# Quantum Communications demostrated for satellite downlink @ MLRO

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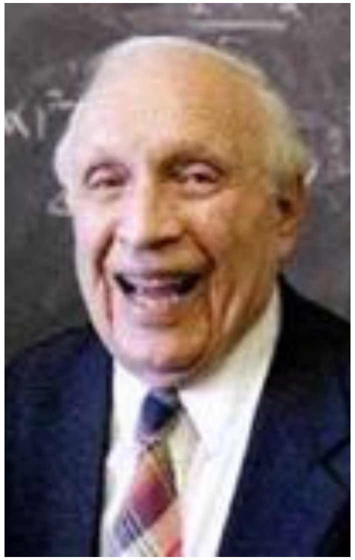
***19° International Workshop on Laser Ranging, Annapolis, Oct.28, 2014***

# What are Quantum Communications?

**Sending and receiving (simple) quantum states**

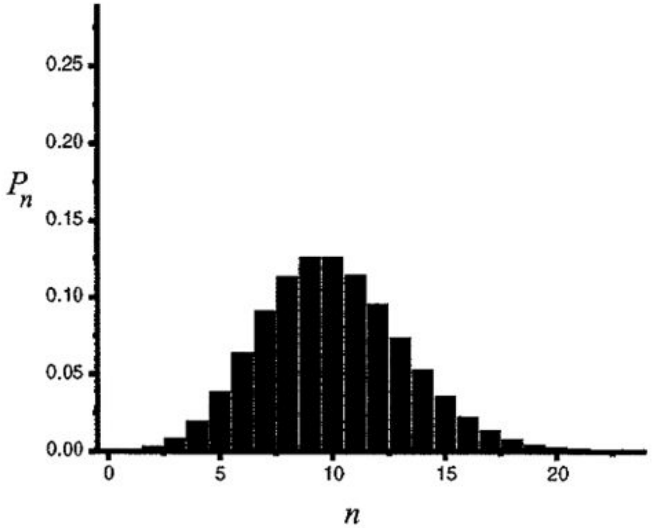
***Is a laser pulse a quantum state?***

Yes, but in general a complicated one..
too many photons!!

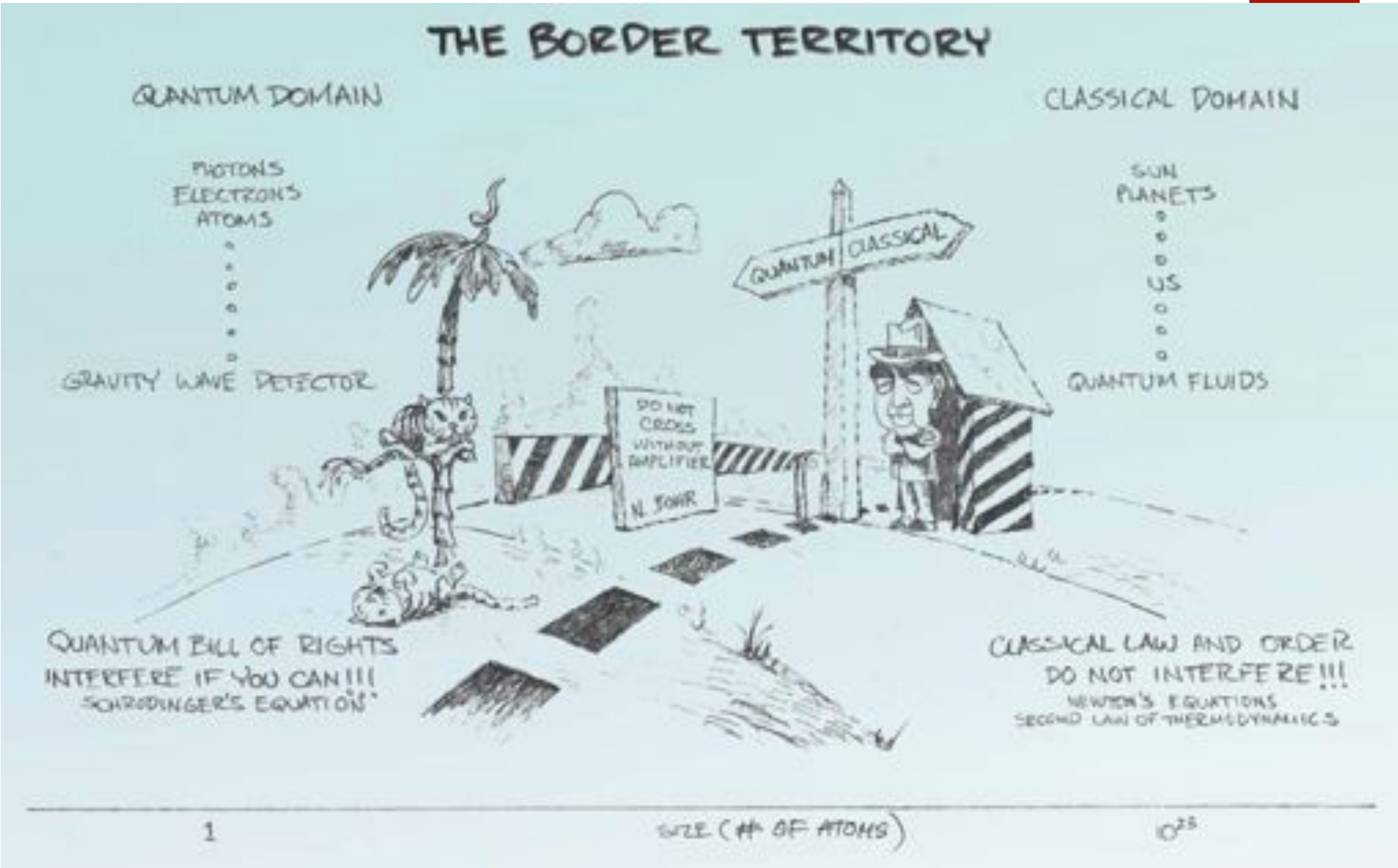


Roy Glauber

Coherent superposition of many quantum (Fock) states:
**A nearly-classical object.**



# Quantum-Classical frontier



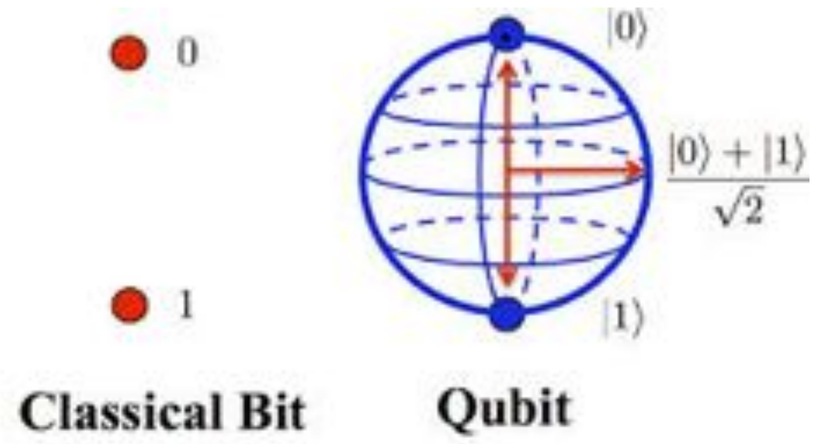

*Wojciech H. Zurek,* Decoherence and the Transition from Quantum to Classical *Physics Today (1991)*

http://www.physics.arizona.edu/~cronin/Research/Lab/some%20decoherence%20refs/zurek%20phys%20today.pdf

See also http://vvkuz.ru/books/zurek.pdf

# What the good of quantum states?


- Take a degree of freedom of a single photon
- EG polarization: 2D (Hilbert) space
- Superposition of base states: simultaneously H and V
- Enrich the concept of bit: welcome the qubit

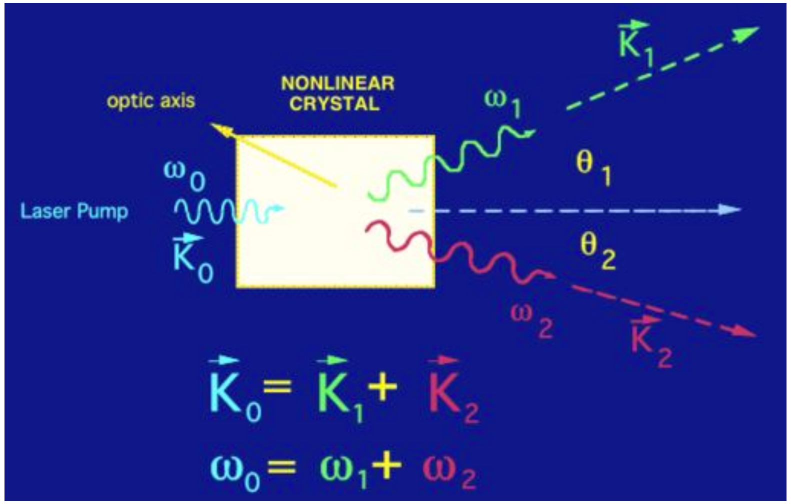


# What the good of quantum states?

## Entanglement

Erwin Schrödinger

**Maximal knowledge of a total system does not necessarily include total knowledge of all its parts**




$$|\psi^-\rangle = \frac{1}{\sqrt{2}}\left(|1\rangle_A|0\rangle_B - |0\rangle_A|1\rangle_B\right)$$

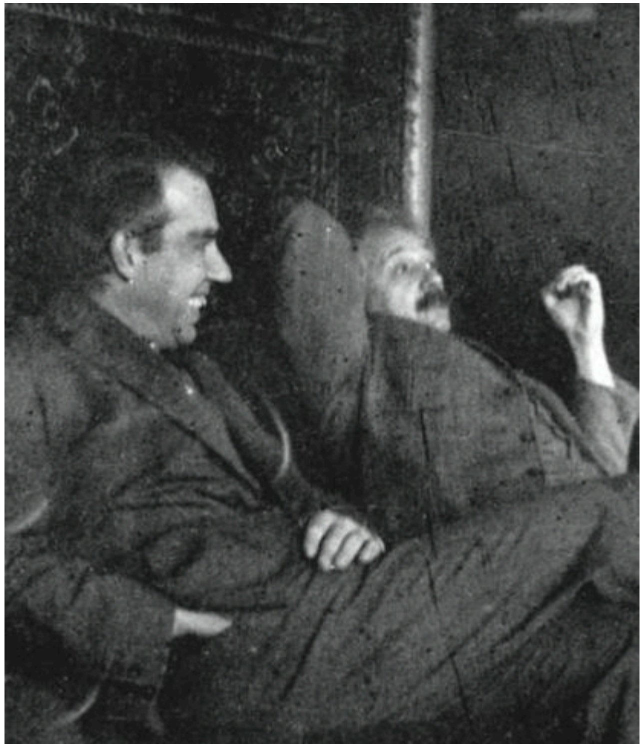
$$\rho_A = \rho_B = \mathbb{I}/2$$

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)

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.



**Locality**

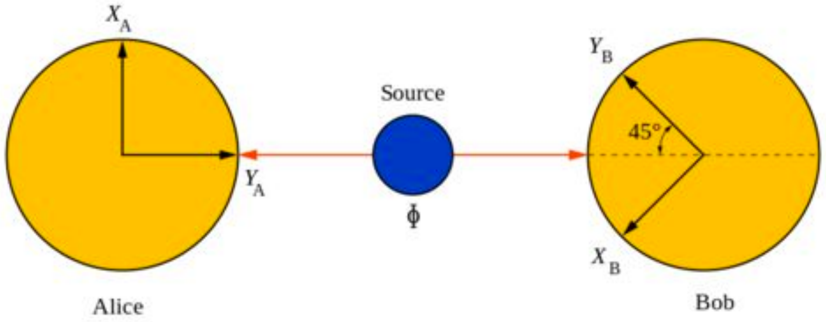
**Realism**

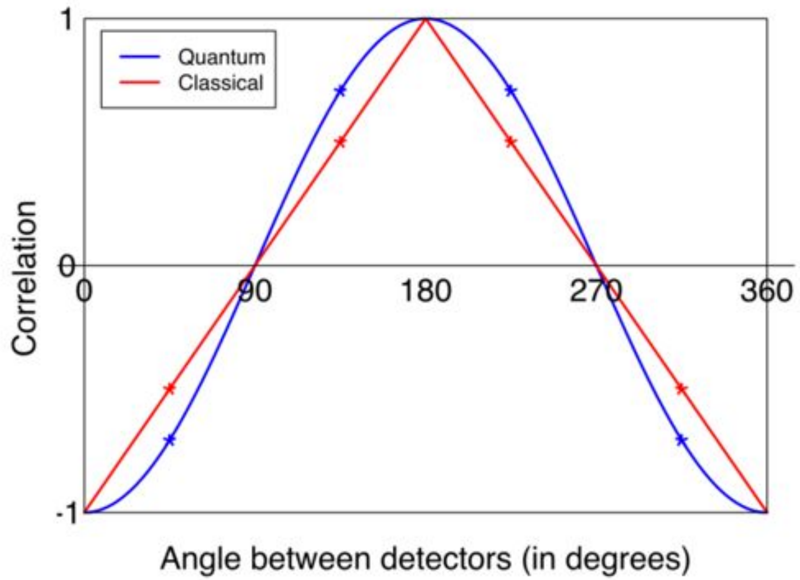
# Bell's Theorem 1964 – 50 anniversary!!

No physical theory of **local hidden variables** can ever reproduce **all of the predictions of quantum mechanics**.

Test using entangled states

John S. Bell



VOLUME 47, NUMBER 7 PHYSICAL REVIEW LETTERS 17 AUGUST 1981

## Experimental Tests of Realistic Local Theories via Bell's Theorem

Alain Aspect, Philippe Grangier, and Gérard Roger
*Institut d'Optique Théorique et Appliquée, Université Paris-Sud, F-91406 Orsay, France*
(Received 30 March 1981)

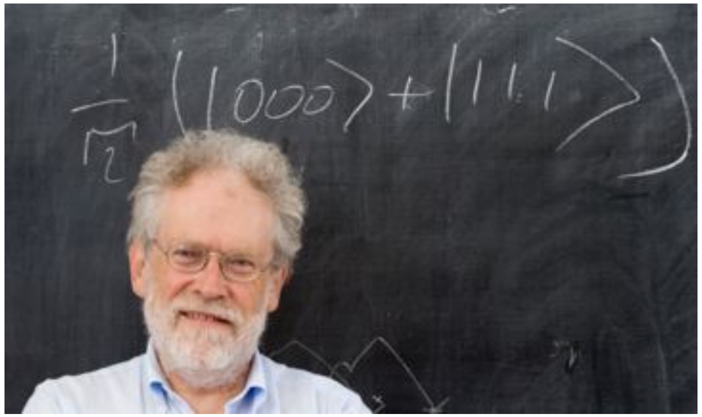
We have measured the linear polarization correlation of the photons emitted in a radiative atomic cascade of calcium. A high-efficiency source provided an improved statistical accuracy and an ability to perform new tests. Our results, in excellent agreement with the quantum mechanical predictions, strongly violate the generalized Bell's inequalities, and rule out the whole class of realistic local theories. No significant change in results was observed with source-polarizer separations of up to 6.5 m.

Alain Aspect

As a conclusion, **our results, in excellent agreement with quantum mechanics predictions**, are to a high statistical accuracy a **strong evidence against the whole class of realistic local theories**; furthermore, *no effect of the distance between measurements on the correlations was observed.*

# Quantum Information was born

- Quantum Computation
- Quantum Dense Coding
- Quantum Cryptography
- Quantum Teleportation
- Quantum Metrology
- Quantum Random-Number Generation
- World Wide Quantum Communications




IOP PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. 29 (2012) 224011 (44pp) doi:10.1088/0264-9381/29/22/224011

# Fundamental quantum optics experiments conceivable with satellites—reaching relativistic distances and velocities

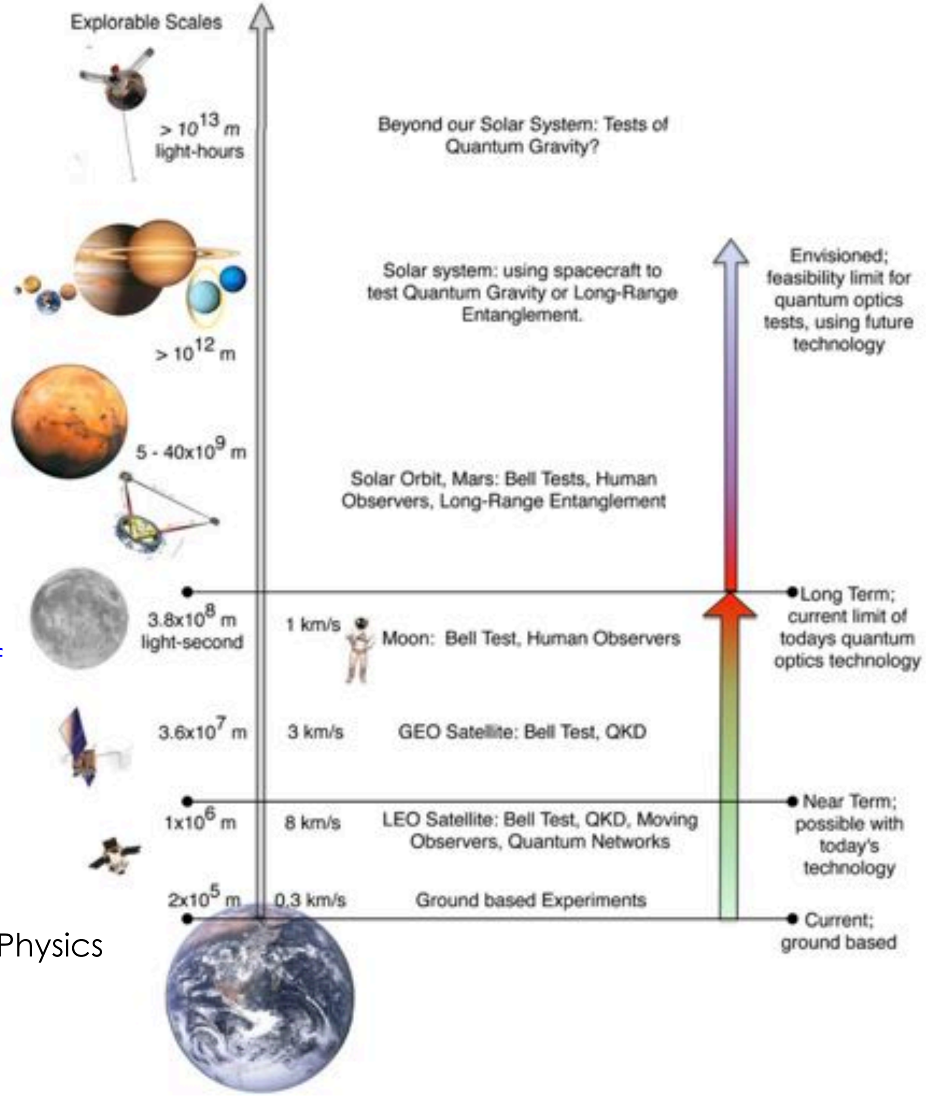
David Rideout[1,2,3], Thomas Jennewein[2,4], Giovanni Amelino-Camelia[6], Tommaso F Demarie[7], Brendon L Higgins[2,4], Achim Kempf[2,3,4,5], Adrian Kent[3,8], Raymond Laflamme[2,3,4], Xian Ma[2,4], Robert B Mann[2,4], Eduardo Martín-Martínez[2,4,5], Nicolas C Menicucci[3,9], John Moffat[3], Christoph Simon[10], Rafael Sorkin[3], Lee Smolin[3] and Daniel R Terno[7]

The tests have the potential **to determine the applicability of quantum theory at larger length scales**, eliminate various alternative physical theories, and **place bounds on phenomenological model**s motivated by ideas about **spacetime microstructure from quantum gravity**.
From a more pragmatic perspective, **as quantum communication technologies such as quantum key distribution advance into space towards large distances..**

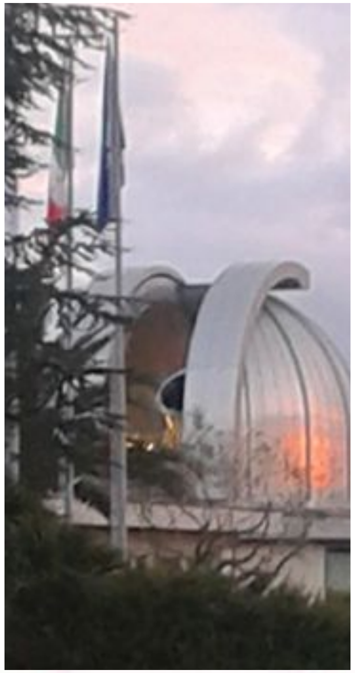
Tony Leggett

'A truly definitive blocking of this loophole would presumably require that the detection be directly conducted by **two human observers with a spatial separation such that the signal transit time exceeds human reaction times, a few hundred milliseconds** (i.e. a separation of several tens of thousand kilometres). Given the extraordinary progress made in quantum communication in recent years, **this goal may not be indefinitely far in the future**.'

Leggett A 2009 Aspect experiment Compendium of Quantum Physics



# Context

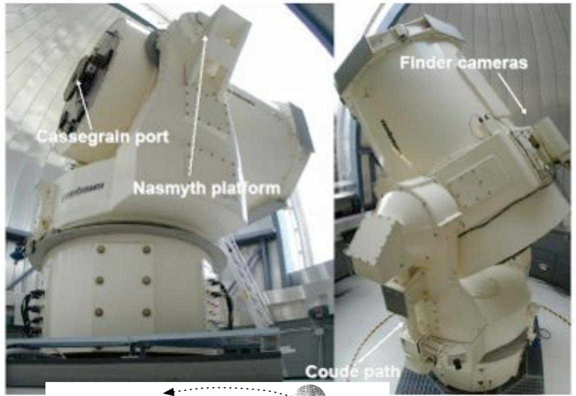


- **Quantum Communications on planetary scale** require complementary channels including ground and satellite links.
- **Ground QC** have progressed up to commercial stage using fiber-cables
- **Space QC** and **demonstration of protocols** such as quantum-key-distribution (QKD) and quantum teleportation **along satellite-to-ground or intersatellite links**.
- Ongoing programs for QC on satellite in **Japan, China and Canada as well as in Singapore and USA**.

Padua
University

Est. 1222

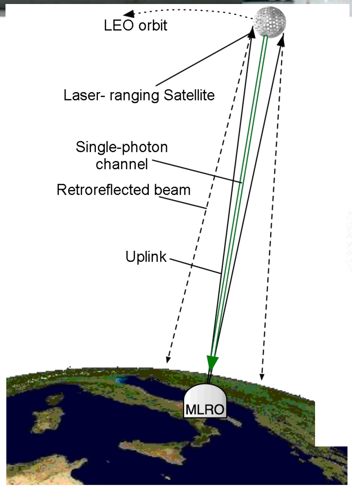
Universa
Universis
Patavina
Libertas

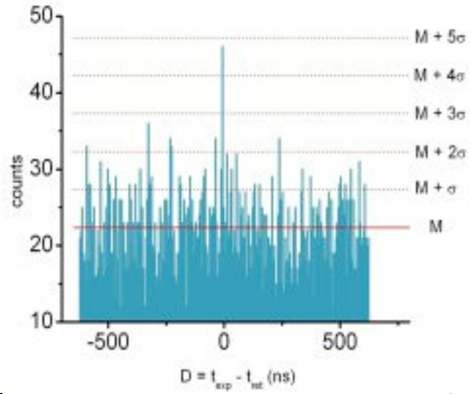


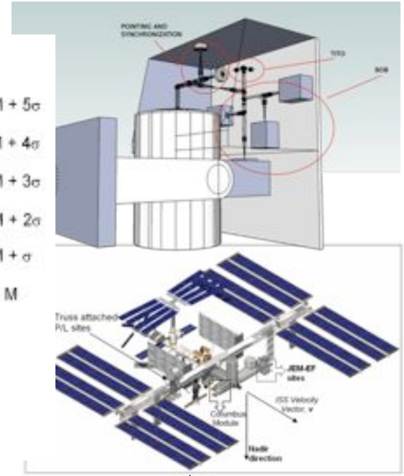

# **Italian** Space QComms

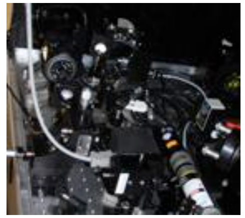
**University of Padova** operated at **Matera Laser Ranging Observatory,** owned by the **Italian Space Agency** and directed by Dr. Giuseppe "Pippo" Bianco.

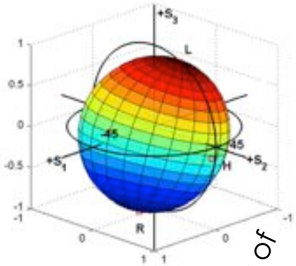
With its **1.5 m telescope an millimeter resolution in SLR,** Matera is our research hub for Space Quantum Communications since 2003.

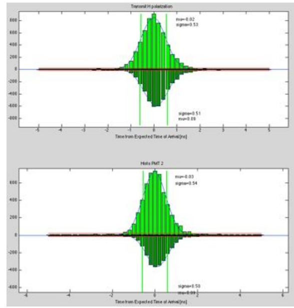








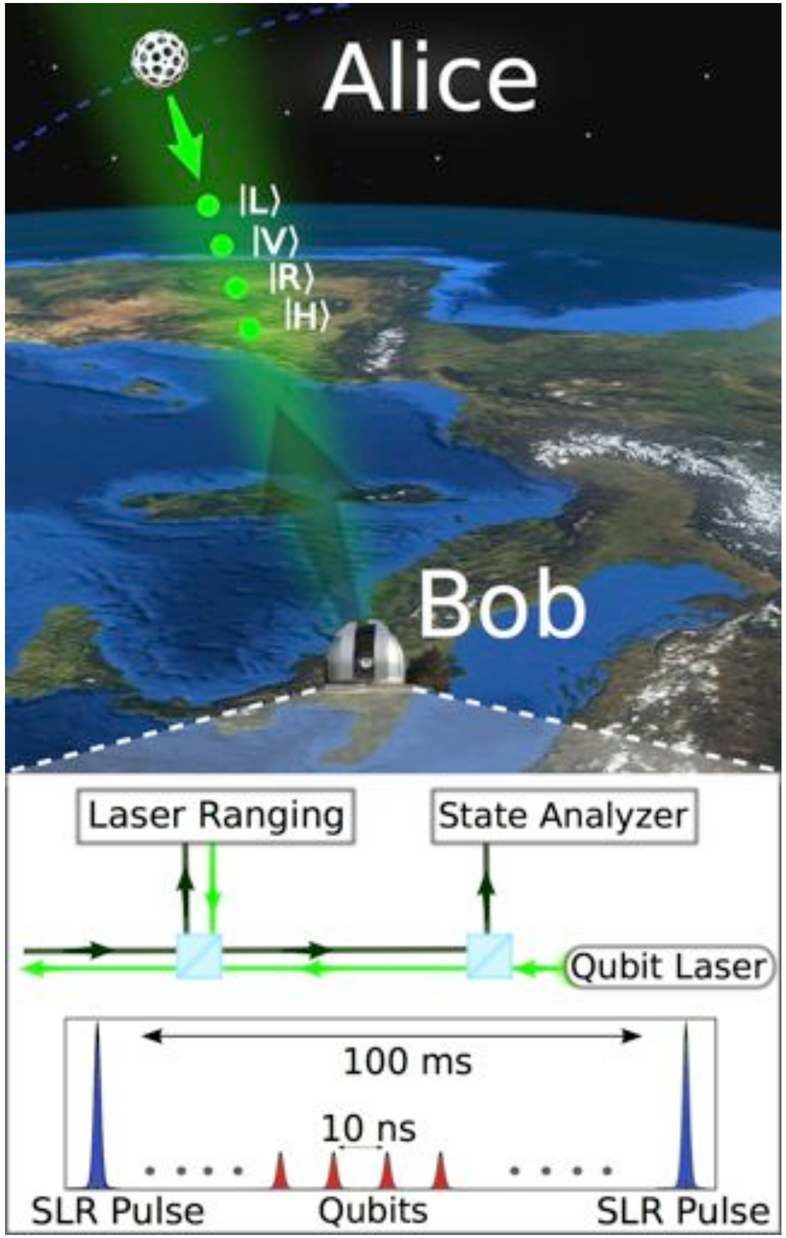
P. Villoresi et al.
New J. Phys.
10 033038 (2008)

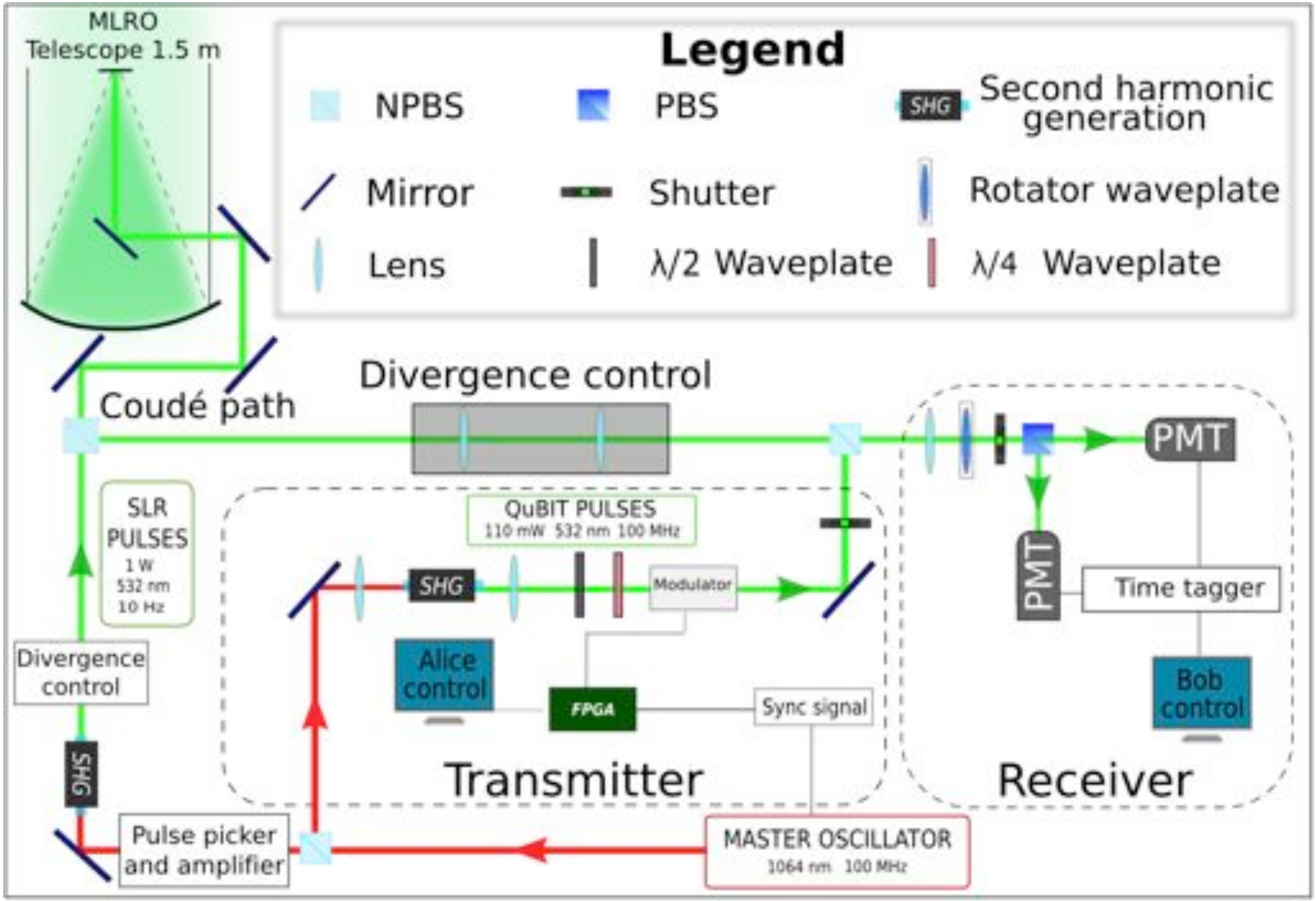
*Orbital param. from ILRS*

- 2003 – UniPD SpaceQ project
- First MLRO tests
- Optical front-end, high rep rate laser installed and single photon receiver @ MLRO
- Setup for the returns search
- 2008 – first single-photon return from Ajisai announced
- 2009 - Feasibility study for a quantum payload for the ISS
- Design and test of setup for polarization analysis
- Characterization of MLRO Mueller Matrix
- 2012 - Analysis of response for different satellites CCR
- 2013 – state preparation, state analysis – satellite synchronization
- 2014 – Q-Comm on satellites downlink demonstrated

# Objectives

- To simulate a quantum source in Space using orbiting retroreflectors
- To demonstrate the measurement of quantum states in the downlink
- To address the mitigation of the background noise and to assess its limit
- To demonstrate the faithful transmission of a generic qubits from Space to ground
- To envisage the exploitation of this type of link

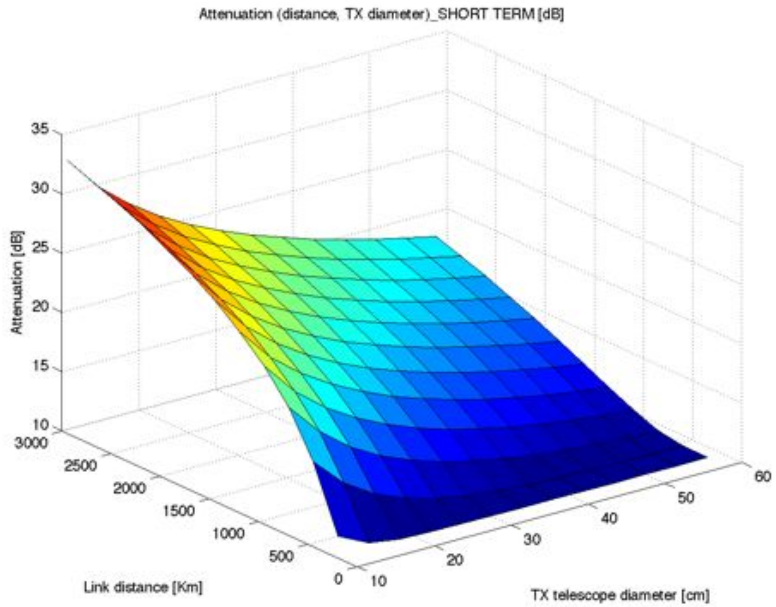





G. Vallone et al, arXiv:1406.4051

# The making of the qubits

- The source on satellite is intended to be at the single photon level
- The attenuation in the downlink from a LEO source of ≈ 3 cm are in the range of 55-70 dB.
- Transmission rate is crucial
- Short pulses are consequently necessary
- Not too short for causing a bandwidth opening (to noise)

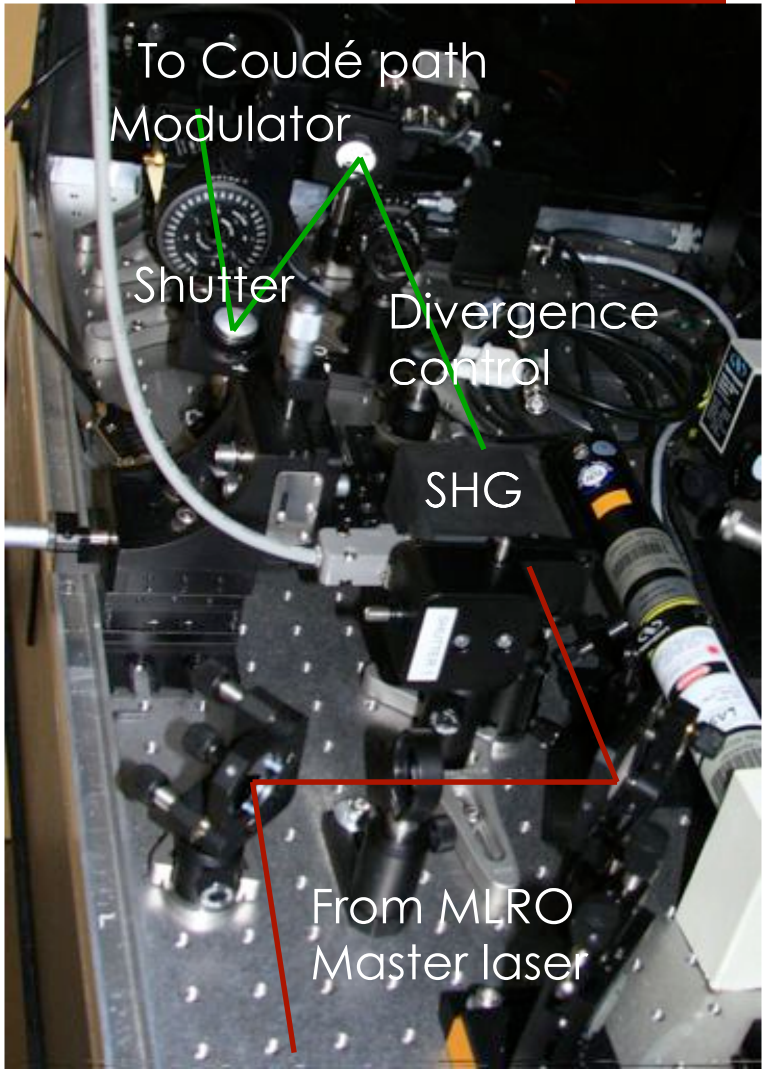



J. Degnan, *Geodynamics Series* 25 (1993).
D. A. Arnold, Cross sections of ILRS satellites (2003)
Bonato et al. *New Journal of Physics* **11** (2009) 045017

# The making of the qubits

- MLRO master laser provided the solution.
- Mode-locking source used for the seeding 100 MHz (-10 Hz ! ), 100 ps FWHM TL, usable output about 100 mW, 1064 nm.
- Pulse energy in nJ range.
- Second harmonics needed.
- First order (6,2 μm) PPLN

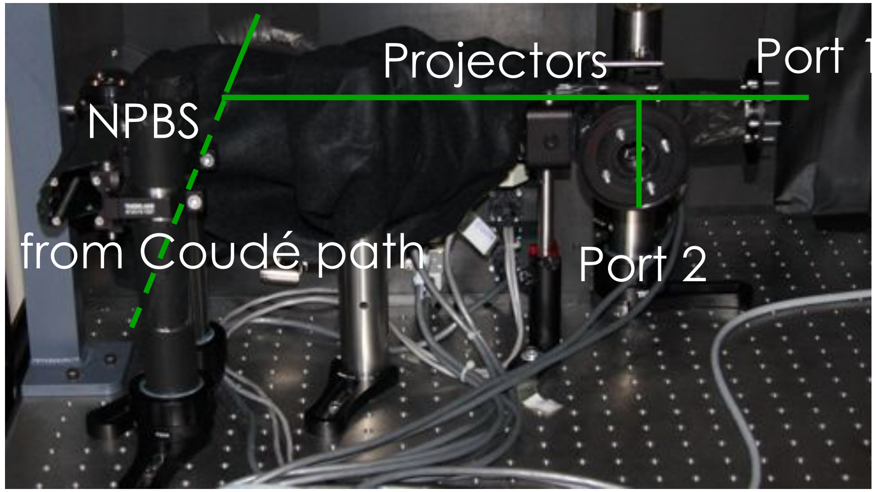
5mol% MgO doped Congruent Lithium Niobate - 50 mm – thermally stabilized.




G. D. Boyd and D. A. Kleinman,
"Parametric interaction of focused gaussian light beams,"
J. Appl. Phys. 39, 3596-3639 (1968)

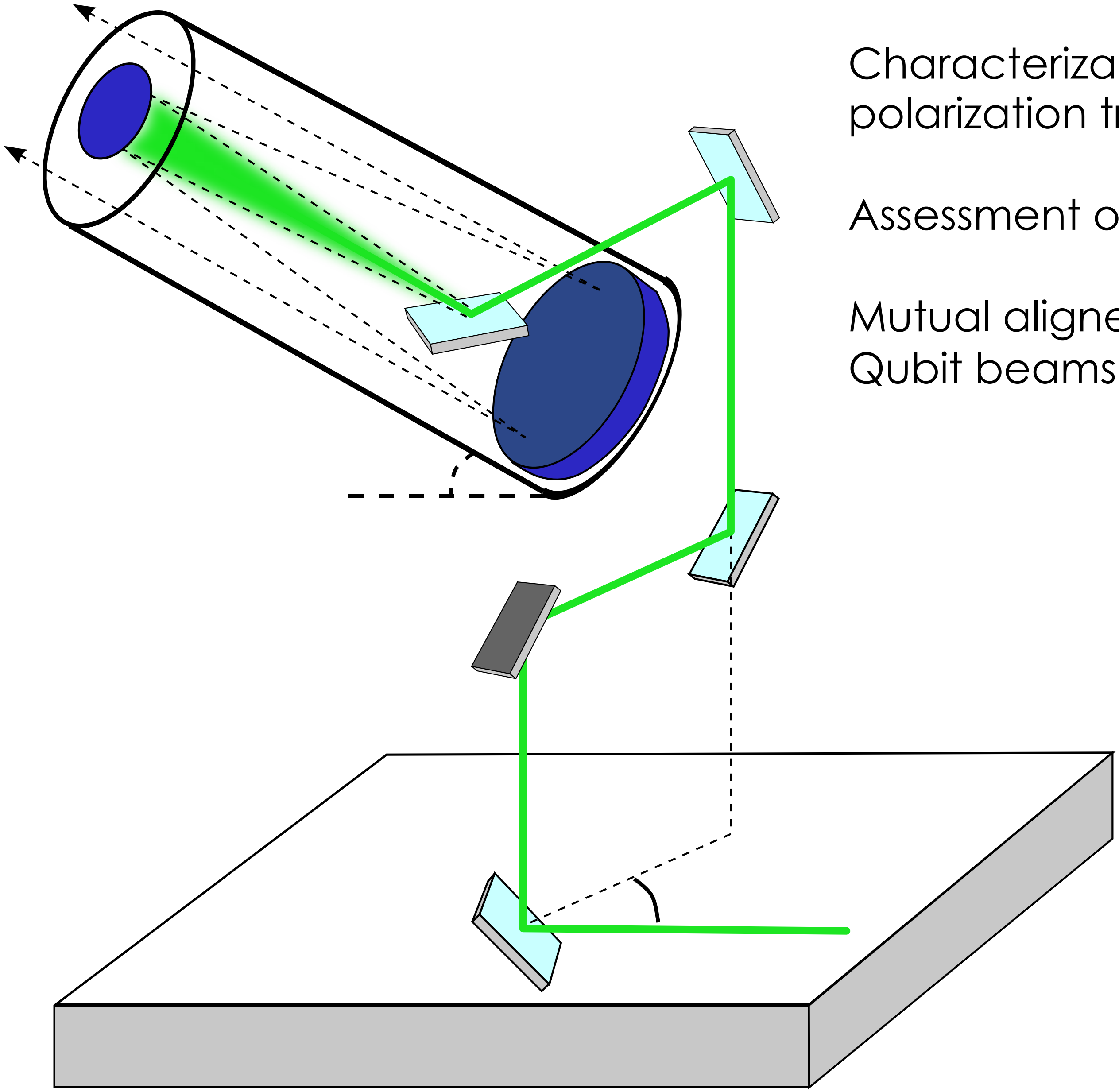
# Measuring the qubits

- The Coudè path is used in both directions for both the SLR beam and the qubits
- The upward and inward beams are combined using a non polarizing beam splitter
- Two large ares SPADs mounted to the exit ports, designed to address the velocity-aberration
- 81 ps timetagging of 8 channels




Hamamatsu H7360-02
Single photon counting PMT
Dia 22 mm – very low dark

# Coudé path of in-and-out



Characterization of the polarization transformation

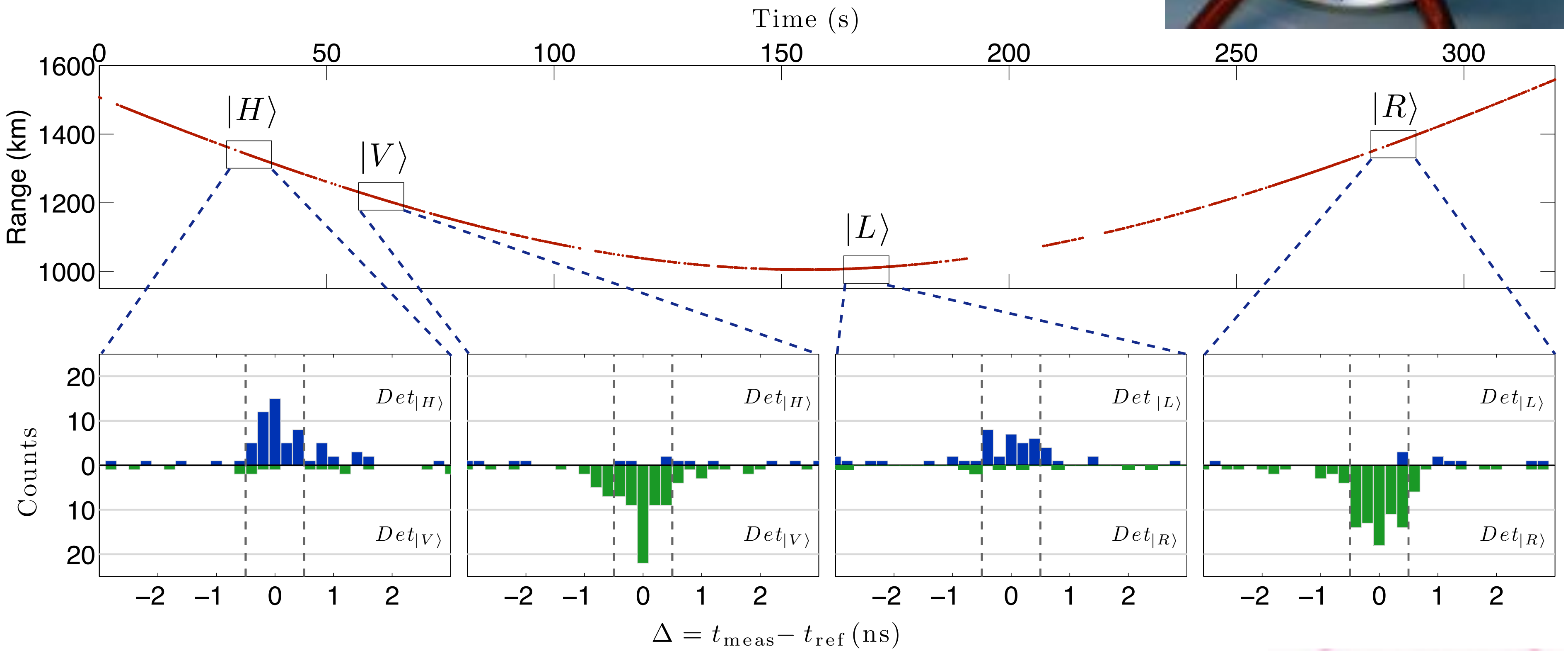
Assessment of total efficiency

Mutual alignement of SLR and Qubit beams

# Single passage of LARETS

Orbit height 690 km - spherical brass body
24 cm in diameter, 23 kg mass,
60 cube corner retroreflectors (CCR)
Metallic coating on CCR

Apr 10th, 2014, start 4:40 am CEST




- **10 s windows**
- **Timebin width ≤ 1 ns**
- **QBER ≃ 6.5 %**
- **Return rate 147 cps**

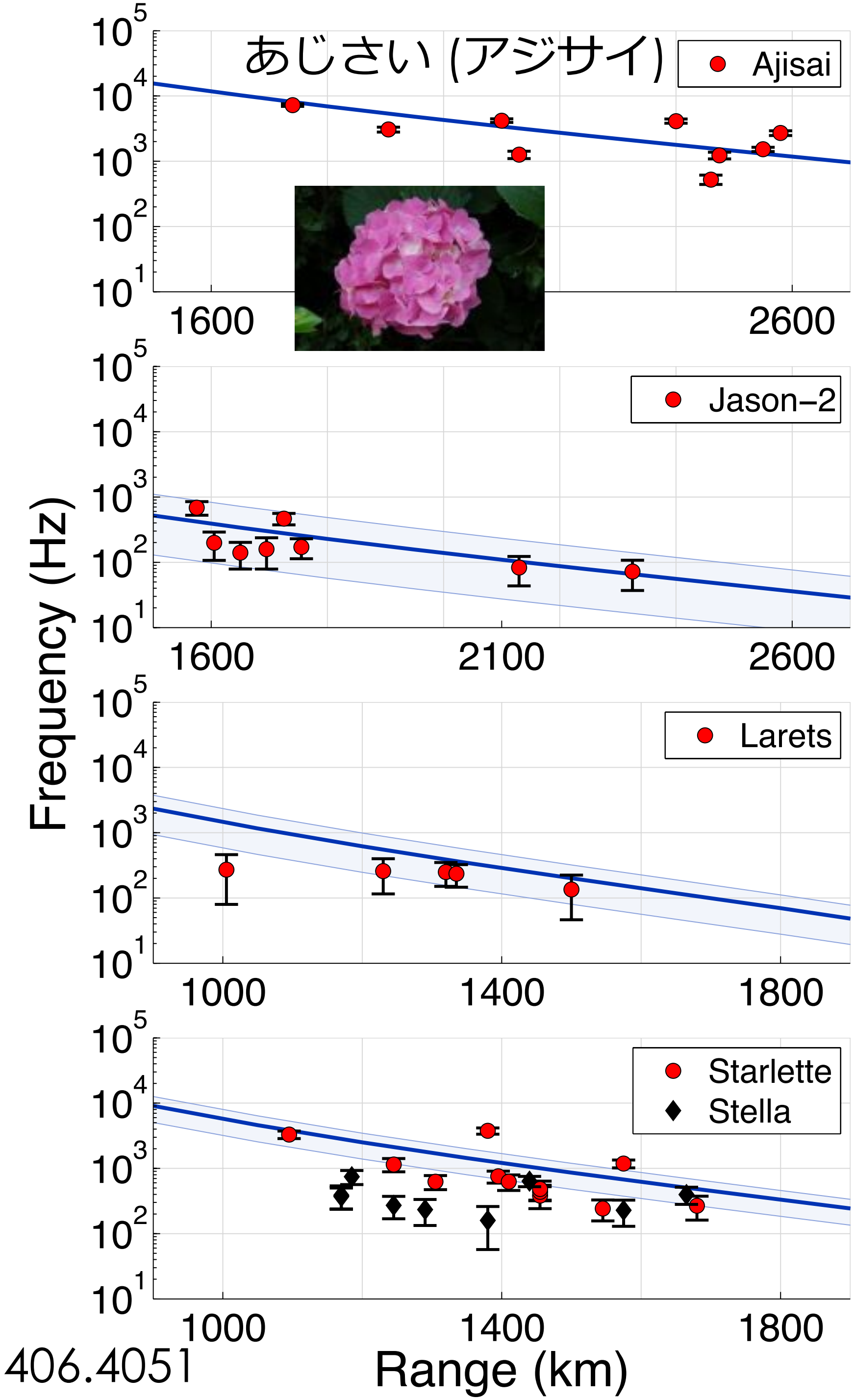
G. Vallone et al, arXiv:1406.4051

# Link Budget and photon return rate

Radar equation for the prediction of detected number of photons per pulse

$$\mu_{rx} \quad = \quad \mu_{tx}\,\eta_{tx}\,G_t\,\Sigma\left(\frac{1}{4\pi R^2}\right)^2\,T_a^2\,A_t\,\eta_{rx}\,\eta_{det}$$

The results show that **radar equation model provides a precise fit** for the measured counts and the $\mu$ value for the different satellites




G. Vallone et al, arXiv:1406.4051

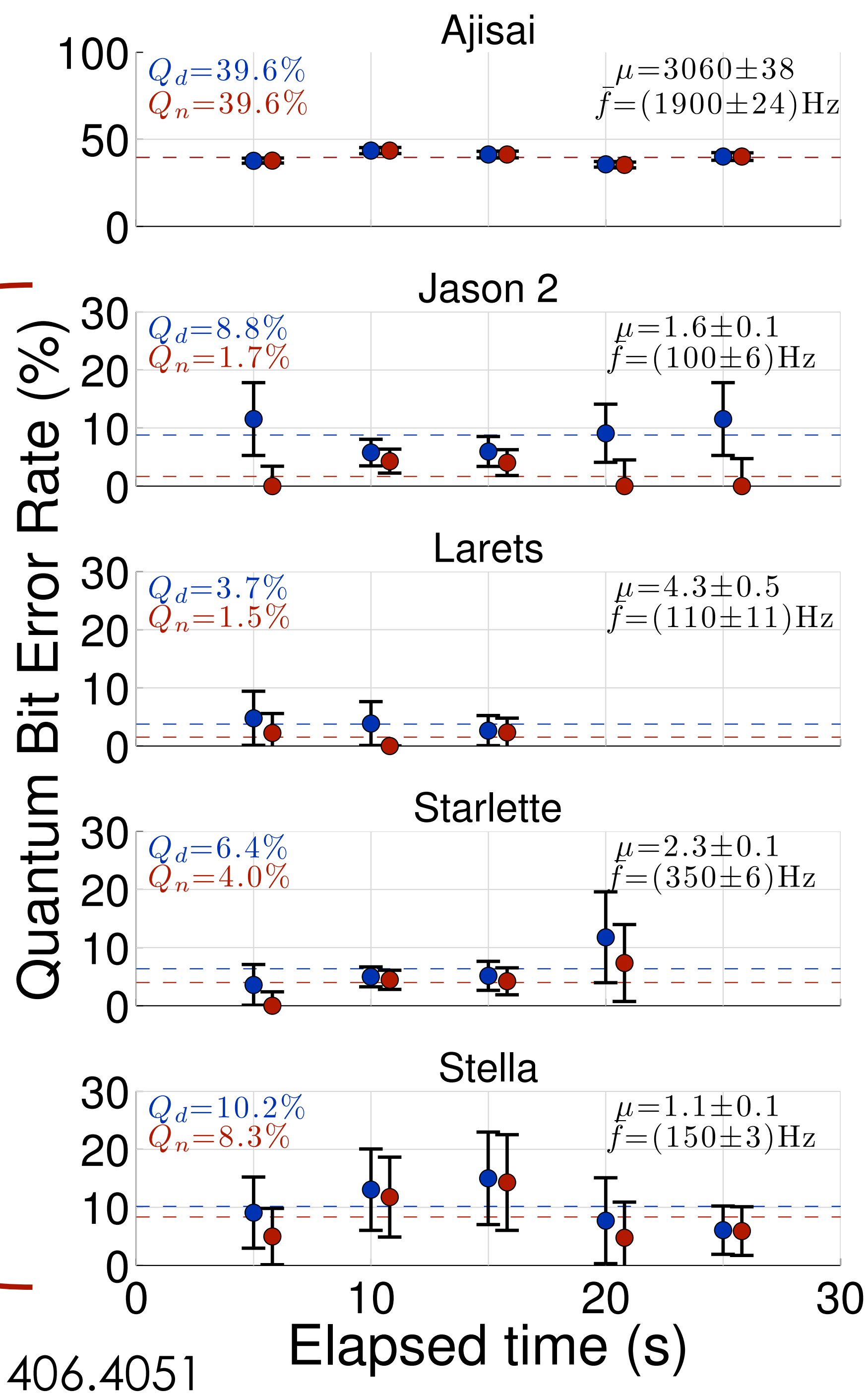
# QBER

**Non** polarization maintaining CCR
***Polarization Qcomm not possible***

**Polarization maintaining** CCR

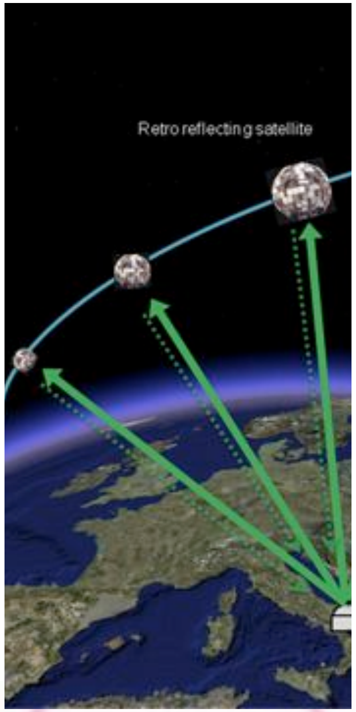
***Polarization QComm with QBER compatible with applications***

**Demonstration of stable QBER over extended link duration**




G. Vallone et al, arXiv:1406.4051

# *New QKD satellite protocol using retroreflectors*

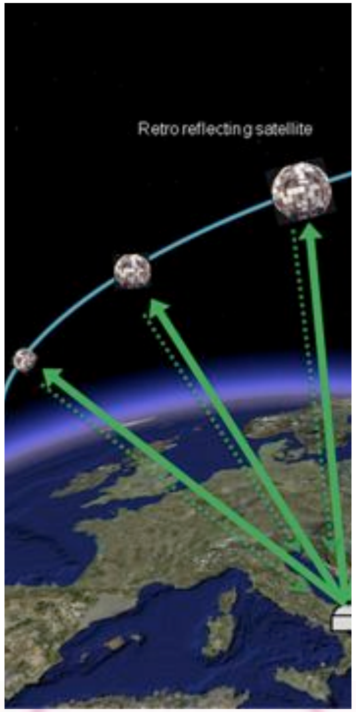



On the base of this experiment, we propose **a two-way QKD protocol for space channels**:

- In the ground station, **a linearly polarized train of pulses** is injected in the Coudé path.
- The beam is directed toward **a satellite with CCRs having a Faraday Rotator** (or equivalent), that **rotate the returning polarization by** $\theta$ , according to QKD protocol.
- In the CCR a suitable attenuator lowers **the mean photon number to the single photon level**.
- A measure of the intensity of the incoming beam **avoid Trojan horse attack**.
- The **state measure** is done as in present experiment.

G. Vallone et al, arXiv:1406.4051

# *New QKD satellite protocol using retroreflectors*




The two- way QKD protocol:

- By this scheme, **a decoy state BB84 protocol can be realised between satellite and ground**.

- Such protocol **is currently realizable using few centimeter retroriflector** as optical part in orbit.

G. Vallone et al, arXiv:1406.4051

# *New QKD satellite protocol using retroreflectors*

Such protocol **is currently realizable using few centimetres CCRs.**

**MLRO station as many others may be soon ready for Space QCs !!**

# **QuantumFuture** Research Group


**Founded in 2003** (PV) at the Dept. of Information Engineering of the UniPD

**Interdisciplinary expertise** – faculties:

***Quantum and Classical Optics***, *G. Vallone, G. Naletto, V. Da Deppo, PV*

***Quantum communications engineering***, *N. Laurenti, R. Corvaja, G. Cariolaro, (A. Assalini, G. Pierobon)*

***Quantum Control theory*** *F. Ticozzi, A. Ferrante, M. Pavon*

***Quantum Astronomy*** *C. Barbieri, S. Ortolani*

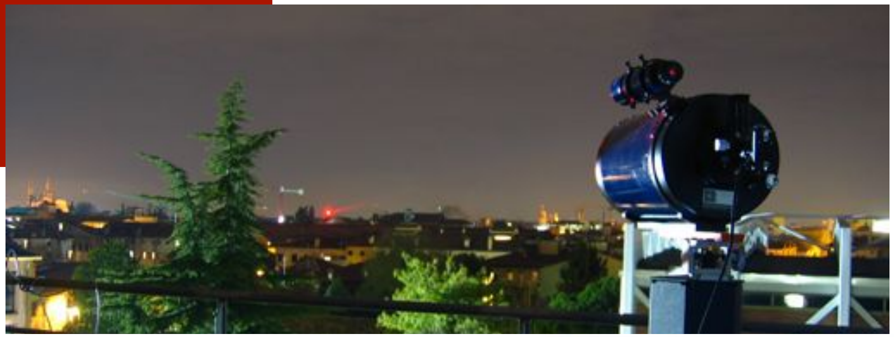
Fundend by **Italian Space Agency, European Space Agency, UniPD**, and industrial research contracts

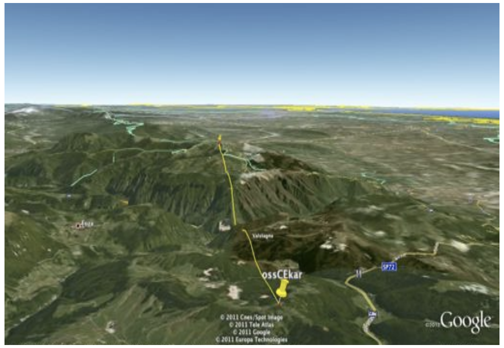
Strategic Res. Project of UniPD 2009-2013 ( 35 man-years PhD and Assegnisti)

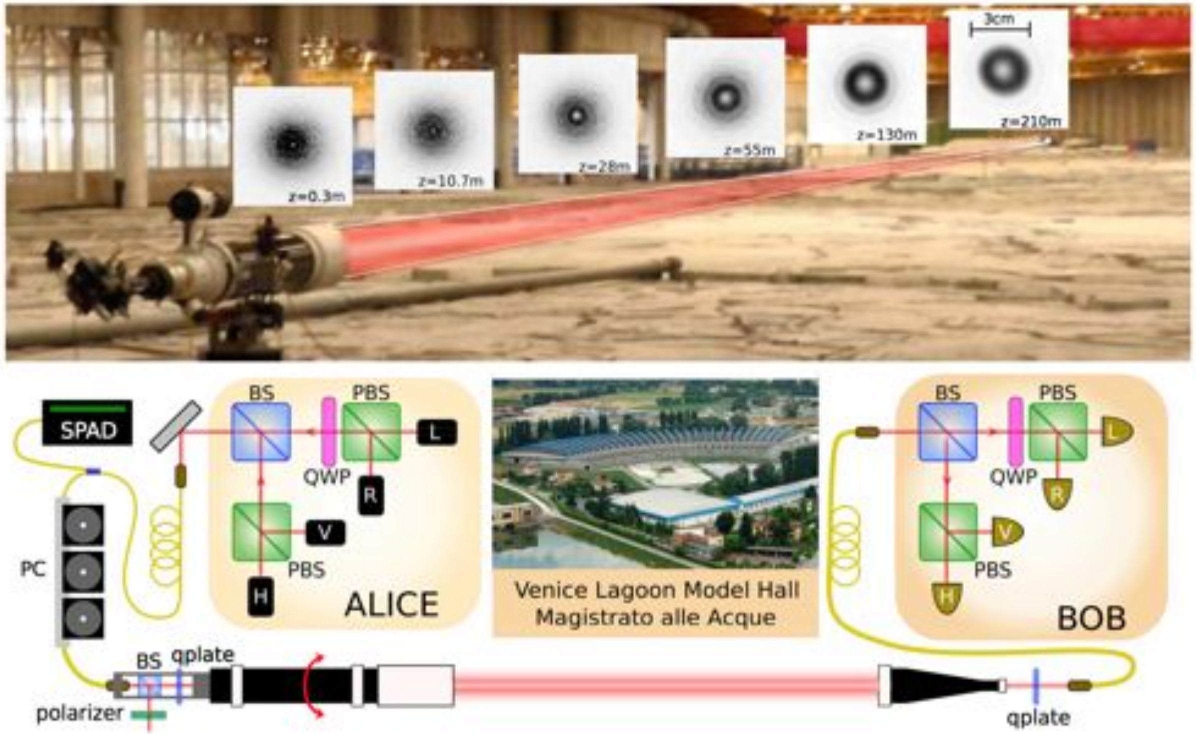
Currently **8 Faculties+6 PhD Students+5 Assegnisti and Post-Docs+ undergraduates**




# QuantumFuture Free-space links

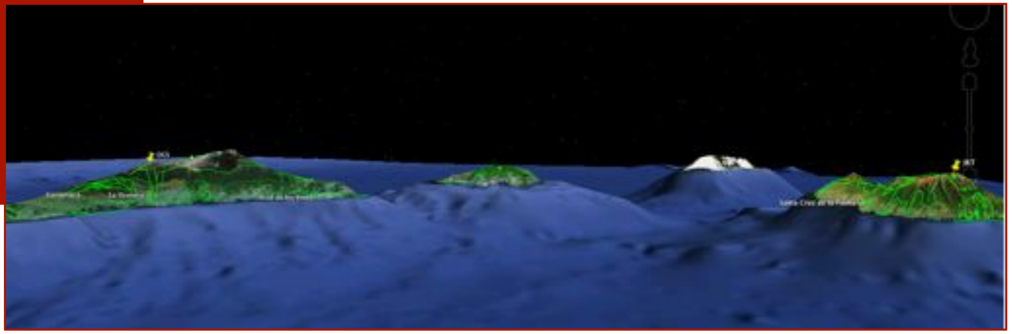





G. Vallone et al., **PRL** 113:050603 (2014) *Editors' Suggeston*

# The Canarias OGS-JKT link - 143 km

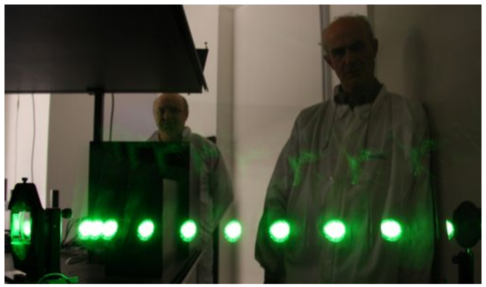



**Q Comms with wavefront dynamics in strong turbulence**


D. Bacco et al. Nature Comm. 4, 2363 (2013)
G. Vallone et al, Phys. Rev. Lett. 113, 060503 (2014)
G. Vallone et al, New J. Phys. 16, 063064 (2014)
D. Marangon et al, Sci. Rep. 4, 5490 (2014)
I. Capraro et al. Phys. Rev. Lett. 109, 200502 (2012)
M. Minozzi et al. Opt. Lett. 38 489 (2013)
P. Villoresi et al. New J. Phys. 10 033038 (2008)
C. Bonato et al. Phys. Rev. Lett. 101, 233603 (2008)

G. Vallone et al, arXiv:1401.7917
G. Vallone et al, arXiv:1404.1272
G. Vallone et al, arXiv:1406.4051


# QComms: not limits but horizons


http://www.improbable.com/airchives/paperair/volume7/v7i6/doubleslit.html