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Experimental demonstrations of teleportation of photons

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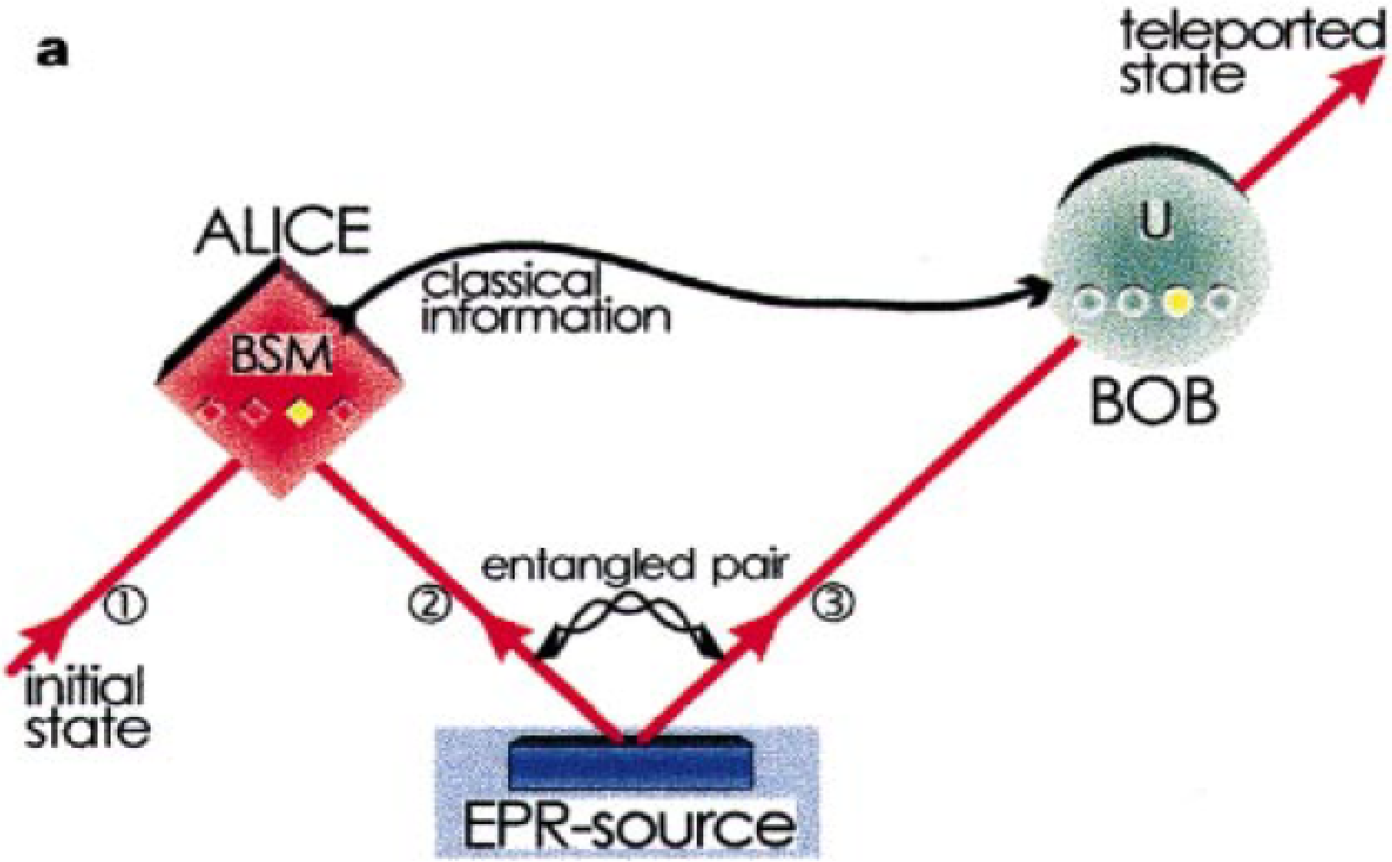
Outline

- Quantum teleportation (QT) protocol.
- Laboratory experimental demonstration:
  Bouwmeester at al. (1997).
- Experimental demonstration of QT over 143 km:
  Xiao-Song Ma et al. (2012).
- Comparison to QT using superconducting qubit.

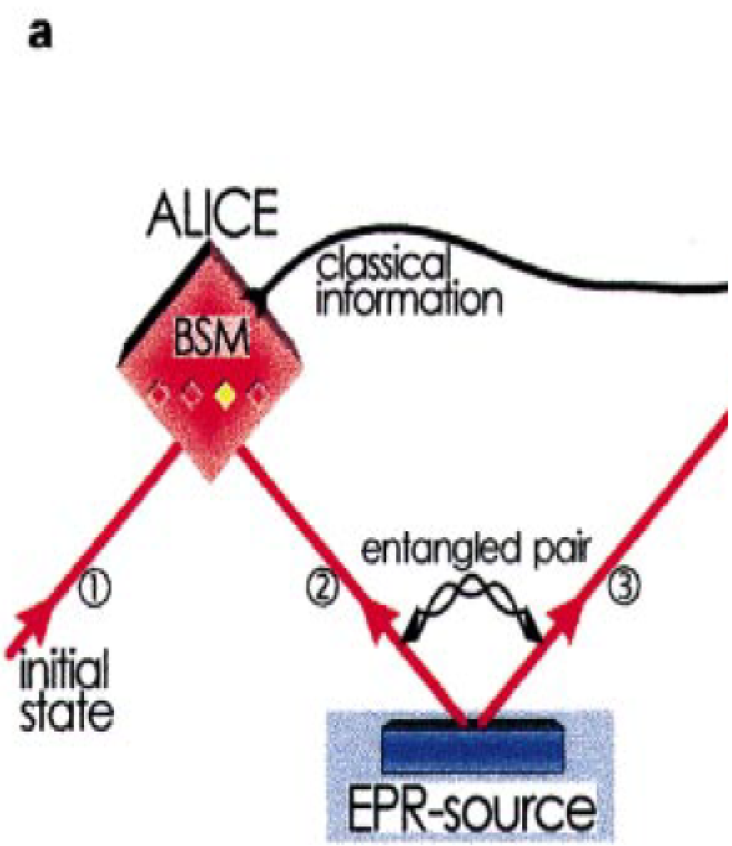
General principles

- Quantum teleportation: transfer of a quantum state to another state that is physically separated from it.
- Quantum no cloning theorem → the input photon must be destroyed or lose his initial state.
- Relativity: trasmission of information not faster than the speed of light.
- Motivation: teleportation of qubits between quantum computers at different locations.

Photon teleportation



Input, correlated photon pair and total wavefunction



- Arbitrary input:

$$|\psi\rangle_1 = \alpha|\leftrightarrow\rangle_1 + \beta|\updownarrow\rangle_1$$

- EPR source

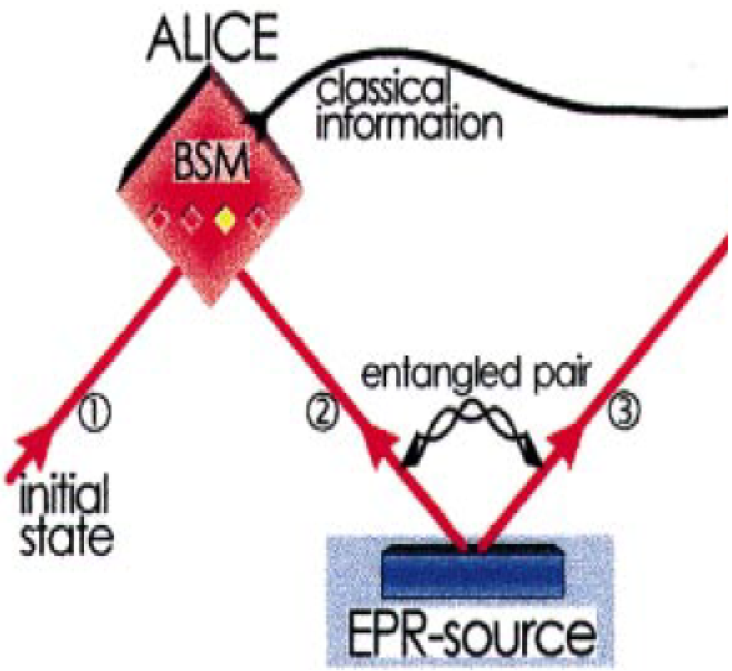
$$|\psi^-\rangle_{23} = \frac{1}{\sqrt{2}}\Big(|\leftrightarrow\rangle_2|\updownarrow\rangle_3 - |\updownarrow\rangle_2|\leftrightarrow\rangle_3\Big)$$

- Alice's full wavefunction

$$|\psi\rangle_{123} = \frac{1}{\sqrt{2}}\Big(\alpha|\leftrightarrow\rangle_1|\leftrightarrow\rangle_2|\updownarrow\rangle_3 - \alpha|\leftrightarrow\rangle_1|\updownarrow\rangle_2|\leftrightarrow\rangle_3 + \beta|\updownarrow\rangle_1|\leftrightarrow\rangle_2|\updownarrow\rangle_3 - \beta|\updownarrow\rangle_1|\updownarrow\rangle_2|\leftrightarrow\rangle_3\Big)$$

Bell's states measurement

a



- Bell-states:

$$|\psi^-\rangle_{12} = \frac{1}{\sqrt{2}}\Big(|\leftrightarrow\rangle_1|\updownarrow\rangle_2 - |\updownarrow\rangle_1|\leftrightarrow\rangle_2\Big)$$

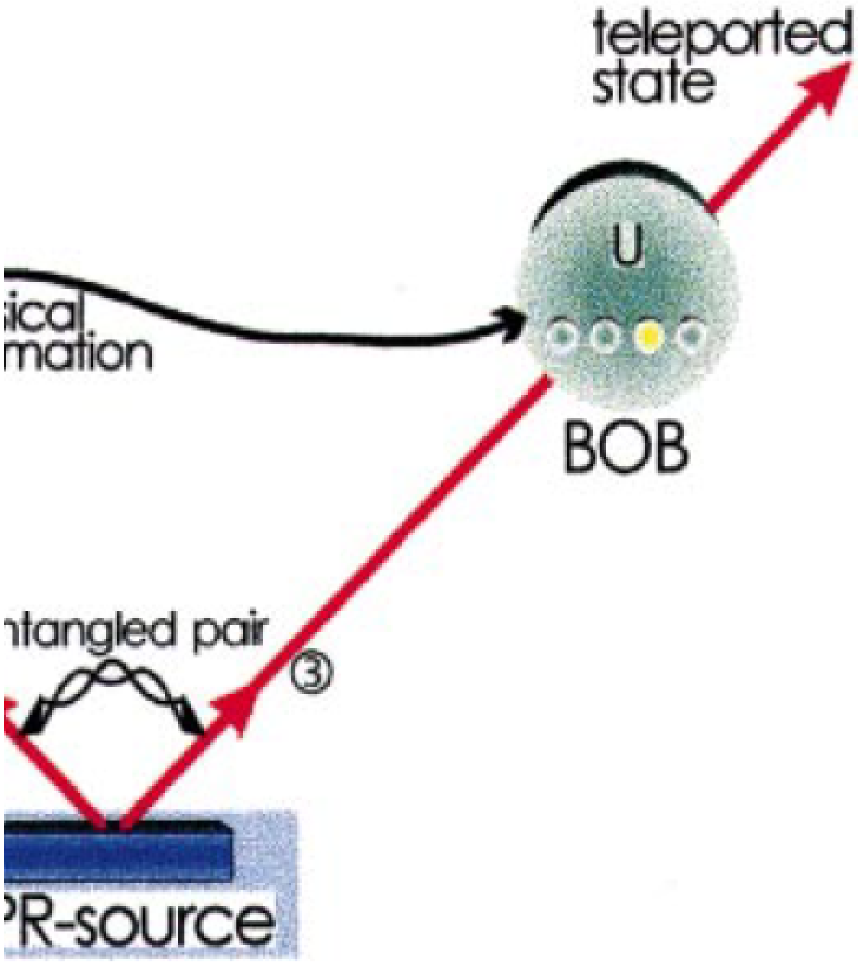
$$|\psi^+\rangle_{12} = \frac{1}{\sqrt{2}}\Big(|\leftrightarrow\rangle_1|\updownarrow\rangle_2 + |\updownarrow\rangle_1|\leftrightarrow\rangle_2\Big)$$

$$|\phi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}\Big(|\leftrightarrow\rangle_1|\leftrightarrow\rangle_2 \pm |\updownarrow\rangle_1|\updownarrow\rangle_2\Big)$$

- Bell -State Measurement (BSM): detect a Bell-state

$$|\psi\rangle_{123} = \frac{1}{2}\Big[|\phi^+\rangle_{12}(\alpha|\updownarrow\rangle_3 - \beta|\leftrightarrow\rangle_3) + |\phi^-\rangle_{12}(\alpha|\updownarrow\rangle_3 + \beta|\leftrightarrow\rangle_1)$$
$$+ |\psi^+\rangle_{12}(-\alpha|\leftrightarrow\rangle_3 + \beta|\updownarrow\rangle_3) - |\psi^-\rangle_{12}(\alpha|\leftrightarrow\rangle_3 + \beta|\updownarrow\rangle_3)\Big]$$

Output

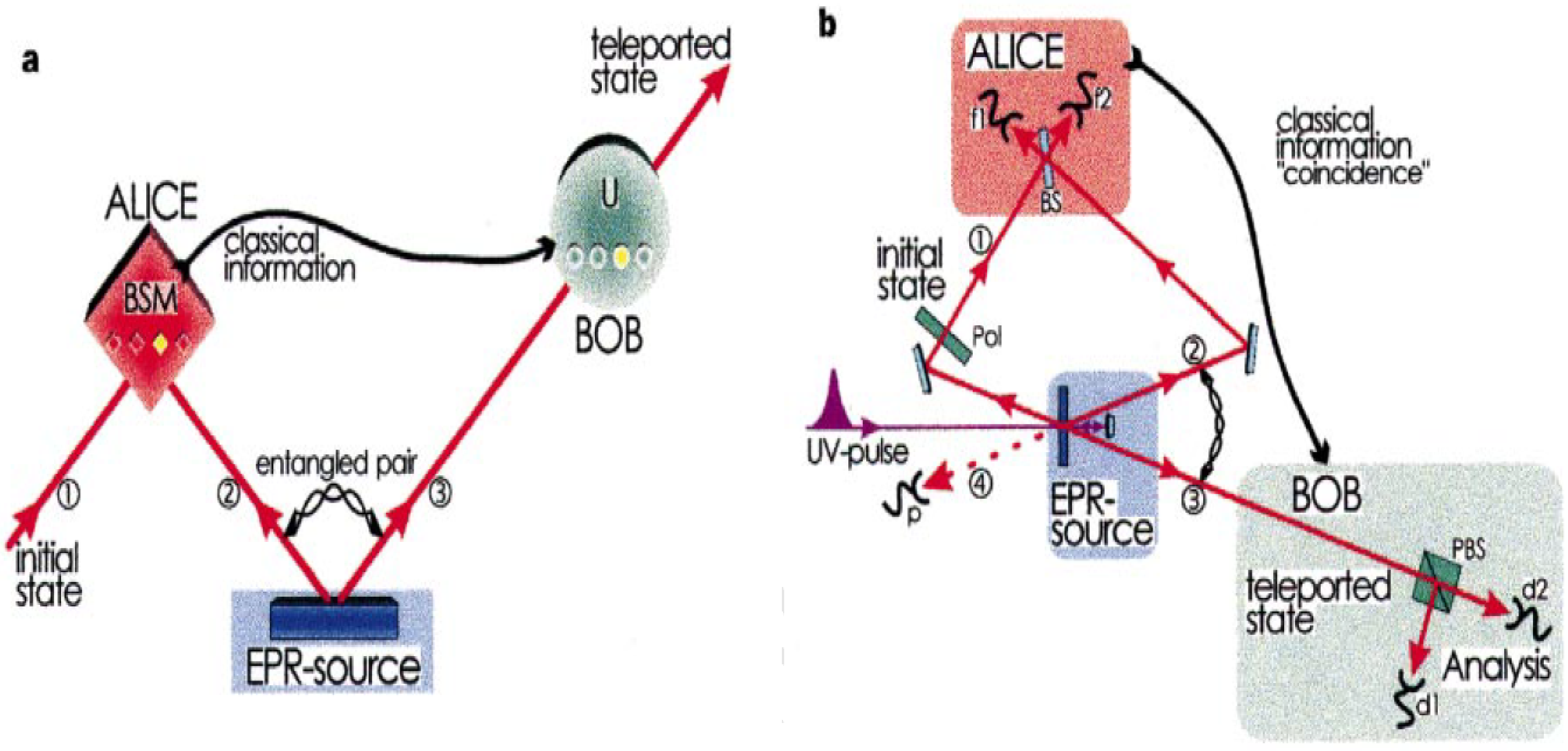


- Input was: $|\psi\rangle_1 = \alpha|\leftrightarrow\rangle_1 + \beta|\updownarrow\rangle_1$
- Example: result of BSM $|\psi^+\rangle_{12}$

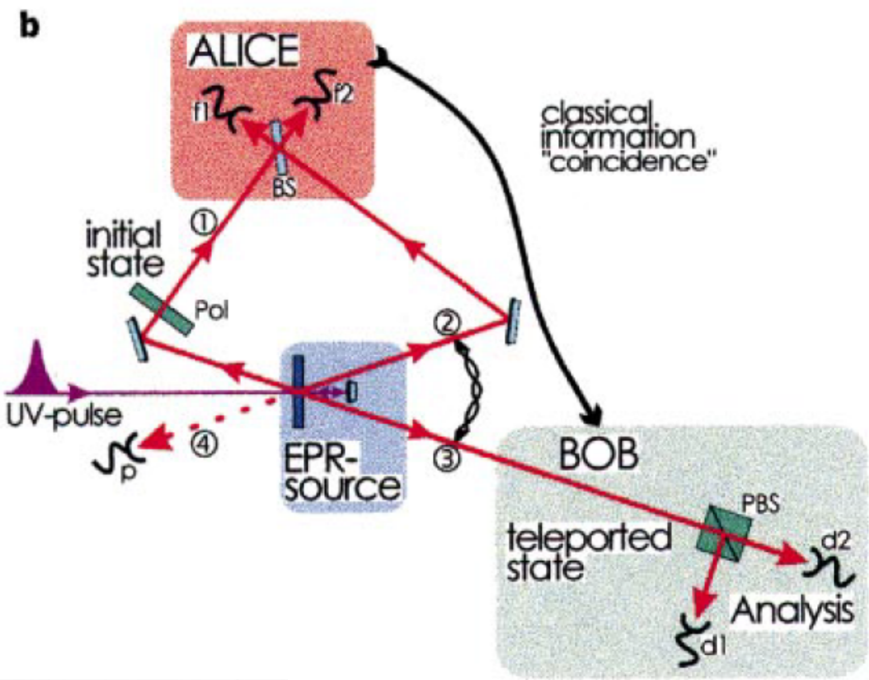
$$|\psi\rangle_{123} = \frac{1}{2}\Big[|\phi^+\rangle_{12}(\alpha|\updownarrow\rangle_3 - \beta|\leftrightarrow\rangle_3) + |\phi^-\rangle_{12}(\alpha|\updownarrow\rangle_3 + \beta|\leftrightarrow\rangle_1) + |\psi^+\rangle_{12}(-\alpha|\leftrightarrow\rangle_3 + \beta|\updownarrow\rangle_3) - |\psi^-\rangle_{12}(\alpha|\leftrightarrow\rangle_3 + \beta|\updownarrow\rangle_3)\Big]$$

- Apply a unitary transformation on: $(-\alpha|\leftrightarrow\rangle_3 + \beta|\updownarrow\rangle_3)$ in order to optain the input state.
- Unitary transformation U: $\begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$

Experimental demonstration: Bouwmeester et al. (1997)



Experimental demonstration: Theoretical prediction



- Photon 1 polarized at 45°.

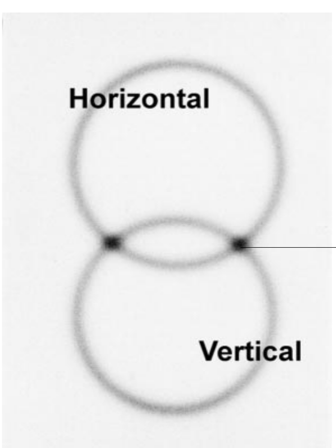
  $$|\psi\rangle_1 = \alpha|\leftrightarrow\rangle_1 + \beta|\updownarrow\rangle_1$$

- Photon 2 & 3 generated by degenerate down conversion (DDC).

  $$|\psi^-\rangle_{23} = \frac{1}{\sqrt{2}}\Big(|\leftrightarrow\rangle_2|\updownarrow\rangle_3 - |\updownarrow\rangle_2|\leftrightarrow\rangle_3\Big)$$

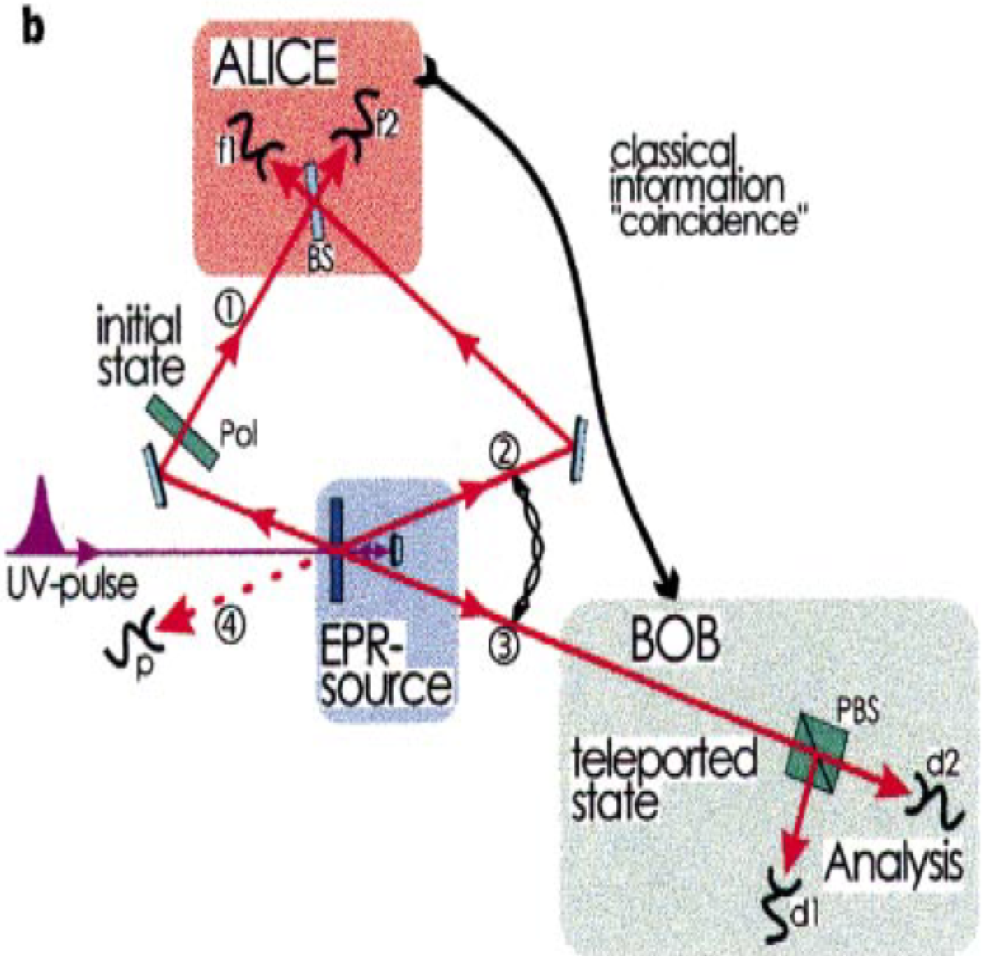
- BSM by Alice: detect one of the four Bell-states.
- In the experiment:

  $$|\psi^-\rangle_{12} = \frac{1}{\sqrt{2}}\Big(|\leftrightarrow\rangle_1|\updownarrow\rangle_2 - |\updownarrow\rangle_1|\leftrightarrow\rangle_2\Big)$$

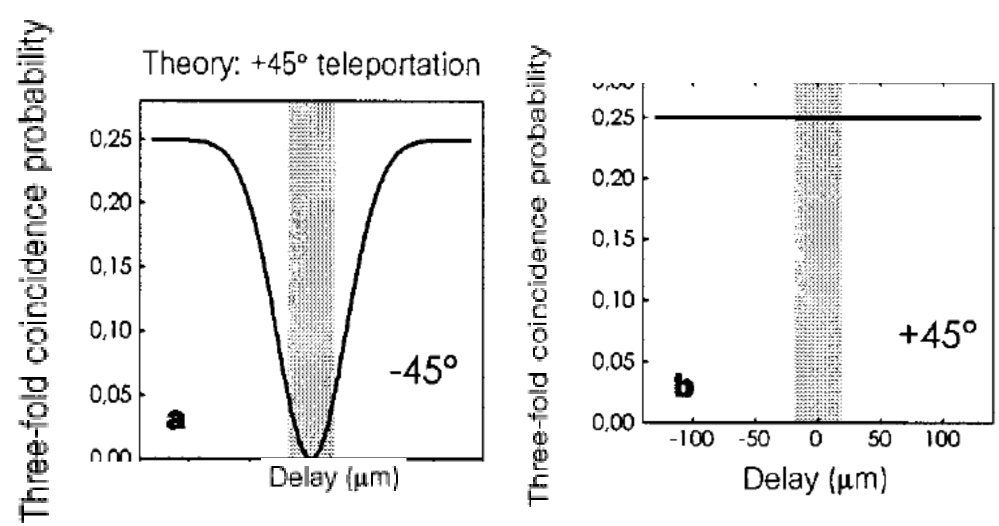


Entangled pair produced by DDC.

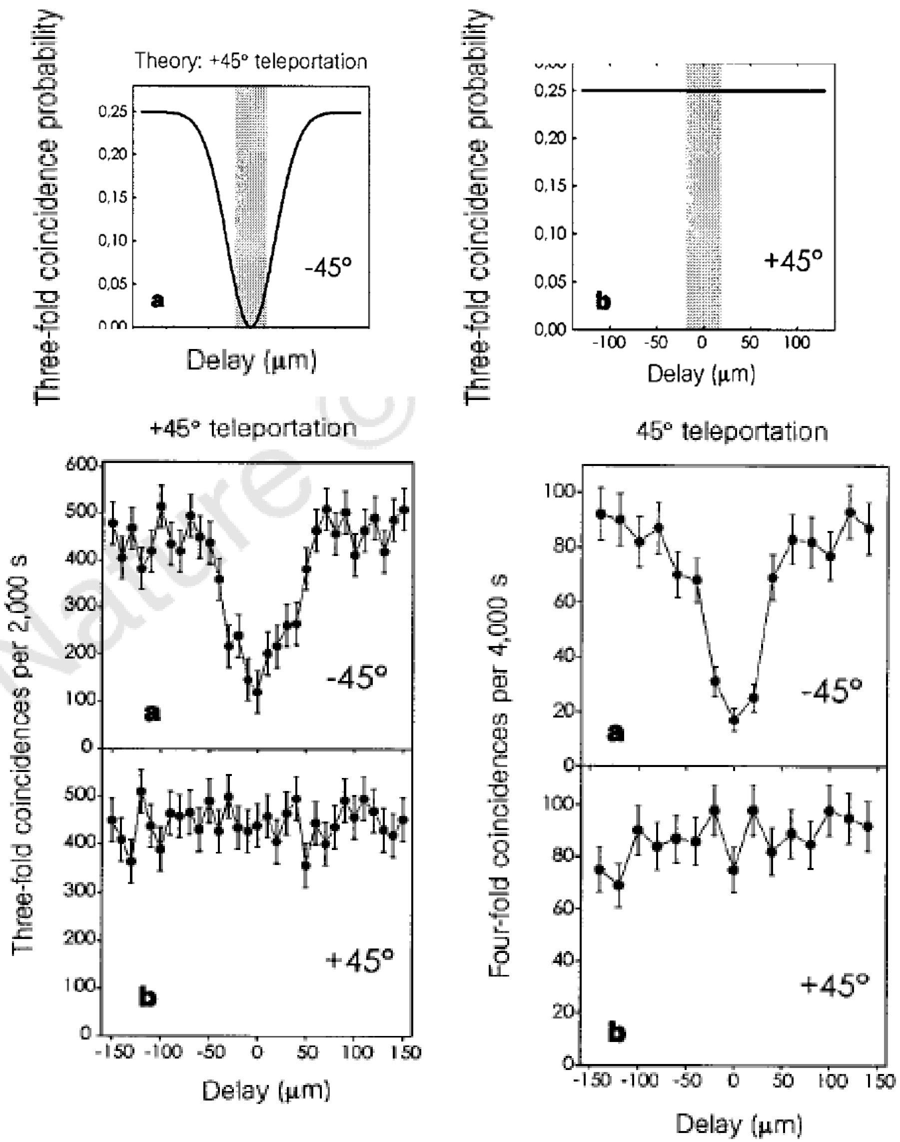
Experimental demonstration: Theoretical prediction



- In order to find $|\psi^-\rangle_{12}$ look for coincidences on detectors f1 and f2.
- PBS of Bob detects the 45° polarization.
- Compare coincidence rates of f1f2d1 (a) and f1f2d2 (b).



Results: Coincidence rates



- Coincidence rates at detectors d1f1f2 (-45°, a) and d2f1f2 (45°, b) in the case photon polarized at 45°.
- The Delay is between the arrival of photon 1 and photon 2 to Alice's beam splitter.
- Photon 1 used as trigger.

  ⇨ Photon 1 was sendet to Alice, if detected by p.
- Four-fold coincidence at detectors pd1f1f2 (-45°, a) and pd2f1f2 (45°, b).

Quantum teleportation over 143km using active feed forward

Xiao – Song Ma et al.

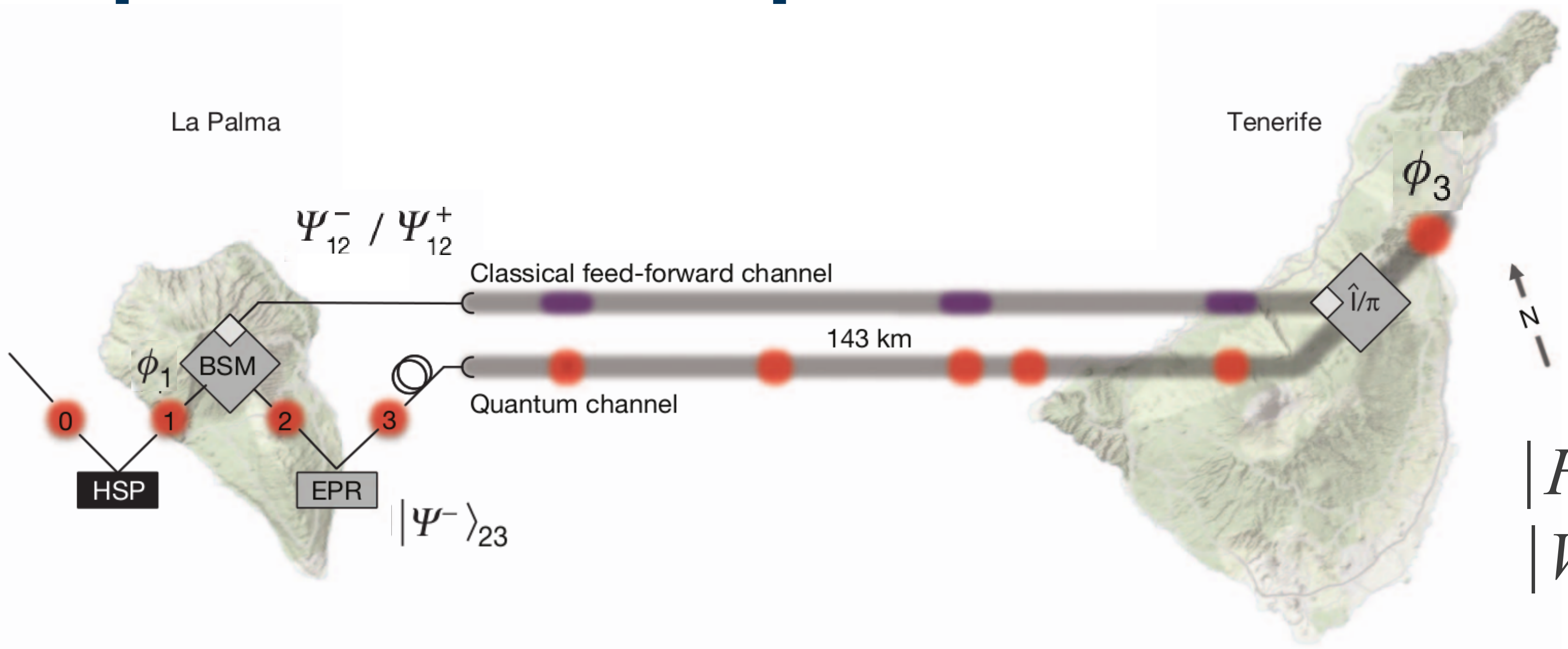
- Long – distance free – space teleportation of independent quantum state
- Similar experiment done independently in China:

Yin, J.et al.

Quantum teleportation and entanglement distribution over 100-kilometre free-space channels.

Nature488,185(2012)

Experimental setup

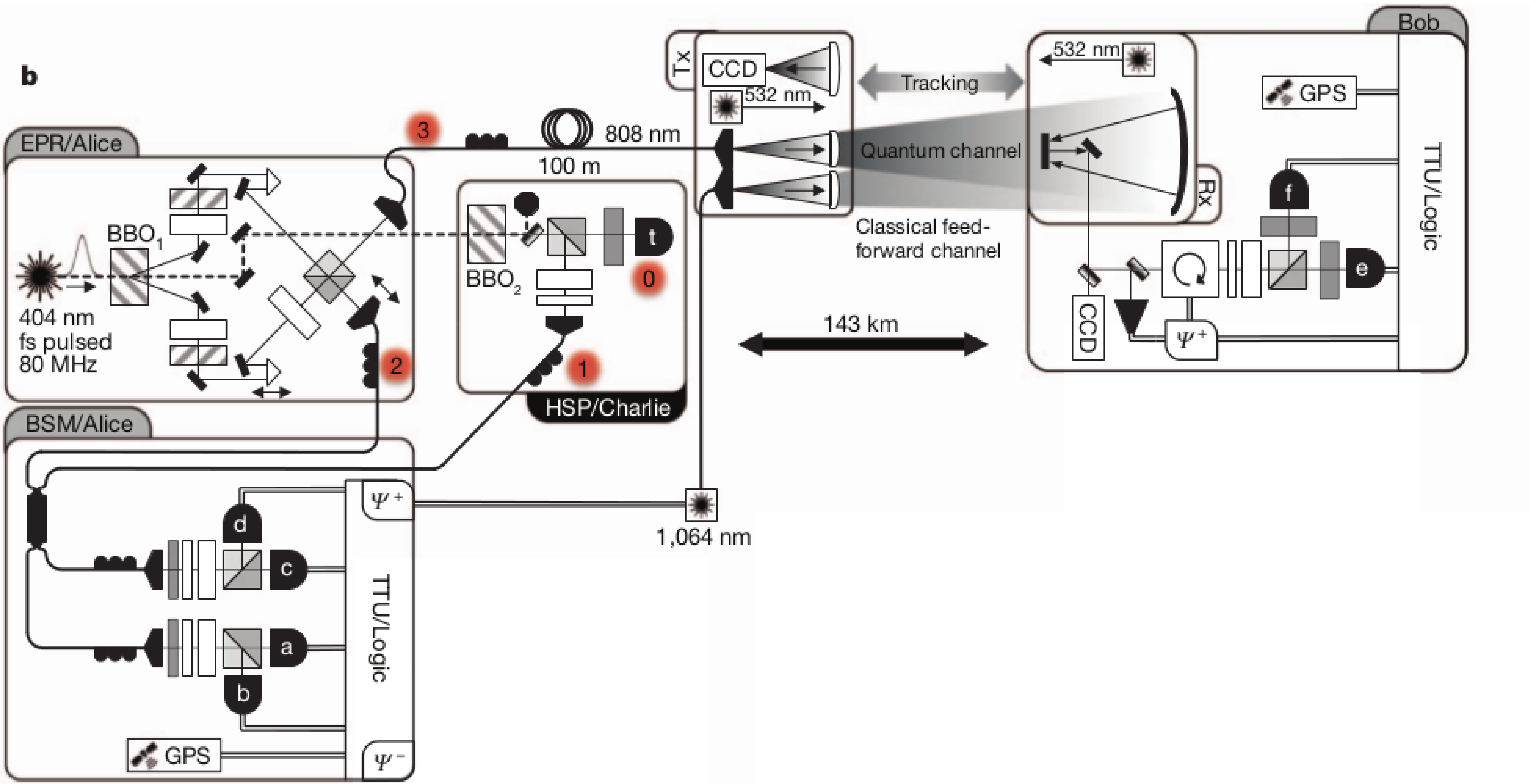


$|H\rangle =$ ↔

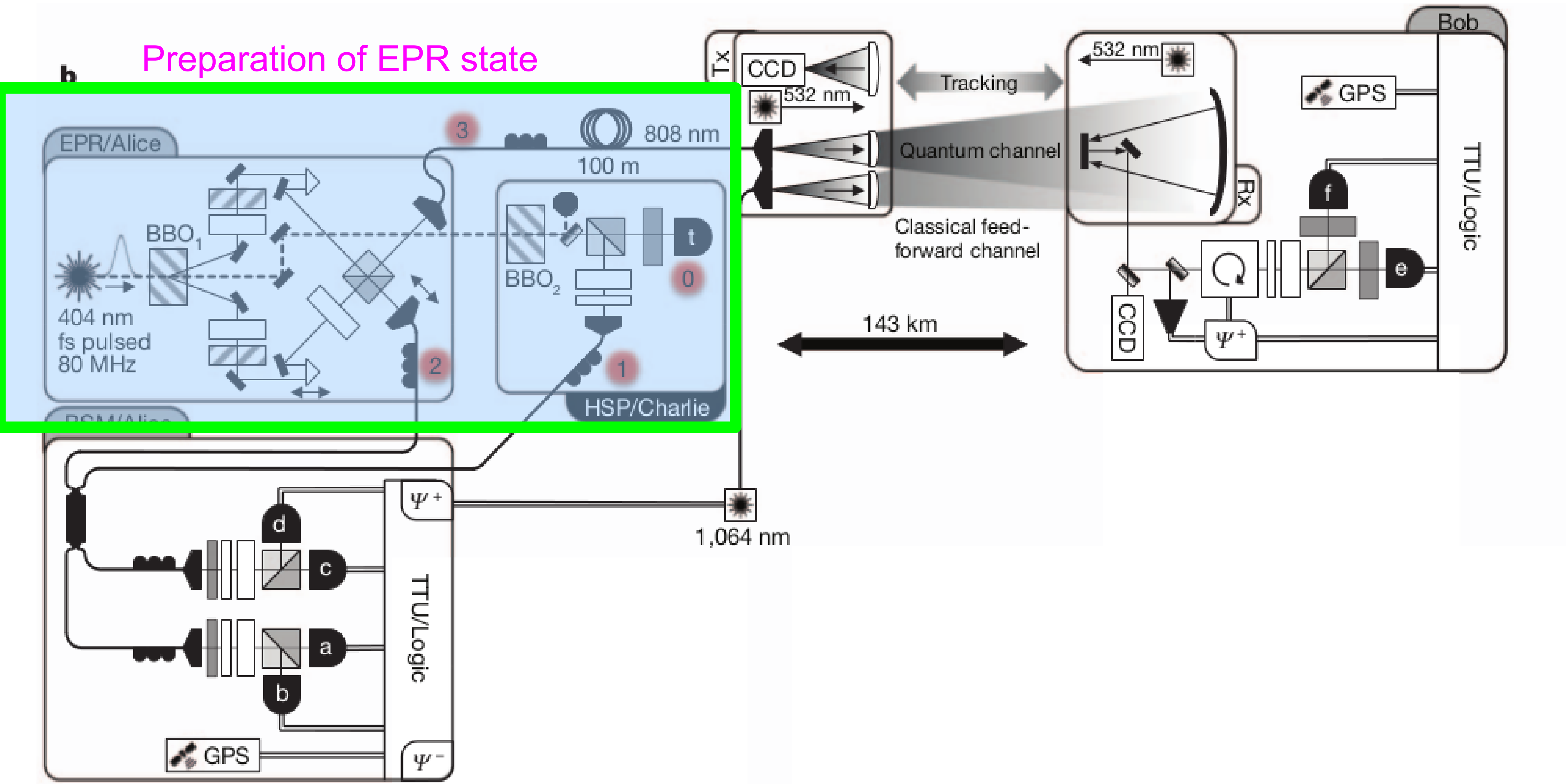
$|V\rangle =$ ↕

- Alice and Charlie at La Palma, Bob at Tenerife
- Alice and Bob share $|\Psi^-\rangle = \frac{1}{\sqrt{(2)}}(|H\rangle_2 |V\rangle_3 - |V\rangle_2 |H\rangle_3)$
- Charlie provides a photon $|\Phi\rangle = \alpha|H\rangle + \beta|V\rangle$

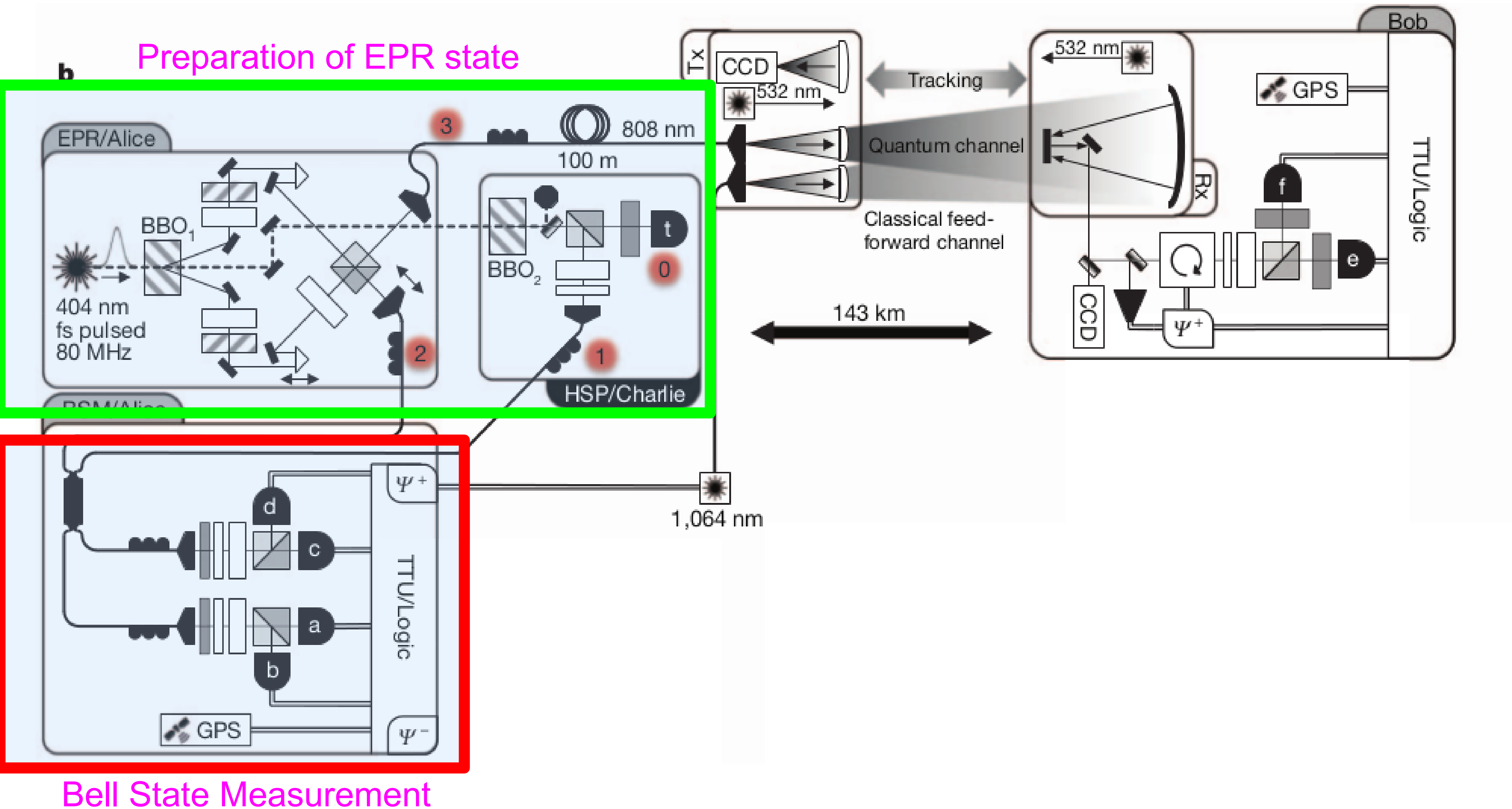
Experimental setup – detailed view



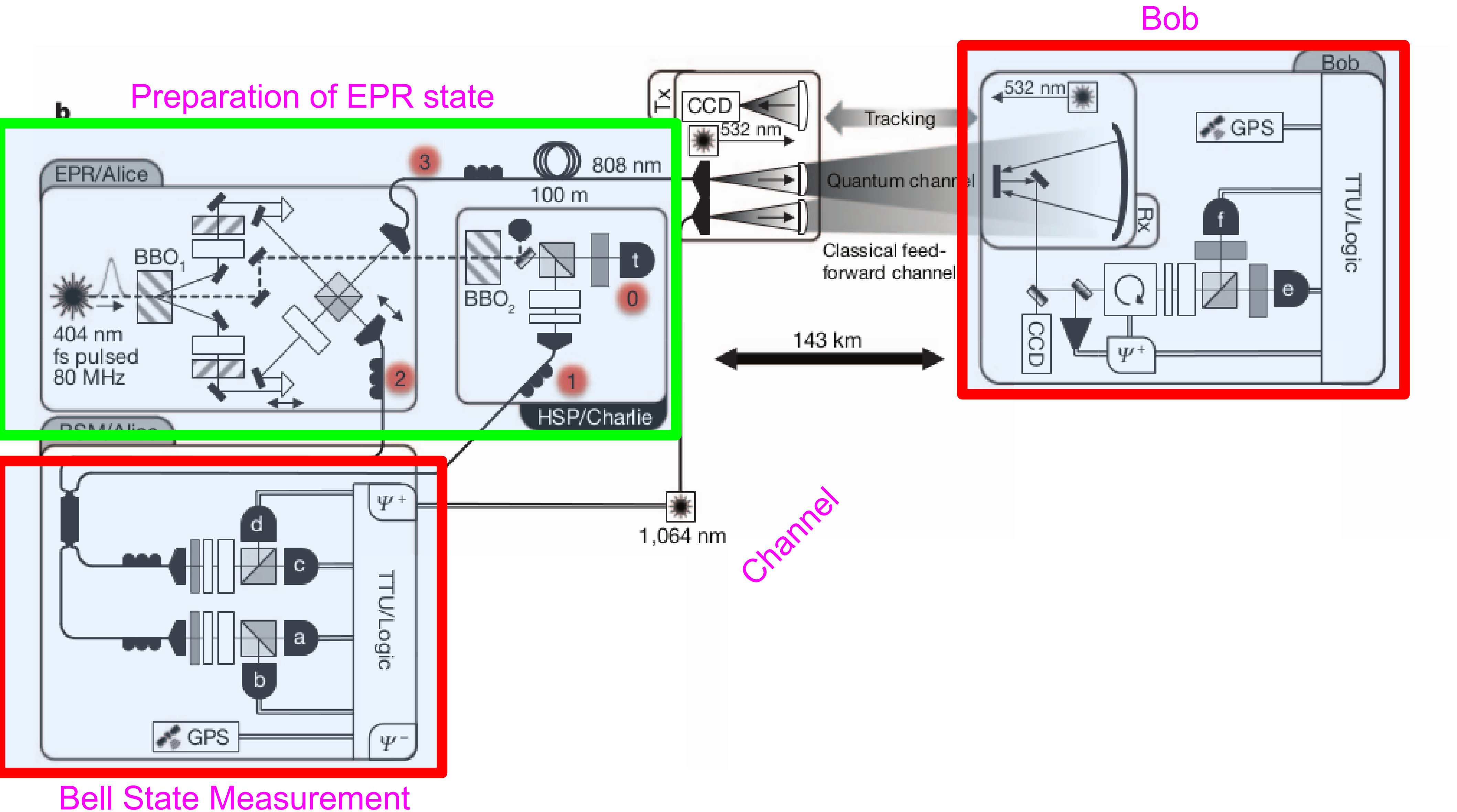
Experimental setup – detailed view



Experimental setup – detailed view



Experimental setup – detailed view



Results – state tomography

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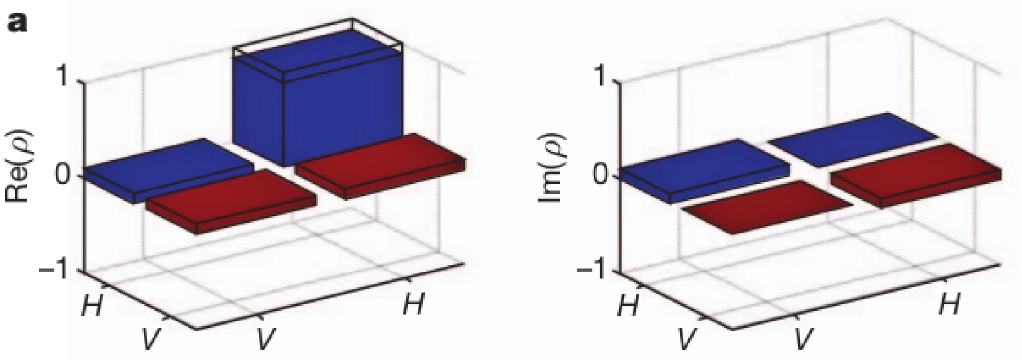
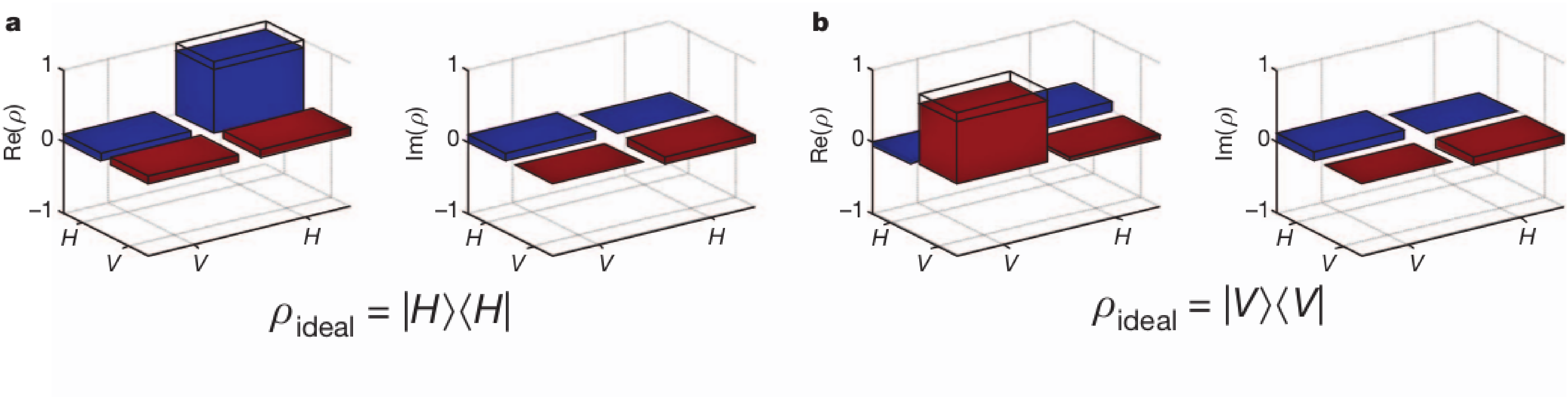
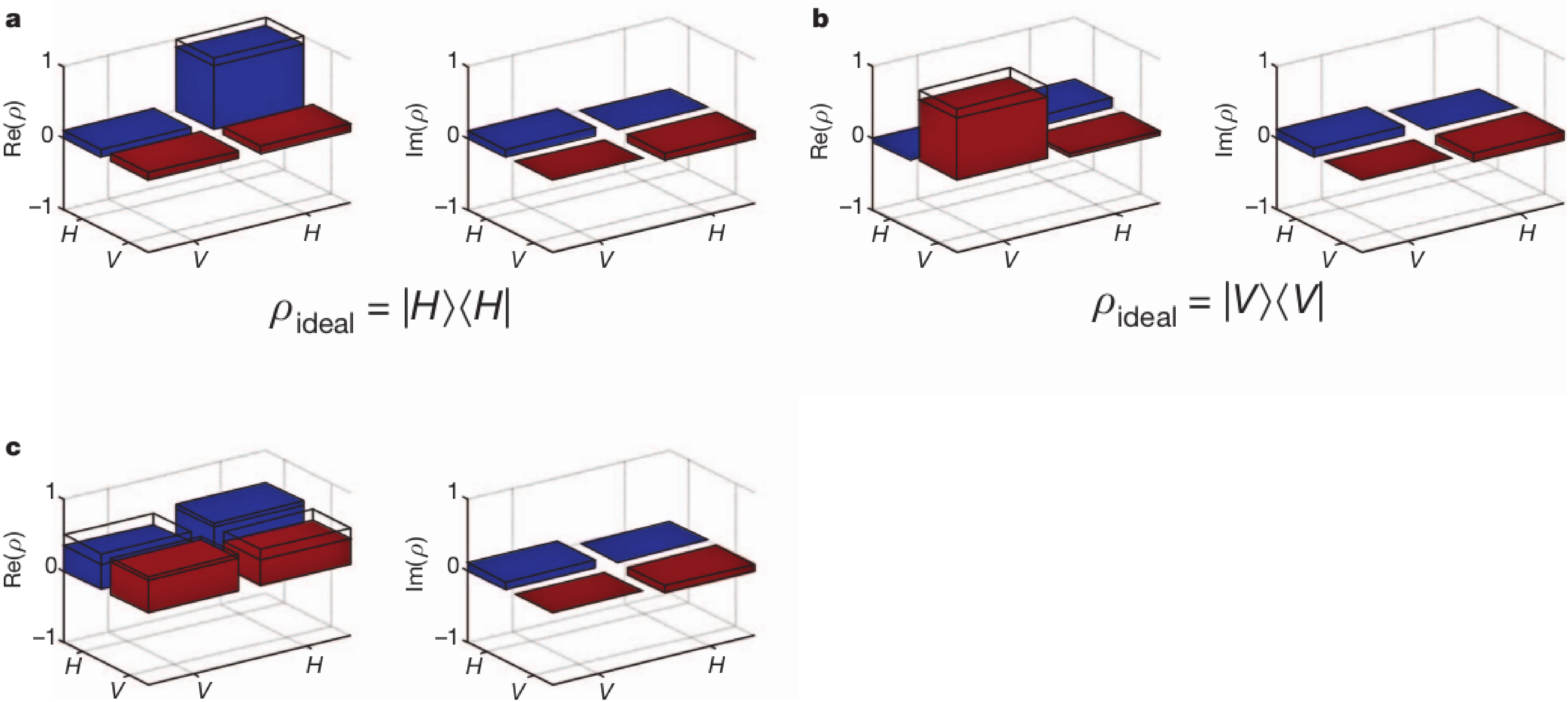


$$\rho_{\text{ideal}} = |H\rangle\langle H|$$

Results – state tomography



Results – state tomography

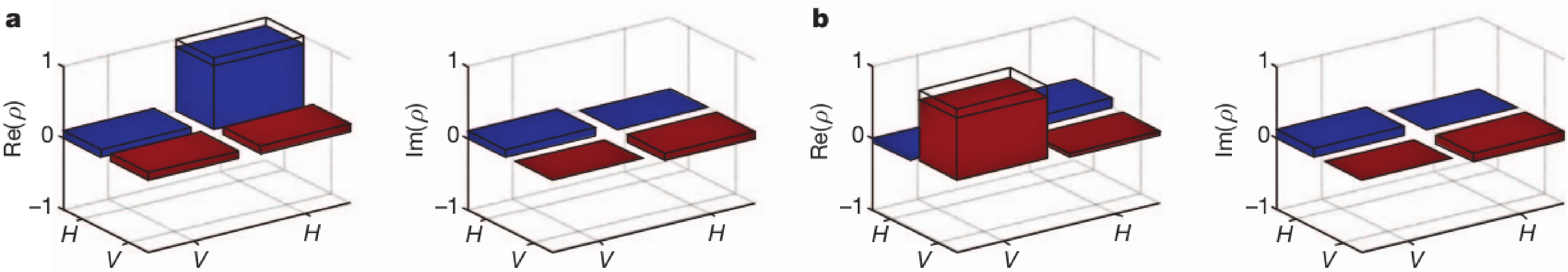


a: $\rho_{\text{ideal}} = |H\rangle\langle H|$

b: $\rho_{\text{ideal}} = |V\rangle\langle V|$

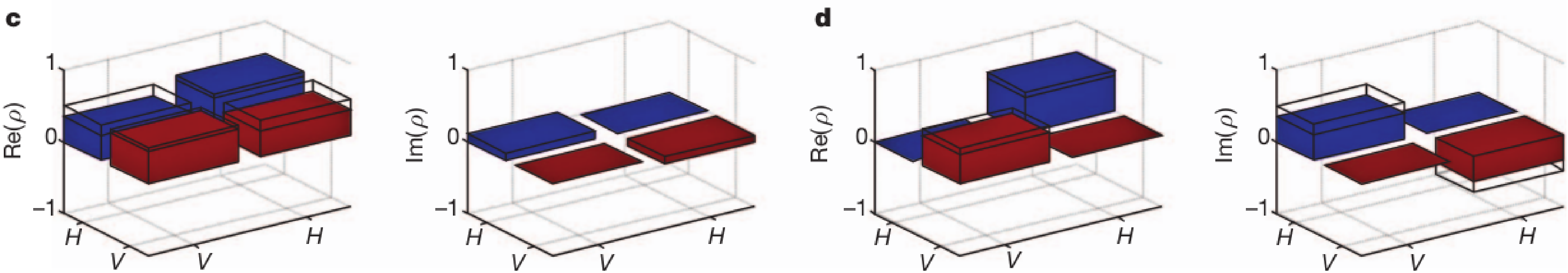
c: $$\rho_{\text{ideal}} = \frac{1}{2}(|H\rangle\langle H| + |H\rangle\langle V| + |V\rangle\langle H| + |V\rangle\langle V|)$$

Results – state tomography



$$\rho_{\text{ideal}} = |H\rangle\langle H|$$

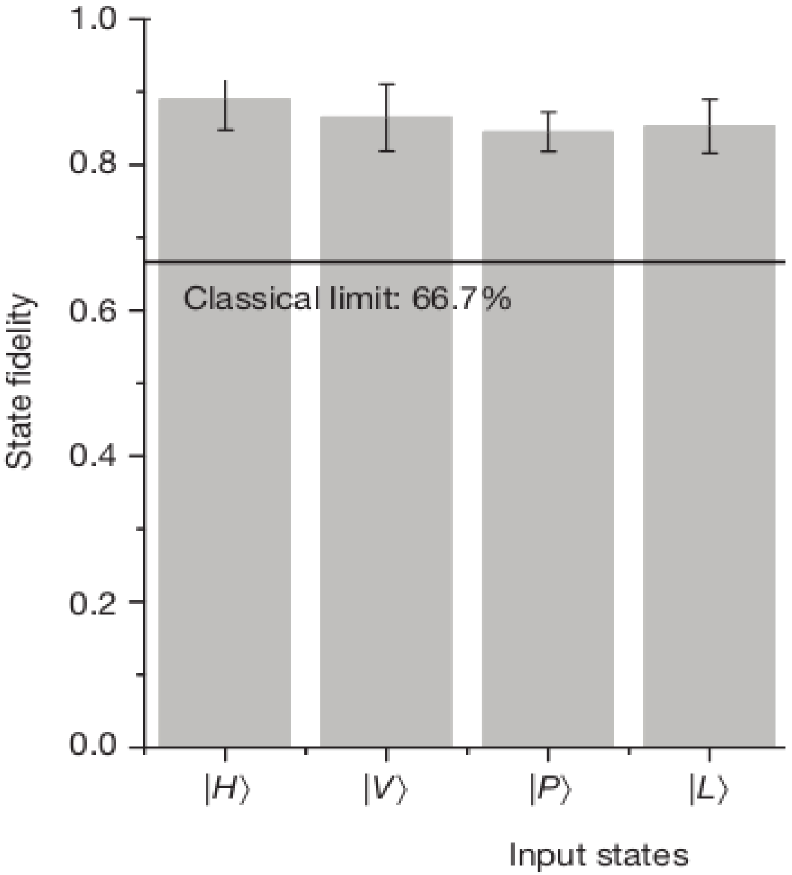
$$\rho_{\text{ideal}} = |V\rangle\langle V|$$



$$\rho_{\text{ideal}} = \frac{1}{2}(|H\rangle\langle H| + |H\rangle\langle V| + |V\rangle\langle H| + |V\rangle\langle V|)$$

$$\rho_{\text{ideal}} = \frac{1}{2}(|H\rangle\langle H| + i|H\rangle\langle V| - i|V\rangle\langle H| + |V\rangle\langle V|)$$

Results – state fidelities



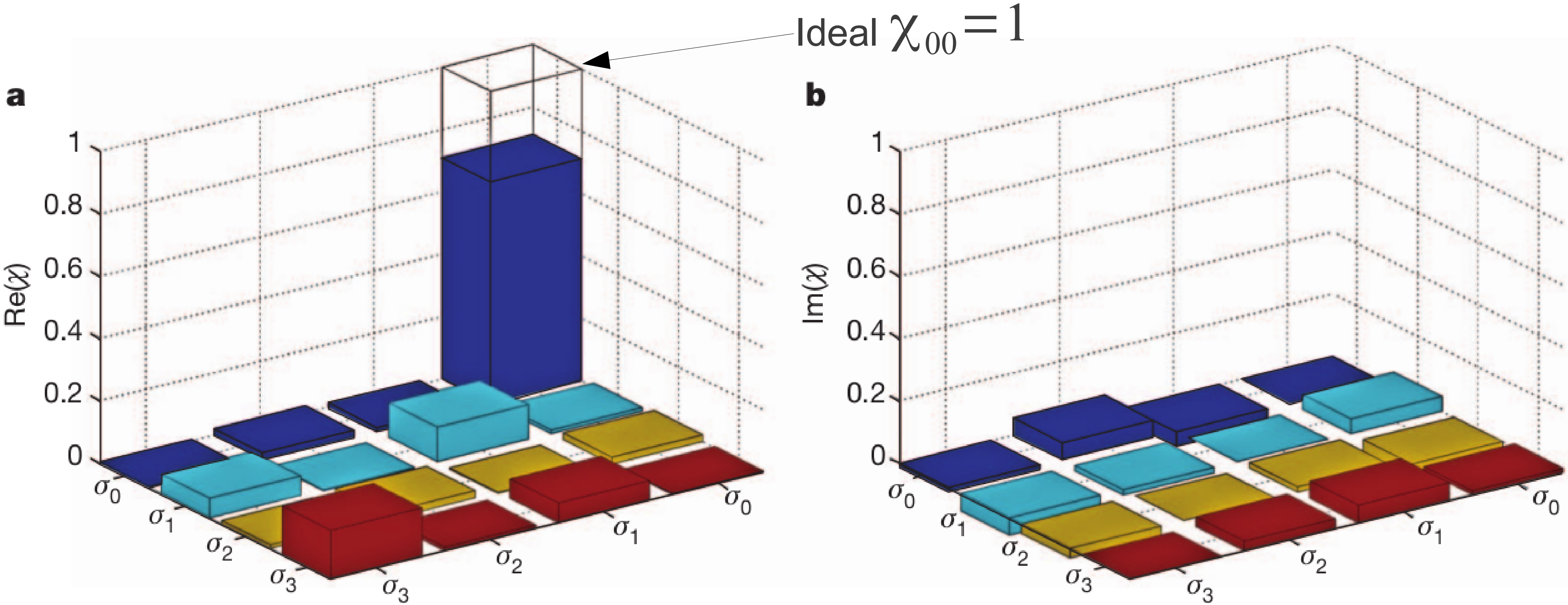
$$f = \langle \Phi_{ideal} | \rho | \Phi_{ideal} \rangle$$

$$|\Phi_{ideal}\rangle \in \{ |H\rangle, |V\rangle, \\ |P\rangle = (|H\rangle + |V\rangle)/\sqrt{(2)}, \\ |L\rangle = (|H\rangle - i|V\rangle)/\sqrt{(2)} \}$$

Average fidelity

$$\bar{f} = 0.863 \pm 0.038$$

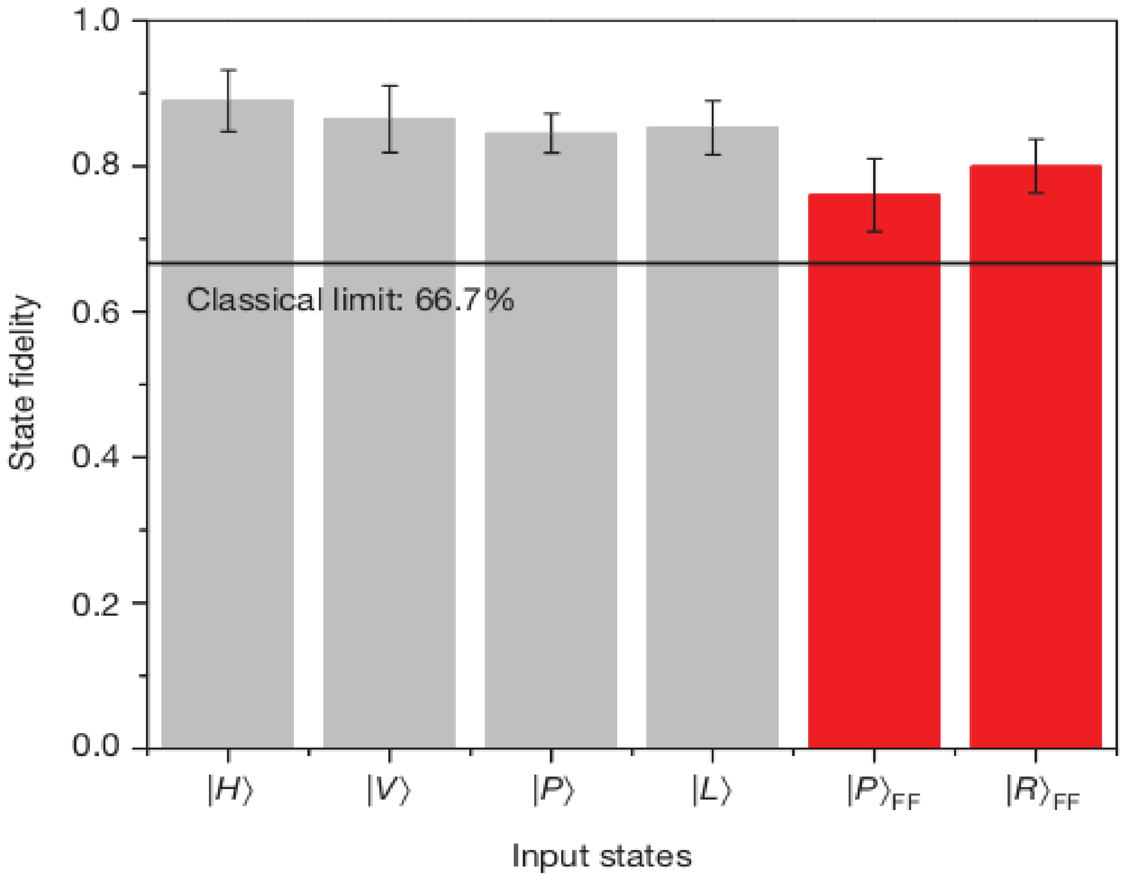
Results – Process Matrix



$$\rho = \sum_{l,k=0}^{3} \chi_{lk}\, \sigma_l\, \rho_{ideal}\, \sigma_k$$

$$f_{process} = 0.72 \pm 0.042$$

Results – state fidelities with feed – forward



- At Tenerife photon #3 analyzed in the eigenbasis of input state:

$$|P\rangle / |M\rangle$$

$$|M\rangle = (|H\rangle - |V\rangle)/\sqrt{(2)}$$

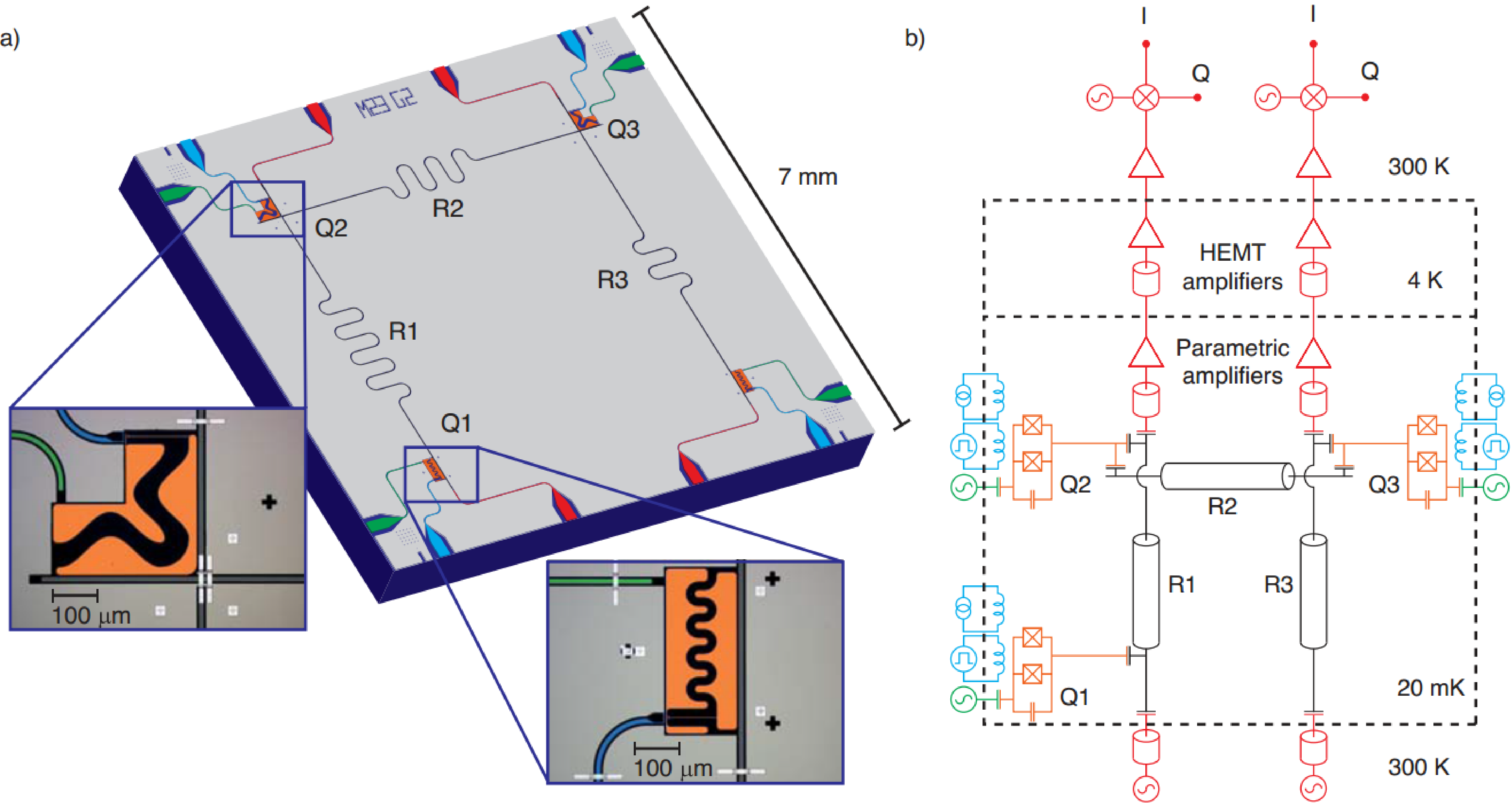
or

$$|R\rangle / |L\rangle$$

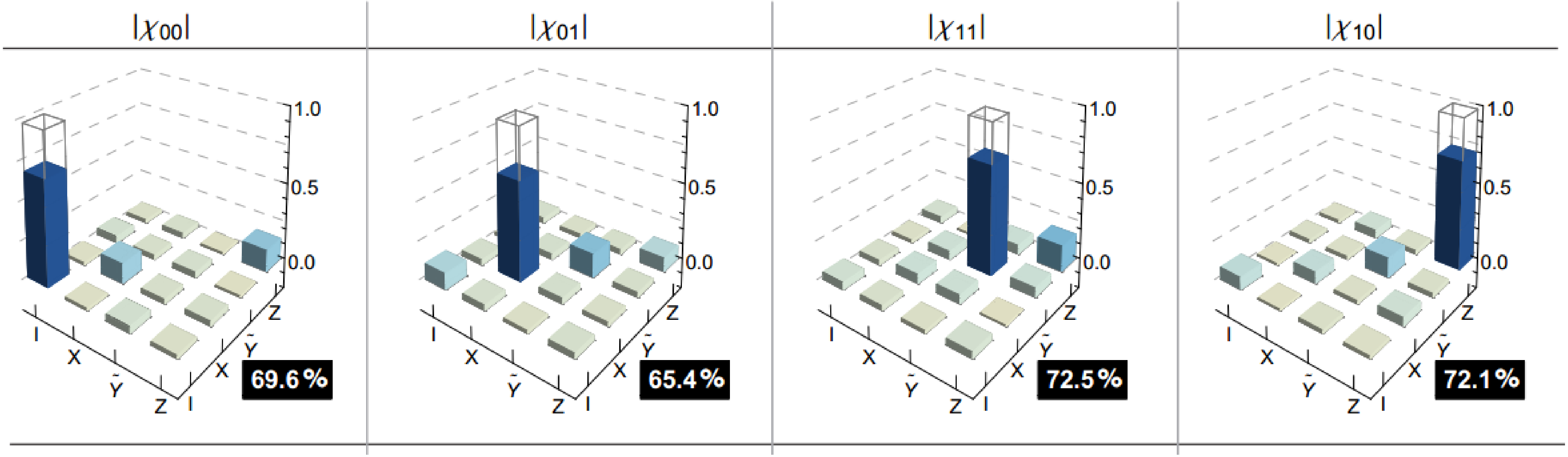
$$f_{P_{FF}} = 0.760 \pm 0.05$$

$$f_{R_{FF}} = 0.8 \pm 0.037$$

Teleportation using superconducting qubits



Teleportation using superconducting qubits



- Post selected on one of the measurement outcomes

Average fidelity

$$\bar{f} = 0.807 \pm 0.02$$

Process fidelity

$$\bar{f}_p = 0.699 \pm 0.02$$

Teleportation using superconducting qubits

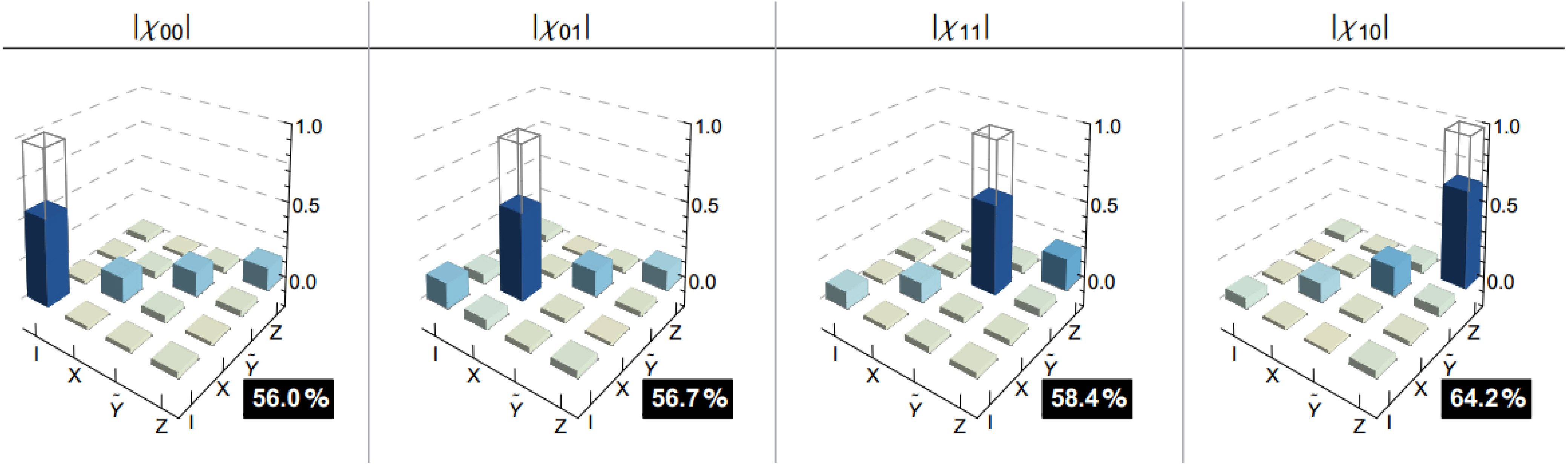
- Simultaneos detection

Average fidelity

$$\bar{f} = 0.725 \pm 0.026$$

Process fidelity

$$\bar{f}_p = 0.588 \pm 0.024$$



Summary

- Quantum teleportation of a single photon quantum state was proved.
- Quantum teleportation over a 143km free-space channel demonstrated.
- Fidelities obtained are above classical limit, even with lossy channel.
- Comparable with demonstrated teleportation with SC qubits, but innate inefficiency due to 50% efficiency of BSM.
- However, crucial step towards quantum networks and quantum internet is made!