(SINGLE) PHOTONS IN SPACE

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INFN - SEZ. PADOVA

WORKSHOP SULLA GRAVITAZIONE SPERIMENTALE: MISURE LASER, FISICA FONDAMENTALE E APPLICAZIONI IN INFN-CSN2 NOV 13TH, 2020

INFN Istituto Nazionale di Fisica Nucleare

1222·2022 800 ANNI

UNIVERSITÀ DEGLI STUDI DI PADOVA

ASI Agenzia Spaziale Italiana

Progetto INFN MoonLIGHT-2, Sez. Padova
Resp. Nazionale Luca Porcelli, Simone Dell'Agnello

I-QKD

CUP: F92F20000000005

QCommSpaceOne

CUP: F92F17000020005

QSecGroundSpace

CUP: E16J16001490001

QRNG

CUP: F52CI7000130005

ASI

Agenzia Spaziale Italiana

QCALL

EU-ITN GA675662

OPEN-QKD

EU-H2020 GA857156

OPEN QKD

European Commission

HORIZON 2020

Quasar

Progetto sostenuto dalla

Fondazione Cassa di Risparmio di Padova e Rovigo

Nell'ambito del Bando

RICERCA SCIENTIFICA DI ECCELLENZA

QUANTERA

ERA-NET Cofund in Quantum Technologies

SECRET

SECuRe quantum communication based on Energy-Time/time-bin entanglement

INFN

Istituto Nazionale di Fisica Nucleare

PROSEQO

H2020-OPL

esa

Authors

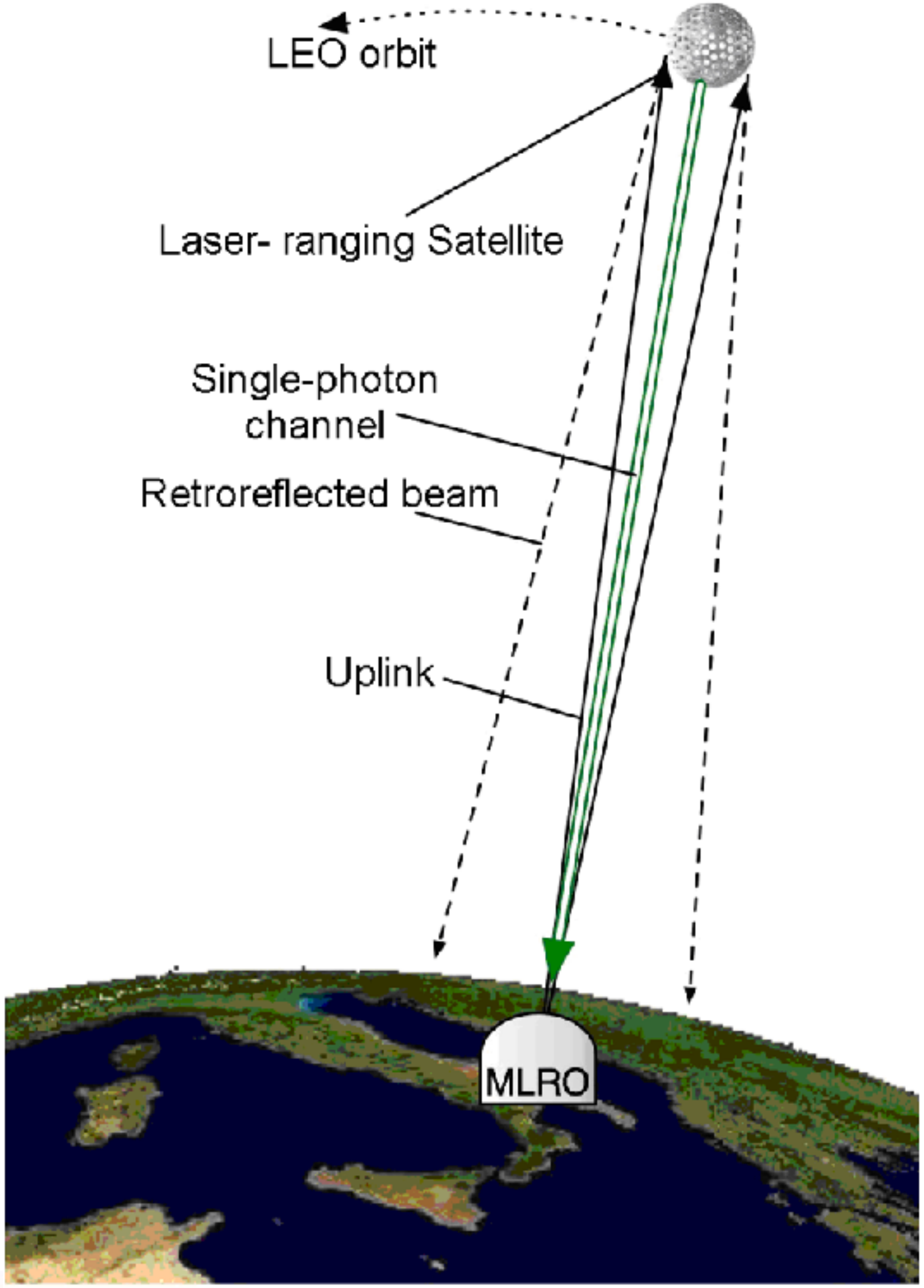
Agnesi Costantino, Avesani Marco, Calderaro Luca, Berra Federico, Foletto Giulio, Picciariello Francesco, Santagiustina Francesco, Scalcon Davide, Scriminich Alessia, Stanco Andrea, Vedovato Francesco, Zahidy Mujtaba, Vallone Giuseppe e Villoresi Paolo

and the ASI MLRO team.. since 2003

Giuseppe Bianco, Vincenza Luceri, Daniele Dequal and the MLRO staff

two main paths

1. **improving single photon detection along space channels**
    - A. tracking
    - B. link modeling
    - C. state measurement (3 filtering spatial spectral temporal), noise rejection
    - D. daylight free-space QComms - spectral diversity
2. **Quantum Optics experiments in Space**
    - E. polarization coding
    - F. temporal modes, time-bin, interference, Doppler
    - G. combination of degrees of freedom,
    - H. Wheeler’s delayed choice experiment in waveparticle duality
    - I. preparation to single mode receiver



New Journal of Physics
The open-access journal for physics

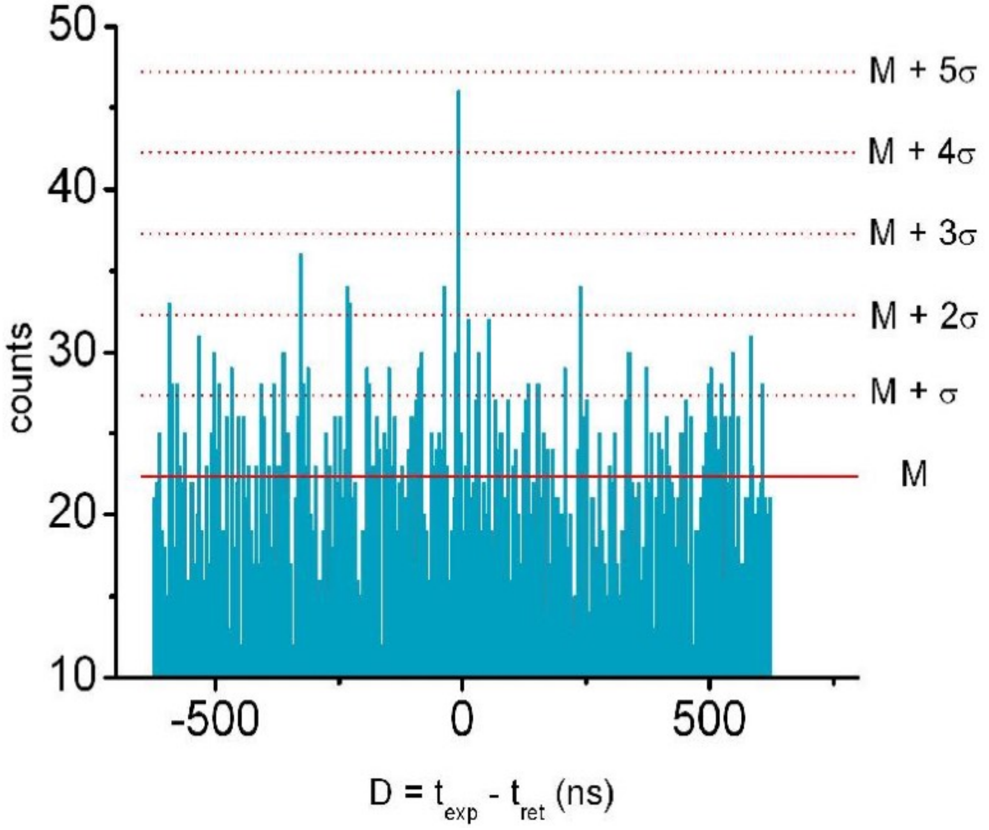
Experimental verification of the feasibility of a quantum channel between space and Earth

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

Return peak of 5 cps was observed at
D=0 above the background.

Total losses are of -157 dB.

In the downlink channel, $\mu = 0.4$,
for single-photon regime



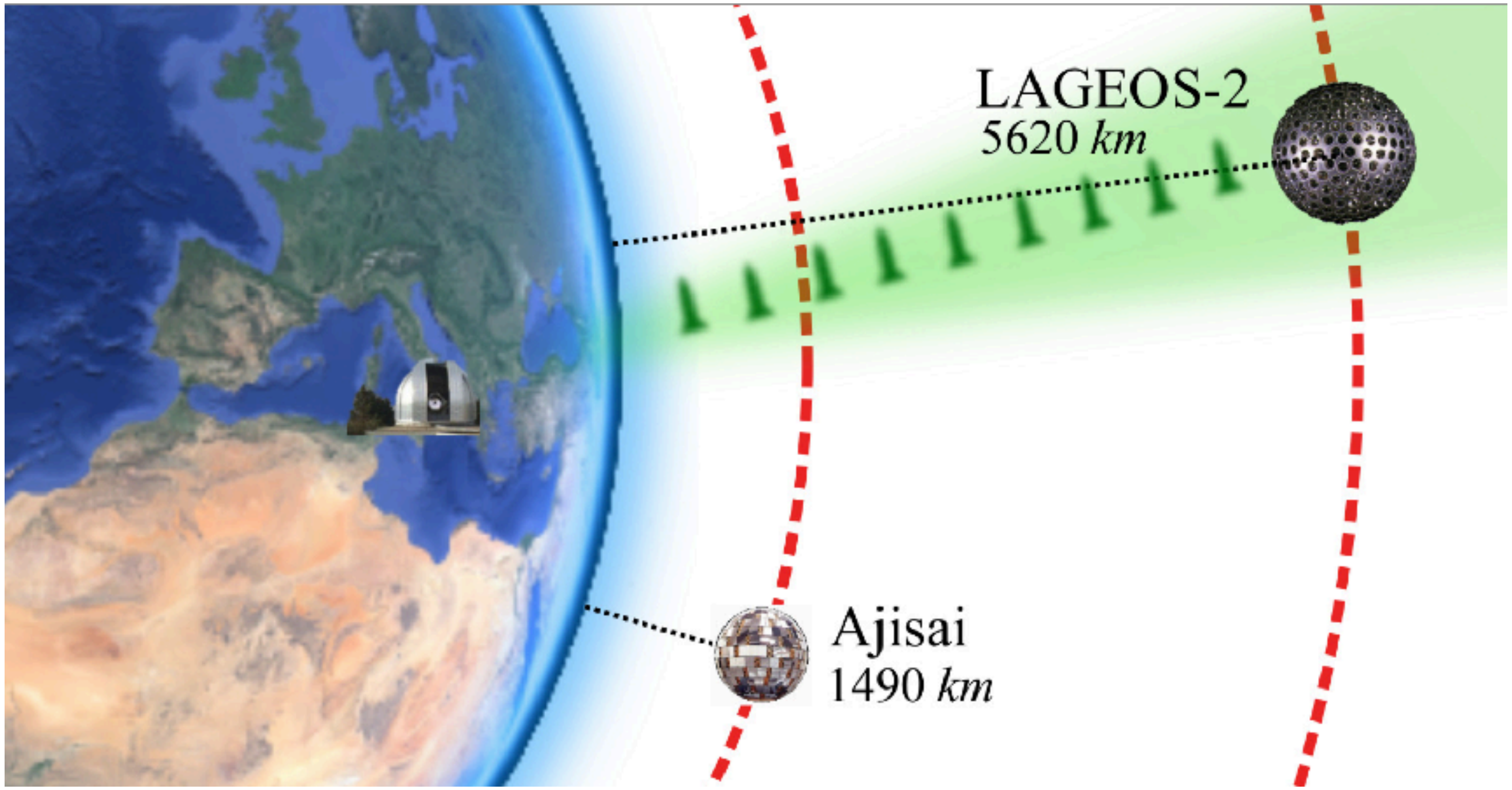
RAPID COMMUNI

PHYSICAL REVIEW A **93**, 010301(R) (2016)

Experimental single-photon exchange along a space link of 7000 km

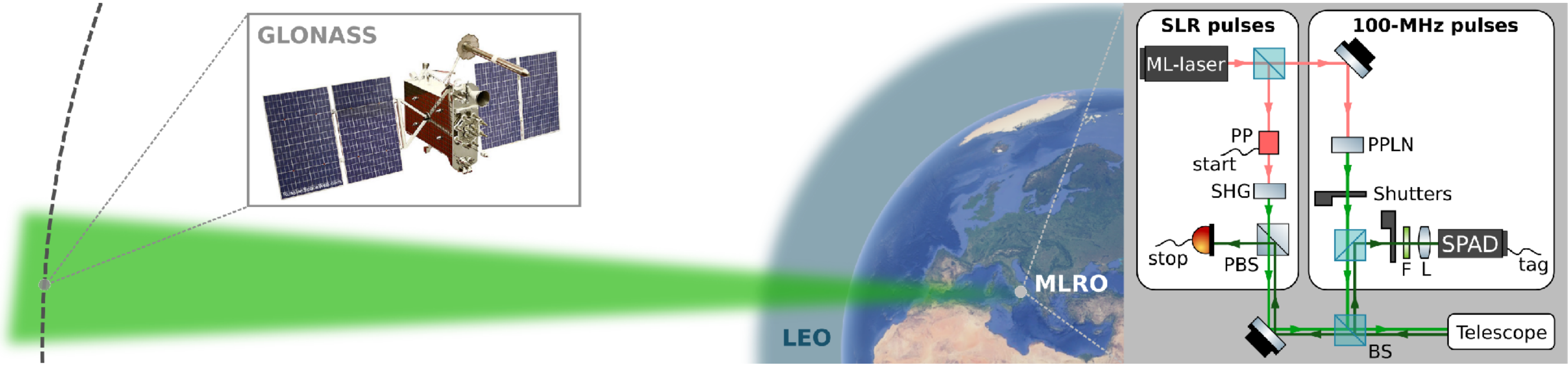
Daniele Dequal,[1] Giuseppe Vallone,[1,2] Davide Bacco,[1] Simone Gaiarin,[1] Vincenza Luceri,[3]
Giuseppe Bianco,[4] and Paolo Villoresi[1,2,*]

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.



Single photon exchange exploiting GLONASS CCRs at 20000 km

Satellite passage	Slant distance (km)	Detector	$\overline{R}_{\mathrm{det}}$ (Hz)	SNR	$\overline{\mu}_{\mathrm{sat}}$	l_{down} (dB)	l_{rec} (dB)
Glonass-134	19,500	SPAD	58	0.53	15	62.1	11.8
	20,200	SPAD	59	0.41	16	62.5	11.8
Glonass-131	20,250	SPAD	27	0.43	15	62.6	14.8
		PMT	6	0.21	16	62.6	21.8



L. Calderaro et al. *Towards Quantum Communication from Global Navigation Satellite System*, **Quantum Sci. Technol. 4 015012** (2019).

Qcomms on Galileo: connected graph with 4 independent paths

Design optimization for quantum communications in a GNSS intersatellite network

Francesca Gerlin, Nicola Laurenti
Giuseppe Vallone, Paolo Villoresi
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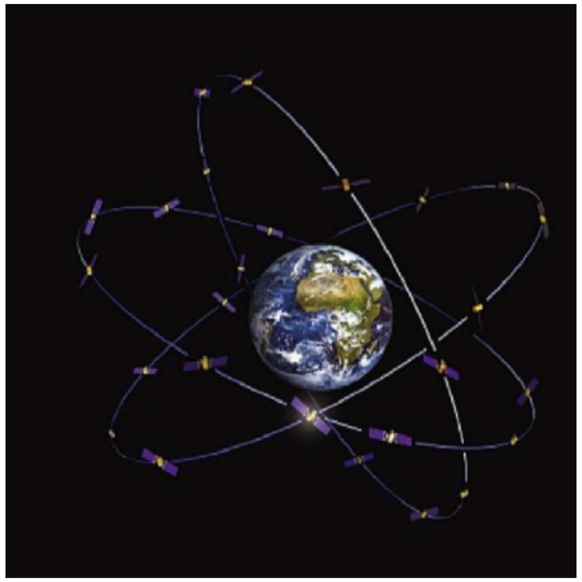
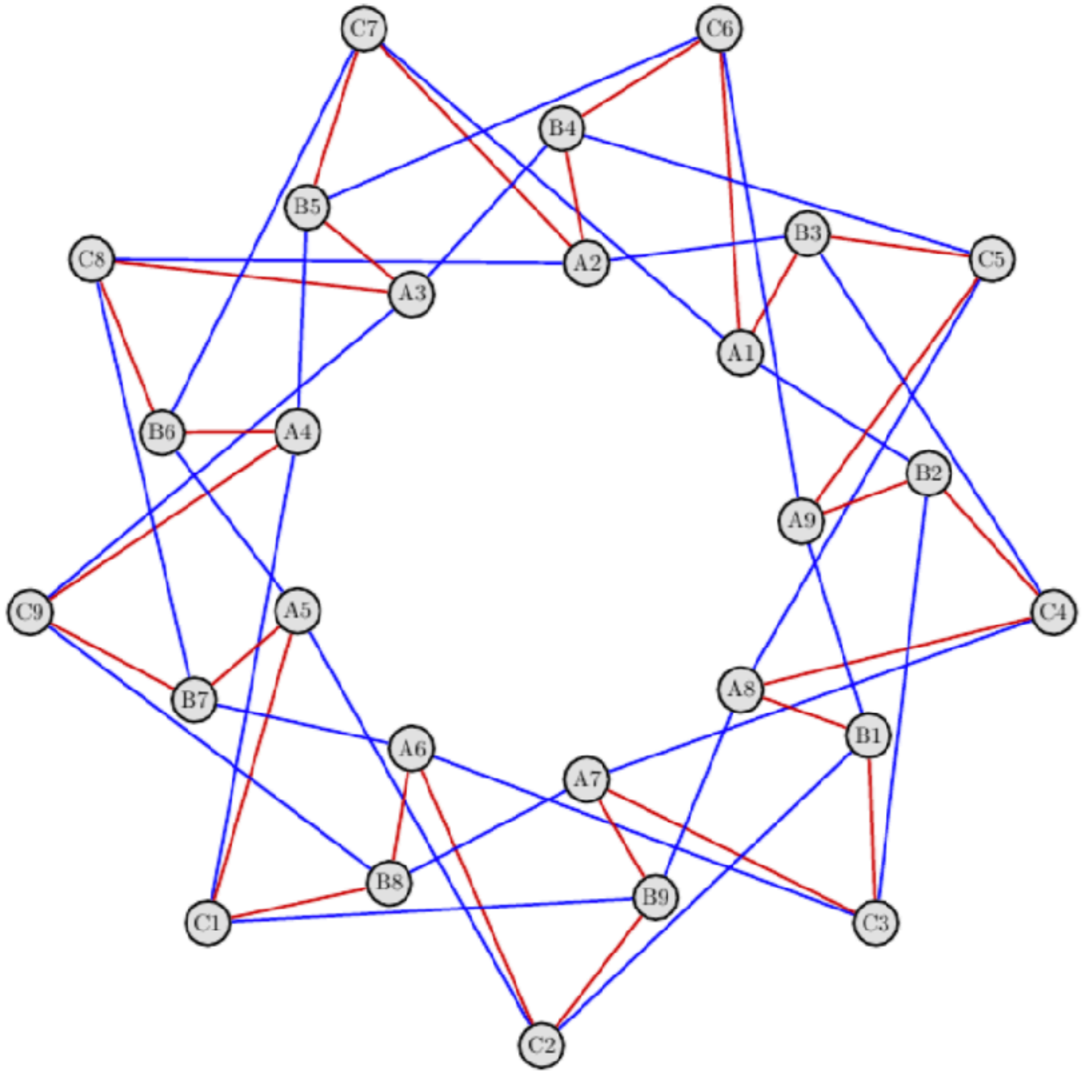


The multihop strategy covering the whole network by means of binary exchanges demonstrates to be effective by exploiting **links size about a tenths of the constellation diameter.**



F. Gerlin et al., ***Design optimization for quantum communications in a GNSS intersatellite network***, *Int. Conf. on Localization and GNSS (ICL-GNSS) Torino (2013)*

New Journal of Physics
The open-access journal for physics

Feasibility of satellite quantum key distribution

C Bonato[1], **A Tomaello, V Da Deppo, G Naletto and P Villoresi**
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LUXOR Laboratory for Ultraviolet and X-Ray Optical Research,
via Gradenigo 6, 35131 Padova, Italy
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Received 28 November 2008
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doi:10.1088/1367-2630/11/4/045017

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nature COMMUNICATIONS

ARTICLE
Received 28 Nov 2012 | Accepted 26 Jul 2013 | Published 6 Sep 2013
DOI: 10.1038/ncomms3363

Experimental quantum key distribution with finite-key security analysis for noisy channels

Davide Bacco[1], Matteo Canale[1], Nicola Laurenti[1], Giuseppe Vallone[1] & Paolo Villoresi[1]

PHYSICAL REVIEW A **88**, 023848 (2013)

Asymmetric architecture for heralded single-photon sources

Luca Mazzarella,[1,*] Francesco Ticozzi,[1,2] Alexander V. Sergienko,[3] Giuseppe Vallone,[1] and Paolo Villoresi

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09, 200502 (2012) PHYSICAL REVIEW LETTERS 16 N

Impact of Turbulence in Long Range Quantum and Classical Communications

Ivan Capraro,[1] Andrea Tomaello,[1] Alberto Dall'Arche,[1] Francesca Gerlin,[1] Ruper Ursin,[2]
Giuseppe Vallone,[1] and Paolo Villoresi[1,*]

PHYSICAL REVIEW A **91**, 042320 (2015)

real time selection for quantum key distribution in lossy and turbulent free-space channels

ieppe Vallone,[1] Davide G. Marangon,[1] Matteo Canale,[1] Ilaria Savorgnan,[1] Davide Bacco,[1] Mauro Barbieri,[2]
Simon Calimani,[1] Cesare Barbieri,[2] Nicola Laurenti,[1] and Paolo Villoresi[1,*]

PHYSICAL REVIEW A **93**, 012331 (2016)

Ieralded single-photon sources for quantum-key-distribution applications

Matteo Schiavon,[*] Giuseppe Vallone, Francesco Ticozzi, and Paolo Villoresi

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Optimization of two-photon wave function in parametric down conversion by adaptive optics control of the pump radiation

M. Minozzi,[1] S. Bonora,[2] A. V. Sergienko,[3] G. Vallone,[1,2] and P. Villoresi[1,2,*]

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ScienceDirect
Advances in Space Research 47 (2011) 802–810
ADVANCES
SPACE
RESEARC
(a COSPAR pub
www.elsevier.com/l

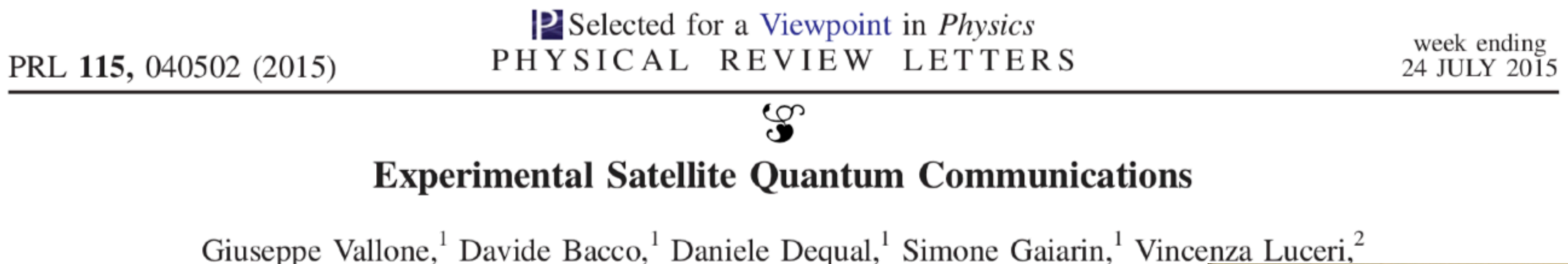
Link budget and background noise for satellite quantum key distribution

Andrea Tomaello[a,b,*], Cristian Bonato[a,b,c], Vania Da Deppo[a,b], Giampiero Naletto
Paolo Villoresi[a,b]

PRL **113,** 060503 (2014) PHYSICAL REVIEW LETTERS week en
8 AUGUS

Free-Space Quantum Key Distribution by Rotation-Invariant Twisted Photons

Giuseppe Vallone,[1] Vincenzo D'Ambrosio,[2] Anna Sponselli,[3] Sergei Slussarenko,[4,*] Lorenzo Marrucci,[4]
Fabio Sciarrino,[2] and Paolo Villoresi[1,†]



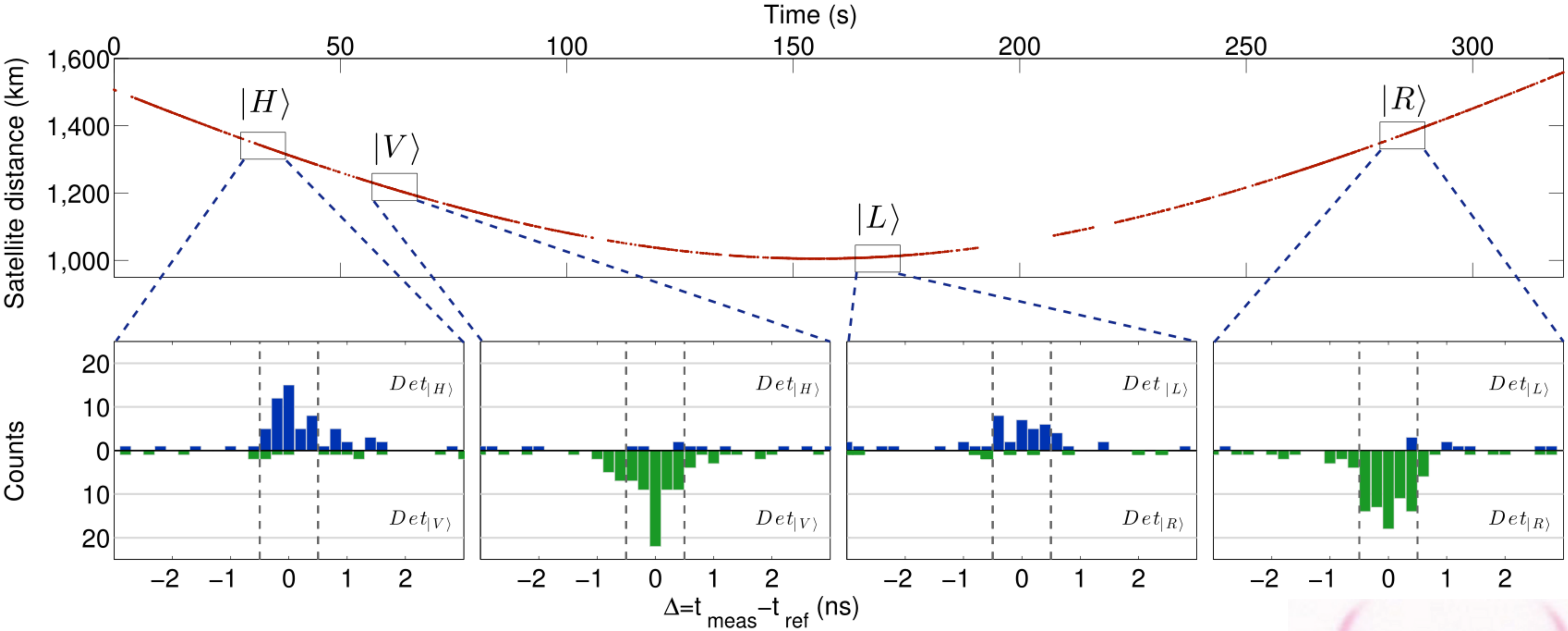
Selected for a Viewpoint in *Physics*

PRL **115,** 040502 (2015) PHYSICAL REVIEW LETTERS week ending 24 JULY 2015

Experimental Satellite Quantum Communications

Giuseppe Vallone,[1] Davide Bacco,[1] Daniele Dequal,[1] Simone Gaiarin,[1] Vincenza Luceri,[2]
Giuseppe Bianco,[3] and Paolo Villoresi[1,*]

LARETS orbit height 690 km - 24 cm in diameter
60 CCR with metallic coating
Apr 10th, 2014, start 4:40 am CEST



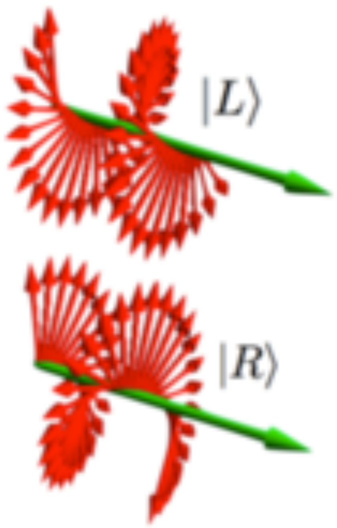
- **10 s windows**
- **Timebin width ≤ 1 ns**

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

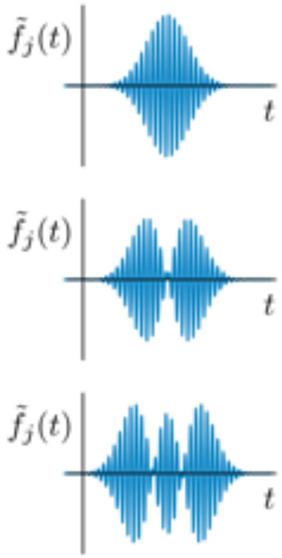
up to 10^4 bits for each satellite passage

Degrees of freedom (DOF) for light in QComms

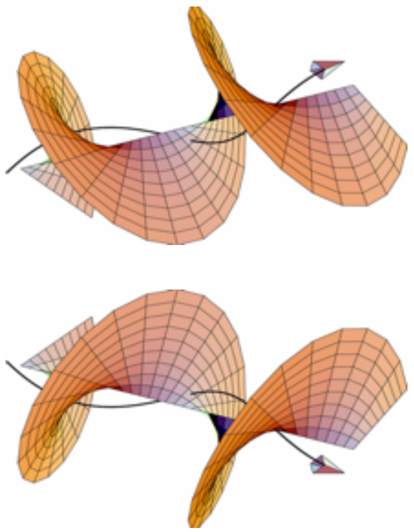
- Polarization modes

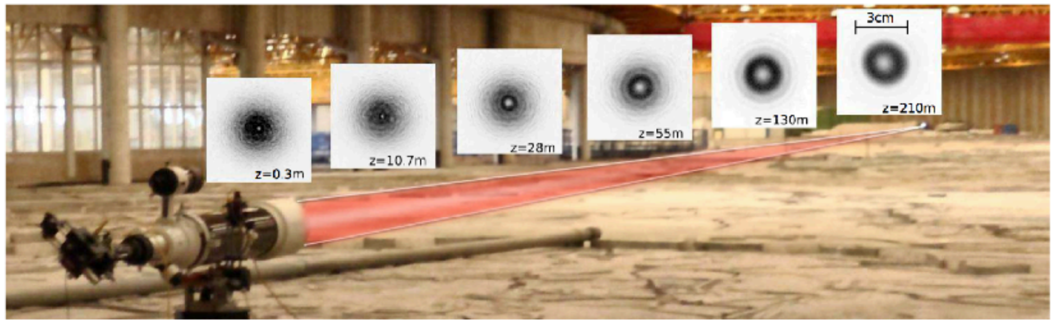


- Temporal modes



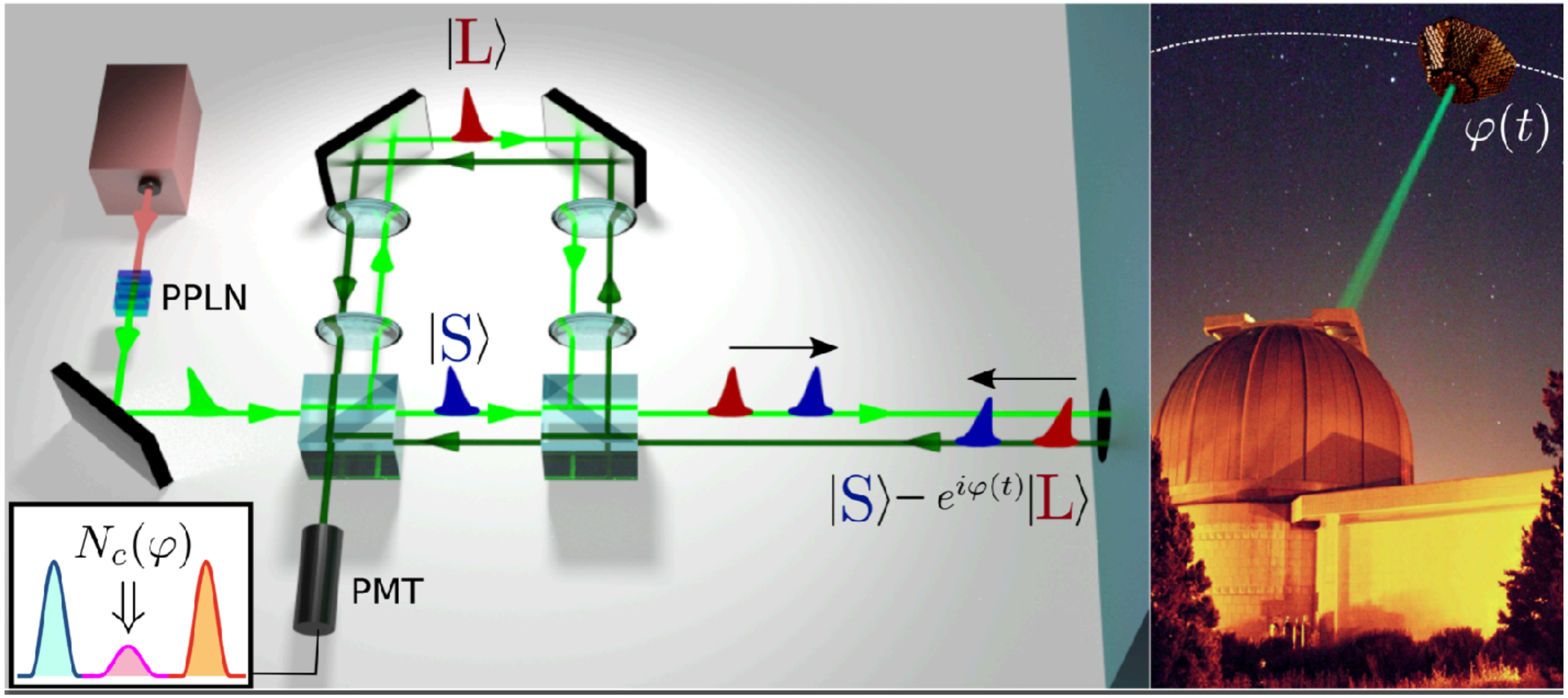
- *For km-scale links: angular momentum modes*

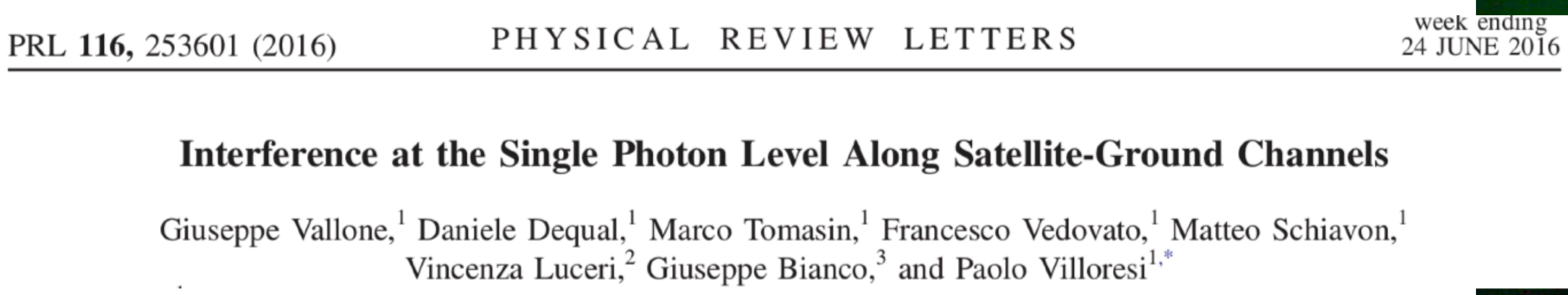




QComms exploiting temporal modes of light

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

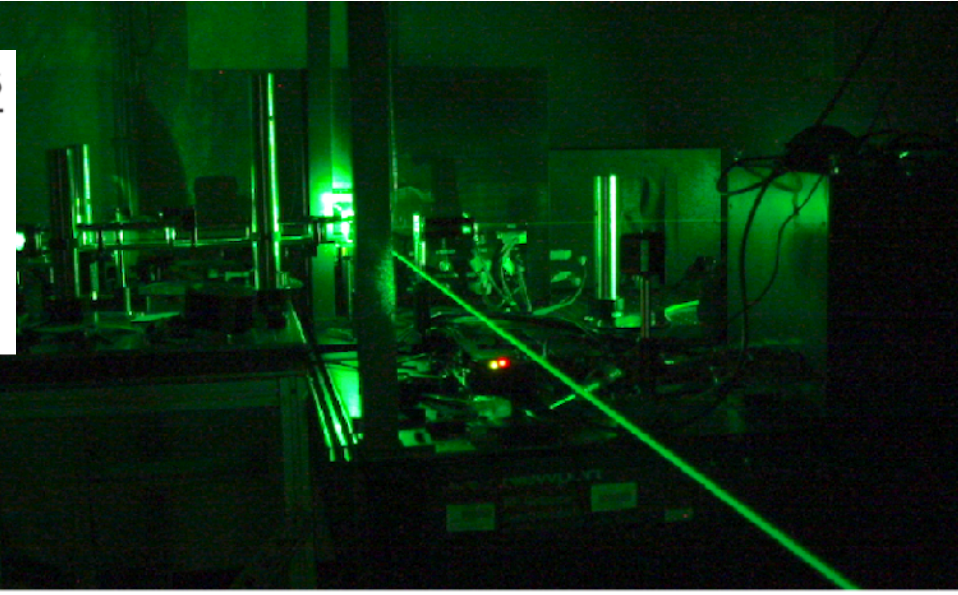


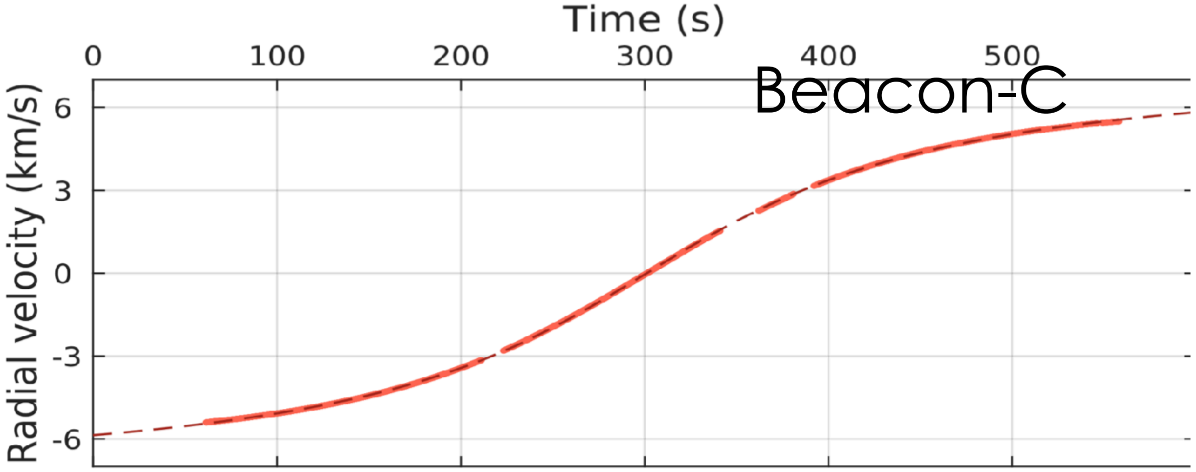


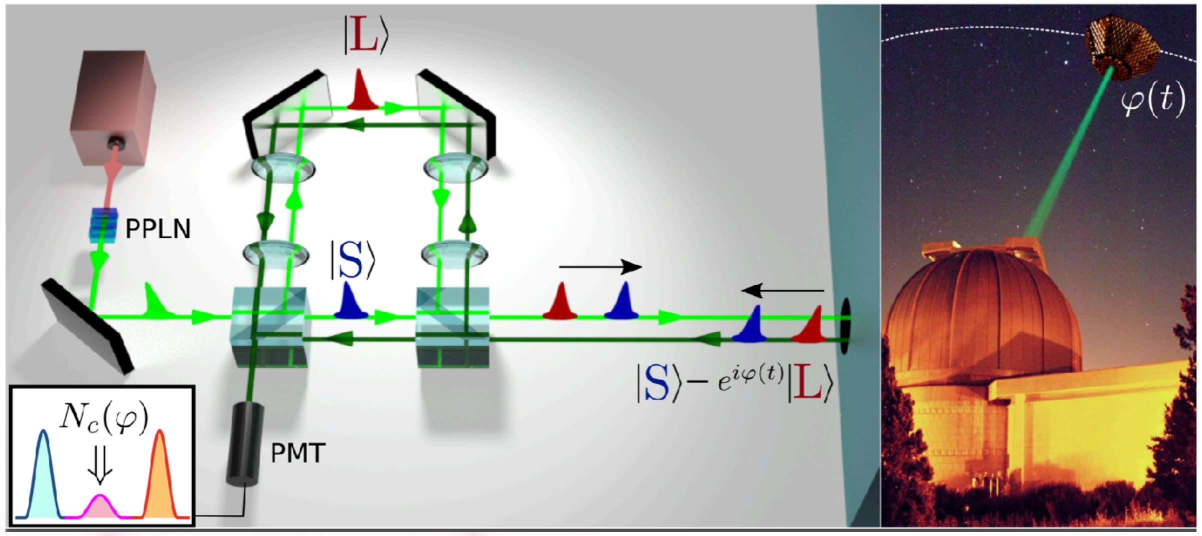
PRL 116, 253601 (2016) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2016

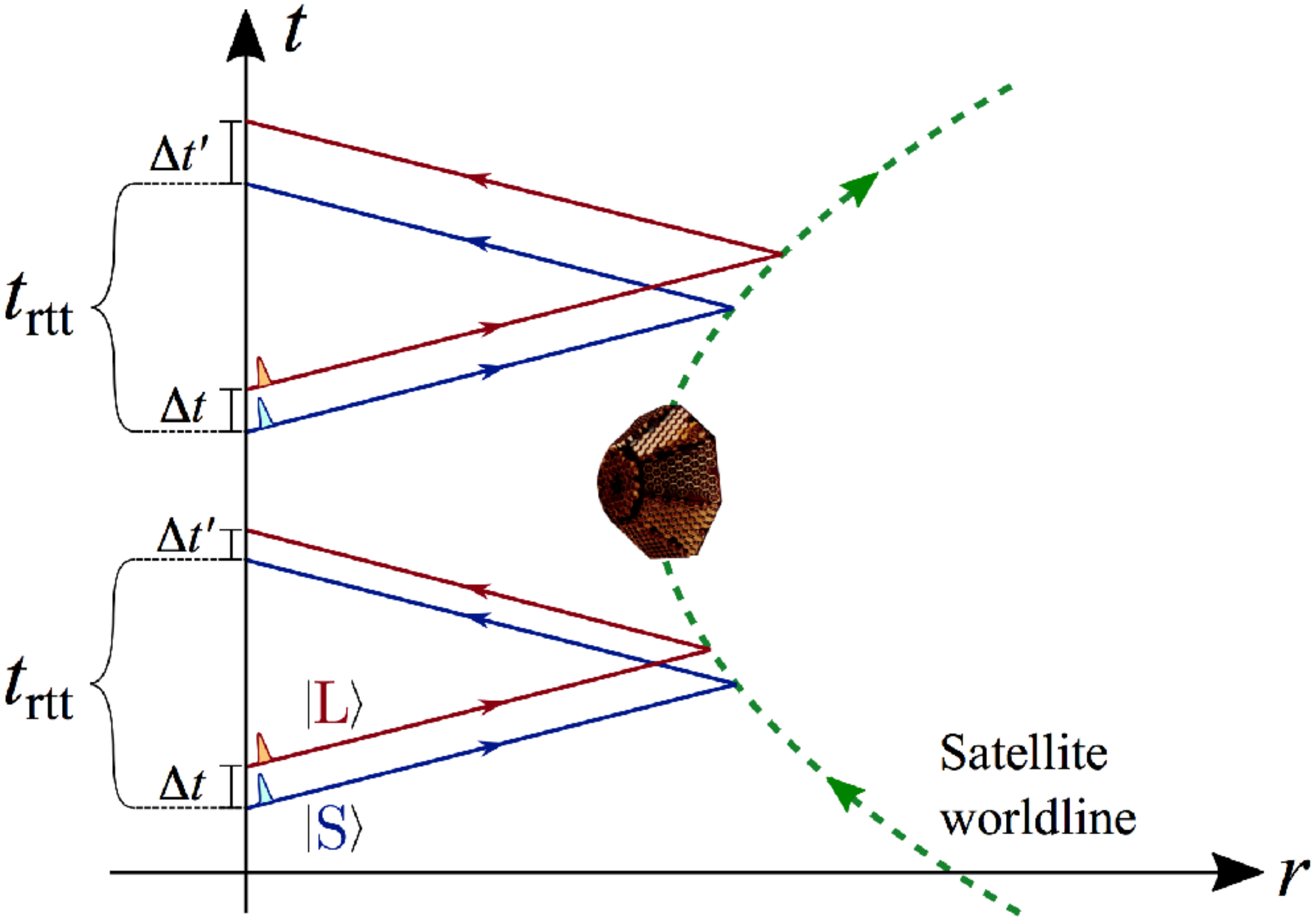
Interference at the Single Photon Level Along Satellite-Ground Channels

Giuseppe Vallone,[1] Daniele Dequal,[1] Marco Tomasin,[1] Francesco Vedovato,[1] Matteo Schiavon,[1]
Vincenza Luceri,[2] Giuseppe Bianco,[3] and Paolo Villoresi[1,*]









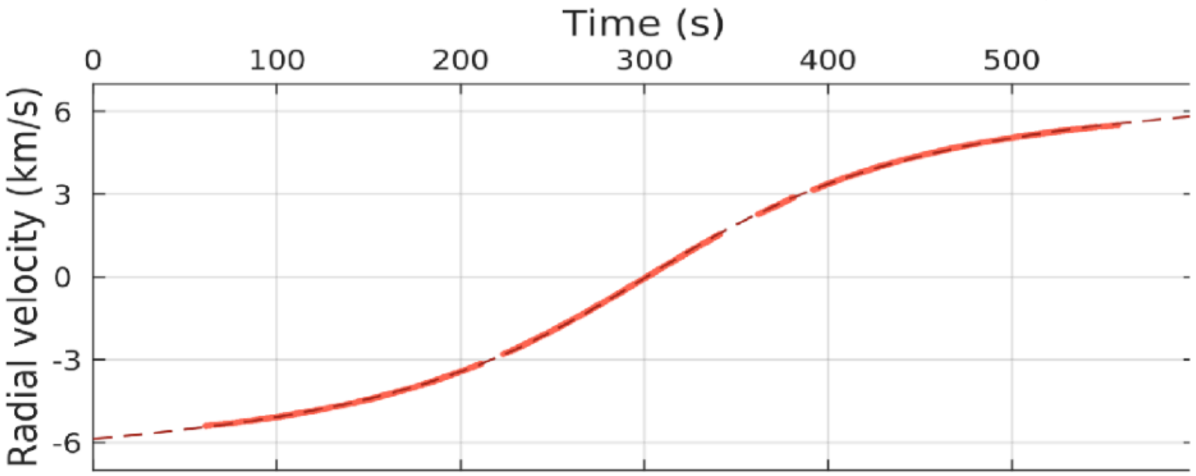
Relativistic effects on the photon interference

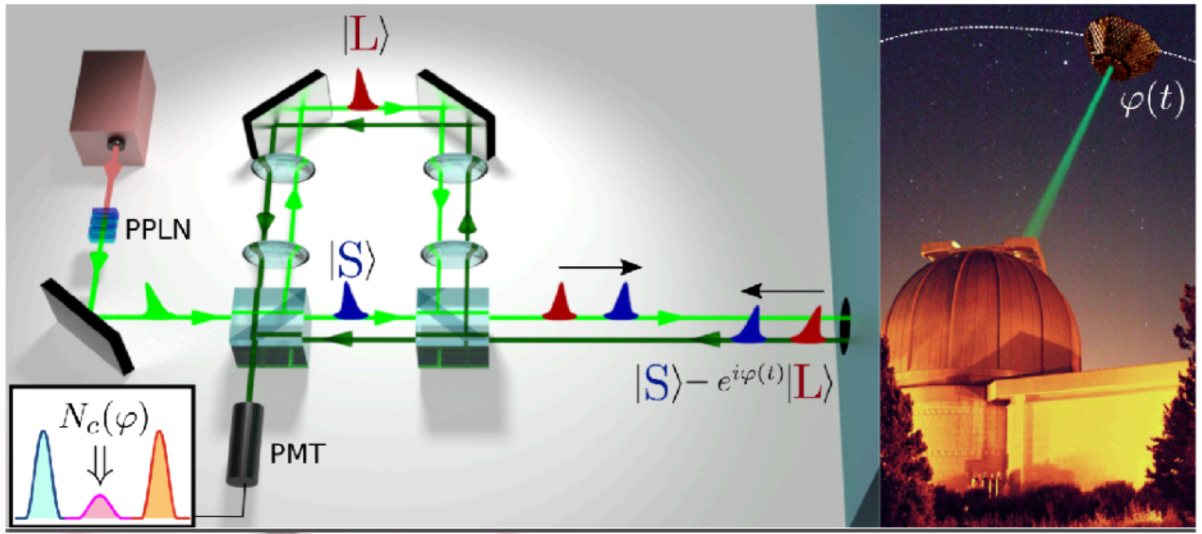
G. Vallone et al., **Interference at the Single Photon Level Along Satellite-Ground Channels**, Phys. Rev. Lett. **116** 253601 (2016)

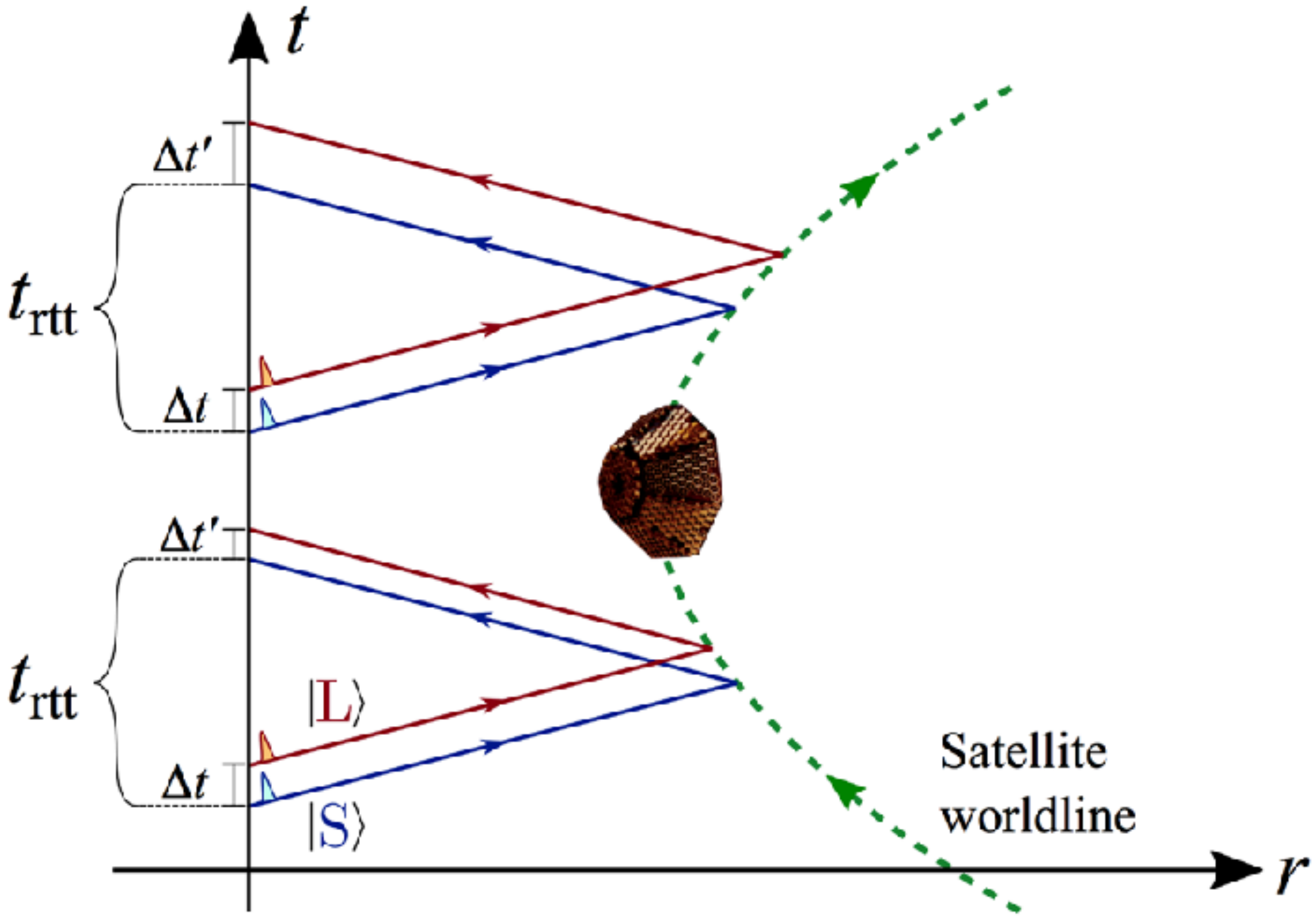
Kinematic Phase modulation

Relativistic effects on the photon interference

Beacon-C







Transformation in the channel

Pulse before the interferometer

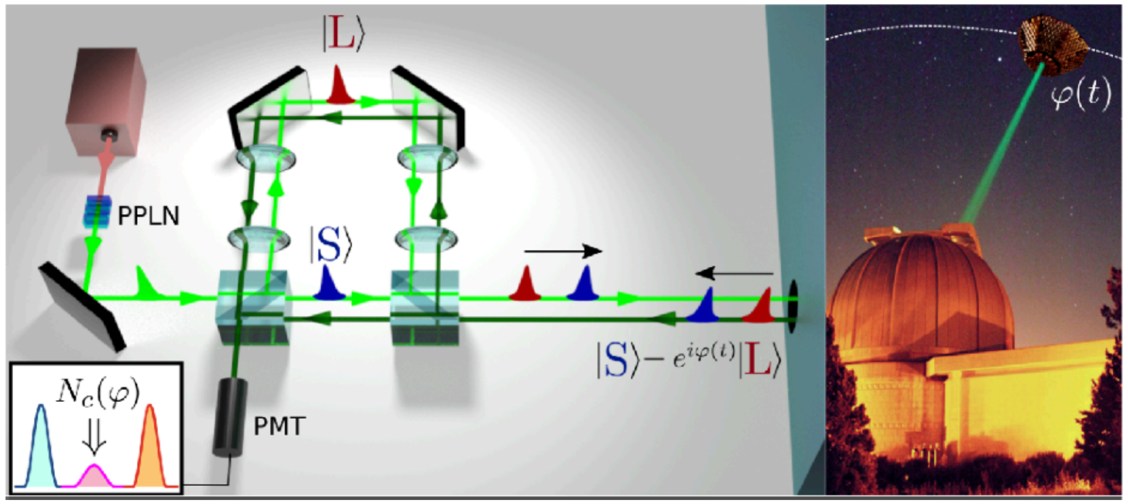
$$\psi_0(\tau_-) = \sqrt[4]{\frac{2}{\tau_c^2}}\, e^{-\pi \frac{\tau_-^2}{\tau_c^2}}\, e^{i\omega_0 \tau_-}$$

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

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

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

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

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

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

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

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**

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

Round trip time at the ground station

$$t_{\mathrm{rtt}} = \frac{2}{1-\beta}\frac{r_{\mathrm{sat}}}{c}$$

Probability of click in the central peak

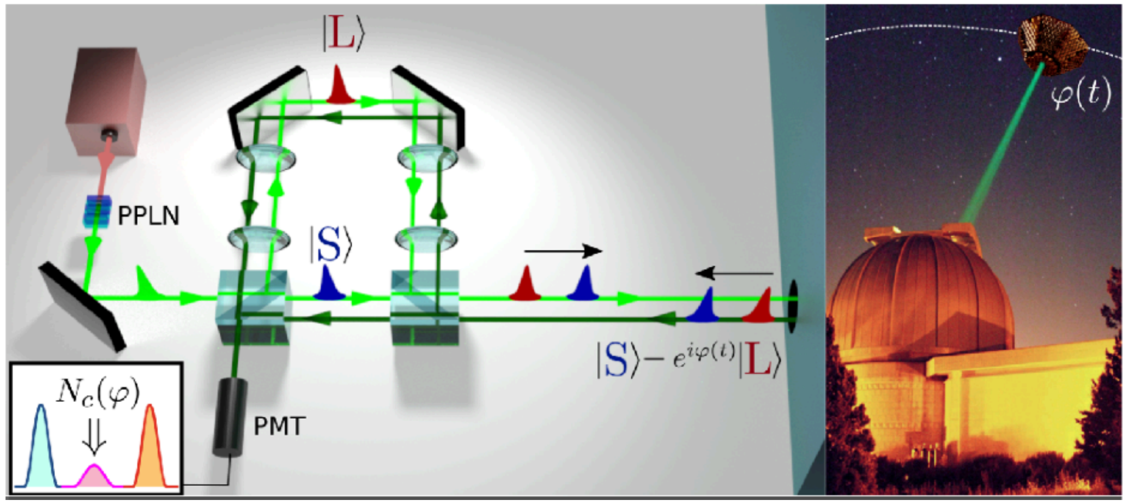
$$P_c(t) = \frac{\gamma^2(1-\beta(t))^2}{4}\int dt'|\psi_0(-f_\beta(t'+\Delta t)) - \psi_0(-\Delta t - f_\beta t')|^2$$

$$= \frac{1}{2}\left\{1 - \sqrt{\frac{2}{\tau_c^2}}\int dt'\Re e\left[e^{-\pi\frac{(t'+f_\beta\Delta t)^2}{\tau_c^2}}\, e^{-\pi\frac{(t'+\Delta t)^2}{\tau_c^2}}\, e^{i\omega_0(1-f_\beta)\Delta t}\right]\right\}$$

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

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

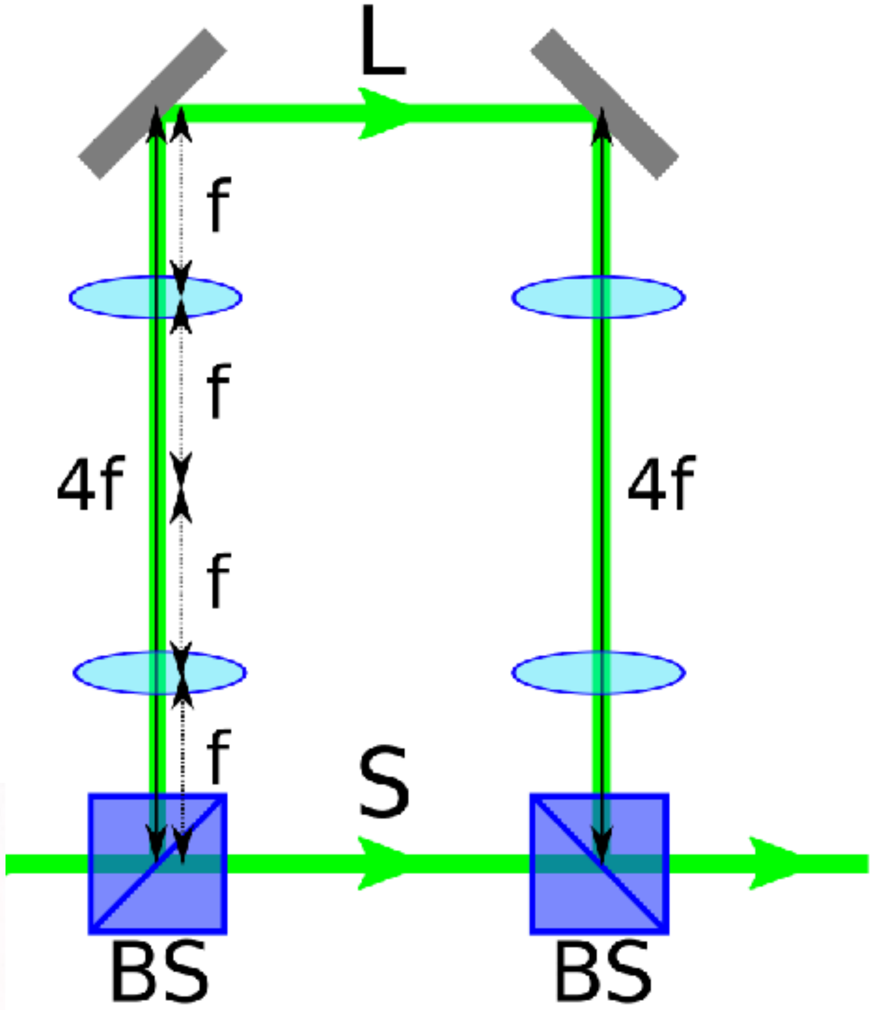
Visibility $$\mathcal{V}(t) = \sqrt{\frac{2}{\tau_c^2}}\int dt'\, e^{-\pi\frac{(t'+f_\beta\Delta t))^2}{\tau_c^2}}\, e^{-\pi\frac{(t'+\Delta t)^2}{\tau_c^2}} = \exp\{-2\pi\left[\frac{\Delta t}{\tau_c}\frac{\beta(t)}{1+\beta(t)}\right]^2\}$$

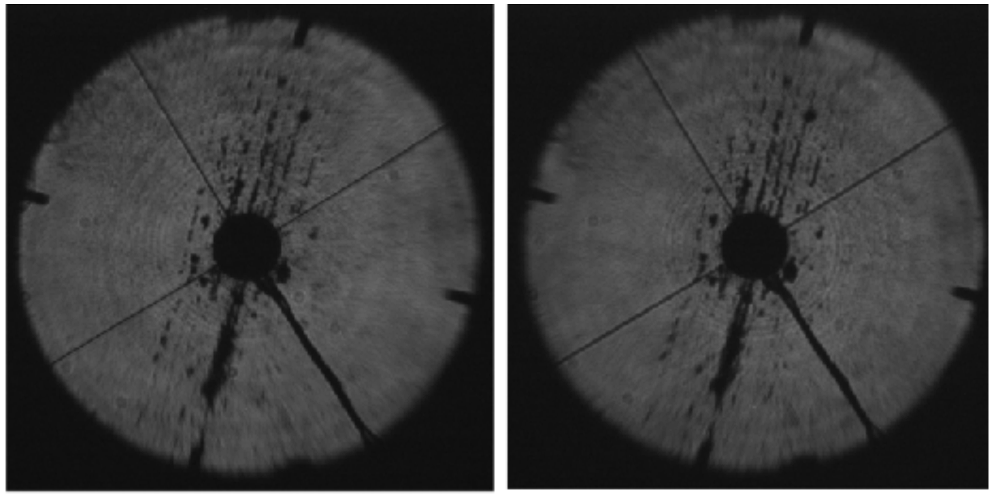


For LEO satellites
it may be
approximate as 1

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 $\beta(t) = v_r(t)/c$.

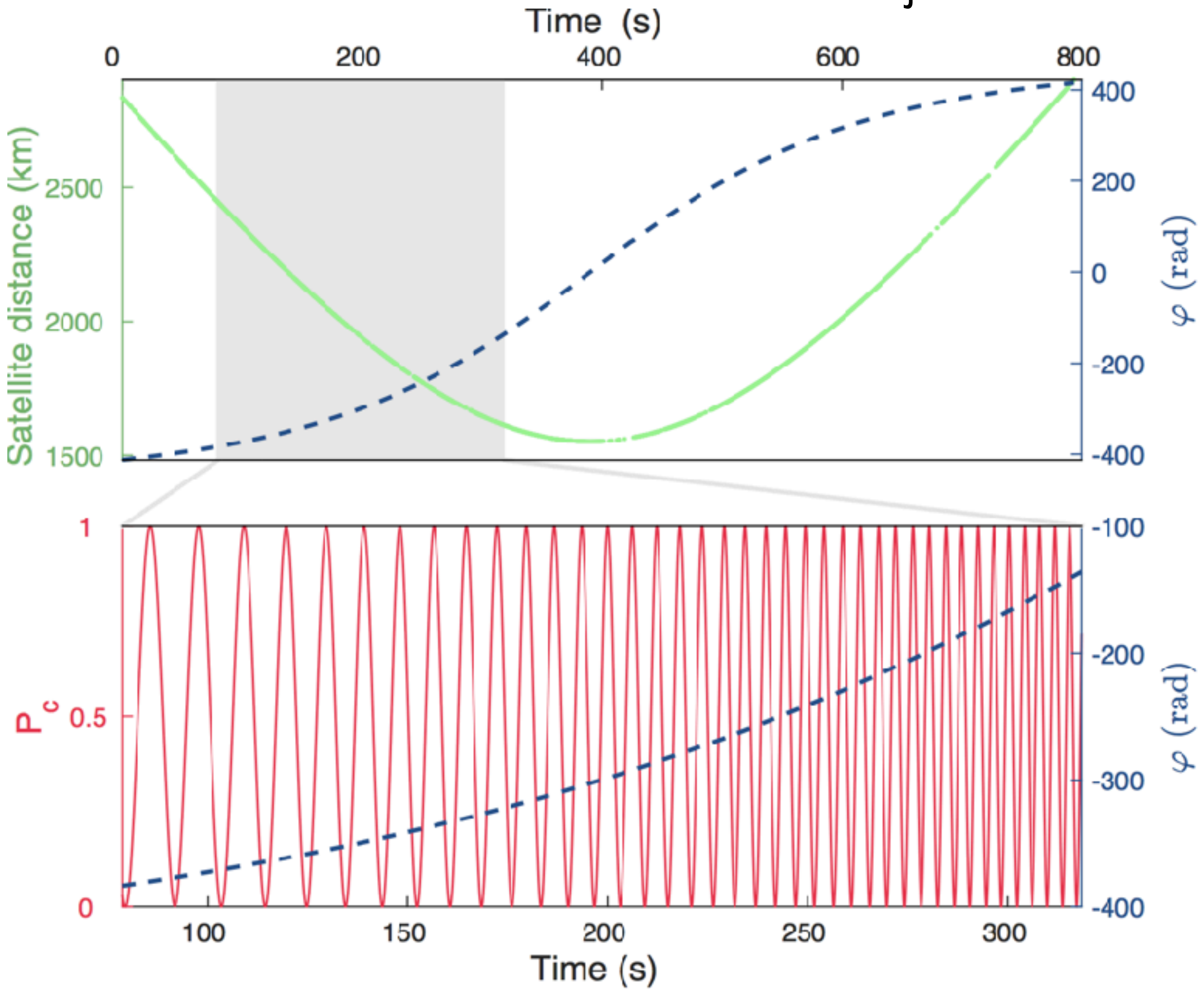
P_c *probability of detecting the photon in the central peak*

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

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

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

Ajisai



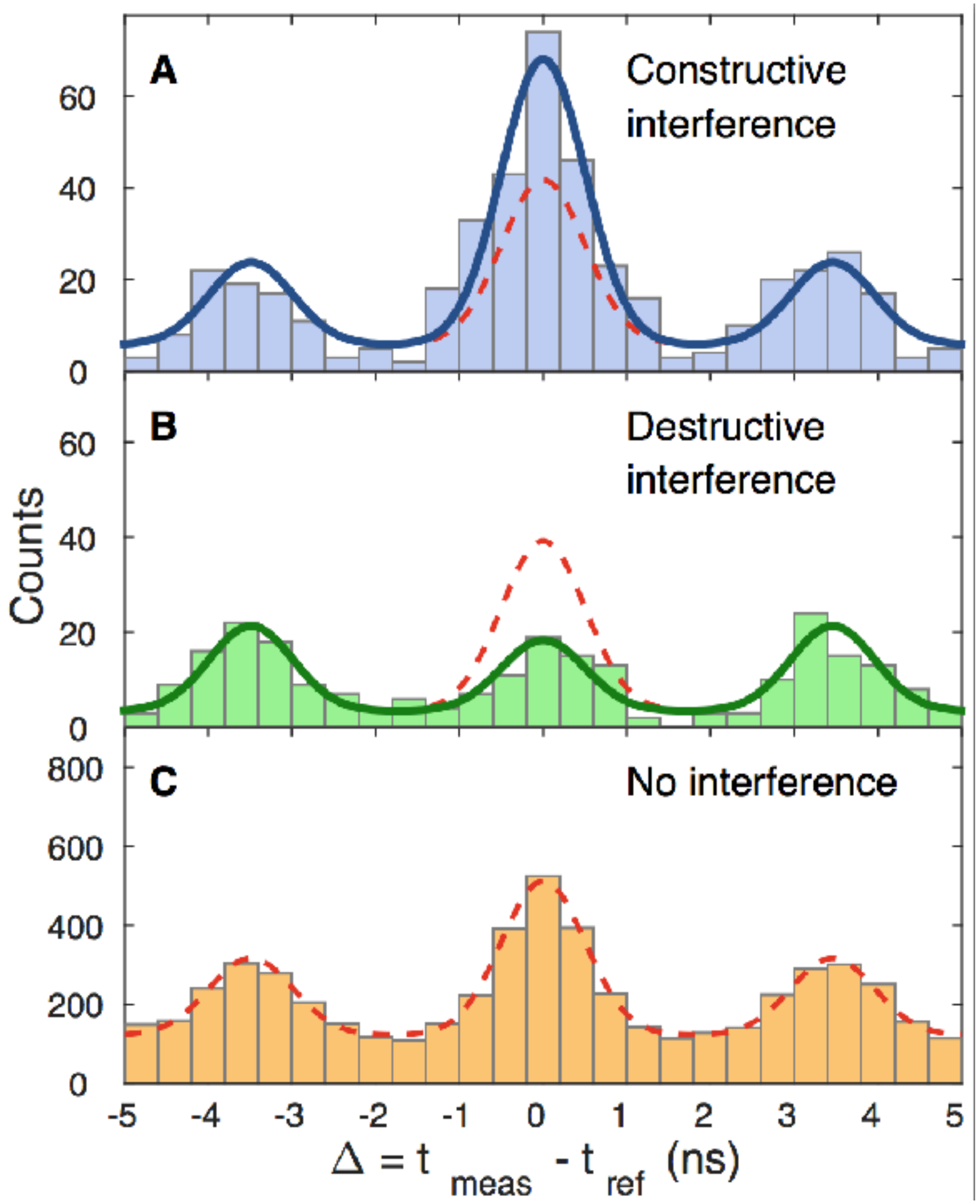
Evidence of the interference

Beacon C

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

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

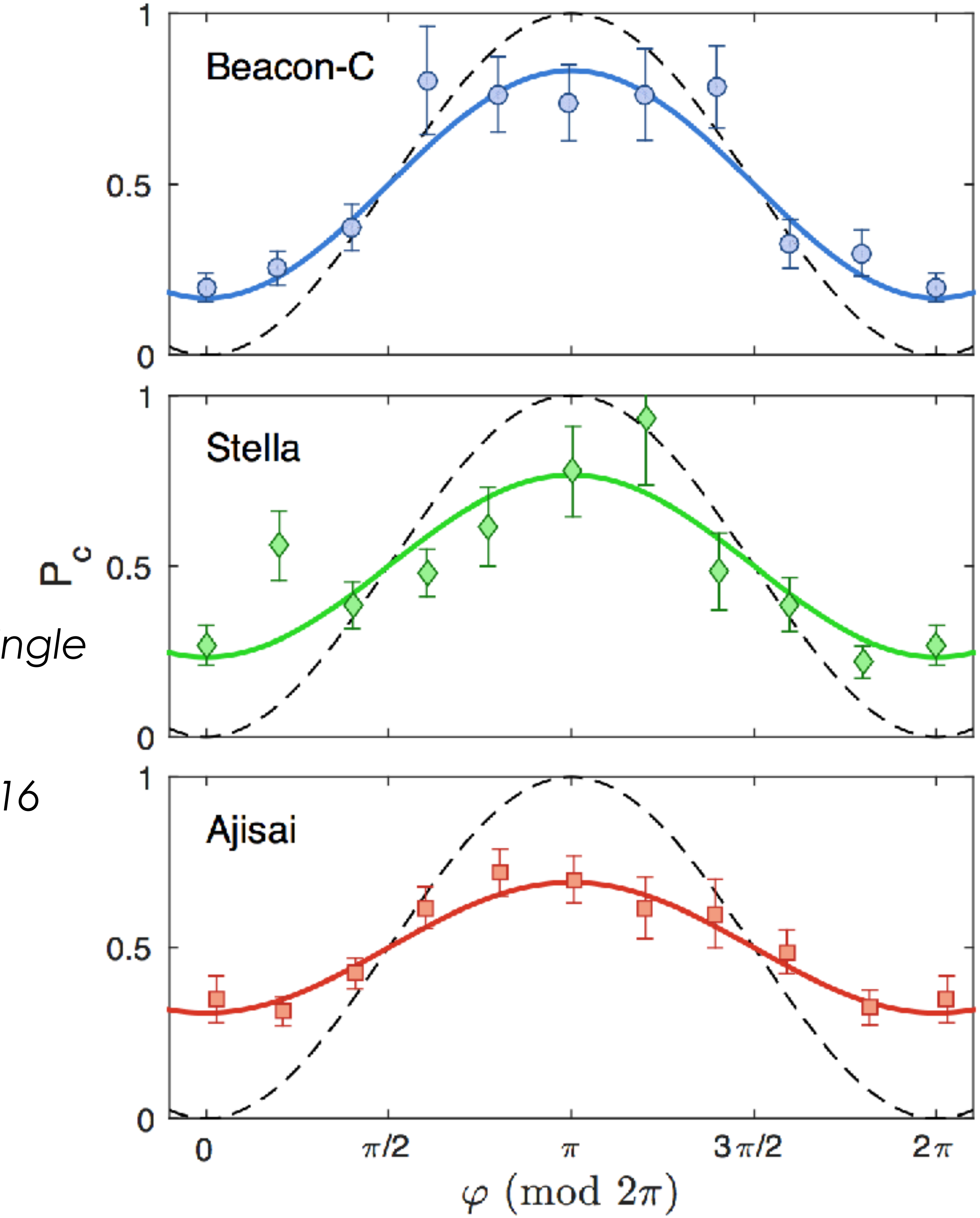
$$\mathcal{V}(t) = e^{-2\pi\left(\frac{\Delta t}{\tau_c}\frac{\beta(t)}{1+\beta(t)}\right)^2} \simeq 1\,.$$



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

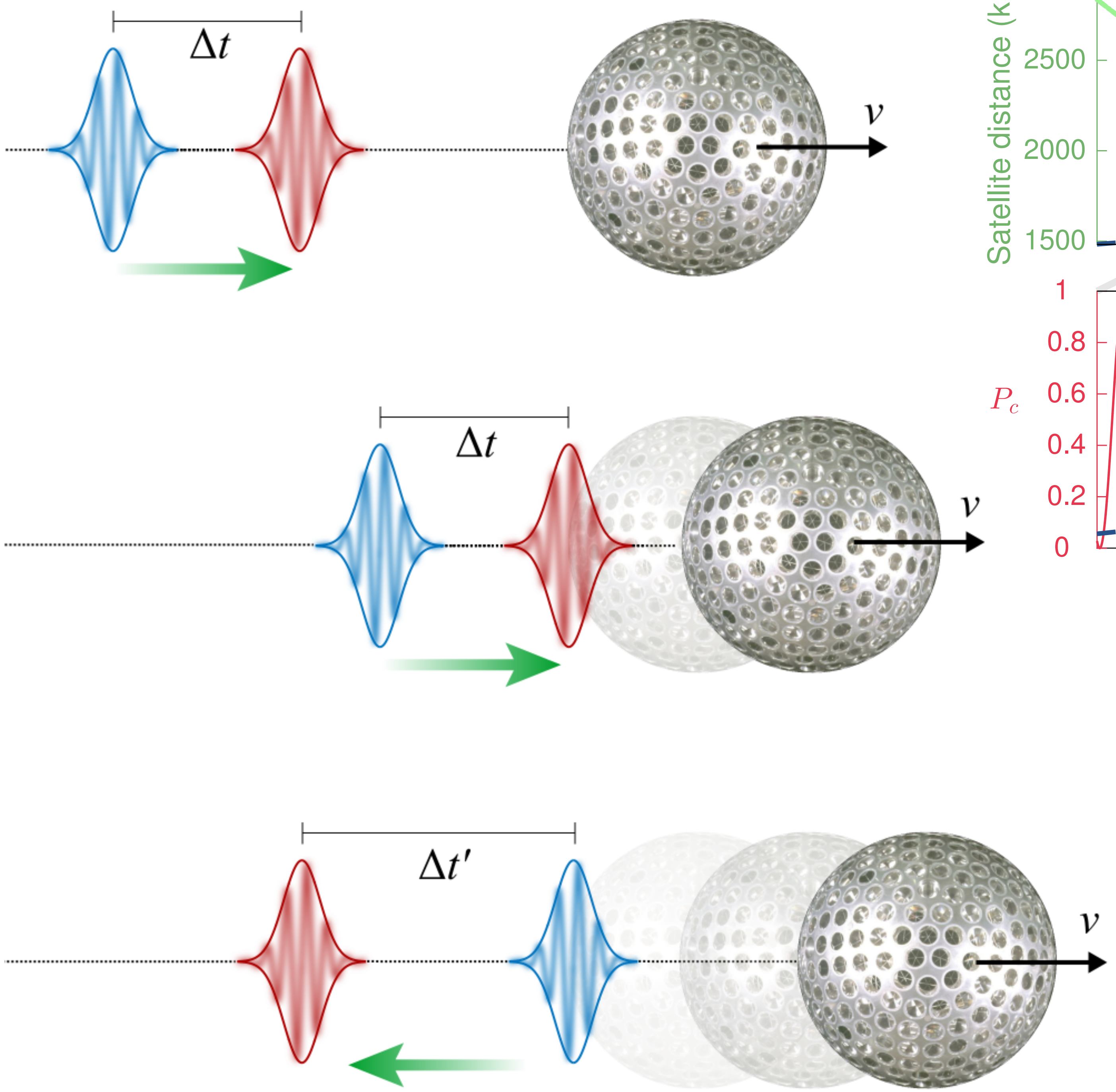
Visibility vs. φ(t)

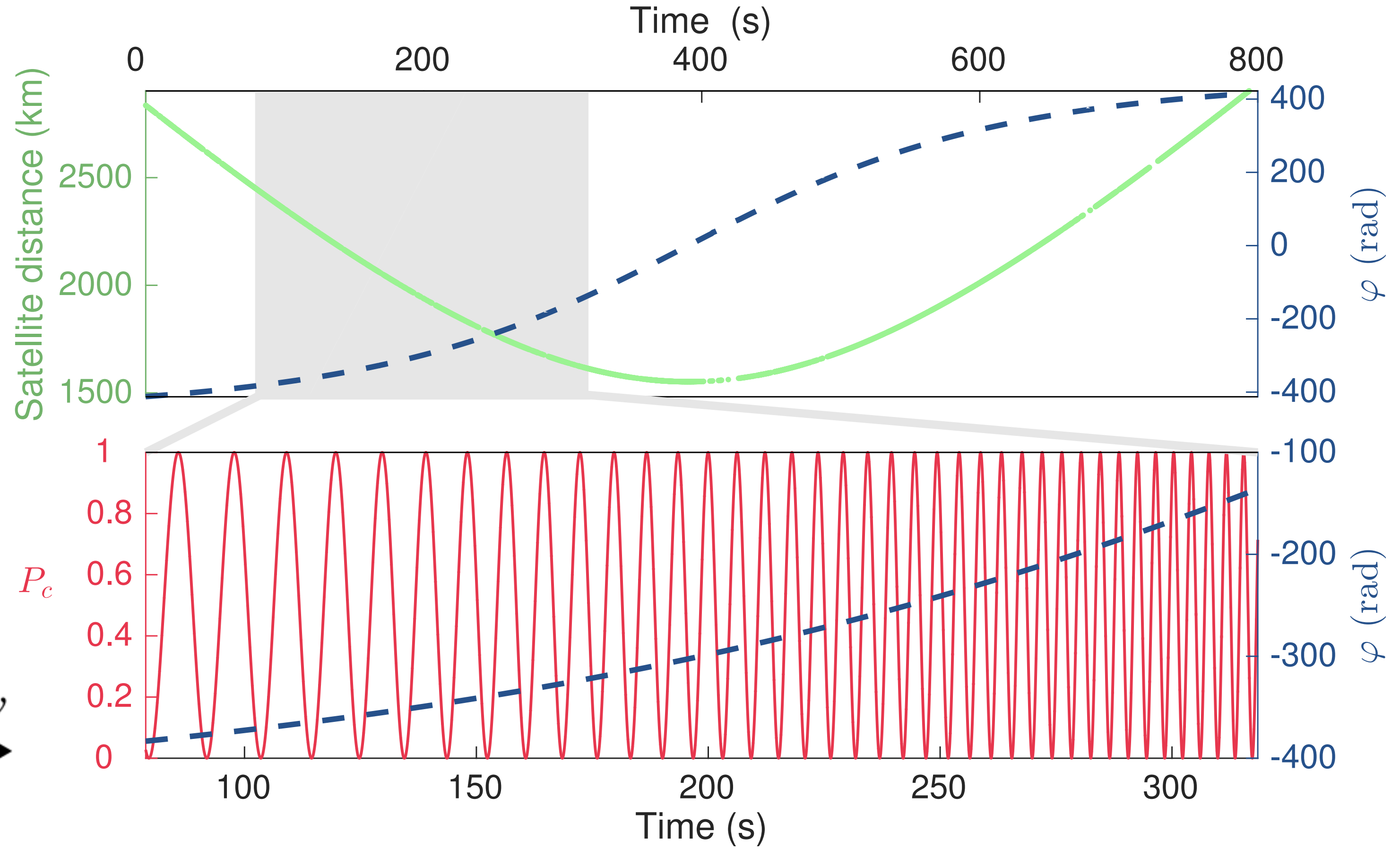
V_{exp}=67±11% for Beacon-C



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

Satellite-induced interference pattern





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

$$\mathcal{V}(t)=e^{-\frac{\lambda^2\varphi^2(t)}{8\pi c^2\tau_c^2}}\approx 1$$

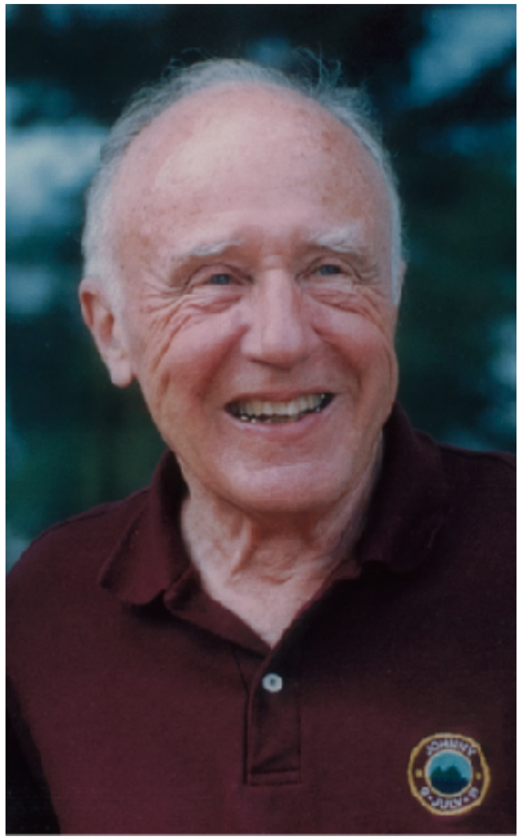
$$\varphi(t)=\frac{2\beta(t)}{1+\beta(t)}\frac{2\pi c}{\lambda}\Delta t \qquad \beta(t):=\frac{v_r(t)}{c}$$

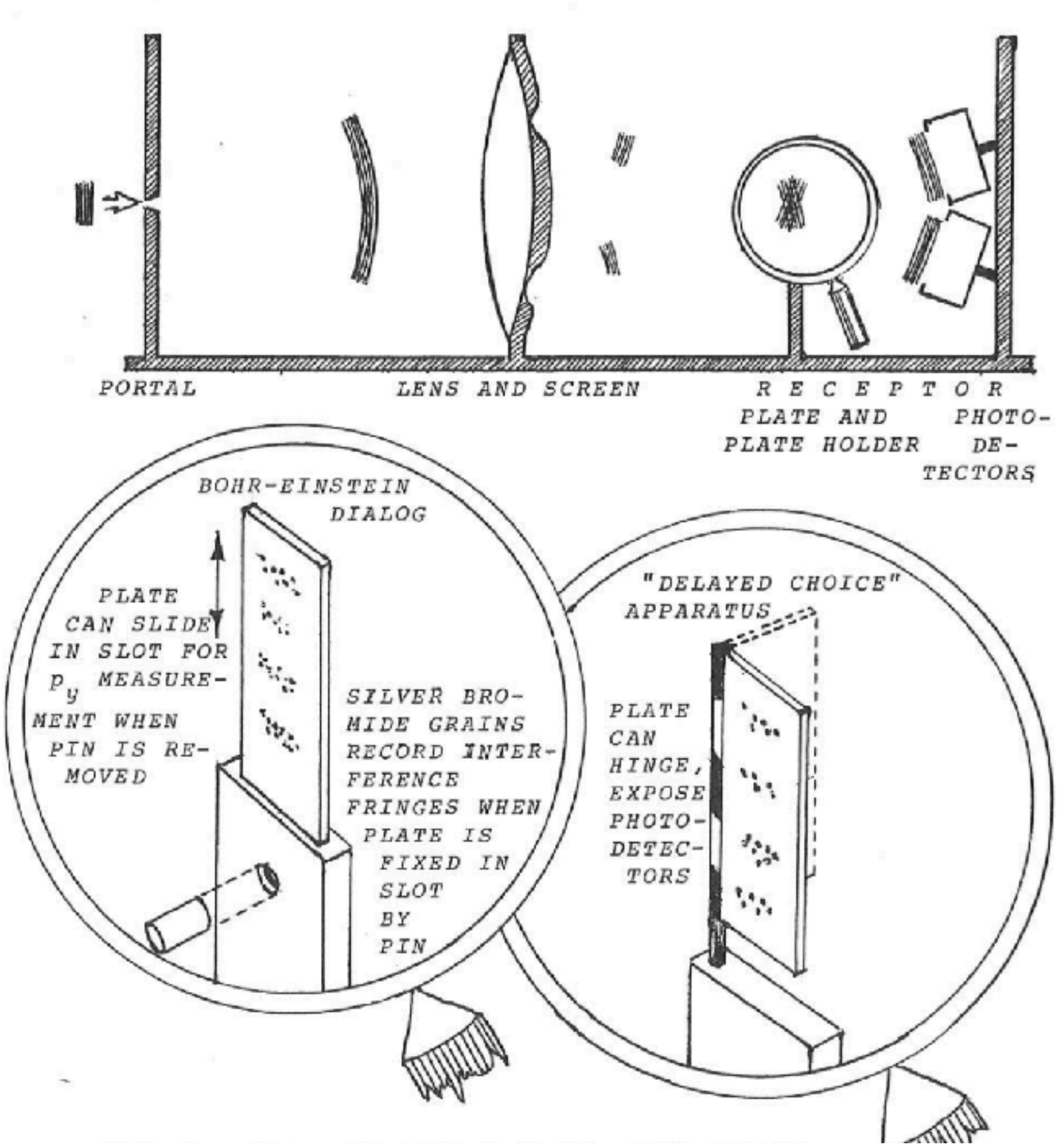
G. Vallone et al., **Interference at the Single Photon Level Along Satellite-Ground Channels**, Phys. Rev. Lett. **116** 253601 (2016)

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"**

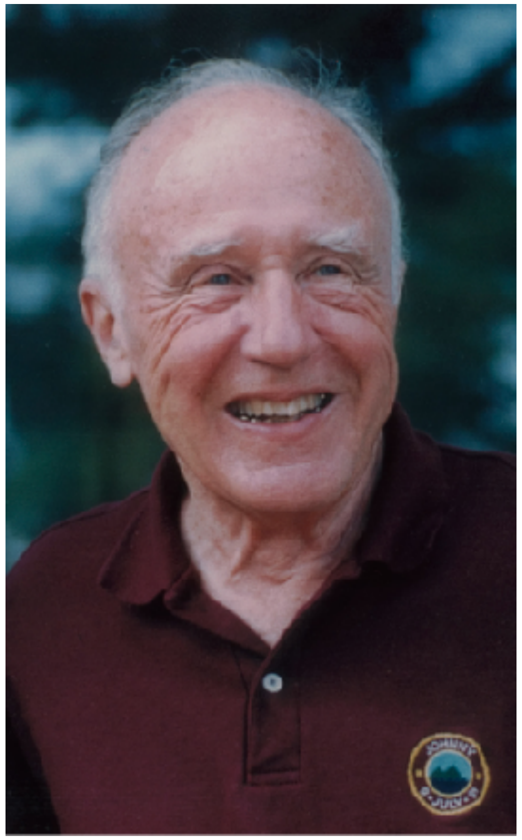
John Wheeler Delayed-choice gedanken experiment

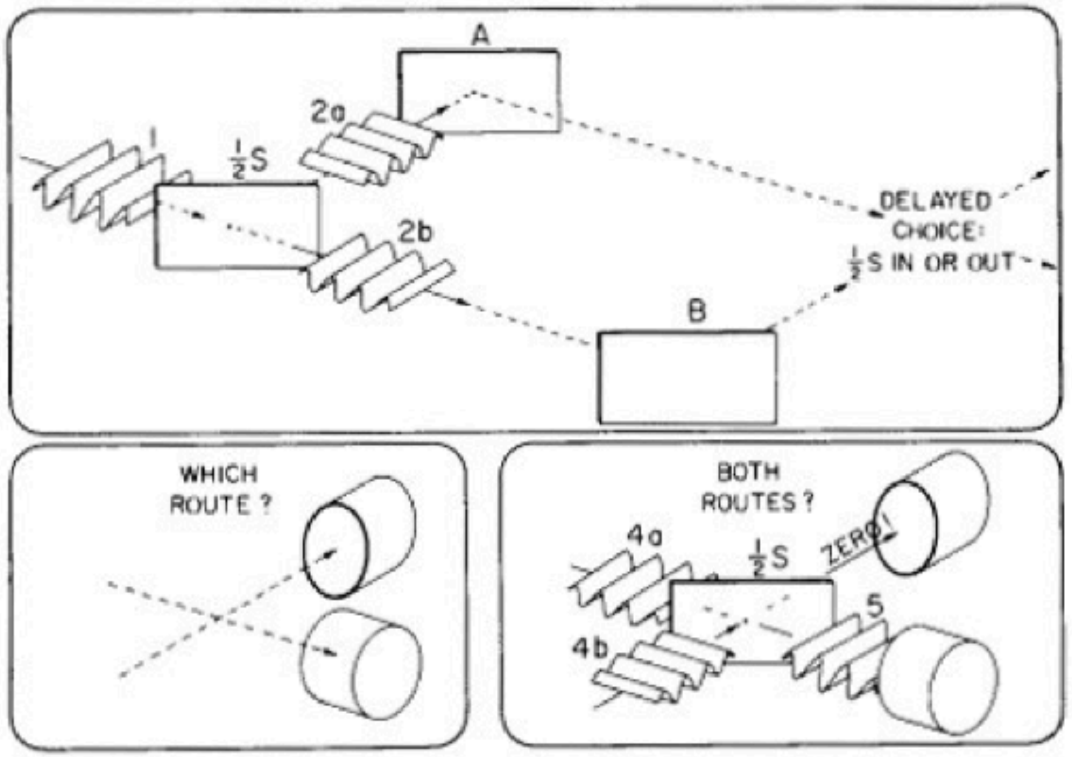


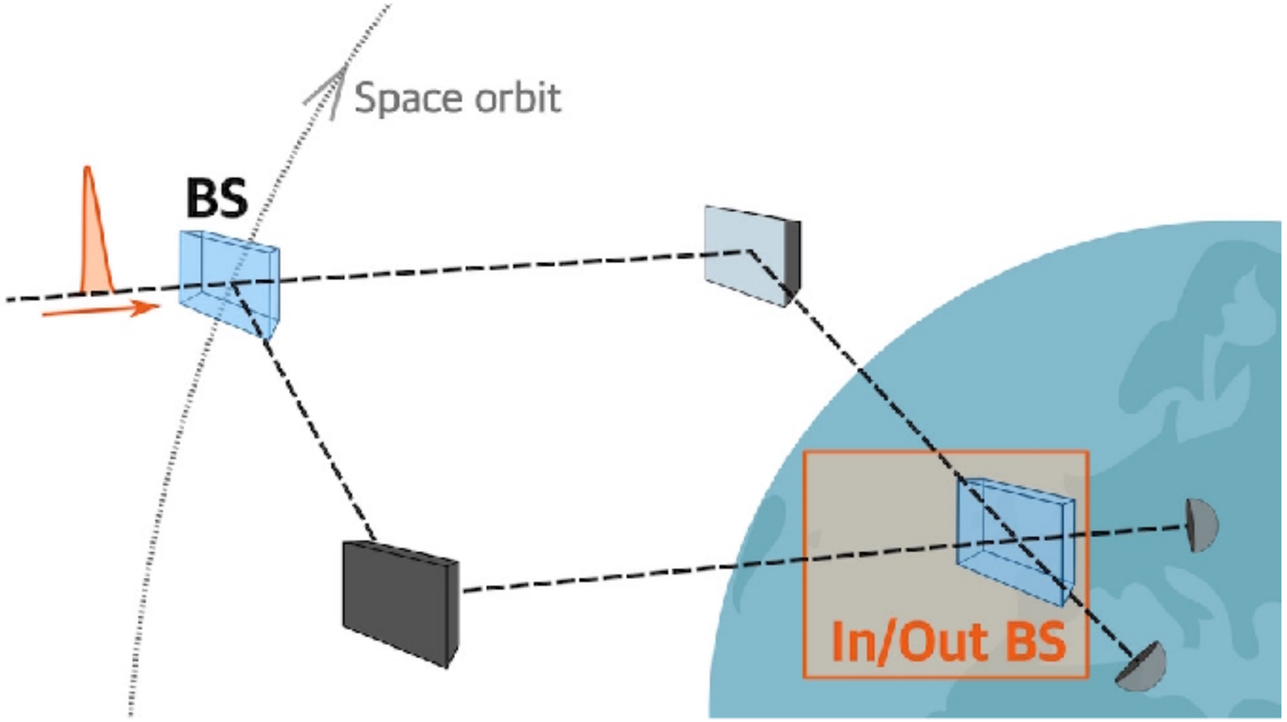


Wheeler JA (1978) **The "past" and the "delayed-choice" double-slit experiment.** Mathematical Foundations of Quantum Theory (Academic, New York), pp 9–48.

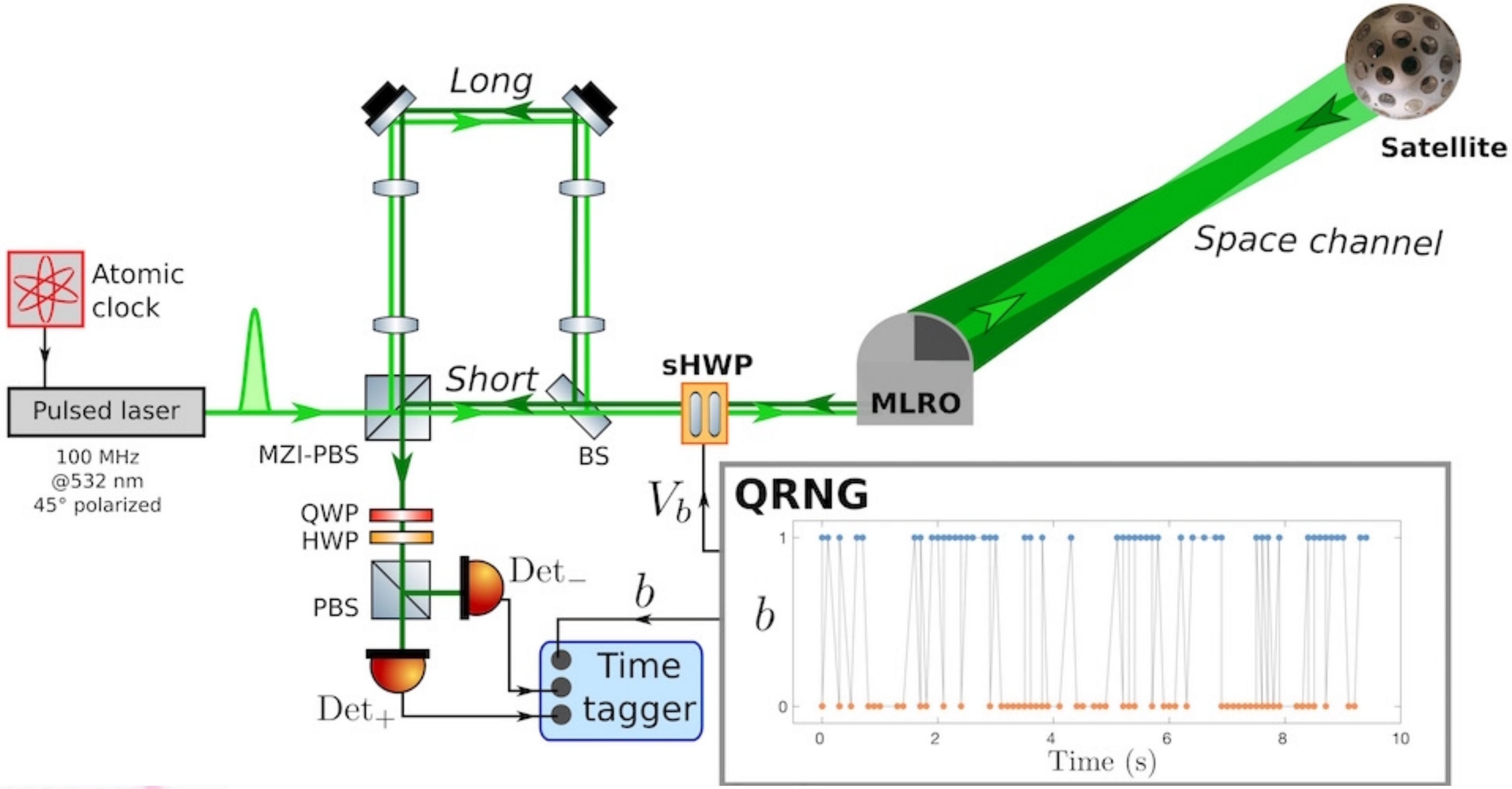
Step forward in Space QComms: inquiring the wave-particle duality along a Space channel



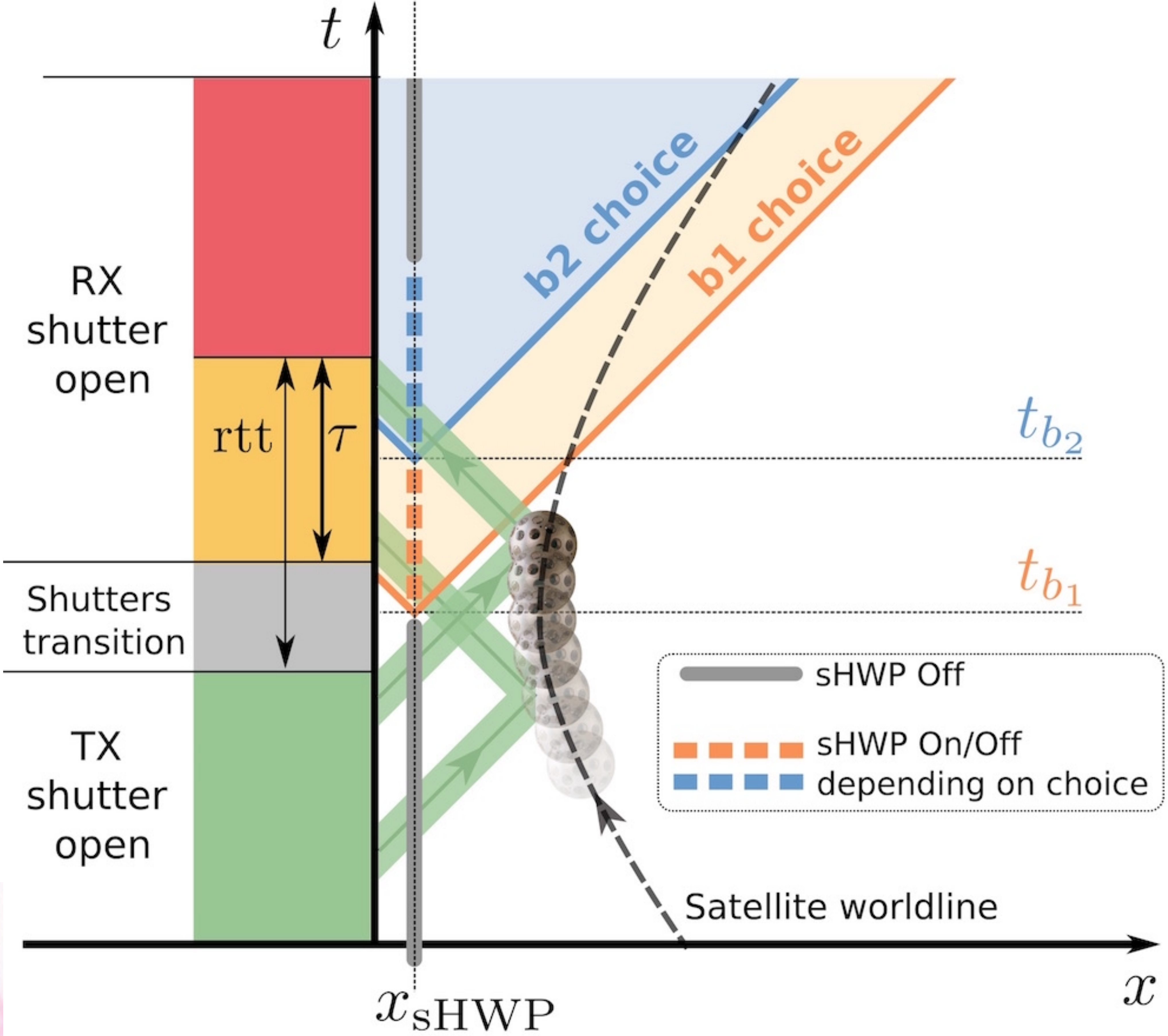




Step forward in Space QComms: inquiring the wave-particle duality along a Space channel



F. Vedovato et al. – Science Adv. **3** e1701180 (2017)
QRNG: A. Stanco, D.G. Marangon et al. - Phis. Rev. Res. **2** 023287 (2020)



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


SCIENCE ADVANCES | RESEARCH ARTICLE

QUANTUM MECHANICS

Extending Wheeler's delayed-choice experiment to space

Francesco Vedovato,[1]* Costantino Agnesi,[1]* Matteo Schiavon,[1] Daniele Dequal,[1,2] Luca Calderaro,[1] Marco Tomasin,[1] Davide G. Marangon,[1] Andrea Stanco,[1] Vincenza Luceri,[3] Giuseppe Bianco,[2] Giuseppe Vallone,[1] Paolo Villoresi[1]†

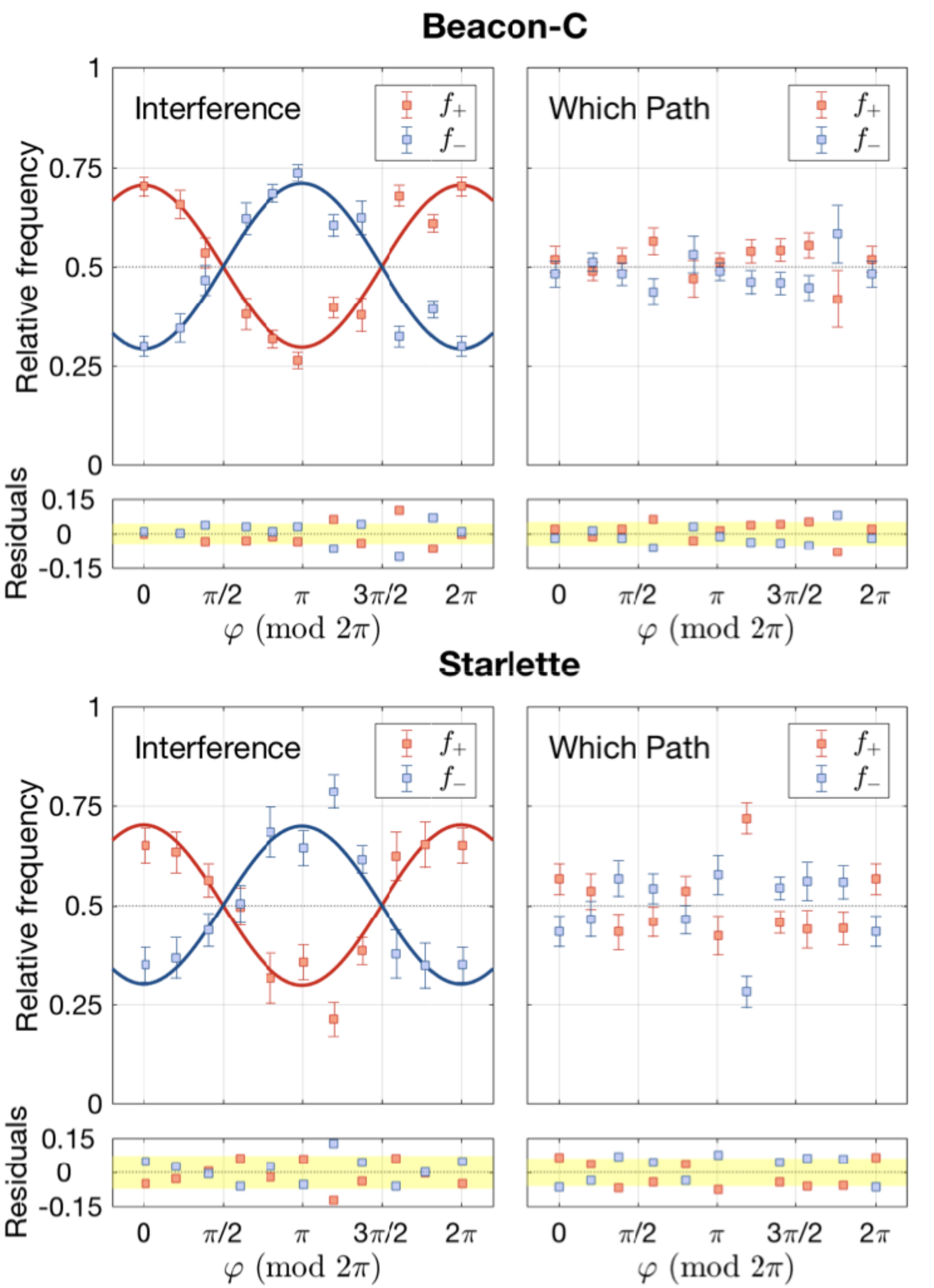
particle-like:
which-path information
$p_{wp} = 95 \pm 1\%$ (Starlette)

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

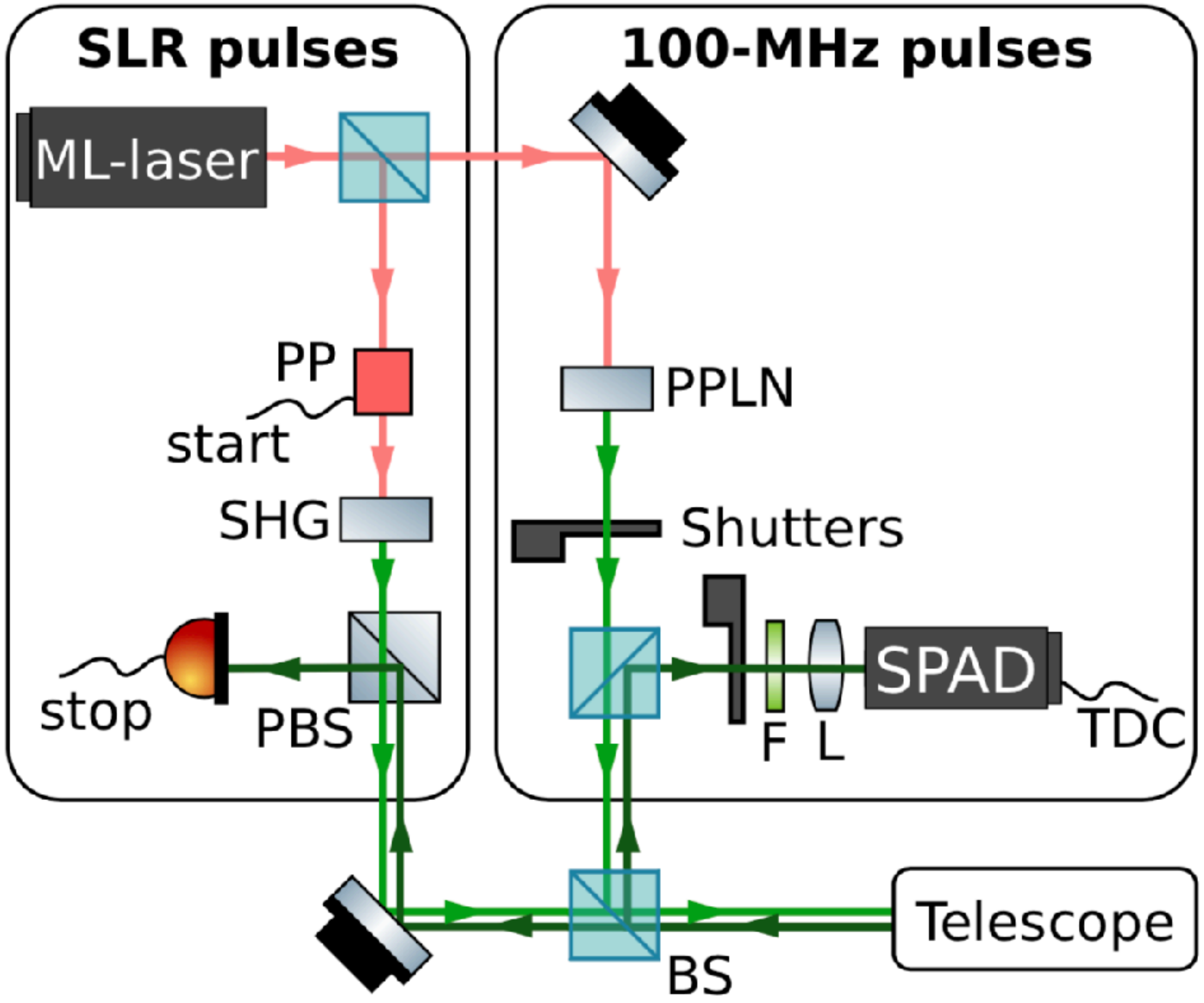
$$f_{\pm}^{b=0} = \frac{N_{\pm}}{N_{+}+N_{-}}$$

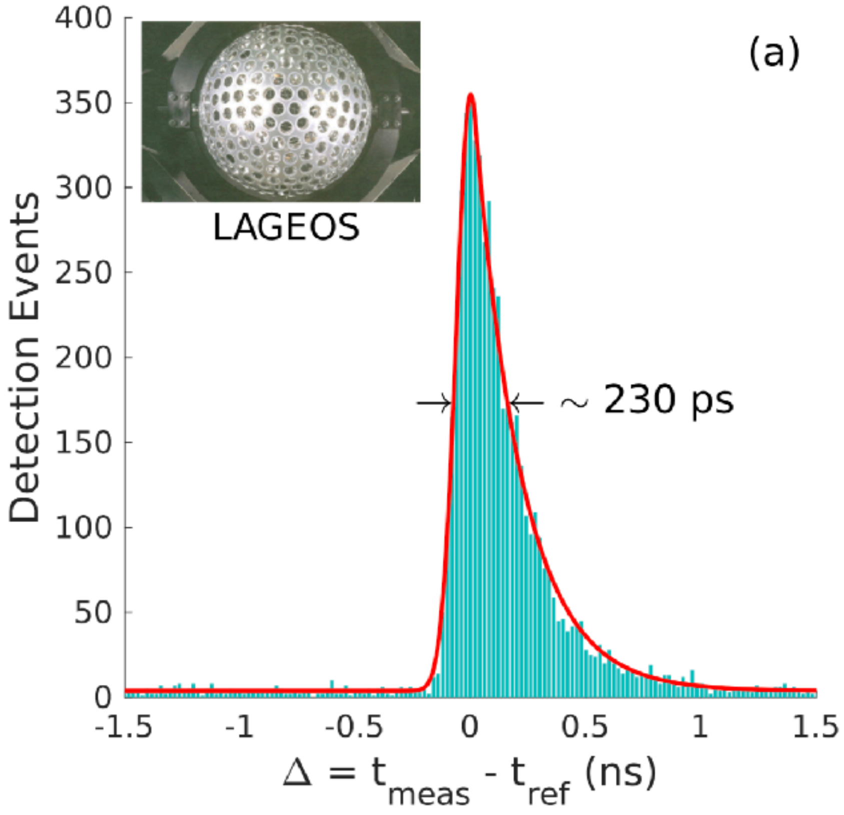
$$\mathcal{V}^{\text{Beacon-C}} = 41 \pm 4\%,$$

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



Temporal resolution *in the single photon* ***time tagging reduced to 230 ps over 7000km***





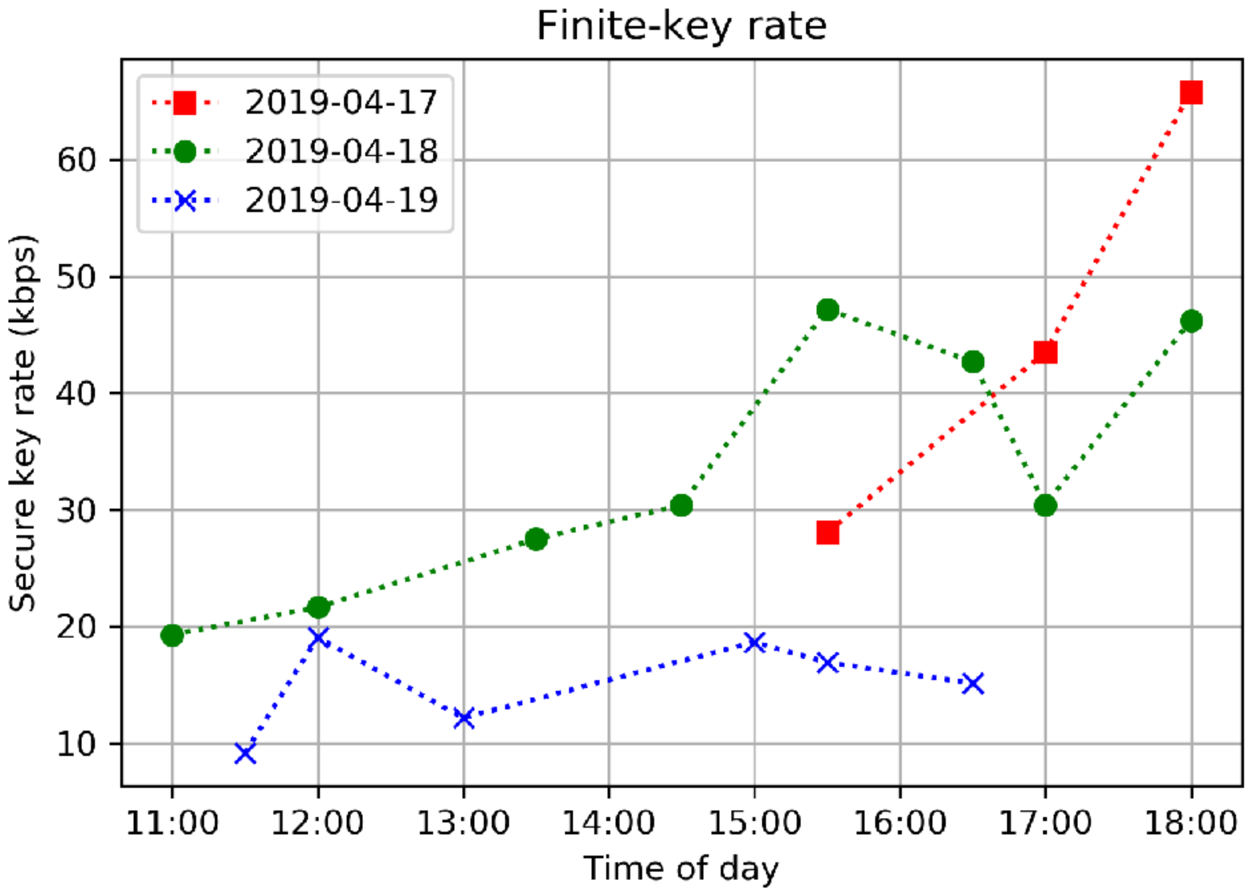
The 100-MHz pulse train is detected after a 50:50 BS to separate the outgoing and incoming beams and 3 nm spectral filter a **silicon single photon avalanche detector (SPAD), provided by Micro-Photon-Devices Srl, with ≈ 50% quantum efficiency, ≈ 400 Hz dark count rate and 40 ps of jitter**.

The time of arrival is tagged with **1 ps** resolution (quTAG TDC from qutools GmbH)

C. Agnesi et al., *Sub-ns timing accuracy for satellite quantum communications*, J. Opt. Soc. Am. B, **36**, B59, 2019

Daylight free-space QKD Link: rate

- **QBERR < 1%**
- **> 50 kbps @50 MHz clocking**
- **also operative with commercial fiber with standard attenuation (30 km)**
- **continuous operation (over weeks)**

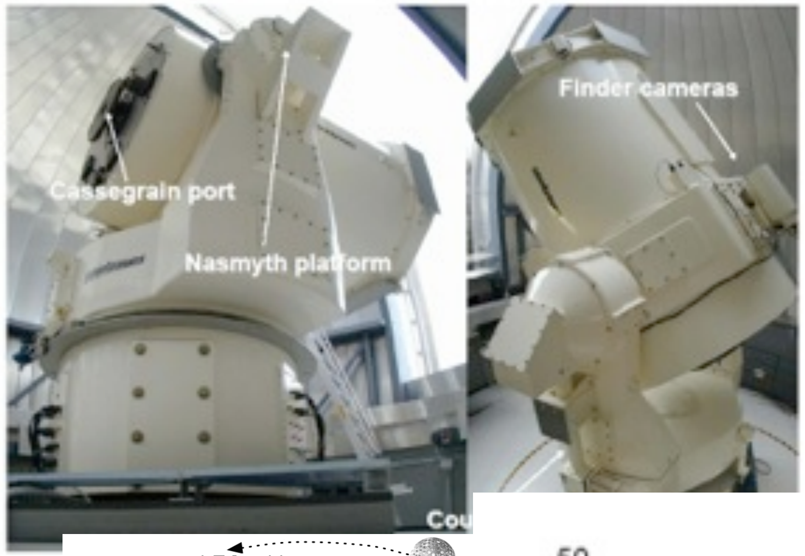


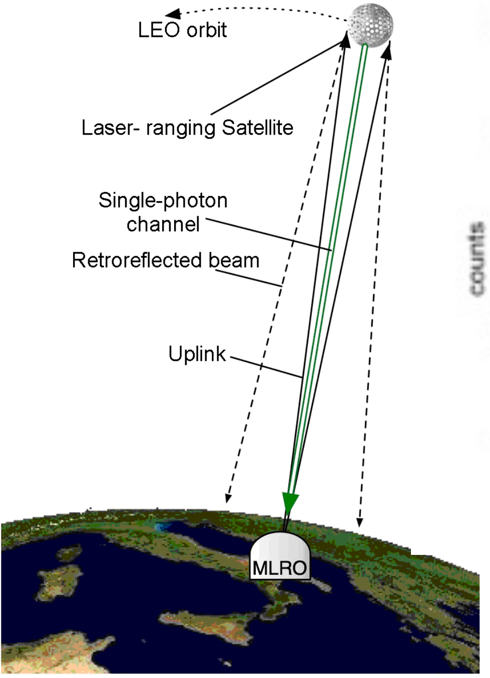
Secret key generation rate obtained with the chip source in the definitive package

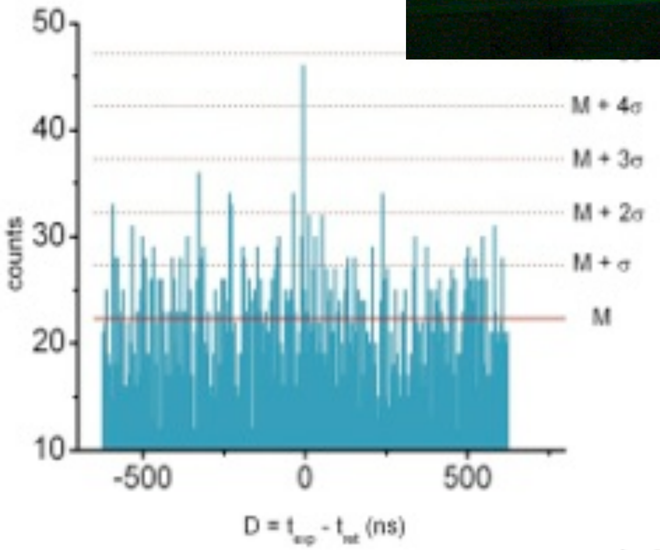
M. Avesani et al. Full daylight quantum-key-distribution at 1550 nm enabled by integrated silicon photonics arXiv:1907.10039

Italian Space Quantum Communications

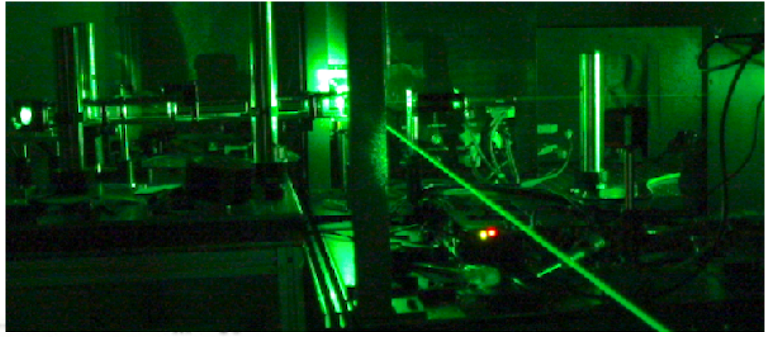
Experimental results since 2003 by QuantumFuture Research Group of University of Padova at ASI **Matera Laser Ranging Observatory**, using its **1.5 m telescope**

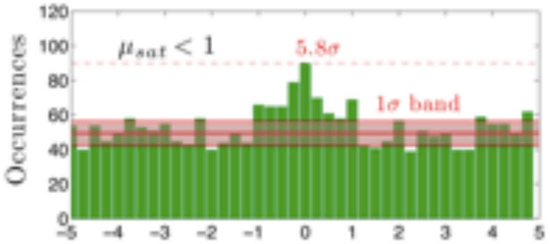


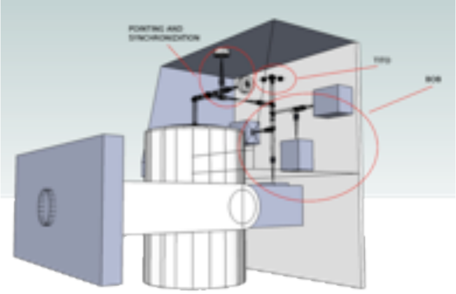


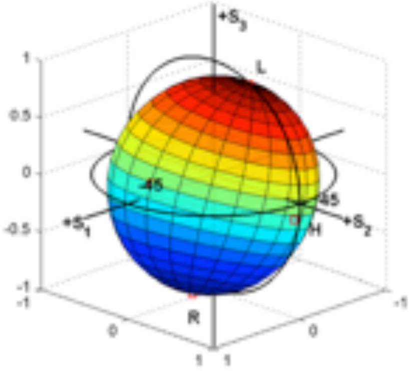


P. Villoresi et al.
New J. Phys.
10 033038 (2008)

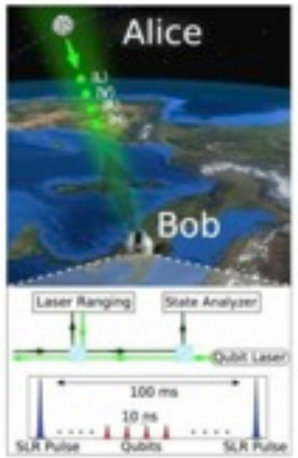




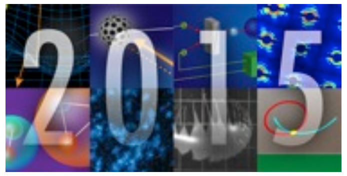




G. Vallone et al. Phys. Rev. Lett. vol 115 040502 (2015)

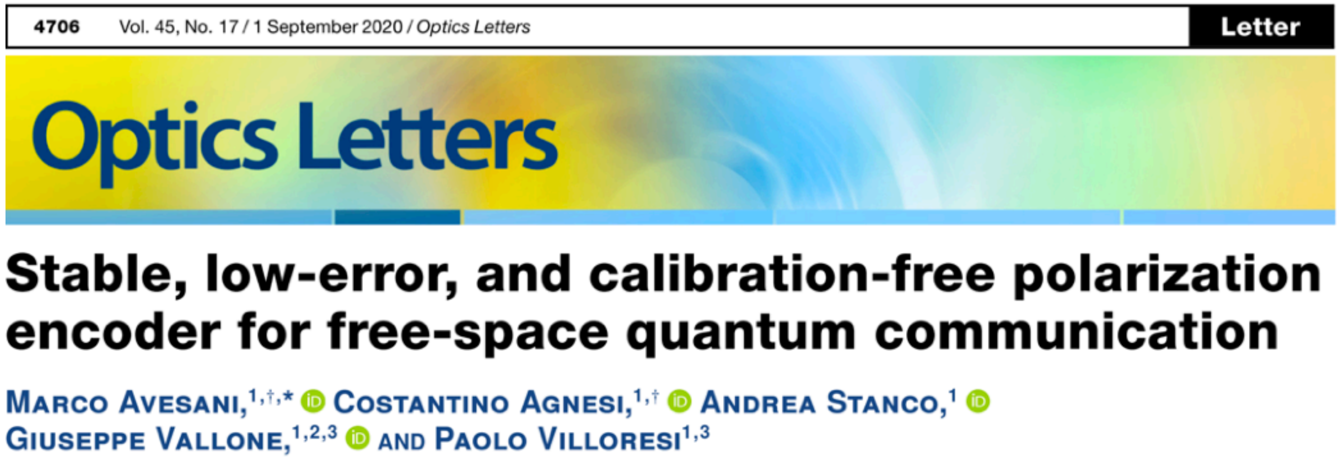


- 2003 – UniPD SpaceQ project: single photon transceiver @ MLRO
- 2008 – first single-photon return from Ajisai announced
- 2009 ASI Feasibility study Q payload for the ISS
- 2009-2011 Characterization of MLRO Mueller Matrix
- 2012 - Analysis of response for different satellites CCR
- 2013 state preparation and analysis, satellite synch
- 2014 – Q-Comm on satellites demonstrated
- 2015 Temporal modes demonstrated in satellite qubit
- 2016 – New limit in single photon exchange at 7000 km
- 2017-Testing wave-particle duality in Space
- 2018 New limit in single photon exchange from MEO 20000 km
- 2019 sub-ns resolution - daylight free-space QKD
- 2020 daylight QComms and <0.001 QBER



D. Dequal et al. Phys Rev. A Rapid Comm **93** 010301(2016)
F. Vedovato et al. - Science Adv. **3** e1701180 (2017)

recent results on **Photonics for Space Quantum Comms**


4706 Vol. 45, No. 17 / 1 September 2020 / *Optics Letters* **Letter**

Optics Letters

Stable, low-error, and calibration-free polarization encoder for free-space quantum communication

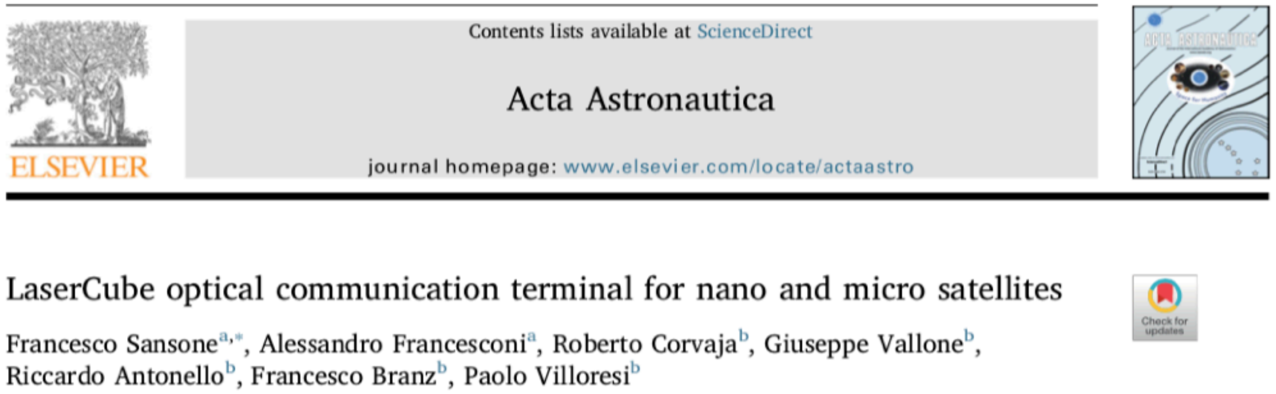
Marco Avesani,[1,†,*] Costantino Agnesi,[1,†] Andrea Stanco,[1] Giuseppe Vallone,[1,2,3] and Paolo Villoresi[1,3]


284 Vol. 7, No. 4 / April 2020 / *Optica* **Research Article**

optica

Simple quantum key distribution with qubit-based synchronization and a self-compensating polarization encoder

Costantino Agnesi,[1,2,†] Marco Avesani,[1,†] Luca Calderaro,[1,2,†] Andrea Stanco,[1,2] Giulio Foletto,[1] Mujtaba Zahidy,[1] Alessia Scriminich,[1] Francesco Vedovato,[1,2] Giuseppe Vallone,[1,2,3] and Paolo Villoresi[1,2,*]


Contents lists available at ScienceDirect

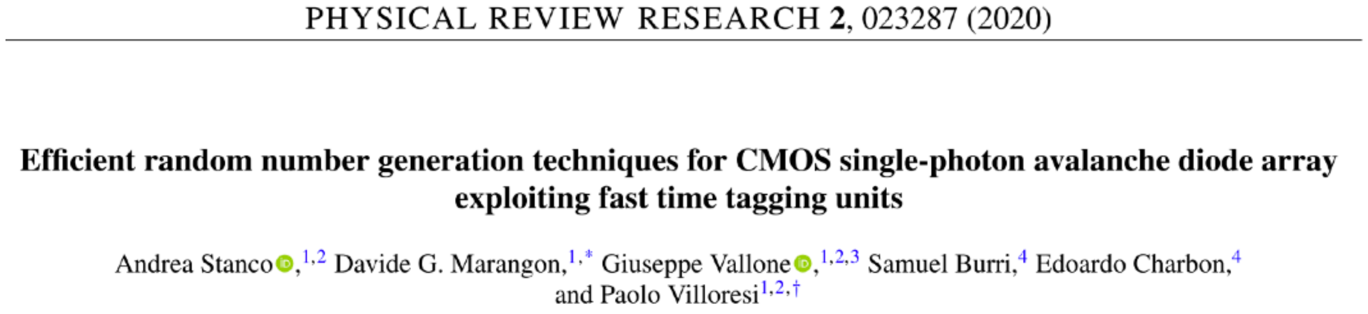
Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

ELSEVIER

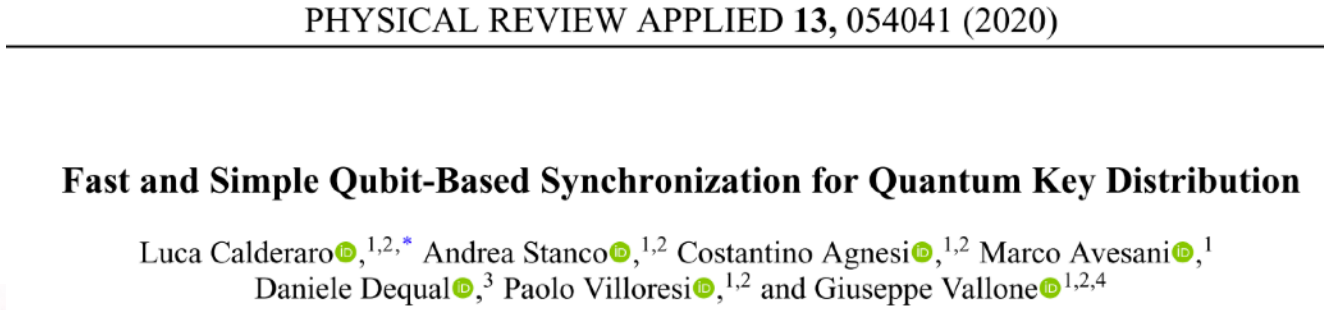
LaserCube optical communication terminal for nano and micro satellites

Francesco Sansone[a,*], Alessandro Francesconi[a], Roberto Corvaja[b], Giuseppe Vallone[b], Riccardo Antonello[b], Francesco Branz[b], Paolo Villoresi[b]


PHYSICAL REVIEW RESEARCH **2**, 023287 (2020)

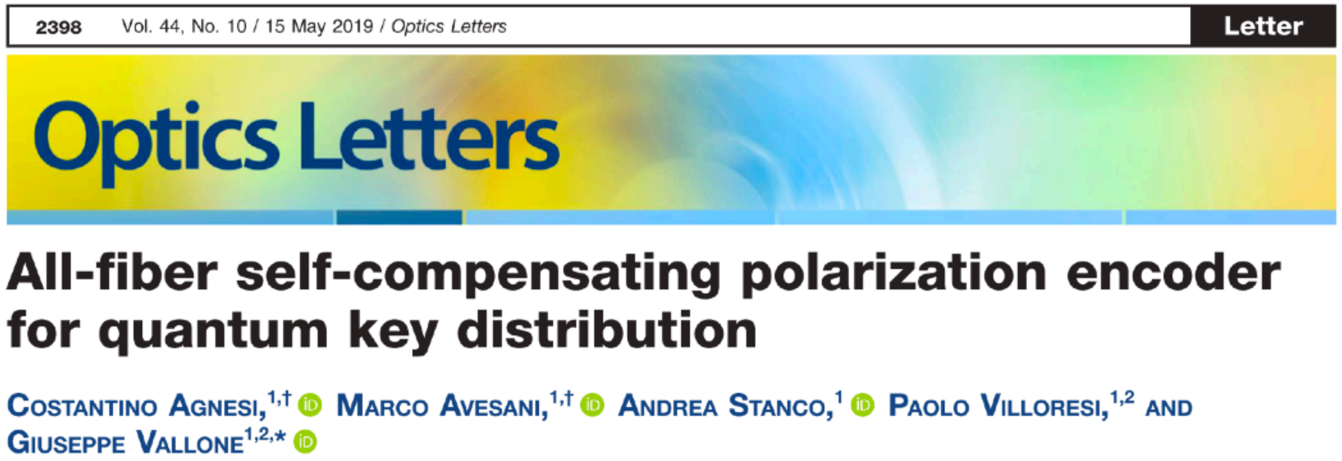
Efficient random number generation techniques for CMOS single-photon avalanche diode array exploiting fast time tagging units

Andrea Stanco,[1,2] Davide G. Marangon,[1,*] Giuseppe Vallone,[1,2,3] Samuel Burri,[4] Edoardo Charbon,[4] and Paolo Villoresi[1,2,†]


PHYSICAL REVIEW APPLIED **13**, 054041 (2020)

Fast and Simple Qubit-Based Synchronization for Quantum Key Distribution

Luca Calderaro,[1,2,*] Andrea Stanco,[1,2] Costantino Agnesi,[1,2] Marco Avesani,[1] Daniele Dequal,[3] Paolo Villoresi,[1,2] and Giuseppe Vallone[1,2,4]


2398 Vol. 44, No. 10 / 15 May 2019 / *Optics Letters* **Letter**

Optics Letters

All-fiber self-compensating polarization encoder for quantum key distribution

Costantino Agnesi,[1,†] Marco Avesani,[1,†] Andrea Stanco,[1] Paolo Villoresi,[1,2] and Giuseppe Vallone[1,2,*]

in orbit validation of QComms

- night-time and daylight QComms - 1550 nm
- integrated photonics for quantum protocols (QKD and QRNG)
- bulk (and intrinsically aligned) qubit source
- large scale (MLRO) and small scale Padua (400 mm) ground stations
- I-QKD IOV in progress by ASI

IOP PUBLISHING CLASSICAL AND QUANTUM GRAVITY

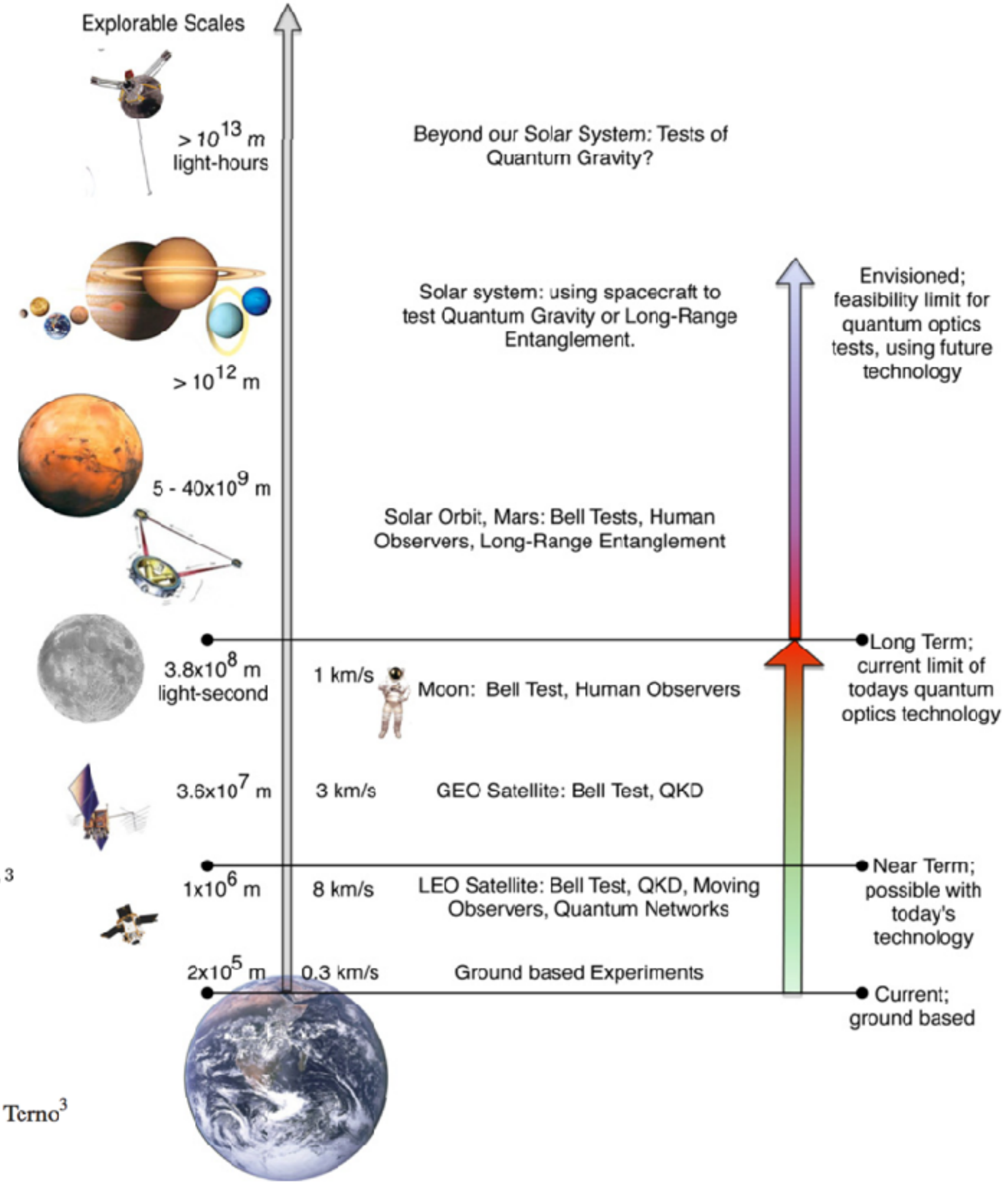
Class. Quantum Grav. **29** (2012) 224011 (44pp) doi:10.1088/0264-9381/29/22/224011

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..**



General Relativity and Gravitation, Vol. 28, No. 5, 1996

On Gravity's Role in Quantum State Reduction

Roger Penrose[1,2]

Received August 22, 1995. Rev. version December 12, 1995

General relativistic effects in quantum interference of photons

Magdalena Zych,[1] Fabio Costa,[1] Igor Pikovski,[1] Timothy C. Ralph,[2] and Časlav Brukner[1,3]

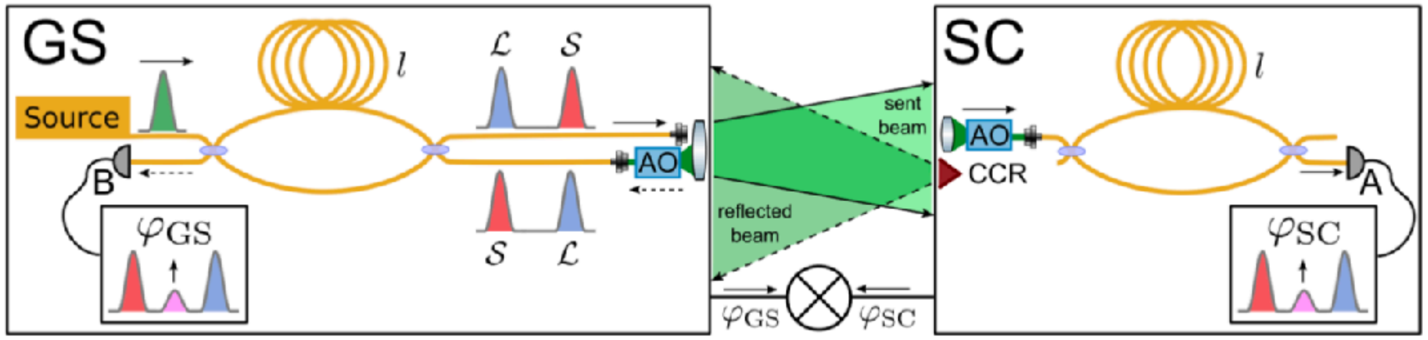
Nature Communications **2** 505 (2011)

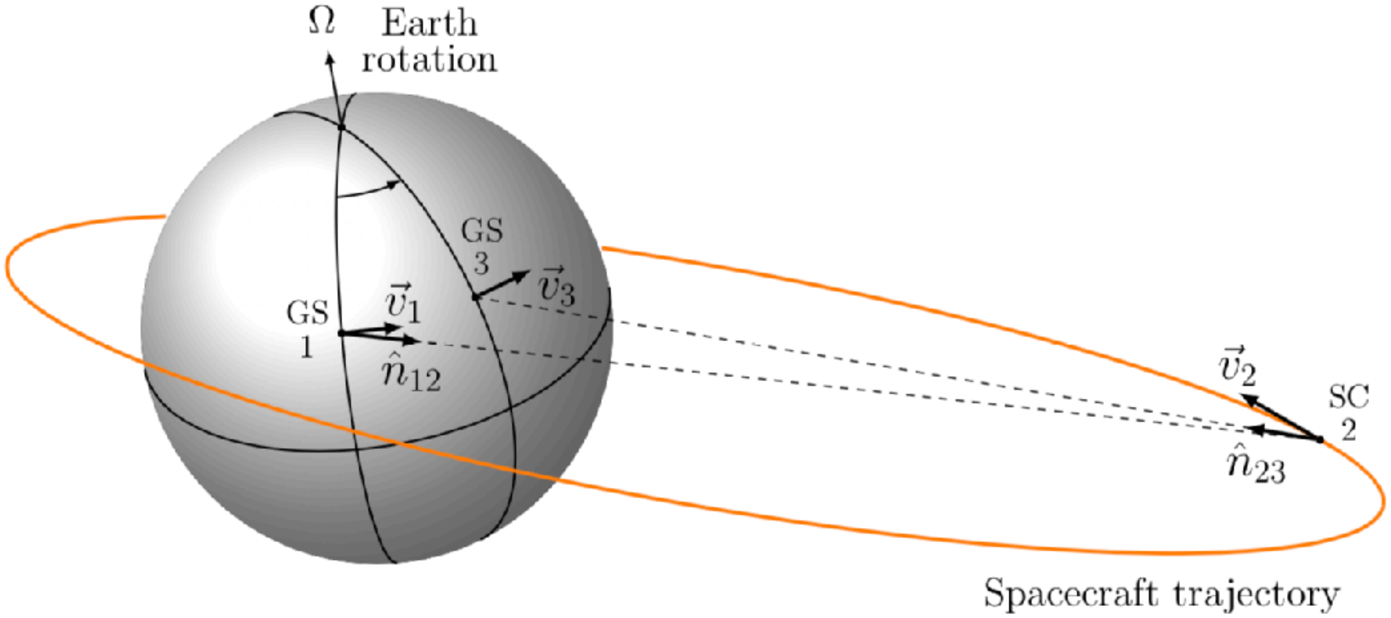
PHYSICAL REVIEW D **91**, 064041 (2015)

Post-Newtonian gravitational effects in optical interferometry

Aharon Brodutch,[1,2] Alexei Gilchrist,[4] Thomas Guff,[3] Alexander R. H. Smith,[2,3] and Daniel R. Terno[3]

Einstein Equivalence Principle test using single photon interference





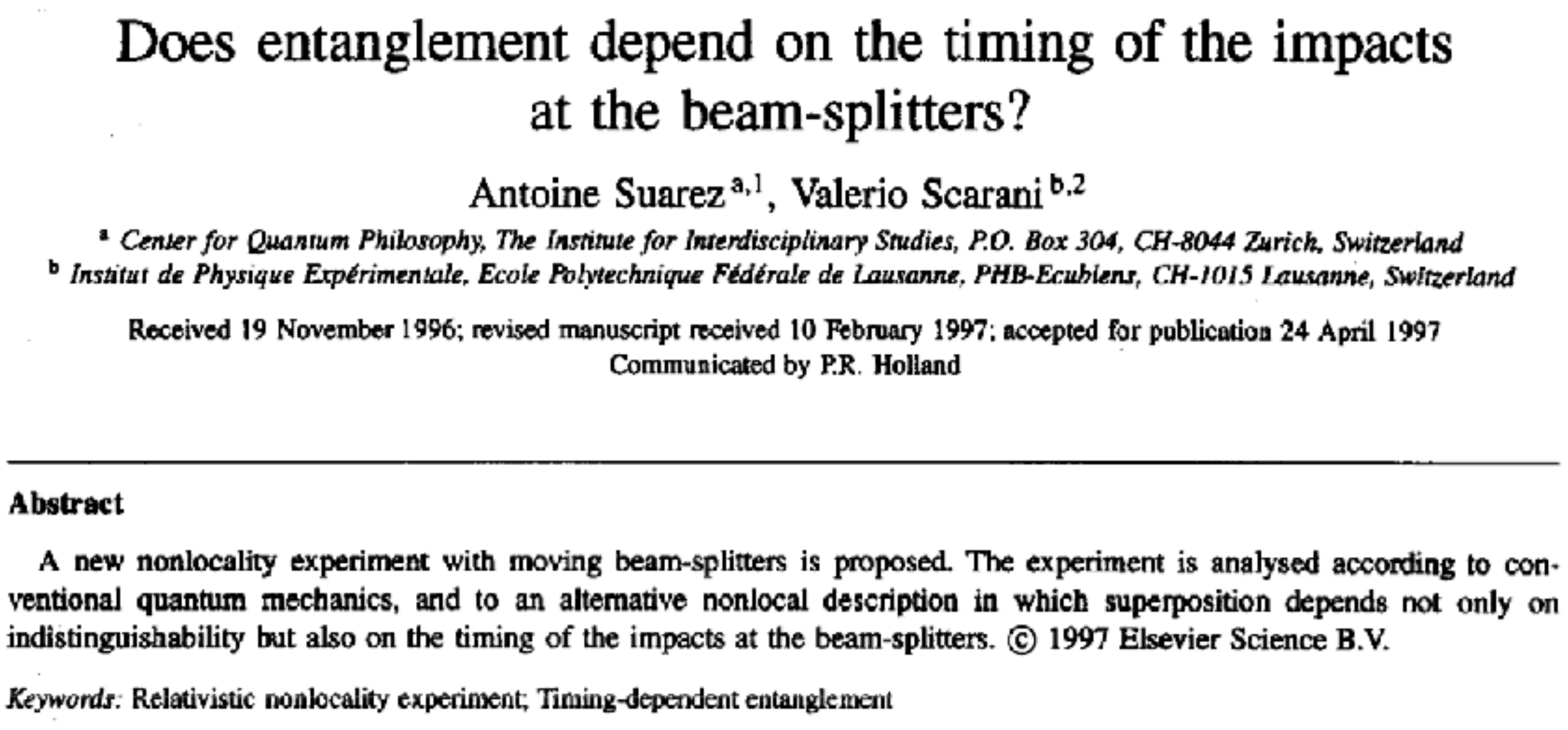
Local Position Invariance (LPI) -a form of the **Einstein Equivalence Principle (EEP)** - asserts that ***the outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed***

The "*where*" is a ***comparison of two identical frequency standards in two different locations in a static gravitational field***.

The so-called red-shift implied by the **EEP affects the locally measured frequencies of a spectral line that is emitted at location 1 with ω_1 and then detected at location 2 with ω_2.**

Proposal for an **Optical Test of the Einstein Equivalence Principle** D.R. Terno et al, arxiv. 1811.04835 (2018)

Early/early or late/late entaglement measurement schemes



Does entanglement depend on the timing of the impacts at the beam-splitters?

Antoine Suarez [a,1], Valerio Scarani [b,2]

[a] Center for Quantum Philosophy, The Institute for Interdisciplinary Studies, P.O. Box 304, CH-8044 Zurich, Switzerland
[b] Institut de Physique Expérimentale, Ecole Polytechnique Fédérale de Lausanne, PHB-Ecublens, CH-1015 Lausanne, Switzerland

Received 19 November 1996; revised manuscript received 10 February 1997; accepted for publication 24 April 1997
Communicated by P.R. Holland

Abstract

A new nonlocality experiment with moving beam-splitters is proposed. The experiment is analysed according to conventional quantum mechanics, and to an alternative nonlocal description in which superposition depends not only on indistinguishability but also on the timing of the impacts at the beam-splitters. © 1997 Elsevier Science B.V.

Keywords: Relativistic nonlocality experiment; Timing-dependent entanglement

Due to the mutual time shifts, the two observers may each measure their particle later than the other (an 'after–after' scenario) in the case that the observers move apart from each other, or each measure their particle earlier than the other ('earlier–earlier'), in the case of approaching motion.

Class. Quantum Grav. 29 (2012) 224011 D Rideout *et al*

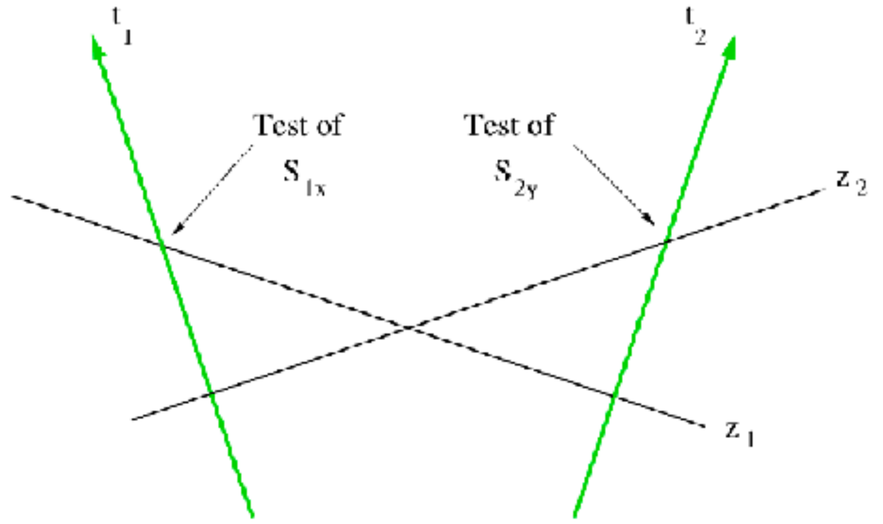
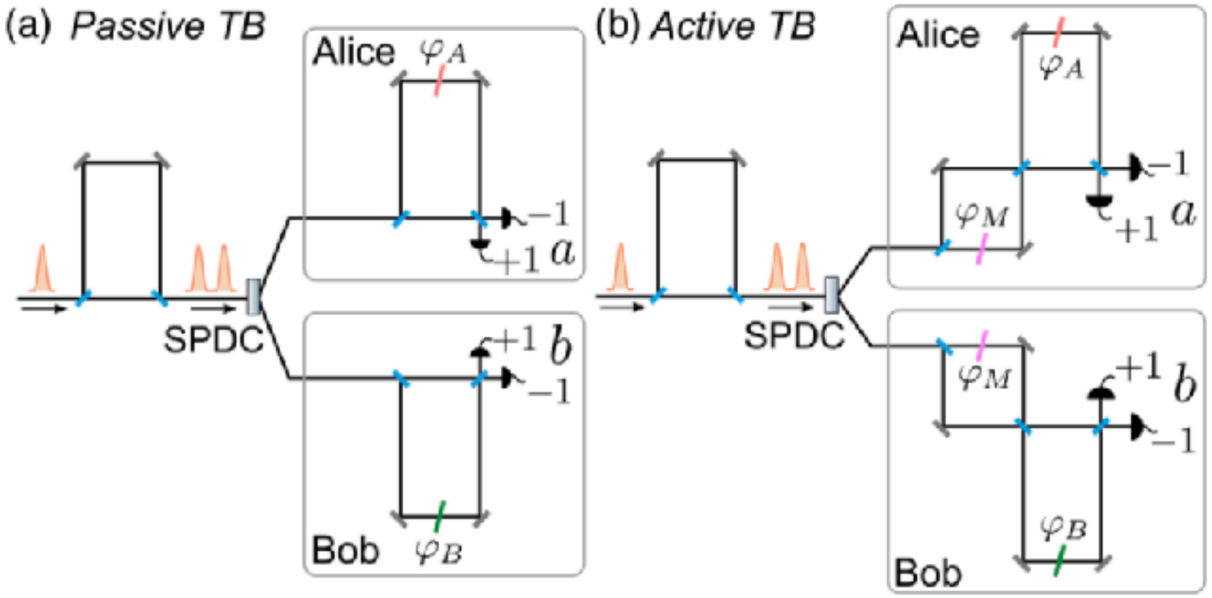
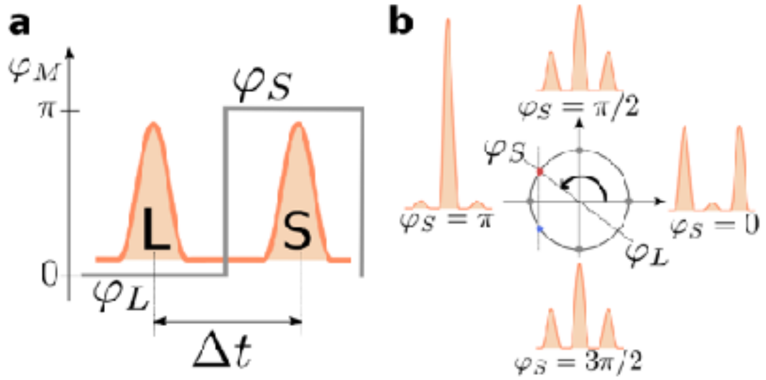


Figure 4. From [30], this spacetime diagram shows the coordinate systems and the locations of the two tests, S_1 and S_2. The t_1 and t_2 axes are the world lines of observers who are receding from each other. In each Lorentz frame, the z_1 and z_2 axes are isochronous: $t_1 = 0$ and $t_2 = 0$, respectively.

Bell test post-selection loophole-free with ***genuine*** time-bin entanglement





Franson type
Bell's test using
time-bin encoding

i) the *passive time-bin with post-selection;*

ii) the *passive time-bin with no post-selection;*

iii) the *active time-bin with no post-selection.*

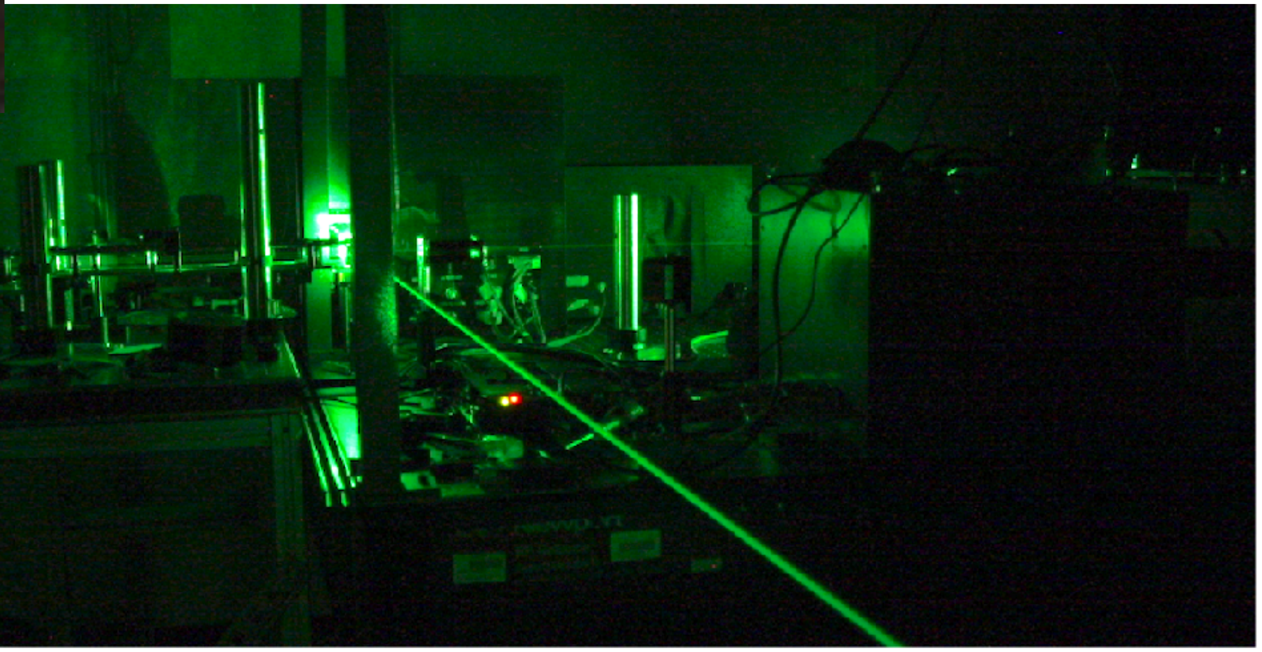
Time-bin scheme	Δw	Post-Selection Loophole	$\mathcal{V}_{\text{exp}}$	S_{exp}	SD
i) passive	2.4 ns	Yes	0.95 ± 0.05	2.58 ± 0.03	18.3
ii) passive	8.1 ns	No	0.23 ± 0.02	0.67 ± 0.02	—
iii) active	8.1 ns	No	0.89 ± 0.03	2.30 ± 0.03	9.3

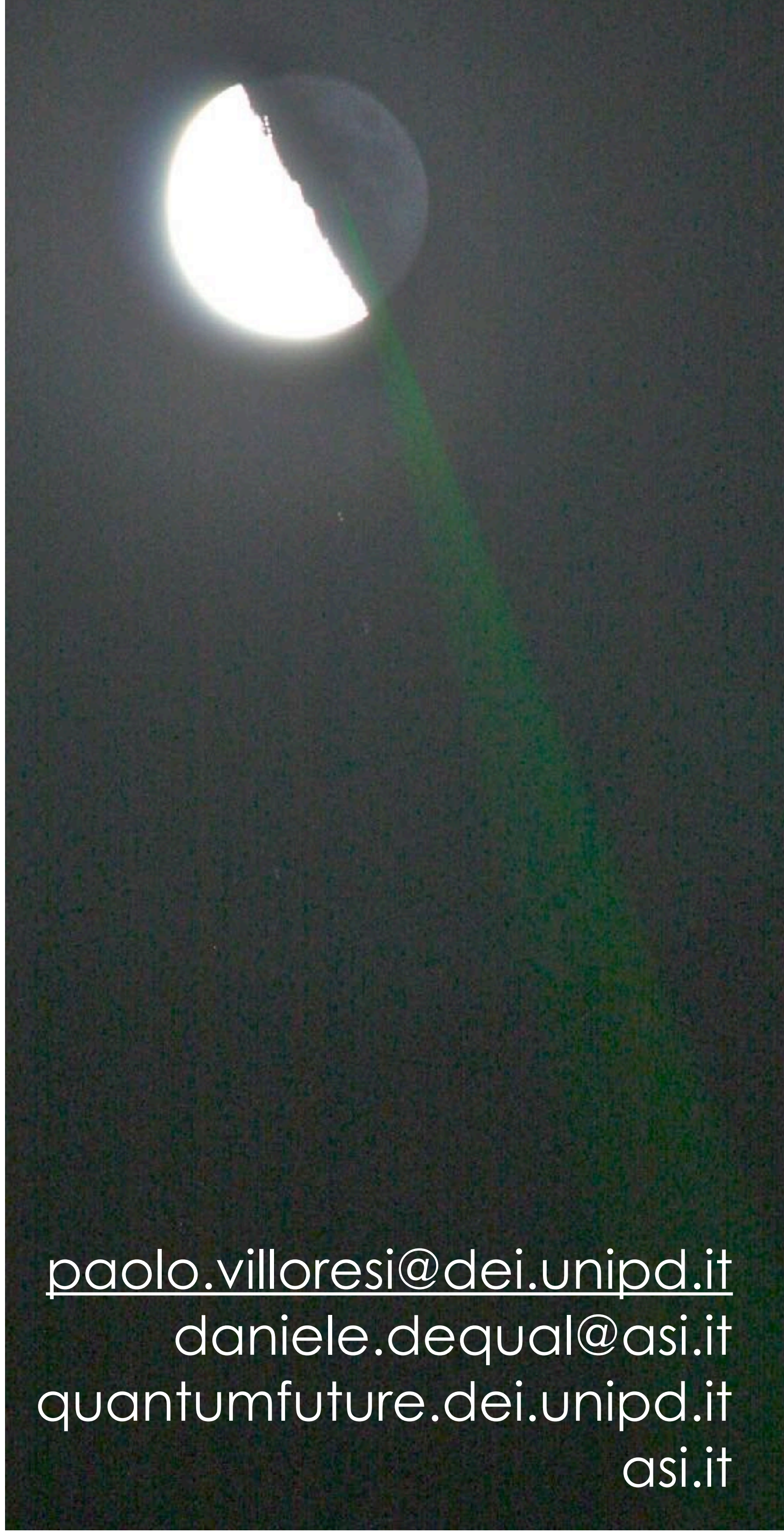
F. Vedovato et al. *Postselection-Loophole-Free Bell Violation with Genuine Time-Bin Entanglement*
Phys. Rev. Lett. **121** 190401 (2018)

Conclusions and perspectives

- Single photons are interesting tools for Space fundamental investigations and applications
- Space QComms polarization and temporal modes were developed in Space channels
- perspectives in Einstein Equivalence Principle test proposal with matching interferometers on ground and in Space
- Active cancellation of post selection in time-bin entanglement assessment for Bell test over very long scale
- Moreover Space QComms is a fruitful area for international cooperation

QComms in Space: not limits but horizons





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