Photon quantum teleportation

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Outline

- Motivation
- Theory of quantum teleportation
- Experimental quantum teleportation
- Outlook

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References

Experimental quantum teleportation

Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter & Anton Zeilinger

Nature 390, 575–579 (1997)

Quantum teleportation over 143 kilometres using active feed-forward

Ma, X.-S., Herbst, T., Scheidl, T. et al.

Nature 489, 269 (2012)

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

Juan Yin, Ji-Gang Ren, He Lu, Yuan Cao, et al

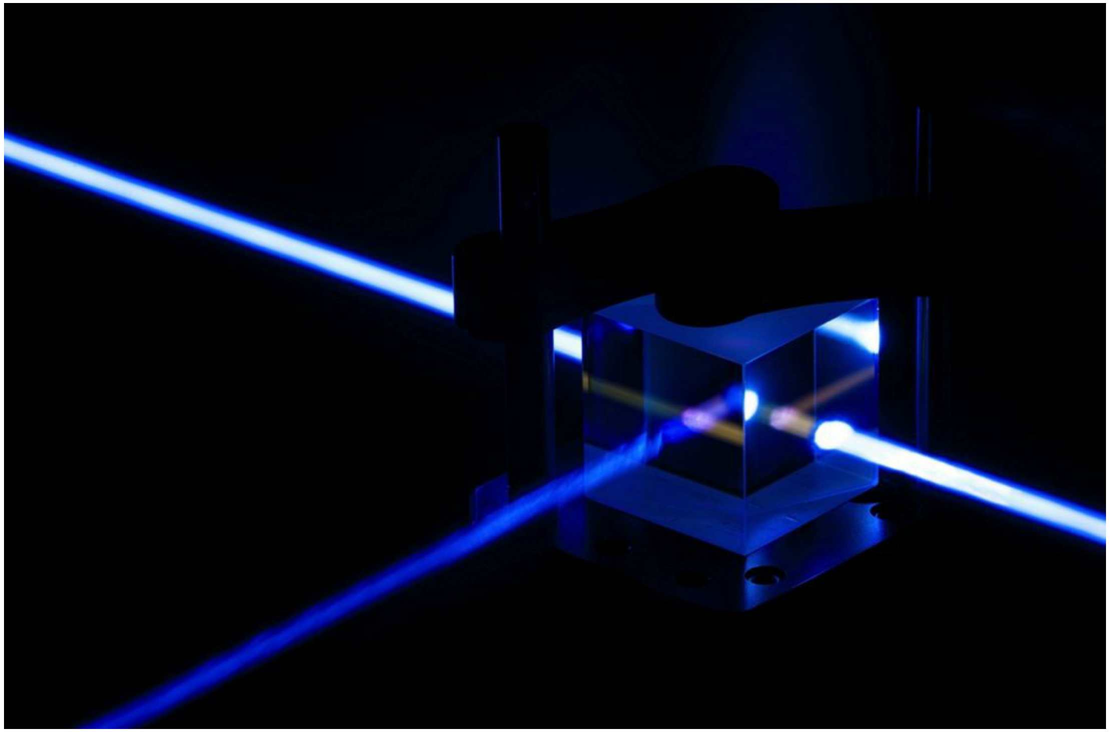
Nature 488, 185–188 (09 August 2012) doi:10.1038/nature11332

Motivation for Quantum Teleportation

- Exchange of qubits, when direct exchange is not possible
- Indirect transfer of entanglement
- Used in error correction algorithms

Quantum Teleportation with photons

We'll be using the polarisation of photons as our qubits



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What is Quantum Teleportation?

Transfer of an arbitrary quantum state

$$|\psi\rangle_1 = \alpha\,|H\rangle_1 + \beta\,|V\rangle_1$$

from Alice (1, 2) using the common maximally entangled state

$$|\psi^-\rangle_{23} = \frac{1}{\sqrt{2}}\left(|H\rangle_2\,|V\rangle_3 - |V\rangle_2\,|H\rangle_3\right)$$

to Bob (3).

How does it work?

Projecting the product state $|\psi\rangle_1 \otimes |\psi^-\rangle_{23}$ onto the Bell basis

$$|\psi^\pm\rangle = |HV\rangle \pm |VH\rangle \qquad |\phi^\pm\rangle = |HH\rangle \pm |VV\rangle$$

(for photon 1 and 2) leads to

$$\begin{aligned}|\psi\rangle_1 \otimes |\psi^-\rangle_{23} = \ldots = \tfrac{1}{2}\big(&|\phi^+\rangle_{12}\,(\alpha\,|V\rangle_3 - \beta\,|H\rangle_3)\\ &+ |\phi^-\rangle_{12}\,(\alpha\,|V\rangle_3 + \beta\,|H\rangle_3)\\ &+ |\psi^+\rangle_{12}\,(-\alpha\,|H\rangle_3 + \beta\,|V\rangle_3)\\ &+ |\psi^-\rangle_{12}\,(-\alpha\,|H\rangle_3 - \beta\,|V\rangle_3)\big)\end{aligned}$$

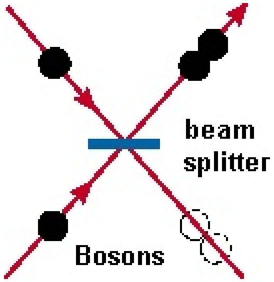
after measuring photons 1 and 2 in the Bell basis, Bob needs to apply the following operations, to get $|\psi\rangle_3$.

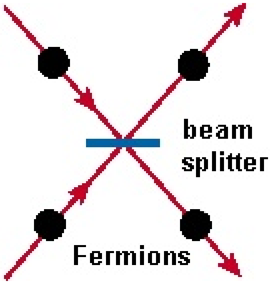
$$|\phi^+\rangle \to XZ \qquad |\phi^-\rangle \to X$$
$$|\psi^+\rangle \to Z \qquad |\psi^-\rangle \to id$$

How can we measure these Bell states?

We let the 2 photons hit the beam splitter simultaneously, the states with a sym. wavefunction will then bunch and the ones with an antisym. wavefunction will anti-bunch.

bunching





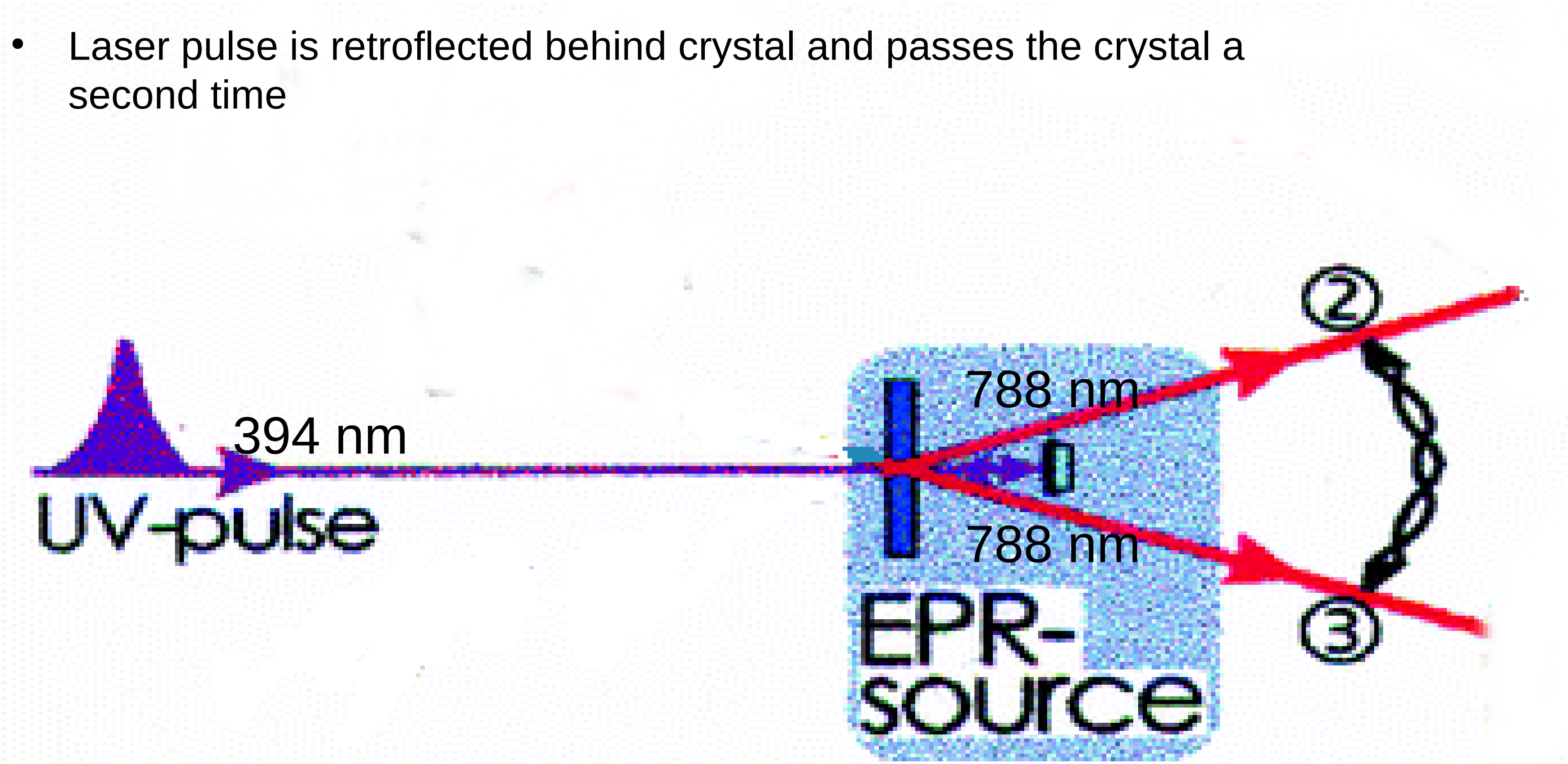
anti-bunching

$$|\psi^{+}\rangle = |HV\rangle + |VH\rangle$$
$$|\psi^{-}\rangle = |HV\rangle - |VH\rangle$$
$$|\phi^{+}\rangle = |HH\rangle + |VV\rangle$$

$$|\phi^{-}\rangle = |HH\rangle - |VV\rangle$$

Experimental quantum teleportation

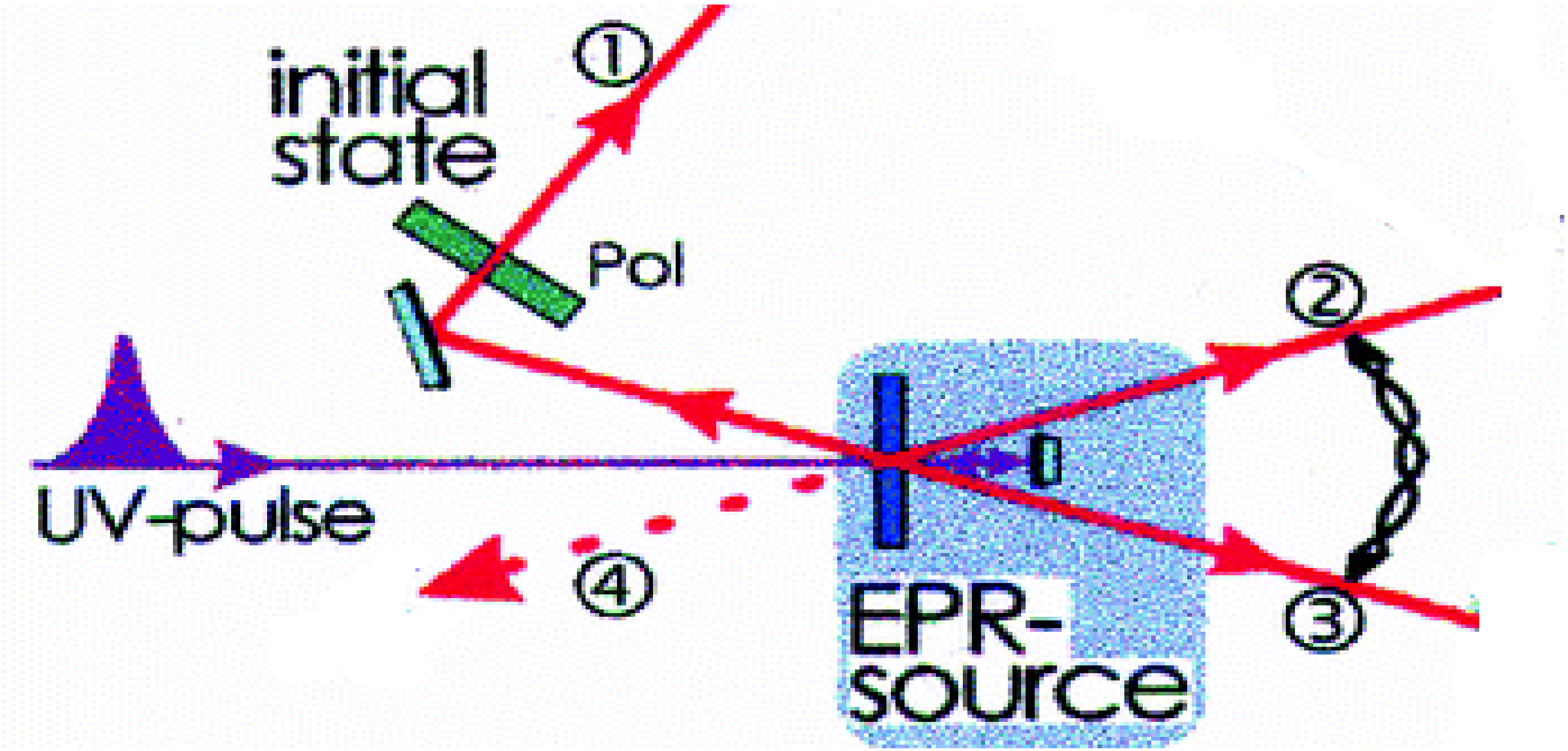
- Entangled photon state $|\psi^-\rangle_{23}$ created in nonlinear crystal by type II parametric down-conversion
- Laser pulse is retroflected behind crystal and passes the crystal a second time



Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Experimental quantum teleportation

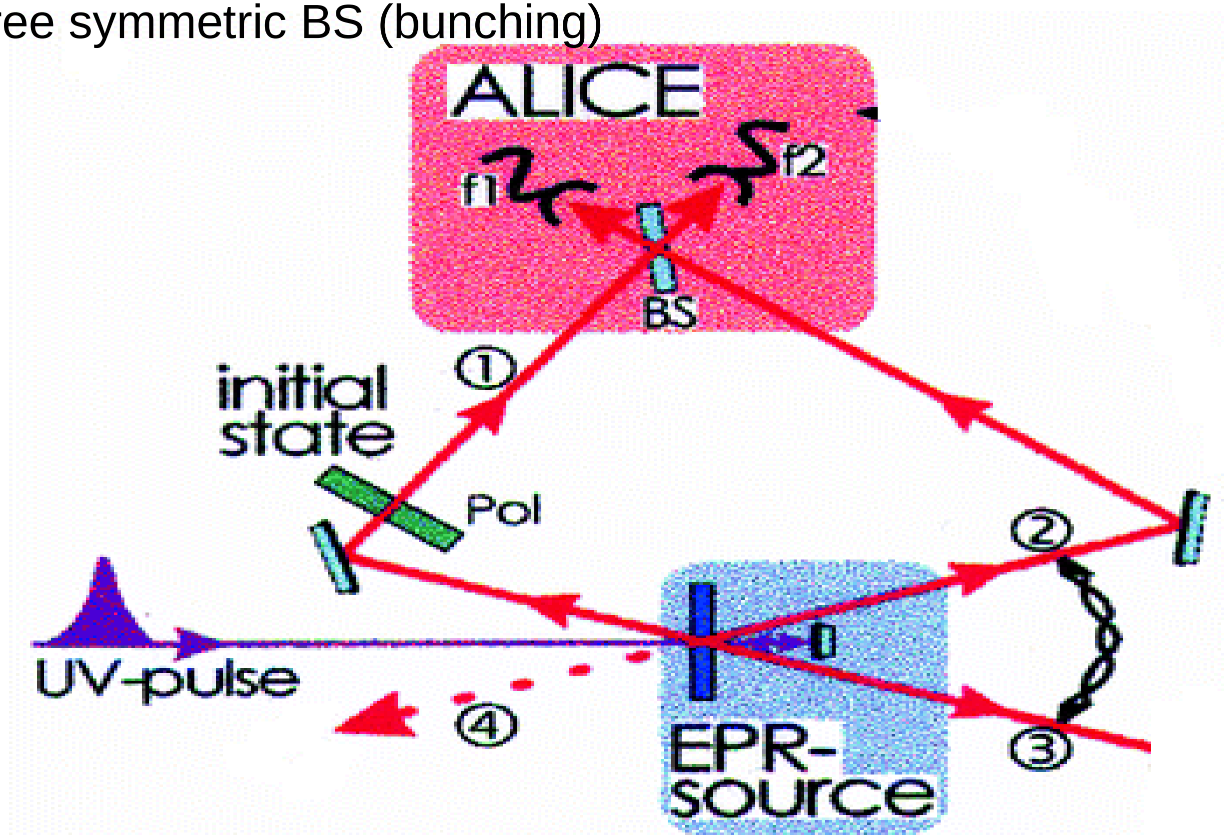
- Photon 1 created through parametric down-conversion when reflected pulse passes BBO crystal
- State of photon 1 is produced by a polarizing element (green)



Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Experimental quantum teleportation

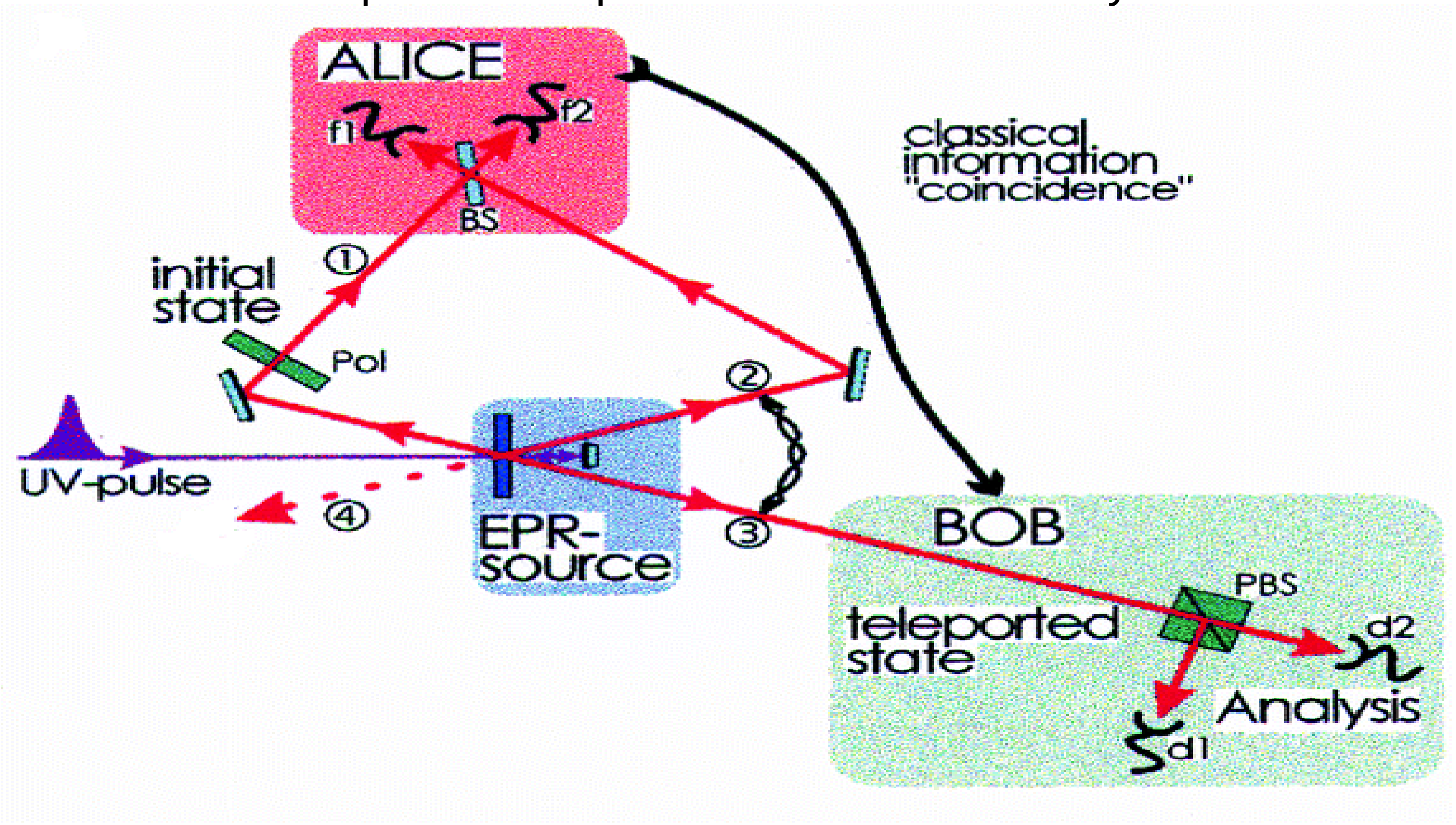
- Bell state measurement of photons 1 & 2 at 50/50 beam splitter
- Only the antisymmetric Bell state (antibunching) can be distinguished from the other three symmetric BS (bunching)



Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Experimental quantum teleportation

- Measurement of teleported state of photon 3 at polarizing beam splitter
- Due to BSM teleportation is probabilistic with efficiency of 25 %

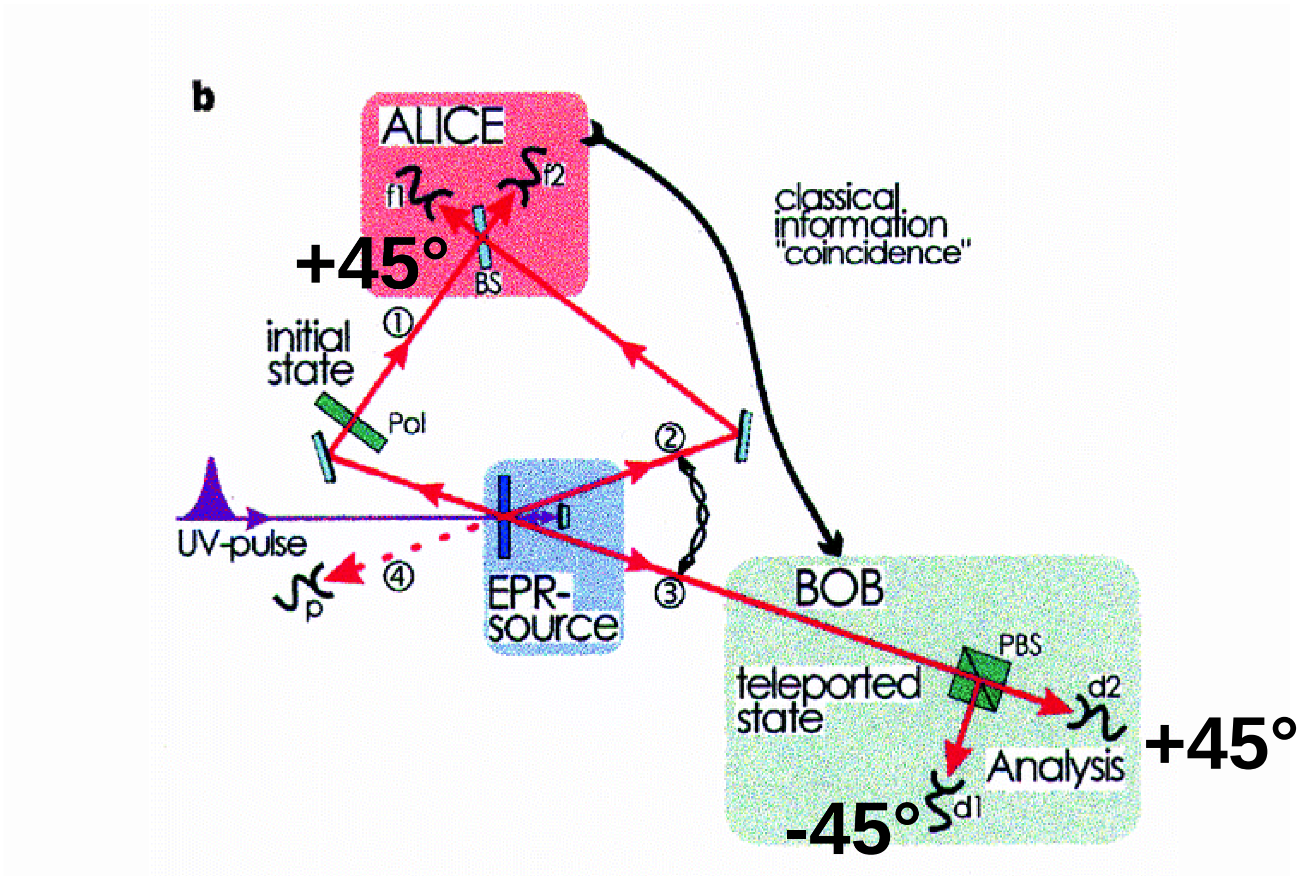


Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Measurement

- Photon 1 is polarized at +45°
- PBS selects +45° and -45° polarization
- In teleportation region at Bob's side only detector d2 should click after

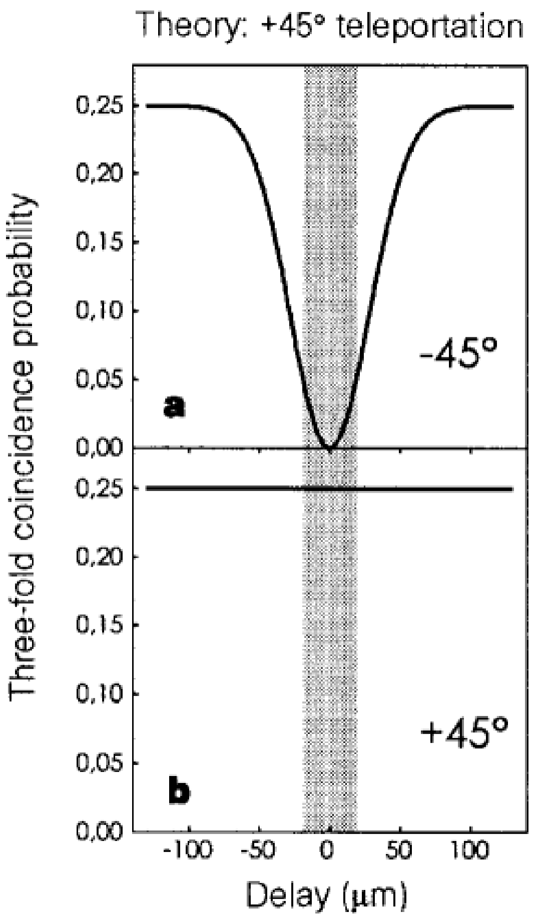
  f1f2 coincidence

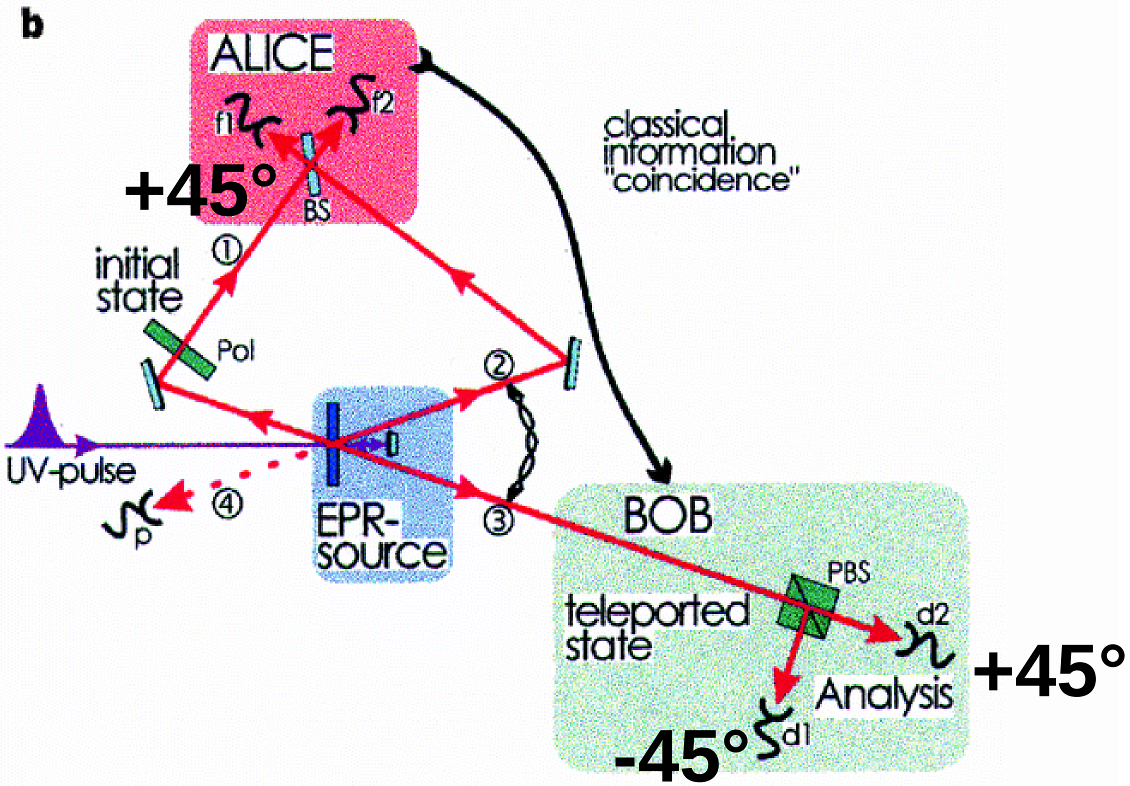


Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Theoretical prediction – threefold coincidence

- In teleportation region at Bob's side only detector d2 should click → threefold coincidence rate between detectors f1,f2,d1 should vanish

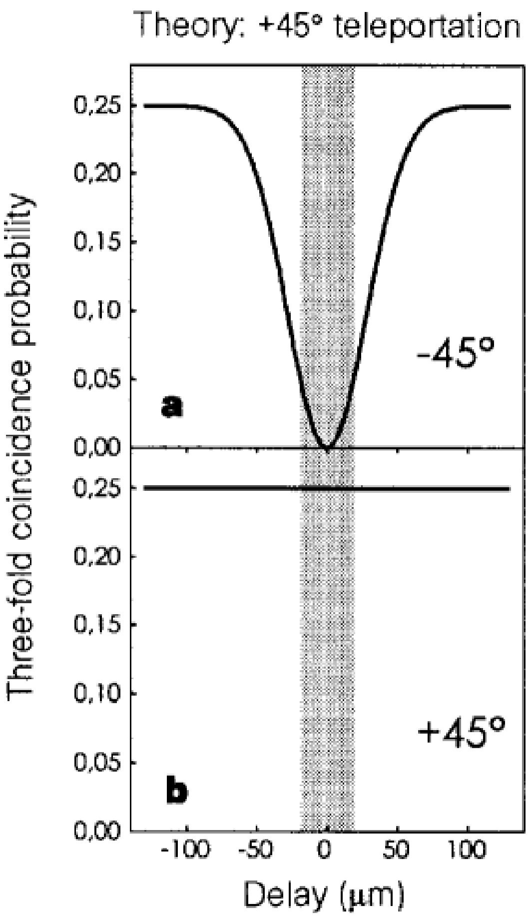


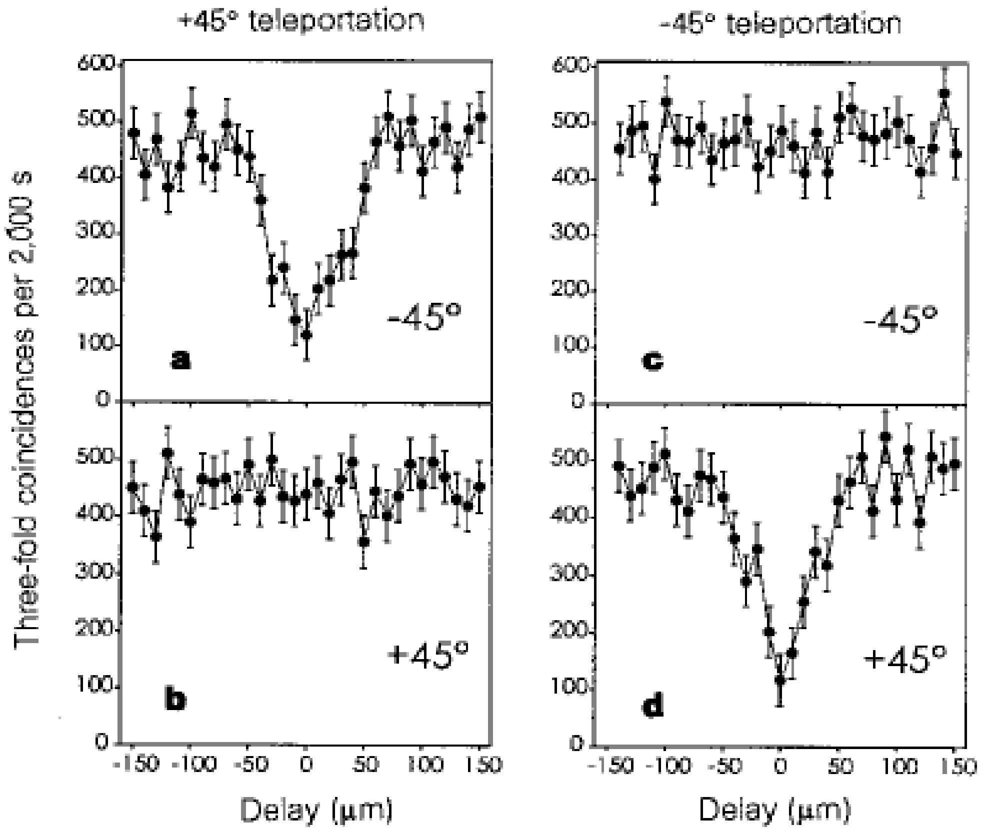


Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Measurement outcome - threefold coincidence

- After subtraction of spurious threefold coincidences → Visibility = 63%
- Visibility = depth of dip/(height of plateau)

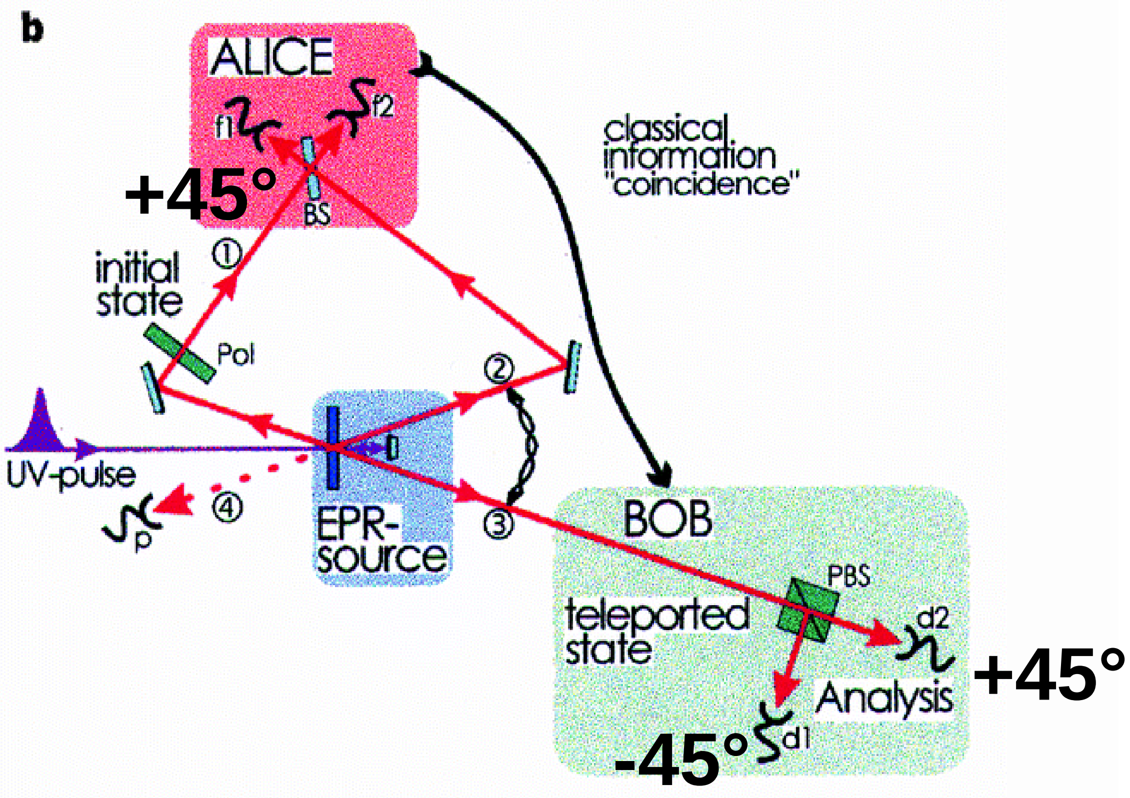




Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Fourfold - coincidence

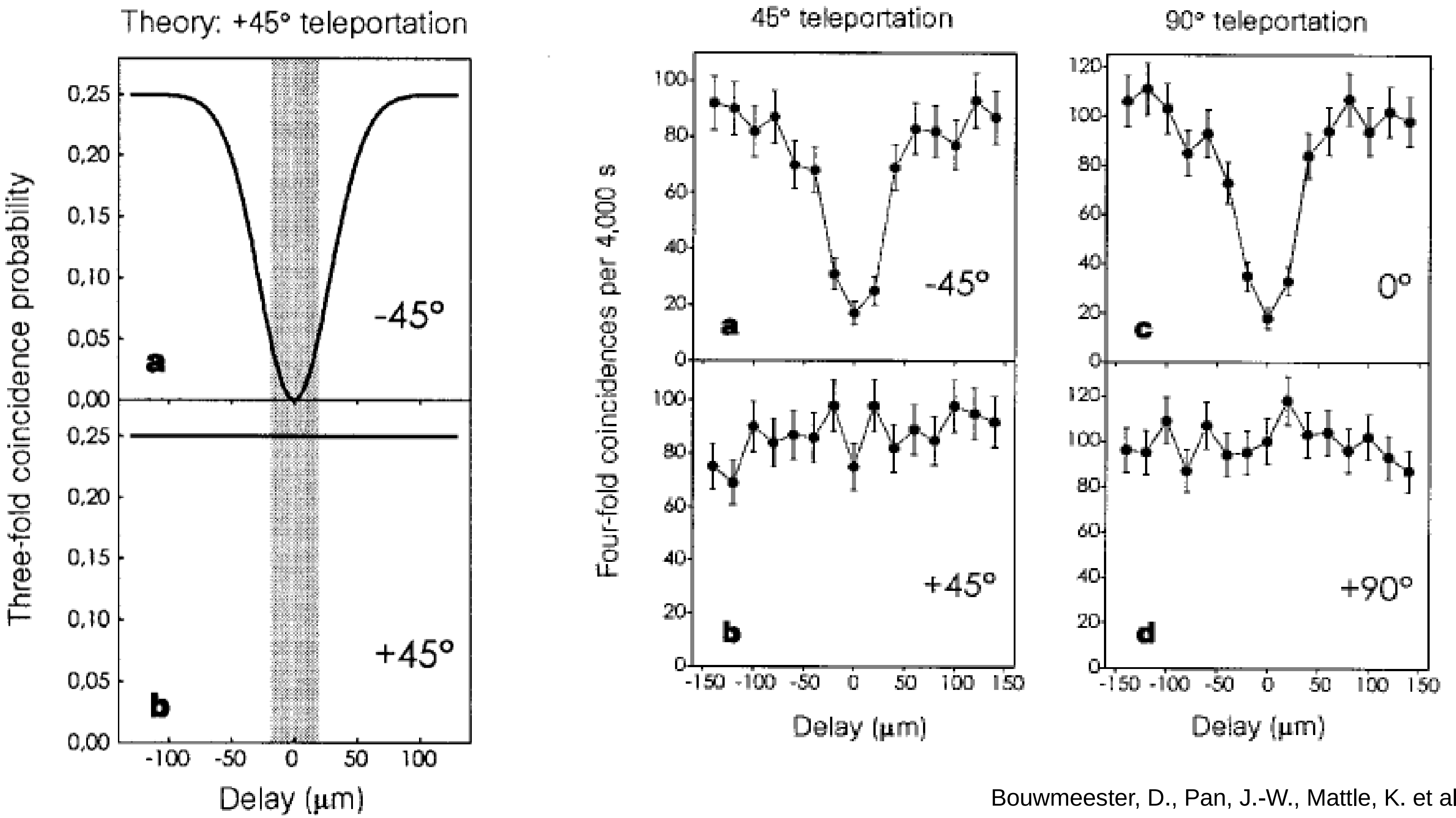
- Emission of two pairs of entagled photons by a single source is equally likely as production of photons 1,2 & 3 → spurious events
- Photon 1 is produced as an entangled state with Photon 4
- Measuring fourfold coincidence between detectors p,f1,f2,d2 leads to less spurious events



Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Measurement outcome - fourfold coincidence

- No additional subtraction of spurious events → Visibility = 70%



Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Summary

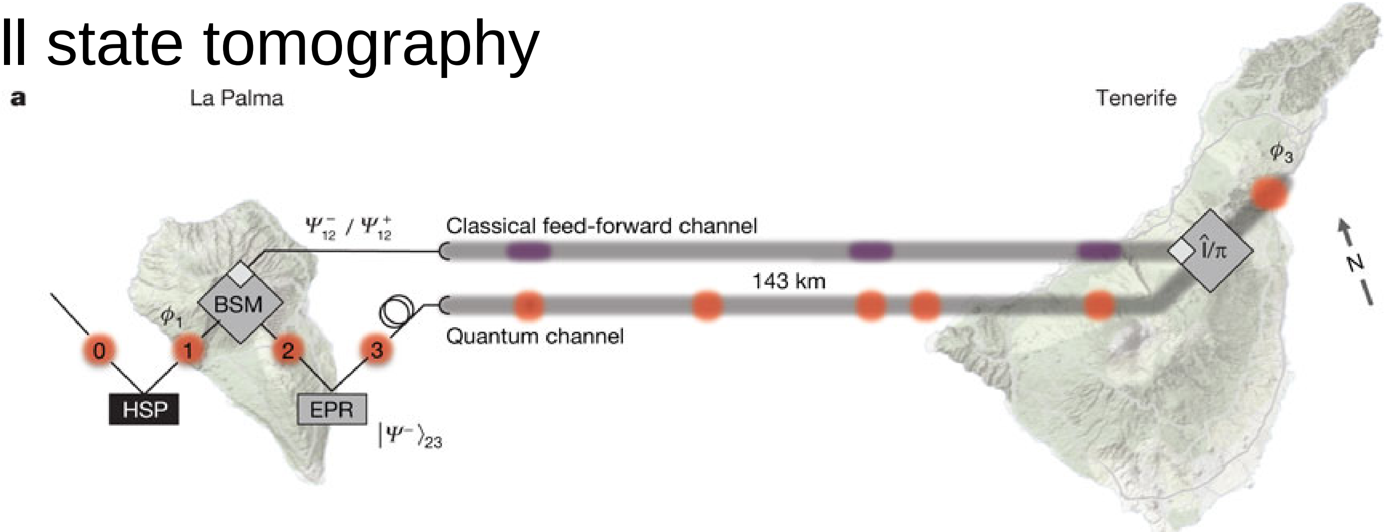
- Demonstration of teleportation protocol for a complete set of basis states (+45° & -45°) and for superposition states (circular polarized)

- Achieved visibilities lie in the range of 57% - 70%

Bouwmeester, D., Pan, J.-W., Mattle, K. et al. 1997

Quantum teleportation over 143 kilometers using active feed forward

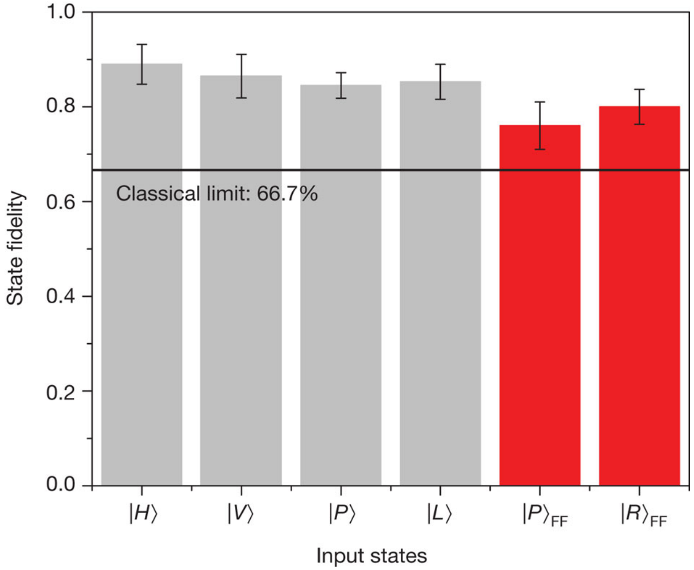
- Free space link
- Two BS can be distinguished
- Active feed-forward of BSM
- Full state tomography



Ma, X.-S., Herbst, T., Scheidl, T. et al. 2012

Results

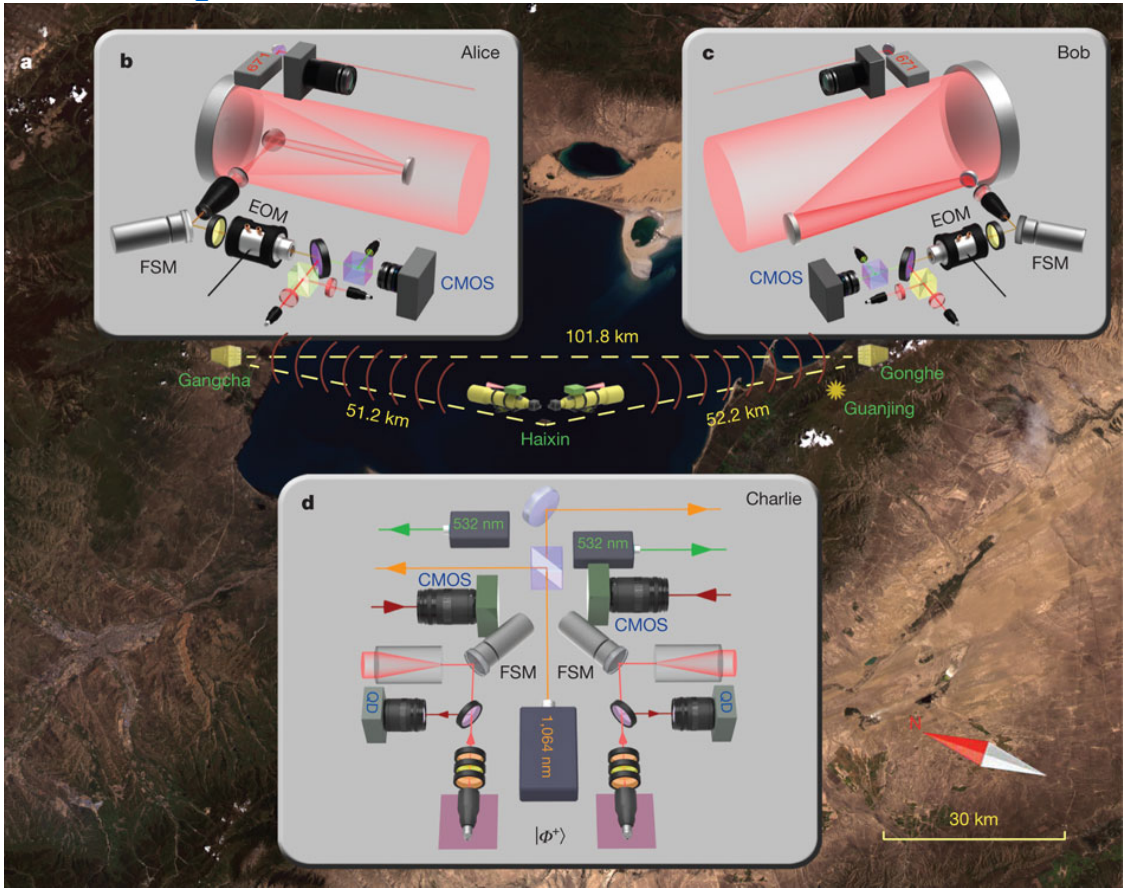
- $|\phi_1\rangle \in \{|H\rangle, |V\rangle, |P\rangle = (|H\rangle + |V\rangle)/\sqrt{2}, |L\rangle = (|H\rangle - i|V\rangle)/\sqrt{2}\}$
- Teleported state measured with average fidelity = 86.3% well above classical limit of 2/3



- Grey – without FF
- Red – with FF

Ma, X.-S., Herbst, T., Scheidl, T. et al. 2012

Two-link entanglement distribution



Juan Yin, Ji-Gang Ren, He Lu et al. 2012

Progress in quantum teleportation

Photons

- 1997 first (probabilistic) teleportation experiment[1]
- 2012 long distance, free space teleportation (>100 km), only 2 BS could be distinguished[2,3]
- 2013 fully deterministic teleportation of photonic qubit[4]

Ions

- 2004 fully deterministic teleportation protocol using pair of trapped Ca atoms[5]

Superconducting qubits

- 2013 deterministic teleportation with high efficiency and high transfer rates using transmon qubits[6]

1. Bouwmeester, D. et al. Nature 390, 575–579 (1997)
2. Juan Yin, Ji-Gang Ren, He Lu et al. 2012
3. Ma, X.-S., Herbst, T., Scheidl, T. et al. 2012
4. Shuntaro Takeda,Takahiro Mizuta, Maria FuwaPeter van Loock , Akira Furusawa Nature 500, 315-318 (2013)
5. Riebe, M. et al. Nature 429, 734–737 (2004)
6. L. Steffen, et al. Nature 500, 319-322 (2013)

Conclusion

- Probabilistic quantum teleportation has been demonstrated using photonic qubits
- Teleportation using photons also works over great distances and could be used today if one is willing to accept low efficiencies due to probabilistic nature of experiment and high losses (e.g. for quantum cryptography)
- Fully deterministic quantum teleportation has been achieved (recently) for different systems as photons, ions, and superconducting qubits

Outlook

- Fully deterministic teleportation of photonic qubits over large distances
- Using photons to transmit quantum states between spatially seperated quantum systems

Questions?