# Building the Quantum Internet

AP Seminar
"Qubits in the News"
October 24, 2018

In the news…

- (*Nature*, Oct 23, 2018) **Here's what the quantum internet has in store** — Physicists say this futuristic, super-secure network could be useful long before it reaches technological maturity.

- (*Nature*, Oct 23, 2018) **Teleportation over a 6-kilometre cable, courtesy of quantum powers** — 'Continuous-variable' quantum teleportation is accomplished outside the lab with fibre-optic gear.

- (*Science Advances,19 Oct 2018: Vol. 4, no. 10, DOI: 10.1126/sciadv.aas9401*) **Deterministic quantum teleportation through fiber channels** — The deterministic teleportation of optical modes over a fiber channel of 6.0 km is realized.

Simple Example: photon polarization
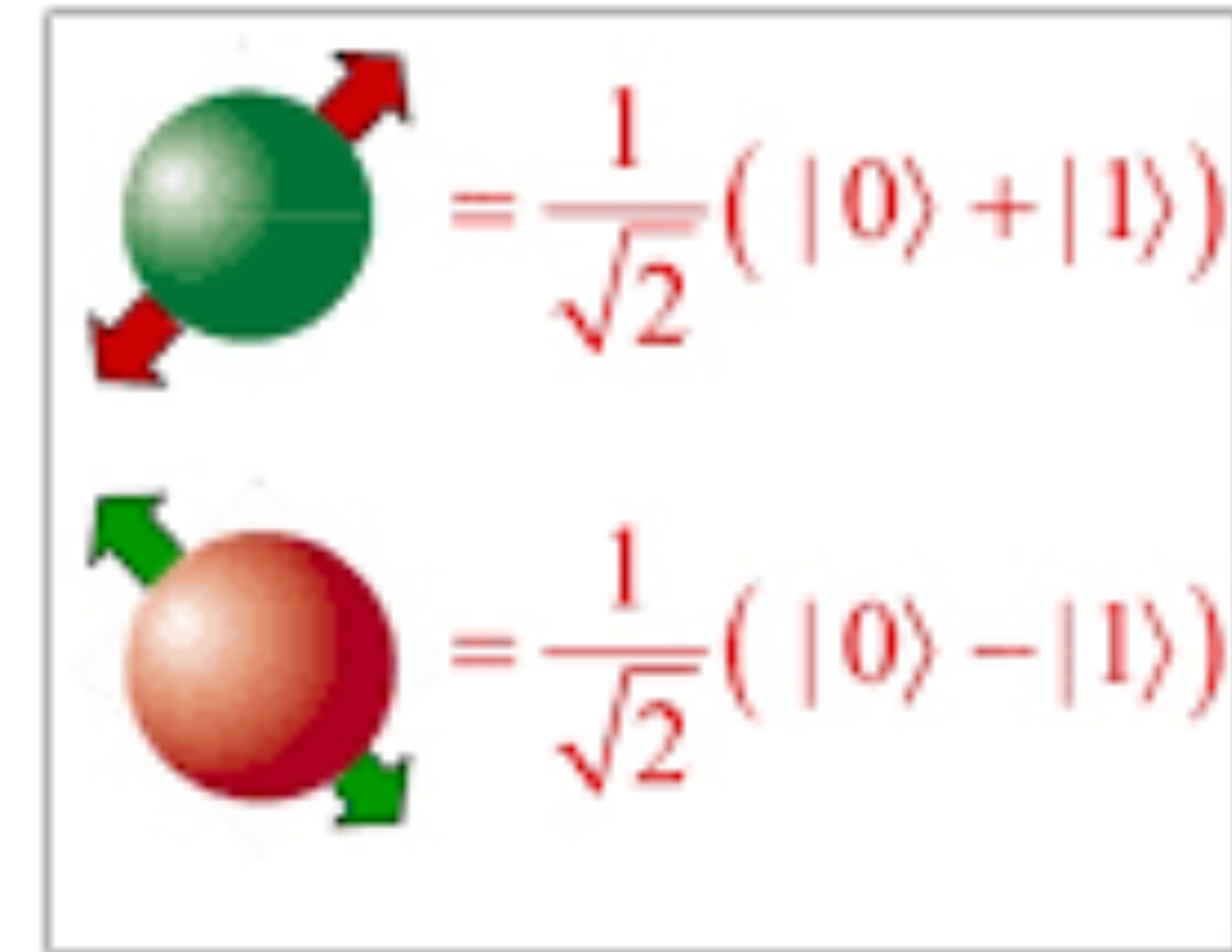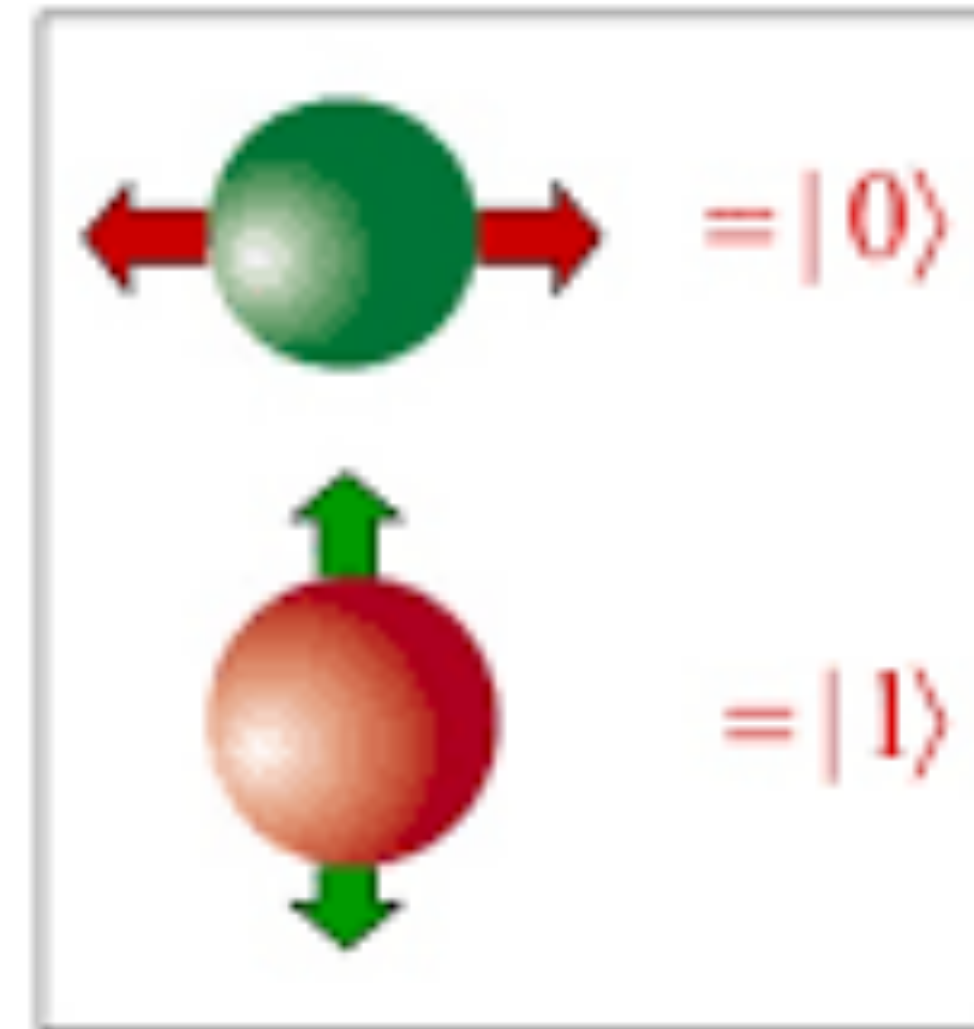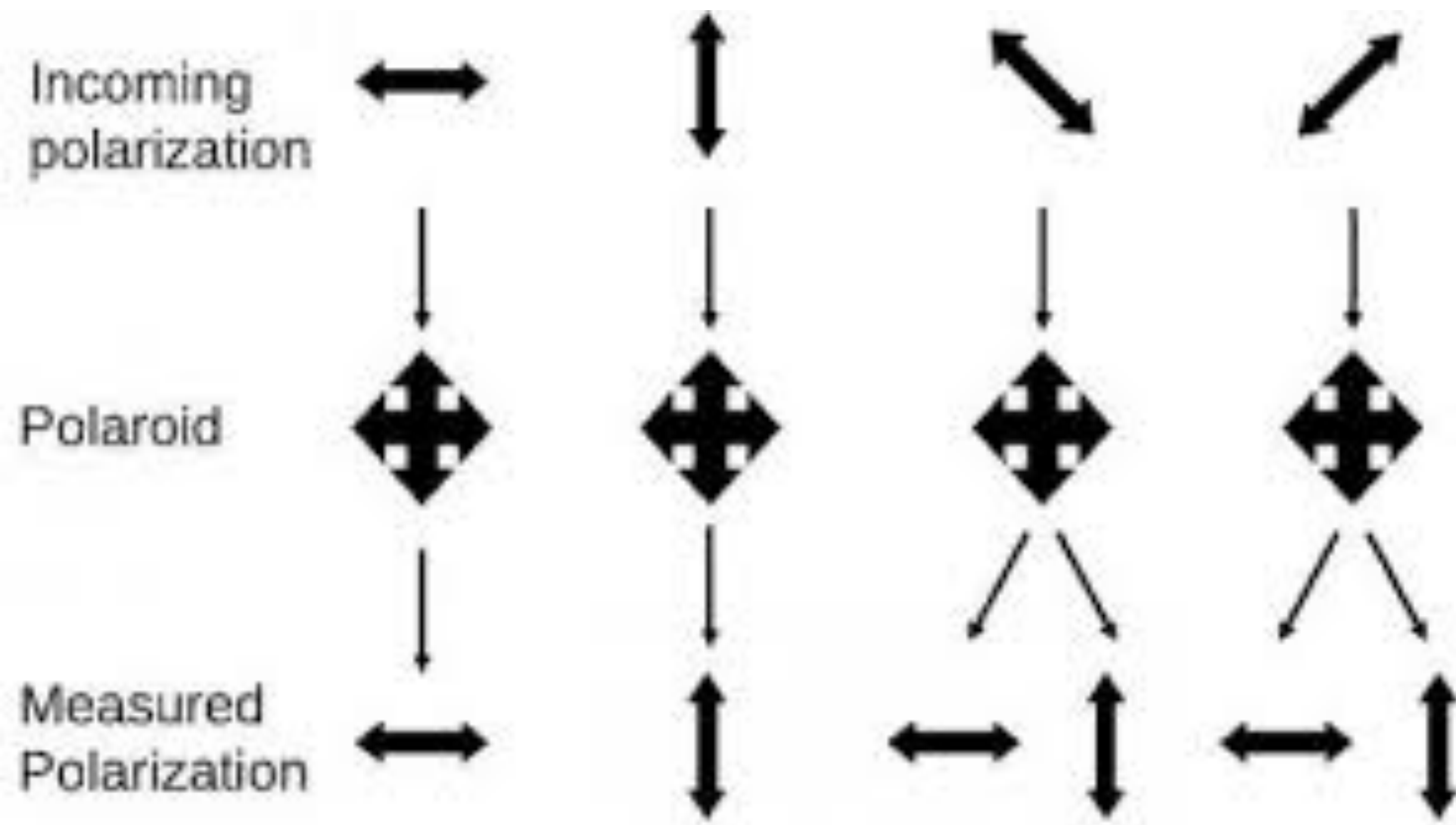
Simple Example: two photons

$$|\psi_1\rangle = a_h\,|H_1\rangle + a_v\,|V_1\rangle$$

$$|\psi_2\rangle = b_h\,|H_2\rangle + b_v\,|V_2\rangle$$

$$|\psi_1\psi_2\rangle = a_{hh}\,|H_1H_2\rangle + a_{hv}\,|H_1V_2\rangle + a_{vh}\,|V_1H_2\rangle + a_{vv}\,|V_1V_2\rangle$$

Example: two *not* tangled photons

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\,|H_1\rangle + \frac{1}{\sqrt{2}}\,|V_1\rangle$$

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}\,|H_2\rangle - \frac{1}{\sqrt{2}}\,|V_2\rangle$$

$$|\psi_1\psi_2\rangle = \frac{1}{2}\,|H_1 H_2\rangle - \frac{1}{2}\,|H_1 V_2\rangle + \frac{1}{2}\,|V_1 H_2\rangle - \frac{1}{2}\,|V_1 V_2\rangle$$

$$|\psi_1\psi_2\rangle = \left(\frac{1}{\sqrt{2}}\,|H_1\rangle + \frac{1}{\sqrt{2}}\,|V_1\rangle\right) \otimes \left(\frac{1}{\sqrt{2}}\,|H_2\rangle - \frac{1}{\sqrt{2}}\,|V_2\rangle\right)$$
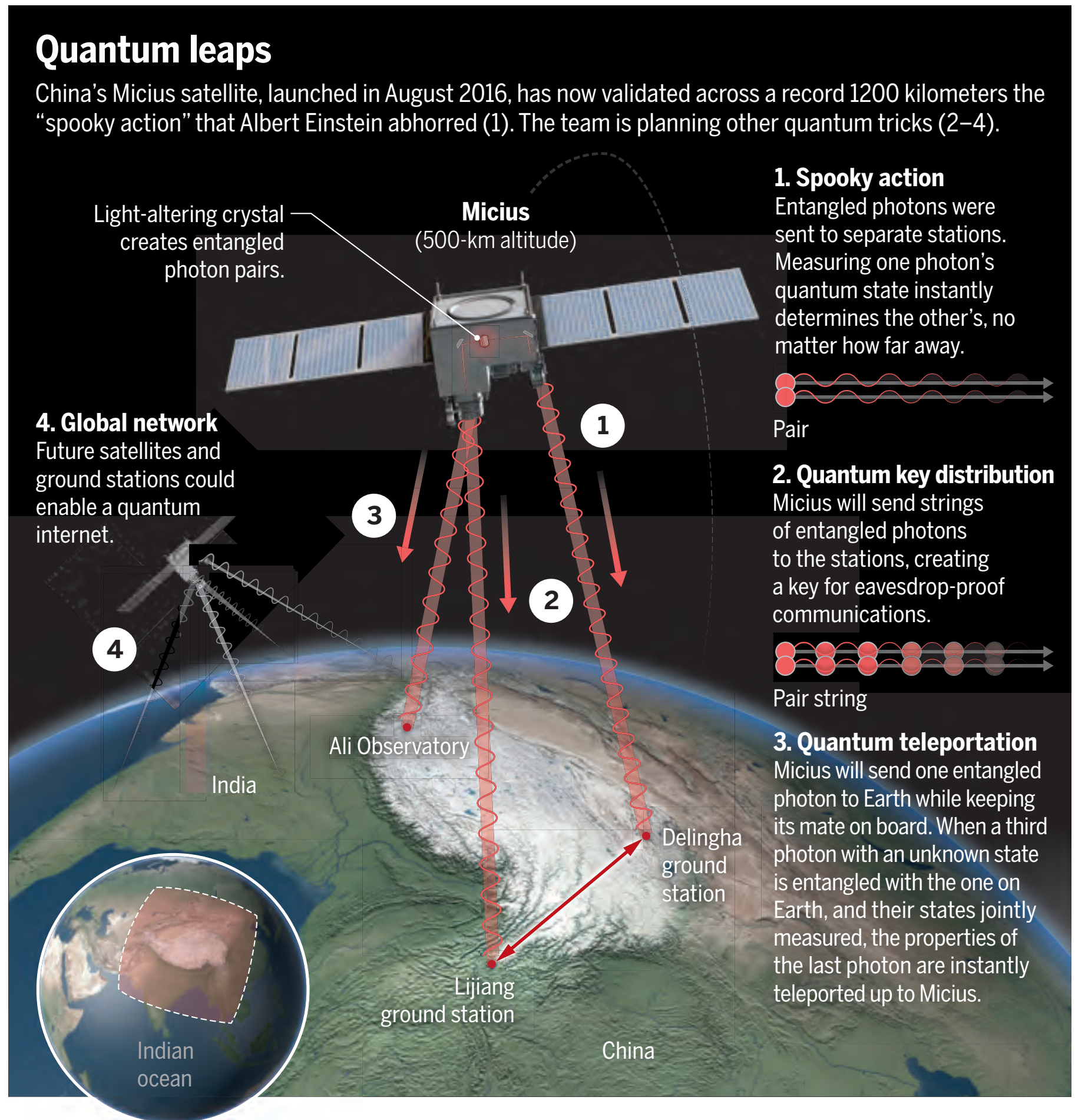
Example: two ***entangled*** photons

$$|\psi_1\psi_2\rangle = \frac{1}{\sqrt{2}}|H_1 H_2\rangle + \frac{1}{\sqrt{2}}|V_1 V_2\rangle$$

$$|\psi_1\psi_2\rangle = \frac{1}{\sqrt{2}}|H_1 H_2\rangle - \frac{1}{\sqrt{2}}|V_1 V_2\rangle$$

$$|\psi_1\psi_2\rangle = \frac{1}{\sqrt{2}}|H_1 V_2\rangle + \frac{1}{\sqrt{2}}|V_1 H_2\rangle$$

$$|\psi_1\psi_2\rangle = \frac{1}{\sqrt{2}}|H_1 V_2\rangle - \frac{1}{\sqrt{2}}|V_1 H_2\rangle$$
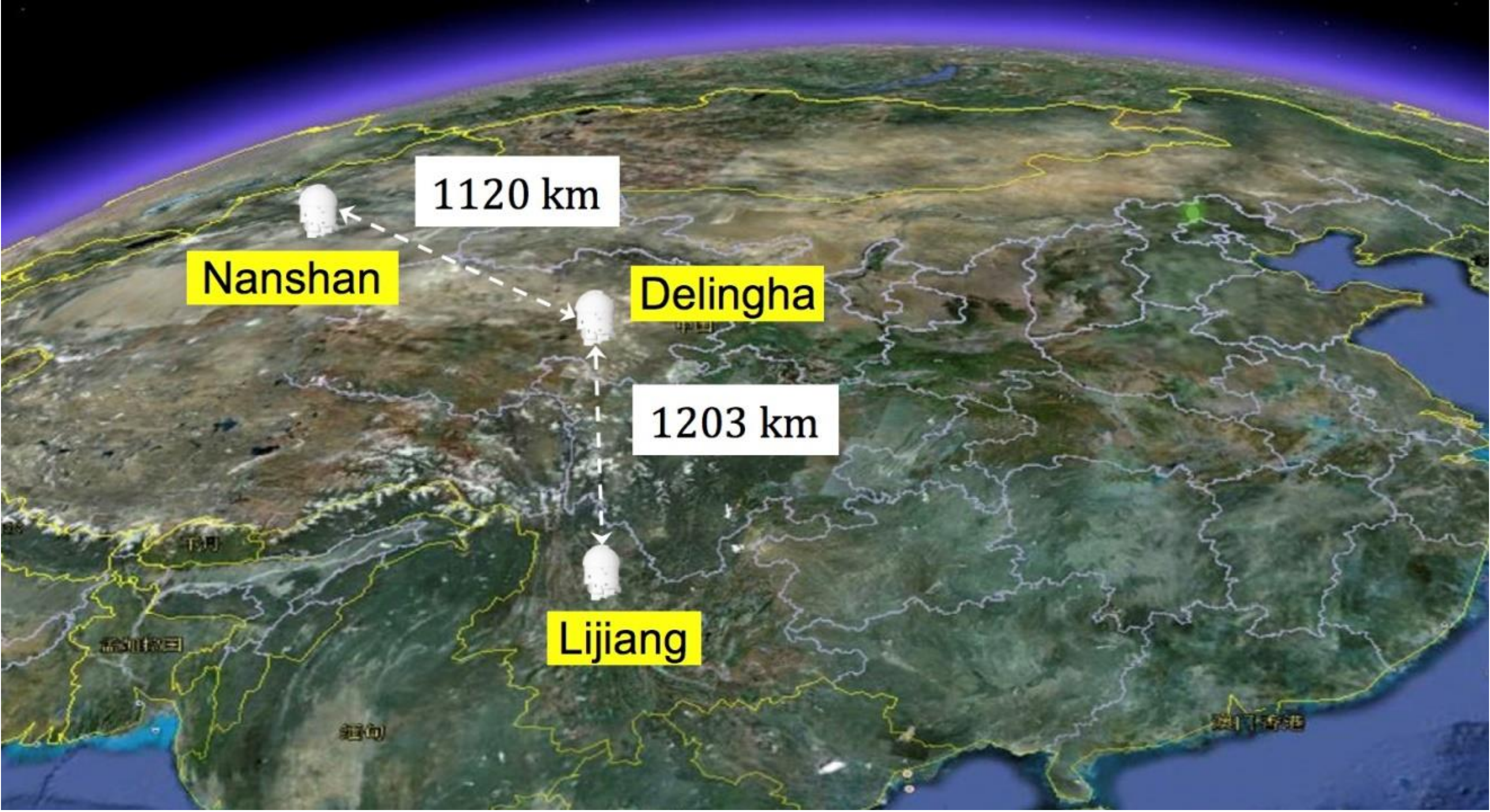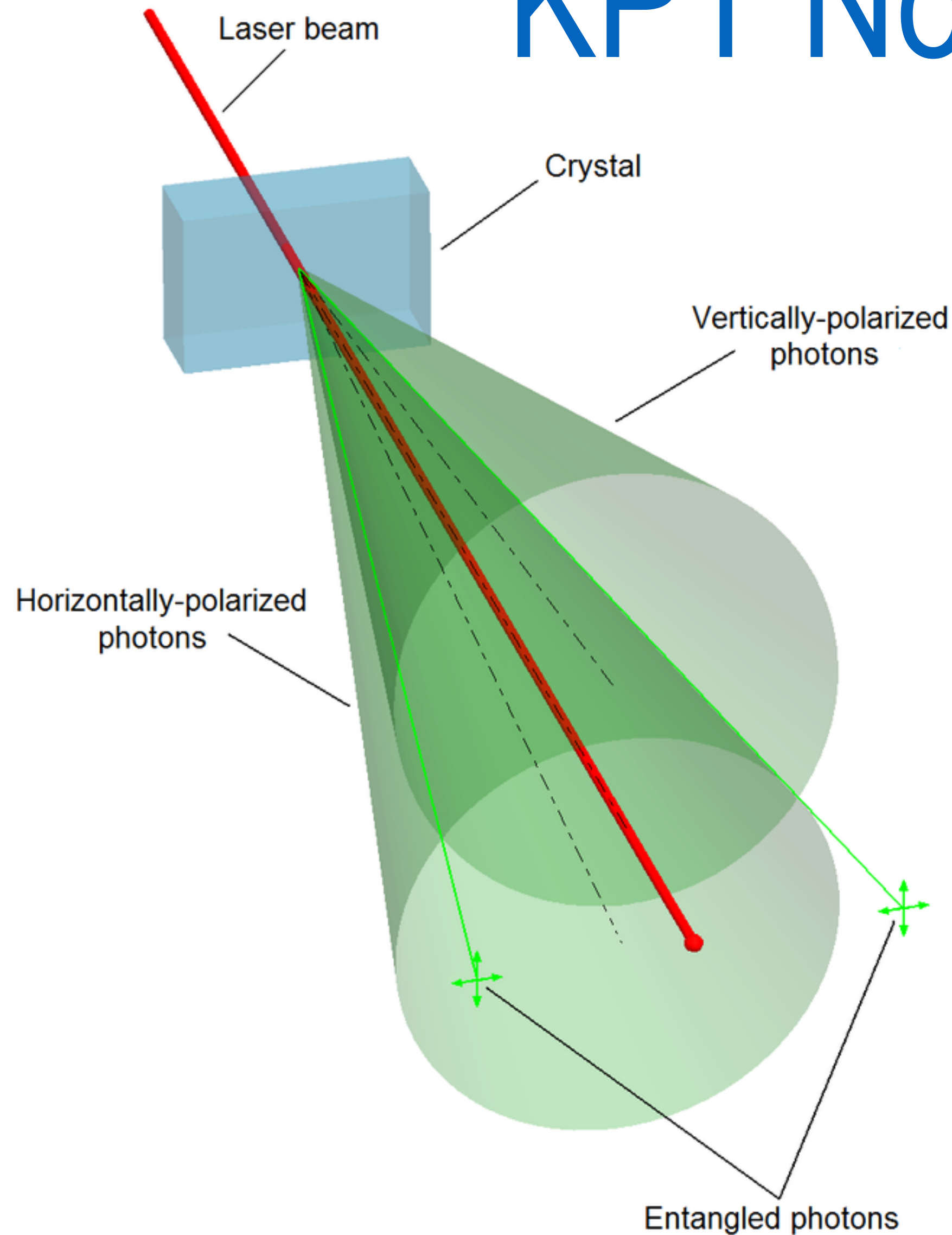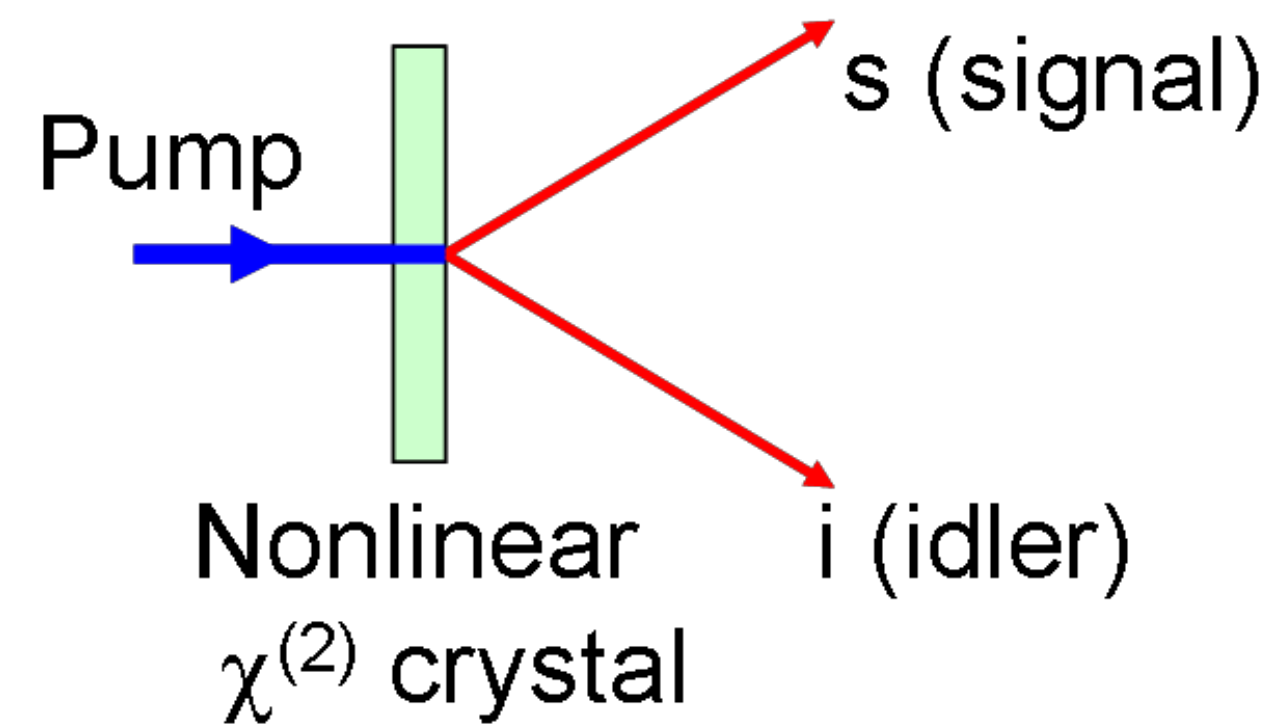
Maximally entangled "Bell States"

Fig. S5

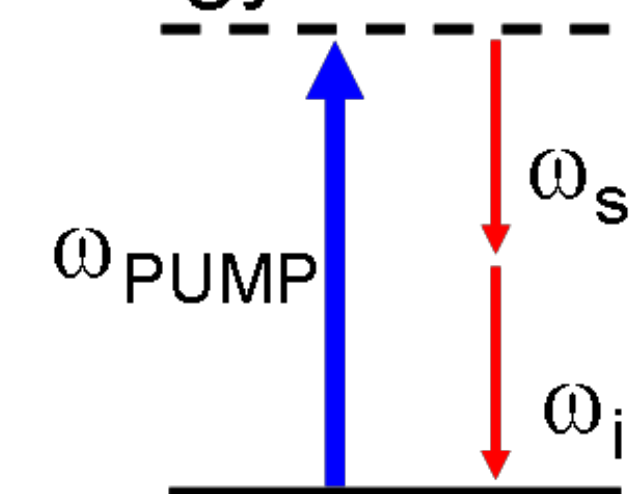Geographic map of the ground stations.

KPT Nonlinear Optical Crystal

Laser beam

Crystal

Vertically-polarized photons

Horizontally-polarized photons

Entangled photons

Spontaneous Parametric Downconversion

Pump

Nonlinear $\chi^{(2)}$ crystal

s (signal)

i (idler)

Momentum Conservation

k_s k_i

k_{PUMP}
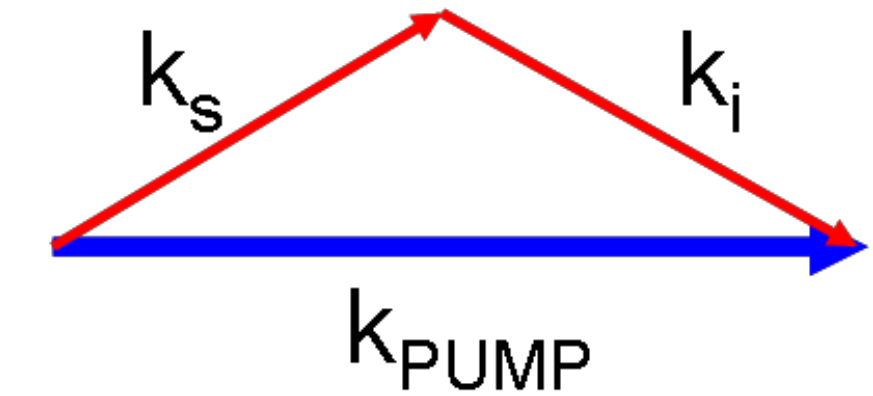
Energy conservation

ω_{PUMP} ω_s

ω_i

$\varphi_{PUMP} = \varphi_s + \varphi_i$

POTASSIUM TITANYL PHOSPHATE – KTP CRYSTALS

KTP (KTiOPO4) is a nonlinear optical crystal, which possesses excellent nonlinear, electrooptical and acoustooptical properties.
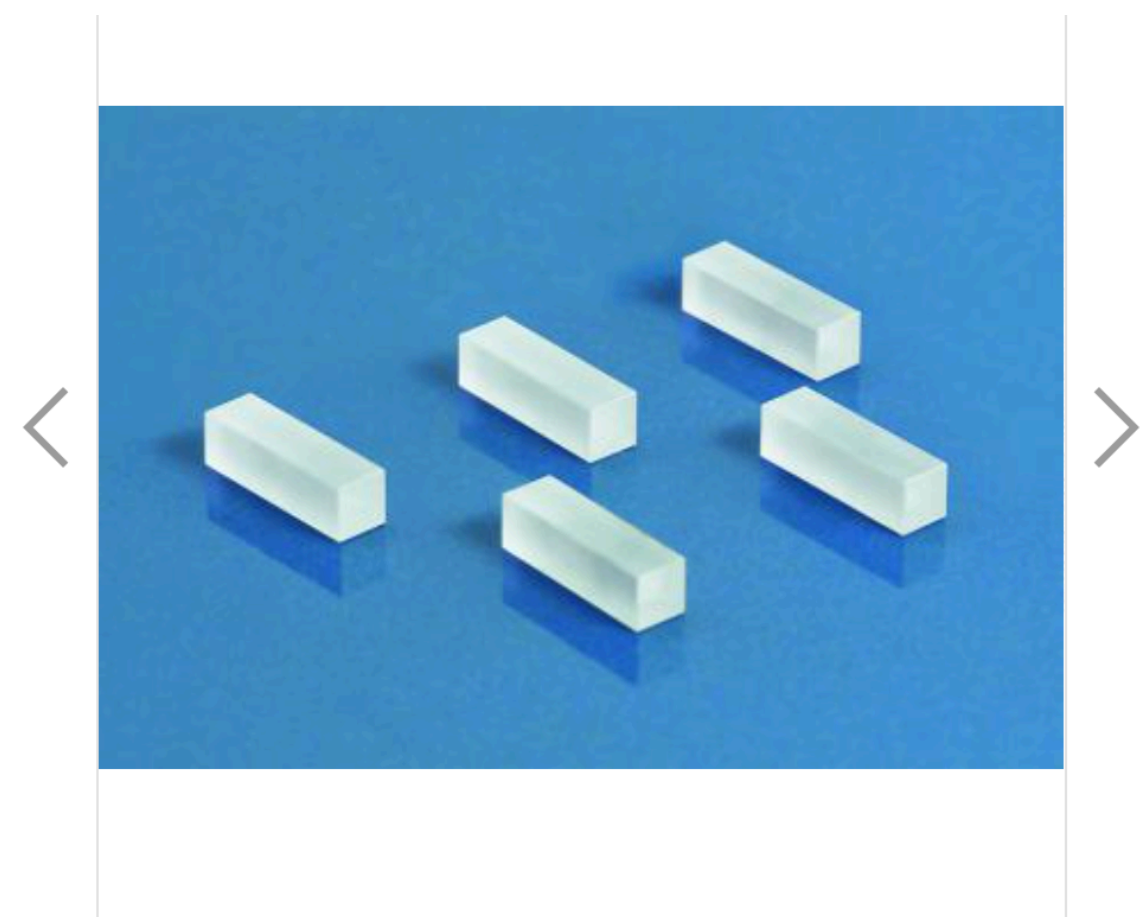
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Deterministic quantum teleportation through fiber channels

Meiru Huo[1], Jiliang Qin[1], Jialin Cheng[1], Zhihui Yan[1,2], Zhongzhong Qin[1,2], Xiaolong Su[1,2], Xiaojun Jia[1,2]*, Changde Xie[1,2], Kunchi Peng[1,2]

Quantum teleportation, which is the transfer of an unknown quantum state from one station to another over a certain distance with the help of nonlocal entanglement shared by a sender and a receiver, has been widely used as a fundamental element in quantum communication and quantum computation. Optical fibers are crucial information channels, but teleportation of continuous variable optical modes through fibers has not been realized so far. Here, we experimentally demonstrate deterministic quantum teleportation of an optical coherent state through fiber channels. Two sub-modes of an Einstein-Podolsky-Rosen entangled state are distributed to a sender and a receiver through a 3.0-km fiber, which acts as a quantum resource. The deterministic teleportation of optical modes over a fiber channel of 6.0 km is realized. A fidelity of 0.62 ± 0.03 is achieved for the retrieved quantum state, which breaks through the classical limit of $1/_2$. Our work provides a feasible scheme to implement deterministic quantum teleportation in communication networks.

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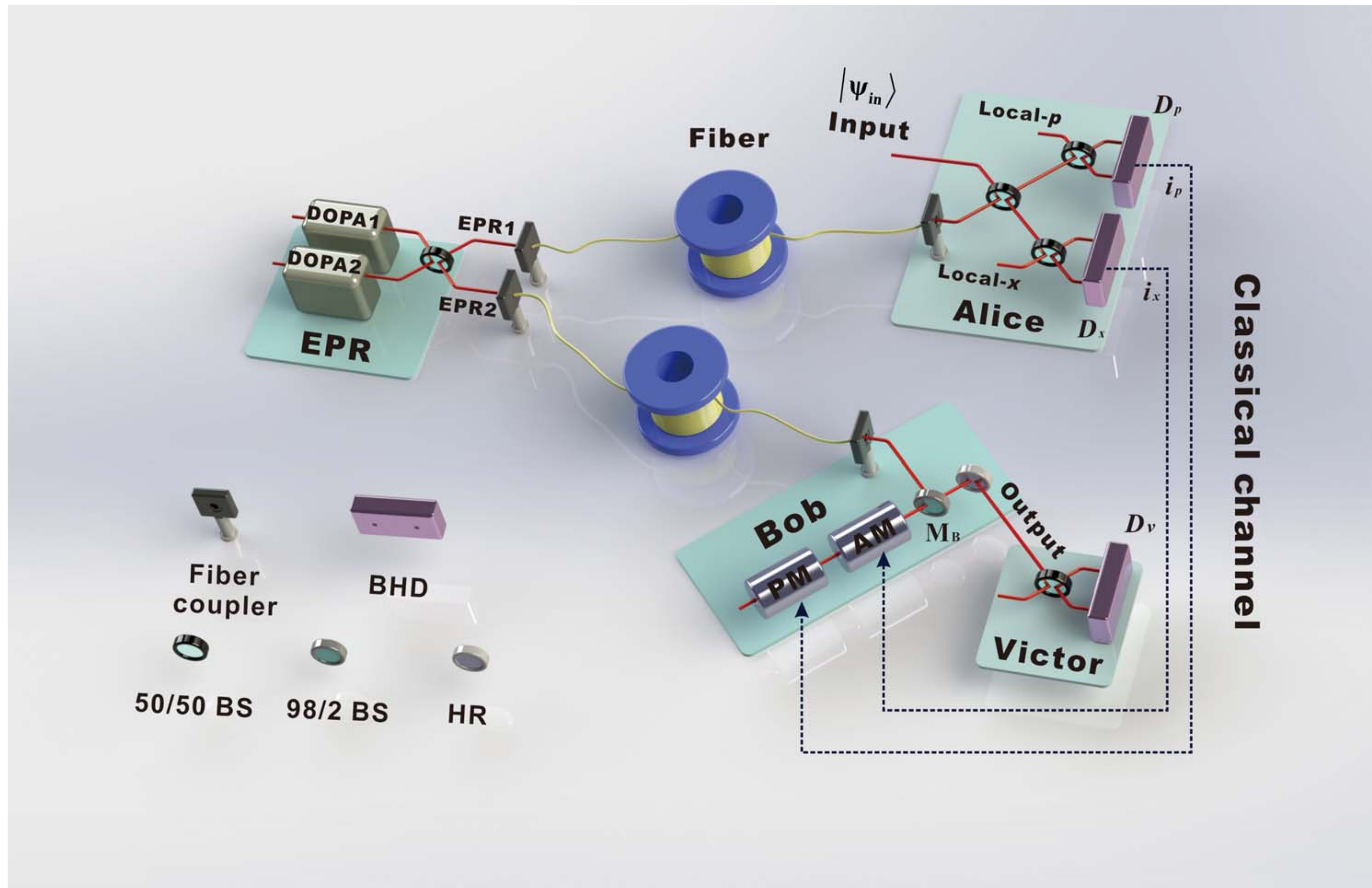*Corresponding author. Email: jiaxj@sxu.edu.cn

Fig. 1. Experimental scheme of fiber-channel CV quantum teleportation. Two single-mode squeezed states generated by a pair of degenerate optical parametric amplifiers (DOPAs) are coupled to produce an EPR entangled state. The two sub-modes of the EPR entangled state are sent to Alice and Bob through two optical fiber channels, respectively. Then, Alice implements a joint measurement on the unknown input state and the sub-mode EPR1 and sends the measured results to Bob through classical channels. Bob implements a translation for EPR2 by coupling a coherent beam, which is modulated by two joint-measured classical signals, respectively, via an AM and a PM. Last, Victor accomplishes the verification for quantum teleportation. 98/2 BS, beam splitter with reflectivity of 98%; HR, mirror with a reflectivity larger than 99.9%; fiber coupler, used to couple optical modes into the fiber; BHD, balance homodyne detector.
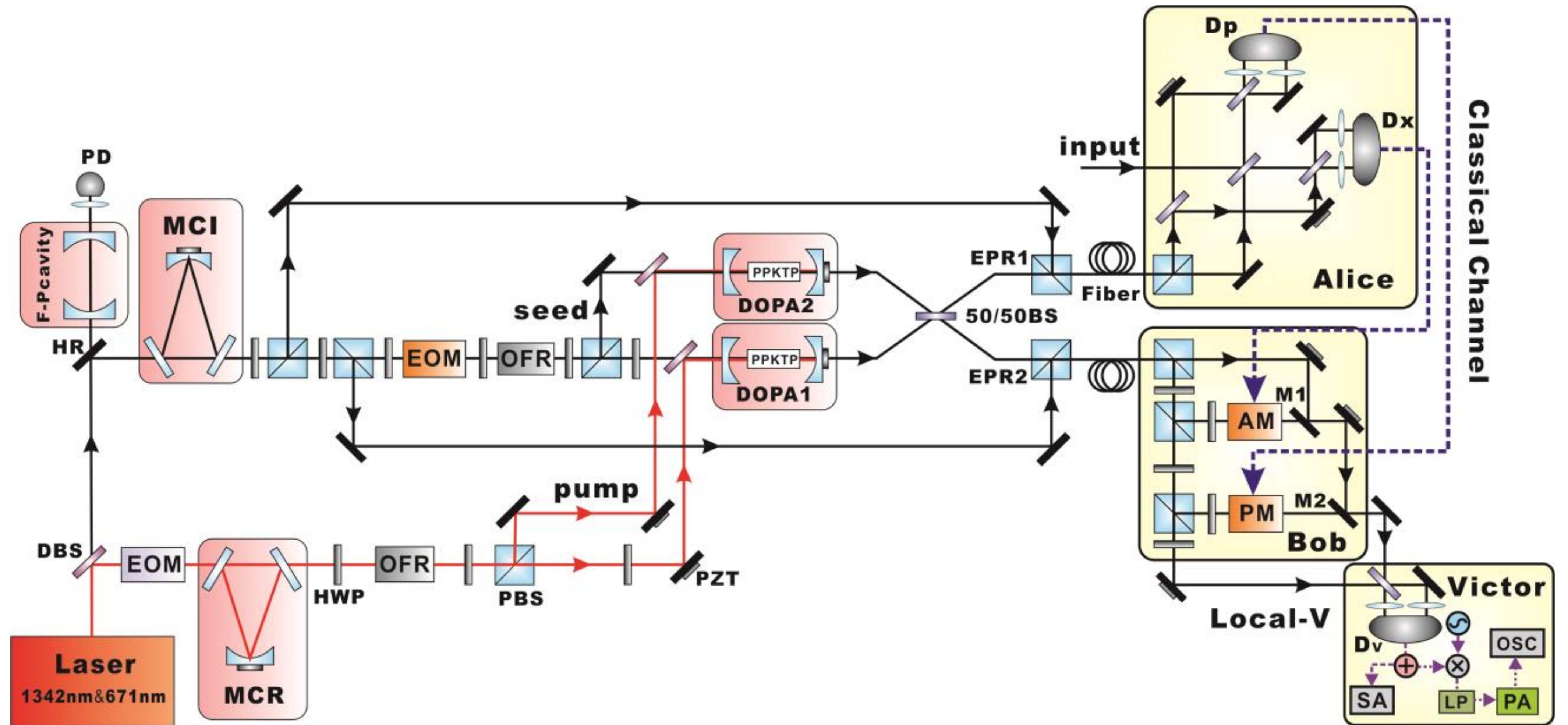
Fig. S1. Experimental setup for fiber-channel CV quantum teleportation. Laser: Nd:YVO4/LBO; DBS: dichroic beam splitter; HR: mirror with reflectivity higher than 99.9%; EOM: electro-optical modulator; MCR (MCI): mode-cleaner for red mode (infrared mode); OFR: optical Faraday rotator; HWP: half-wave plate; PBS: polarization beam splitter; DOPA: degenerate optical parametric amplifier; M1,2: mirror with reflectivity of 98% at 1342nm; 50/50 BS: 50/50 beam splitter; PD: photoelectric detector; PZT: piezoelectric ceramic; D_x, D_p, D_V: homodyne detector; SA: spectrum analyzer; LP: low-pass filter; PA: low-noise preamplifier; OSC: oscilloscope.
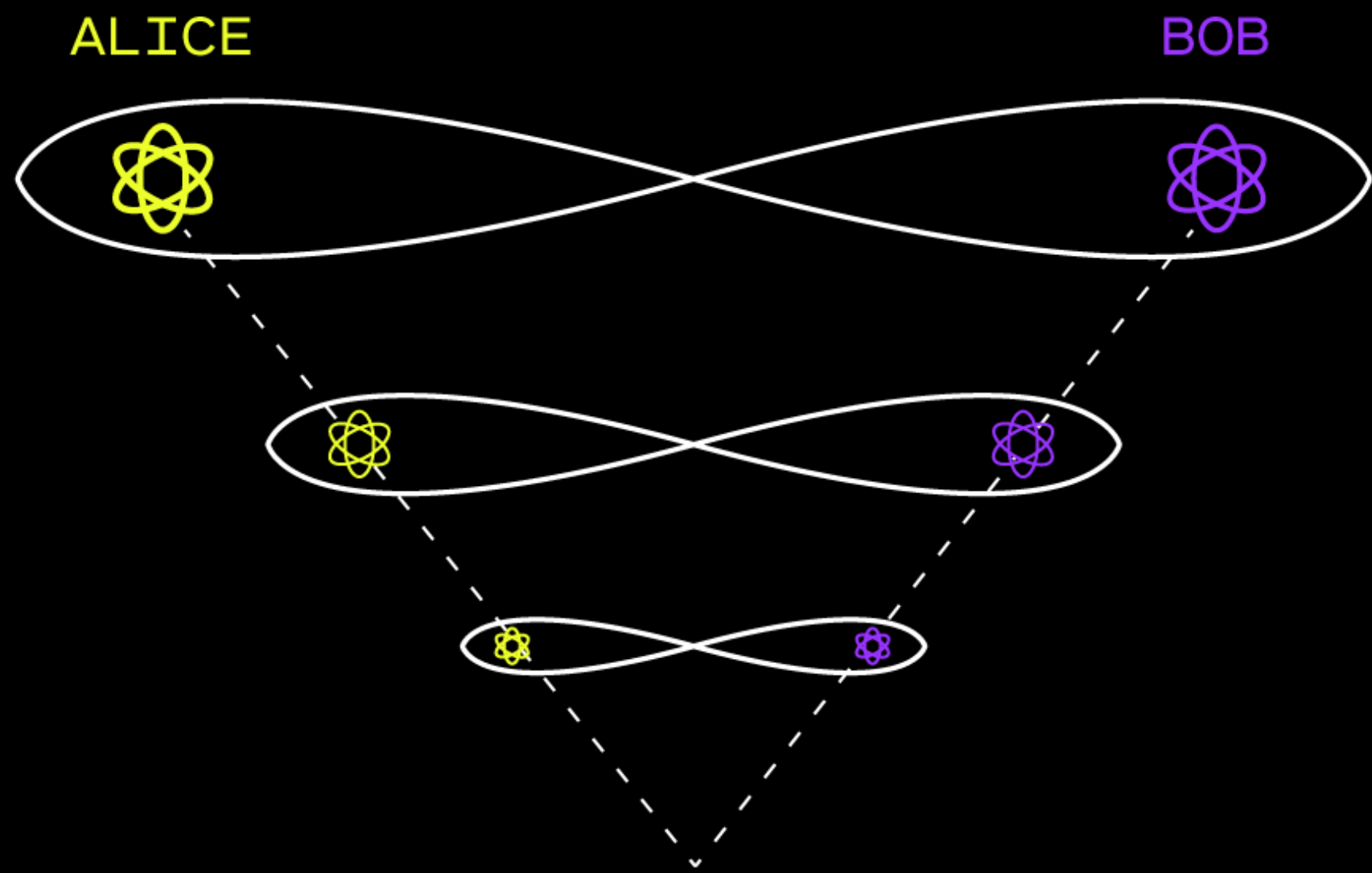
How quantum teleportation works

ALICE

BOB

Alice and Bob receive pairs of entangled qubits in the form of photons.
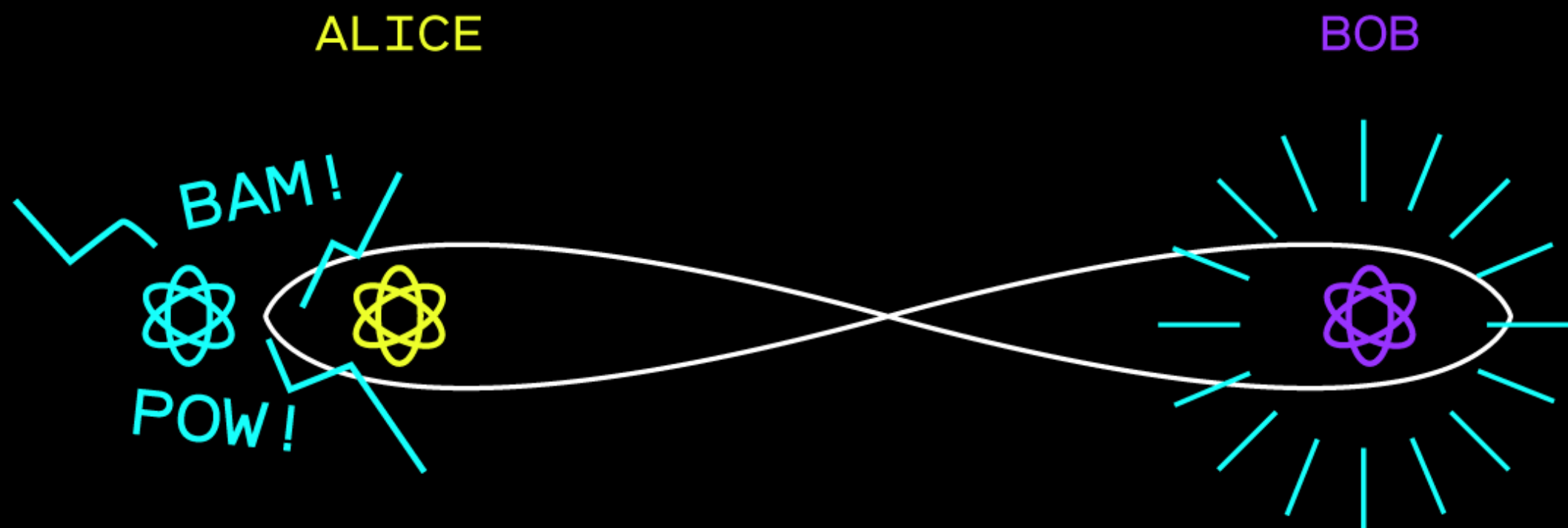
ALICE

BOB

BAM!

POW!

Figure 2.
The photon received by Alice interacts with a qubit of hers that contains quantum data. She measures the state of the entangled photon and this qubit at the same time. This measurement changes the state of Bob's entangled photon.
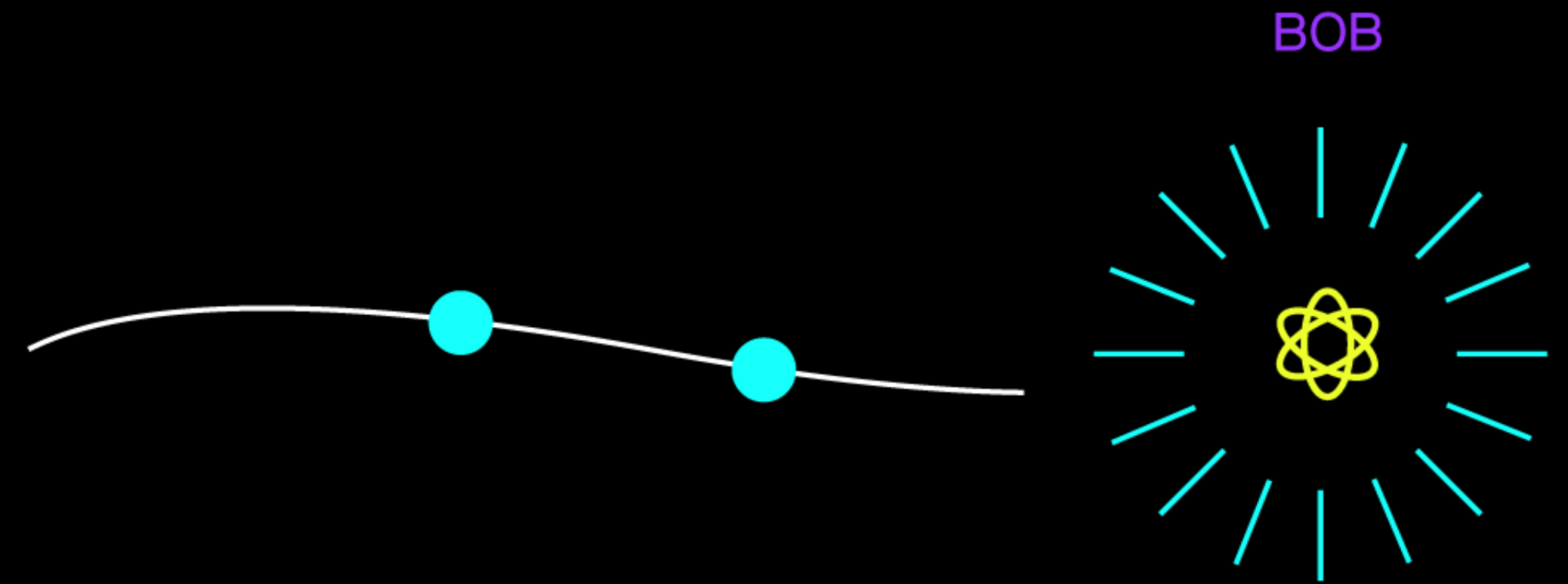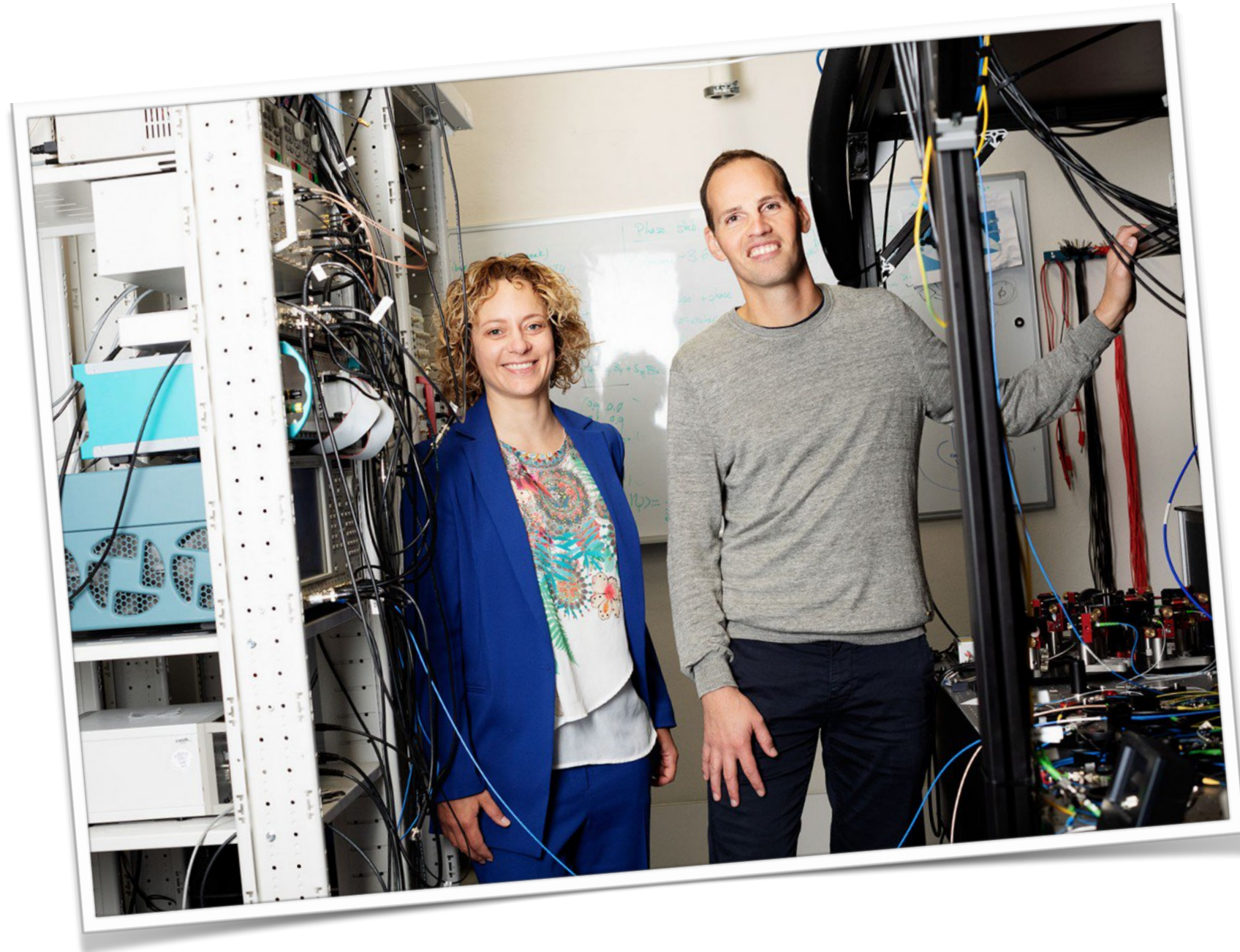
BOB

Figure 3.
However, Bob can't tell what's happened to his photon until he receives the result of the measurement. Alice sends this to him in the form of classical bits via fiber-optic cables or other means. With this information, Bob can now work out how his photon has changed and the quantum data that's been teleported to it.

QuTech researchers put forward a roadmap for quantum internet development

A quantum internet may very well be the first quantum information technology to become reality. Researchers at QuTech in Delft, The Netherlands, today published a comprehensive guide towards this goal in Science. It describes six phases, starting with simple networks of qubits that could already enable secure quantum communications – a phase that could be reality in the near future. The development ends with networks of fully quantum-connected quantum computers. In each phase, new applications become available such as extremely accurate clock synchronization or integrating different telescopes on Earth in one virtual 'supertelescope'. This work creates a common language that unites the highly interdisciplinary field of quantum networking towards achieving the dream of a world-wide quantum internet.

SIX STEPS TO A QUANTUM INTERNET

Researchers have laid out six stages of sophistication that a future quantum internet could reach, and what users could do at each level.

0 Trusted-node network: Users can receive quantum-generated codes but cannot send or receive quantum states. Any two end users can share an encryption key (but the service provider will know it, too).

1 Prepare and measure: End users receive and measure quantum states (but the quantum phenomenon of entanglement is not necessarily involved). Two end users can share a private key only they know. Also, users can have their password verified without revealing it.

2 Entanglement distribution networks: Any two end users can obtain entangled states (but not to store them). These provide the strongest quantum encryption possible.

3 Quantum memory networks: Any two end users to obtain and store entangled qubits (the quantum unit of information), and can teleport quantum information to each other. The networks enable cloud quantum computing.

4 & 5 Quantum computing networks: The devices on the network are full-fledged quantum computers (able to do error correction on data transfers). These stages would enable various degrees of distributed quantum computing and quantum sensors, with applications to science experiments.