

# Free-Space quantum cryptography over 144 km and a mission proposal for going into space.

## Free-space QC

- Demonstration over 144 km
- Delayed choice quantum eraser

**Rupert Ursin**

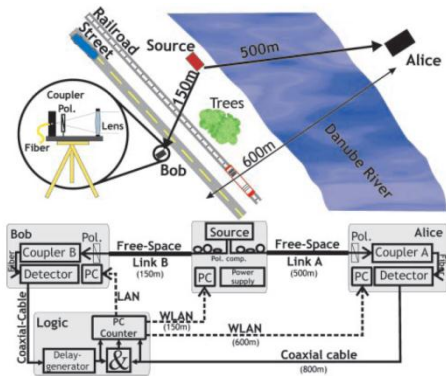
Institute for Quantum Optics and Quantum  
Information, Austrian Academy of Sciences, Austria



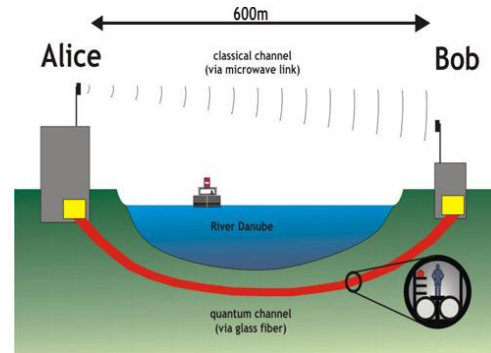
## Quantum optics in space

- Motivation
- Feasibility
- State-of-the-art (links, source)

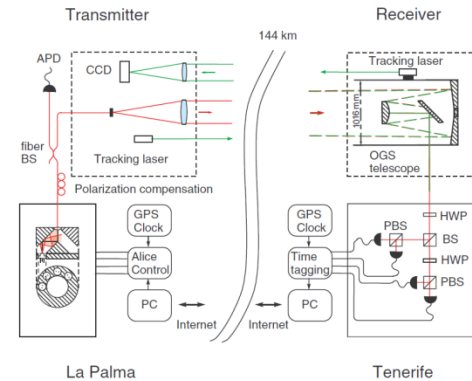
# Little history on QC experiments



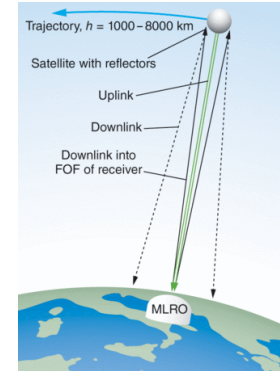
M. Aspelmeyer et al,  
**Science** 301, 621-623 (2003)



R. Ursin et al,  
**Nature** 430, 849 (2004)

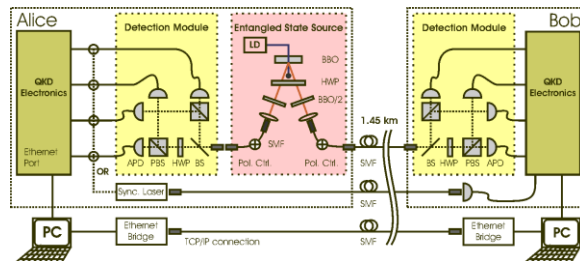


T. Schmitt-Manderbach et al,  
**Phys. Rev. Lett.** 98, 010504 (2007)

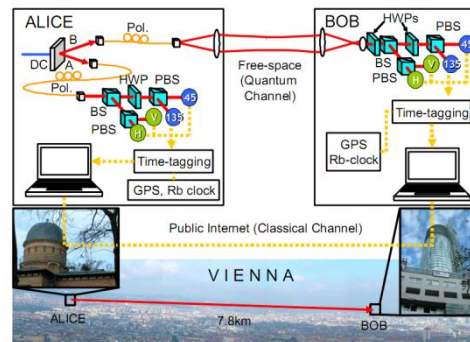


P. Villoresi et al,  
**NJP** 10 033038 (2008)

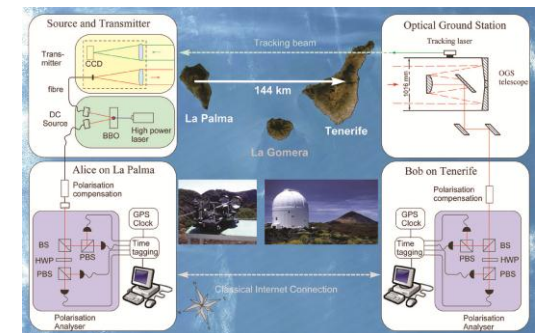
## Real World Quantum Communication History



A. Poppe et al,  
**Opt. Express** 12, 3865-3871 (2004)



K. Resch et al,  
**Optics Express** 13, 202-209 (2005)



R. Ursin et al,  
**Nature Physics** 3, 481 - 486 (2007)

# The Transmitter: La Palma



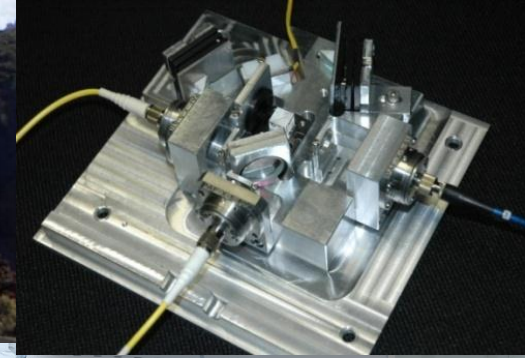
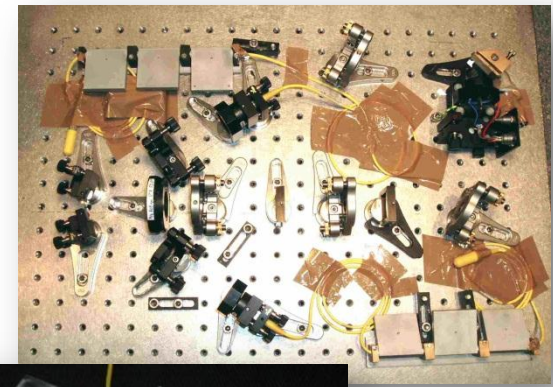


# Receiver Station: Tenerife





# The Transmitter: La Palma

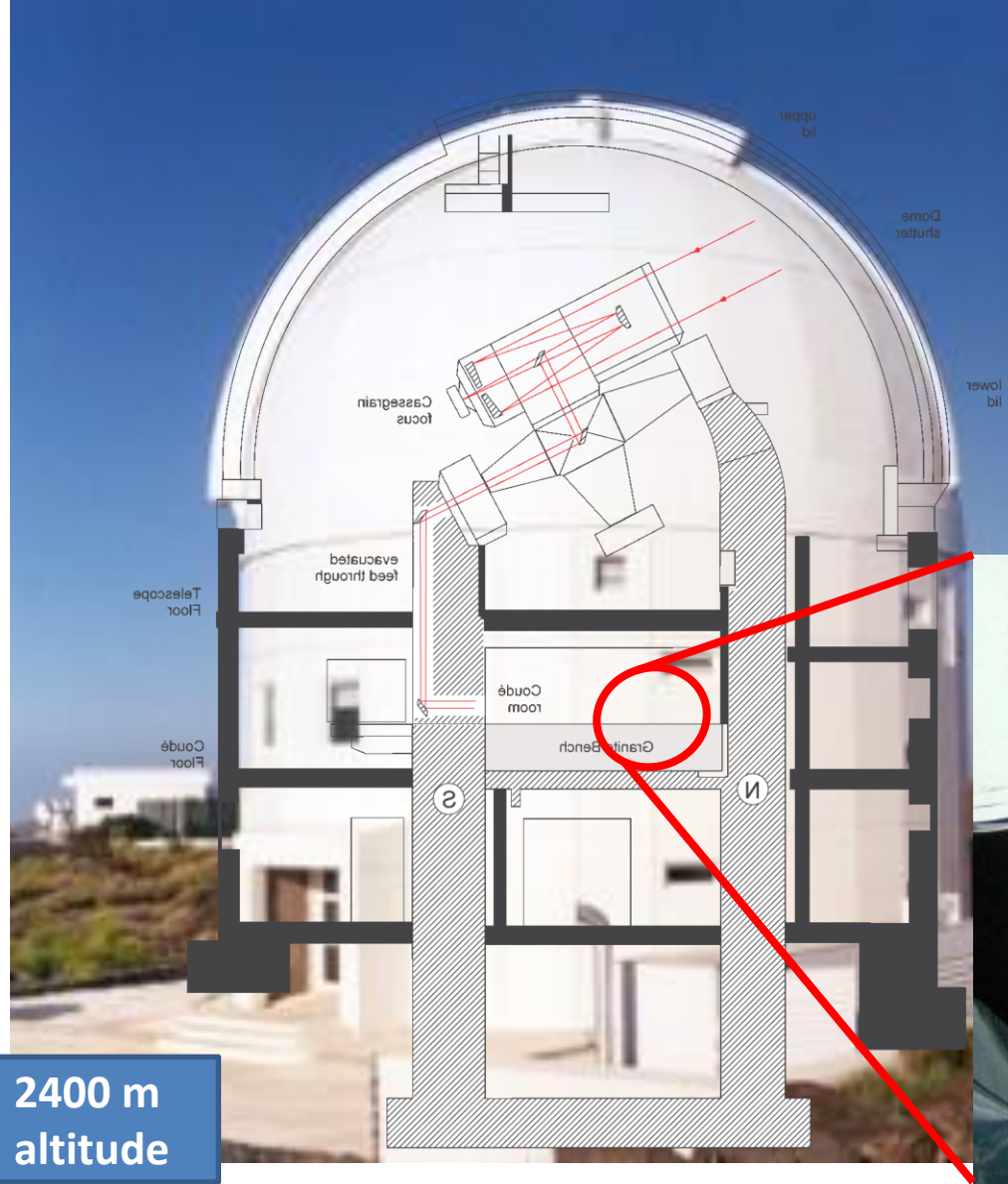


2400 m  
altitude

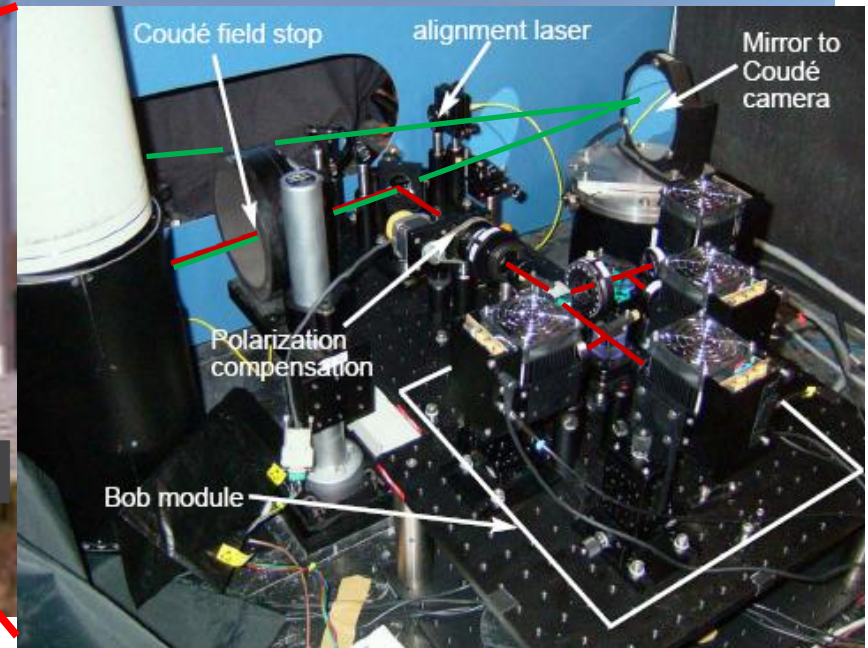




# Receiver Station: Tenerife



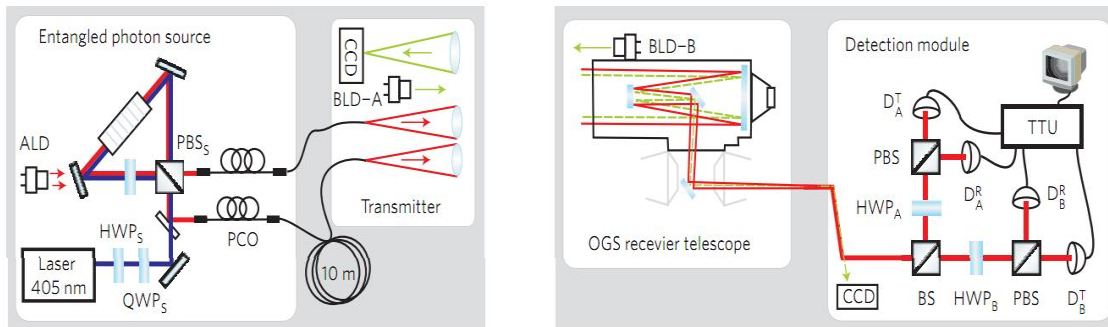
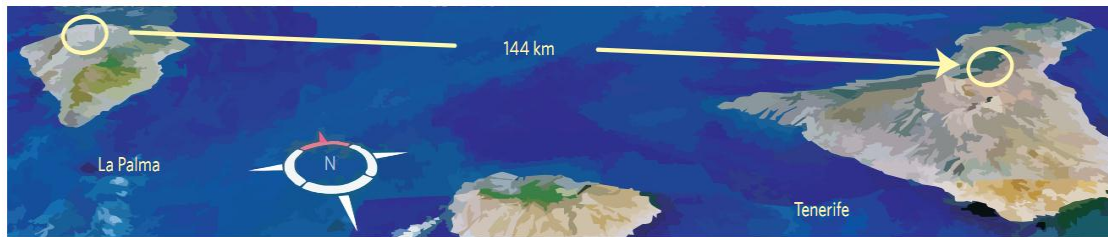
2400 m  
altitude



# Two-photon quantum communication

## Simulating two-photon downlinks:

- Sending both photons over 144 km
- Total attenuation -70dB
- More than realistic conditions for satellite experiments

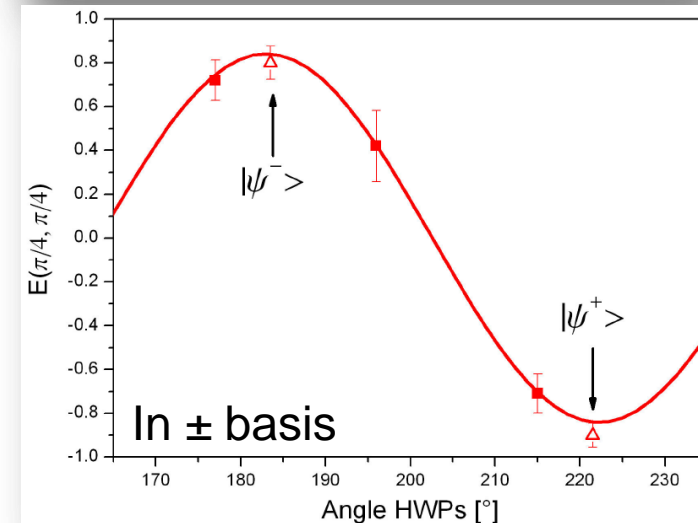
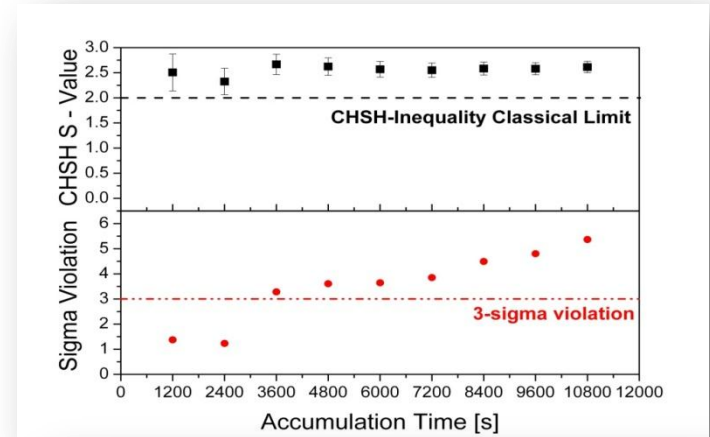


### ➤ Quantum Communication over a -70 dB Link

- 2-fold count rate: 2 Hz @ 1 Mio. detection locally

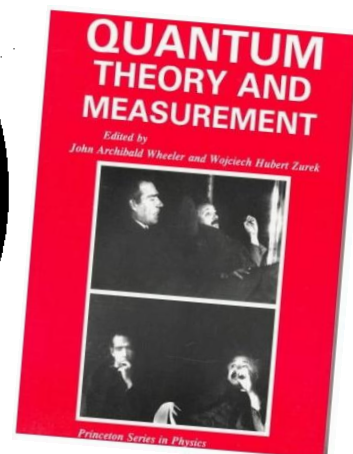
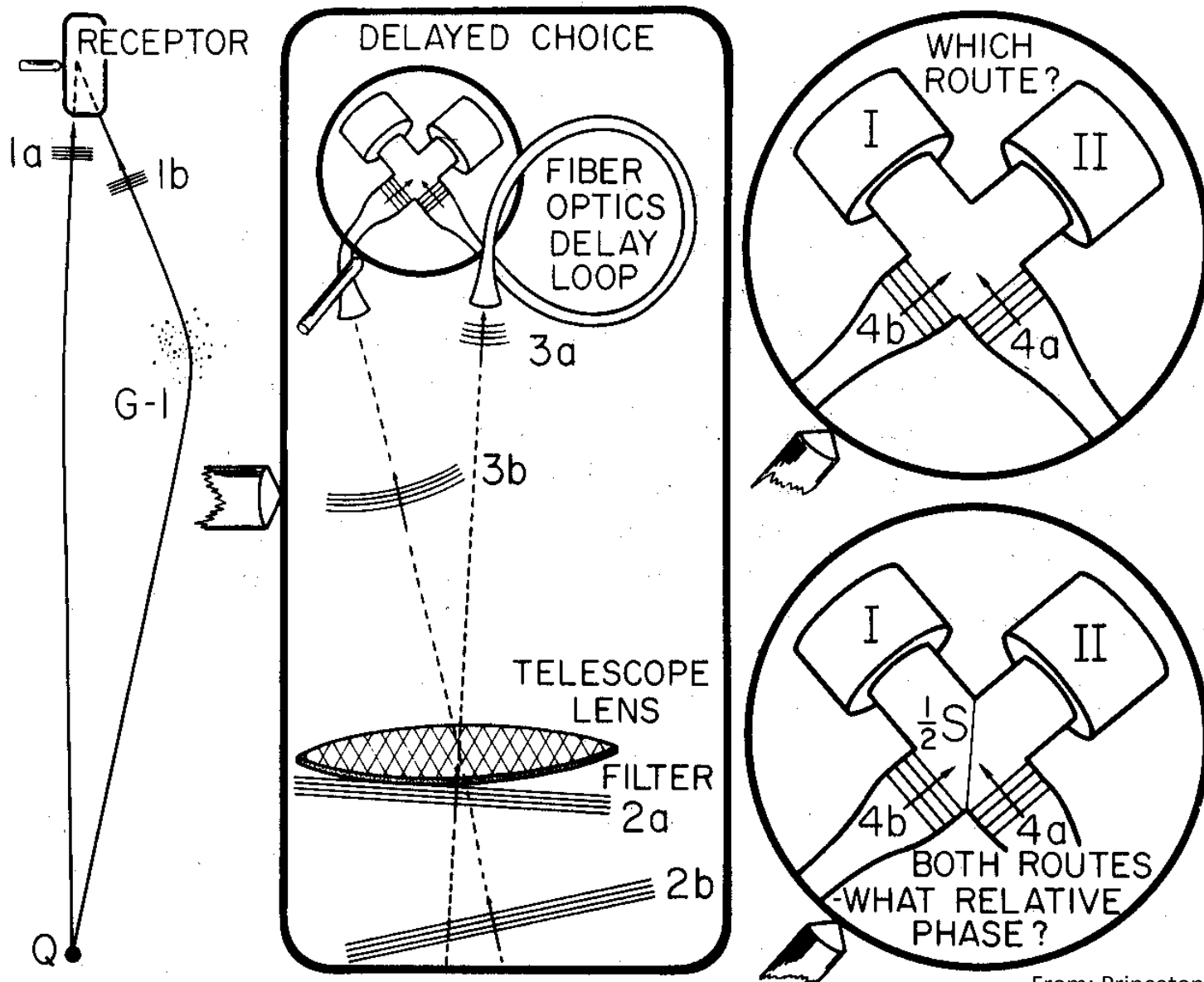
### ➤ Bell parameter: $S=2,61 \pm 0,11$

- 5 standard derivations



A. Fedrizzi et al., 5, 389, Nature Physics 2009

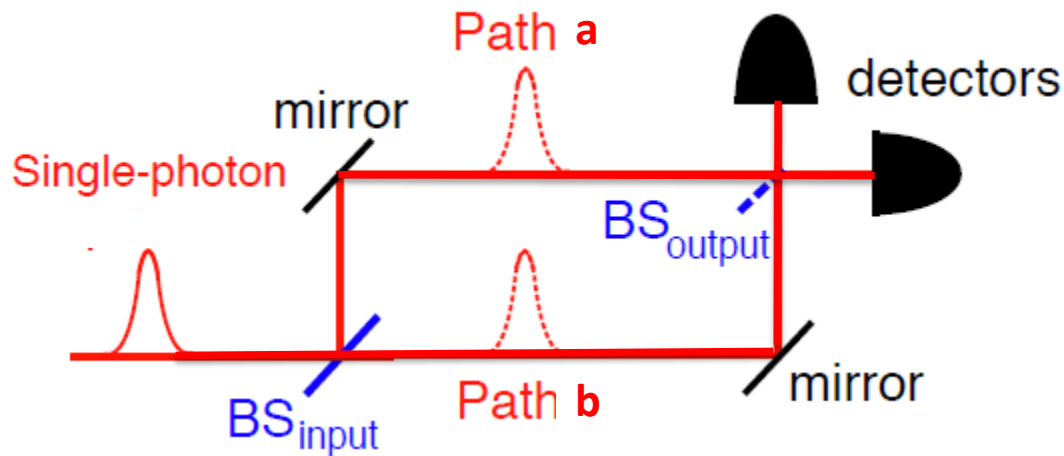
# Delayed choice proposal – the original



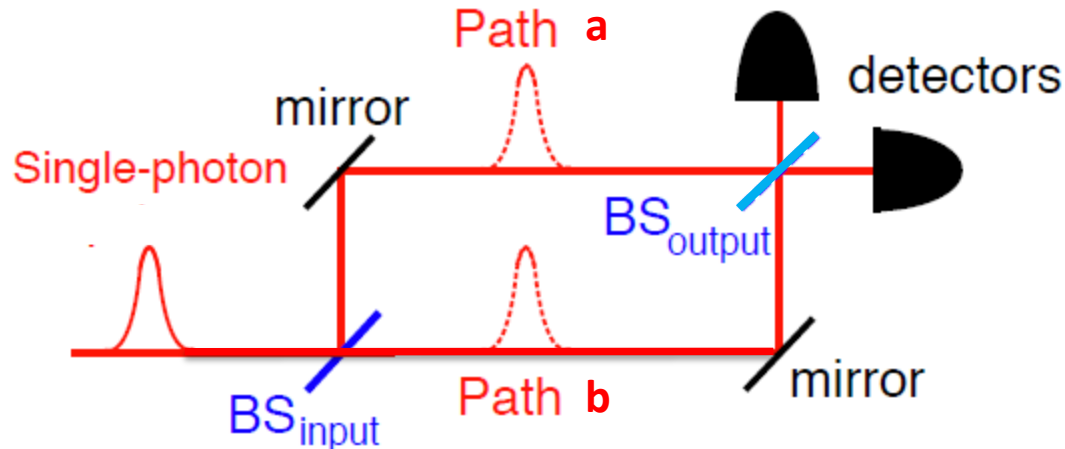
From: Princeton Univ Press (January 1984)



# The original proposal



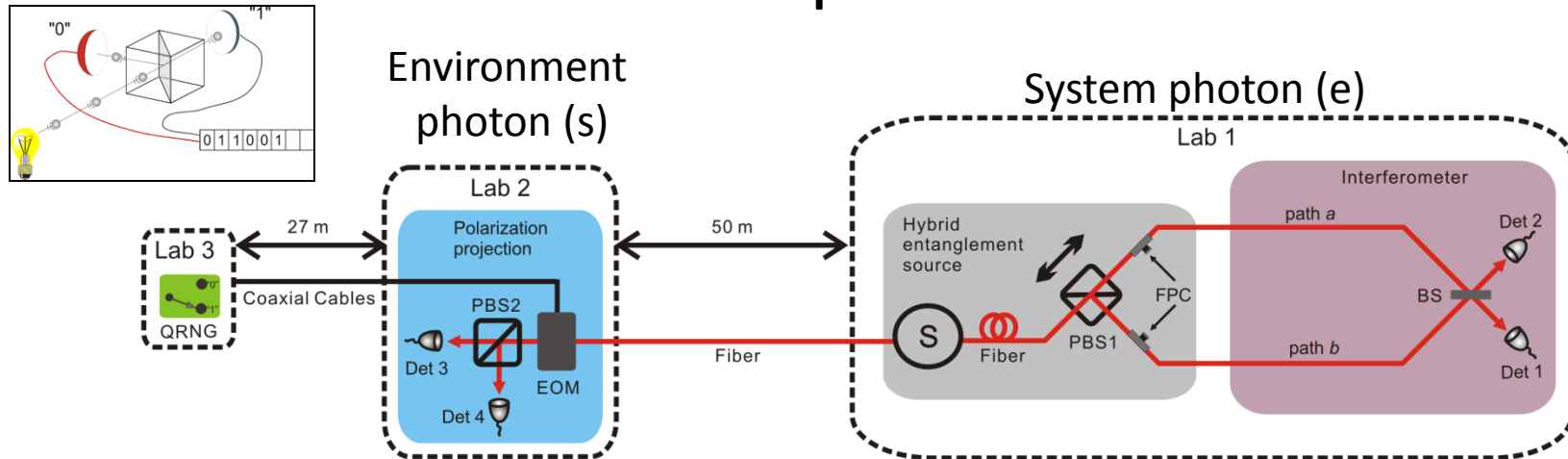
The choice to introduce or remove  $BS_{output}$  is made only after the passage of the photon at the input beamsplitter  $BS_{input}$



The photon entering the interferometer “cannot know” which of the complementary measurements (path difference vs. which-way) will be performed at the output.

From: Vincent Jacques et al., Experimental Realization of Wheeler's Delayed-Choice Gedanken Experiment, Science, Vol. 315. no. 5814, pp. 966 - 968 (2007) - [arXiv:quant-ph/0610241v1](https://arxiv.org/abs/quant-ph/0610241v1)

# A nonlocal quantum eraser



$$|\Phi_{source}\rangle_{se} = \frac{1}{\sqrt{2}} (|H\rangle_s |V\rangle_e + |V\rangle_s |H\rangle_e)$$

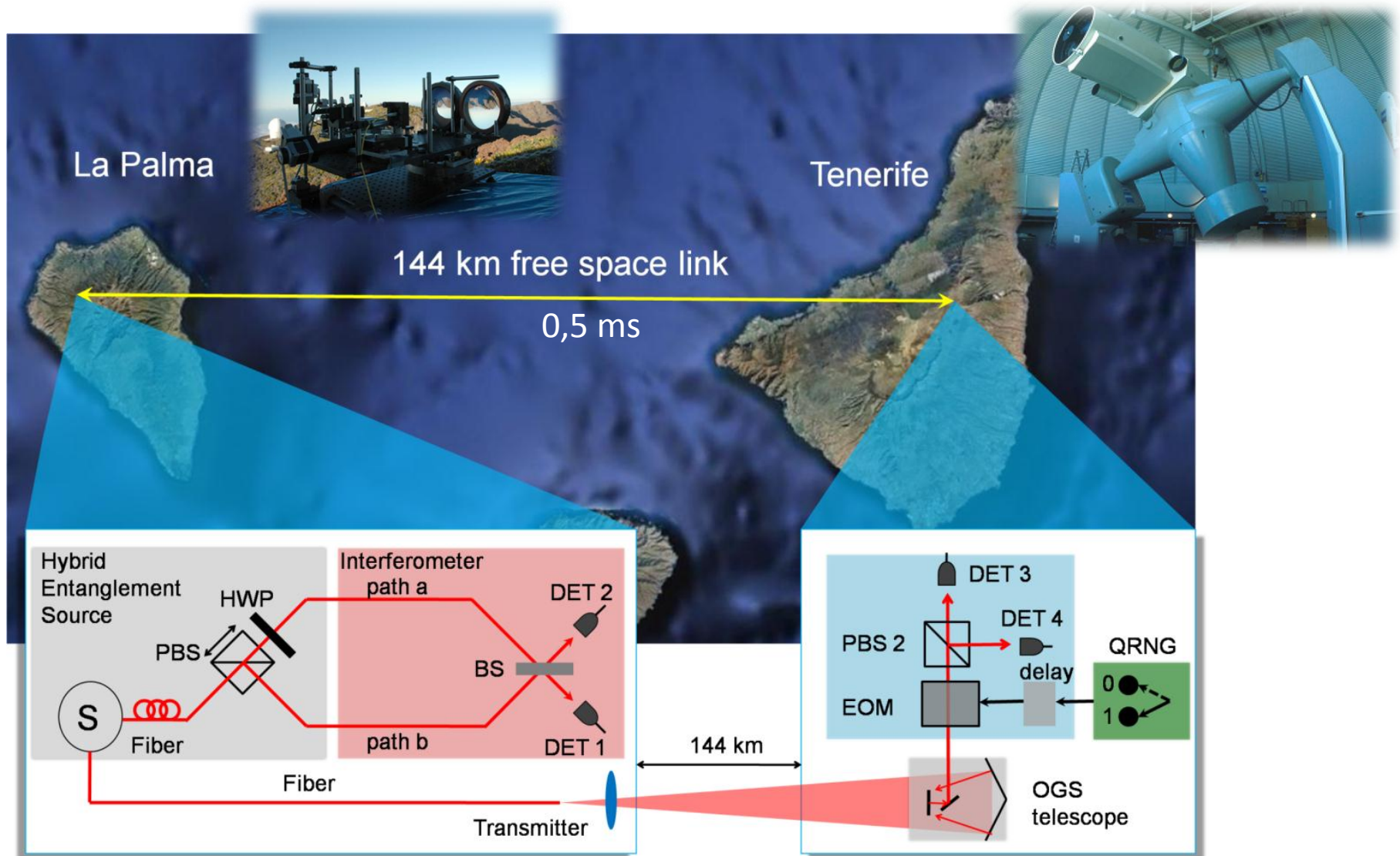
Path info  $\rightarrow |\Phi_{hybrid}\rangle_{se} = \frac{1}{\sqrt{2}} (|b\rangle_s |V\rangle_e + |a\rangle_s |H\rangle_e) \rightarrow$  EOM off

No path info  $\rightarrow |\Phi_{hybrid}\rangle_{se} = \frac{1}{2} [(|a\rangle_s + i|b\rangle_s) |L\rangle_e + (|a\rangle_s - i|b\rangle_s) |R\rangle_e] \rightarrow$  EOM on

M. O. Scully *et al.*, *Phys. Rev. A* **25**, 2208 (1982); B.-G. Englert, *et al.*, *Nature* **351**, 111 (1991)  
 J. A. Wheeler, pp. 182–213 in *Quantum Theory and Measurement*,



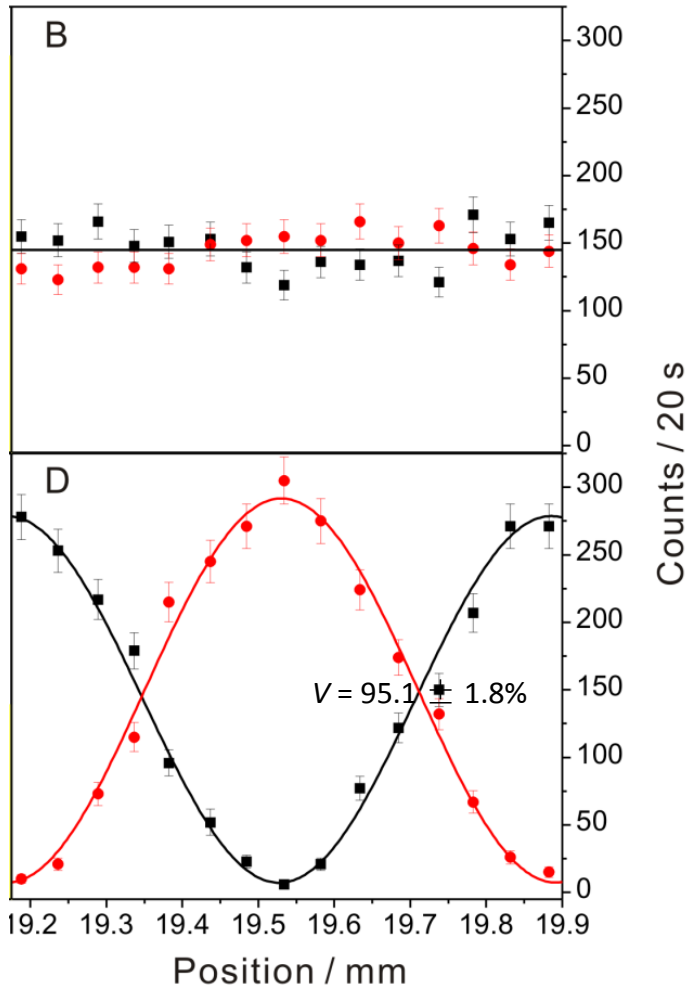
# A nonlocal quantum eraser--Scheme



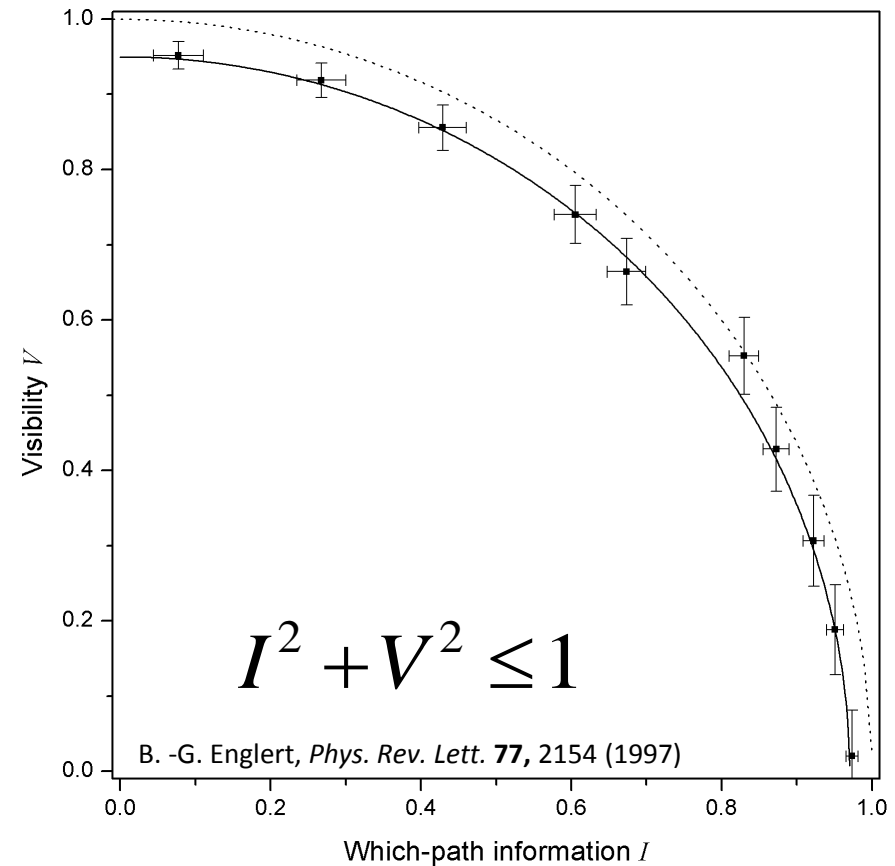
# A nonlocal quantum eraser--result

Quantum eraser under enforced *Einstein locality condition* for the experimental configuration

Reveal  
path info



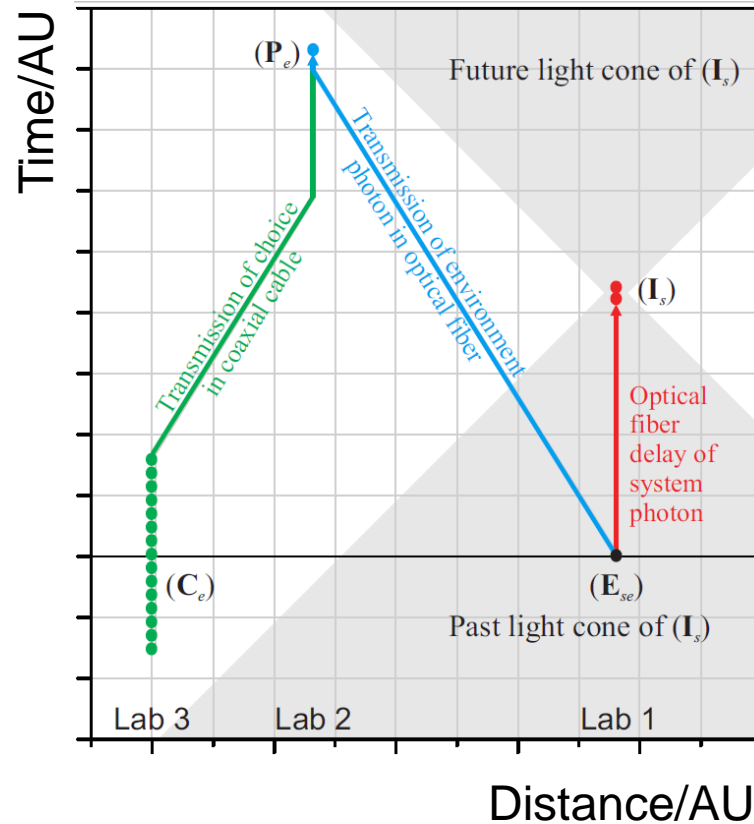
*Bipartite complementarity inequality*



X.-S Ma, J. Kofler, A. Qarry, N. Tetik, T. Scheidl, R. Ursin, S. Ramelow, L. Ratschbacher, T. Herbst, T. Jennewein, A. Zeilinger  
Accepted by Nature Physics for publication

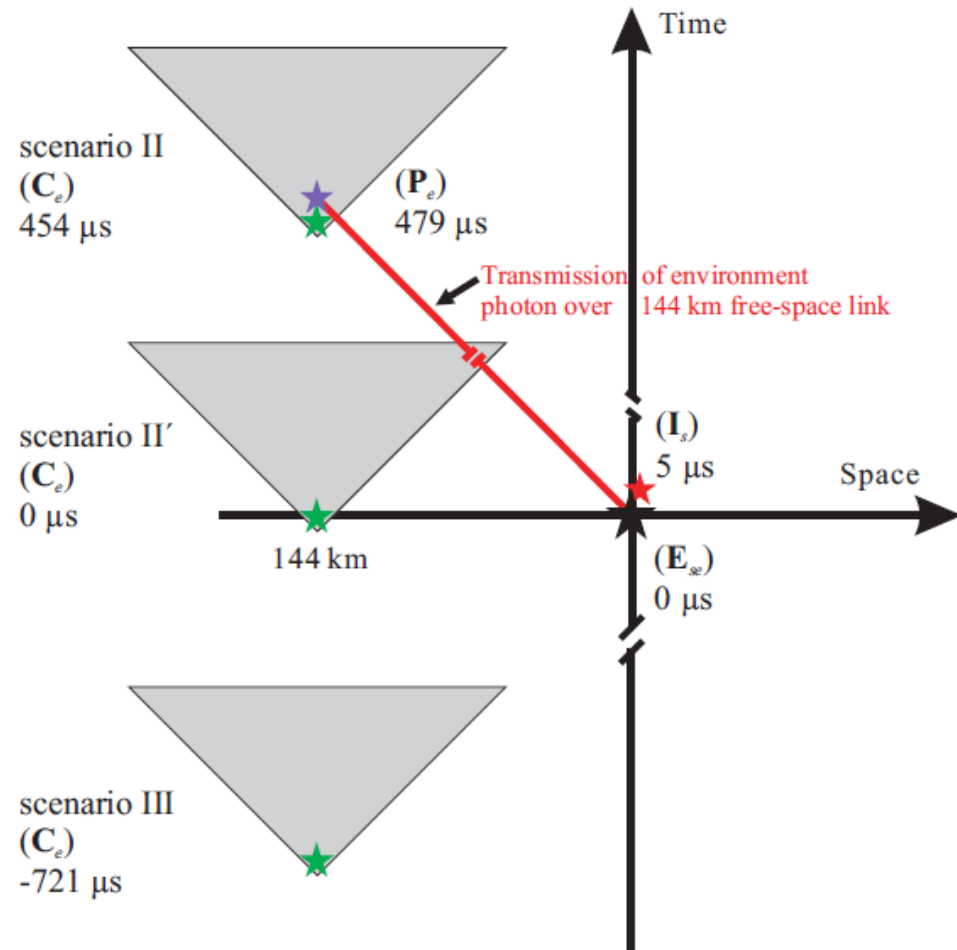


# Space-time separation of the events



Choice

Interferometer



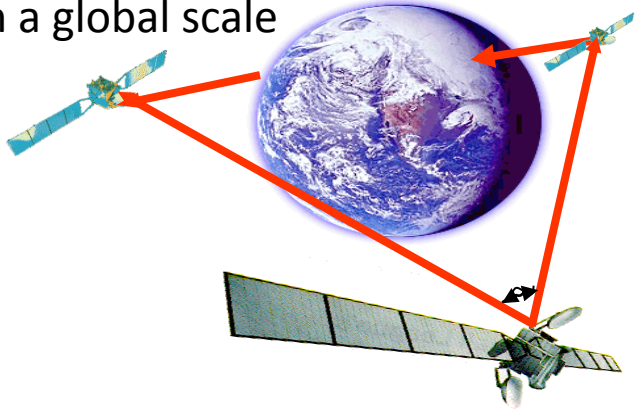
Choice

Interferometer

# Motivation for quantum optics in space

To test quantum mechanics on astronomical scales

Quantum communication  
on a global scale

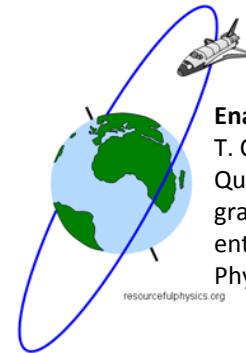


$$|\Psi\rangle_{12} = \frac{1}{\sqrt{2}}(|0\rangle_1|0\rangle_2 + |1\rangle_1|1\rangle_2)$$



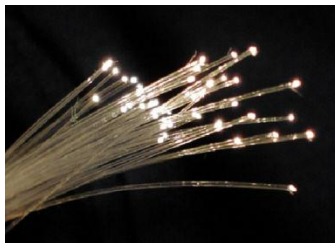
Schrödinger, E. Die gegenwärtige Situation in der Quantenmechanik. Die Naturwissenschaften 49, 823–828 (1935).

Bell

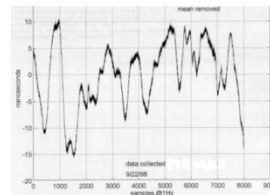


**Entanglement and Gravitation**  
T. C. Ralph, G. J. Milburn, and T. Downes,  
Quantum connectivity of space-time and  
gravitationally induced de-correlation of  
entanglement,  
Phys. Rev. A 79, 022121 (2009)  
resourcefulphysics.org

QKD



**QKD over such distances are not possible in fiber. Maximum is:**  
High rate, long-distance quantum key distribution over **250km** of  
ultra low loss fibres High rate, long-distance quantum key  
distribution over  
250km of ultra low loss fibres. D. Stucki et al., New Journal of  
Physics 11 (2009) 07500

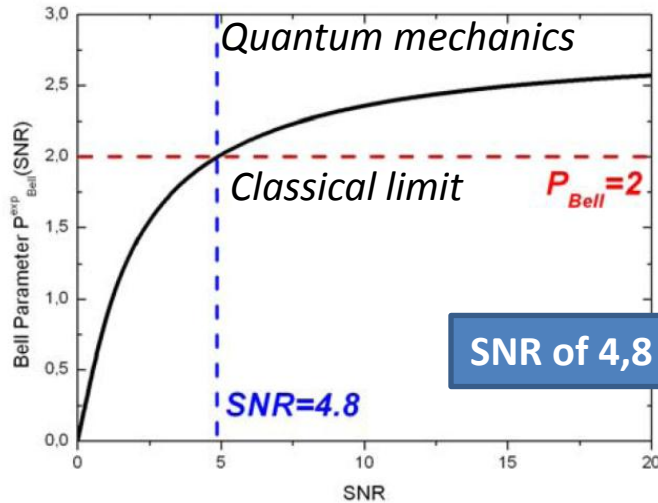


**Quantum Enhanced Clock Synchronization**  
Lamas-Linares et al., Optics Exp. Vol.15 Nr. 15 (2007)  
A. Valencia et al., **Phys. Rev. Lett.** 88, 183601 (2002)



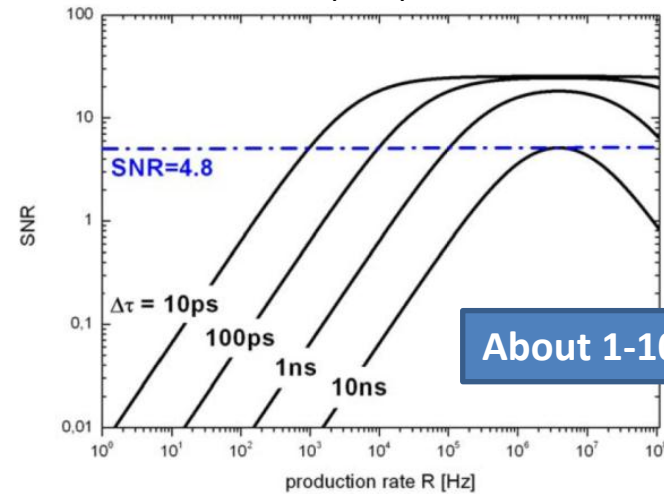
# Is it realistic?

Bell parameter as a function of SNR



SNR of 4,8 is required

SNR as a function of pair production rate R.



About 1-10 MHz is ideal

- Background:**

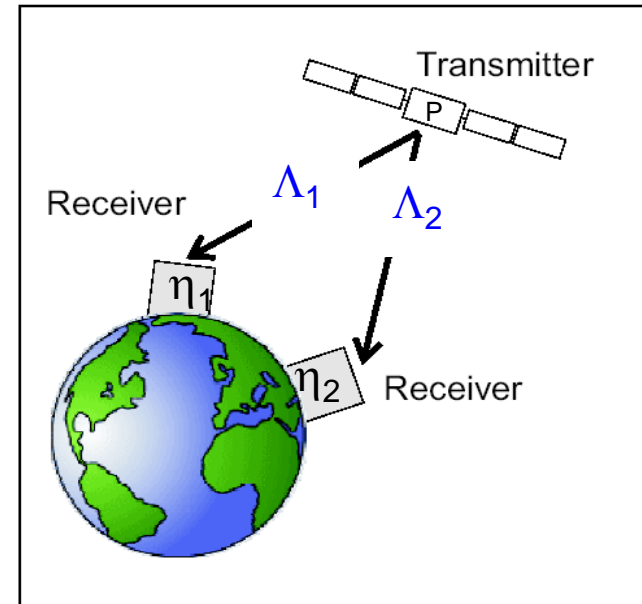
- Background coincidences:  $C_b = S_1 S_2 \tau$
- Background  $S = 2$  kHz per detector
- Coincidence window  $\tau = 5$  ns

- Signal:**

- Signal coincidences:  $C_s = P \eta_1 \eta_2 \Lambda_1 \Lambda_2$ 
  - $P$  is pair production rate of about 1 MHz
  - $\eta_{1,2}$  is detector efficiencies about 0.4 (SiAPD)
  - $\Lambda_{1,2}$  is **required** link efficiencies

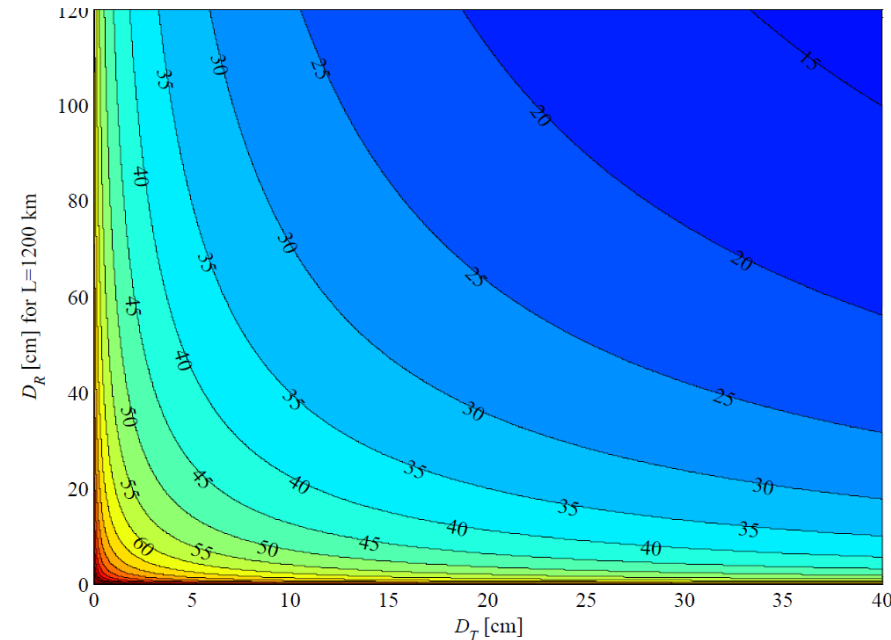
- Quantum link budget:**

- $SNR = 5 = C_s / C_b \Rightarrow \Lambda_1 \Lambda_2 \geq 10^{-6} \sim -60 \text{ dB}$



# Simulations for a satellite-earth link

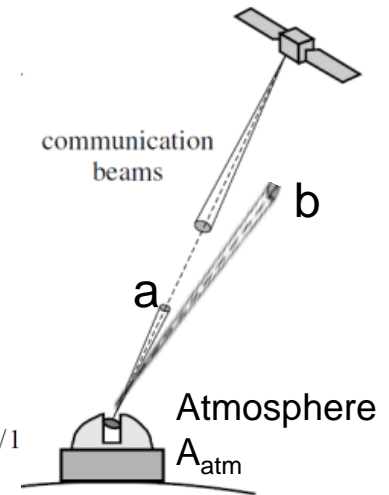
link attenuation  $A$  [dB] for  $\lambda=808\text{nm}$ ,  $T_R=T_T=0.8$ ,  $L_p=0.2$ ,  $A_{atm}=4.4\text{dB}$ .



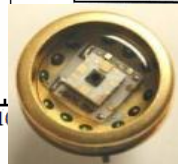
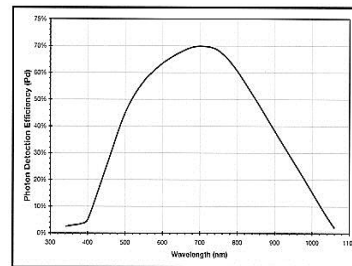
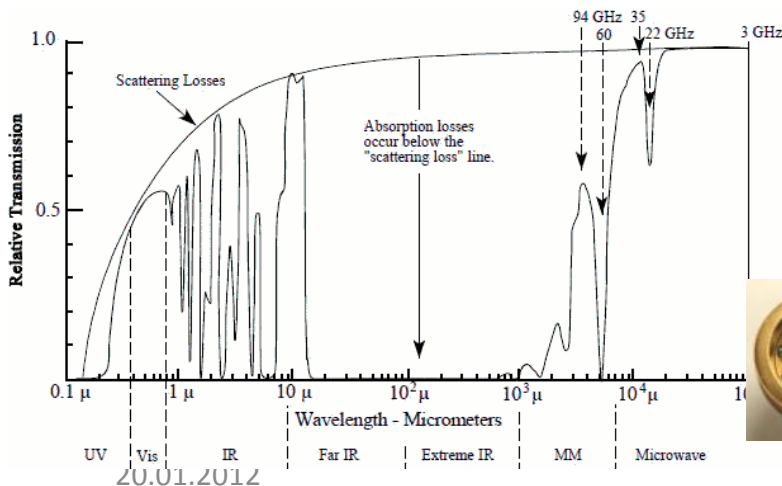
## Link attenuation

- Rx/Tx diameter
- Wavelength
- Atm. Attenuation
- Distance
- Pointing error loss
- Telescopes transmission

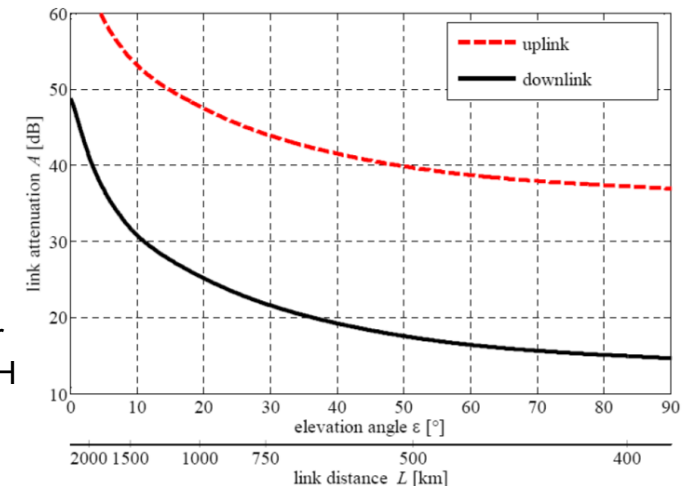
$$A = \frac{L^2 \lambda^2}{D_T^2 D_R^2} \frac{1}{T_T (1 - L_P) T_R} \cdot 10^{A_{atm}/10}$$



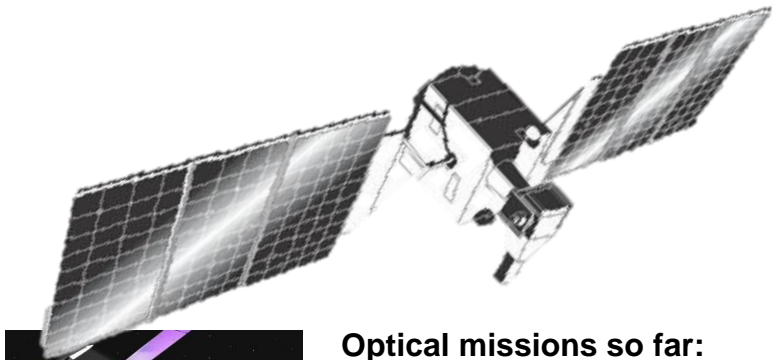
Turbulence cause attenuation to be larger in uplink than for the downlink.



Perkin Elmer  
SPCM-AQRH



# State-of-the-art optical classical space communication



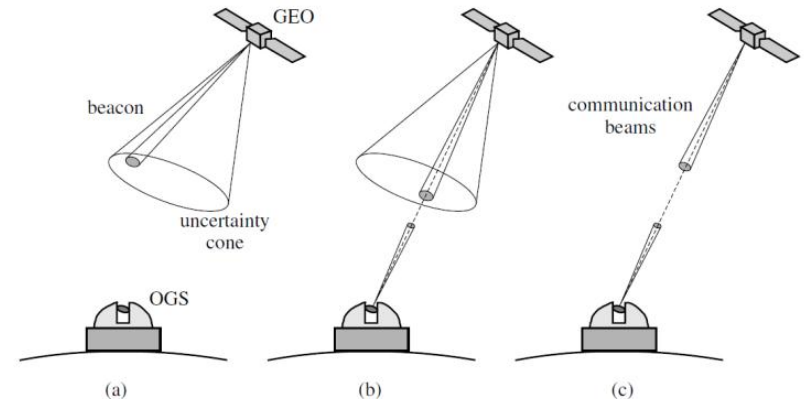
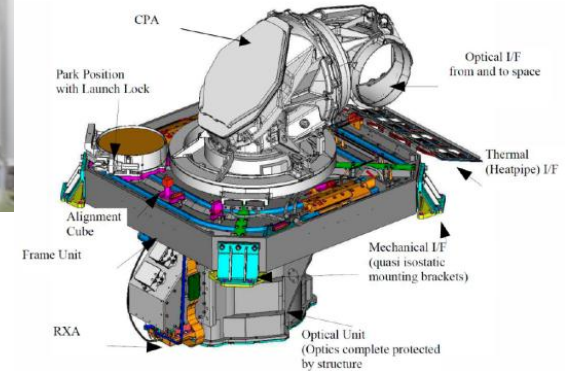
ARTEMIS-Spota  
Silex Experiment

## Optical missions so far:

- ARTEMIS (ESA) in GEO (2Mbps-819nm)
- SPOT-4 (CNES) in LEO (50Mbps-847nm)
- OICETS (JAXA) in LEO (50Mbps-847nm)
- TerraSAR-X (DLR) in LEO (5.5Gbps-1064nm)
- NFIRE (USA) in LEO (5.5Gbps-1064nm)

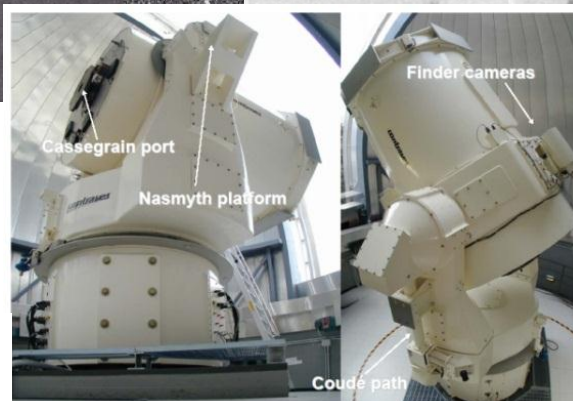
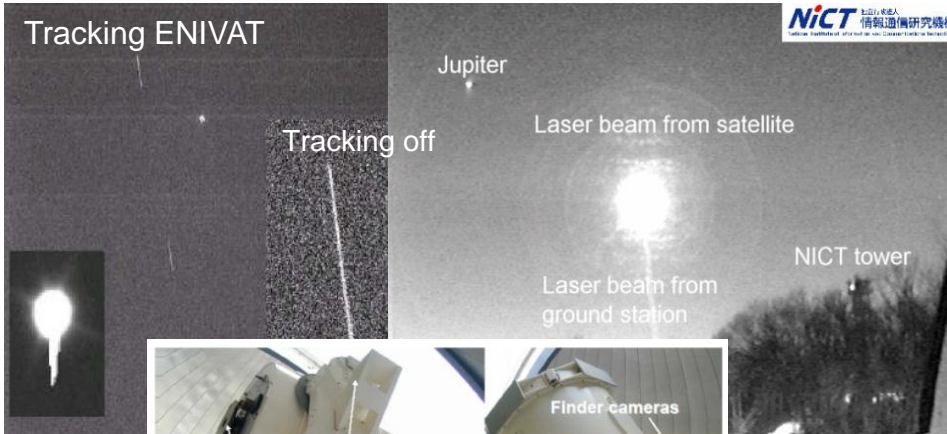


TESAT



Dynamic radial pointing error:  $3.0 \mu\text{rads}$   
Fine pointing angular resolution:  $0.05 \mu\text{rad}$

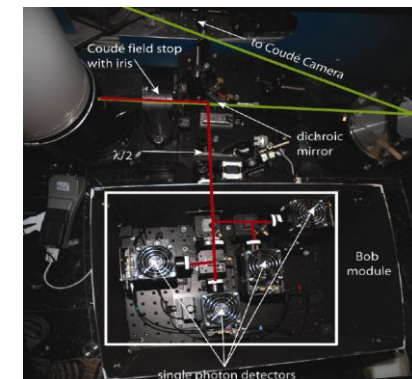
## Tracking ENIVAT



MLRO  
Italy

## SiAPD e.g. Perkin-Elmer

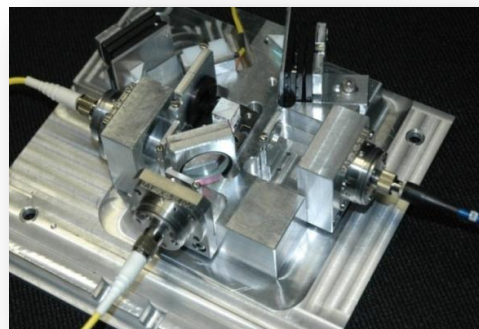
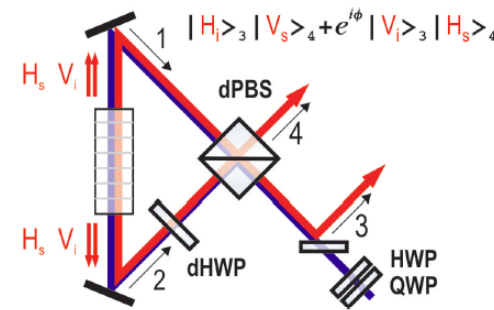
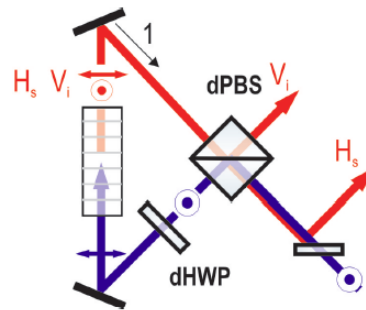
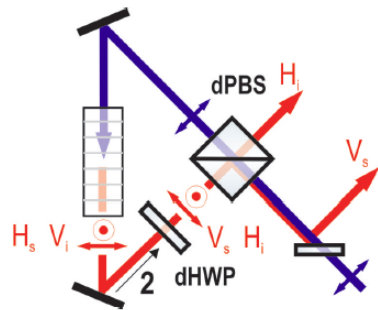
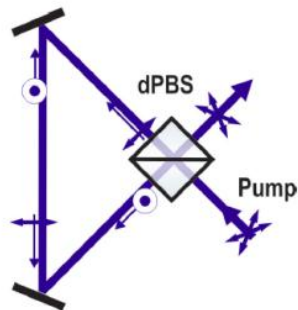
- Mean Count Rate: 5 Mc/s
- QE @ 810 nm: 40% Typical
- Dark count: 40 cps
- Active Area:  $480 \mu\text{m}$
- Timing Resolution of 800 ps FWHM





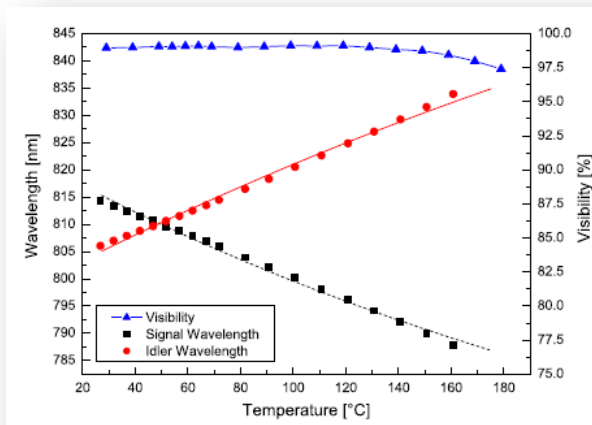
# Entangled photon source

In Kollaboration with:  
ALTER (E), ICFO (E), UPV (E), UCM (E), Lidax (E),  
Emxys (E), TAS-E (E), IQOQI (A),



**Wavelength: 810 nm (tunable)**  
**2-fold rate: > 3,2 cps**  
**Coupling: ~50% incl. det.**  
**Pump power: 18 mW (12V)**  
**Bandwidth: 0,6nm**  
**2-fold Visibility: 99,5 %**

A. Fedrizzi et al., **Opt. Express** 15,  
15377-15386 (2007)



## General requirements

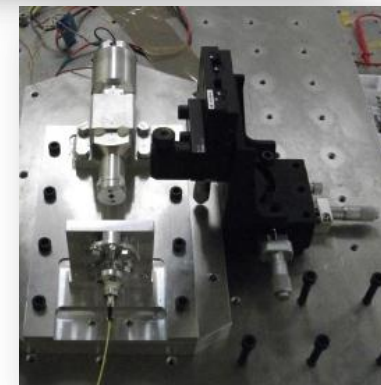
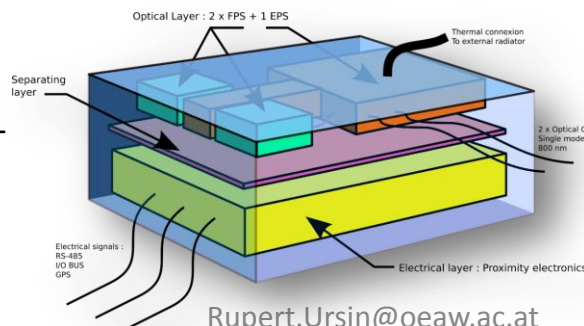
- Total mass ≤ 3 kg
- Total size ≤ 200x150x100 mm<sup>3</sup>
- Total power consumption ≤ 15 W (peak)

## Optical requirements

- Bandwidth ≤ 3 nm
- Coincidences rate > 10<sup>5</sup> s<sup>-1</sup>
- Visibility > 95 % (in 0/90 and +45/-45 basis)
- Weak pulses repetition rate > 10 MHz
- Timing resolution < 1nsec

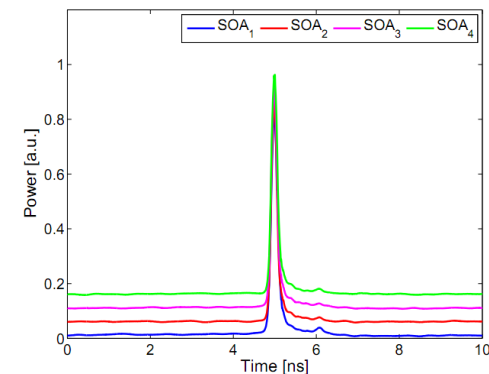
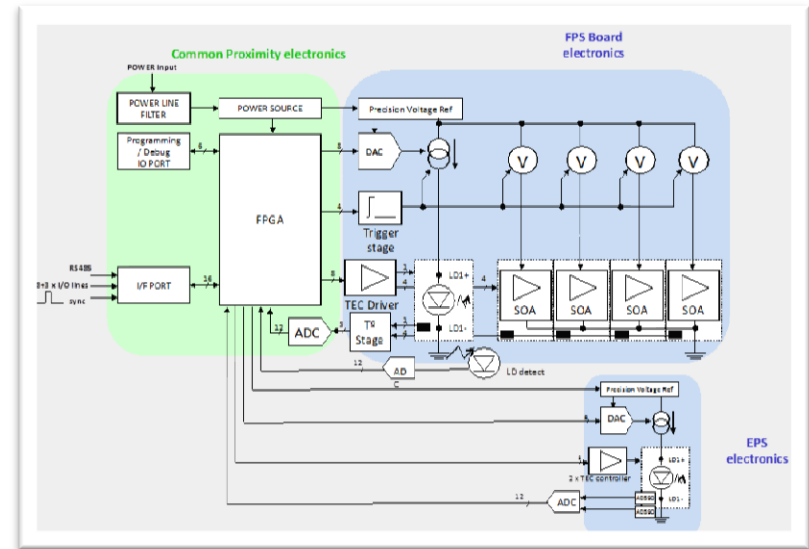
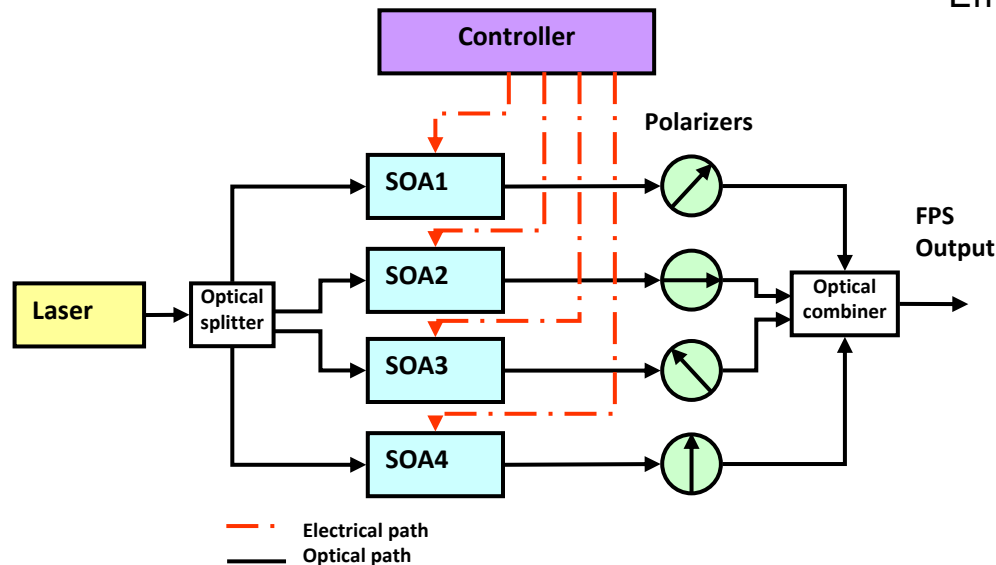
## Environmental constraints

- Operational temperature range:  
- 35C/+60C
- Vacuum compatible
- Radiation tolerant (Proton, γ)

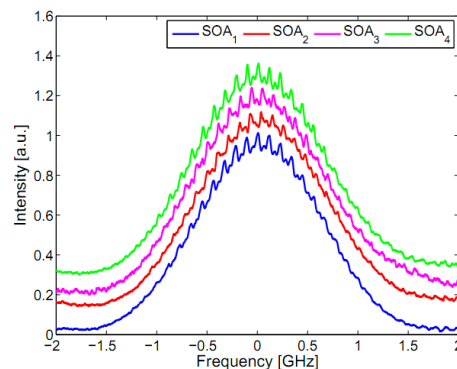


# Decoy BB84 source

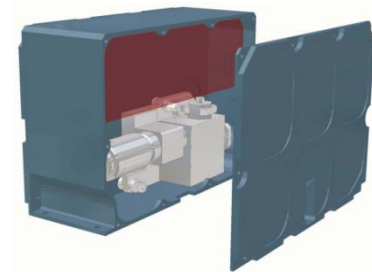
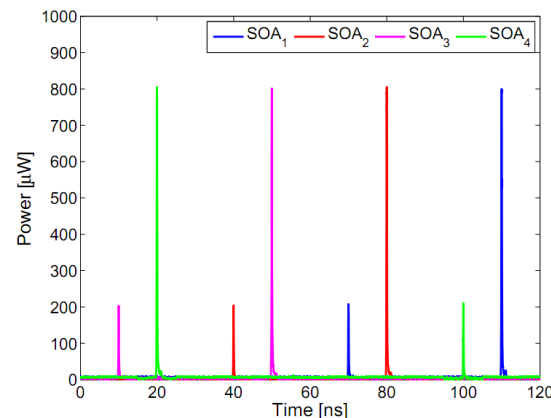
In Kollaboration with:  
ALTER (E), ICFO (E), UPV (E), UCM (E), Lidax (E),  
Emxys (E), TAS-E (E), IQOQI (A),



(a) Temporal profiles.



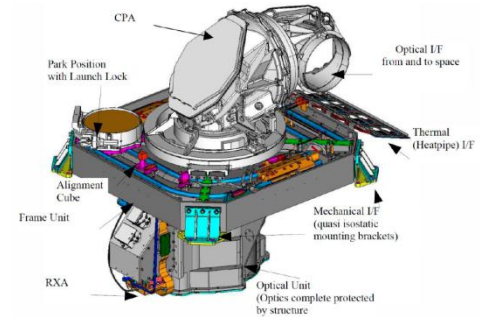
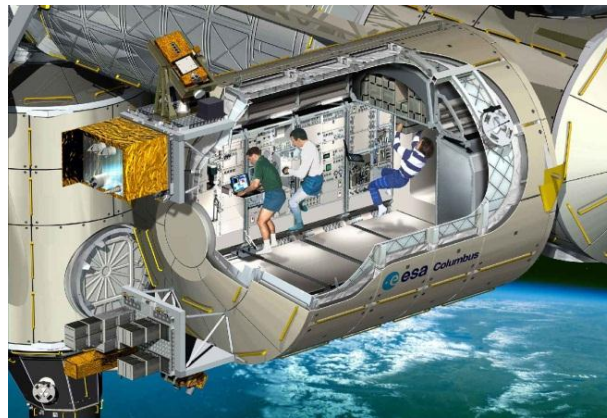
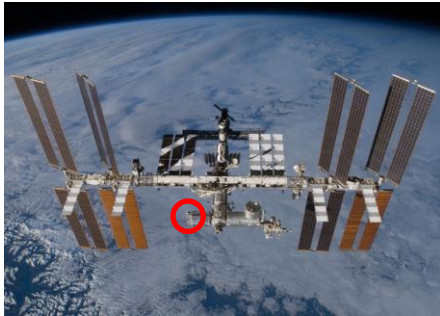
(b) Spectral profiles.



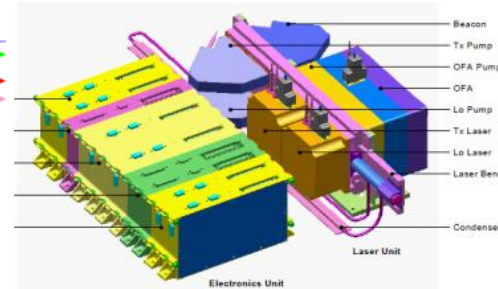
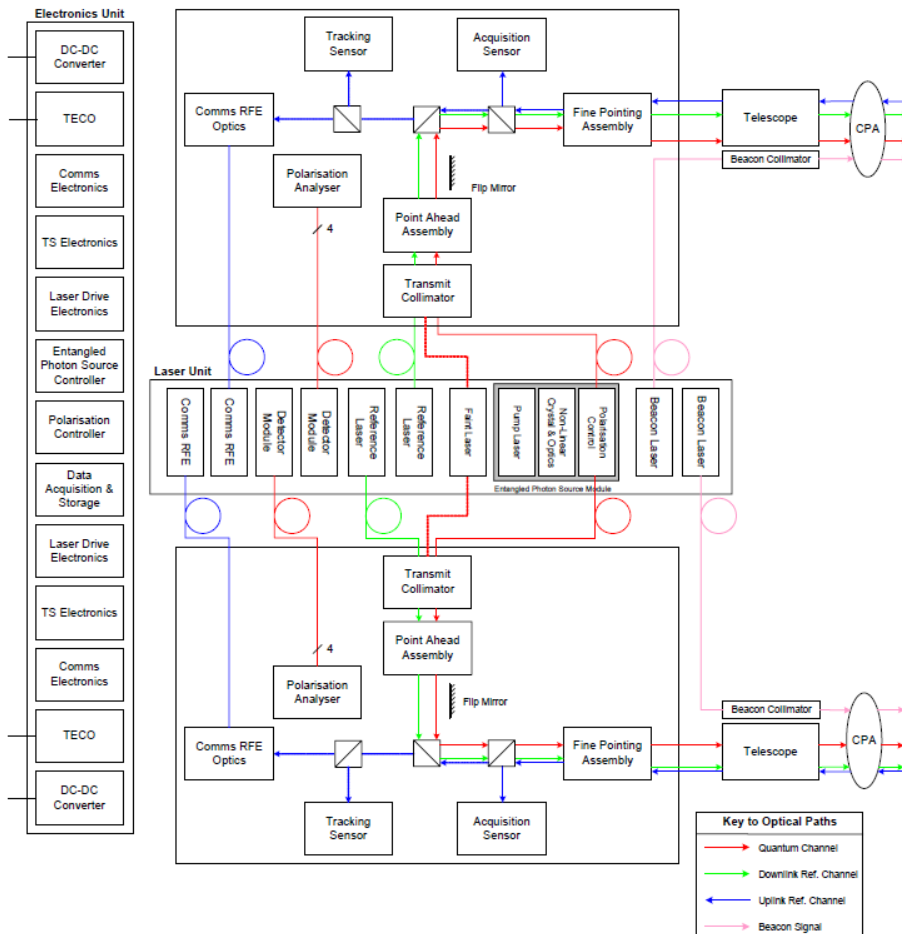
Now: 100 MHz Rate producing 3.64 Mbps at QBER:  $1.14 \times 10^{-2}$

Next: >10GHz at 1550 nm

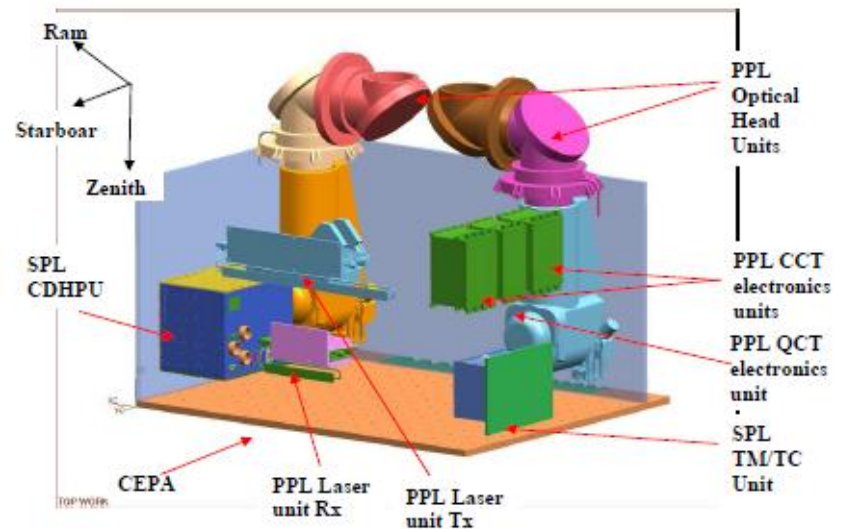
# Space segment



## • Pointing and Tracking

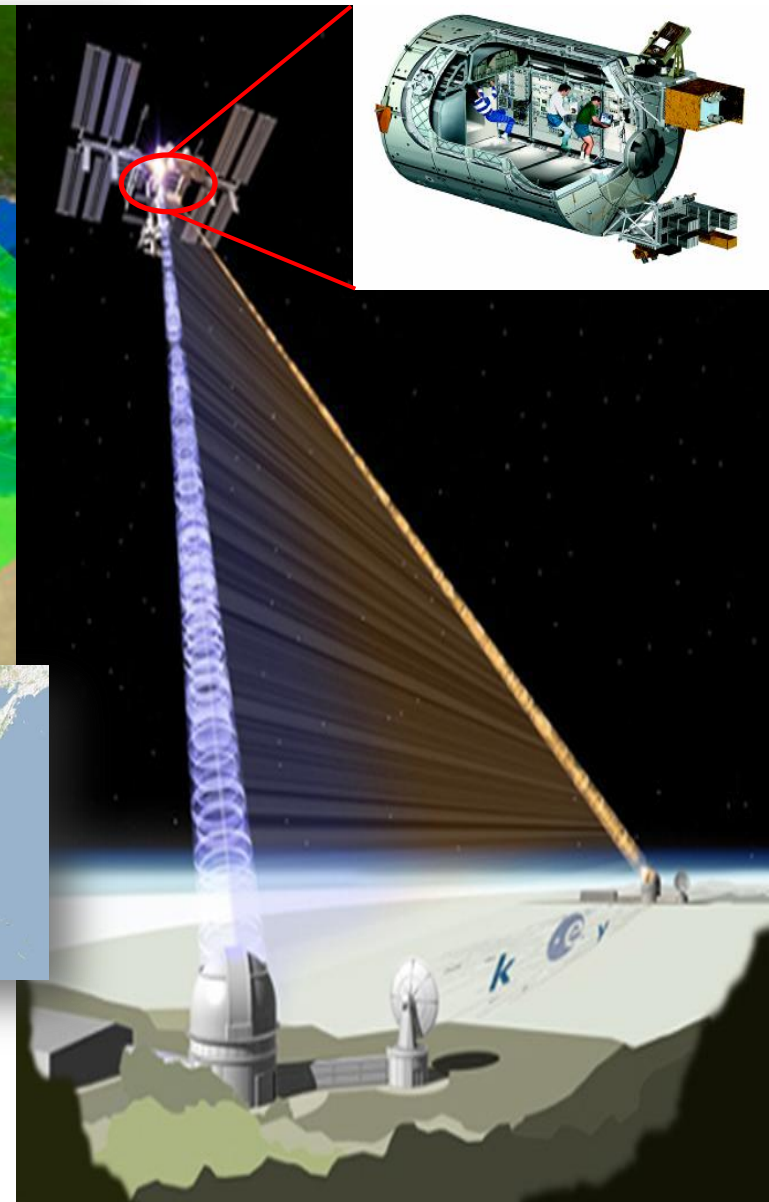
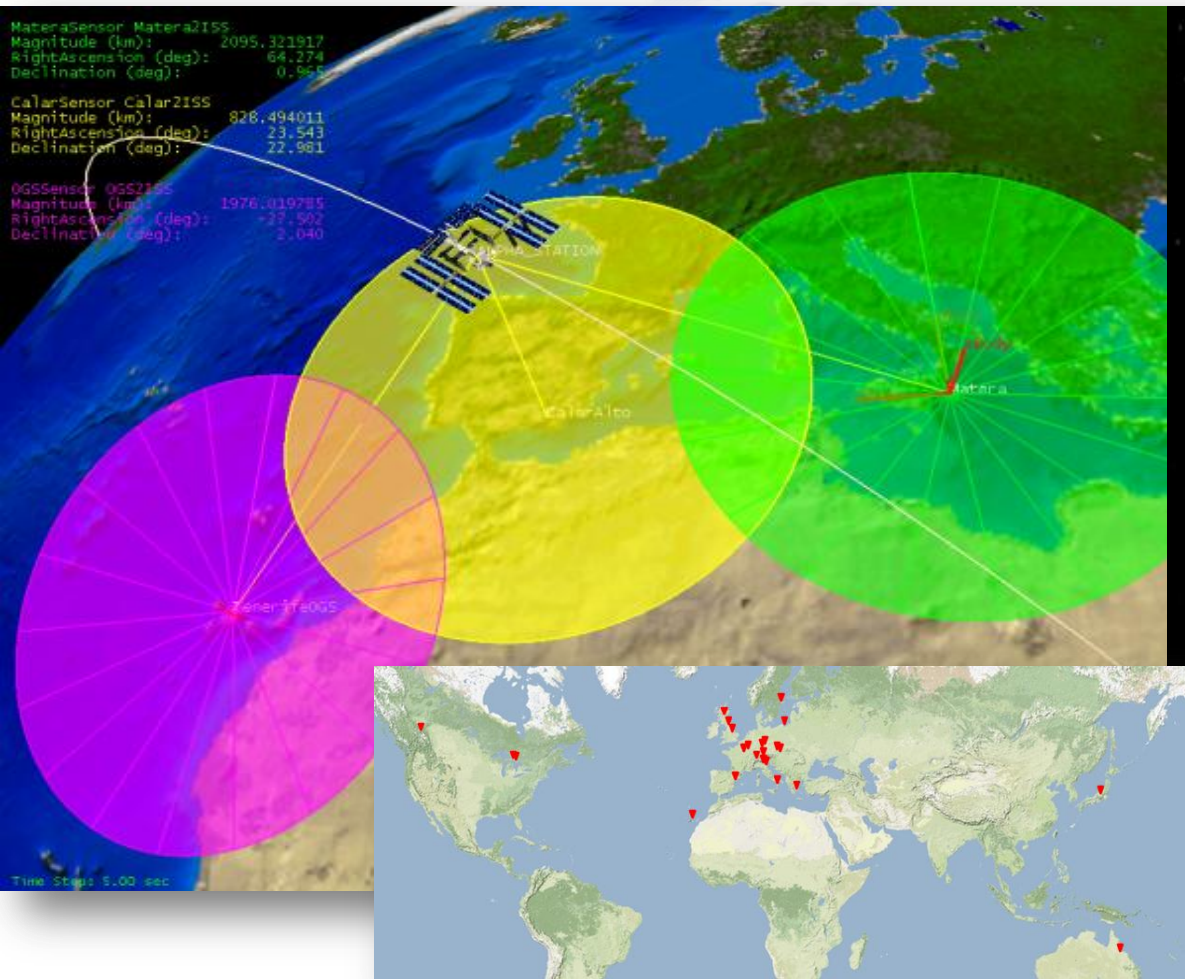


- Entangled photon source
- Decoy BB84 Source





# Space-QUEST



## Space-QUEST: Experiments with quantum entanglement in space

R. Ursin, T. Jennewein, J. Kofer, J. Perdigues, L. Cacciapuoti, C. de Matos, M. Aspelmeyer, A. Valencia, T. Scheidl, A. Acin, C. Barbieri, G. Bianco, S. Cova, D. Giggenbach, W. Leeb, R. H. Hadfeld, R. Lafamme, N. Lütkenhaus, G. Milburn, M. Peev, T. Ralph, J. Rarity, R. Renner, N. Solomos, W. Tittel, J. P. Torres, M. Toyoshima, P. Villoriesi, I. Walmsley, G. Weihs, H. Weinfurter, M. Zukowski and A. Zeilinger

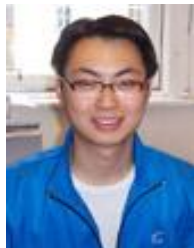
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# Thanks



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## Collaborations:

- ESA
- IQOQI
- LMU
- Univ. Bristol
- ICFO
- Univ. Padova
- TESAT
- CONTRAVES
- ASTRIUM
- AIT



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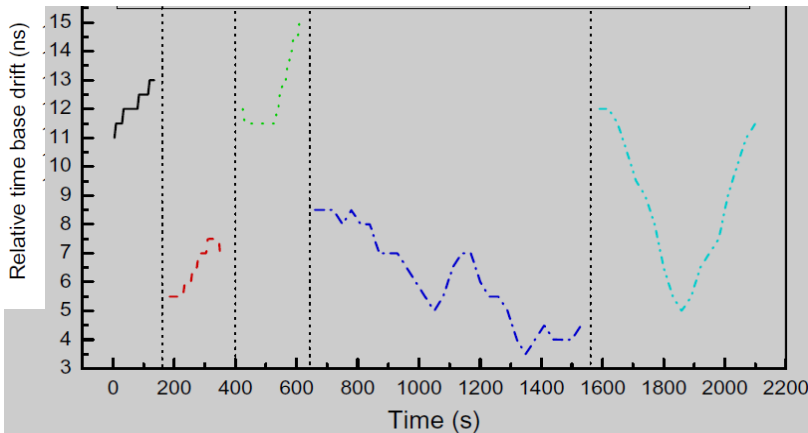
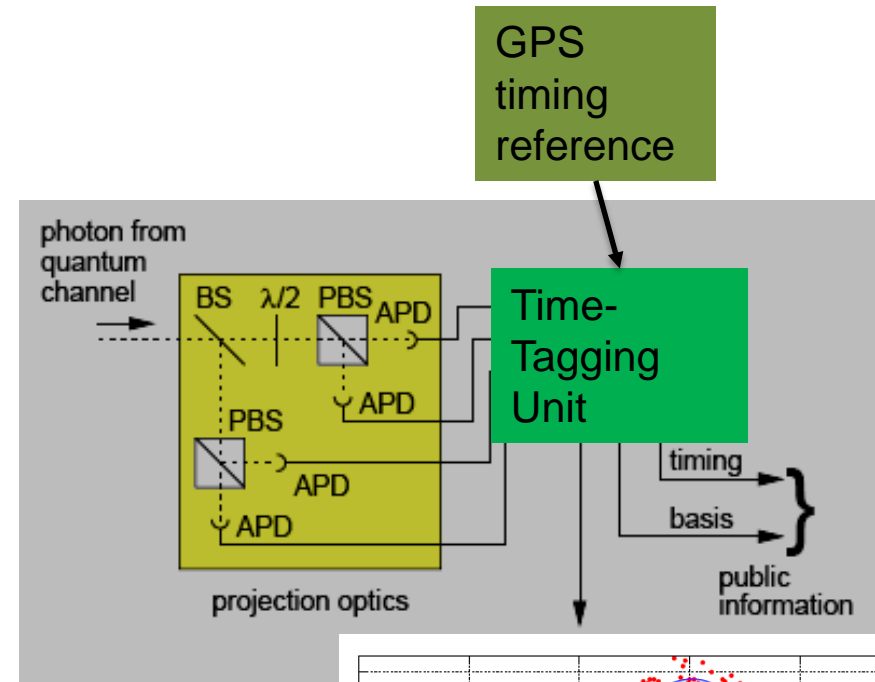
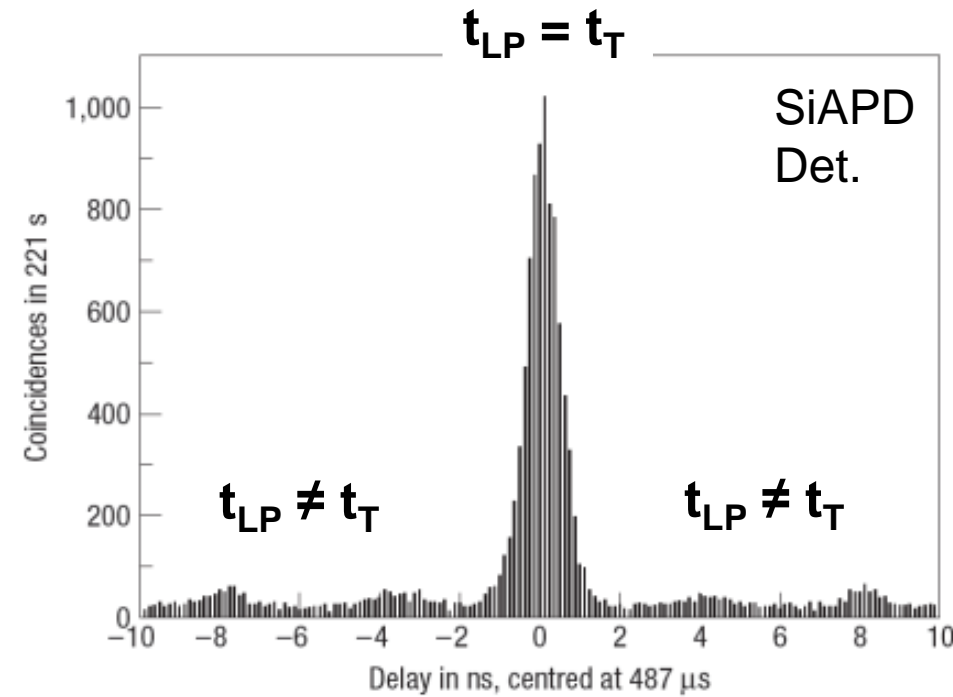


Nathan Langford



J. Rarity

# Timing and synchronization



Timing constraints:

- Si APD T(FWHM)~800ps (Nanowire: T(FWHM)~50ps)
- Time-tagging: 156ps time-slots

