QUANTUM OPTICS EXPERIMENTS IN SPACE

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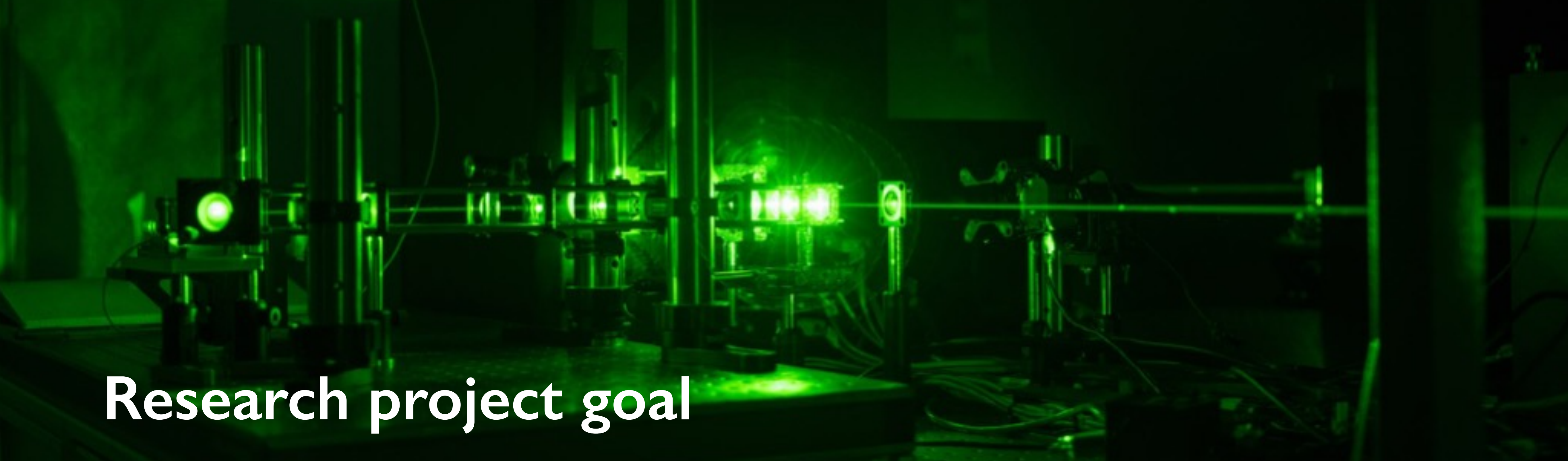
Admission to final exam
14 September 2018

CISAS G. COLOMBO

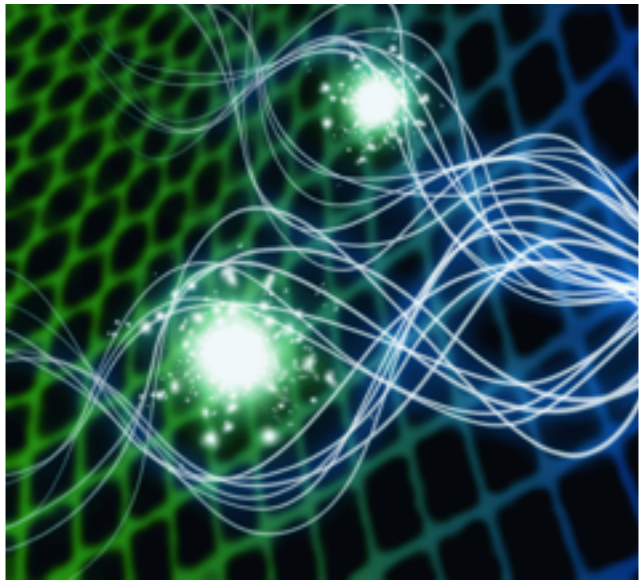
DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

agenzia spaziale italiana

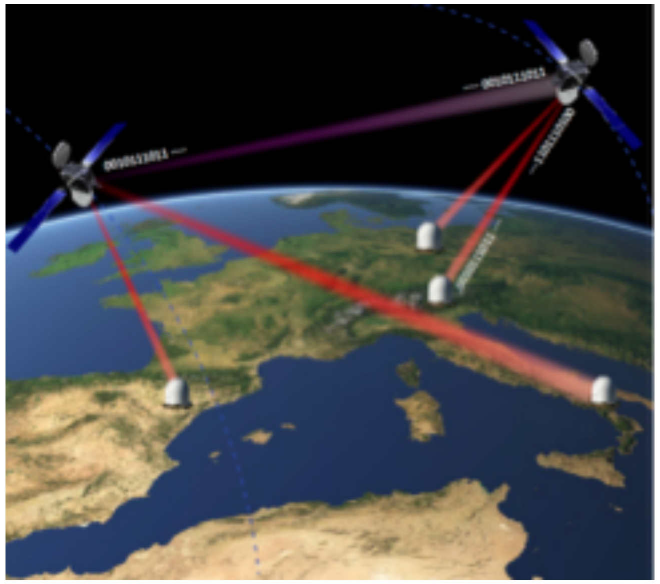


Research project goal

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

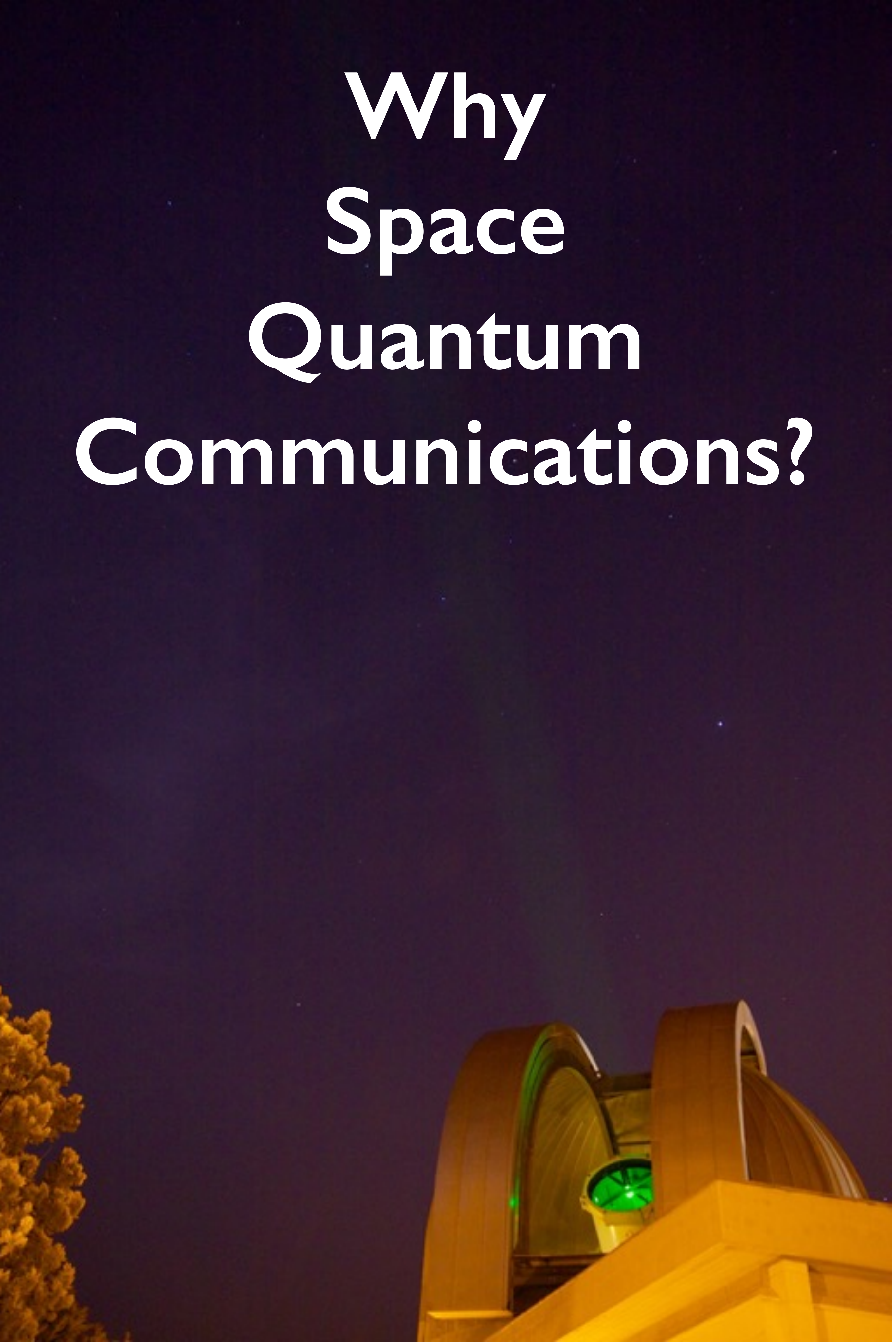


Fundamental tests of physics
in a completely new scenario



Secure communications
at planetary scale

Why 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…
the Chinese Micius satellite

nature
International journal of science

Letter | Published: 09 August 2017

Ground-to-satellite quantum teleportation

Ji-Gang Ren, Ping Xu [...] Jian-Wei Pan

Nature **549**, 70–73 (07 September 2017)

nature
International journal of science

Article | Published: 09 August 2017

Satellite-to-ground quantum key distribution

Sheng-Kai Liao, Wen-Qi Cai [...] Jian-Wei Pan

PHYSICAL REVIEW LETTERS

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Featured in Physics Editors' Suggestion

Satellite-Relayed Intercontinental Quantum Network

Sheng-Kai Liao *et al.*
Phys. Rev. Lett. **120**, 030501 – Published 19 January 2018

Physics See Focus story: Intercontinental, Quantum-Encrypted Messaging and Video

RESEARCH ARTICLES | PHYSICS

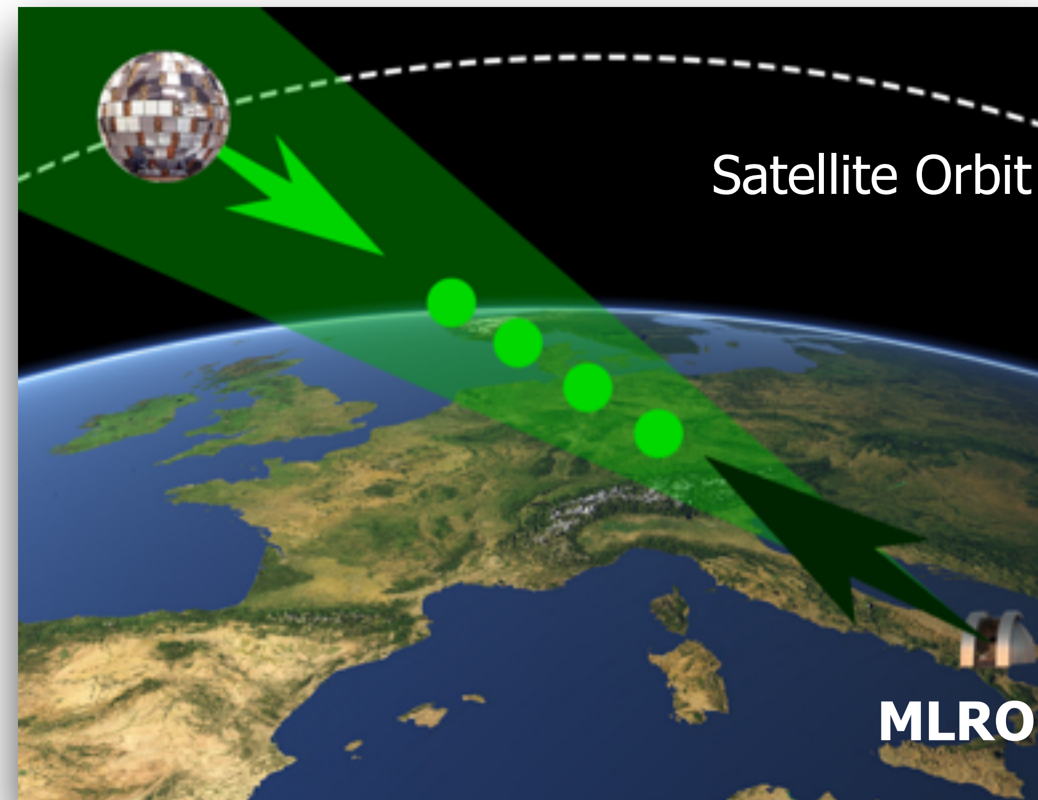
Satellite-based entanglement distribution over 1200 kilometers

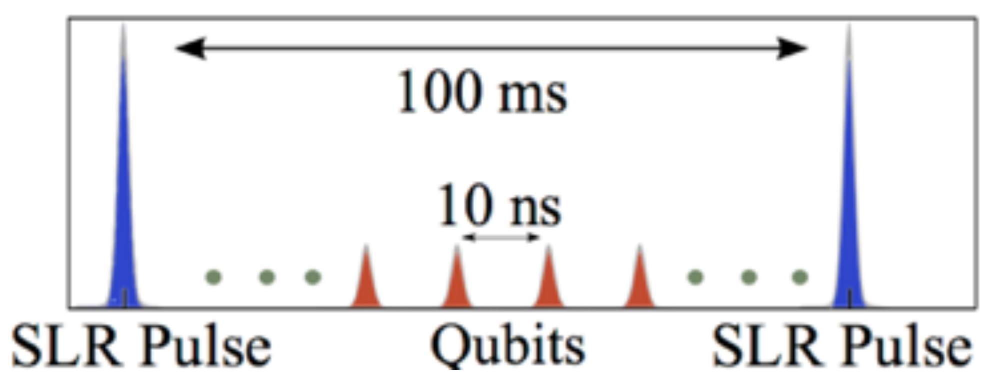
Juan Yin[1,2], Yuan Cao[1,2], Yu-Huai Li[1,2], Sheng-Kai Liao[1,2], Liang Zhang[2,3], Ji-Gang Ren[1,2], Wen-Qi Cai[1,2], Wei-Yue Liu[1,2], Bo ...
+ See all authors and affiliations

Science 16 Jun 2017:
Vol. 356, Issue 6343, pp. 1140-1144
DOI: 10.1126/science.aan3211

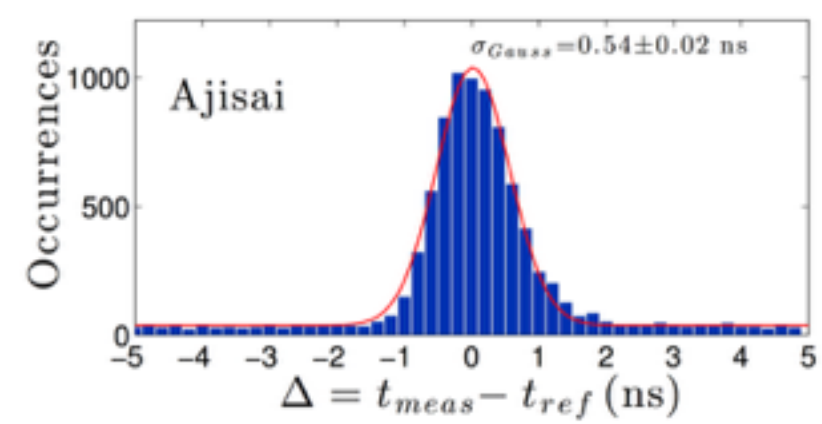
Experimental study of single photon transmission from satellites

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





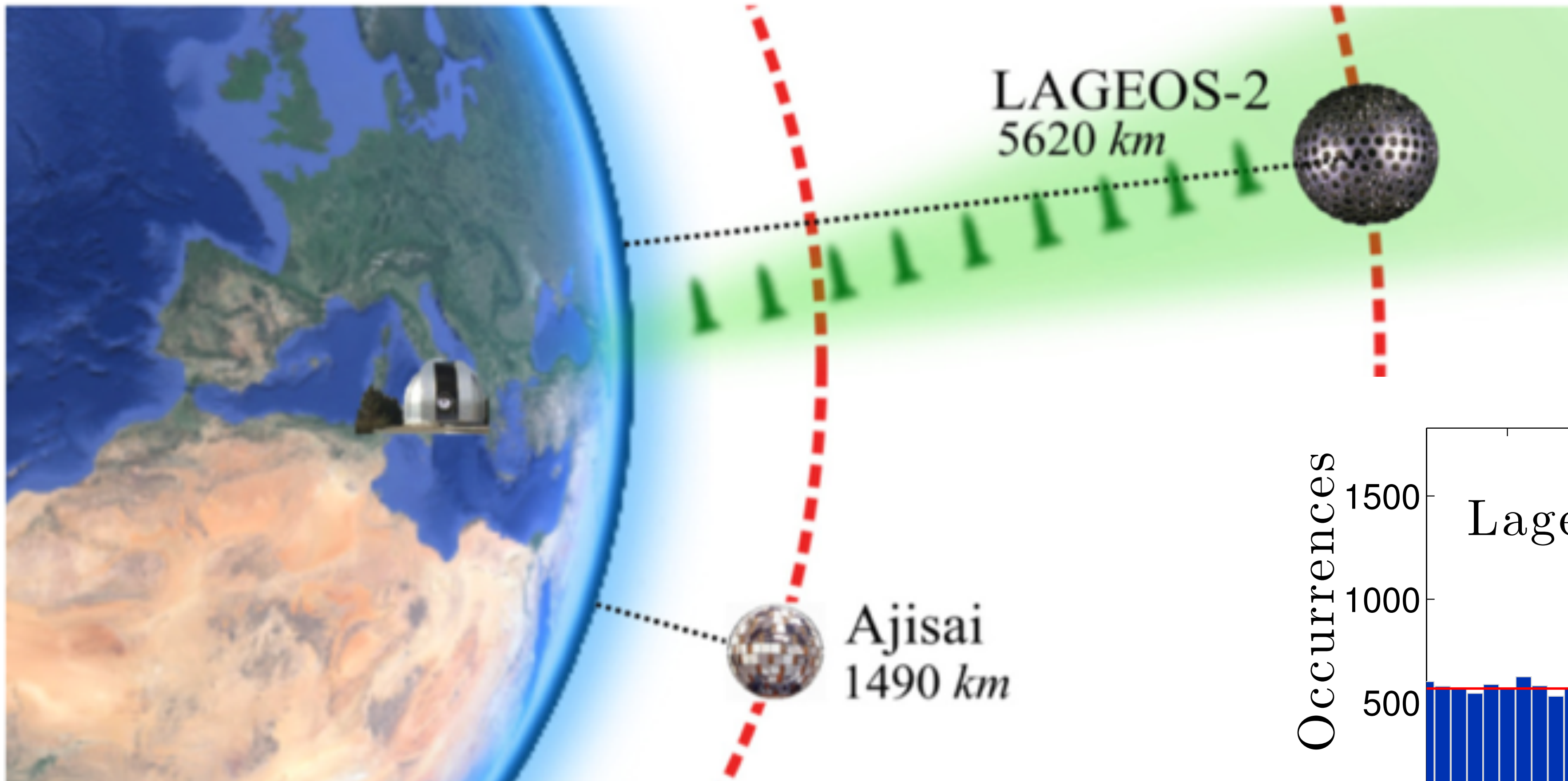
SLR laser: 10 Hz, ~100 mJ, @532 nm
Qubit laser: 100 MHz, ~1 nJ, @532 nm

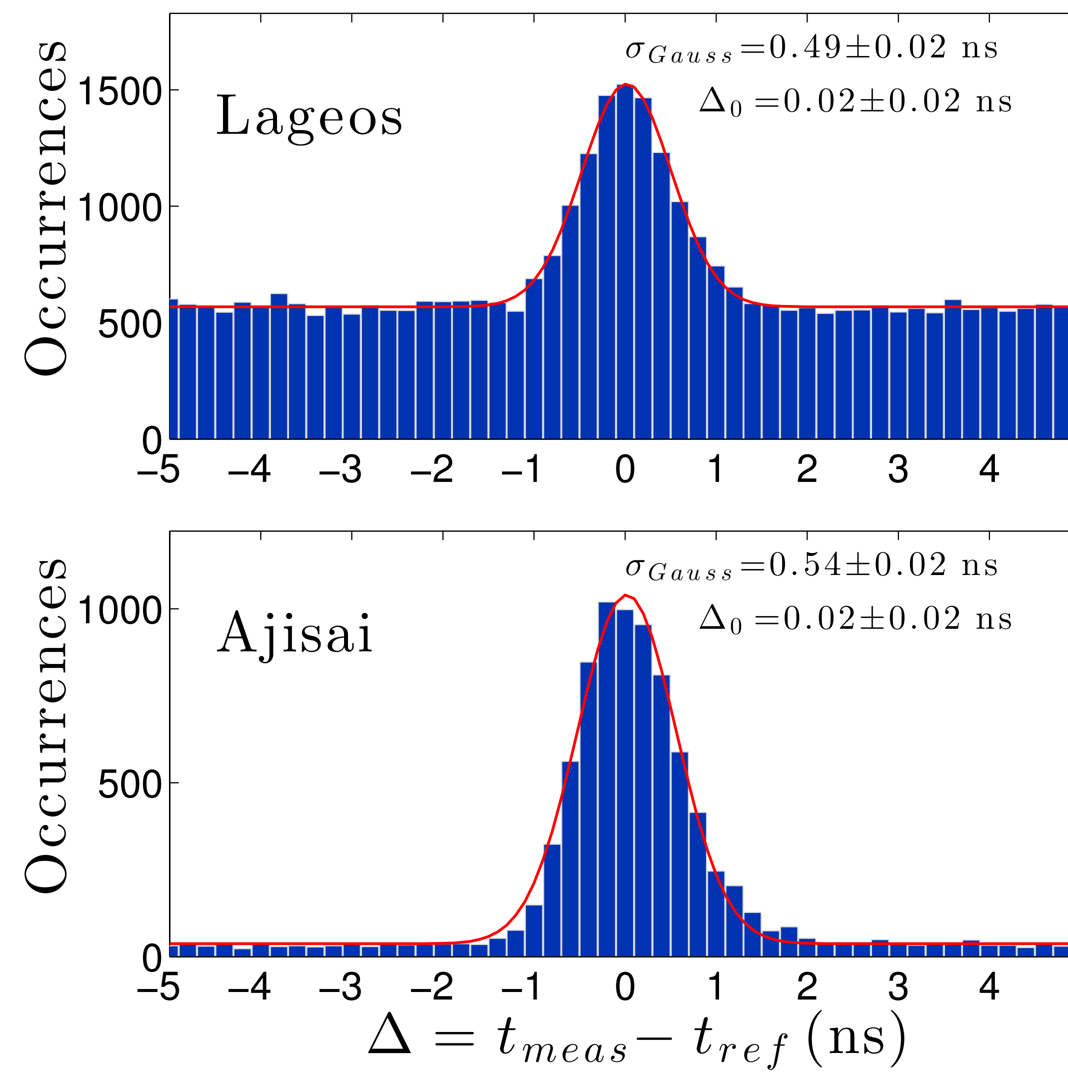


Typical detections histogram

C. Agnesi *et al.*, Phil. Trans. R. Soc. A **376**, 20170461 (2018)

Exchanging single-photons with satellites



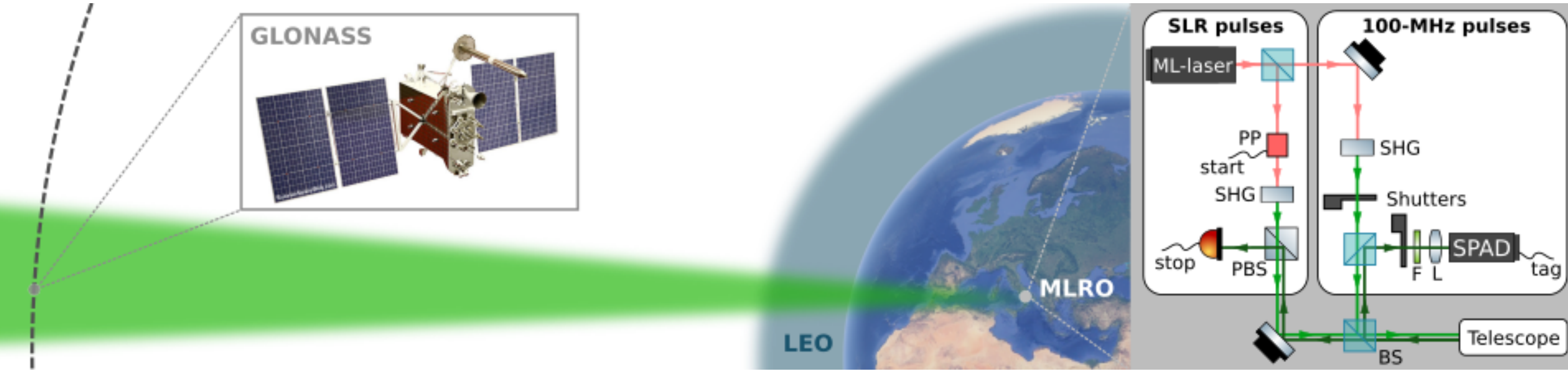


Extending the range of satellite QCs

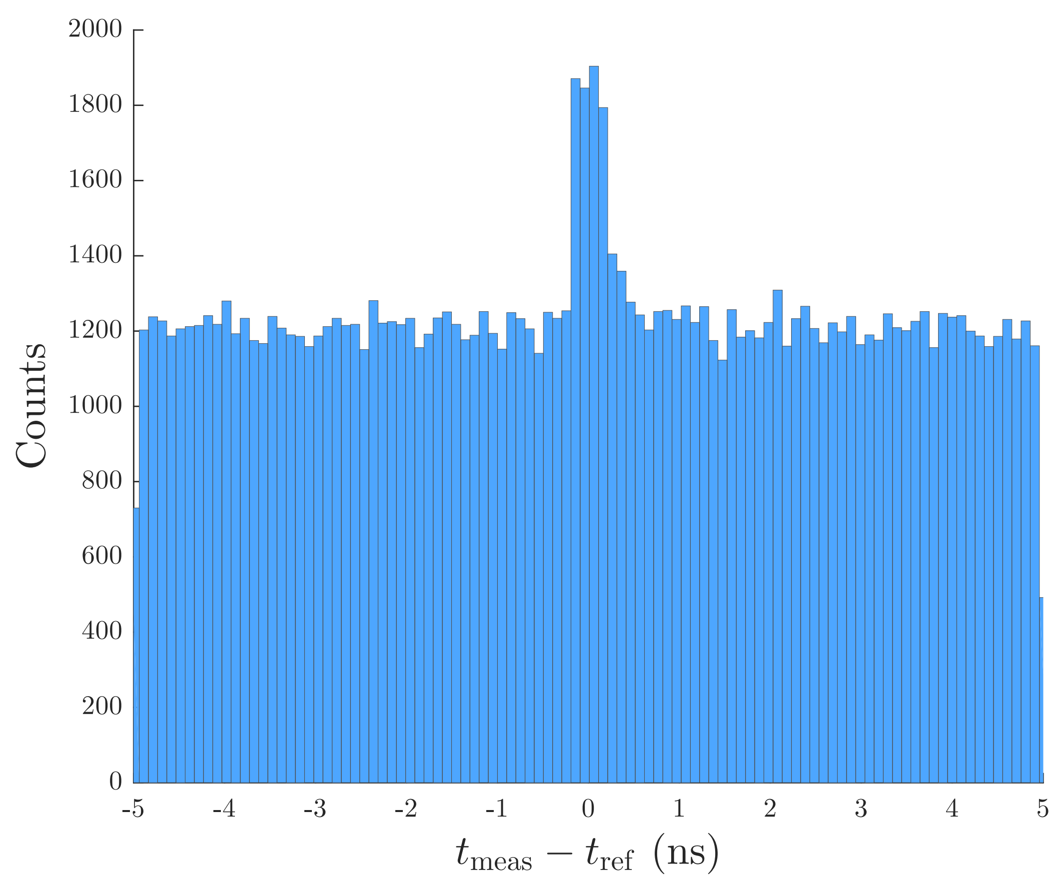
D. Dequal *et al.*, Phys. Rev. A **93**, 010301(R) (2016)

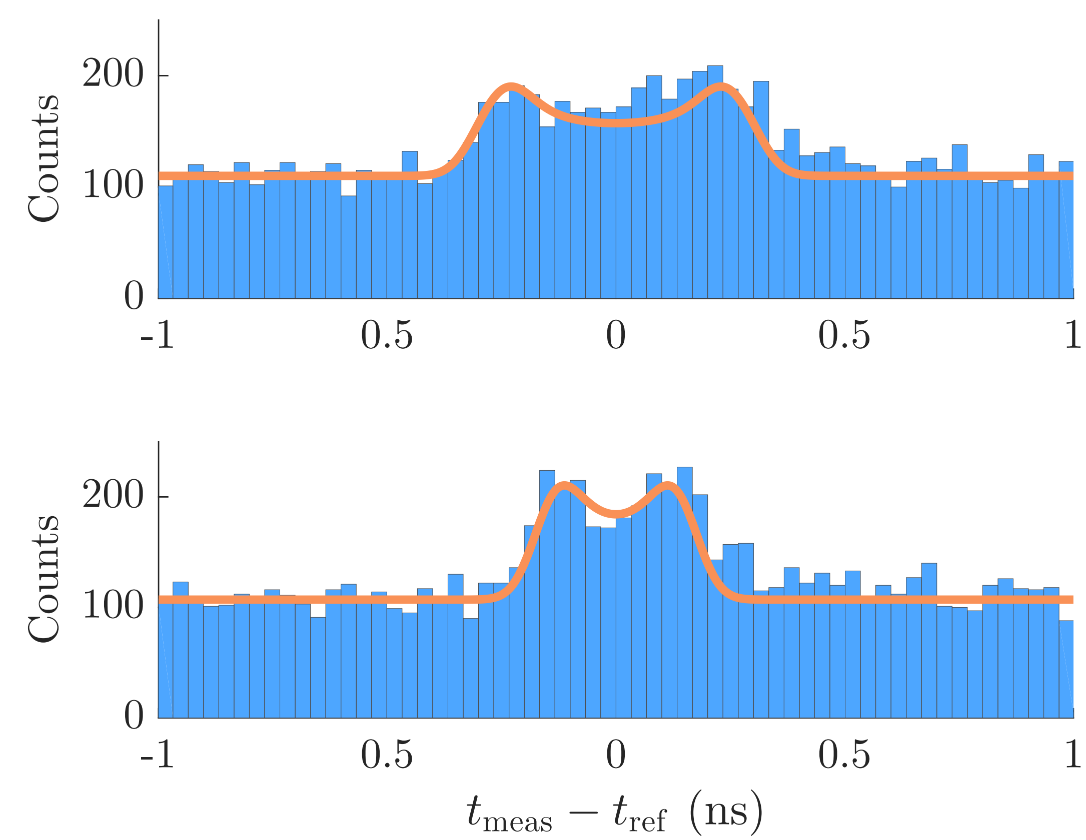
Exchanging single-photons with GNSS terminals

III PhD year



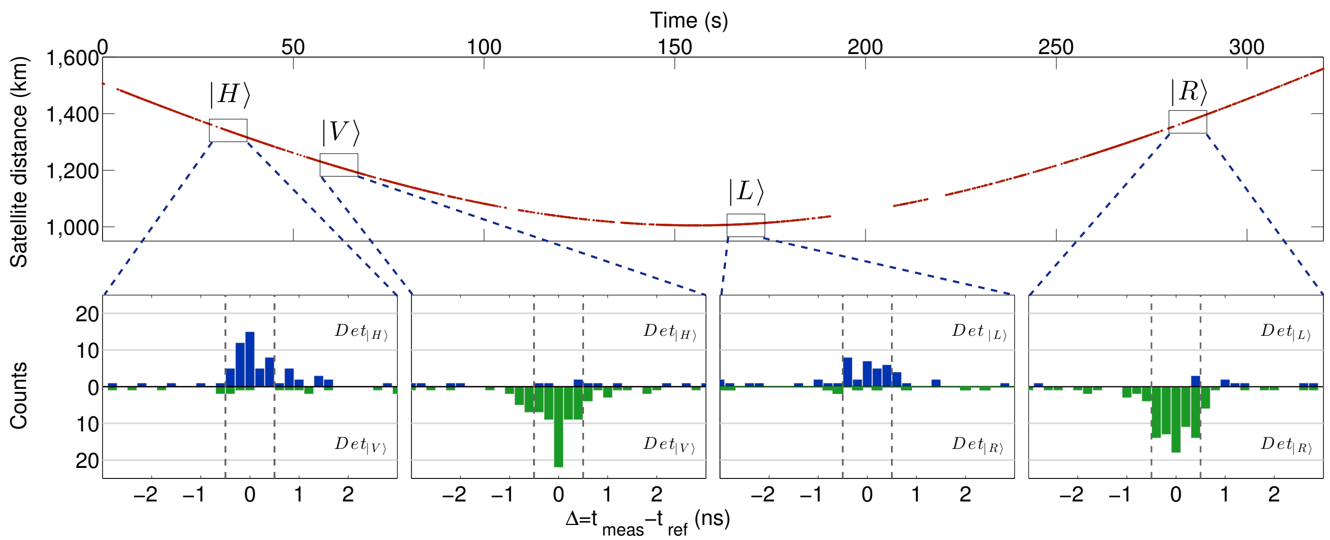
L. Calderaro *et al.*, arXiv:1804.05022 [quant- ph] (2018)





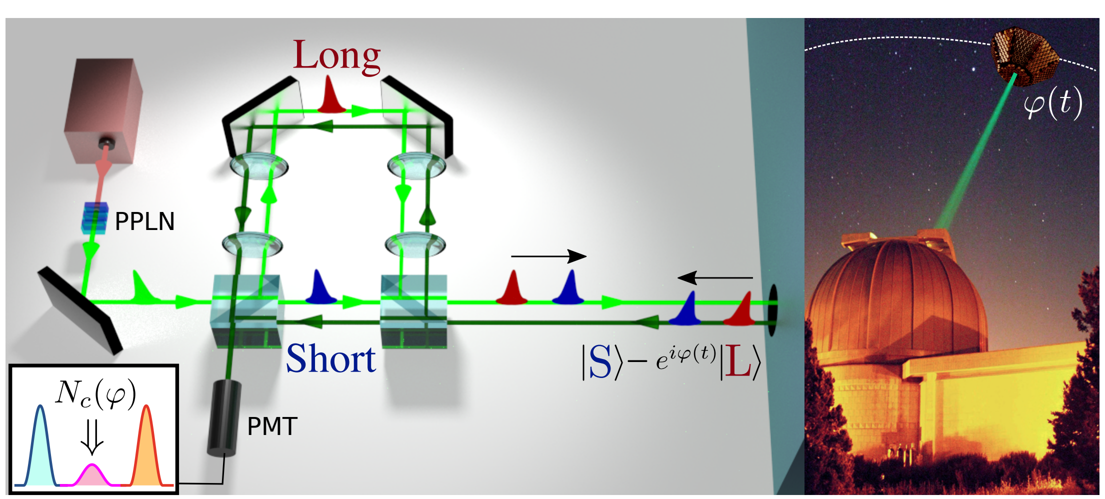
Feasibility of different photon encodings

Polarization



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

Time-bin



G. Vallone *et al.*, Phys. Rev. Lett. **116**, 253601 (2016)

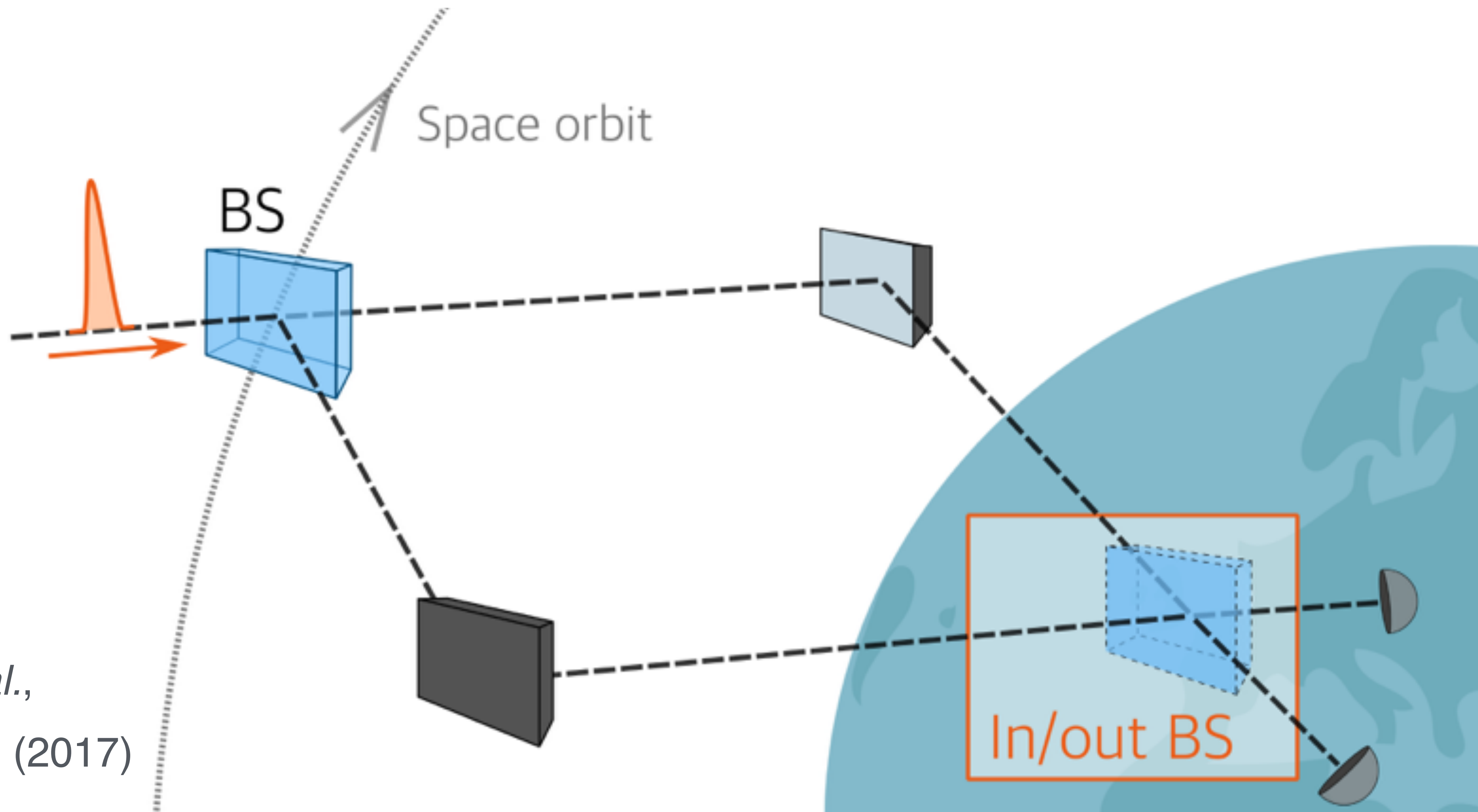
- **Photon polarization is preserved** along the free-space propagation
- We have access to **an interferometer which extends for thousands of kilometers in Space (I PhD year)**

Idea!

Extending Wheeler's delayed-choice to Space

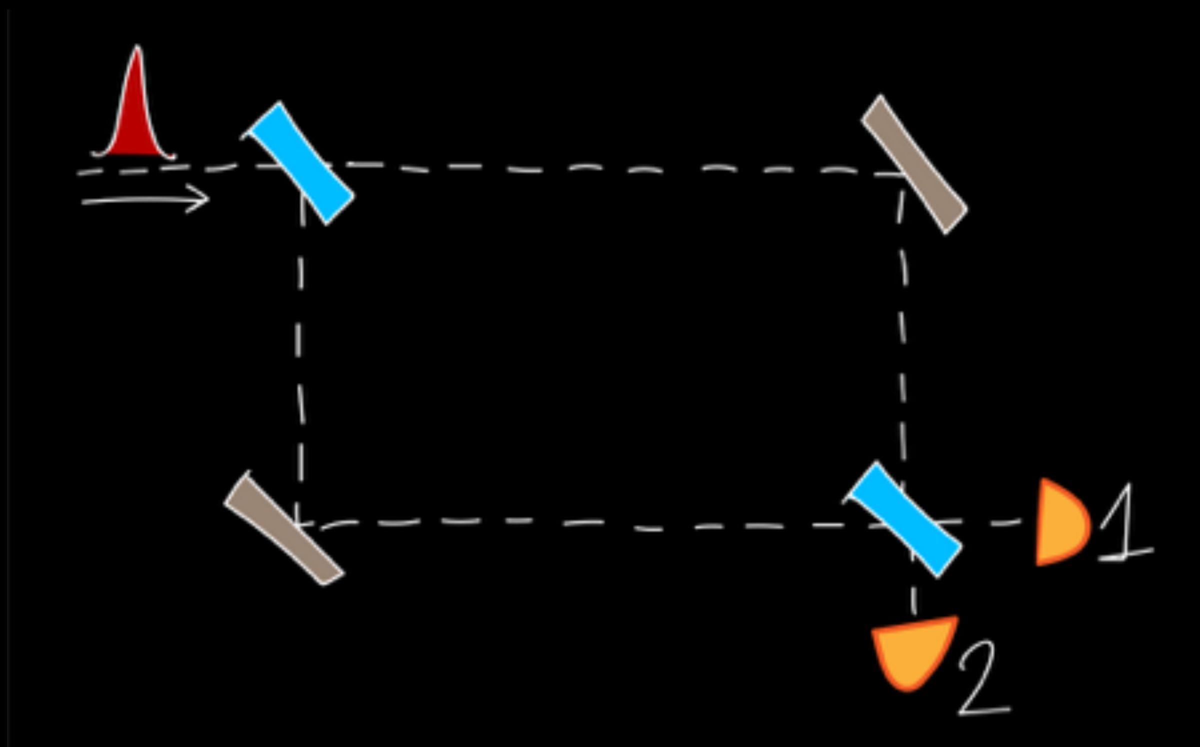
We implemented Wheeler's experiment **along a satellite-ground interferometer** which extends for thousands of kilometers **in space** allowing us to probe the laws of Nature at this unprecedented scale

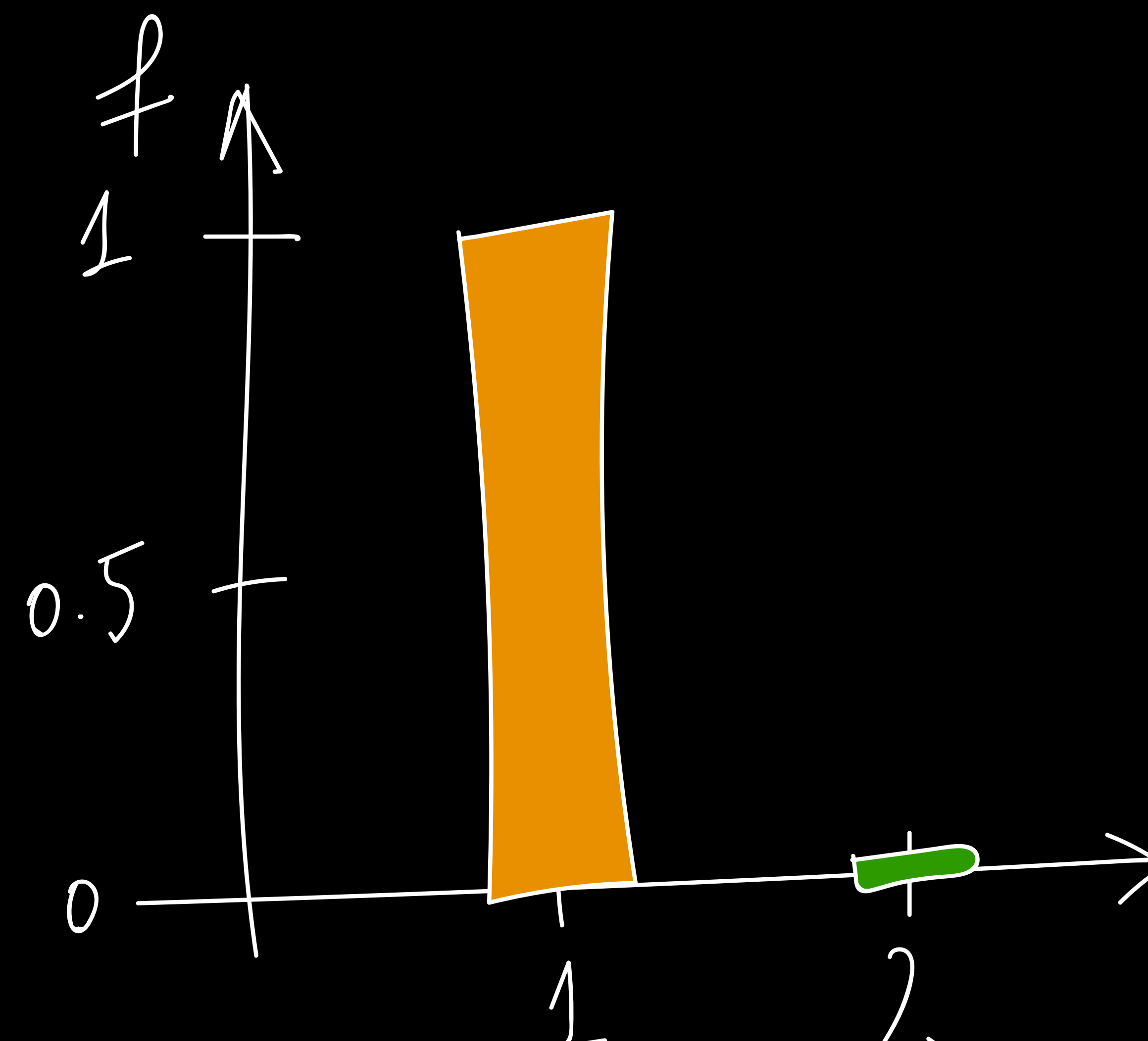
II PhD year

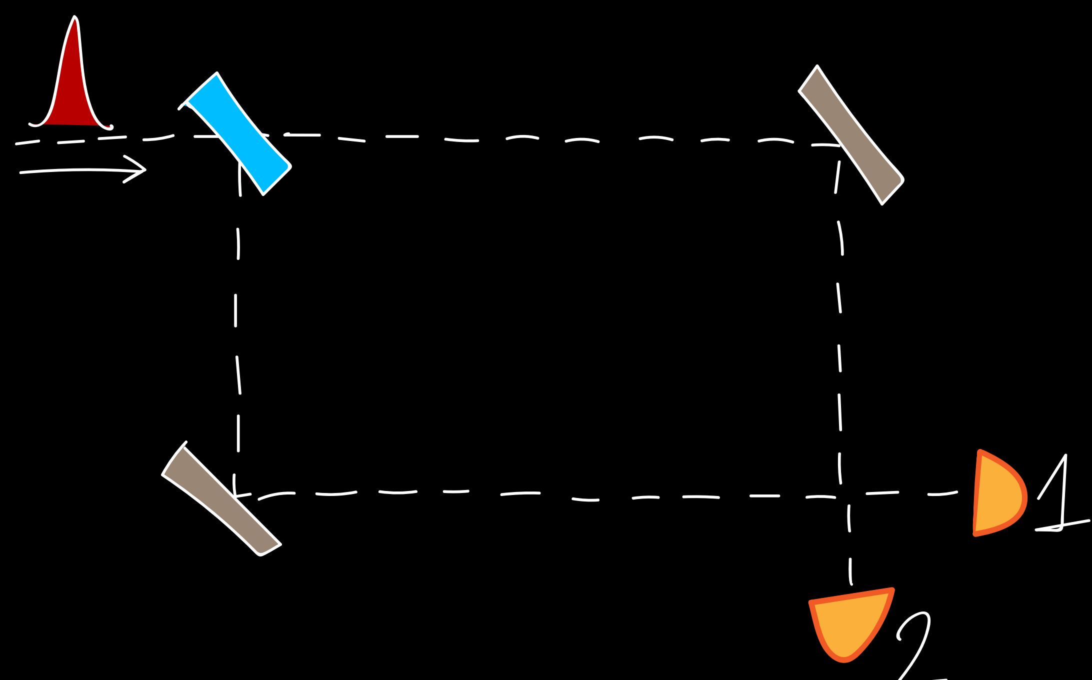


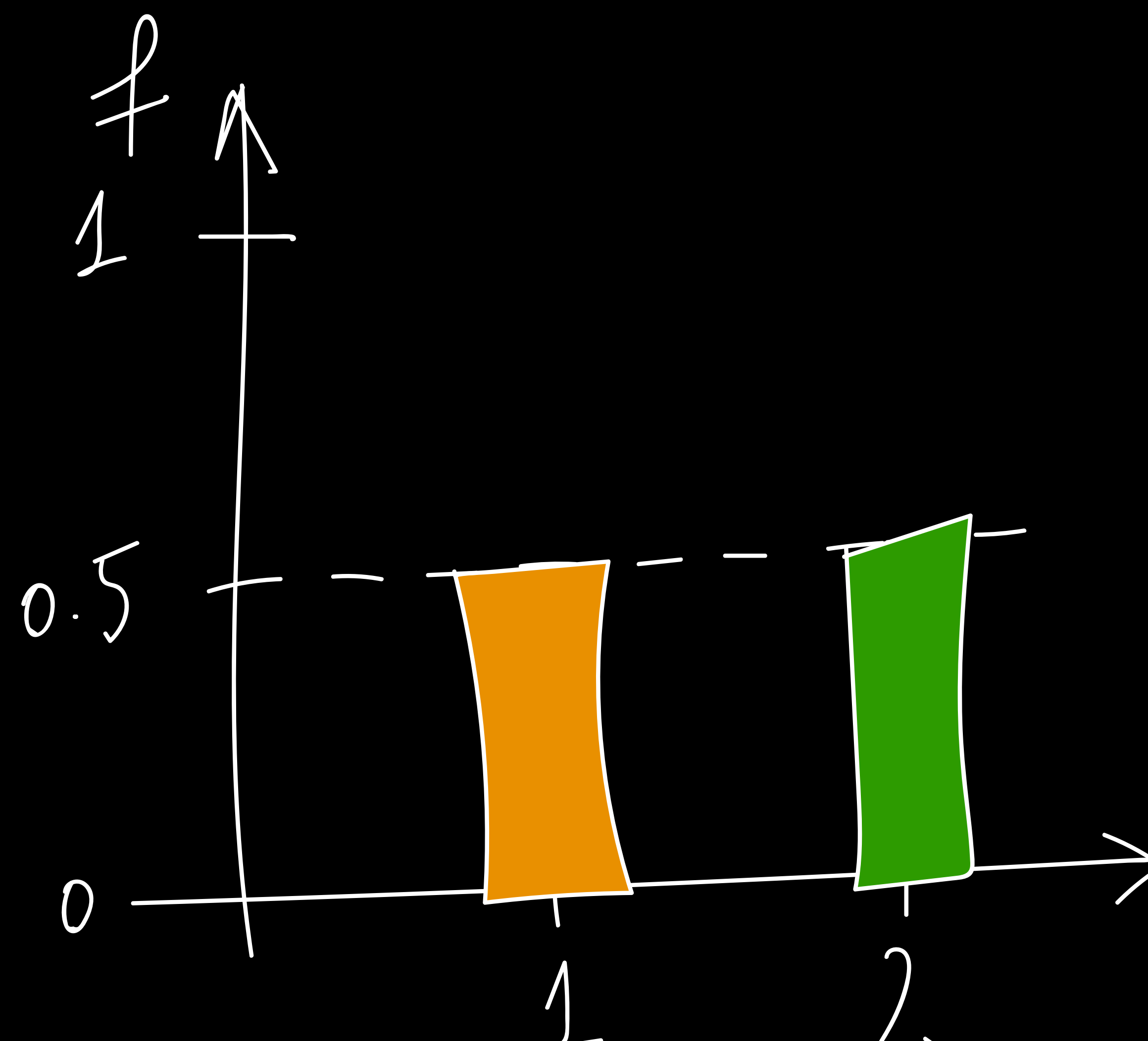
F. Vedovato *et al.*,

Sci. Adv. **3,** e1701180 (2017)


1
2


f
1
0.5
0
1
2


1
2


f
1
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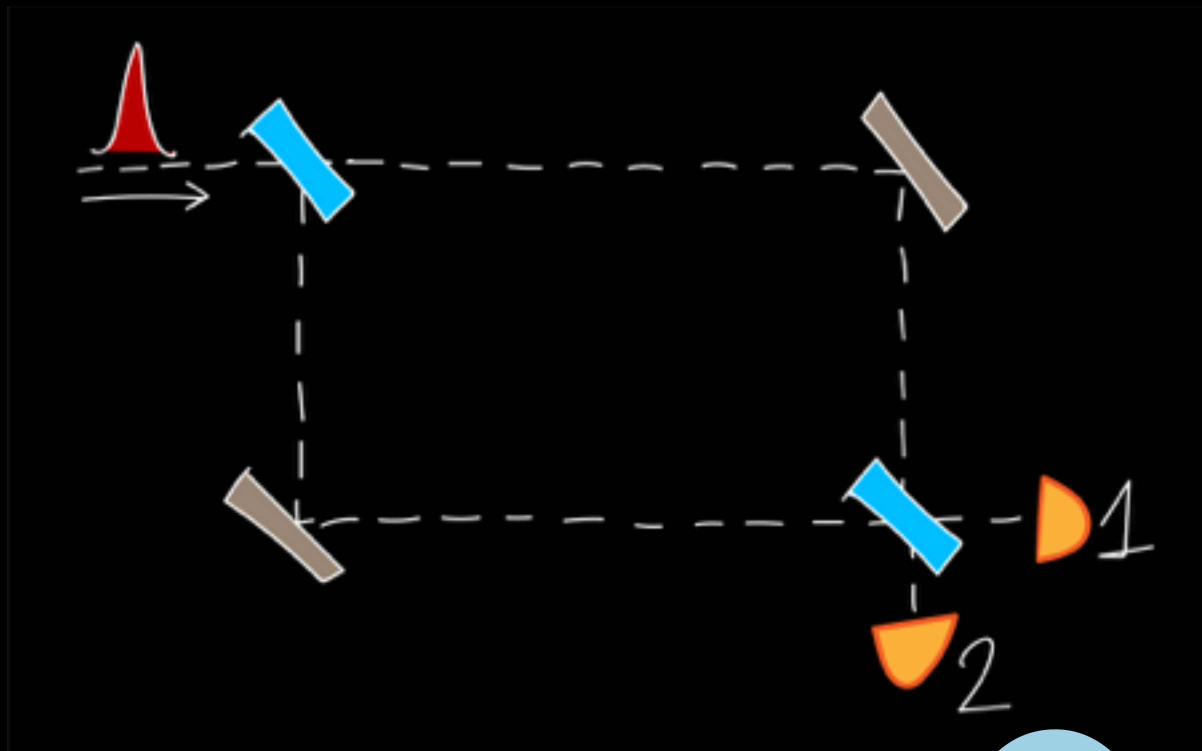
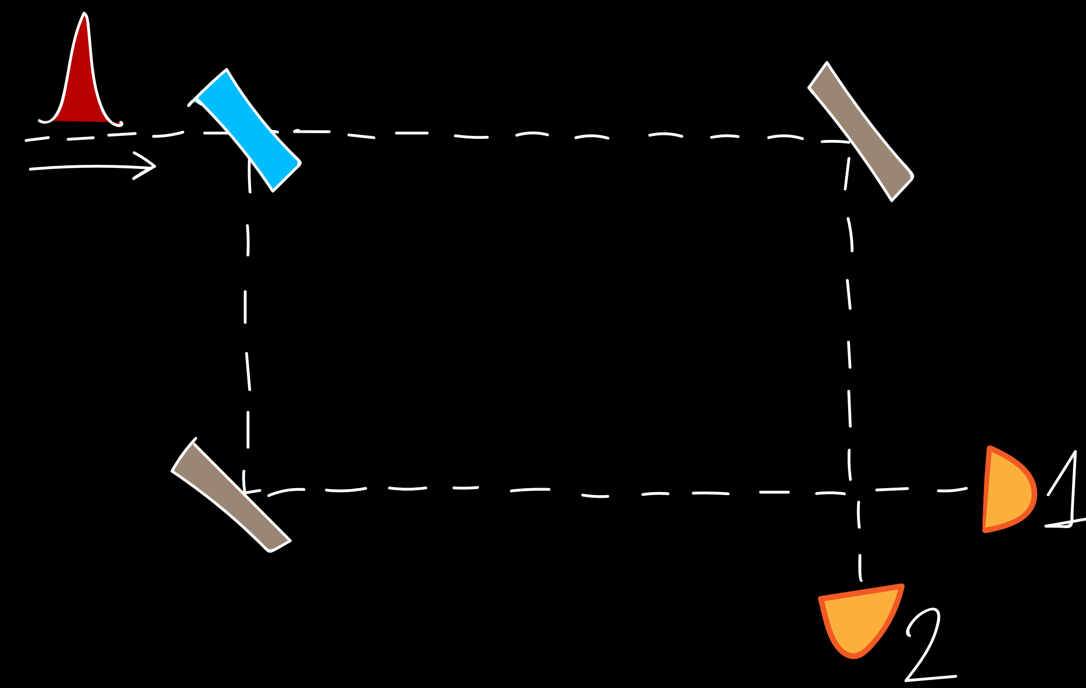
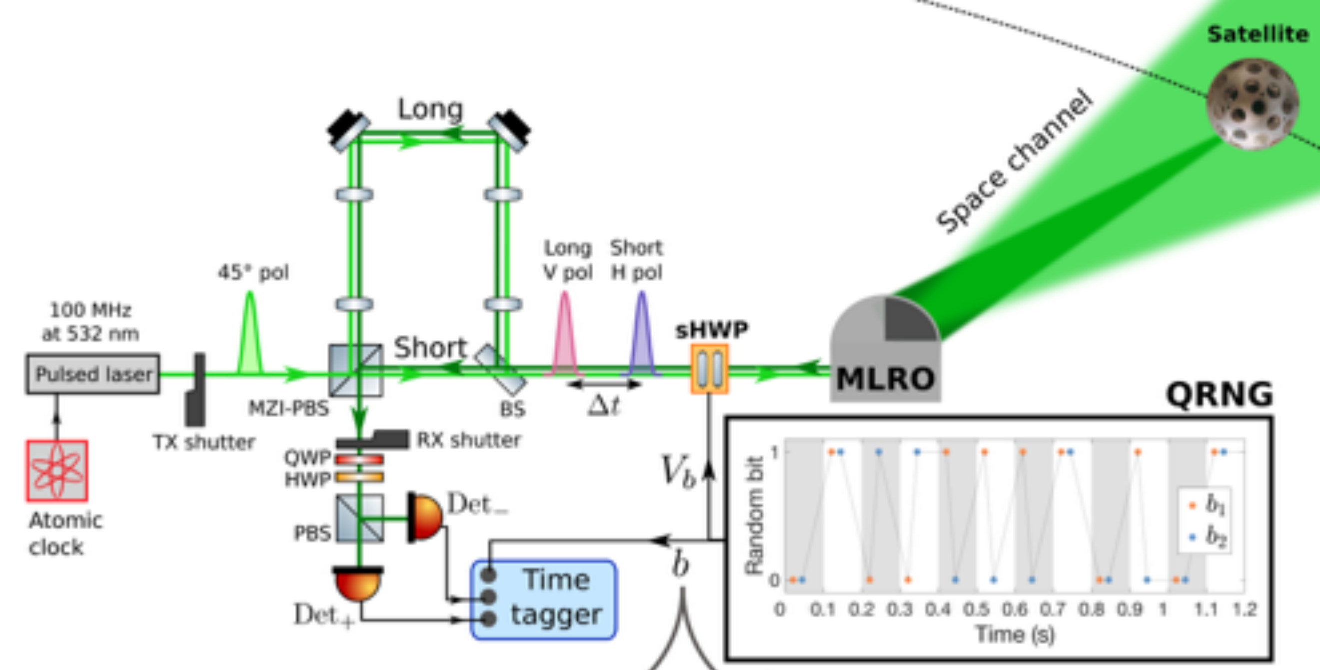


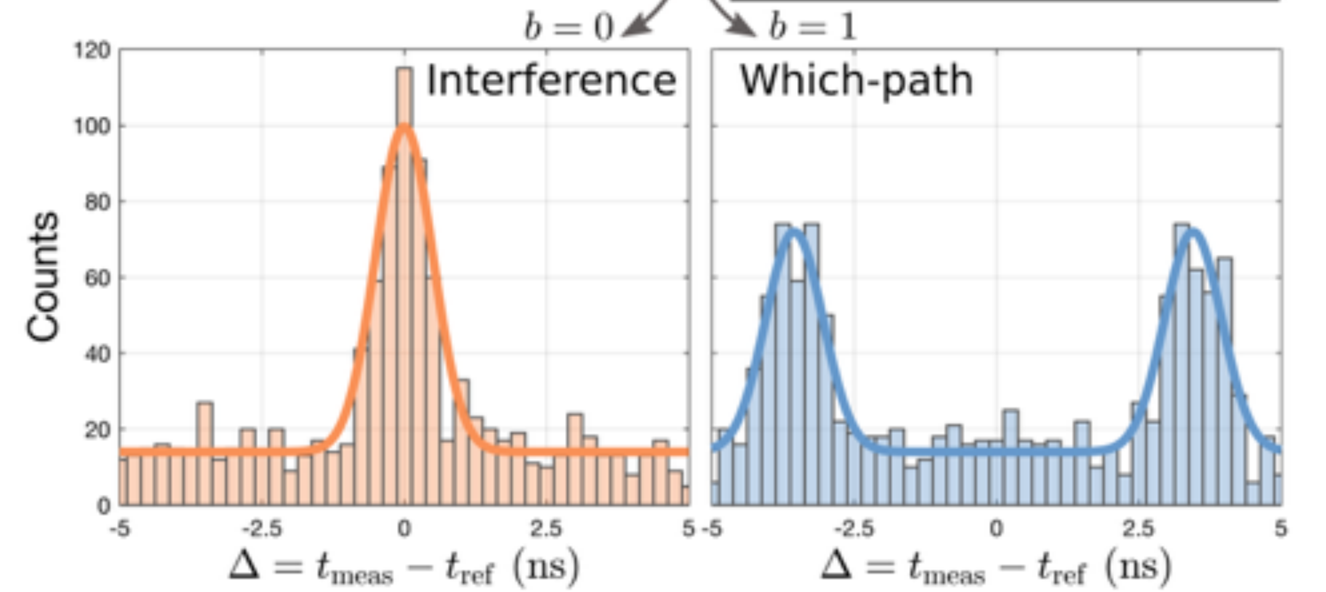


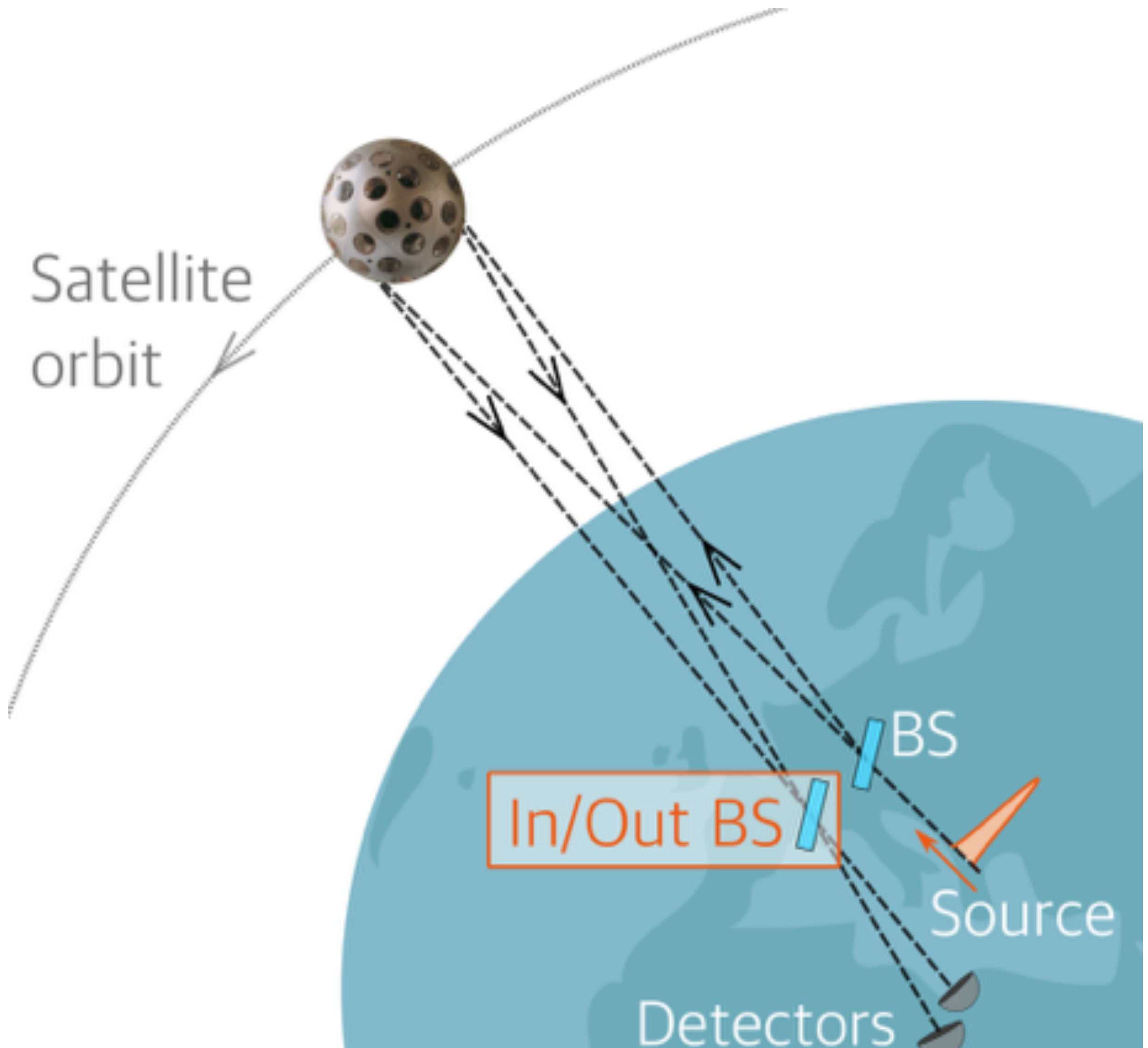
What if we delay the measurement choice?

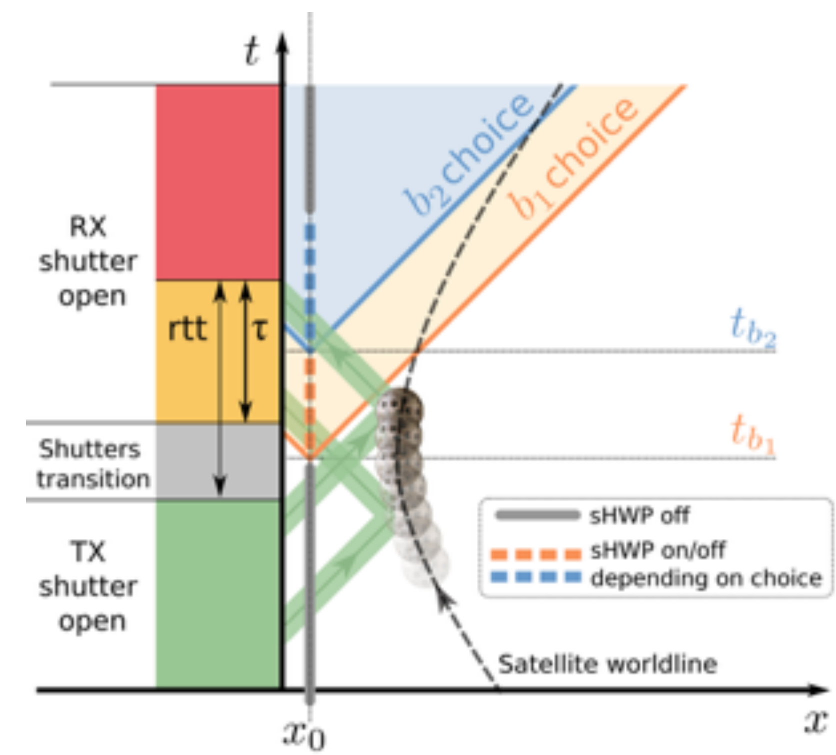
The actual implementation

- Two-way scheme
- Experimental setup combining time-bin and polarization encodings
- Random choice set by a QRNG
- Measurement choice space-like separated from photon-reflection at the satellite

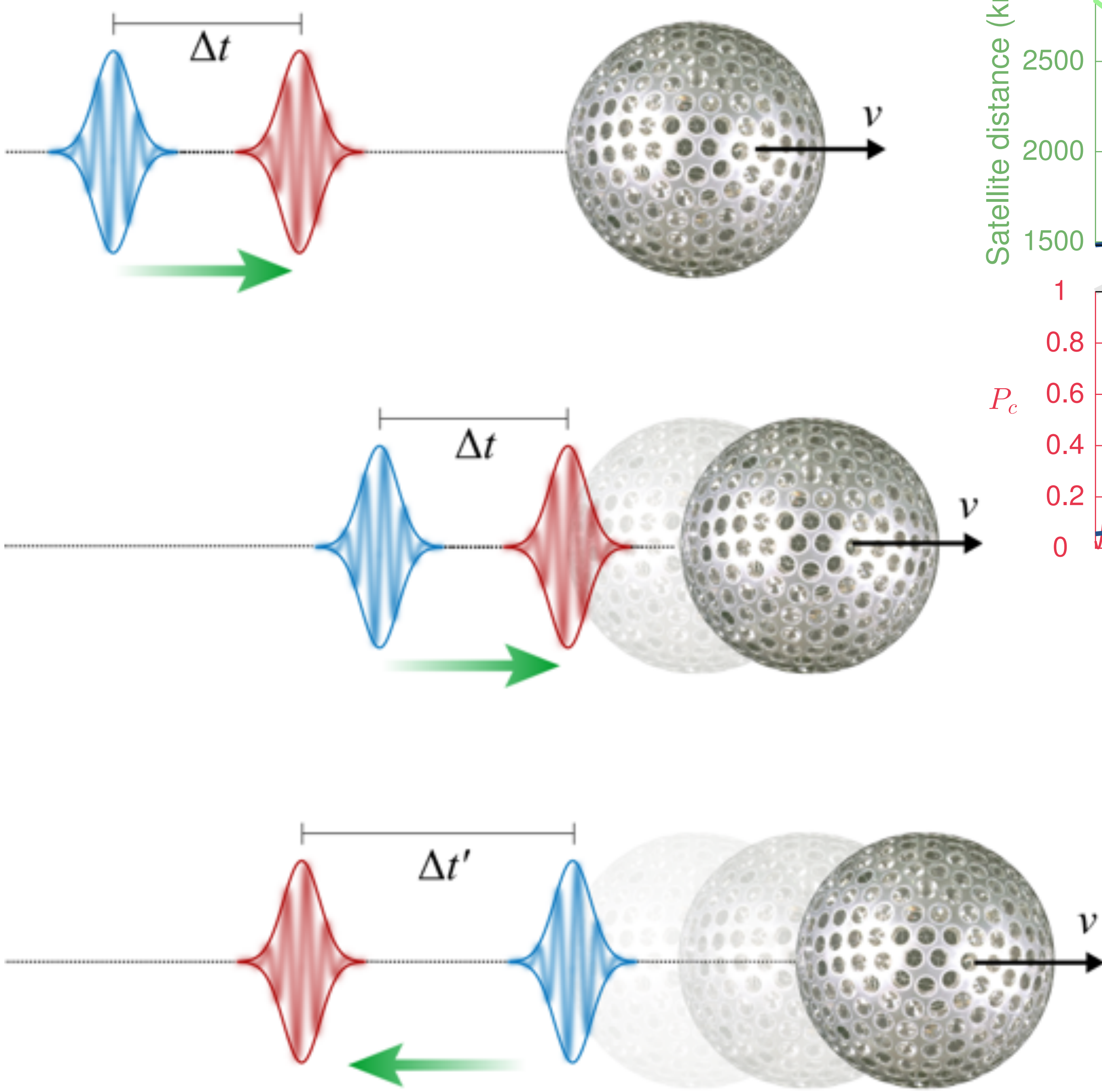


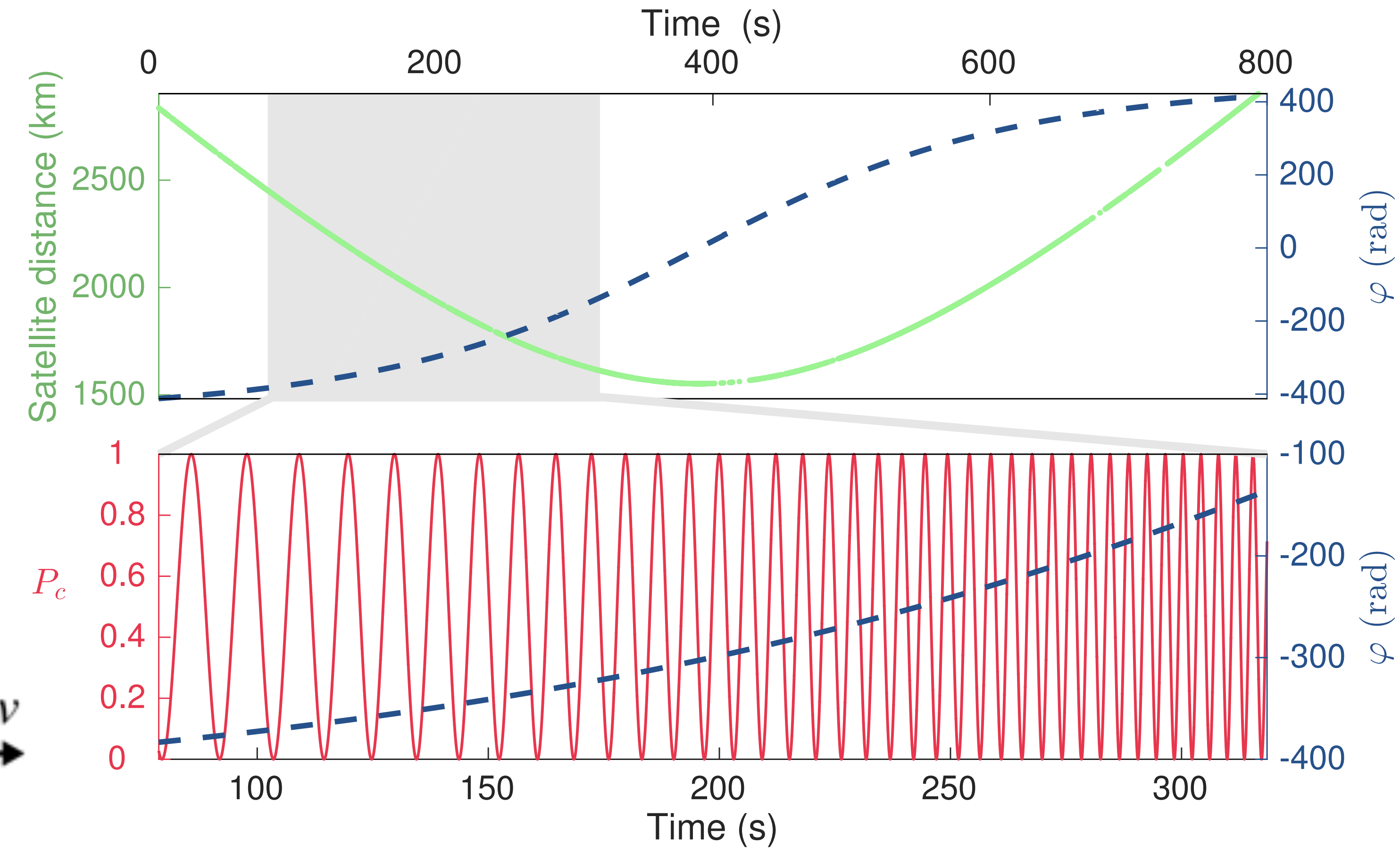






Satellite-induced interference pattern



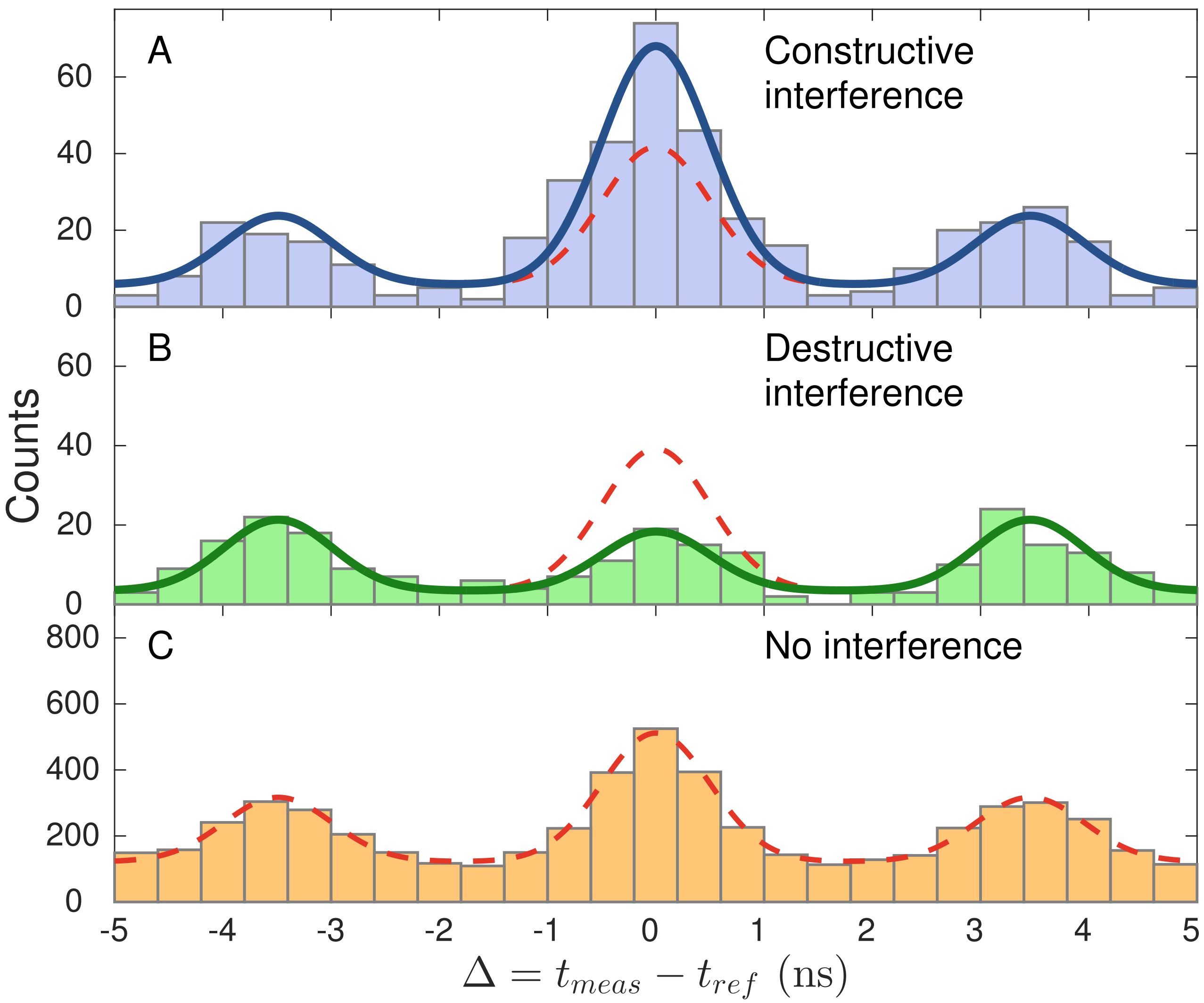


$$P_c(t) = \frac{1}{2}[1 - \mathcal{V}(t)\cos\varphi(t)]$$

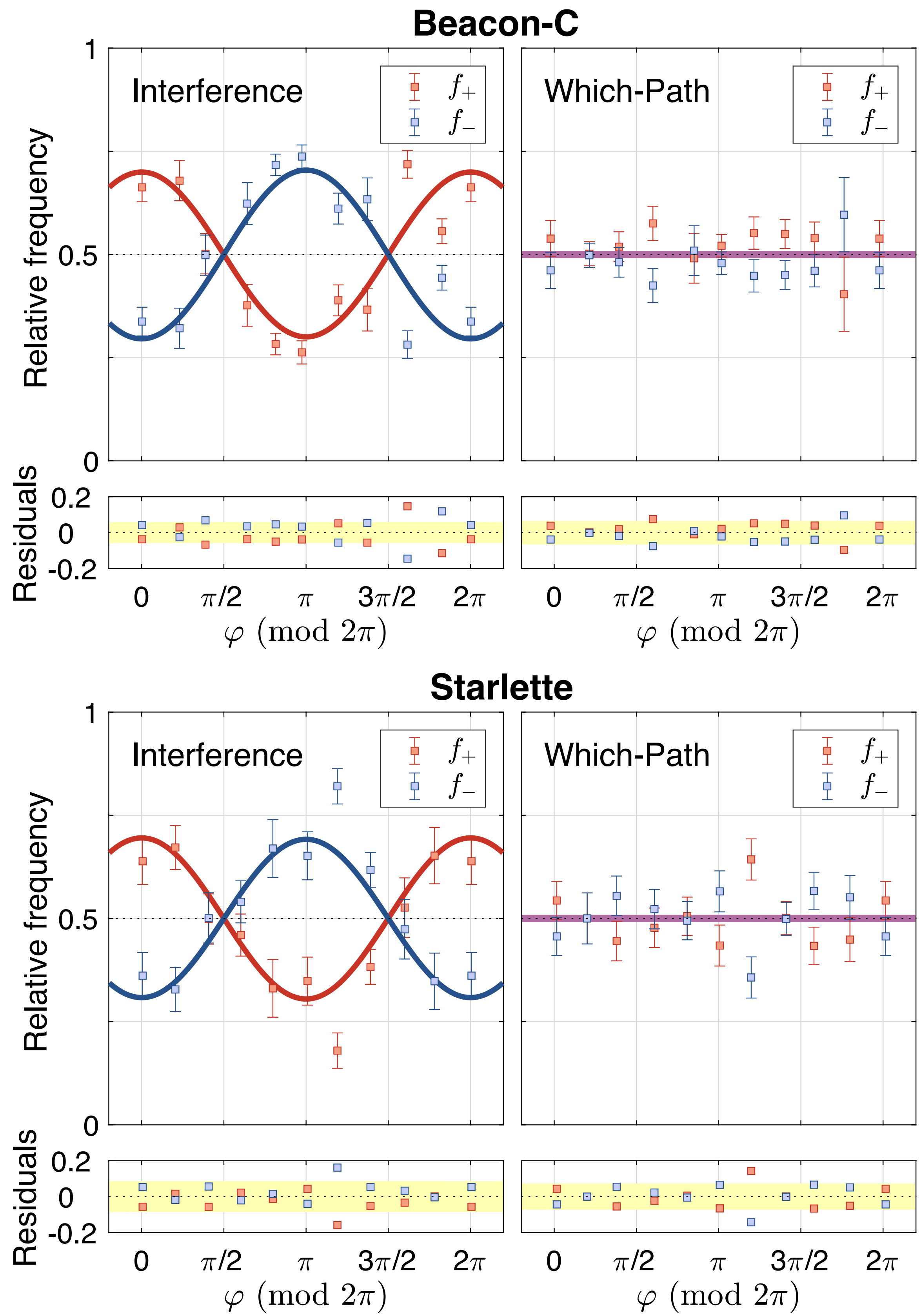
$$\mathcal{V}(t) = e^{-\frac{\lambda^2\varphi^2(t)}{8\pi c^2\tau_c^2}} \approx 1$$

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

Results



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

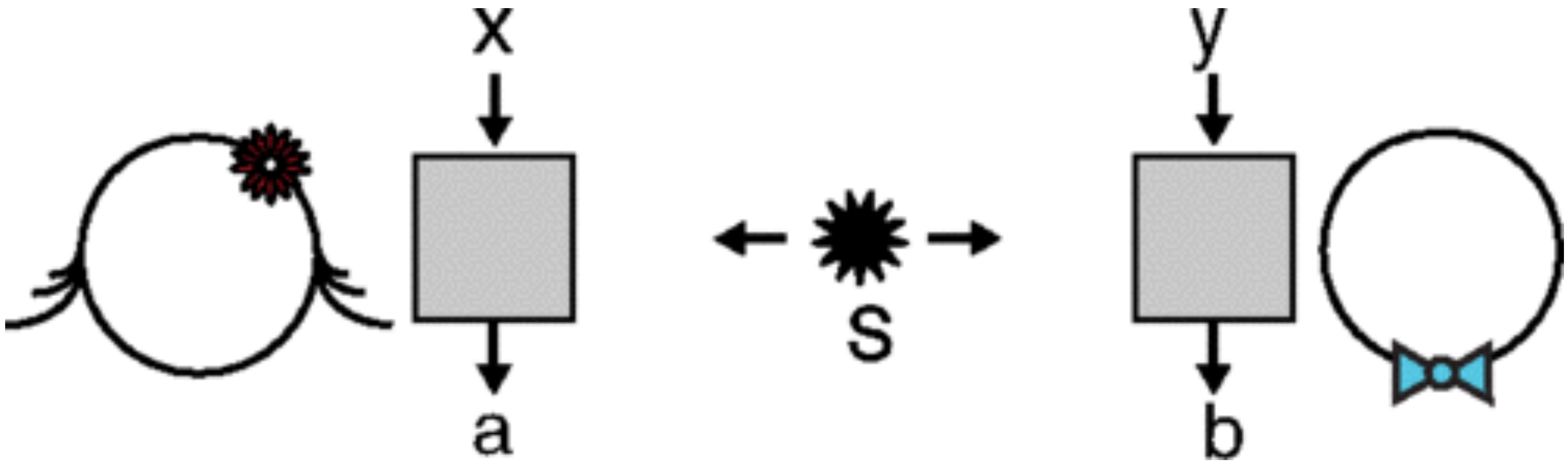


G. Vallone *et al.*,
Phys. Rev. Lett. **116**, 253601 (2016)

F. Vedovato *et al.*,
Sci. Adv. **3,** e1701180 (2017)

Bell test of local realistic theories

II-III PhD year



Inputs: $x, y \in \{0, 1\}$

Outputs: $a, b \in \{-1, +1\}$

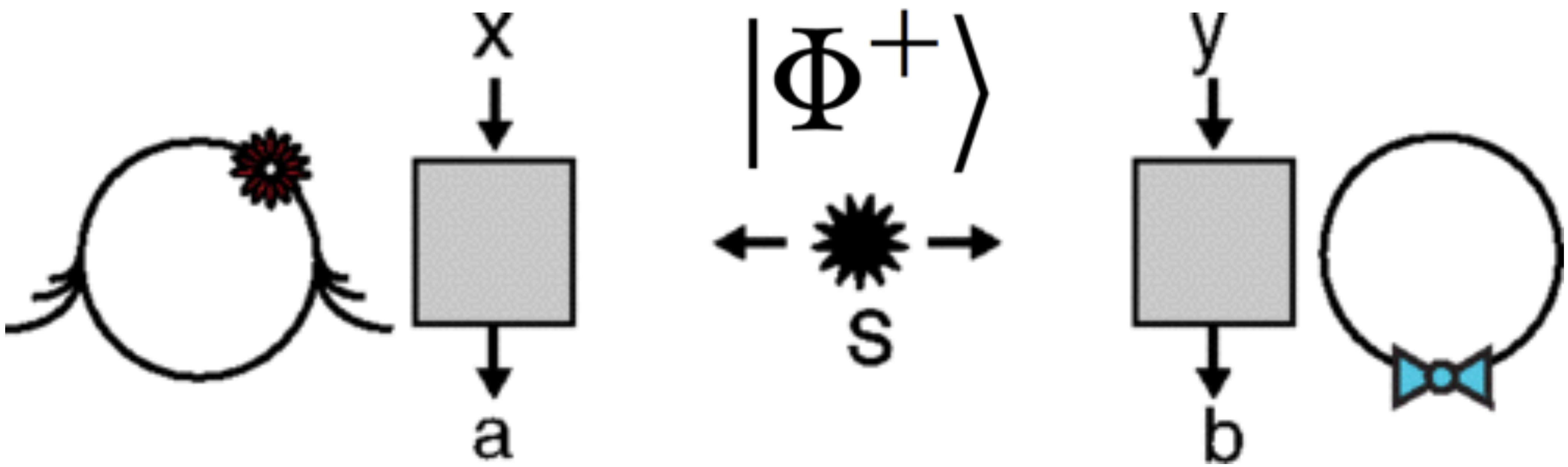
$$\langle a_x b_y \rangle = \sum_{a,b} a\, b\, p(a, b|x, y)$$

$$S_{\mathrm{LR}} := \langle a_0 b_0 \rangle + \langle a_0 b_1 \rangle + \langle a_1 b_0 \rangle - \langle a_1 b_1 \rangle \leq 2$$

Bell-CHSH inequality

Bell test with entangled states

II-III PhD year



Inputs: $x, y \in \{0, 1\}$

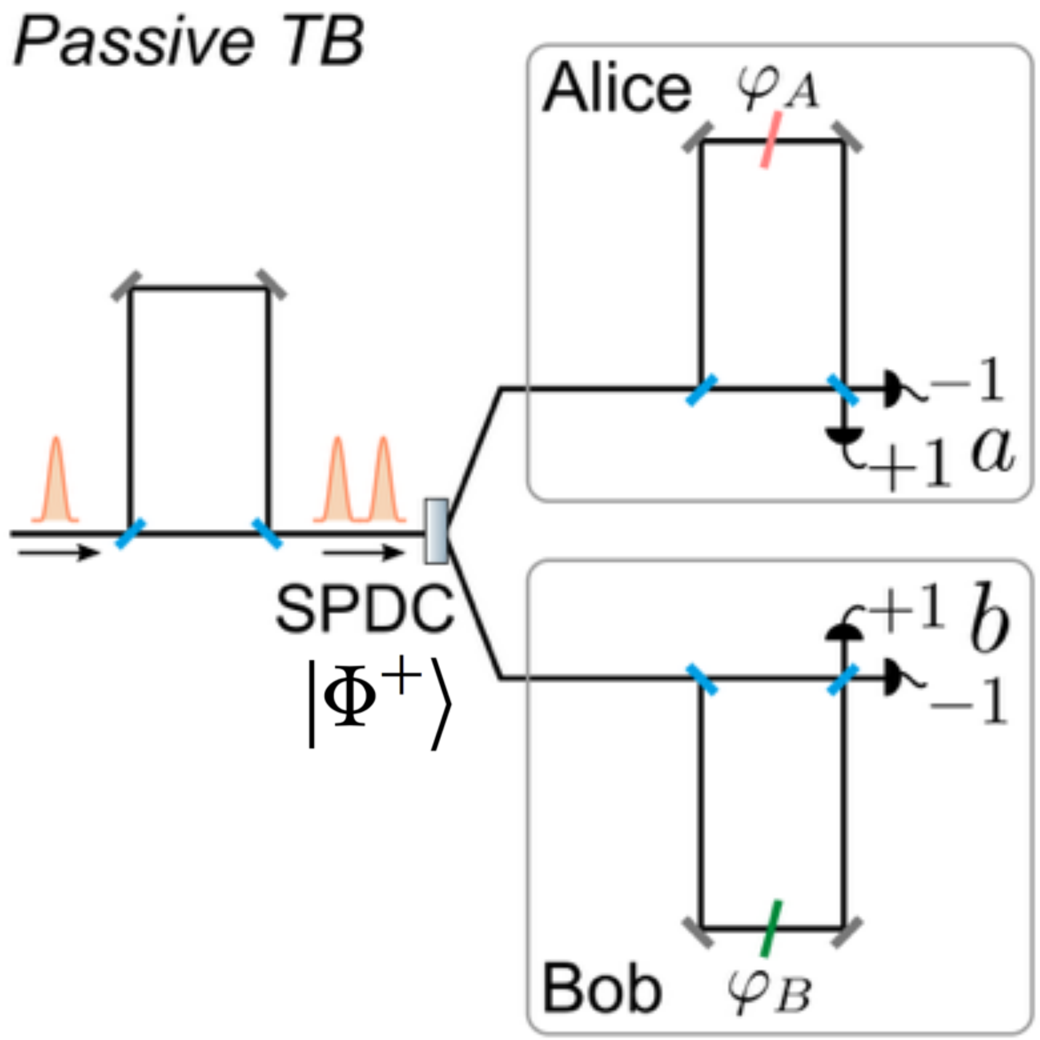
Outputs: $a, b \in \{-1, +1\}$

$$\langle a_x b_y \rangle = \langle \Phi^+ | \hat{O}_{a|x} \otimes \hat{O}_{b|y} | \Phi^+ \rangle$$

$$S_{QM} = 2\sqrt{2} > 2$$

Franson's Bell test with time-bin entanglement

II-III PhD year



Inputs: $\varphi_A \in \{-\pi/4, \pi/4\}$, $\varphi_B \in \{0, \pi/2\}$

Outputs: $a, b \in \{-1, +1\}$

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|S\rangle_A|S\rangle_B + |L\rangle_A|L\rangle_B)$$

$$\hat{P}_{a|\varphi_A} = |\psi_a^{\varphi_A}\rangle\langle\psi_a^{\varphi_A}|$$

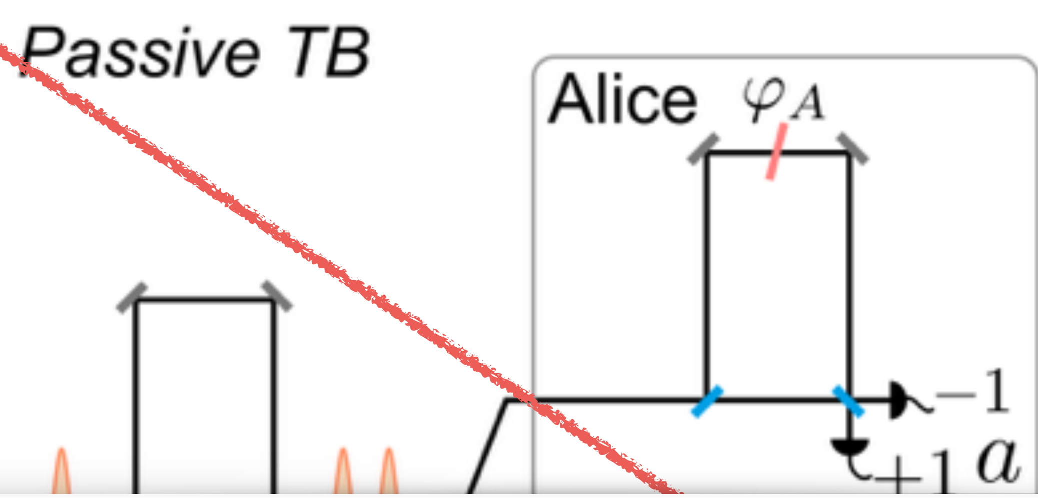
$$|\psi_a^{\varphi_A}\rangle = \frac{1}{\sqrt{2}}(|S\rangle + a\ e^{i\varphi_A}|L\rangle)$$

$$p(a,b|\varphi_A,\varphi_B) = \langle\Phi^+|\hat{P}_{a|\varphi_A}\otimes\hat{P}_{b|\varphi_B}|\Phi^+\rangle = \frac{1}{4}[1 + ab\,\mathcal{V}\cos(\varphi_A+\varphi_B)]$$

$$S_{\max} = 2\sqrt{2}\mathcal{V} > 2 \text{ if } \mathcal{V} > 0.71$$

Franson's Bell test with time-bin entanglement

II-III PhD year



Inputs: $\varphi_A \in \{-\pi/4, \pi/4\}$, $\varphi_B \in \{0, \pi/2\}$

Outputs: $a, b \in \{-1, +1\}$

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|S\rangle|S\rangle + |L\rangle|L\rangle)$$

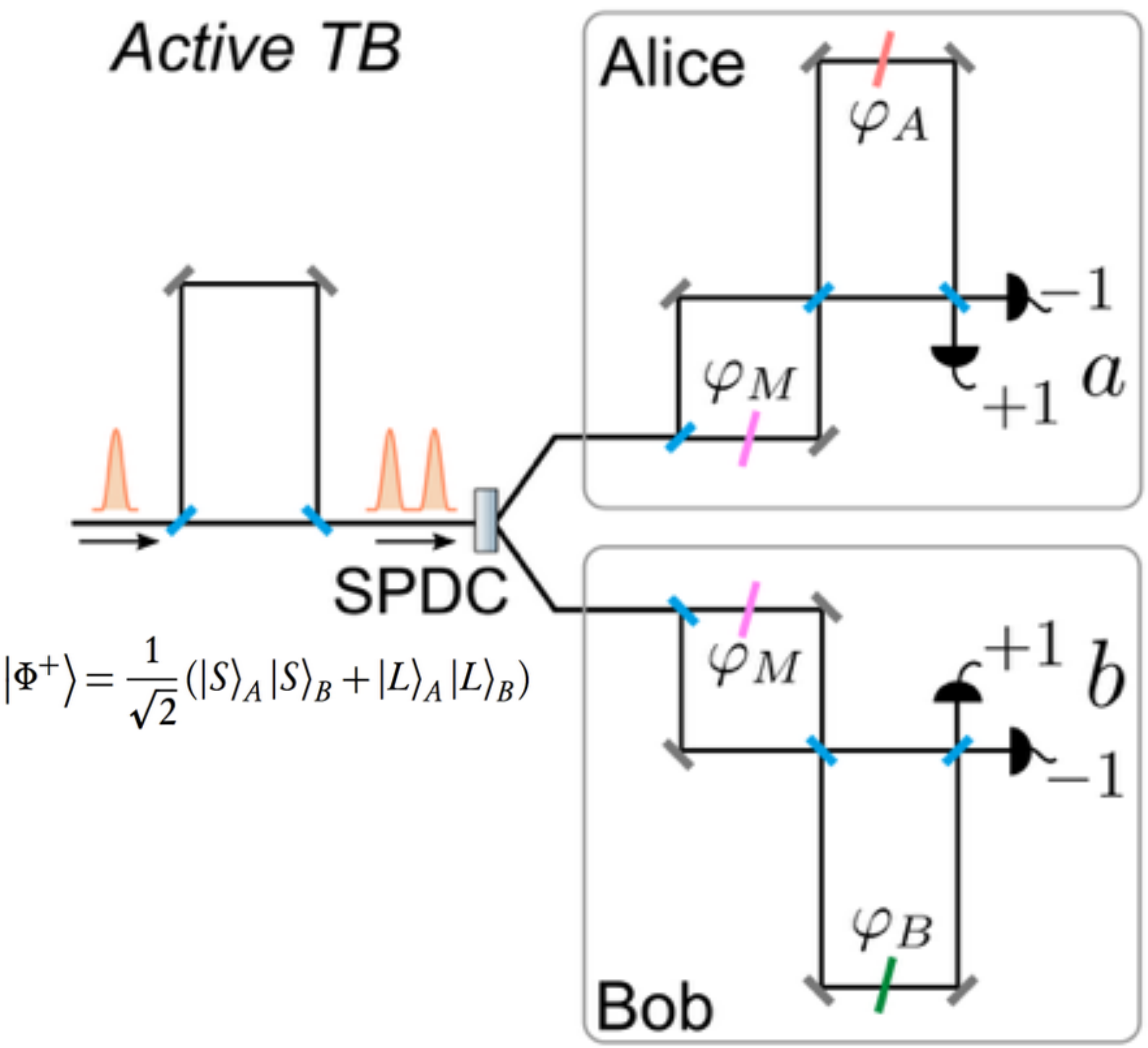
POST-SELECTION LOOPHOLE

$$p(a,b|\varphi_A,\varphi_B) = \langle\Phi^+|\,\hat{P}_{a|\varphi_A} \otimes \hat{P}_{b|\varphi_B}\,|\Phi^+\rangle = \frac{1}{4}[1 + ab\,\mathcal{V}\cos(\varphi_A + \varphi_B)]$$

$$S_{\max} = 2\sqrt{2}\,\mathcal{V} > 2 \text{ if } \mathcal{V} > 0.71$$

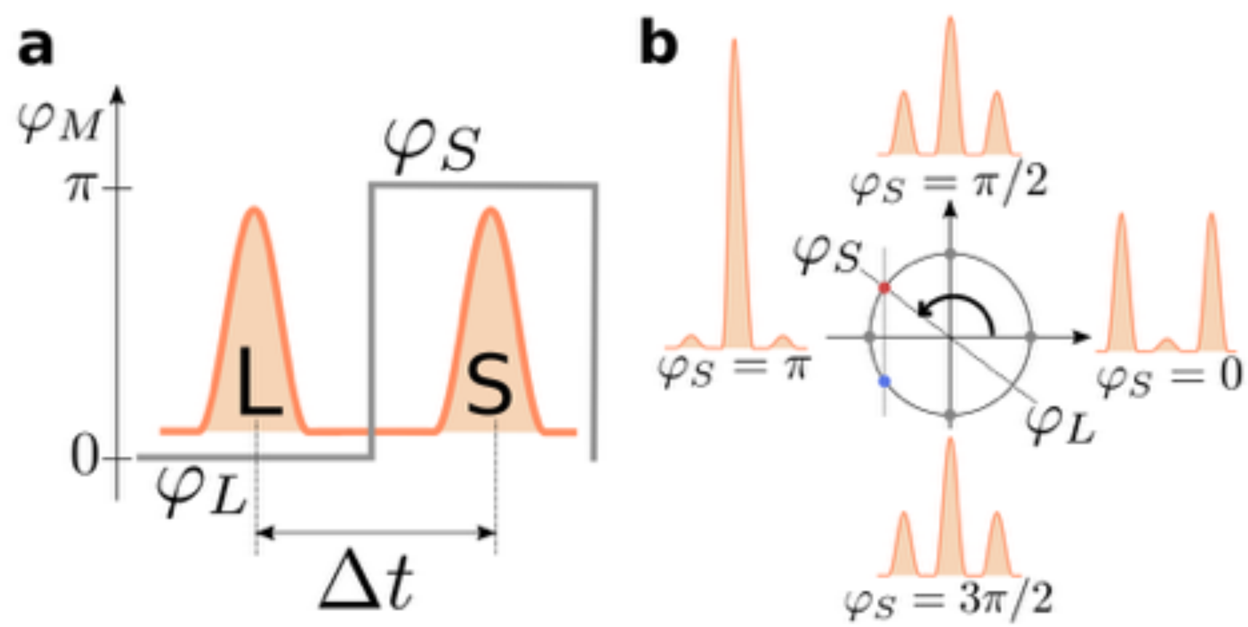
Bell test with *genuine* time-bin entanglement

II-III PhD year



Inputs: $\varphi_A \in \{-\pi/4, \pi/4\}$, $\varphi_B \in \{0, \pi/2\}$

Outputs: $a, b \in \{-1, +1\}$

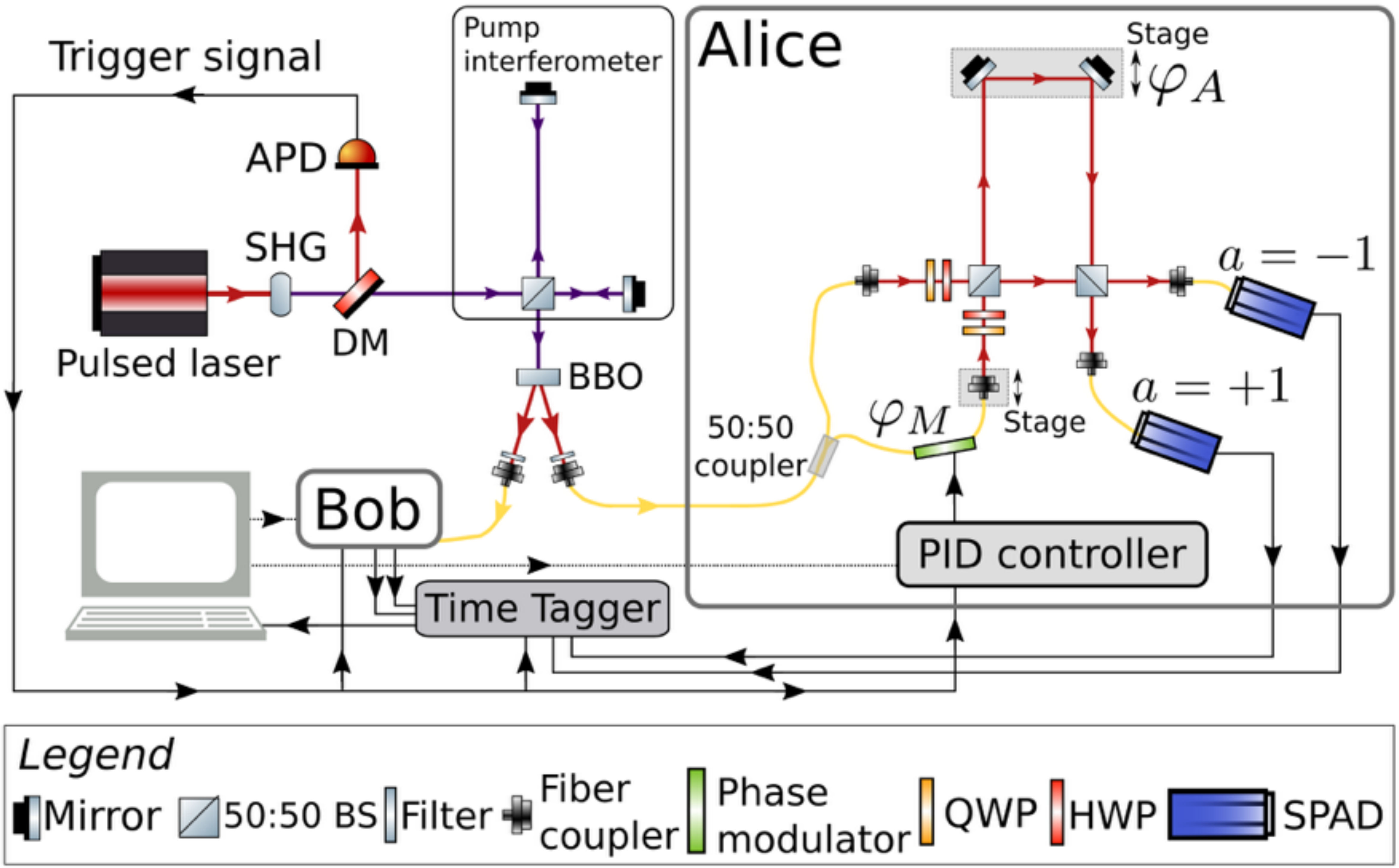


$$\hat{\Pi}_{a|\varphi_A} = \frac{1}{2}\cos^2\left(\frac{\varphi_S}{2}\right)\mathbb{1} + \sin^2\left(\frac{\varphi_S}{2}\right)\hat{P}_{a|\varphi_A} \xrightarrow{\varphi_S=\pi} \hat{P}_{a|\varphi_A}$$

$$p(a,b|\varphi_A,\varphi_B) = \langle\Phi^+|\hat{\Pi}_{a|\varphi_A}\otimes\hat{\Pi}_{b|\varphi_B}|\Phi^+\rangle = \frac{1}{4}[1 + a\,b\,\mathcal{V}\cos(\varphi_A+\varphi_B)]$$

The experimental set-up

II-III PhD year



Results of the Bell tests

II-III PhD year

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.*, arXiv:1804.10150 [quant- ph] (2018)

Outputs of my PhD

Publications and pre-prints:

1. G. Vallone *et al.*, *Interference at the single-photon level along satellite-ground channels*, Phys. Rev. Lett. **116**, 253601 (2016)
2. G. Vallone *et al.*, *Satellite quantum communication towards GEO distances*, Proc. SPIE 9900, Quantum Optics, 99000J (April 29, 2016)
3. G. Vallone *et al.*, *Interference for Quantum Time-Bin States in Satellite Channels*, Frontiers in Optics 2016, OSA Technical Digest (online) (Optical Society of America, 2016), paper FTh4F.2
4. **F. Vedovato** *et al.*, *Extending Wheeler's delayed-choice experiment to Space*, Sci. Adv. **3**, e1701180 (2017)
5. C. Agnesi *et al.*, *Exploring the boundaries of quantum mechanics: advances in satellite quantum communications*, Phil. Trans. R. Soc. A **376**, 20170461 (2018)
6. **F. Vedovato** *et al.*, *Post-selection-loophole-free Bell violation with genuine time-bin entanglement,* arXiv:1804.10150 [quant-ph] (2018)
7. L. Calderaro *et al.*, *Towards Quantum Communication from Global Navigation Satellite System*, arXiv: 1804.05022 [quant-ph] (2018)

Contributed talks at international conferences:

- "*Satellite Quantum Communications: experimental results and implications*" - YQIS 2016, Barcelona, Spain
- "Quantum Interference Along Satellite-Ground Channels" - RQI-N Conference 2016, Waterloo, Canada
- *"Testing Quantum Mechanics with Satellite Quantum Communications"* - IQIS 2018, Catania