Satellite Quantum Communications exploiting SLR at MLRO

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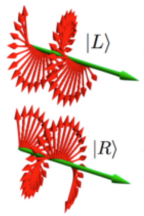
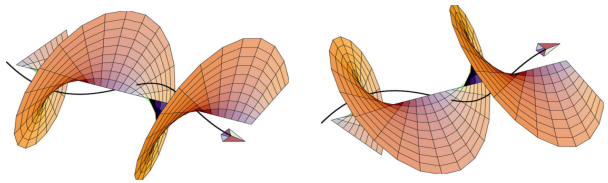
Quantum Communications in Space

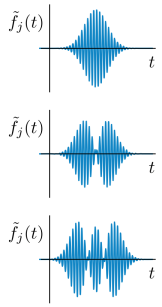
- **Exchange of quanta** between an orbiting terminal and a ground station
- The quanta are best chosen by taking **photons**
- **Coding of information** as **qubits** using one or more photon ***degree of freedom:***
  - Polarization modes



  - Angular momentum modes



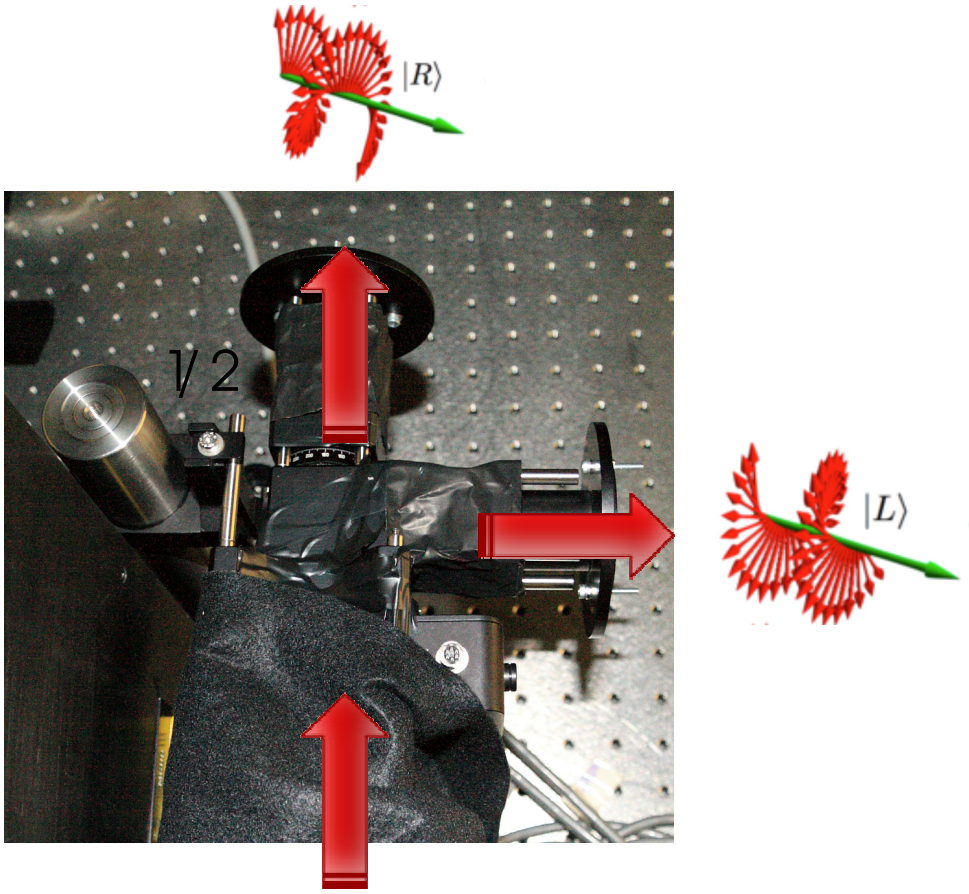
  - Temporal modes



Quantum Coding

Single photon in a **superposition of states,** with normalized **amplitude α and β.**

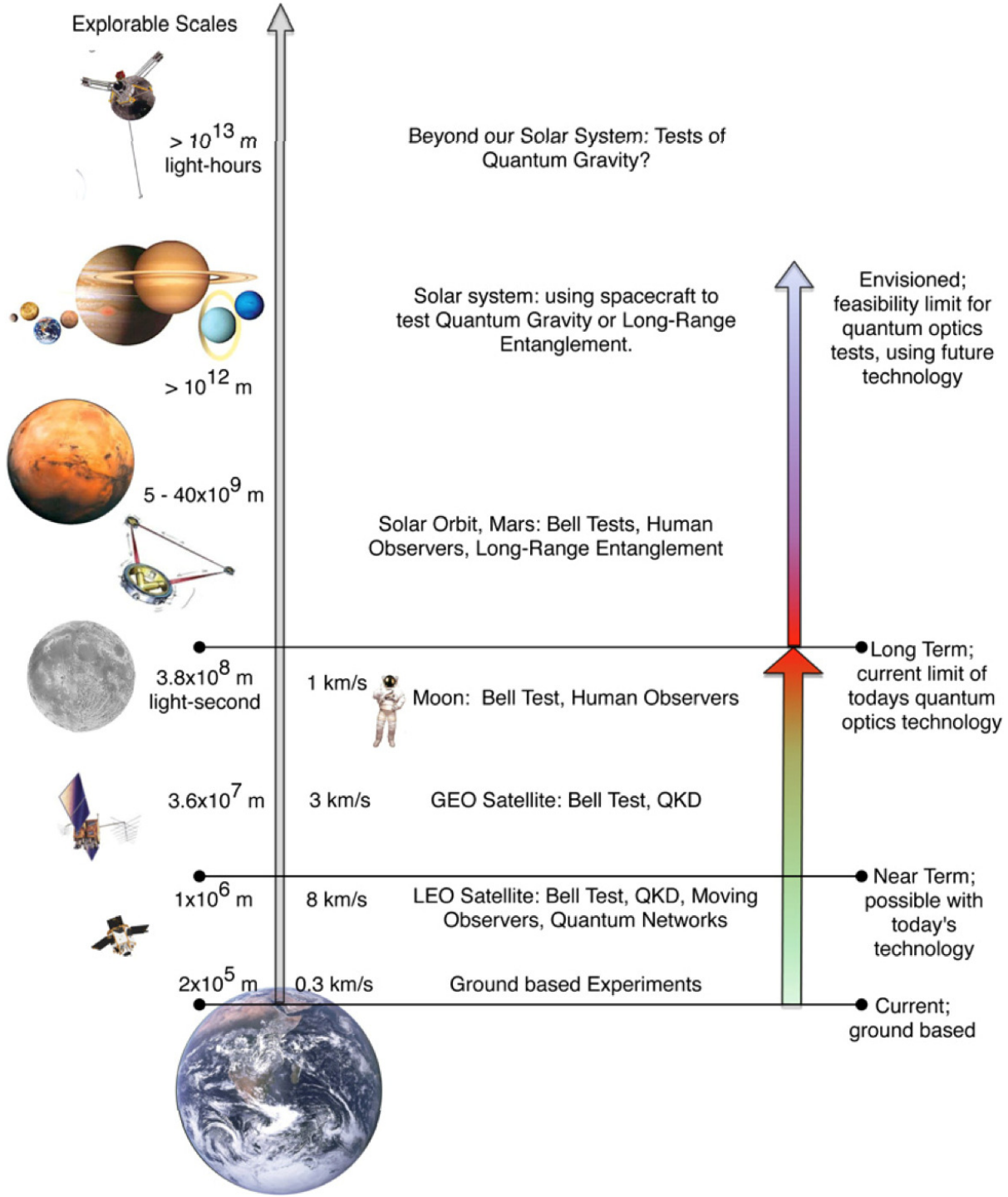
The measure gives a **click** of a SPAD on **one port**.



$$|\alpha|R\rangle + \beta|L\rangle\rangle$$

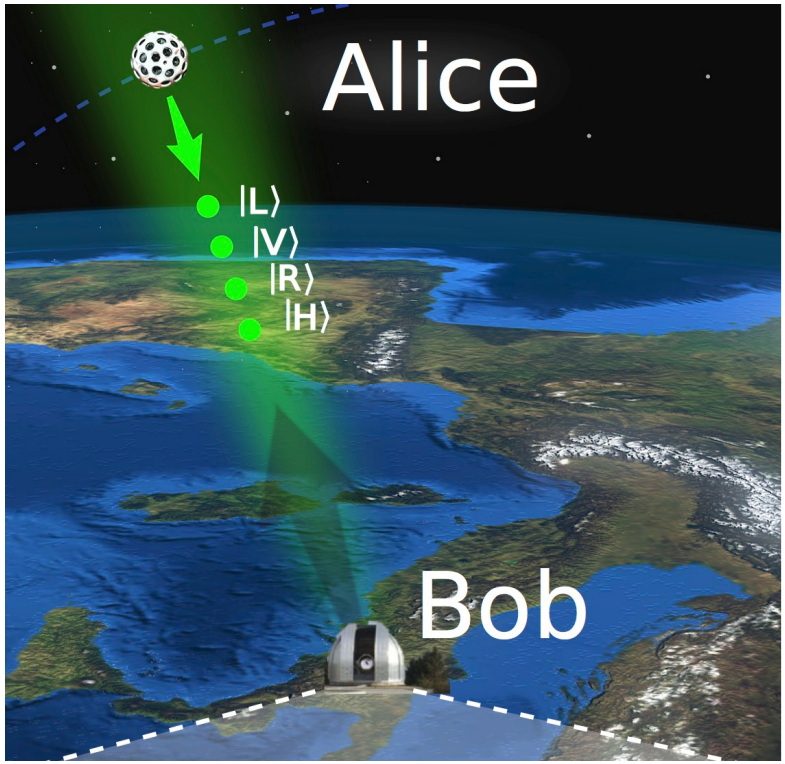
Fundamental Physics tests in Space Roadmap on topics and necessary technology

D. Rideout et al., Classical and Quantum Gravity **29** 224011 (2012)

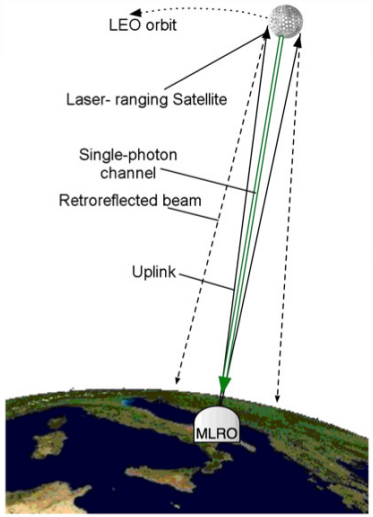


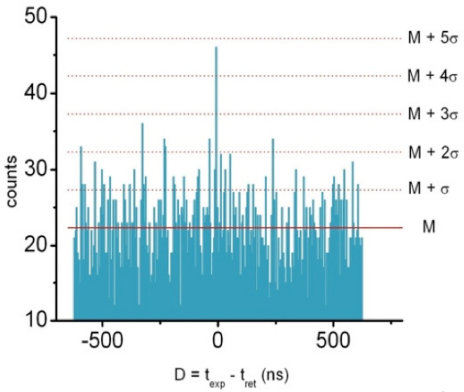
Quantum Communications in Space

- **Exchange of qubits** between Alice and Bob to create a correlation that can be exploited for generating a random cryptographic key.
- Demonstration of protocols such as quantum-key-distribution (**QKD**) and **quantum teleportation** along **satellite-to-ground** or **intersatellite** links.

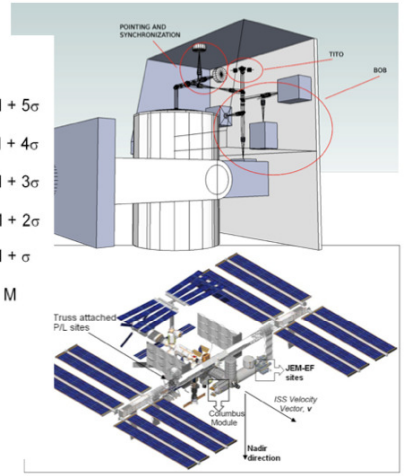


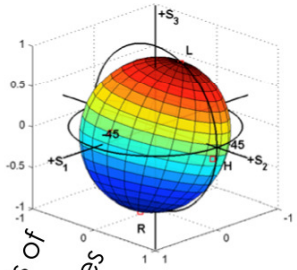
Italian roadmap for Space QC

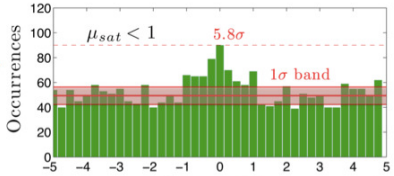




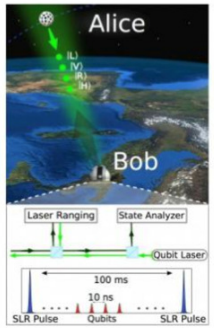
P. Villoresi et al.
New J. Phys.
10 033038 (2008)







G. Vallone et al. Phys. Rev. Lett. vol 114 (2015)



2003 – UniPD SpaceQ project

First MLRO tests

Optical front-end, high rep rate laser installed and single photon receiver @ MLRO

2008 – first single-photon return from Ajisai announced

2009 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 Expanding range and improve SNR

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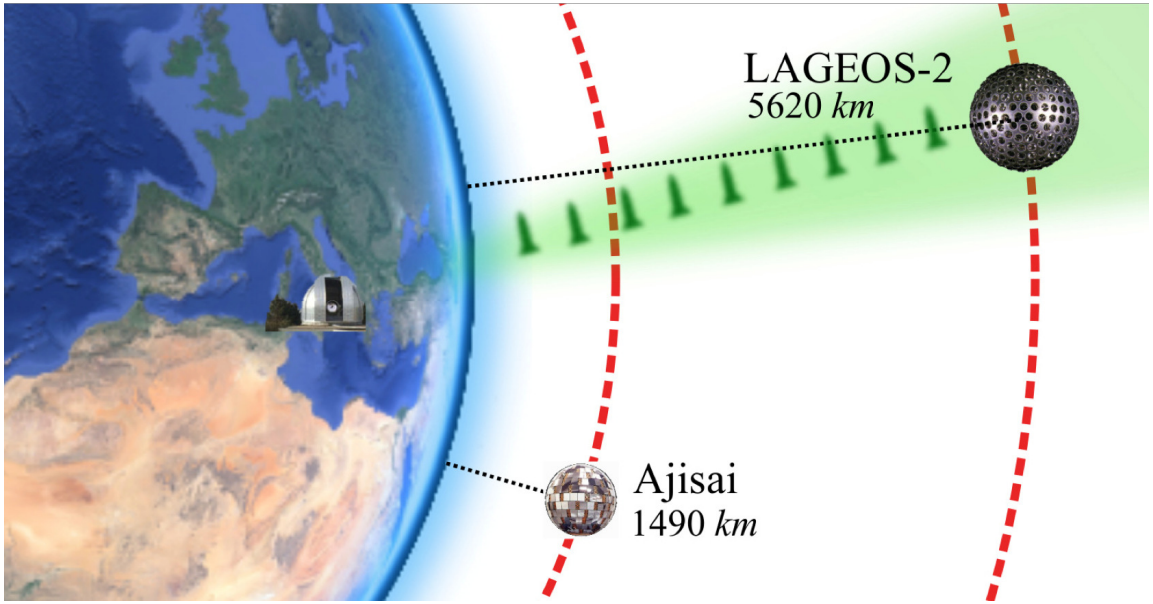
Single Photon exchange: from LEO to MEO

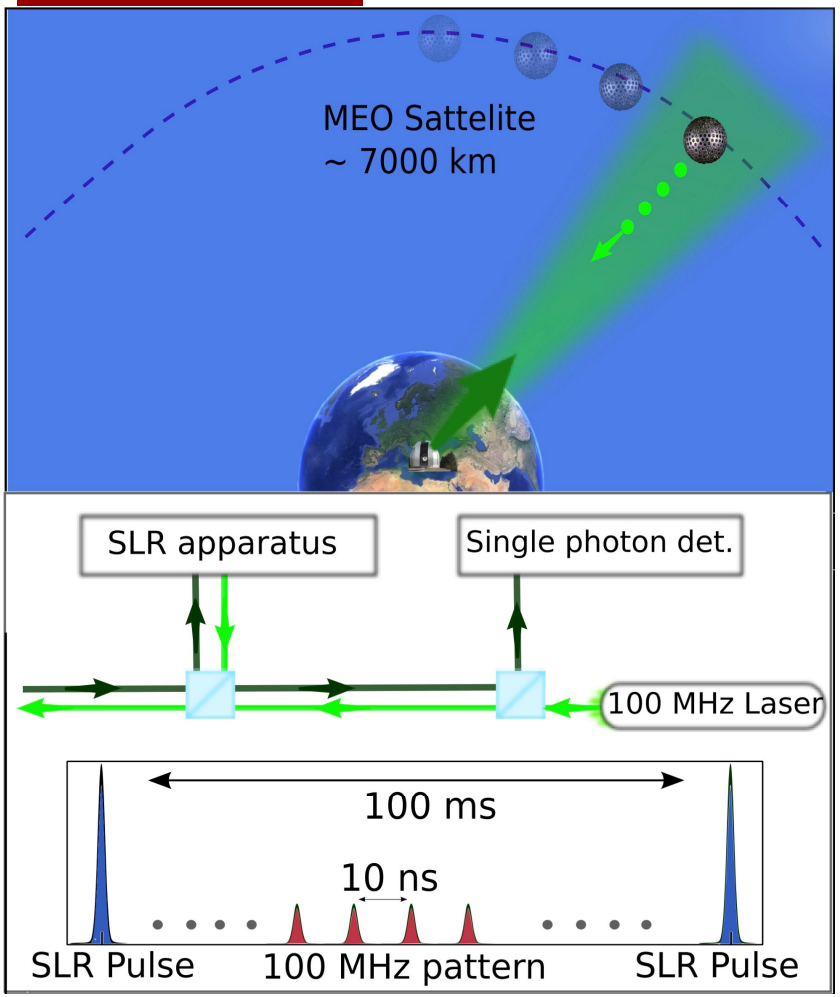
Demonstration of the detection of photon from the satellite which, according to the radar equation, is emitting a single photon per pulse.

Status as of 2014, LEO orbits – 156 dB losses.

This work: moving to MEO sats.



100 MHz photon emission rate from sat



- ✓ 100 MHz, 100 mW laser @532 nm is generated at MLRO and pointed toward the satellite.

The high loss in the uplink reduce the intensity to μ_{sat} 1 photon per pulse. The single photon signal is retroreflected toward the ground station, where it is detected.

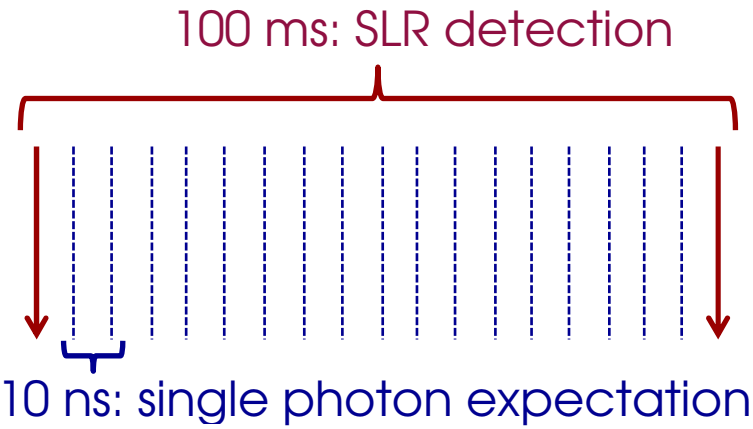
- ✓ PMT single photon detectors, 22 mm dia. , ~50 Hz dark counts, 10% efficiency

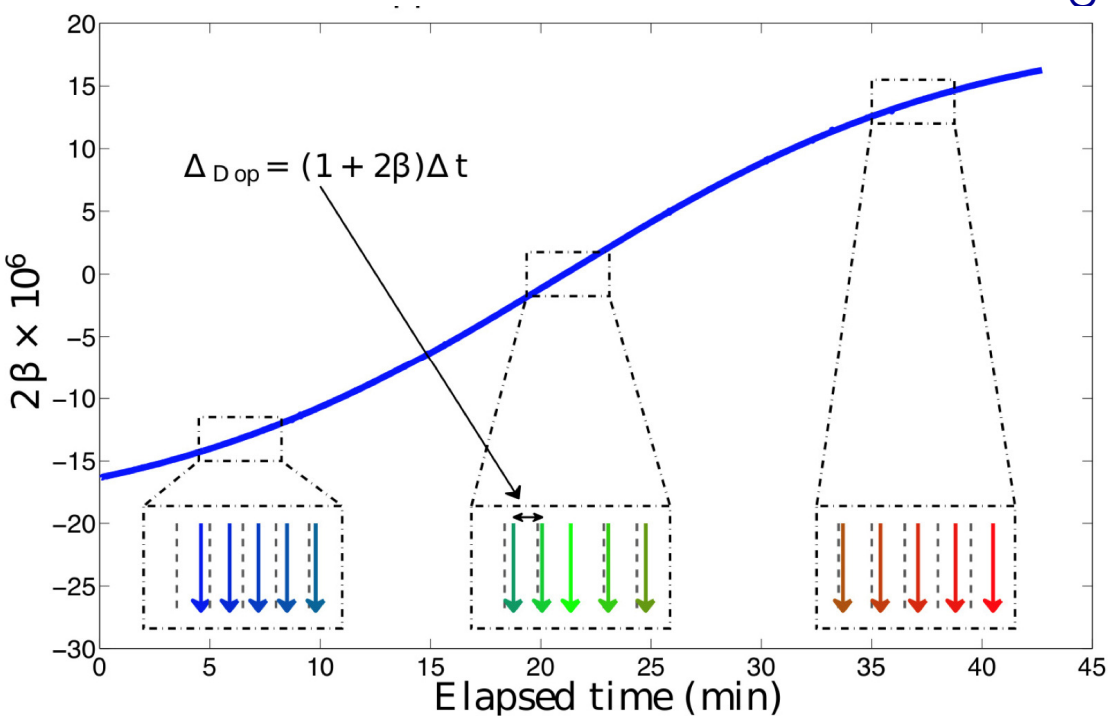
- ✓ A beam splitter merges the 100 MHz laser with the stronger 10 Hz Satellite Laser Ranging (SLR) pulses.

The SLR signal is used for pointing and as a synchronization reference.

Synchronization of photon detection with MLRO

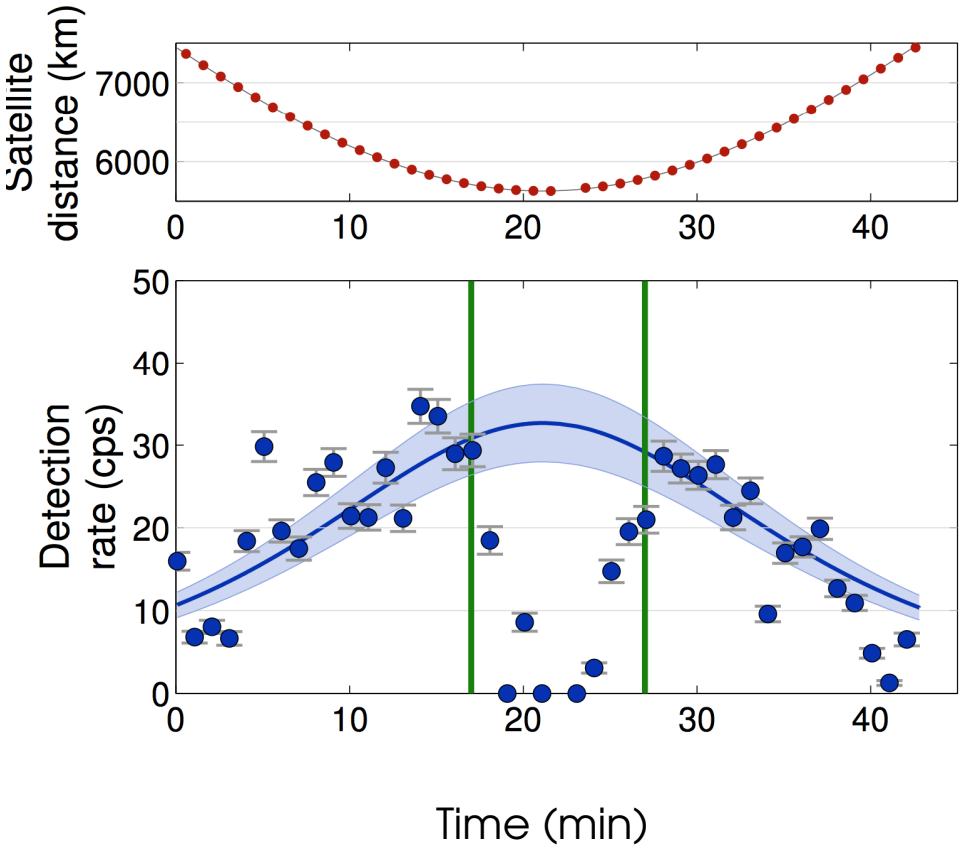
Photon expected time of arrival (T_{ref}) has been derived dividing the interval between two consecutive SLR detection





Single photon exchange for 7000 km with LAGEOS

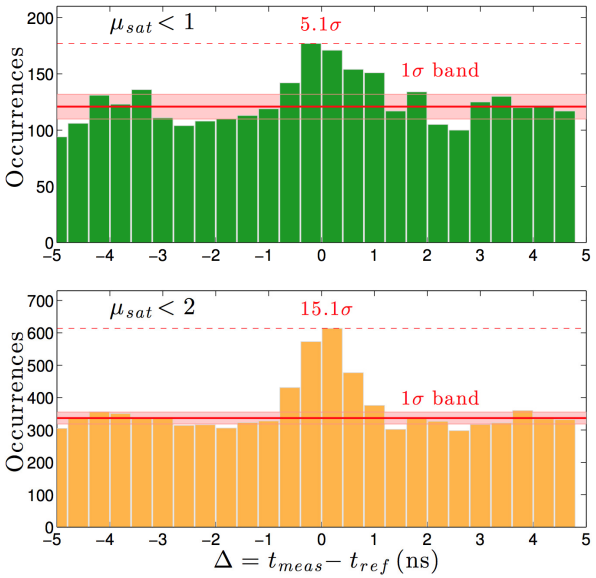
- The conditions of $\mu_{sat} < 1$ have been pointed out along the orbit.
- Evidence of a peak over the background at a slanted range up to 7500 km

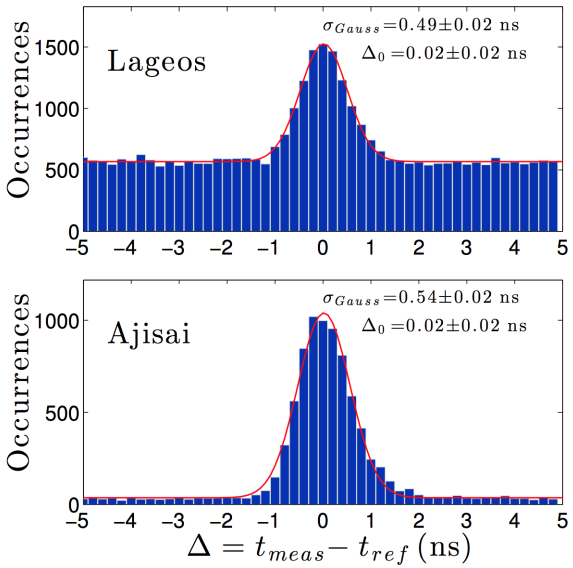


D. Dequal et al. *Experimental single photon exchange along a space link of 7000 km*, arXiv:1509.05692 (2015).

Single photon exchange

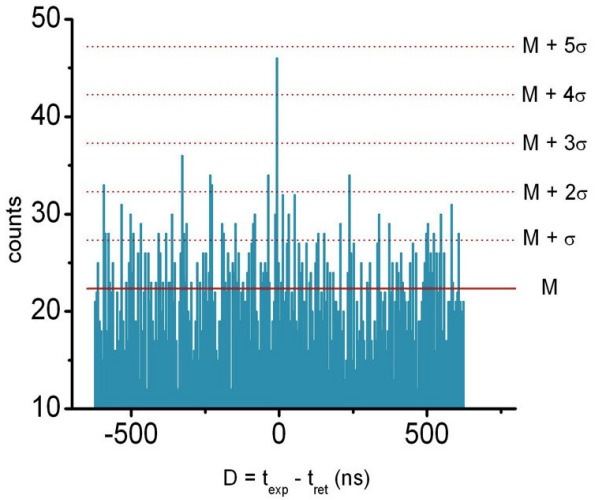
Lageos 2015





D. Dequal et al. *Experimental single photon exchange along a space link of 7000 km*, arXiv:1509.05692 (2015)

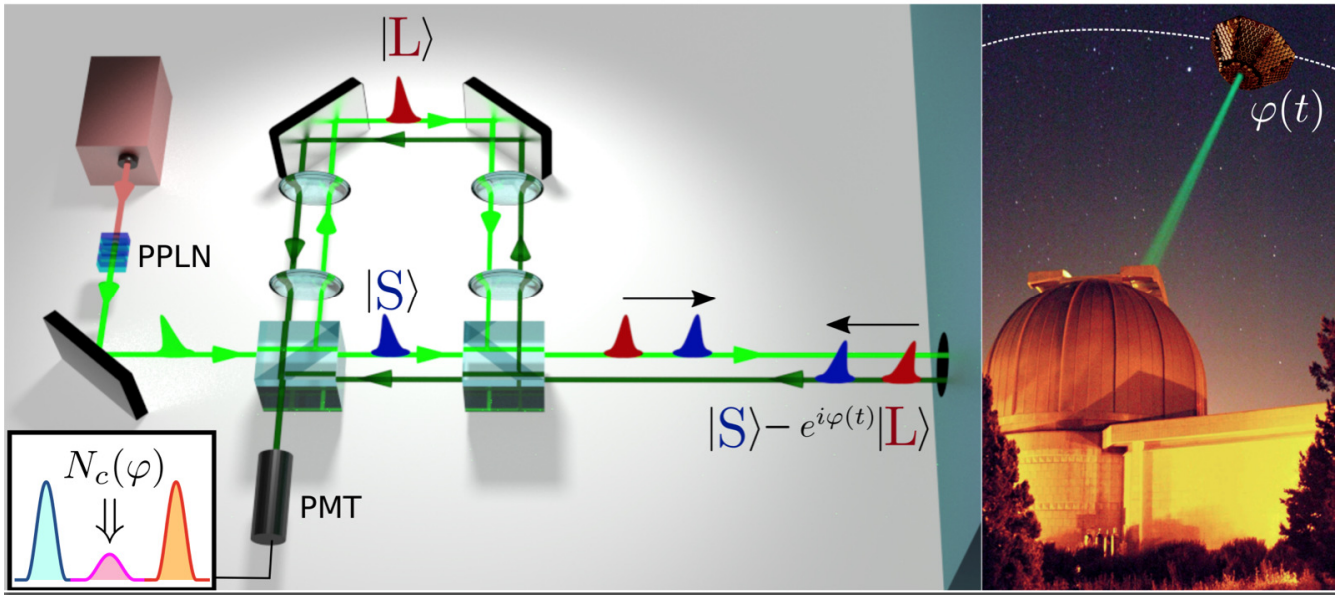
Ajisai 2008



P. Villoresi et al. *Experimental verification of the feasibility of a quantum channel between space and Earth*, New J. Phys. **10** 033038 (2008)

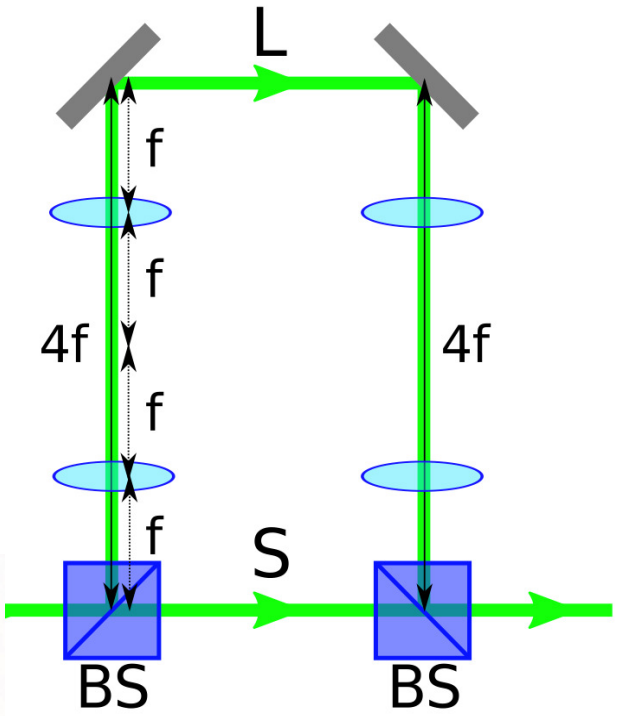
The temporal modes of light

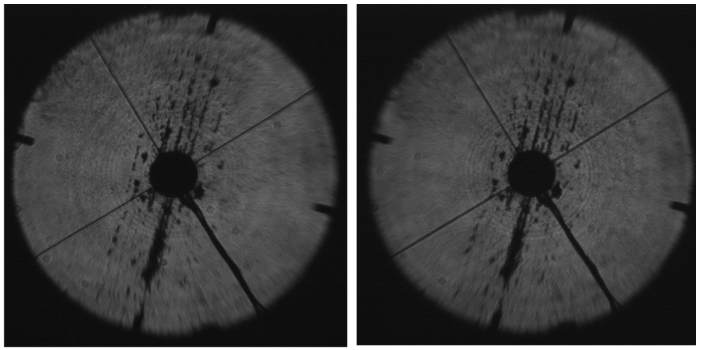
- A two-modes state is created with an unbalanced Mach-Zehnder Interferometer (MZI)
- The satellite reflections induces a phase modulation, measured using the same interferometer used for the generation.



4-f optical relay in the MZI

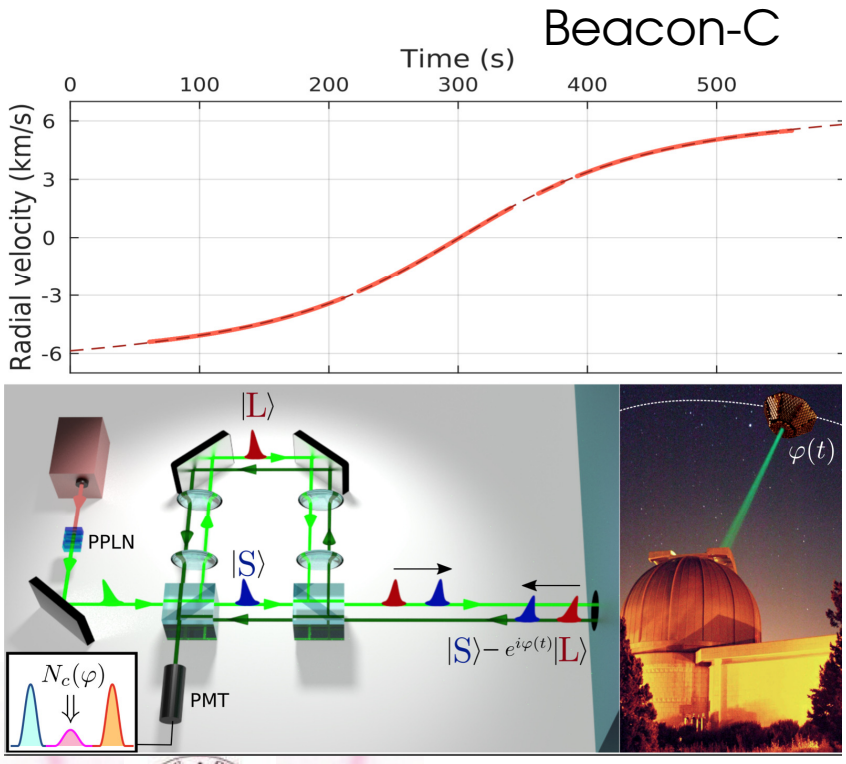
Pupil imaging for the interference

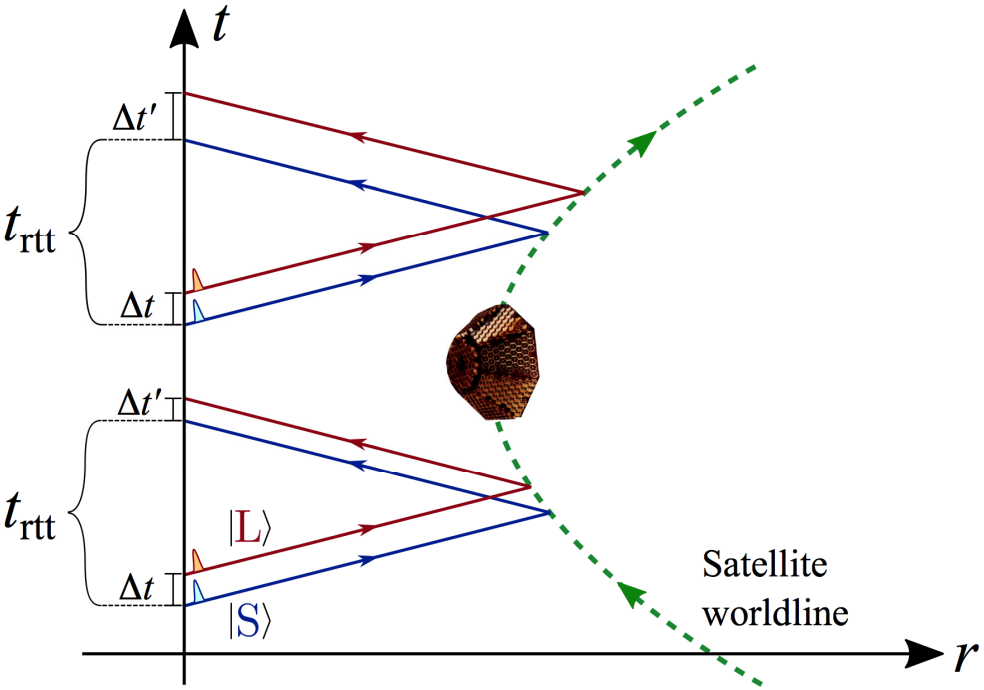




Short arm Long arm

Kinematic Phase modulation





The phase reconstruction

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

P_c probability of detecting the photon in the central peak

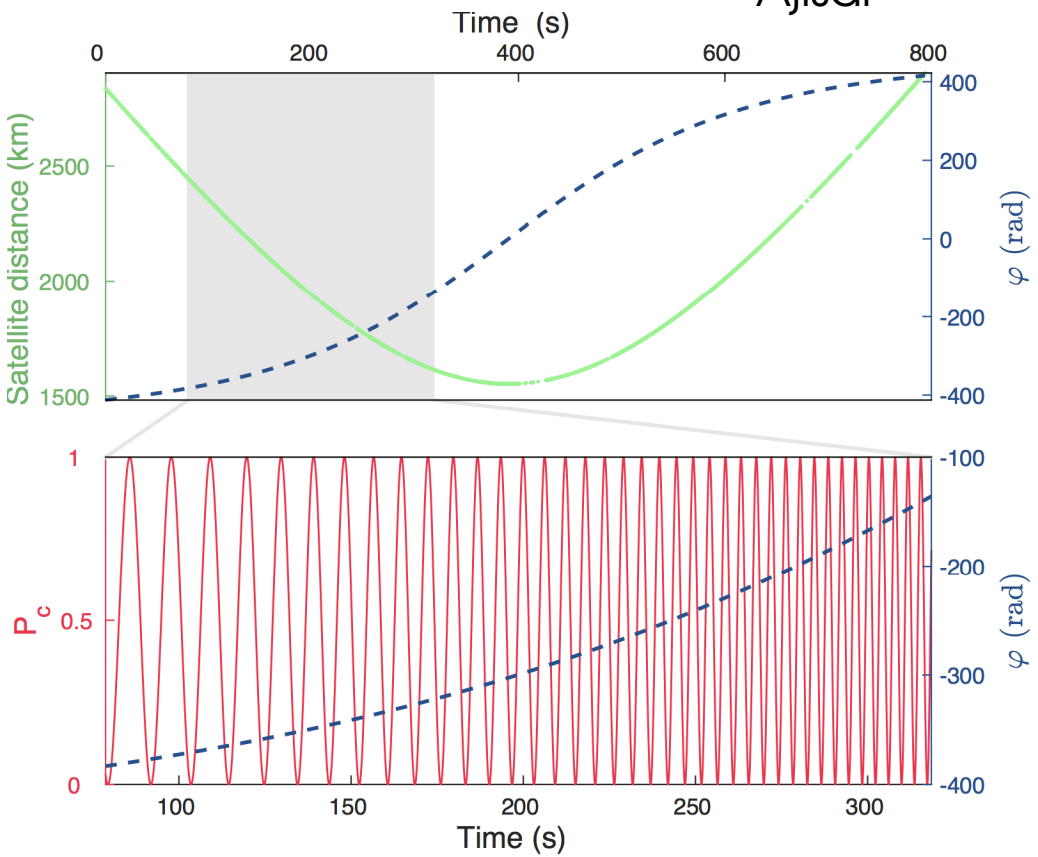
$$|\Psi_r\rangle = (1/\sqrt{2})(|S\rangle - e^{i\varphi(t)}|L\rangle)$$

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

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

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

Ajisai

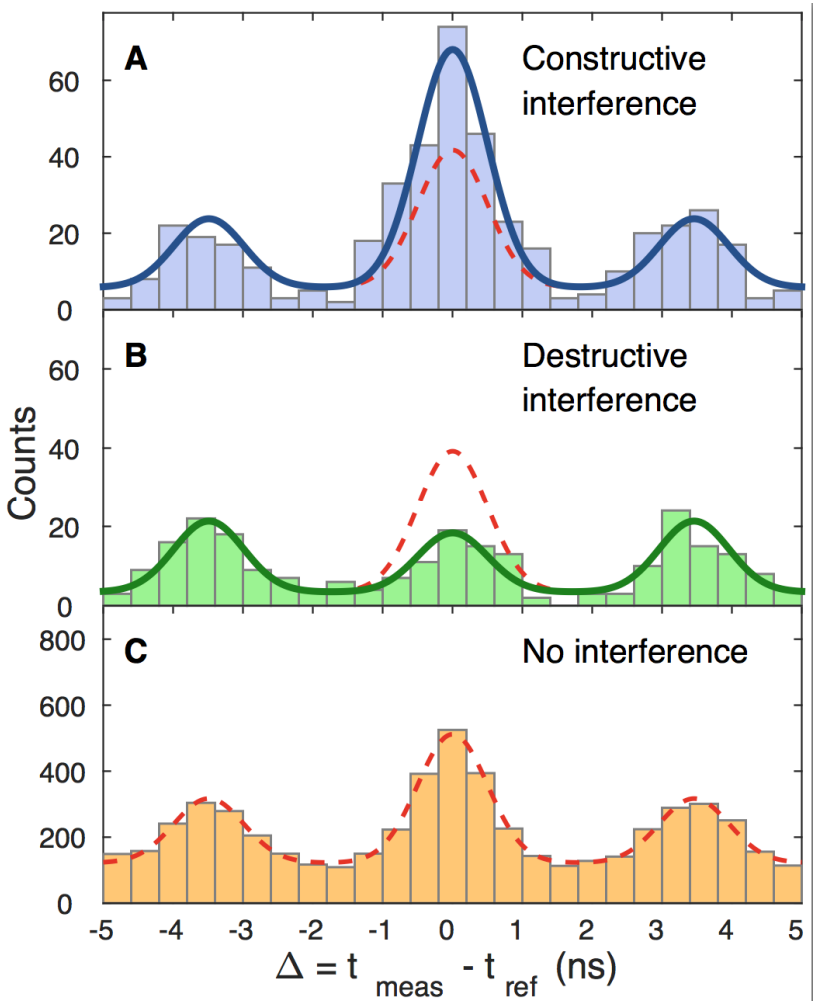


Evidence of the interference

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

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

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

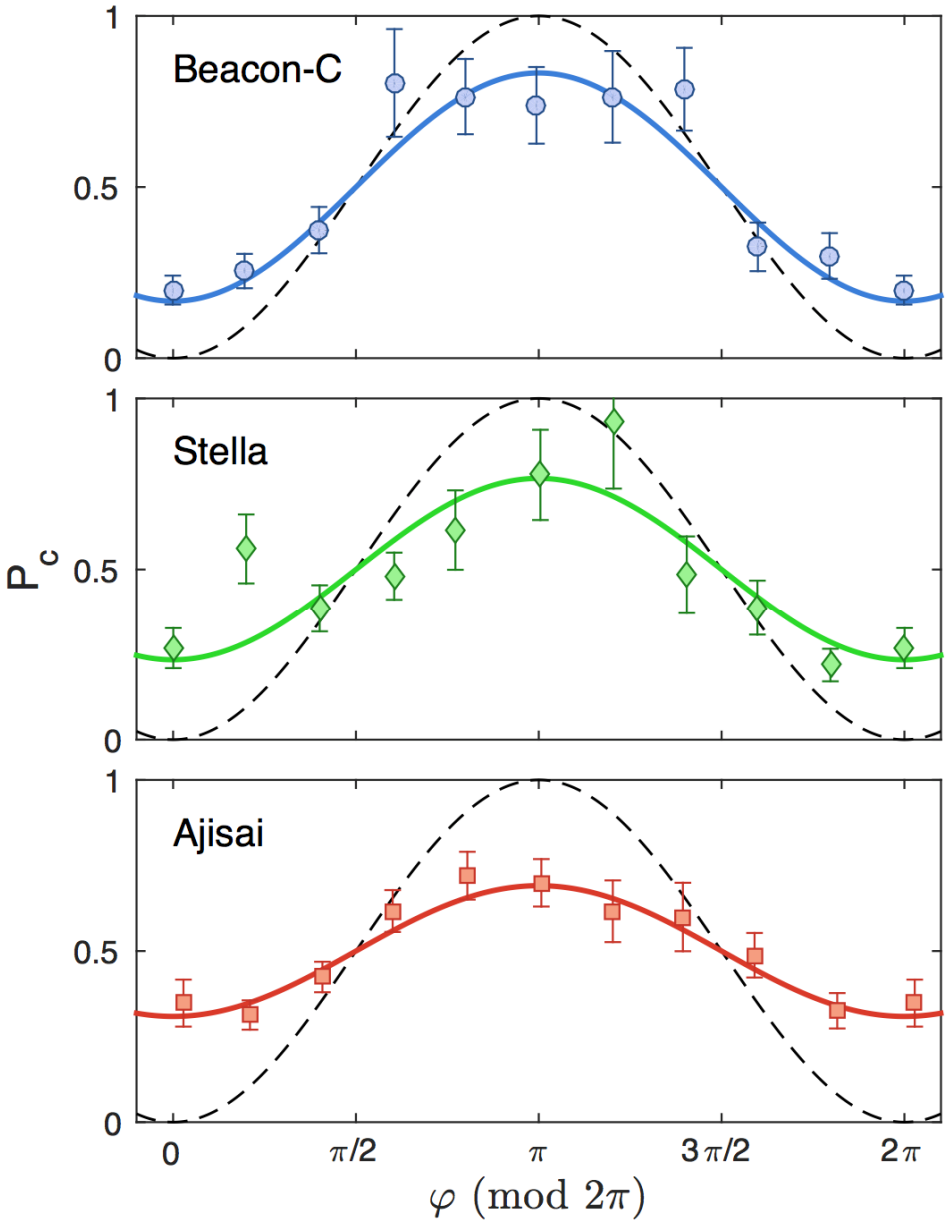


Beacon C

Vallone et al.
Quantum interference along satellite-ground channels,
arXiv:1509.07855 (2015)

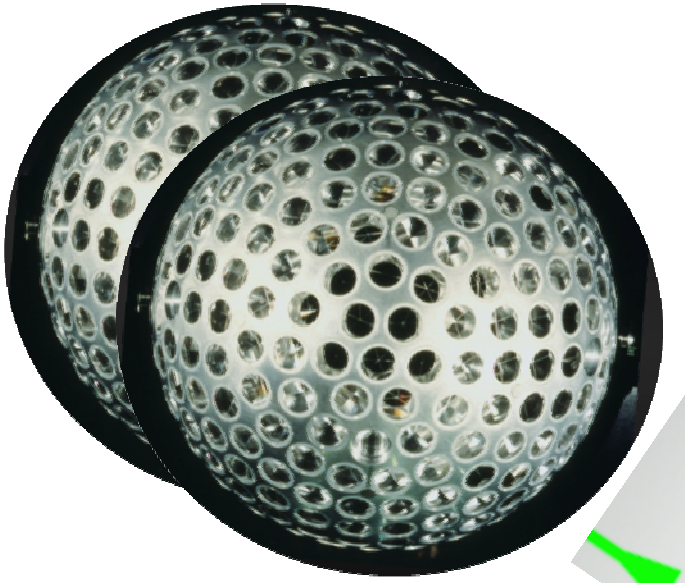
Visibility vs. φ(t)

Vallone et al.
Quantum interference along satellite-ground channels,
arXiv:1509.07855 (2015)

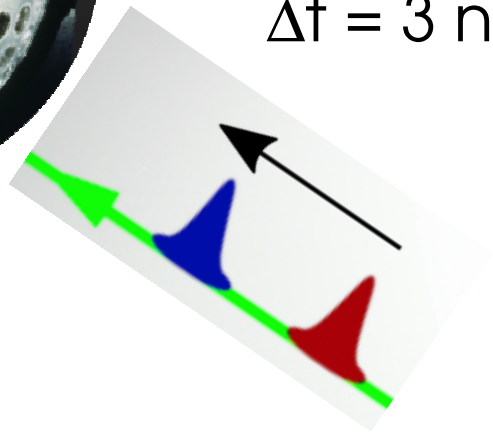


Istantaneous velocity effect

- The qubit modulation is depending on the **instantaneous satellite velocity.**

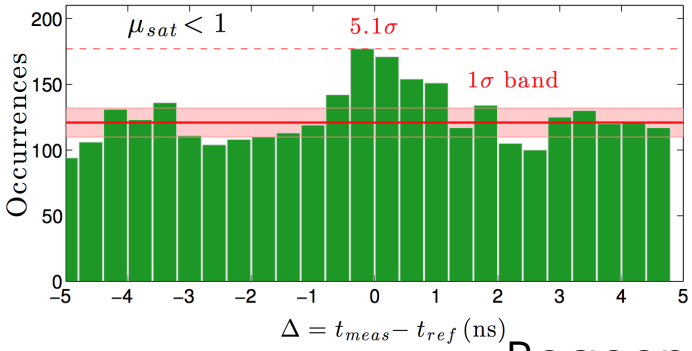


$\Delta t = 3$ ns

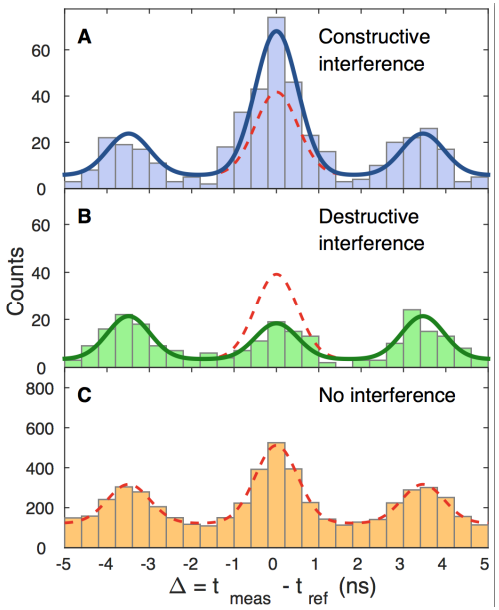


Conclusions

Lageos 2



Beacon C



- SLR pulse reference is continuing demonstrating a very valuable framework for realizing demonstration in Space QC also from **MEO sats**.
- Possible applications of the present results spans from precise metrology of satellite dynamic, investigation on **quantum correlations over long distances** as well as **secure communications on planetary scale**.

Acknowledgments

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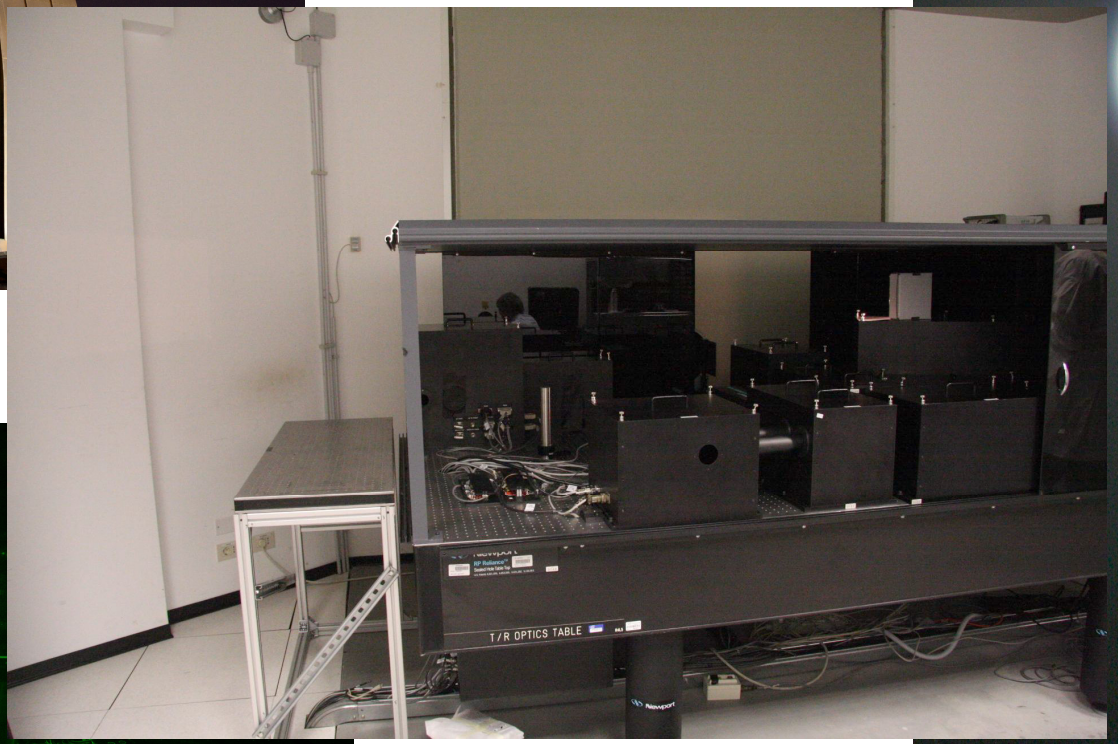
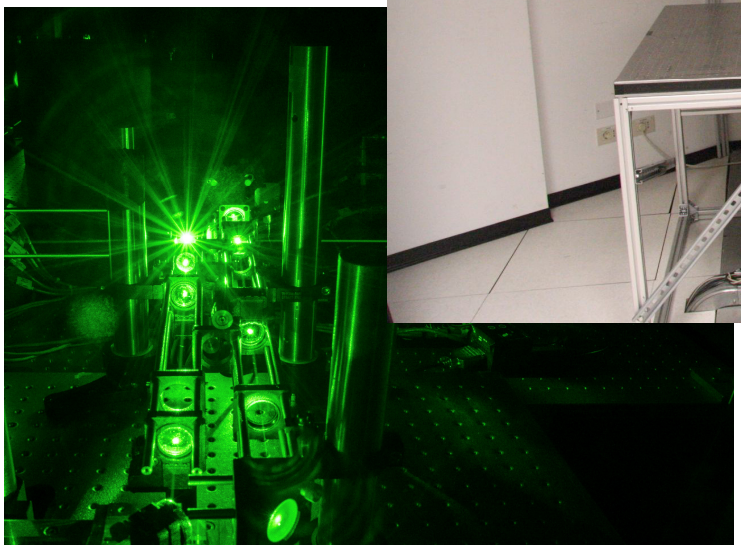
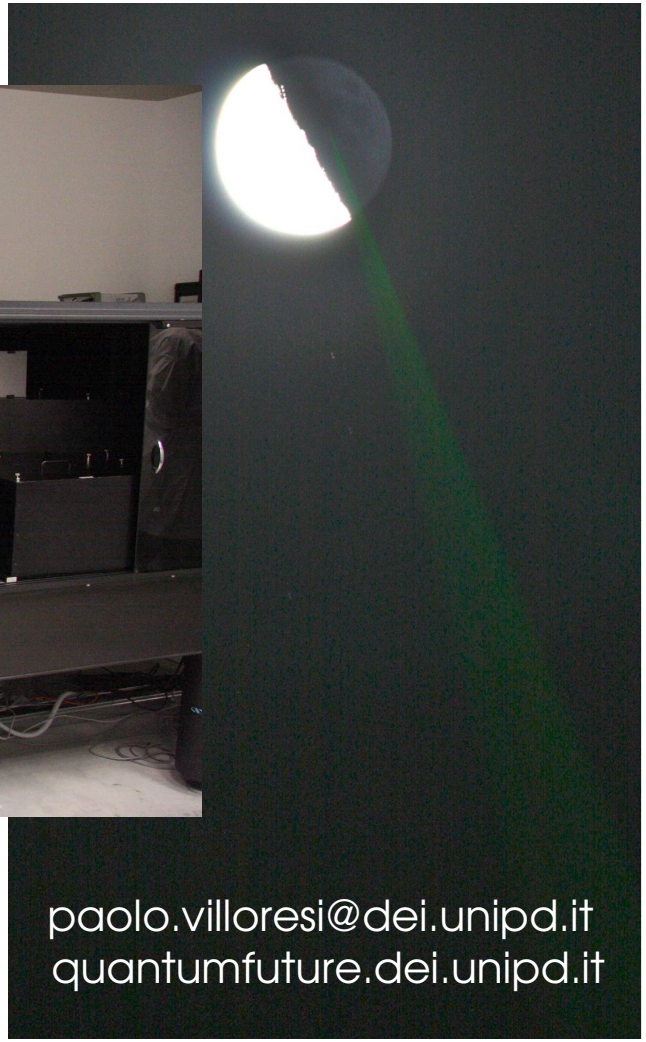
- Our work was supported by the Strategic-Research- Project *QUINTET* of the **Department of Information Engineering, University of Padova**, the Strategic- Research-Project of the **University of Padova**. *QUANTUMFUTURE* and the **Italian Space Agency.**

QComms: not limits but horizons







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