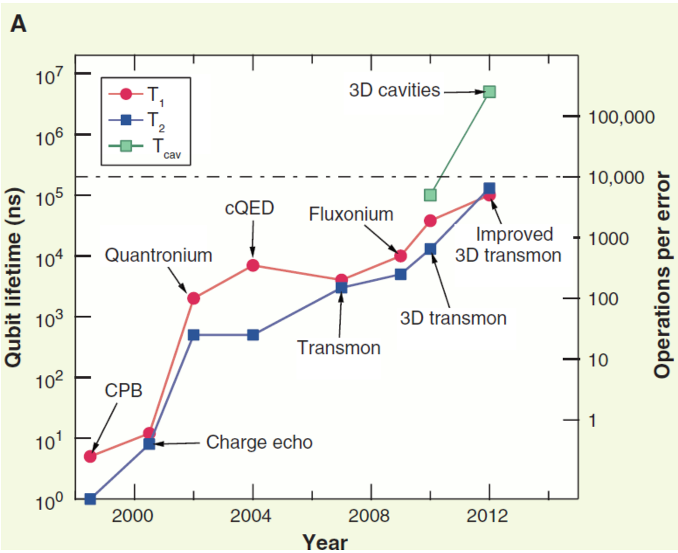
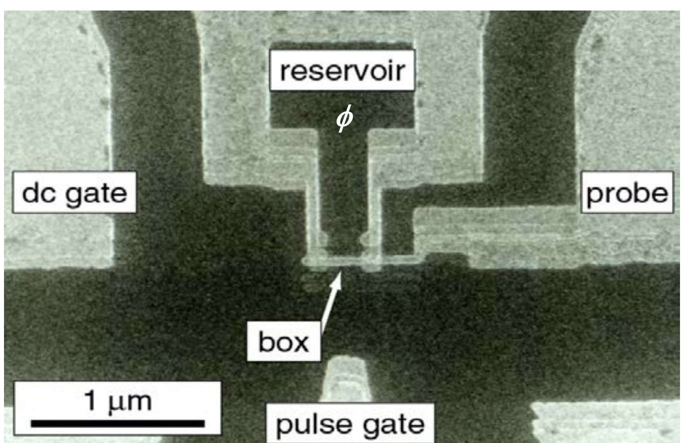
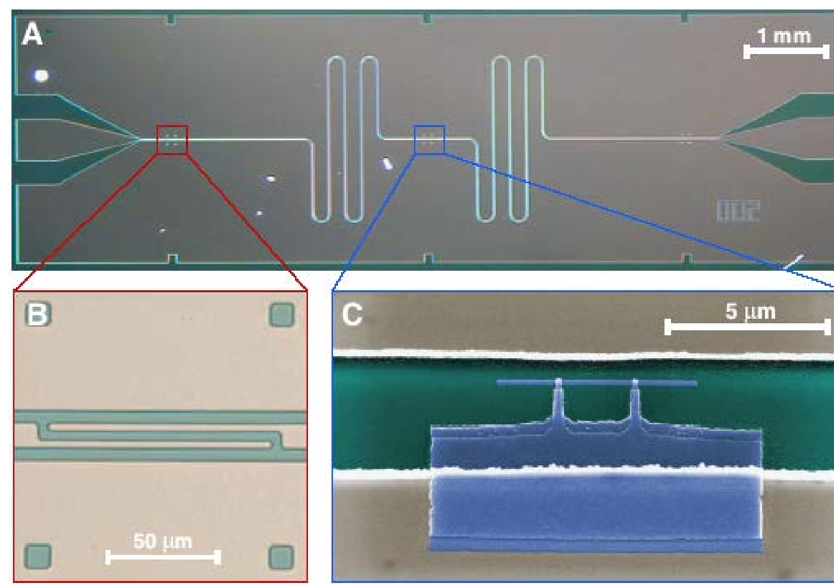
Quantum Computing Architectures

Budapest University of Technology and Economics 2018 Fall



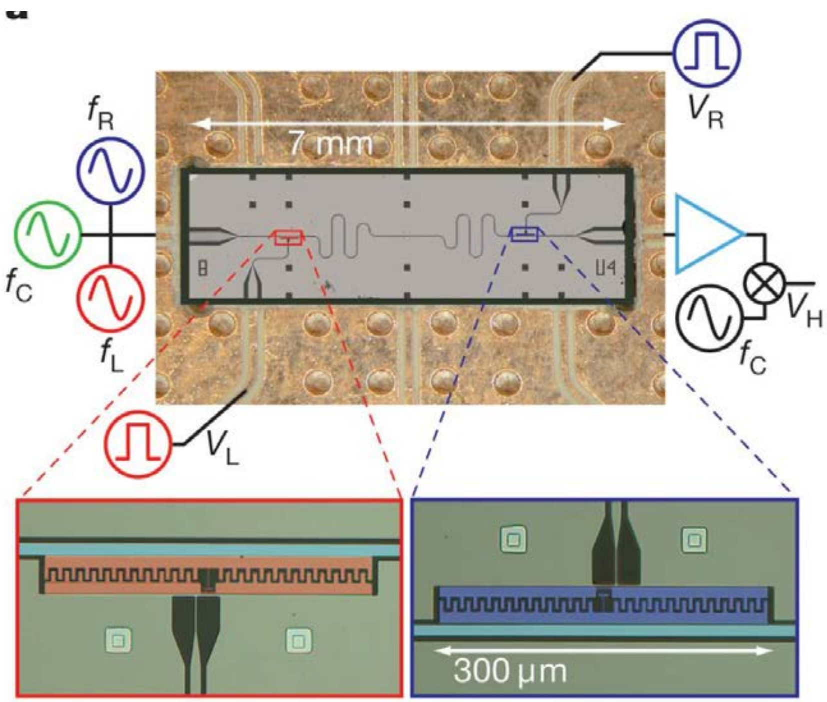
Lecture 10: Grover algorith
Teleportation



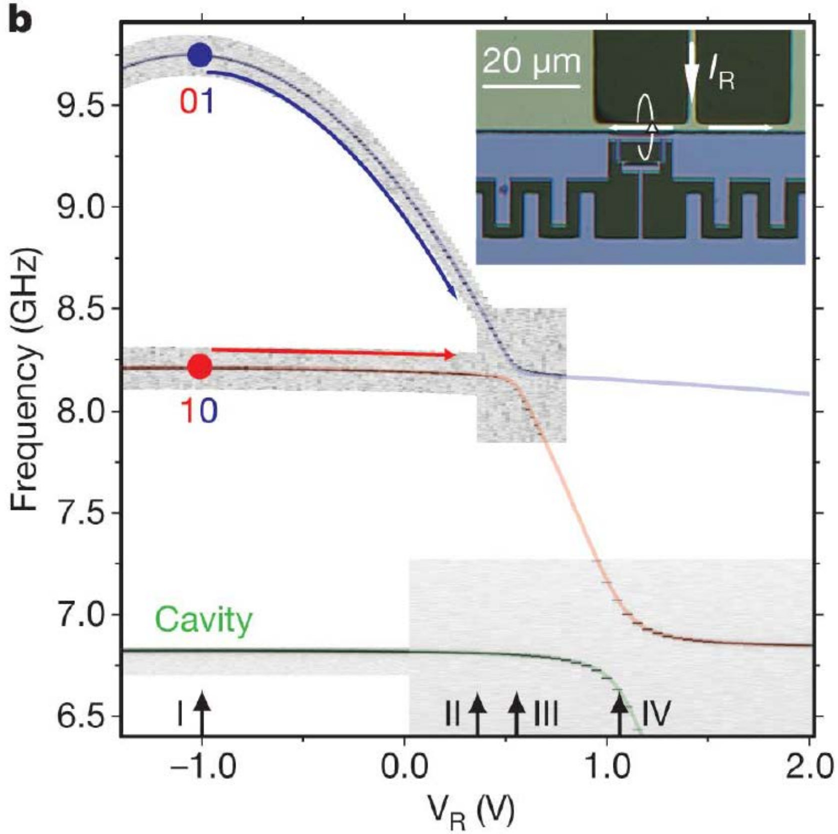


Coupling qubits
Coupling transmons

Individual flux lines for controlling the qubit itself (not via Stark shift)



L. Dicarlo et al., Nature 460, 240 (2009)



Point I

Far detuning – effectively decoupled states L and R qubit can be addressed separately

Computational states

00 - GS

10 - L excited

01 - R excited

11 - both excited

μs lifetimes of individual qubits

Point IV

Cavity – qubit strong coupling

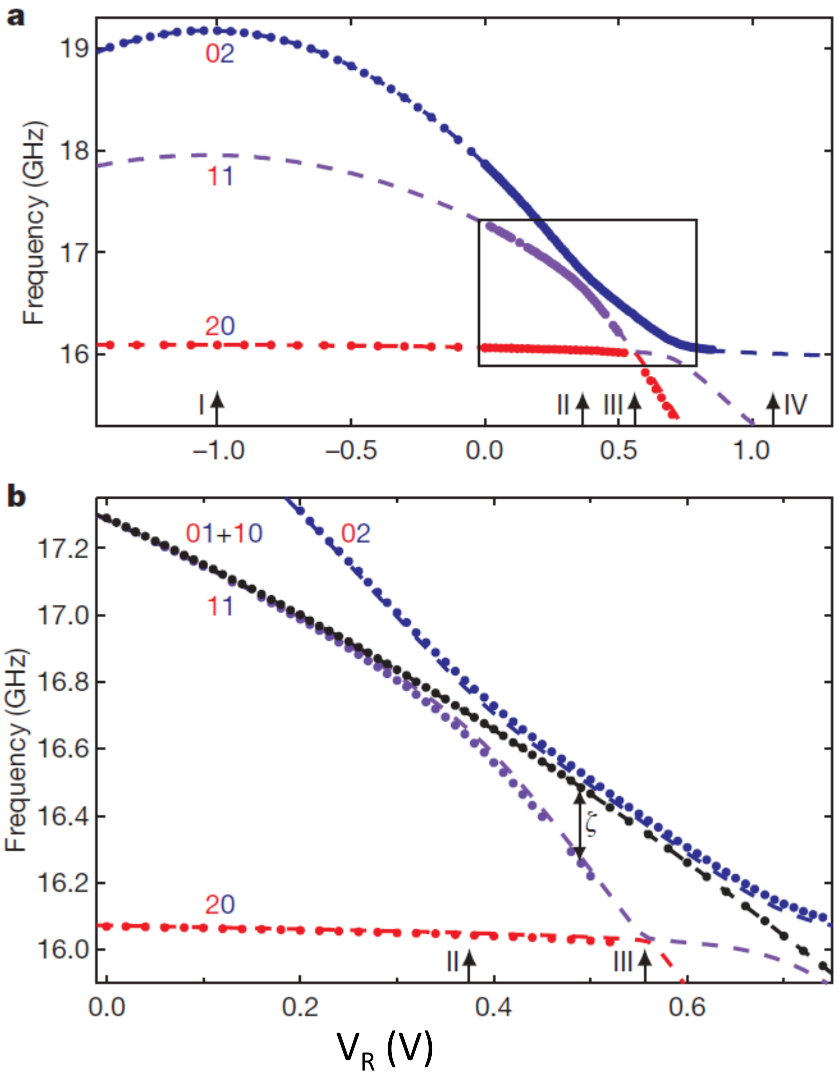
Point III

Qubit-qubit coupling via cavity (2^{nd} order perturbation as seen previously)

Point II

Point of operation

L. Dicarlo et al., Nature 460, 240 (2009)



Point II

Point of operation
Transmon: higher levels can also play a role
02 state also becomes important
Should cross with 11 at point II, however avoided crossing is seen.
f_{11} should be $f_{10} + f_{01}$, but lowered with $\zeta/2\pi$

c-Phase gate can be implemented with this

$$\zeta \sigma_z^1 \otimes \sigma_z^2$$

Usually small interaction, however using second levels can be enhanced, when becomes close to resonant

$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\phi_{01}} & 0 & 0 \\ 0 & 0 & e^{i\phi_{10}} & 0 \\ 0 & 0 & 0 & e^{i\phi_{11}} \end{pmatrix} \qquad \theta_z^{ij} = \int \delta\omega_{ij}(t)\,dt$$

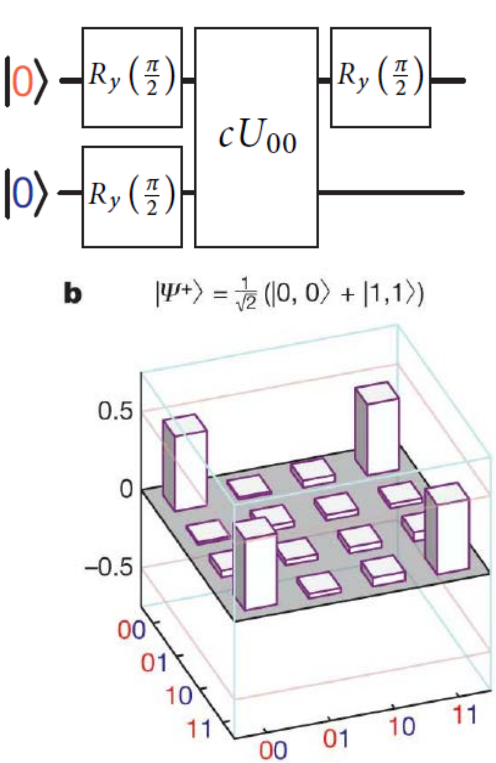
$$\int_0^{t_f} \zeta(t)\,dt = (2n+1)\pi \qquad \theta_z^{01} = \theta_z^{10} = 0$$

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

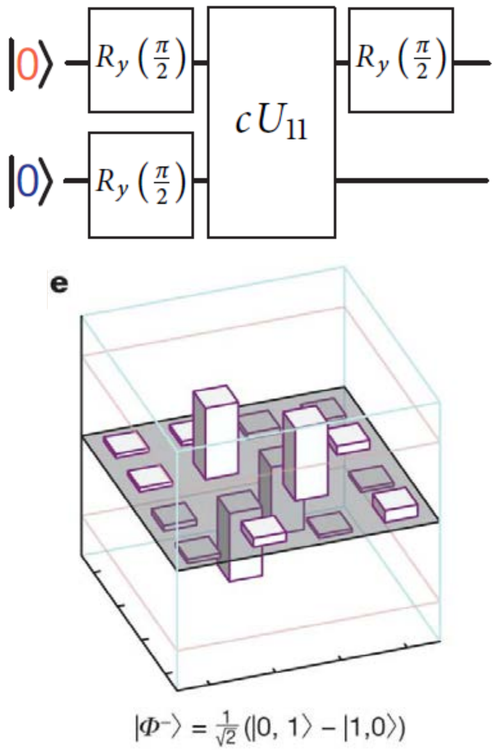
Phase gate
Adjust single qubit phase gates – adiabatic pulses are fine
Measure ζ by spectroscopy or by Ramsey of L for 10 and 11

J. M. Chow Phd thesis

Entanglement with C-Phase



F~0.91



F~0.87

Re part

Different C-phase gates – tuning the sign of Φ_{01} and Φ_{10}
Imaginary part of density matrix is small (≤0.05)

Tomography:
Measure the elements of the density matrix, using 00 measurements and single qubit rotations

$$F(\rho,\psi) = \langle\psi|\rho|\psi\rangle$$

L. Dicarlo et al., Nature 460, 240 (2009)

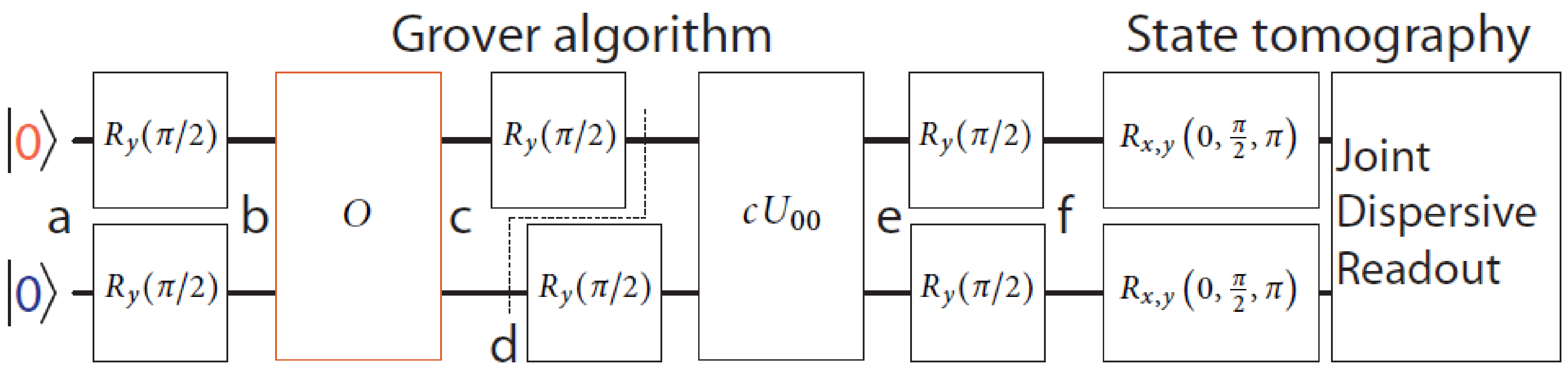
Grover search algorithm

<u>Motivation: find a given name in an unordered list of N</u>
Classical: ~N trial
Quantum ~ sqrt(N)

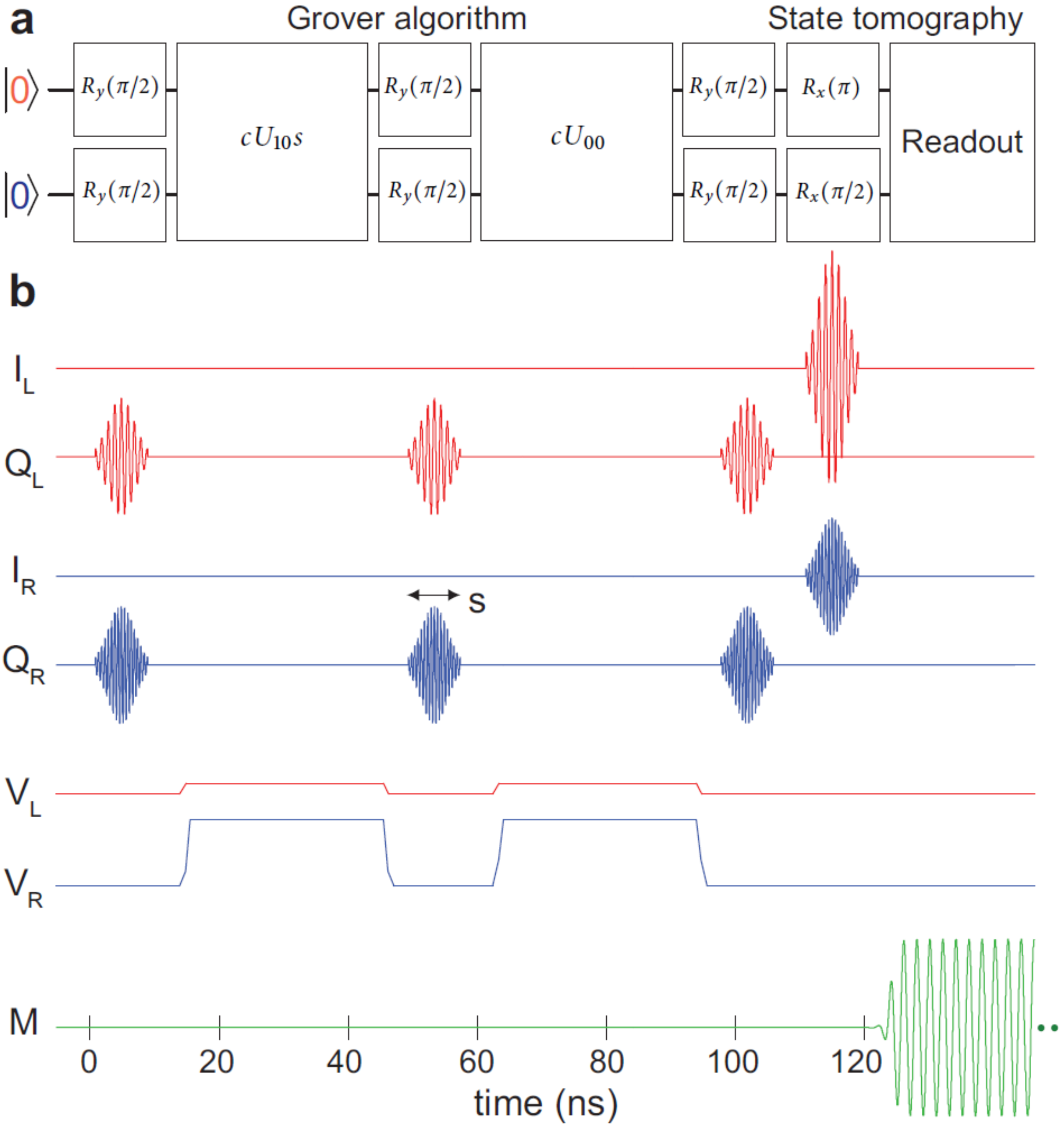
Grover: $N=2^n$, can be represented with basis states: e.g. N=4: 00,01,10,11
Oracle: O operator: recognizes the solution

$$O\,|x\rangle = (-1)^{f(x)}\,|x\rangle$$

state is marked – still has to be read out
For more than 4 states, iteration of these operations are needed



L. Dicarlo et al., Nature 460, 240 (2009)

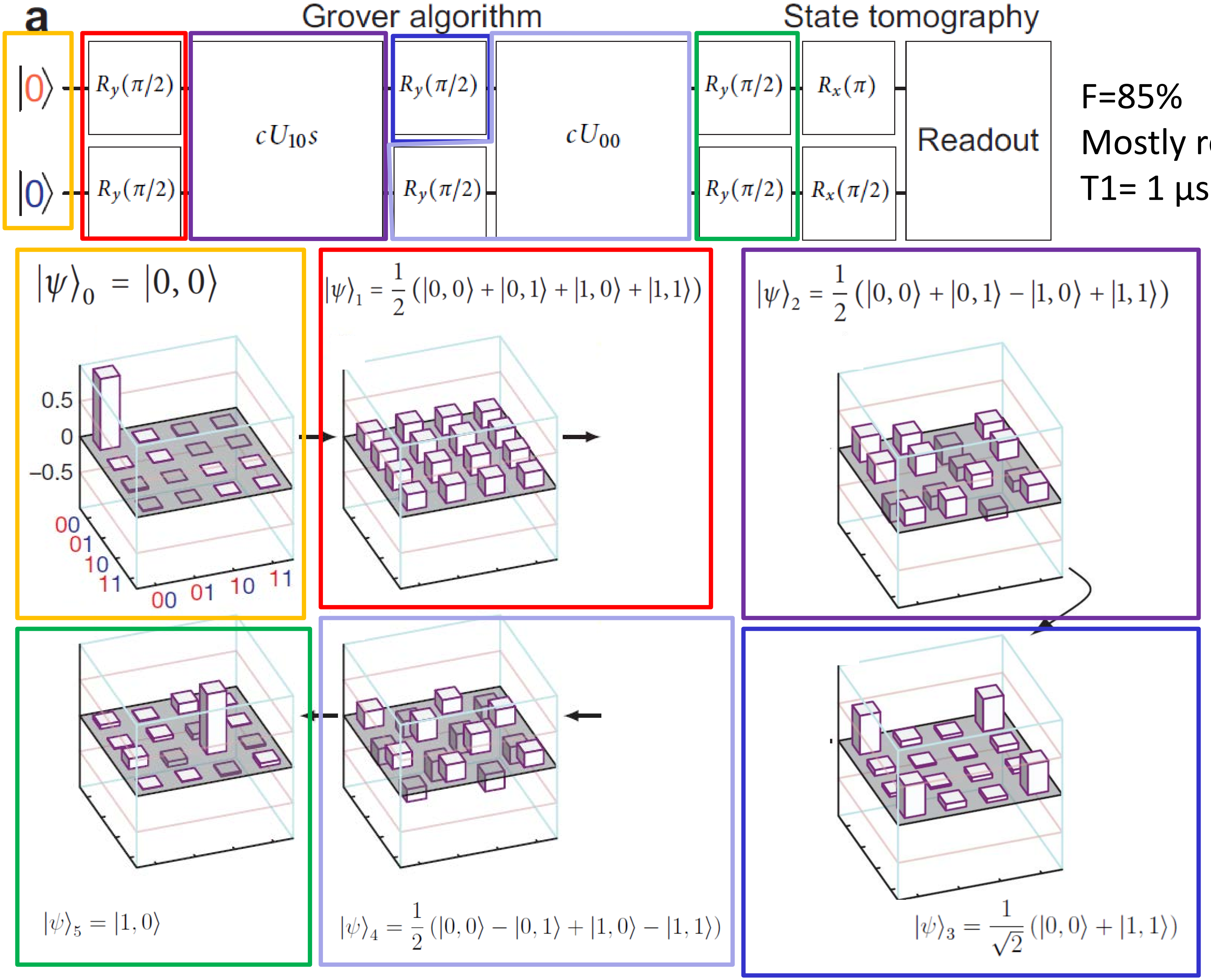


<u>Realization of</u>
<u>Gorver algorithm</u>
searching for 10

Pulse sequency (I, Q – 90 degrees phase shift) These are the single qubit rotations

Phase gates to make the qubits interact

Readout tone



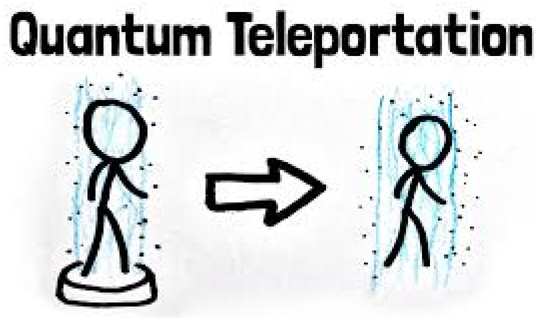
F=85%

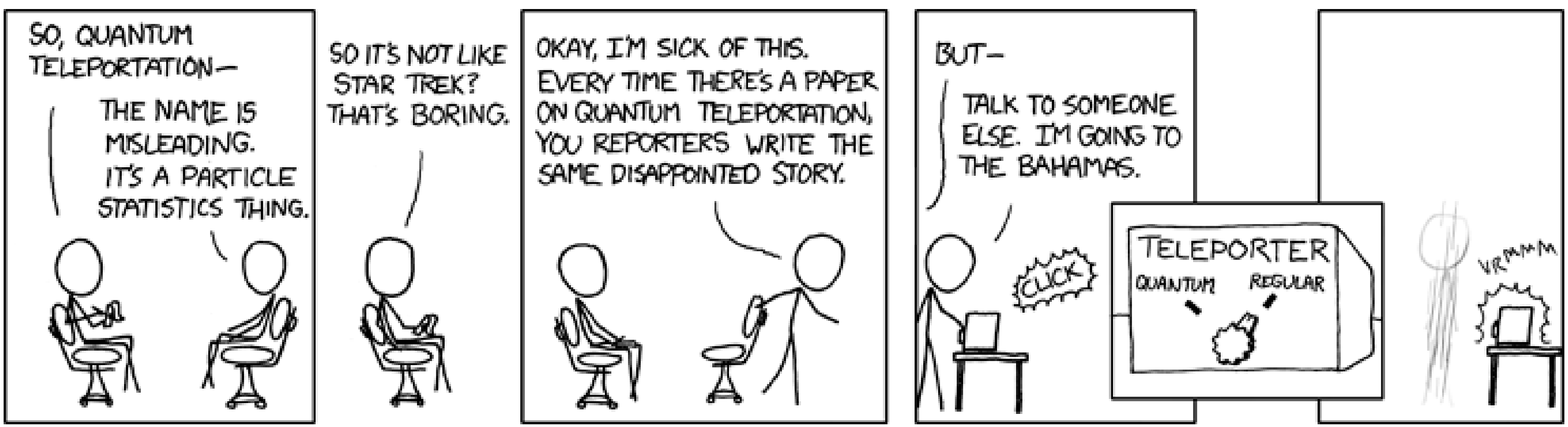
Mostly relaxation

T1= 1 μs

L. Dicarlo et al., Nature 460, 240 (2009)

Quantum teleportation

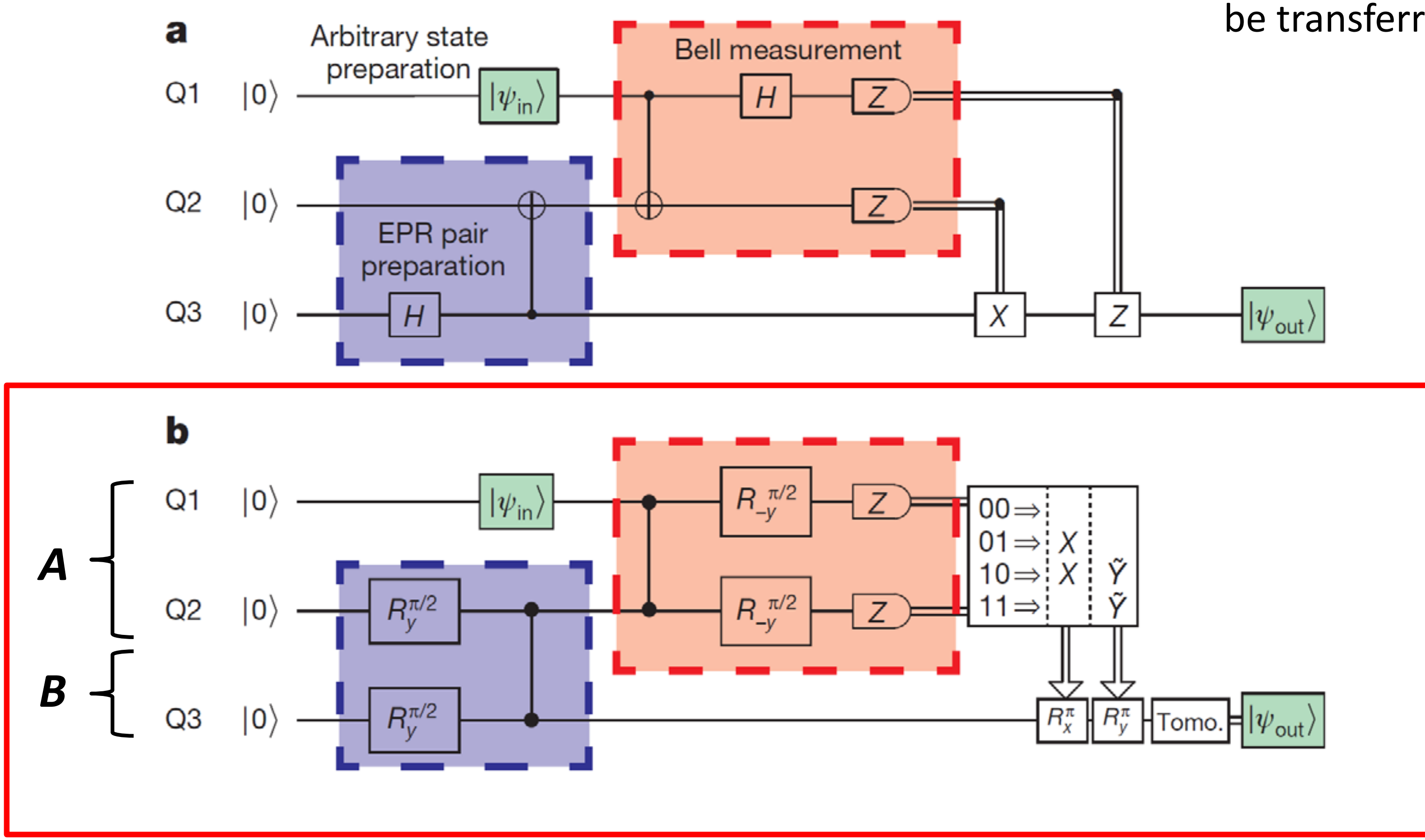




XKCD

Quantum teleportation

A has a qubit which should be transferred to B



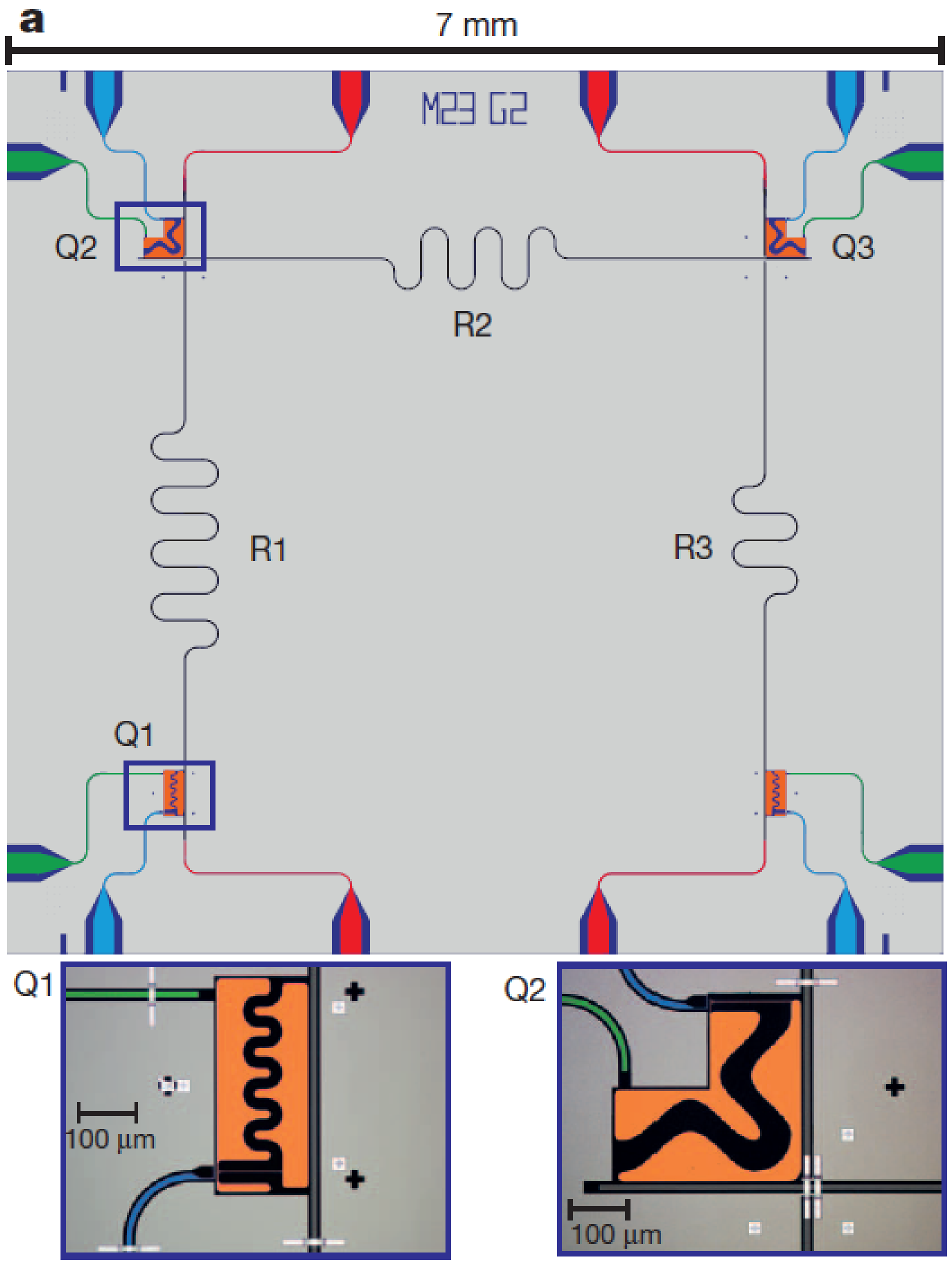
Idea:

- share entangled state between A-B
-A: Entangle it with the input state and measure in a Bell basis
- B: during the measurement the state will collapse
- A send as a *classical information* the measurement result
- B can rotate his state to recover the input state

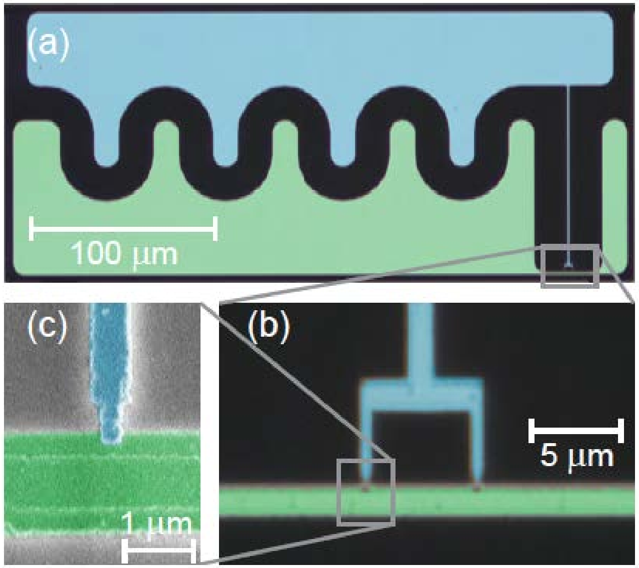
L. Steffen et al., Nature, 500, 319 (2013)

Quantum teleportation
Setup

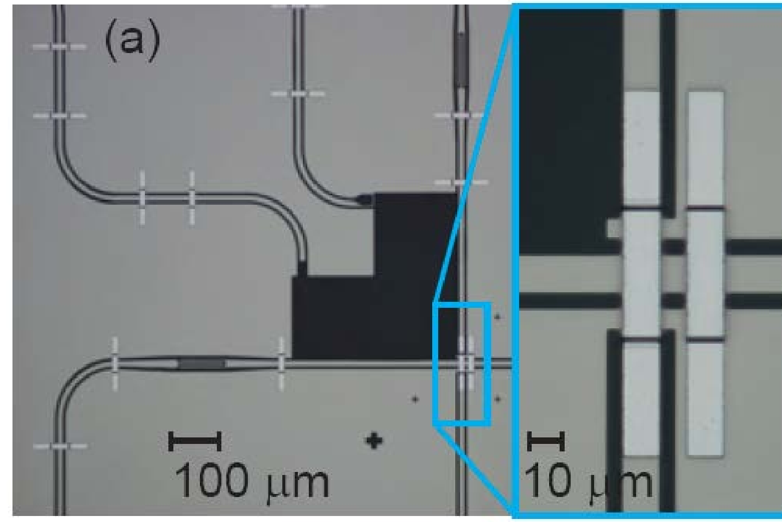
3 qubits: Q1, Q2, Q3
2 Resonators which can be read out: R1, R3
Not directly coupled to the external world:
R2 – couples Q2 and Q3
Read: resonotor ports
Blue/green: Qubit manipulation ports



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



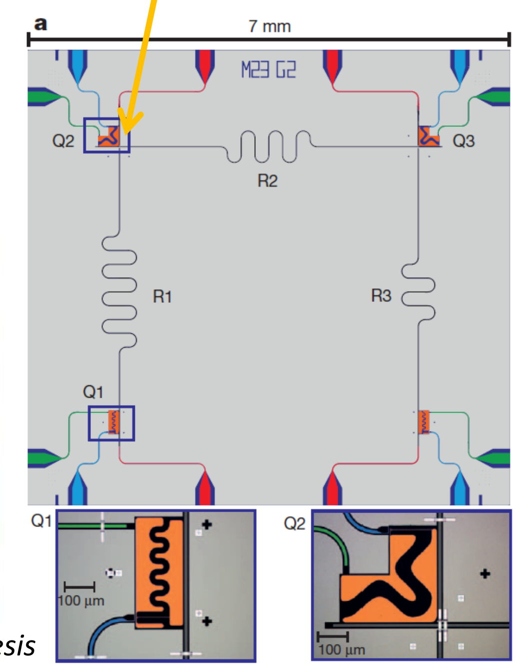
Transmon

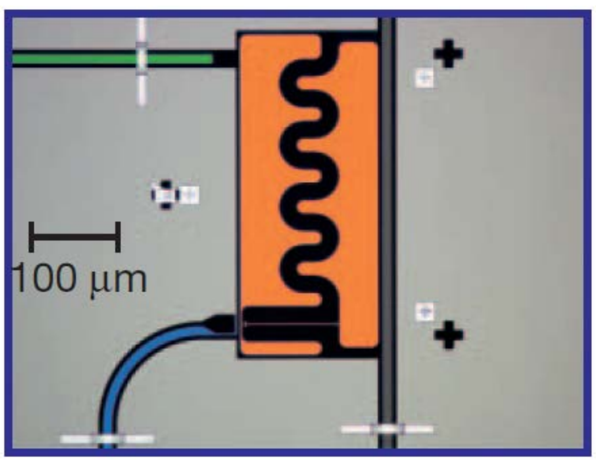


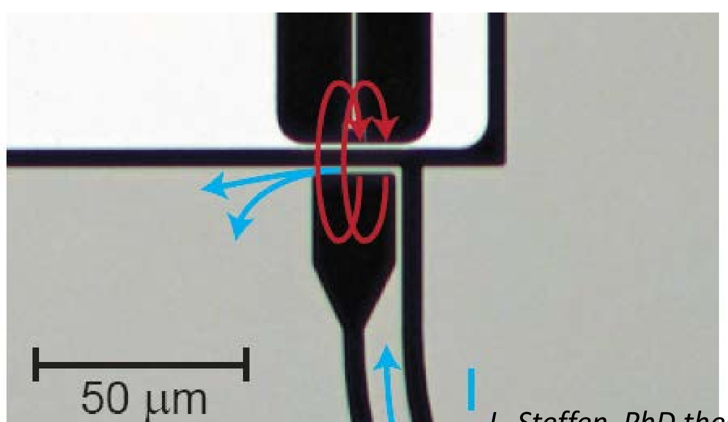
Air bridges for resonator crossing

Qubit control:
Via capacitive coupling
(green electrode)

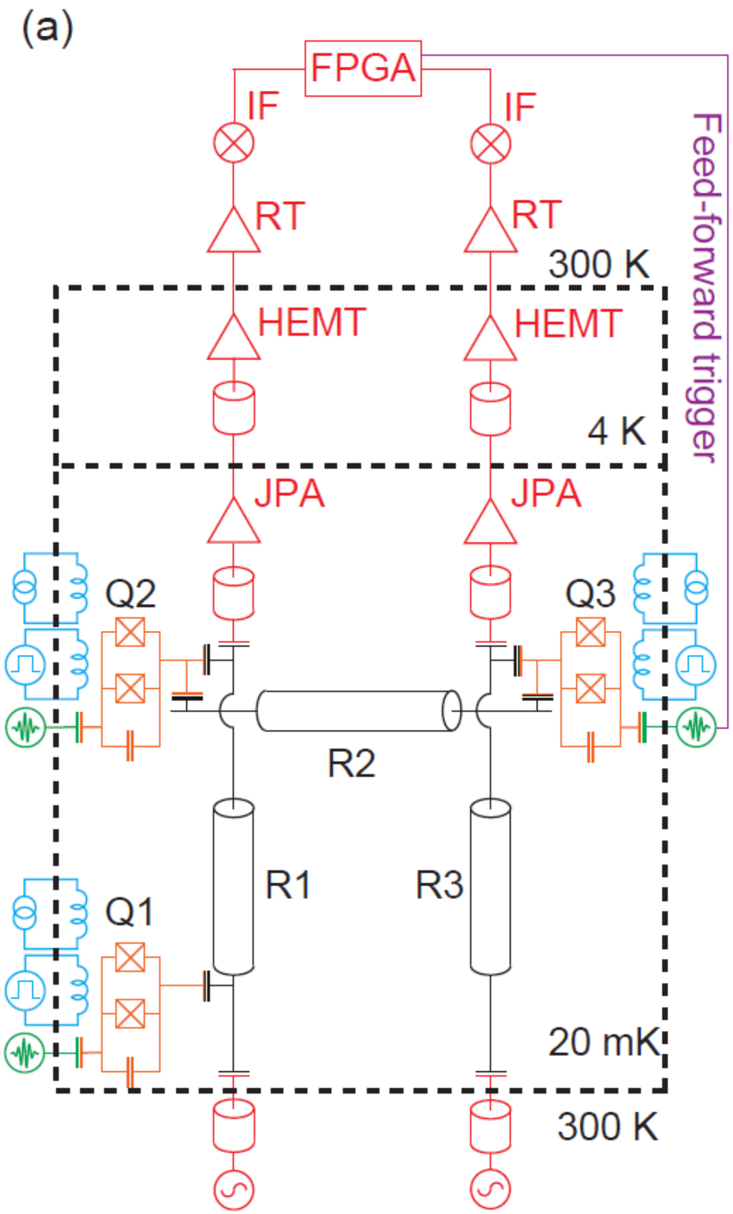
Flux biasing (blue)
3 small coils to tune E_J+
flux lines for fast tuning







L. Steffen, PhD thesis

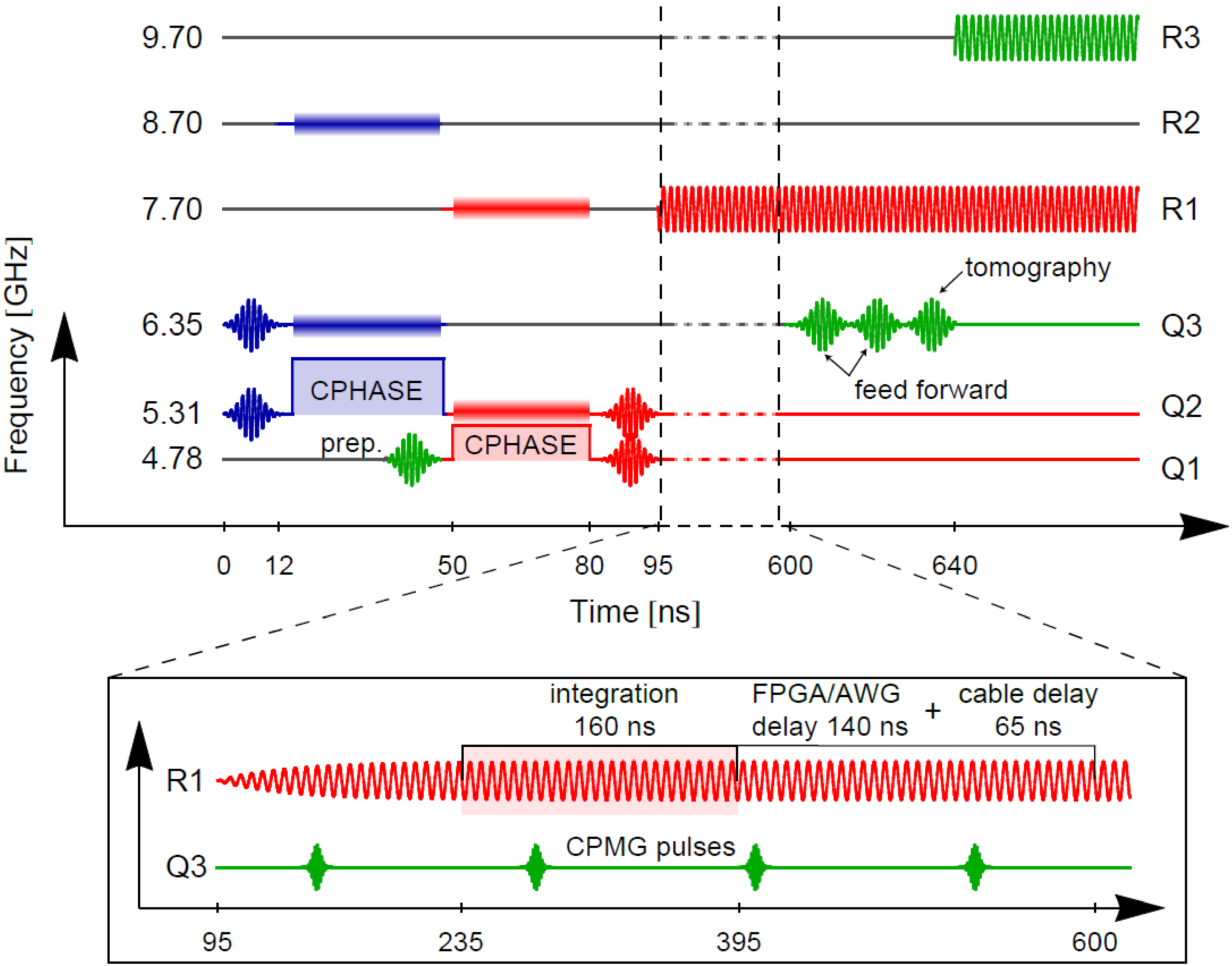


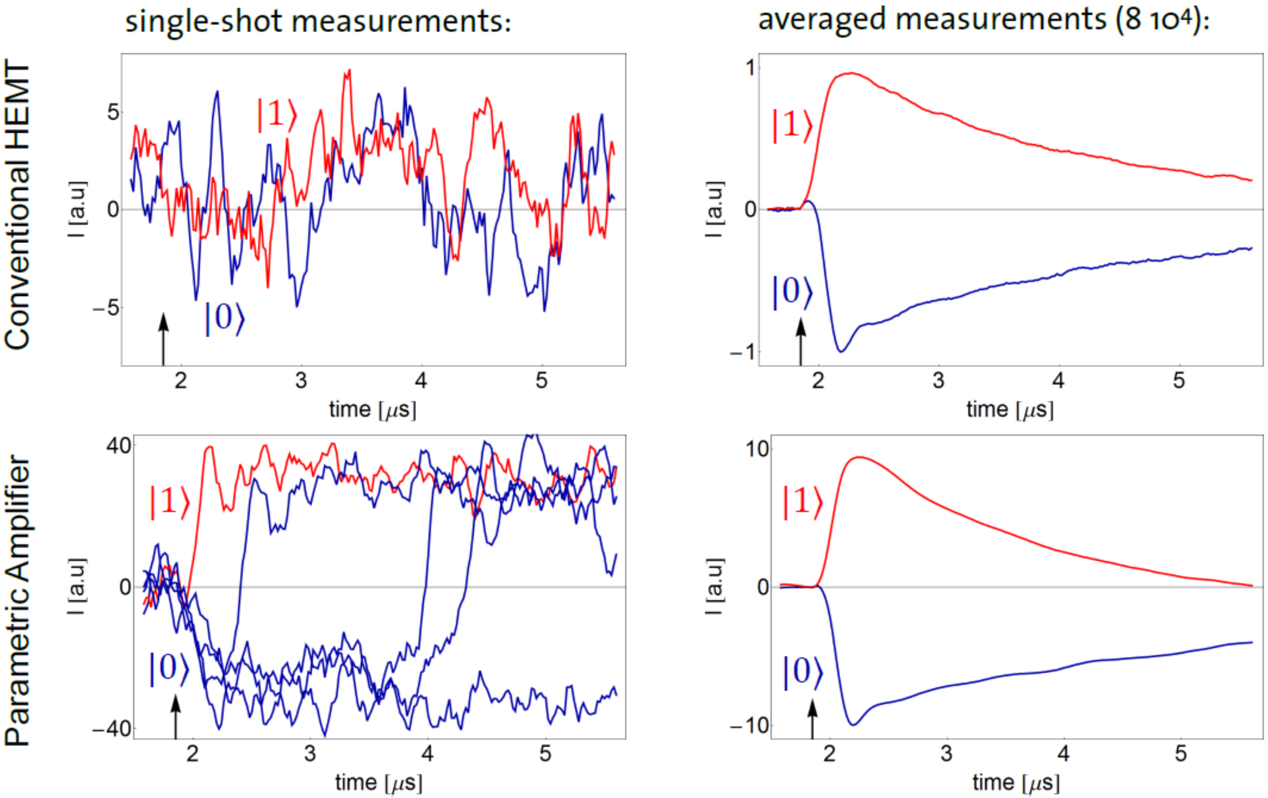
Measurement setup

Feed forwards implemented with FPGA
Measures the state of the qubit and triggers a fast rotation

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

Teleportation sequence

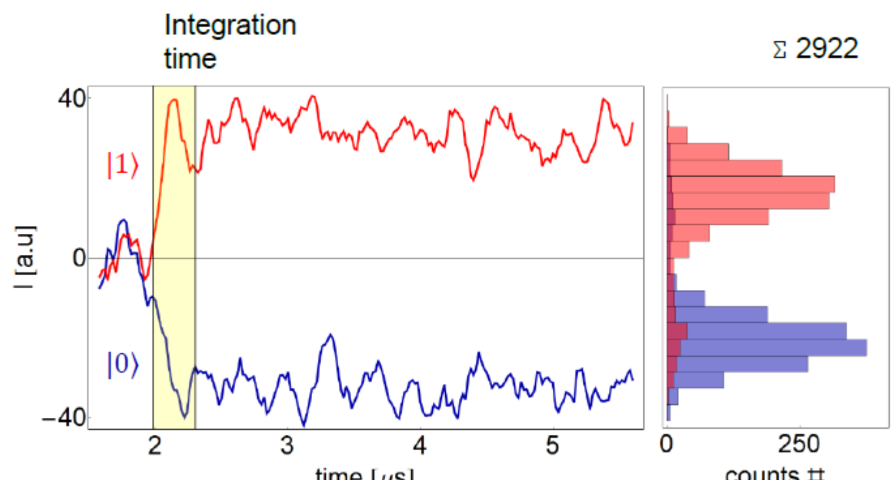




P. Kurpiers, Y. Salathe *et al, ETH Zurich* (2013)
R. Vijay *et al., PRL* 106, 110502 (2011)

The role of amplifiers

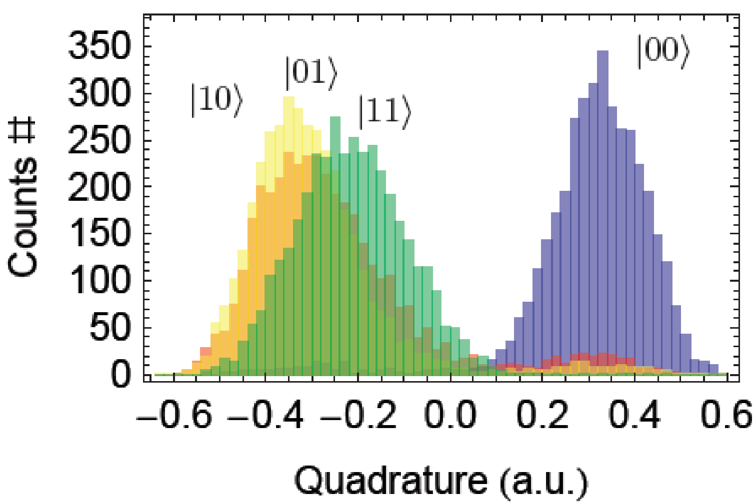
With special amplifiers single shot measurements became possible



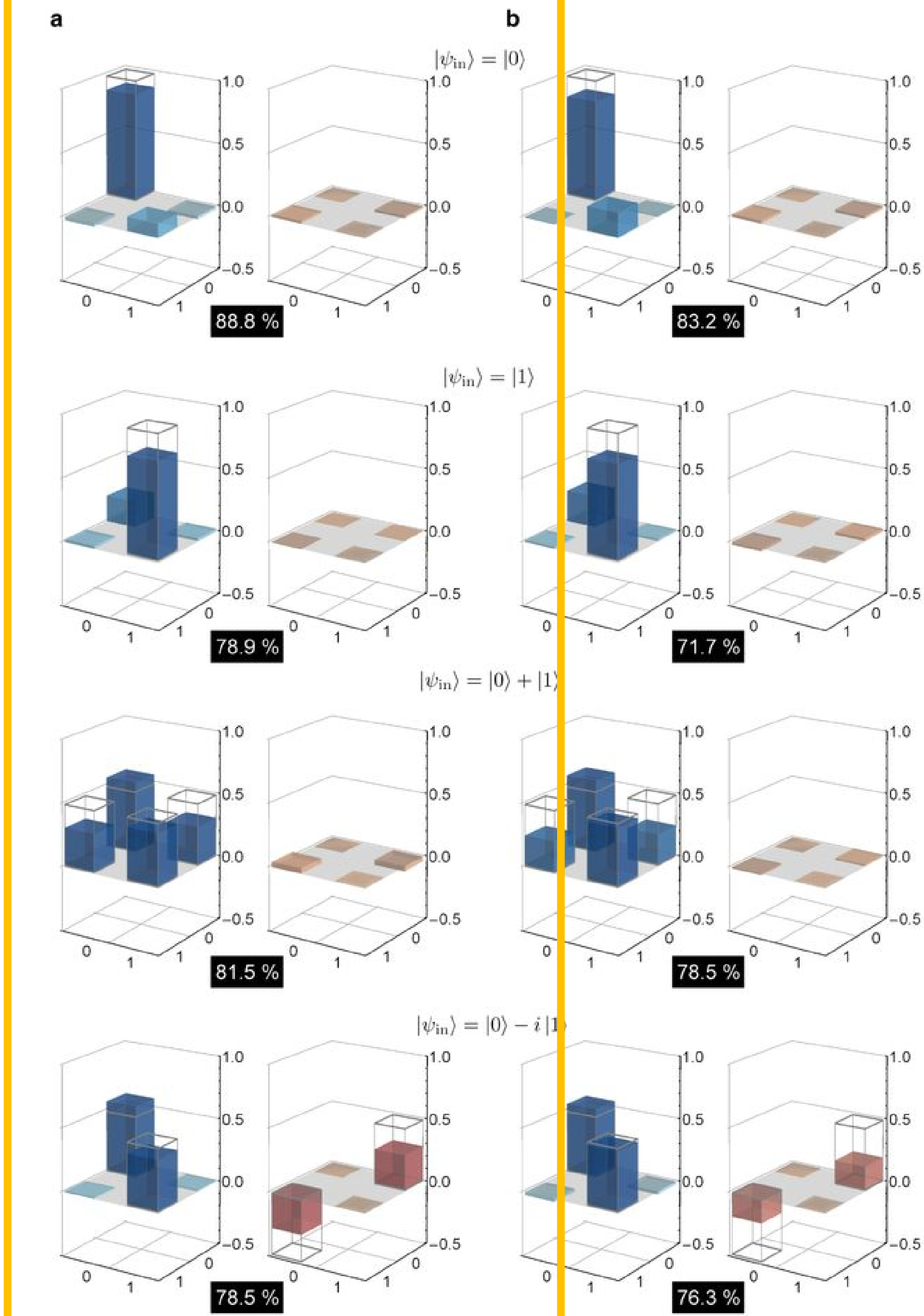
A. Walfraff, Lecture notes

Teleportation
Post-selection

- Only measure 0, 0 state
If it was 0,0, than the output state was the teleported one
Otherwise: discard the experiment
Set the amplifier such, that it is sensitive to 0,0
(Can be also done for other states) – 91% fidelity
Analysis: state tomography:
Output should be input state



~transmission of resonator



Process tomography

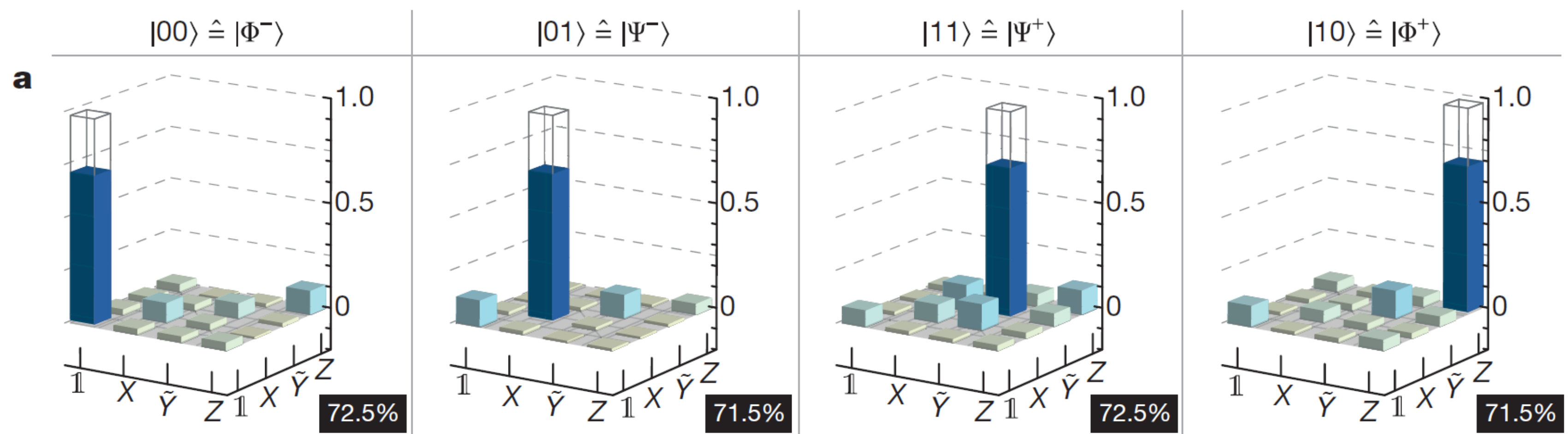
Charcterization of a process (not close system): ρ →ρ', acts on density matrices

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

Here χ caracterizes the process (this is what we are looking for), size of 4^n x 4^n, *E* is an operator basis, which can be chosen as the Pauli matrices e.g.:

$$\tilde{E} = \{I, \sigma_X, -i\sigma_Y, \sigma_Z\}^{\otimes n}$$

Process: has to be done on 4^n independent states (e.g. 0,1, +, -)
Here: 1 qubit process – χ 4 x 4 matrix

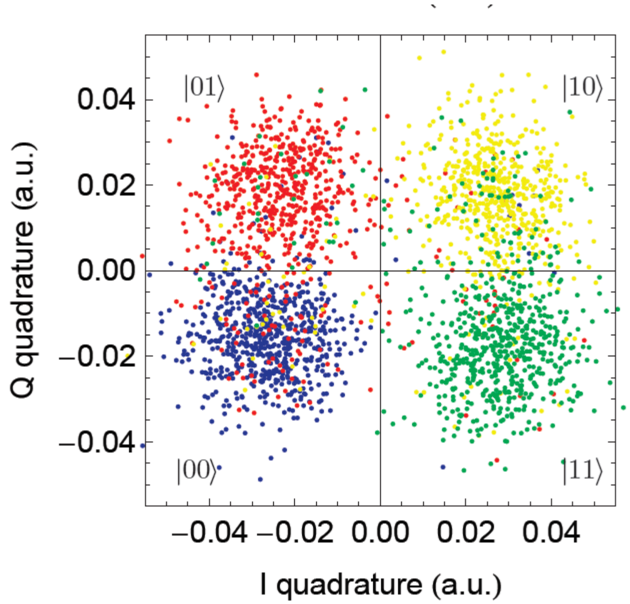


$-i\sigma_Y$ ↗

Example: a) after measurement of 0,0 the output state is in the same state as the input, hence the denisty matrix is not transformed, E_m=E_n=1
b) After measurement the ouput state is the input state times X – hence the only the X,X element is non-zero (rotated density matrix).

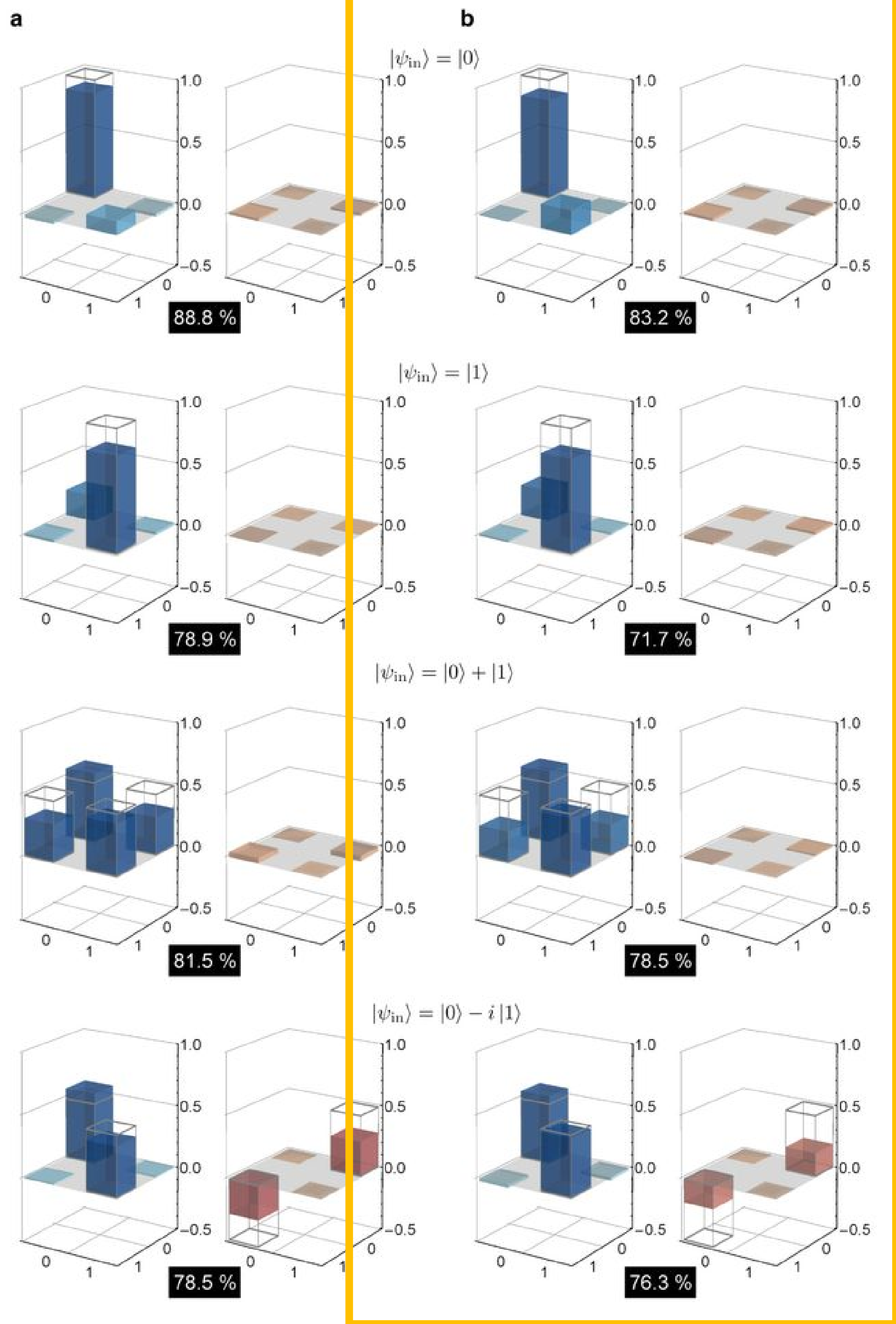
L. Steffen, PhD thesis

Teleportation
Feed forward



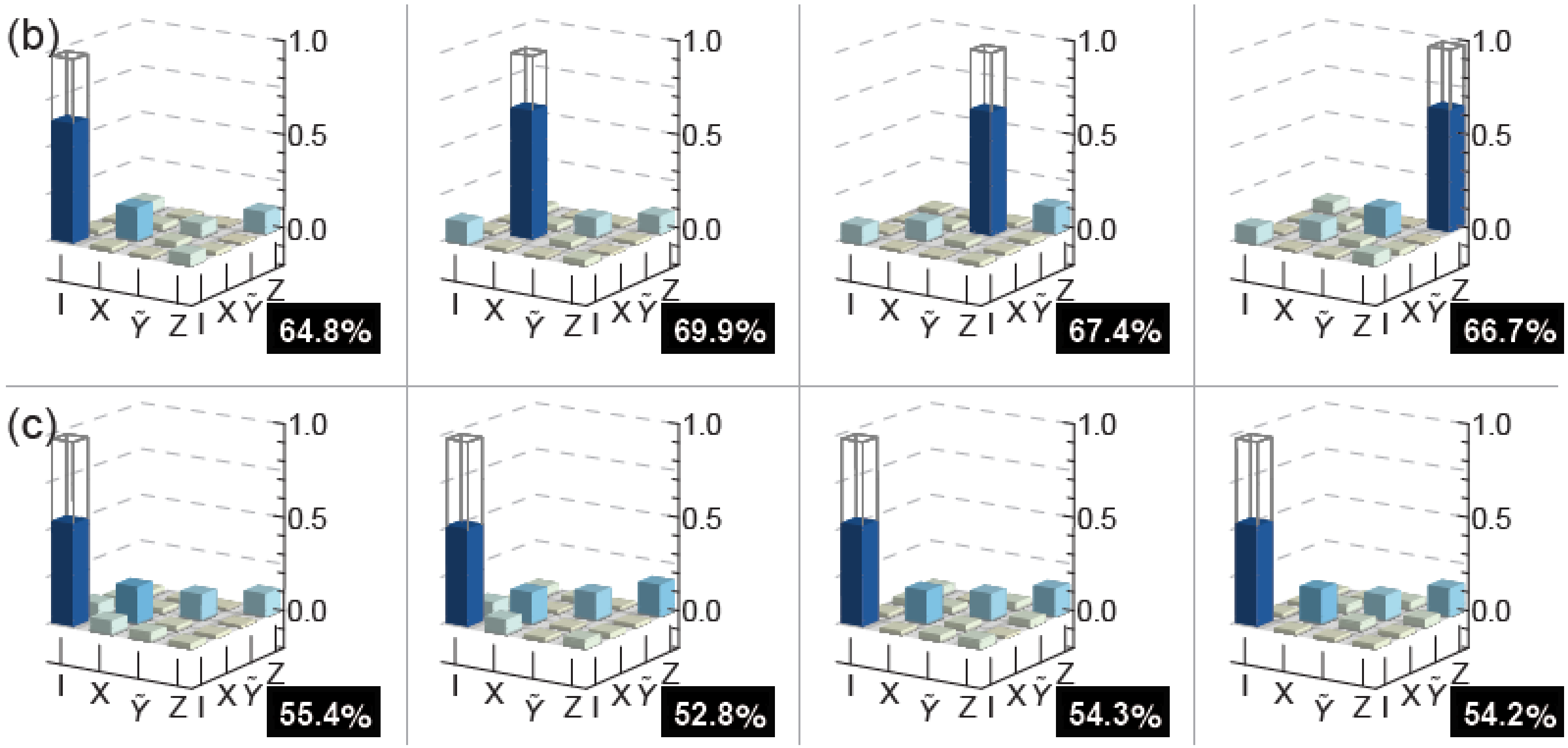
Amplifier and measurement is set such, that the 4 states can be differentiated - 84% fidelity

After the measurement (with an FPGA), the measurement initiates hardwer triggers and rotates the the qubit of the reciever to get the initial state



Process tomography

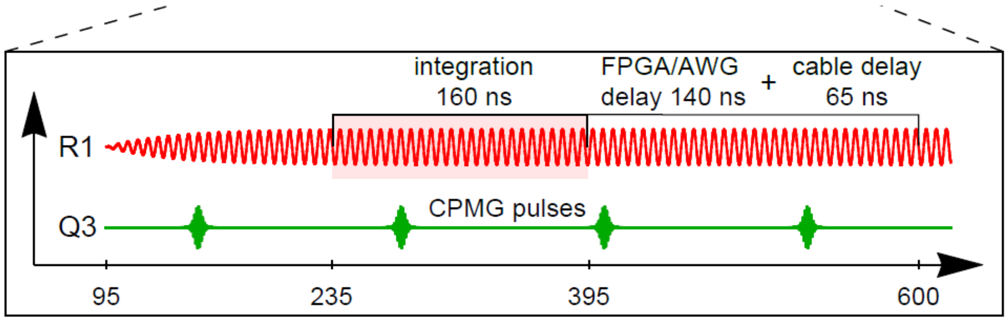
Simultanous deterministic measurements



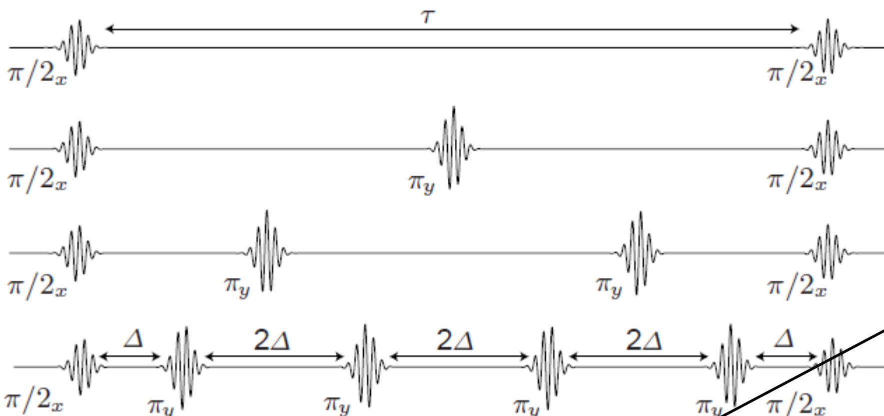
Simultanous deterministic measurements + post-selection

Lower yield: relaxation during the feed-forward mostly

L. Steffen, PhD thesis



Risetime of the pulse, integration, FPGA etc. adds up. During that time qubit is conditioned with CMPG pulses

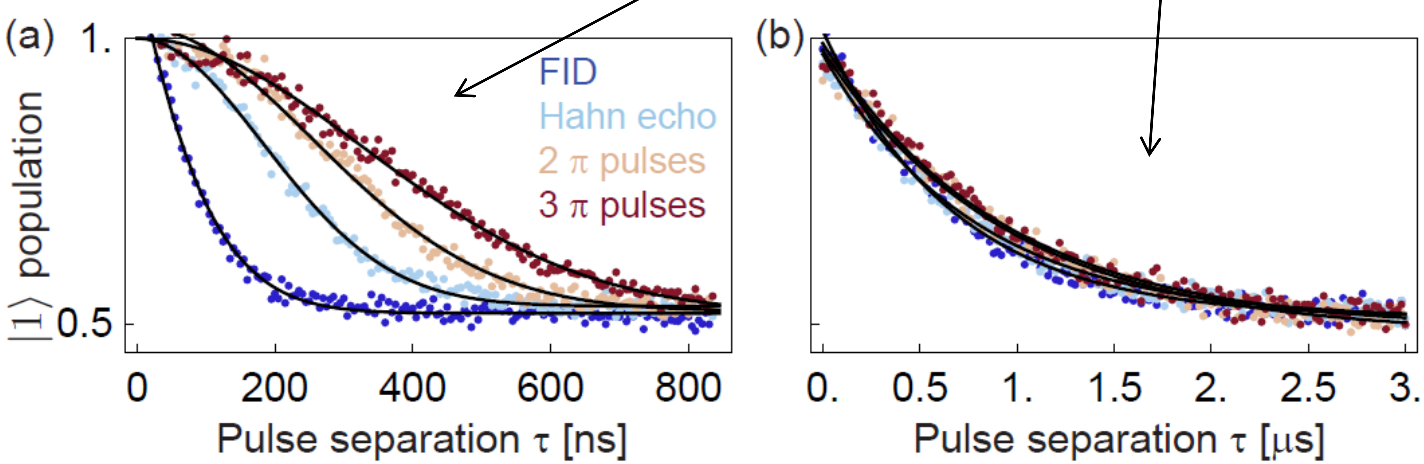


Example of CMPG (dynamical decoupling) on a Ramsey experiment – extended Hahn echo (several precession switching)

Only works for slow noise

Extends lifetime (flux noise)

In flux sweetspot in does not do anything



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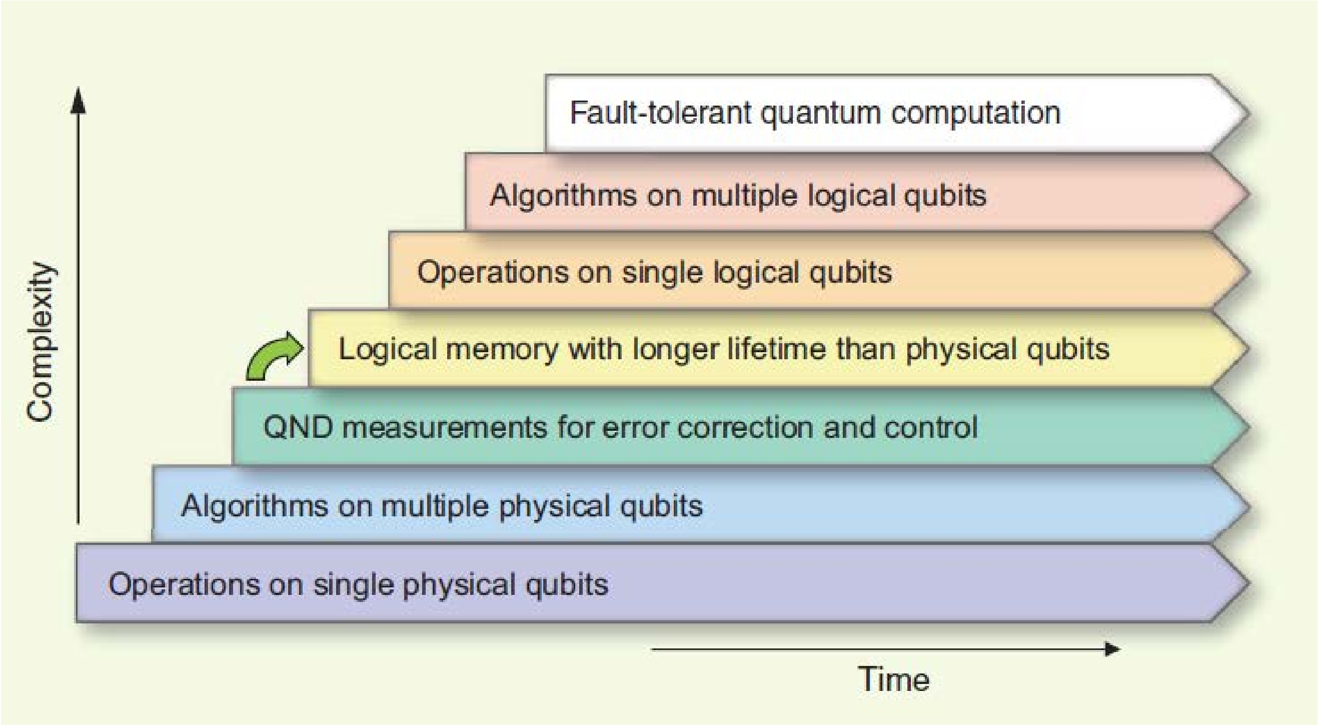
Implementation		Success probability	Rate [Hz]	Events [1/s]	Distance [m]	Avg. state fidelity	Det	FF
Photons	first[1]	$\approx 3 \times 10^{-10}$	76×10^6	≈ 0.025	(≈ 1)	0.68	–	–
	furthest[2]	$\approx 3 \times 10^{-10}$	80×10^6	≈ 0.026	$143\ 10^3$	0.863	–	–
	furthest[2]	$\approx 3 \times 10^{-10}$	80×10^6	≈ 0.026	$143\ 10^3$	0.78	–	✓
	determ.[3]	$\approx 8 \times 10^{-11}$	82×10^6	≈ 0.007	(≈ 1)	0.83	✓	–
Ions	one trap[4]	1	250	250	$5\ 10^{-6}$	0.78	✓	✓
	two traps[5]	$2.2\ 10^{-8}$	75 000	$1.65\ 10^{-3}$	1	0.9	–	–
Neutral atoms	[6]	10^{-3}	10 000	10	(≈ 1)	0.789	–	–
Atomic ensembles	[7]	10^{-4}	71.4	0.007	150	0.95	–	–
Circuit QED		0.6	40 000	24 000	0.006	0.695	✓	✓

L. Steffen, PhD thesis

DiVincenzo criteria for quantum computation:

Outlook

1. Scalable system with well-characterized qubits, $n = 2^N$ states: eg. |101..01> (N qubits)
2. Initialization protocol: e.g. setting it to |000..00>
3. Universal set of quantum gates: 1- and 2-qubit gates, e.g. Hadamard gates: $U_H|0\rangle = (|0\rangle + |1\rangle)/2$, and CNOT gates to create entangled states, $U_{CNOT}U_H|00\rangle = (|00\rangle + |11\rangle)/2$
4. Read-out : $|\psi\rangle = a|0\rangle + be^{i\Phi}|1\rangle \rightarrow a, b$
5. Long decoherence times, much longer than the gate operation time
6. Transport qubits and to transfer entanglement between different coherent systems (quantum-quantum interfaces).
7. Create classical-quantum interfaces to convert stationary qubits to flying qubits

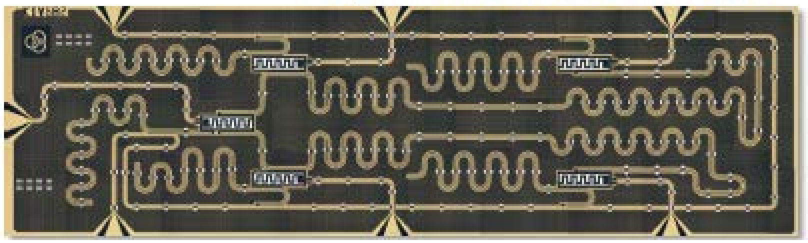


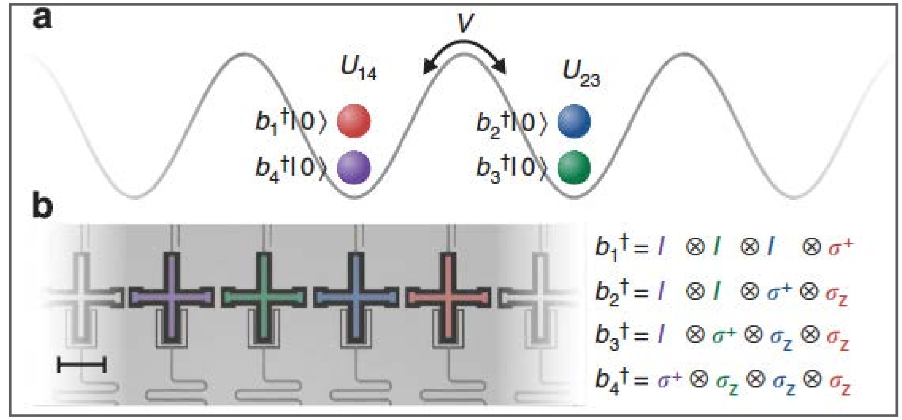
	2D Tmon	3D Tmon	Xmon	Fluxm	C-shunt	Flux	Gatemon
	[25]	[26]	[149]	[137]	[139, 140]	[13]	[153]
DV1, #q	5 [34, 205]	4 [141]	9 [32, 37]	1	2 [140]	4 [206]	2
DV2	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
DV3	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
t_{1q} (ns)	10–20	30–40	10–20	—	5-10	5–10	30
$n_{\mathrm{op},1q}$	$>10^3$	$>10^3$	$>10^3$	—	$\sim10^3$	$\sim10^3$	$\sim10^2$
F_{1q}	$\sim$0.999	>0.999	0.9995	—	—	—	>0.99
t_{2q} (ns)	10–40	$\sim$450	5-30	—	—	—	50
$n_{\mathrm{op},2q}$	$\sim10^3$	$\sim10^2$	$\sim10^3$	—	—	—	$\sim10^2$
F_{2q}	>0.99	0.96–0.98	0.9945	—	—	—	0.91
DV4	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
DV5	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
T_1 (μs)	$\sim$40	100	50	1000	55	20 [135]	5.3
T_2^* (μs)	$\sim$40	>140	20	>10	40	—	3.7
T_2^{echo} (μs)	$\sim$40	>140	—	—	85	—	9.5

– The number of qubits ($DV1$, $\#q$) refers to operational circuits with all qubits connected.
– t_{1q} and t_{2q} are gate times for 1q- and 2q-gates.
– $n_{\mathrm{op},1q}$ and $n_{\mathrm{op},2q}$ are the number of 1q- and 2q-gate operations in the coherence time.
– F_{1q} and F_{2q} are average fidelities of 1q- and 2q-gates, measured e.g. via randomised benchmarking (section 7.1).
– T_1 is the qubit energy relaxation time.
– T_2^* is the qubit coherence time measured in a Ramsey experiment.
– T_2^{echo} is the qubit coherence time measured in a spin-echo (refocusing) experiment.
– Table entries marked with a hyphen (-) indicate present lack of data.
– Note that average gate fidelities F_{1q} and F_{2q} do not necessarily correspond to thresholds for error correction [208].
– The t_{2q} gate time for the 3D Tmon refers to a resonator-induced phase gate.

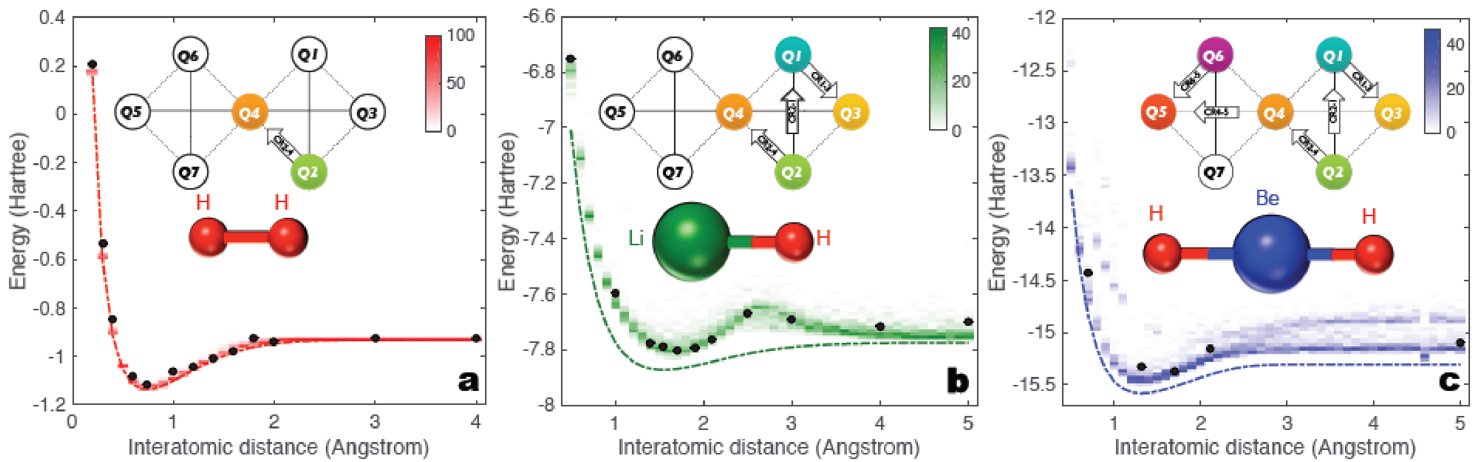
Error Correction

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)





R. Barends et al., Nature Comm. 6, 7654 (2015)



A. Kandala et al., Nature 549, 242 (2017)