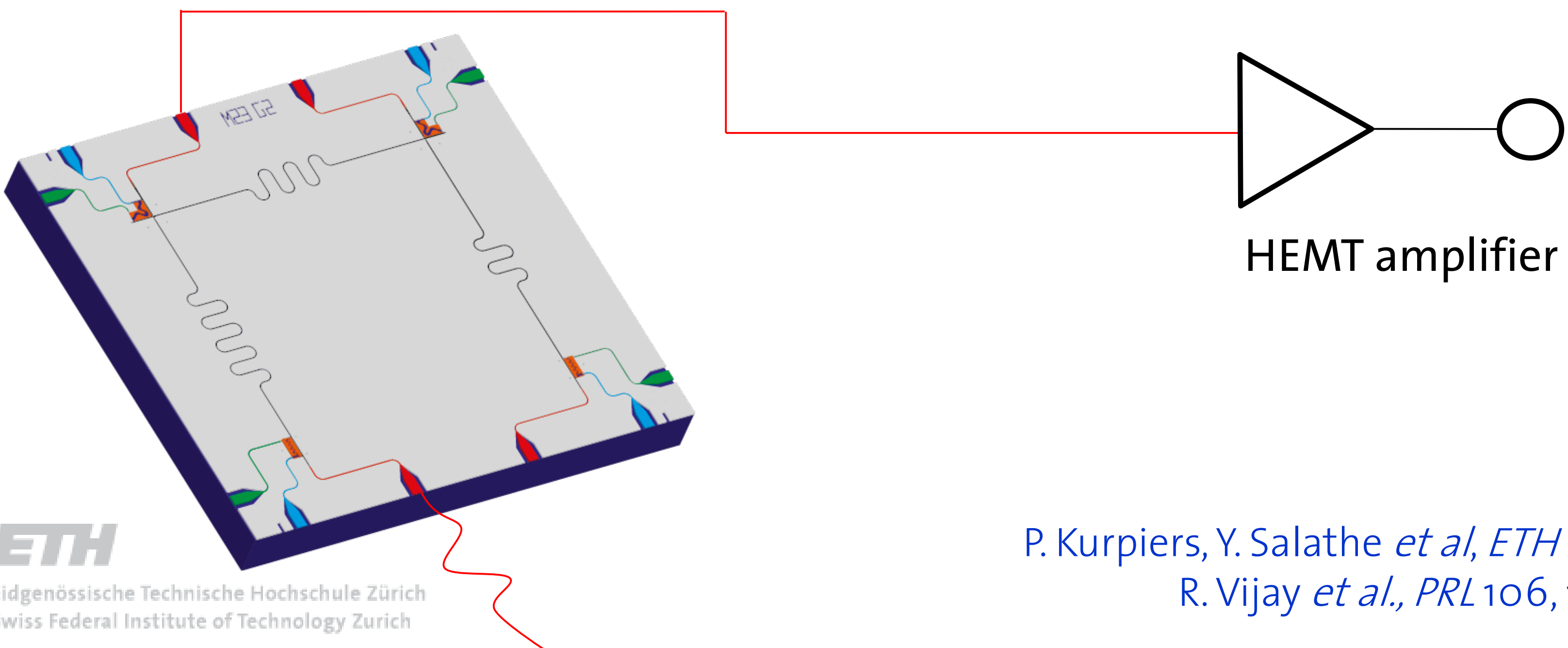
Single-Shot Single-Qubit Readout

single-shot measurements:

averaged measurements (8 10⁴):



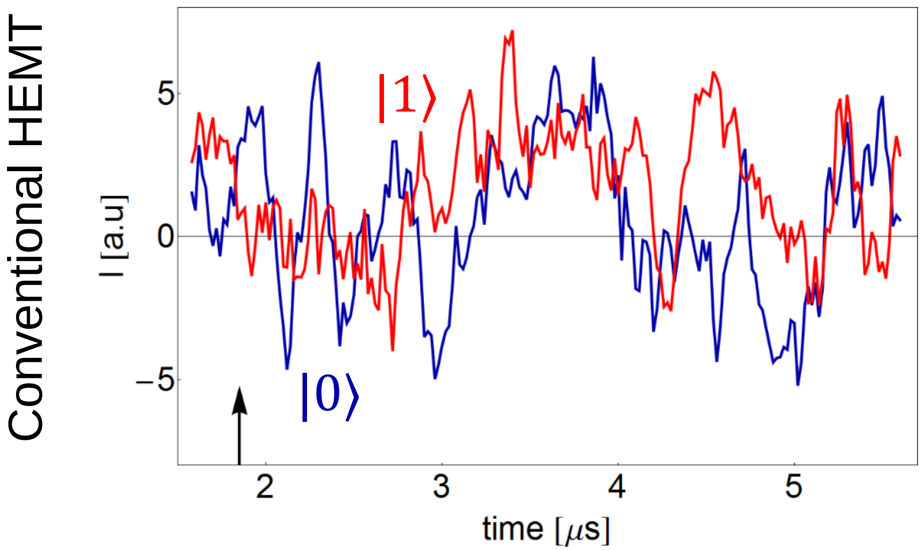




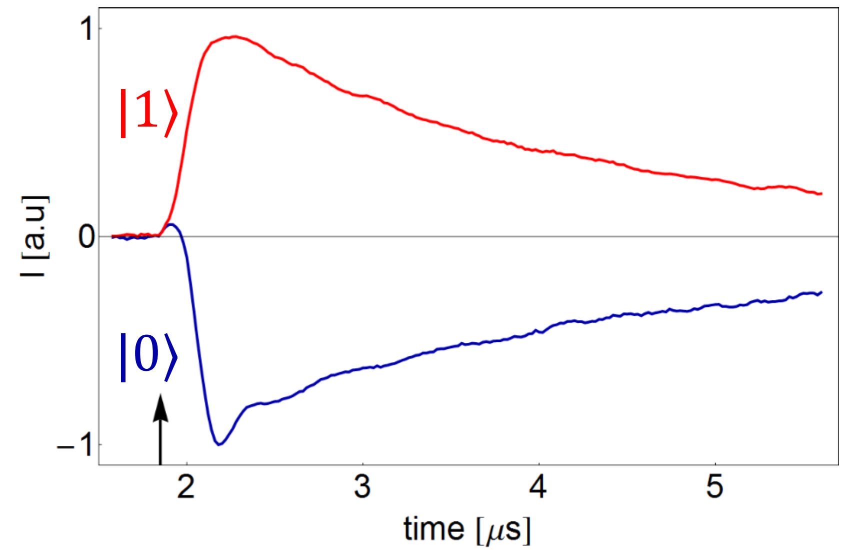
P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)
R. Vijay *et al.*, *PRL* 106, 110502 (2011)

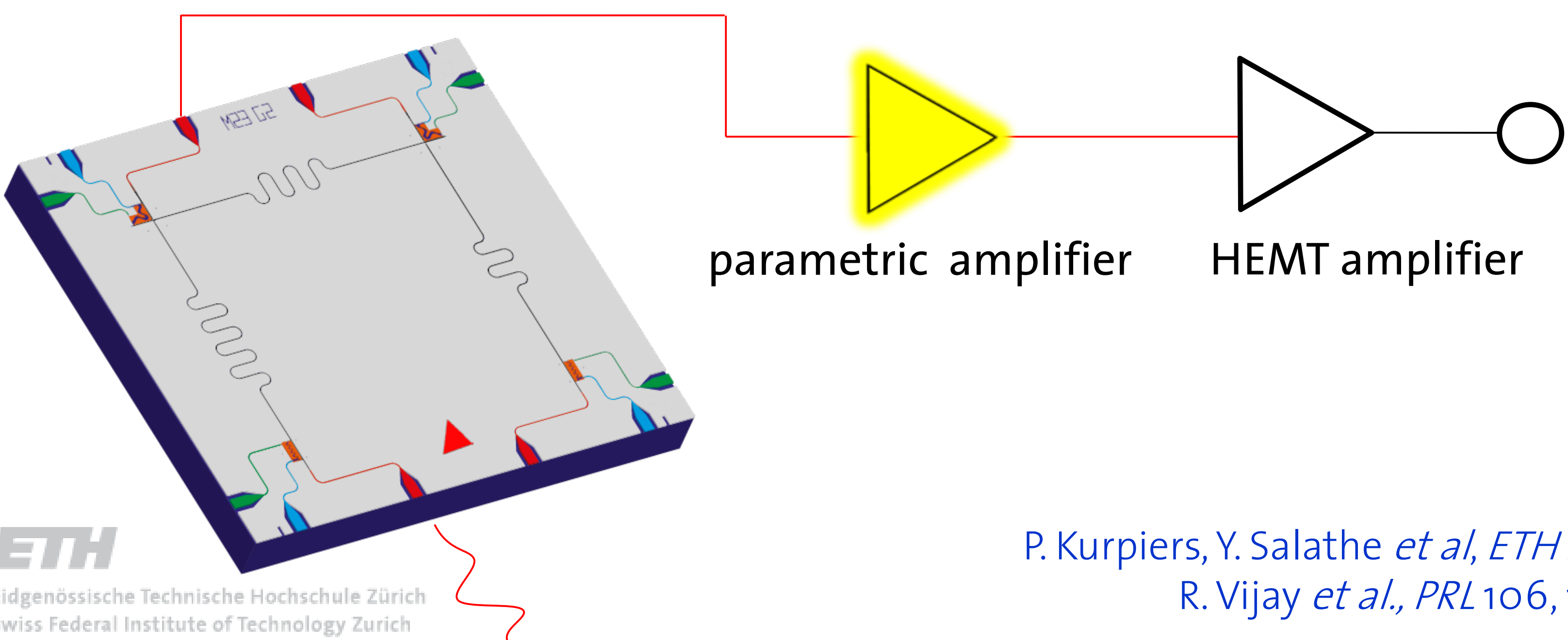
Single-Shot Single-Qubit Readout

single-shot measurements:



averaged measurements (8 10⁴):





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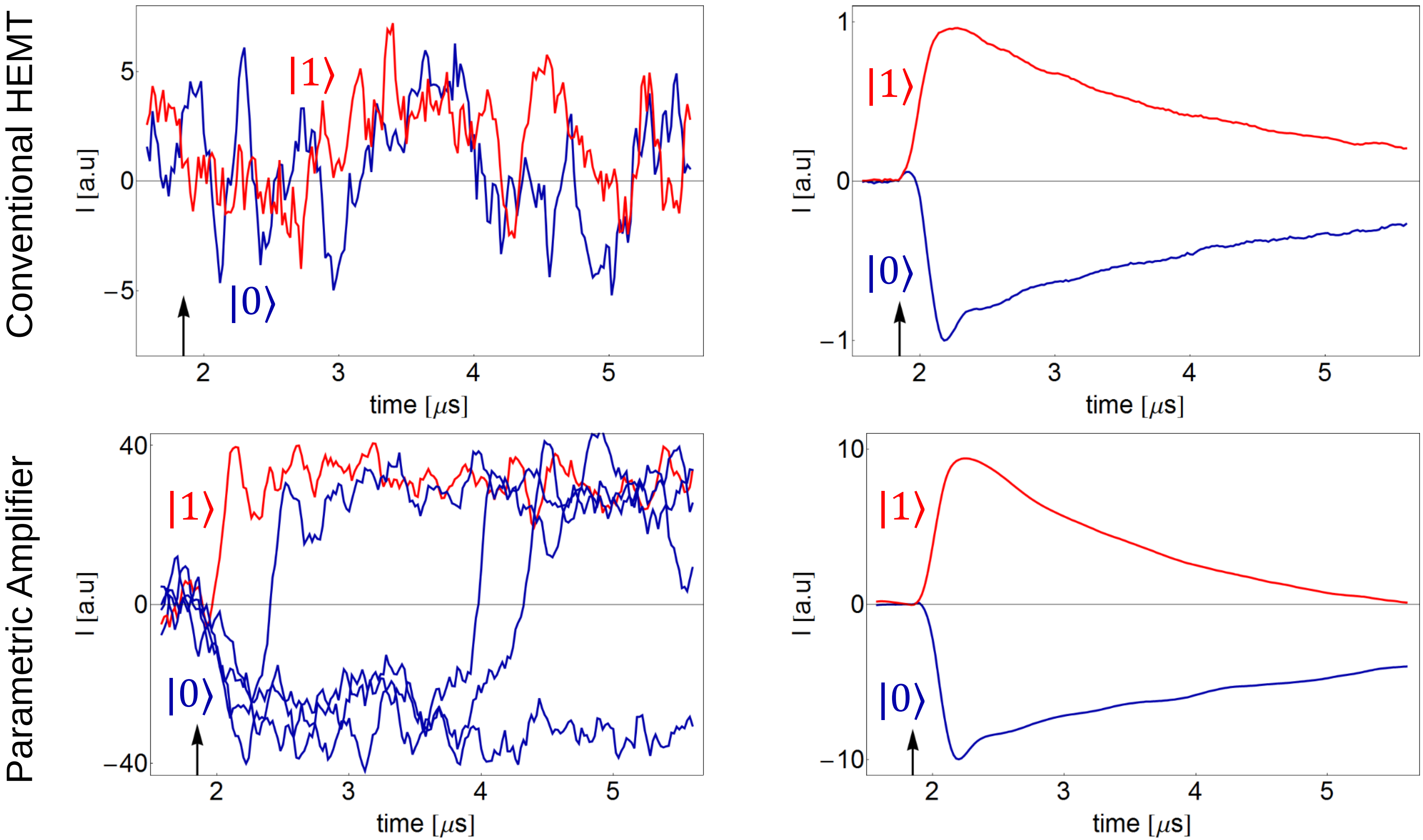
Swiss Federal Institute of Technology Zurich

P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)
R. Vijay *et al.*, *PRL* 106, 110502 (2011)

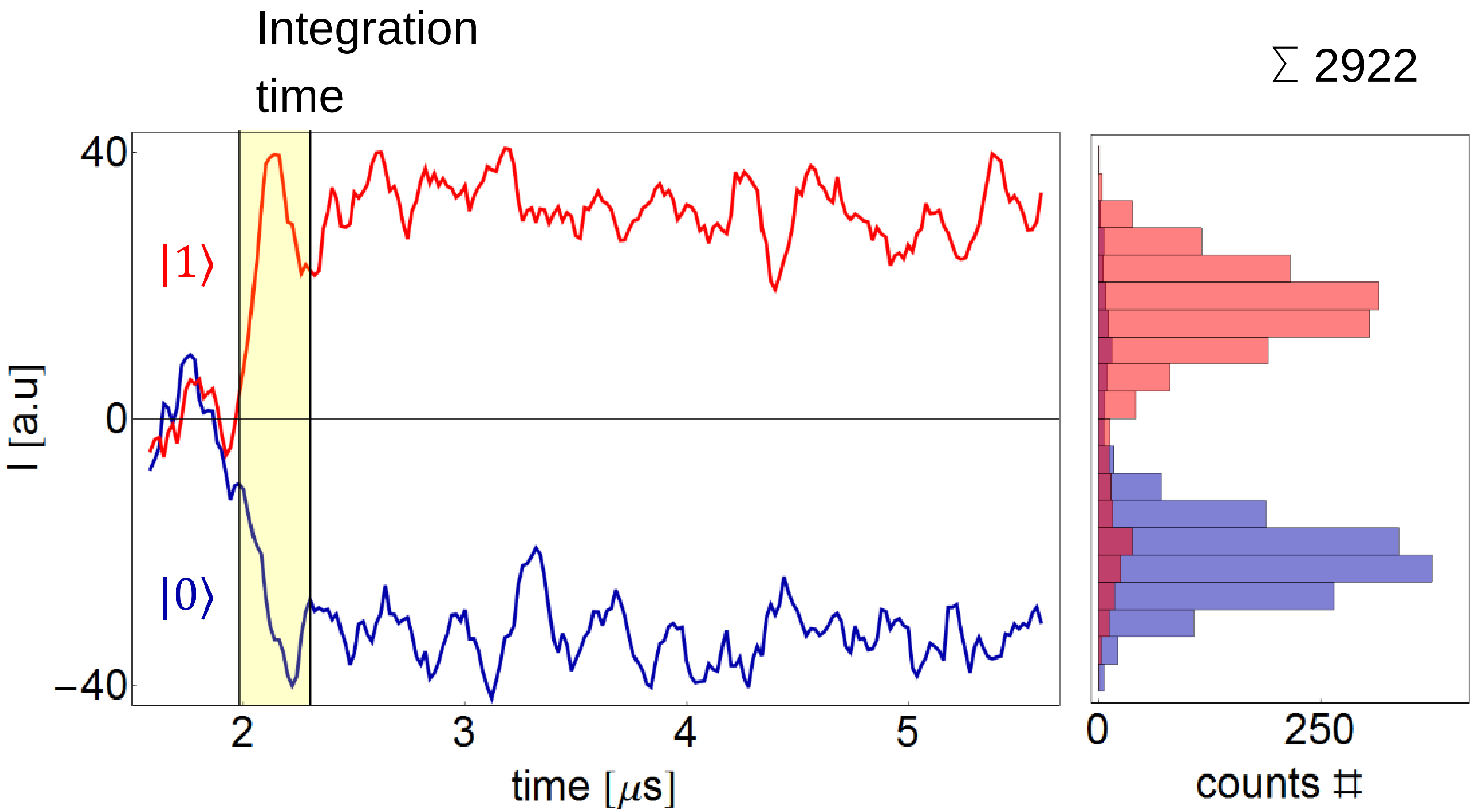
Single-Shot Single-Qubit Readout

single-shot measurements: averaged measurements (8 10^4):



P. Kurpiers, Y. Salathe *et al, ETH Zurich* (2013)
R. Vijay *et al., PRL* 106, 110502 (2011)

Statistics of Integrated Single-Shot Readout

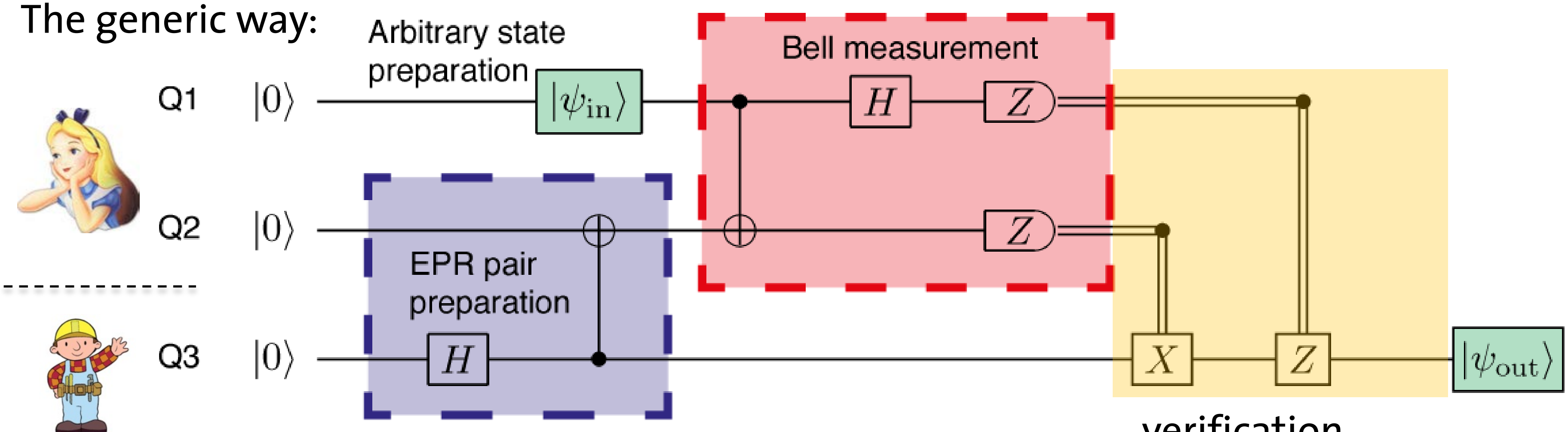


P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)


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

Implementation of the Teleportation Protocol

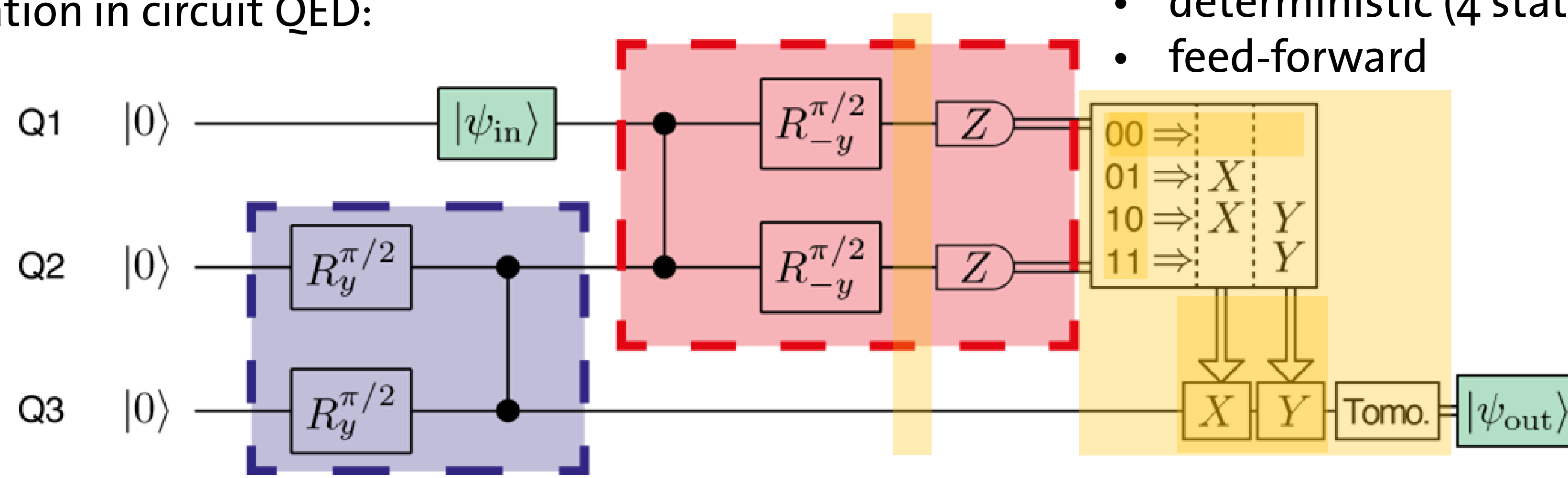
The generic way:



verification

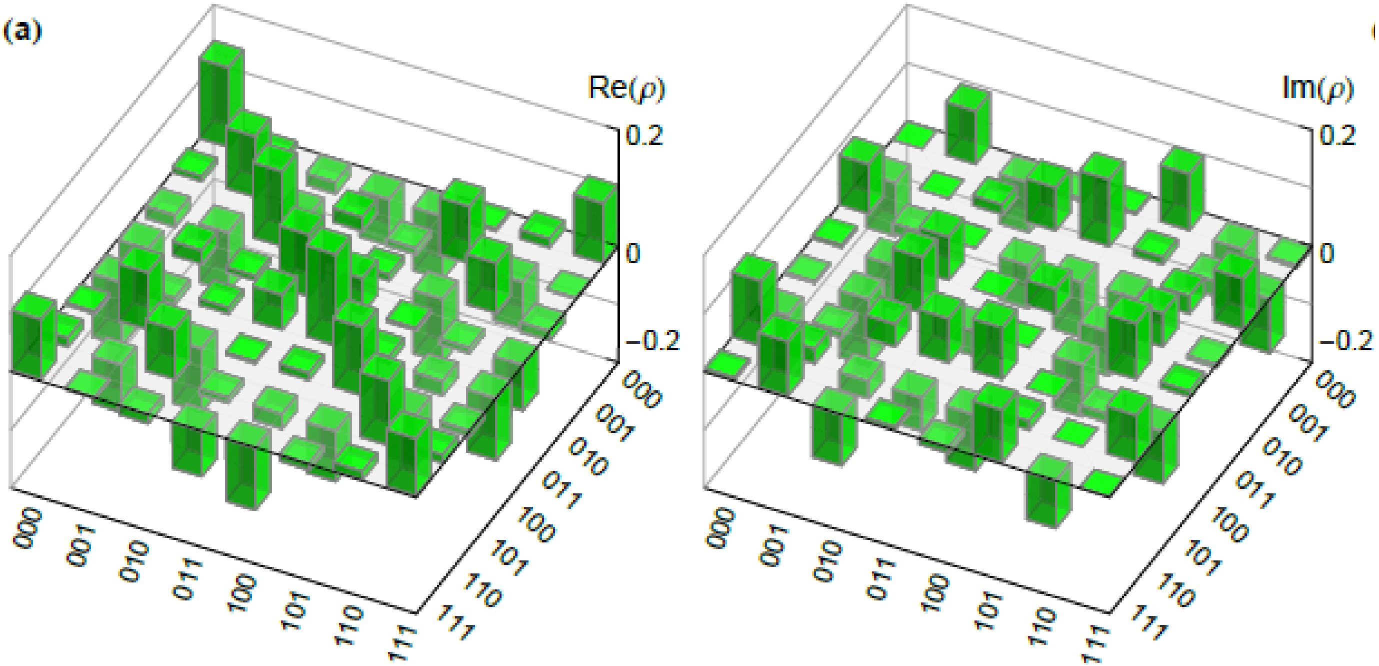
- 3-qubit tomography
- post selection (1 state)
- deterministic (4 states)
- feed-forward

Realization in circuit QED:



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

Characterizing the Full System State



measured 3-qubit entangled state after execution of circuit:

input state: $|\psi\rangle = (|0\rangle - i|1\rangle)/\sqrt{2}$

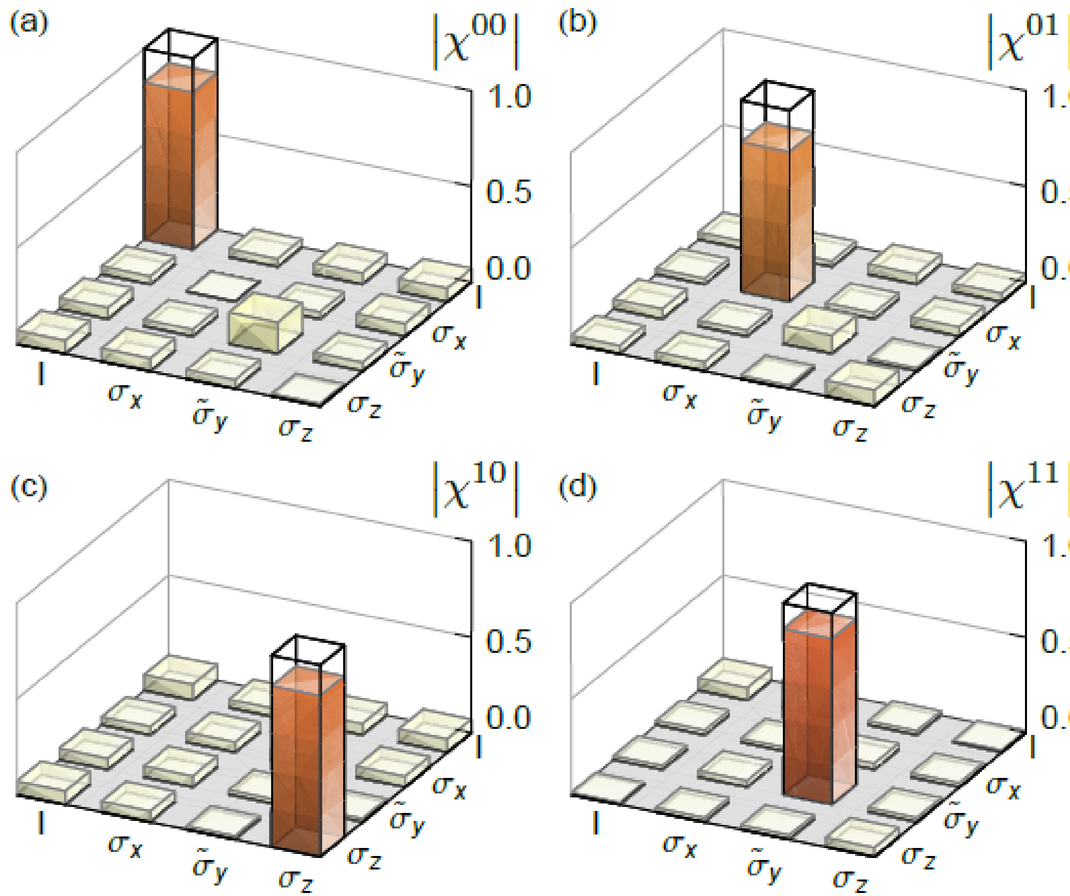
density matrix of teleported state when projecting qubits A & B onto |00>

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

Benchmarking the Teleportation Process

procedure:

- prepare set of input states
- run circuit
- perform tomography on full system state
- project on basis states for qubits A and B
- analyze process acting on qubit C (see a-d)
- average fidelity of teleportation 83%

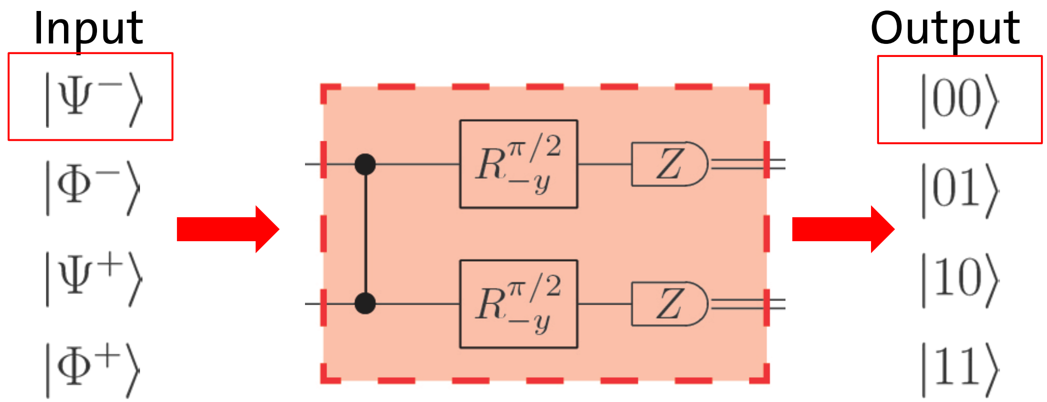


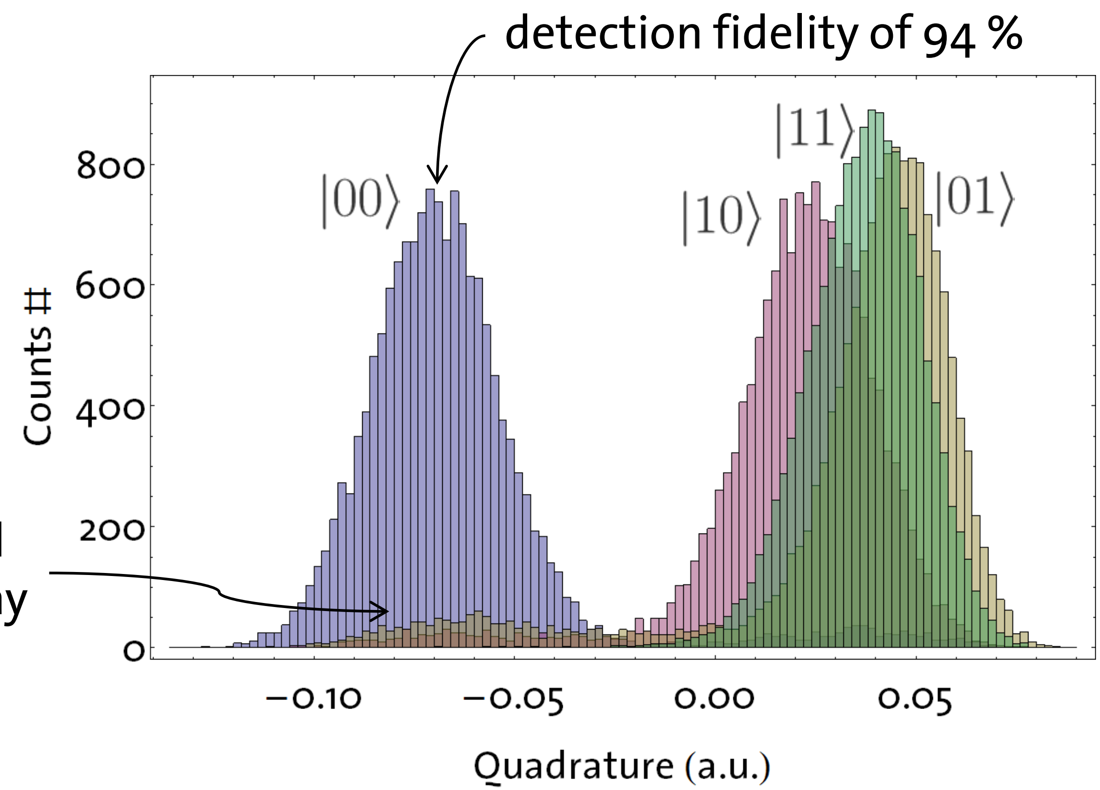
summary:

- verified operation of teleportation circuit & demonstrated 3-qubit quantum processor
- without single-shot projective read-out or feed-back

M. Baur *et al., Phys. Rev. Lett.* 108, 040502 (2012)

Post-Selected Teleportation: Bell Measurement





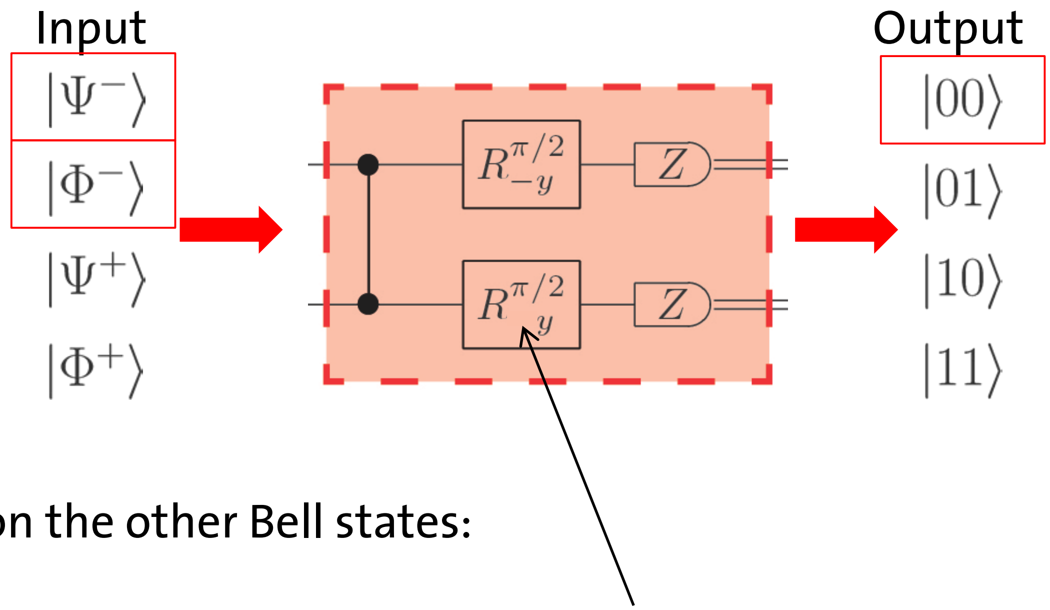
Operate parametric amplifier in phase sensitive mode

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

Limited by decay

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

Post-Selecting Every State Individually

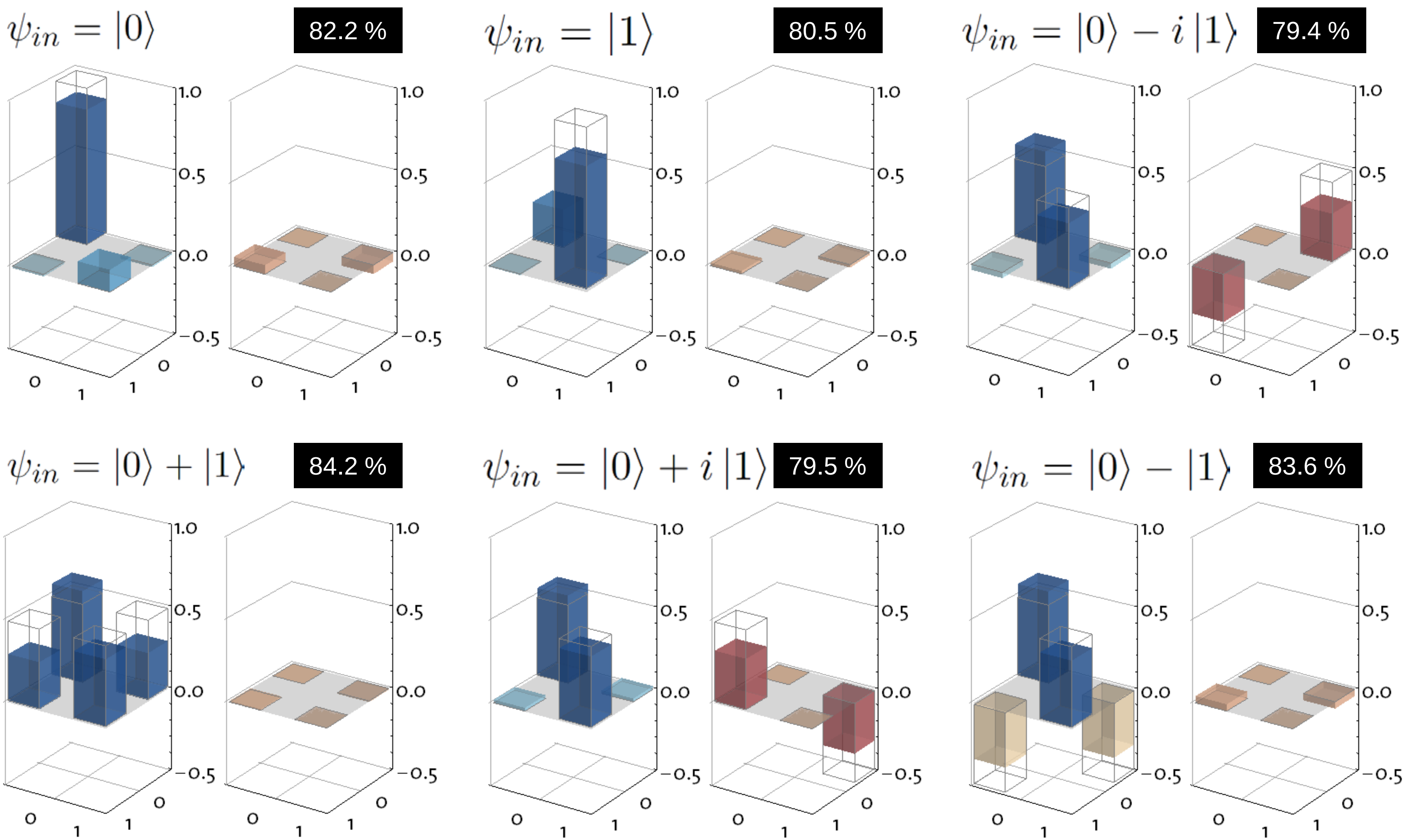


How to post-select on the other Bell states:

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

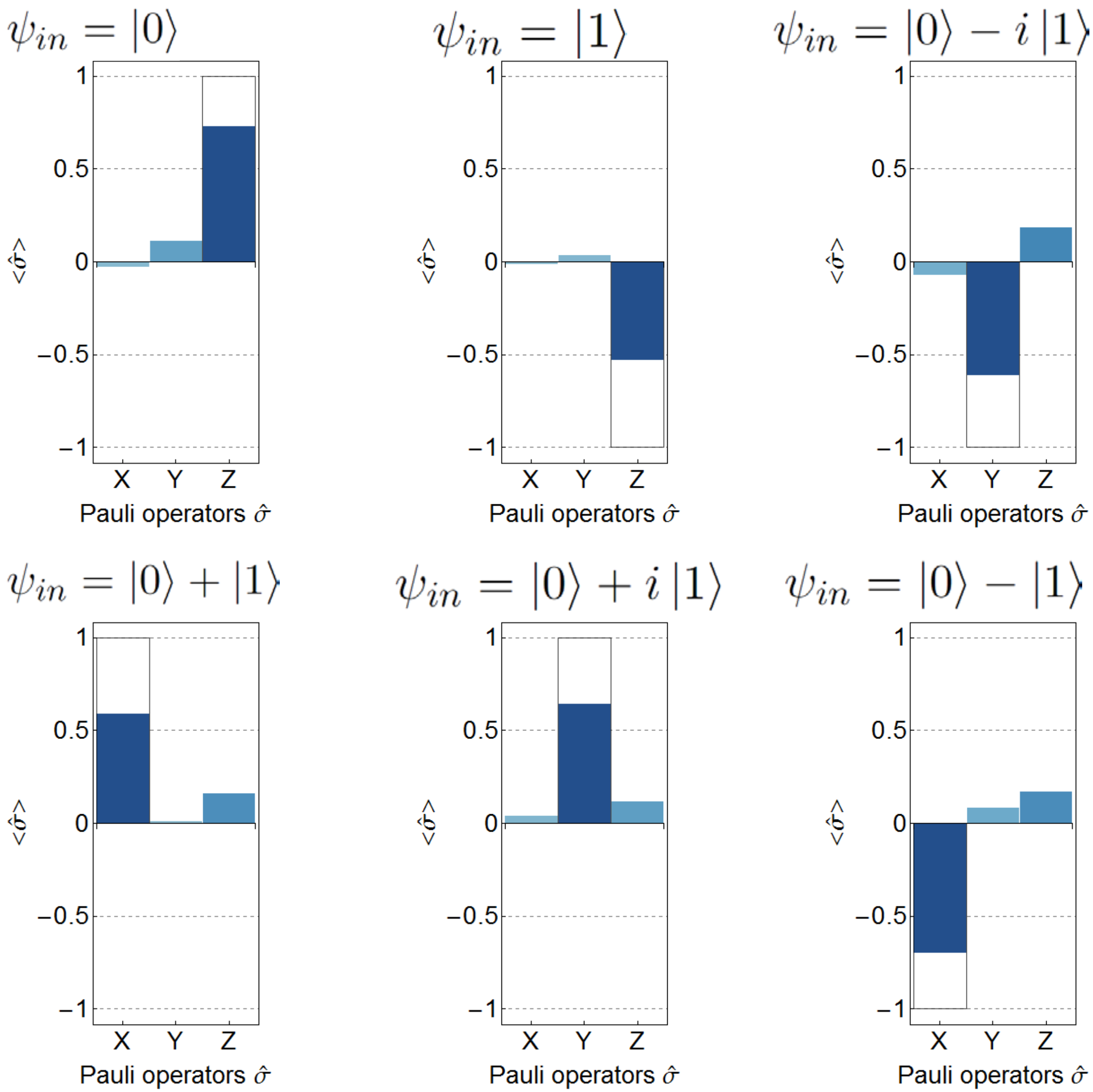
Steffen *et al.*, *Nature* 500, 319 (2013)

Tomography of Teleported States with Post-Selection



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

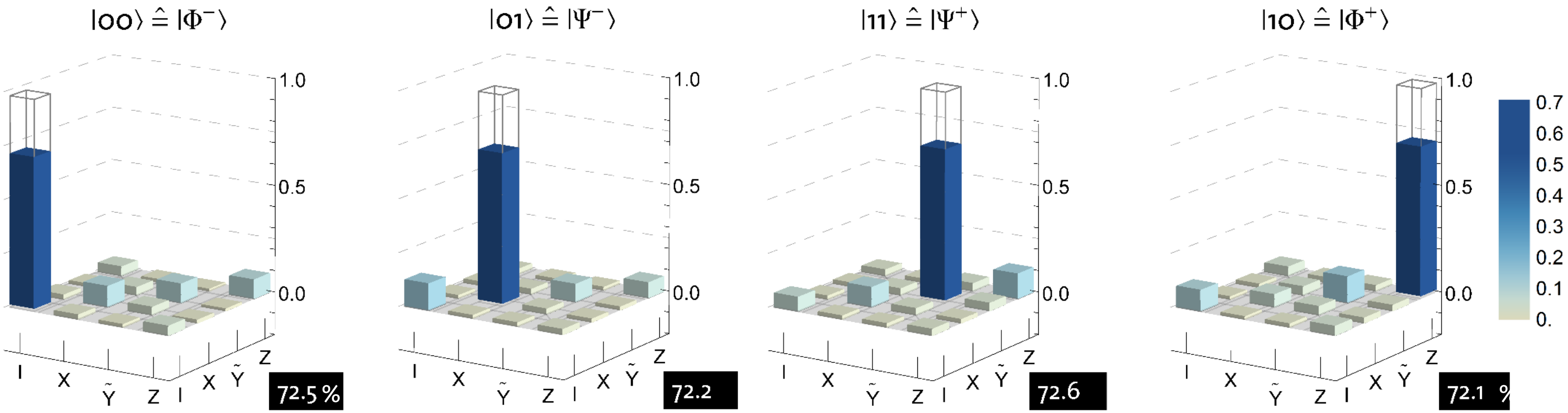
Post-Selection: Pauli-Sets of Teleported States



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:



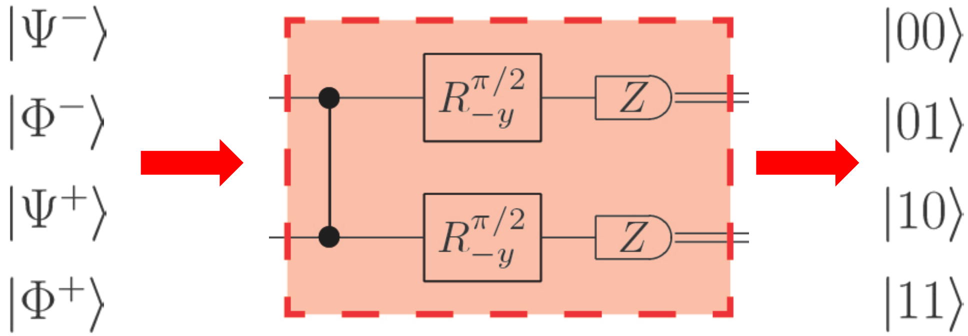
$|\psi_{\text{out}}\rangle = |\psi_{\text{in}}\rangle$ $\quad |\psi_{\text{out}}\rangle = X\,|\psi_{\text{in}}\rangle$ $\quad |\psi_{\text{out}}\rangle = \tilde{Y}\,|\psi_{\text{in}}\rangle$ $\quad |\psi_{\text{out}}\rangle = Z\,|\psi_{\text{in}}\rangle$

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

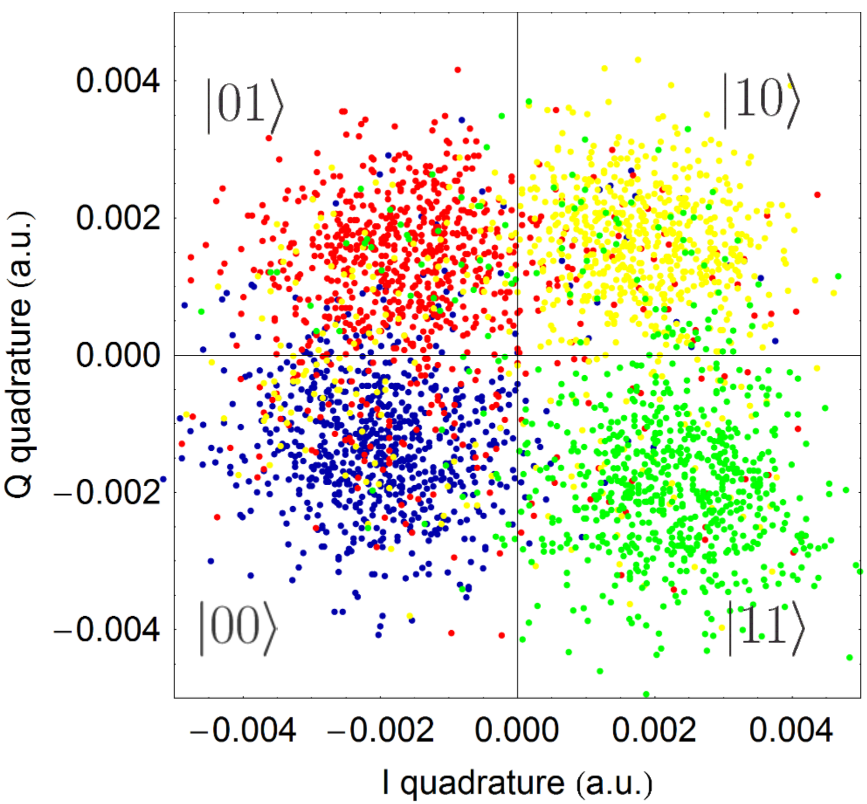
Average process fidelity **72.3 ± 0.7 %**

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



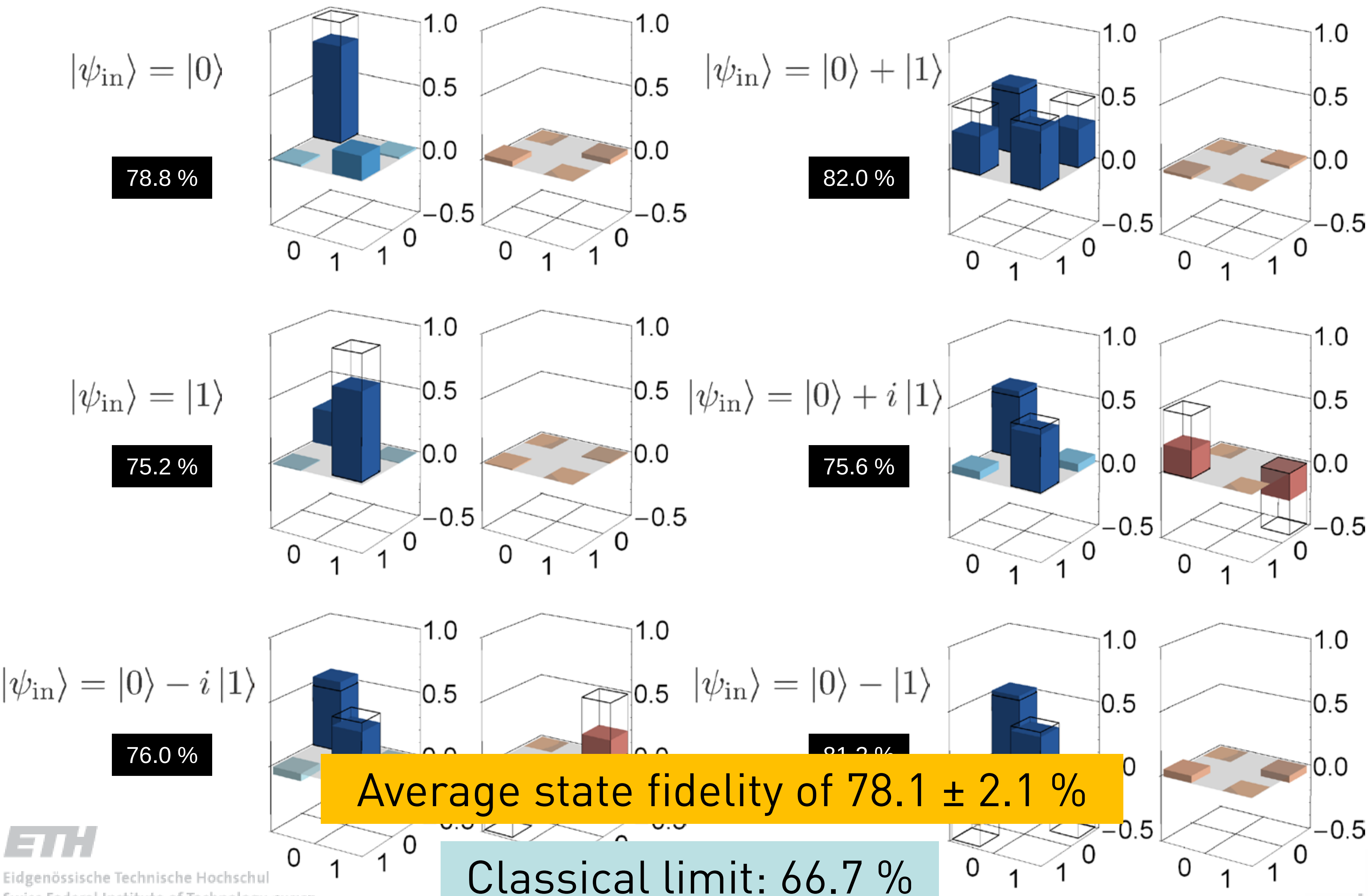
States are identified correctly with ~80% probability

identified as

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

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

Deterministic Teleportation – State Tomography

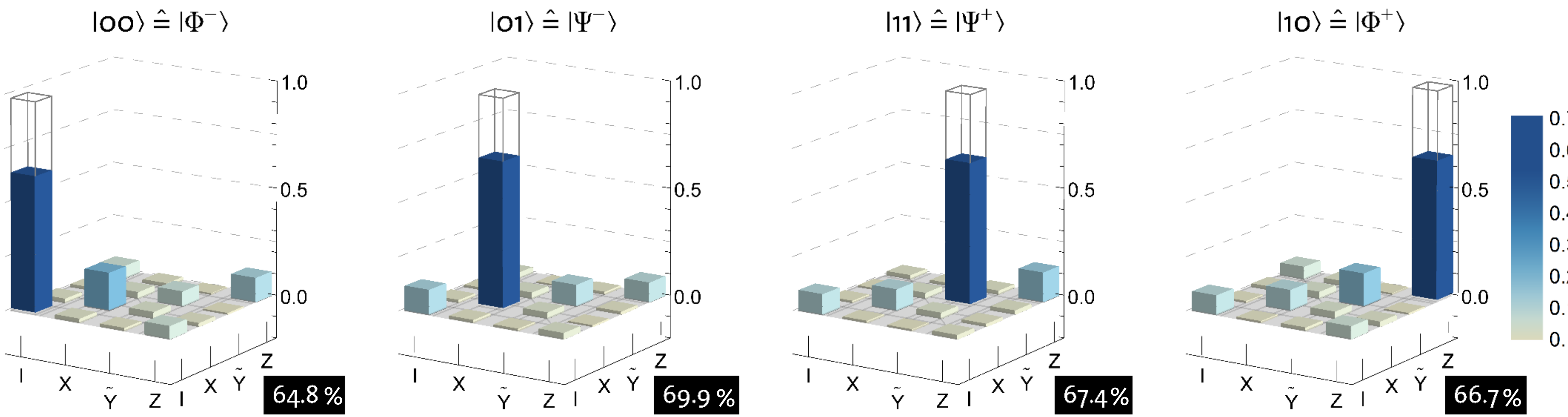


Average state fidelity of 78.1 ± 2.1 %

Classical limit: 66.7 %

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Deterministic Teleportation – Process Tomography



$|\psi_{\rm out}\rangle = |\psi_{\rm in}\rangle$ $\quad |\psi_{\rm out}\rangle = X\,|\psi_{\rm in}\rangle$ $\quad |\psi_{\rm out}\rangle = \tilde{Y}\,|\psi_{\rm in}\rangle$ $\quad |\psi_{\rm out}\rangle = Z\,|\psi_{\rm in}\rangle$

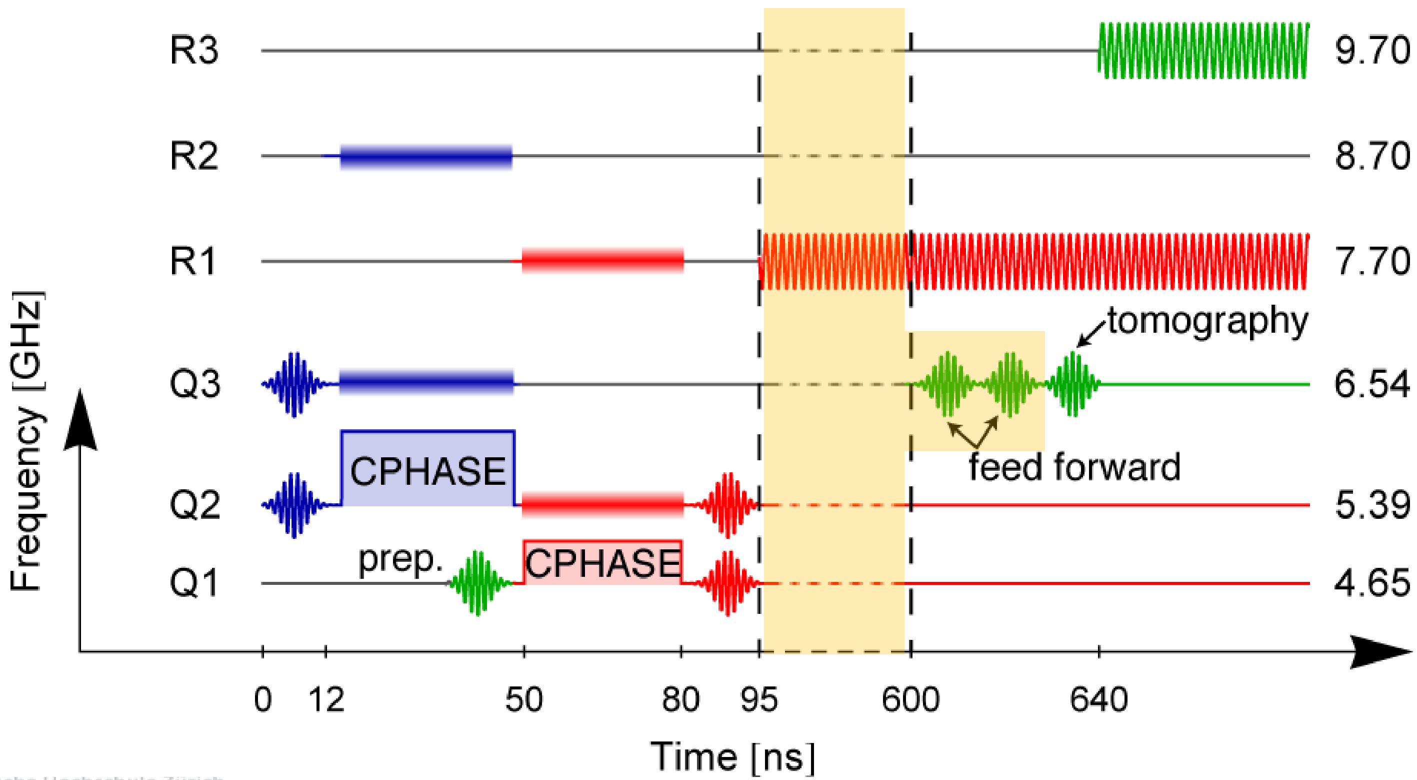
Average process fidelity **67.1 ± 0.5 %**

Average state fidelity **78.1 ± 0.9 %**

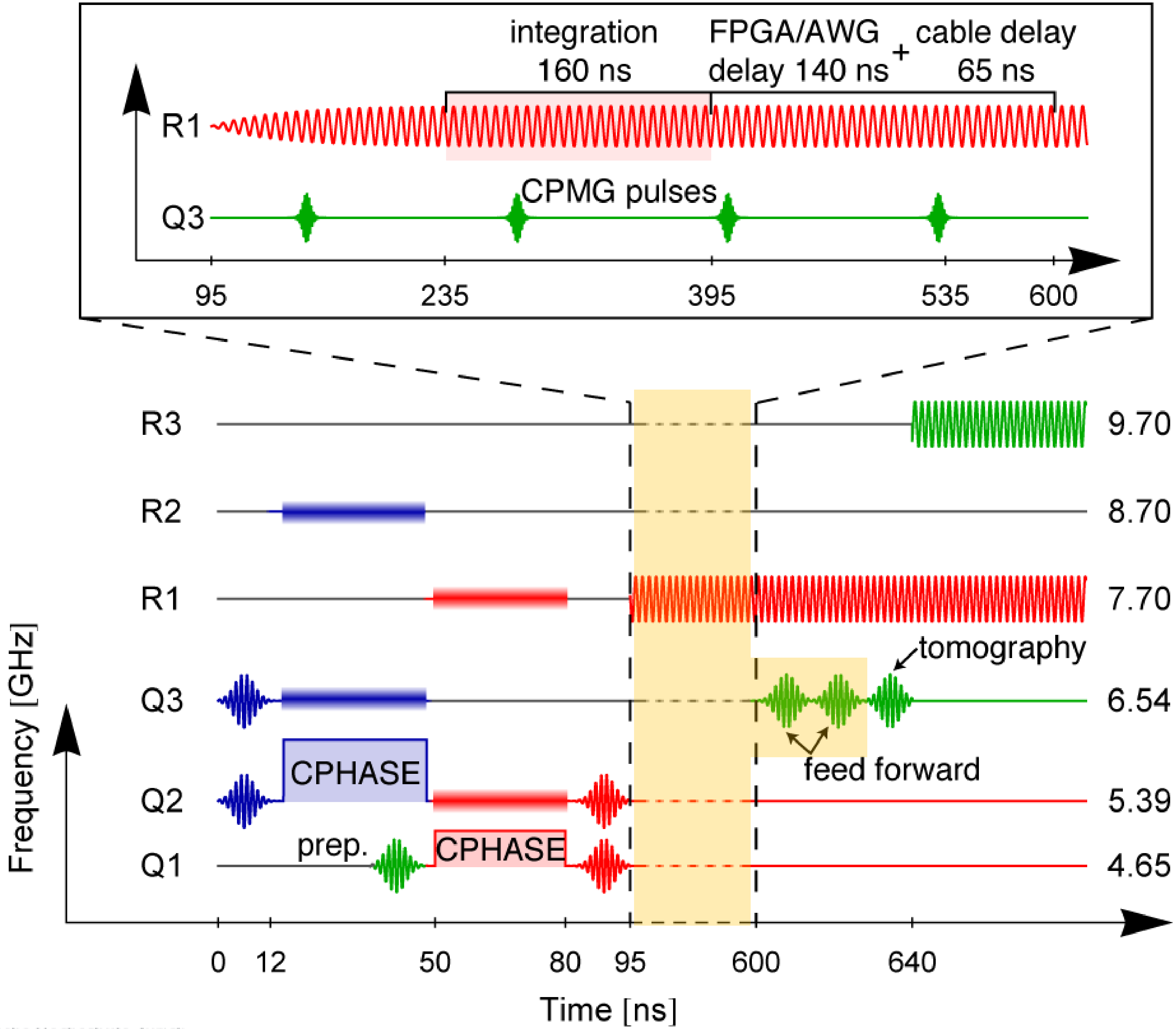
$$\mathcal{F}_p = (\mathcal{F}_s(d+1)-1)/d$$

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

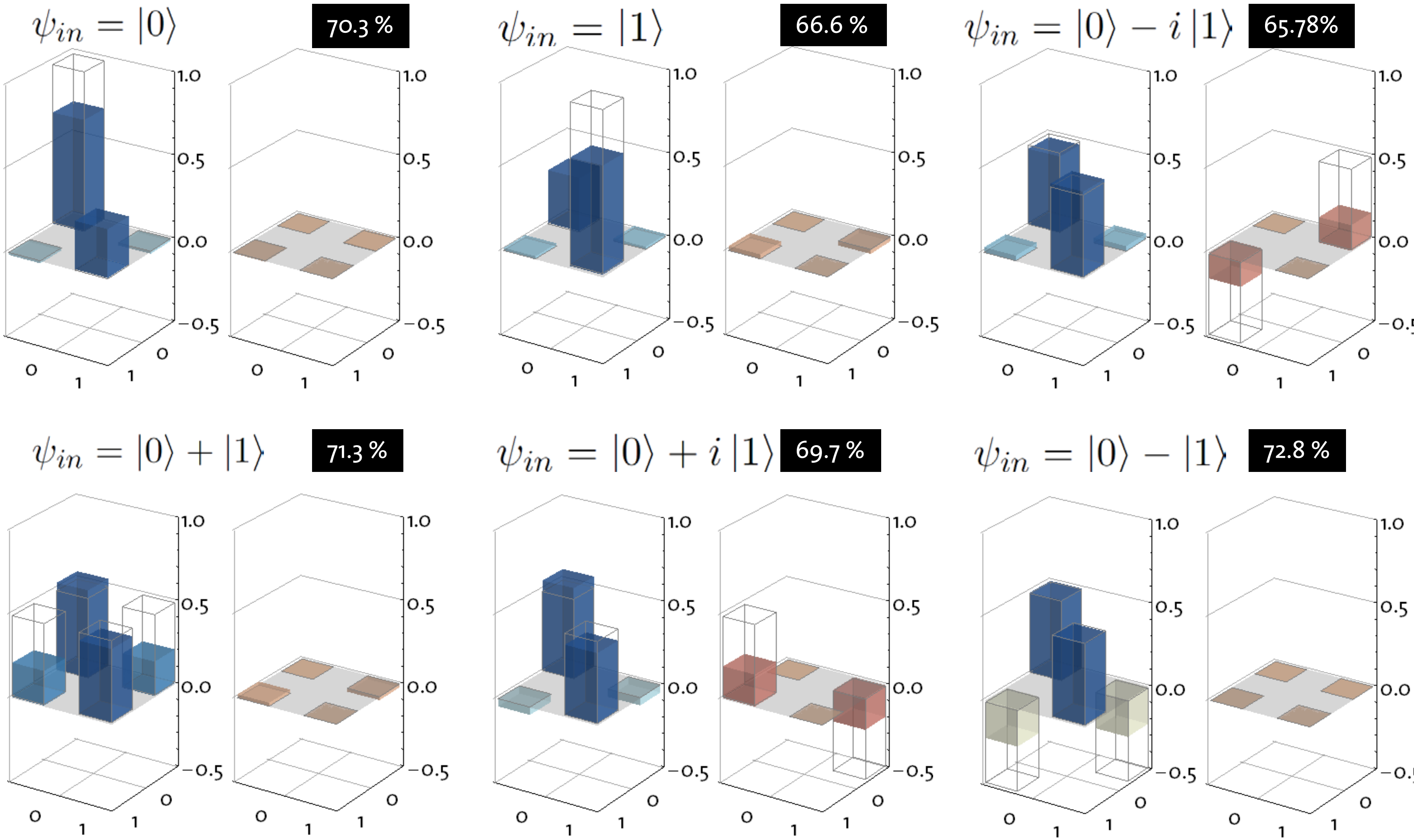
Pulse Scheme



Pulse Scheme



Tomography of Teleported States with Feed-Forward



Average state fidelity of **69.5±0.1 %**

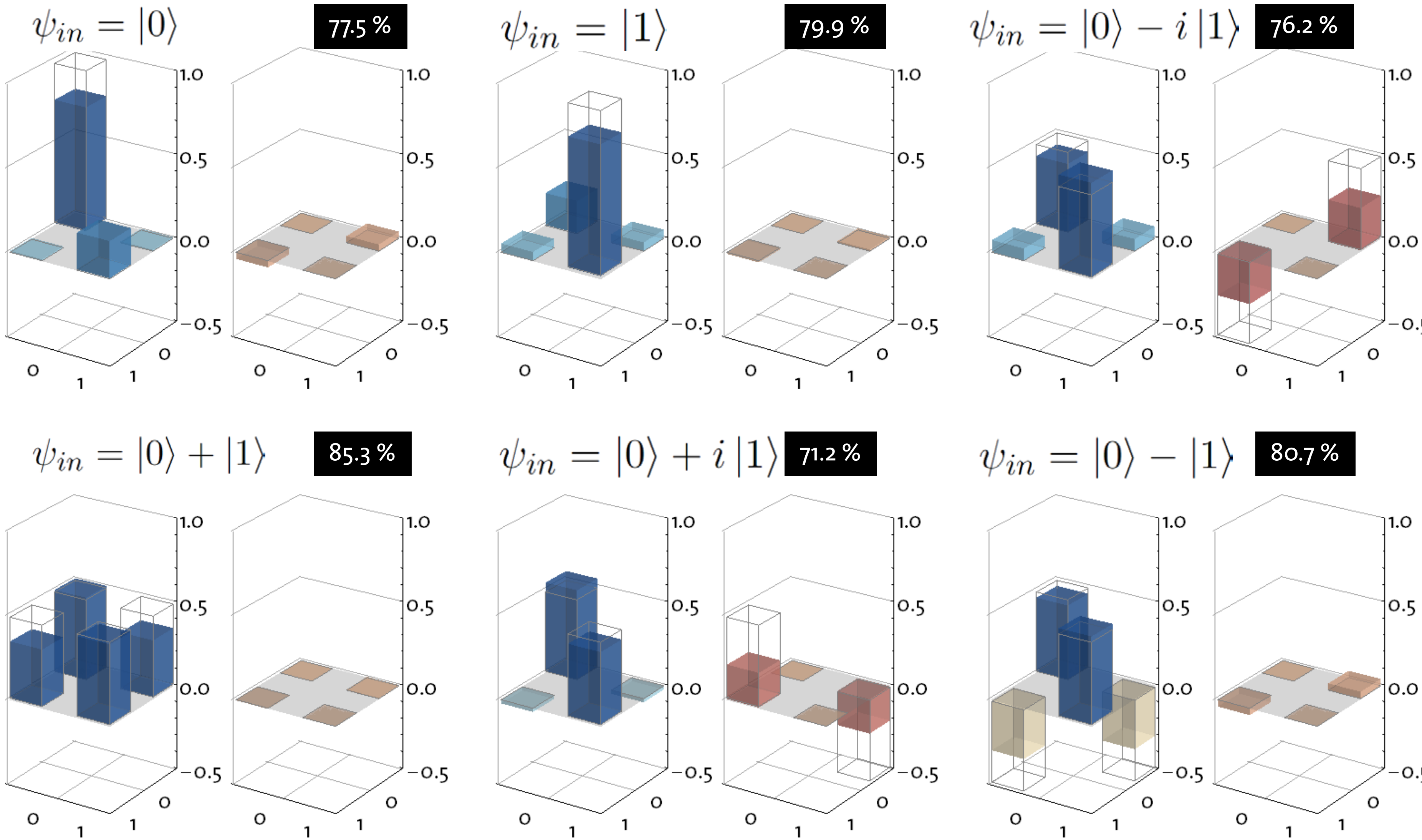
classical limit: 66.7 %

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

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Tomography of Teleported States with Feed-Forward

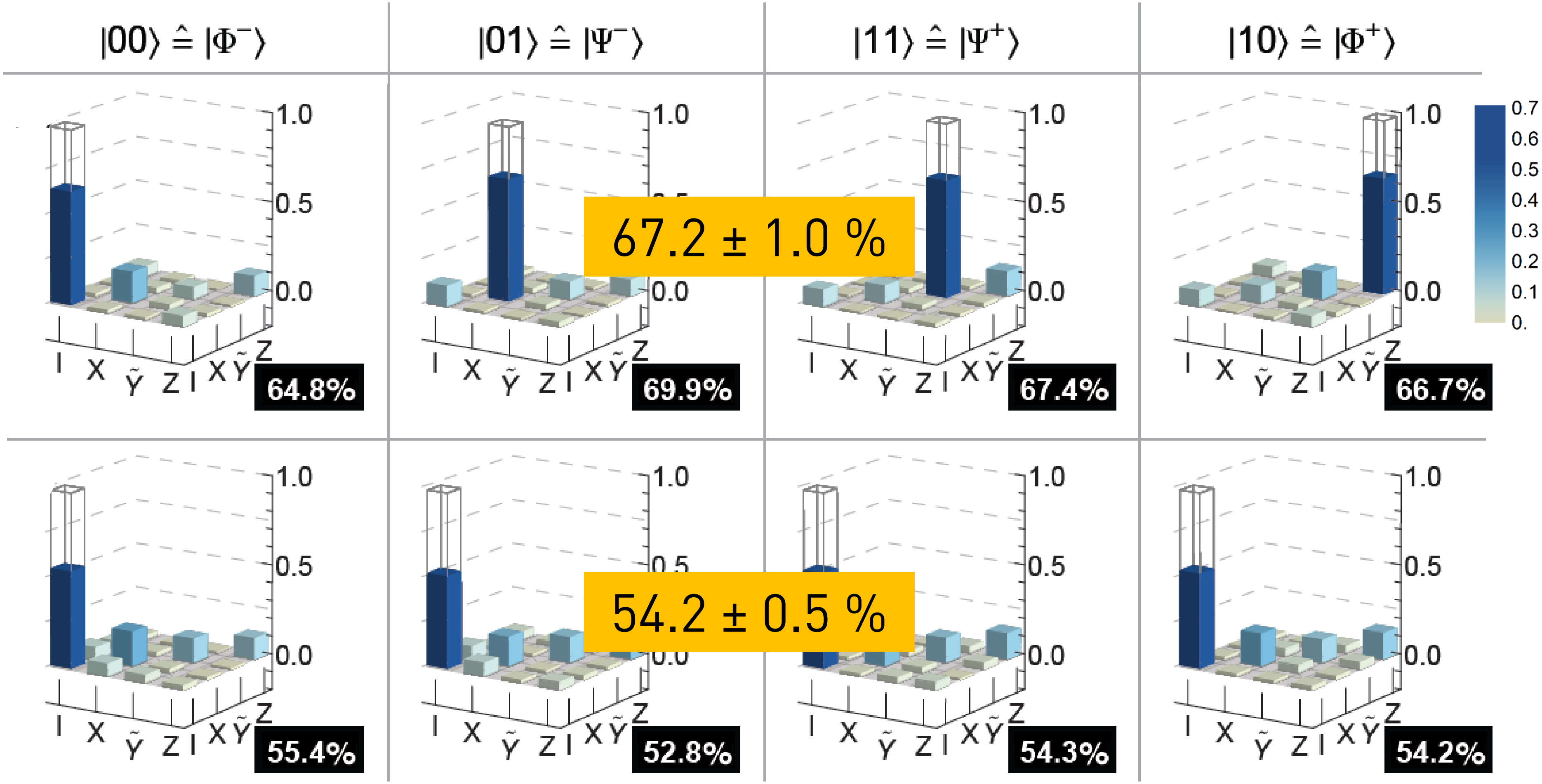
averaged readout of qubit 3



Average state fidelity of **78.5± 0.9%**

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

Process Tomography – w/o and with Feed-Forward



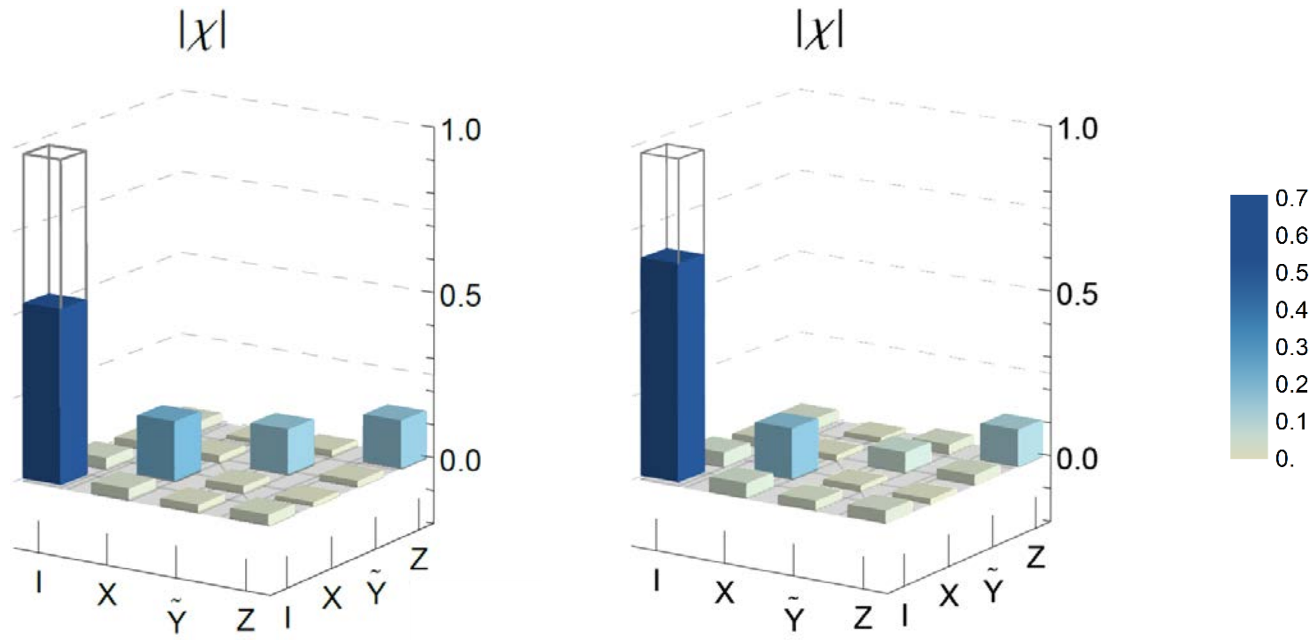
$|\psi_{\text{out}}\rangle = |\psi_{\text{in}}\rangle$ $|\psi_{\text{out}}\rangle = \quad |\psi_{\text{in}}\rangle$ $|\psi_{\text{out}}\rangle = \quad |\psi_{\text{in}}\rangle$ $|\psi_{\text{out}}\rangle = \quad |\psi_{\text{in}}\rangle$

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

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)

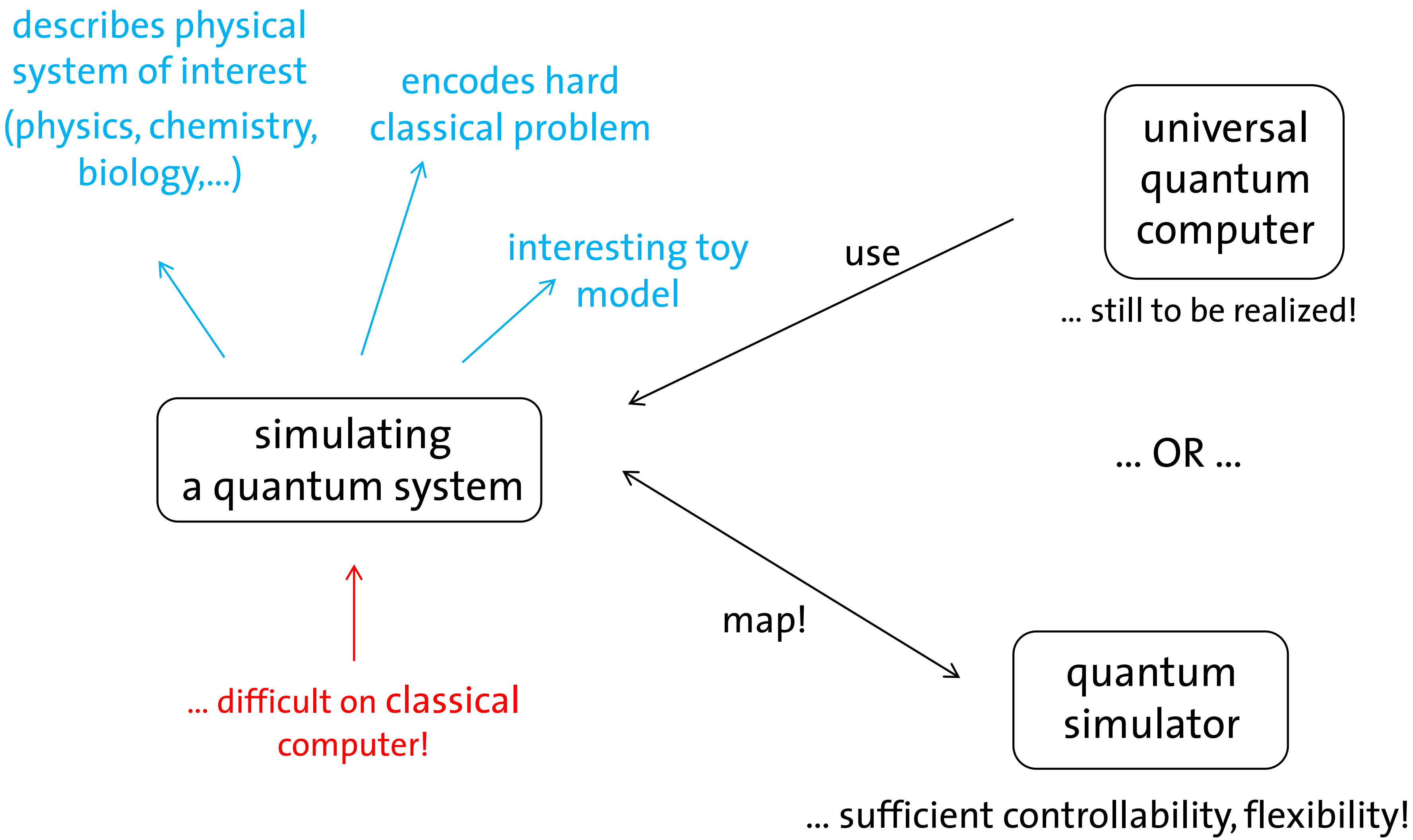
Teleportation State and Process Fidelities Summary

	States:	Processes:
Thresholds	66.7 %	50 %
Post-selection	81.6 ± 3.0 %	72.3 ± 1.4 %
Deterministic	78.1 ± 2.1 %	67.2 ± 1.0 %
Feed-forward	69.5 ± 0.5 %	54.2 ± 0.5 %
Averaged	78.5 ± 1.0 %	67.7 ± 0.6 %

- First experimental implementation of full quantum teleportation in a solid state system
- High qubit teleportation rate (~10.000/s)

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

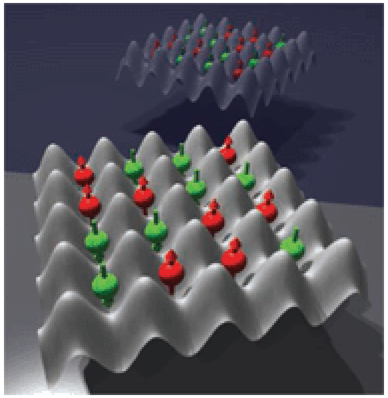
Quantum Simulation



Feynman, *Int. Journal of Th. Phys.* 21, 467 (1982)
Llloyd, *Science* 273, 5278 (1996)

Systems for Quantum Simulation

Ultracold gases

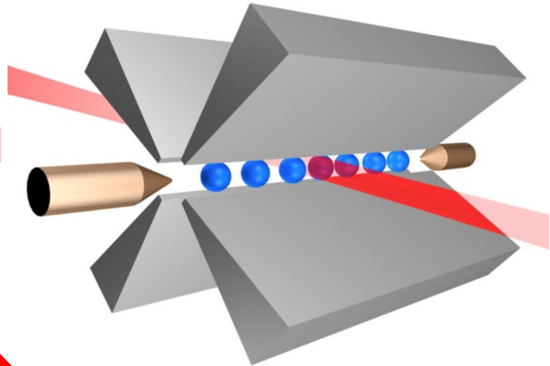


Bloch et al.,
Nat. Phys. 8, 267 (2012)

more established

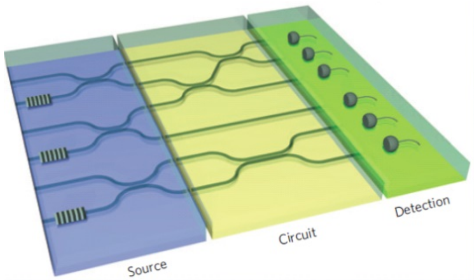
under development

Trapped ions



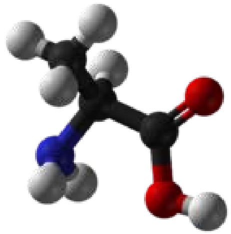
Blatt & Roos,
Nat. Phys. 8, 277 (2012)

Optical photons



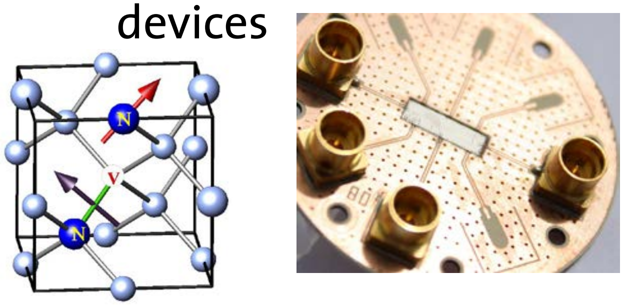
Aspuru-Guzik & Walther,
Nat. Phys. 8, 258 (2012)

Nuclear magnetic resonance



Vandersypen & Chuang,
RMP 76, 1037 (2004)

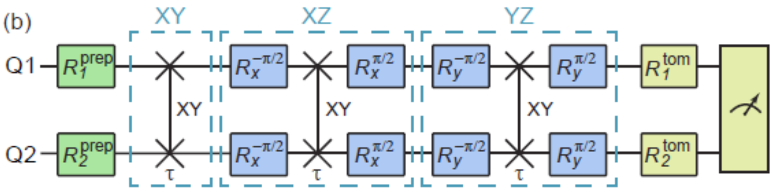
Solid state quantum devices



Georgescu et al., *RMP* 86, 153 (2014)

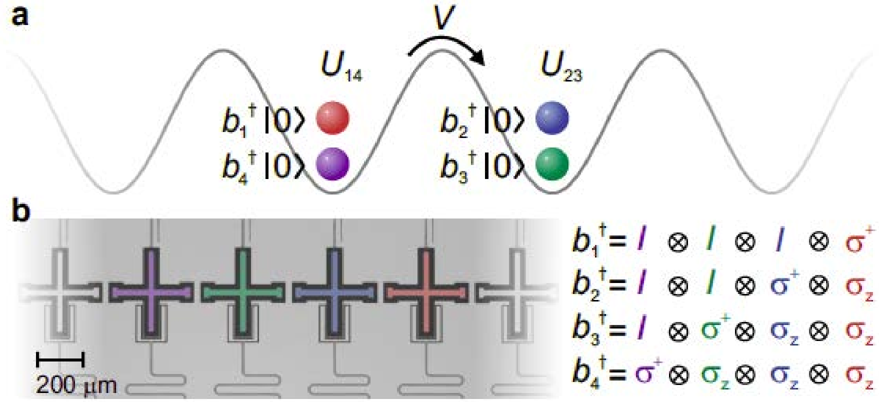
Quantum Simulation with Superconducting Circuits

Digital simulation of exchange, Heisenberg, Ising spin models



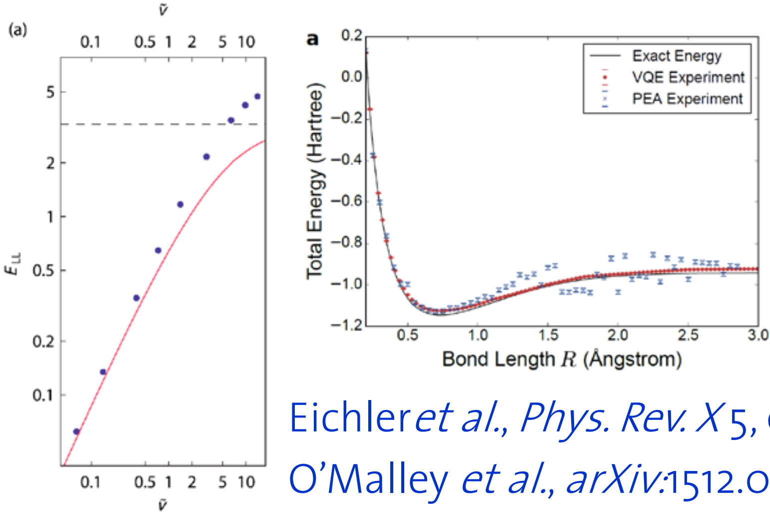
Salathe *et al.*, *PRX* 5, 021027 (2015)

... two-mode fermionic Hubbard models



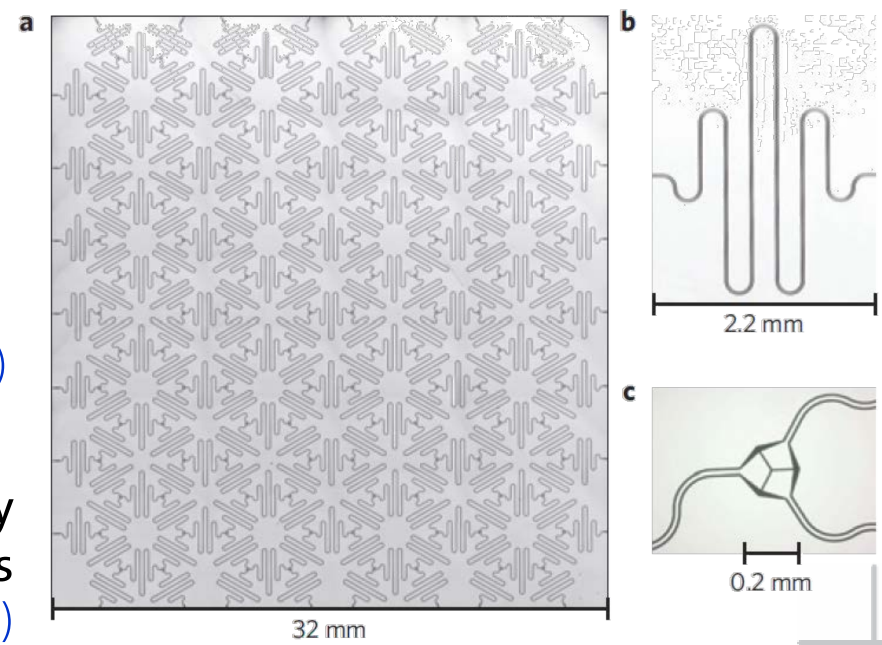
Barends *et al.*, *Nat. Com.* 6, 7654 (2015)

Quantum simulation of correlated systems with variational Ansatz based on MPS



Eichler *et al.*, *Phys. Rev. X* 5, 041044 (2015)

O'Malley *et al.*, *arXiv:*1512.06860 (2015)

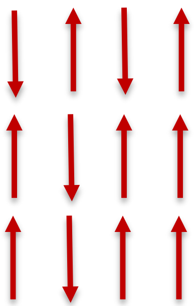


Analog simulations with cavity and/or qubit arrays

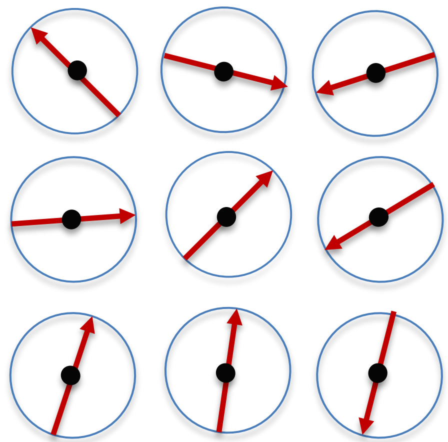
Houck *et al.*, *Nat Phys.* 8, 292 (2012)

Digital Quantum Simulation of Spin Models

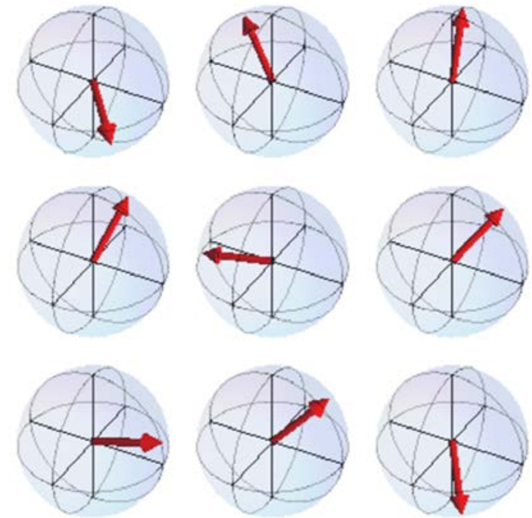
Ising (up-down)



XY (Compass)



XYZ (Heisenberg)



interaction term

$$J \sum_{(i,j)} \sigma_i^x \sigma_j^x$$

$$\sum_{(i,j)} J_x \sigma_i^x \sigma_j^x + J_y \sigma_i^y \sigma_j^y$$

$$\sum_{(i,j)} J_x \sigma_i^x \sigma_j^x + J_y \sigma_i^y \sigma_j^y + J_z \sigma_i^z \sigma_j^z$$

+ magnetic field term, e.g. $B \sum_{i=1}^{n} \sigma_i^z$

Potential applications in physics, chemistry and material science.

Number of spins > 100 → classical simulations intractable

Digital Quantum Simulation

model Hamiltonian
to be realized in 'software'

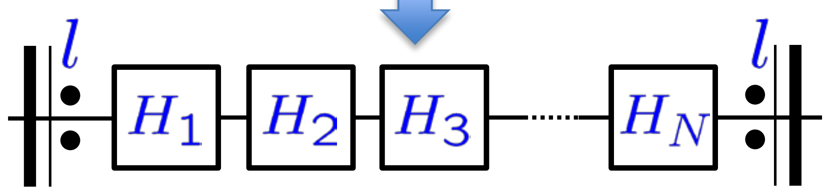
$$H = \sum_{k=1}^{N} H_k$$

realizable in 'hardware'

time evolution: Suzuki-Lie-Trotter approximation

higher-order terms

$$\exp(-iHt) = \left(\prod_{k=1}^{N} \exp(-iH_k t/l) \right)^l + E(t,l)$$



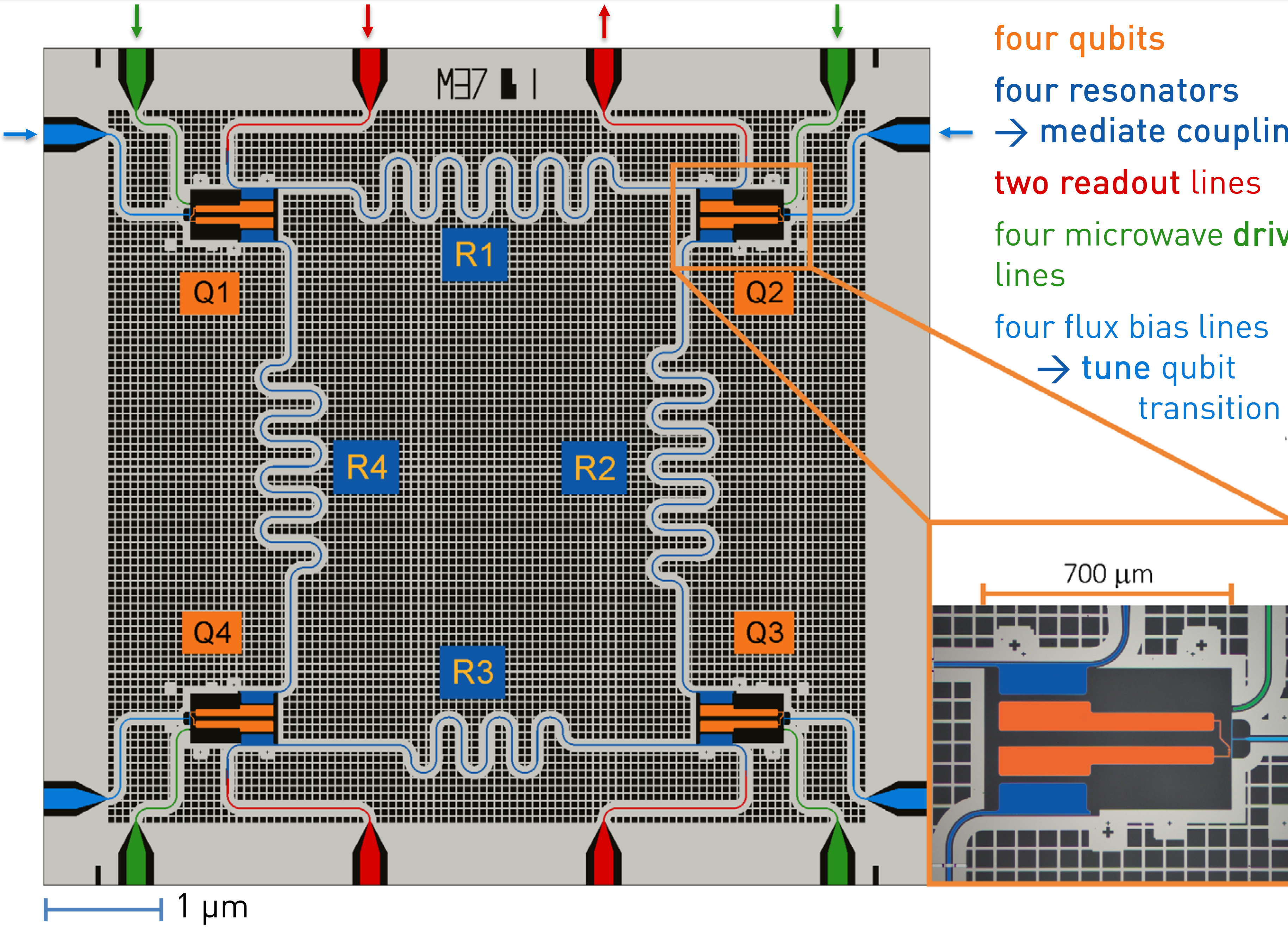
"digital quantum simulation"

$E(t,l) \to 0$ if $l \to \infty$

works for all Hamiltonians with local interactions (universal)

Lloyd, S. *Science* **273**, 1073 (1996)

4 Qubit Device with Nearest Neighbor Connectivity



four qubits

four resonators
→ mediate coupling

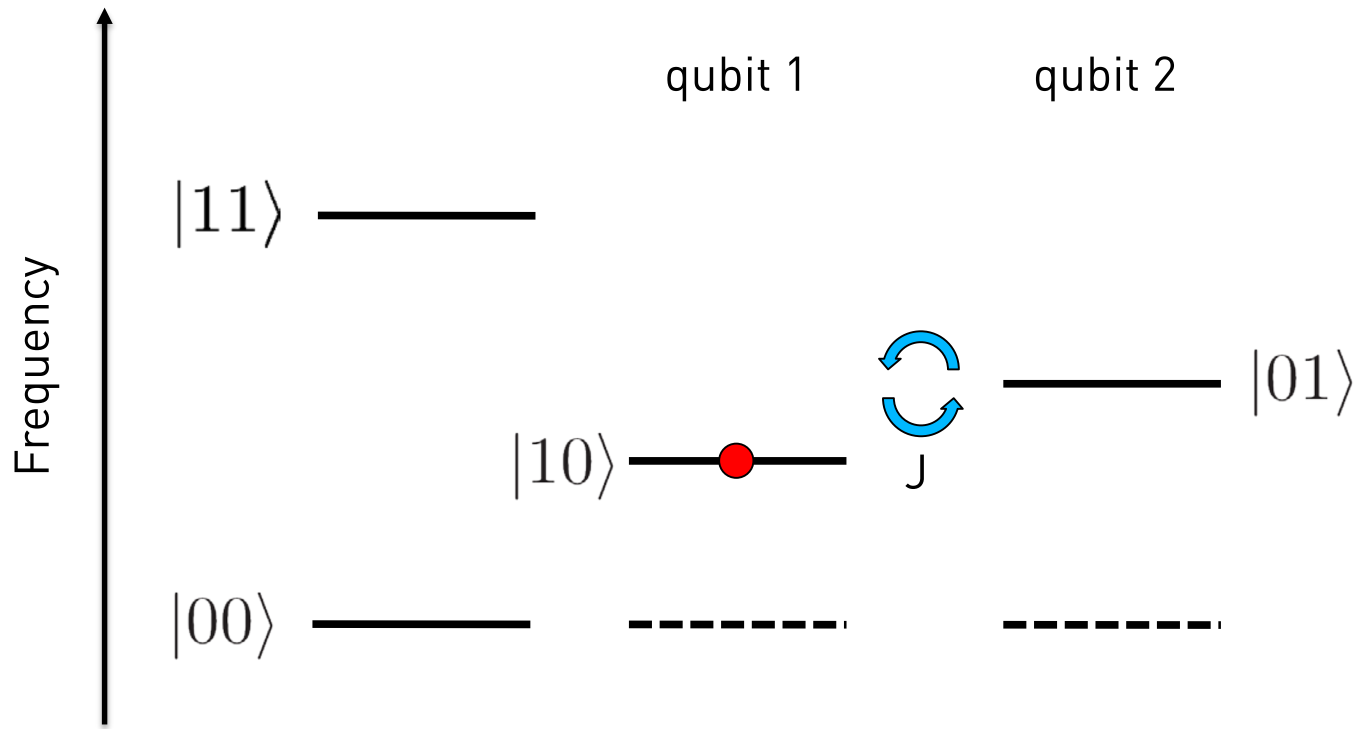
two readout lines

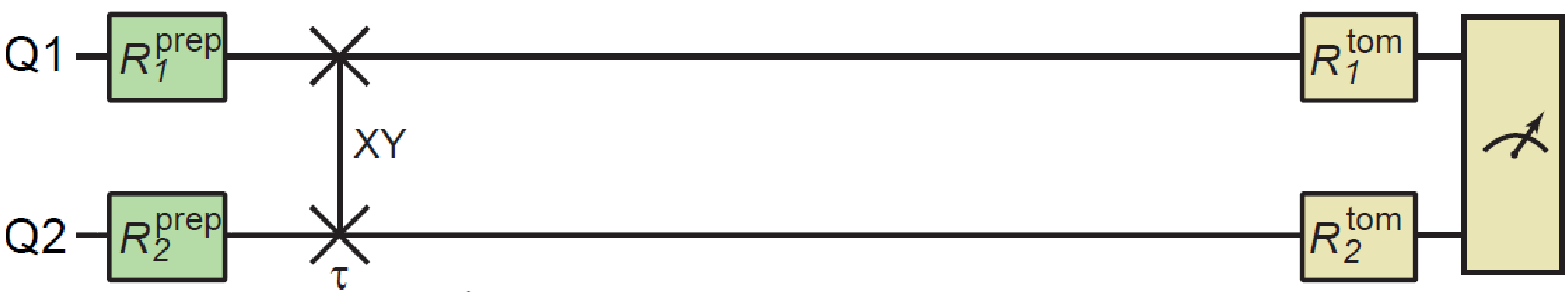
four microwave **drive** lines

four flux bias lines
→ **tune** qubit transition

XY Interaction (Hardware) Controlled by Detuning

$$H_{2Q} = -\frac{1}{2}\omega_1\hat{\sigma}_1^z - \frac{1}{2}\omega_2\hat{\sigma}_2^z + J\left(\hat{\sigma}_1^+\hat{\sigma}_2^- + \hat{\sigma}_1^-\hat{\sigma}_2^+\right)$$

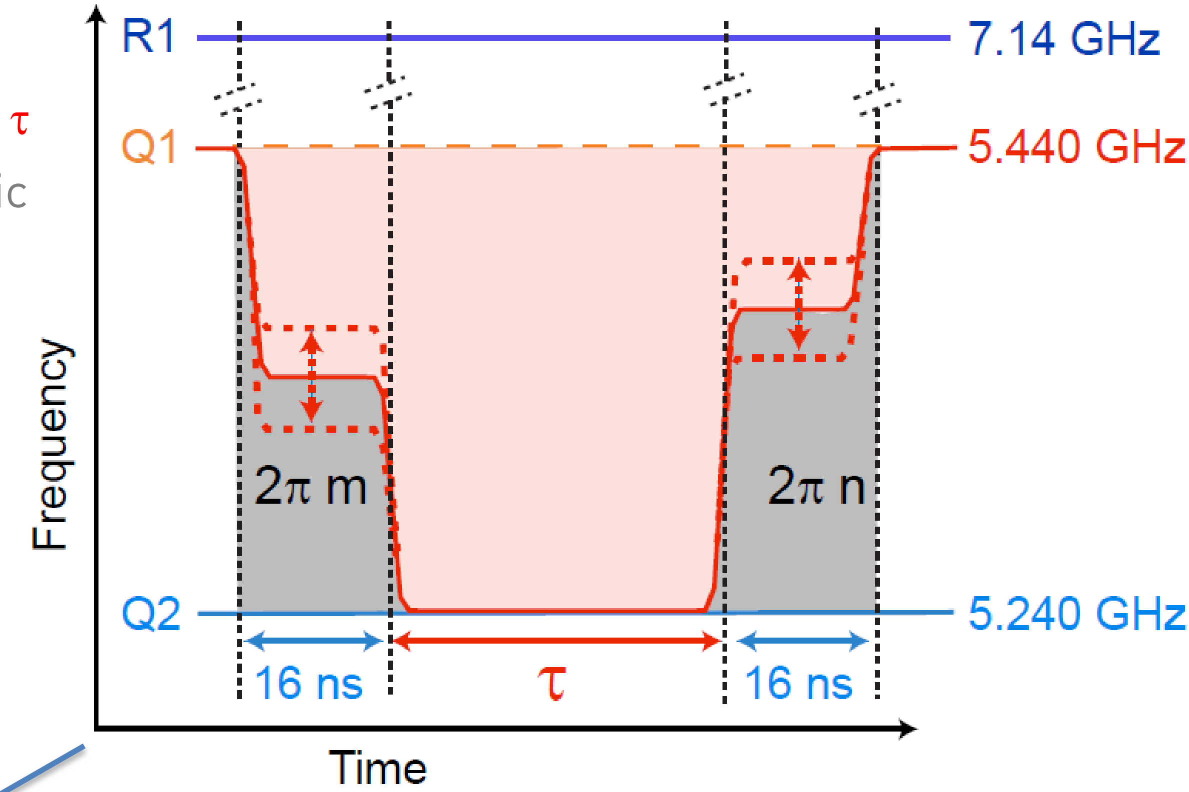




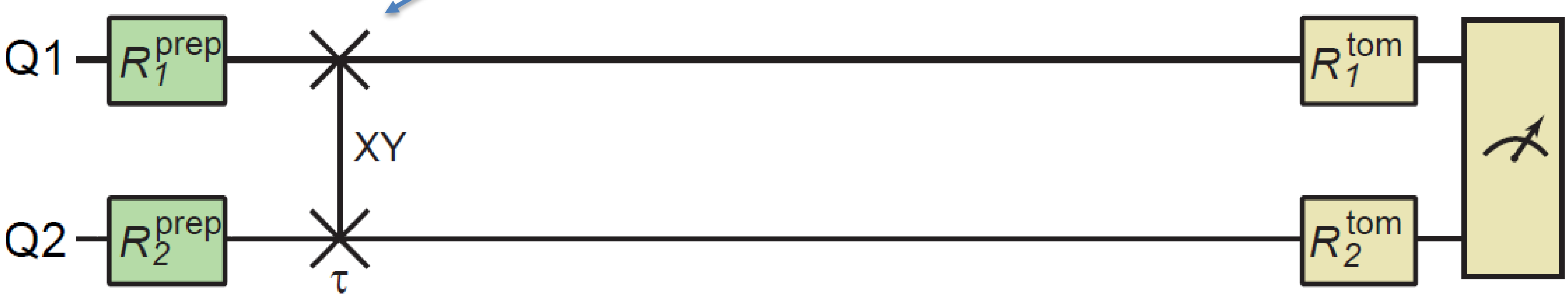
Frequency Control through Flux Bias

Profile of flux pulse:

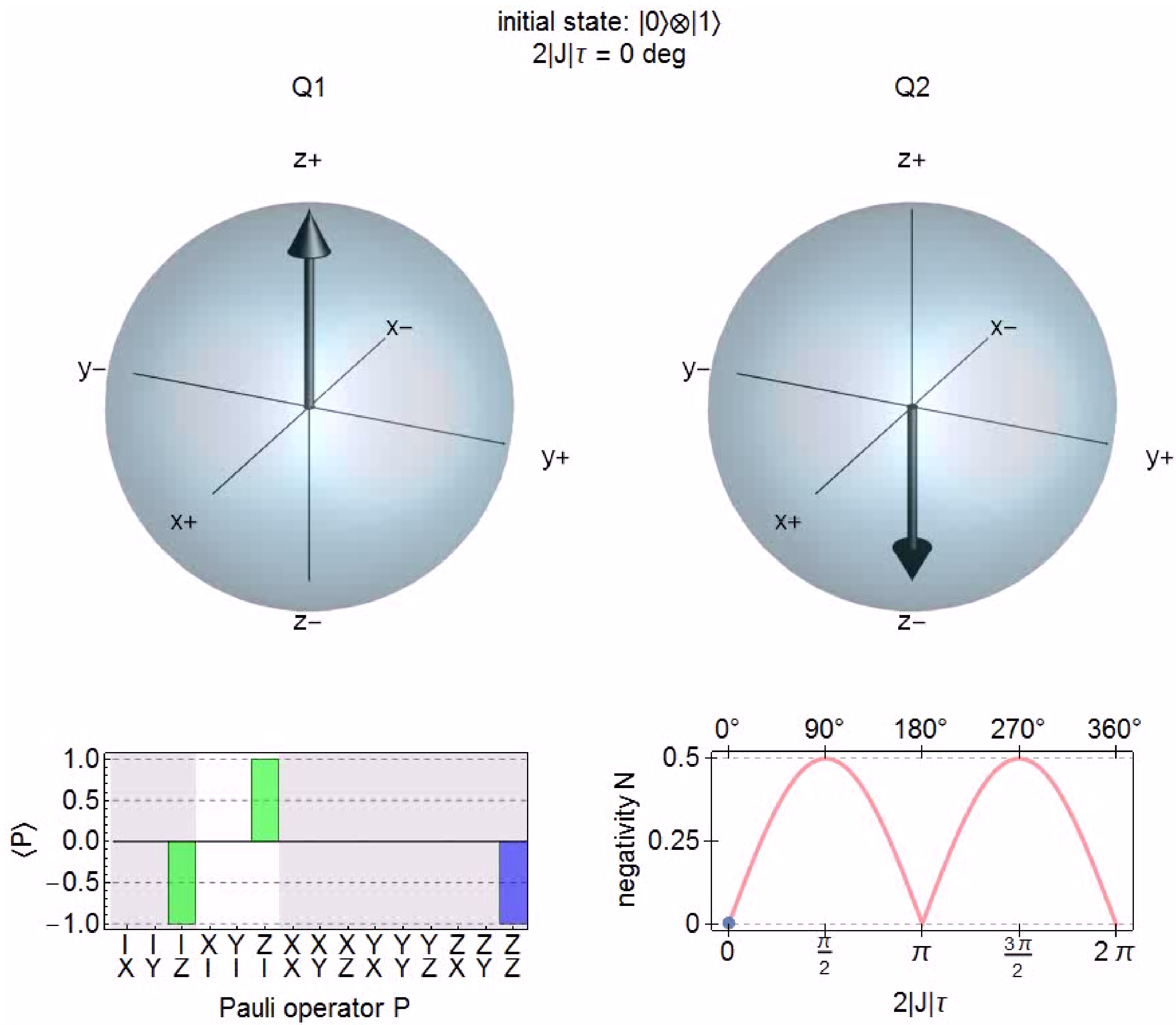
- tunable interaction time τ
- compensation of dynamic phase



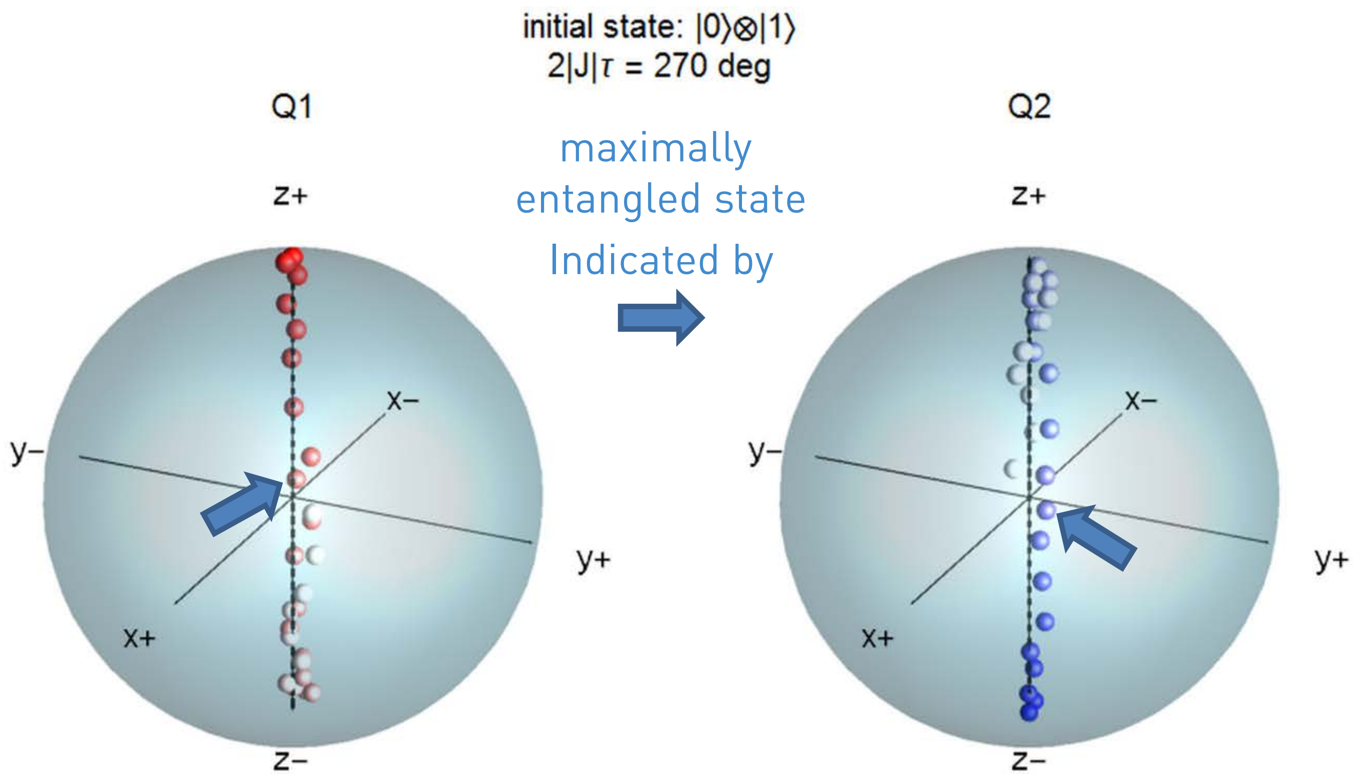
Circuit representation of gate sequence:



XY Interaction: Calculation

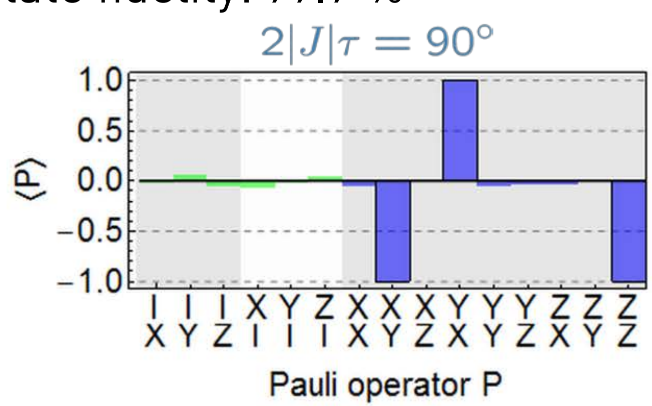


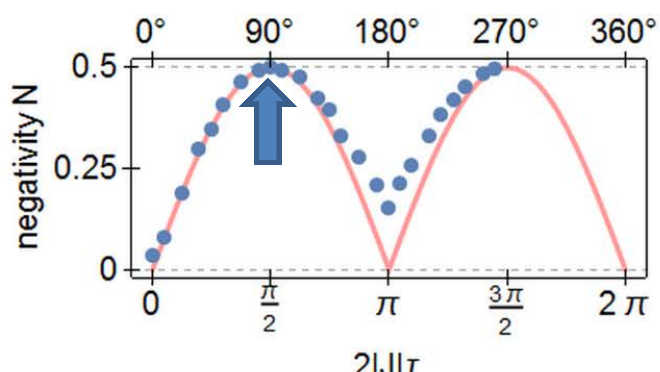
XY Interaction: Experimental Data



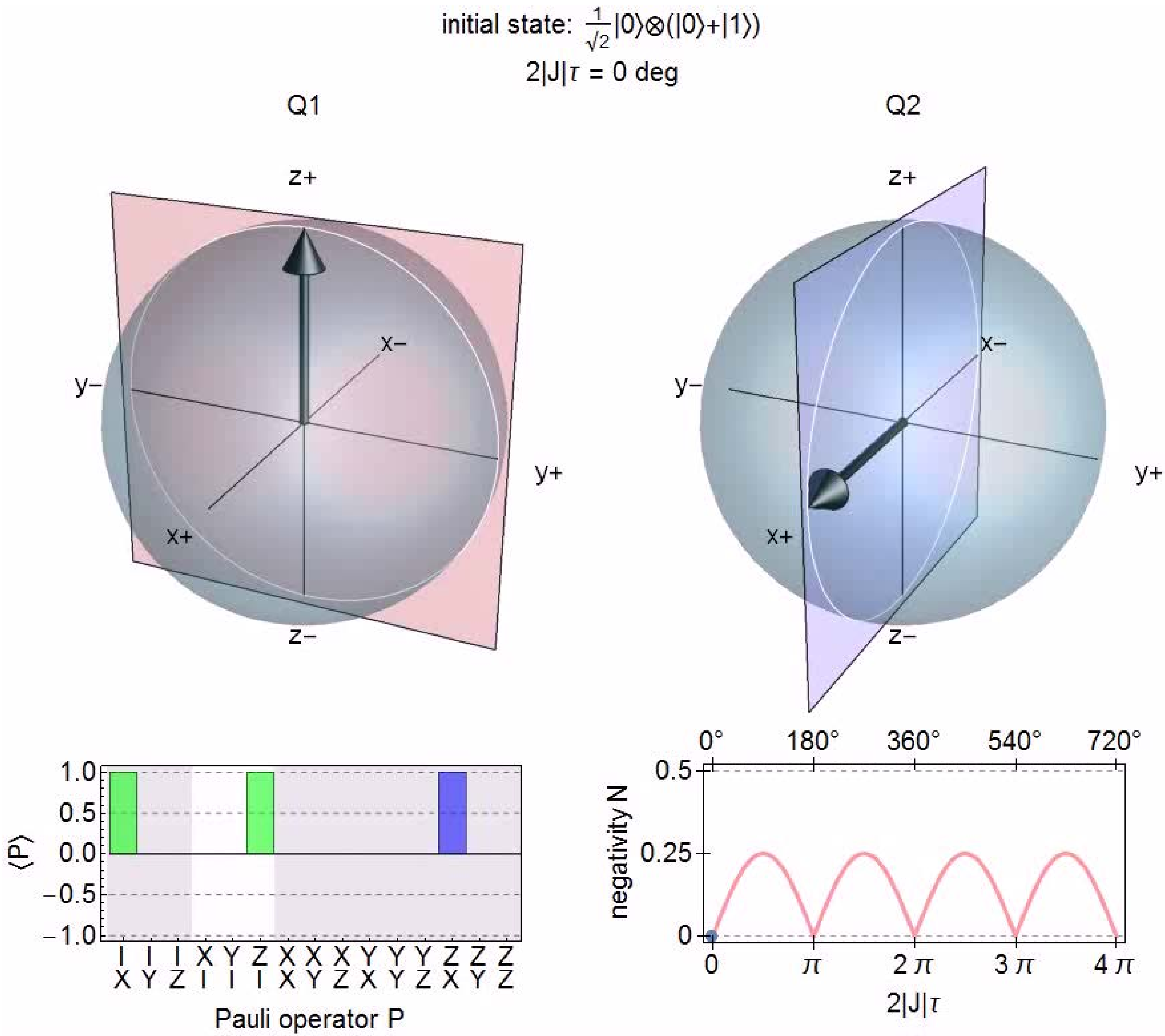
maximally entangled state Indicated by

state fidelity: 99.7 %

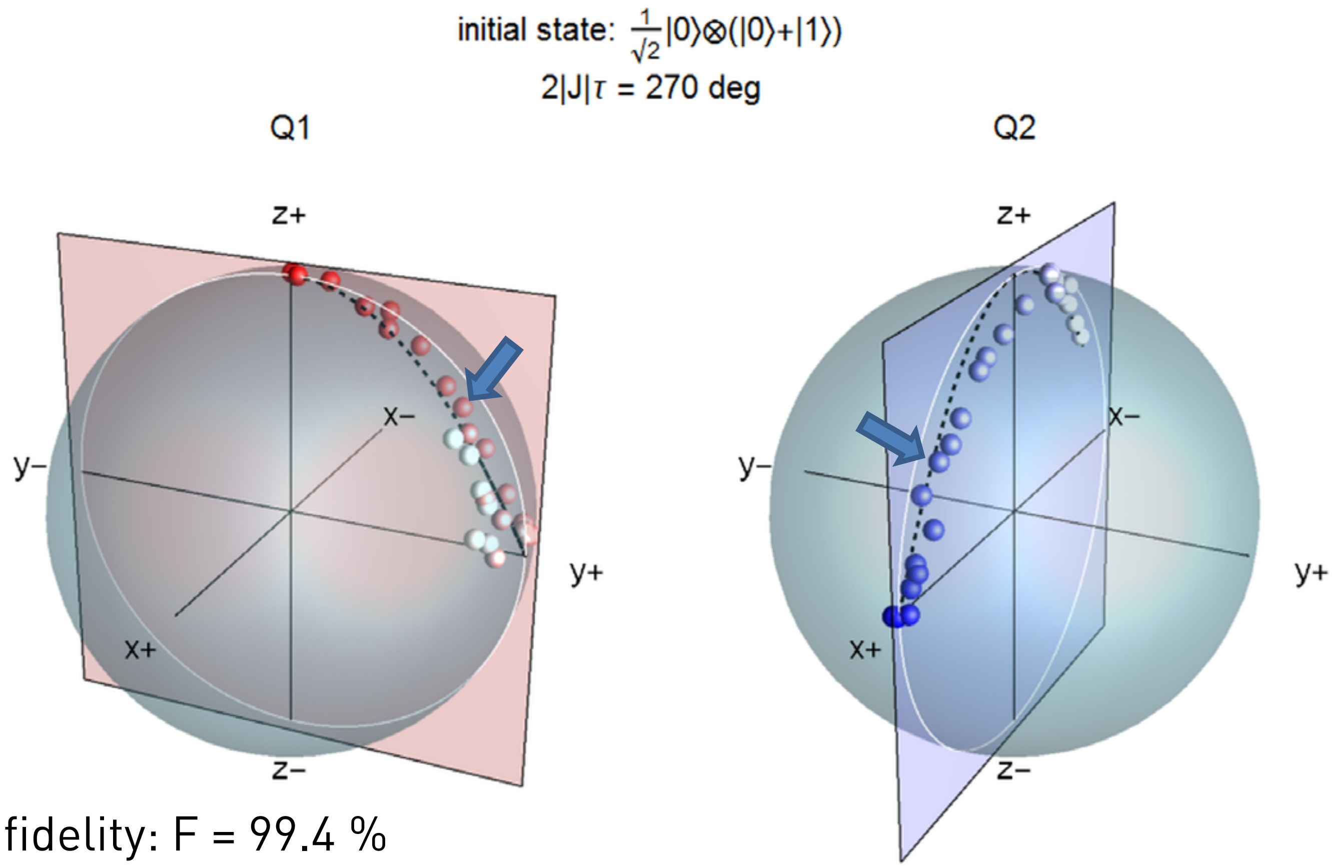




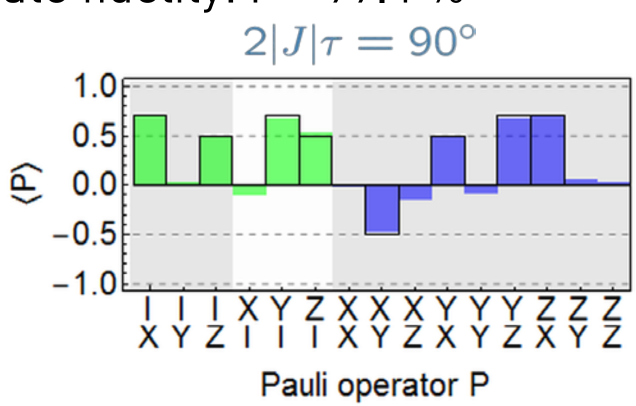
XY Interaction: Calculation

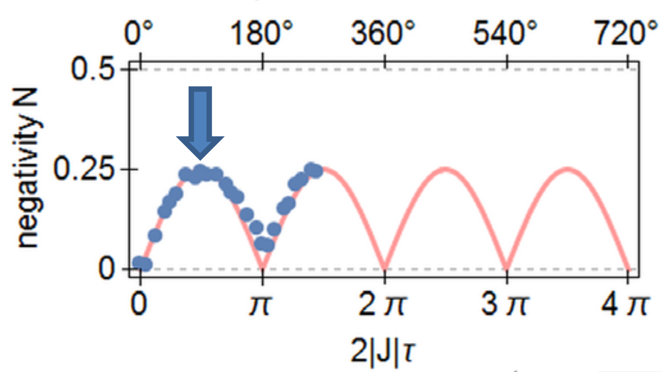


XY Interaction: Experimental Data



state fidelity: F = 99.4 %





$$F \equiv \left(\mathrm{Tr}\sqrt{\sqrt{\rho_{\text{theo}}}\rho_{\text{exp}}\sqrt{\rho_{\text{theo}}}}\right)^2$$

Digital Simulation of Heisenberg XYZ Interaction

Hamiltonian to be simulated: $H_{xyz} = J(\sigma_1^x \sigma_2^x + \sigma_1^y \sigma_2^y + \sigma_1^z \sigma_2^z)$

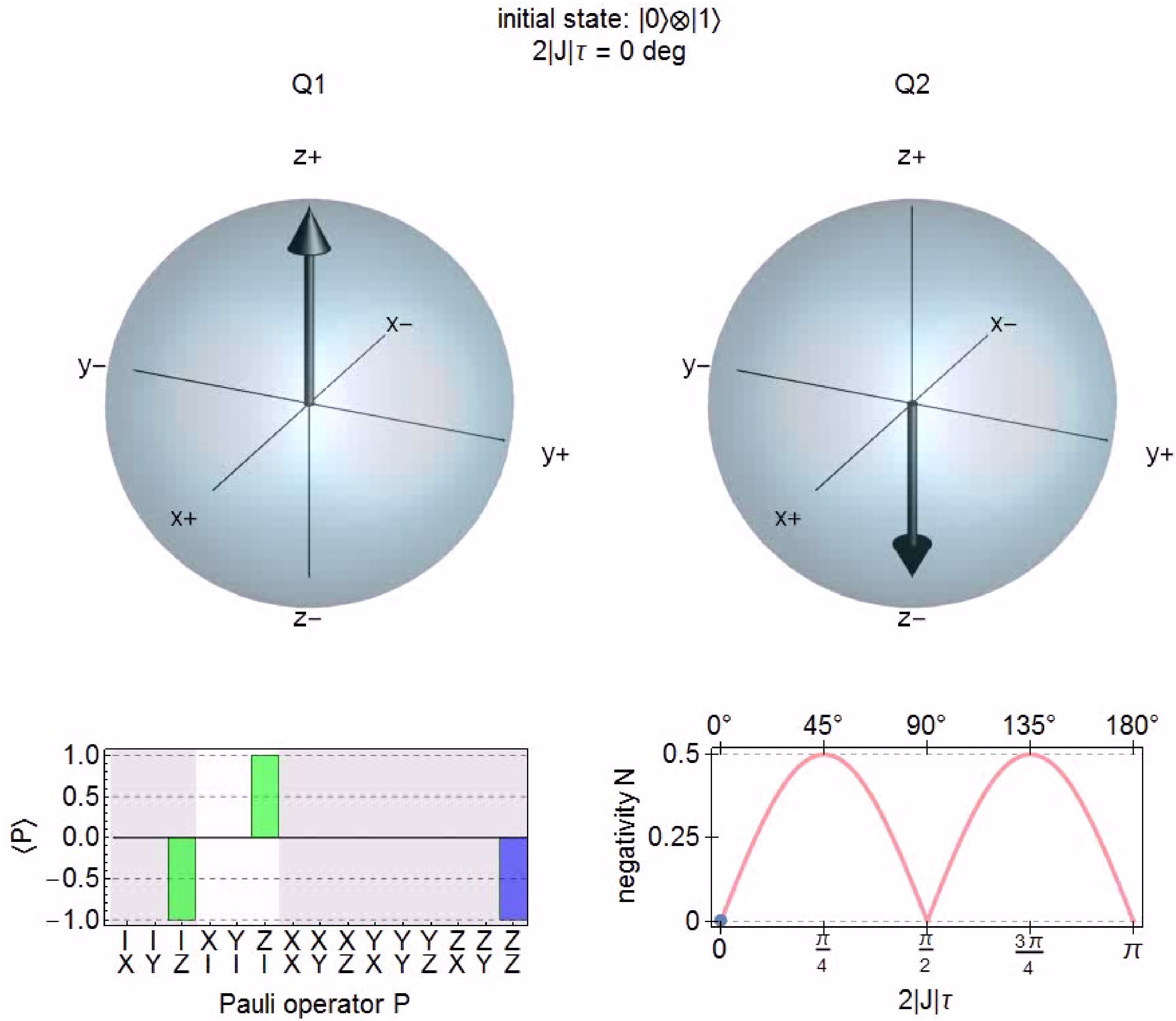
operators commute

-> no Trotter decomposition required, exact result in one step

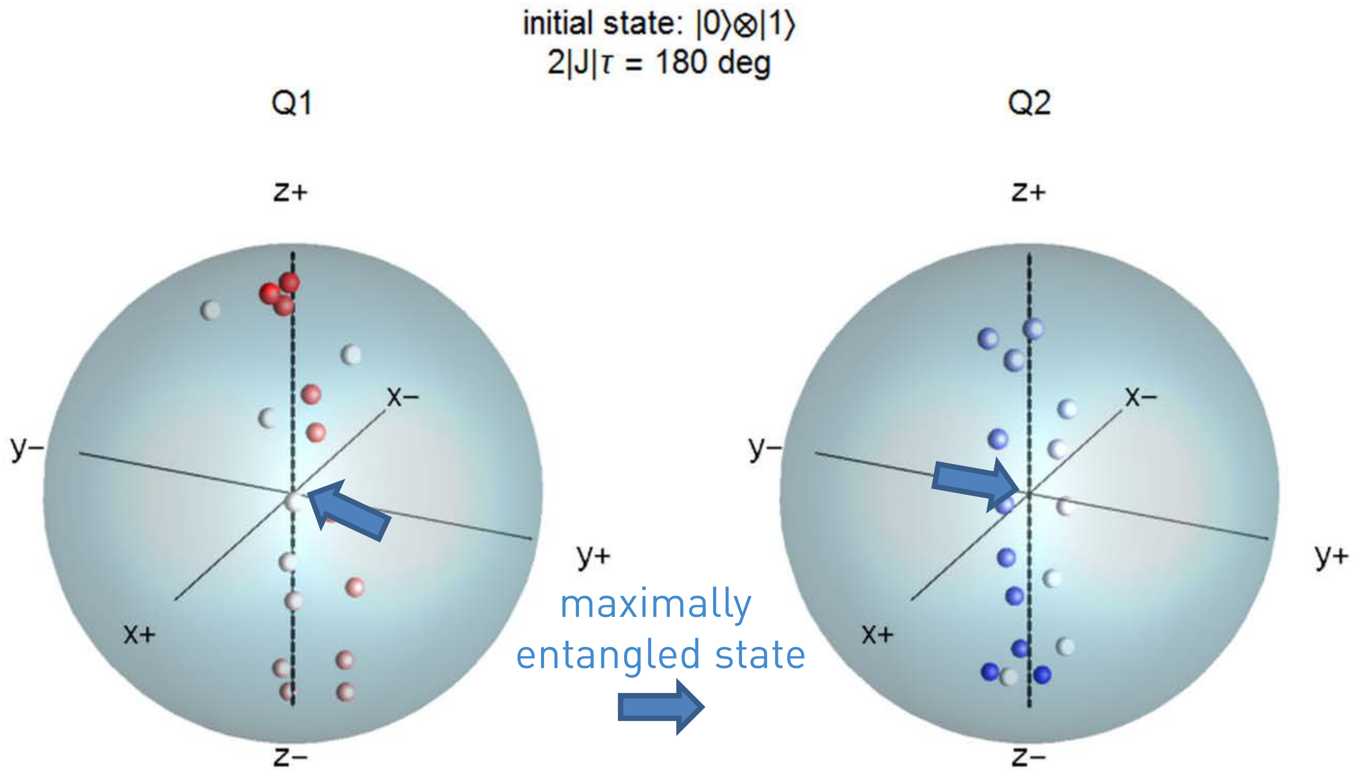
$$e^{-iH\tau} = e^{-iH_{xz}\tau}$$

Las Heras, U., et al. *Phys. Rev. Lett.* **112,** 200501 (2014)

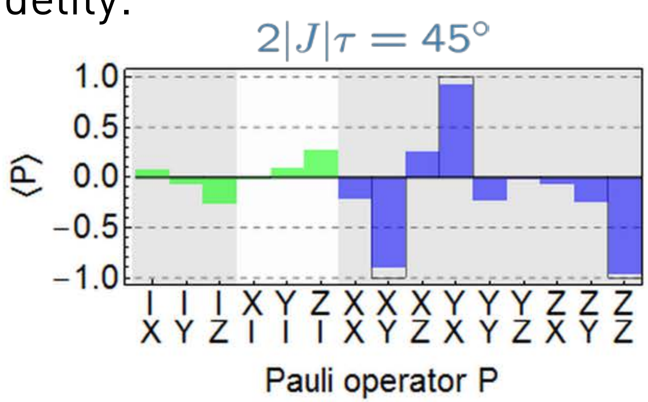
Heisenberg XYZ Interaction: Calculation

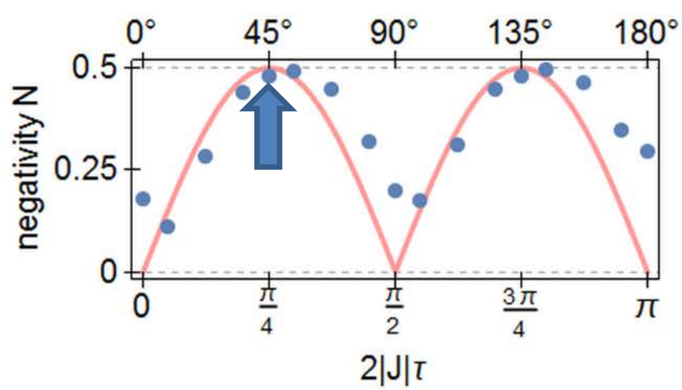


Heisenberg XYZ Interaction: Experimental Data



state fidelity:
94.7 %





Salathé, Y. *PRX* **5**, 021027 (2015)

Heisenberg XYZ Interaction: Calculation

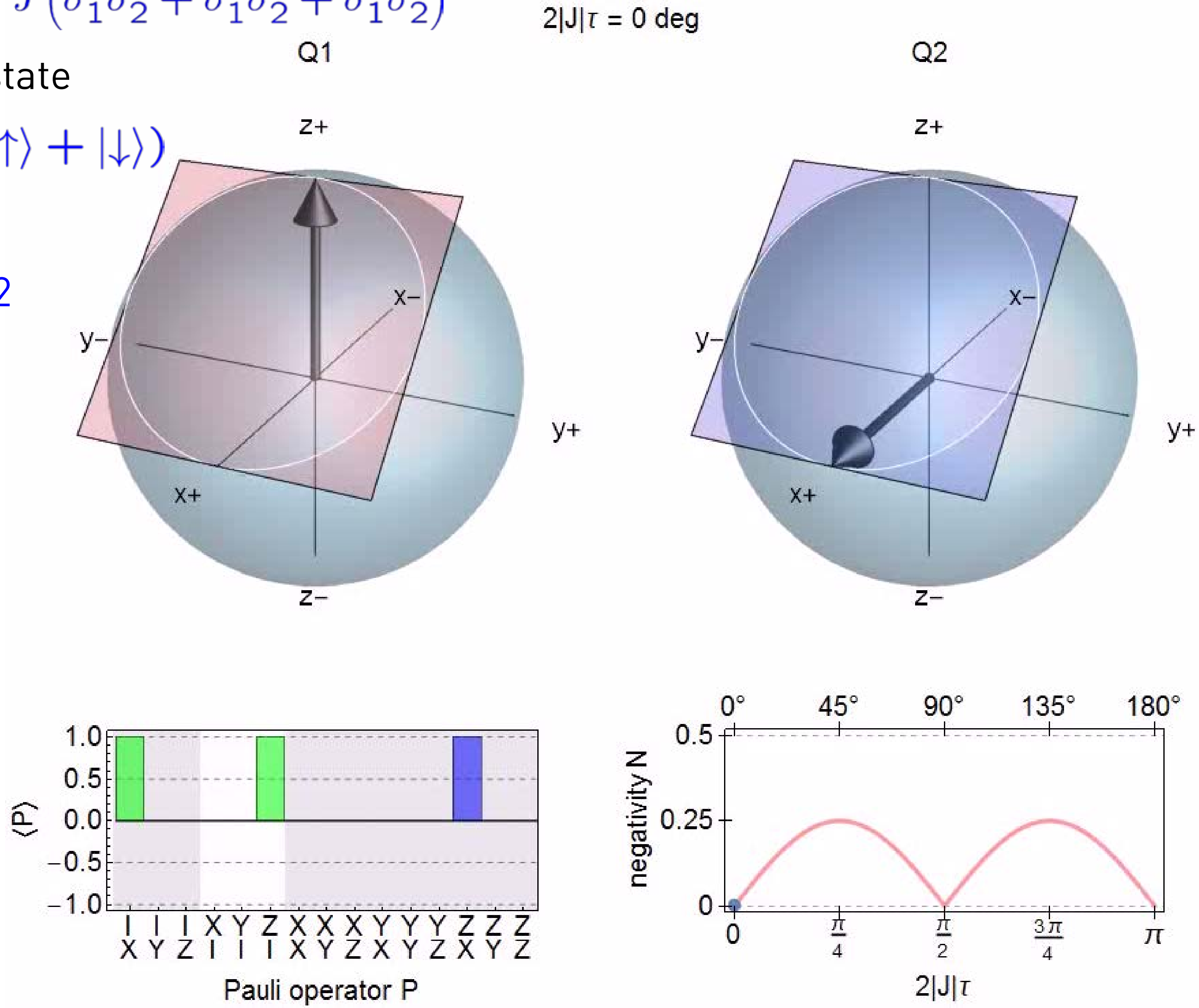
$$H_{xyz} = J\left(\sigma_1^x\sigma_2^x + \sigma_1^y\sigma_2^y + \sigma_1^z\sigma_2^z\right)$$

initial state

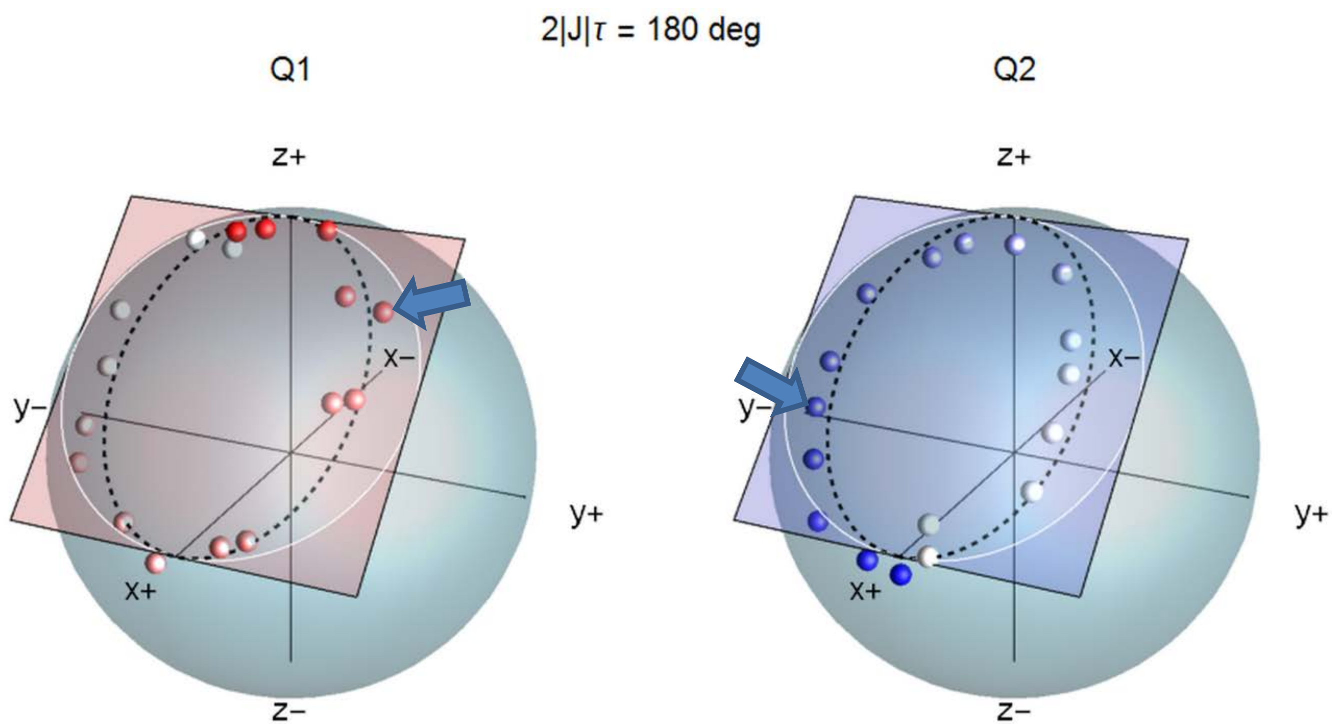
$$\frac{1}{\sqrt{2}}|\uparrow\rangle(|\uparrow\rangle + |\downarrow\rangle)$$

red: Q1

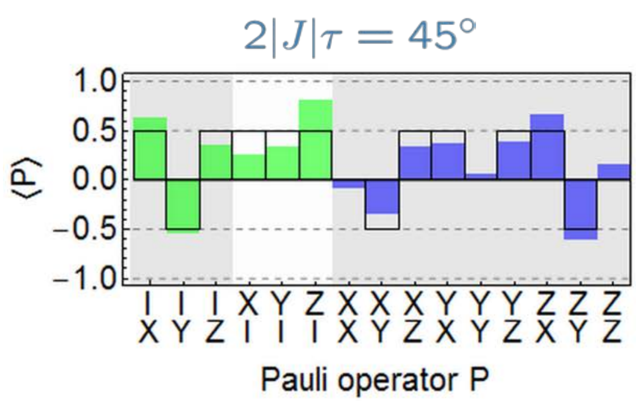
blue: Q2

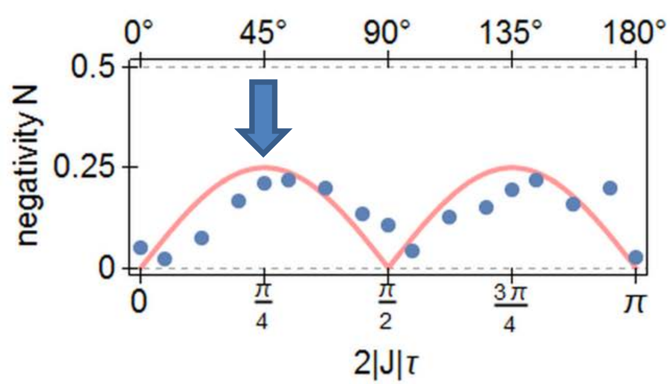


Heisenberg XYZ Interaction: Experimental Data



state fidelity: 95.3 %





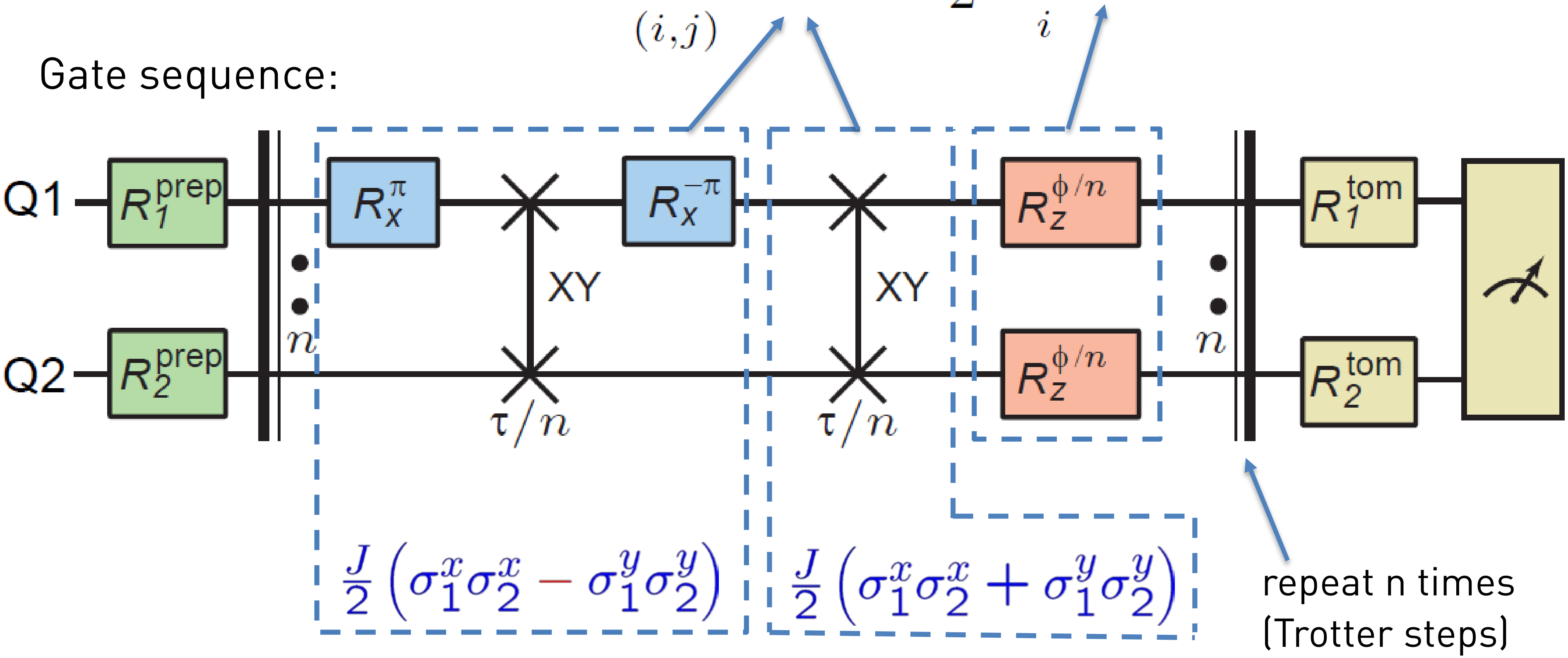
Salathé, Y. *PRX* **5**, 021027 (2015)

Ising Model with External Field

Hamiltonian to be simulated:

$$H_I = J \sum_{(i,j)} \sigma_i^x \sigma_j^x + \frac{B}{2} \sum_i \sigma_i^z$$

Gate sequence:



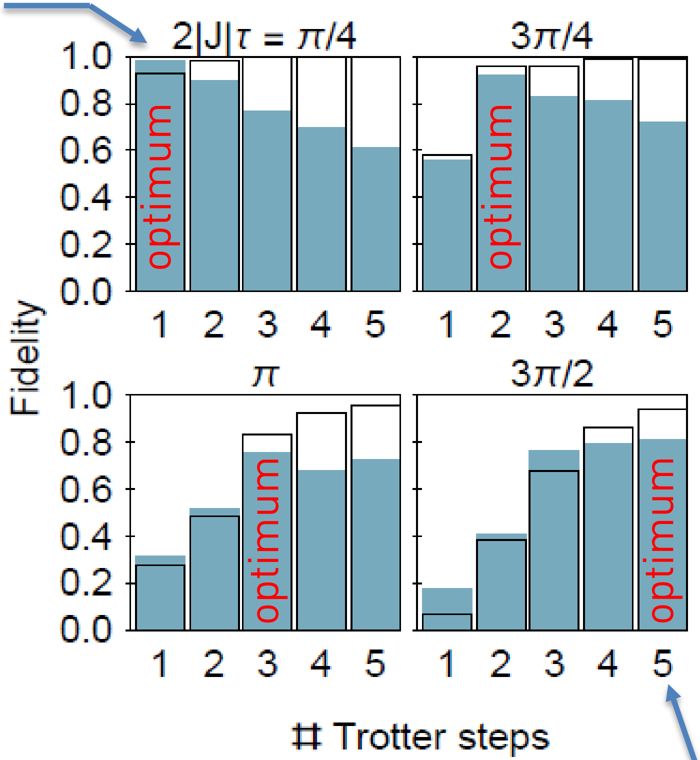
Salathé, Y. *PRX* **5**, 021027 (2015)

Fidelity of Simulation *vs.* Trotter Step and Int. Angle

Fidelity of simulated state: $$F = \left(\mathrm{Tr}\sqrt{\sqrt{\hat{\rho}_{\mathrm{theo}}}\hat{\rho}_{\mathrm{meas}}\sqrt{\hat{\rho}_{\mathrm{theo}}}}\right)^2$$

fewer Trotter steps needed for **small** phase angles (higher-order terms are less important)

Optimal final state fidelity reached at **finite** number of Trotter steps due to limited fidelity individual gates



wire frame: ideal Trotter fidelity

colored bars: experimental fidelity

more Trotter steps needed for **large** interaction phase angles (higher order terms are important)

Salathé, Y. *PRX* **5**, 021027 (2015)

Summary and Outlook

Conclusions:

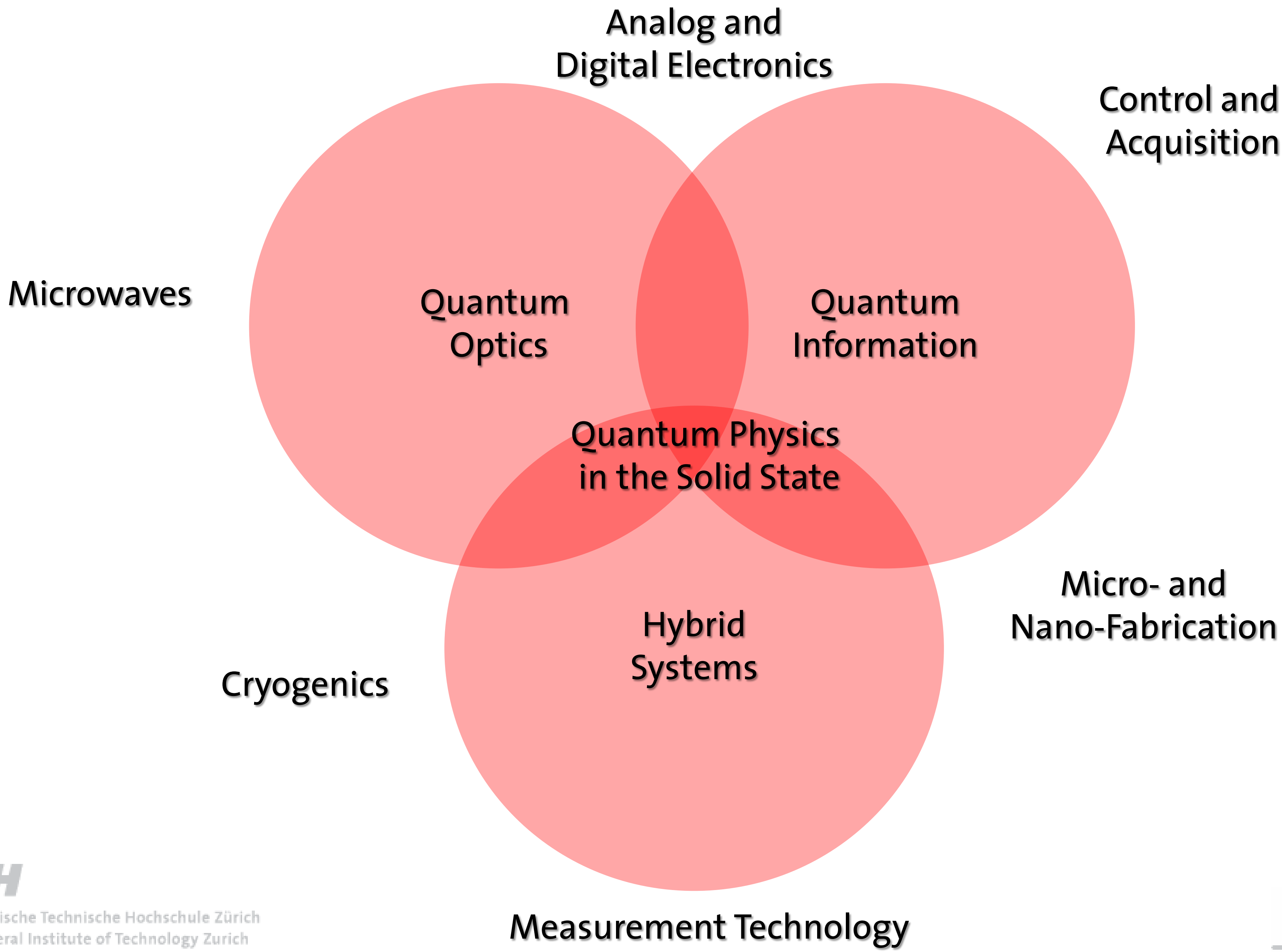
- one of the first digital quantum simulation with superconducting qubits
- simulated time-evolution of paradigmatic spin models
- typical state fidelities above 80% for XYZ and Ising
- used up to 10 two-qubit gates with a continuous interaction parameter combined with 25 single-qubit gates
- challenge: gate calibration with continuous control parameter

Interesting perspectives:

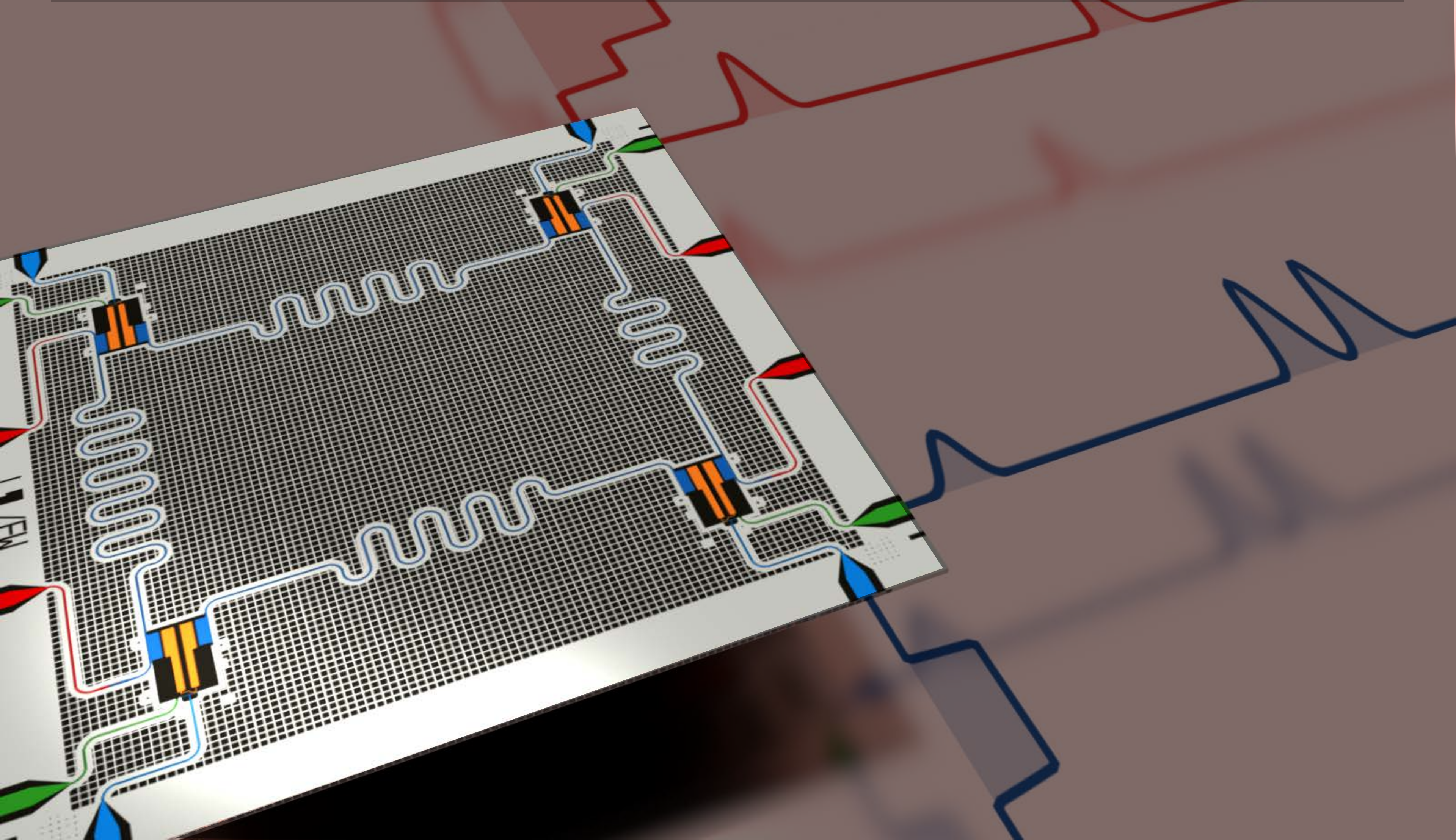
- simulation of Hamiltonians with local interactions using Trotter decomposition
- combine analog and digital methods
- explore time-dependent Hamiltonians
- use bosonic building blocks explicitly
- expand to larger number of spins

Collaboration: Salathé, Mondal, Oppliger, Heinsoo, Kurpiers, Potočnik, Mezzacapo, Las Heras, Lamata, Solano, Filipp, Wallraff *Phys. Rev. X* **5**, 021027 (2015)

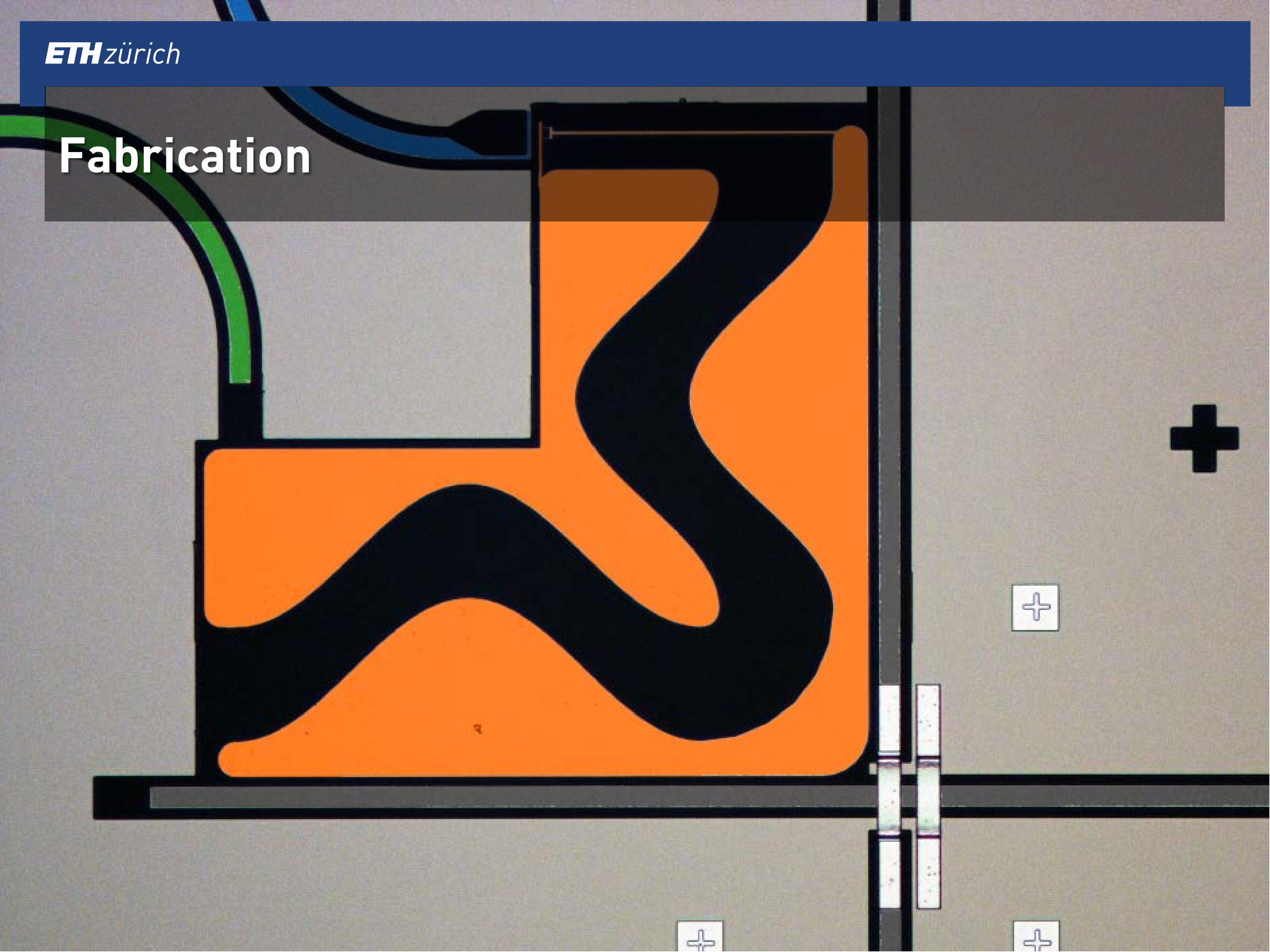
Superconducting Circuits for Quantum Technologies



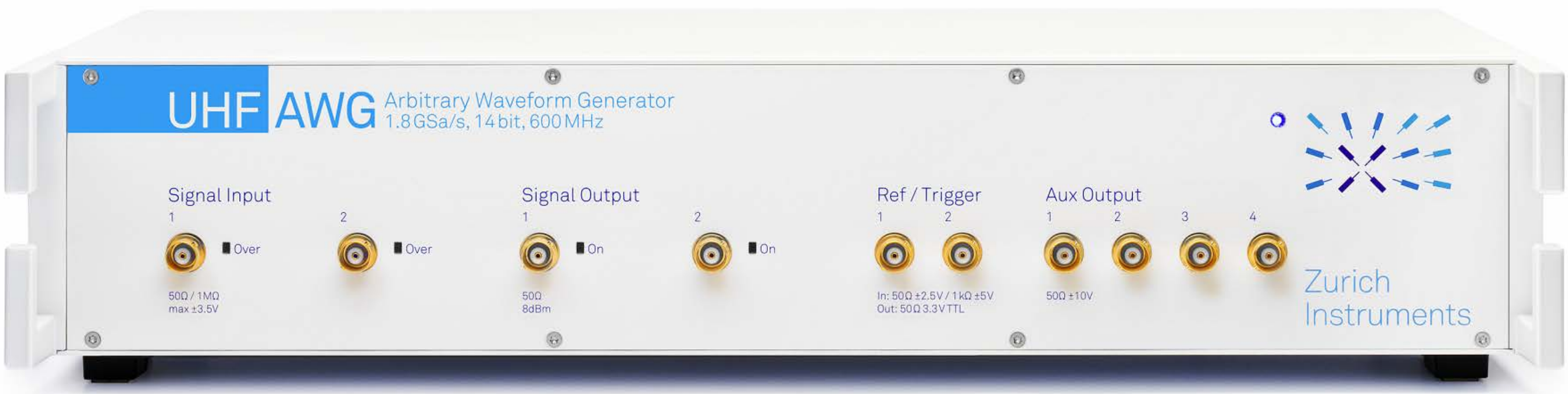
Design



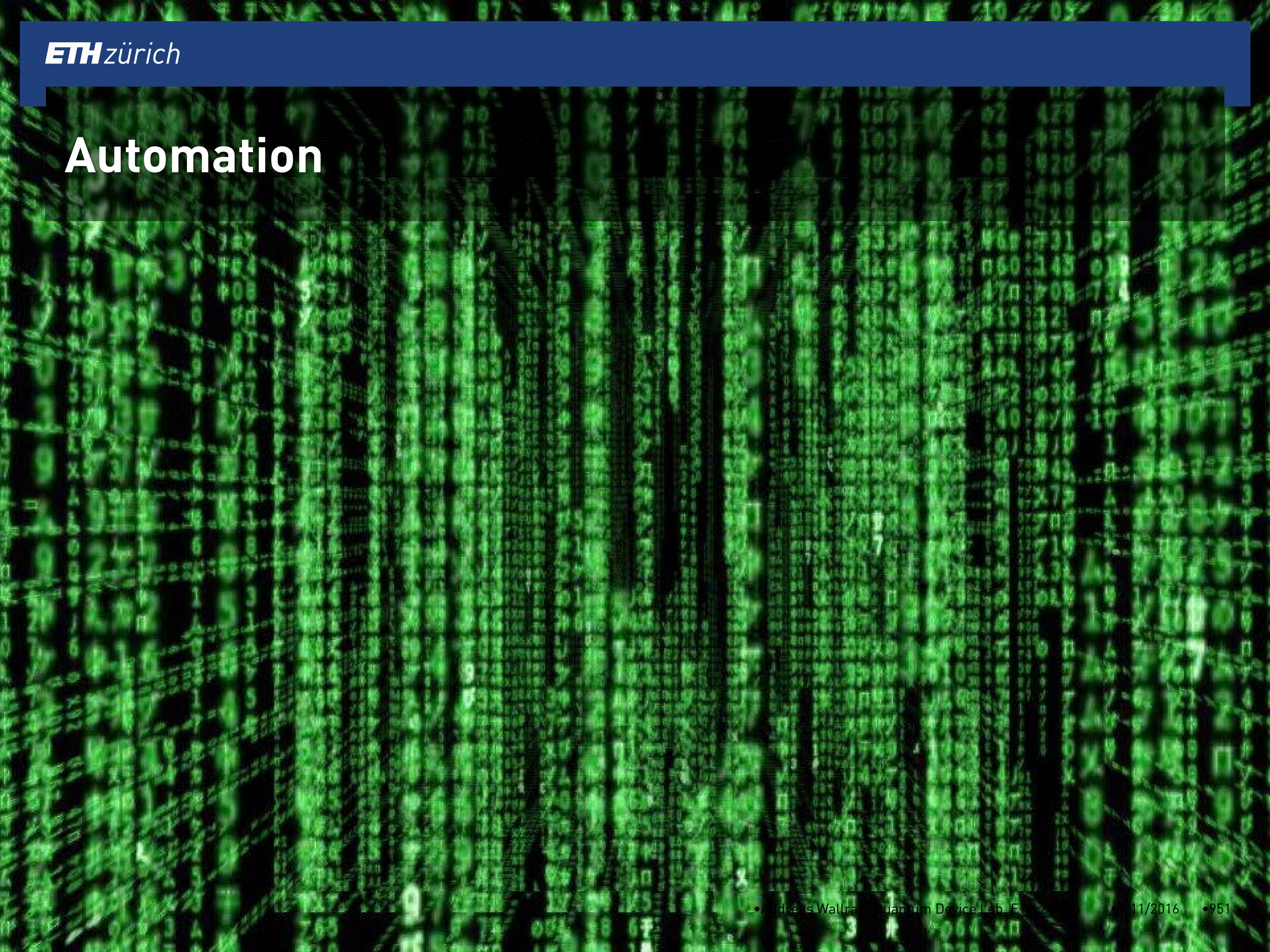
Fabrication



Control


UHF AWG
Arbitrary Waveform Generator
1.8 GSa/s, 14 bit, 600 MHz
Signal Input
1
2
Over
Over
50Ω / 1MΩ
max ±3.5V
Signal Output
1
2
On
On
50Ω
8dBm
Ref / Trigger
1
2
In: 50Ω ±2.5V / 1kΩ ±5V
Out: 50Ω 3.3V TTL
Aux Output
1
2
3
4
50Ω ±10V
Zurich
Instruments

Automation



Cryogenics

ETH zürich

Quantum Engineering

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

FNSNF
Swiss National Science Foundation

erc

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Looking for Grad Students, PostDocs and Technical Staff.

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Swiss Federal Institute of Technology Zurich