GREEPHON

GRavitational Effects on Entangled PHOtoNs

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Sezione di Padova

16 Giugno 2020

Experiments testing Quantum Mechanics or General Relativity

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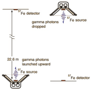
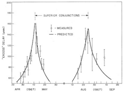
Classical physics in curved space-time



Pound-Rebka experiment
[PRL 4, 337 (1960)]



Shapiro delay
[PRL 20, 1265 (1968)]

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[SCI 177, 168 (1972)]

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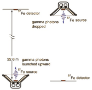

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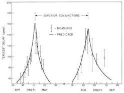

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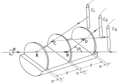
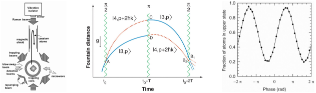
QM with gravitational potential in flat space-time



COW experiment with neutrons
[PRL 34, 1472 (1975)]



atom interferometry [NAT 400, 849 (1999); SCI 315, 74 (2007); NAT 510, 518 (2014)]

State of the art

Experiments testing Quantum Mechanics or General Relativity

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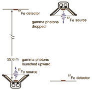

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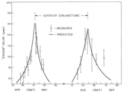

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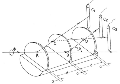

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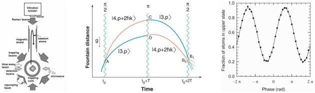


atom interferometry [NAT 400, 849 (1999); SCI 315, 74 (2007); NAT 510, 518 (2014)]

No experiment has shown directly the combined effect of QM and GR

Research questions

- Can genuine general relativistic effects be detected on quantum systems?

- Can Quantum Field Theory in curved-spacetime be tested?

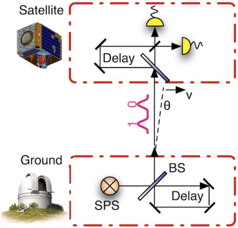
Any gravitational influence detected on massless particles is a witness of genuine general relativistic effects

Recent proposals

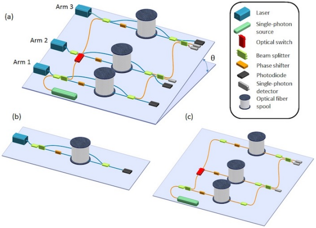
Any gravitational influence detected on massless particles is a witness of genuine general relativistic effects

⇓

Proposals to test the gravitational effect on photons



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



C. Hilweg, *et al.*,
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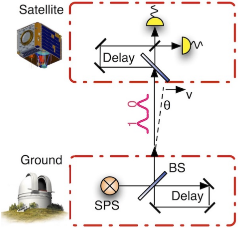

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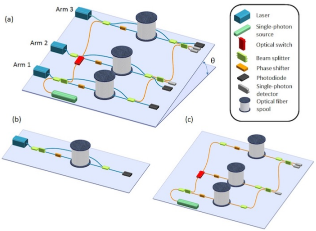

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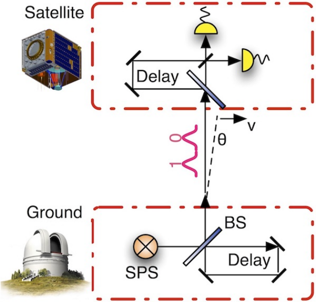
None of them has been experimentally implemented
GREEPHON overcomes the difficulties of the above proposals

Challenges with satellites



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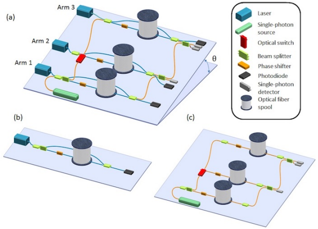
Class. Quant. Grav. 29, 224011 (2012).

- For a Low Earth Orbit satellite at 1000 km, the gravitational fractional redshift is at the 10^{-10} level
- Necessary to know the relative speed with an accuracy of $10^{-11}c \simeq 3\ mm/s$
- With geostationary satellites no Doppler shift and larger redshift: disadvantage of large losses in the propagation

Challenges in Hilweg et al proposal

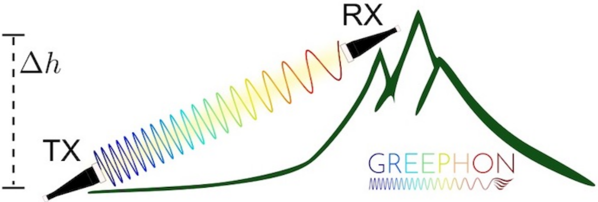


C. Hilweg, *et al.*,
New J. Phys. 19, 033028 (2017)

- Low effect at the lab scale: the gravitational redshift is of the order of 10^{-5} rad with 100 km of fiber spool
- Stabilization of the interferometer during the movement

OBJECTIVE of GREEPHON

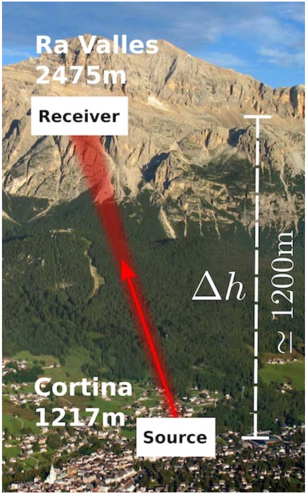
To experimentally demonstrate a general relativistic effect on single and entangled photons

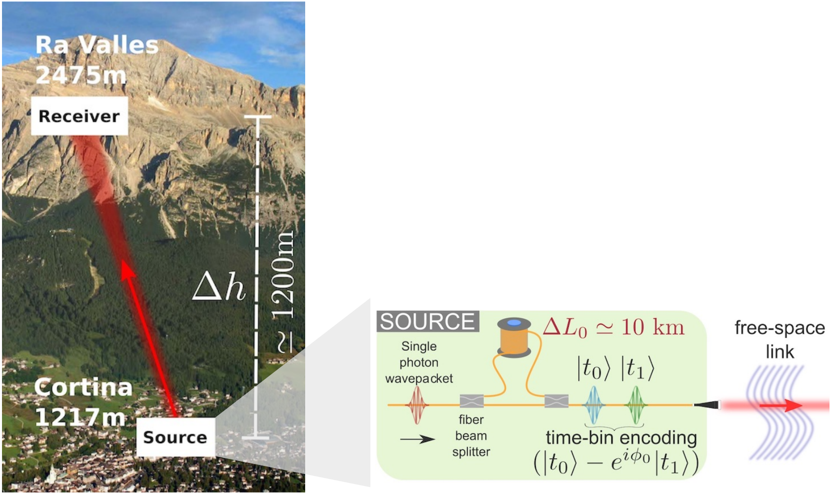


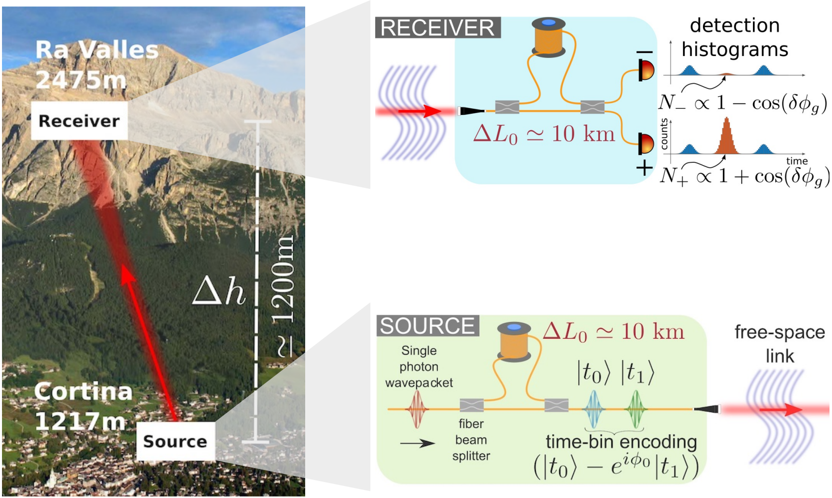
$$\frac{\delta\omega}{\omega} \simeq 10^{-16}\frac{\Delta h}{1m}$$

The change in the photon energy can be observed by converting the redshift into a measurable phase $\delta\phi_g$ by exploiting two unbalanced interferometers.

Methodology




Ra Valles
2475m
Receiver
Δh
$\simeq 1200$m
Cortina
1217m
Source
SOURCE
Single photon wavepacket
$\Delta L_0 \simeq 10$ km
$|t_0\rangle$ $|t_1\rangle$
fiber beam splitter
time-bin encoding
$(|t_0\rangle - e^{i\phi_0}|t_1\rangle)$
free-space link


Ra Valles
2475m
Receiver
Cortina
1217m
Source
Δh
$\simeq 1200$m
RECEIVER
detection
histograms
$\Delta L_0 \simeq 10$ km
$-$
$+$
counts
time
$N_- \propto 1 - \cos(\delta\phi_g)$
$N_+ \propto 1 + \cos(\delta\phi_g)$
SOURCE
$\Delta L_0 \simeq 10$ km
Single
photon
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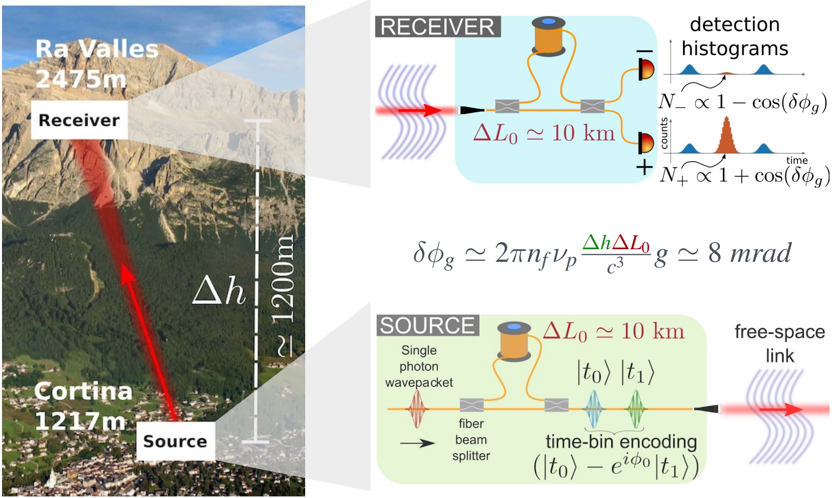
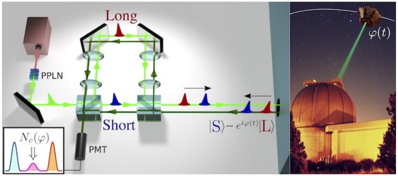
Methodology

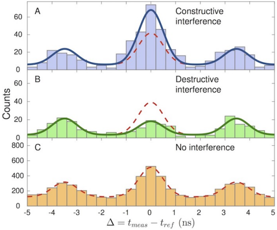


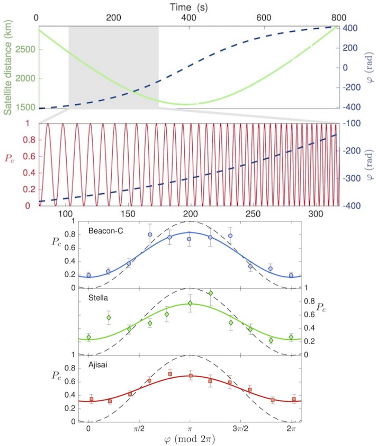
$$\delta\phi_g \simeq 2\pi n_f \nu_p \frac{\Delta h \Delta L_0}{c^3} g \simeq 8\ mrad$$

Time-bin interference in free space

Interference of two time-bins observed on ground after the reflection by a moving satellite at a distance of thousands of kilometres

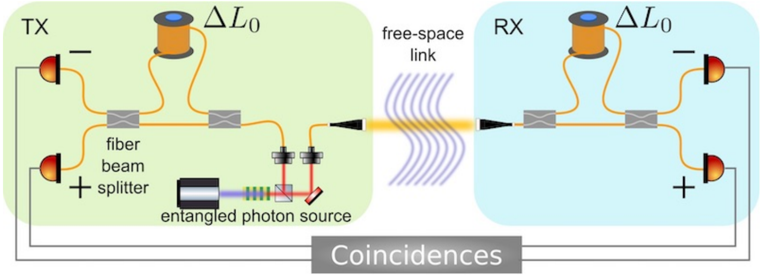






G. Vallone, *et al.*, *Interference at the Single Photon Level Along Satellite-Ground Channels*, **Phys. Rev. Lett. 116, 253601 (2016)**

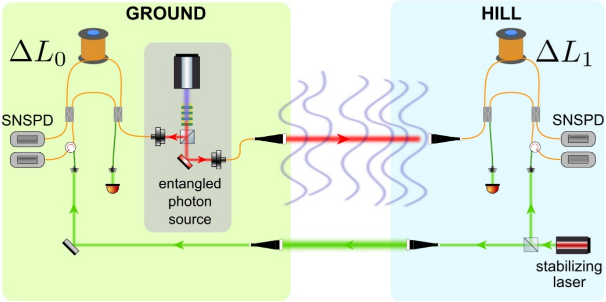
Gravitational effect on entanglement



The number of coincidences depends on the gravitational induced phase

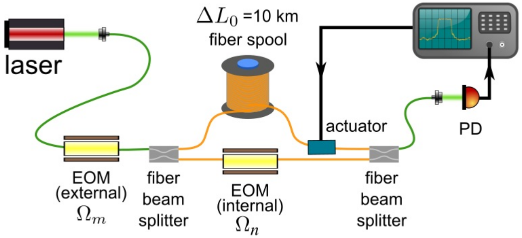
$$\delta\phi_g \simeq 2\pi n_f \nu_p \frac{\Delta h \Delta L_0}{c^3} g \simeq 8\ mrad$$

Our approach



- ASSUMPTION: gravitational redshift of classical electromagnetic waves is a scientific fact
- Same laser used to stabilize both TX and RX interferometers
- no phase shift on entangled photons imply that the classical laser and the entangled photons experienced the same gravitational redshift

Stabilization of the MZ interferometer at μrad level



External modulation

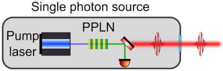
- modulate the phase of the calibration laser at Ω_m
- Detect the PD signal at frequency Ω_m

Internal modulation

- modulate interferometer phase at Ω_n
- Detect the PD signal at frequency Ω_n

Shot noise limit: precision lower bounded by $\Delta(\delta\Phi_g) \geq \frac{1}{\sqrt{N_{det}}}$

- High generation rate of photons



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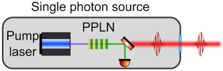
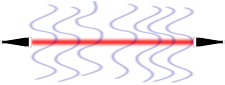


- Efficient transmission of photons

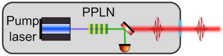


adaptive optics

Challenges

Shot noise limit: precision lower bounded by $\Delta(\delta\Phi_g) \geq \frac{1}{\sqrt{N_{det}}}$

- High generation rate of photons



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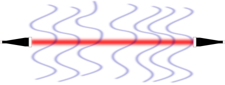
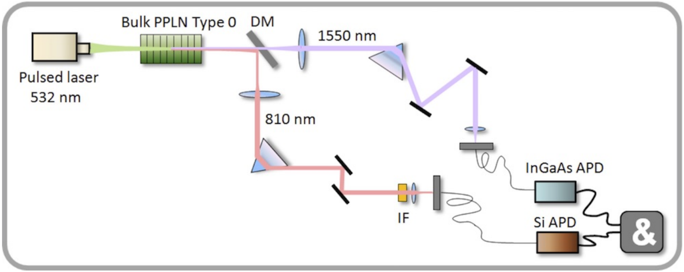


adaptive optics

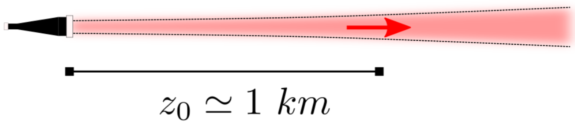
- Efficient detection of photons

Source of photons



From **Optics Express 20, 23846 (2012)**:
“single telecom photons can be announced at 4.4 MHz rate with 45% heralding efficiency”

free-space link



with $w_0 \simeq 5\ cm$ the Rayleigh range is $z_0 \simeq 1\ km$

- Aperture diameter $D = 10\ cm$ at transmitter
- aperture diameter $D' = 10\ cm$ at receiver
- $3\ db$ geometric losses with $d = 5\ km$ link due to diffraction
- $\simeq 0.5\ db/km$ attenuation in free-space due to scattering/absorption (good visibility conditions)

Detection

IDQ

ID281

SUPERCONDUCTING NANOWIRE

Detector Specifications

Parameter	Min	Typical	Max	Units
Wavelength range	400		2500	nm
Optical fibre type		SMF		
Efficiency range at 1550nm	75	80		%
Dark count rate at 0.8K			100	Hz
Maximum count rate		15		MHz
Jitter (FWHM)		50		ps
Pulse width		adjustable		
Output connector		SMA		
Operating temperature		0.8		K
Dimensions		13 x 20 x 25		mm
Optical connector		FC/PC		

Commercial ID281 Superconducting Nanowire (SNSPD) of IdQuantique:

- quantum efficiency at 1550 nm (80%),
- low dark counts (100Hz)
- high Timing Resolution (50 ps): required to reject background radiations

Team

Sezione di Padova


G. Vallone


M. Bazzan


G. Ciani


L. Conti


P. Villoresi


J.P. Zendri

- Quantum Optics
- Free-space propagation
- Interferometry
- thermo-mechanic stabilization

Sezione di Bologna


M. Prevedelli

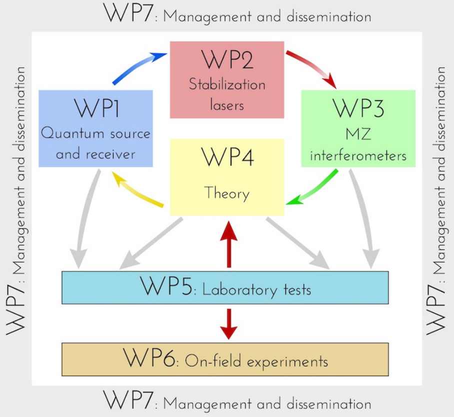
- frequency control of lasers

Sezione di Trieste


S. Liberati

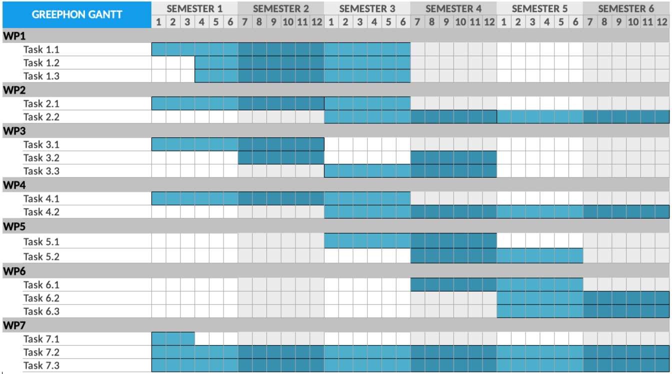
- Quantum Gravity

WP structure



- **WP1:** development of quantum source and receiver.
- **WP2:** characterization of stabilization lasers
- **WP3:** interferometers realization and stabilization
- **WP4:** Development of theoretical framework and new proposals
- **WP5:** Lab tests
- **WP6:** On-field experiment

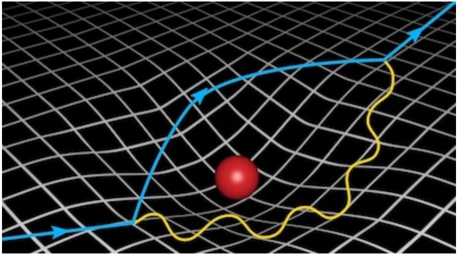
GANTT and Budget



	Year 1	Year 2	Year 3	Total
Padova	264 k€	309 k€	76 k€	**649 k€**
Bologna	58 k€	3 k€	3 k€	**64 k€**
Trieste	38 k€	38 k€	38 k€	**114 k€**

GREEPHON: great challenges but a step forward
in our understanding of the basic principles of physics

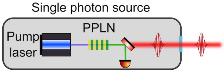
- **First direct test** of the validity of Quantum Field Theory in curved-spacetime



- Stimulate further researches on the overlap between General Relativity and Quantum Mechanics

Impacts in other fields

- Quantum information applications



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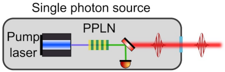
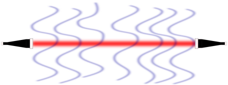


- Optical communication at large distances



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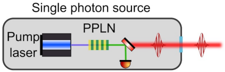

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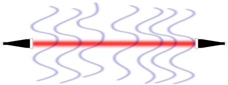
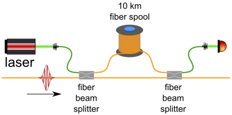
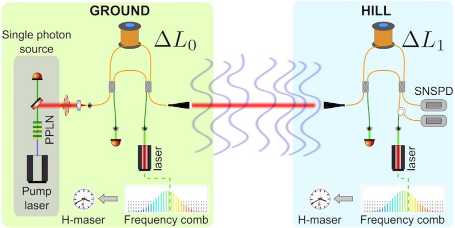
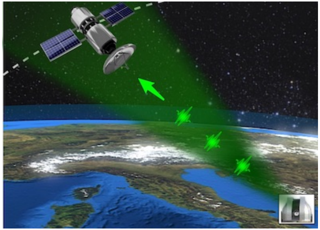


- Metrology and sensing applications



Extension to future experiments

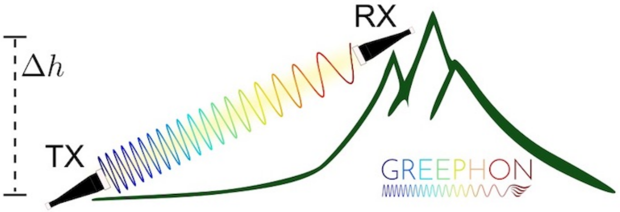




- local absolute calibration of the MZ interferometers
- complete and self-consistent demonstration of gravitational induced phase shift
- long-term extension as satellite-based experiment
- gravitational phase shift three orders of magnitude larger

GREEPHON

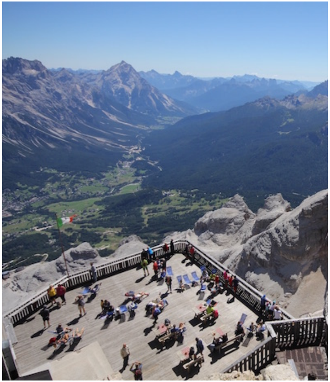
A new method to demonstrate, **for the first time**, a general relativistic effect on quantum interference of photons



In particular, first demonstration of gravitational effects on entangled systems

EXTRA SLIDES

Possible locations



Cortina

CV of G. Vallone

GREEPHON

UNIVERSITÀ DEGLI STUDI DI TORINO	**1998-2002**: undergraduate **2002-06**: PhD in Jan. 2006, thesis on String Theory
NORDITA The Nordic Institute for Theoretical Physics	**2004**: 11 months as “Marie Curie training site” fellow at NORDITA institute (Copenhagen)
SAPIENZA UNIVERSITÀ DI ROMA	**2006-11**: Post-doc in experimental Quantum Optics
UNIVERSITÀ DEGLI STUDI DI PADOVA	**2011-2019**: Ricercatore a tempo indeterminato **2019-now**: Professore Associato

92 publications on peer-reviewed journals
including 3 **Nature Communications**, 1 **Science Advances**,
1 **Optica**, 19 **Phys. Rev. Lett.**

	Google Scholar	Scopus	ISI Web Of Science
# of citations:	**4230**	**2855**	**2616**
h-index:	**32**	**28**	**27**