

# Qubits and Quantum Teleportation



Anton Zeilinger

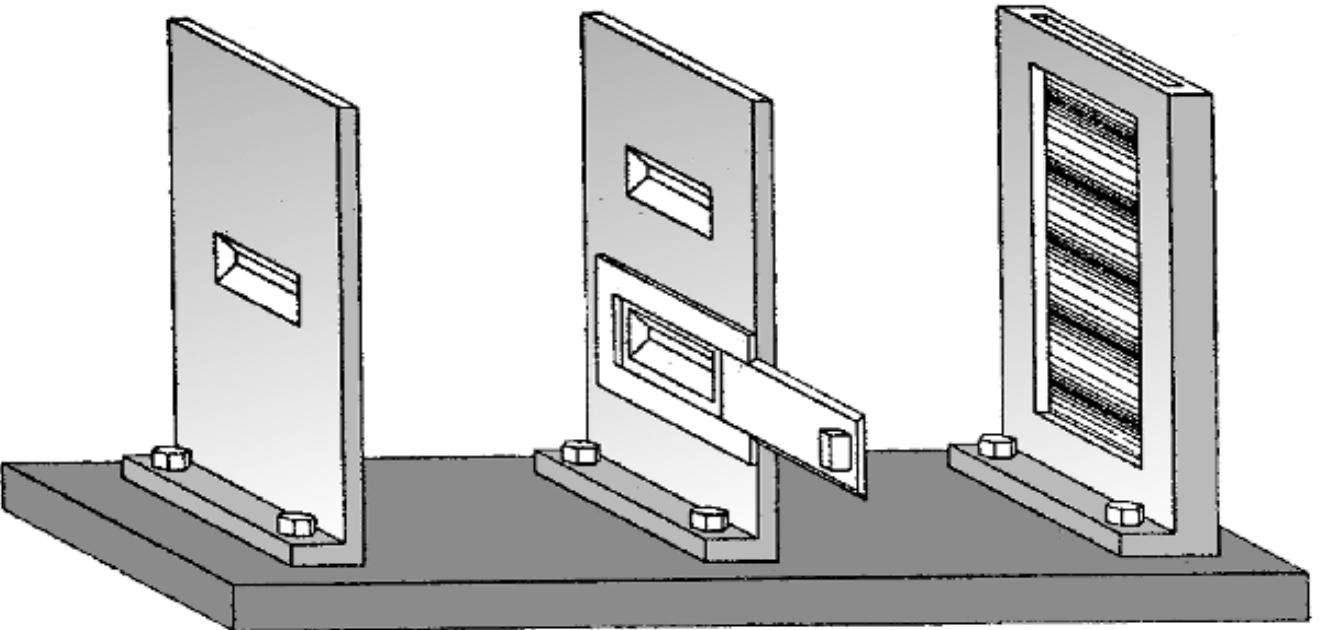
Vienna

[www.quantum.at](http://www.quantum.at)

K.V.Laurikaisen  
Juhlasymposium  
Luonnonfilosofian Seura  
25 Vuotta  
Helsinki  
11 November 2013



# Double Slit Interference

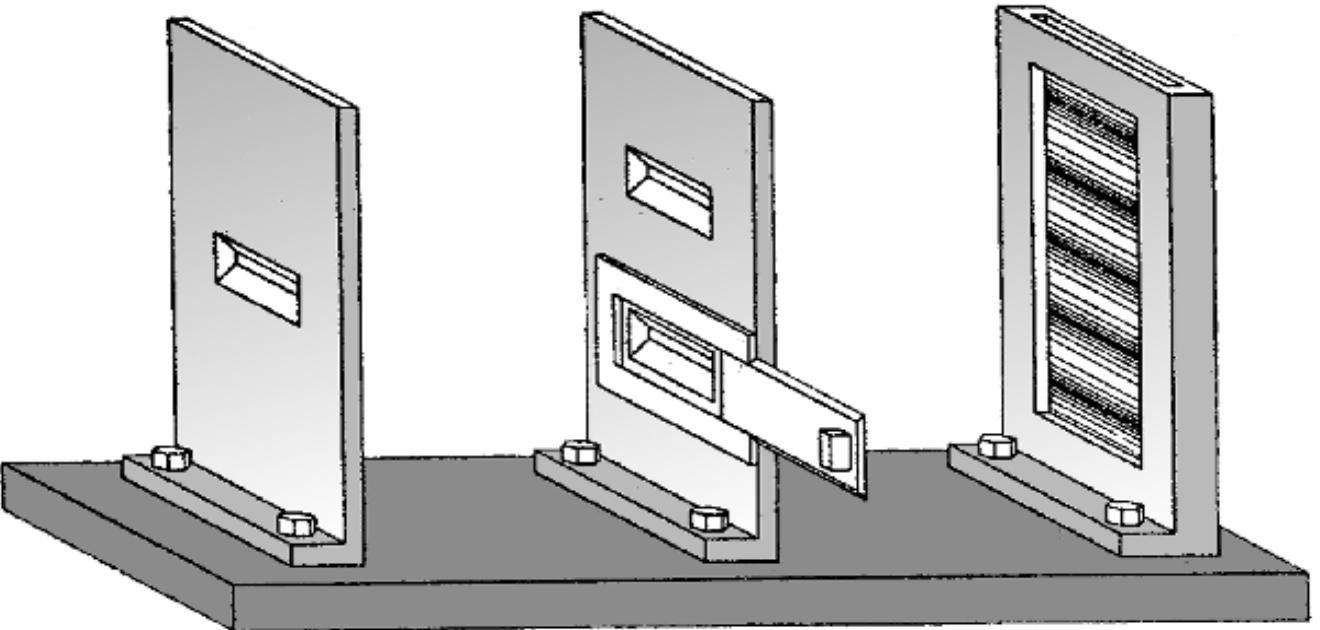


Einstein: What is real?

Bohr: What can be said?



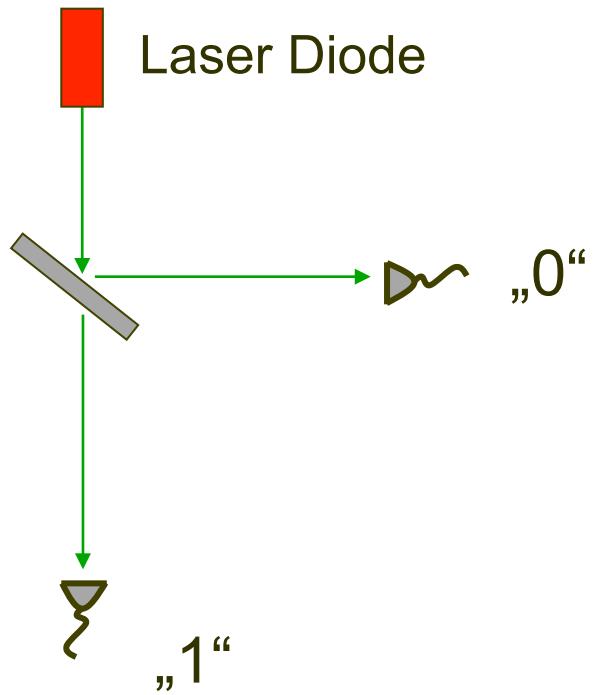
# Double Slit Interference



Interference if and only if no path information anywhere in the Universe



# Ein Quanten-Zufallszahlengenerator



Bit Rate: 1 Mbit/s  
01100110100101001010  
0100010101011010010  
10100100111101001010  
10010101011001011

**QUBIT**



## Bit versus Qubit



Bit

,,0“ or ,,1“



Qubit

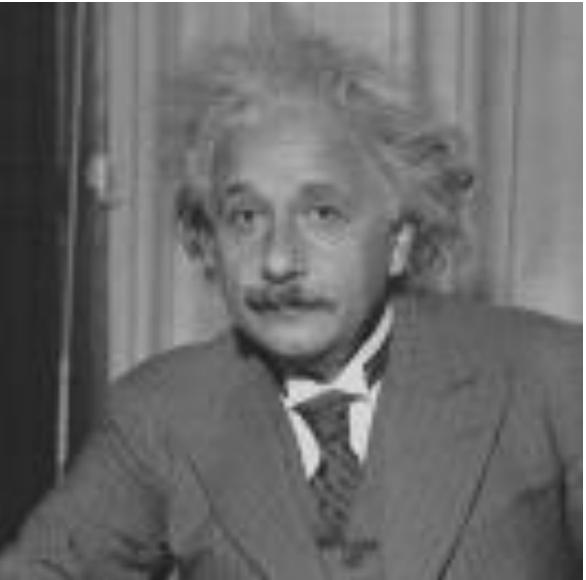
,,0“ and ,,1“



# Albert Einstein 1909

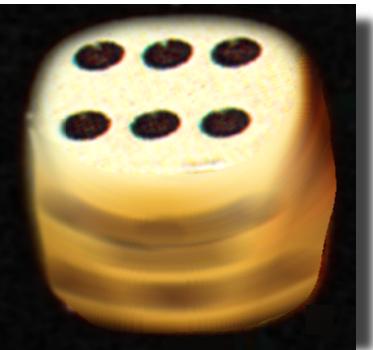
## Salzburg

„Unbehagen“ über die  
neue Natur des  
Zufalls



„Jedenfalls bin ich davon  
überzeugt, daß der Alte nicht  
würfelt“

*Einstein an Max Born, 4. 12. 1926*



# 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)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in

quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Albert Einstein: Spooky Action



Erwin Schrödinger: Entanglement, Verschränkung



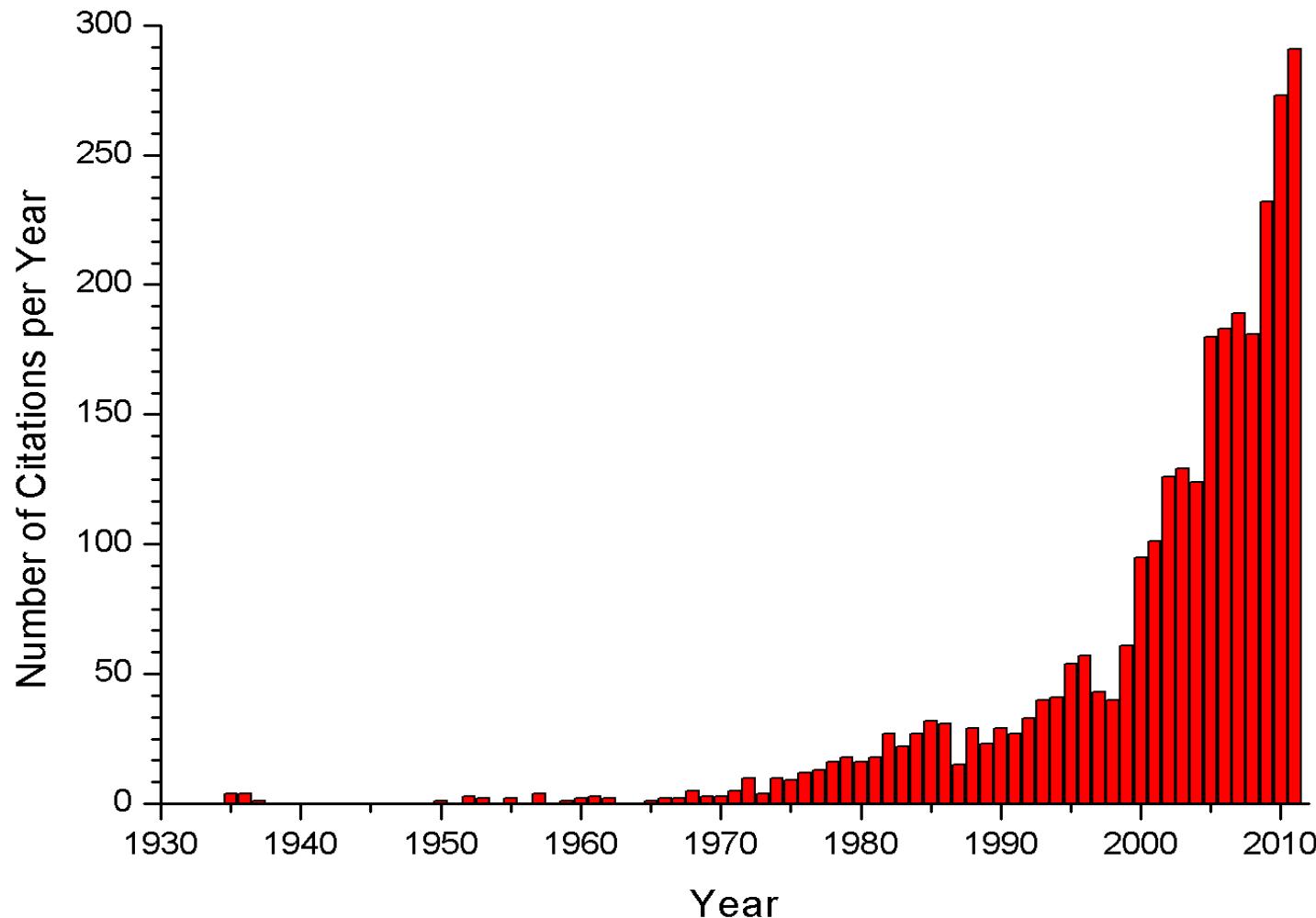
## Buch: Physik im Wandel meiner Zeit

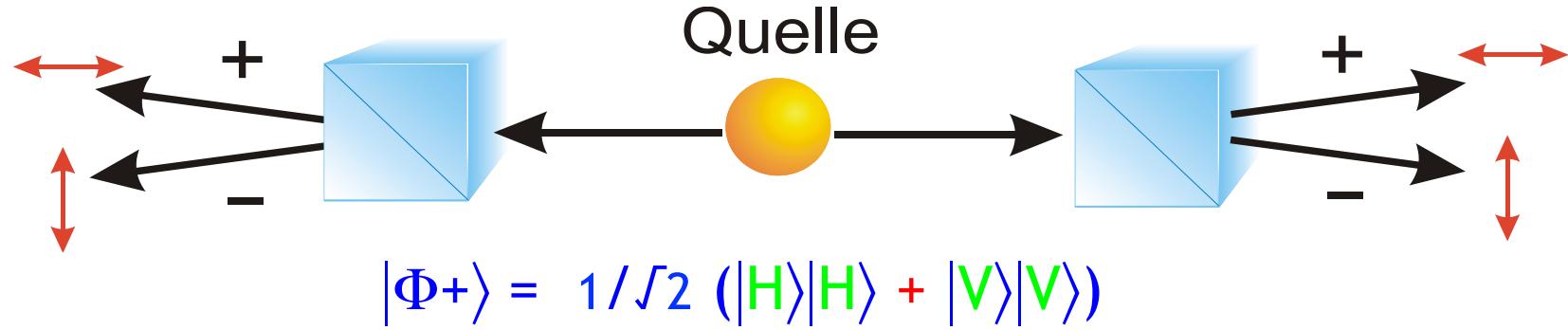
Max Born Seite 228

Einstiens Brief an Max Born am 3. Dezember 1947

Ich kann aber deshalb nicht ernsthaft  
daran glauben, weil die Theorie mit dem Grundsatz unvereinbar ist, daß  
die Physik eine Wirklichkeit in Zeit und Raum darstellen soll ohne spuk-  
hafte Fernwirkungen. . .

# Einstein-Podolsky-Rosen Citations



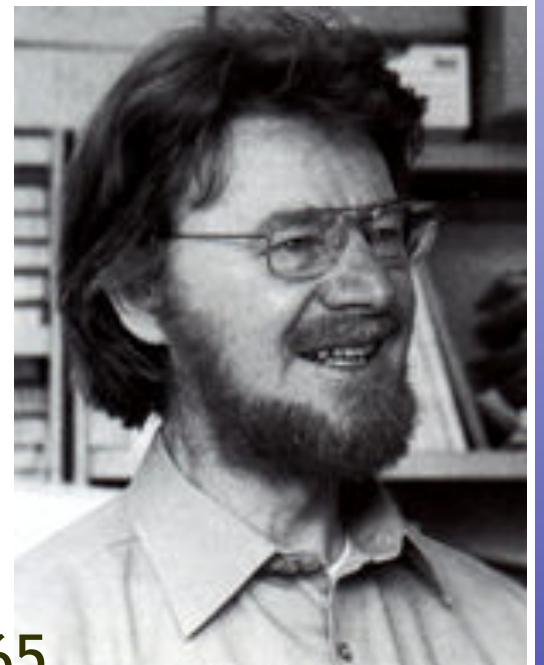


**Local Realism:**  $E_{11} + E_{12} + E_{21} - E_{22} \leq 2$

**Quantum Physics:**

$$2\sqrt{2}$$

**Conflict of Quantum Physics with  
Local Realism**



John Bell 1965

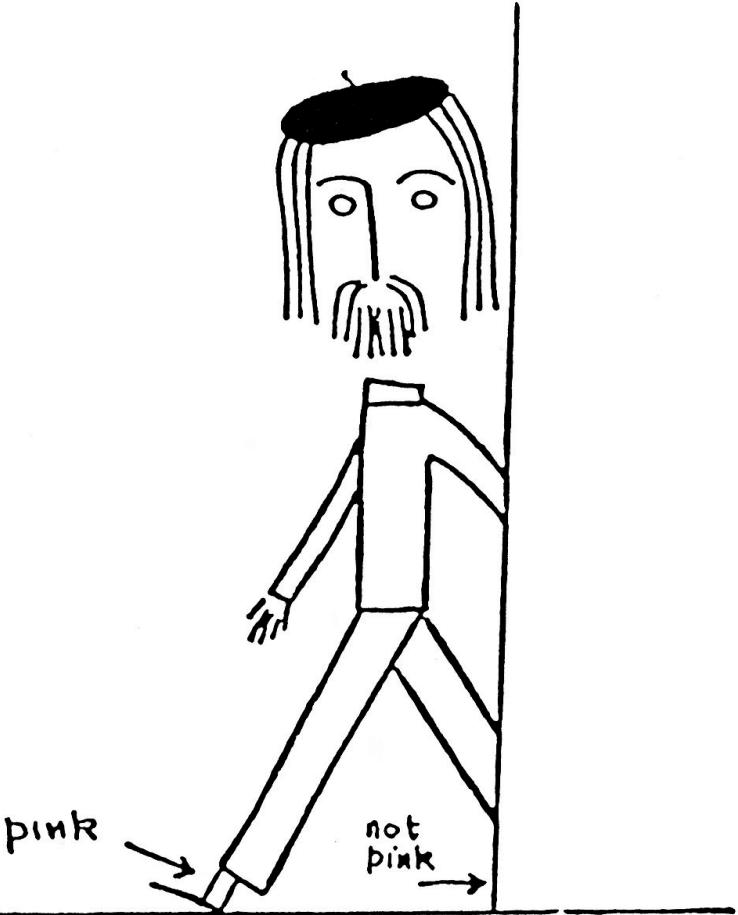


# Bertlmann's Socks and the Nature of Reality

John Bell

Les chaussettes  
de M. Bertlmann  
et la nature  
de la réalité

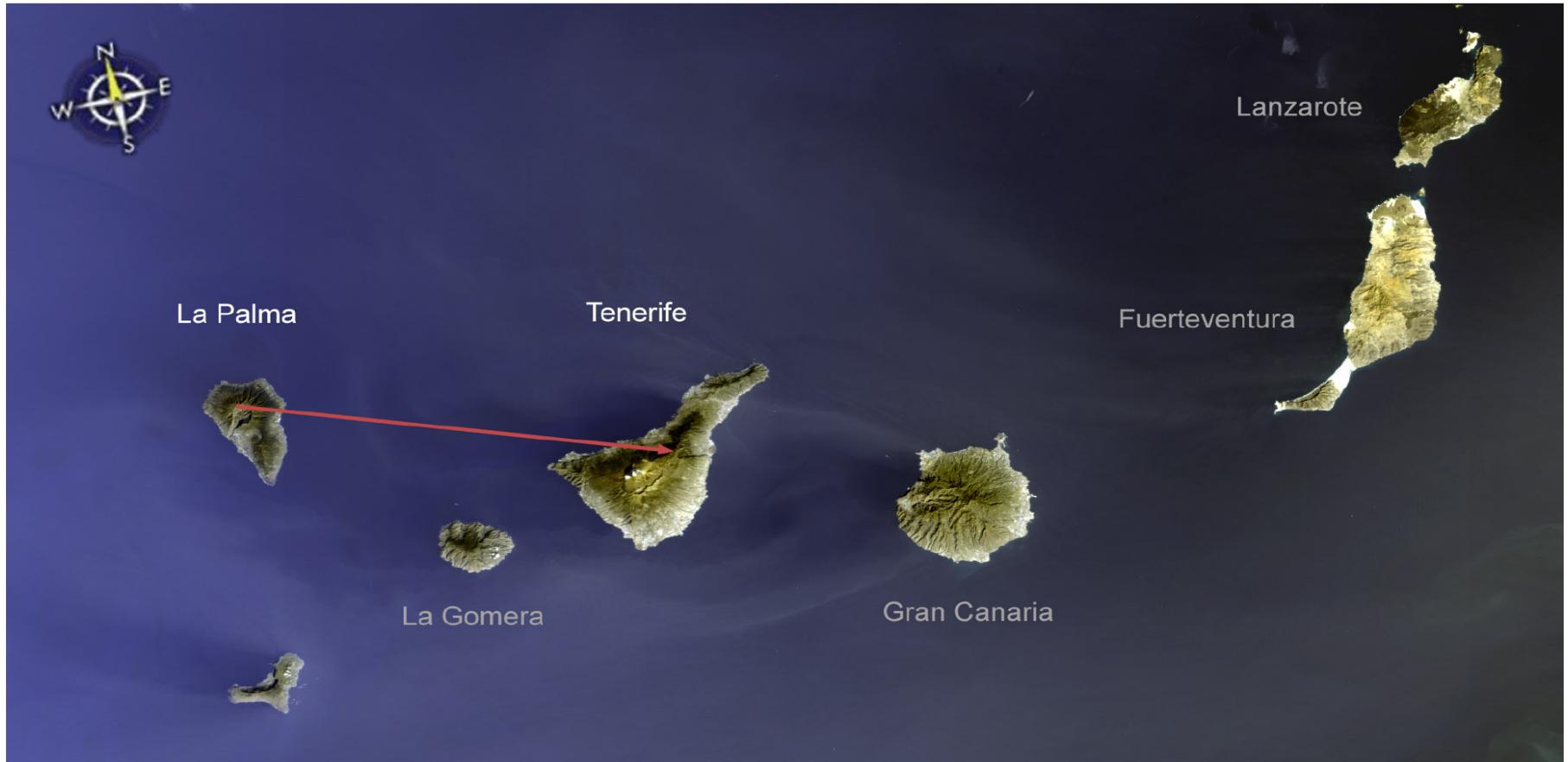
Fondation Hugot  
juin 17 1980





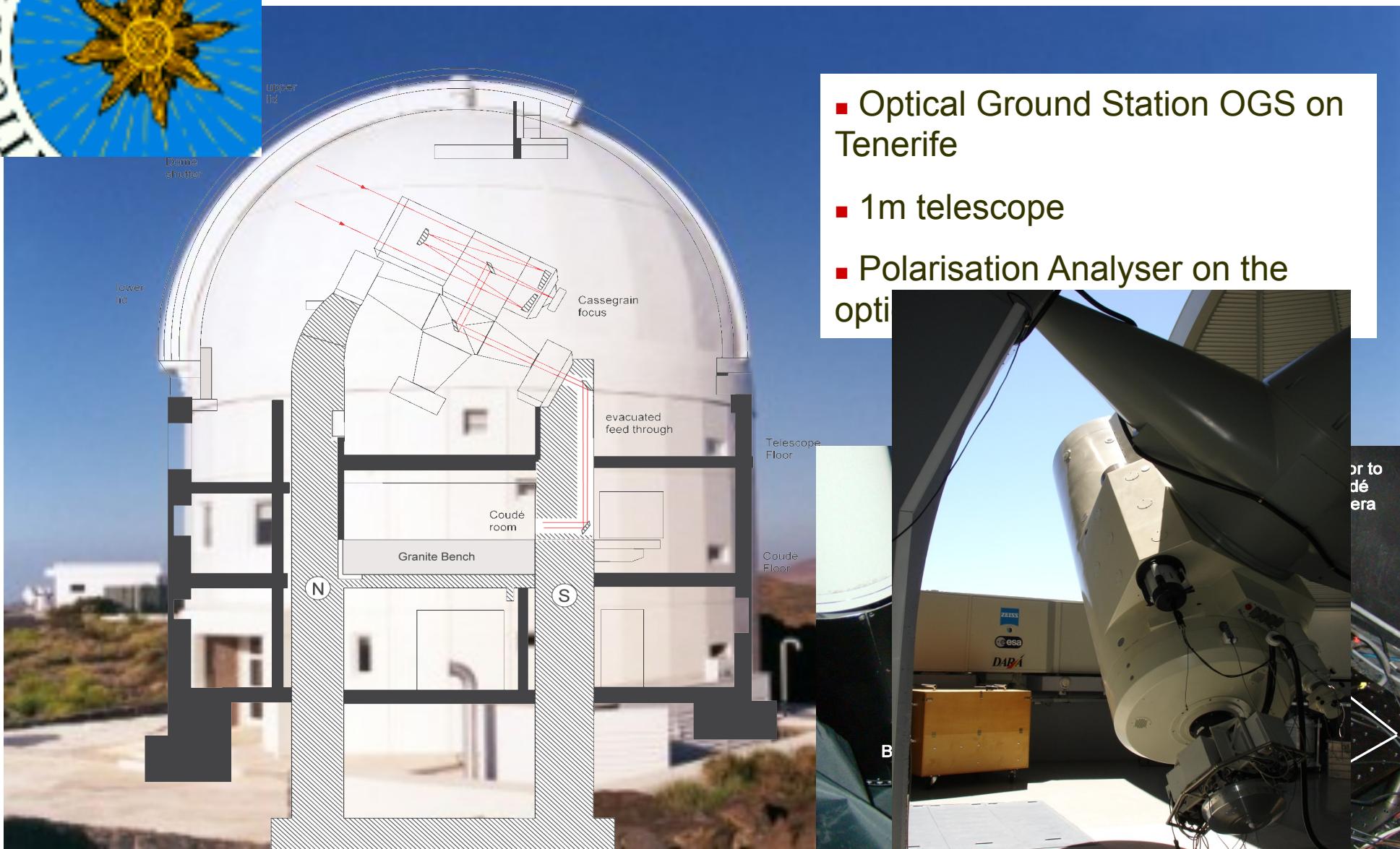
# Long-Distance Entanglement

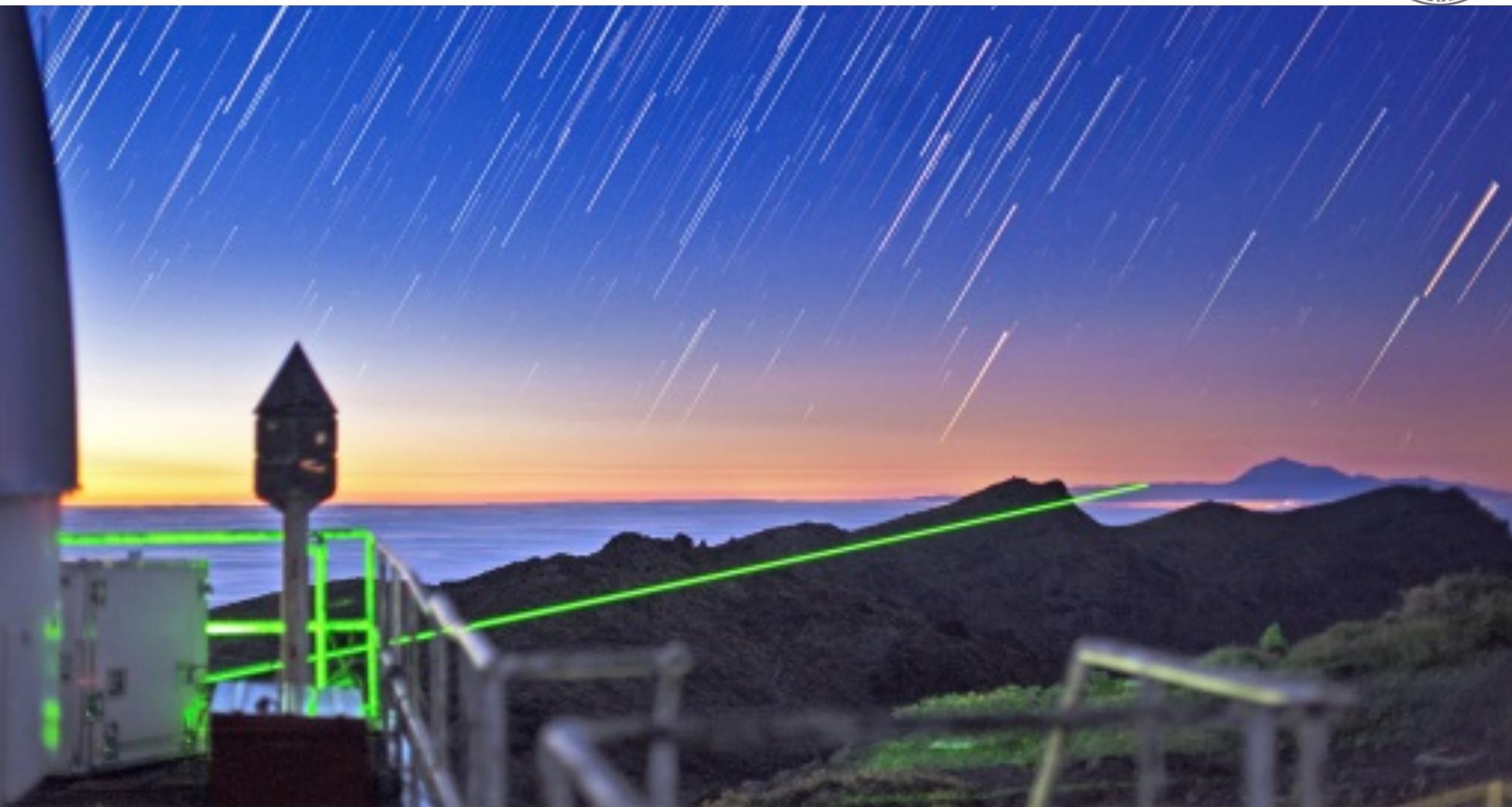
Canary Islands 143 km





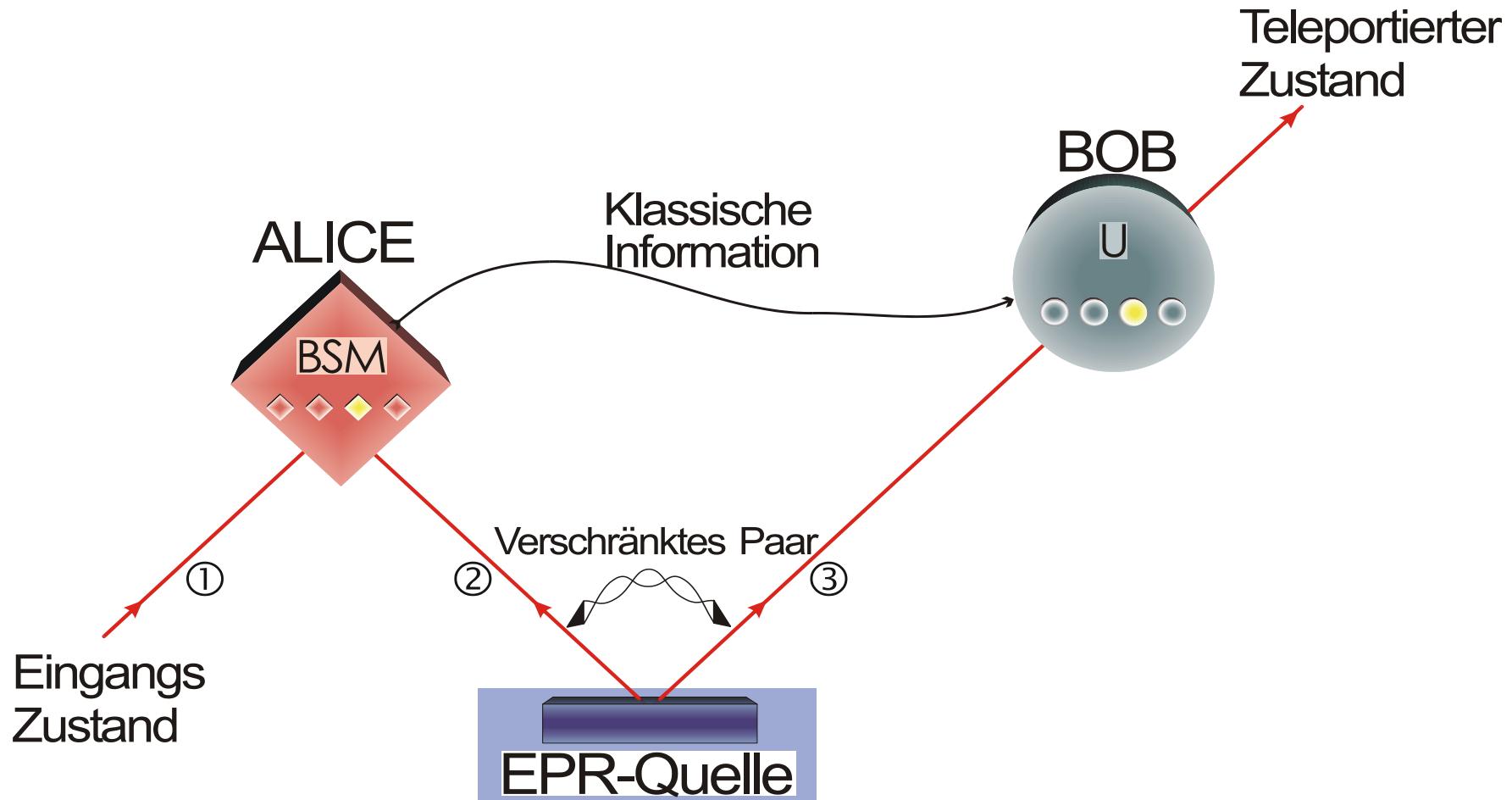
# Receiver







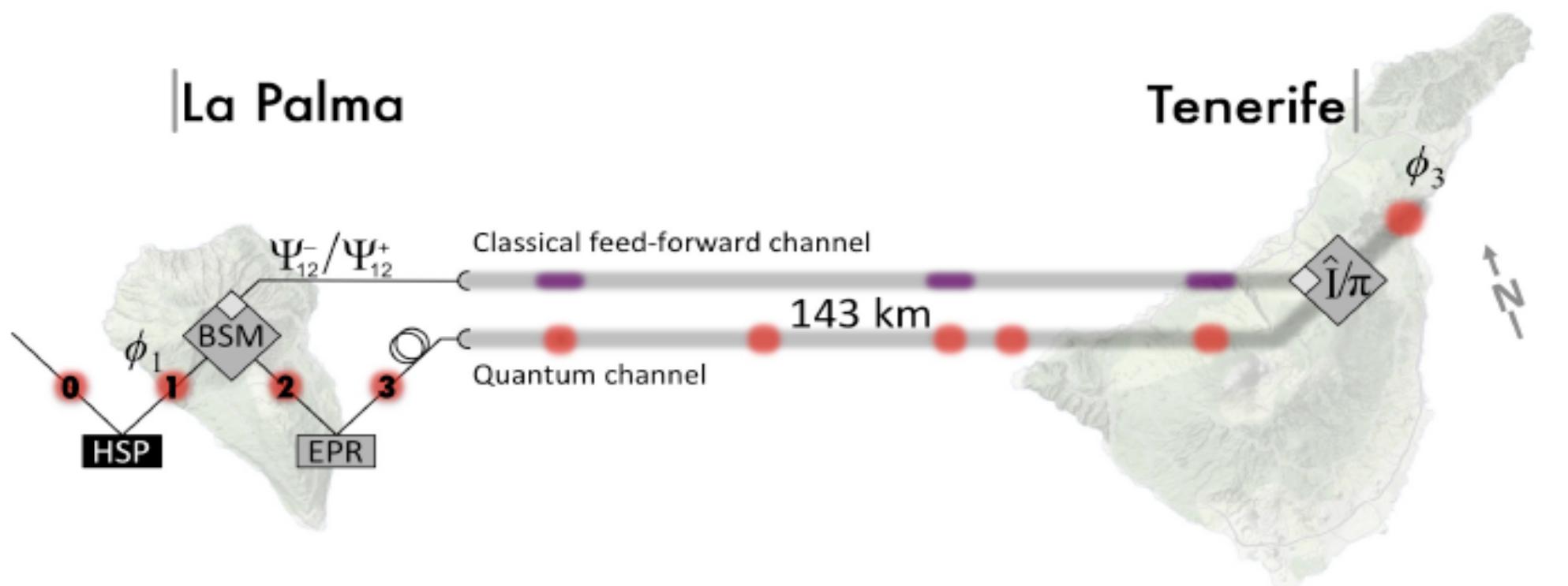
# Teleportation eines Quantenzustandes



Weg? Nichtlokale Information



# Long-Distance Free-Space Teleportation

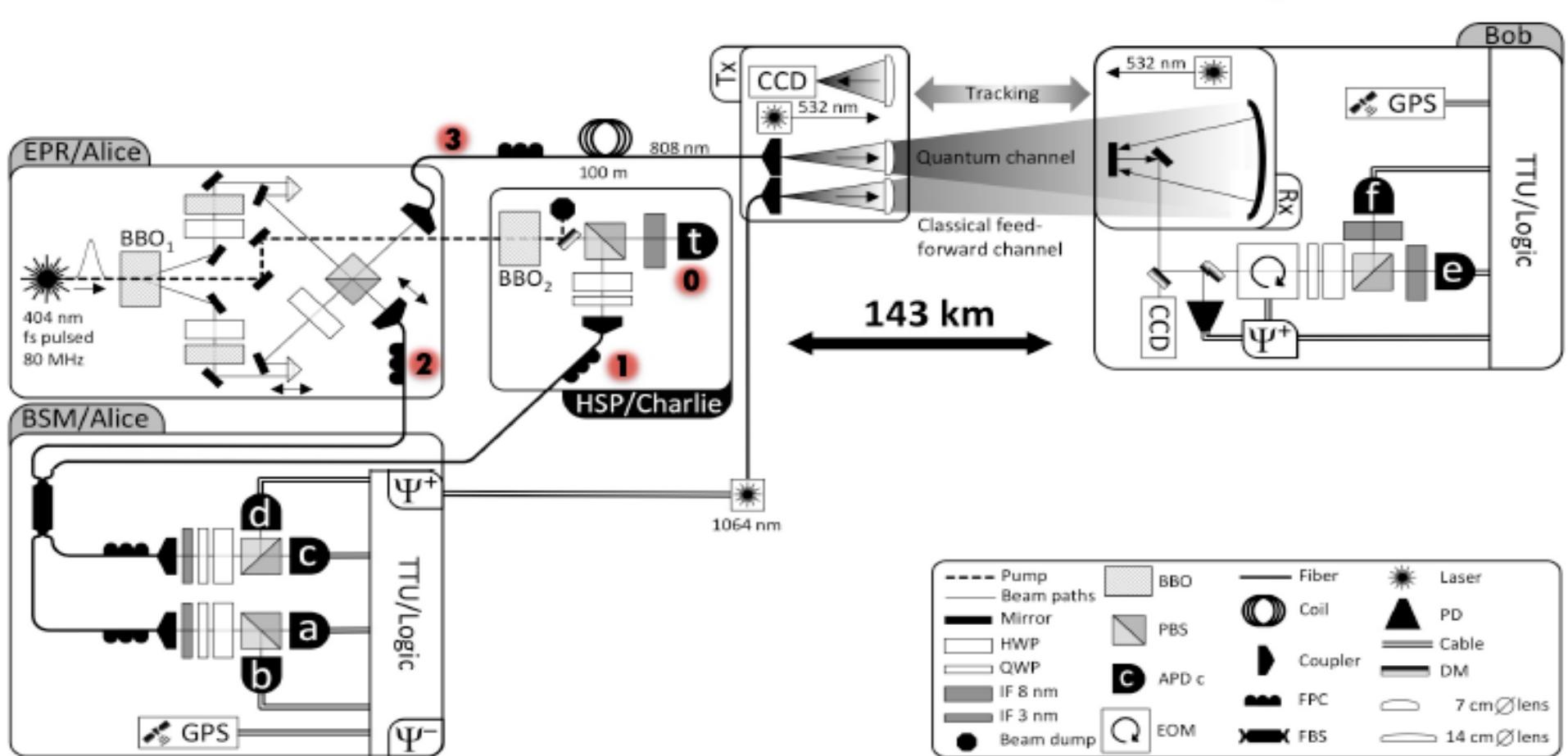


Ma, Herbst, Scheidl, Wang, Kropatschek, Naylor, Mech, Wittmann, Kofler, Anisimova,  
Makarov, Jennewein, Ursin, A.Z., Nature 2012

Also: Jian-Wei Pan group Nature 2012



# Teleportation Setup

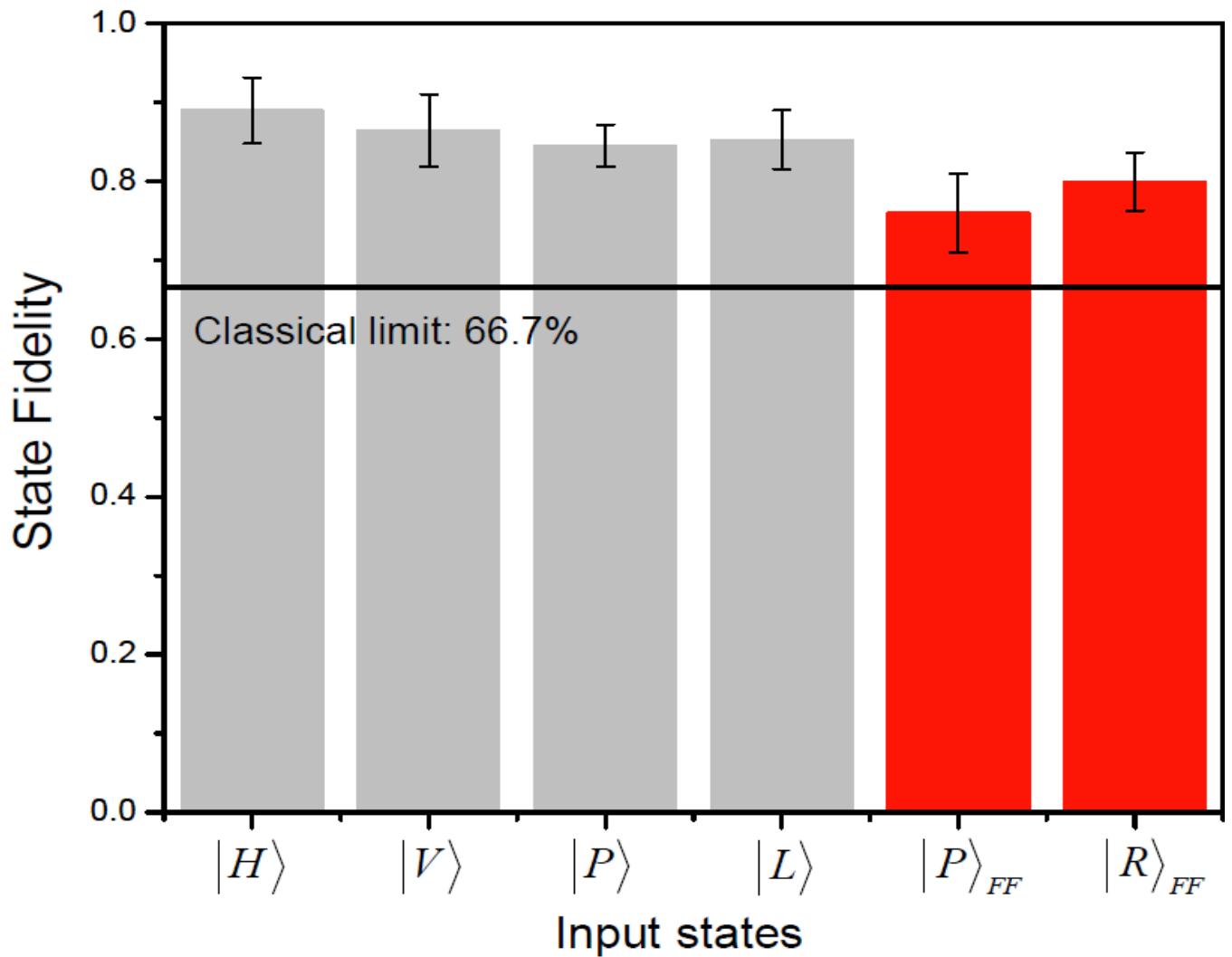








# Teleportation Results



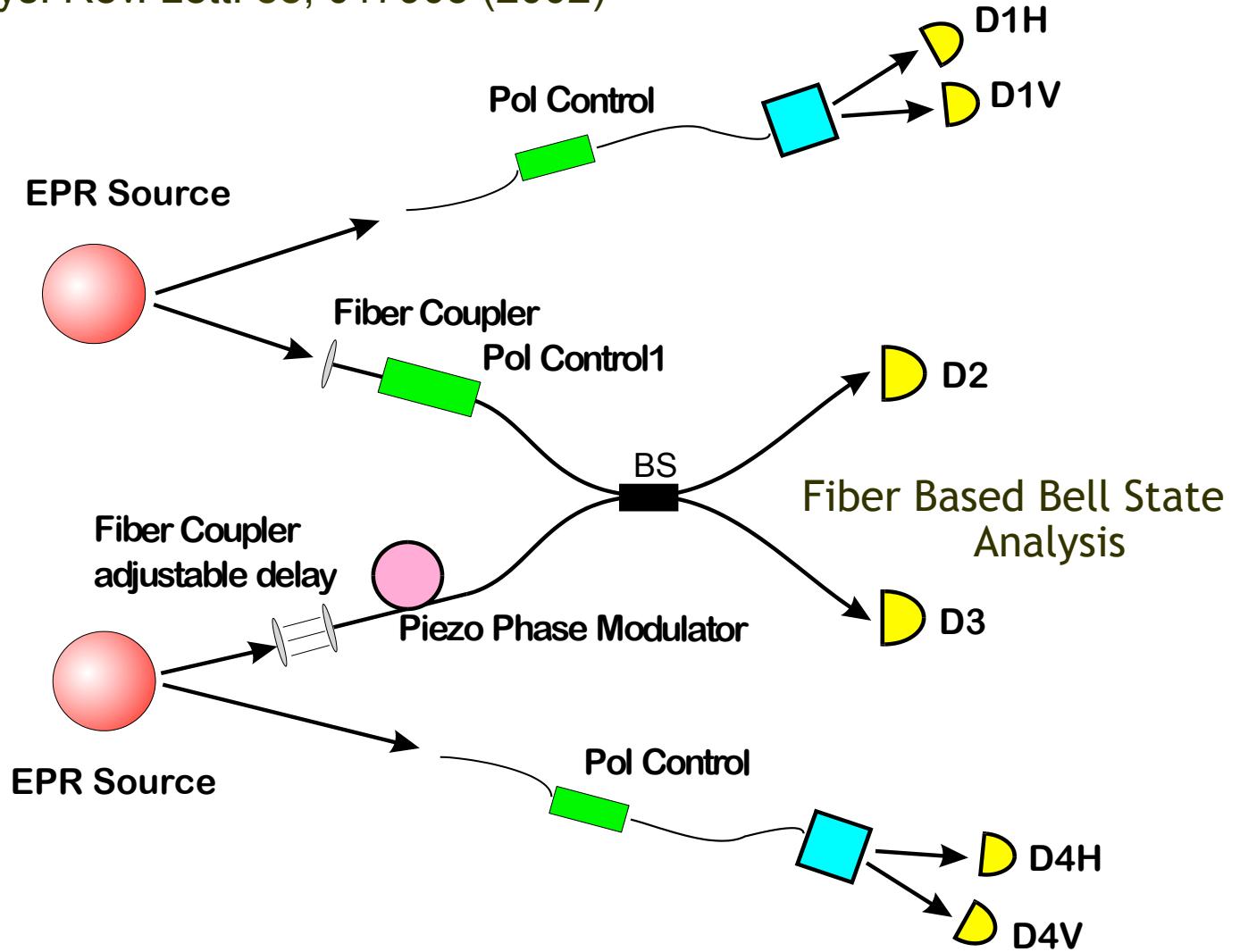


# Entanglement Swapping

## Teleportation of Entanglement

J.-W. Pan et al., Phys. Rev. Lett. **86**, 4435 (2001)

T. Jennewein et al., Phys. Rev. Lett. **88**, 017903 (2002)





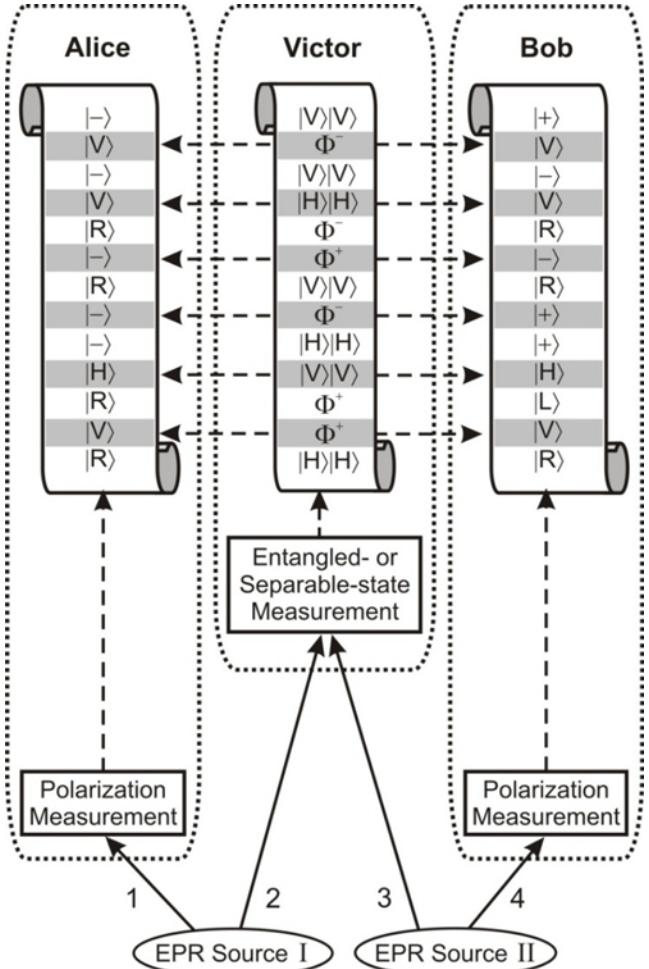
# Delayed – Choice Teleportation of an Entangled State Entanglement Swapping

Photon 1 and 4  
Become Entangled  
after their  
Registration!

Relational Bits!

Idea: Asher Peres 2001

Experiment: without Switching  
T. Jennewein, et al 2002  
With Switching: X. Ma, et al 2010

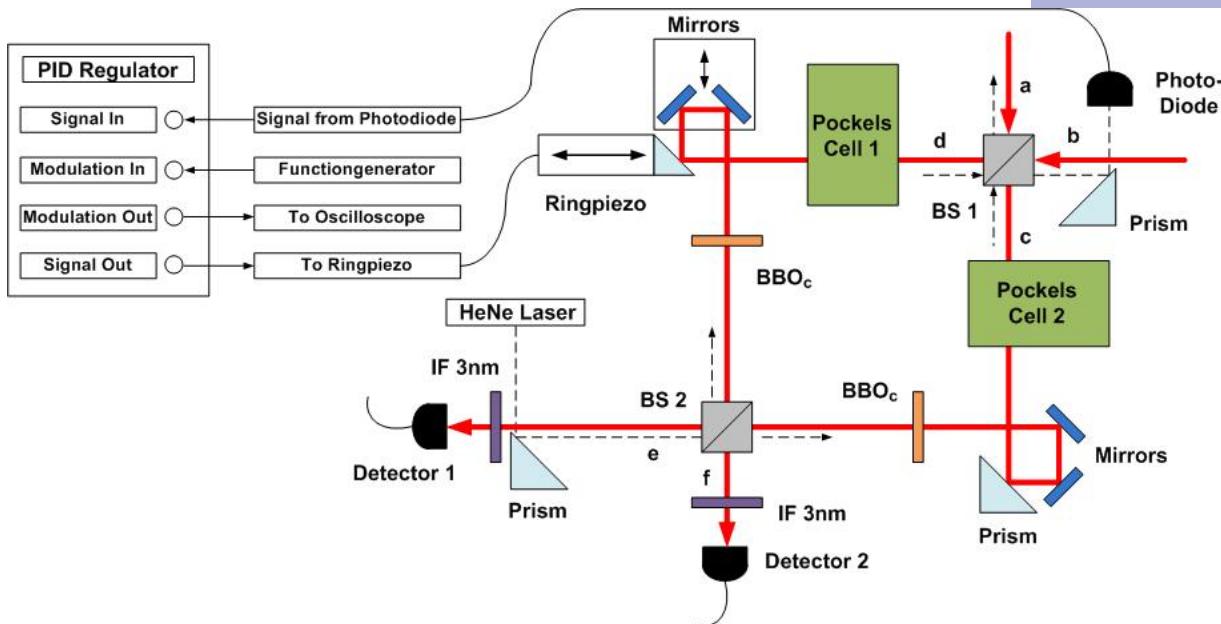
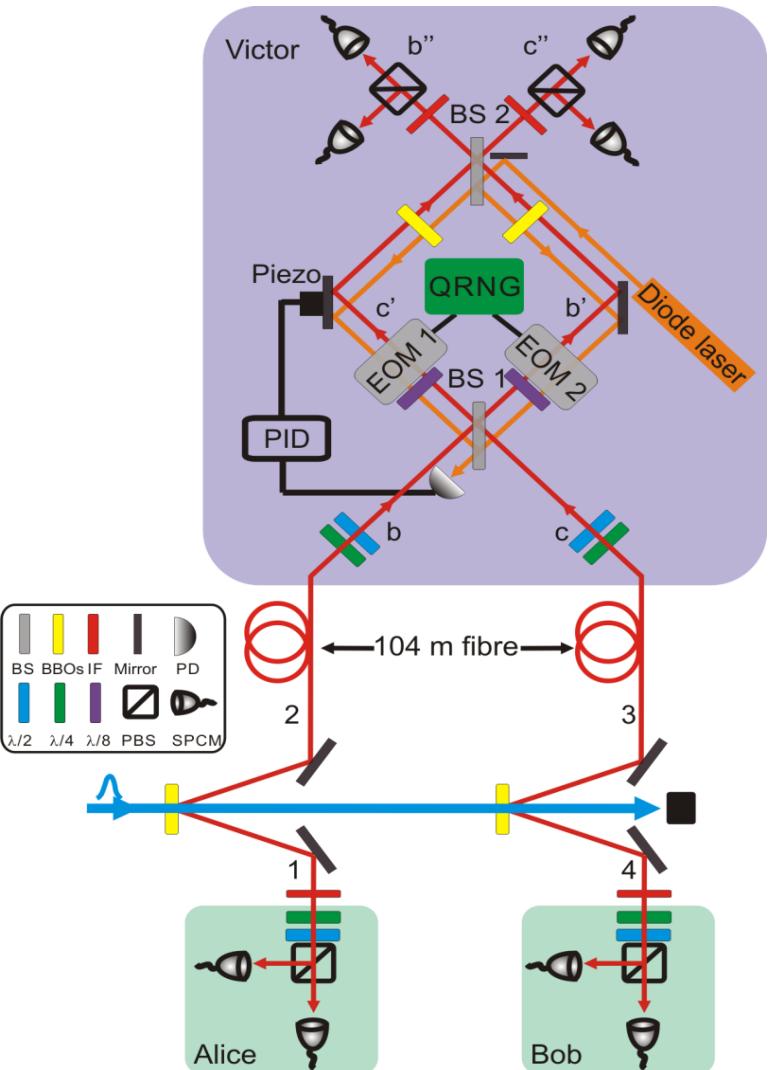


Einstein: What is?

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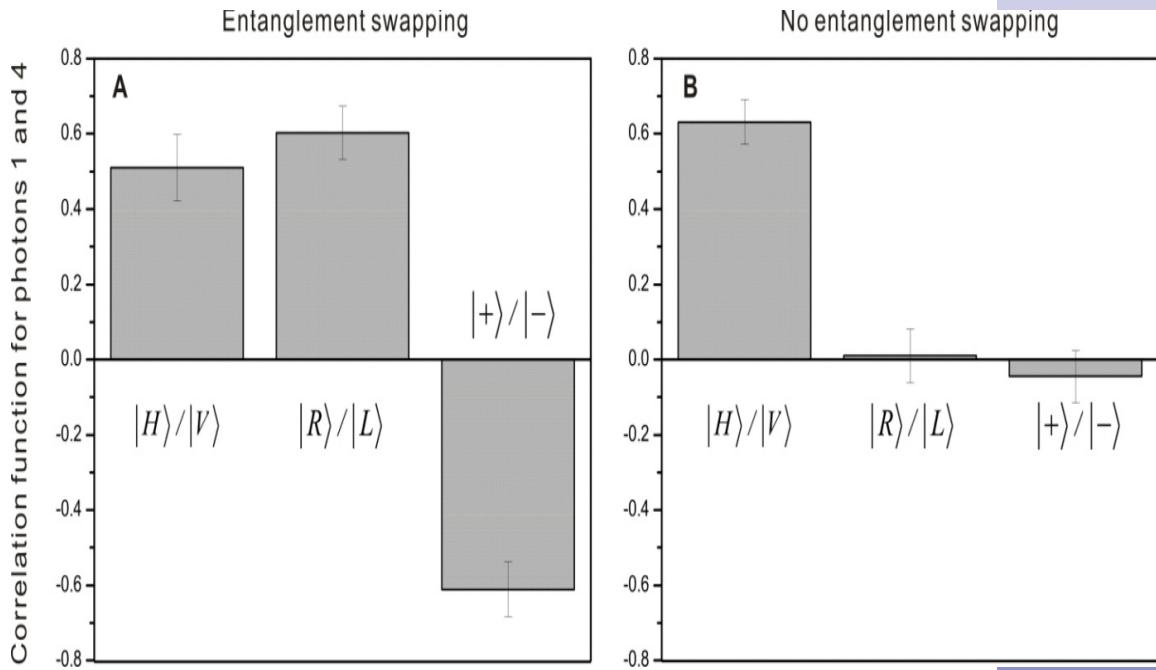
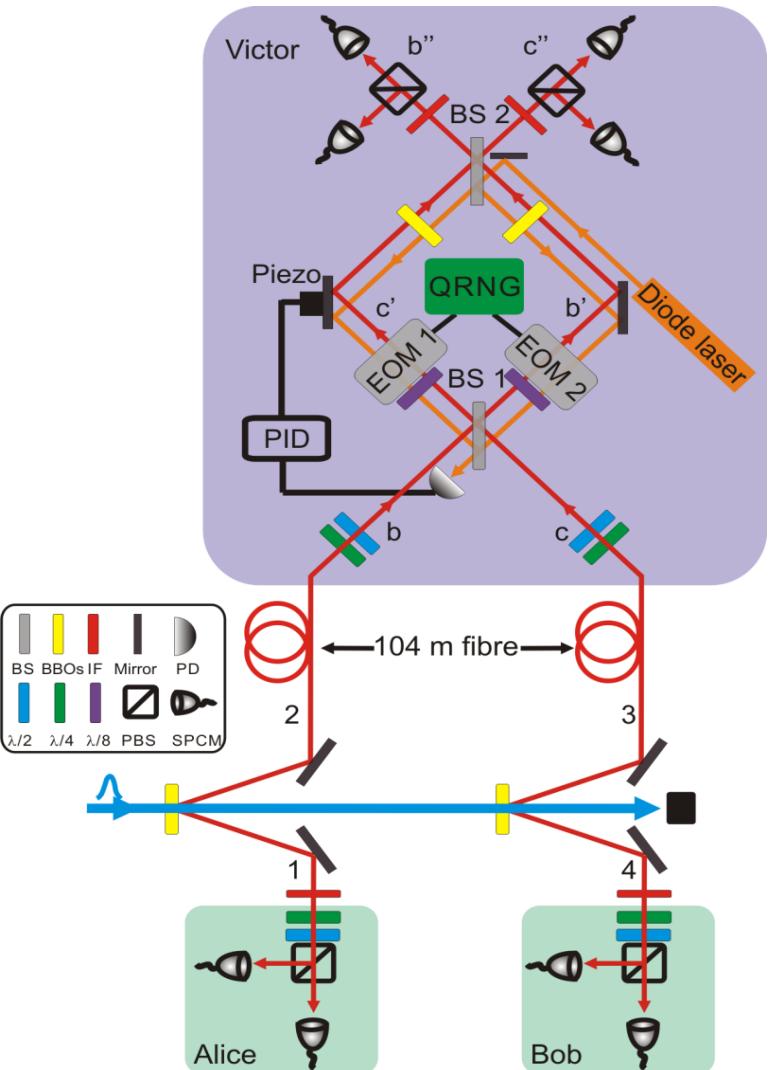
# Delayed-choice entanglement swapping



Ma, Ursin, Zotter, Kofler,, Z  
Nature Physics 2012 (May 14 issue)



# Delayed-choice entanglement swapping



Photon pairs	Measurement <i>i</i>		Measurement <i>ii</i>	
	State fidelities	Entanglement witness	State fidelities	Entanglement witness
Photons 2 and 3	$0.645 \pm 0.031$	$-0.145 \pm 0.031$	$0.379 \pm 0.026$	$0.120 \pm 0.026$
Photons 1 and 4	$0.681 \pm 0.034$	$-0.181 \pm 0.034$	$0.421 \pm 0.029$	$0.078 \pm 0.029$
Photons 1 and 2	$0.301 \pm 0.039$	$0.199 \pm 0.039$	$0.908 \pm 0.016$	$-0.408 \pm 0.016$
Photons 3 and 4	$0.274 \pm 0.039$	$0.226 \pm 0.039$	$0.864 \pm 0.019$	$-0.364 \pm 0.019$

Events are a more fundamental reality than quantum states

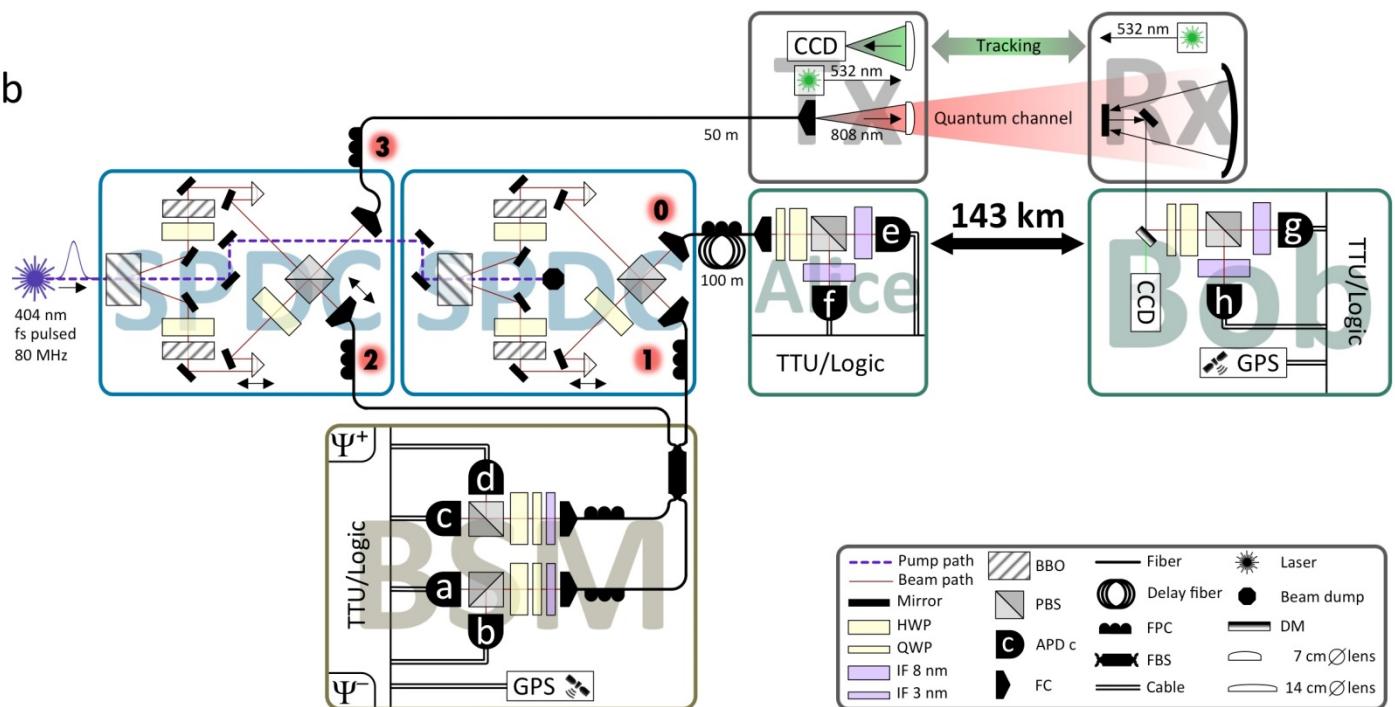


# Teleportation of Entanglement

a



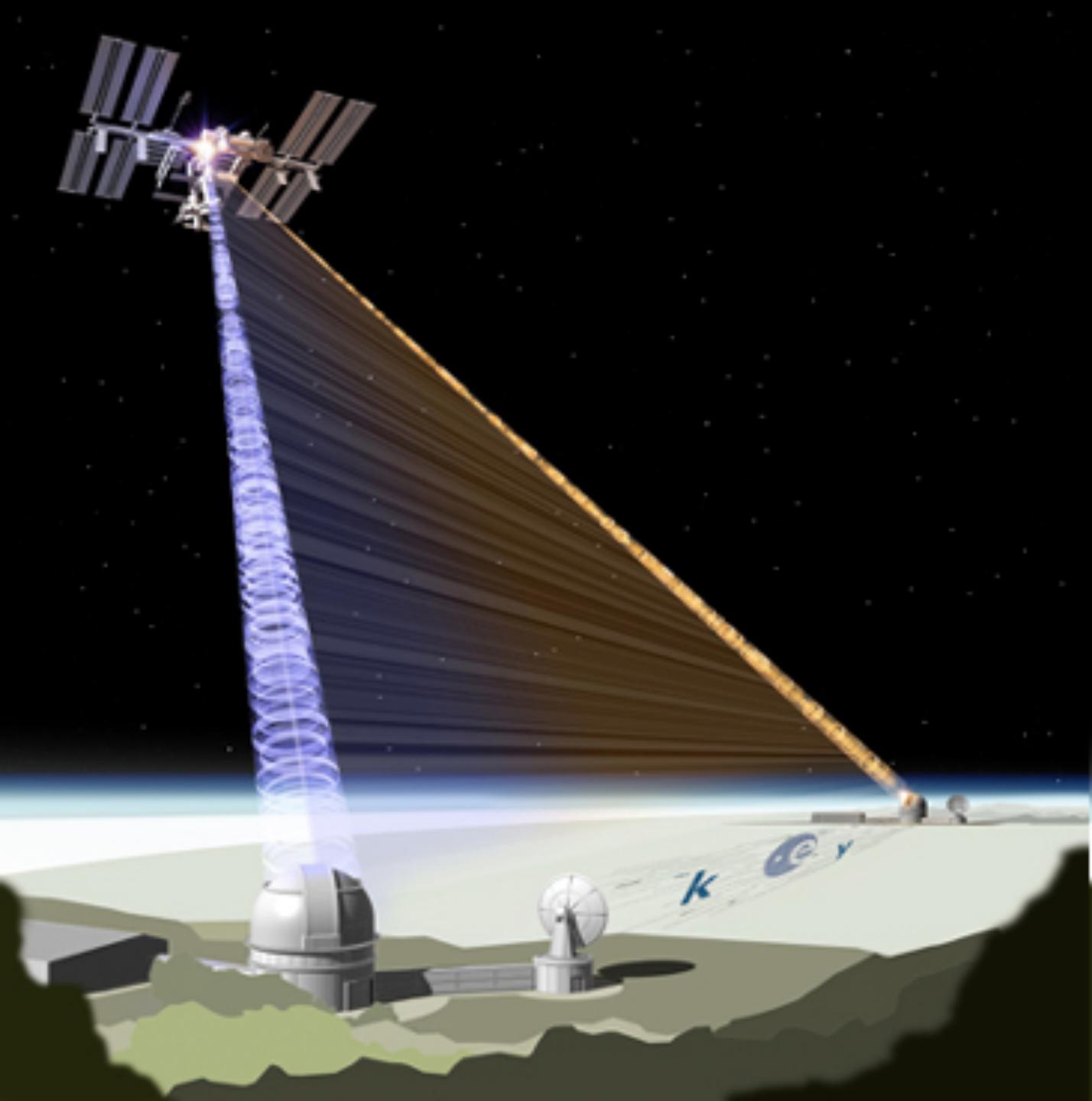
b





No Phenomenon is a  
Phenomenon unless it is an  
Observed Phenomenon

Niels Bohr



Collaboration with  
Jian-Wei Pan



# Definition of Steering

## DISCUSSION OF PROBABILITY RELATIONS BETWEEN SEPARATED SYSTEMS

BY E. SCHRÖDINGER

[Communicated by Mr M. Born]

[Received 14 August, read 28 October 1935]

Attention has recently\* been called to the obvious but very disconcerting fact that even though we restrict the disentangling measurements to *one* system, the representative obtained for the *other* system is by no means independent of the particular choice of observations which we select for that purpose and which by

\* A. Einstein, B. Podolsky and N. Rosen, *Phys. Rev.* 47 (1935), 777.

the way are *entirely* arbitrary. It is rather discomforting that the theory should allow a system to be steered or piloted into one or the other type of state at the experimenter's mercy in spite of his having no access to it. This paper does not aim at a solution of the paradox, it rather adds to it, if possible. A hint as regards the presumed obstacle will be found at the end.

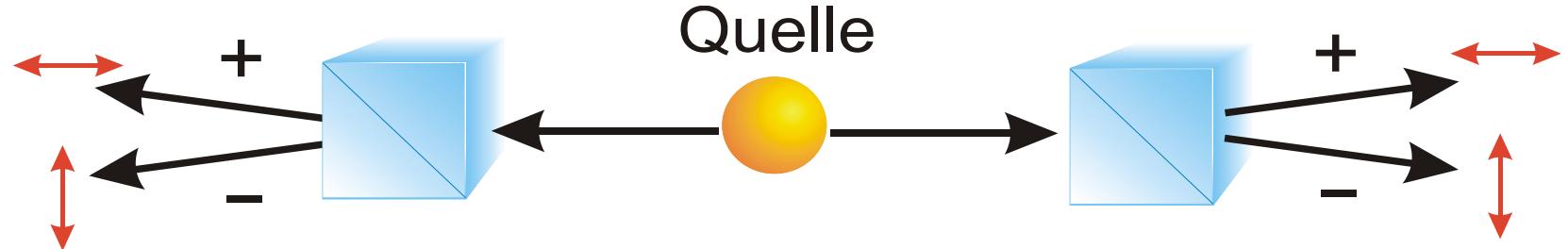
“The EPR criterion is also a criterion for steering, as defined by the violation of the LHS model. **EPR steering confirms the incompatibility of local realism with the completeness of quantum mechanics, just as with the approach of EPR in their original paper”**

# Alpbach, Tyrol, Austria





# Quantum Steering



$$|\Phi^+\rangle = 1/\sqrt{2} (|H\rangle|H\rangle + |V\rangle|V\rangle)$$

$$|\Phi^+\rangle = 1/\sqrt{2} (|H'\rangle|H'\rangle + |V'\rangle|V'\rangle)$$

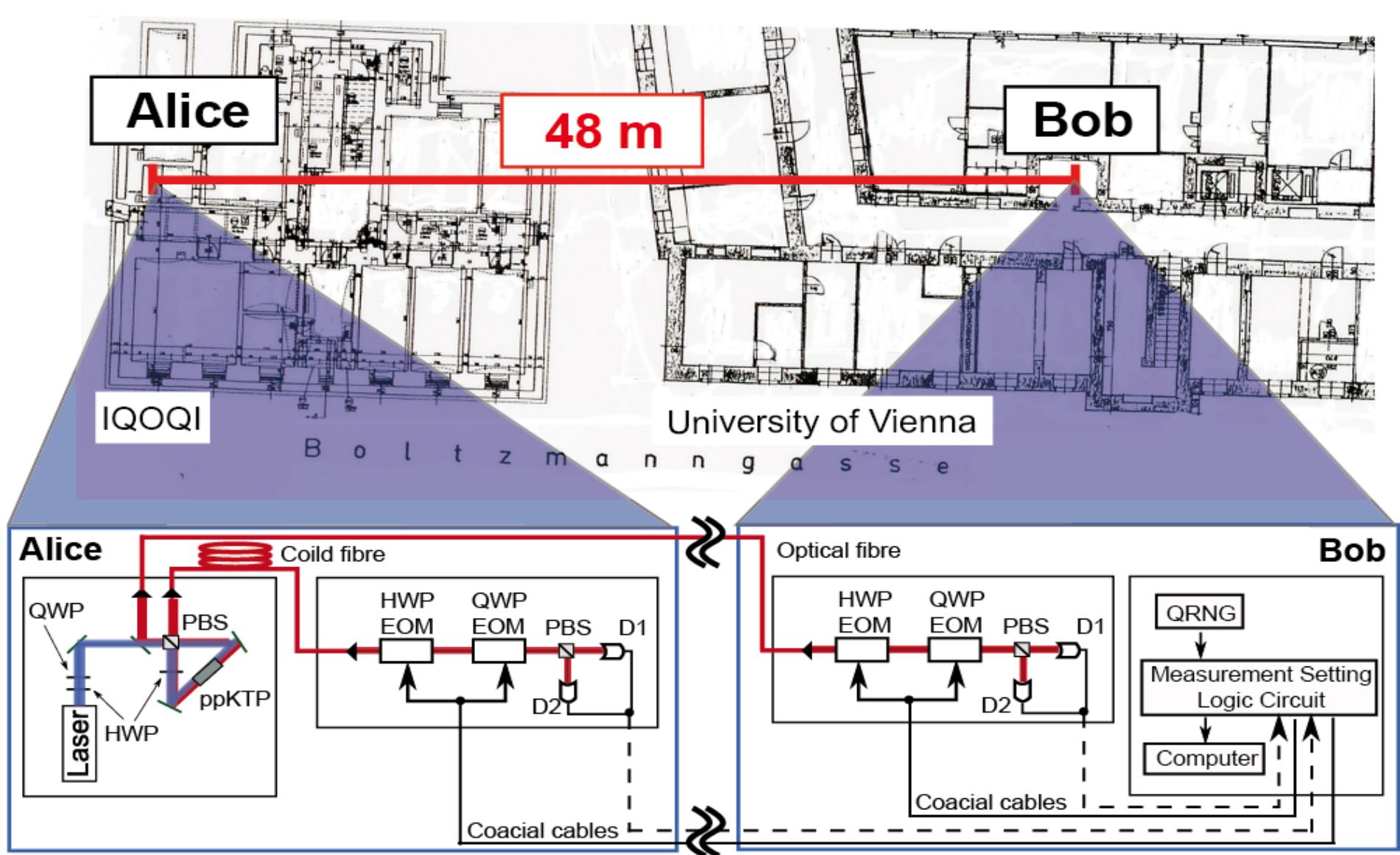
$$|\Phi^+\rangle = 1/\sqrt{2} (|R\rangle|L\rangle + |L\rangle|R\rangle)$$

Schrödinger 1935

Einstein 1948

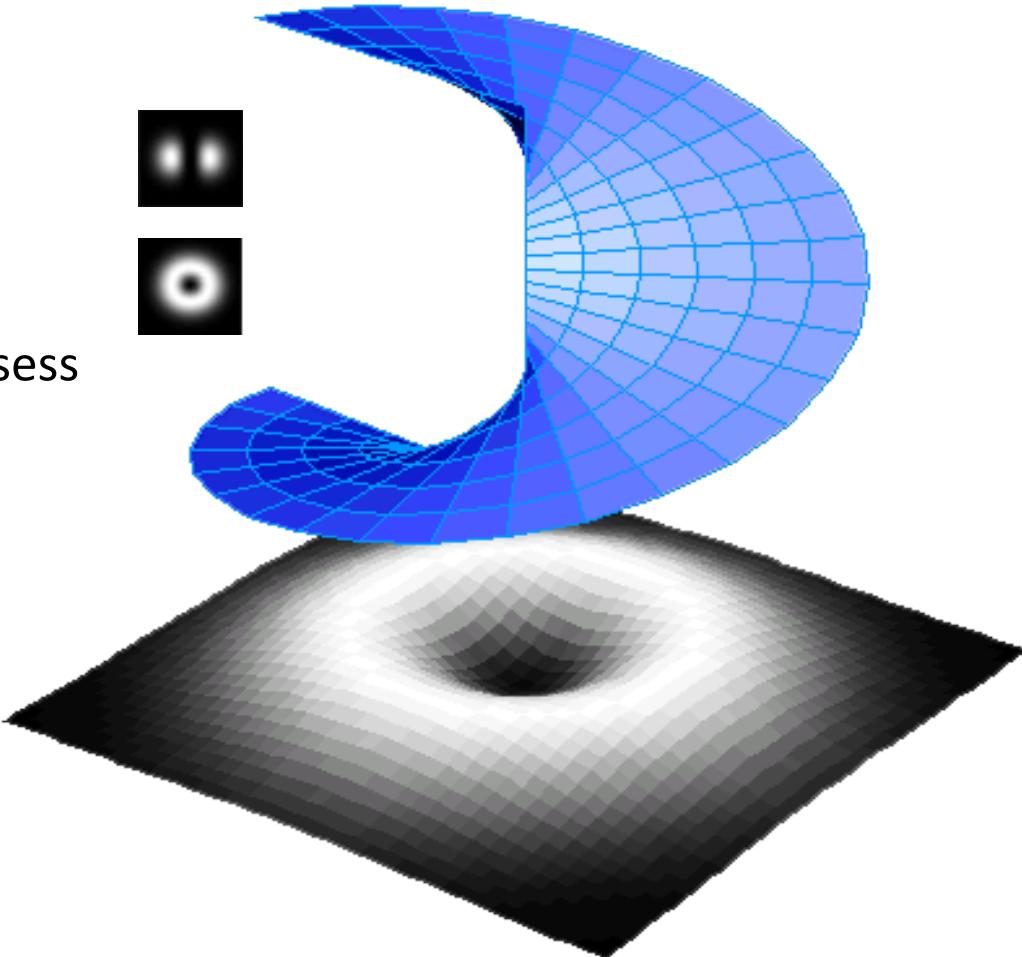
Mutually Unbiased Bases MUBs

# Realization



# Use External Modes, e.g OAM states

- Mode systems of the paraxial approximation
  - Hermite-Gaussian (HG)
  - Laguerre-Gaussian (LG)  
("Doughnuts")
- Laguerre-Gaussian modes possess external ("orbital") angular momentum [1]



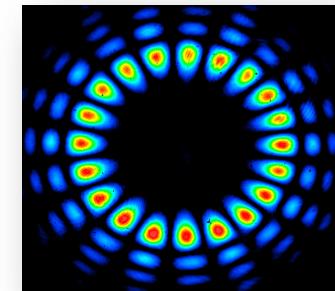
[1] L. Allen, M.W. Beijersbergen, R.J.C. Spreeuw, J.P. Woerdman, Phys. Rev. A **45** (1992)

# High OAM entanglement

- superposition with phase -> 2 MUBs
- visibility in two MUBs ->  
entanglement detection criterion
- Creation and verification of entanglement up to

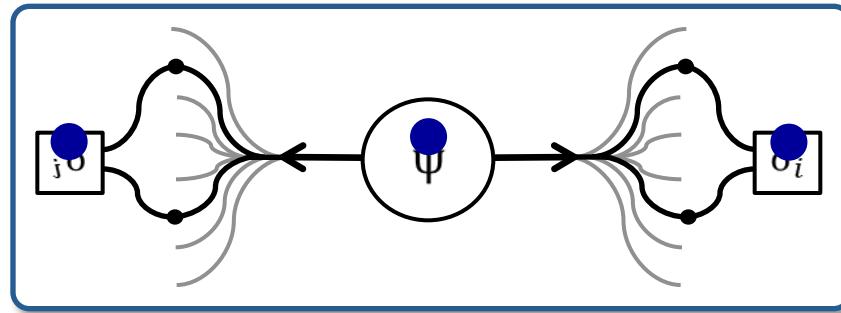
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|300, -300\rangle + | -300, 300\rangle)$$

- OAM per photon: 300 h
- OAM difference: 600 h



# multi-mode entanglement

- 2-dimensional subspaces



- Entanglement detection criterion

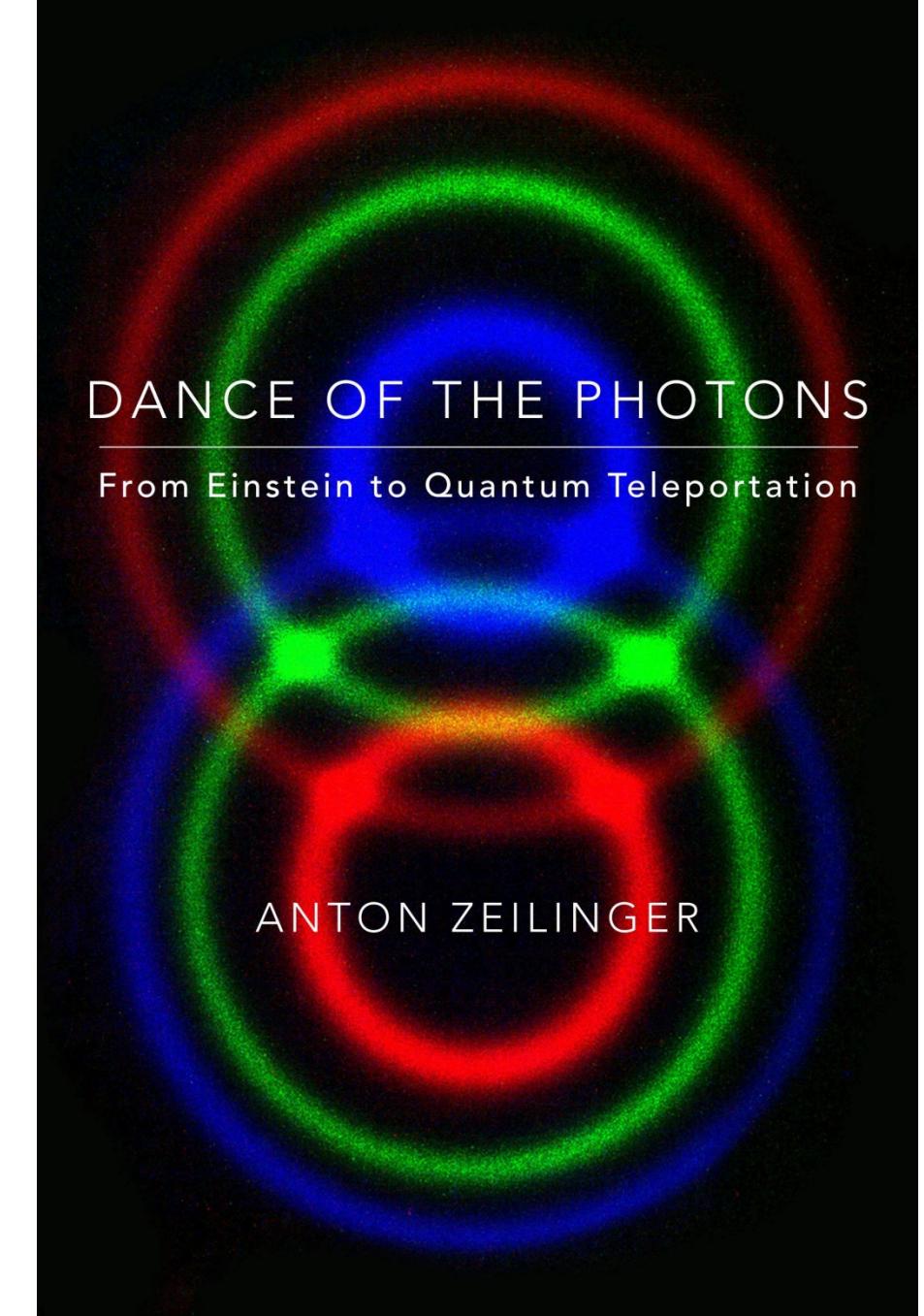
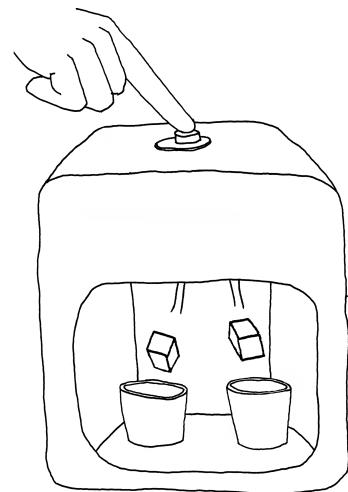
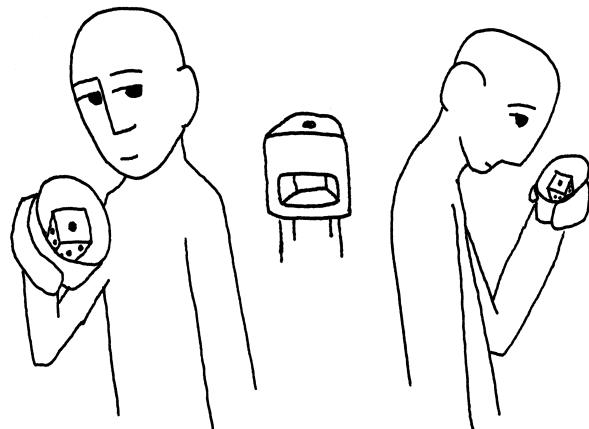
$$\langle \hat{W} \rangle = \sum_{a=0}^{D-1} \sum_{b=0}^{b < a} \frac{1}{N_{a,b}} \left( \langle \sigma_x^{a,b} \otimes \sigma_x^{a,b} \rangle + \langle \sigma_y^{a,b} \otimes \sigma_y^{a,b} \rangle + \langle \sigma_z^{a,b} \otimes \sigma_z^{a,b} \rangle \right)$$

$$\langle \hat{W} \rangle \leq Dd + \frac{D(D-3)}{2}$$

103-dimensional

D = 186 Hilbert Space Dimension  
d dimension of entanglement

# FOTONIEN TANSSI



# Some Possibilities

- Locality ?
- Total Determinism ?
- Actions back into Past ?
- Aristotelean Logic ?
- Counterfactual Reasoning ?
- Realism ????
- Many Worlds ?



# Thank you very much

