The Abdus Salam International Centre for Theoretical Physics

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International Atomic Energy Agency

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WINTER COLLEGE
on
QUANTUM AND CLASSICAL ASPECTS
of
INFORMATION OPTICS

30 January - 10 February 2006

Free Space Quantum Cryptography

J.G. RARITY

Department of Electrical & electronic Engineering
University of Bristol
Bristol
UK

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

ESA: QIPS

Trieste lecture 2
Free Space Quantum Cryptography

7th Feb 2006

J. G. Rarity
University of Bristol
john.rarity@bristol.ac.uk

LMU Munich
University of Bristol
University of Vienna
QinetiQ
HP labs Bristol

FP6: IP
SECOQC
www.secoqc.net

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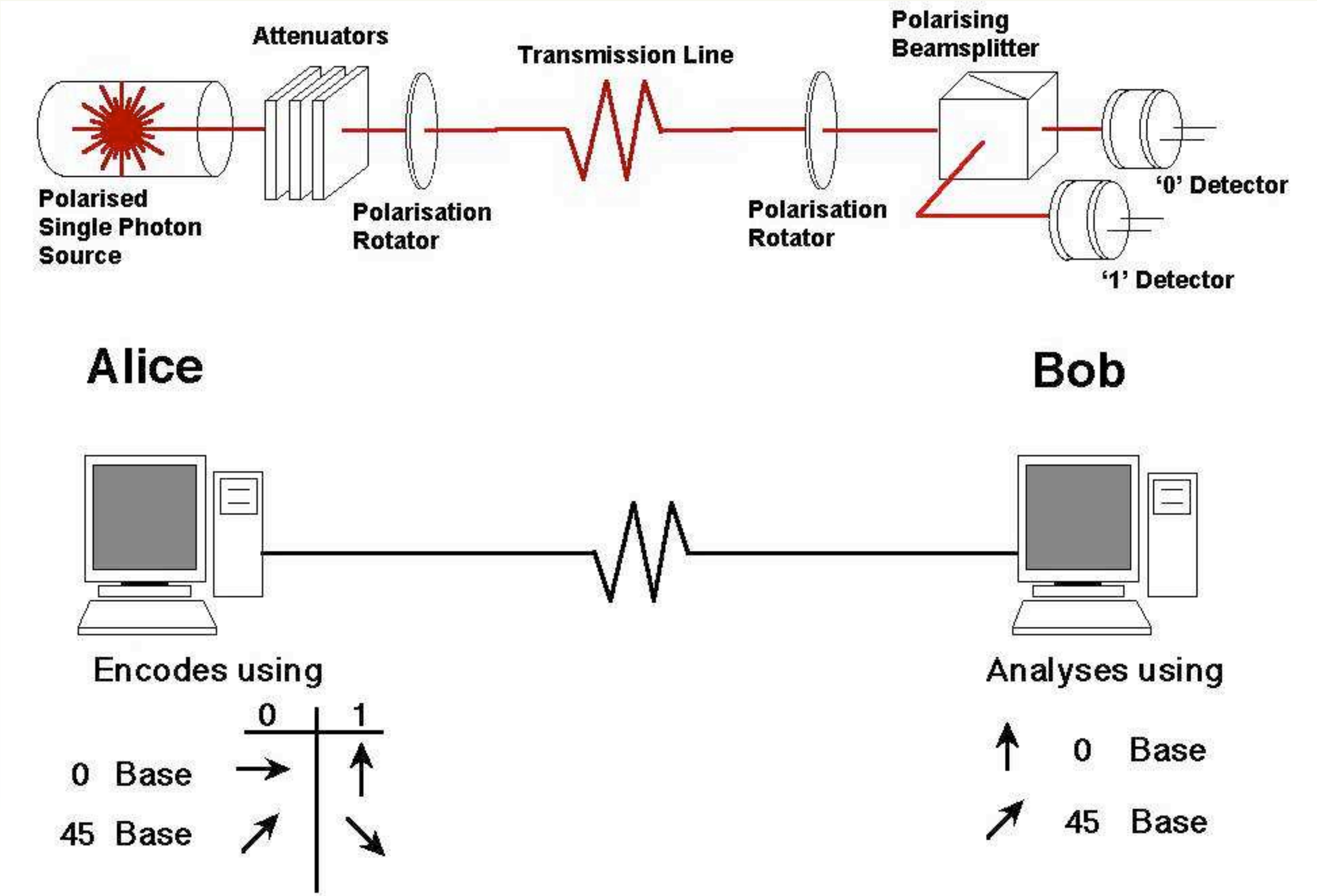
Overview

- Introduction to quantum cryptography
  - Faint pulse
  - Entangled state
- Experiments
  - Faint pulse
  - Heralded entangled photon
- Performance limits
- Future experiments

Bennett and Brassard 1984
Secure key exchange using quantum cryptography

Sends

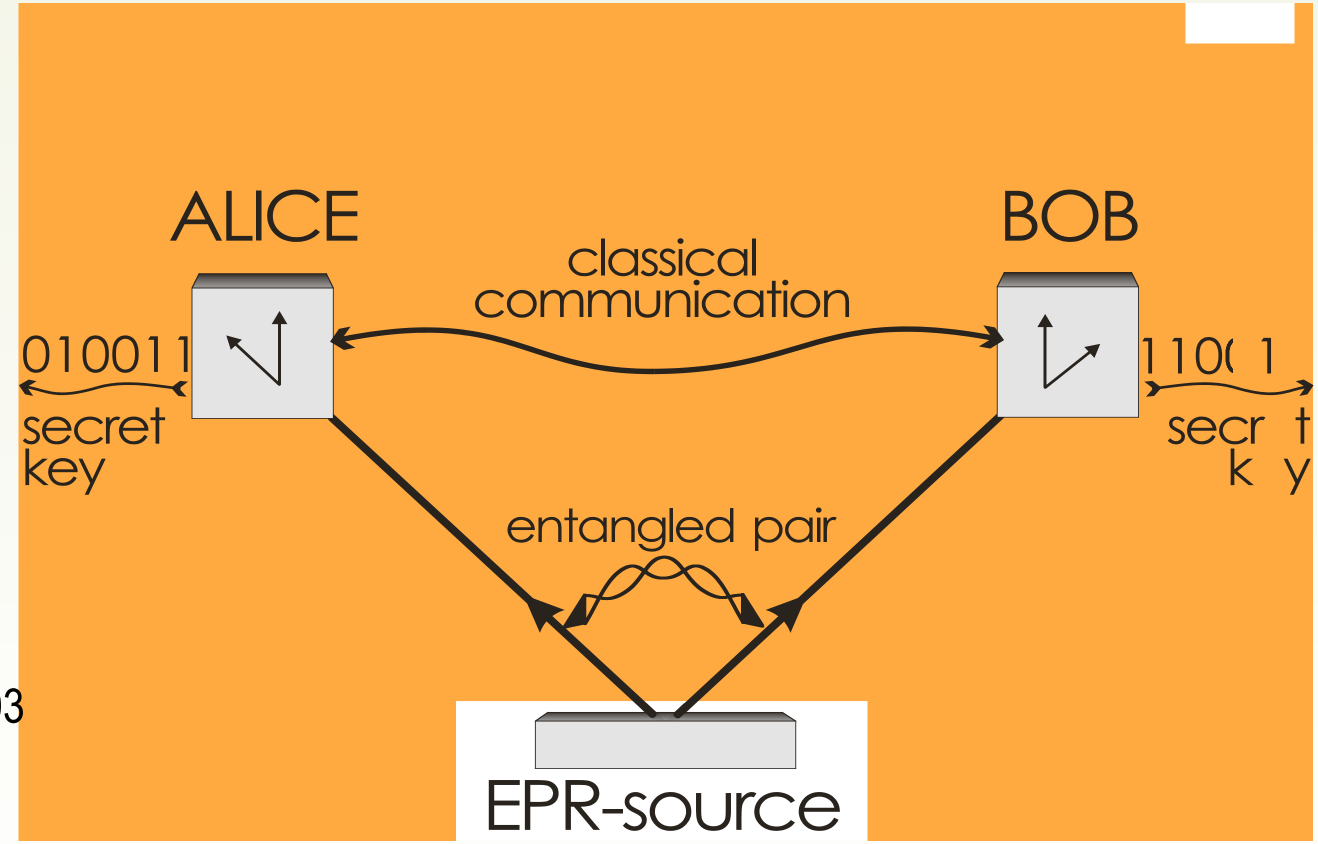
no.	bit	pol.
1	1	45
2	0	45
3	0	0
4	1	45
5	1	0
6	0	45
7	1	45
…		
1004	0	45
1005	1	0
….		
3245	1	45
…		



Receives

no.	Bit	Pol.
246	1	45
1004	0	45
2134	0	0
3245	0	0
4765	1	0
5698	0	45

Entanglement and key exchange



Aspelmeyer et al
Science August 2003

$$|\Psi\rangle = \tfrac{1}{\sqrt{2}}\left(|H\rangle_A |H\rangle_B + |V\rangle_A |V\rangle_B\right)$$

$$\equiv \tfrac{1}{\sqrt{2}}\left(|'45'\rangle_A |'45'\rangle_B + |'-45'\rangle_A |'-45'\rangle_B\right)$$

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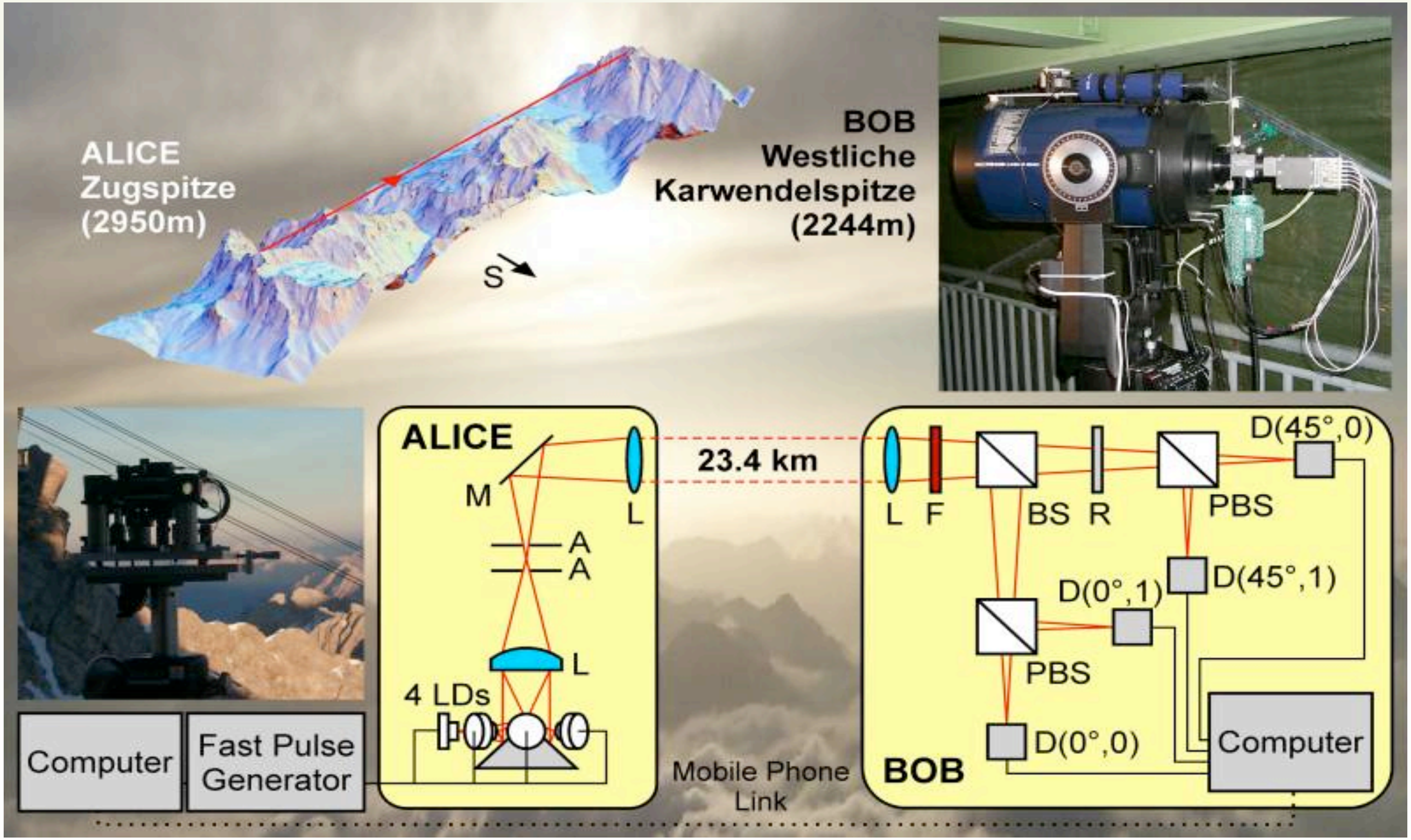
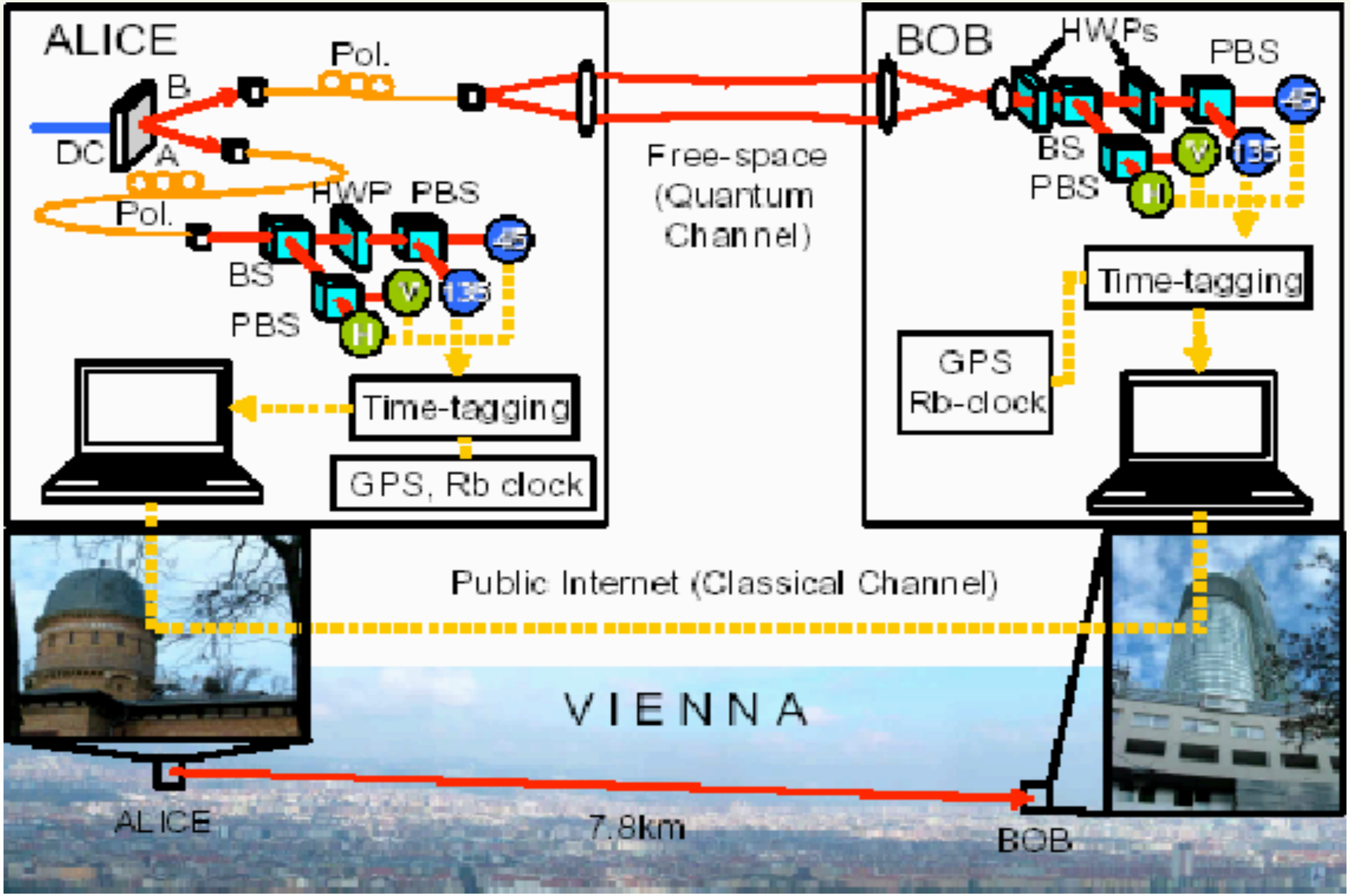
Previous faint pulse free space experiment over 23.4km



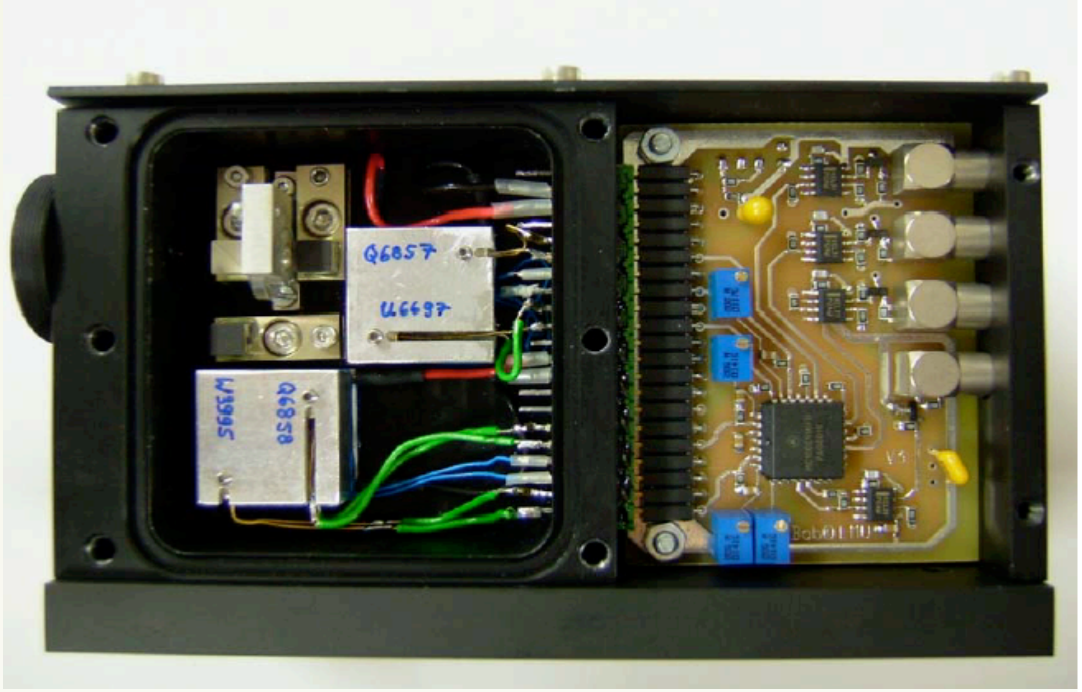
Kurtsiefer et al, (2002), *Nature,* **419**, 450.

Entangled state/heralded single photon system

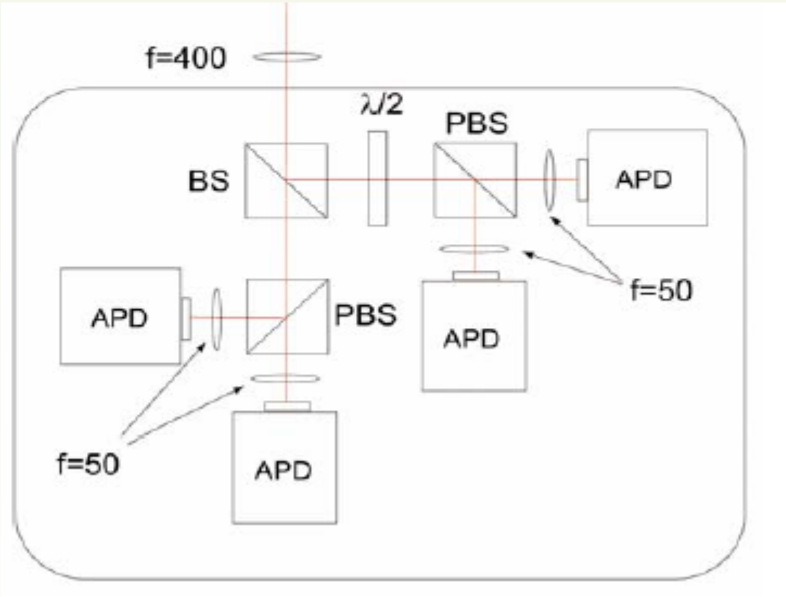


K. J. Resch, Optics Express 13, 202-9 (2005)

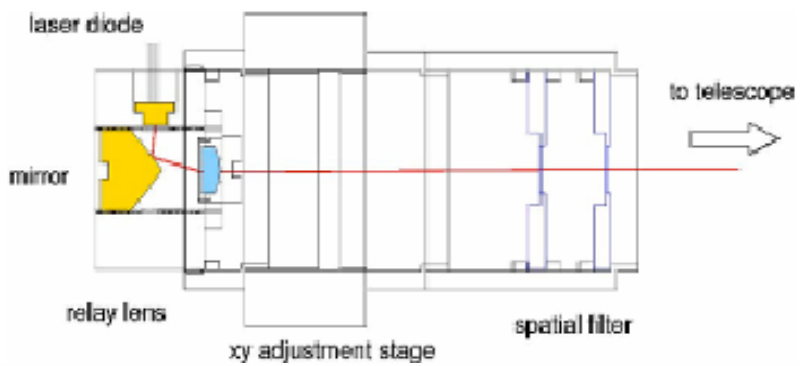
Miniature Bob detector unit:



Medium Bob (F5 optics)



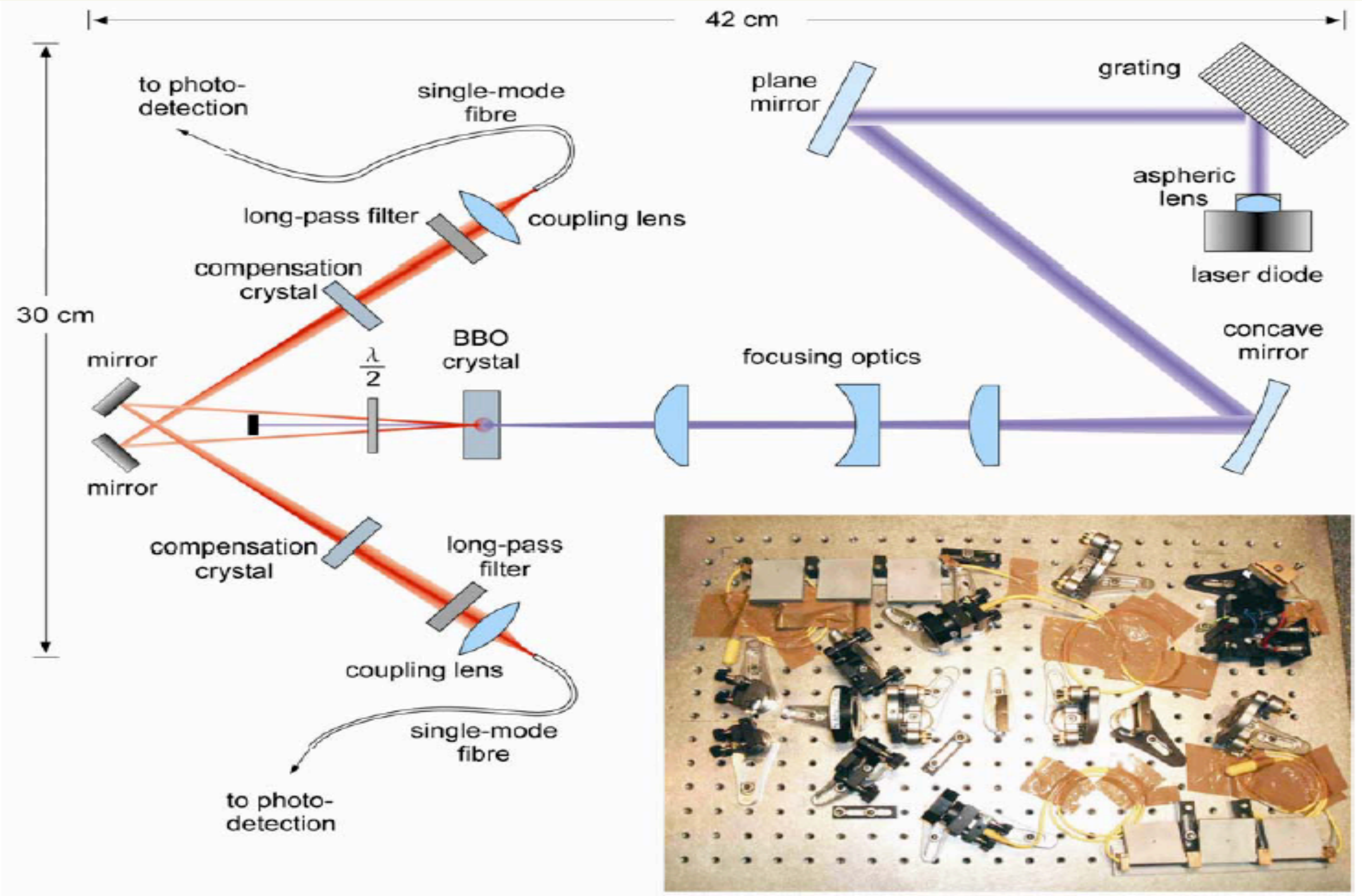
Miniature Alice



Portable Crystal based entangled pair source

150mW diode

70000 detected coincidences/sec



Transmission limitations of any system

Background count error probability per pulse

$P_b = Bt/4$ (half lead to errors)

The photo-count probability

$P_p = \mu T \eta / 2$ (BB84)

μ= photons per bit (0.1 faint pulse, ~0.75 heralded)

T = transmission (variable)

h= efficiency of receiver (20%)

B= background rate (~2000)

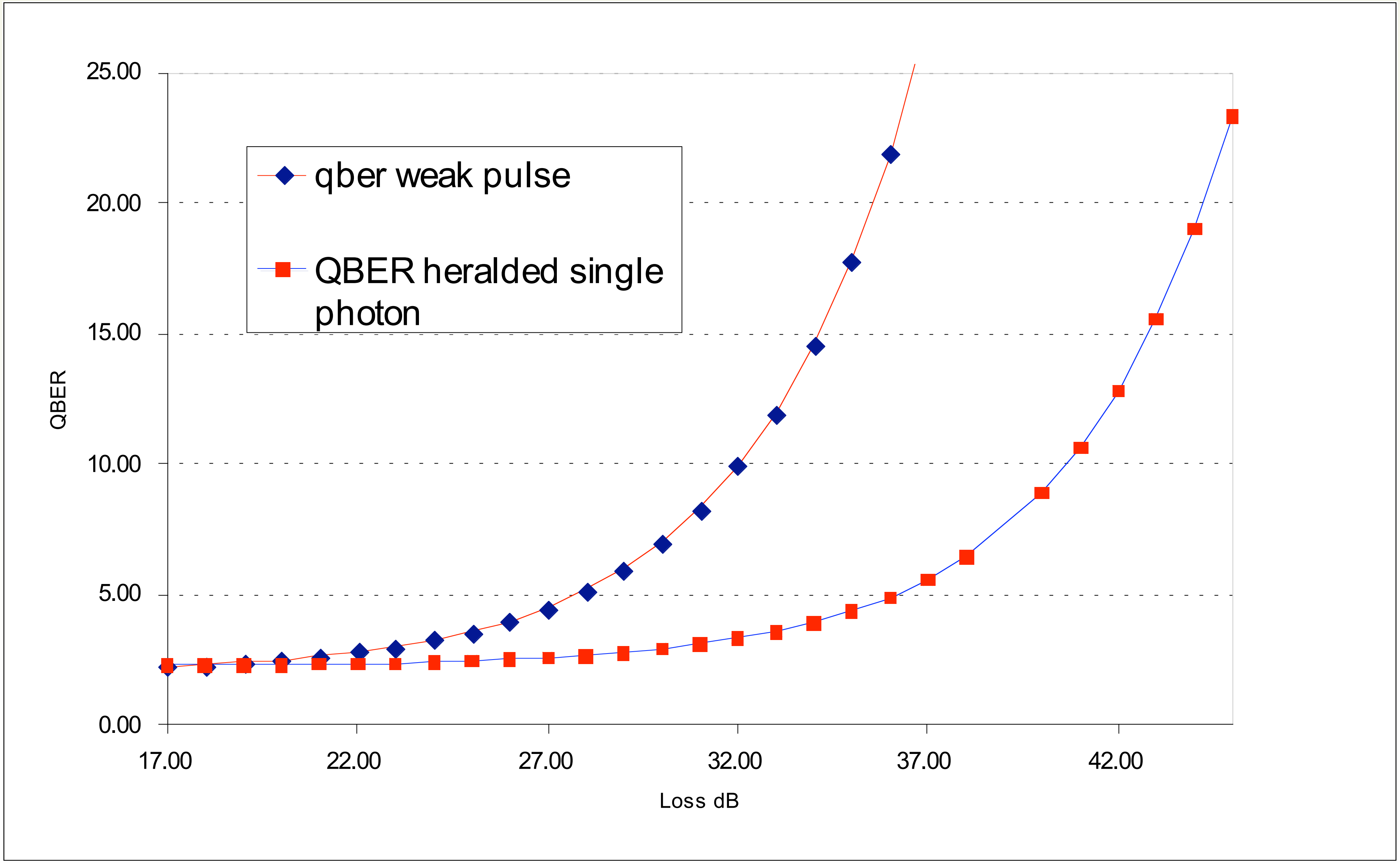
t= gate width (~1ns)

Error rate (QBER)

$$E = E_0 + Bt / 2\mu T \eta$$

E_0 is the technical error

QBER as a function of loss



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Secret bit yields, after error correction and privacy amplification

Raw bit rate

$$K = 10^{-L/10}\mu\eta_B R$$

Number of sifted bits in time *T*

$$n_{rec} = KT/2$$

Number of bits revealed in error correction [1]

$$n_E = n_{rec}(1-E)$$

$$E = \varepsilon\left(7/2 - \log_2(1-\varepsilon)\right)$$

Every error could be a result of eavesdropping

Information leakage [2]:

$$n_{leak} = n_{rec}\left(\log_2\left(1+4\varepsilon-4\varepsilon^2\right)\right)$$

Final key length thus given by:

$$n_{fin} = n_{rec} - n_E - n_{leak} - n_s$$

$$= n_{rec}\left(E - \log_2\left(1+4\varepsilon-4\varepsilon^2\right)\right) - n_s$$

n_s= excess reduction to enhance security

For Poisson sources all multiphoton pulses are insecure

$$n_{fin} = n_{rec}a\left(E - \log_2\left(1+4\frac{\varepsilon}{a}-4\left(\frac{\varepsilon}{a}\right)^2\right)\right) - n_s$$

$$a = \frac{e^{-\mu}.\mu}{1-e^{-\mu}}$$

Is the fraction of pulses containing photons that contain only one

Infinite technology Eve

Multi-photon pulses are split and sent on through a loss free channel to Bob.

$$n_{fin} = n_{rec}b\left(E - \log_2\left(1+4\frac{\varepsilon}{b}-4\left(\frac{\varepsilon}{b}\right)^2\right)\right) - n_s$$

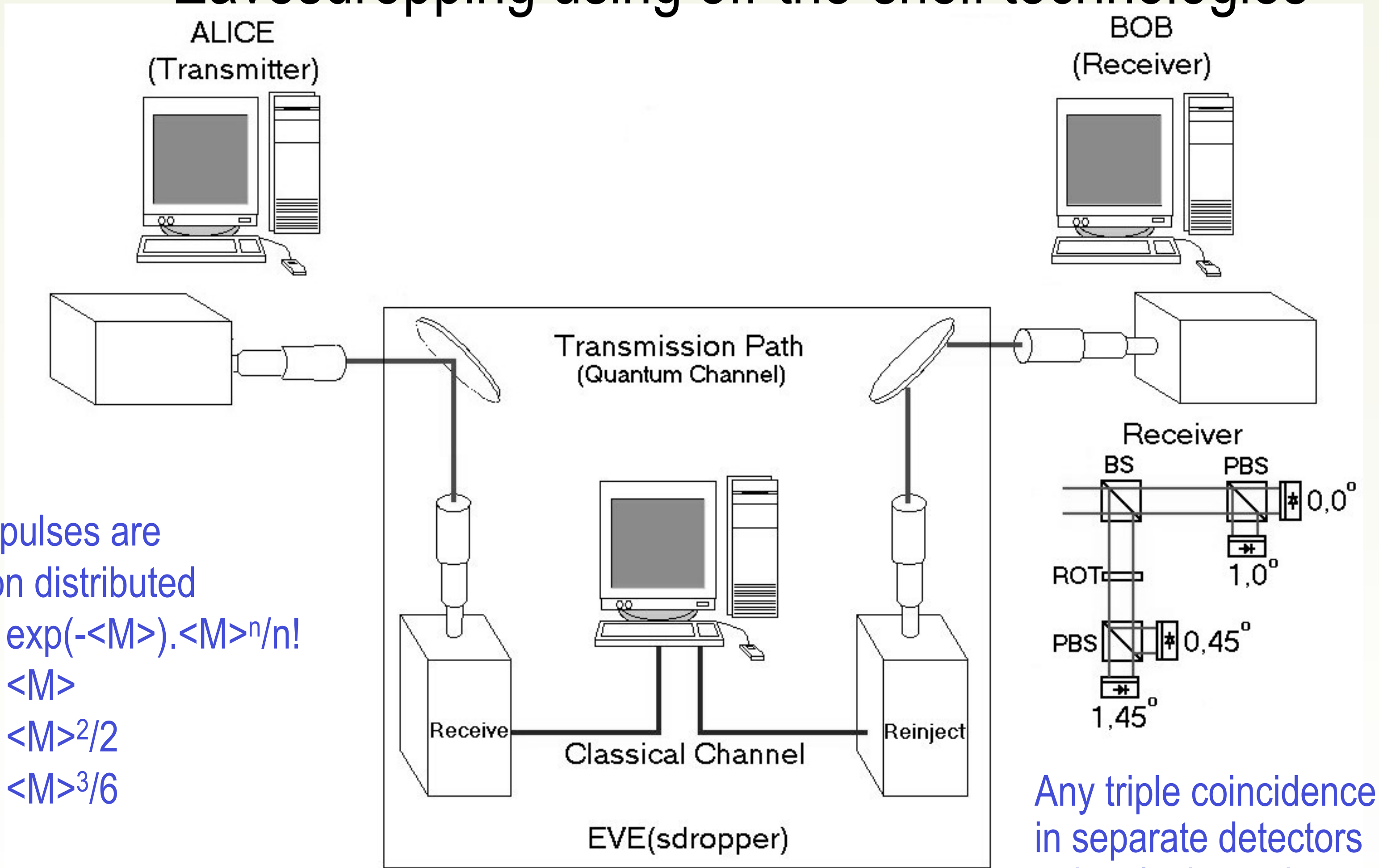
$$b = 1 - \frac{(1-a)}{10^{-L/10}} \quad \mu > 10^{-L/10}, b < 0$$

Eve can only get at >3 photon pulses

$$a' = a(1+M/2) \qquad b = 1 - \frac{(1-a')}{4T}$$

1. L. Tancevski,et al. Proc. SPIE, **3228**, 322-331 (1997).
2. N. Lutkenhaus, Phys. Rev. A 59, 3301–3319 (1999).
3. G. Brassard, et alPhys.Rev.Letts, **85,** pp1330-1333 (2000).

Eavesdropping using off-the-shelf technologies



Weak pulses are Poisson distributed

P(n) = exp(-<M>).<M>^{n}/n!

P(1) ~ <M>

P(2) ~ <M>^{2}/2

P(3) ~ <M>^{3}/6

P3)/P(1)=<M>^{2}/6

Any triple coincidence in separate detectors uniquely determines the state!!

Safe if M^2<24T

M~0.1 T> -33dB

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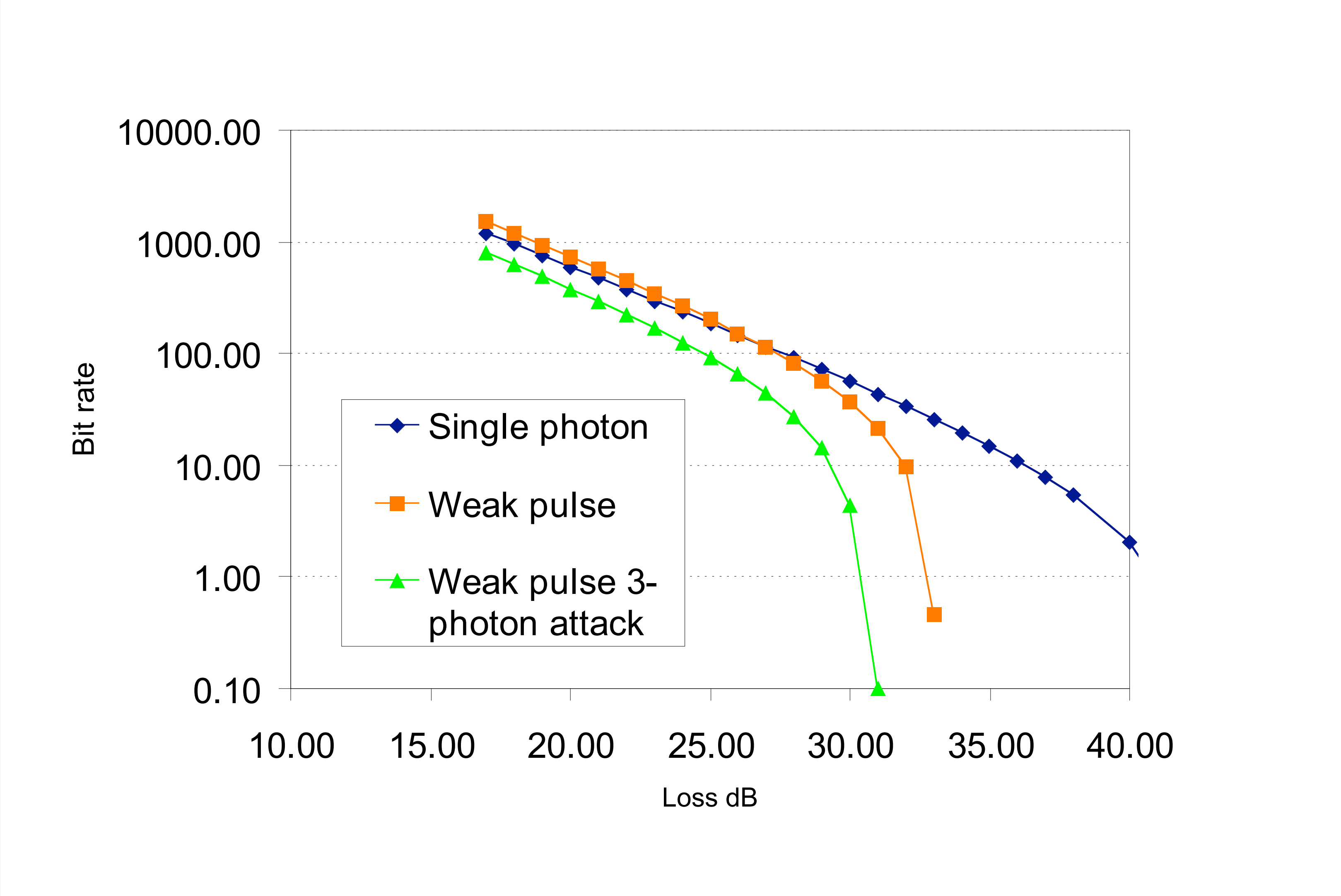
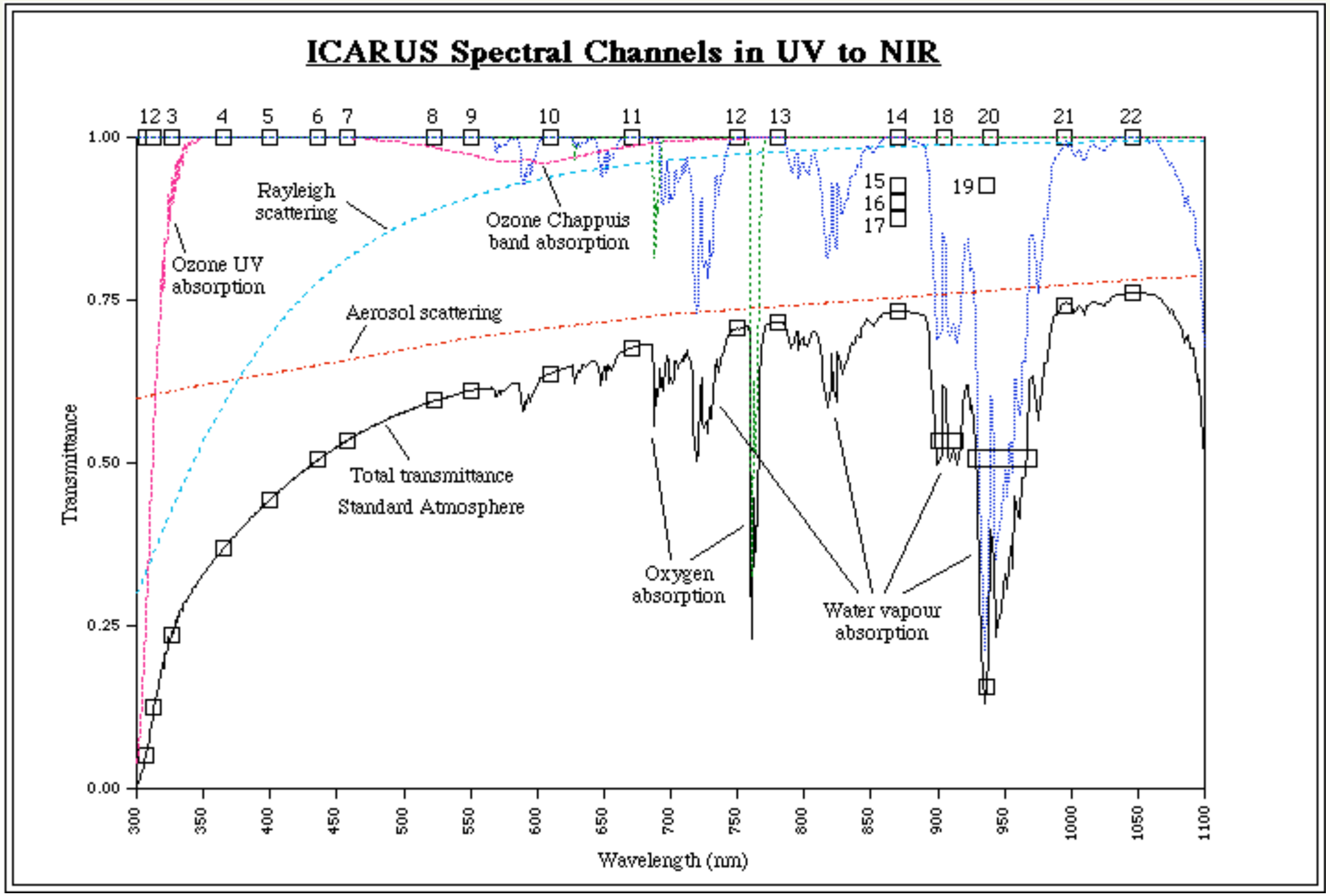
Expected Secret bit yields as a function of loss after error correction and privacy amplification



Atmospheric Transmission Windows for long range.



Chosen trial site:

1 - The Observatorio del Roque de los Muchachos (Island of La Palma)

http://www.iac.es/gabinete/orm/indice.html

2 - The Observatorio del Teide (Island of Tenerife)

http://www.iac.es/ot/indice.html

The design and loss budget

- 10 MHz pulse rate, 0.1 photons/pulse
- Entangled source with >5.10^6 pairs/sec (>100000/s locally)
- 700/810/850nm wavelength
- <20 μR beam divergence
- Diffraction spot <3 m diameter after 144 km
- Expect ~40 μR from turbulence + ~10 dB absorption/scatter
- Collection and atmospheric transmission, 25-35dB loss
- Aim for background counts <2000 cps/detector through 10nm filter at night

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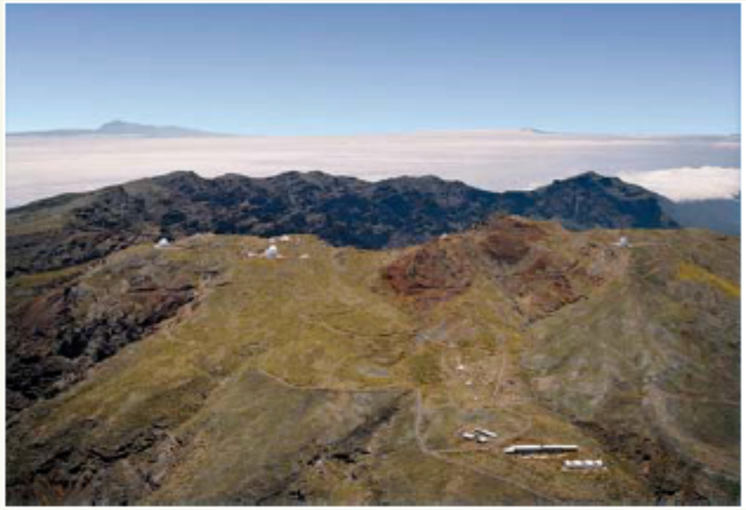
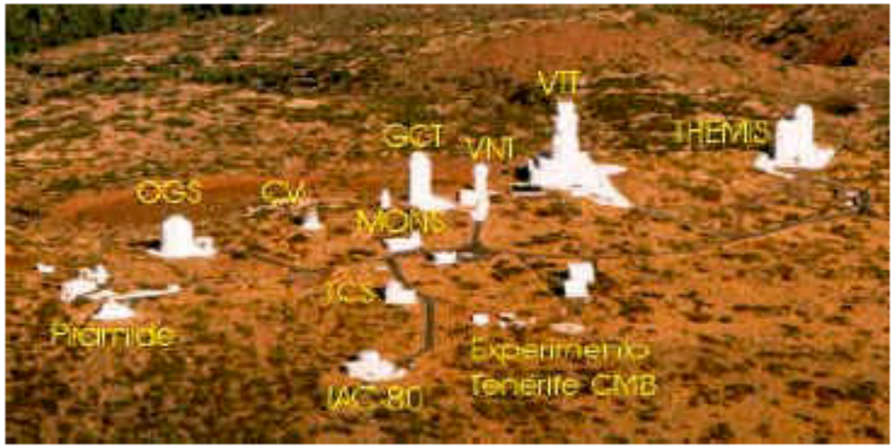
La Palma: Roque de los Muchachos



Overview of Roque with Tenerife in background

La Palma from Tenerife

Optical ground station Tenerife



Overview of Izana (Tenerife) site

OGS with mount Tiede in background

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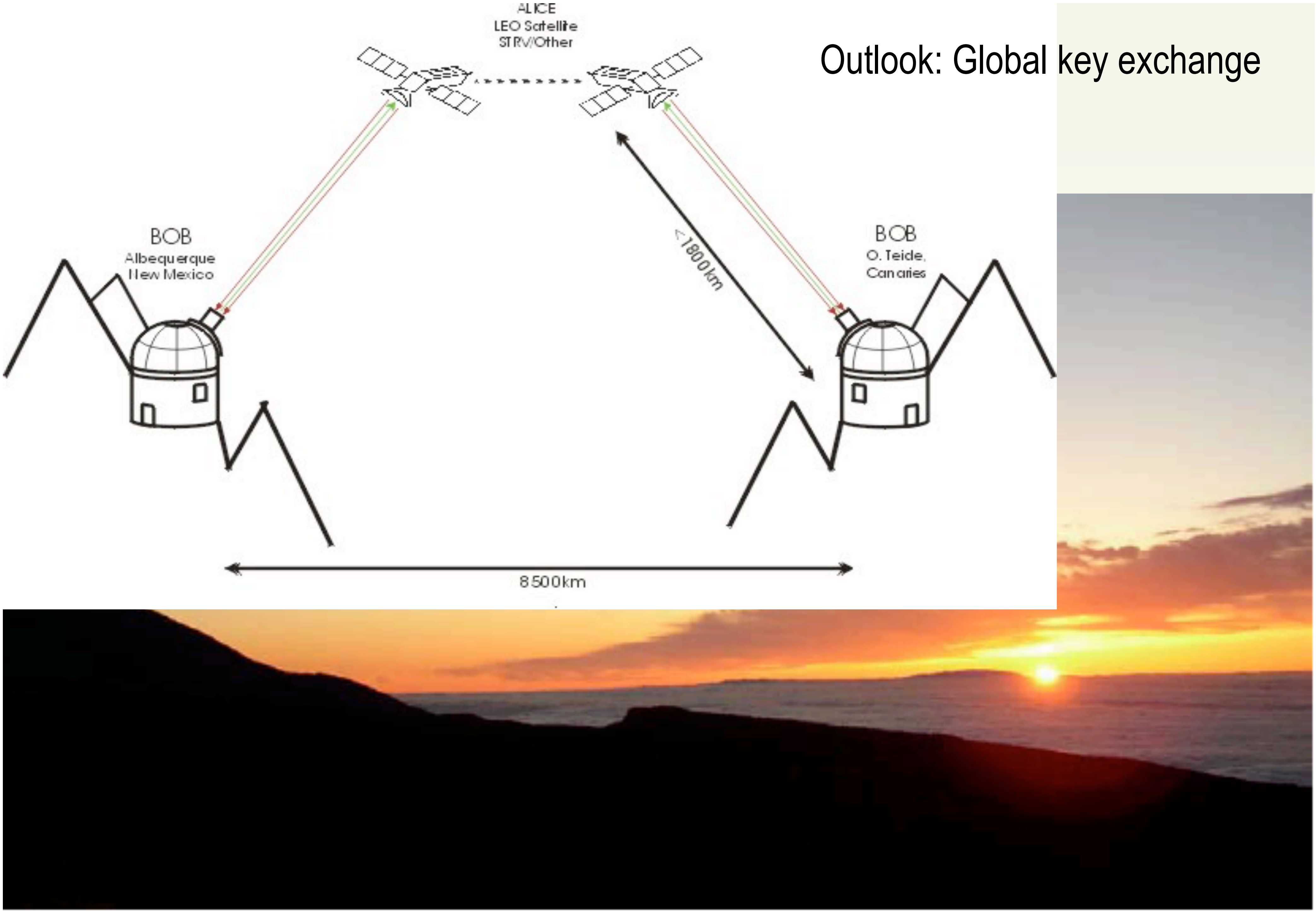
ESA OGS 1 metre telescope (Bob)

Metrology:

- Cartesian distance OGS - NOT : 143.630 km
- in position angle (North trough West) : 251°.
- Angle TNG-NOT-Teide: 123°.7 (vertex at NOT).

- Also possible Teide-OGS-La Palma (see TN4)

Outlook: Global key exchange



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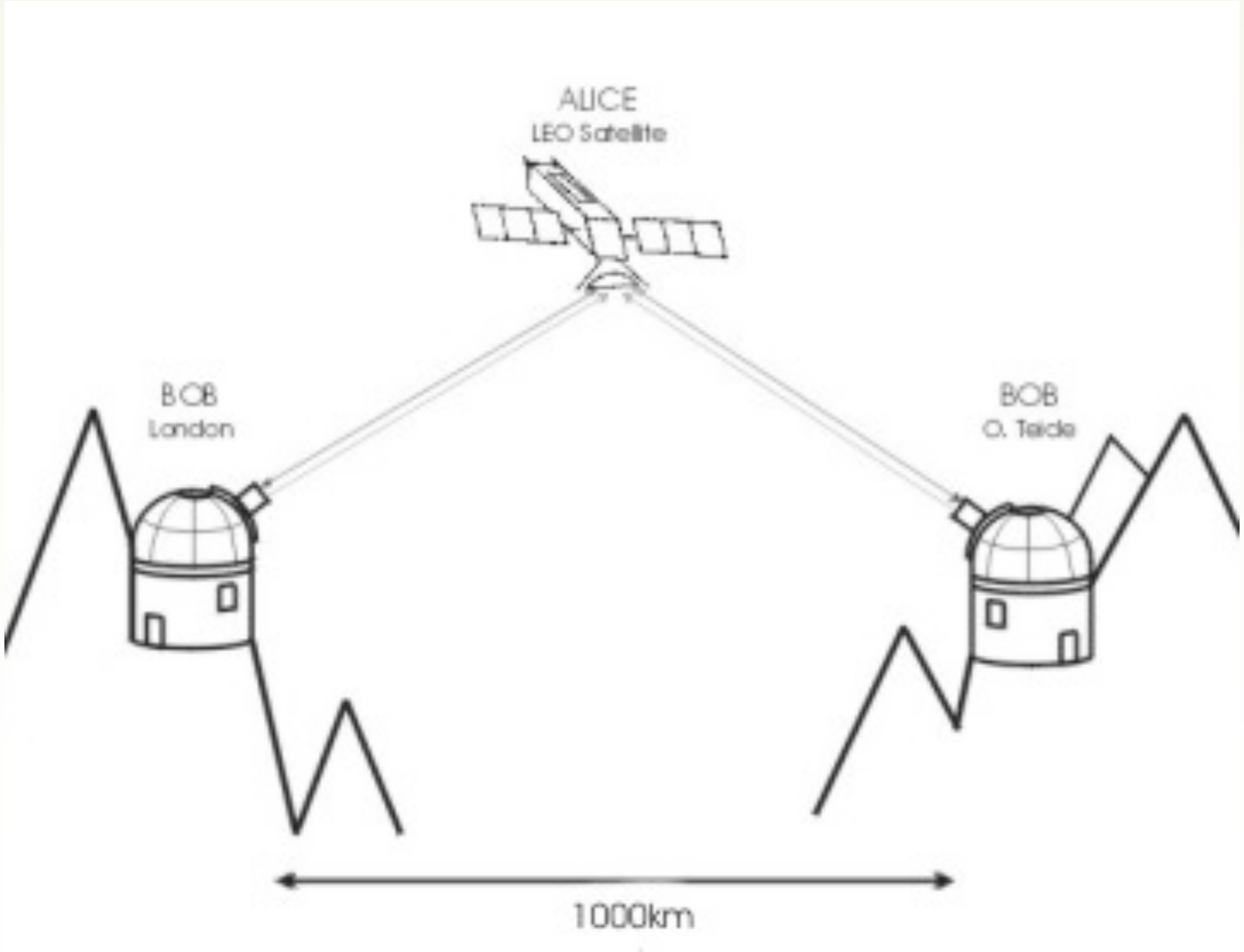
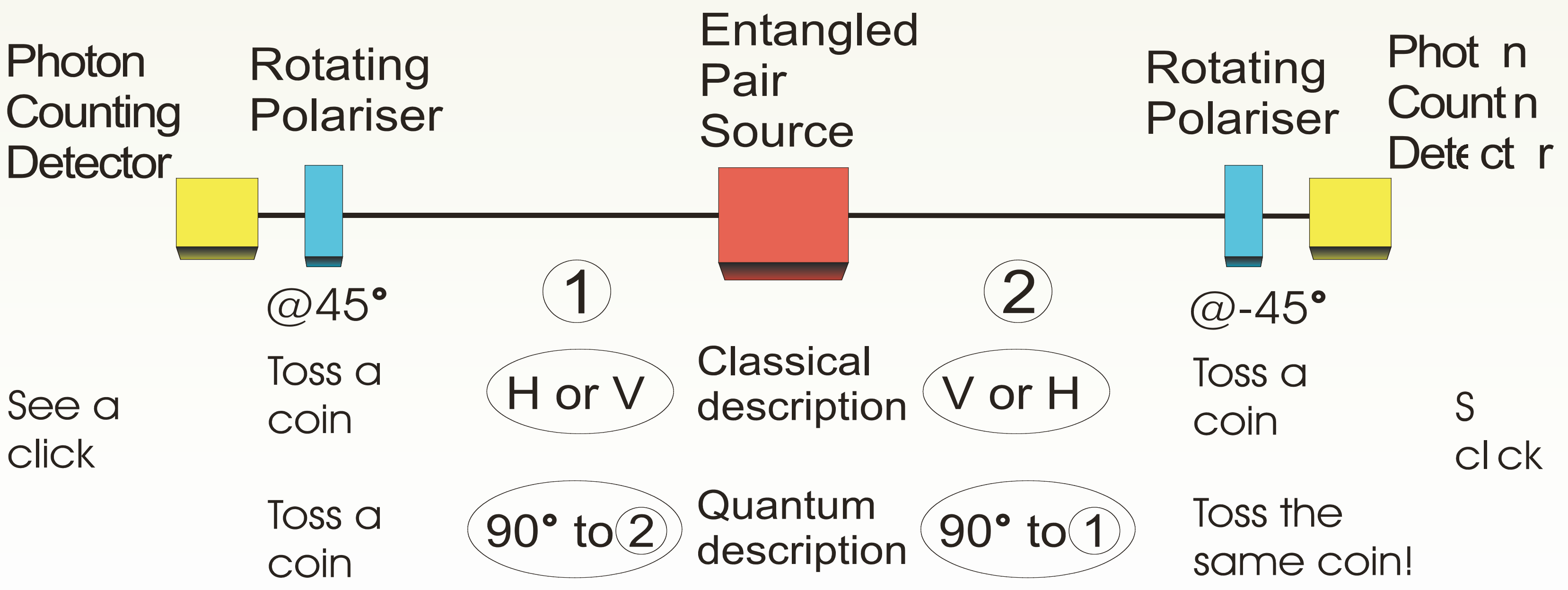
Coincident key generation at 1000km separations using satellite, also tests the non-locality of QM



Philosophical questions
Non-locality of entangled photon pairs



Rarity: Science Perspective August 2003