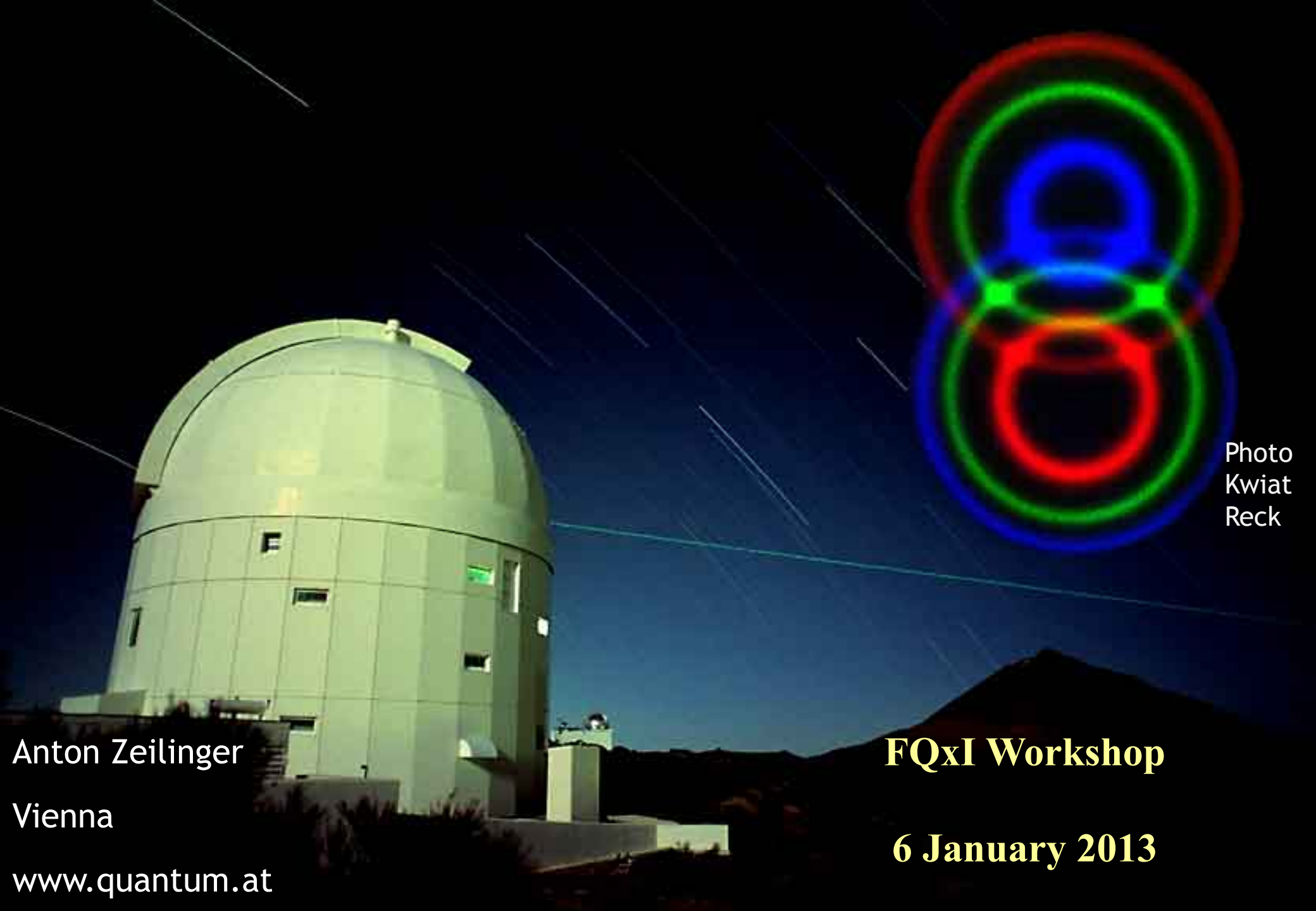


Photo
Kwiat
Reck

Anton Zeilinger

Vienna

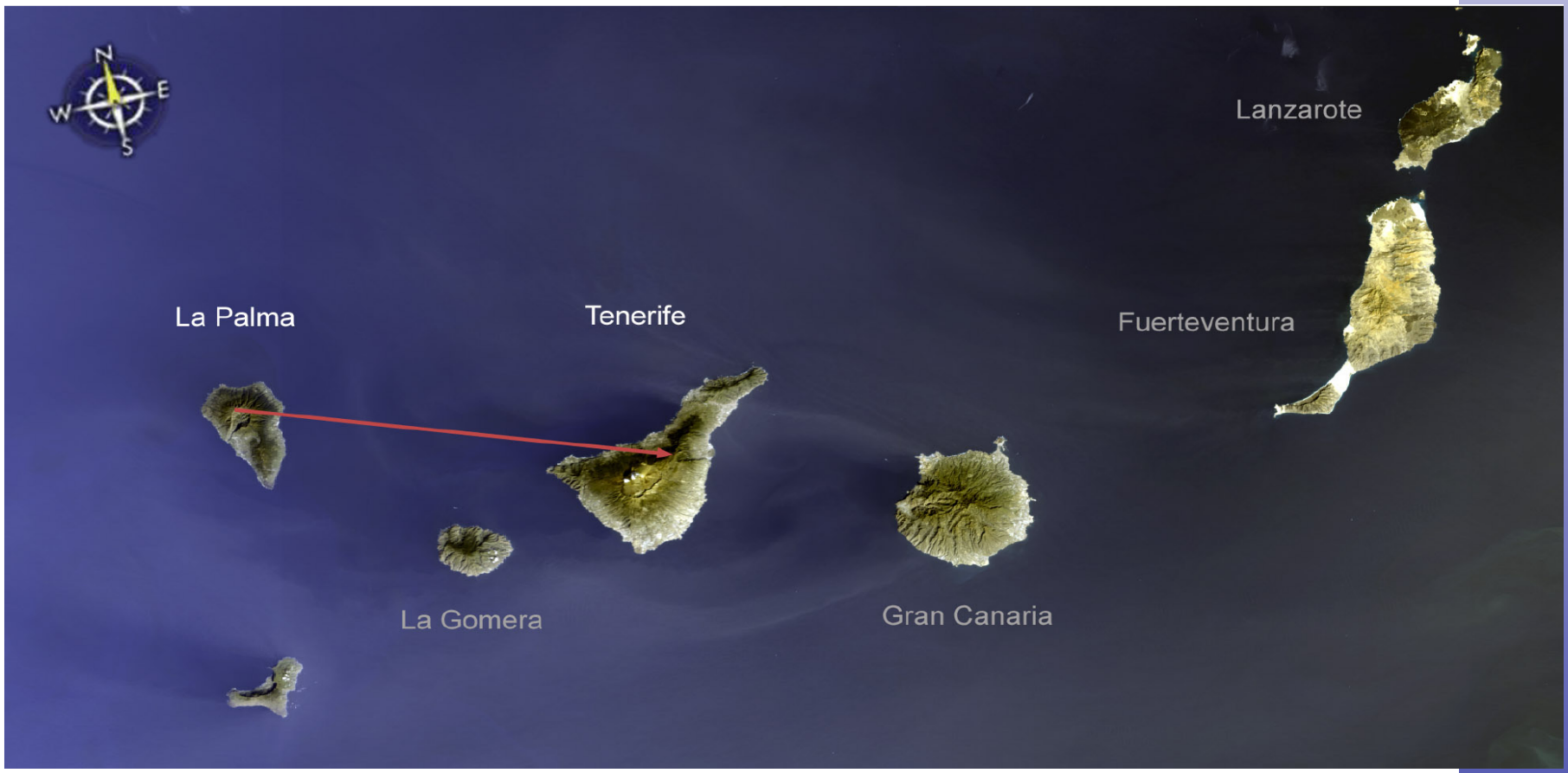
www.quantum.at

FQxI Workshop

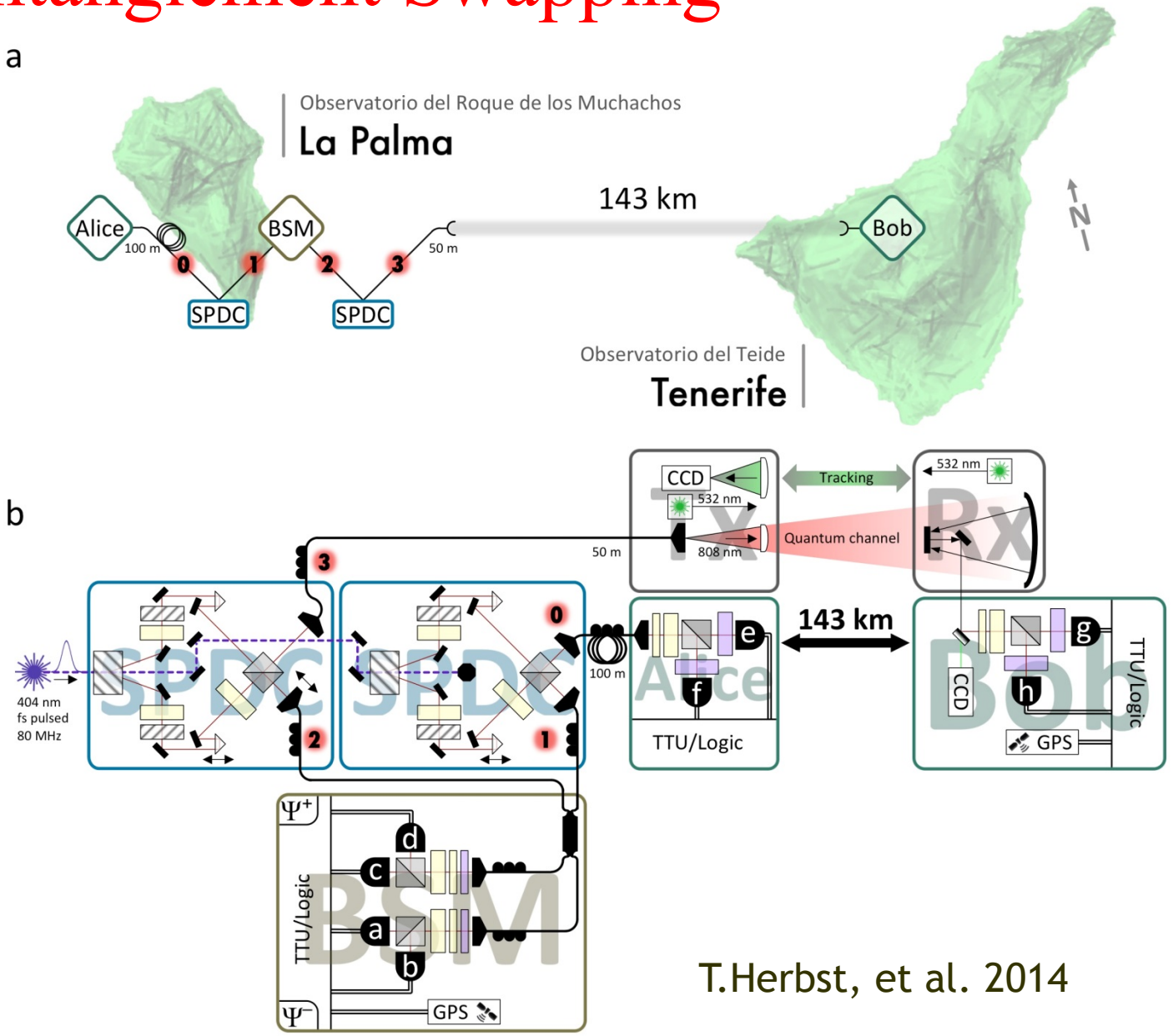
6 January 2013

Long-Distance Entanglement

Canary Islands 143 km

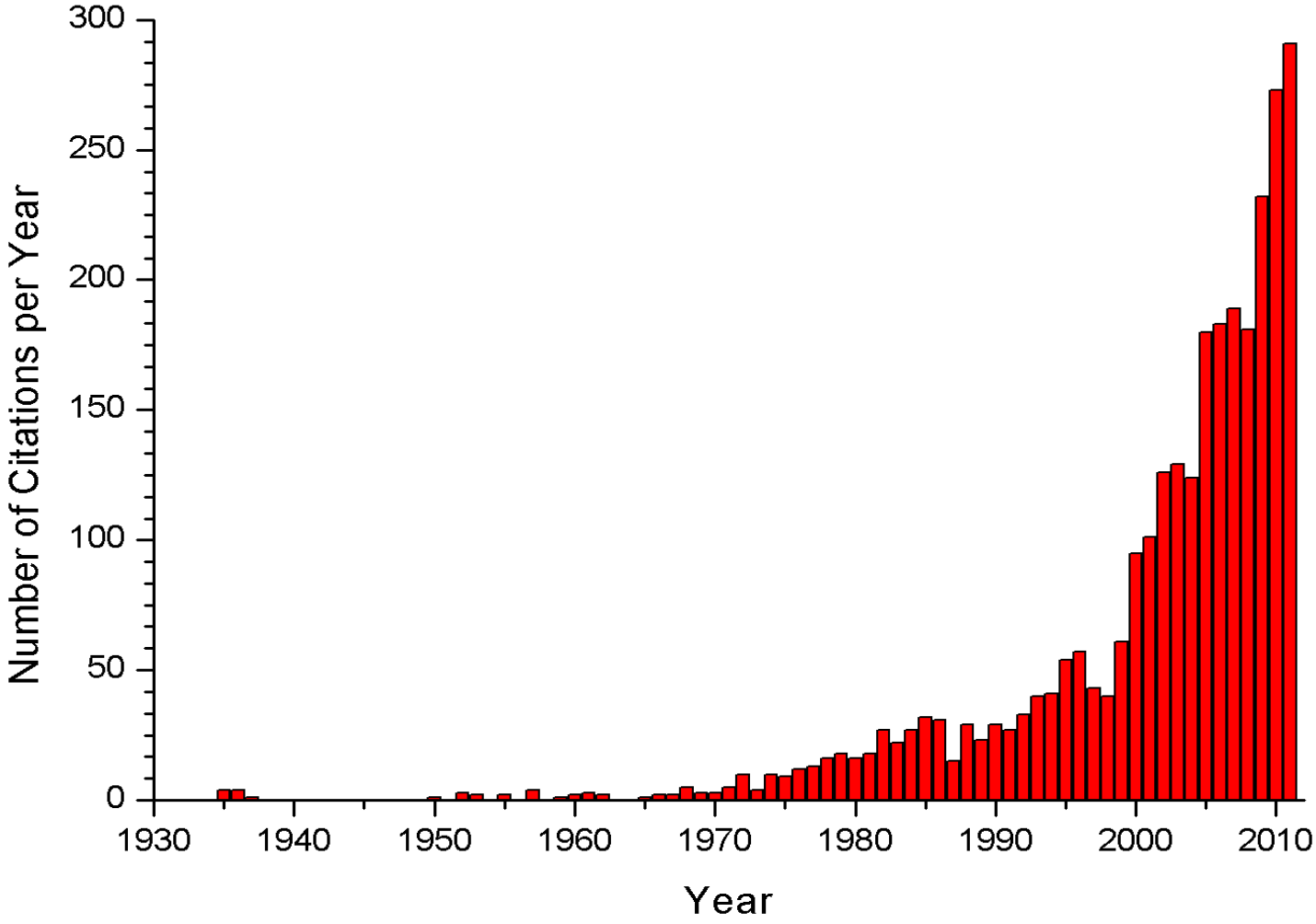


Teleportation of Entanglement
Entanglement Swapping



T.Herbst, et al. 2014

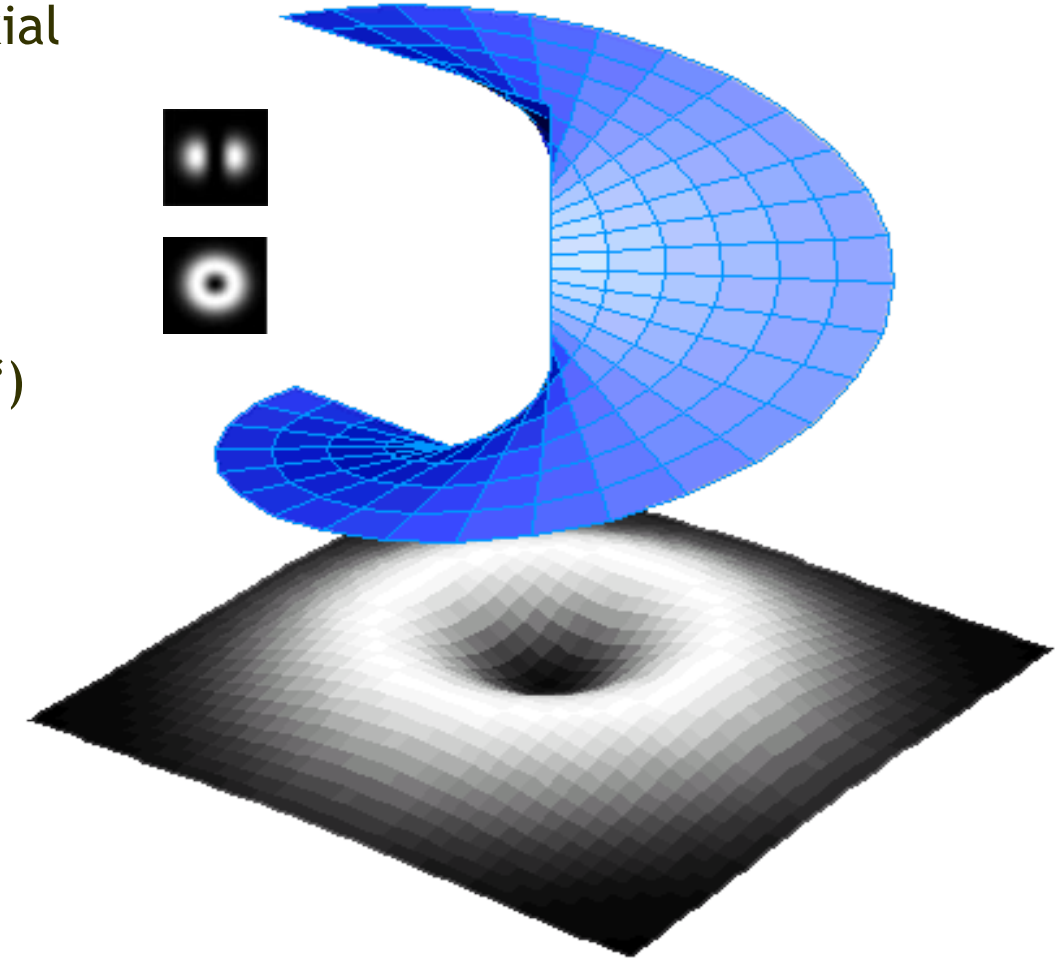
Einstein-Podolsky-Rosen Citations



Use External Modes,
e.g OAM states

- Mode systems of the paraxial approximation
  - Laguerre-Gaussian (LG) („Doughnuts“)
- Laguerre-Gaussian modes possess external („orbital“) angular momentum [1]
- Phase Singularity
- Topological Charge l
- Quantum:

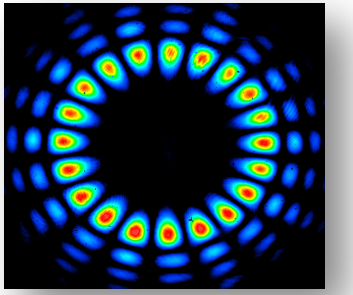
$$L = l\hbar$$



[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

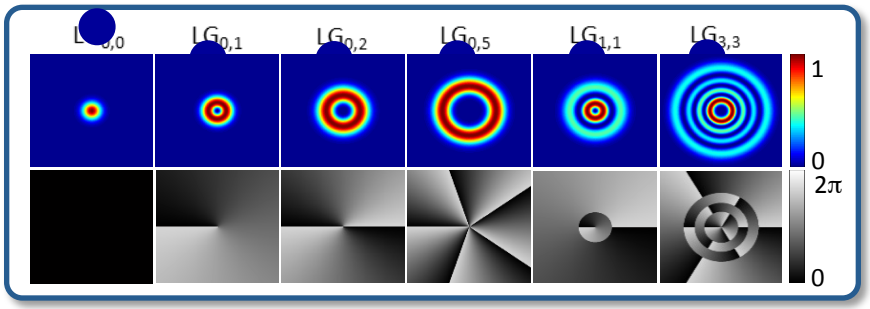
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|300,-300\rangle + |-300,300\rangle\right)$$

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

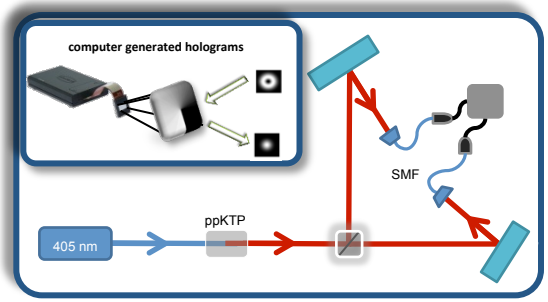
Robert Fickler *et.al.* "Quantum Entanglement of High Angular Momenta", Science **338** (2012).

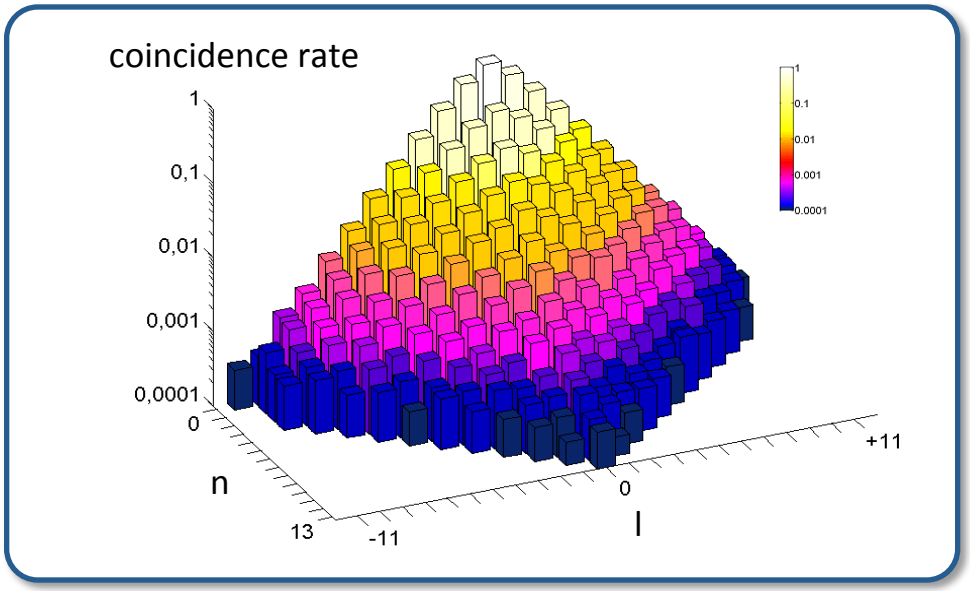
multi-mode entanglement

- High-dimensional Hilbert-space: Laguerre-Gauss modes



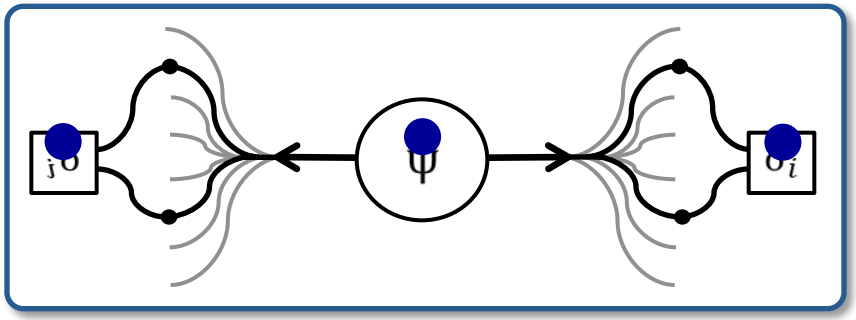
- SPDC in ppKTP creates high-order modes
- correlations





multi-mode entanglement

- 2-dimensional subspaces



- Entanglement detection criterion

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

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

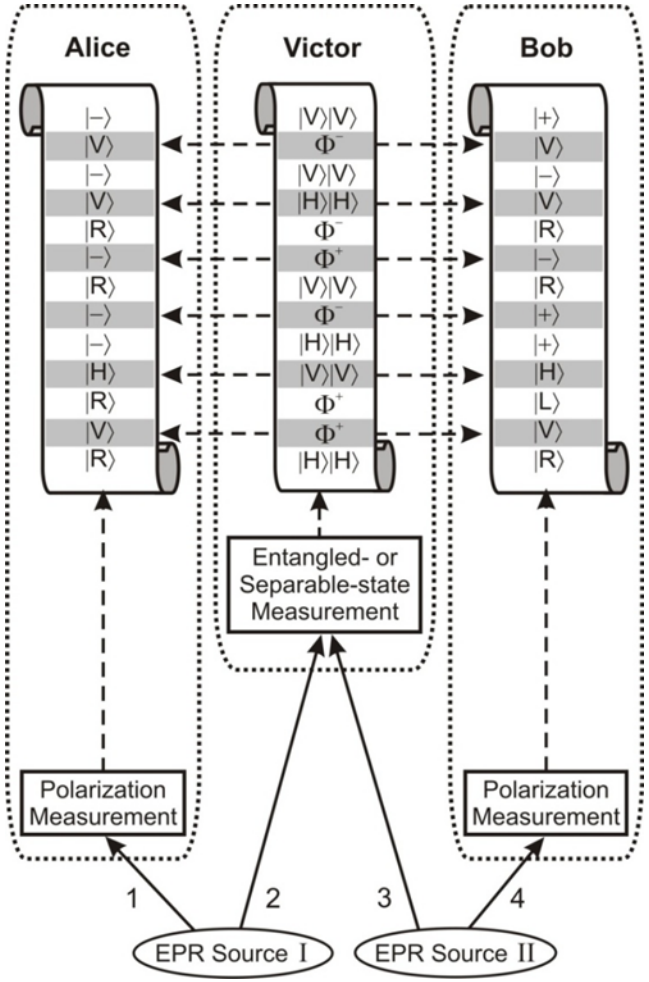
103x103-dimensional Entanglement

D = 186 Hilbert Space Dimension

d dimension of entanglement

Krenn et al. Arxiv recently

Delayed – Choice Teleportation of an Entangled State
Entanglement Swapping



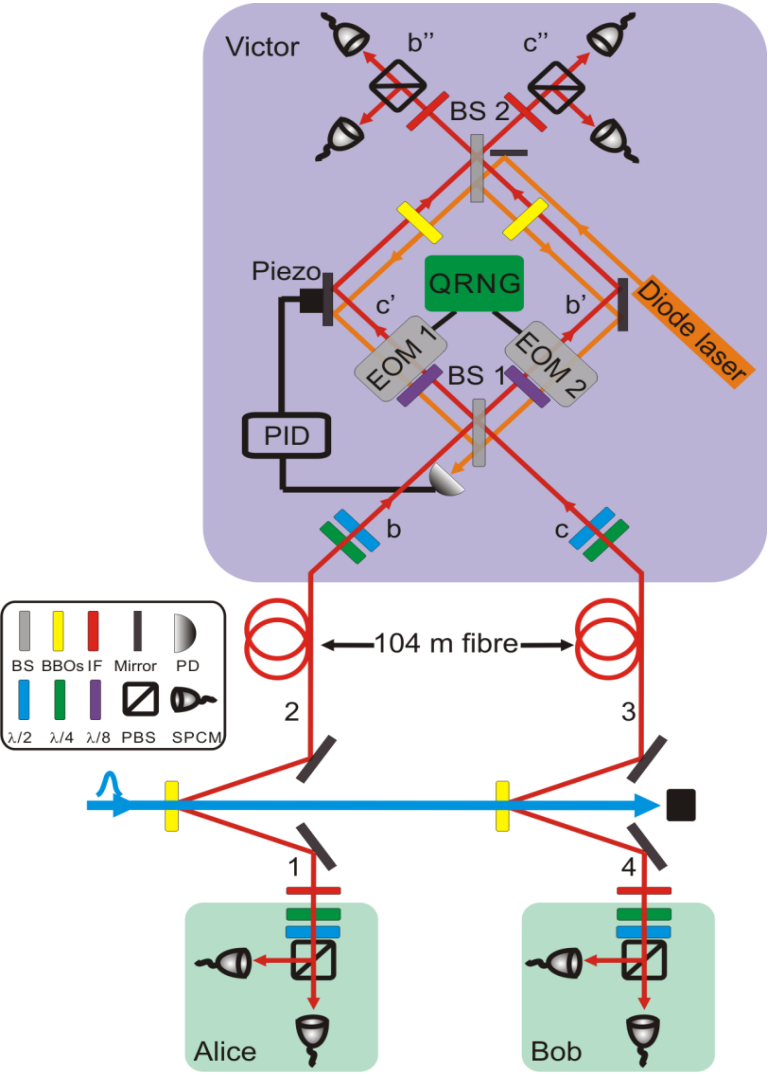
Photon 1 and 4
Become Entangled
after their
Registration!

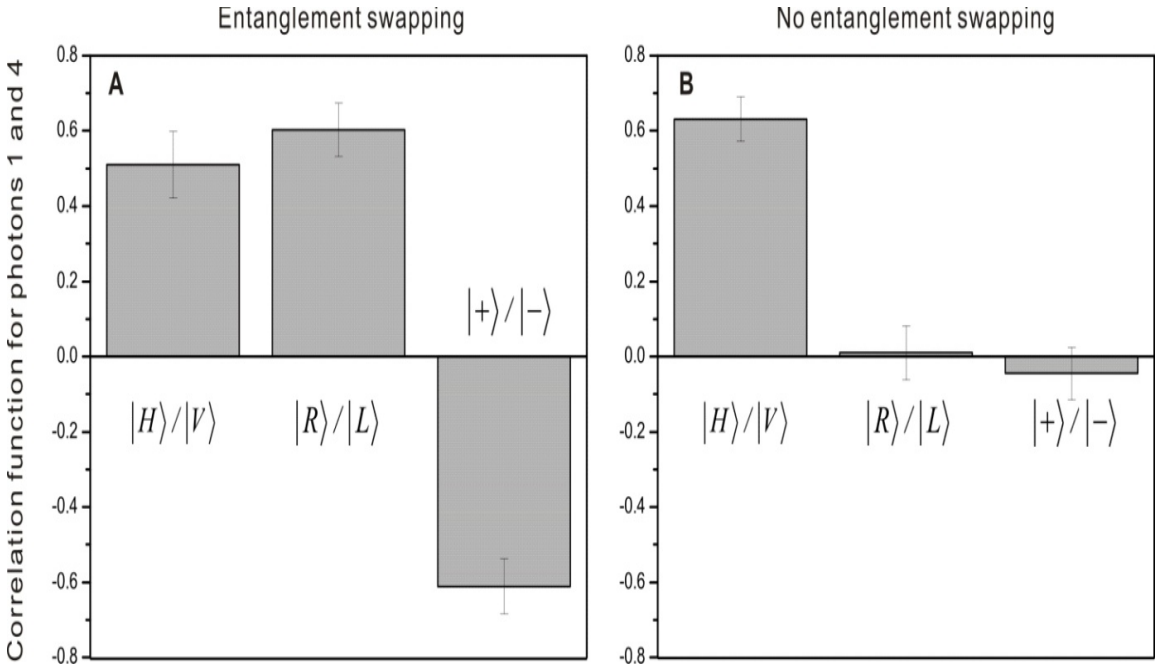
Relational Bits!

Idea: Asher Peres 2001

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

Delayed-choice entanglement swapping





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

Events are a more fundamental reality than quantum states

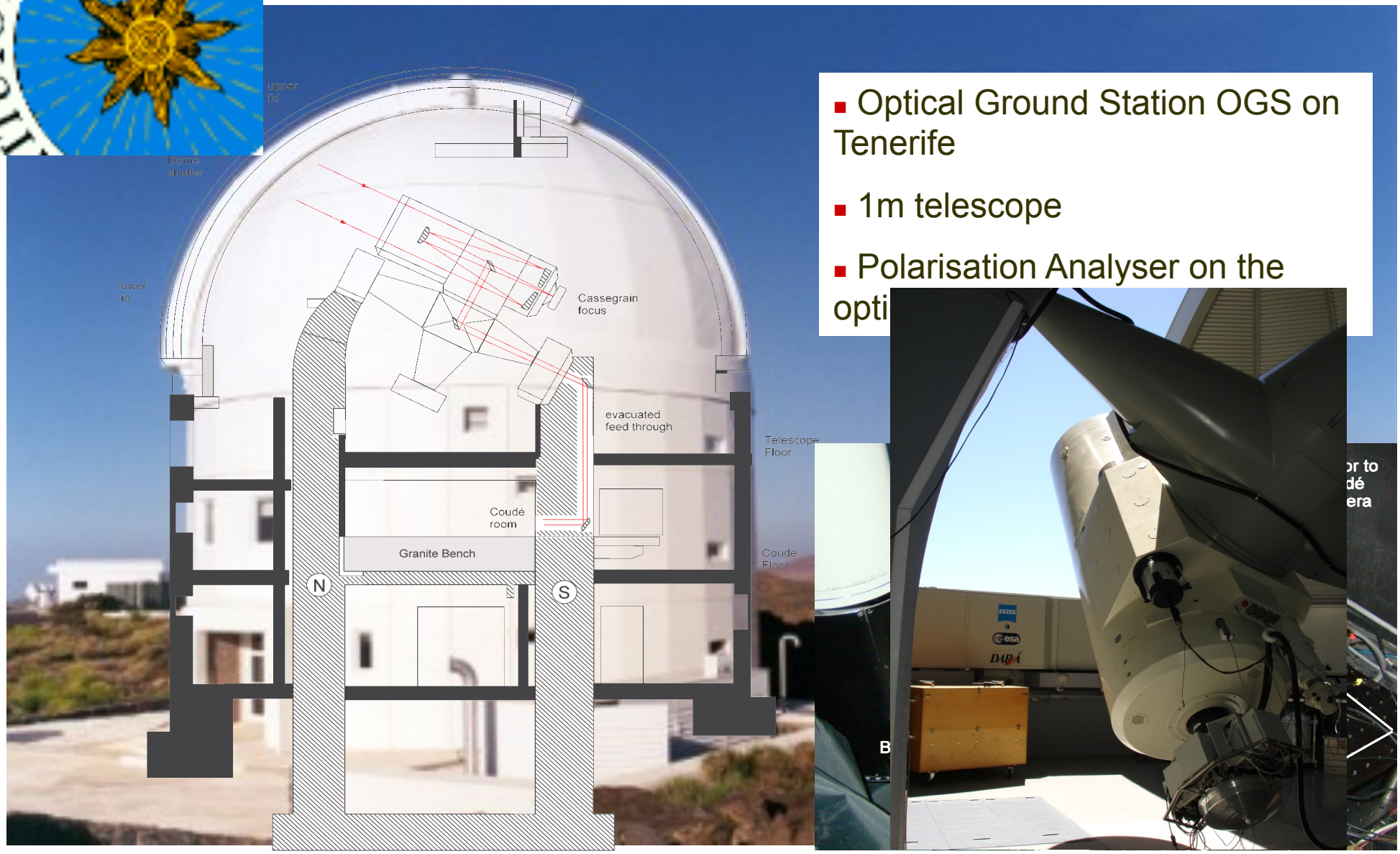
Wigner

Amer.J.Phys. (1963)

… the state vector is only a shorthand expression of that part of our information concerning the past of the system which is relevant for predicting (as far as possible) the future behaviour thereof.

AZ.: So it connects knowledge about a classical apparatus with knowledge about future possible features of classical apparatus

Receiver



- Optical Ground Station OGS on Tenerife
- 1m telescope
- Polarisation Analyser on the opti

Randomness and Measurement

Randomness of the individual quantum event is our strongest evidence for the existence of an outside world

That randomness limits our ability to control the world

Our ability is limited to the choice of apparatus

Two Freedoms:

My freedom to define which measurement apparatus to use and thus determine which quality can become reality

Nature‘s freedom to give the answer she likes

What new findings, developments, impulses are at the heart of your hopes for the future?

- The huge progress of experiments

My hope: none of them will show a deviation from present quantum mechanics

Why: then the counterintuitive prediction have to be faced by everyone

What then?

What new findings, developments, impulses are at the heart of your hopes for the future?

Hope for the future:
That we find the fundamental, simple principle from it follows that quantum physics is a necessity that governs the World

Quantum Physics: What is the Relation of Information and Reality ?

If we only admit concepts which can be operationally verified:

It is impossible to operationally verify any distinction between reality and information

Decartes:

I think,therefore I am

Decartes:

I think,therefore I am

Augustinus:

I doubt therefore I am

Decartes:

I think,therefore I am

Augustinus:

I doubt therefore I am

Greenberger:

I am confused therefore I am

Thank you very much