# Comunicare con i quanti

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EXPLOIT THE PHOTONS
SPINOFF OF THE UNIVERSITY OF PADOVA


Paolo Villoresi

*Professore di Fisica Sperimentale*

*Università degli Studi di Padova - Dipartimento di Ingegneria dell'Informazione*

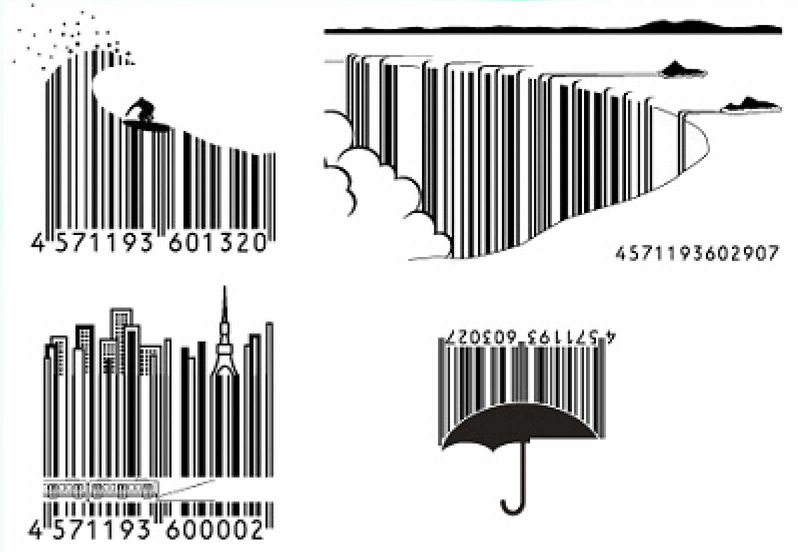

*Progetto* **Per una scelta consapevole – Liceo Galilei – Verona 19 II 9**

# Comunicare, una necessità

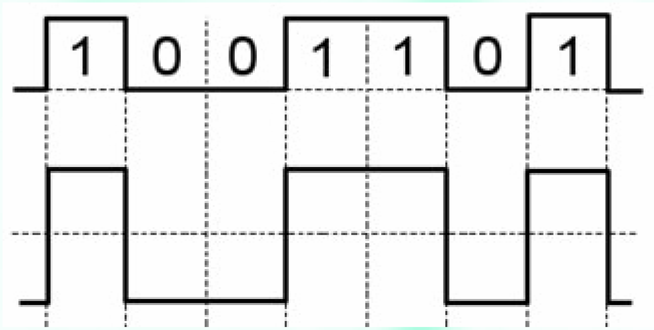

- Il progresso dell'uomo è veicolato dalla comunicazione.
- La tecnica per comunicare cambia con l'estendersi delle conoscenze.
- Certi metodi funzionano meglio di altri.

# Comunicare, codificare, trasmettere

- Per comunicare devo definire un codice.
- Per trasmettere un messaggio devo prima codificarlo

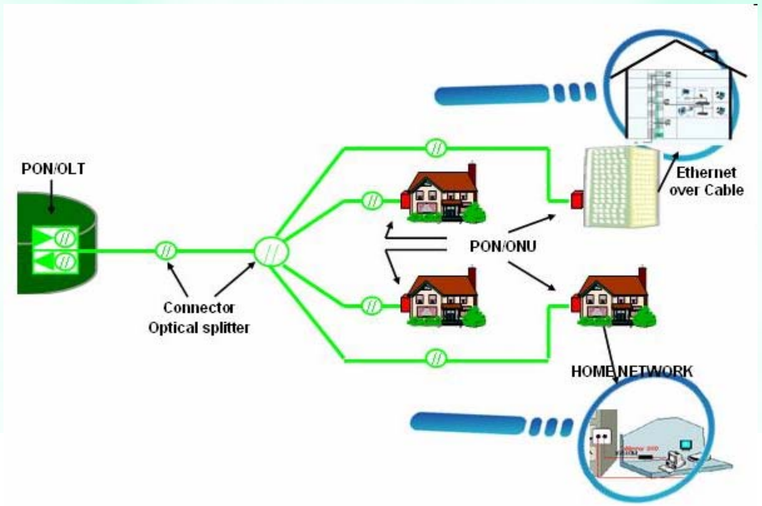






# Comunicare sempre di più

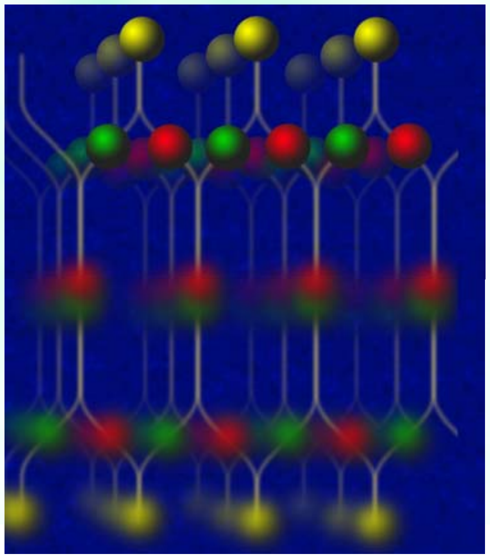
- L’evoluzione dai segnali analogici a quelli digitali ha permesso di aumentare a quantità di informazione trasmessa al secondo.
- La codifica binaria è stata estesa a tutti i tipi di messaggi/dati/segnali.

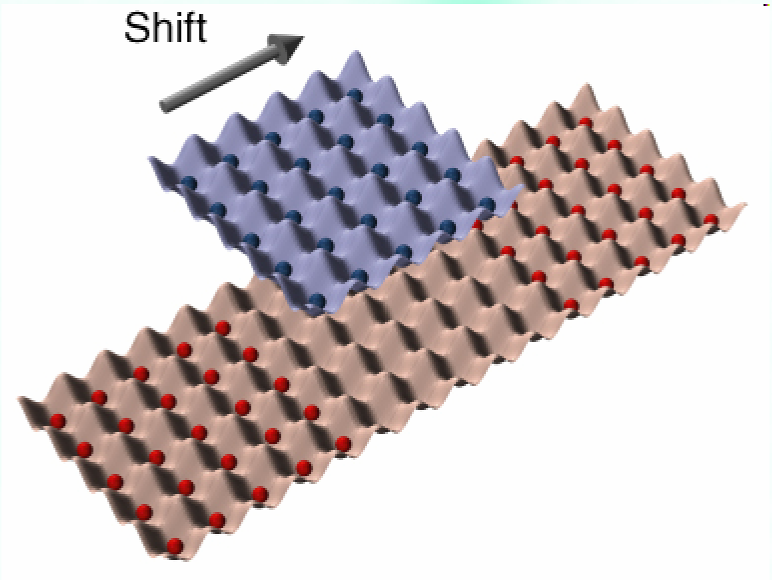



# Quale limite alla comunicazione ?

- Poniamoci il problema di dove si può arrivare a codificare un’informazione.

- Partiamo da un classico.





# There's Plenty of Room at the Bottom

Richard Feynman's talk at annual meeting of the American Physical Society - December 29th 1959

http://www.zyvex.com/nanotech/feynman.html

# Posso scrivere l'intera Treccani sulla punta di uno spillo?

L'informazione: la **Treccani** è il nome con cui è più comunemente nota l'***Enciclopedia Italiana di scienze, lettere ed arti.*** Complessivamente l'Enciclopedia consta di 62 volumi, per un totale di 56.000 pagine: l'area totale è pari a $3.4\ 10^3\ m^2$

Lo spillo ha una capocchia sferica di 1.5 mm di diametro, pari ad una superficie di $7\ 10^{-6}\ m^2$

# Posso scrivere l'intera Treccani sulla punta di uno spillo?

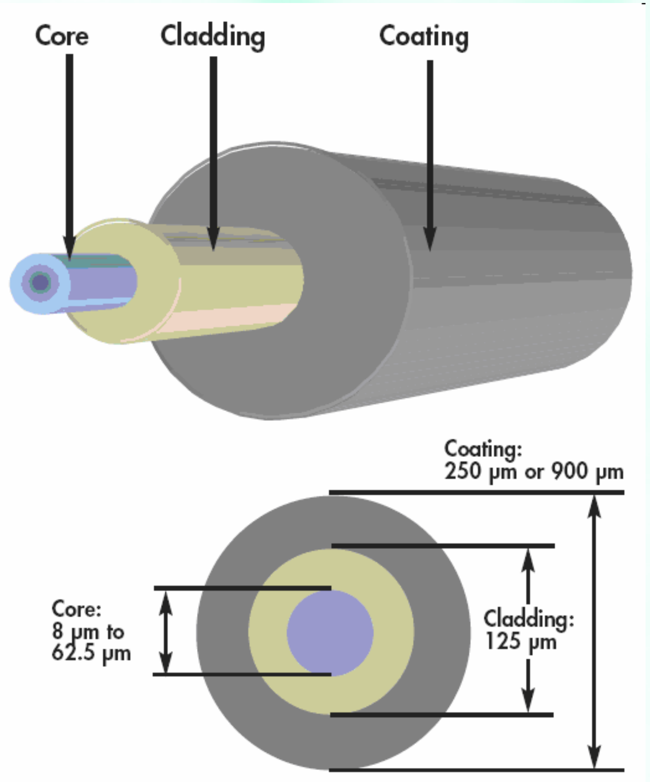
Il rapporto tra le aree è di $5\ 10^8$ e quello tra i lati di circa 22000.

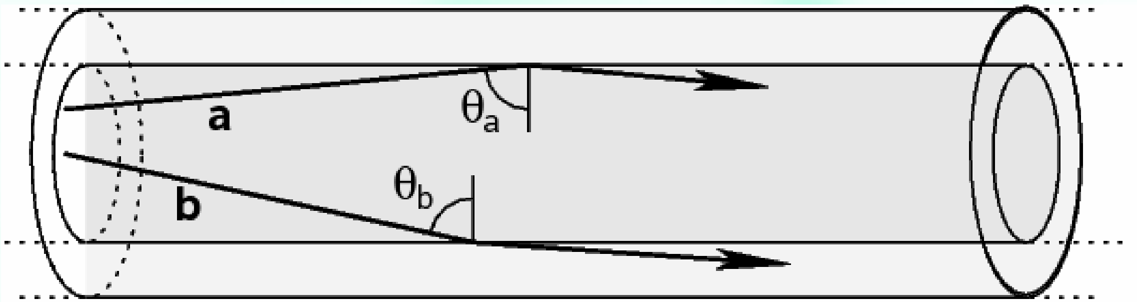
Con questo rapporto di rimpicciolimento, un punto della pagina ( 200 μm) diventa di 9 nm.

Ci sono circa 30 atomi in fila in questo spazio – in un cubetto ci sono 1000 atomi: usando nanotecnologie posso farcela!

# E se volessi inviare l'informazione?

- Consideriamo le fibre ottiche: l'informazione codificata in binario viene trasmessa con impulsi luminosi

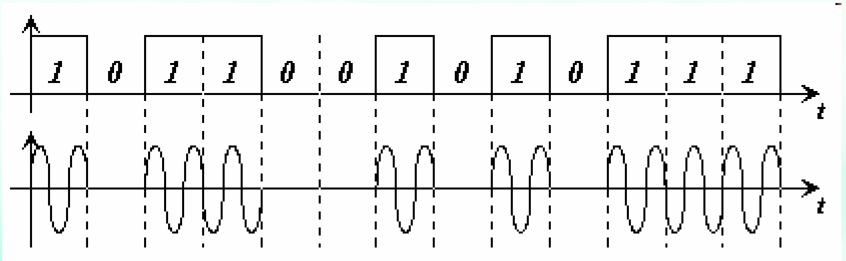



*Riflessione totale interna (a) e rifrazione esterna (b) per due fasci luminosi in una fibra ottica.*

# Impulsi luminosi in fibra

- Associo un breve impulso all’1 e il buio allo 0.




- La scelta di quanto intenso deve essere l’”1” è il risultato di un compromesso.

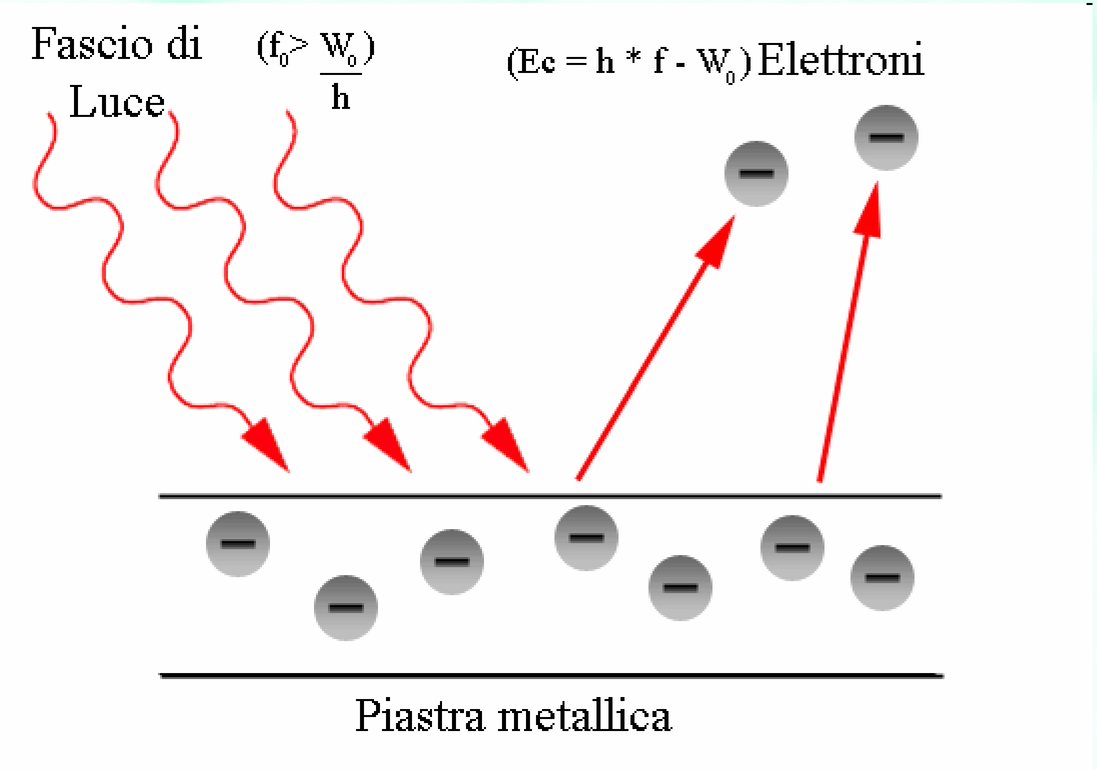
# Quale limite all'"1"?

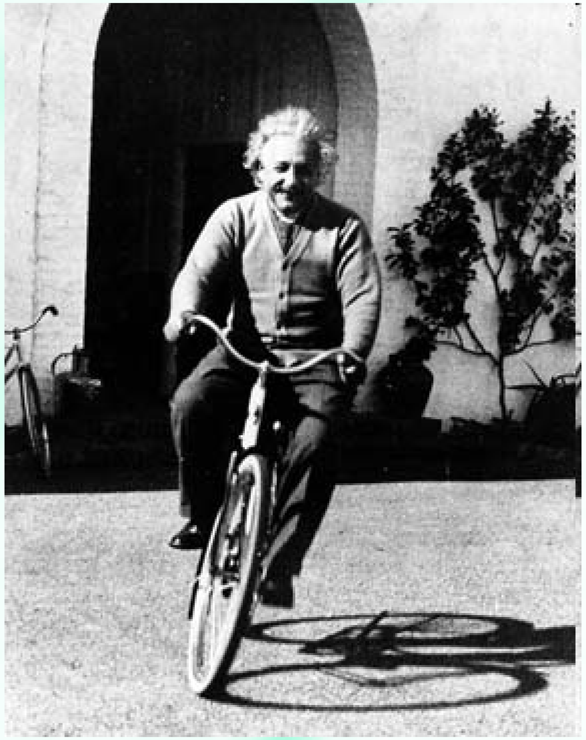
- Per aumentare linformazione trasmessa devo calare l'energia associata a ciascun inpulso.
- Che limite c'è all'attenuazione?

- Il limite quantico: la radiazione è quantizzata.

# Come ci accorgiamo di ciò?

- L'effetto fotoelettrico – spiegato da Einstein nel 1905.



# Breve introduzione alla luce

Tipi diversi di luce

Come si genera

Il laser

La comunicazione a singolo fotone

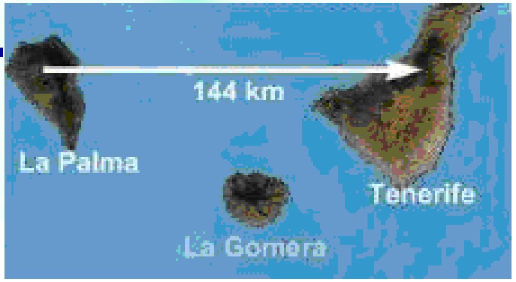
# La frontiera della comunicazione quantistica

- Scambiare un singolo fotone lungo distanze sempre crescenti.

- Il limite terrestre / il passo verso lo spazio.

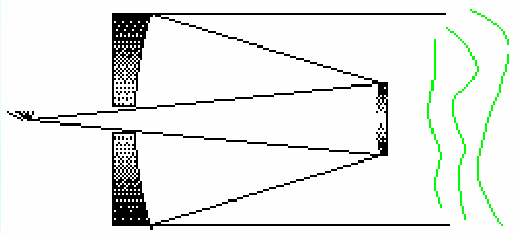
# Quantum Communication frontier

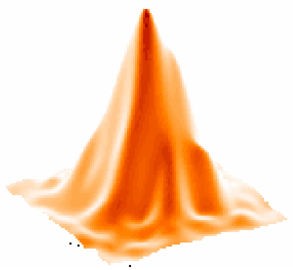
- Extending the spatial scale of the QC allows to explore the nonlocality on very long paths, exploring the connection with relativistic space-time or the global distribution of keys.
- On Earth the communication up to 144 km was recently demonstrated *(Ursin et al Nature Phys* ***3*** *481, 2007 – 2008 2009)*. The receiver was an astronomical telescope and the path was subtended between two island in the Canary archipelagos.



# Quantum Communication frontier

- Further extension of terrestrial QC is hampered by many factors, common to optical free-space communication:
  - Atmospheric turbulence
  - Geography – Earth curvature
  - Optical stability of transceivers
  - Large corrected optics
  - Absorption and scattering of air





# Objectives of QC in Space

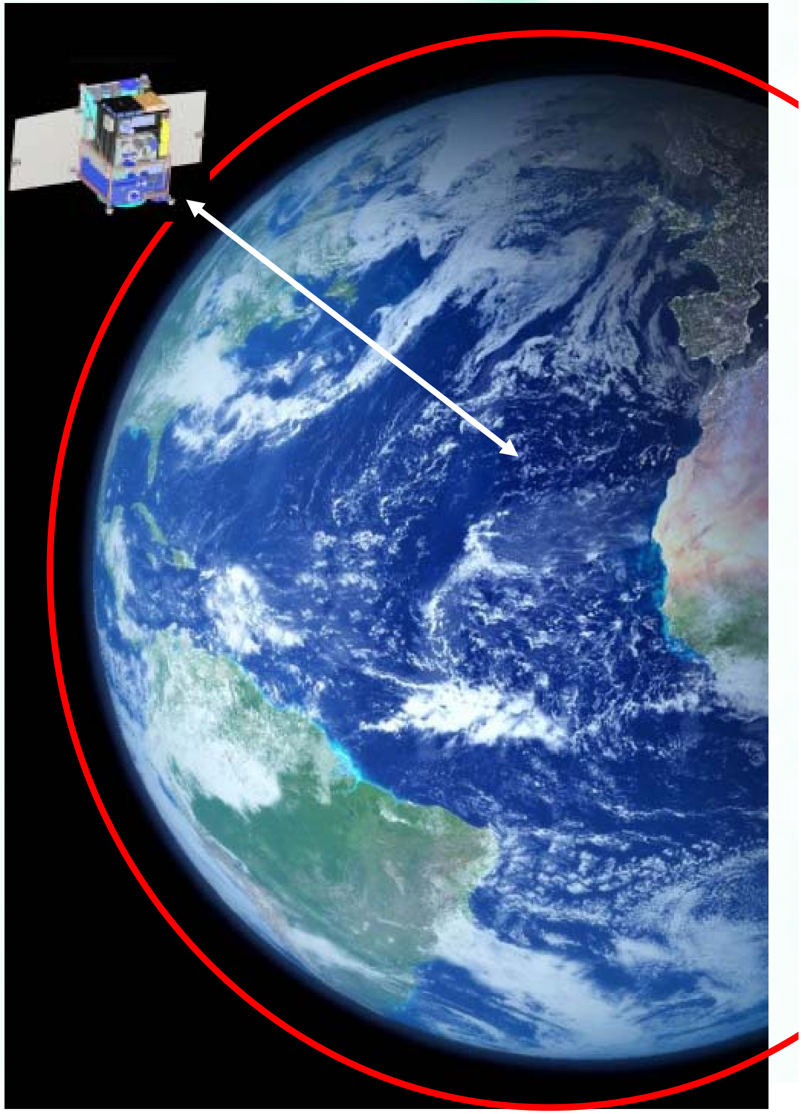
- To extend experimental investigations of quantum phenomena to the Space.
- To realize a quantum channel between an orbiting and a ground transceivers.
- To develop a space-borne quantum terminal (source – state analyzer – real-time processing)
- To obtain that the quantum stuff will comply with spatial infrastructure.

# Motivations

- To increase the length of the quantum channels so far realized.
- To test of basic QM with these long channels
- To demonstrate Quantum Cryptography around the planet.
- To teleport quantum states to Space and back.
- To aim at the mixing of Quantum Information with other areas, as Relativity and Metrology.

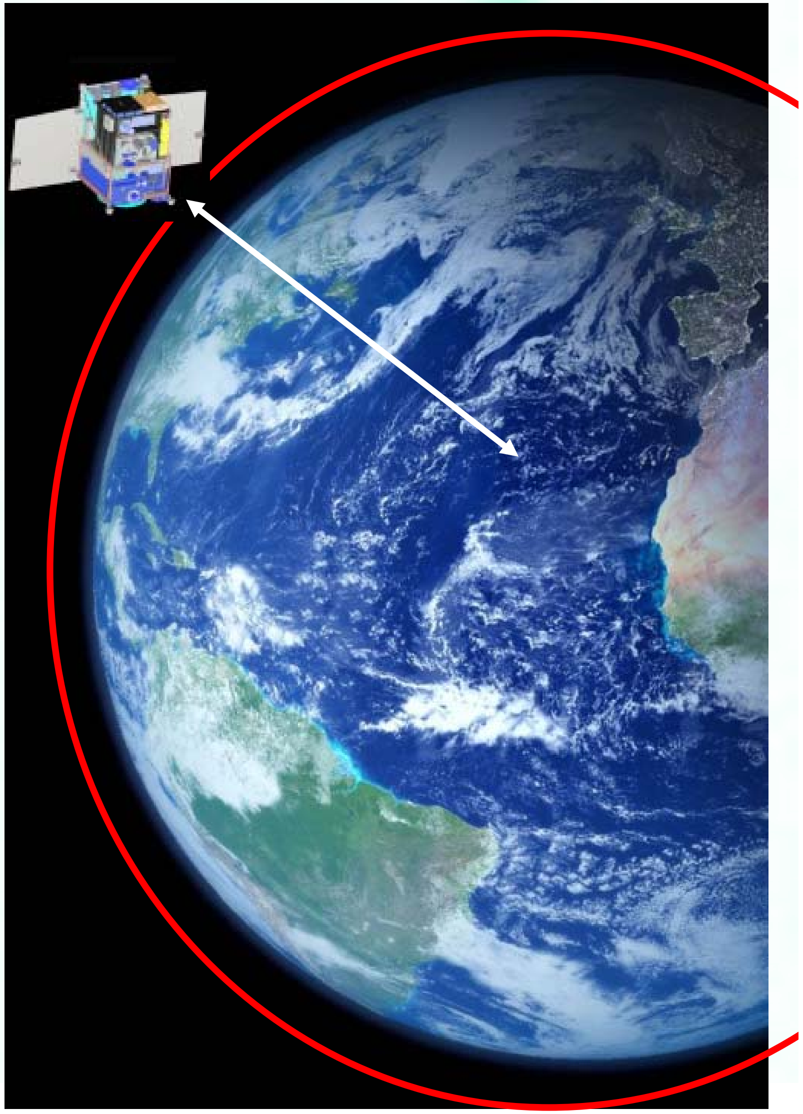
# QC in Earth-Space channel

- The natural step forward from QC on Earth is to mount the sender or the receiver on a **orbiting station**.
- The equivalent atmospheric thickness is reduced to about 10 km at sea-level.
- The leg length could be extended to $10^3$ km scale and more.



# Challenges in Space QC

- A (big) new problem: the sender is moving (and fast!) and a strong background is expected.
- The extension of the ground-QC is not trivial.
- The spaceborne terminal must be ***space qualified*** *and become* ***very costly***.



# Experimental Study of a Quantum Channel From a LEO Satellite to the Earth

P. Villoresi[1], T. Jennewein[2], F. Tamburini[3], M. Aspelmeyer[2,4], C. Bonato[1], R. Ursin[4], C. Pernechele[5], V. Luceri[6], G. Bianco[7], A. Zeilinger[2,4] and C. Barbieri[3]

[1]Department of Information Engineering, **University of Padova, ITALY** and **INFM-CNR LUXOR** Laboratory for Ultraviolet and X-ray Optical Research, **Padova, ITALY**
[2]Inst for Quantum Optics and Quantum Information, **Austrian Academy of Sciences, Vienna, AUSTRIA**
[3]Department of Astronomy, **University of Padova, ITALY**
[4]Faculty of Physics, Institute for Experimental Physics, **University of Vienna**, **AUSTRIA**
[5]**INAF**-Cagliari, Capoterra (CA), **ITALY**,
[6]Centro di Geodesia Spaziale "G. Colombo", **e-GEOS S.p.A., Matera, ITALY**,
[7]Centro di Geodesia Spaziale "G. Colombo", **Agenzia Spaziale Italiana, Matera, ITALY**.

**University of Padova Advanced Research Project QSpace 2003-2006**

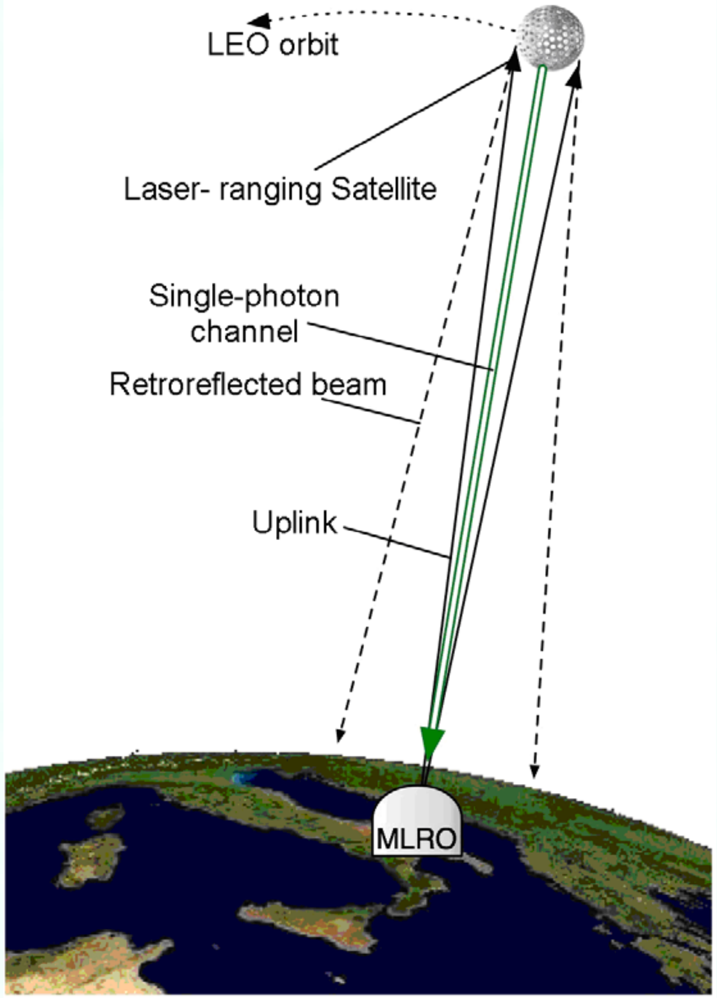
# Space quantum channel exploration

Aims of the experiment:

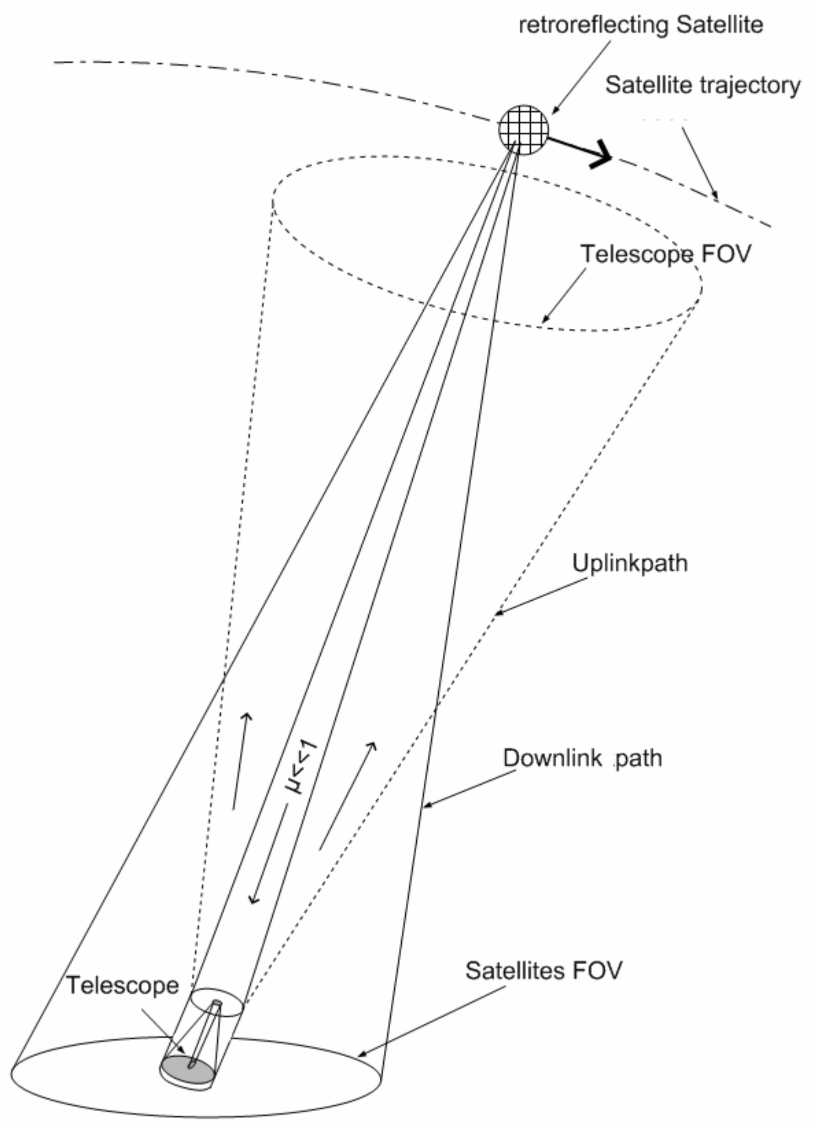
- To demonstrate the single-photon exchange from a orbiting sender.
- To test the ability of present technologies (2003-2005) for sending, timing and detecting single quanta from Space.
- To point out the critical aspects of space QC system in the perspective of a dedicated mission.

# Orbiting single-photon source

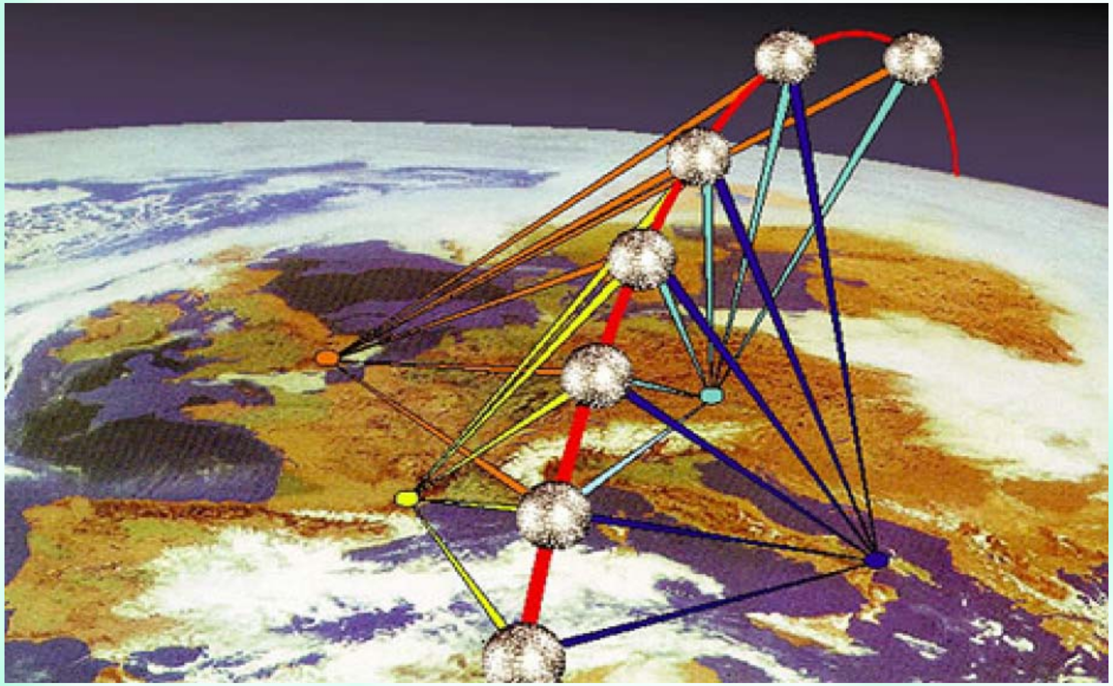
- The source is realized using orbiting retroreflectors.
- These belong to the network of the geodetic satellites for Satellite-Laser-Ranging (SRL).
- A station on Earth will send the pulse up and the satellite sends it back.



# Scheme of the link



# Concept of SLR Geodesy

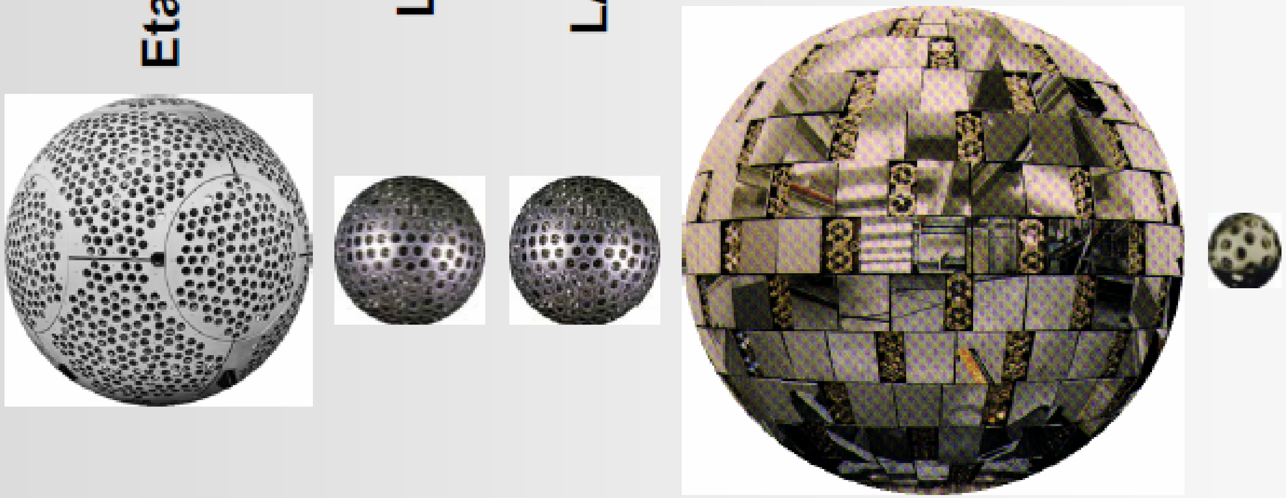


Measurements of

- Global tectonic plate motion,
- Regional crustal deformation,
- Earth gravity field,
- Earth orientation parameters

# Cube-corners cover the satellite

# SLR geodetic “cannonballs”



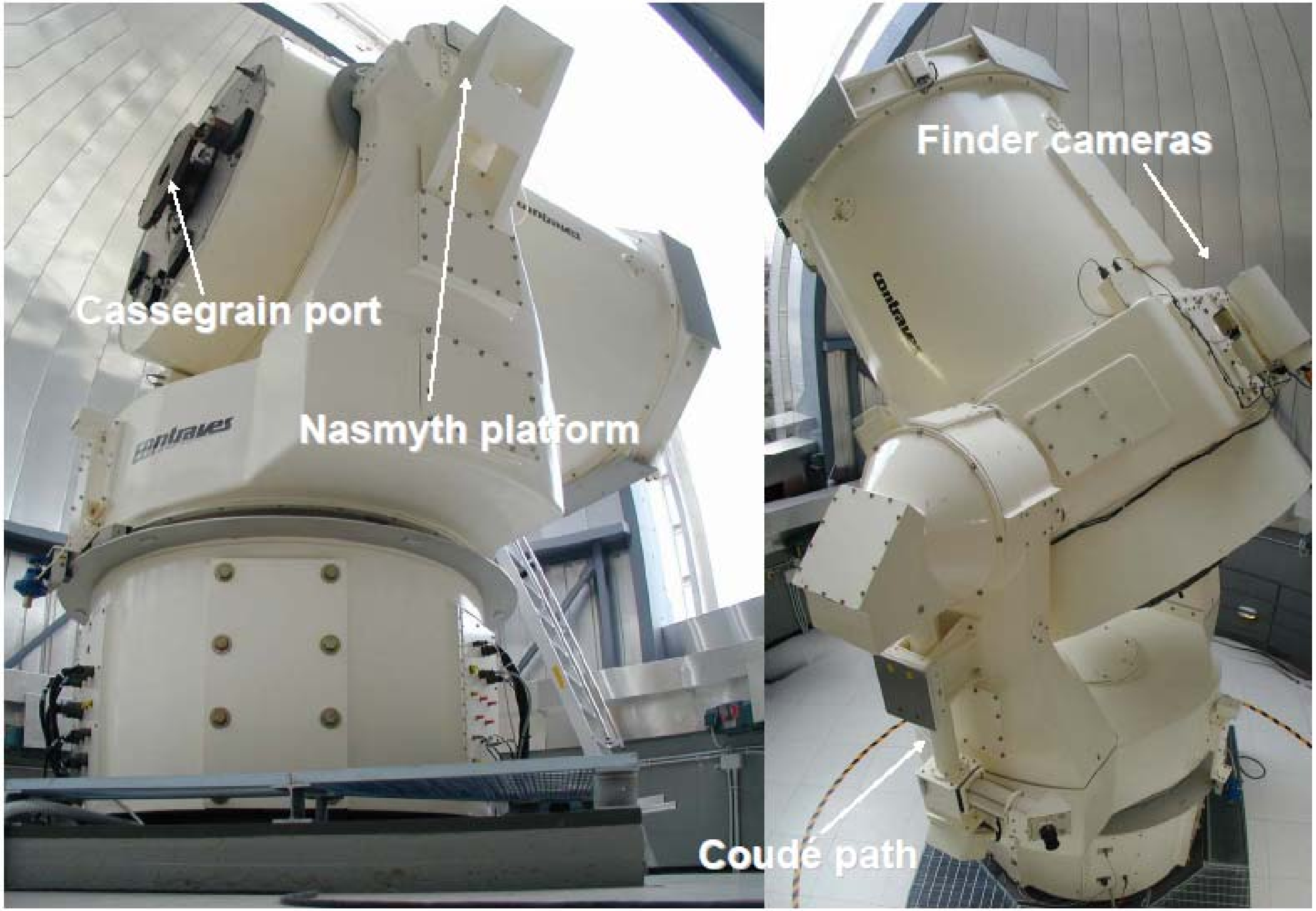
| | Etalon-I & -II | LAGEOS-I | LAGEOS-II | Ajisai | Starlette |
|---|---|---|---|---|---|
| Inclination | 64.8° | 109.8° | 52.6° | 50° | 50° |
| Altitude (km) | 19,120 | 5,860 | 5,620 | 1,490 | 810 |
| diameter (cm) | 129.4 | 60 | 60 | 215 | 24 |
| mass (kg) | 1415 | 411 | 405.4 | 685 | 47.3 |

# The ground station: Matera MLRO

- *Giuseppe Colombo* Space Geodesy Centre of Italian Space Agency.
- Matera Laser Ranging Observatory (MLRO).
- World highest accuracy in SLR: mm-level!


# Matera Laser Ranging Observatory

# 1.5m fast and accurate telescope




# Photon link budget

- The conditions for a single-photon downlink have to be pointed out on the base of the modeling of the link.
- The detector count rate (DCR) is estimated using the radar equation *(Degnan 1993):*

$$DCR = \Lambda \eta_d N_0 \eta_t G_t \sigma \left( \frac{1}{4\pi R^2} \right)^2 A_t \eta_r T_a^2 T_c^2$$

# Case of Ajisai satellite

| | | |
|---|---|---|
| Laser repetition rate | $\Lambda$ | 17 KHz |
| Energy per laser pulse | $E_0$ | 490 nJ (532 nm) |
| Photons per second | $N_0\Lambda$ | $2.3 \cdot 10^{16}$ |
| Detector quantum efficiency | $\eta_d$ | 0.1 |
| Efficiency transmitting optics | $\eta_T$ | $5 \cdot 10^{-3}$ |
| Transmitter gain | $G_T$ | $7 \cdot 10^{9}$ |
| Satellite cross-section | $\sigma$ | $1.2 \cdot 10^{7}\ m^2$ |
| Satellite slant distance | R | 1650 km |
| Telescope area | $A_T$ | $1.77\ m^2$ |
| Efficiency of receiving optics | $\eta_R$ | $4 \cdot 10^{-3}$ |
| One-way atmospheric trans. | $T_A$ | $8.1 \cdot 10^{-1}$ |
| One-way cirrus transmission | $T_C$ | 1 |
| **Expected detector rate** | **DCR** | **4.6 cps** |

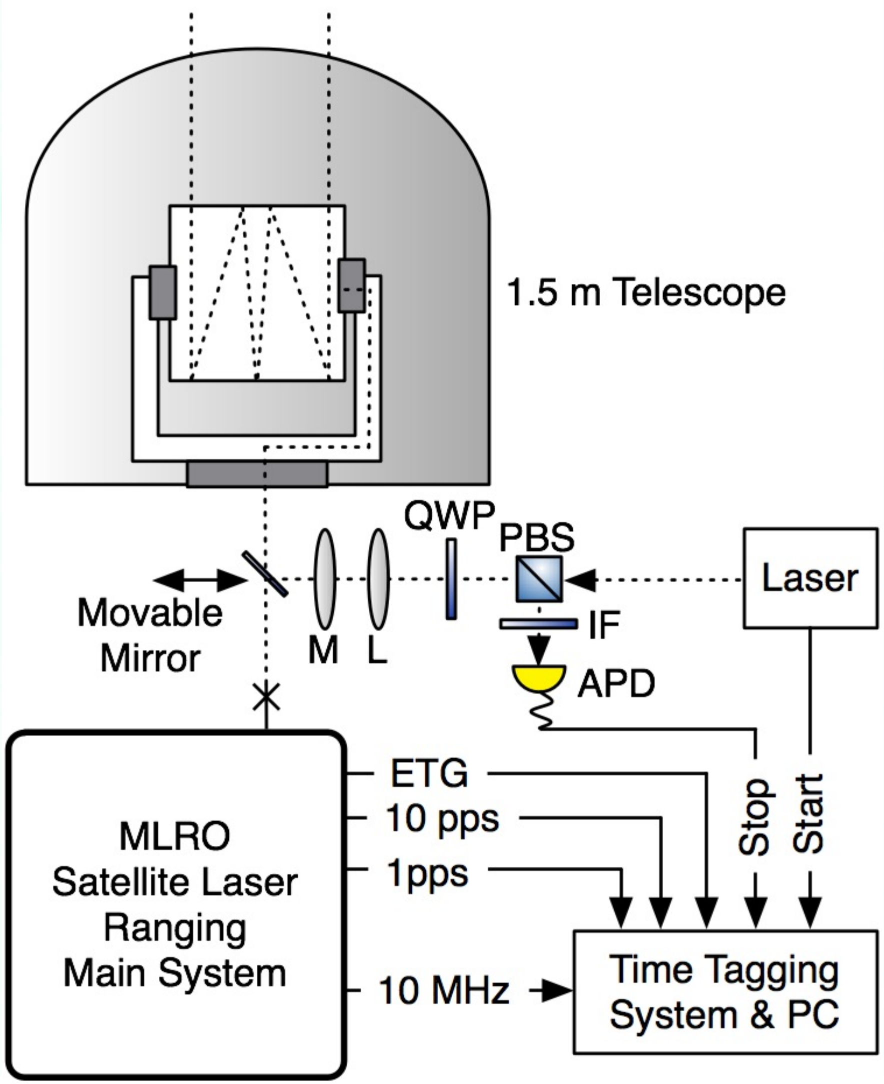
$$DCR = \Lambda \eta_d N_0 \eta_t G_t \sigma \left( \frac{1}{4\pi R^2} \right)^2 A_t \eta_r T_a^2 T_c^2$$

# The brightest satellites for MLRO

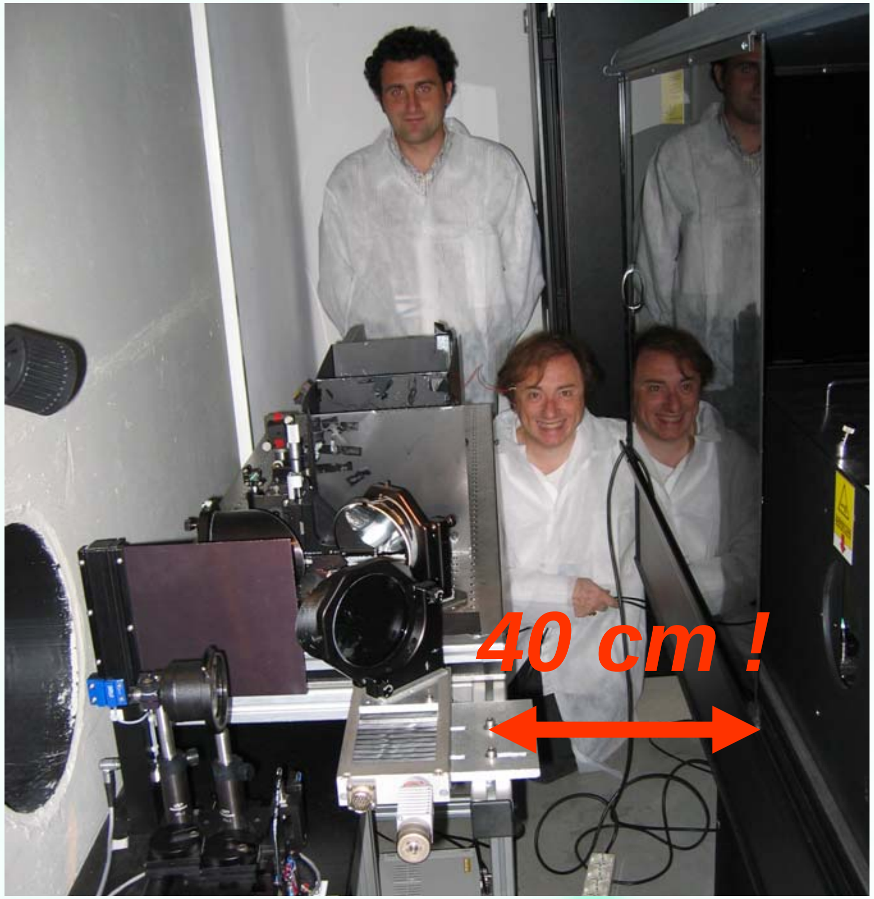
| | Ajisai | Beacon | Topex | Lageos |
|---|---|---|---|---|
| DCR | 4.6 | 1.2 | 0.8 | 0.01 |
| loss in downlink | $2.2 \cdot 10^{-9}$ | $6.6 \cdot 10^{-10}$ | $3.7 \cdot 10^{-10}$ | $8.4 \cdot 10^{-11}$ |
| photons in the channel per shot | 0.38 | 0.10 | 0.06 | 0.0009 |

# Prescriptions for the setup

- The outward laser pulse has to be tailored to the link budget and to the telescope size.
- The receiver has to be coaxial to transmitter.
- The gathered field of view (FOV) must consider the broadening due to satellite velocity aberration.
- The actual setup is not preserving the polarization state.



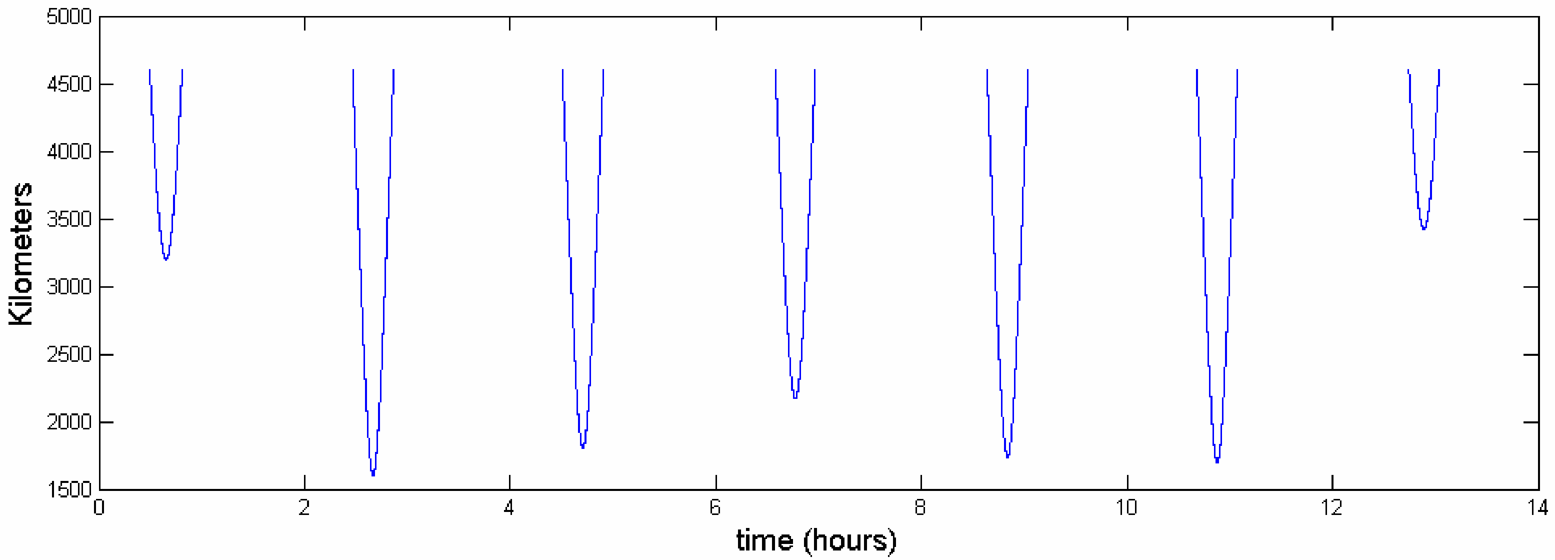
# Single-photon transceiver setup


Difficult to make it at *tableside*

# Actual orbital data from NASA

- Real time temporal filtering: calculating the gating time.
- Post processing using Geodyn code, to 1 ns precision.




Ajisai orbit

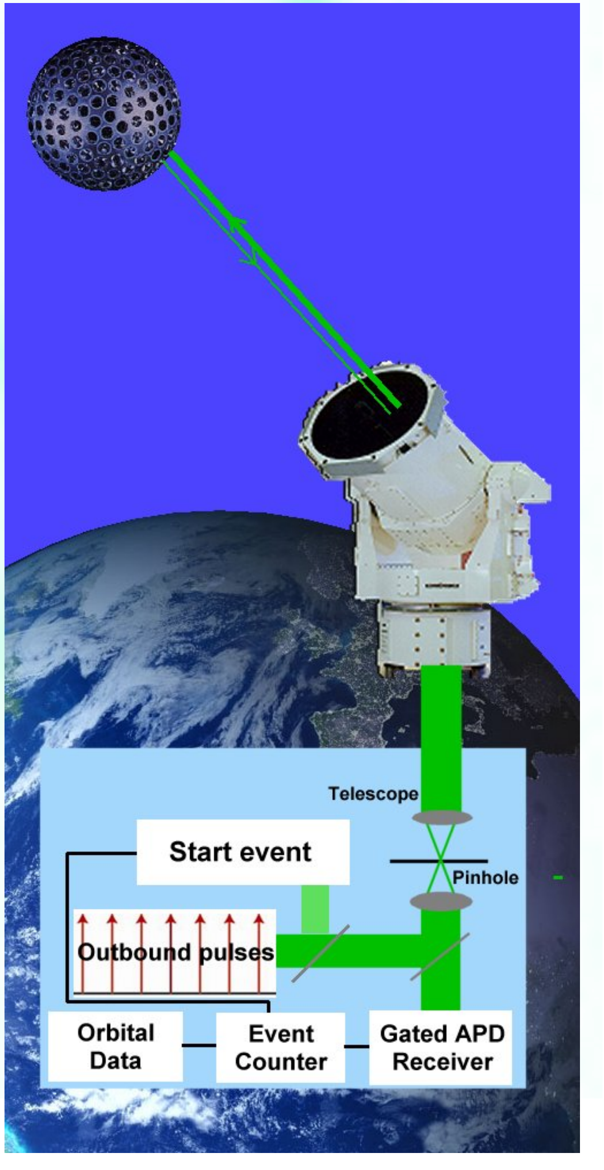
# Point out the return time

- For every detector click was calculated the difference from the expected arrival instant

$$D = t_{exp} - t_{ret}$$

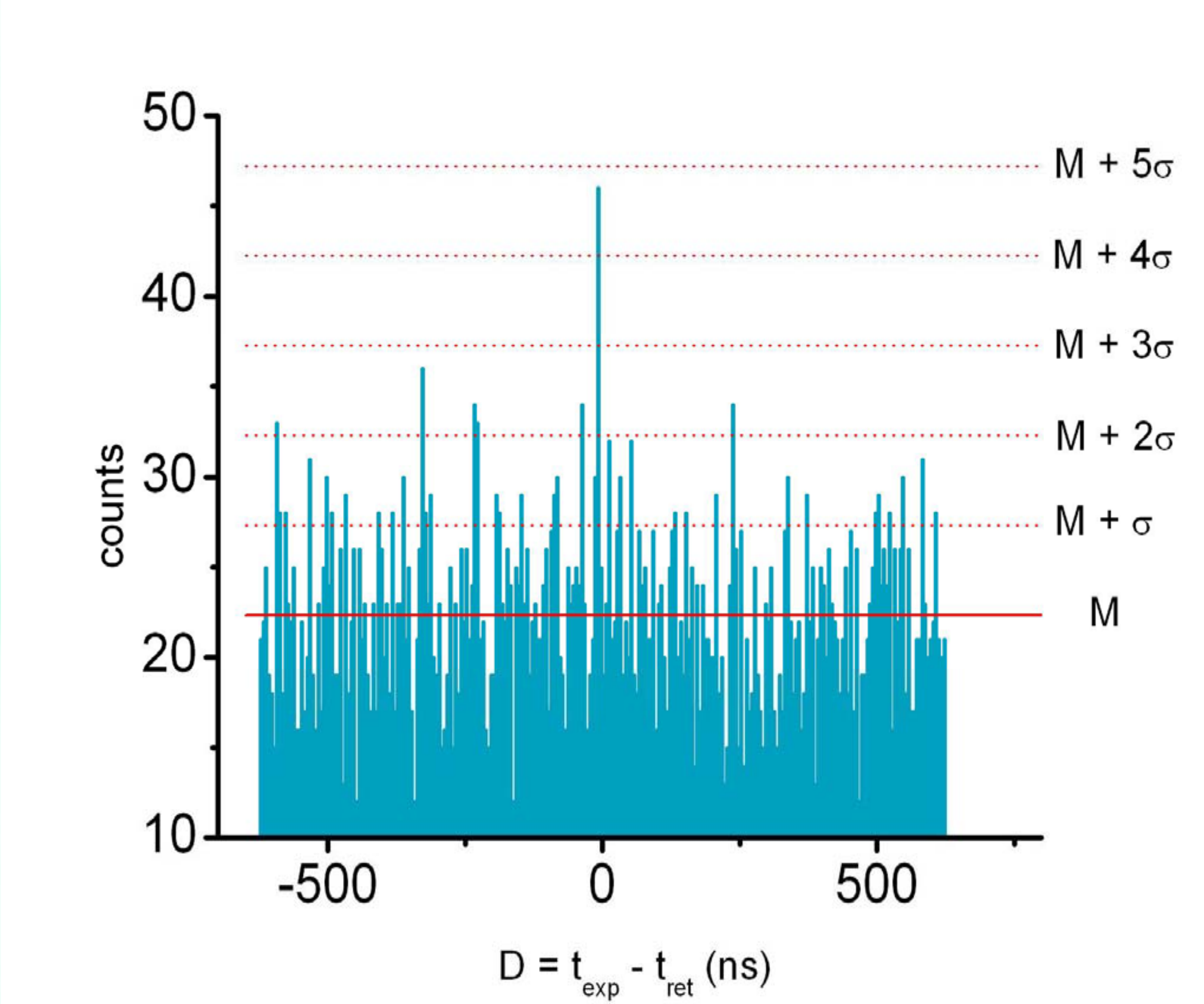
- D was then grouped in histograms.

- The link implies a peak at D=0 over the background level.



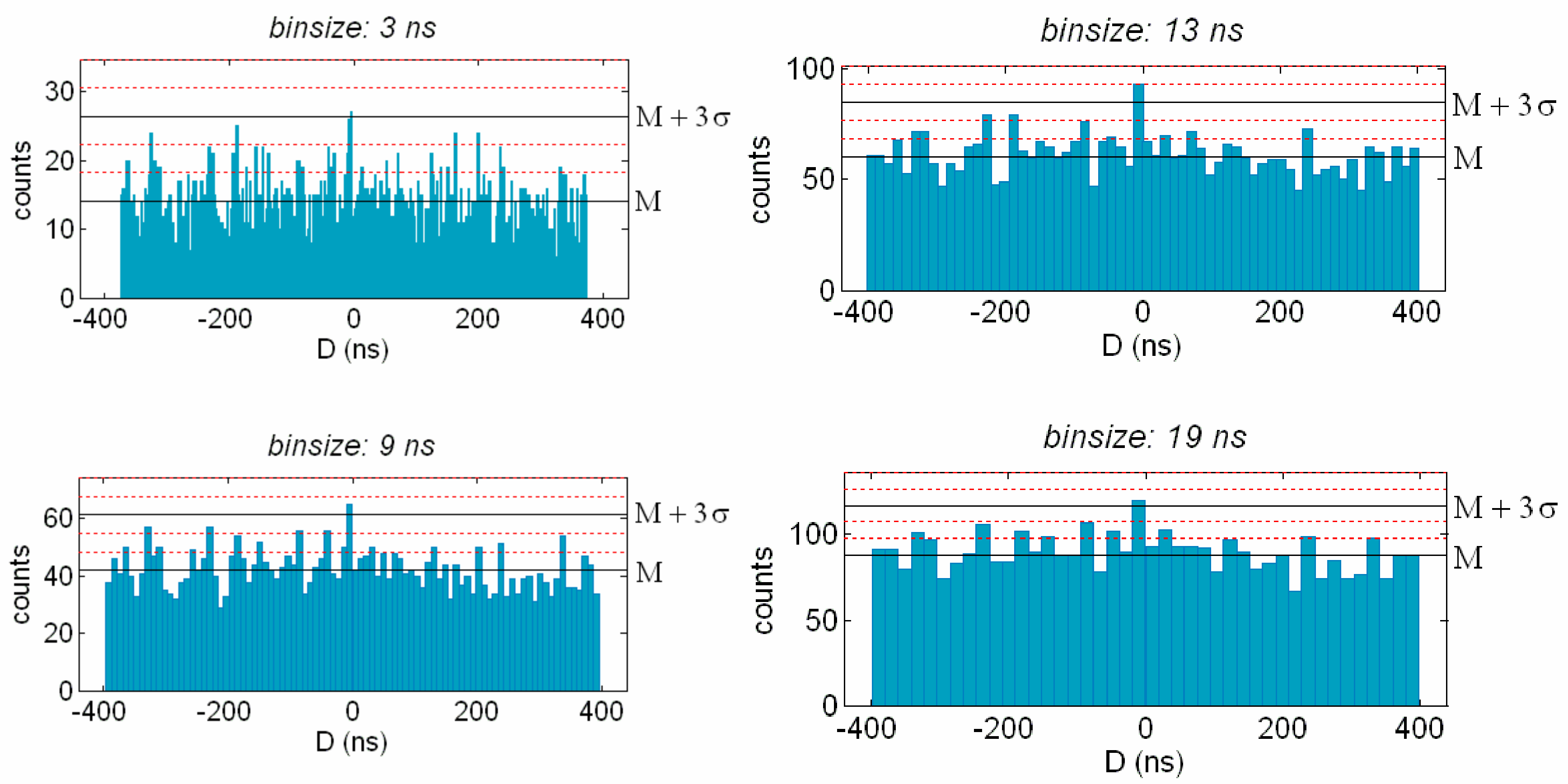
# Single-photon link with Ajisai

- Integration 5 s
- Bin-size 5 ns
- FOV 30”
- Filter 10 nm BW




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

# Single-photon link with Ajisai




Robustness against statistical effects on bin size

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

# Returns rate

- A peak of 5 cps was observed at D=0 above the background.
- The peak height exceeds 4 times the rms of the background.
- Total losses are of -157 dB.
- In the downlink channel, $\mu = 0.4$, and so clearly in the single-photon regime.
- DCR = 17 kHz X p(*click*) 3 $10^{-4}$ per pulse.

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

# Conclusions of QSpace

- The feasibility of a single-photon link from an orbiting source and a ground received has been demonstrated for the first time.
- The experimental DCR is in good agreement with the radar equation predictions.
- The transmission is scalable to higher laser repetition rate (detector far from saturation).
- **Space QC**: A really interdisciplinary subject!

# The next step: feasibility study of a dedicated satellite for QC

The space quantum channel or

*To investigate the quantum nature without boundaries*

- **Space** Bell experiment or *is there a limit for the "spooky action"?,*
- Novel approach to the study of decoherence,
- Long distance teleportation,
- Quantum key distribution around the planet,
- Quantum Astronomy.


# Padova SpaceQ team

Right to left: Cristian Bonato, Andrea Tomaello, Vania Da Deppo, Ivan Capraro, Giampiero Naletto, Cesare Barbieri, Paolo Villoresi

Not in the photo: Gabriele Anzolin, Tommaso Occhipinti, Fabrizio Tamburini

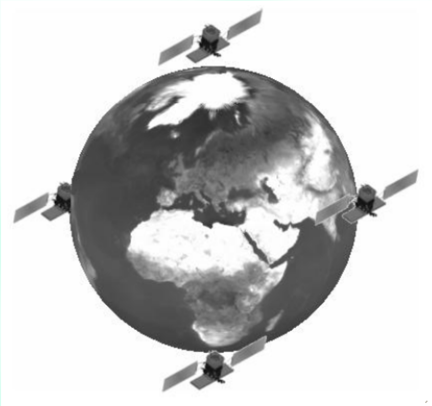
*Department of Information Engineering, CISAS and Department of Astronomy*

*University of Padova, ITALY and*

*INFM-CNR LUXOR Laboratory for Ultraviolet and X-ray Optical Research, Padova, ITALY*

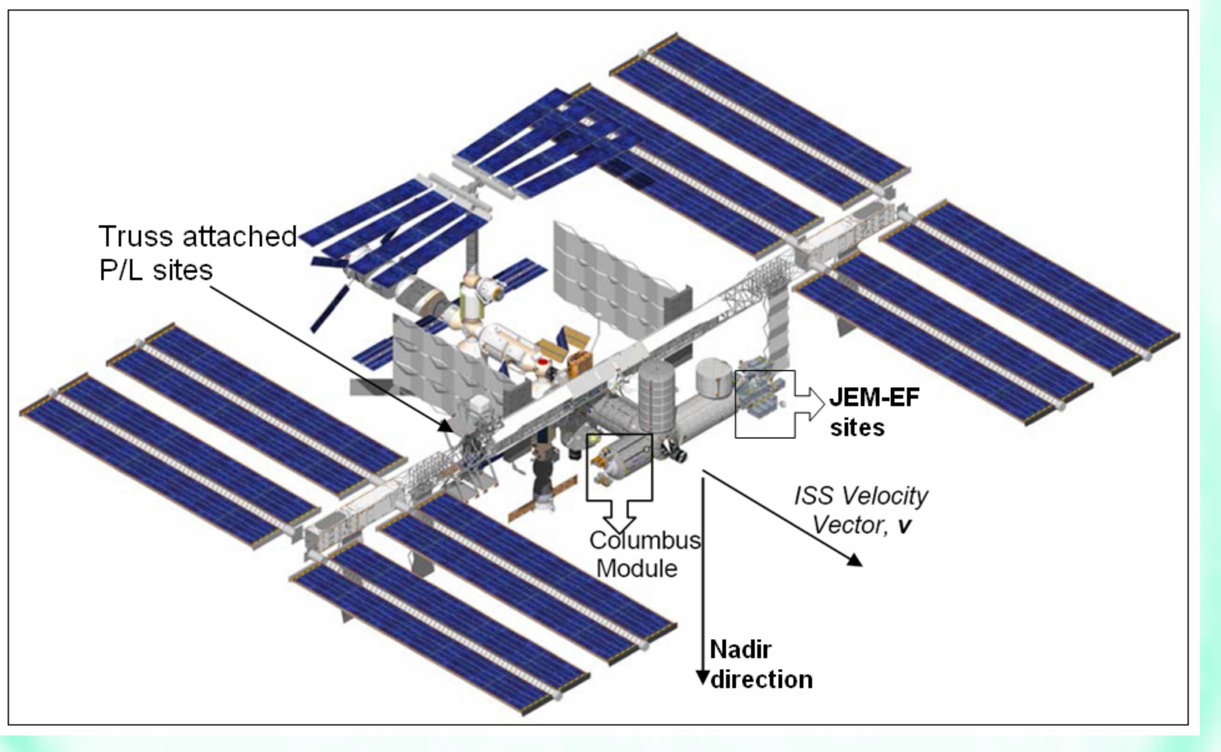
# SpaceQ opportunities

- Detailed analysis of the possibilities for the orbiting terminal:
- Constraints:
  - Launch date;
  - Orbit < 1500 km
  - Size, weight, power, data-rate available;
  - Cost of the opportunity;
  - Type of orbit.
- Many opportunities were not doable because of last point: polar **but** dawn-dusk orbit



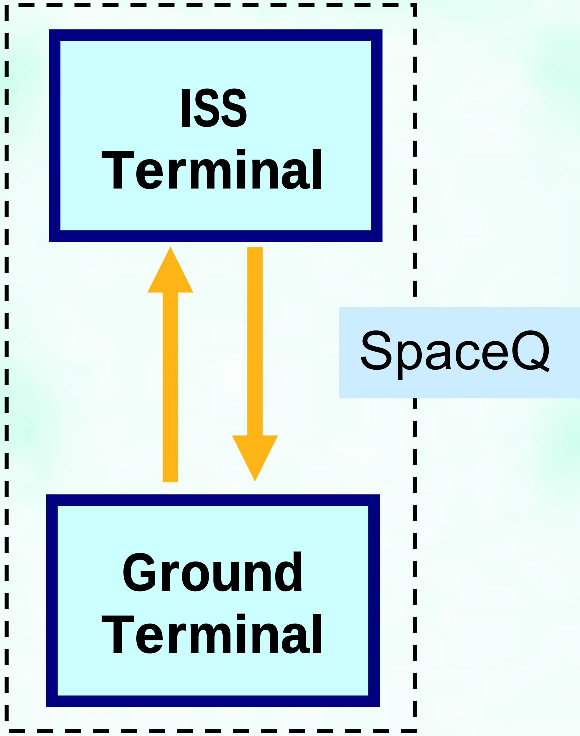
# ISS possible accommodations

- ***International Space Station Tour** on youtube*



# General Scheme of SpaceQ

SpaceQ blocks: to establish a bidirectional polarization quantum channel between a LEO satellite and a ASI-MLRO ground station.



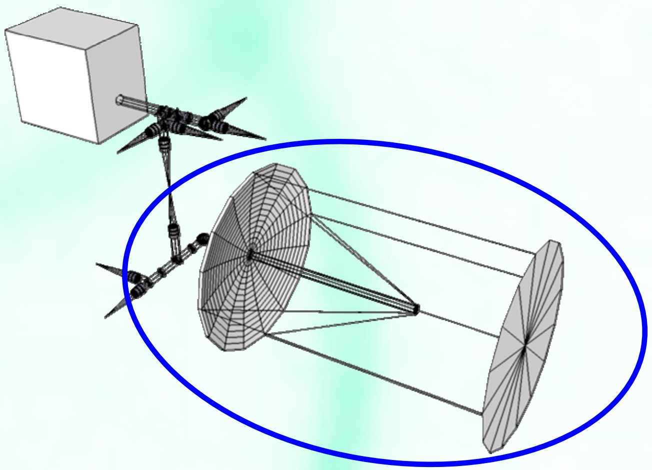
# Telescope design

Telescope configuration: afocal Gregorian type (two paraboloidal mirrors)

Advantages: collimated output, very small obscuration, optimal optical performance for on-axis source (very small active FoV: 10 arcsec), large magnification

A simple baffling system is foreseen to limit diffused light

No critical point is seen in the telescope realization



# the Quantum Channel

QUBITS encoded in the polarization states of single photons

Quantum Channel requirements:

- link budget and SNR
- noise rejection techniques
- pointing, acquisition and tracking (PAT)
- synchronization
- polarization control

# SNR requirements for the Quantum Channel

SNR required: **6:1**

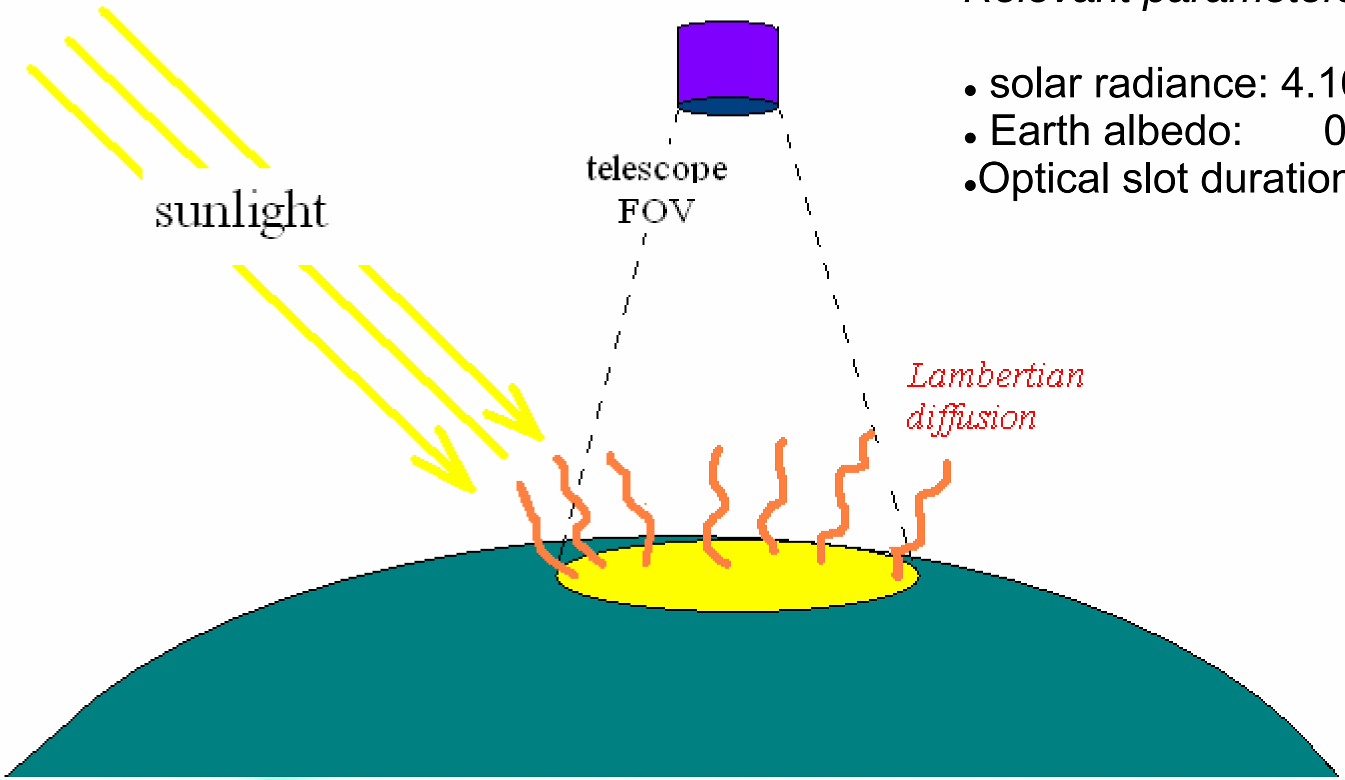
*Details:*

M. Aspelmeyer, T. Jennewein, M. Pfennigbauer, R. Leeb, A. Zeilinger, *Long-Distance Quantum Communication With Entangled Photons Using Satellites*, IEEE Vol. 9 (2003)

for single-photon communication:

- the amount of signal is fixed to **ONE PHOTON,** emitted by the transmitter
- the only tool to increase SNR is to **decrease noise!**

# Background Noise in uplink




*Relevant parameters:*

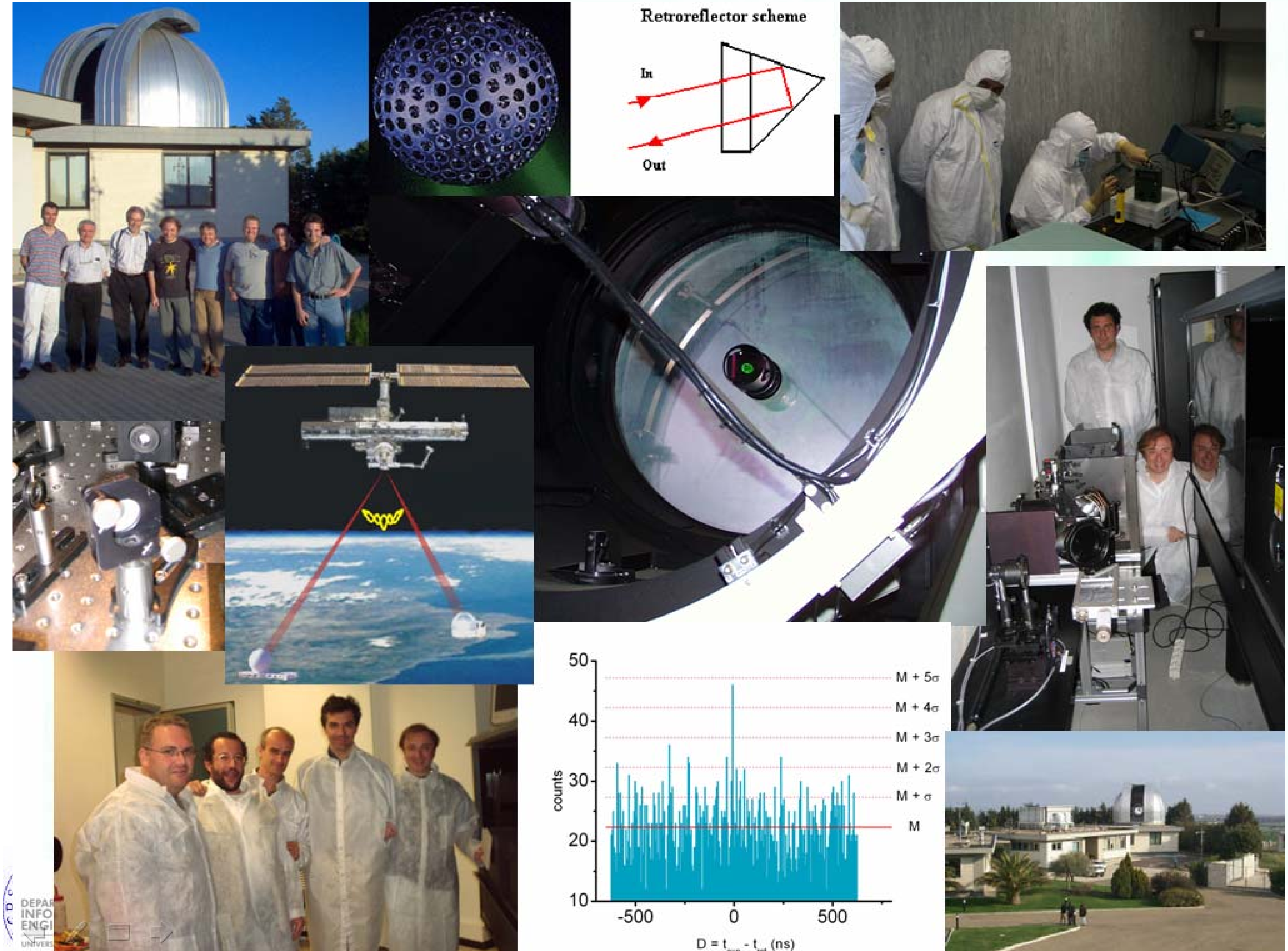
- solar radiance: $4.16 \cdot 10^{18}$ photons/(s nm m$^2$)
- Earth albedo: 0.3
- Optical slot duration 5 ns

# MLRO facilities and Nasmyth platform

• 1.5 meter telescope with astronomical quality optics, Cassegrain configuration f/212, long Coudé path
• ranging laser: active hybrid Nd:YAG, 40 ps pulses @ 523 nm, 100 mJ/pulse; 10 Hz repetition rate, range accuracy less than 2 mm
• the transmitted beam divergence is "diffraction limited" and can be tuned in a continuous way from around 1" to 20".
• a Hydrogen Maser atomic clock is used to synchronize all operations to better than 10 ps
•as safety device, a radar aircraft detection system is present

# Conclusioni

- Le comunicazioni hanno la loro frontiera nel trasmettere singoli quanti (QC).
- La ricerca di estendere la QC ha in parte abbandonto la Terra per interessare lo Spazio.
- Si apre un nuovo modo per interpretare le informazioni.
- La teoria non prevede sorprese: è il caso di fare esperimenti!



Retroreflector scheme
In
Out
50
40
30
20
10
counts
-500
0
500
M + 5σ
M + 4σ
M + 3σ
M + 2σ
M + σ
M