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TOMORROW TODAY

ENTANGLEMENT FROM A TO Z

The Nobel Prize in Physics in 2022 (Aspect, Clauser and Zeilinger)

Quantum Day 4 Students

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THE NOBEL PRIZE IN PHYSICS

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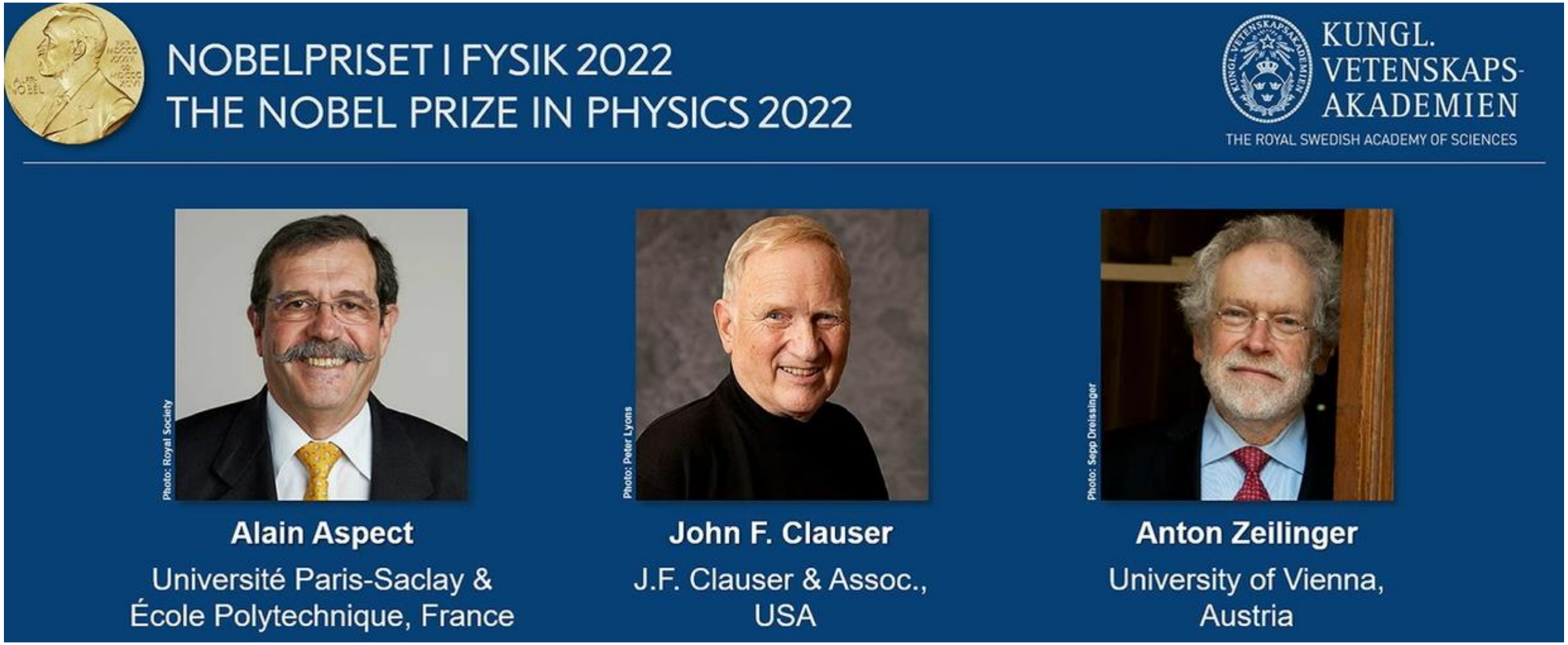

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

WHAT IS ENTANGLEMENT

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Extension of superposition to many-particle system

Single quantum state (two level system): $|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle$ $|0\rangle$ and $|1\rangle$ are the basis vectors

Two party quantum state: $|\psi\rangle_{12} = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$

Two possibilities

$|\psi\rangle_{12} = |\psi\rangle_1 \otimes |\psi\rangle_2$

Seperable state

$|\psi\rangle_{12} \neq |\psi\rangle_1 \otimes |\psi\rangle_2$

Entangled state

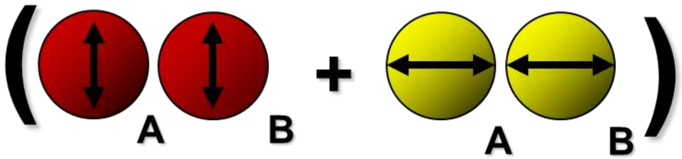
Example of entangled state: $|\psi\rangle_{12} = \alpha|00\rangle + \delta|11\rangle$

ENTANGLEMENT, AN EXAMPLE

Consider polarization of light

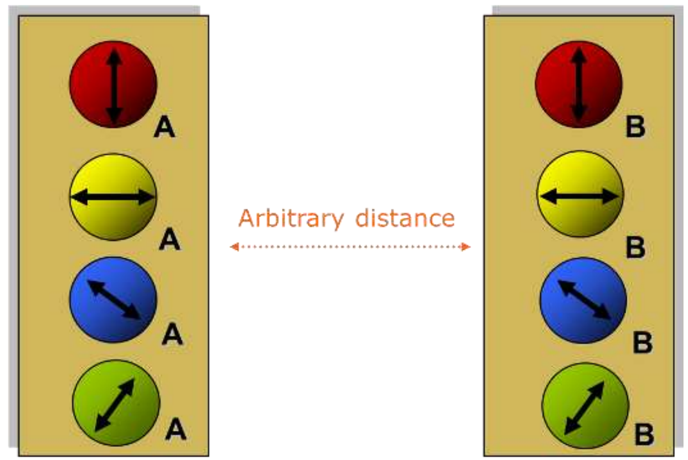
Basis vectors are now horizontal and vertical polarization: $|V\rangle$ and $|H\rangle$

Entangled state: $|\psi\rangle_{AB} = |VV\rangle + |HH\rangle$



Measurement at A

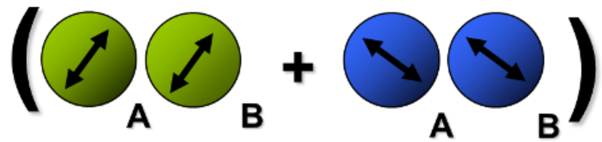
Measurement at B



Change of basis:

Basis vectors are now: $|+45\rangle$ and $|-45\rangle$

$$|\psi\rangle_{AB} = |+\,+\rangle + |-\,-\rangle$$



EPR PARADOX

1935: Einstein , Podolsky and Rosen criticised Quantum mechanics.
Claim: QM is not complete

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

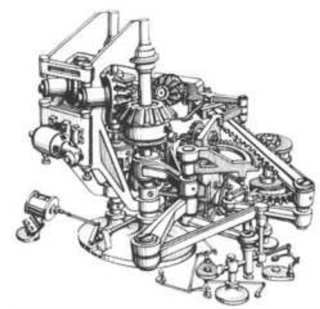
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

Based on current understanding of the world at that time: **Local Realism**

- **Realism:** The measurement results are determined by properties the particles carry prior to and independent of observation.

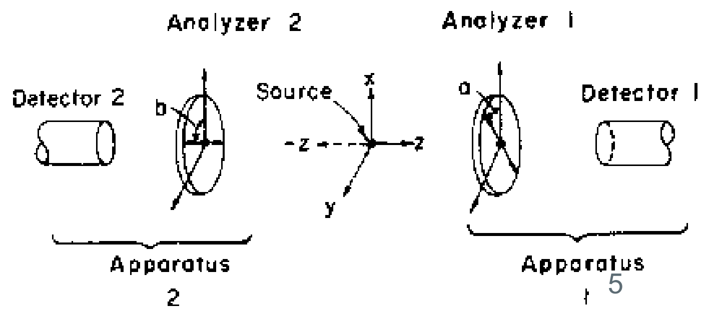
- **Locality:** Properties of one particle cannot be affected by operations on the other (by influences that propagate faster than c)

EPR postulated that QM is not complete and so-called **hidden variables** need to be introduced.



„World"

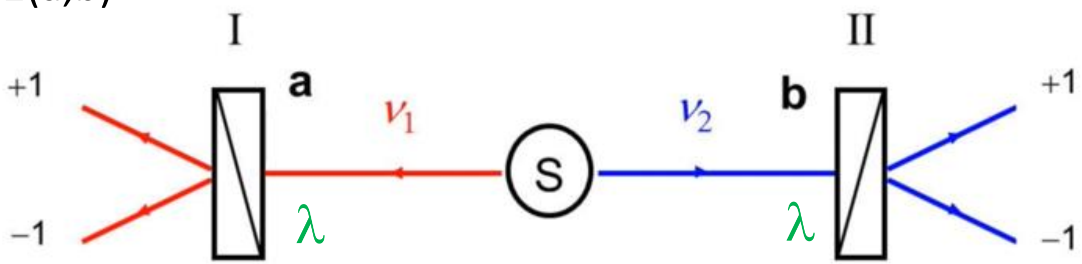
„passive observer"



BELL‘S THEOREM

1964: John Bell decides to have a go at it.

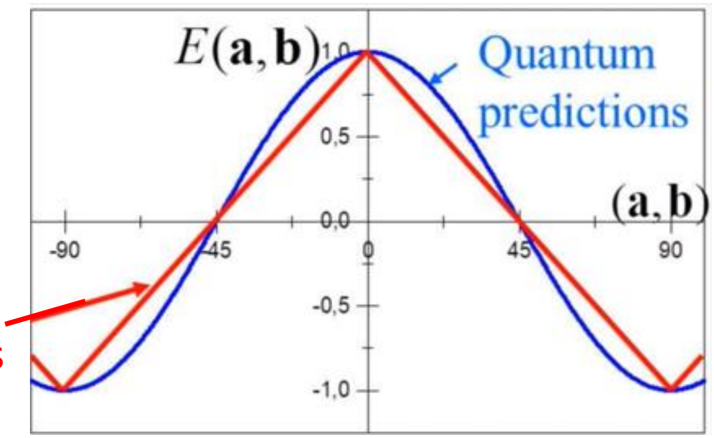
- Analytical description of EPR experiment
- Calculate expectation values (of **joint results** (I and II) for different analyser settings, **a** and **b**
- For QM: *E*(**a**,**b**) = cos 2(a,b)



λ is the common supplementary parameter, “hidden variable”

- λ determines the results of measurements at I and II
- Comparison with QM shows discrepancies

Bell‘s theorem states that no local hidden variable theory can redproduce all QM predictions



CHSH INEQUALITY

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VOLUME 23, NUMBER 15 PHYSICAL REVIEW LETTERS 13 OCTOBER 1969

PROPOSED EXPERIMENT TO TEST LOCAL HIDDEN-VARIABLE THEORIES*

Clauser, Horne, Shimony and Holt inequality from 1969

Extended Bell's theorem to polarisation entangled photons

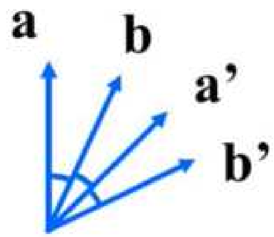
$$S = E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{b}') + E(\mathbf{a}',\mathbf{b}) + E(\mathbf{a}',\mathbf{b}')$$

Predictions:
For local hidden variable theories: $-2 \leq S \leq 2$
Quantum Mechanics: $S_{QM} = 2\sqrt{2} = 2.828...$

First experimental tests by Clauser and Freedman in 1972
Results showed that $S > 2$

QM cannot be explained by local hidden variable theory

John F. Clauser



Polariser settings

ASPECT'S EXPERIMENTS

Final nail in the coffin in 1981

VOLUME 49, NUMBER 2 — PHYSICAL REVIEW LETTERS — 12 JULY 1982

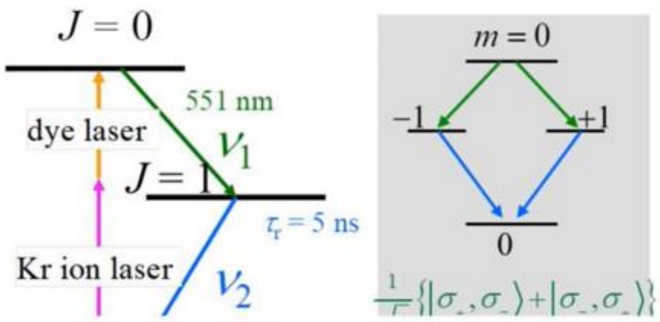
Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

Alain Aspect, Philippe Grangier, and Gérard Roger

Alain Aspect

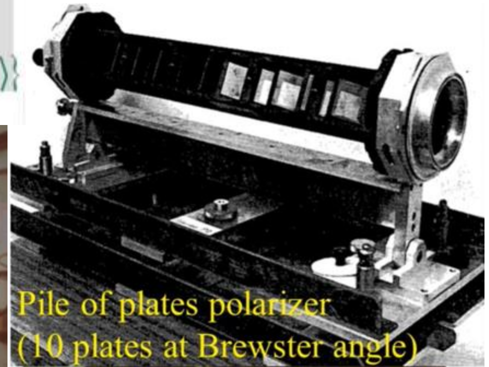
Much improved experimental setup

Measured S parameter of $S = 2.70 \pm 0.02$



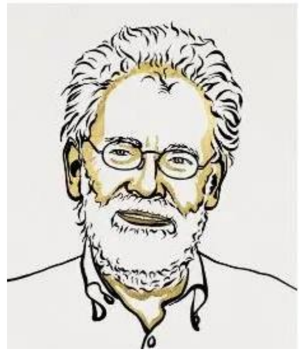
Closer to ideal GedankenExperiment:

- Fast switching between polarizer settings
- Space-like separation of measurements
- "Long" distance distribution of 6 m between source and analysers
- Higher generation rate of entangled photons



ZEILINGER YEARS

Perfecting the experimental setups and closing loopholes (1995 -2015)



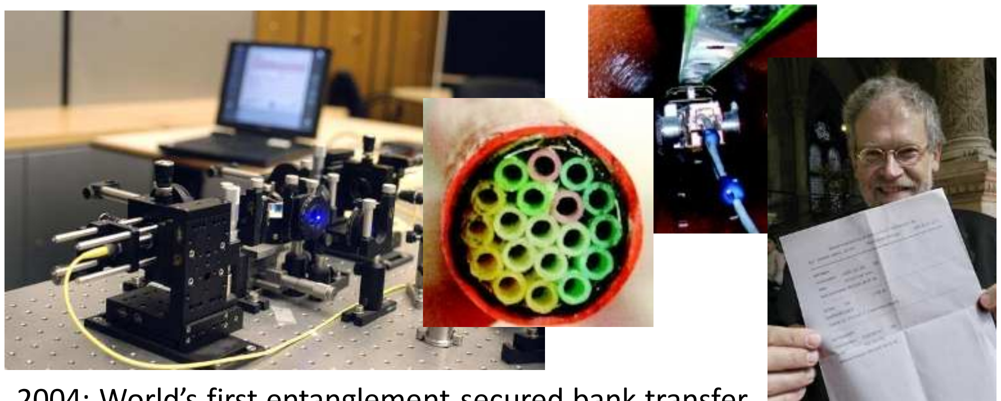
Anton Zeilinger

Experimental improvements

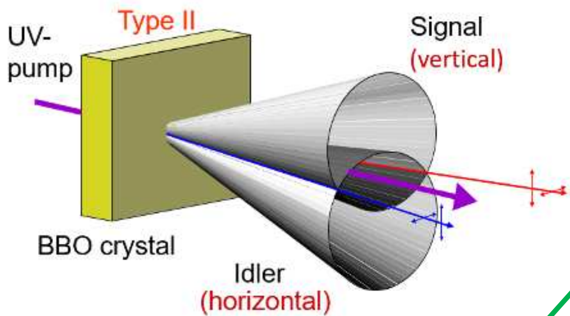
- Generation of entanglement via spontaneous parametric downconversion
  - Orders of magnitude higher generation rates
- Fast switching of polarisers to any angle
- Quantum random number generators to determine setting of polarisers

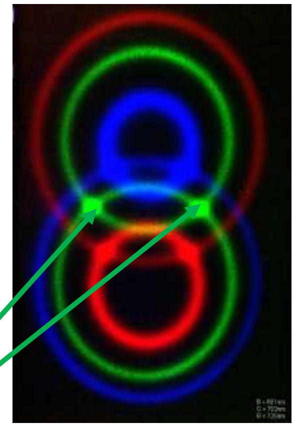
Going the distance and out of the lab

- Free-space transmission for entanglement at visible wavelength
- Moving wavelength to 1550 nm for low-loss transmission in optical fibers



2004: World's first entanglement secured bank transfer





$$|\Psi\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)$$

LOOPHOLES

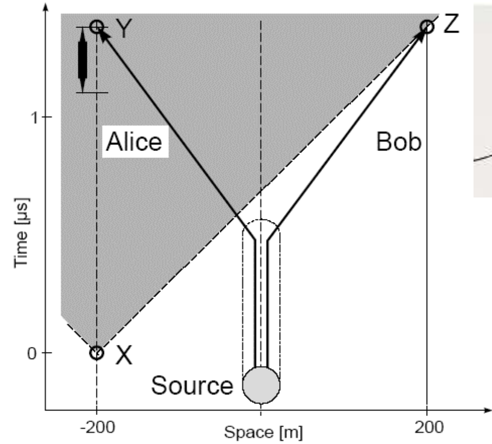
Some scepticism still remained…

Locality loophole

- Choice and setting of polarisers (**a** and **b)** must be space like separated.

CLOSED !

Separation 400m, so that individual measurements are faster than 1.3 ms
Done in 100ns



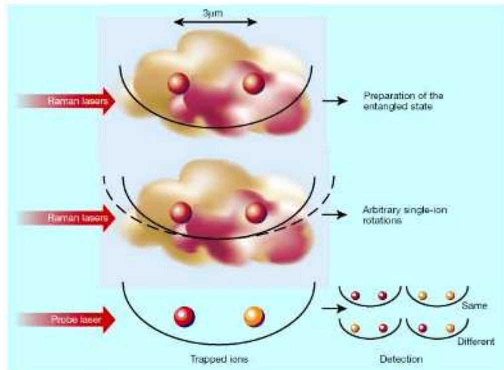
Weihs et al., PRL **81**, 5039 (1998)]

Detection loophole (Fair sampling assumption)

- Photon detection is never perfect. Photons could conspire against the experimenter. All non-detected photons do not violate Bell's inequality.

CLOSED !

Entangled Beryllium atoms. Can be measured with 100% efficiency



Rowe et al., Nature **409**, 791 (2001)

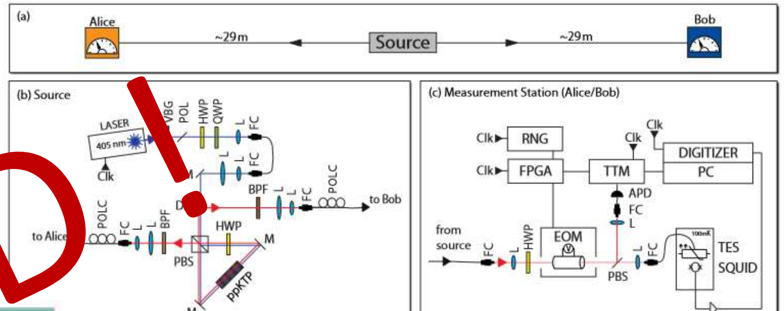
LOOPHOLES II

Both loopholes closed, but not at the same time!
Took until 2015, when 3 groups achieved the final goal simultaneously

CLOSED!

1. Entangled photons I

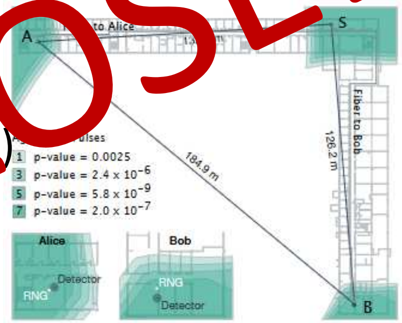
- Use of transition-edge sensor (TES). 98% detection efficiency, operating temperature in mK range



Phys. Rev. Lett. 115, 250401 (2015)

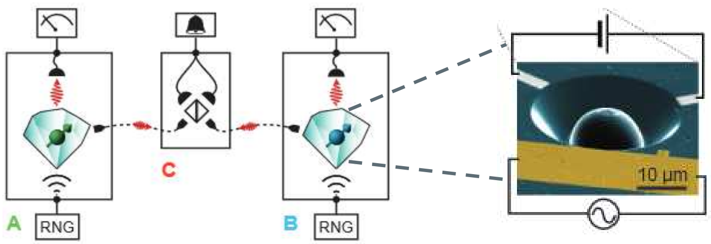
2. Entangled photons II

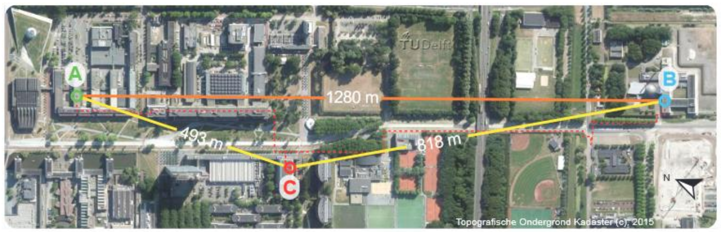
- Use of superconducting single photon detectors (75%) and 1550nm photons (low loss in fibers)



Phys. Rev. Lett. 115, 250402 (2015)

3. Entangled electron-spin in diamonds





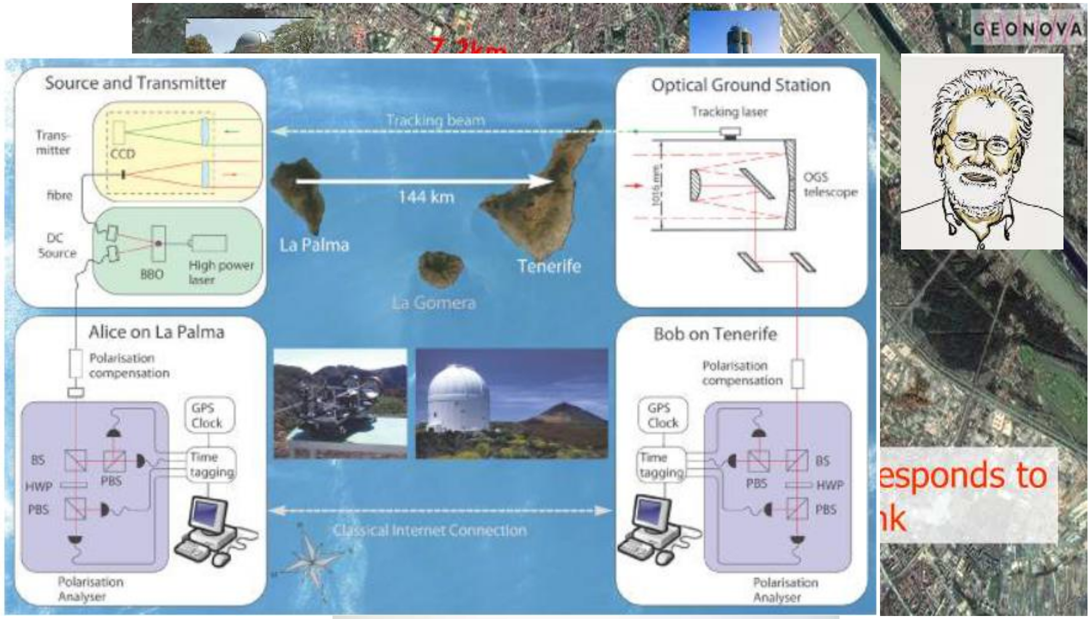
Nature **526**, 682-686 (2015)

TESTING THE LIMITS

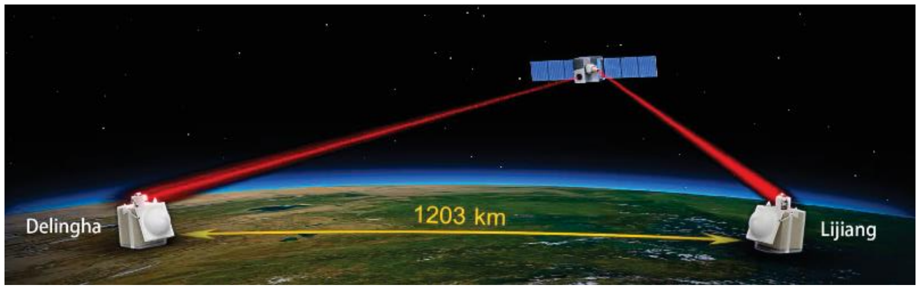
Test entanglement in different physical environments and over long distances

Free-space distribution

- Intra City (2005 in Vienna)
- Inter-Island (2007 in Tenerife) over 144 km
- Entanglement distribution via satellite (2017); Entangled source on satellite, ground stations separate by 1200 km $S = 2.37$

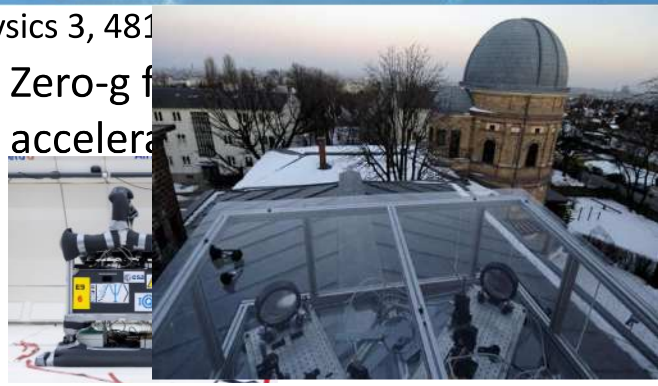


Nature Physics 3, 481



Science 356, 1140-1144 (2017)

- Zero-g f
accelera



24)

TELEPORTATION

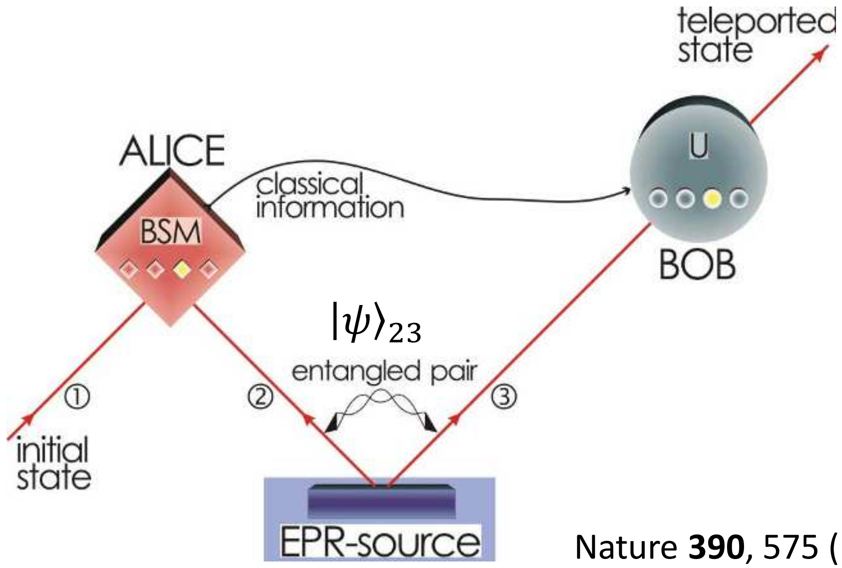
A fascinating use of entanglement is in Quantum Teleportation

Use entanglement as a resource to teleport the quantum state of a photon $|\varphi\rangle_1$

1. Start with initial state $|\varphi\rangle_1$ and entangled state $|\psi\rangle_{23}$
2. Joint measurements between photon 1 and 2 (Bell state measurement)
3. Photon 3 is projected into initial state of photon 1

$$|\varphi\rangle_3 = \alpha|H\rangle + \beta|V\rangle$$

$$|\varphi\rangle_1 = \alpha|H\rangle + \beta|V\rangle$$



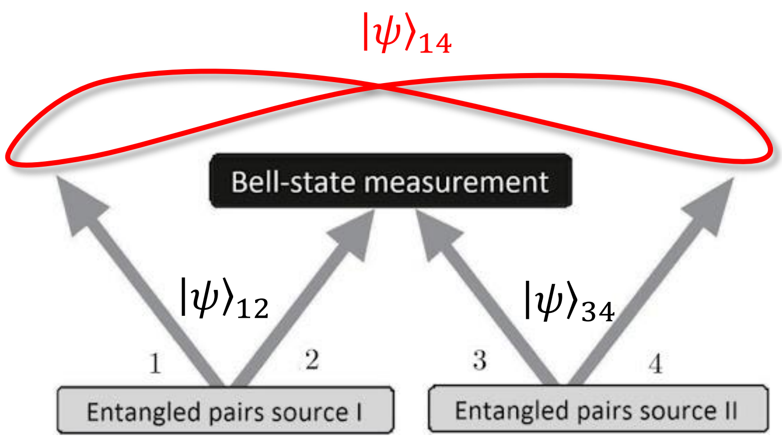
Nature **390**, 575 (1997)

FROM TELEPORTATION TO QUANTUM INTERNET

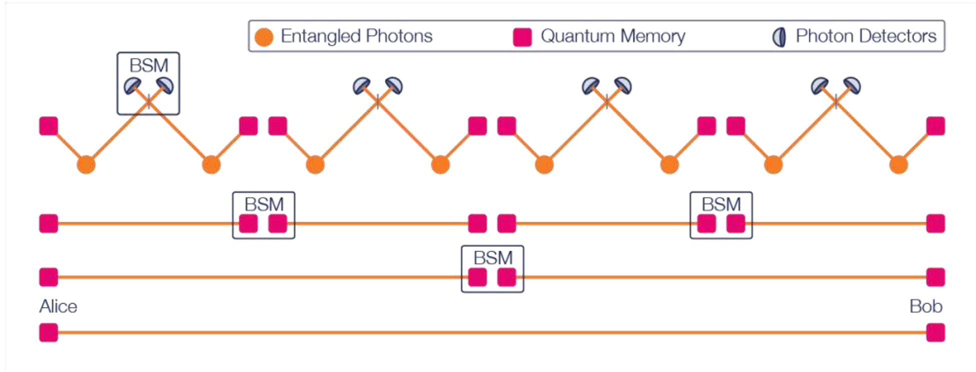
Entanglement swapping

What if input photon is part of another entangled state?

Photons 1 and 2 will end up entangled



Extend chain of entangled sources:
Quantum repeater



Create entanglement between any two places on earth

Applications:

- Connect distributed Quantum Computers
- Support Quantum Sensing network
- Offer Quantum Communication protocols without distance limitations

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Many thanks!

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