John Templeton Foundation

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Seminar organized within the project:
"Hunt for the "impossible atoms":
the quest for a tiny violation of the Pauli Exclusion Principle. Implications for physics, cosmology and philosophy,"
ID 58158, funded by the John Templeton Foundation

Quantum Mechanics under test along Space channels

Paolo Villoresi

QuantumFuture Research Group
Università degli Studi di Padova, DEI, Padova, Italy

Workshop Quantum Foundations/ New frontiers in testing quantum mechanics from underground to the space - 1 December 2017

QuantumFuture Research Group


IQIS Padova 2012

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 **University of Padova**, **Italian Space Agency, European Space Agency,** industrial research contracts

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

Currently **6 Faculties+6 PhD Students + 3 Post-Docs+ undergraduates + 2 EU MSCT PhD stud (2017)**


La Palma – Tenerife quantum link

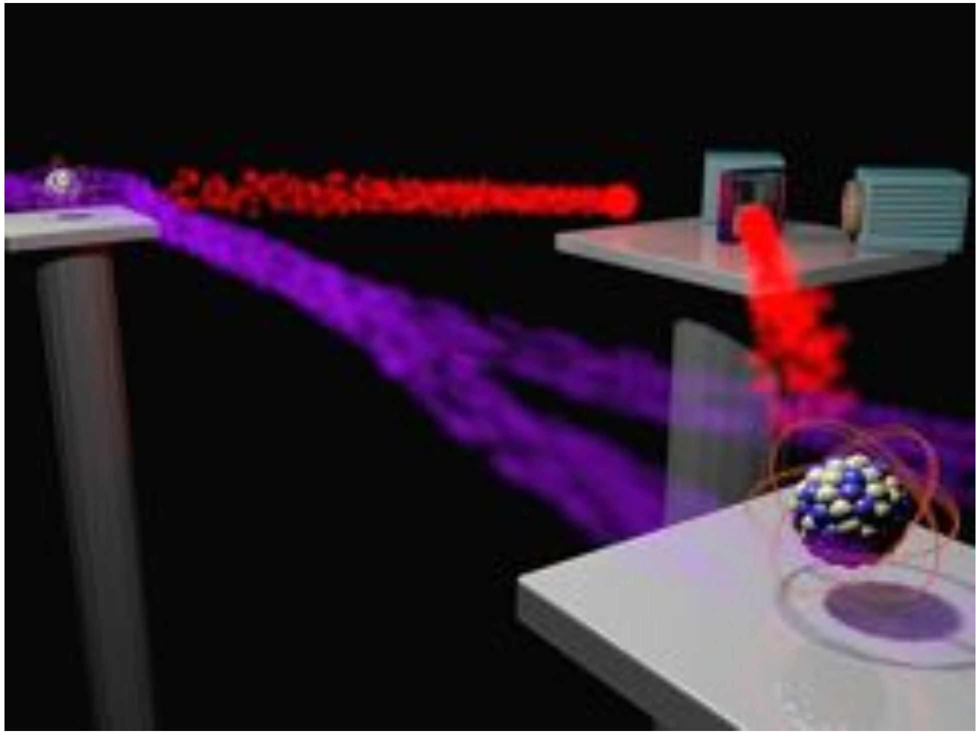

PhD Winter School 2011


PhD Winter School 2013

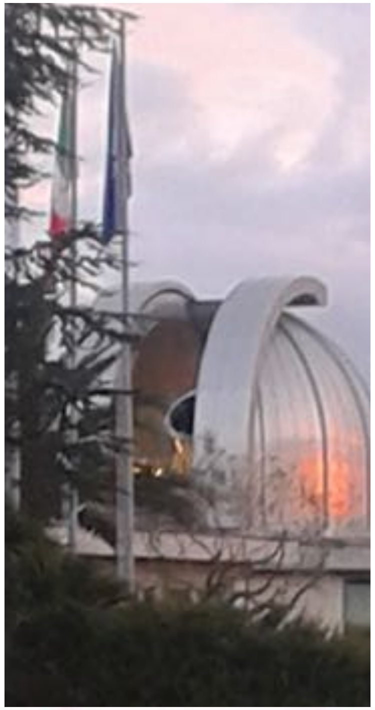
QF group in 2016

Quantum Communications

Quantum Communications is the art of **sharing quantum states** between distant partners.



Quantum Communications in Space



- **Space QC: demonstration of protocols for secure communications** such as quantum-key-distribution (QKD) and quantum teleportation **along**
    - **satellite-to-ground or**
    - **intersatellite links.**
- **Quantum Communications: faithful sharing of qubits between separate correspondents**
    - **Test for the Principles of Quantum Physics in a new context**
    - **Massless Probe from a moving terminal, along a channels where Relativistic effects may be revealed using quantum interferometry, polarization, etc.**

Our knowledge is ultimately restricted by the boundaries of what we have explored by direct observation or experiment.

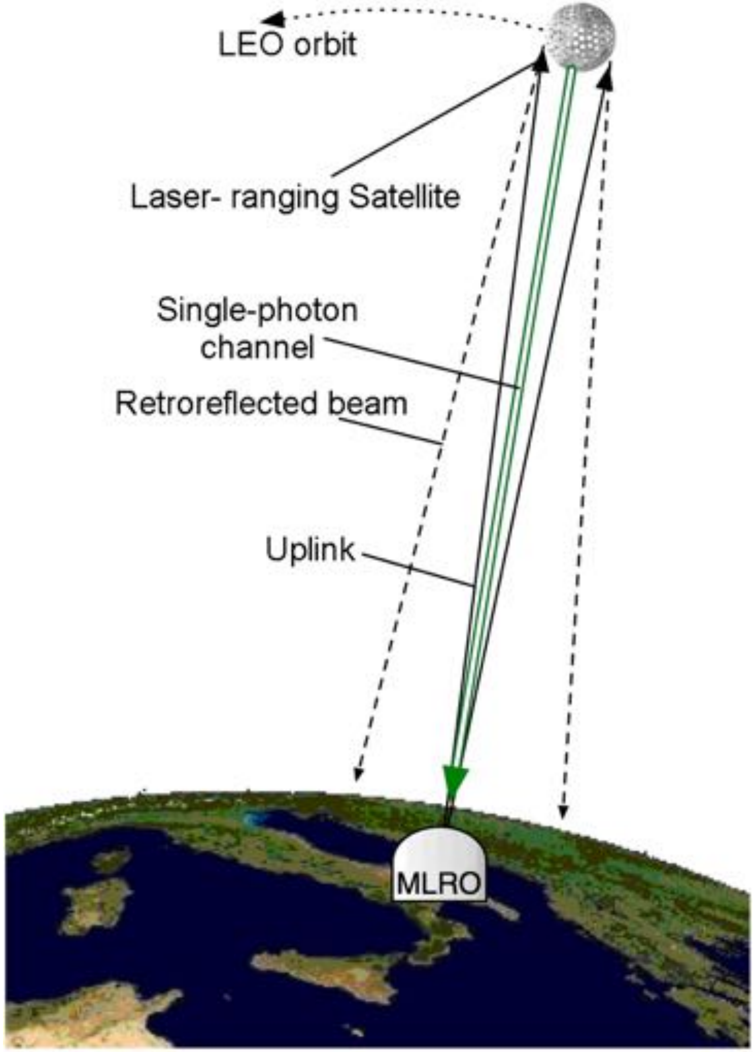

Quantum Manifesto
A New Era of Technology
May 2016
Quantum Technologies Timeline
ATOMIC QUANTUM CLOCK
QUANTUM SENSOR
INTERCITY QUANTUM LINK
QUANTUM SIMULATOR
QUANTUM INTERNET
UNIVERSAL QUANTUM COMPUTER
2015
2035

Investigation of QC along space channel without active satellite

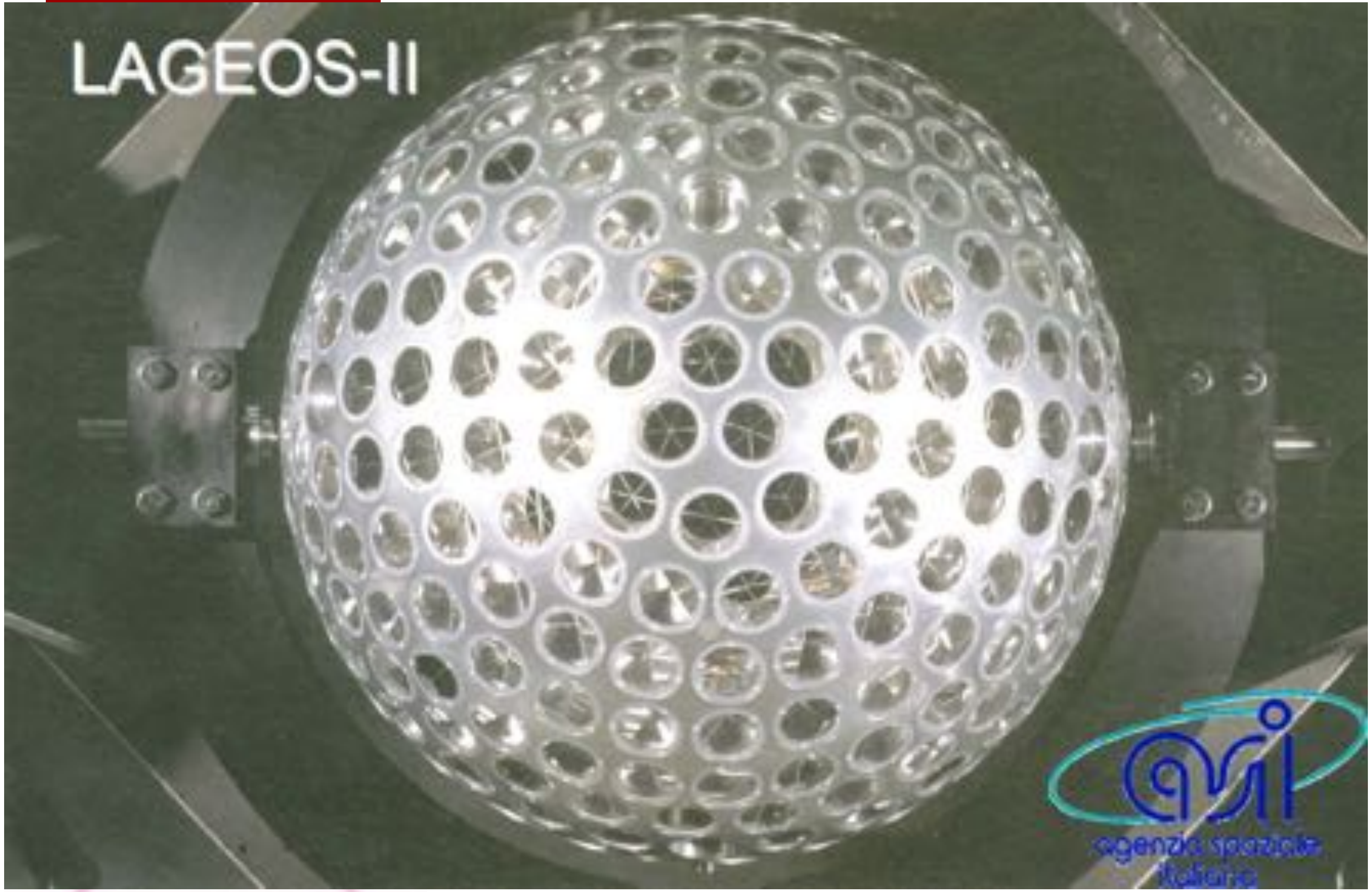
- **Orbiting retroreflectors may be used in a two-way link with a single telescope on ground**

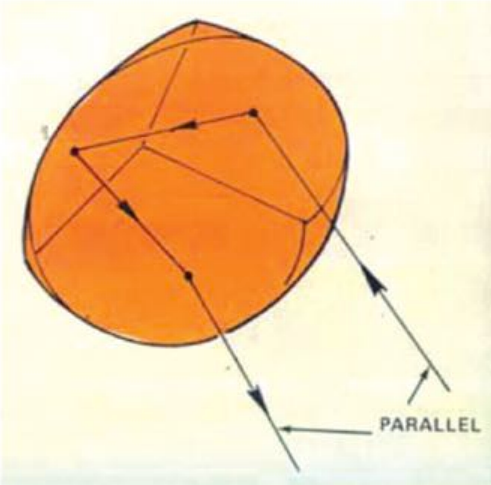
- They ***may*** preserve
  - **the polarization state**
  - **the temporal coherence**

- **The channel transfer function** is modeled according to:
  - **diffraction losses,**
  - **atmospheric absorption,**
  - **wavefront degradation due to turbulence**
  - **reflectivity of the retroreflector**
  - **optical characteristic of the ground station**

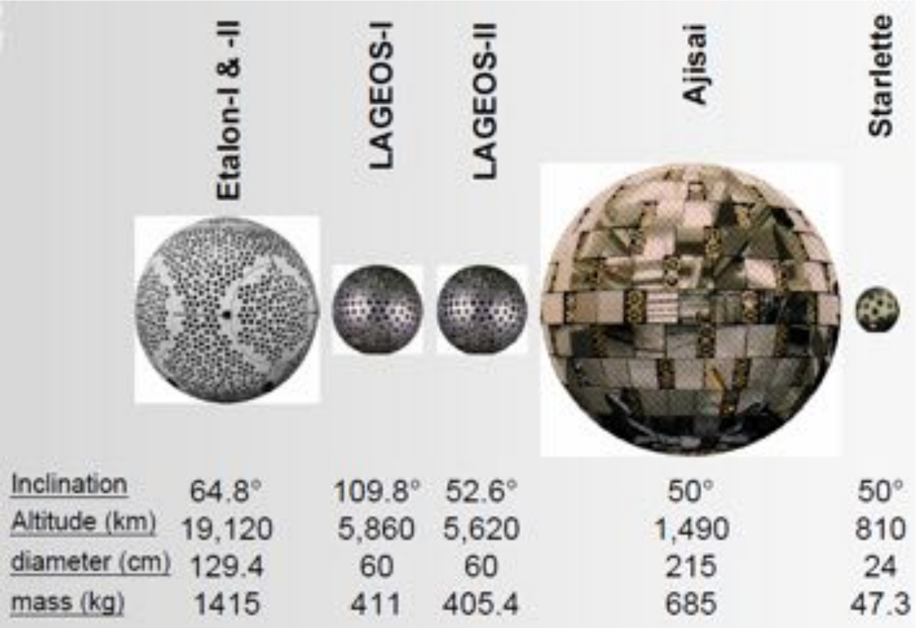


Corner-cube retroreflectos

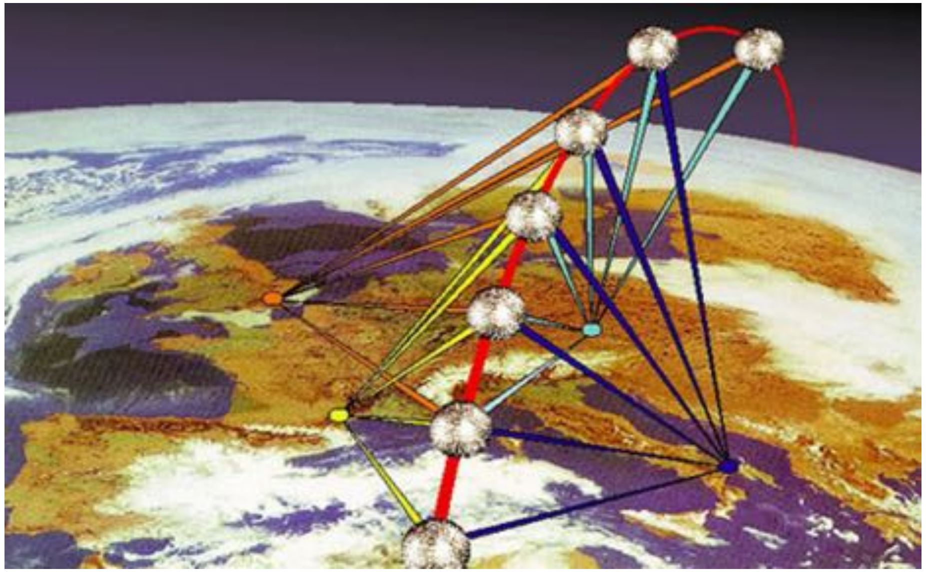




Large selection of space retroreflectos for Space Geodesy and more



	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

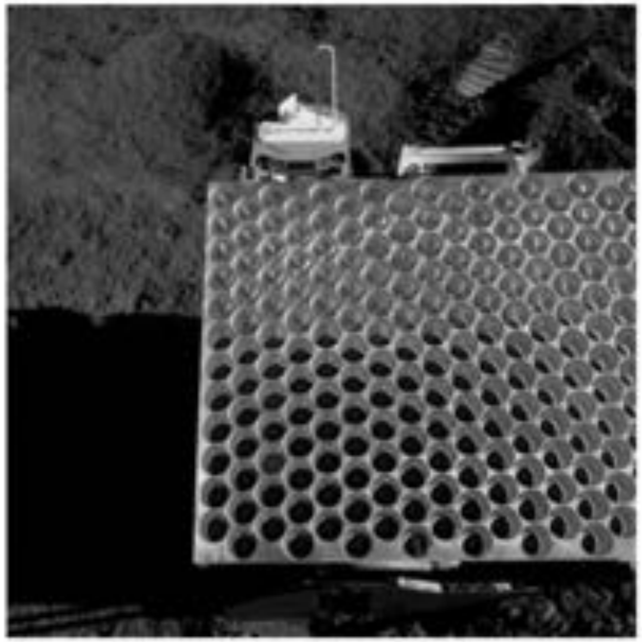


- Global tectonic plate motion
- Regional crustal deformation
- Earth gravity field
- Earth orientation parameters

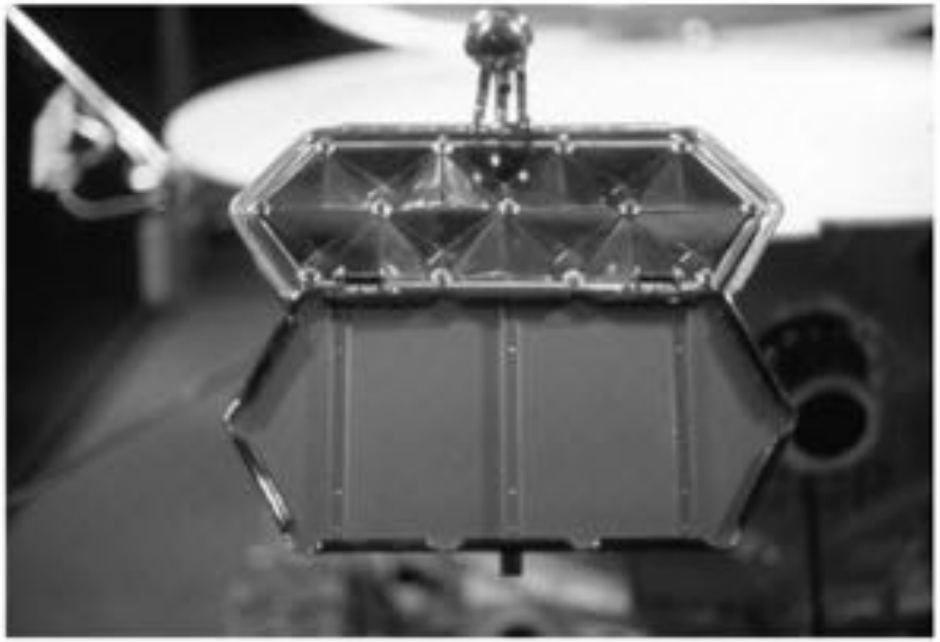
http://ilrs.gsfc.nasa.gov

Lunar corner-cube retroreflectos

Apollo11 CCR module



Apollo15 reflectors: *300 corner cube 3.8 cm dia*



Lunokhod reflector

..from

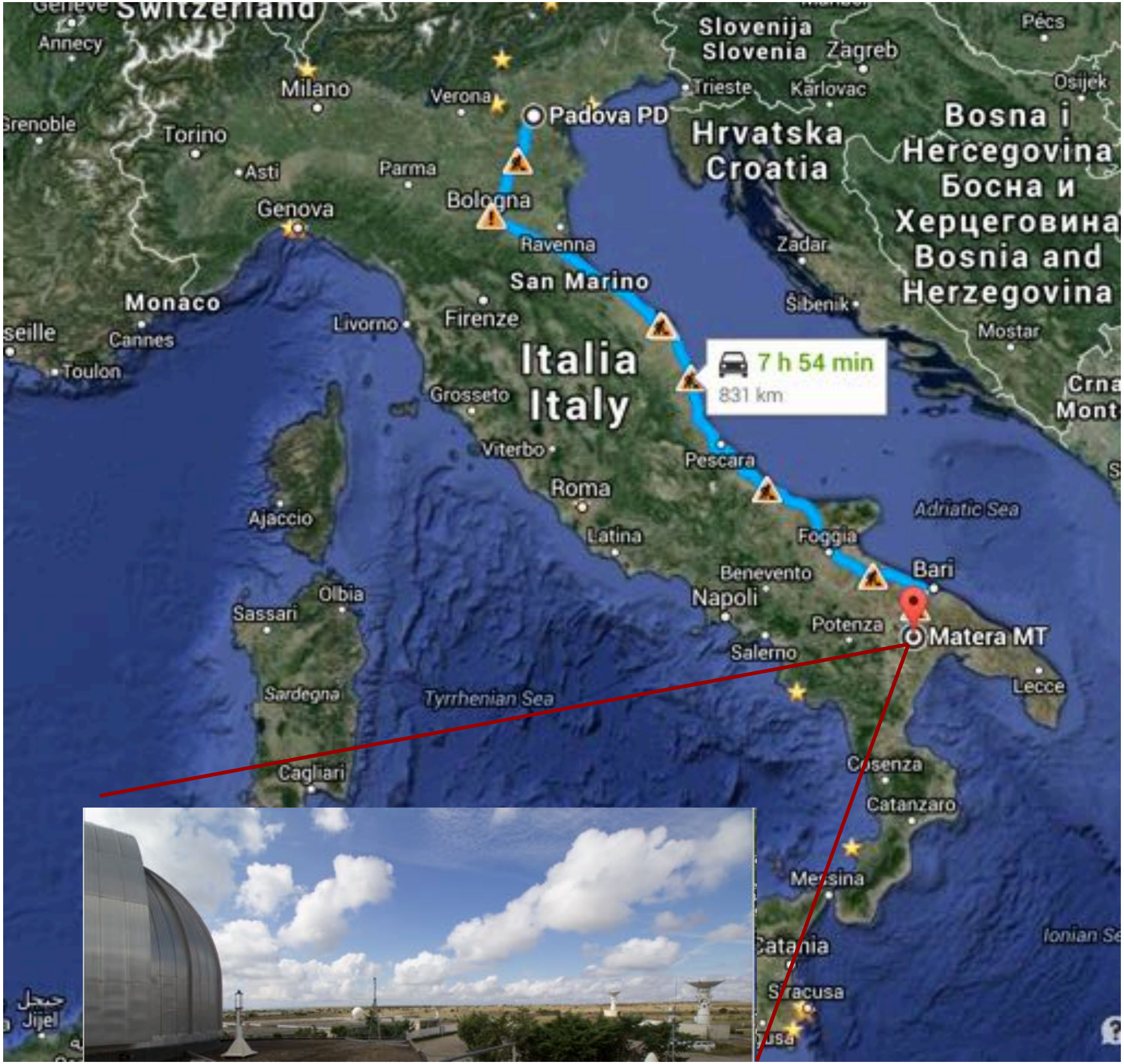
Padua University

to..

Matera Laser Ranging Observatory

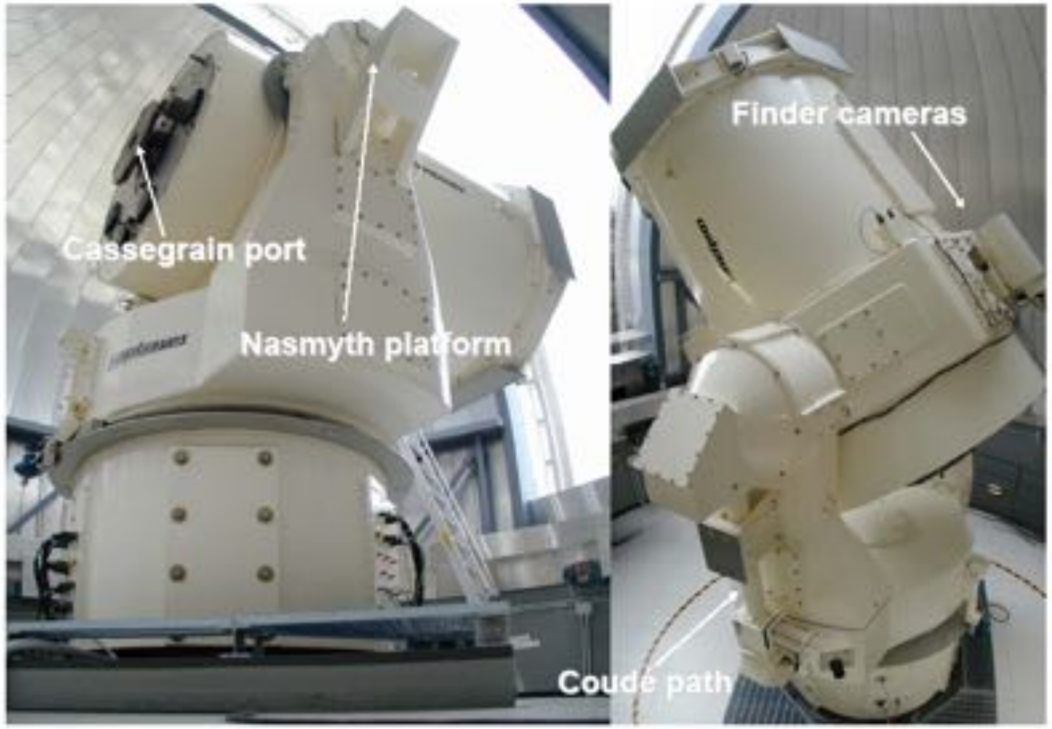
of the Italian Space Agency

Universa
Universis
Patavina
Libertas



The ground station: Matera ASI-MLRO

- *Giuseppe Colombo* Space Geodesy Centre of Italian Space Agency - Matera Laser Ranging Observatory (MLRO)
- Director Dr. Giuseppe Bianco President of ILRS
- World highest accuracy in SLR: **mm-level** for about 10^7 m range
- Accurate **lunar** ranging



Beginning: single photon exchange

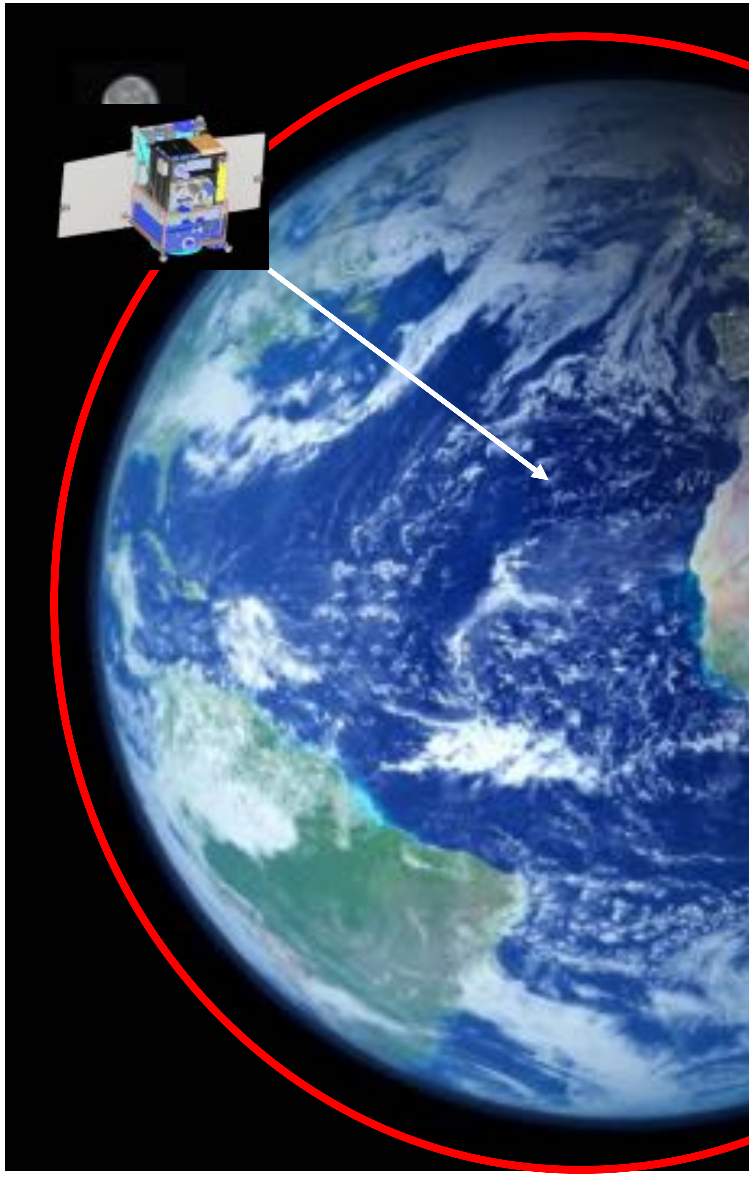
The satellite is acting as a source emitting a single photon in the receiving cone from a moving reference.

There are rapid variations of:

- Link length, timing
- Pointing
- Velocity aberration ∂~2v/c

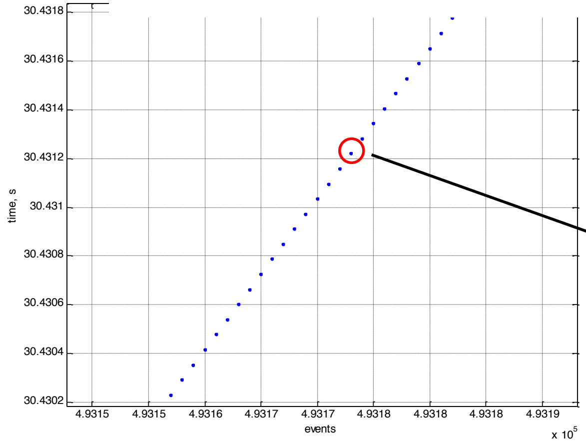
QComm requires to point out when to measure to the ns or better

the Earth gravitational field is stronly influencing the motion: no Keplerian orbit approximation!

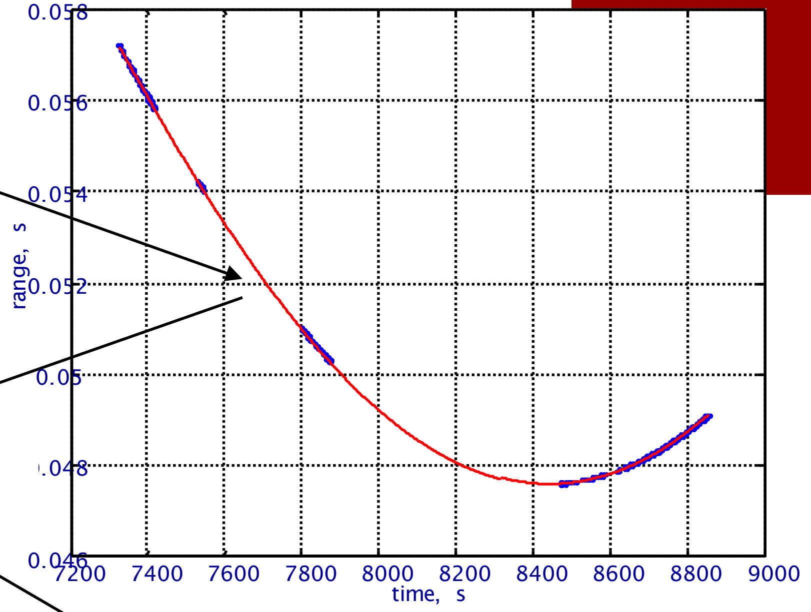


Scheme for the search of the returns

Launched laser pulses

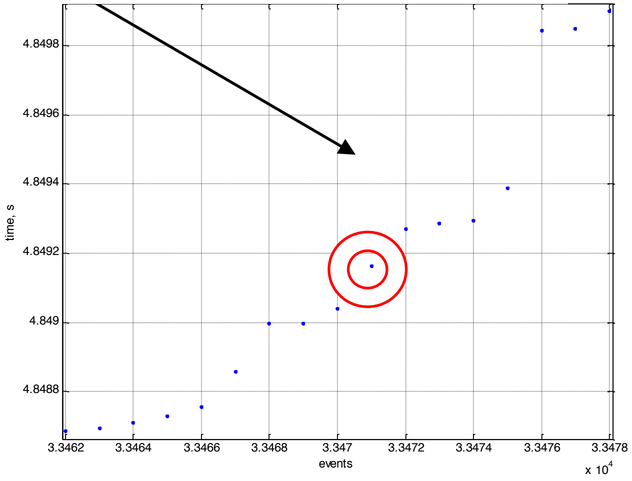


Satellite range



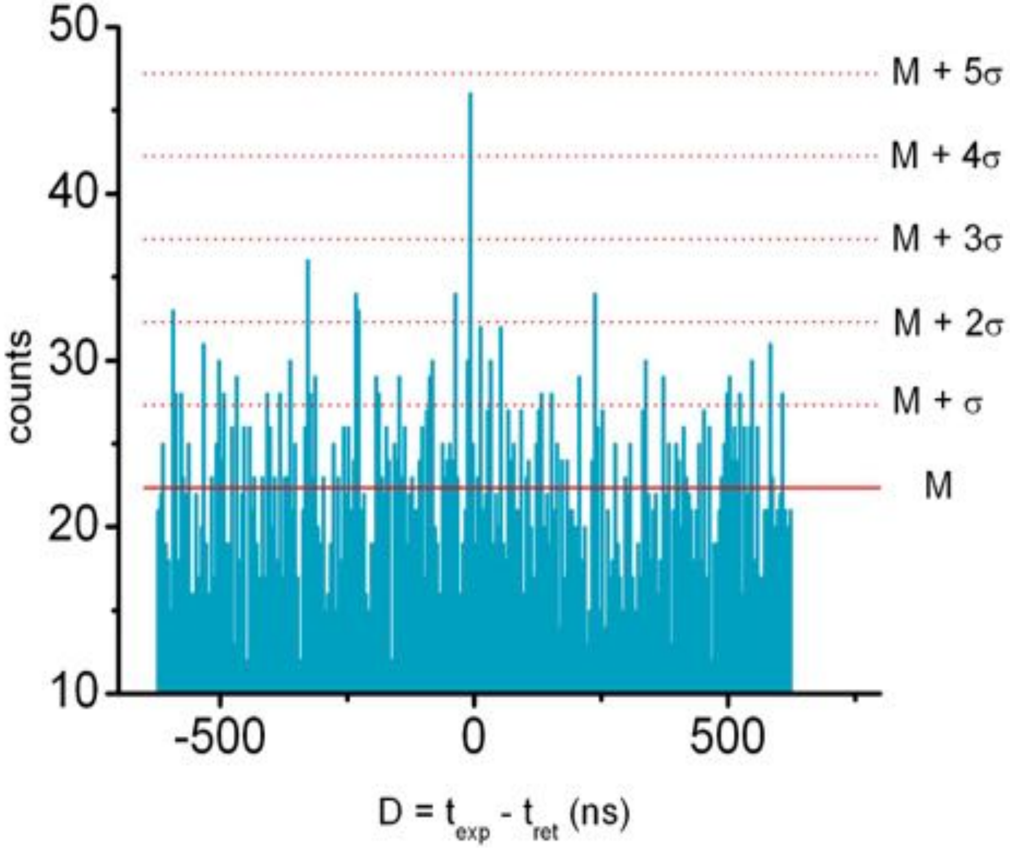
Instrumental offset

Detector clics vs. time



Single-photon link with Ajisai

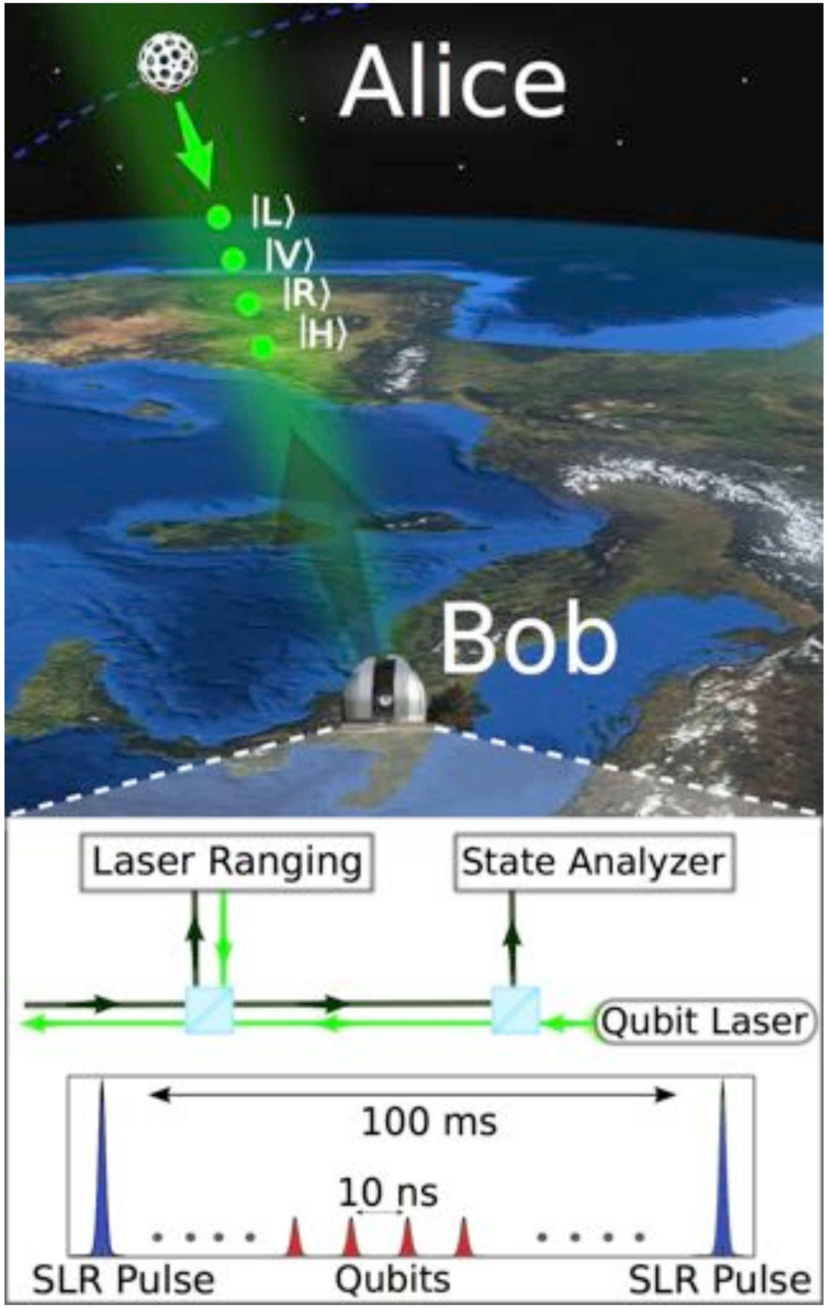
- A peak of 5 cps was observed at D=0 above the background.
- The peak height exceeds 4 times the rms of the background.
- **Total losses are of -157 dB.**
- In the downlink channel, μ = 0.4, and **so clearly in the single-photon regime**.
- DCR = 17 kHz X p(click) 3 10^{-4} per pulse.
  - Integration 5 s
  - Bin-size 5 ns
  - FOV 30”
  - Filter 10 nm BW



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

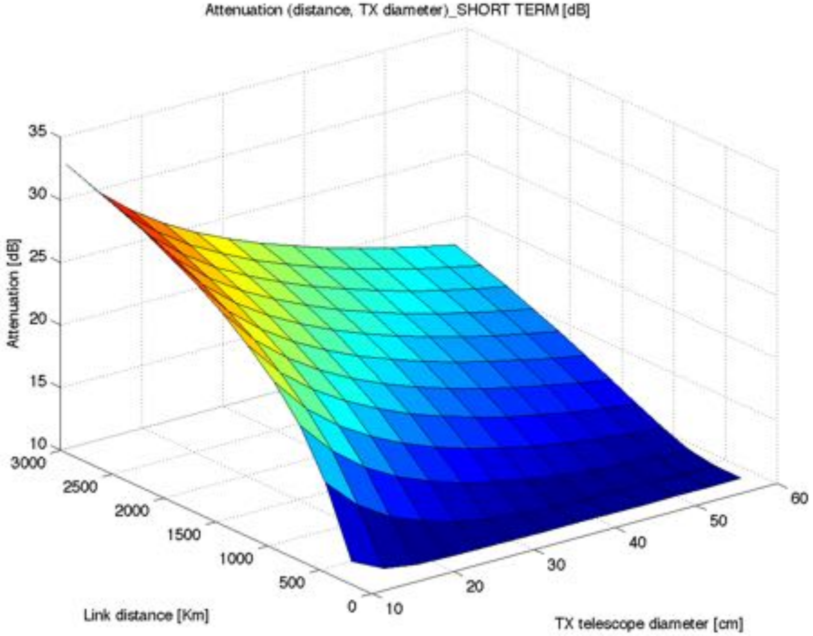
Coding of qubits

- 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



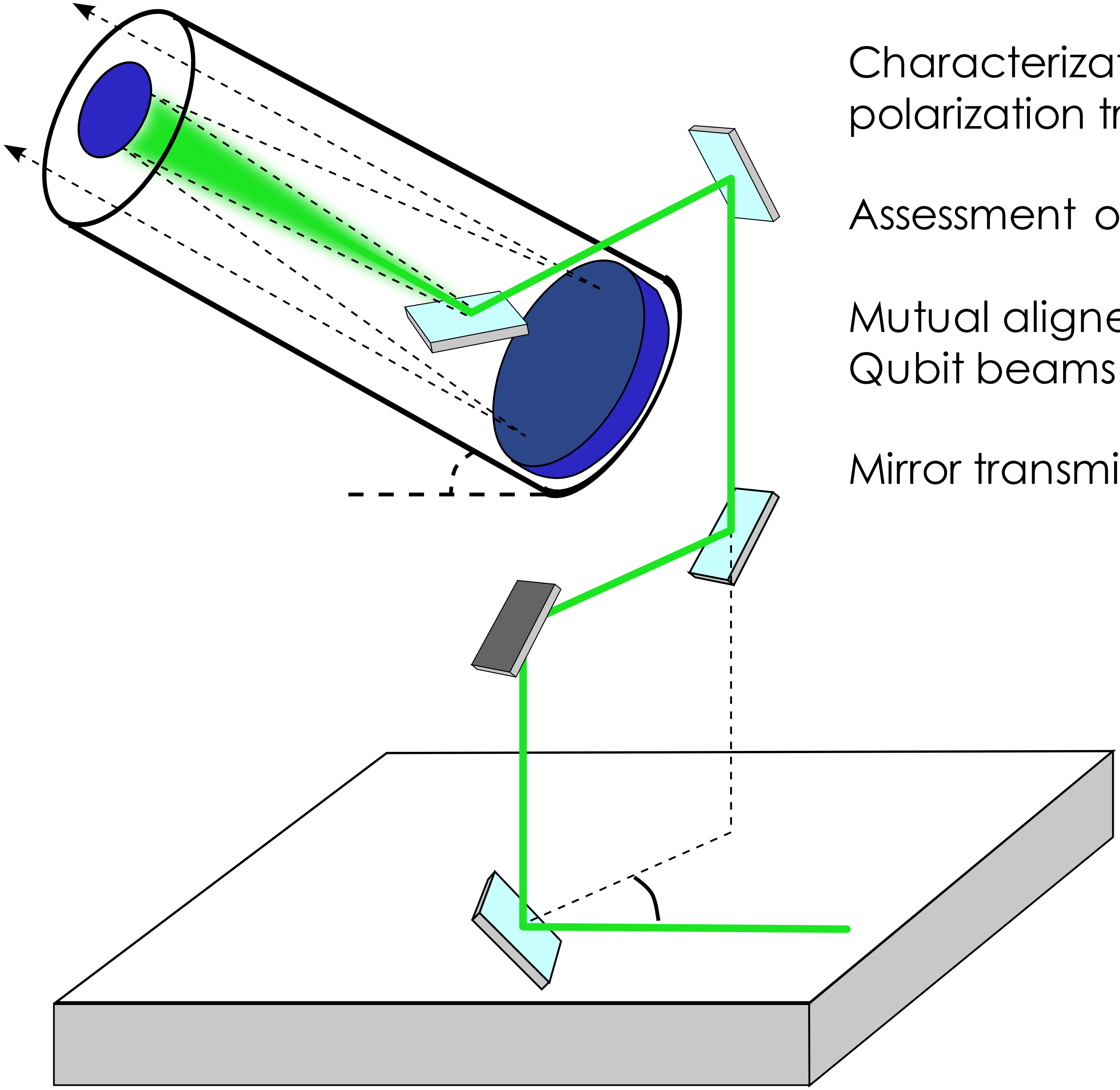
The making of the qubits

- Source on satellite: at **single photon level**
- The **attenuation in the downlink** from a LEO source of ≈ 3 cm dia. is in the range of **55-70 dB**.
- **Transmission rate** is crucial
- **Short pulses and sub-ns synchronization** 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

Coudé path of in-and-out



Characterization of the polarization transformation

Assessment of total efficiency

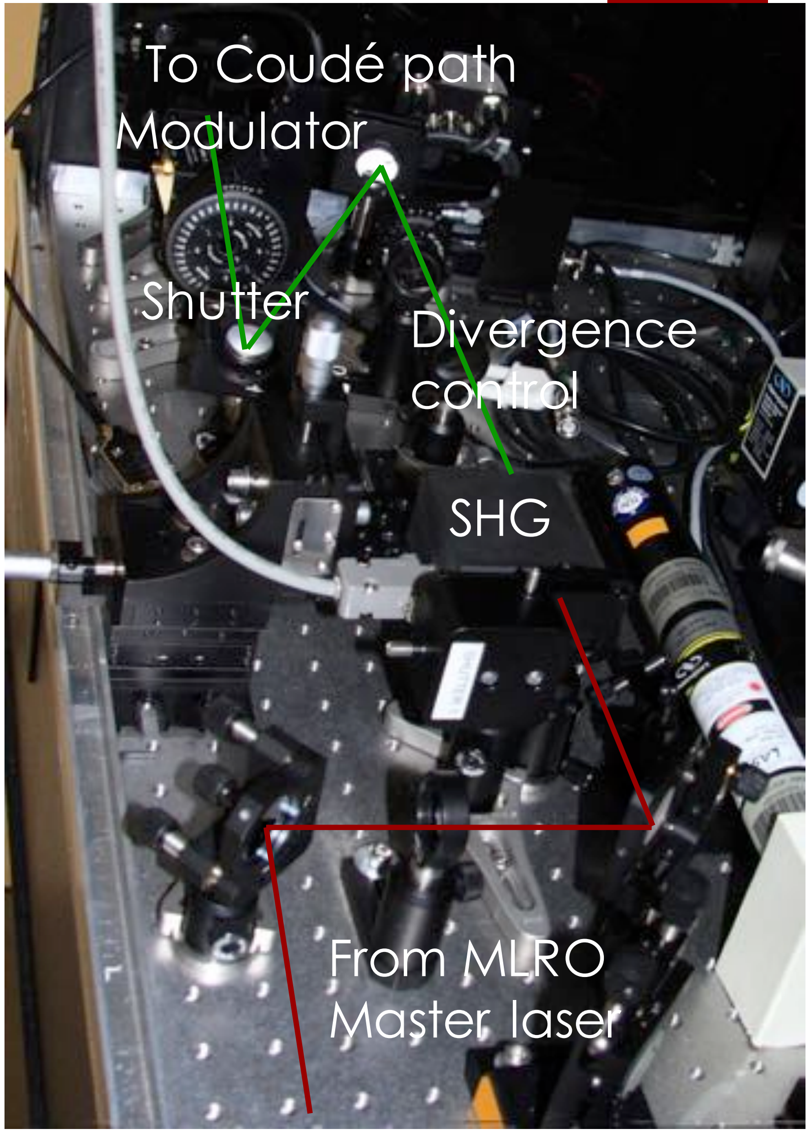
Mutual alignement of SLR and Qubit beams

Mirror transmissivity at 532 nm

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

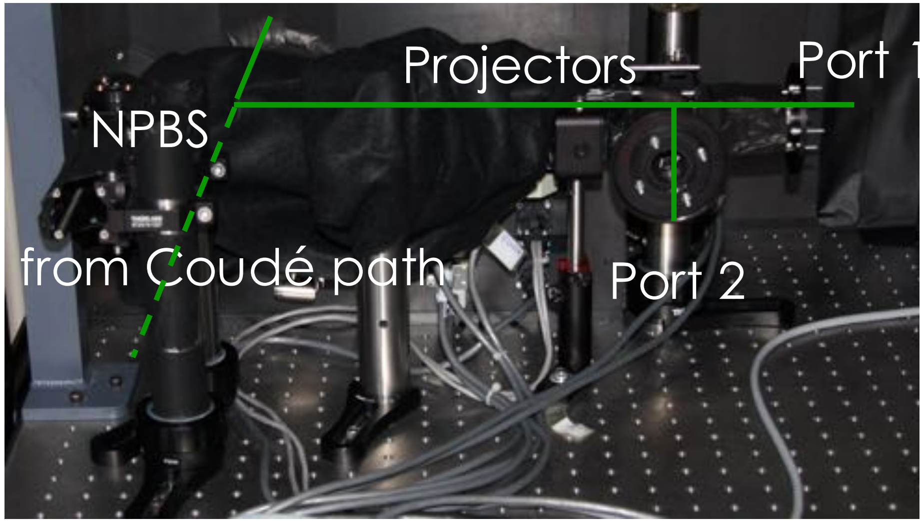
5mol% MgO doped congruent Lithium Niobate - 50 mm – thermally stabilized.



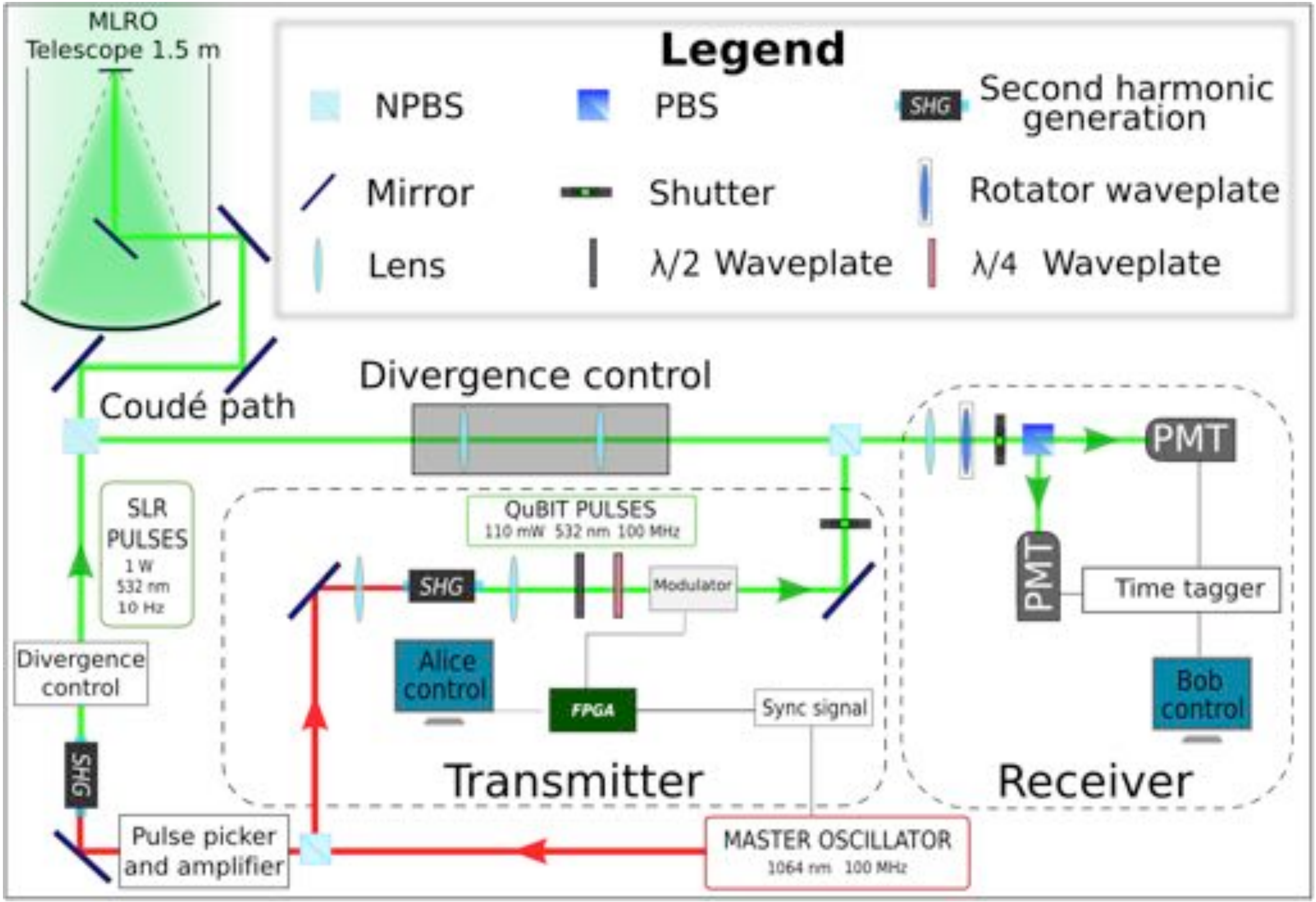
G. D. Boyd and D. A. Kleinman,
"Parametric interaction of focused gaussian light beams,"
J. Appl. Phys. 39, 3596-3639 (1968)

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

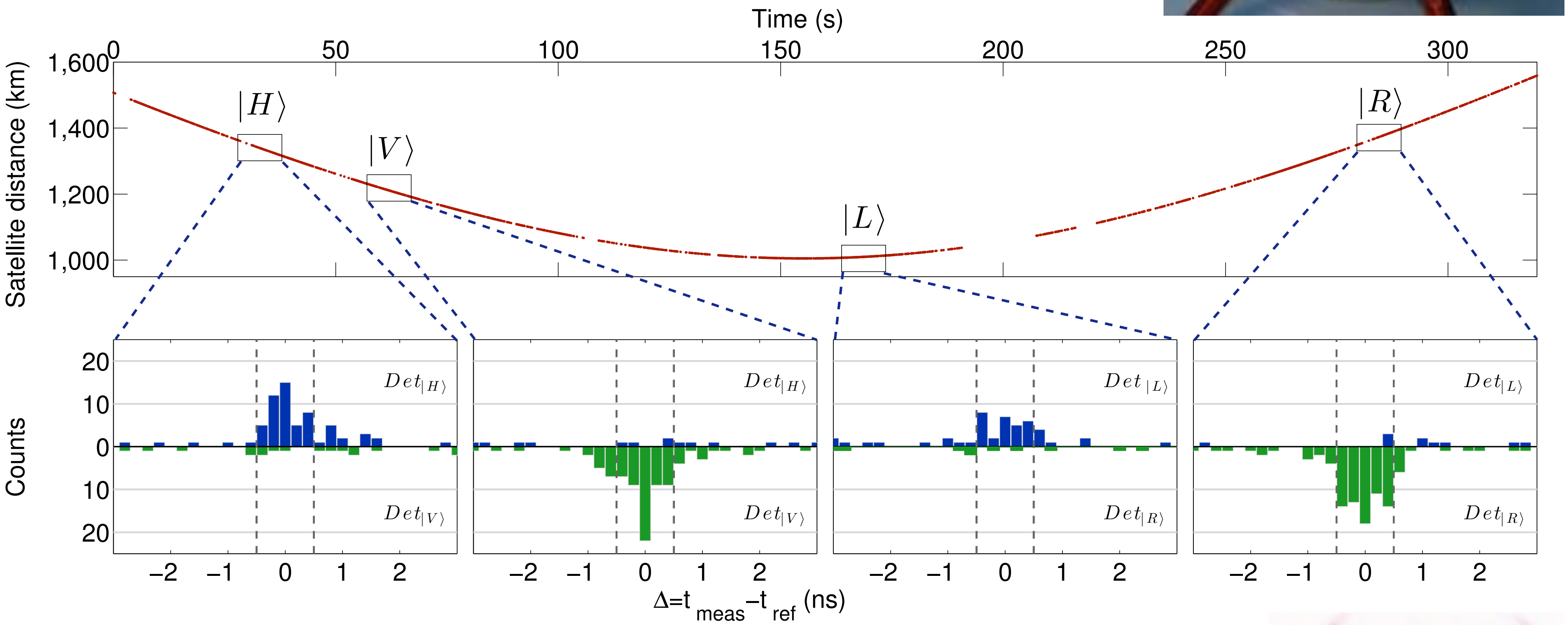


G. Vallone et al, Physical Review Letters, **115** 040502, 2015

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 ≃ (6.6±1.7) %**
- **Return rate 147 cps**

up to 10^4 bits for each satellite passage

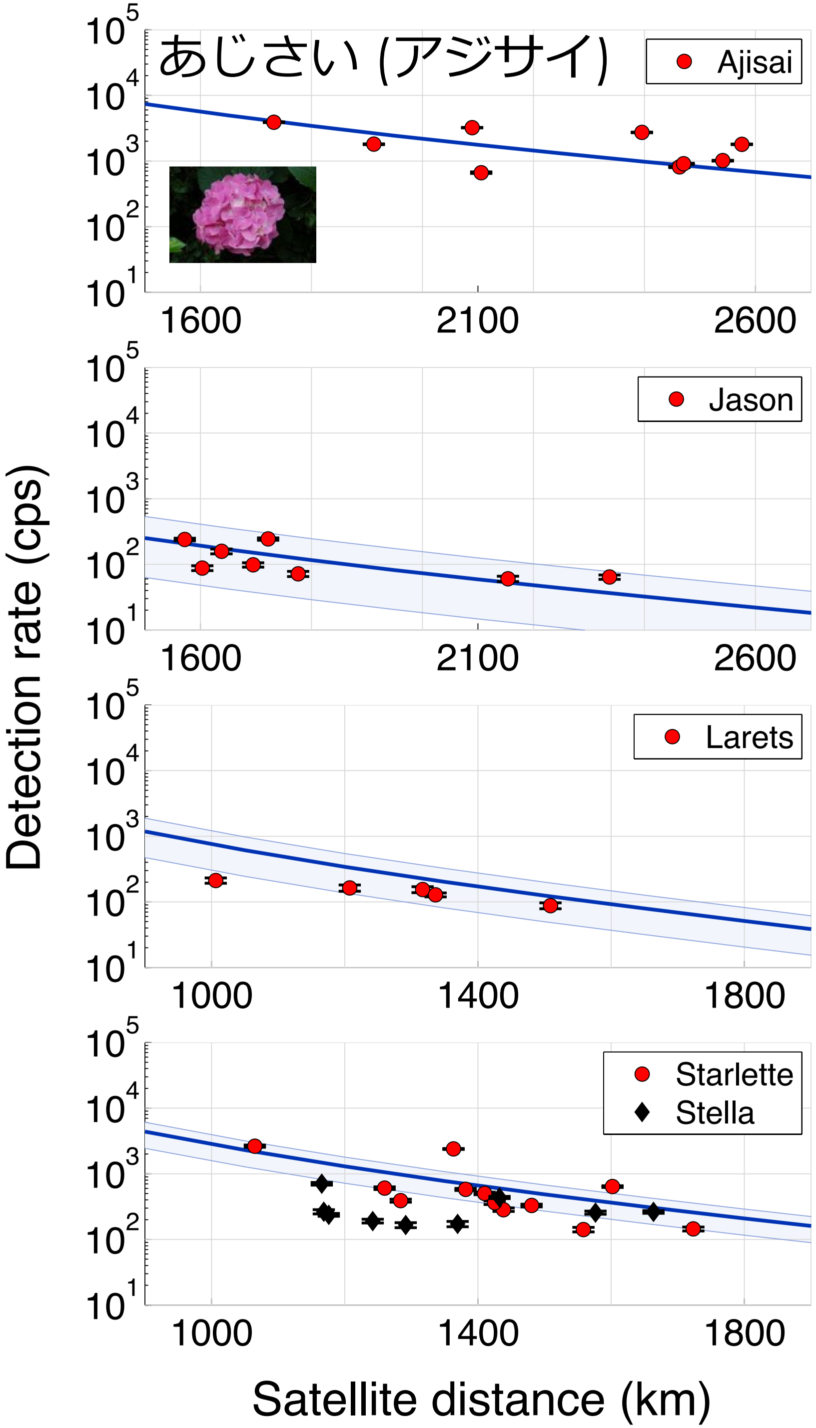
G. Vallone et al, Physical Review Letters, **115** 040502, 2015

Link Budget and photon return rate

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

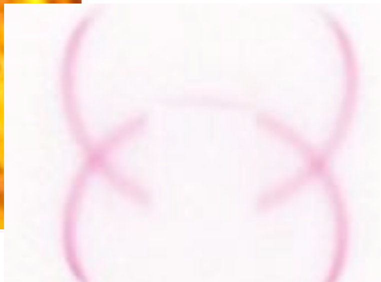
$$\mu_{rx} = \mu_{tx}\,\eta_{tx}\,G_t\,\Sigma\left(\frac{1}{4\pi R^2}\right)^2 T_a^2\,A_t\,\eta_{rx}\,\eta_{det}$$

The results show that **radar equation model provides a precise fit** for the measured counts and the μvalue for the different satellites.



G. Vallone et al, Physical Review Letters, **115** 040502, 2015

Observers of LARETS passages

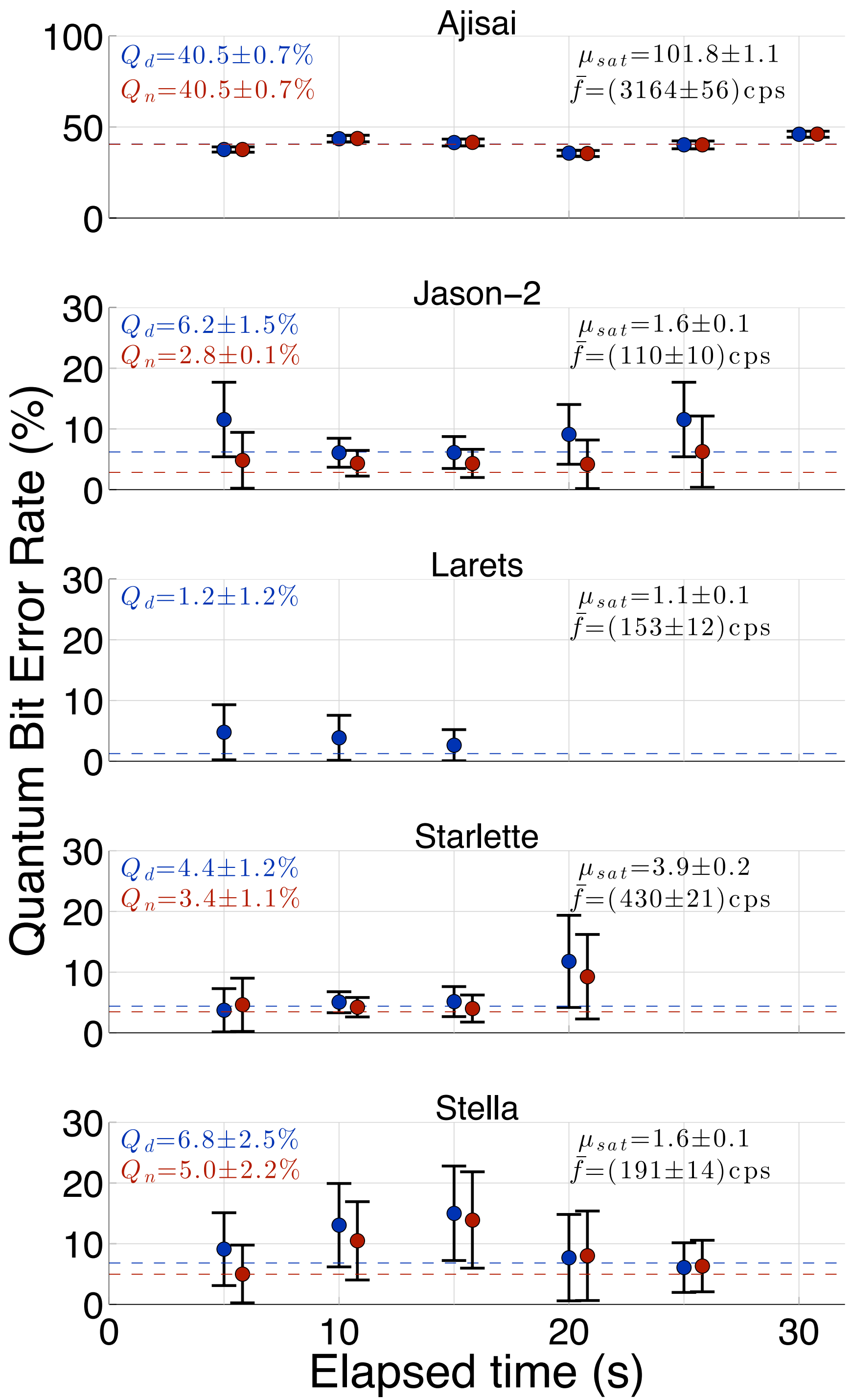


QBER

Non polarization maintaining CCR
Polarization QComm not possible

Polarization maintaining CCR

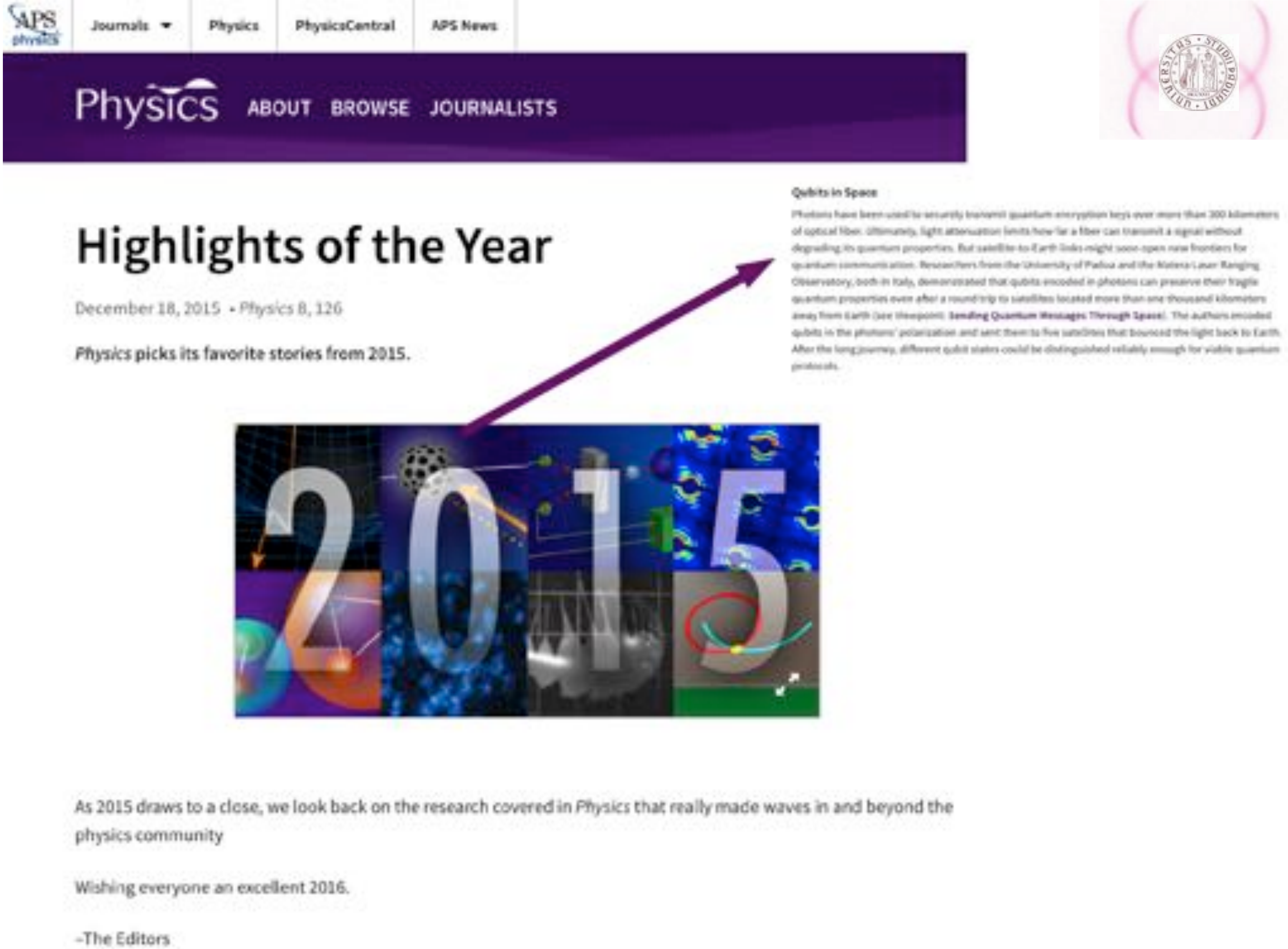
Polarization QComm with QBER compatible with applications



Demonstration of stable QBER over extended link duration

With LARETS μ=1.1 and QBER 1.2%

G. Vallone et al, Physical Review Letters, **115** 040502, 2015



Highlights of the Year

December 18, 2015 • Physics 8, 126

Physics picks its favorite stories from 2015.

Qubits in Space

Photons have been used to securely transmit quantum encryption keys over more than 200 kilometers of optical fiber. Ultimately, light attenuation limits how far a fiber can transmit a signal without degrading its quantum properties. But satellite-to-Earth links might soon open new frontiers for quantum communication. Researchers from the University of Padua and the Matera Laser Ranging Observatory, both in Italy, demonstrated that qubits encoded in photons can preserve their fragile quantum properties even after a round trip to satellites located more than one thousand kilometers away from Earth (see Viewpoint: **Sending Quantum Messages Through Space**). The authors encoded qubits in the photons' polarization and sent them to five satellites that bounced the light back to Earth. After the long journey, different qubit states could be distinguished reliably enough for viable quantum protocols.

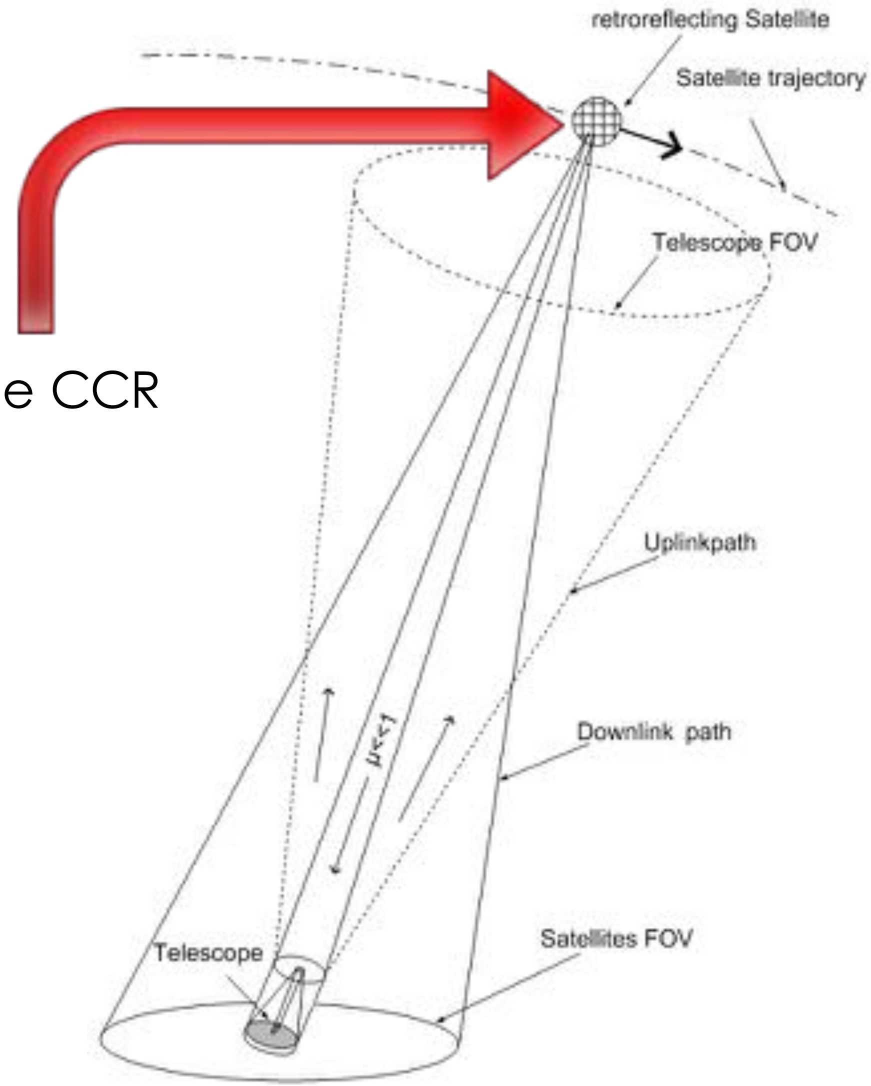
As 2015 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community

Wishing everyone an excellent 2016.

–The Editors

New QKD satellite protocol using retroreflectors

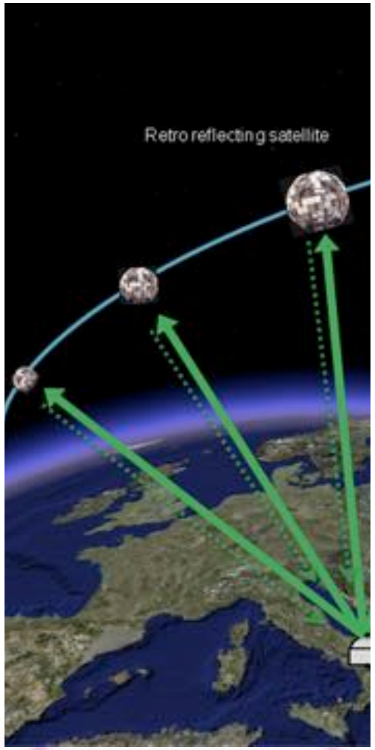
On the base of this experiment, we propose **a two-ways QKD protocol for space channels**



Active CCR

G. Vallone et al, Physical Review Letters, **115** 040502, 2015

New QKD satellite protocol using retroreflectors

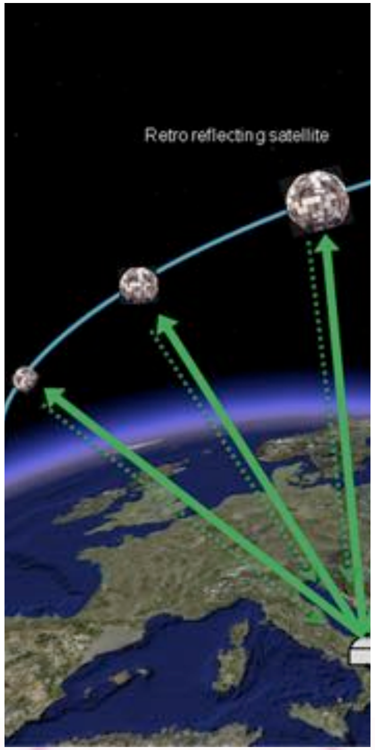


On the base of this experiment, we propose **a two-way QKD protocol for space channels**:

- 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 θ**, 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, Physical Review Letters, **115** 040502, 2015

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**.

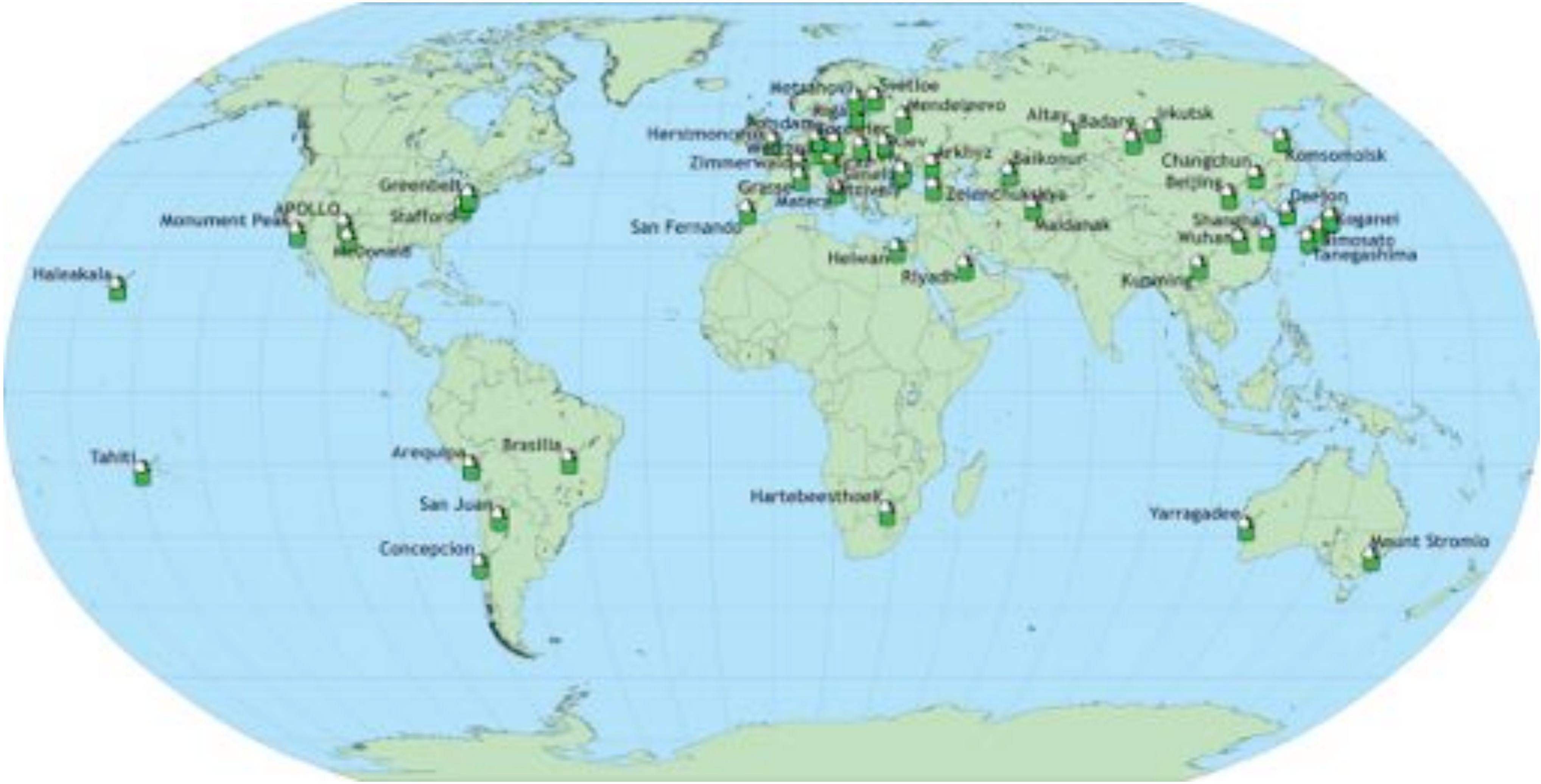
- Such protocol **is currently realizable using few centimeter retroriflector** as optical part in orbit.

G. Vallone et al, Physical Review Letters, **115** 040502, 2015

New QKD satellite protocol using retroreflectors

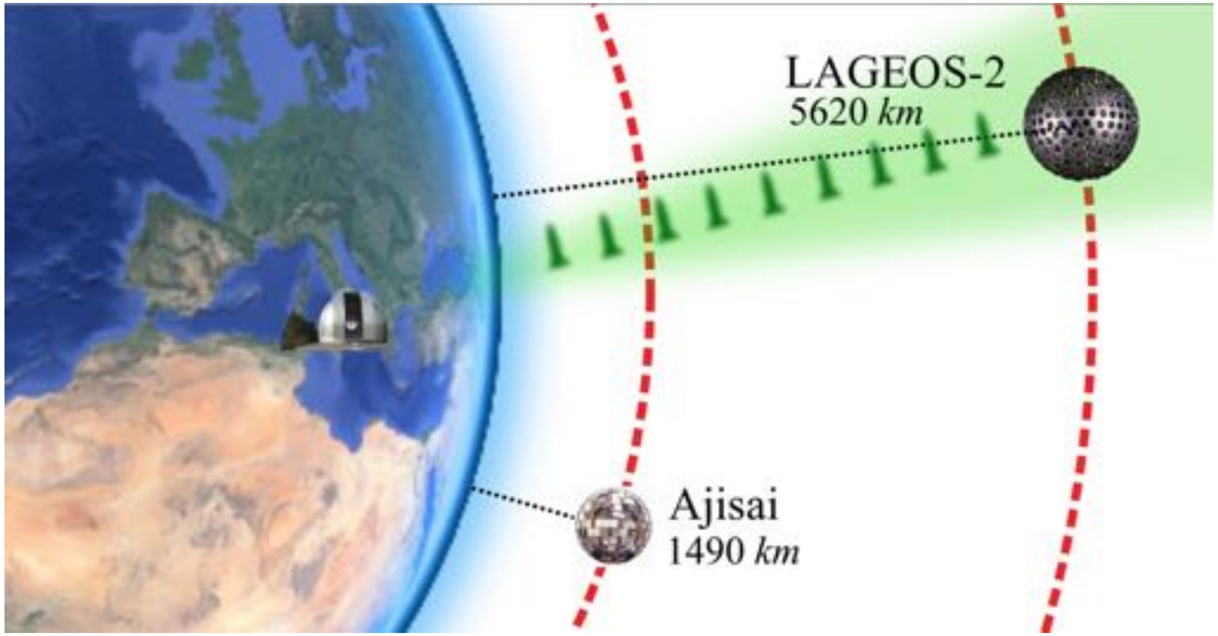
Such protocol **is currently realizable using few centimetres CCRs.**

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



Single Photon exchange: from LEO to MEO

Demonstration of the detection of photon from the satellite which, according to the radar equation, is emitting a single photon per pulse from a **Medium-Earth-Orbit MEO** satellite.

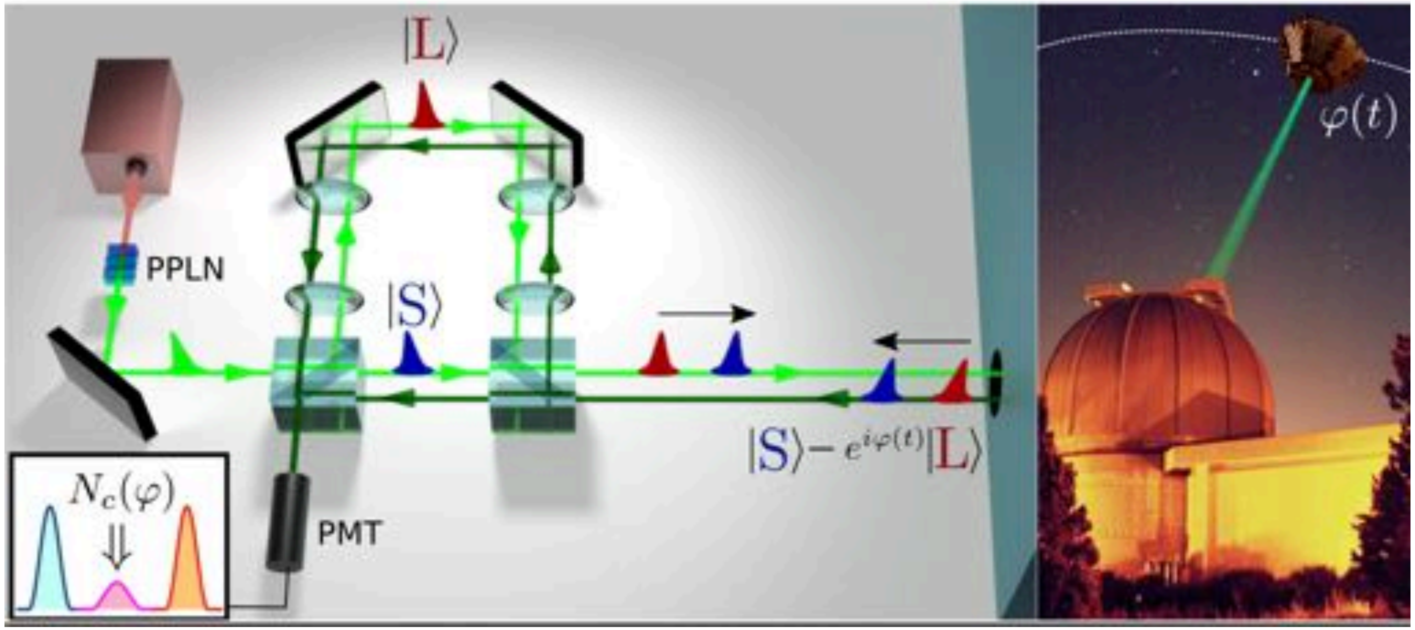


D. Dequal et al. *Experimental single photon exchange along a space link of 7000 km*, PRA Rapid Comm **93** 010301, 2016.

QComms exploiting temporal modes of light

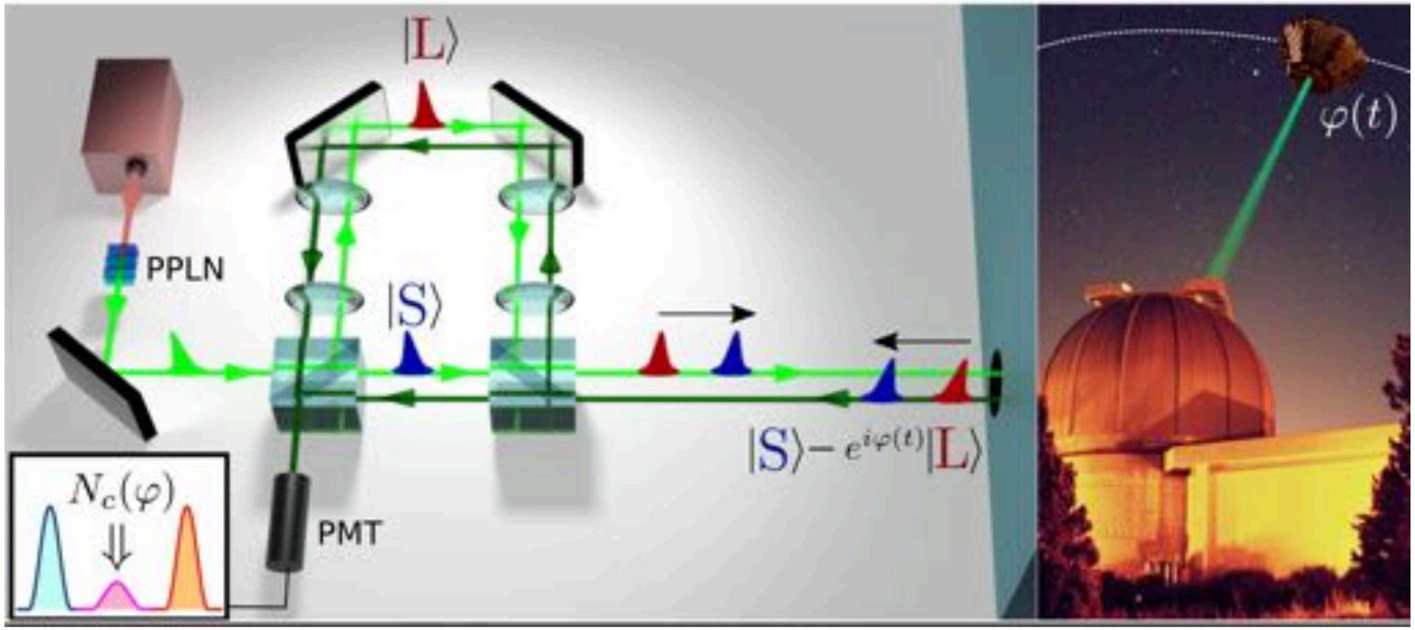
- Quantum interference arising from superposition of states is a striking evidence of the validity of Quantum Mechanics, confirmed in many experiments and also exploited in applications.

- We aim to the single-photon interference at a ground station due to the coherent superposition of two temporal modes reflected by a rapidly moving satellite thousand kilometers away.



QComms exploiting temporal modes of light

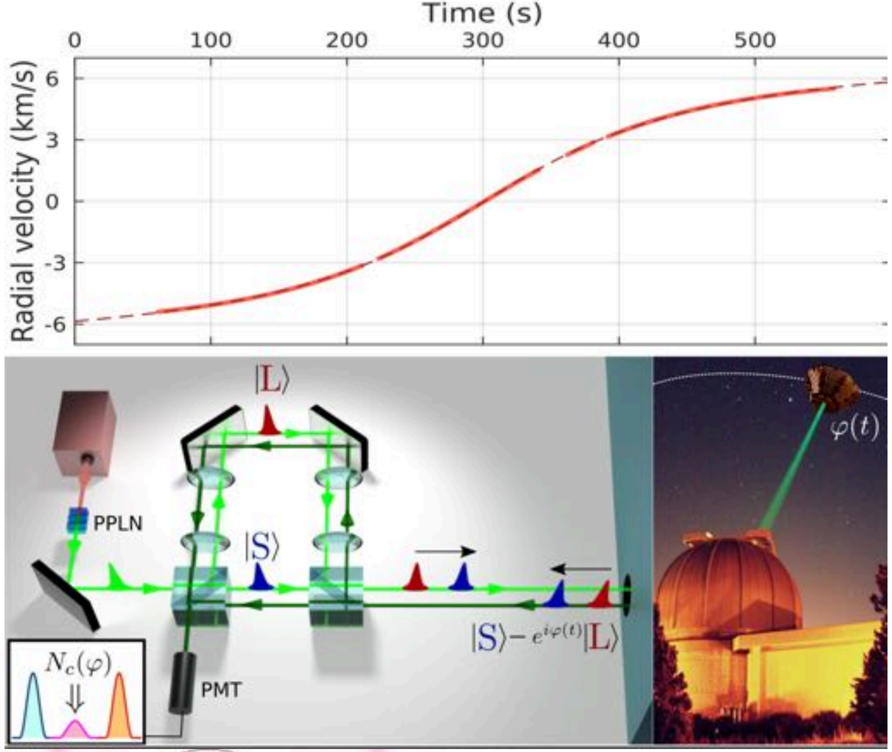
- A two-modes state is created with an unbalanced Mach-Zehnder Interferometer (MZI)
- The satellite reflections induces a phase modulation, measured using the same interferometer used for the generation.

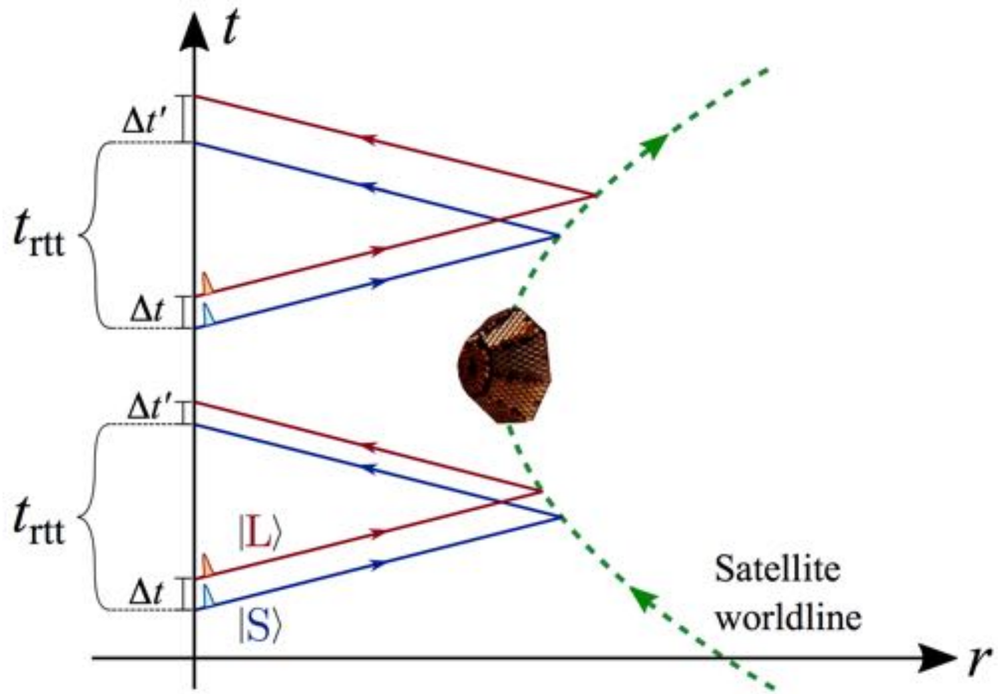


Kinematic Phase modulation

Relativistic effects on the photon interference

Beacon-C





Transformation in the channel

Pulse before the interferometer

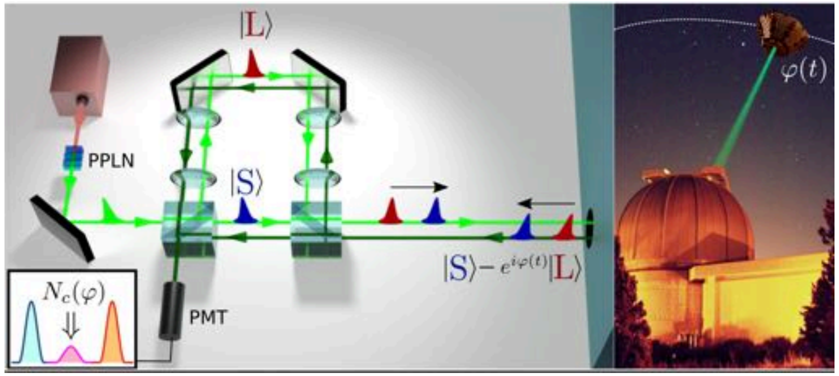
$$\psi_0(\tau_-) = \sqrt[4]{\frac{2}{\tau_c^2}}\, e^{-\pi \frac{\tau_-^2}{\tau_c^2}}\, e^{i\omega_0 \tau_-}$$

$$\tau_\pm = \frac{r}{c} \pm t$$

$$\tau_c = \int |g(\tau)|^2 \mathrm{d}\tau$$

Pulse after the interferometer, **directed to the satellite**

$$\psi_1(\tau_-) = \frac{1}{\sqrt{2}}[\psi_0(\tau_-) - \psi_0(\tau_- - \Delta t)] = \frac{1}{\sqrt[4]{2\tau_c^2}} \left[e^{-\pi \frac{\tau_-^2}{\tau_c^2}} - e^{-\pi \frac{(\tau_- - \Delta t)^2}{\tau_c^2}} e^{-i\omega_0 \Delta t} \right] e^{i\omega_0 \tau_-}$$



Reference frames

Boost
at
satellite

$$\begin{cases} r' = \gamma(r - r_{\text{sat}} - \beta c t) \\ t' = \gamma(t - \beta \dfrac{r - r_{\text{sat}}}{c}) \end{cases} \quad , \quad \begin{cases} r = r_{\text{sat}} + \gamma(r' + \beta c t') \\ t = \gamma(t' + \beta \dfrac{r'}{c}) \end{cases}$$

$$\tau_{\pm} = \gamma(1 \pm \beta)\tau'_{\pm} + \frac{r_{\text{sat}}}{c} = \sqrt{\frac{1 \pm \beta}{1 \mp \beta}}\tau'_{\pm} + \frac{r_{\text{sat}}}{c}$$

At the reflection $\tau'_{-} \rightarrow -\tau'_{+}$

$$\tau'_{+} = \frac{1}{\gamma(1+\beta)}(\tau_{+} - \frac{r_{\text{sat}}}{c})$$

Satellite distance from the station: r_{sat}

Sequence of boosts

$$\tau_- \xrightarrow{\text{boost to mirror ref. frame}} \gamma(1-\beta)\tau'_- + \frac{r_{\text{sat}}}{c}$$

$$\xrightarrow{\text{reflection}} -\gamma(1-\beta)\tau'_+ + \frac{r_{\text{sat}}}{c}$$

$$\xrightarrow{\text{boost back to ground ref. frame}} -f_\beta(\tau_+ - t_{\text{rtt}})$$

Reference frames

Pulse after the reflection, **at the telescope**

$$\psi_3(\tau_+ + t_{\rm rtt}) = \frac{i\gamma(1-\beta)}{2}\Big[\psi_0(-f_\beta\tau_+) + \psi_0(-f_\beta(\tau_+ + \Delta t)) \\ - \psi_0(-\Delta t - f_\beta\tau_+) - \psi_0(-\Delta t - f_\beta(\tau_+ + \Delta t))\Big]$$

Round trip time at the ground station $t_{\rm rtt} = \frac{2}{1-\beta}\frac{r_{\rm sat}}{c}$

Probability of click in the central peak

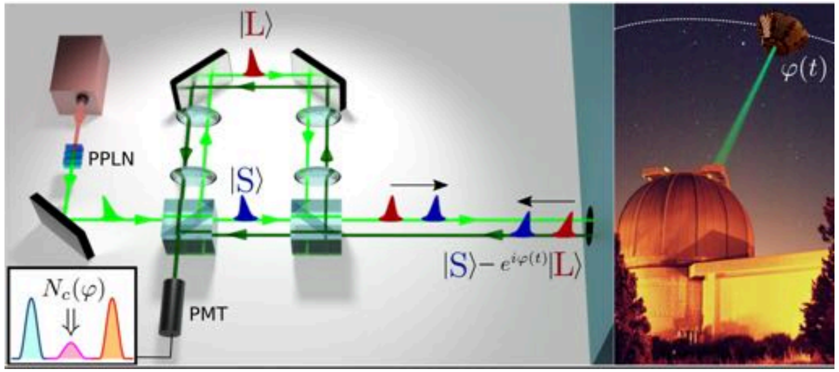
$$
\begin{aligned}
P_c(t) &= \frac{\gamma^2(1-\beta(t))^2}{4}\int \mathrm{d}t' |\psi_0(-f_\beta(t'+\Delta t)) - \psi_0(-\Delta t - f_\beta t')|^2 \\
&= \frac{1}{2}\left\{1-\sqrt{\frac{2}{\tau_c^2}}\int \mathrm{d}t' \Re e\left[e^{-\pi\frac{(t'+f_\beta\Delta t)^2}{\tau_c^2}} e^{-\pi\frac{(t'+\Delta t)^2}{\tau_c^2}} e^{i\omega_0(1-f_\beta)\Delta t}\right]\right\} \\
&= \frac{1}{2}\left[1-\mathcal{V}(t)\cos\varphi(t)\right] ,
\end{aligned}
$$

Kinematic phase

$$
\varphi(t) = \omega_0[1-f_\beta)]\Delta t = \boxed{\frac{2\beta(t)}{1+\beta(t)}\omega_0\Delta t}
$$

Visibility

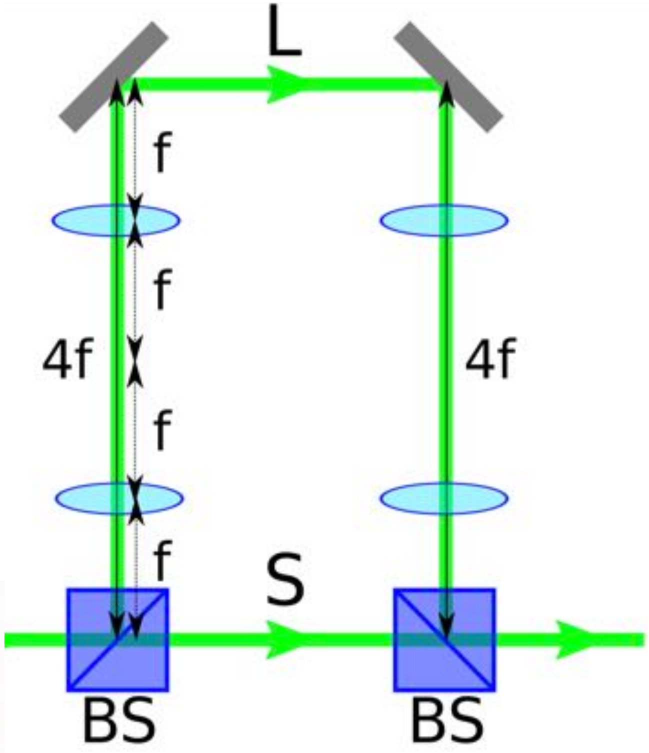
$$
\mathcal{V}(t) = \sqrt{\frac{2}{\tau_c^2}}\int \mathrm{d}t'\, e^{-\pi\frac{(t'+f_\beta\Delta t))^2}{\tau_c^2}} e^{-\pi\frac{(t'+\Delta t)^2}{\tau_c^2}} = \exp\{-2\pi\left[\frac{\Delta t}{\tau_c}\frac{\beta(t)}{1+\beta(t)}\right]^2\}
$$

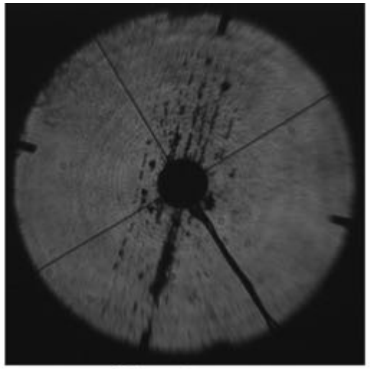


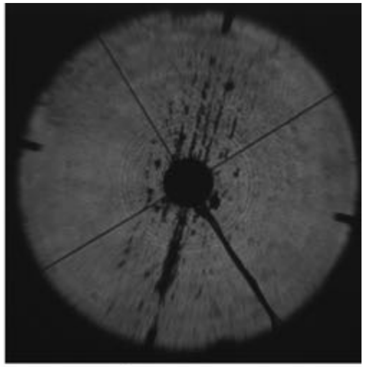
For LEO satellites
it may be
approximate as 1

4-f optical relay in the MZI

Pupil imaging for the interference




Short arm


Long arm

The phase reconstruction

Special Relativity transformations to the CCR reference system and back, depending on β(t) = v_r(t)/c.

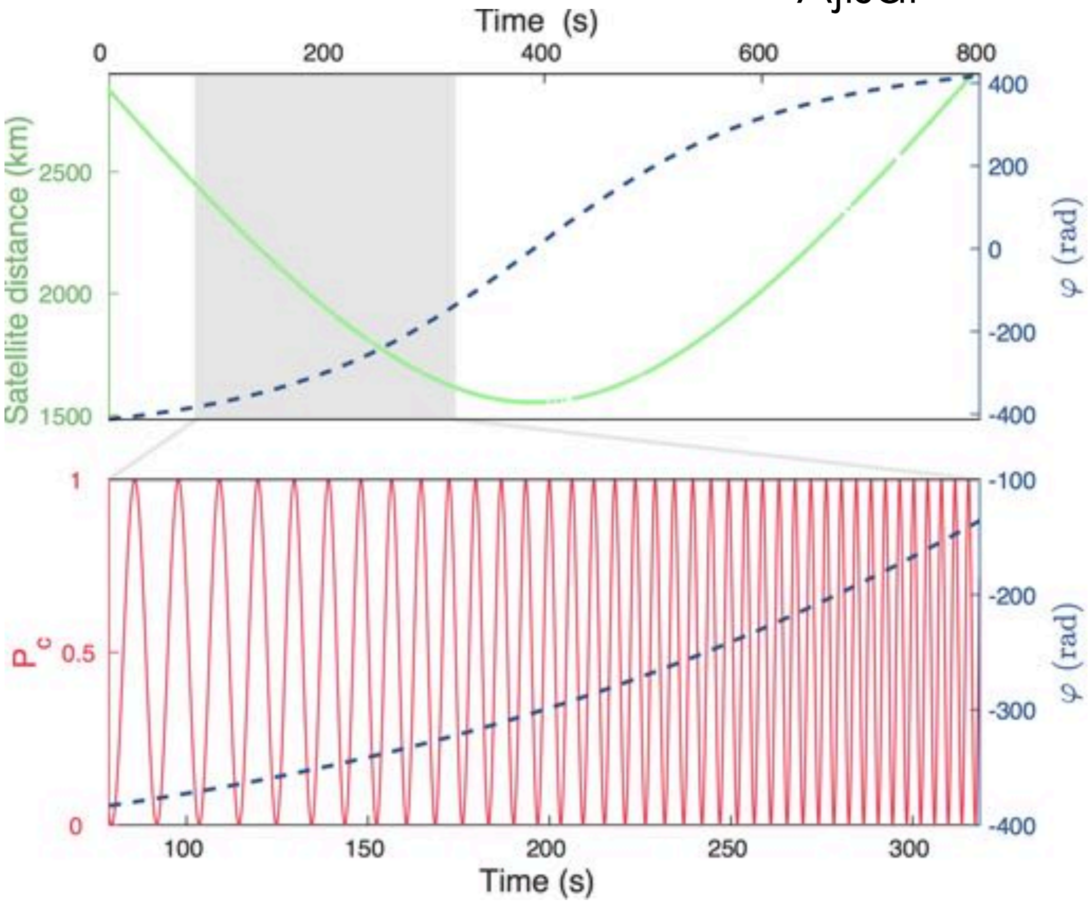
P_c *probability of detecting the photon in the central peak*

$$|\Psi_r\rangle = (1/\sqrt{2})(|S\rangle - e^{i\varphi(t)}|L\rangle)$$

$$P_c(t) = \frac{1}{2}\left[1 - \mathcal{V}(t)\cos\varphi(t)\right]$$

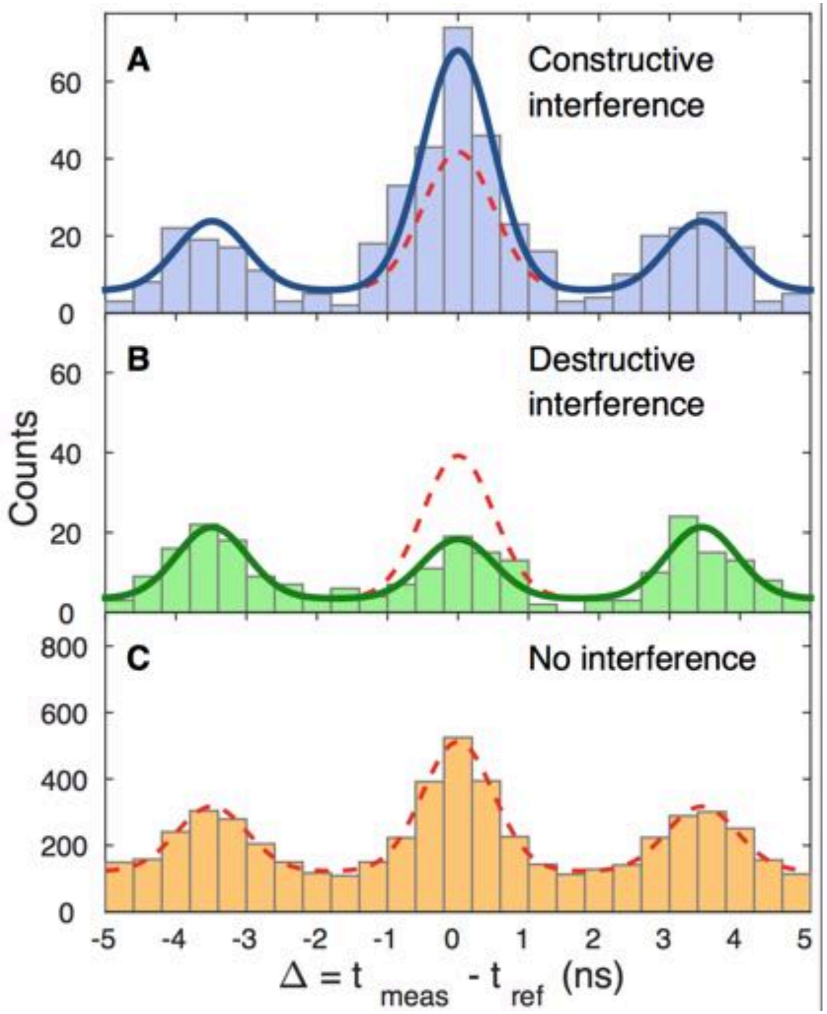
$$\varphi(t) = \frac{2\beta(t)}{1+\beta(t)}\frac{2\pi c}{\lambda}\Delta t$$

Ajisai



Evidence of the interference

Beacon C



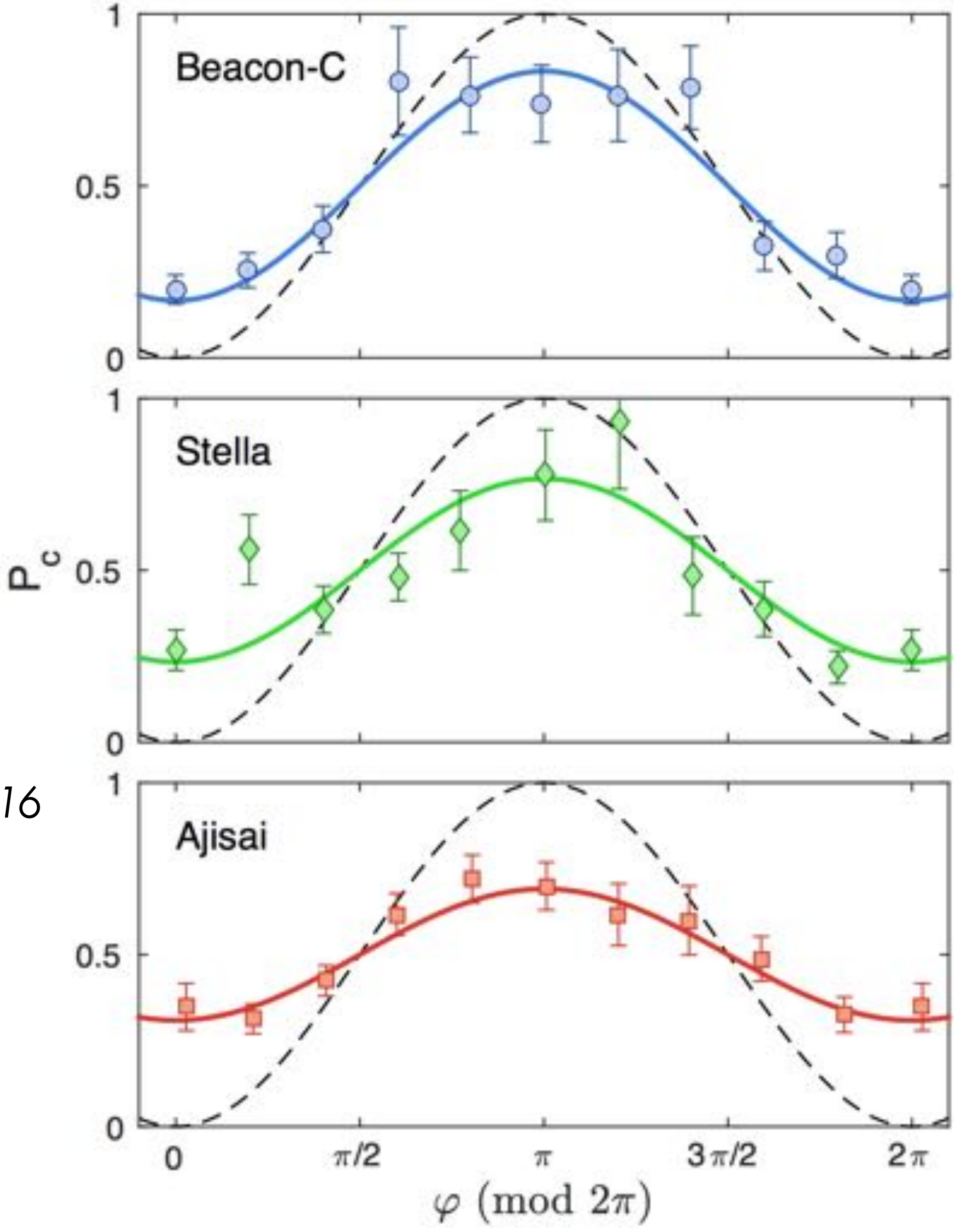
$$P_c(t) = \frac{1}{2}\left[1 - \mathcal{V}(t)\cos\varphi(t)\right]$$

$$\varphi(t) = \frac{2\beta(t)}{1+\beta(t)}\frac{2\pi c}{\lambda}\Delta t$$

$$\mathcal{V}(t) = e^{-2\pi\left(\frac{\Delta t}{\tau_c}\frac{\beta(t)}{1+\beta(t)}\right)^2} \simeq 1\,.$$

G. Vallone et al. *Interference at the Single Photon Level Along Satellite-Ground Channels*
Physical Review Letters ***116*** *253601 2016*
arXiv:1509.07855 (2015)

Visibility vs. $\varphi(t)$

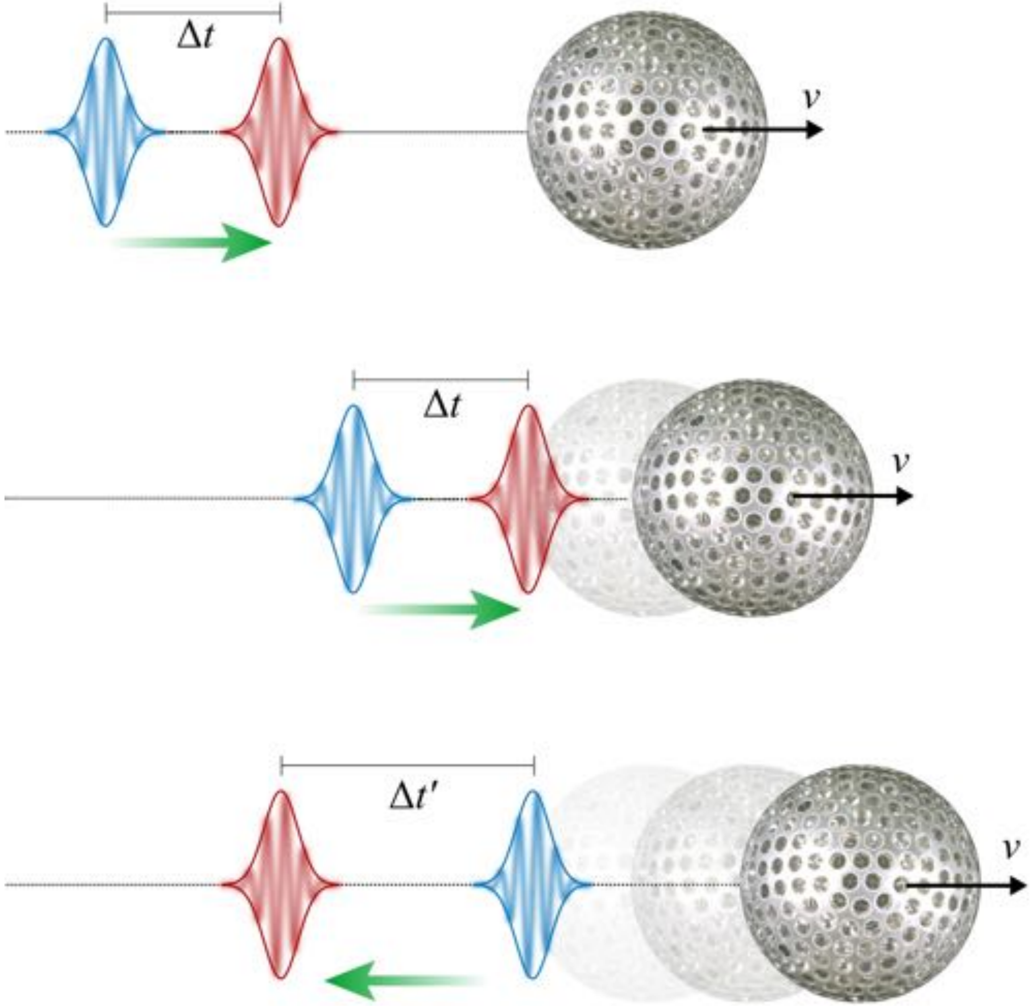


V_{exp}=67±11% for Beacon-C

G. Vallone et al. *Interference at the Single Photon Level Along Satellite-Ground Channels*
Physical Review Letters ***116*** *253601 2016*

Istantaneous velocity effect

$\Delta t = 3$ ns



- The qubit modulation is depending on the **instantaneous satellite velocity.**
- **Fast metrology of the retroreflector kinematics**

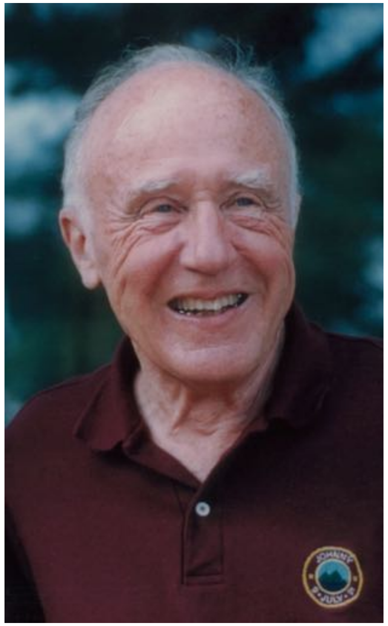
G. Vallone et al. *Interference at the Single Photon Level Along Satellite-Ground Channels*
Physical Review Letters ***116*** *253601 2016*
arXiv:1509.07855 (2015)

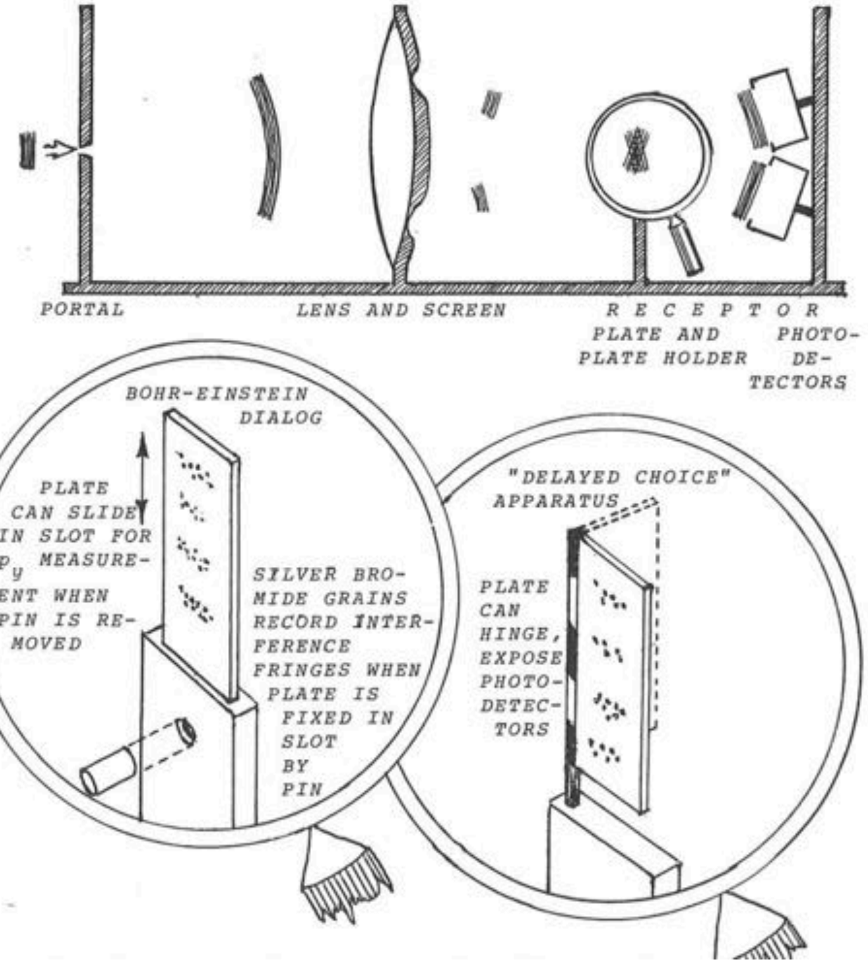
Further step: inquiring the wave-particle duality in Space

- **Particle duality of quantum matter**: impossibility of revealing at *the same time* both the wave-like and particle-like properties of a quantum object.

- **Bohr: there is no difference "whether our plans of constructing or handling the instruments are fixed beforehand or whether we postpone the completion of our planning until a later moment"**

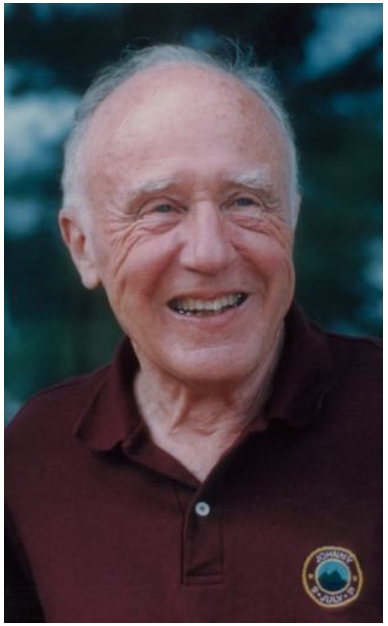
John Wheeler Delayed-choice gedanken experiment

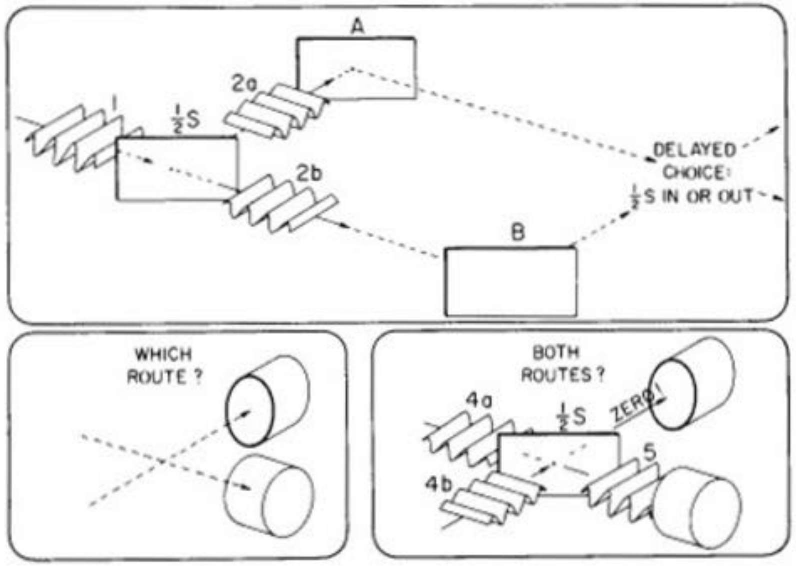


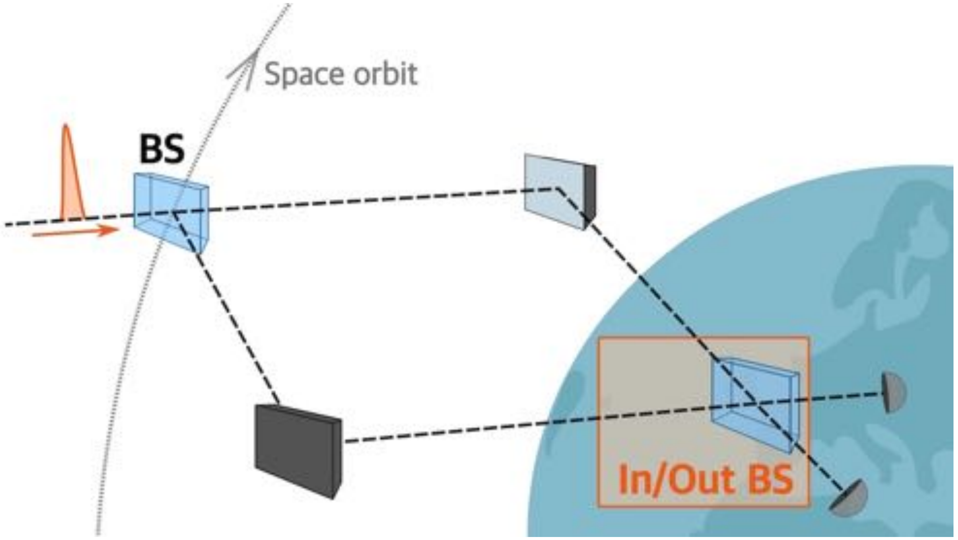


Wheeler JA (1978) **The "past" and the "delayed-choice" double-slit experiment**. Mathematical Foundations of Quantum Theory (Academic, New York), pp 9–48.

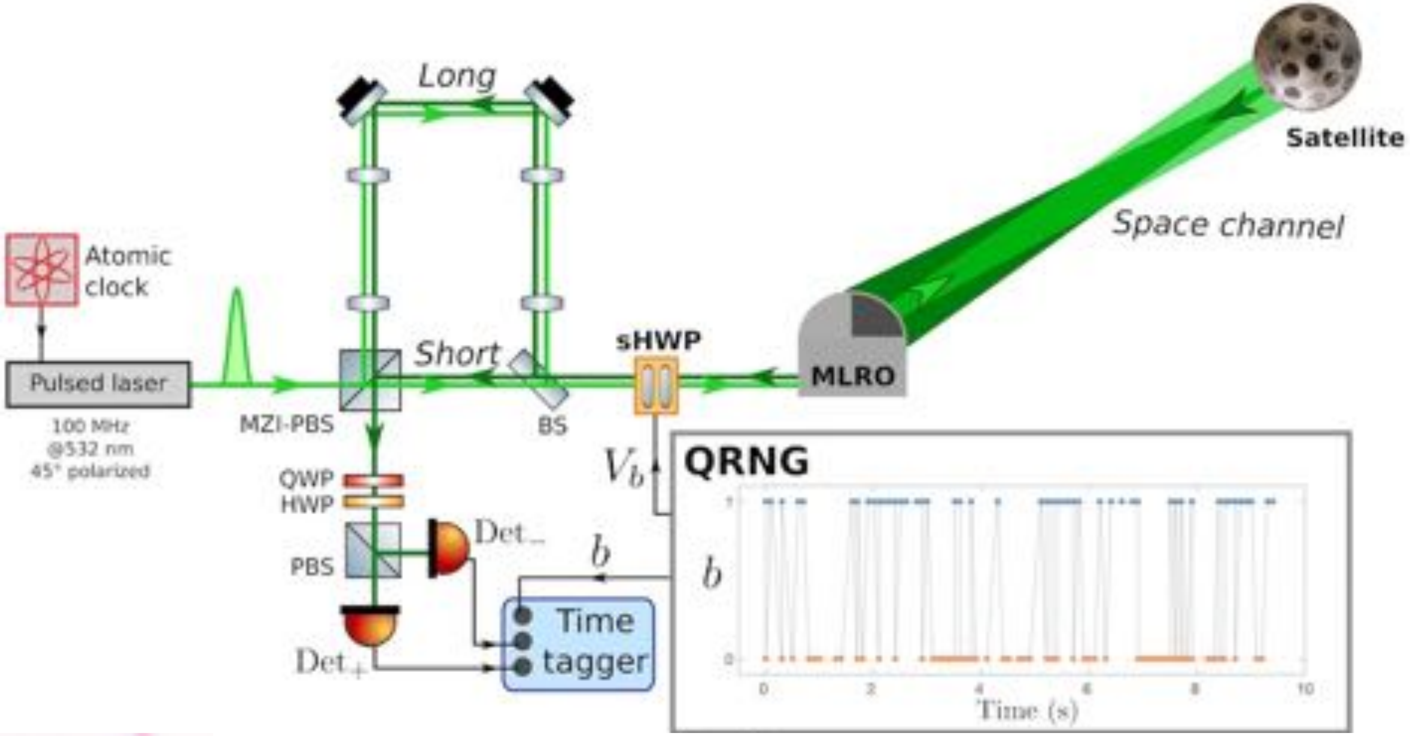
Step forward in Space QComms: inquiring the wave-particle duality along a Space channel



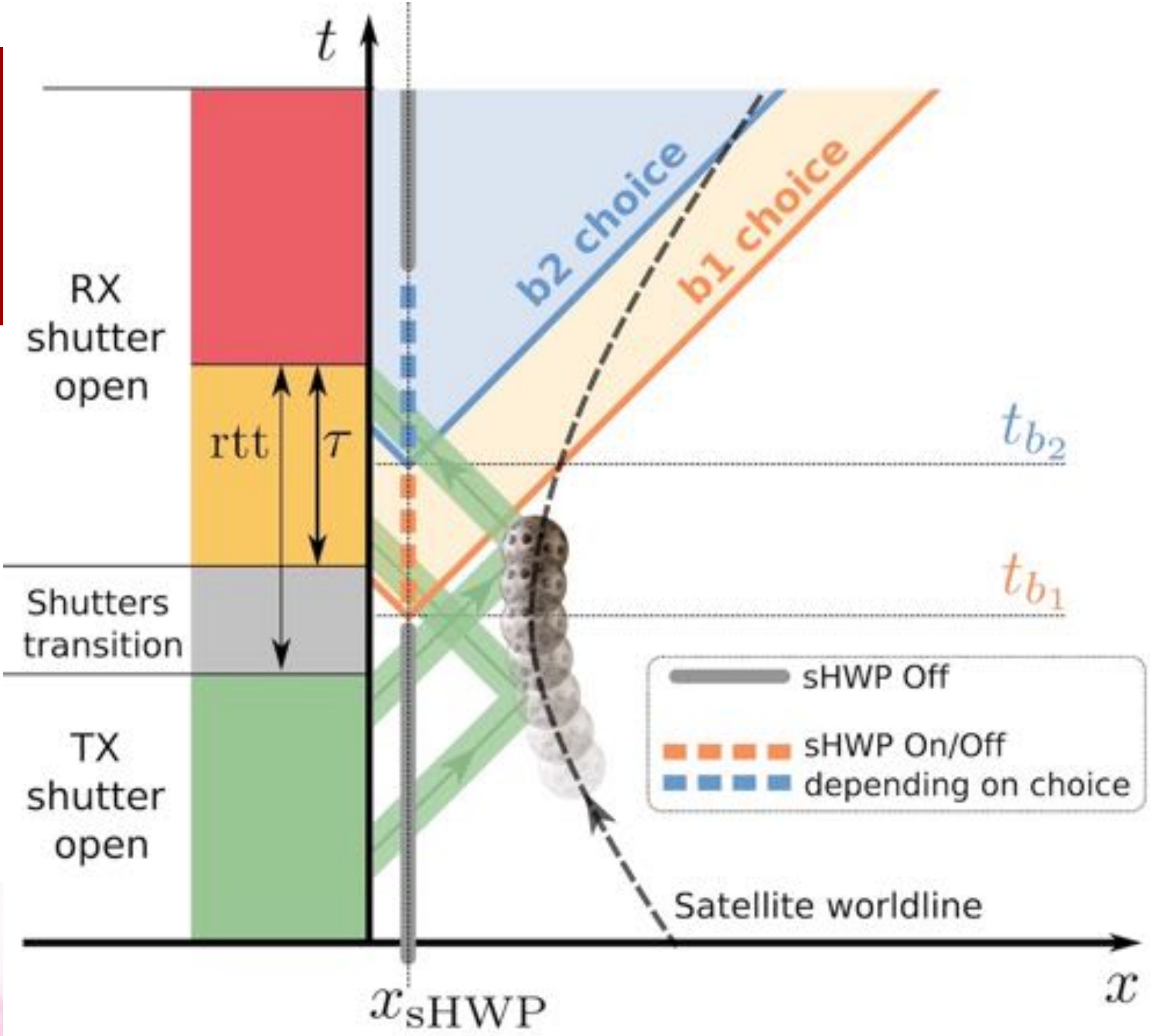




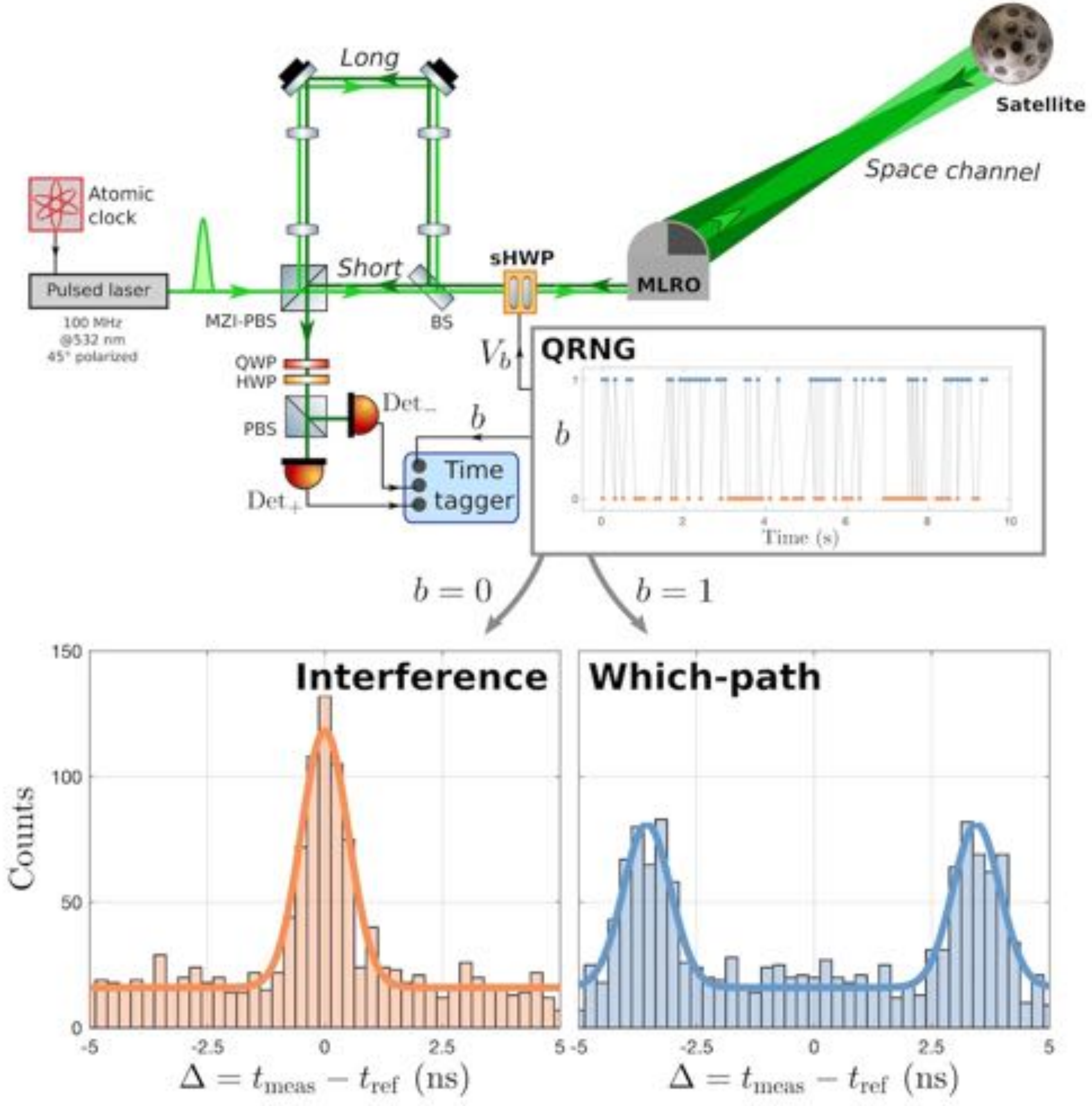
Step forward in Space QComms: inquiring the wave-particle duality along a Space channel



F. Vedovato et al. – Science Adv. **3** e1701180 (2017)
QRNG: A. Stanco, D.G. Marangon et al. - in preparation 2017



F. Vedovato et al. - Science Adv. **3** e1701180 (2017)



F. Vedovato et al. – Science Adv. **3** e1701180 (2017)

wave-like: interference fringe visibility

$$f_{\pm}^{b=0} = \frac{N_{\pm}}{N_{+}+N_{-}}$$

$$\mathcal{V}^{\mathrm{Beacon-C}} = 41 \pm 4\%,$$

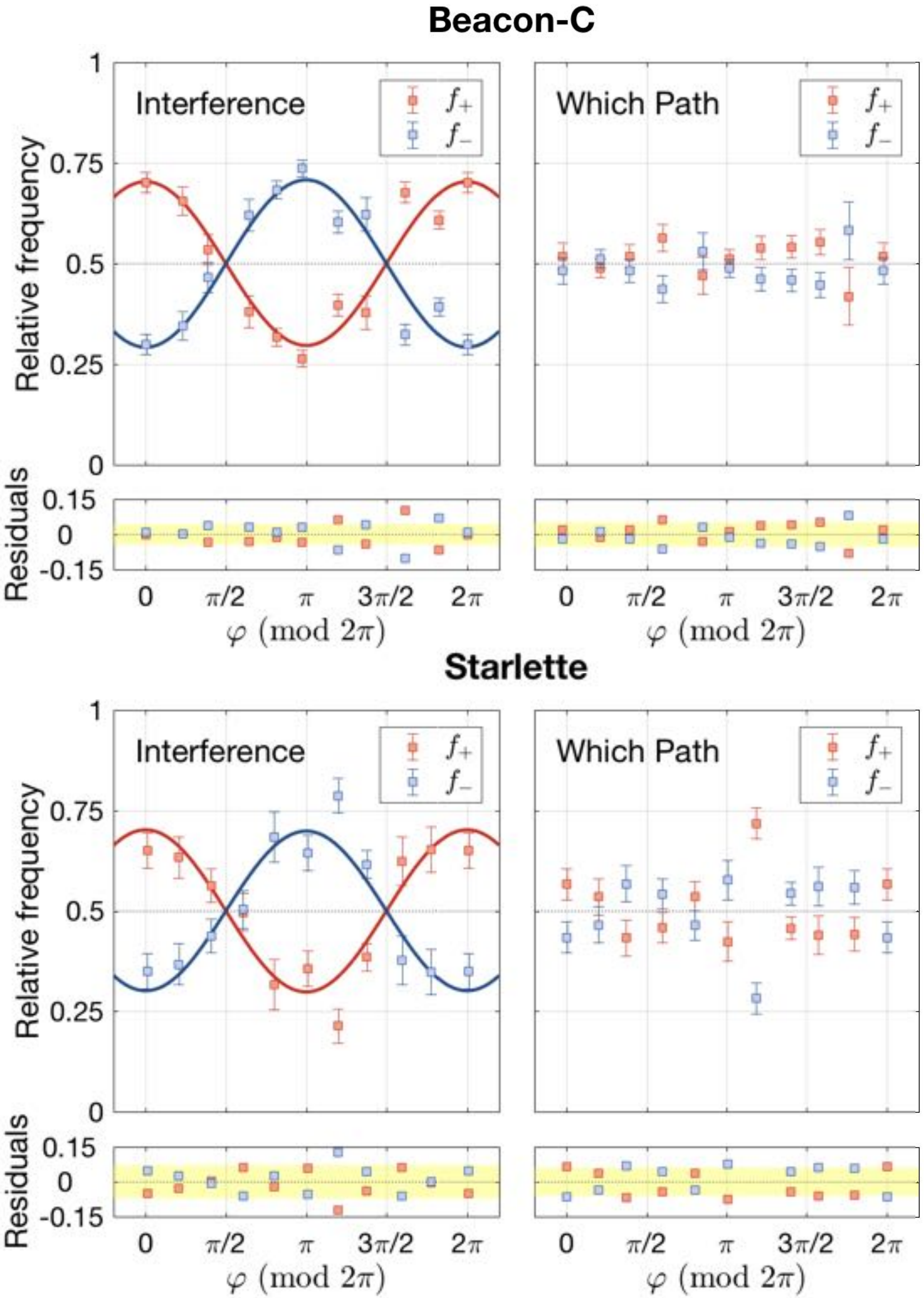
$$\mathcal{V}^{\mathrm{Starlette}} = 40 \pm 4\%$$

particle-like:

which-path information

$p_{\mathrm{WP}} = 95 \pm 1\%$ (Starlette)

➔ excluding the ***objective viewpoint*** by 8σ



F. Vedovato et al. – Science Adv. **3** e1701180 (2017)

Step forward in Space QComms: inquiring the wave-particle duality along a Space channel

- **Phases of the superposition of temporal modes changes constantly due to varying relative velocity of satellite with respect to telescope.**

- **selection of the measure done using a QRNG after the phase modulation**

- **Visibility of complementary observable violating the particle-like nature of phonons.**

- **Combination of photon DoFs to realize the experiment**

- **cancellation of first order gravitational term – again!**

F. Vedovato et al. – Science Adv. **3** e1701180 (2017)

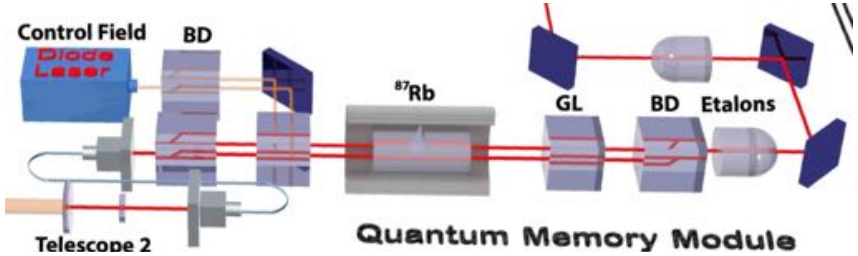
QMemories are crucial tools for QComms!

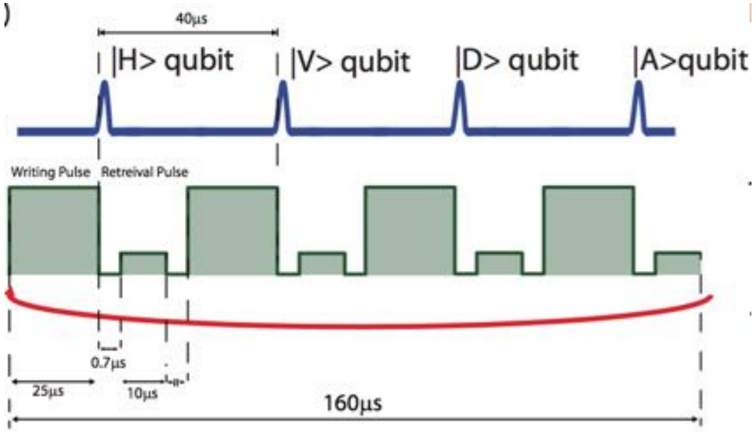
Prof. Eden Figueroa Group @ Stony Brook University

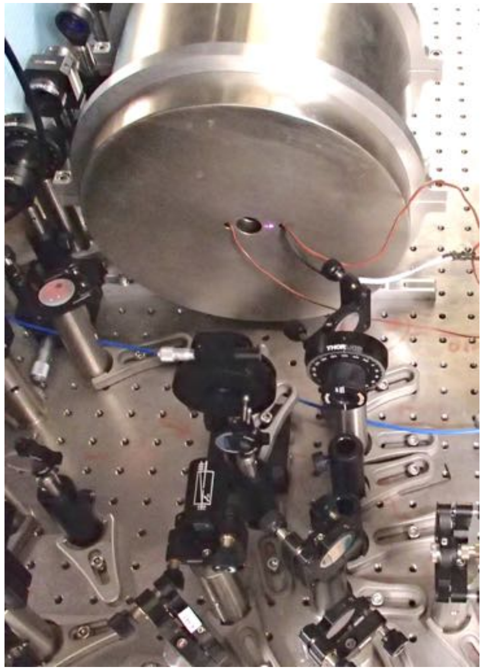
^{87}Rb vapor at room temperature – 795 nm

Based on electromagnetically induced transparency (EIT)

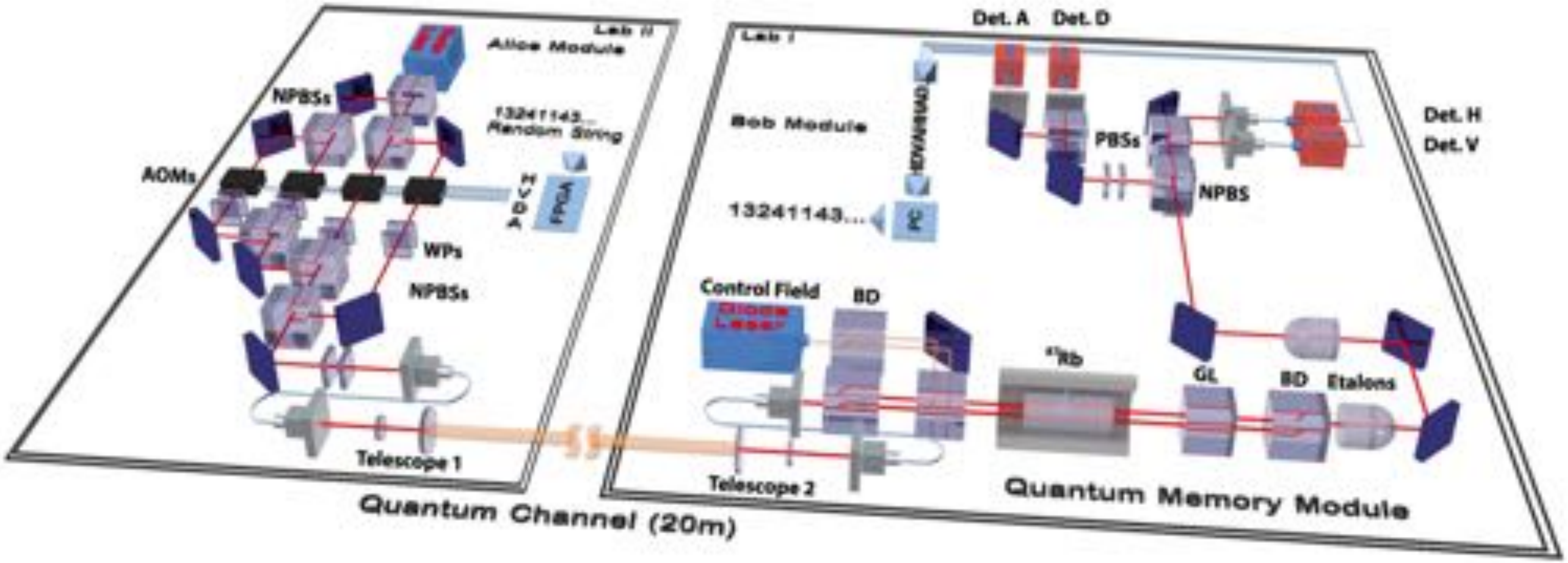
Control and writing beams separated by 6.835 GHz







Rb memory for free-space BB84 QKD

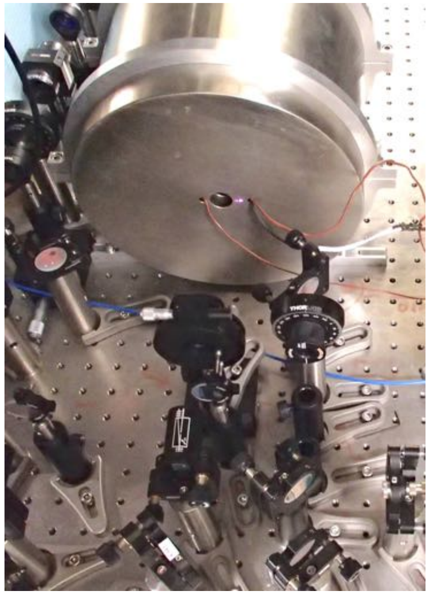


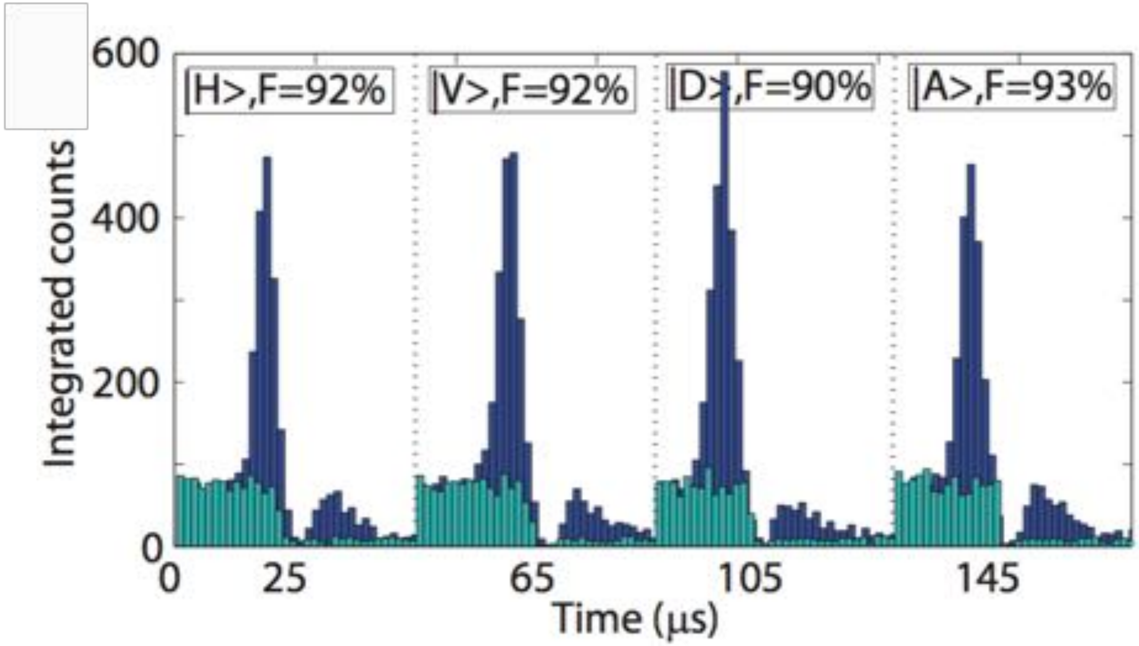
M. Namazi et al,
Free space quantum communication with quantum memory
arXiv:1609.08676– to appear in Phys. Rev. Applied, 2017

Rb memory for a free-space generic qbit

Use of the memory with an input with μ=1.6 photon
Trasmissivity for probe beam 4.5%
Rejection of control beam 130 dB

QBER analysis: <1% for μ~100 ph
<13% for μ~ 1.6 ph
➔need to upgrade the noise rejection
➔very good performance in the state storage & reading



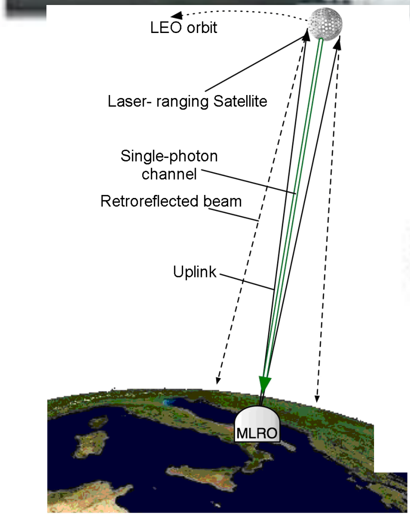


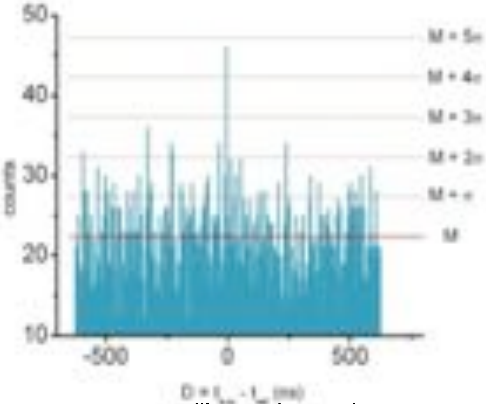
M. Namazi et al, arXiv:1609.08676, to appear in Phys. Rev. Applied, 2017

Italian Space Quantum Communications

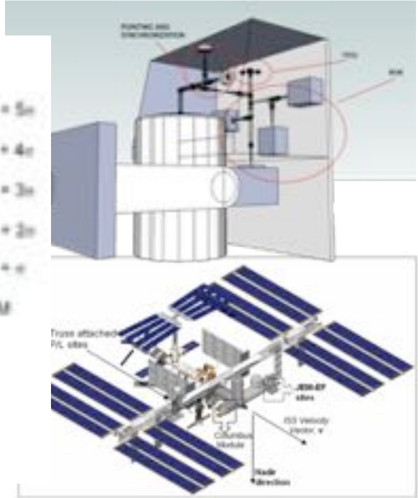
Collaboration of QuantumFuture Research Group of University of Padova with ASI Matera Laser Ranging Observatory, since **2003.**

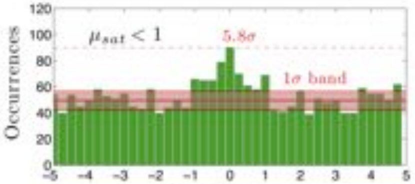
1.5 m telescope with millimeter resolution in Satellite Laser Ranging.

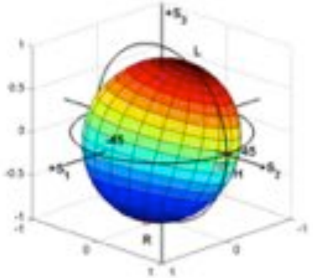


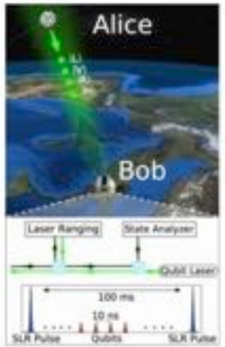


P. Villoresi et al.
New J. Phys.
10 033038 (2008)









G. Vallone et al. Phys. Rev. Lett. vol 115 040502 (2015)

2003 – UniPD SpaceQ project

Optical front-end for single photon transceiver @ MLRO

2008 – first single-photon return from Ajisai announced

2009 ASI Feasibility study for a quantum payload for the ISS

2009-2011 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

2015 Temporal modes demonstrated in satellite qubit

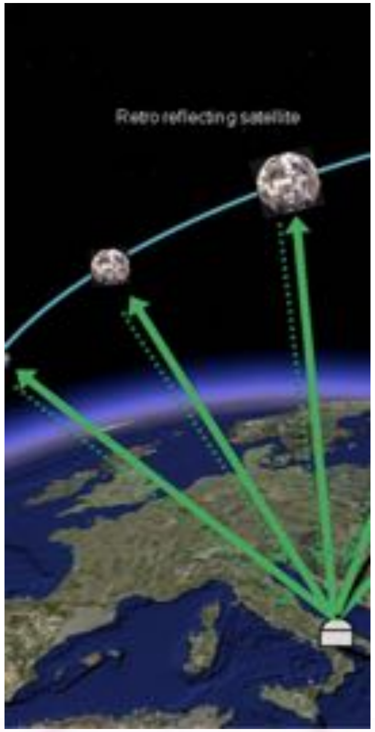
2016 – New limit in single photon exchange from MEO sat

2017-Testing wave-particle duality along Space links

D. Dequal et al.
Phys Rev. A Rapid Comm
93 010301 (2016)

Conclusions

The frontier of Space Quantum Communications has been opened.



QC from a satellite transmitter to the Earth was *experimentally demonstrated as feasible* using

polarization coding – over 2000 km
and **time-bins coding – over 5000 km**

and the single-ph. exchange for **LEO** and **MEO**

Wheeler Delayed Choice scheme
implemented along a Space to ground link confimed that:
no elementary phenomenon is a phenomenon until it is a registered (observed) phenomenon

QC around the Earth is expected to play roles in

- **testing together Quantum Mechanics & Gravitation**
- **applications of quantum protocols as QKD and teleportation**

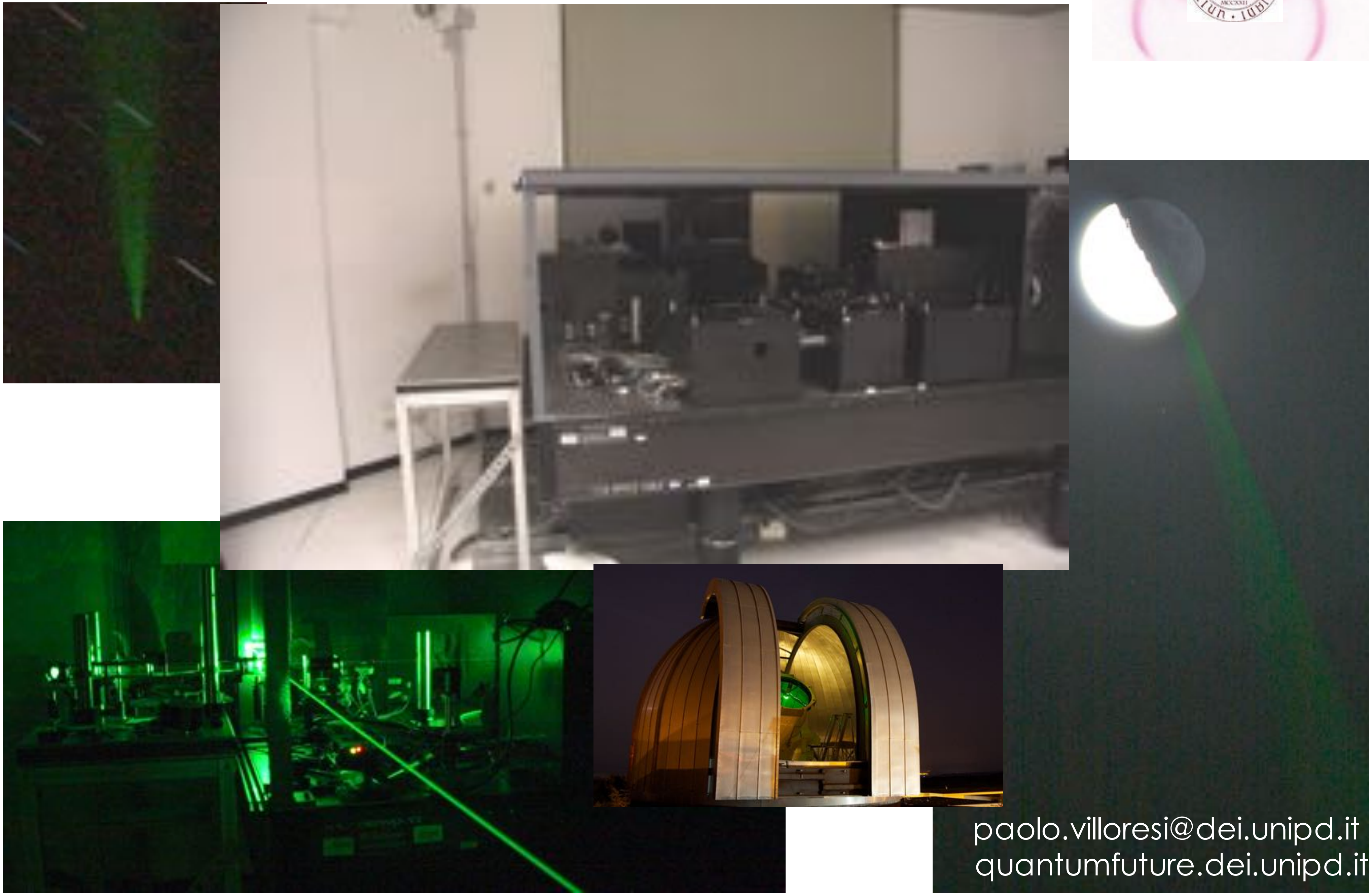
Quantum Communications
and
Satellite Laser Ranging

Two communities running along well separate geodesics by birth, have synergies that proven crucial in favour of the Space QComms and that is working also in the opposite direction.

INFN Moonlight-2 Coordinator Simone Dell'Agnello INFN - LNF

- *Synchronization of qubit detection at sub-ns level*
- *Accurate pointing including atmospheric refraction*
- *Existing infrastructures with very precise time reference (atomic clock + VLBI + GPS)*

QComms: not limits but horizons



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