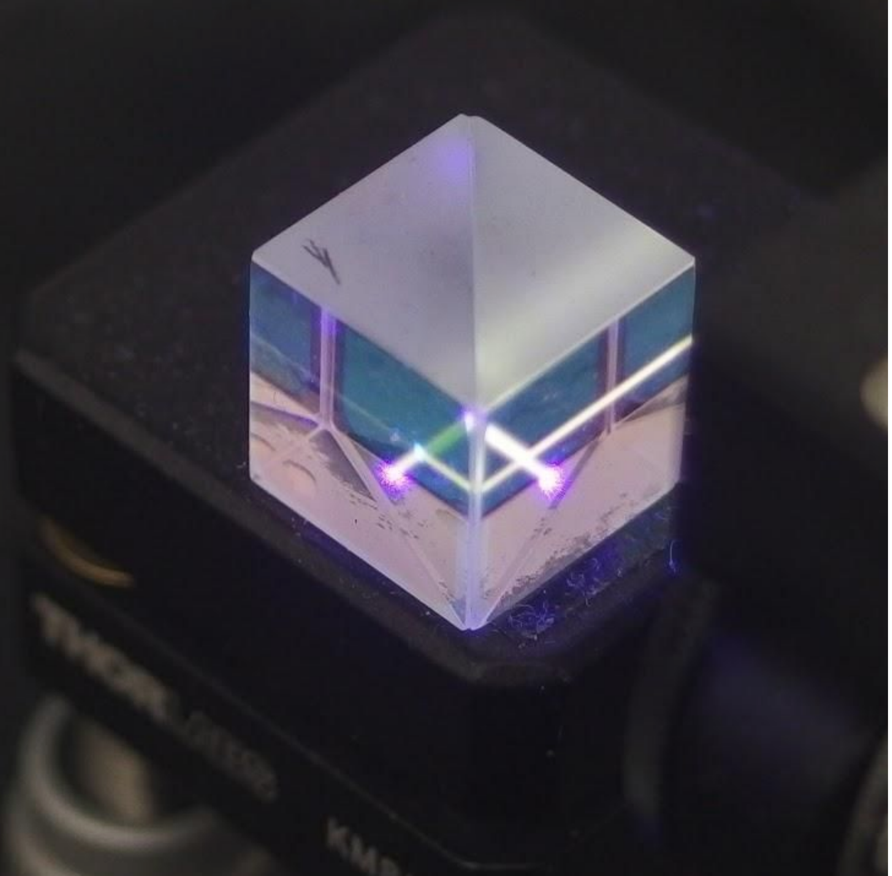
EXPERIMENTAL QUANTUM COMMUNICATION WITH GNSS SATELLITES

Admission to the final exam
14 September 2018

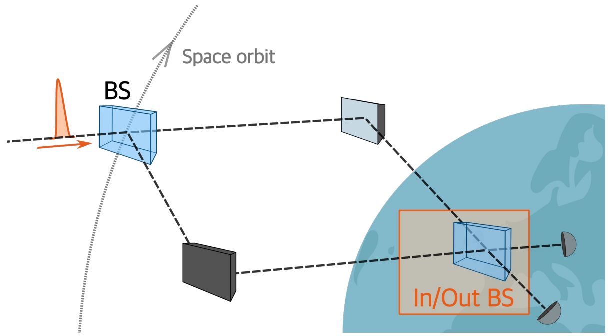
Luca Calderaro



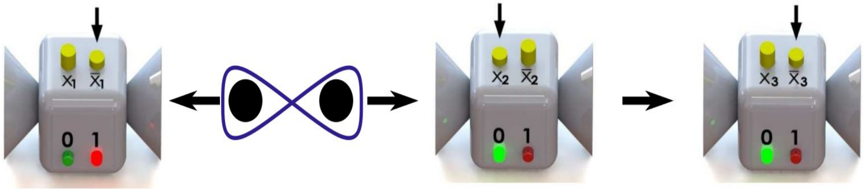
Results of my PhD project

Towards Quantum Communication from GNSS

Wheeler's delayed choice experiment extended on a space channel



Three-observer Bell inequality violation on a two-qubit entangled state



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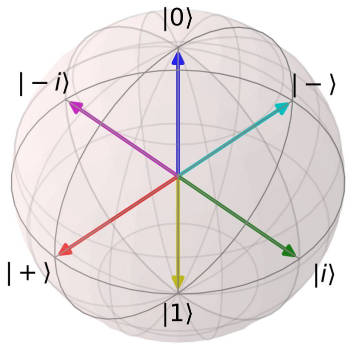
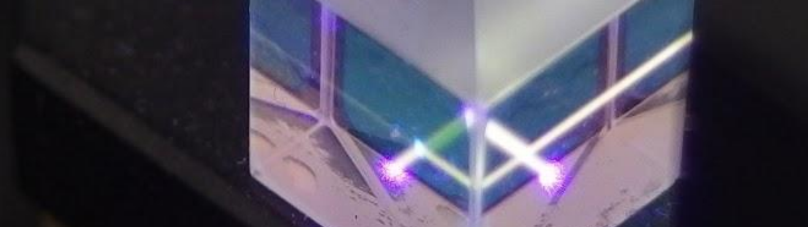


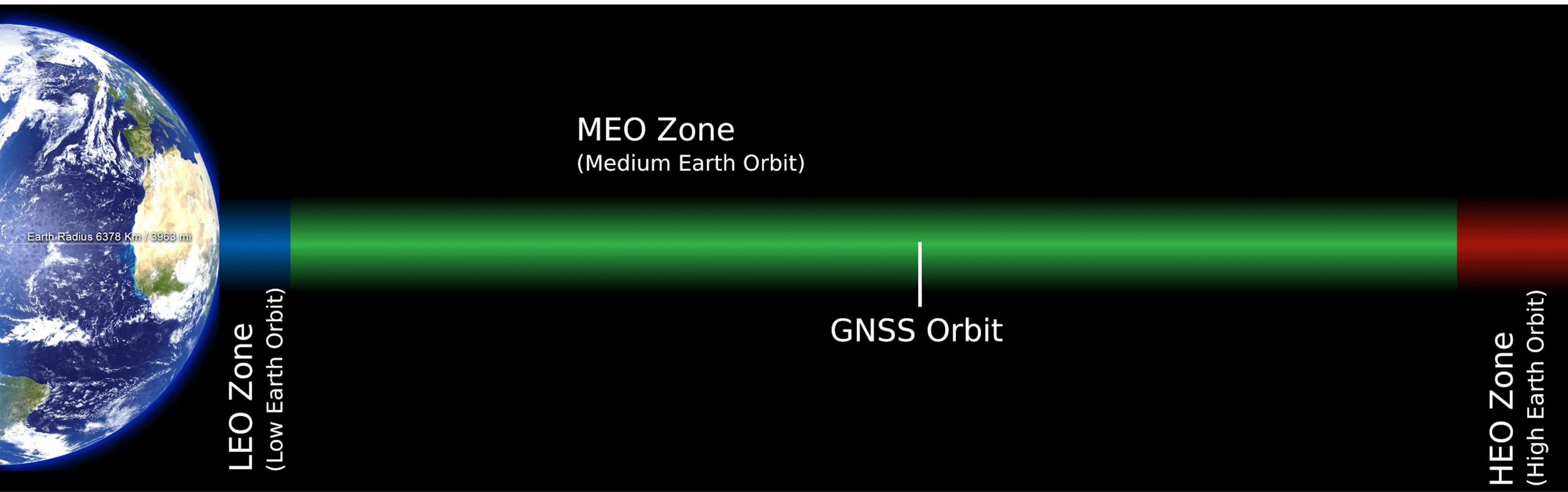
Towards Quantum Communication from GNSS



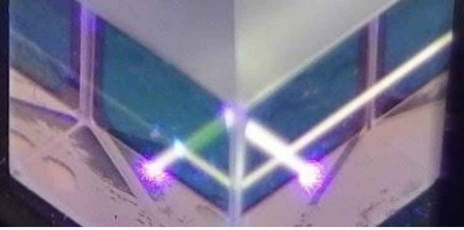
Quantum communication regards all the communication protocols that deal with the faithful transmission of quantum states.

Goal: to demonstrate the feasibility of transmitting quantums states from a MEO satellite to ground. The orbit of Global Navigation Satellite Systems (GNSS) is the target (20000 km altitude).

Motivation:
- To allow the use of Quantum Cryptography for securing GNSS.
- To extend fundamental tests of Quantum Mechanics in a space link with higher satellites.



Towards Quantum Communication from GNSS

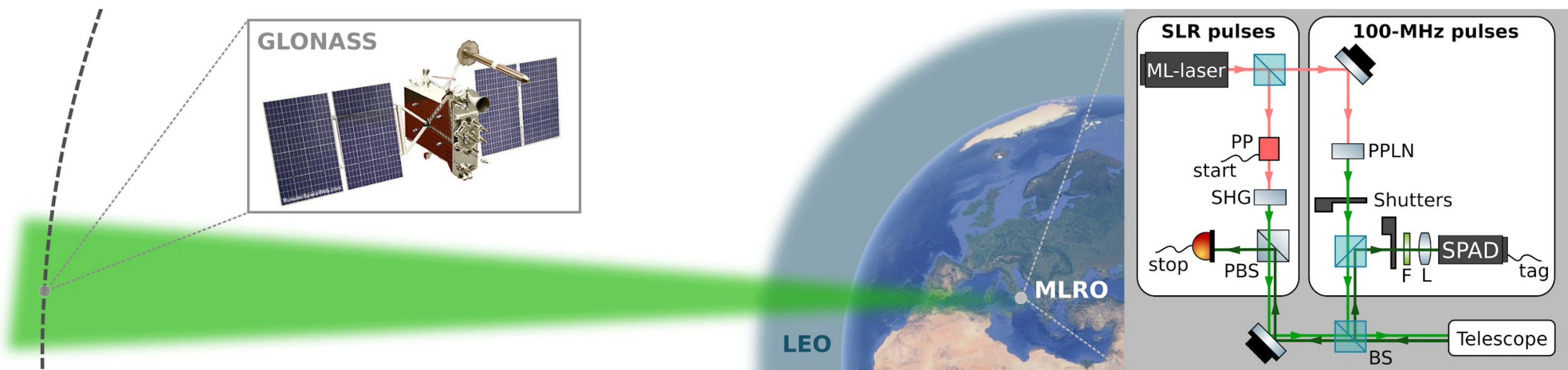


Transmitter on the satellite: Simulated exploiting the reflection of a laser beam, pulsed at 100 MHz, by an array of corner cube retroreflectors. Only a tiny fraction of the pulse is reflected back to the station (10 photons per pulse).

Receiver on ground: The returning beam is collected by the telescope and detected by a Single Photon Avalanche Detector (SPAD).

Challenges:

- High losses of the channel (about 60 dB), mostly due to diffraction.
- Low SNR.

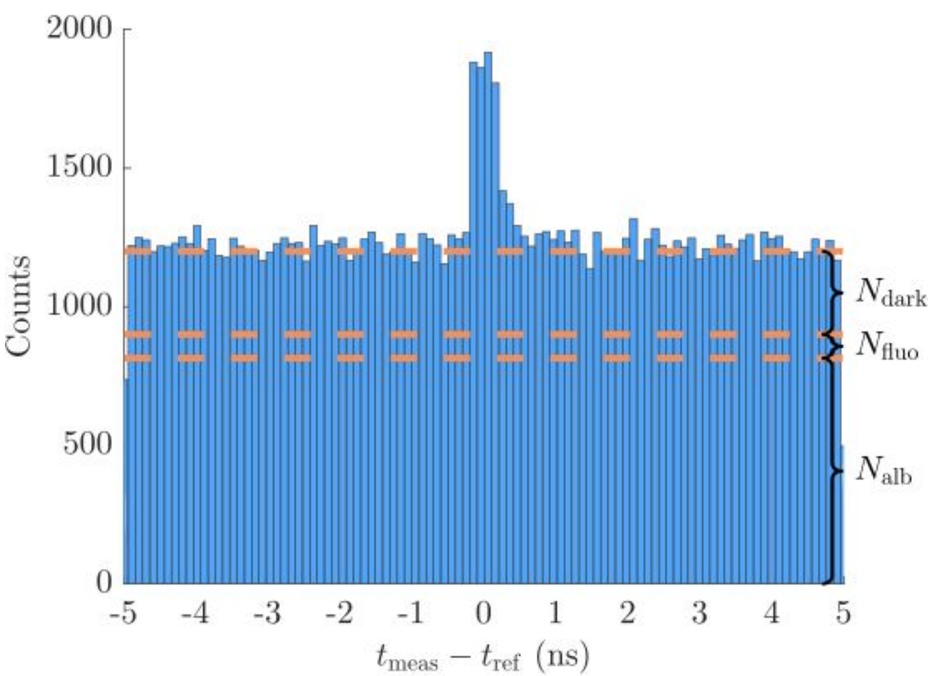


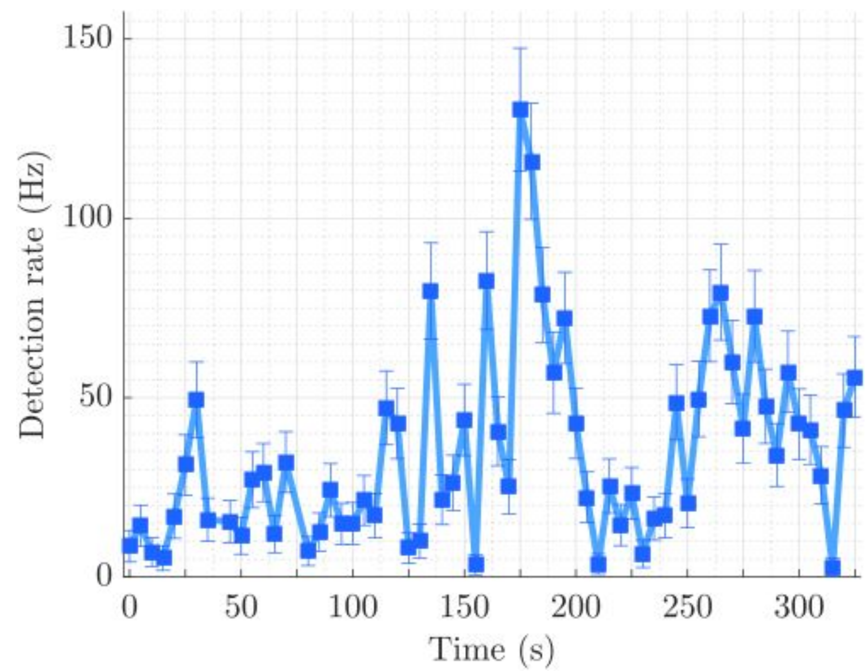
Towards Quantum Communication from GNSS

Results

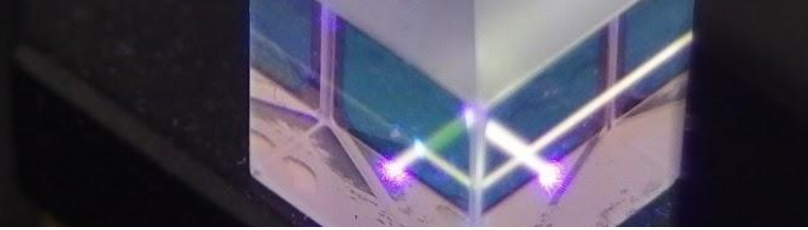
We detected photons reflected by Glonass-134 and Glonass-131, with mean detection rate of 60Hz, SNR of 0.4, and 15 photons per pulse on average reflected by the satellite.

The detection rate and SNR can be drastically improved by means of a telescope on the satellite to lower the diffraction losses. With a 10 μrad of beam divergence we expect to have a detection rate of about 10 kHz and a SNR of the order of 100.

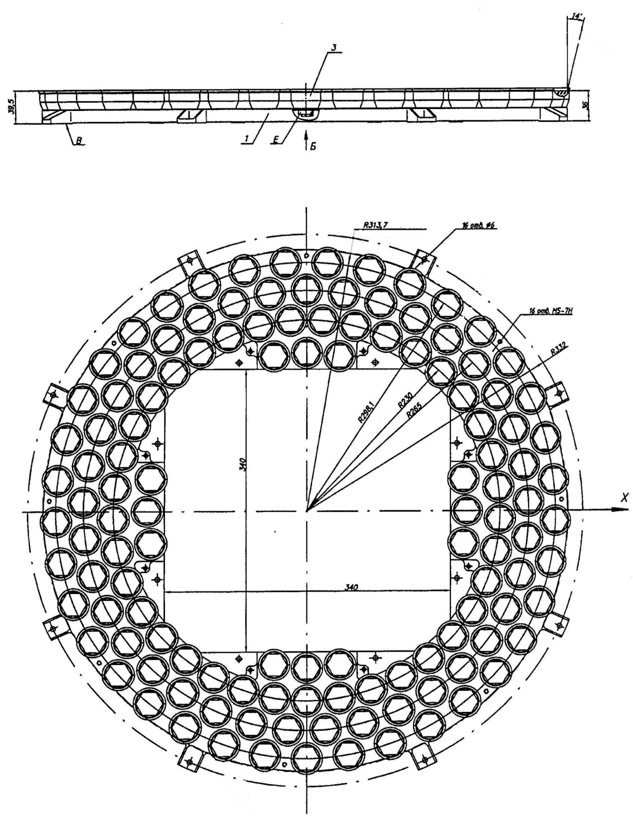


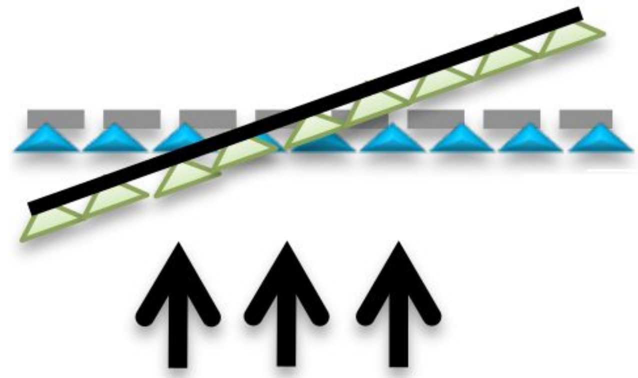


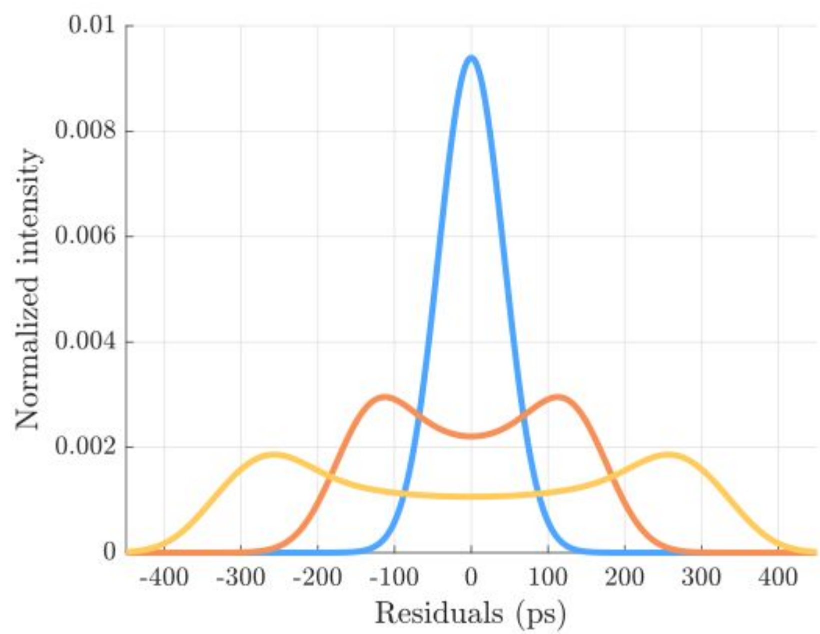
Towards Quantum Communication from GNSS



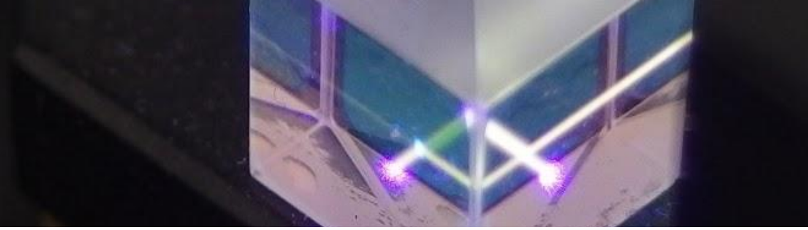
Temporal spread of the pulse due to the reflection of the CCR array.



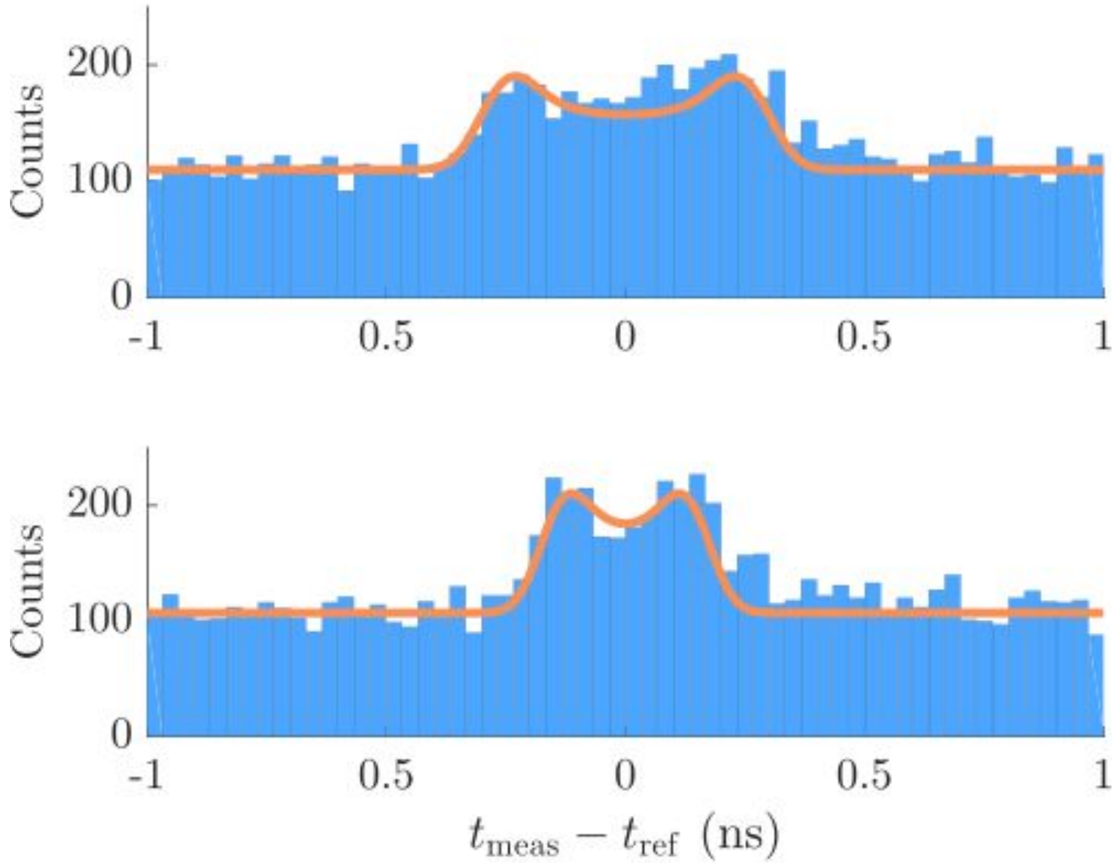




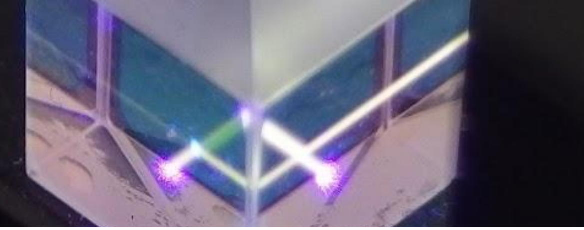
Towards Quantum Communication from GNSS



Thanks to the precision on the measurement of the arrival time of the photon (50ps jitter) we are able to resolve the temporal spread of the pulse. The figure on the **top** (**bottom**) shows the temporal spread for an incident angle of 10° (5°).



Wheeler’s delayed choice experiment extended on a space channel



Goal: demonstrate the wave-particle duality of the photon after travelling a space channel.

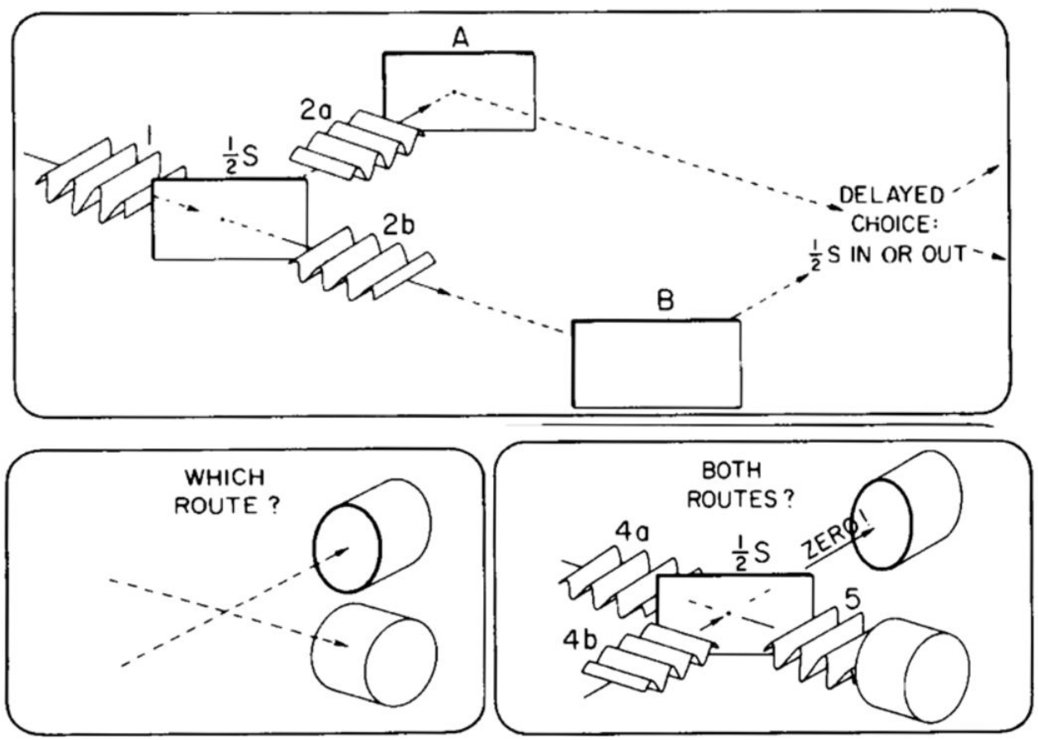
Motivation: show that fundamental tests of quantum mechanics can be performed exploiting satellite-to-ground channels.

Wheeler’s delayed choice experiment extended on a space channel

Is the photon a wave or a particle?

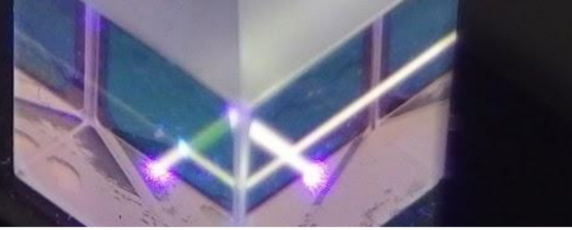
Case 1: For each photon injected only one detector “click”, which one is not known. Hence, the photon behaves like a classical indivisible particle.

Case 2: For each photon only the same detector “click”. Hence, the photon behaves like a classical wave.



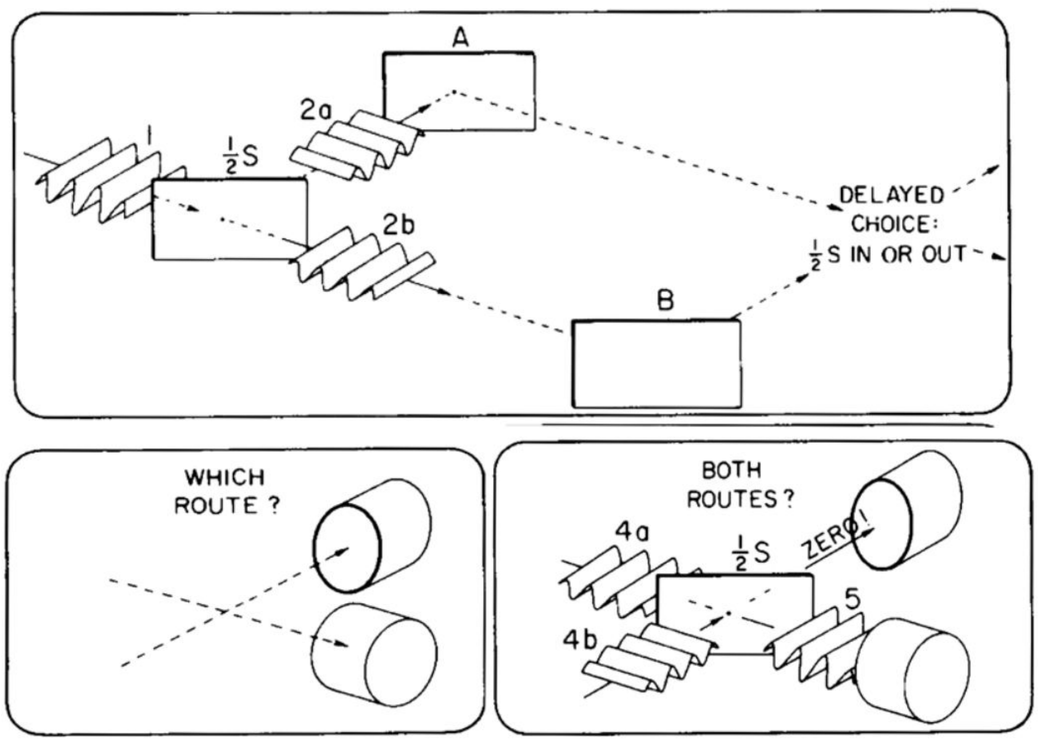
Case 1 **Case 2**

Wheeler's delayed choice experiment extended on a space channel



From a classical standpoint an object cannot be both a wave and a particle at the same time, then the photon should be choosing, before entering the interferometer, whether to behave like a wave or a particle, depending on the setup of the experiment.

Wheeler's idea is to delay the choice of the measurement setup after the photon has entered the interferometer.



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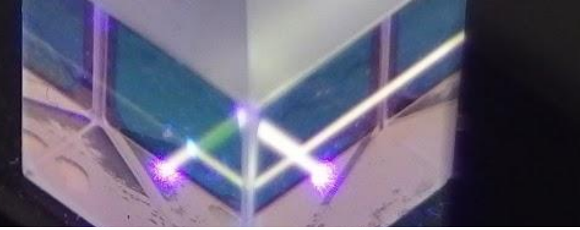
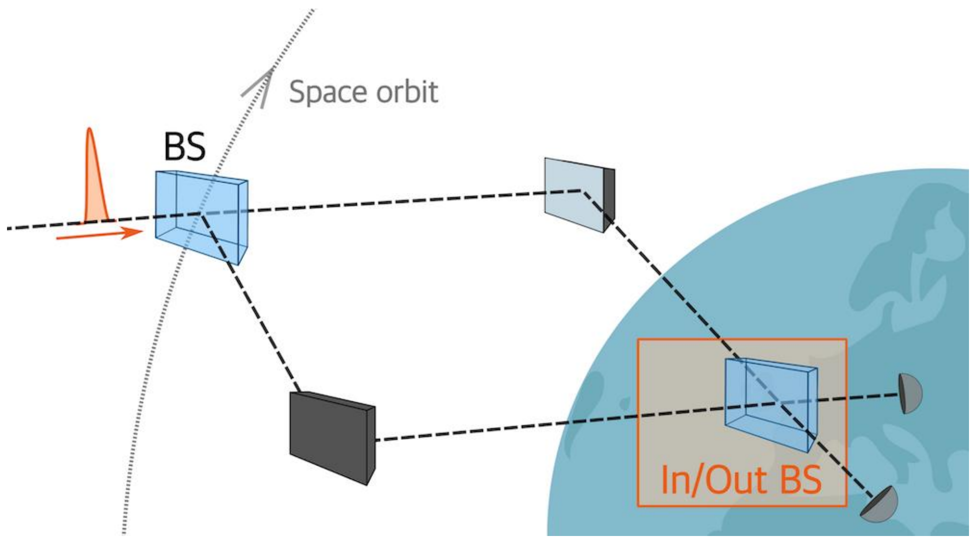
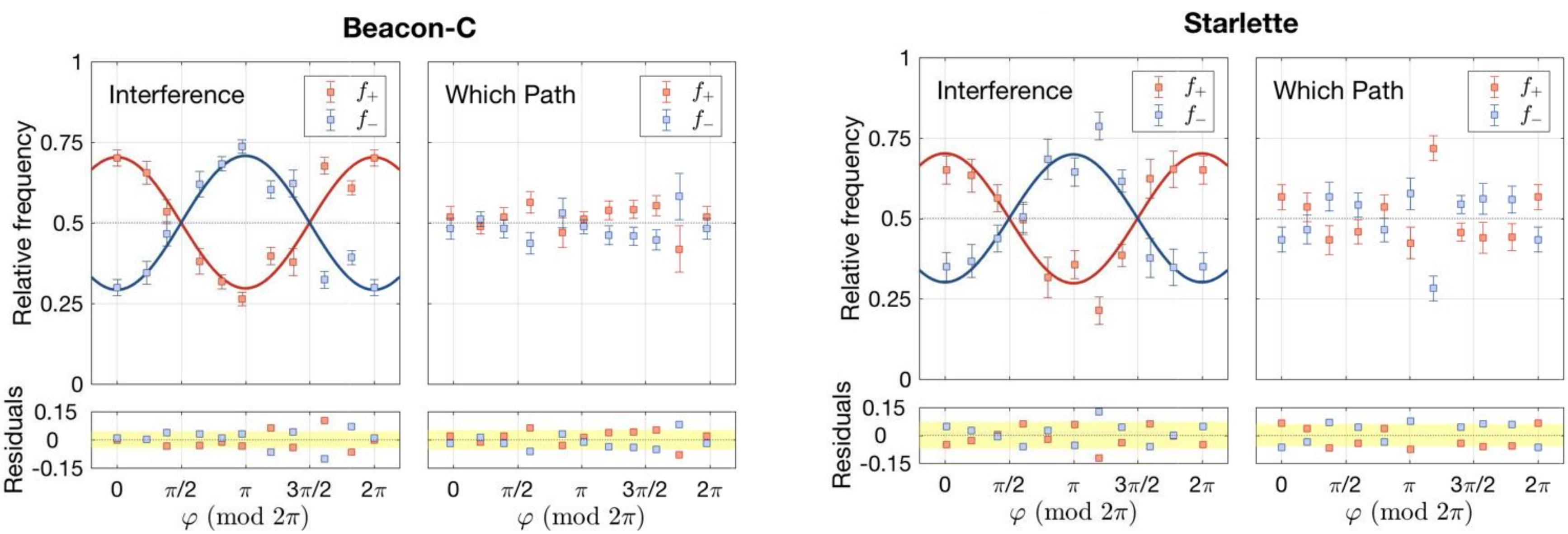
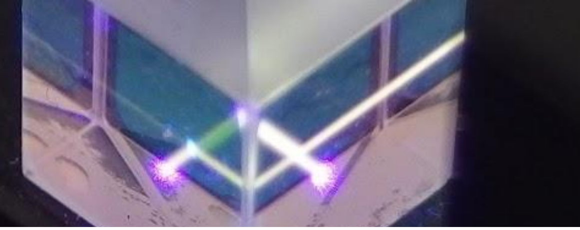






Three-observer Bell inequality violation on a two-qubit entangled state



Goal: to show that two entangled photons are enough to violate two different Bell inequalities at the same time.

Motivation: in this scenario, quantum entanglement may provide a resource to device new quantum protocols for the generation of secure keys and random numbers.

Three-observer Bell inequality violation on a two-qubit entangled state

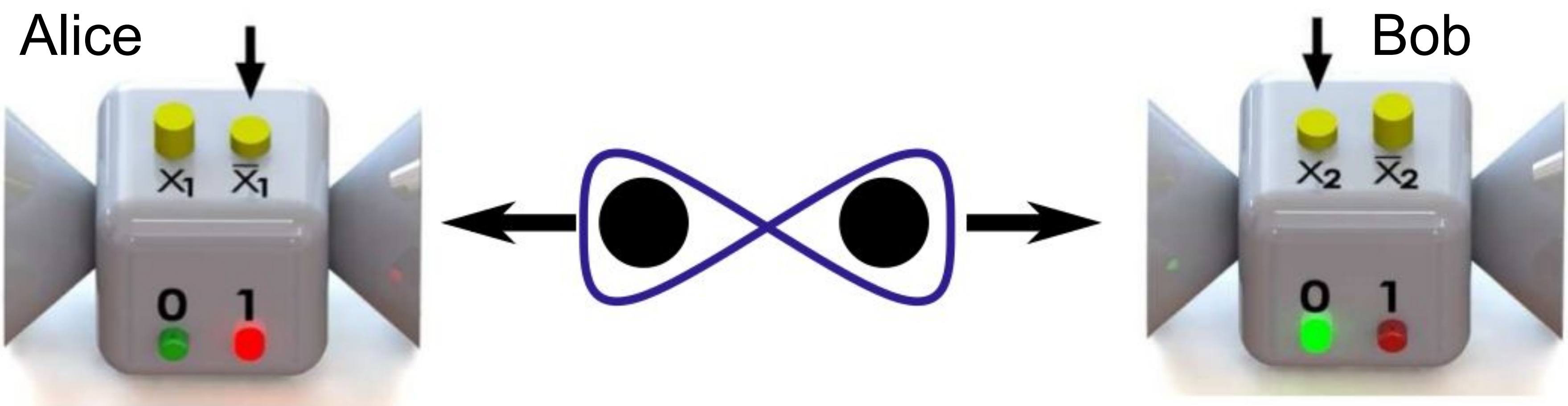
Bell inequality

For any theory which is based on the following assumptions:

- **locality**: the results of two measurements, occurred in causally disconnected events, cannot influence each other due to the limited speed of light.
- **realism**: physical systems possess objective properties whose value does not depend on the choice of measurement. Measurements merely reveal an objective property of the system.

$$I_{\mathrm{CHSH}} = E_{x_1 x_2} + E_{x_1 \bar{x}_2} + E_{\bar{x}_1 x_2} - E_{\bar{x}_1 \bar{x}_2} \leq 2$$

$$E_{x_1 x_2} = \sum_{ab=0,1} (-1)^{a+b} P(a,b)$$



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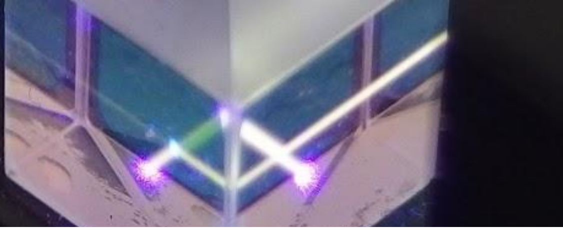
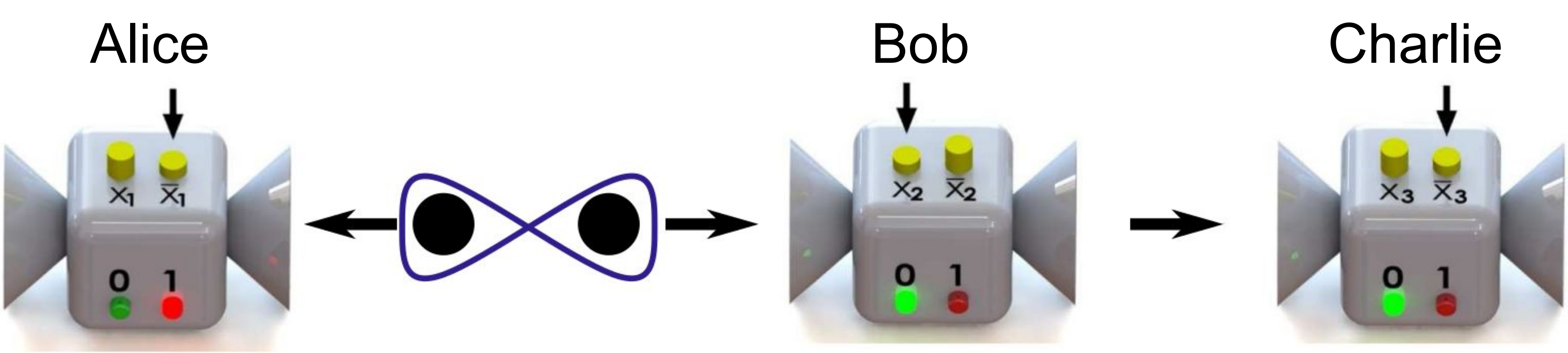


Three partite scenario: Alice, Bob and Charlie

$$I_{\mathrm{CHSH}}^{(1)} = E_{x_1 x_2} + E_{x_1 \bar{x}_2} + E_{\bar{x}_1 x_2} - E_{\bar{x}_1 \bar{x}_2} \leq 2$$

$$I_{\mathrm{CHSH}}^{(2)} = E_{x_1 x_3} + E_{x_1 \bar{x}_3} + E_{\bar{x}_1 x_3} - E_{\bar{x}_1 \bar{x}_3} \leq 2$$



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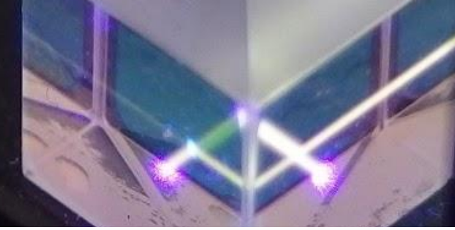

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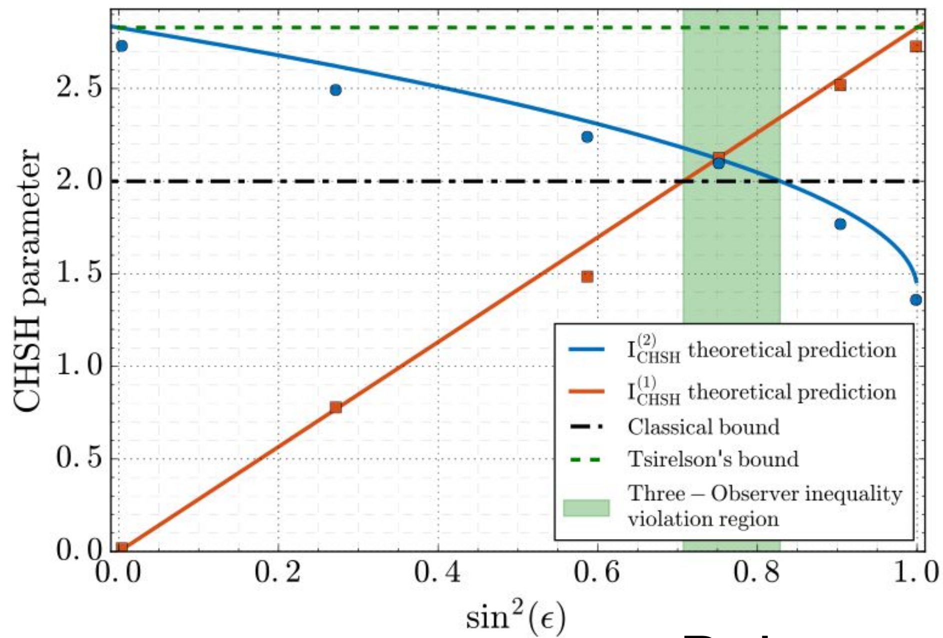
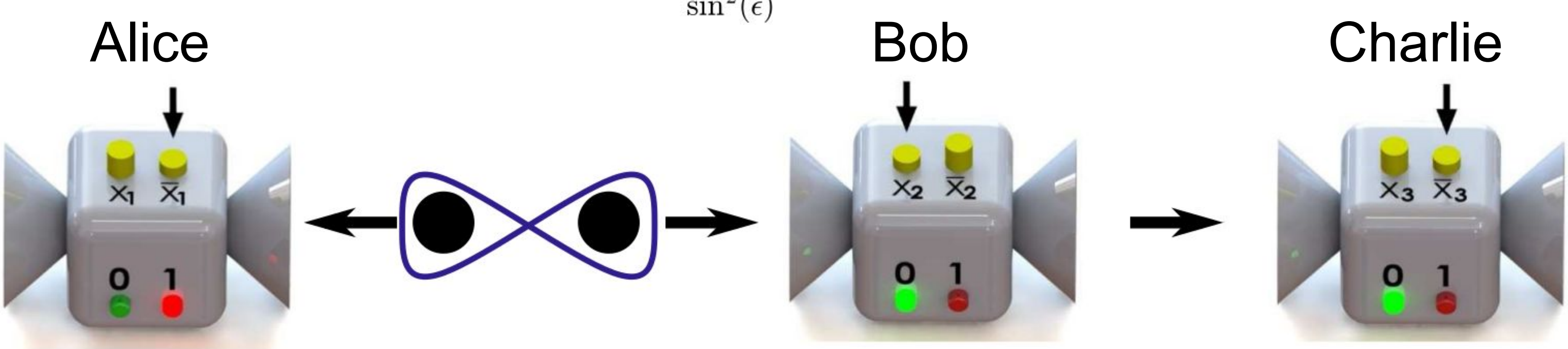
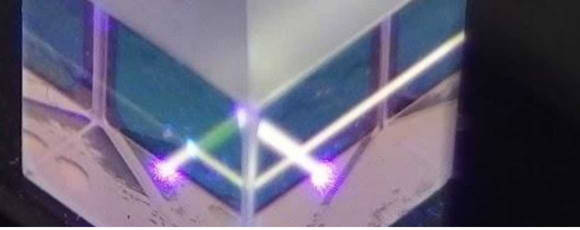




Direct reconstruction of the quantum state by strong measurements



Any physical system is described by a state. In quantum mechanics, a state can be represented by a complex matrix.

The standard method to determine the state of a quantum system is the *quantum state tomography.*

Recently, a new scheme has been proposed, called *direct measurement of the quantum state*, that is based on weak interaction between the system and the probe [Nature vol. 474, pag. 188–191 (2011)].

Goal

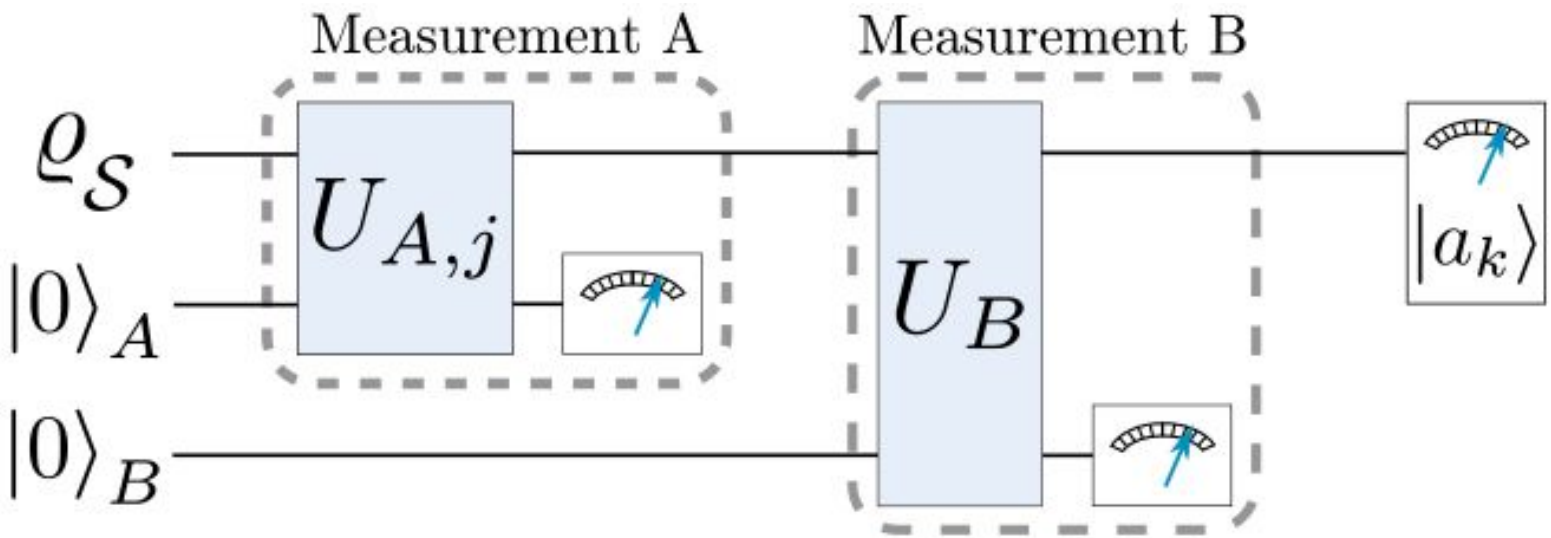
- Propose a *direct measurement of the quantum state* based on strong interaction.
- Realize a proof of principle experiment to compare the methods.

Motivation

- There is no fundamental reason to use a weak interactions. The strong interaction outperform the weak measurement in terms of accuracy of the result.

Direct reconstruction of the quantum state by strong measurements

Direct measurement of a quantum state: circuit representation



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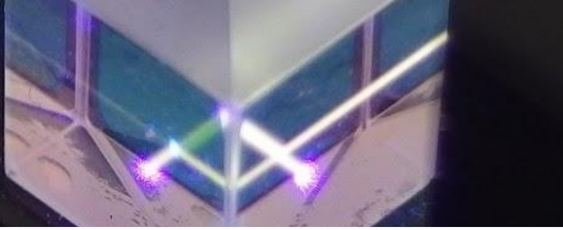
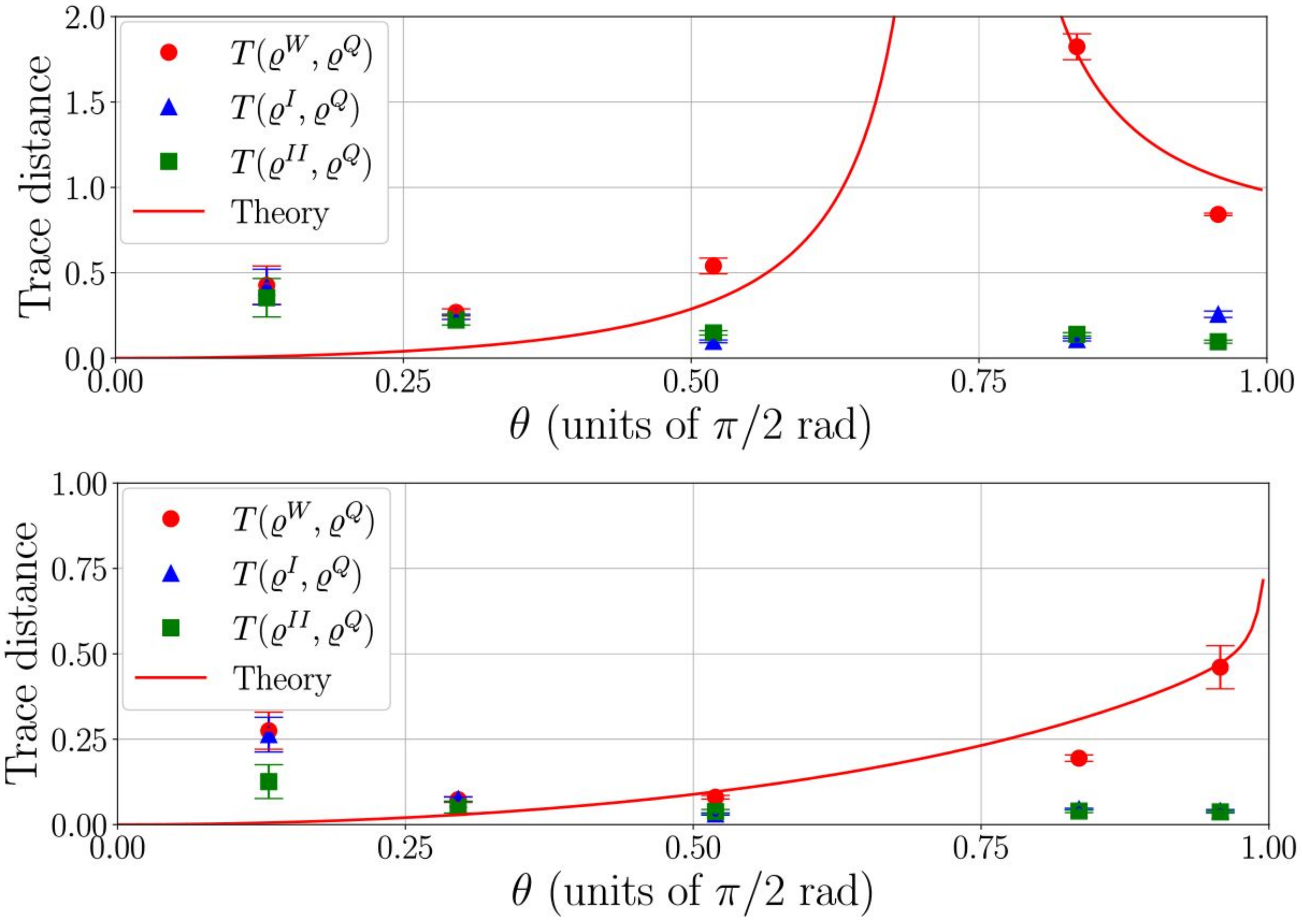


Experimental results



Publications

- L. Calderaro, C. Agnesi, D. Dequal, F. Vedovato, M. Schiavon, A. Santamato, V. Luceri, G. Bianco, G. Vallone, P. Villoresi. "Towards Quantum Communication from Global Navigation Satellite System." (arXiv:1804.05022v1).

- M. Schiavon, L. Calderaro, M. Pittaluga, G. Vallone, Paolo Villoresi. "Three-observer Bell inequality violation on a two-qubit entangled state", Quantum Science and Technology: vol. 2, no 1 (21 Mar 2017).

- F. Vedovato, C. Agnesi, M. Schiavon, D. Dequal, L. Calderaro, M. Tomasin, D. G. Marangon, A. Stanco, V. Luceri, G. Bianco, G. Vallone, P. Villoresi. "Extending Wheeler's delayed-choice experiment to Space". Science Advances: vol. 3, no. 10, e1701180 (25 Oct 2017:).

- C. Agnesi, F. Vedovato, M. Schiavon, D. Dequal, L. Calderaro, M. Tomasin, D. G. Marangon, A. Stanco, V. Luceri, G. Bianco, G. Vallone, P. Villoresi. "Exploring the boundaries of quantum mechanics: Advances in satellite quantum communications." Philosophical Transactions of the Royal Society of London Series A: Mathematical Physical and Engineering Science, vol. 376, 20170461 (28 May 2018).

- L. Calderaro, G. Foletto, D. Dequal, P. Villoresi, G. Vallone. "Direct reconstruction of the quantum density matrix by strong measurements." (arXiv:1803.10703v1).