

Deterministic quantum teleportation with feed-forward in a solid state system

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“Teleportation”



Quantum teleportation

Direct sending of particle is unreliable

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Copying is impossible

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But it is necessary to transmit information and it can be done

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Useful for:

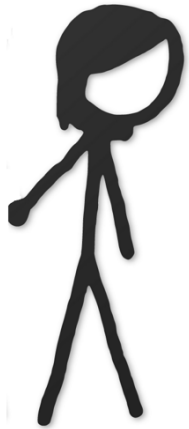
- nice concept in general
- quantum cryptography
- teleportation of gates

The protocol

Alice

$|\psi\rangle$

Q1



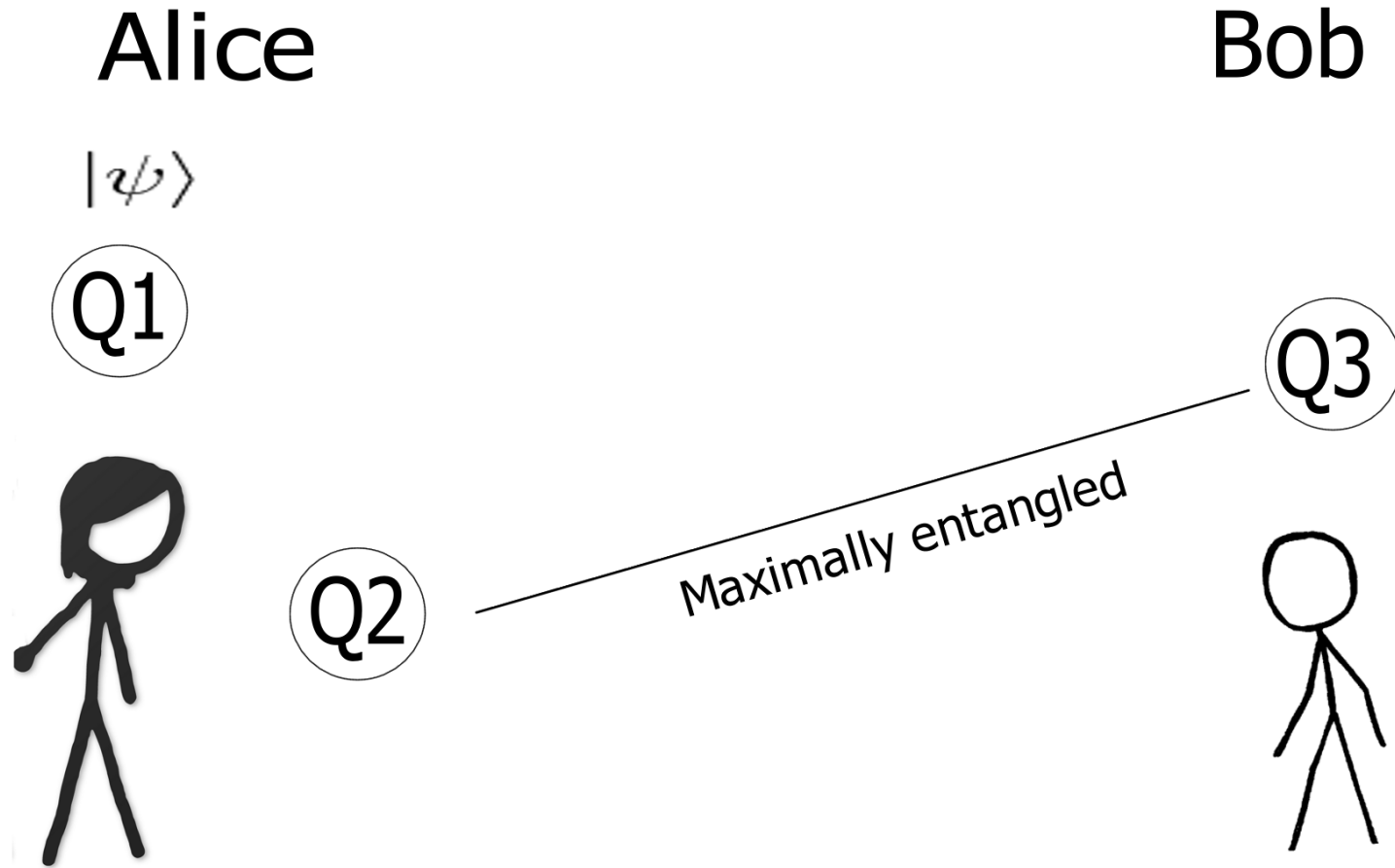
Q2

Bob

Q3



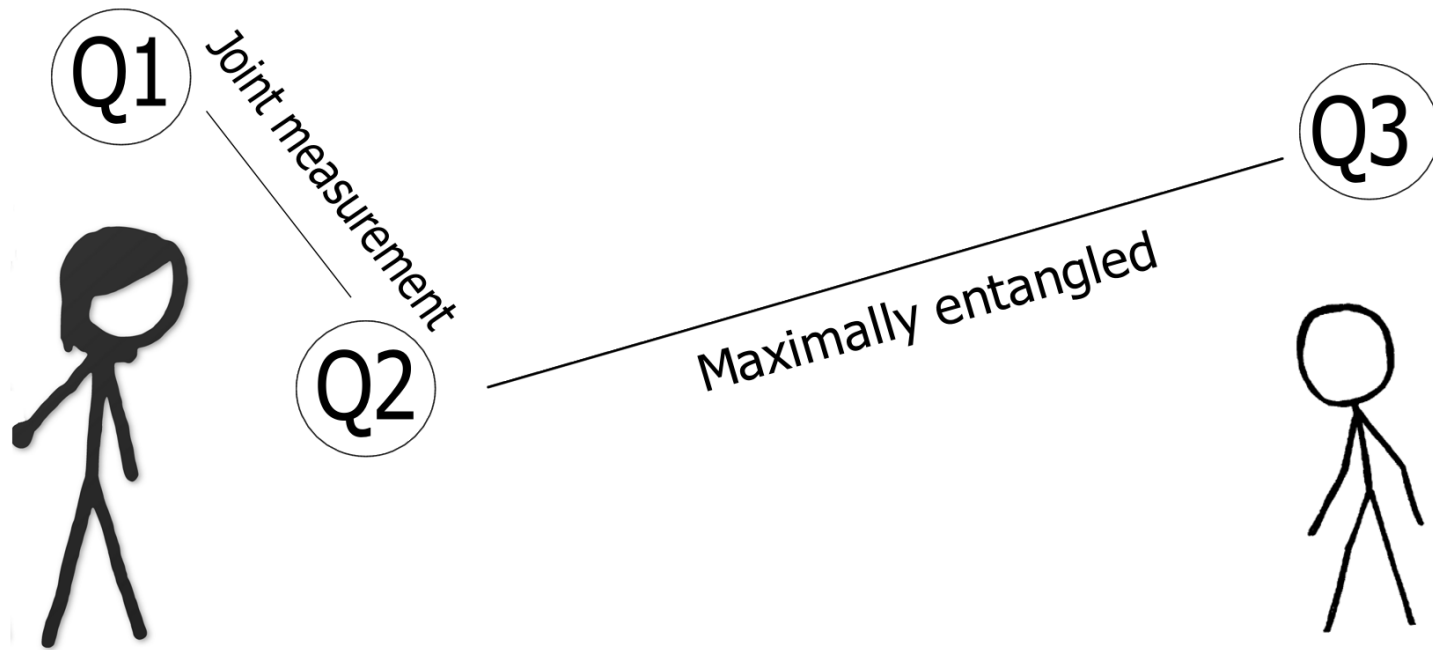
The protocol



The protocol

Alice

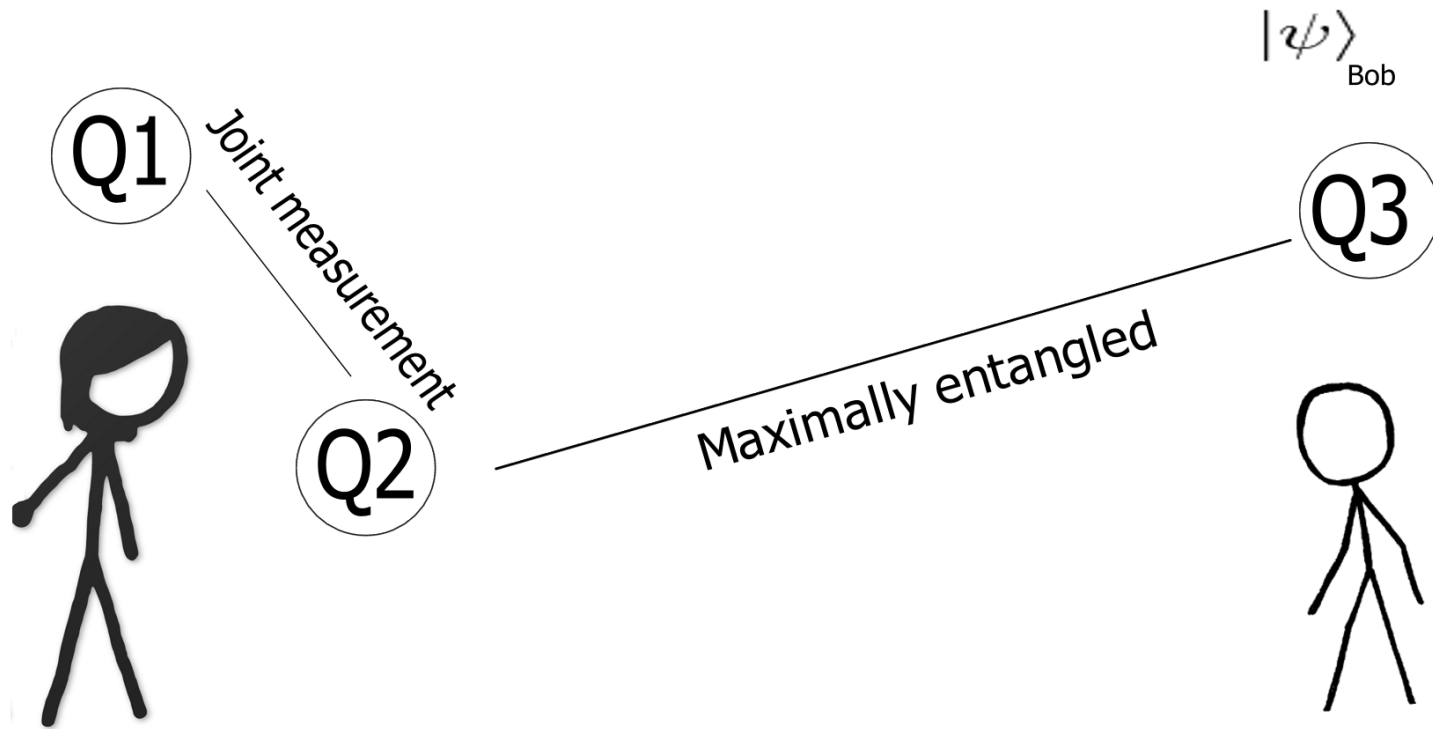
Bob



The protocol

Alice

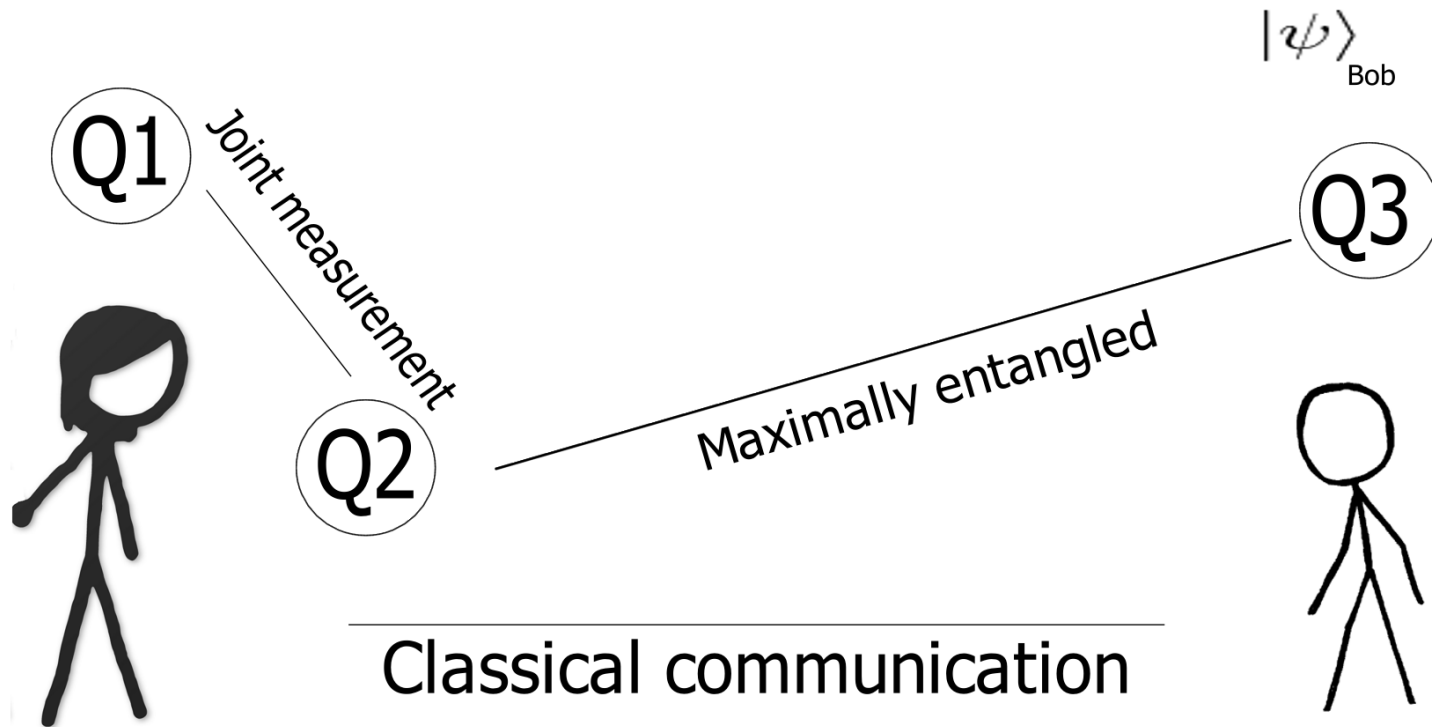
Bob



The protocol

Alice

Bob



Circuit diagram

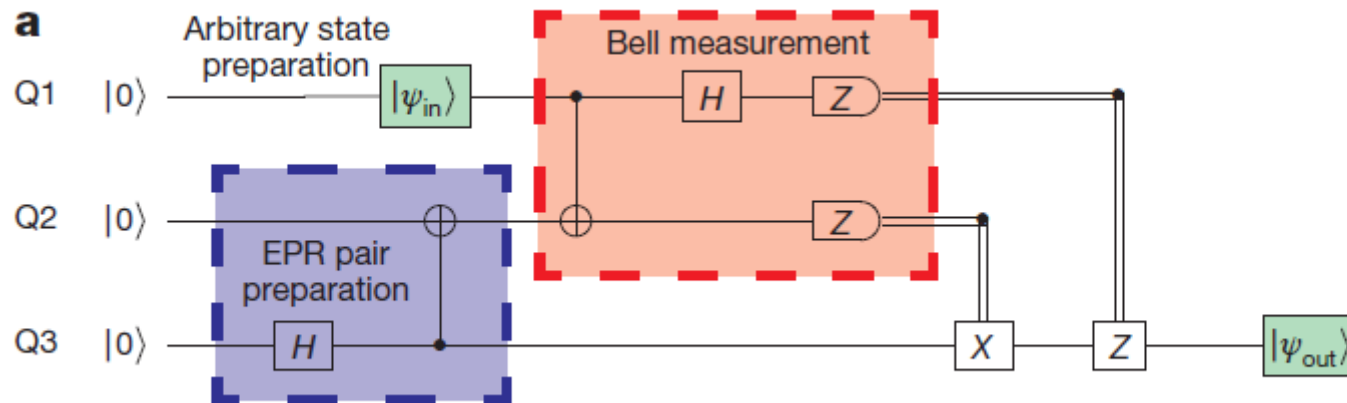


Figure: *Deterministic quantum teleportation with feed-forward in a solid state system*, Steffen et al., *Nature* 500, 319–322, 15.8.2013

Additional notes on the protocol

Information can be lost

Additional notes on the protocol

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Measurement in single shot important

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Information can be lost

Measurement in single shot important

Protocol succeeds every time

Experimental challenges

Entanglement

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Distinguish bell-states in single shot

Experimental challenges

Entanglement

Distinguish bell-states in single shot

Feed-forward of classical information in real time

Earlier experiments

- 1997 Lab distances, 2 bell-states (photons)⁽¹⁾
- 1998 Deterministic for continuous-variable states (photons)⁽²⁾
- 2001 4 bell-states, low detection efficiency (photons)⁽³⁾

1) Bouwmeester, D. et al. Experimental quantum teleportation. Nature 390, 575-579 2) Furusawa, A. et al. Unconditional quantum teleportation. Science 282, 706–709 3) Kim, Y. H., Kulik, S. P. & Shih, Y. Quantum teleportation of a polarization state with a complete Bell state measurement. Phys. Rev. Lett. 86, 1370–1373

Earlier experiments

- 2004 Fully deterministic, ions in same trap⁽¹⁾
- 2012 Km scales, 2 bell-states (photons)⁽²⁾

1) Riebe, M. et al. Deterministic quantum teleportation with atoms. Nature 429, 734–737 2) Ma, X.-S. et al. Quantum teleportation over 143kilometres using active feedforward. Nature 489, 269–273

Achievements of the paper presented

Full deterministic quantum teleportation

Achievements of the paper presented

Full deterministic quantum teleportation

Between macroscopic systems

Achievements of the paper presented

Full deterministic quantum teleportation

Between macroscopic systems

All requirements other than space-like separation realized

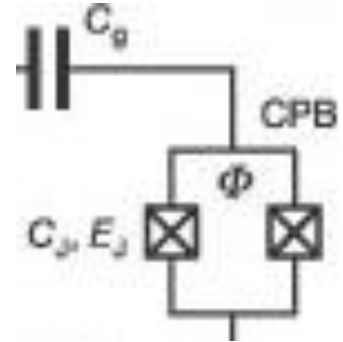
Setup

Reminder: Transmon

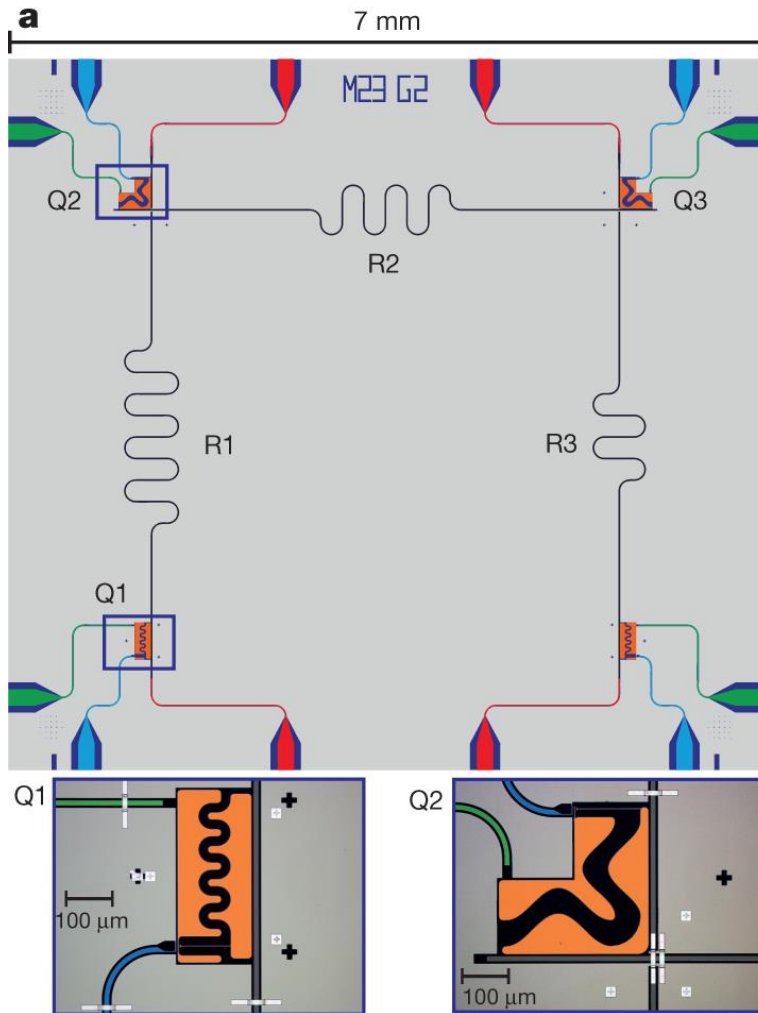
Charge-phase qubit

Frequency is tunable by applying flux

Resilient to charge noise



Circuit implementation



R1, R2, R3: Resonators

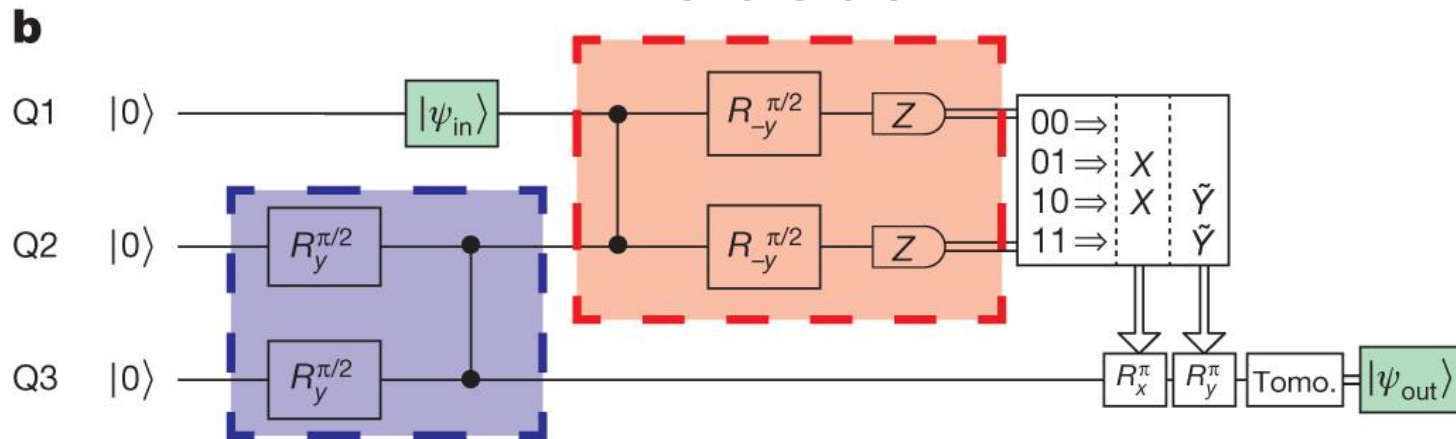
Q1, Q2, Q3: Qubits

Red: Resonator Input/Output lines

Green: Microwave charge gate lines

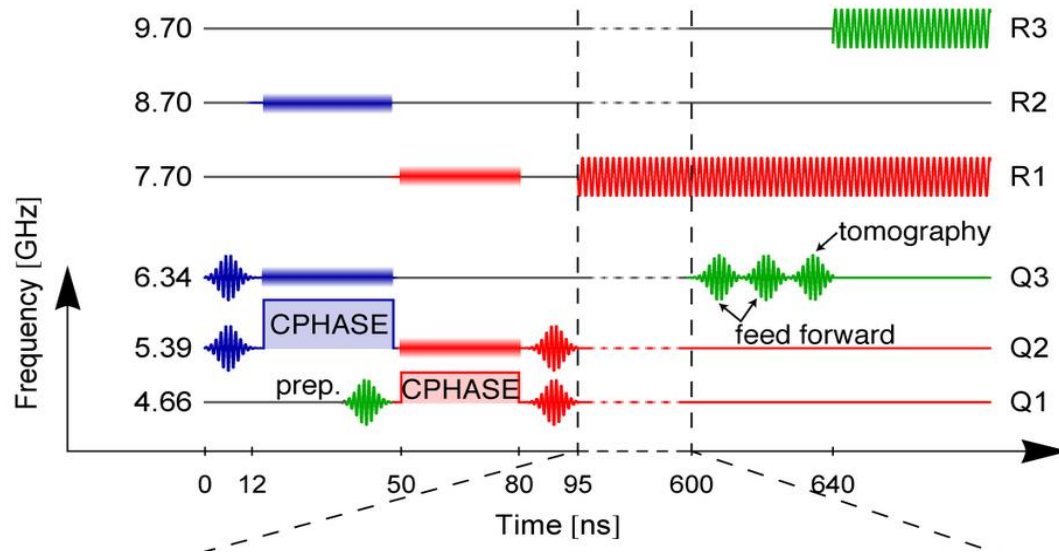
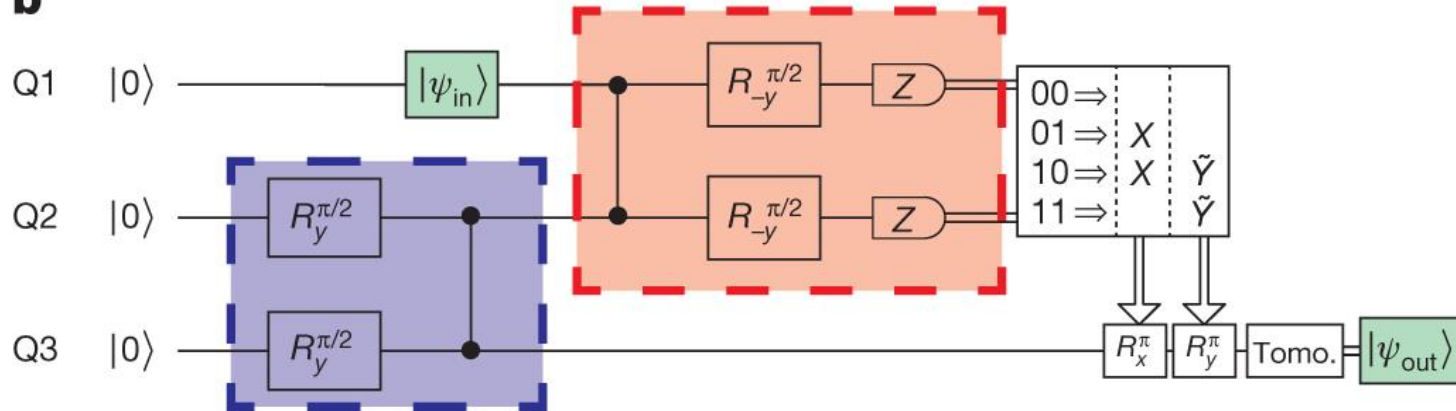
Blue: flux-bias lines

Process



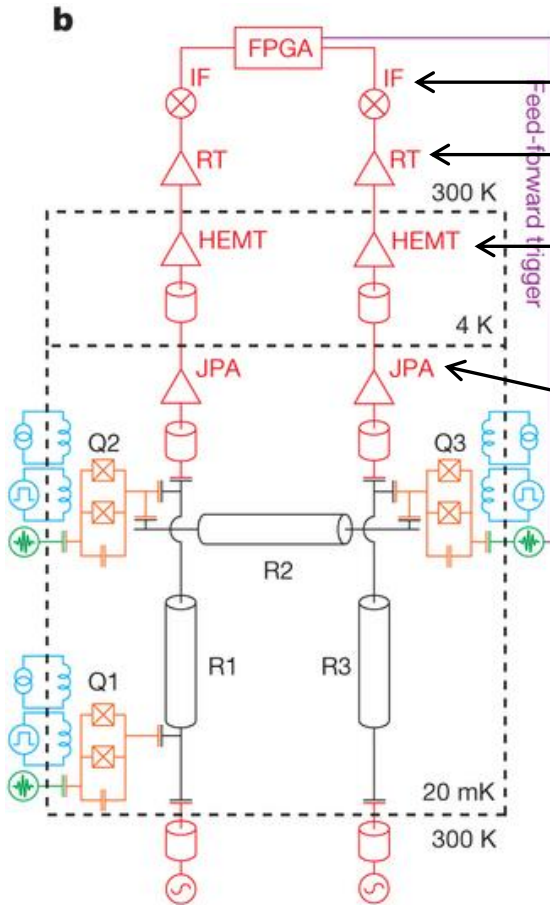
Process

b



Figures: Steffen et al., *Deterministic quantum teleportation with feed-forward in a solid state system*, *Nature* 500, 319–322, 15.8.2013

Read-out



IF: Converts signal to intermediate frequency

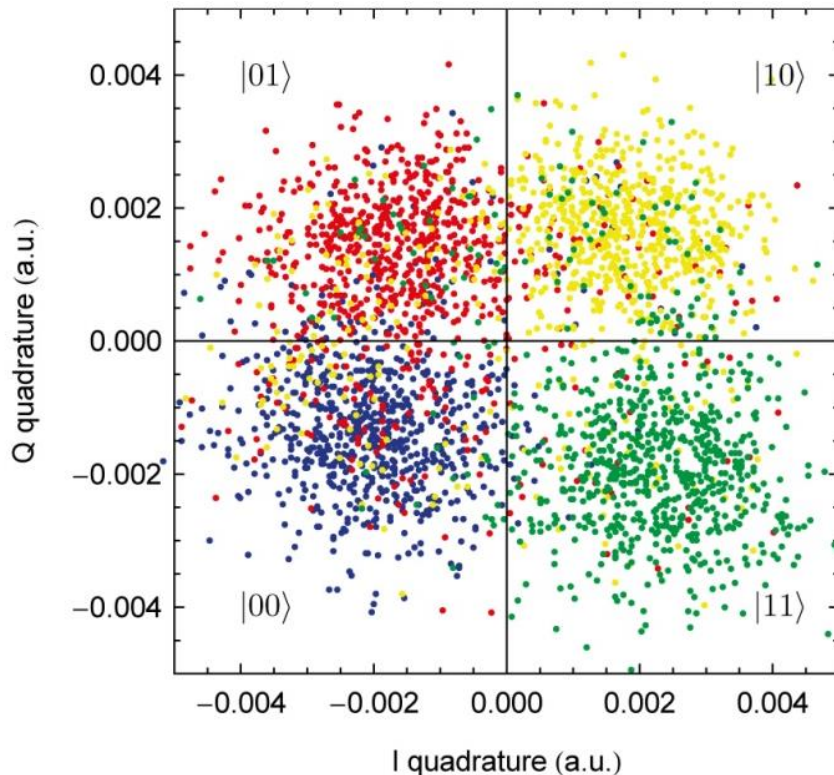
RT: room temperature amplifier

HEMT: High electron mobility transistor
(amplifier)

JPA: Josephson parametric amplifier

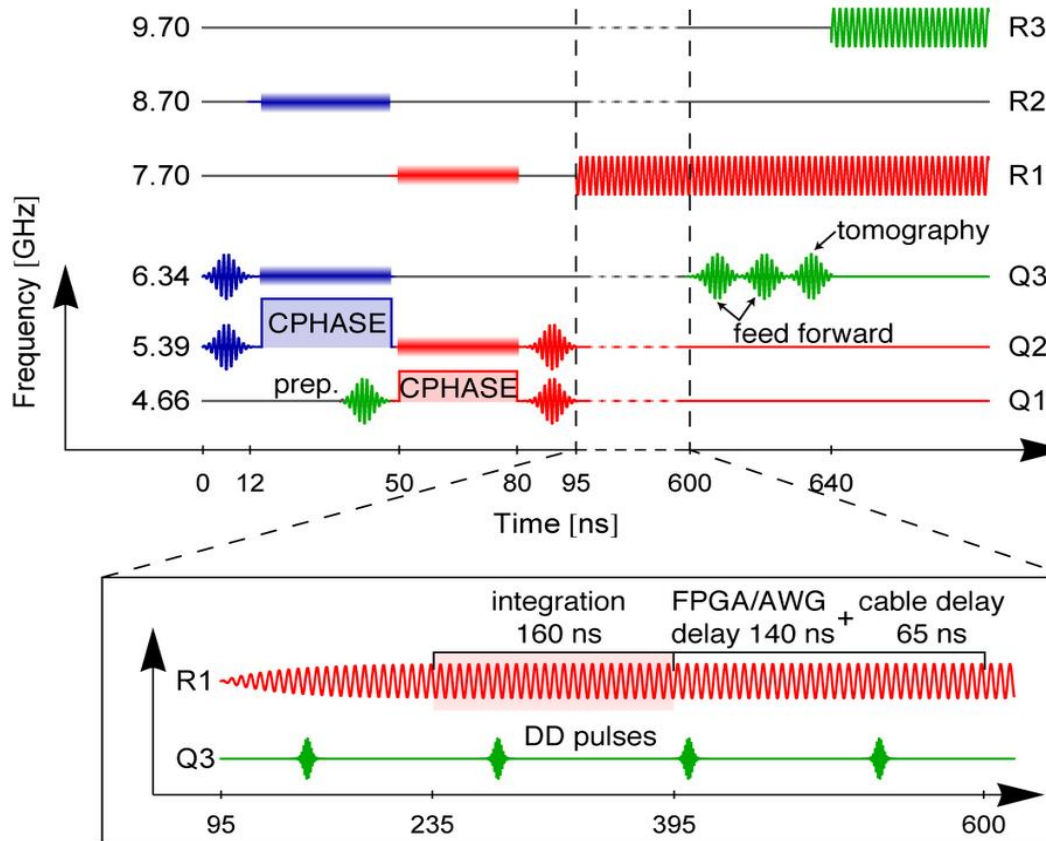
- Qubits Q1/Q3 couple to resonators R1/R3.
- Measure amplitude and phase of the transmitted signal.

Single-shot measurement



- Measurements of each state form a cluster.
- Clusters are separated from each other.
- Single-shot measurement yields 1 data point in graph.
- Cluster separation \gg cluster spread
- Achieved fidelity of 81.8%

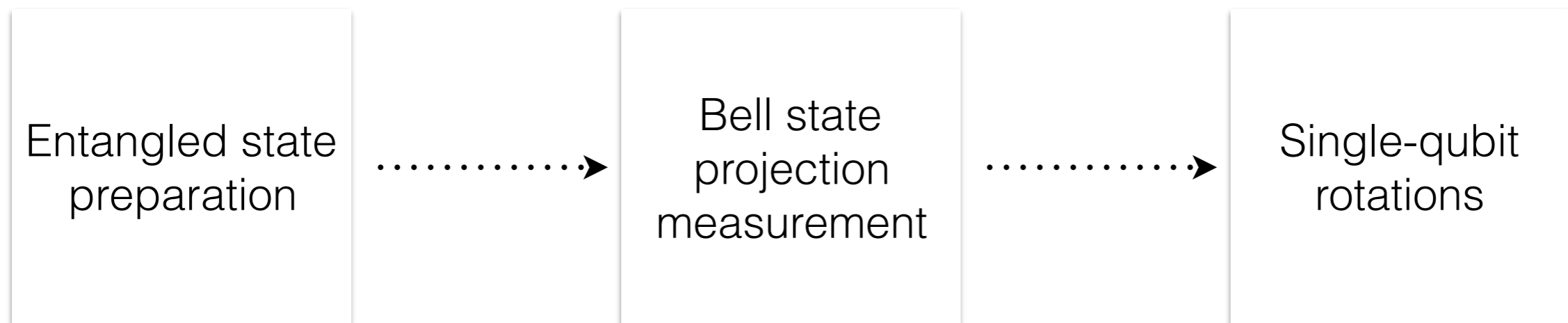
Feed-forward



- Implemented with a field-programmable gate array (FPGA)
- Total time delay for feed-forward is 505 ns
- To avoid decoherence of Q3 during this, apply series of dynamical decoupling pulses

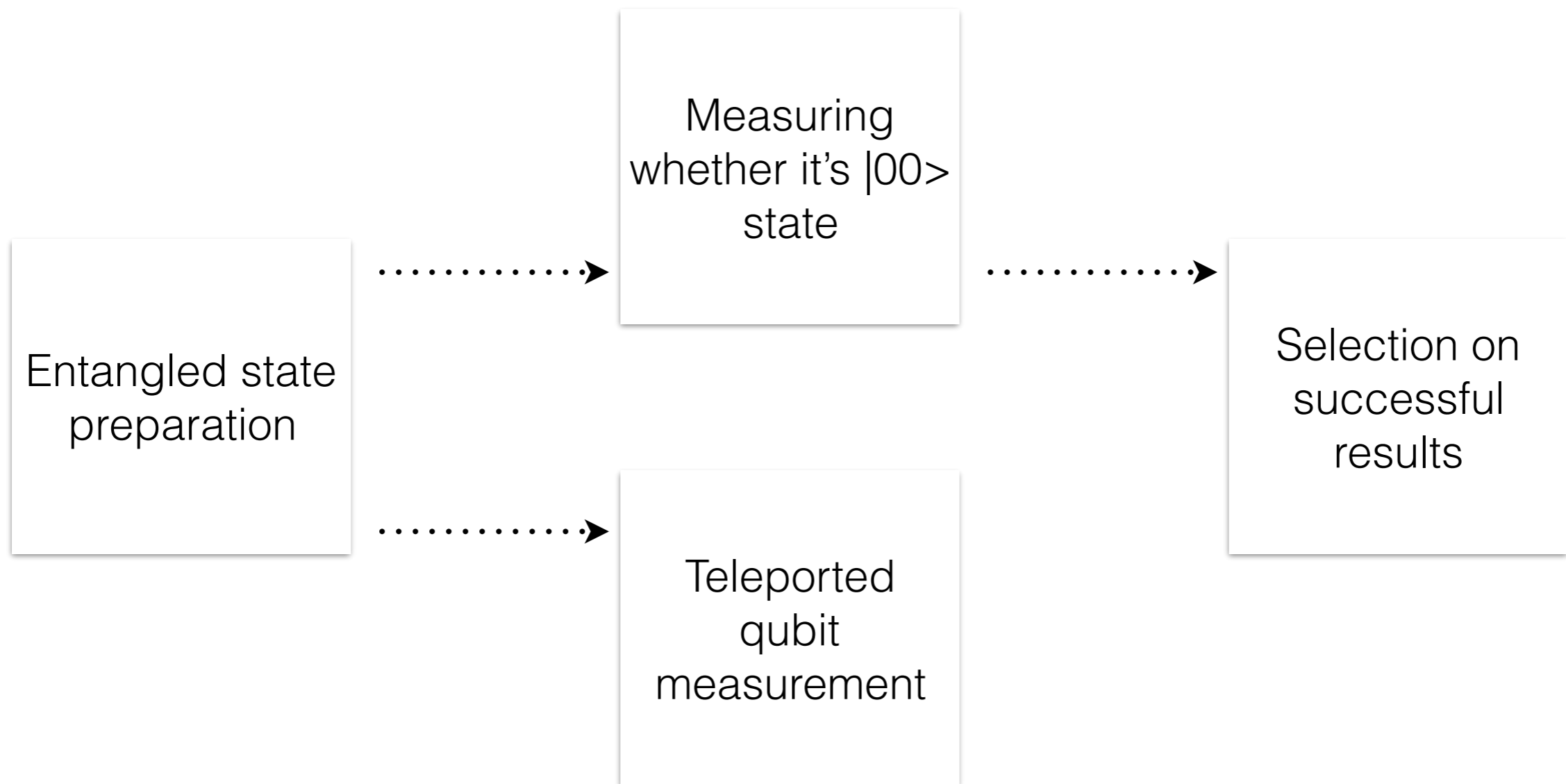
Results

Principal scheme



But there are fidelity losses on every step!

Post-selection – scheme



No need to wait!

Simultaneous deterministic measurement

Delay causes decoherence

Decoherence causes fidelity losses

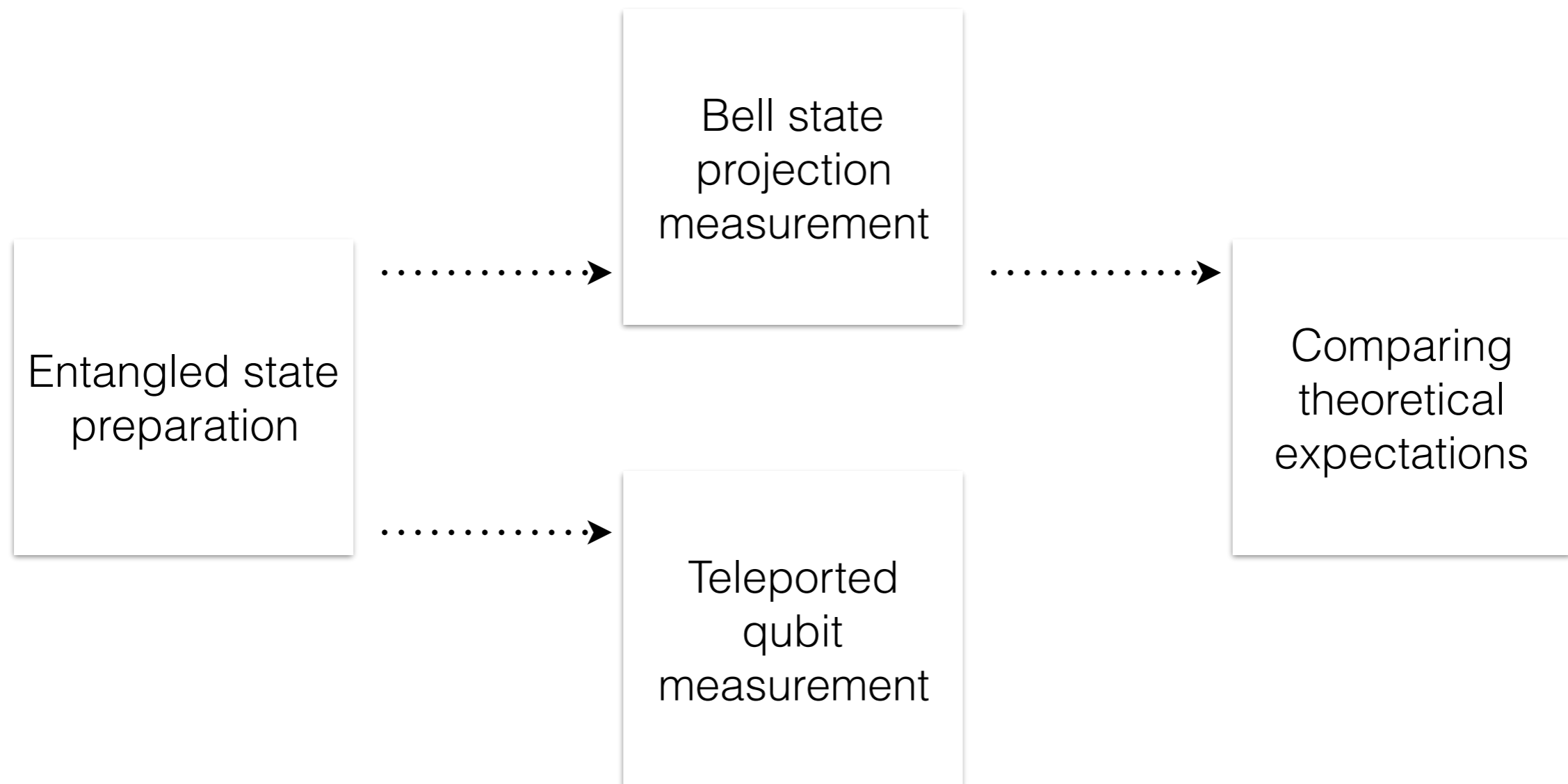
Deterministic

Distinguish all 4 states

Measure Q3 at once

Compare results with expected pre-rotated state

Simultaneous deterministic measurement – scheme



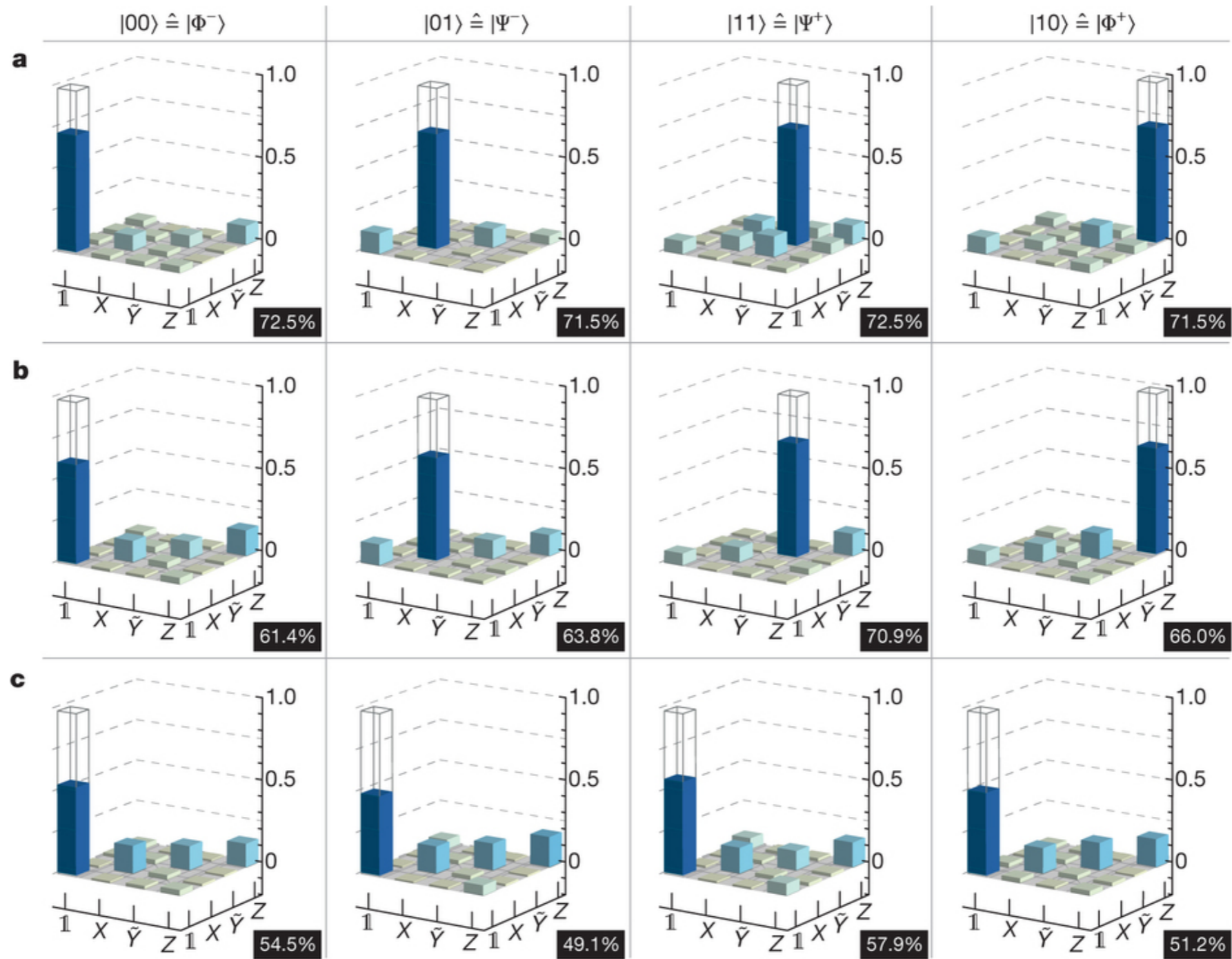
Again, no need to wait!

Implementations comparison

	Post-selection	Simultaneous measurement	Full
Deterministic	✗	✓	✓
Real state achieved	✗	✗	✓
Average process fidelity	$(72.0 \pm 1.4)\%$	$(65.5 \pm 1.1)\%$	$(62.2 \pm 0.3)\%$
Average state-transfer fidelity	$(81.7 \pm 1.4)\%$	$(77.1 \pm 1.2)\%$	$(77.4 \pm 0.2)\%$

Data: *Deterministic quantum teleportation with feed-forward in a solid state system*, L. Steffen, et al

Overview



«He must be very ignorant for he answers every question he is asked».

— Voltaire