Quantum Communications and Fundamental Physics in Space

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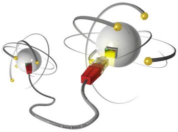
Is Quantum Theory exact? - July 3, 2018

Summary

Summary

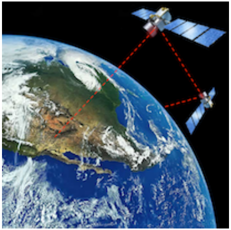
What is Quantum Communication?

- Quantum Communications is the ability of faithful transmit qubit (or generic quantum states) between two distant locations



- Application of ground QC: commercial QKD using fiber-cables

- Quantum Communications on planetary scale require complementary channels including ground and satellite links



Motivations

Why satellite quantum communications?

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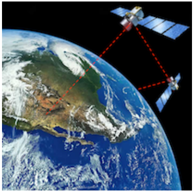
- Creation of a **worldwide quantum network**



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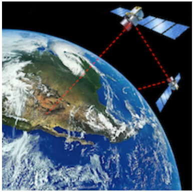

- Creation of a **worldwide quantum network**
- Overcome fiber-loss limitations: transmission in a link with length L scales as

$$t_{\text{fiber}} = t_0 e^{-\alpha L}\,, \qquad t_{\text{vacuum}} = \gamma / L^2$$

$L = 1000\, km$:

fiber-loss ~ 200 db (10^{-20})

satellite-loss $\sim 30 - 60$ db $(10^{-3} : 10^{-6})$

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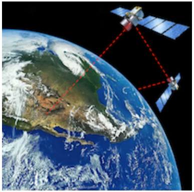

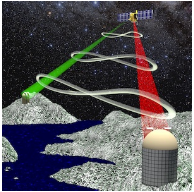

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- **Explore the limits of Quantum Mechanics** and quantum correlations over very long distances

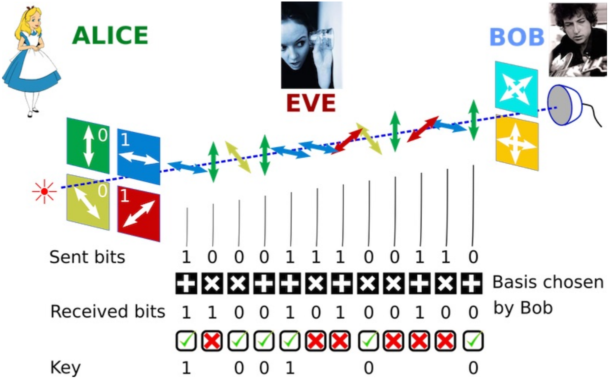
Context

- On May 24, 2014 Japan’s NICT launched SOTA on Socrates satellite.
- On August 16, 2016 China launched QUESS (Quantum Experiments at Space Scale) satellite
- Ongoing programs for QC on satellite in Canada, Singapore and USA.

Summary

QKD in a nutshell

BB84 protocol: exchanging qubits



Necessary a true Random Number Generator (such as a QRNG)

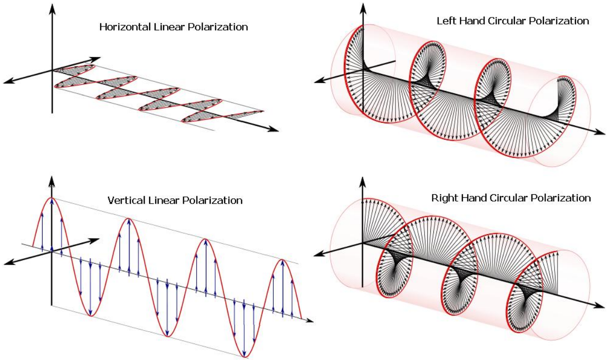
Summary

Qubit encoding

Polarization encoding

$|0\rangle$

$|0\rangle - i|1\rangle$

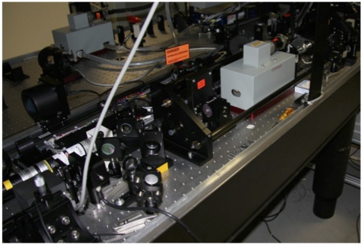


$|1\rangle$

$|0\rangle + i|1\rangle$

MLRO as quantum hub

MLRO: Matera Laser Ranging Observatory
of ASI (Italian Space Agency)
1.5 m telescope with millimeter resolution in SLR
Research hub for Space QC since 2003

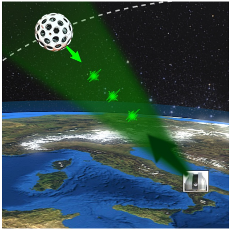


G. Bianco

V. Luceri

How to emulate a single photon source on space?

- Strong laser pulses sent from ground
- qubit source in Space emulated by using orbiting CCR
- Reflected at the single photon level from the satellites
- Downlink attenuation from $\sim 3\ cm$ LEO sources in the range of 50-70 dB.

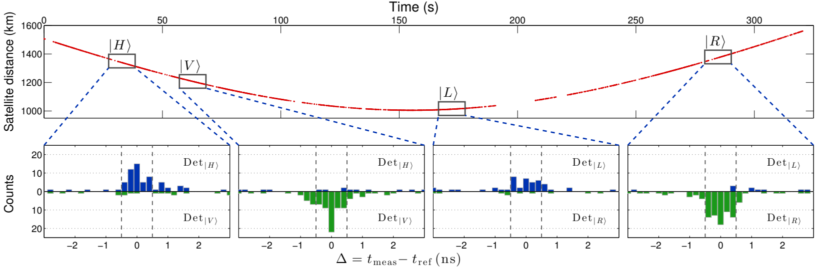


CCR: Corner-Cube Retroreflector

Single passage of LARETS

Orbit height 690 km - spherical brass body
24 cm in diameter, 23 kg mass,
60 Metallic coated Corner-Cube Retroreflectors

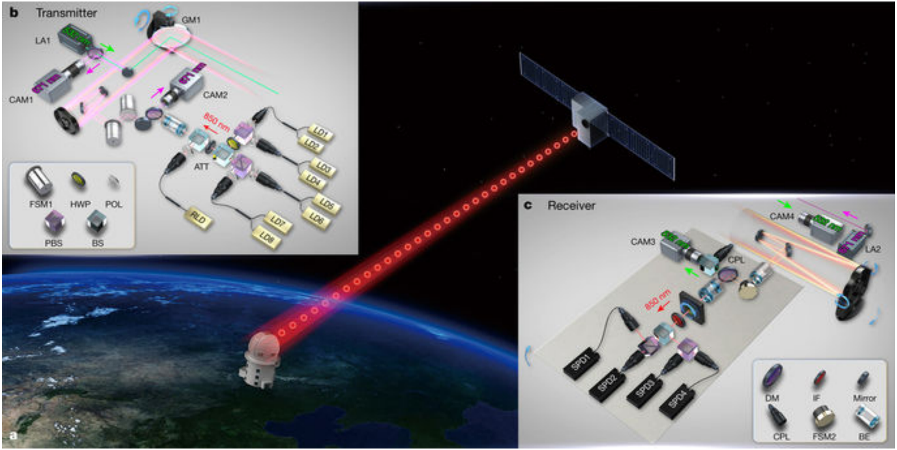
Apr 10th, 2014, start 4:40 am CEST



Detection of four polarization states received from satellite
10 s windows: average QBER 6.5%

G. Vallone, *et al.*, *Experimental Satellite quantum communication*, **Phys. Rev. Lett. 115, 040502 (2015)**

Micius demonstration



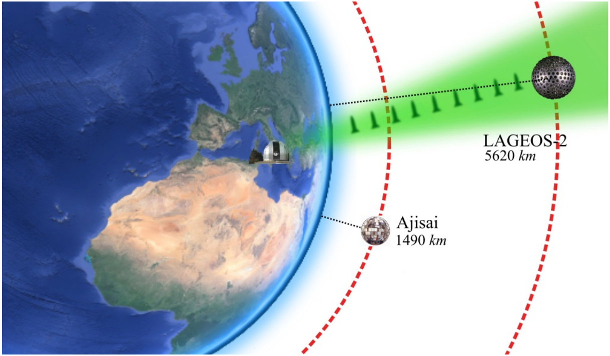
orbital altitude $\simeq 500$ km

average secret key rate of $\simeq 1.1$ kbit/s

S.-K. Liao, *et al.*, *Satellite-to-ground quantum key distribution*, **Nature 549, 43 (2017)**

Extending QC to MEO satellites

MEO=Medium-Earth-Orbit

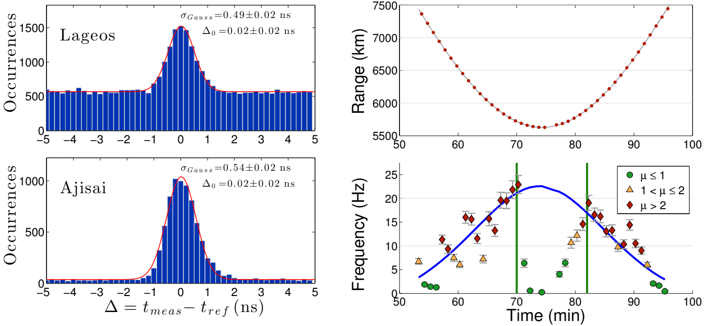


D. Dequal

 D. Dequal, *et al.*, *Experimental single photon exchange along a space link of 7000 km*, **Phys. Rev. A 93, 010301(R) (2016)**

Single photon returns

Histogram of the counts



7000km link

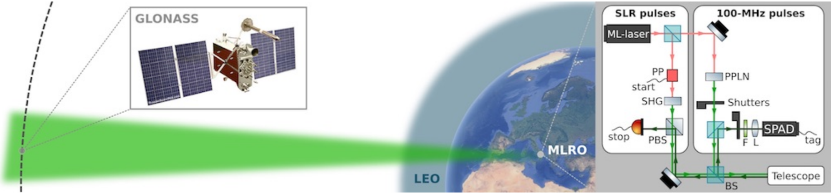
 D. Dequal, *et al.*, *Experimental single photon exchange along a space link of 7000 km*, **Phys. Rev. A 93, 010301(R) (2016)**

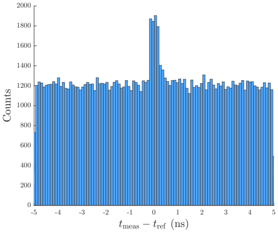
Extending QC to GEO satellites

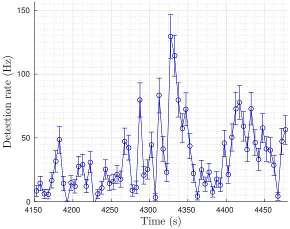
- with GEO distances ($> 20000\ km$) losses increase
- better synchronization is required to discriminate signal from dark/background counts
- in previous experiments we showed synchronization with $1\ ns$ accuracy with PMT detectors
- NEW silicon SPAD detectors with $(200\mu m)^2$ area and $35\ ps$ jitter

 G. Vallone, *et al. Satellite quantum communication towards GEO distances*, **Proc. SPIE 9900 (2016)**

GNSS single photon exchange







first experimental exchange of single photons from Global Navigation Satellite System at a slant distance of 20000 kilometers

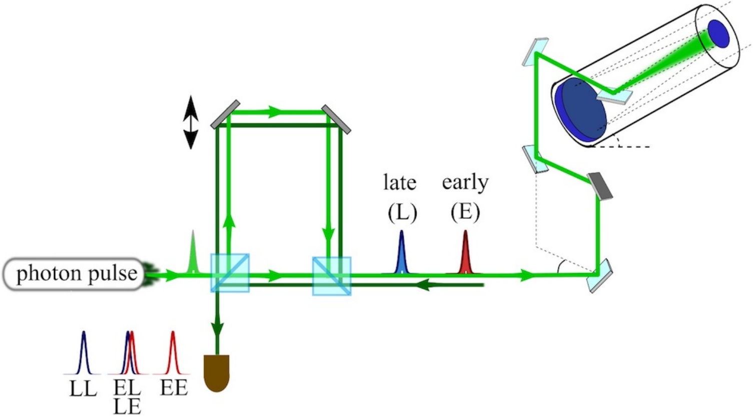
 L. Calderaro, *et al. Towards Quantum Communication from Global Navigation Satellite System*, **[arxiv:1804.05022]**

Summary

Quantum interference (AKA time-bin encoding)

Qubit with time-bin: $|\psi\rangle = \frac{1}{\sqrt{2}}(|E\rangle + e^{i\phi}|L\rangle)$

The relative phase can be used to encode information



G. Vallone, et al., *Quantum interference along satellite-ground channels*, **Phys. Rev. Lett. 116, 253601 (2016)**

4f-system

- Is turbulence spoiling interference?

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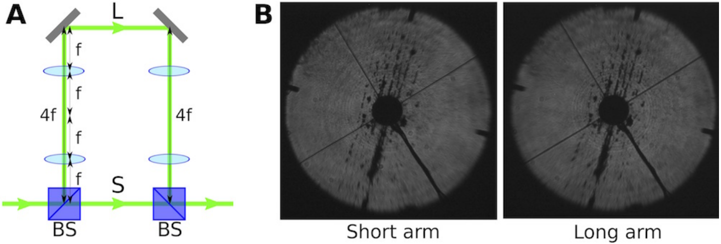
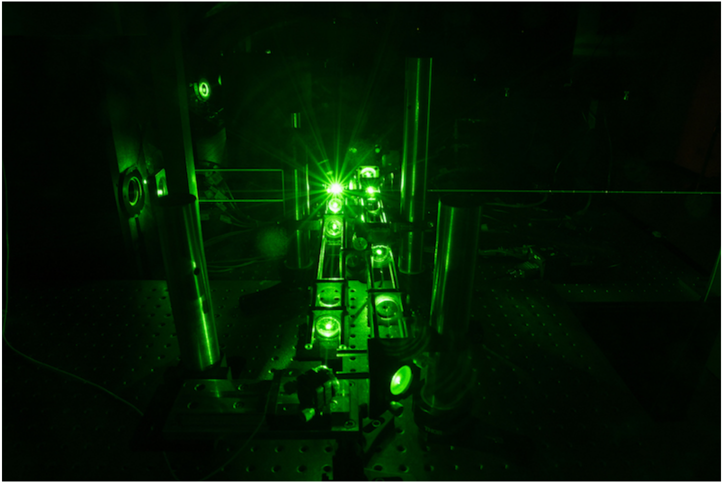


4f-system crucial for wavefront matching

G. Vallone, et al., *Quantum interference along satellite-ground channels*, **Phys. Rev. Lett. 116, 253601 (2016)**

4f-system



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The role of the satellite

Is time-bin encoding stable with moving objects?

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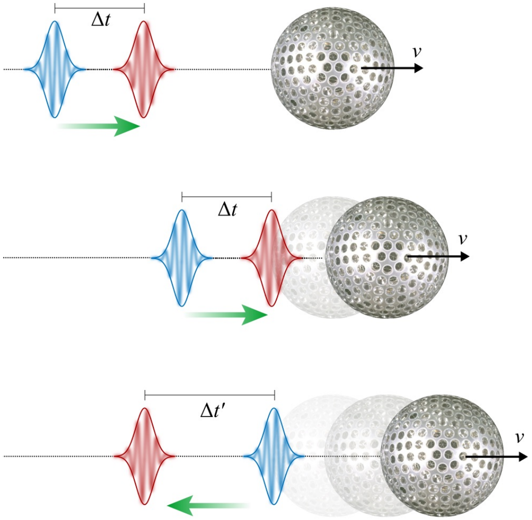
The role of the satellite

Is time-bin encoding stable with moving objects?

YES, if the dynamical phase is taken into account



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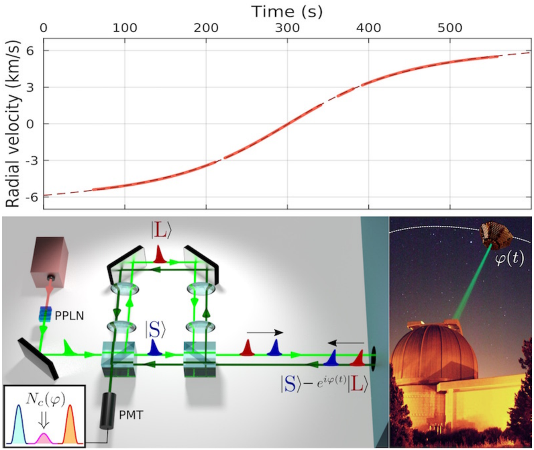
Measurement of interference



Self-stabilized interferometer

Phase shift due to satellite motion:

$$\varphi(t) \simeq 2v_r(t)\frac{2\pi}{\lambda}\Delta t$$

where

$$\Delta t \simeq 3.4\ ns$$

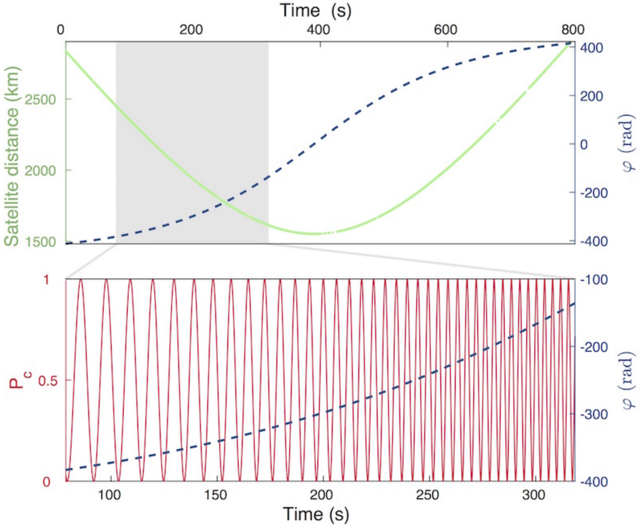
$$v_r(t) = \text{radial velocity}$$

$$N_c(t) \propto 1 - \mathcal{V}(t)\cos\varphi(t)$$

G. Vallone, et al., *Quantum interference along satellite-ground channels*, **Phys. Rev. Lett. 116, 253601 (2016)**

Dynamical phase

Phase variation during the satellite passage



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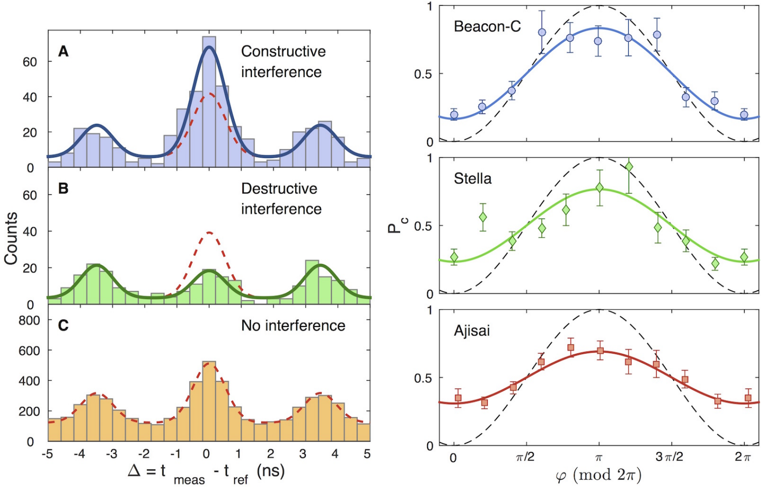
Experimental results

Interference pattern: visibility up to 67%

(can be improved be further stabilizing the interferometer)



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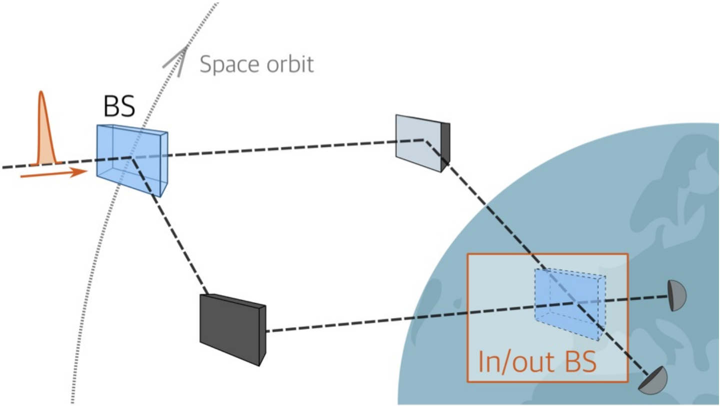
Summary

Wheeler's delayed choice in space



F. Vedovato, et al., *Extending Wheeler's delayed-choice experiment to Space*, **Science Advances 3, e1701180 (2017)**

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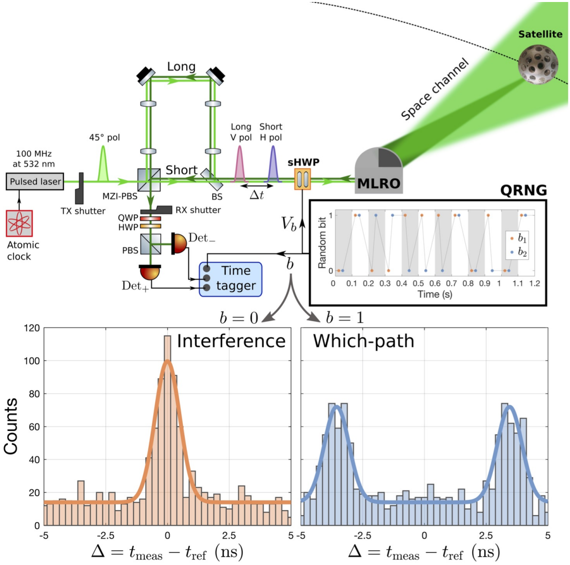

F. Vedovato

C. Agnesi

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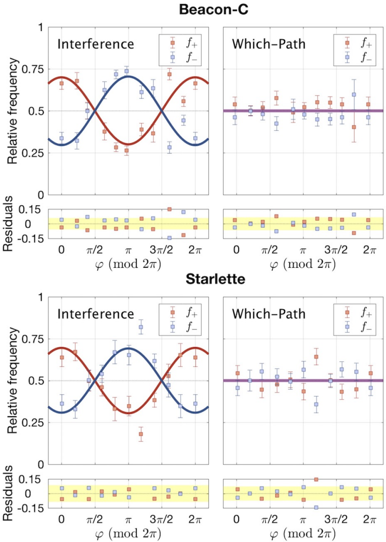

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Summary

Long term opportunities

Unique opportunity of Quantum Physics in Space

Possibility of testing quantum physics in new environment and probing the laws of nature at very large distance

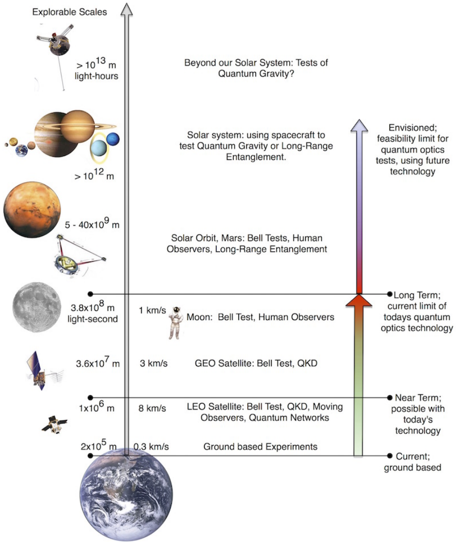
Long term opportunities

Unique opportunity of Quantum Physics in Space

Possibility of testing quantum physics in new environment and probing the laws of nature at very large distance

- Distribution of entanglement from Earth to Space
- Test of Bell's Inequalities with unprecedented conditions: LEO or GEO-orbit, moving terminals, gravitational field
- Teleportation from Earth to Space
- Quantum technologies in long distance applications
- Test of foundations of quantum field theory and general relativity

Different levels of space experiments

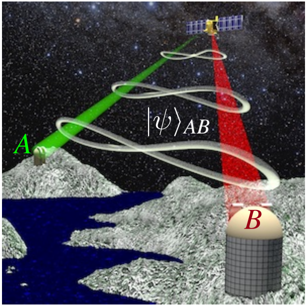


D. Rideou, *et. al*, **Class. Quantum Grav. 29, 224011 (2012)**

Entanglement distribution

- Quantum Entanglement is, according to Erwin Schrödinger, the "characteristic trait of quantum mechanics"
- Entanglement is a unique resource for Quantum Information applications (teleportation, dense coding, etc..)

$$|\psi\rangle_{AB} \neq |\phi\rangle_A \otimes |\chi\rangle_B$$



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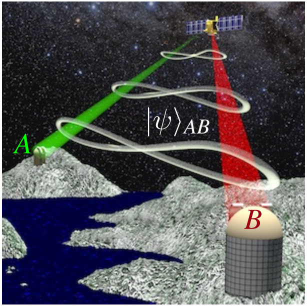


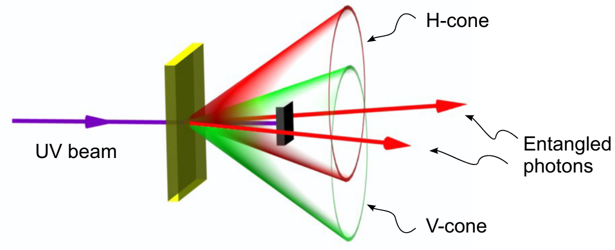
- Limits on the distance between two entangled systems?
- Is entanglement limited to certain mass and length scales or altered under specific gravitational circumstances?

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

Entanglement distribution

Photons are the ideal candidate for distributing entanglement

- Easy to generate entangled photons



- Photons can travel over long distances without decoherence

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

What is the largest distance of entanglement?

J. Yin, *et al.*, Satellite-based entanglement distribution over 1200 kilometers, **Science 356, 1140 (2017)**

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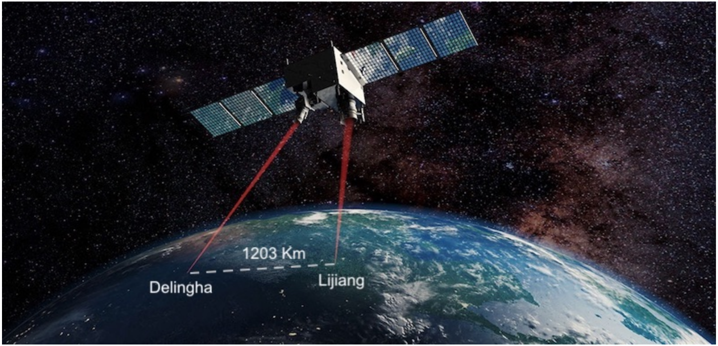


- 2017: entanglement between two ground stations separated by 1203 kilometers
- violation of a Bell inequality by 2.37 ± 0.09 under strict Einstein locality conditions

J. Yin, *et al.*, Satellite-based entanglement distribution over 1200 kilometers, **Science 356, 1140 (2017)**

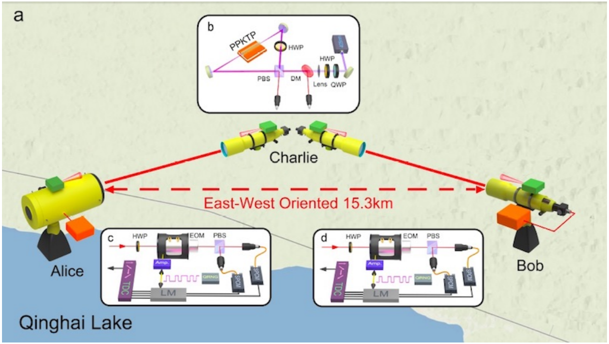
Bell's test

If a set of correlation do not satisfy the Bell's inequality $S \leq 2$, the correlations cannot be explained by a local realistic theory.

Bell’s test

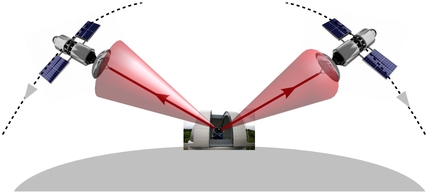
If a set of correlation do not satisfy the Bell’s inequality $S \leq 2$, the correlations cannot be explained by a local realistic theory.

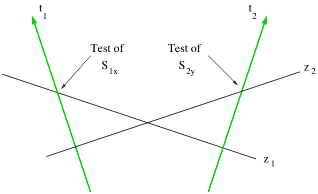
- Bell’inequality violated between fixed location: "spooky action at distance" at speed greater than $10^4 c$.



Phys. Rev. Lett. 110, 260407 (2013)

Bell’s test with detectors in relative motion





- the two observers disagree on the relative time ordering of the measurement events

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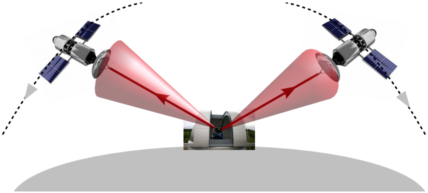
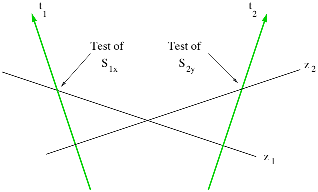
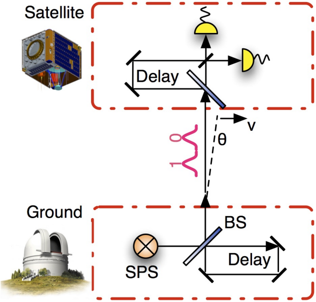




- the two observers disagree on the relative time ordering of the measurement events
- The probabilities predicted by quantum theory do not depend on the time-ordering of spacelike events, so its predictions will not be changed.
- understanding the physical reality of quantum states and the non-local collapse of the wave functions.

COW experiment with photons



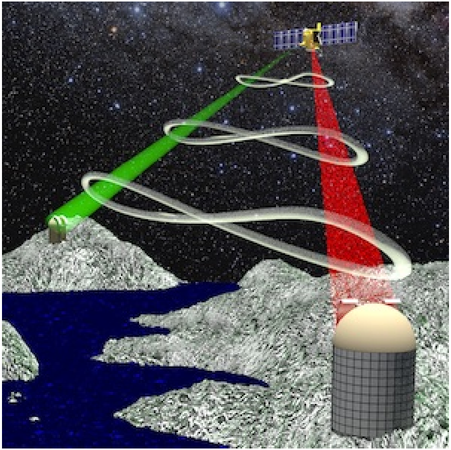
$$\lambda = 800 \text{ nm}$$
$$h \sim 400 \text{ km}$$
$$\ell = 6 \text{ km}$$

$$\Delta\phi = \frac{2\pi\ell}{\lambda}\frac{gh}{c^2} \sim 2 \, \text{rad}.$$

- First direct measurement of quantum interference due to curved spacetime
- Different from a test with massive particle:
  in the Newtonian limit no effect on a massless system would be expected.

M. Zych, *et. al, General relativistic effects in quantum interference of photons.* **Class. Quant. Grav. 29, 224010 (2012)**

Conclusions



Quantum Communication in SPACE

how to explore the limits of Quantum Mechanics and quantum correlations over very long distances

THANK YOU FOR YOUR ATTENTION!

QuantumFuture

The shift in the communication paradigm

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