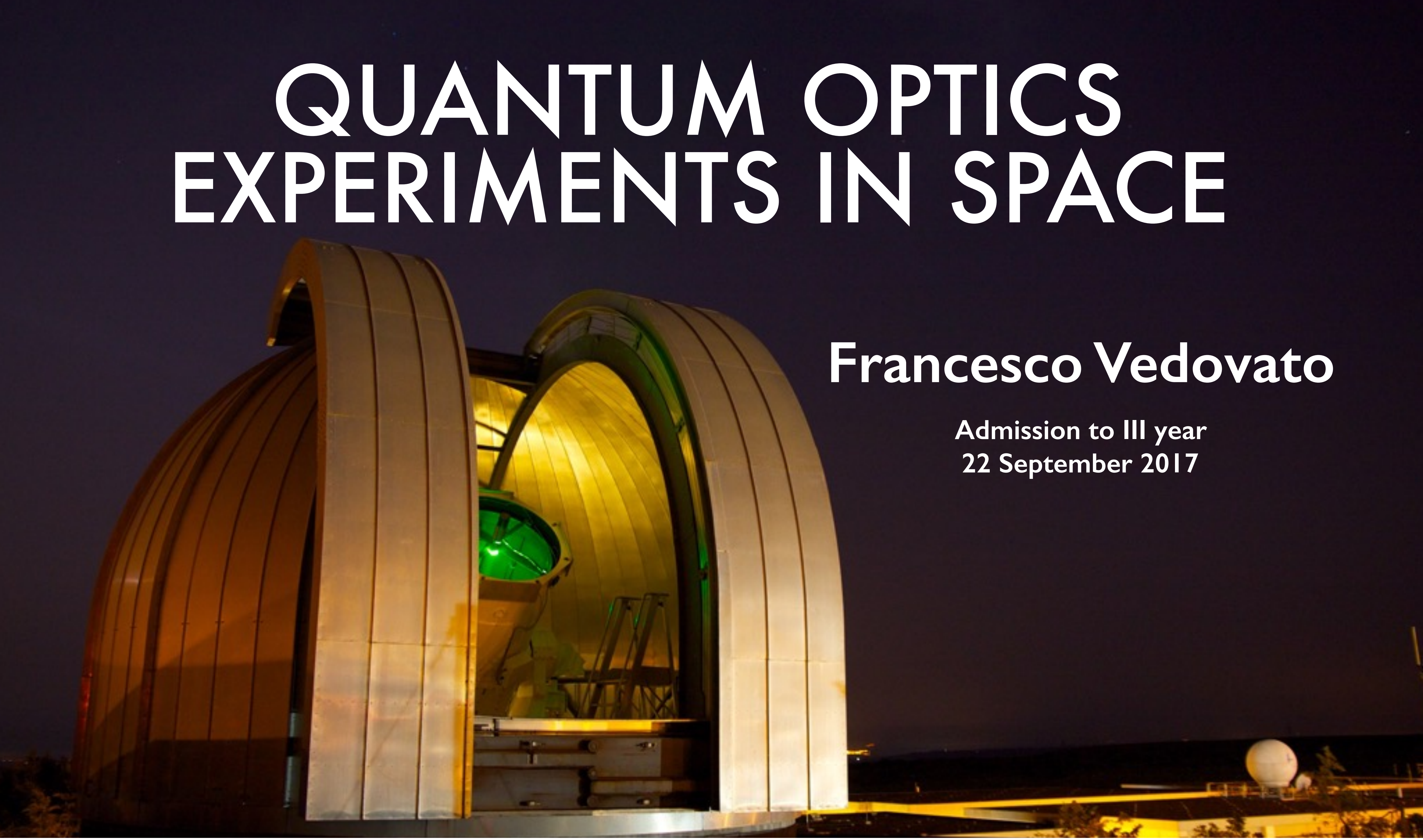
QUANTUM OPTICS EXPERIMENTS IN SPACE



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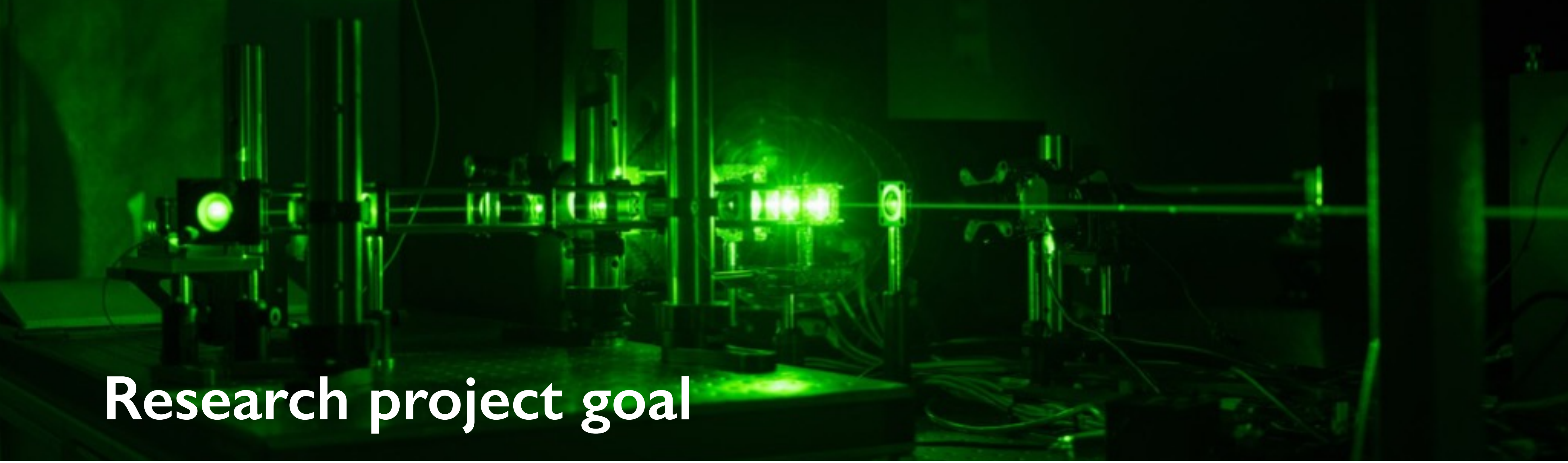
Admission to III year
22 September 2017

CISAS G. COLOMBO

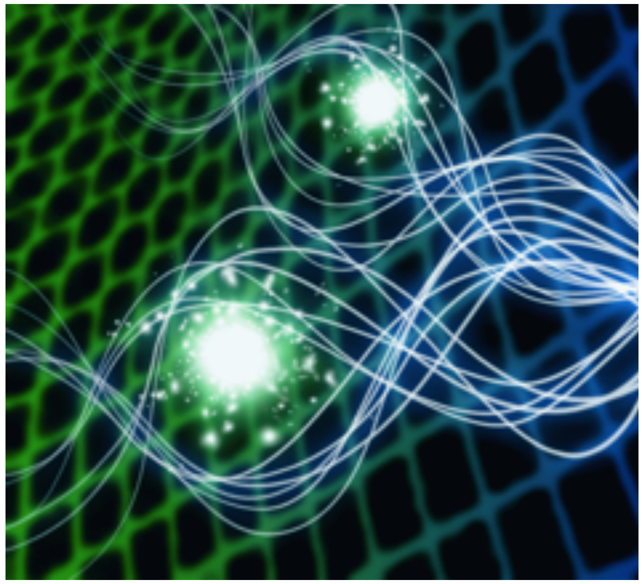
DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

agenzia spaziale italiana

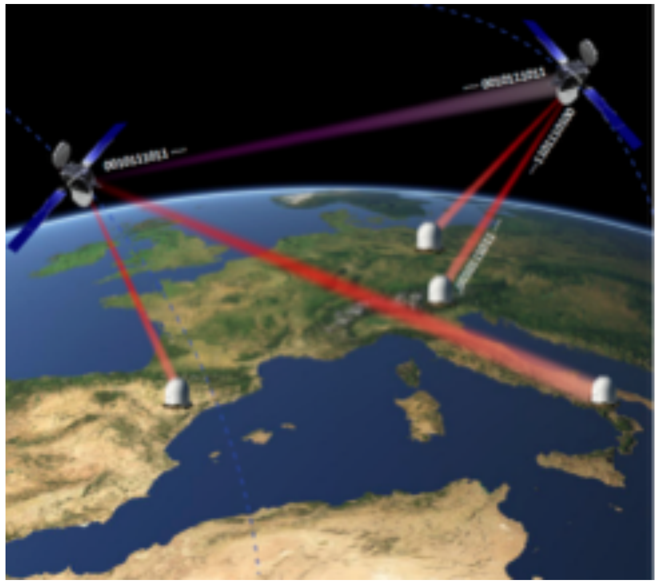


Research project goal

Study the feasibility, from the theoretical and experimental point of view, of different experiments involving Quantum Optics in space with multiple purposes and applications

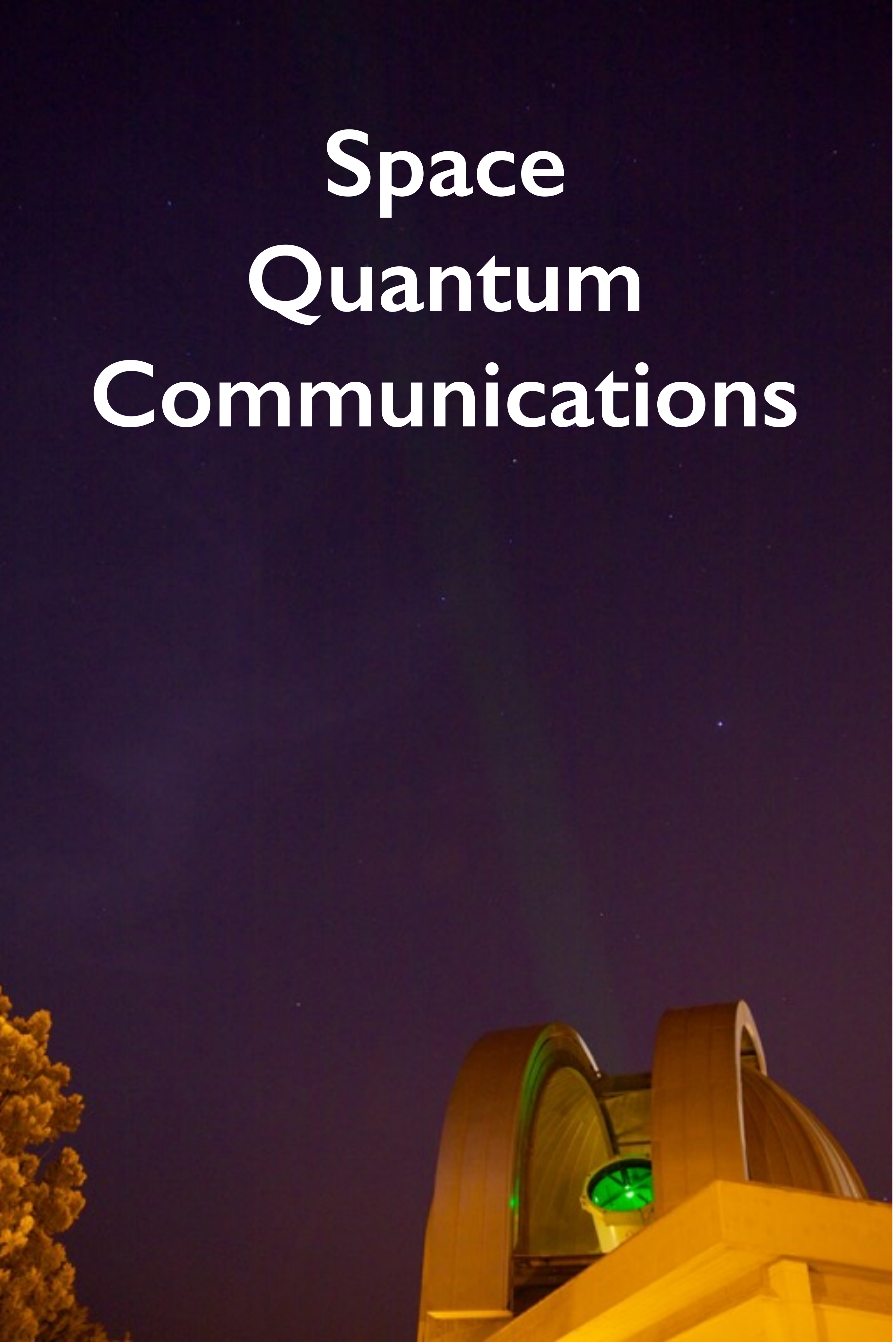


Fundamental tests of physics
in a completely new scenario



Secure communications
at planetary scale

Space Quantum Communications

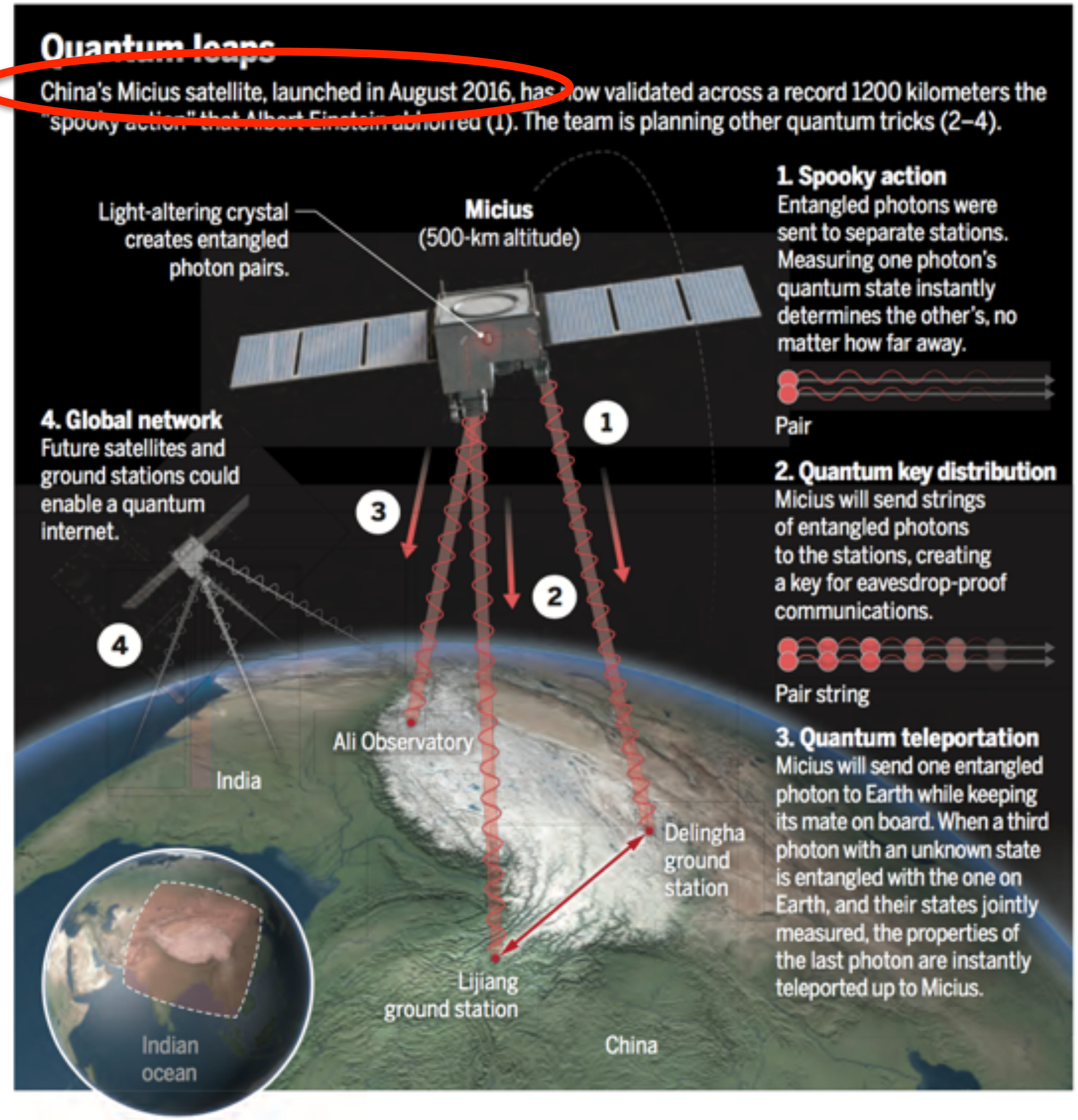


- **Quantum Communication (QC) is the faithful transmission of quantum states** between two distant locations
- **QCs** are at the heart of these experiments, but they **are nowadays limited to within few hundreds of kilometers**
- The aim of Space QCs is to **implement and exploit QC-protocols in the satellite scenario**
- Novel and **very active research field** (Europe, Canada, Japan, Singapore...)

In particular…

Scientific objectives:

- Entanglement distribution from satellite to two ground stations *(Bell test)*
- QKD from satellite to ground
- Quantum teleportation from ground to satellite

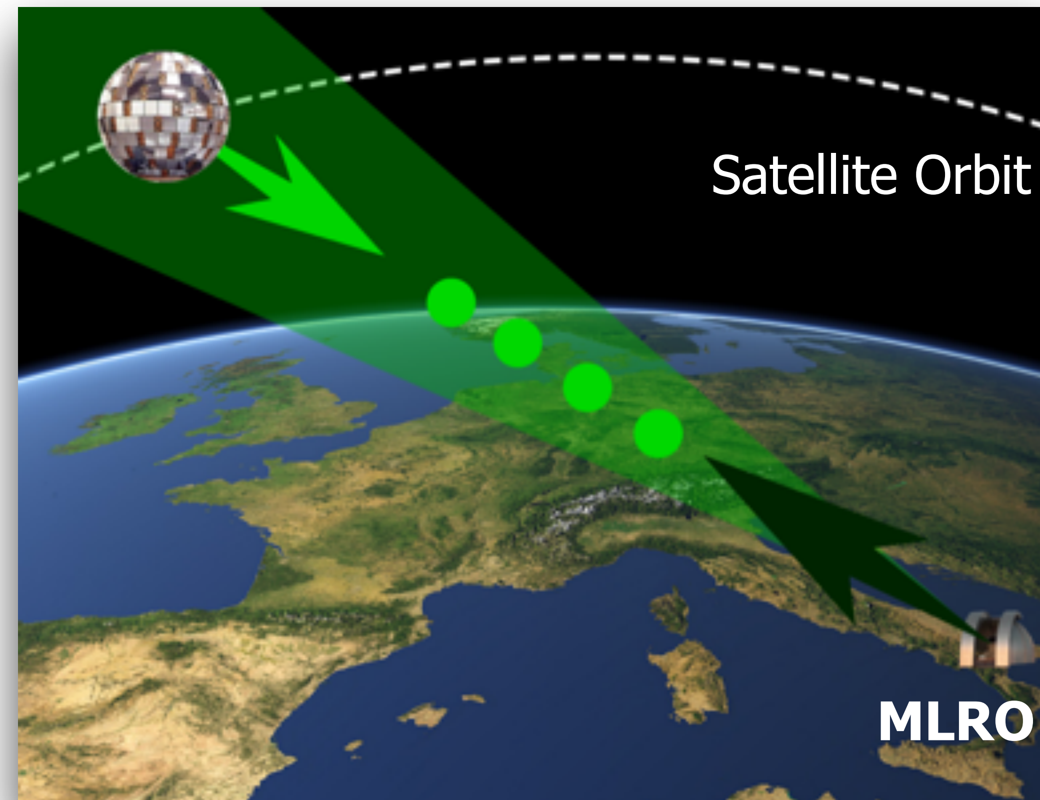


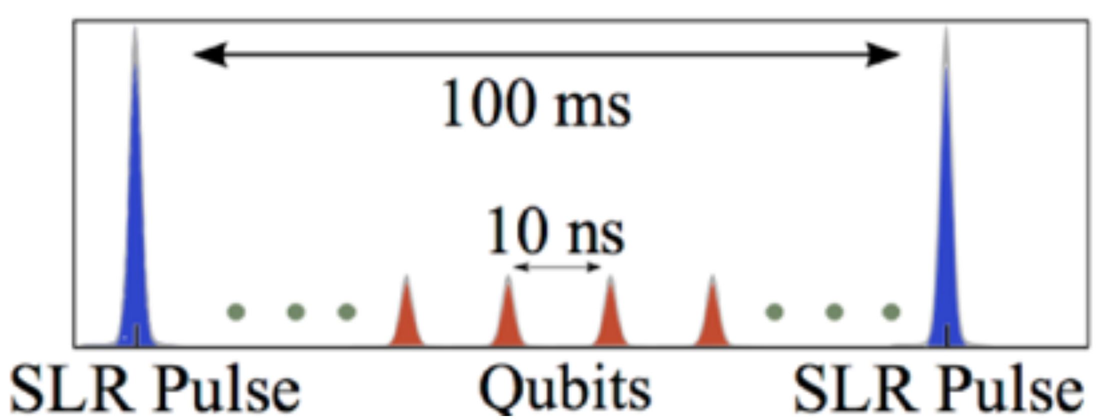
Science, 16 June 2017, VOL 356, ISSUE 6343

The 3 experiments have been realized by July 2017!

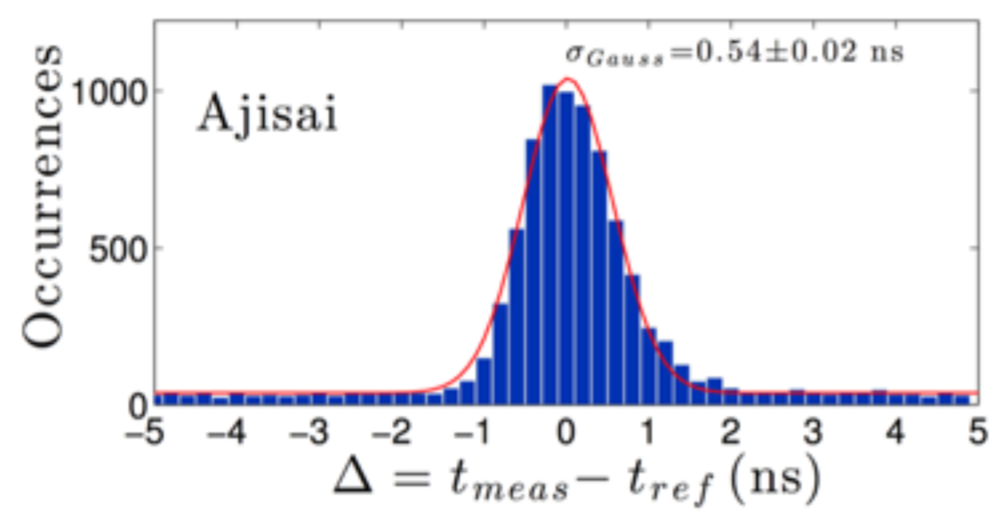
Experimental study of single photon transmission from satellites

- **Mimic a quantum source in orbit** by exploiting **retroreflectors on satellites**
- MLRO for **sending pulses towards the satellites**
- **Mean photon-number per pulse very low at the reflection**
- **Single-photon detections** with 1 ns accuracy
- **Various** photon **degrees of freedom available for encoding information** (as polarization and temporal modes)





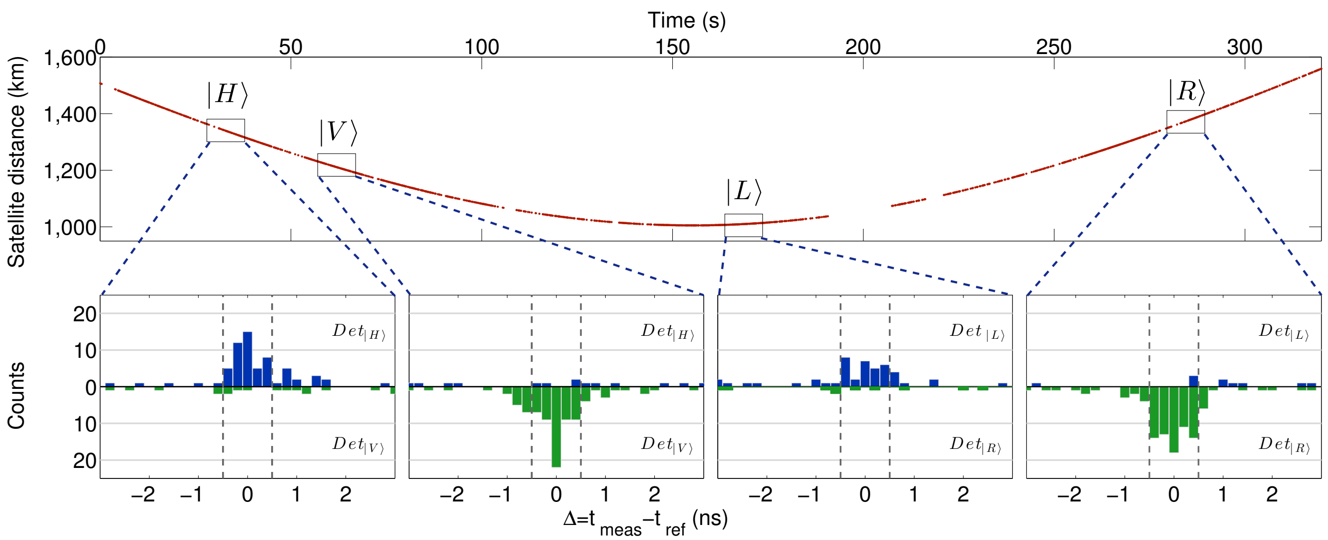
SLR laser: 10 Hz, ~100 mJ, @532 nm
Qubit laser: 100 MHz, ~1 nJ, @532 nm



Typical detections histogram

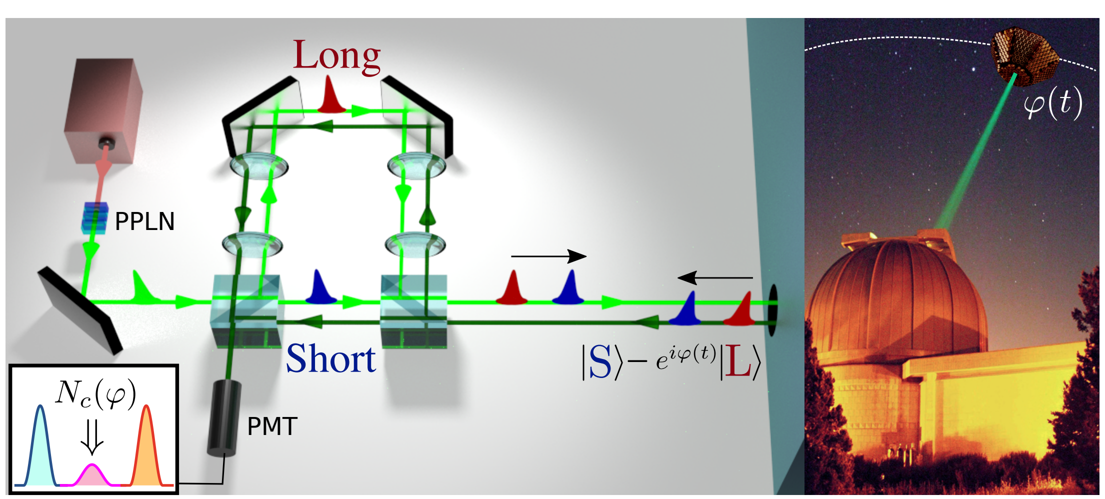
Feasibility of different photon encodings

Polarization



G. Vallone et al., PRL 115, 040502 (2015)

Time-bin



1st PhD objective achieved

G. Vallone et al., PRL 116, 253601 (2016)

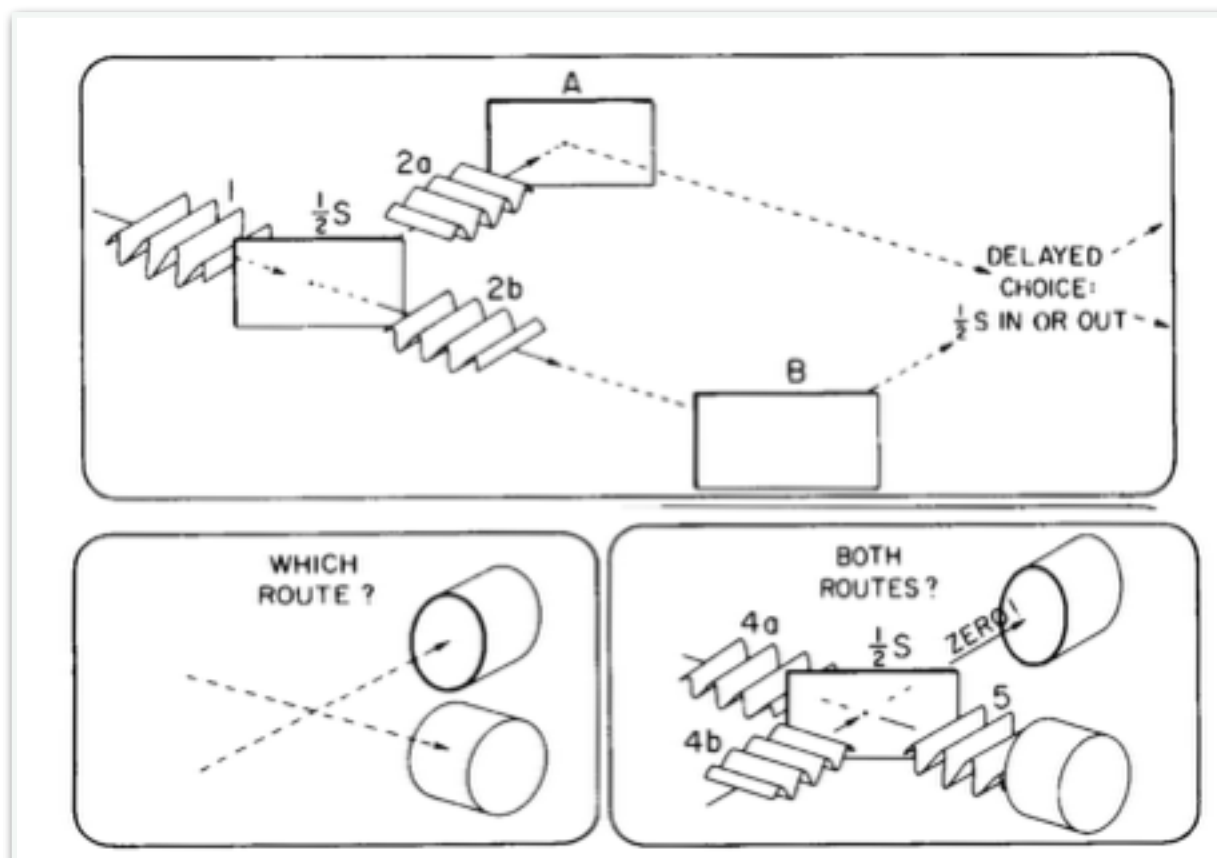
- **Photon polarization is preserved** along the free-space propagation
- We have access to **an interferometer which extends for thousands of kilometers in Space**

Idea!

Extending Wheeler’s delayed-choice to Space

2nd PhD objective achieved

- *Gedankenexperiments* have been conceived to inspect counterintuitive principles of Quantum Mechanics, as ***wave-particle duality***
- **John Wheeler** proposed his **delayed-choice experiment** to test the validity of the dual description of photons and to highlight the naive and contradictory interpretation given by **classical physics** which **leads to a *"strange inversion of the normal order of time"***
- By changing the configuration of a **two-path interferometer** after the photon has entered the setup, one can either investigate the **particle-like character** of the photon by recovering which-path information, or its **wave-like behavior** by observing interference



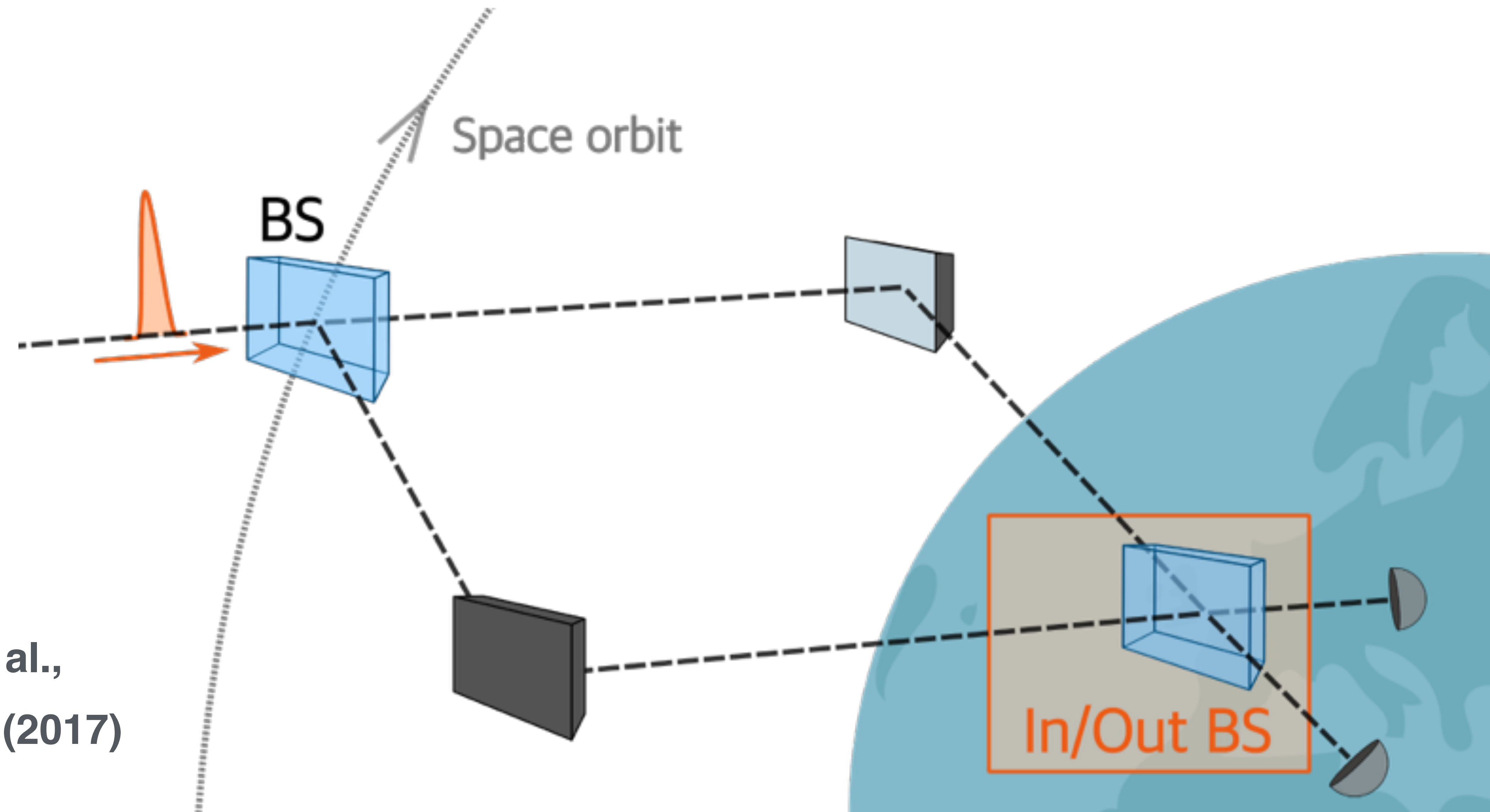
Xiao-song Ma et al.,

Rev. Mod. Phys. 88, 015005 (2016)

Extending Wheeler's delayed-choice to Space

2nd PhD objective achieved

We implemented Wheeler's experiment **along a satellite-ground interferometer** which extends for thousands of kilometers **in space** allowing us to probe the laws of Nature at this unprecedented scale



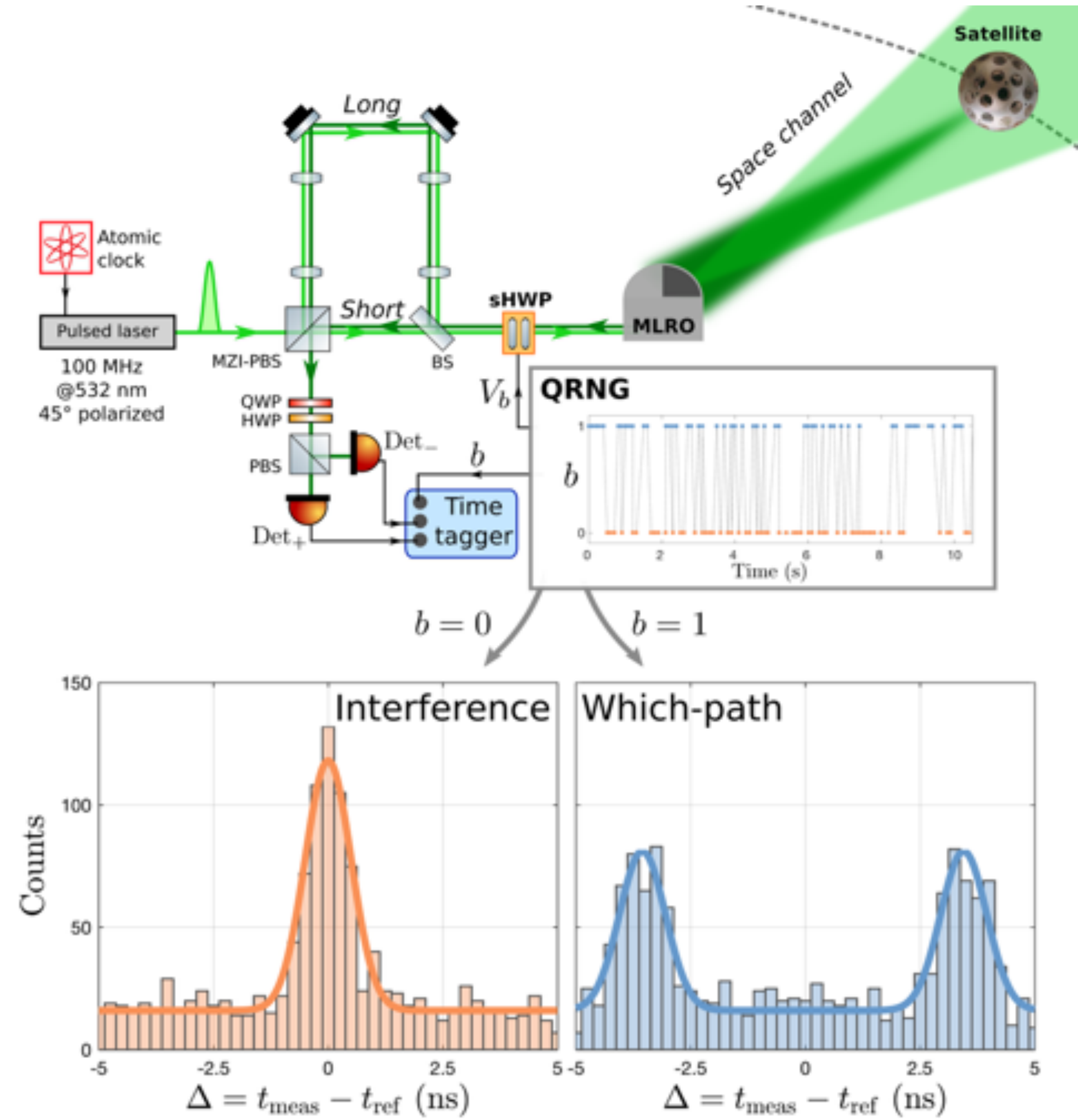
F. Vedovato et al., arXiv:1704.01911 (2017)

Extending Wheeler's delayed-choice to Space

2nd PhD objective achieved

Experimental setup

- A laser pulsed exits an unbalanced interferometer in two **temporal and polarization modes** and it is directed to a target satellite
- After the reflection and the long journey, the photons are collected by the same telescope of the ground station and injected into the optical table
- The returning photons pass through a **switchable half-wave plate** (sHWP) whose behavior is set according to the bit ***b*** extracted from a Quantum Random Number Generator (**QRNG**)
- At the interferometer output a **polarization measurement** is performed and **the two different characters can be observed**



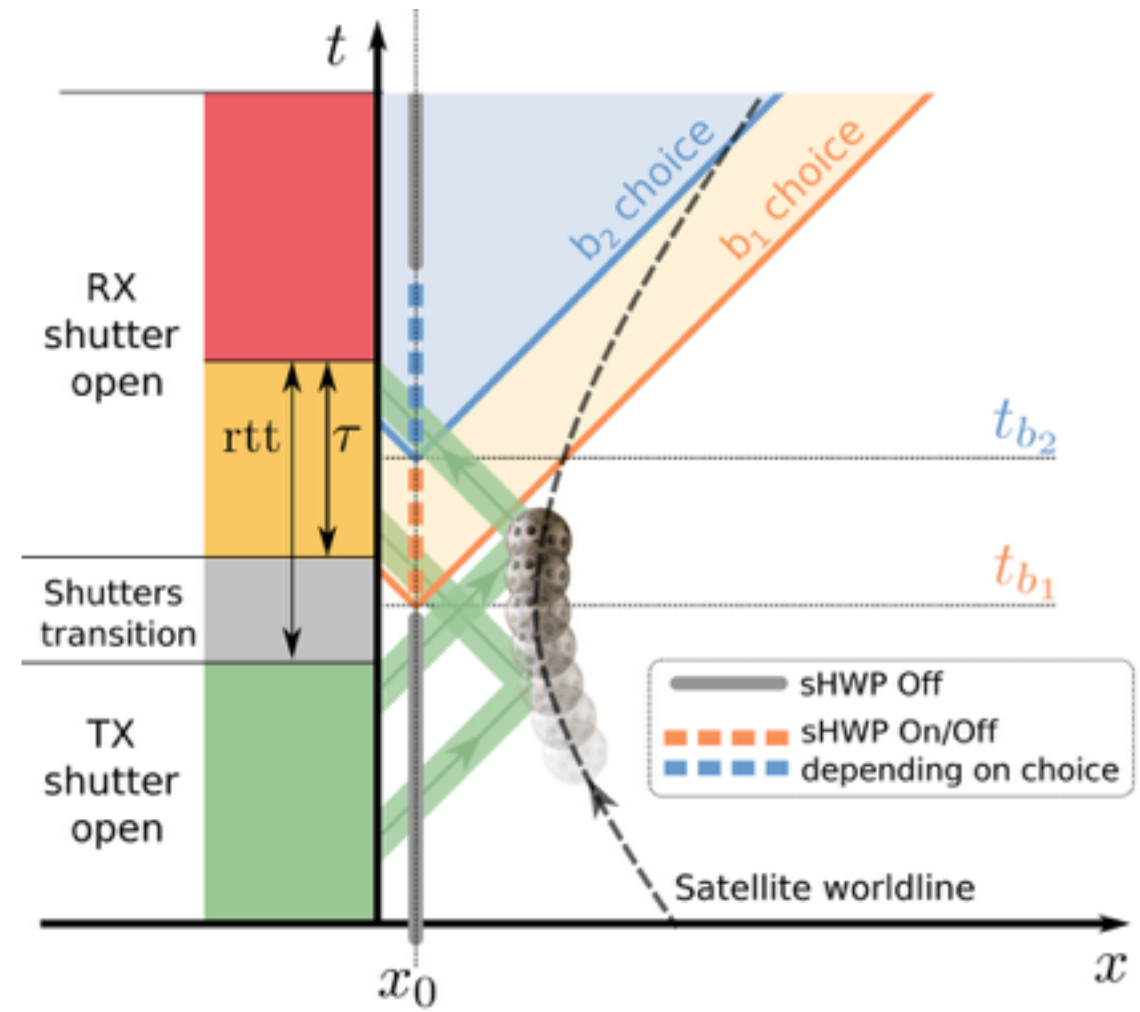
Extending Wheeler's delayed-choice to Space

2nd PhD objective achieved

Implementation of the delayed-choice

As required for a faithful realization of Wheeler's experiment, **each extraction of the bit *b* must be causally disconnected from the photon entry in the interferometer. We decided to delay the choice until the reflection at the satellite**

- Along the temporal axis (not to scale) a 100 ms cycle between two laser ranging pulses is represented
- The x-axis represents the radial coordinate (not to scale) from the detectors. x_0 is the position of both the switchable HWP and the QRNG
- The dotted line is the satellite worldline
- We perform **two independent choices for each cycle** via the random bits extracted by the QRNG



Extending Wheeler's delayed-choice to Space

2nd PhD objective achieved

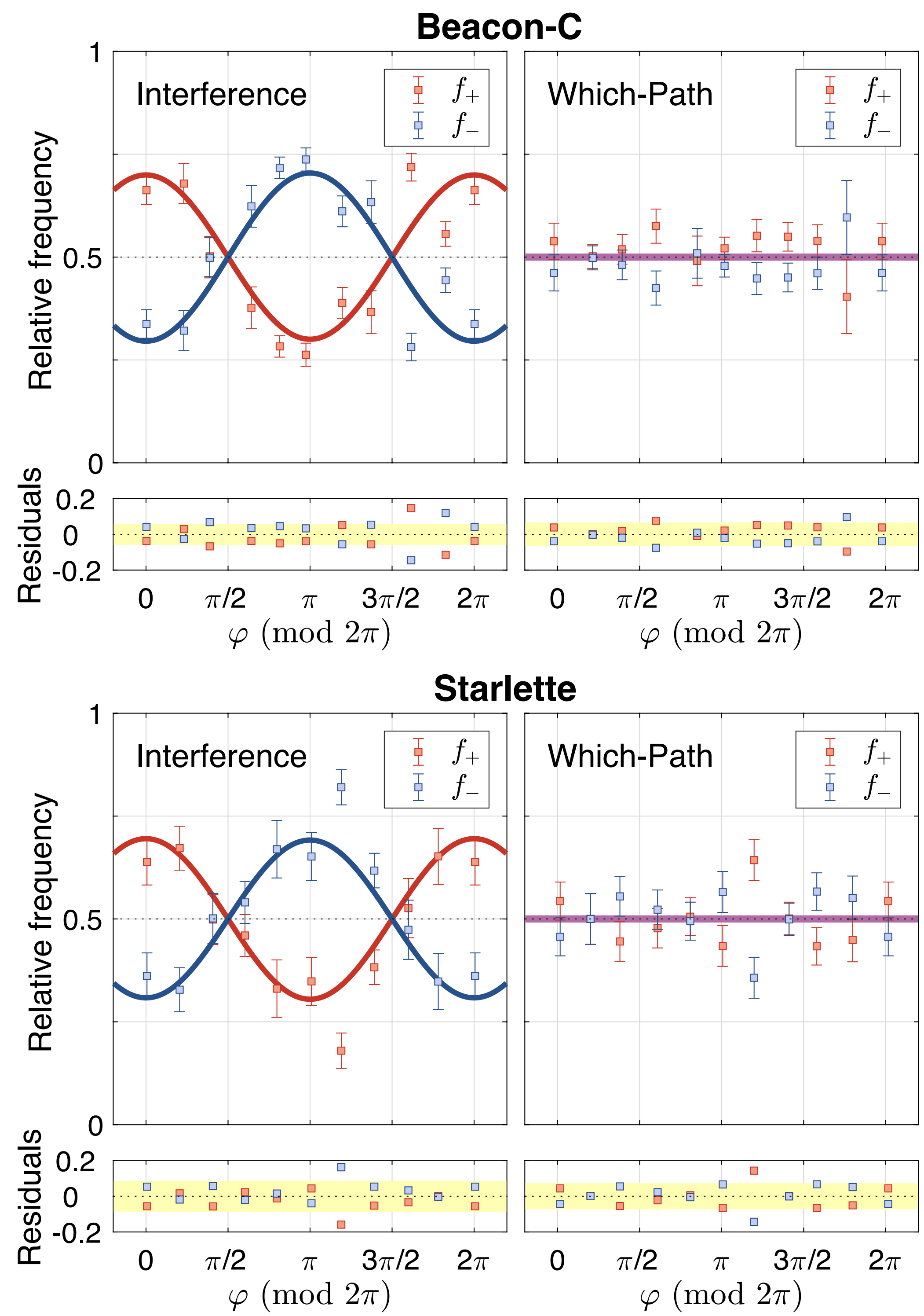
Results

- We divided the collected photons accordingly to the two interferometer configurations **Interference/Which-Path**
- We represented the relative count frequencies at the two detectors as a function of the kinematic phase introduced by satellite motion. They are in good agreement with the **theoretical model** which gives the detection probabilities for the two configurations:

b = 0 ––> P(t) = 1/2 [1 ± V(t) cos φ(t)]

b = 1 ––> P(t) = 1/2

In this way **we observed single-photon interference** and **recovered which-path information** with clear statistical evidence




Thank you!
Questions?