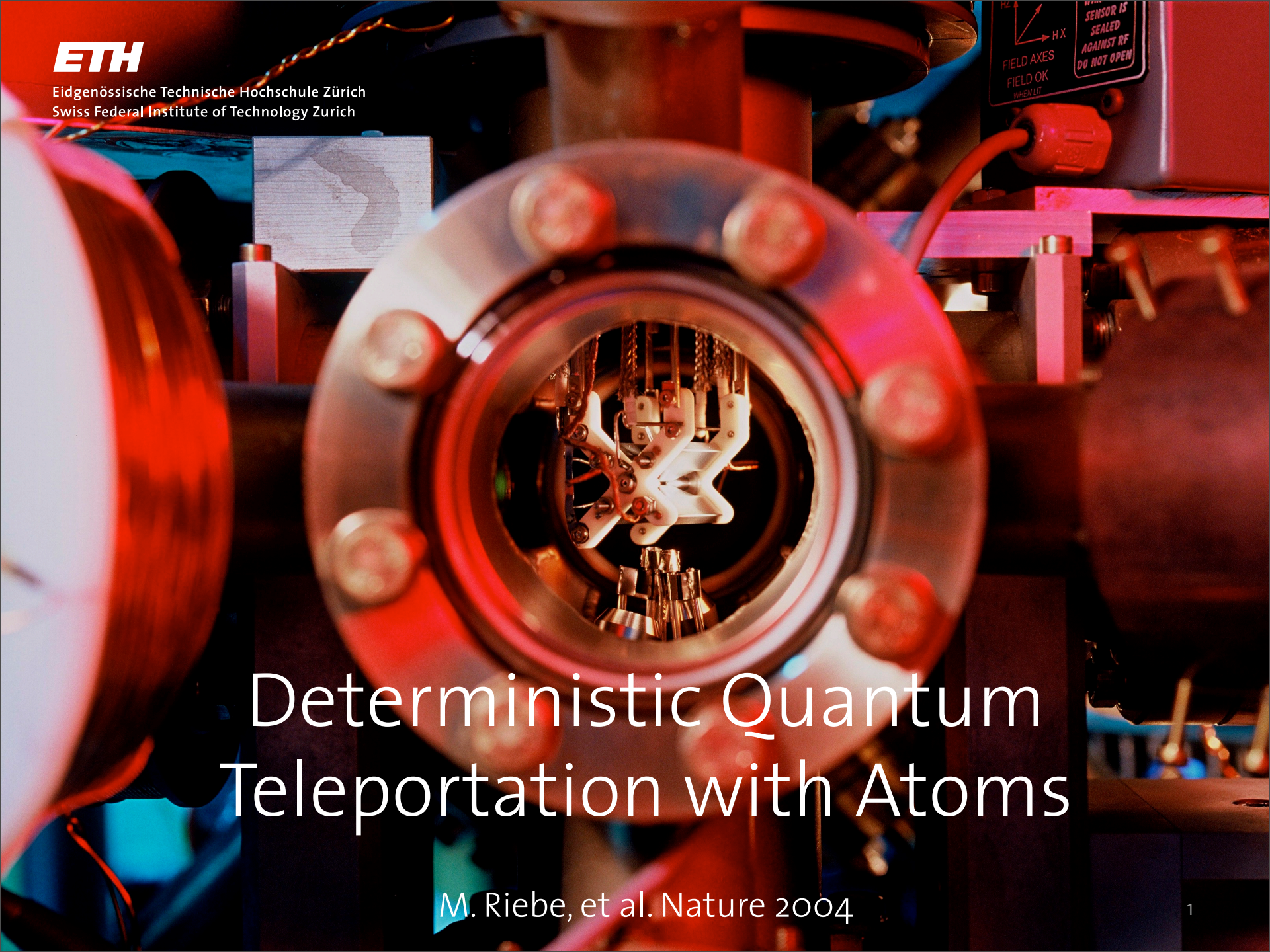


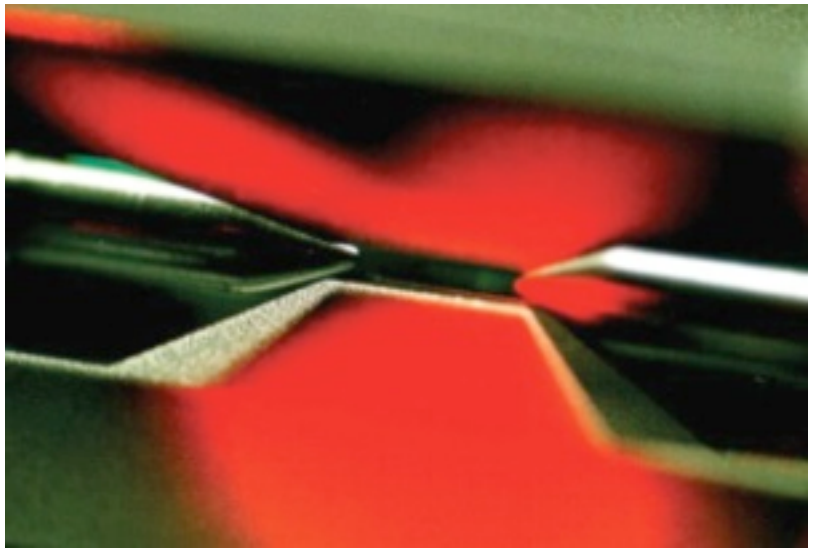
Deterministic Quantum Teleportation with Atoms

M. Riebe, et al. Nature 2004

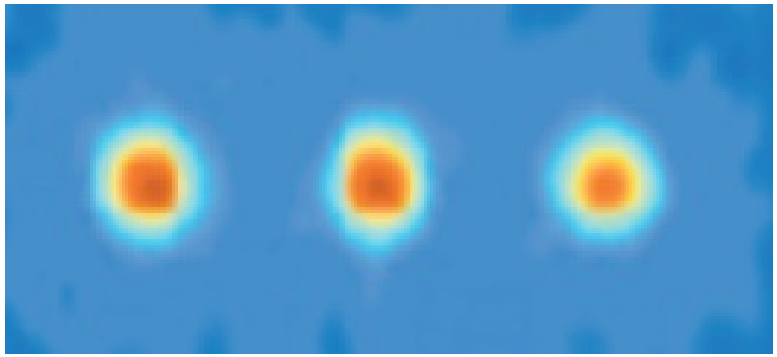
Outline

- $^{40}Ca^{+}$ Experimental Implementation
- Teleportation Algorithm
- Results, Accuracy
- Outlook, Quantum Magic?

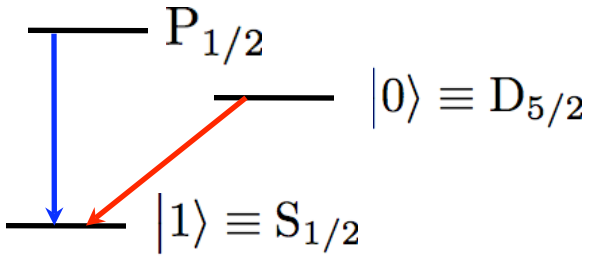
Implementation



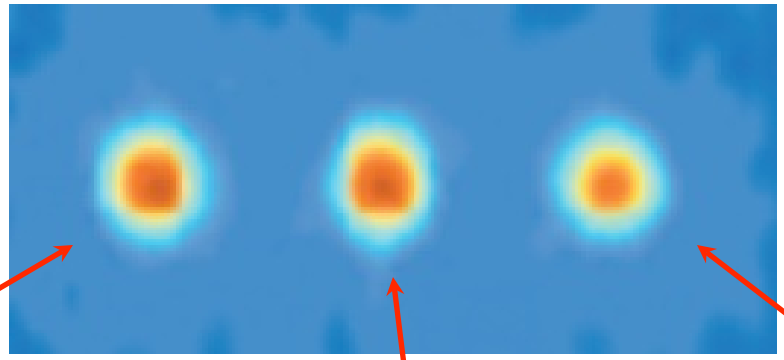
Linear Paul Trap (Nobel Prize 1989)



Trapped Ion: $^{40}Ca^{+}$



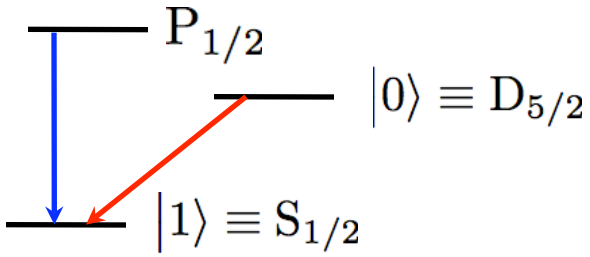
Implementation



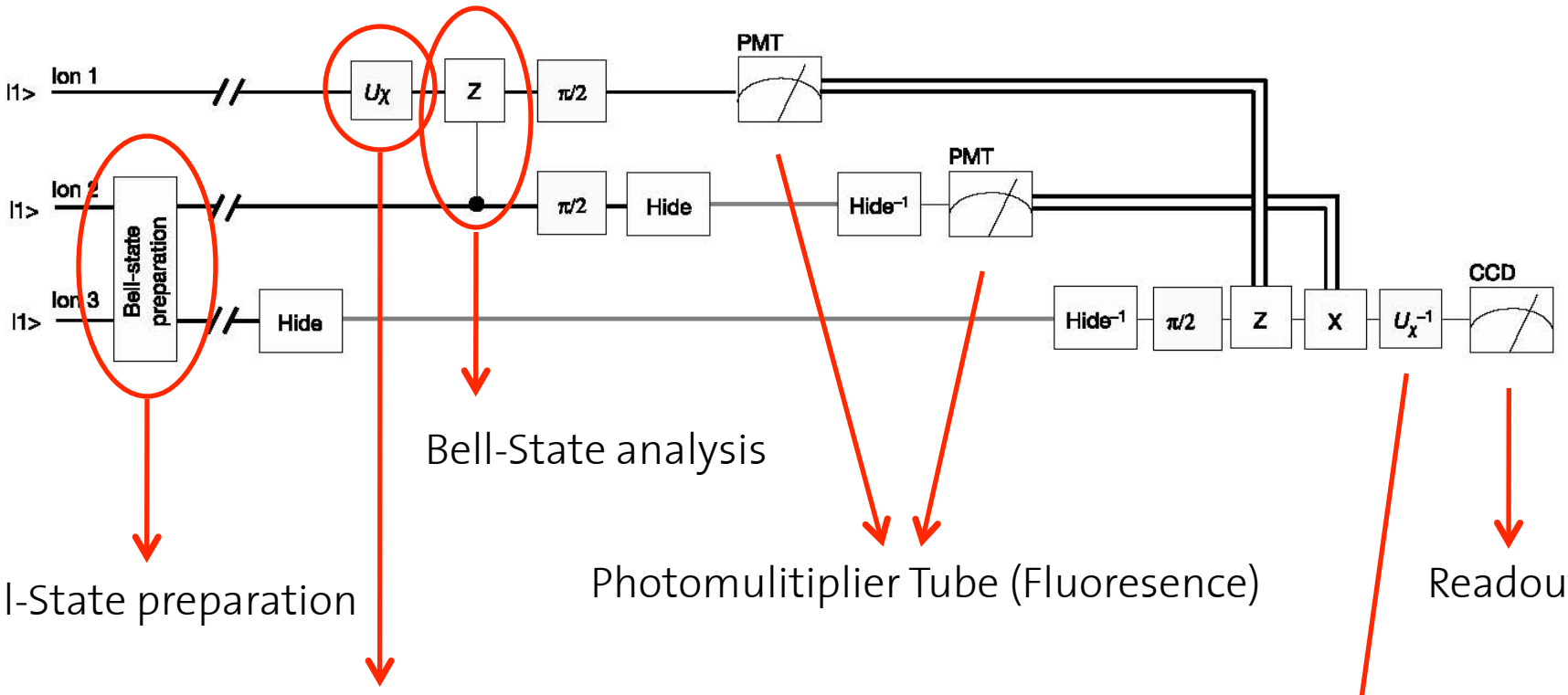
Source Ion

Ancillary Ion

Receiver Ion



Algorithm Overview



Bell-State analysis

Bell-State preparation

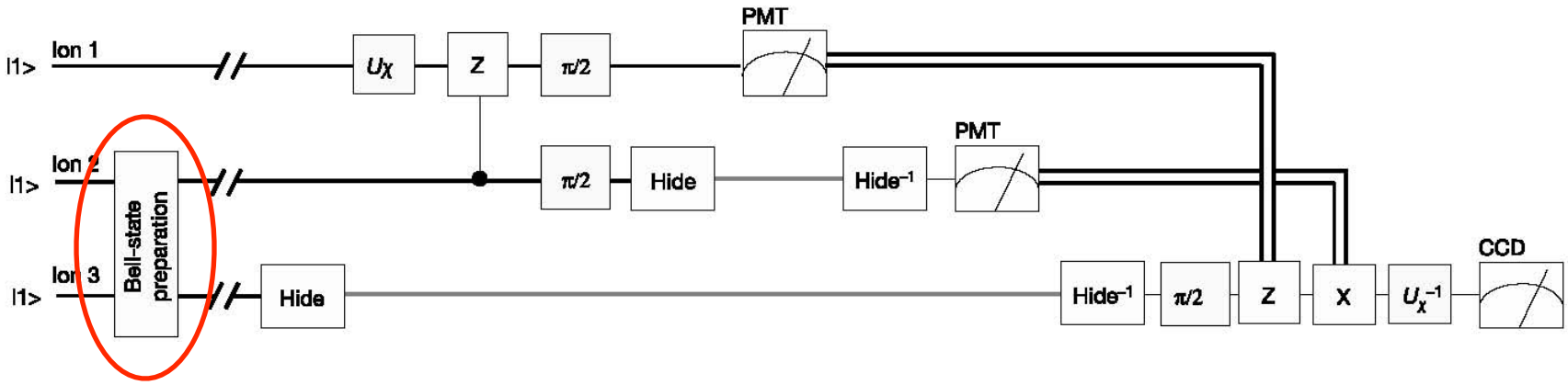
Photomulitiplier Tube (Fluoresence)

Readout

Input preparation (beeing teleported), e.g. arb. rotation

Undo preparation operation

Bell-State Preparation



Highly Entangled: Bell State ← Blue Sideband Transitions

$$\left|\Psi^{+}\right\rangle_{23} = \frac{1}{\sqrt{2}}\left(\left|1\ 0\right\rangle_{23} + \left|0\ 1\right\rangle_{23}\right)$$

Triplet State

Bell-State Preparation

Table 1 **Pulse sequence of the teleportation protocol.**

	Action	Comment
1	Light at 397 nm	Doppler preparation
2	Light at 729 nm	Sideband cooling
3	Light at 397 nm	Optical pumping
Entangle		
4	$R_3^+(\pi/2, 3\pi/2)$	Entangle ion 3 with motional qubit
5	$R_2^C(\pi, 3\pi/2)$	Prepare ion 2 for entanglement
6	$R_2^+(\pi, \pi/2)$	Entangle ion 2 with ion 3
7	Wait for 1 μs – 10,000 μs	Standby for teleportation
8	$R_3^H(\pi, 0)$	Hide target ion
9	$R_1^C(\vartheta_\chi, \varphi_\chi)$	Prepare source ion 1 in state χ
Rotate into Bell basis		
10	$R_2^+(\pi, 3\pi/2)$	Get motional qubit from ion 2
11	$R_1^+(\pi/\sqrt{2}, \pi/2)$	Composite pulse for phasegate
12	$R_1^+(\pi, 0)$	Composite pulse for phasegate
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15	$R_1^C(\pi, \pi/2)$	Spin echo on ion 1
16	$R_3^H(\pi, \pi)$	Unhide ion 3 for spin echo
17	$R_3^C(\pi, \pi/2)$	Spin echo on ion 3
18	$R_3^H(\pi, 0)$	Hide ion 3 again
19	$R_2^+(\pi, \pi/2)$	Write motional qubit back to ion 2
20	$R_1^C(\pi/2, 3\pi/2)$	Part of rotation into Bell basis
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Read out		
22	$R_2^H(\pi, 0)$	Hide ion 2
23	PMDetection for 250 μs	Read out of ion 1 with photomultiplier
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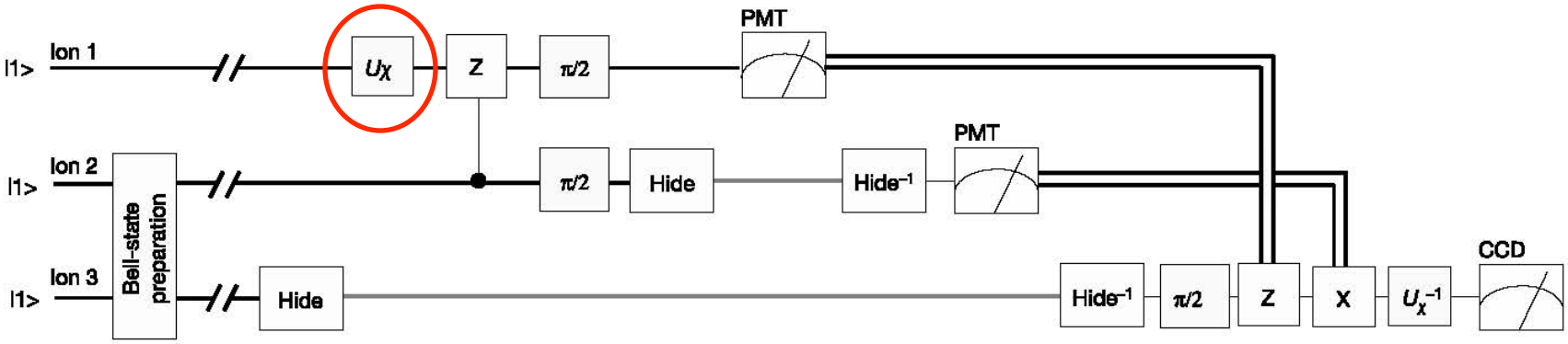
27	$R_2^H(\pi, 0)$	Hide ion 2
28	Wait 300 μs	Let system rephase; part of spin echo
29	$R_3^H(\pi, \pi)$	Unhide ion 3
30	$R_3^C(\pi/2, 3\pi/2+\phi)$	Change basis
Reconstruction		
31	$R_3^C(\pi, \phi)$	$i\sigma_x$
32	$R_3^C(\pi, \pi/2+\phi)$	$-i\sigma_y$ } $= -i\sigma_z$ conditioned on PM detection 1
33	$R_3^C(\pi, \phi)$	$i\sigma_x$ conditioned on PM detection 2
34	$R_3^C(\vartheta_\chi, \varphi_\chi+\pi+\phi)$	Inverse of preparation of χ with offset ϕ
35	Light at 397 nm	Read out of ion 3 with camera

Entanglement, denoted by R^+

Teleportation Step



Encoding of input state

$$U_\chi = |\chi\rangle\langle 1| + |\chi^-\rangle\langle 0|$$

$$\langle\chi|\chi^-\rangle = 0$$

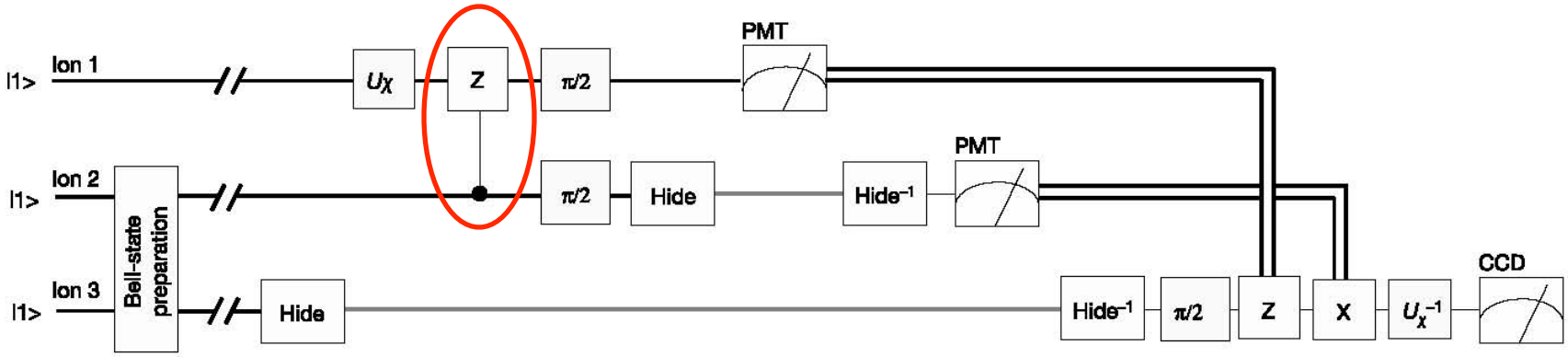
$$|\chi^{(1)}\rangle = |1\rangle$$

$$|\chi^{(2)}\rangle = |0\rangle$$

$$|\chi^{(3)}\rangle = \frac{1}{\sqrt{2}}(|1\rangle + |0\rangle)$$

$$|\chi^{(4)}\rangle = \frac{1}{\sqrt{2}}(|1\rangle + i\,|0\rangle)$$

Bell-State Analyser

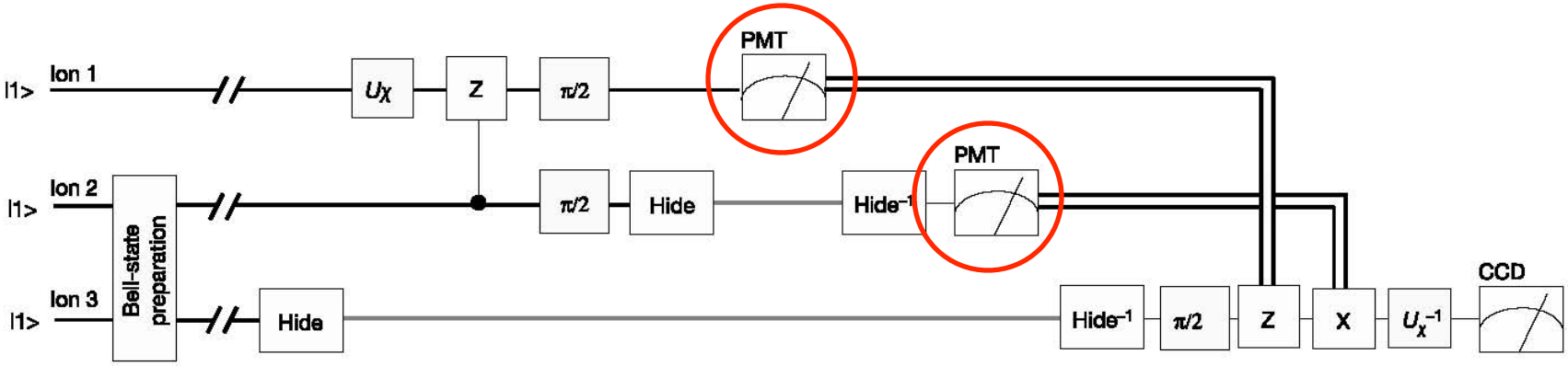


Controlled Z-Gate: 180 degree phase flip

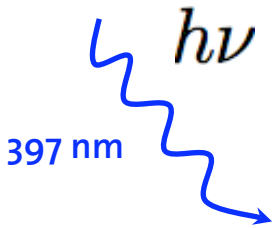
$$Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$|0\rangle \rightarrow |0\rangle$$
$$|1\rangle \rightarrow e^{i\pi}|1\rangle = -|1\rangle$$

State Detection



Readout: Measure joint quantum state

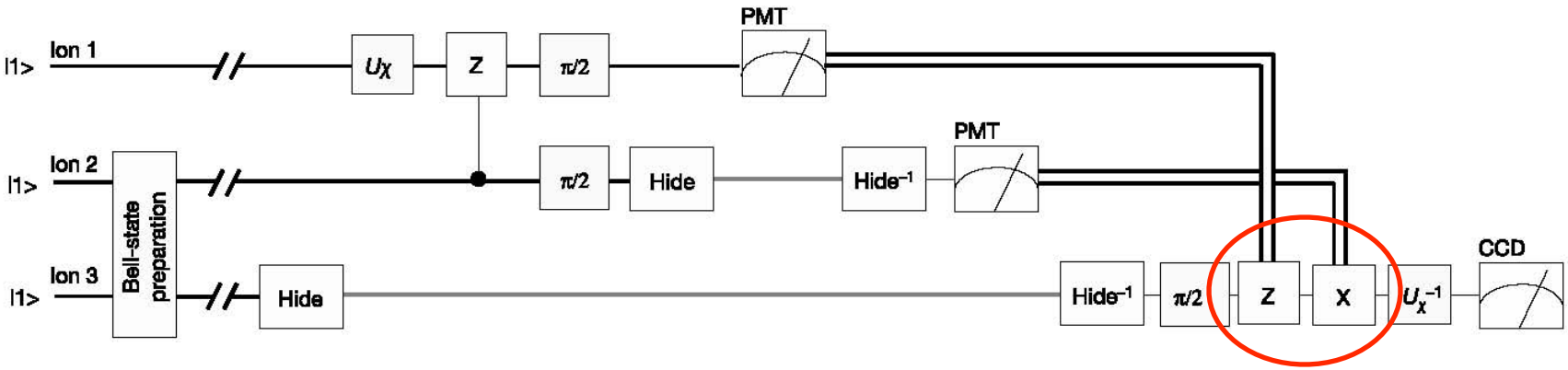


Fluoresence → $|1\rangle \equiv S_{1/2}$

No Fluoresence → $|0\rangle \equiv D_{5/2}$

Hide/Unhide: Preserve coherence of other qubits

Target Ion Reconstruction



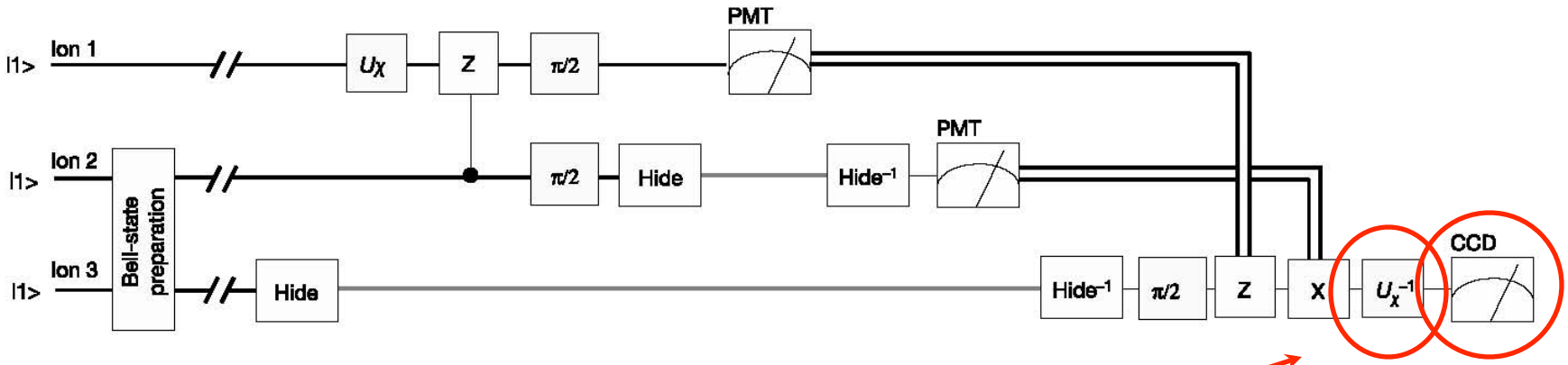
Results from PMT measurement: $\{|00\rangle_{12}, |01\rangle_{12}, |10\rangle_{12}, |11\rangle_{12}\}$

Z, X: Reconstruct state in target ion 3: Apply unitary rotation

$$-i\sigma_y, -i\sigma_z, i\sigma_x, 1$$

$$|\chi^{(\mathrm{exp})}\rangle$$

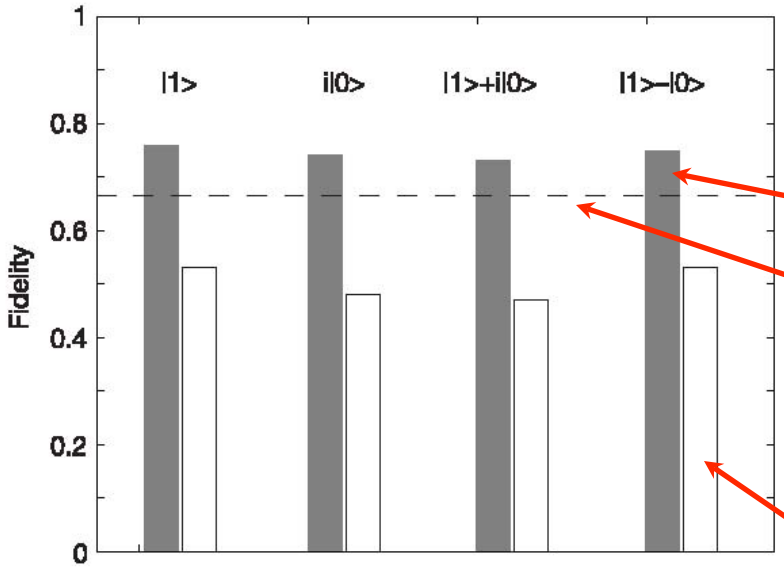
Obtain fidelity



Apply inverse of unitary operation U_χ

Read out teleportated state: resonance fluoresence CCD

Results

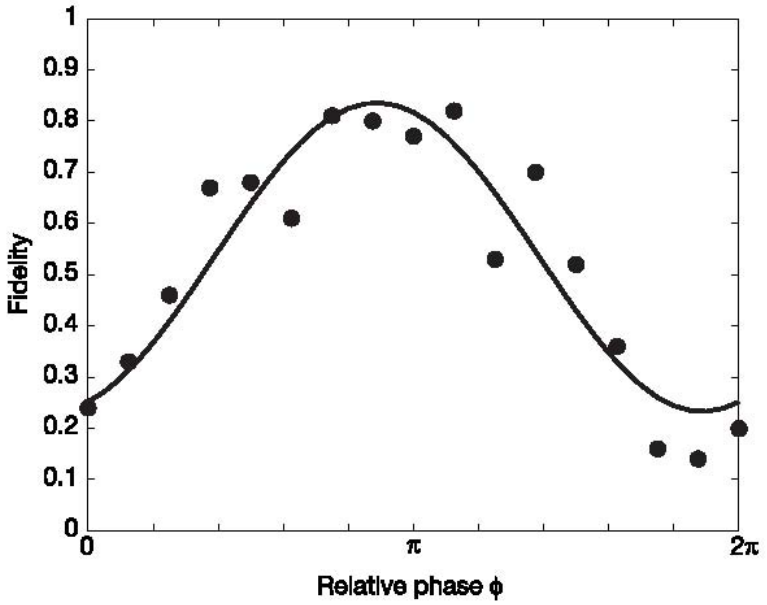


$$F = \langle 1 \,|\, U_\chi^{-1} \rho_{\exp} U_\chi \,|\, 1 \rangle$$

QM: Fidelity up to 75%
Classic limit: 66.7%

reconstruction operations omitted

Results



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Conclusion

- Quantum teleportation seems to work in the lab
- No hidden variables (classical channel necessary)

Outlook

- Processing entangled states in quantum computation
- Distribution of quantum information between different nodes in network