Vadim Makarov

IQC Institute for Quantum Computing

Implementations and security challenges

Lecture at QKD summer school, IQC, 20 August 2015

Image: street mural in Bucharest (fragment)
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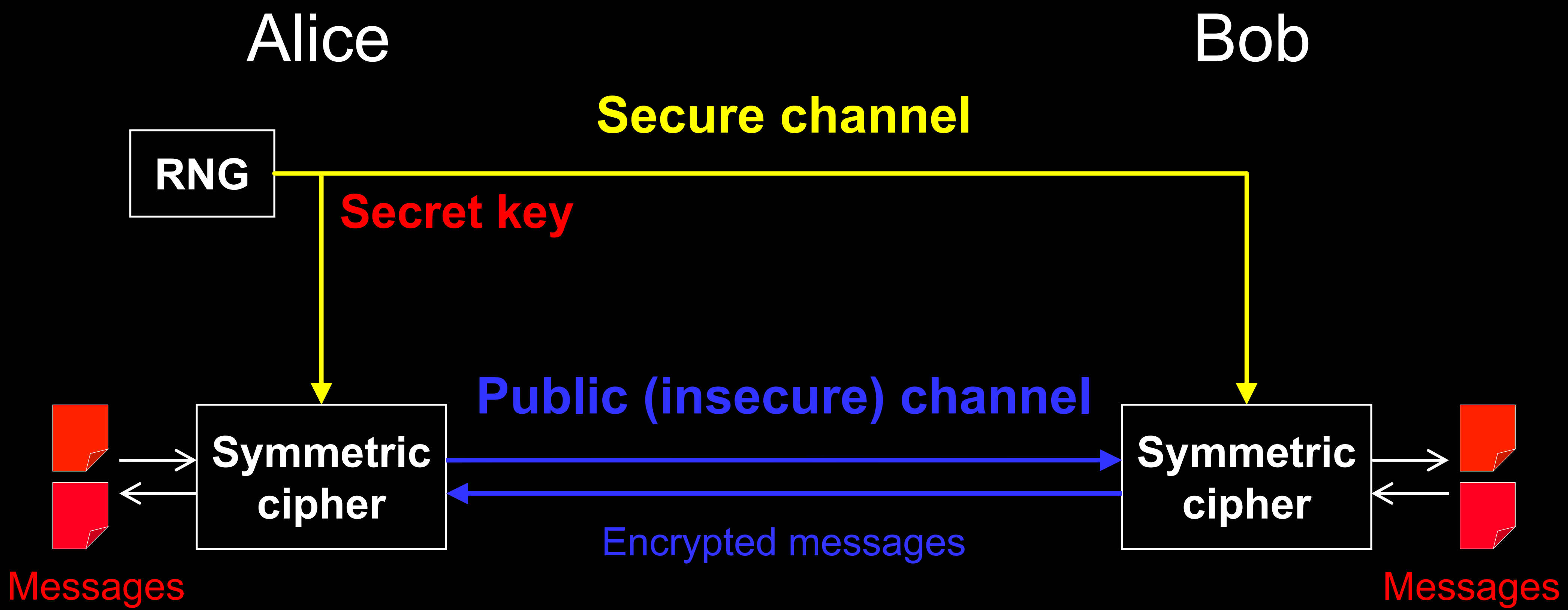
Communication security you enjoy daily

- Paying by credit card in a supermarket
- Cell phone conversations, SMS
- Email, chat, online calls
- Secure browsing, shopping online
- Cloud storage and communication between your devices
- Software updates on your computer, phone, tablet
- Online banking
- Off-line banking: the *bank* needs to communicate internally
- Electricity, water: the *utility* needs to communicate internally
- Car keys, electronic door keys, access control
- Government services (online or off-line)
- Medical records at your doctor, hospital
- Bypassing government surveillance and censorship
- Security cameras, industrial automation, military, spies...

Encryption and key distribution



Public key cryptography

E.g., RSA (Rivest-Shamir-Adleman)

Elliptic-curve

Based on *hypothesized* one-way functions

- Unexpected advances in classical cryptanalysis
- Shor's factorization algorithm for quantum computer

P. W. Shor, SIAM J. Comput. **26**, 1484 (1997)

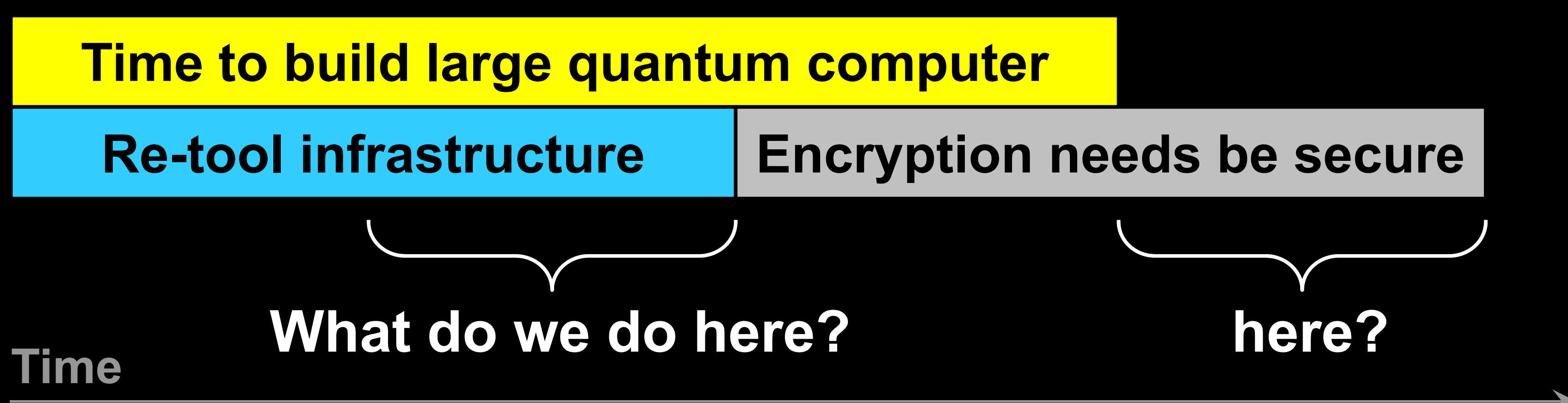


Diagram courtesy M. Mosca

How close is quantum computer?

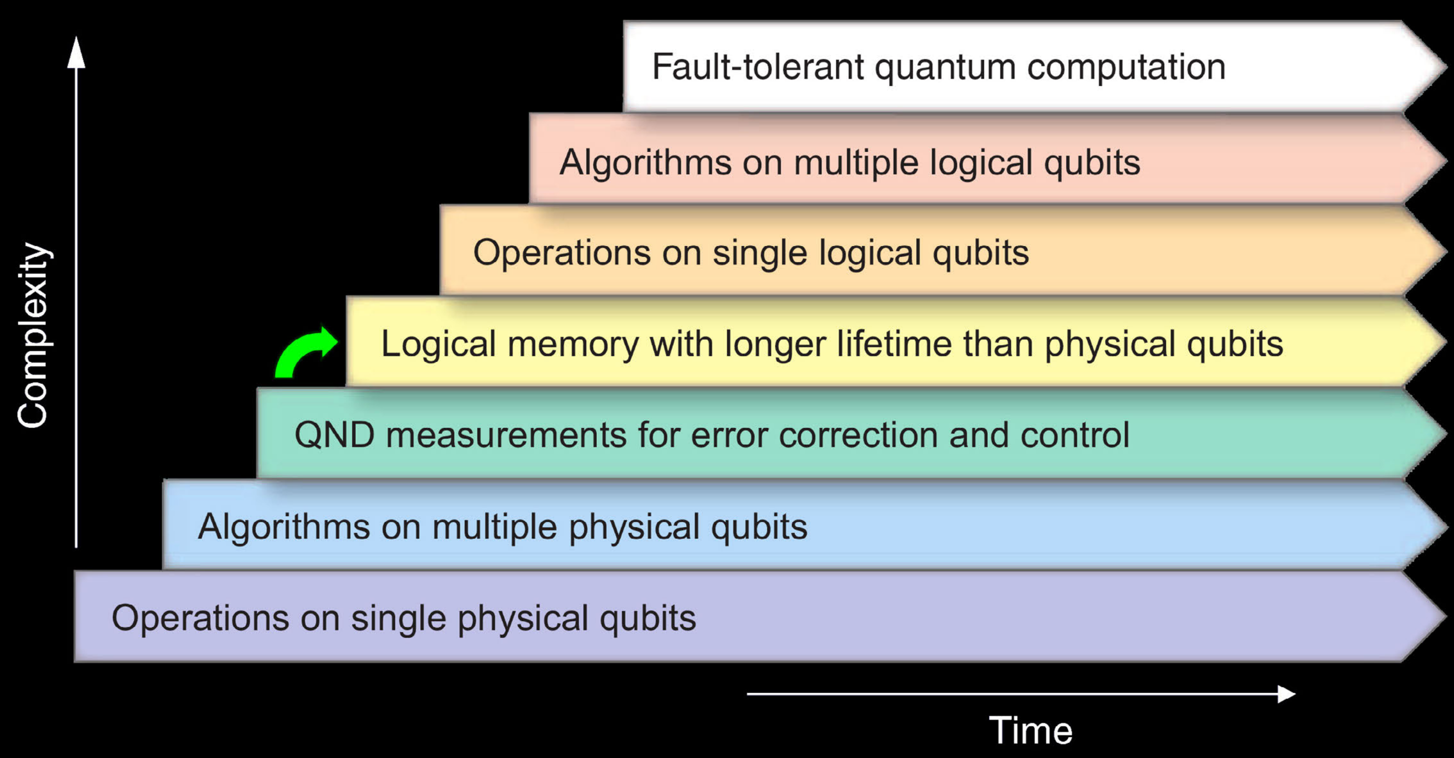


Fig. 1. Seven stages in the development of quantum information processing. Each advancement requires mastery of the preceding stages, but each also represents a continuing task that must be perfected in parallel with the others. Superconducting qubits are the only solid-state implementation at the third stage, and they now aim at reaching the fourth stage (green arrow). In the domain of atomic physics and quantum optics, the third stage had been previously attained by trapped ions and by Rydberg atoms. No implementation has yet reached the fourth stage, where a logical qubit can be stored, via error correction, for a time substantially longer than the decoherence time of its physical qubit components.

M. H. Devoret, R. J. Schoelkopf, "Superconducting circuits for quantum information: An outlook," Science **339**, 1169 (2013)

How close is quantum computer?

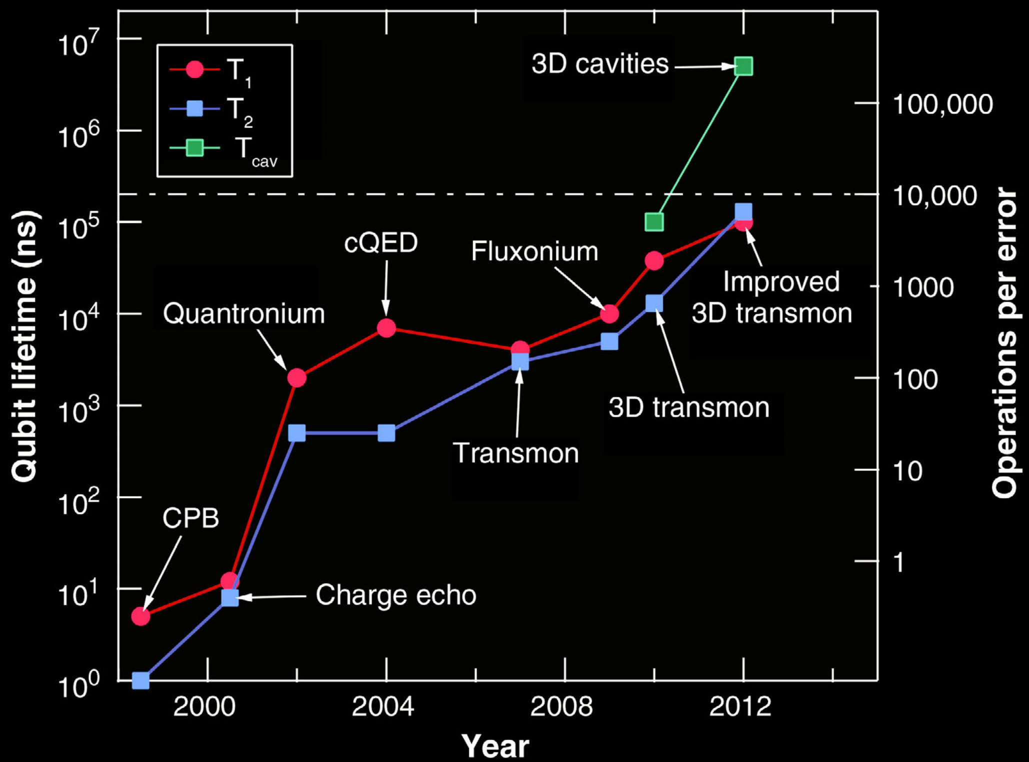


Fig. 3. Examples of the "Moore's law" type of exponential scaling in performance of superconducting qubits during recent years.

Improvement of coherence times for the "typical best" results associated with the first versions of major design changes. The blue, red, and green symbols refer to qubit relaxation, qubit decoherence, and cavity lifetimes, respectively. Innovations were introduced to avoid the dominant decoherence channel found in earlier generations. So far an ultimate limit on coherence seems not to have been encountered.

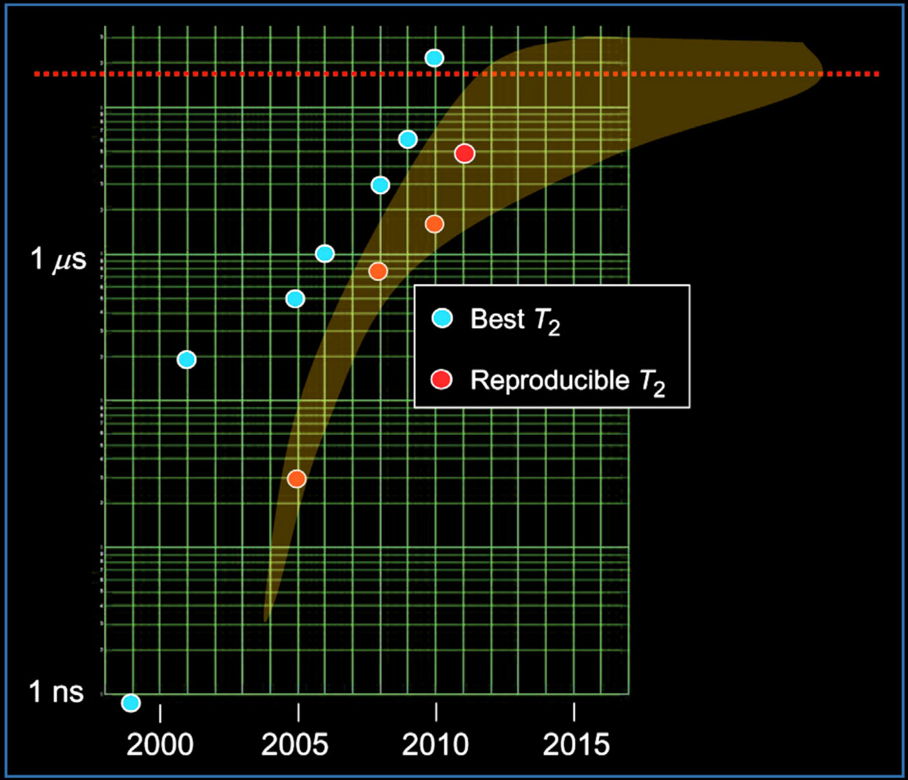


Figure 5

Progress toward reaching long dephasing (T_2) times for superconducting qubits. (Red dashed line) Minimum necessary for fault-tolerant quantum computer, based on a 30-ns two-gate time. (Yellow field) Predicted improvements in T_2.

M. H. Devoret, R. J. Schoelkopf, Science **339**, 1169 (2013)

M. Steffen *et al.*, "Quantum computing: An IBM perspective," IBM J. Res. Dev. **55**, 13 (2011)

Quantum computers capable of catastrophically breaking our public-key cryptography infrastructure are a medium-term threat.

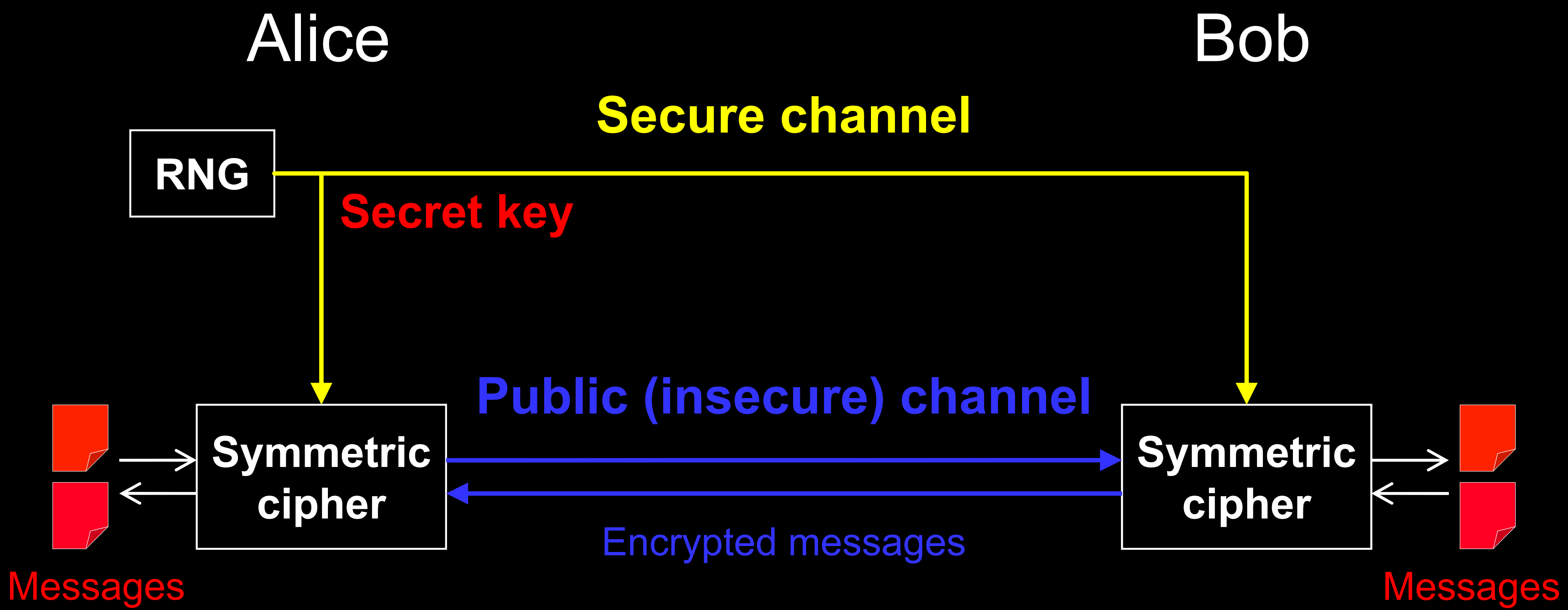
Quantum-safe cryptographic infrastructure

"post-quantum" cryptography	+	quantum cryptography
• Classical tools deployable without quantum technologies		• Quantum tools requiring some quantum technologies (typically less than a large-scale quantum computer)
• Believed/hoped to be secure against quantum computer attacks of the future		• Typically no computational assumptions and thus known to be secure against quantum attacks

Both sets of cryptographic tools can work very well together in quantum-safe cryptographic ecosystem.

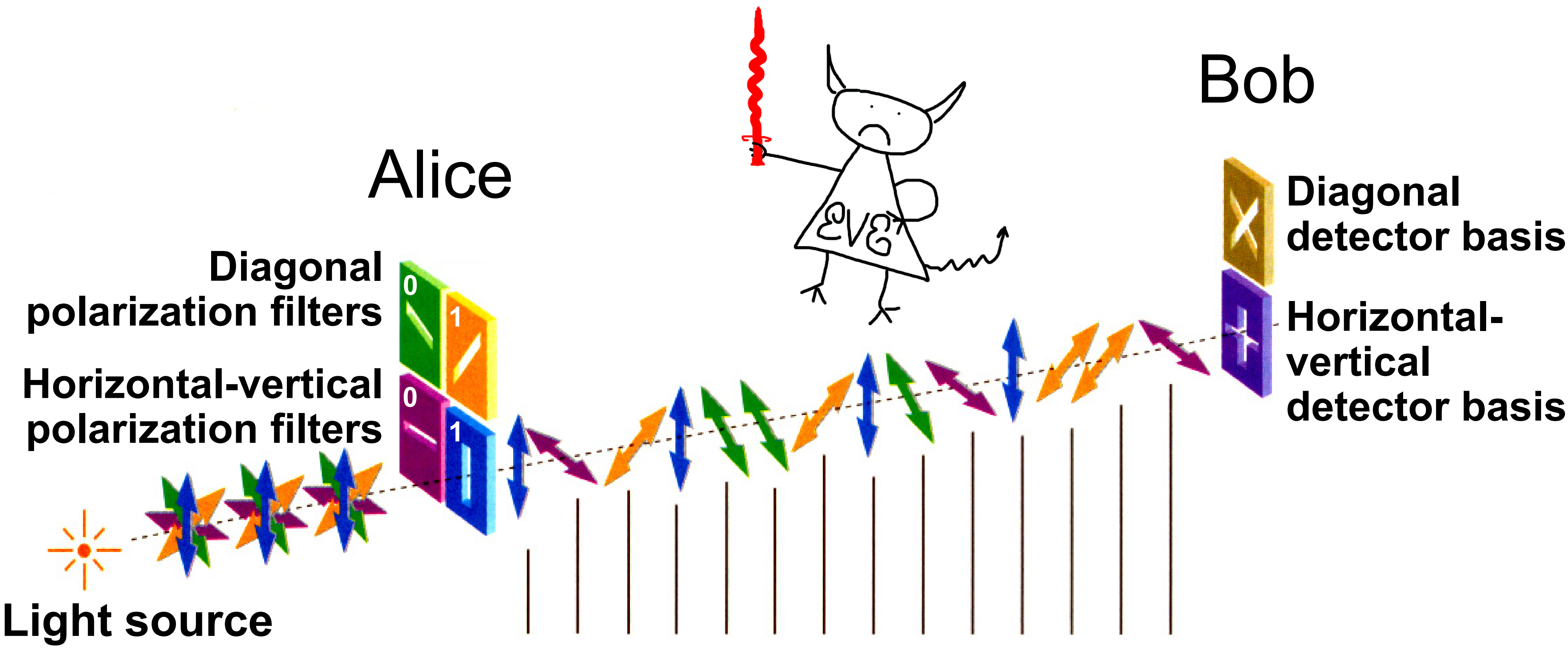
Slide courtesy M. Mosca

Encryption and key distribution



Quantum key distribution transmits secret key by sending quantum states over *open channel.*

Quantum key distribution (QKD)



Alice's bit sequence	1	0	1	1	0	0	1	1	0	0	1	1	1	0
Bob's detection basis	+	×	+	+	×	×	+	+	×	+	×	×	+	+
Bob's measurement	1	0	0	1	0	0	1	1	0	0	0	1	0	0
Retained bit sequence	1	–	–	1	0	0	–	1	0	0	–	1	–	0

Image reprinted from article: W. Tittel, G. Ribordy & N. Gisin, "Quantum cryptography," Physics World, March 1998

Dealing with errors

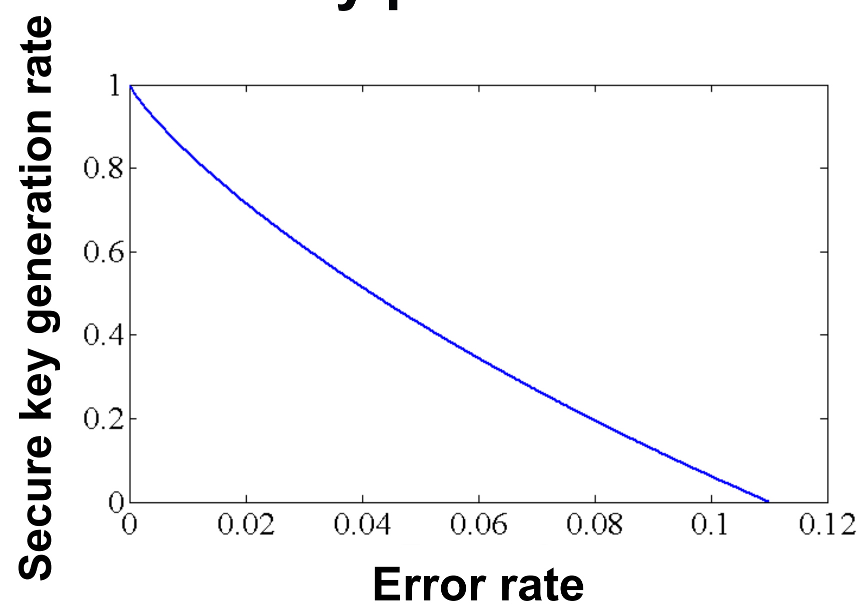
Errors due to imperfections and Eve.
Must assume that all errors are due to Eve!

- **Error correction: standard classical protocols**
- **Privacy amplification:**

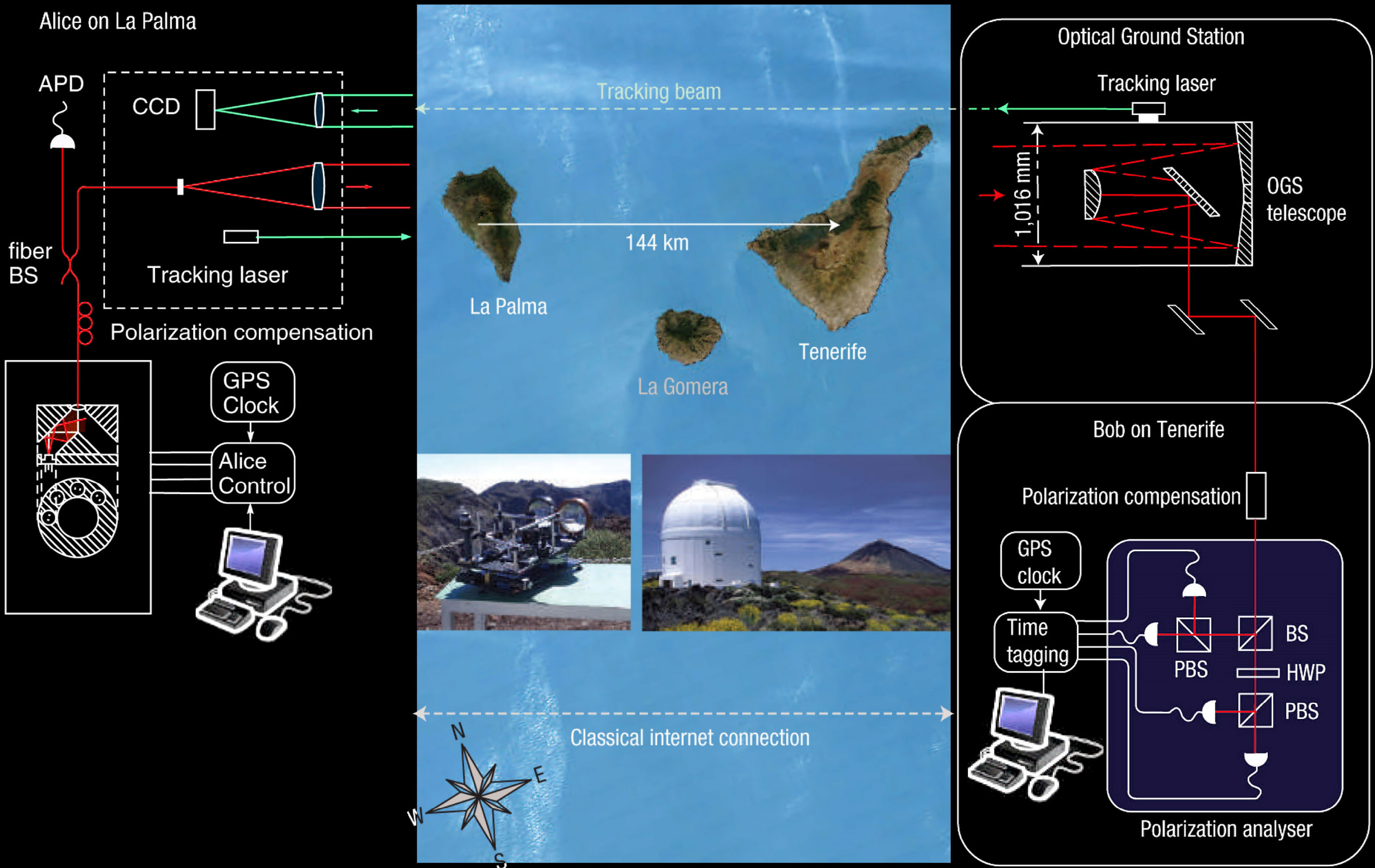
secure key		random matrix	raw key

$$\begin{bmatrix} 0 \\ 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \\ 1 \\ 0 \\ 1 \end{bmatrix}$$

Security proof:

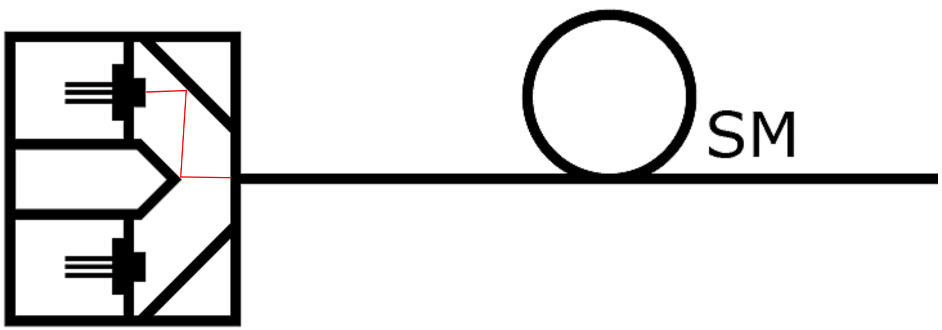


Free-space QKD



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

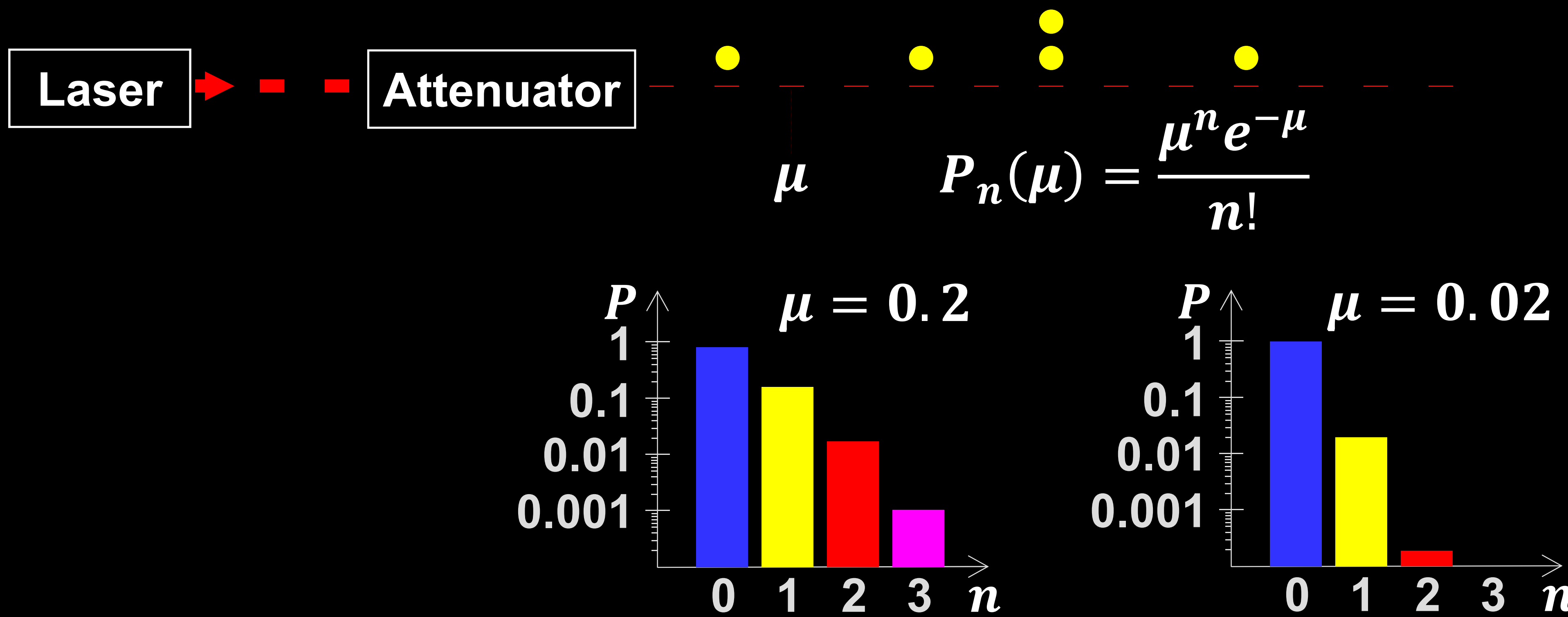
Alice:
Polarized photon source



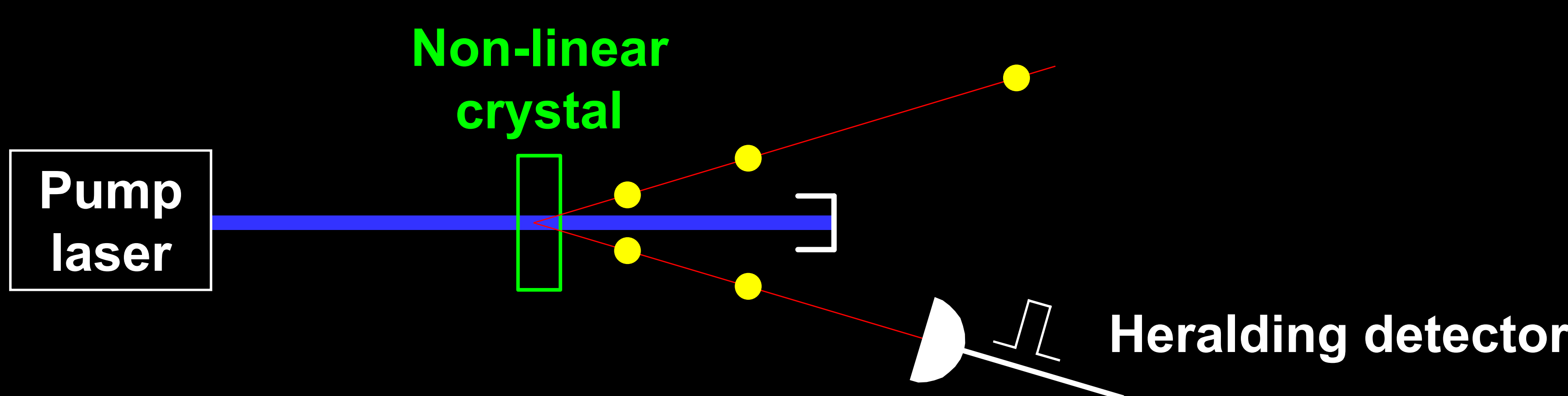
S. Nauerth *et al.*, New J. Phys. **11**, 065001 (2009)

Single-photon sources

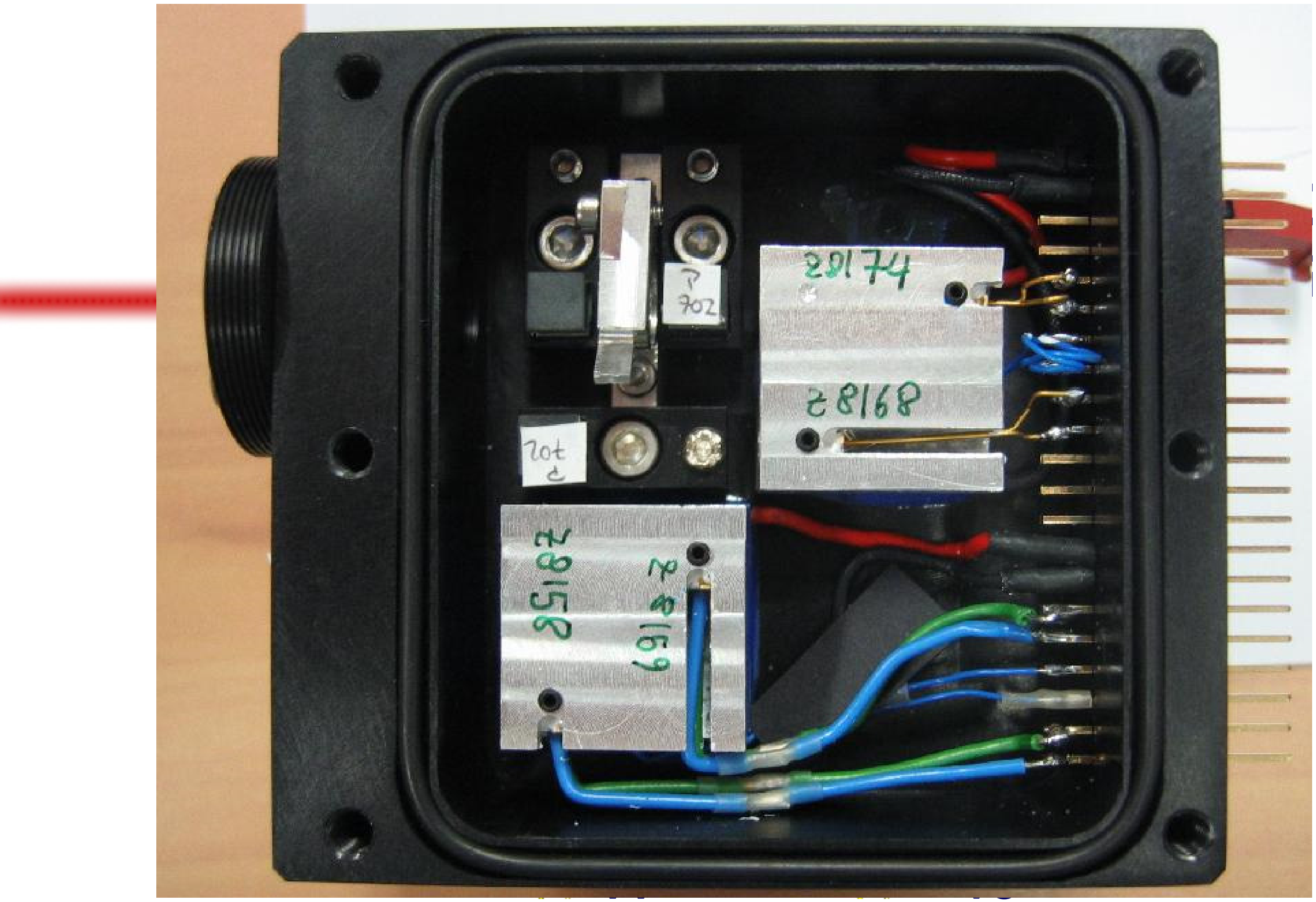
Attenuated laser



Parametric down-conversion

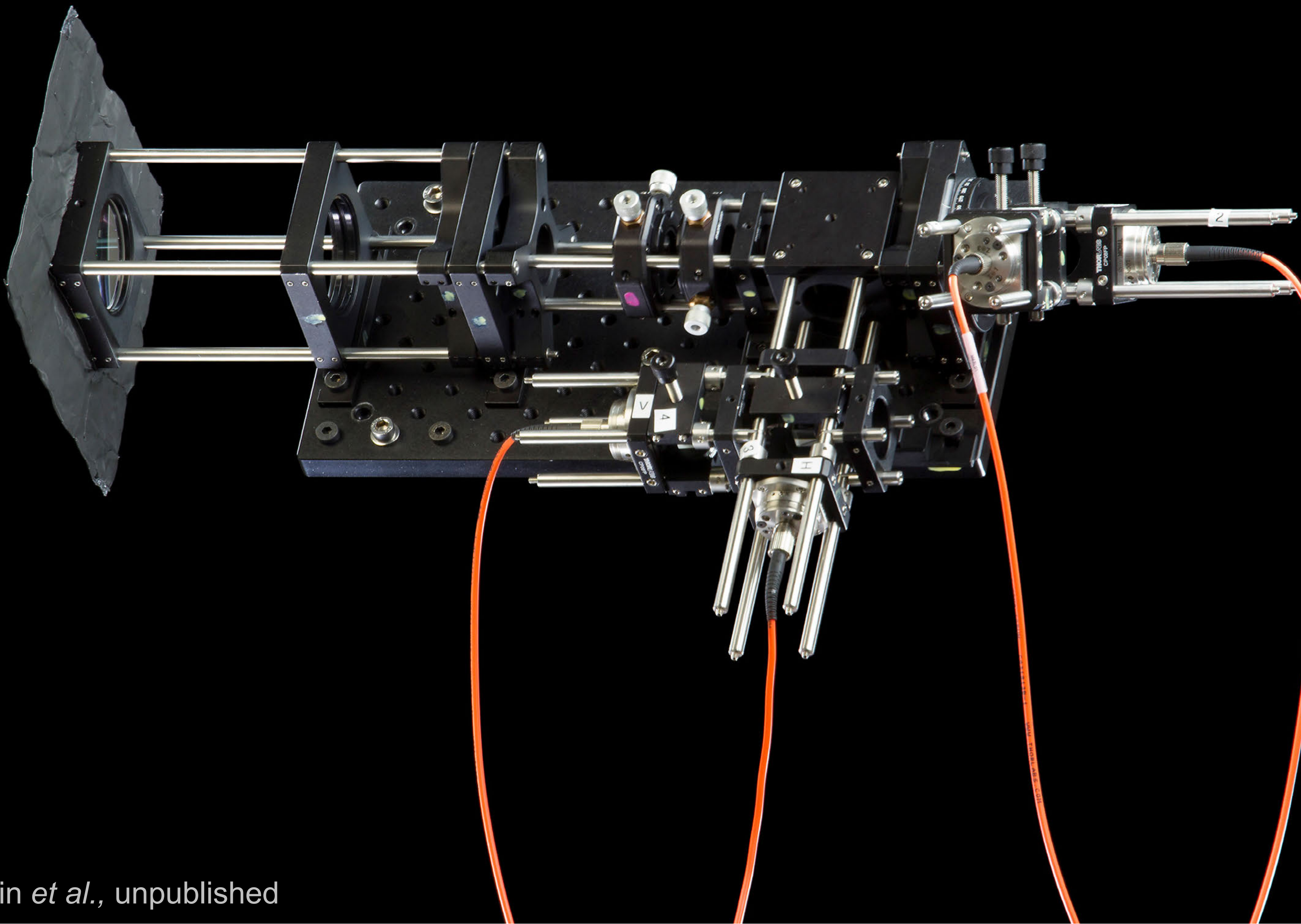


Bob:
Polarization analyzer with single-photon detectors



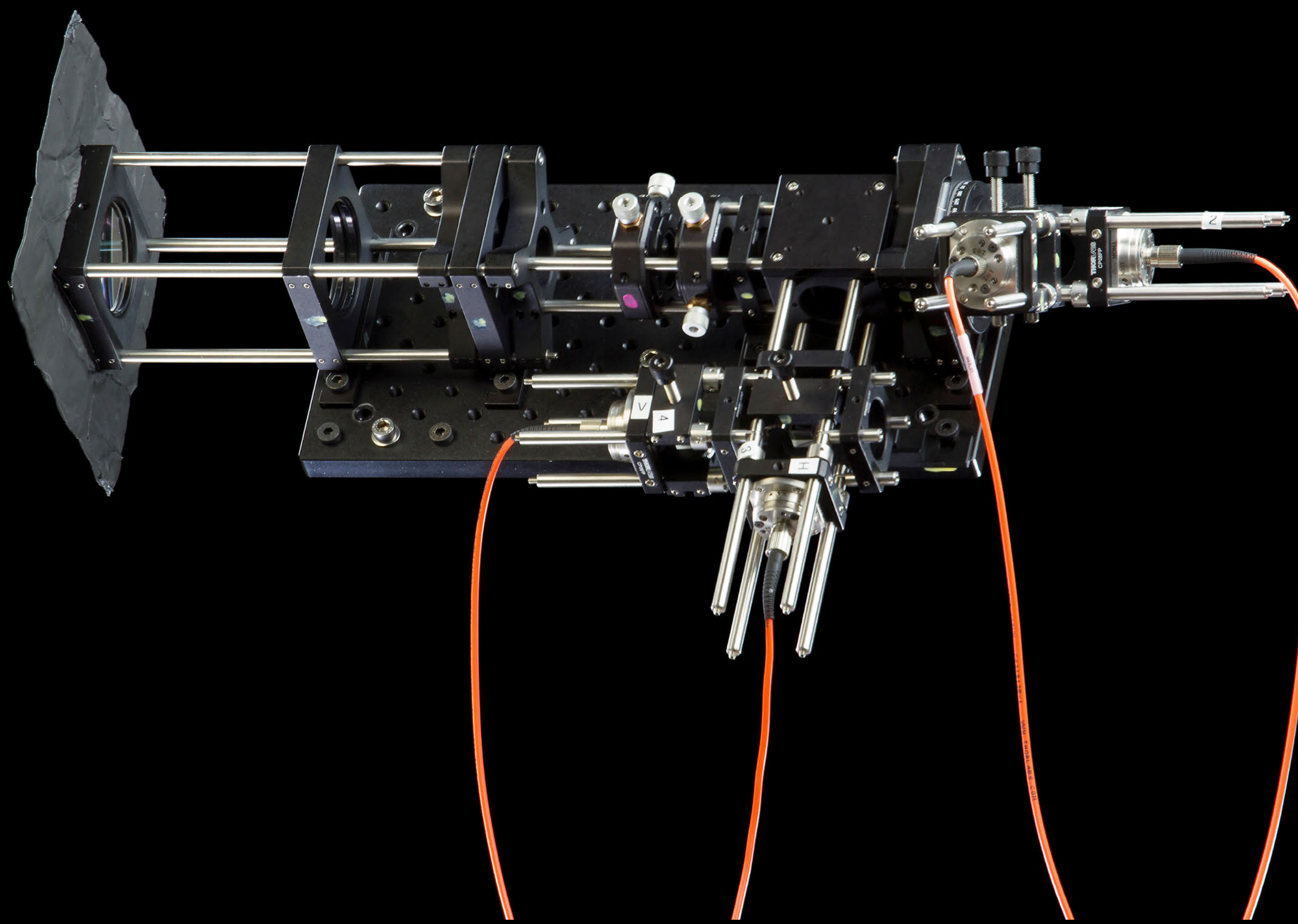
J. G. Rarity, P. C. M. Owens, P. R. Tapster, J. Mod. Opt. **41**, 2435 (1994)

Polarization analyzer



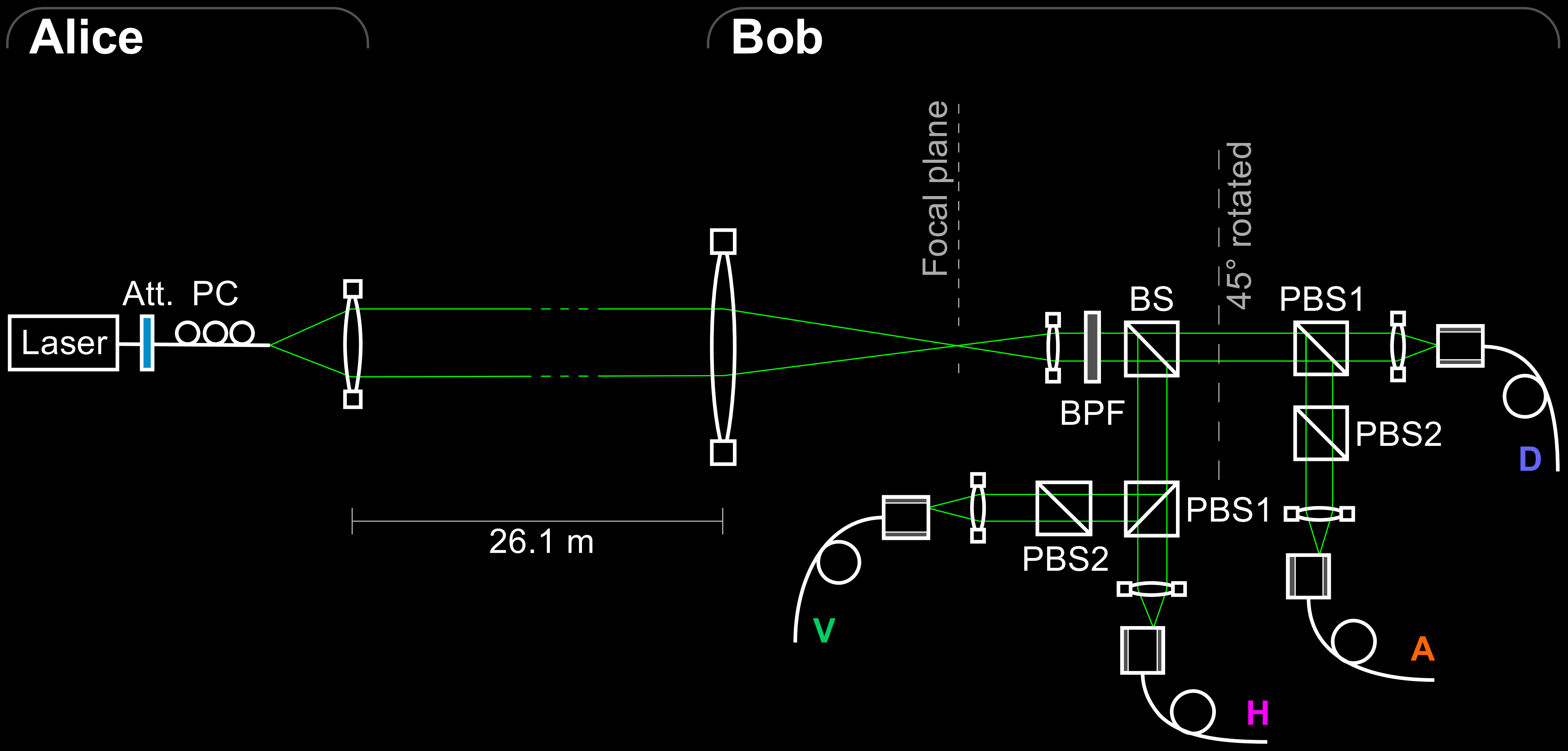
J.-P. Bourgoin *et al.*, unpublished

Polarization analyzer



J.-P. Bourgoin *et al.*, unpublished

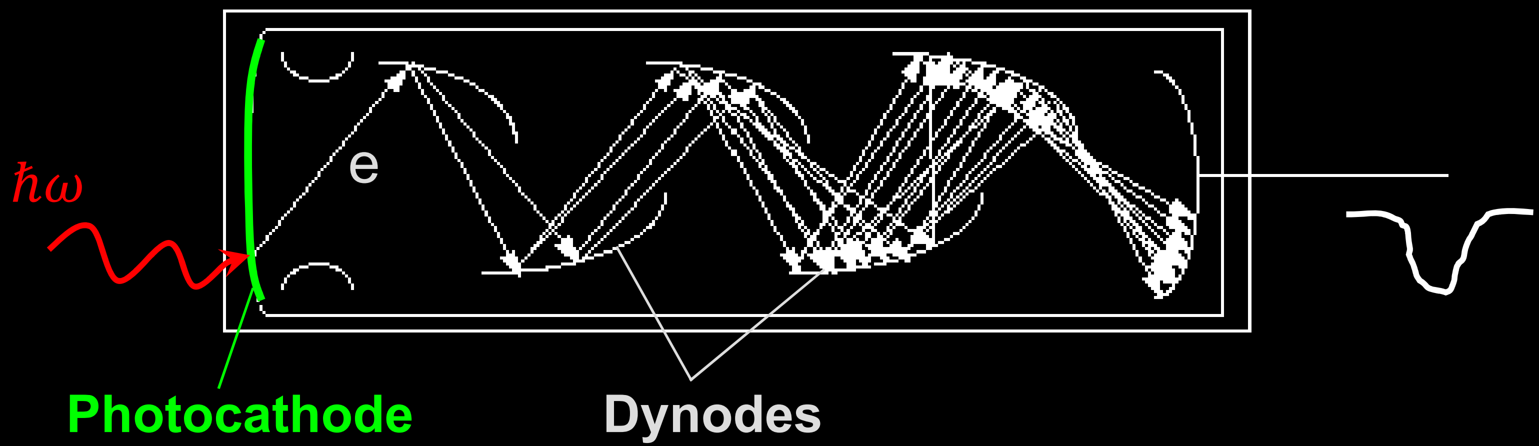
Polarization analyzer



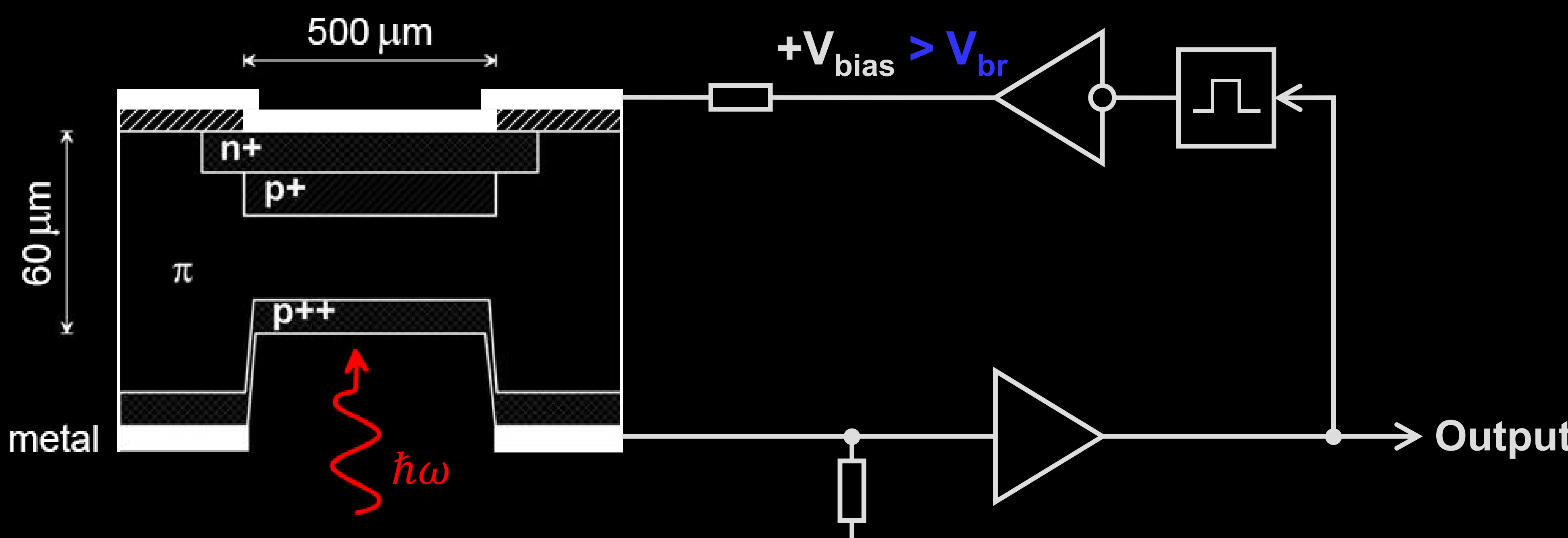
S. Sajeed *et al.*, Phys. Rev. A **91**, 062301 (2015)

Single-photon detectors

Photomultiplier tube



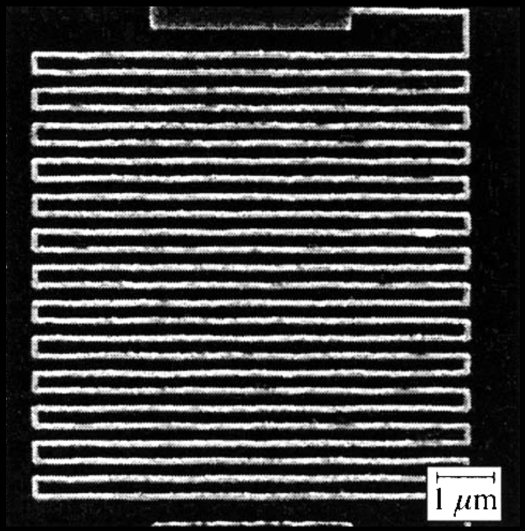
Avalanche photodiode

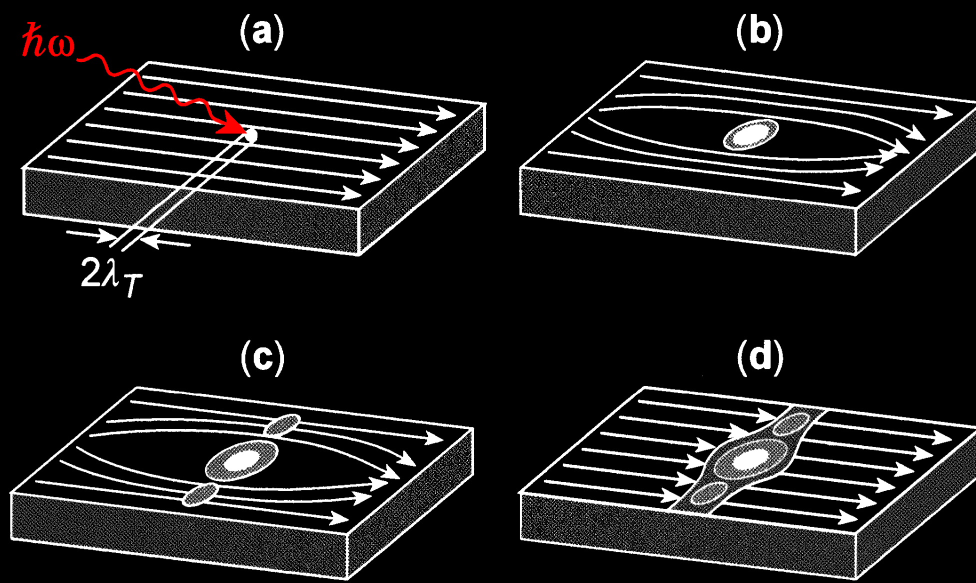


Images reprinted from: http://www.frankswebspace.org.uk/ScienceAndMaths/physics/physicsGCE/D1-5.htm; S. Cova *et al.*, J. Mod. Opt. **51**, 1267 (2004)

Single-photon detectors

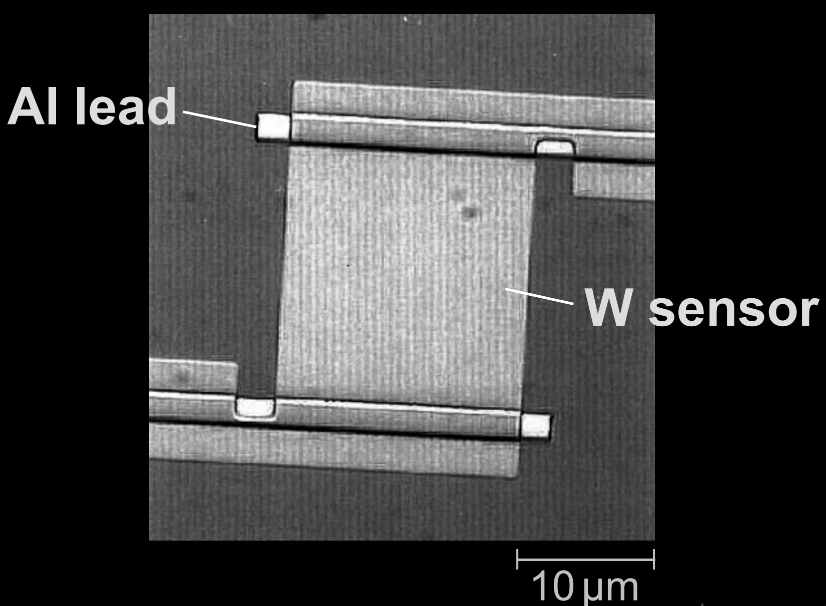
Superconducting nanowire

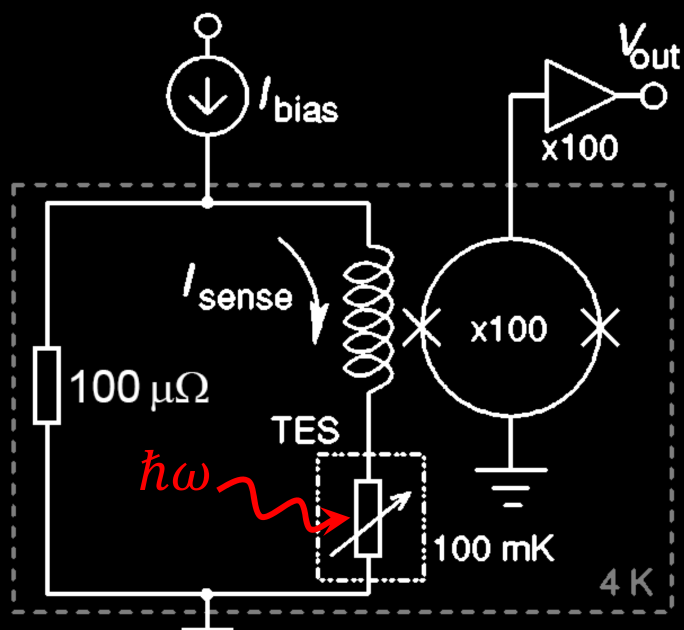




Images reprinted from: R. Sobolewski *et al.*, IEEE Trans. Appl. Supercond. **13**, 1151 (2003)

Transition-edge sensor

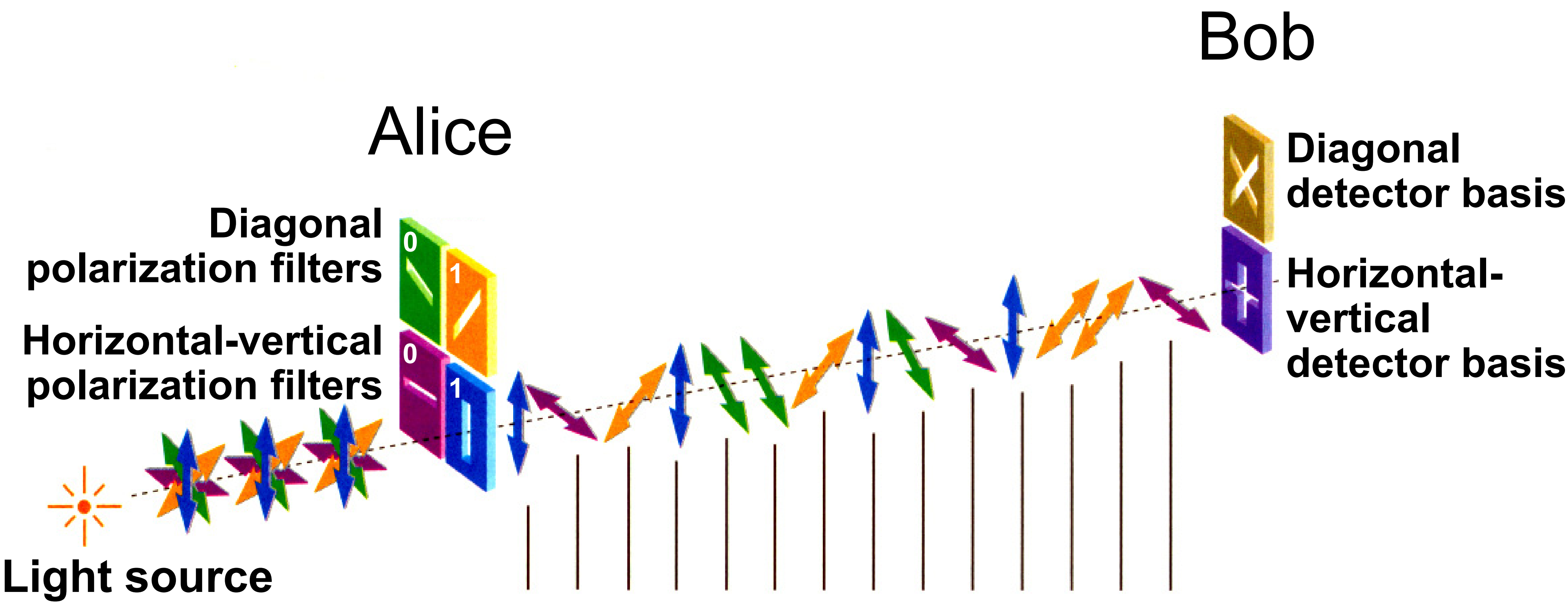




Images reprinted from: B. Cabrera *et al.*, Appl. Phys. Lett. **73**, 735 (1998); A.J. Miller *et al.*, Appl. Phys. Lett. **83**, 791 (2003)

End of lecture 1

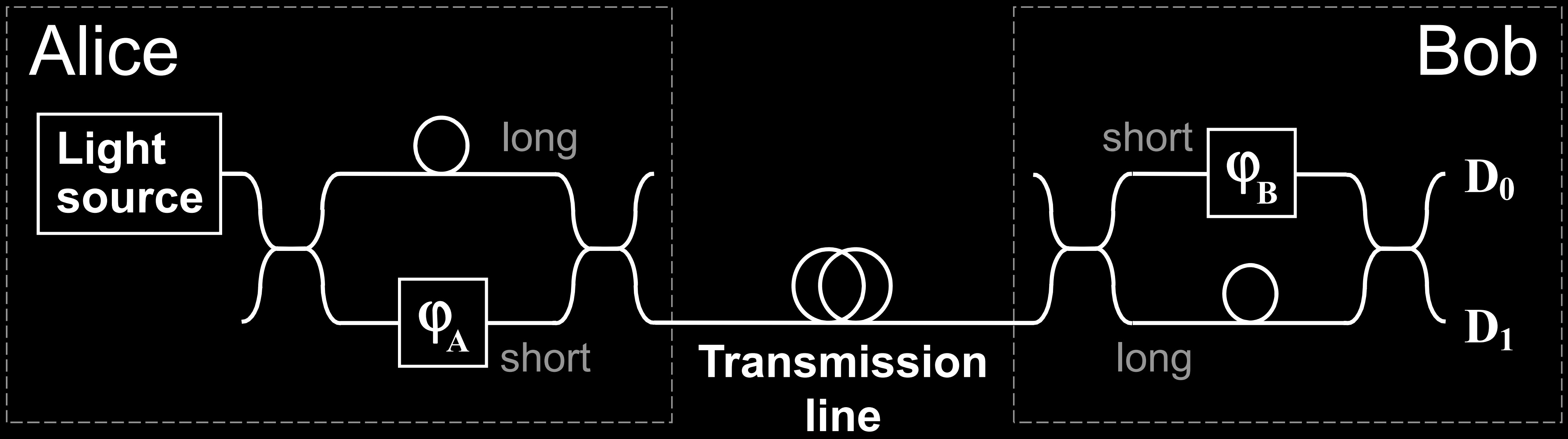
Polarization encoding



Alice's bit sequence	1	0	1	1	0	0	1	1	0	0	1	1	1	0
Bob's detection basis	+	×	+	+	×	×	+	+	×	+	×	×	+	+
Bob's measurement	1	0	0	1	0	0	1	1	0	0	0	1	0	0
Retained bit sequence	1	–	–	1	0	0	–	1	0	0	–	1	–	0

Image reprinted from article: W. Tittel, G. Ribordy & N. Gisin, "Quantum cryptography," Physics World, March 1998

Phase encoding, interferometric QKD channel



Detection basis:

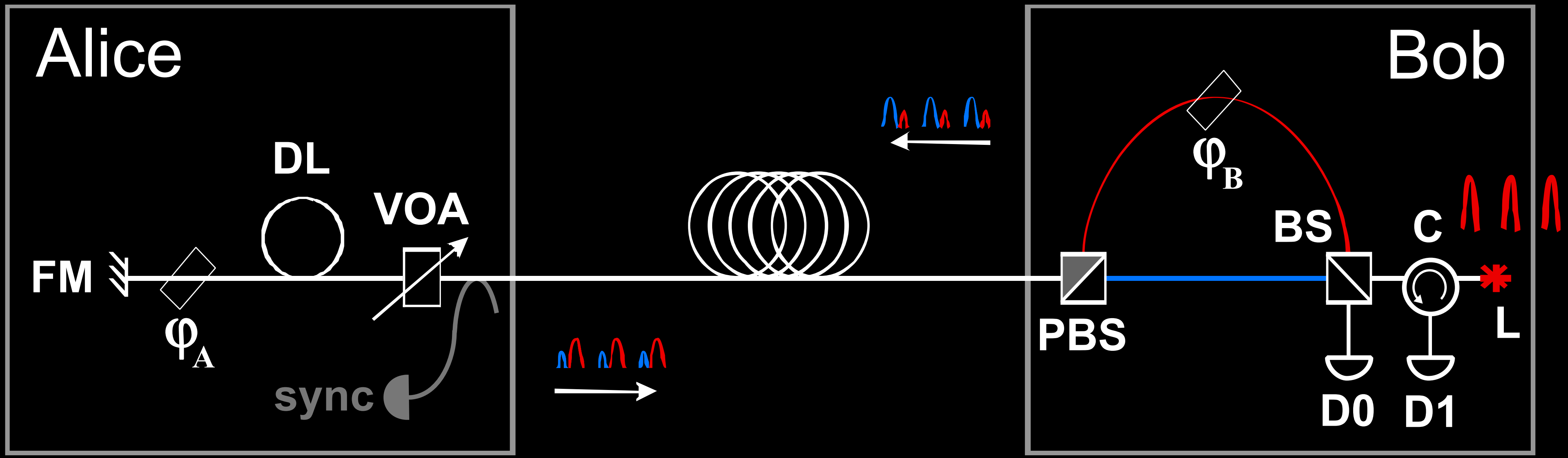
$\varphi_A =$ 0 or $\pi/2$: 0

π or $3\pi/2$: 1

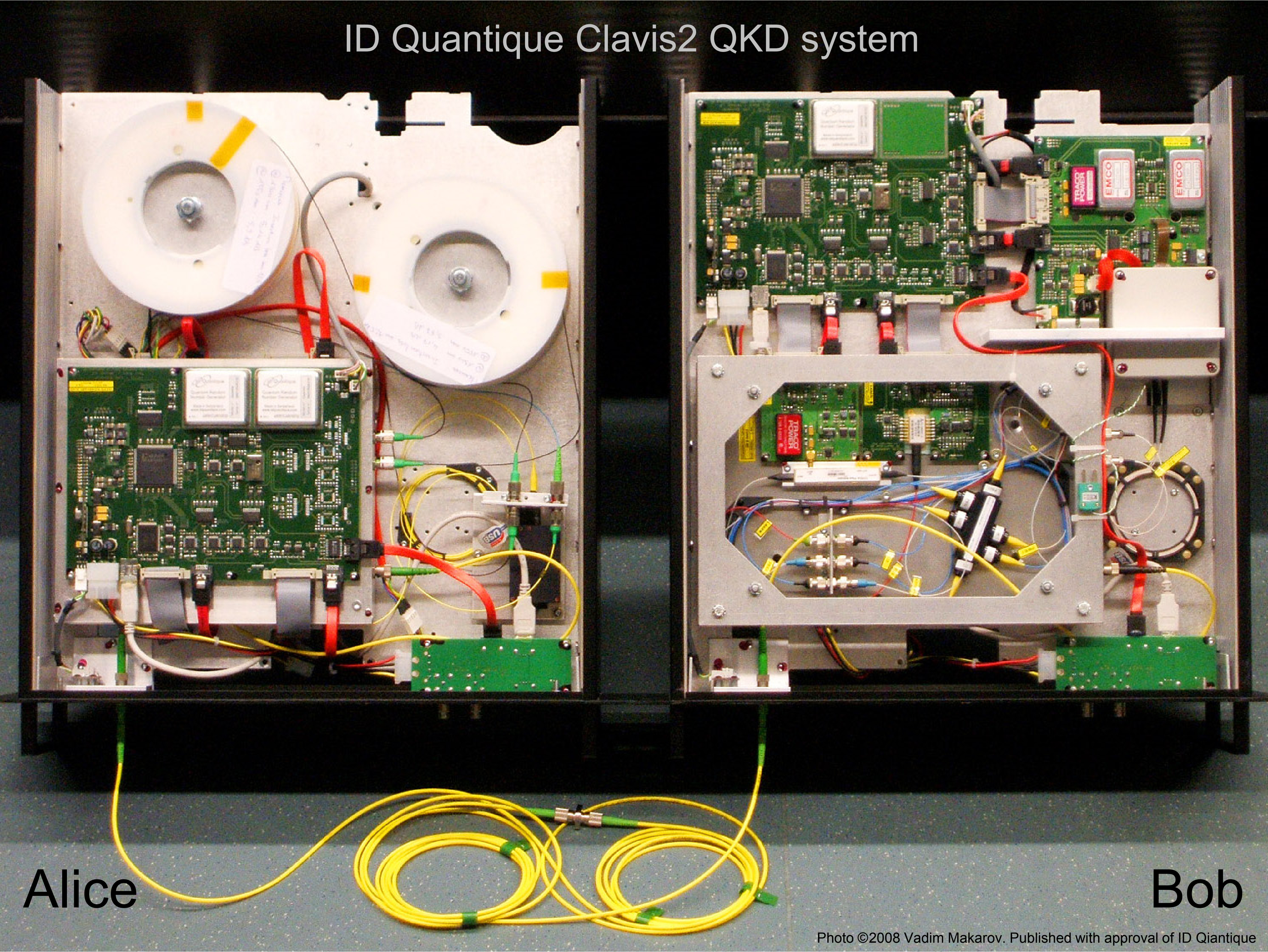
$\varphi_B =$ 0 : X

$\pi/2$: Z

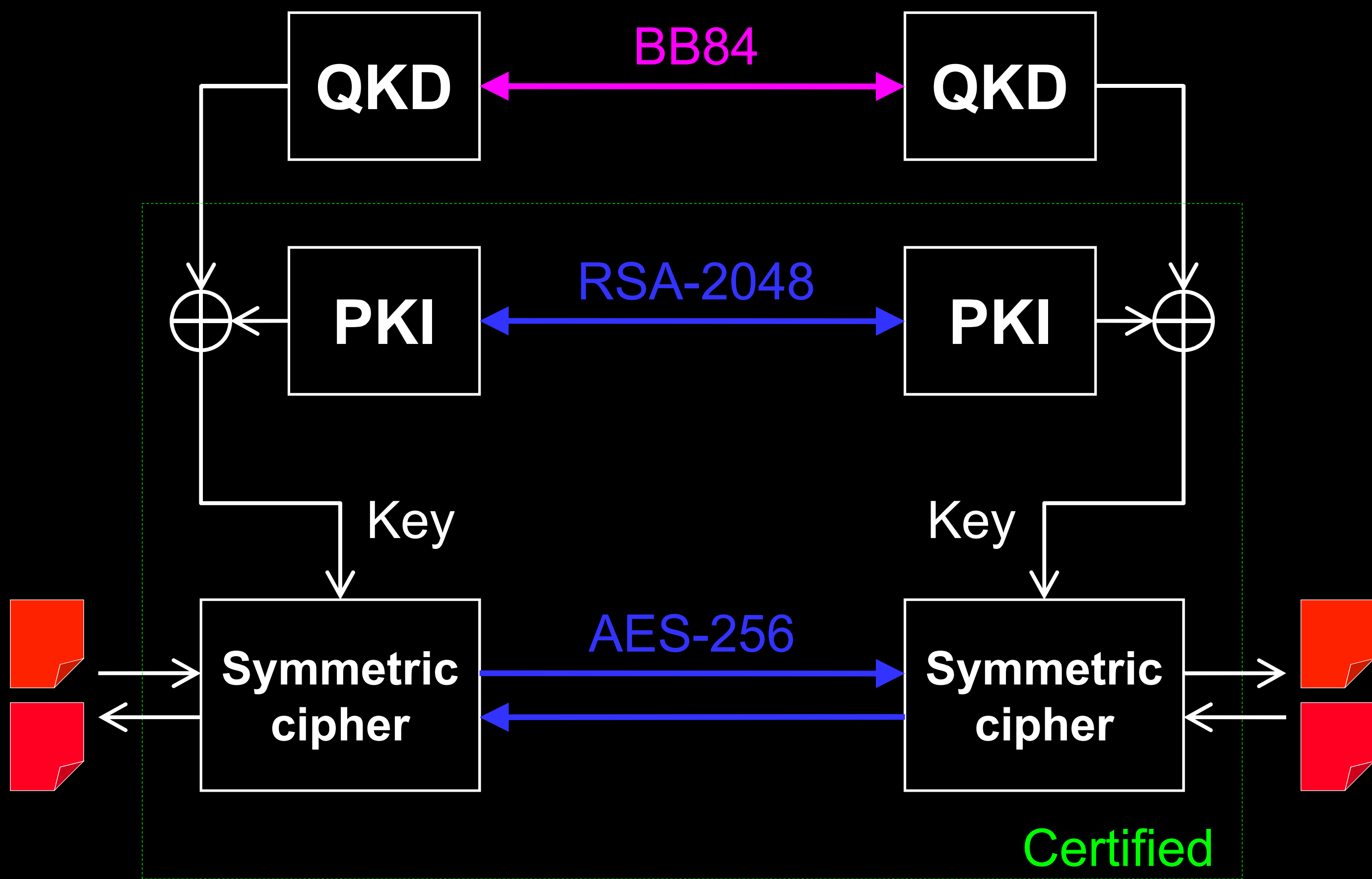
Plug-and-play scheme

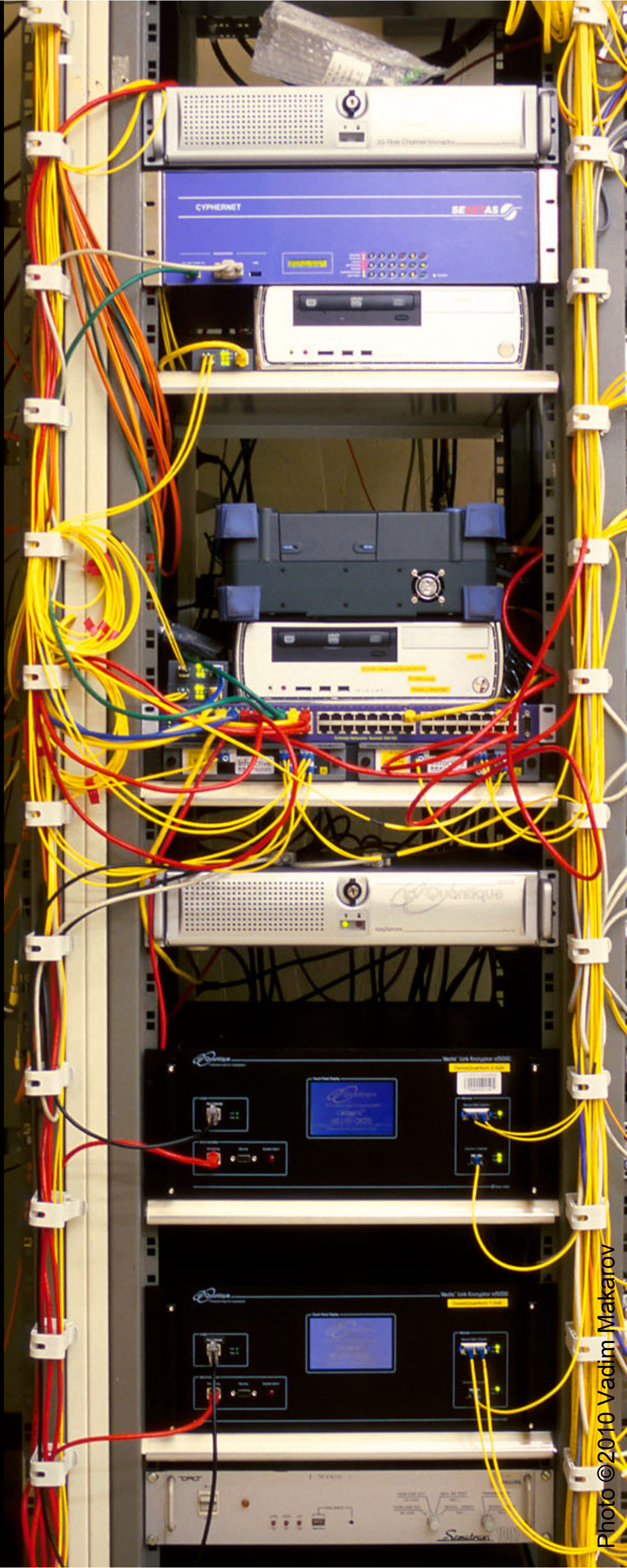


D. Stucki *et al.*, New J. Phys. **4**, 41 (2002)


ID Quantique Clavis2 QKD system
Alice
Bob
Photo ©2008 Vadim Makarov. Published with approval of ID Qiantique

Dual key agreement





www.swissquantum.com
ID Quantique *Cerberis* system (2010)

Commercial QKD

Classical encryptors:

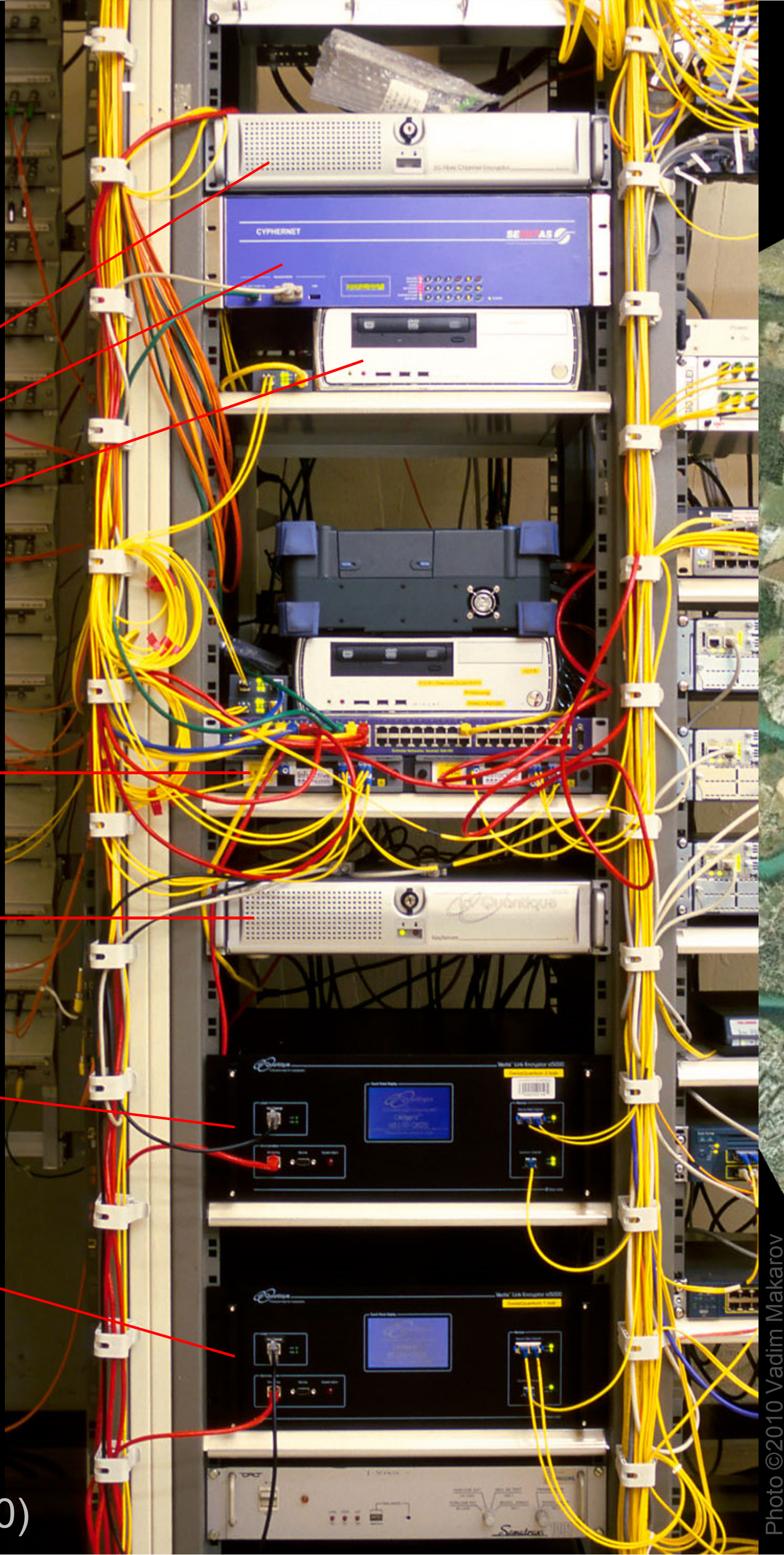
L2, 2 Gbit/s
L2, 10 Gbit/s
L3 VPN, 100 Mbit/s

WDMs

Key manager

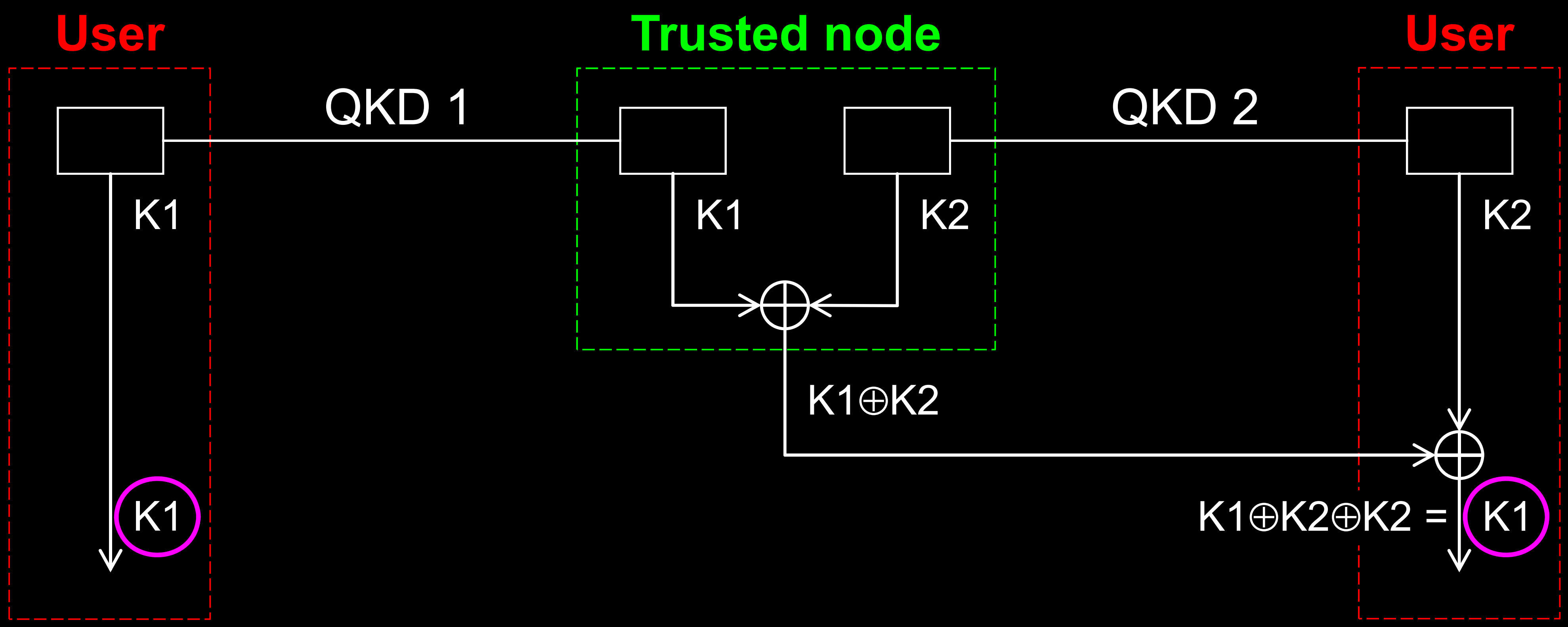
QKD to another node (4 km)

QKD to another node (14 km)

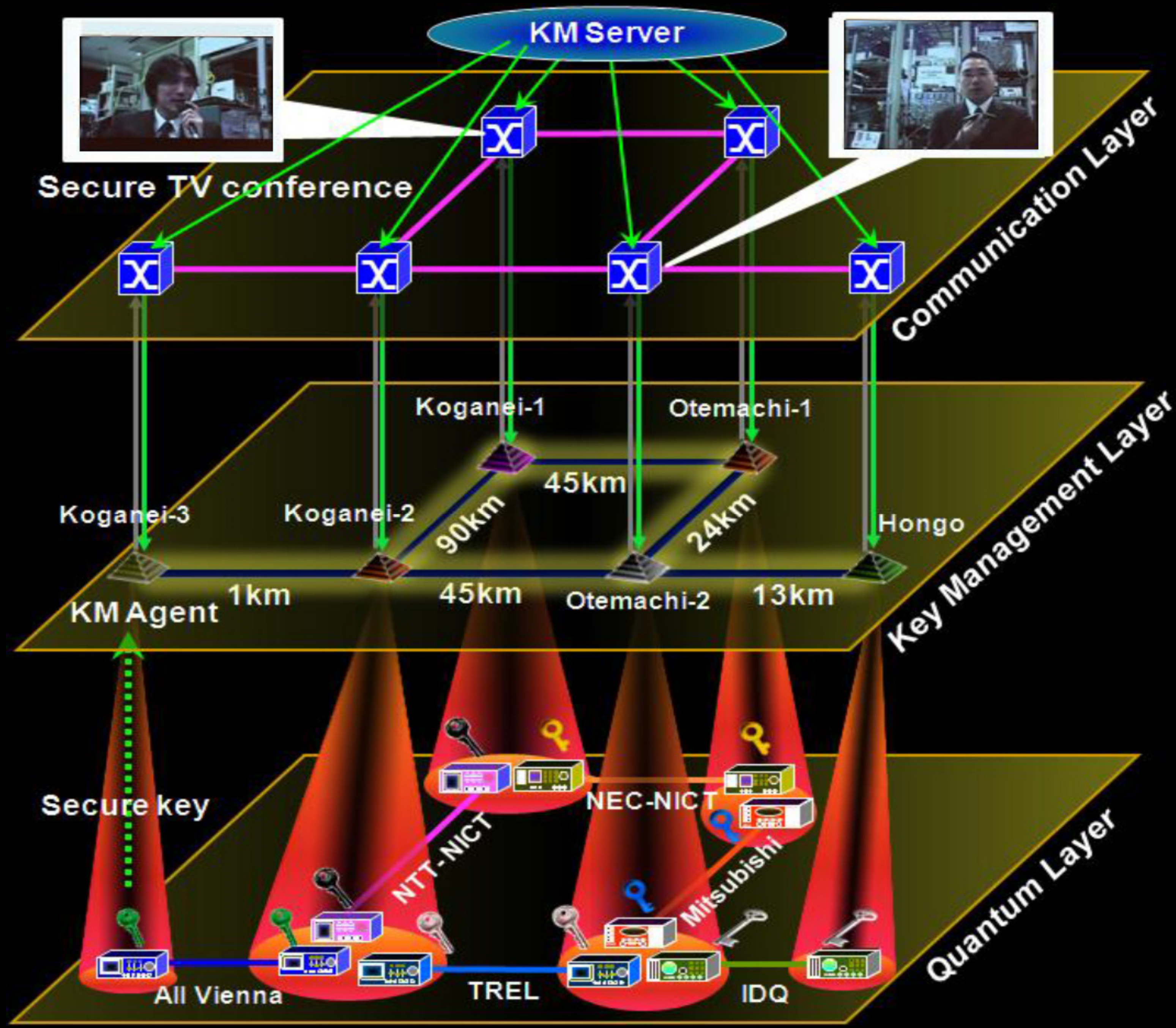


www.swissquantum.com
ID Quantique *Cerberis* system (2010)

Trusted-node repeater



Trusted-node network



M. Sasaki *et al.*, Opt. Express **19**, 10387 (2011)

Quantum Backbone

- Total Length 2000 km
- 2013.6-2016.12
- 32 trustable relay nodes

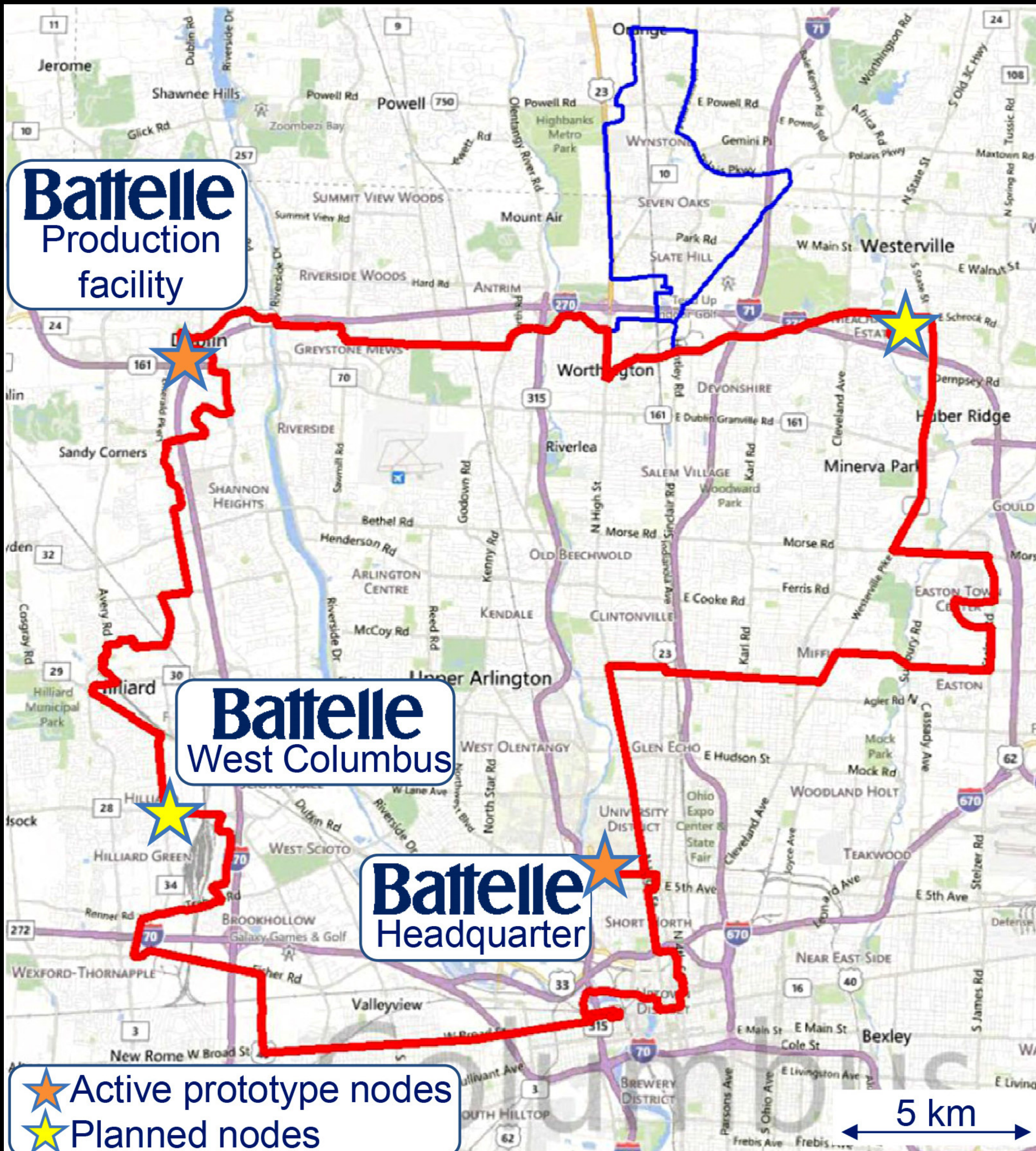
  31 fiber links
- Metropolitan networks

  Existing: Hefei, Jinan

  New: Beijing, Shanghai
- Customer: China Industrial & Commercial Bank; Xinhua News Agency; CBRC

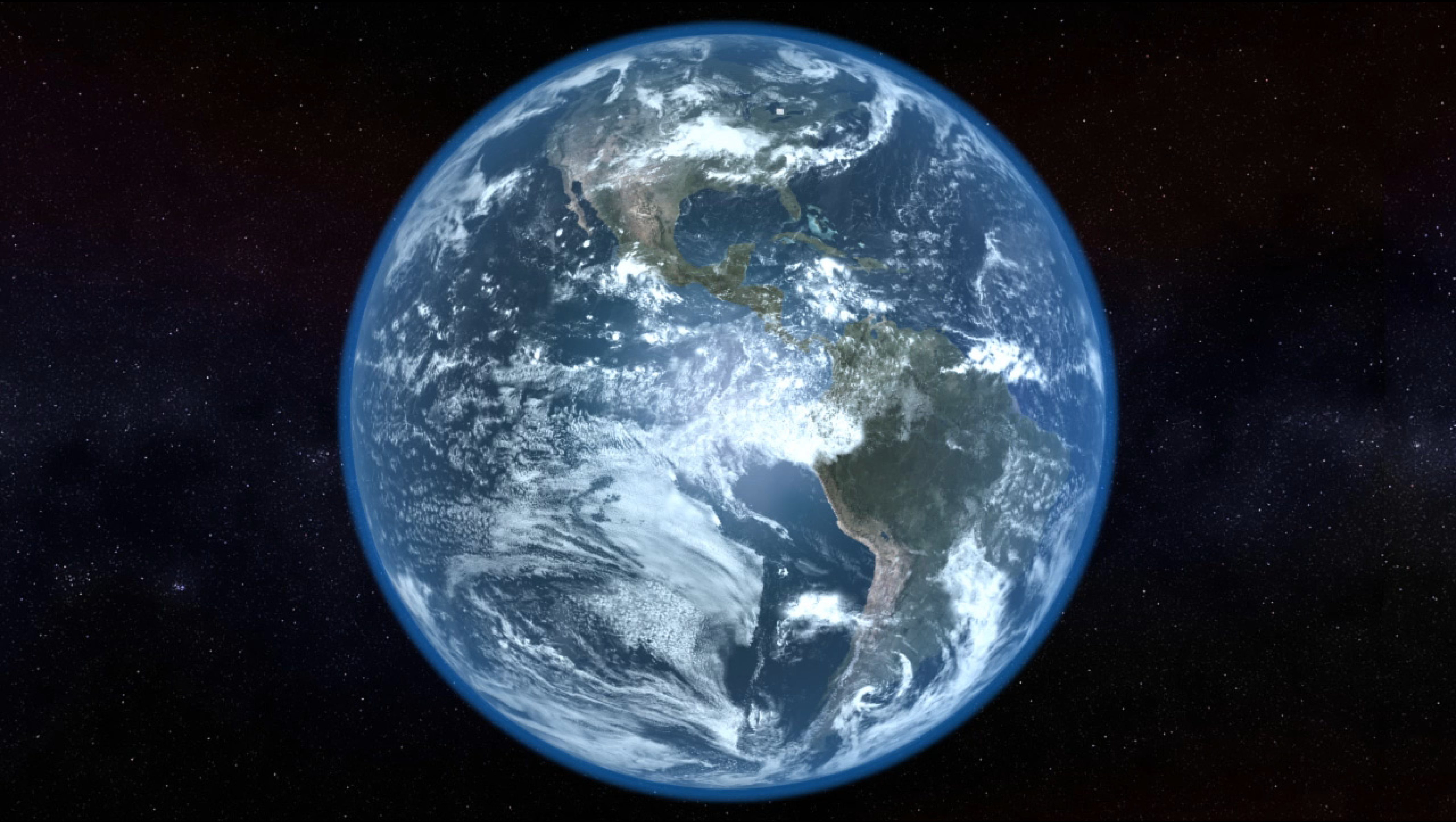
Q. Zhang, talk at QCrypt 2014

The Battelle quantum network

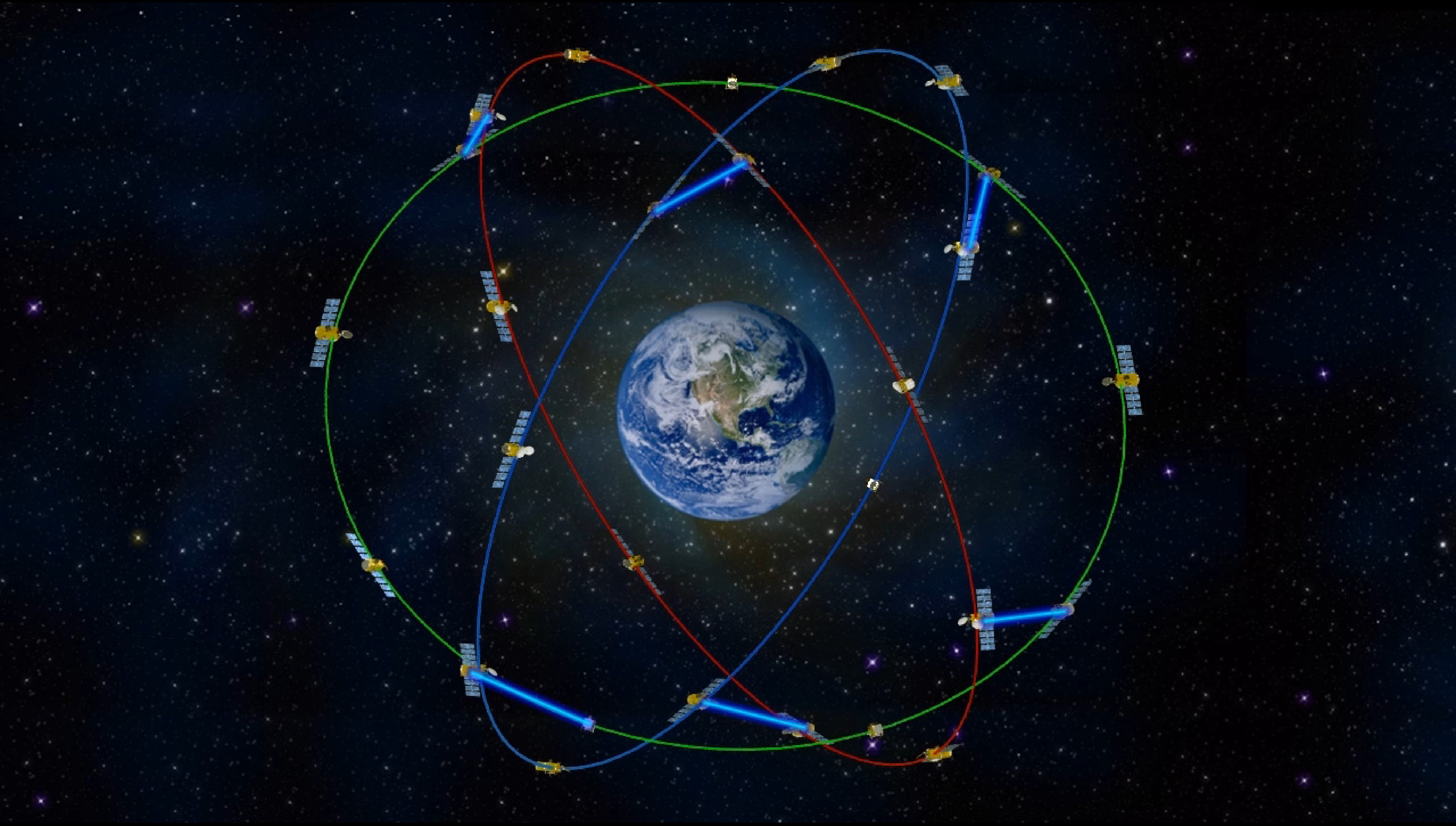


Plans:

N. Walenta *et al.*, poster at QCrypt 2014



Video ©2012 IQC / group of T. Jennewein



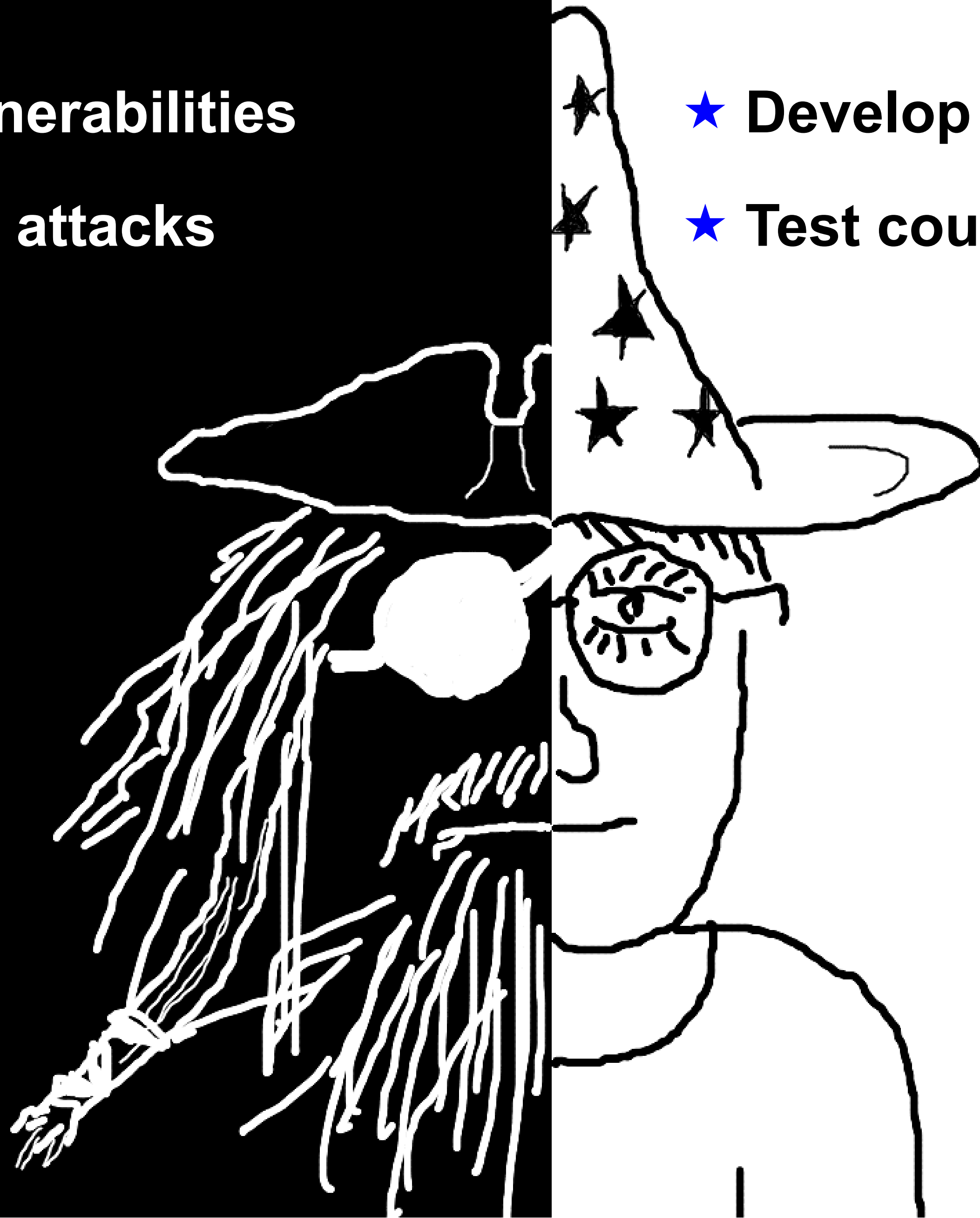
Video © group of P. Villoresi / ESA

End of lecture 2

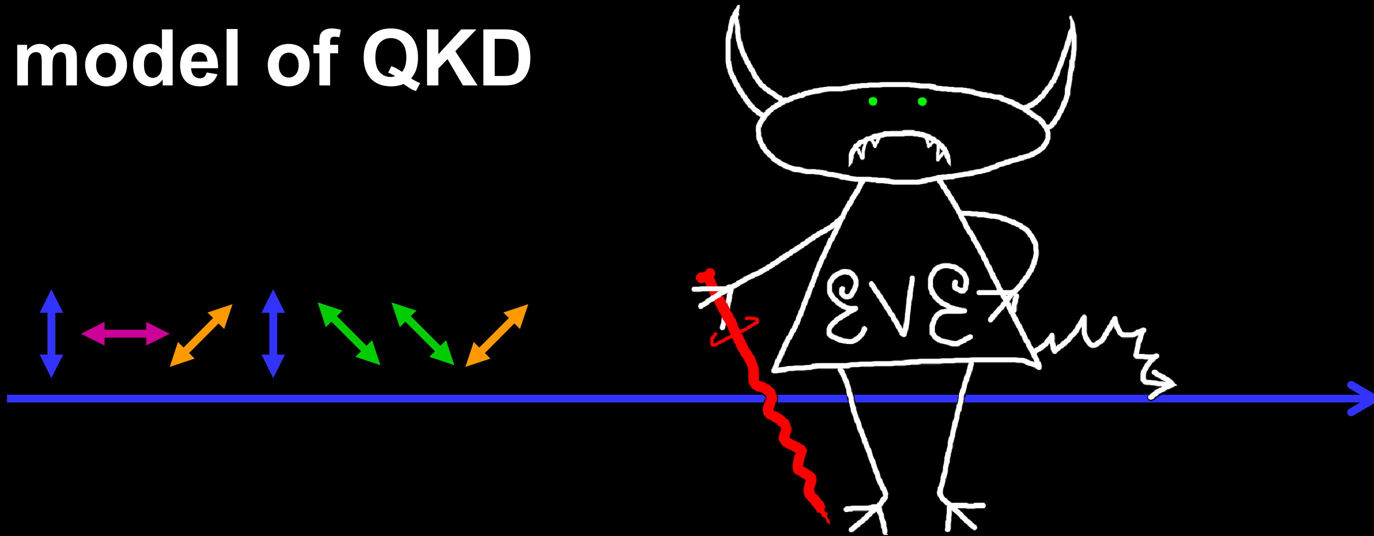
Quantum hacking

- Discover vulnerabilities
- Demonstrate attacks

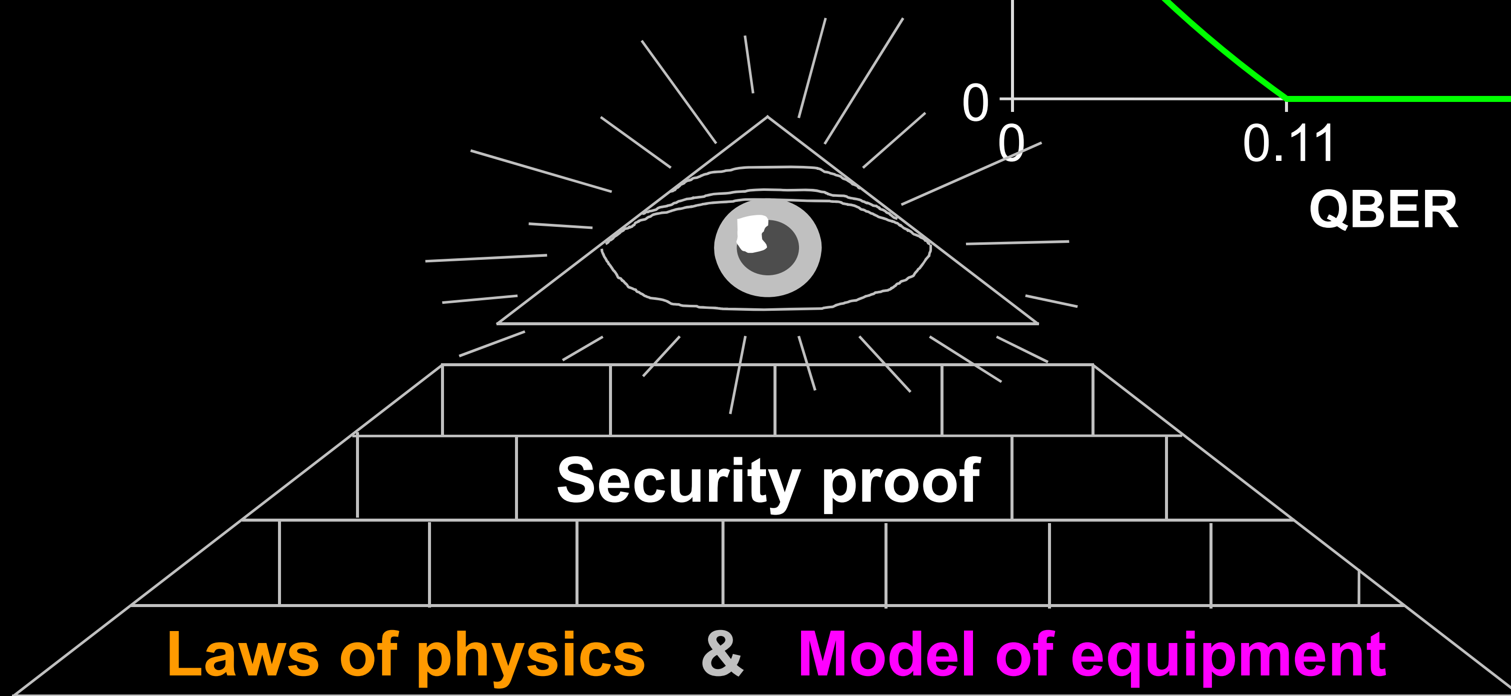
- Develop resistant protocols
- Test countermeasures



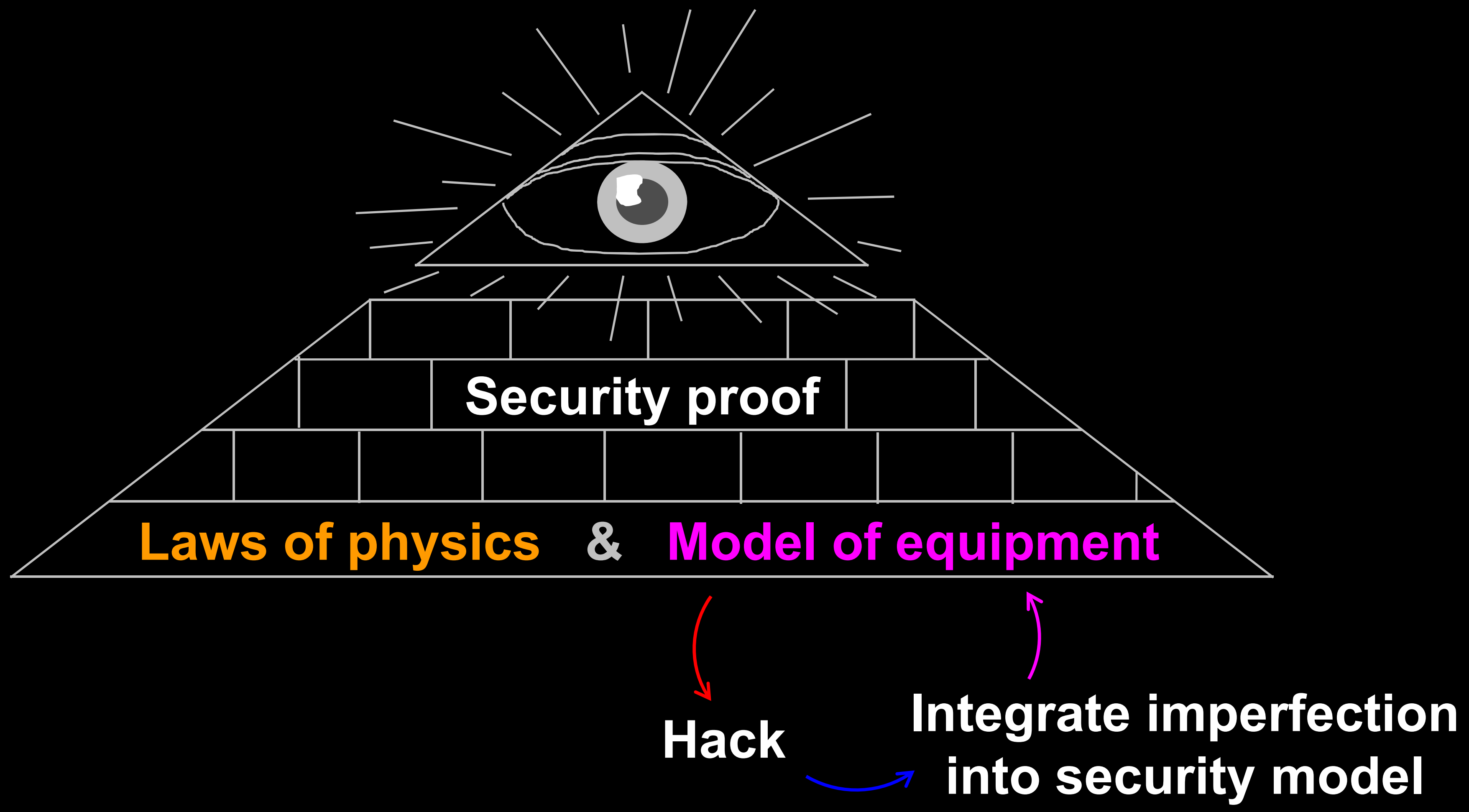
Security model of QKD



Secret key rate $R = f(\mathrm{QBER})$



Security model of QKD



Attack	Target component	Tested system
Spatial efficiency mismatch M Rau *et al.,* IEEE J. Quantum Electron. **21**, 6600905 (2015); S. Sajeed *et al.,* Phys. Rev. A **91**, 062301 (2015)	receiver optics	research system
Pulse energy calibration S. Sajeed *et al.,* Phys. Rev. A **91**, 032326 (2015)	classical watchdog detector	ID Quantique
Trojan-horse I. Khan *et al.,* presentation at QCrypt (2014)	phase modulator in Alice	SeQureNet
Trojan-horse N. Jain *et al.,* New J. Phys. **16**, 123030 (2014)	phase modulator in Bob	ID Quantique*
Detector saturation H. Qin, R. Kumar, R. Alleaume, Proc. SPIE 88990N (2013)	homodyne detector	SeQureNet
Shot-noise calibration P. Jouguet, S. Kunz-Jacques, E. Diamanti, Phys. Rev. A **87**, 062313 (2013)	classical sync detector	SeQureNet
Wavelength-selected PNS M.-S. Jiang, S.-H. Sun, C.-Y. Li, L.-M. Liang, Phys. Rev. A **86**, 032310 (2012)	intensity modulator	(theory)
Multi-wavelength H.-W. Li *et al.,* Phys. Rev. A **84**, 062308 (2011)	beamsplitter	research system
Deadtime H. Weier *et al.,* New J. Phys. **13**, 073024 (2011)	single-photon detector	research system
Channel calibration N. Jain *et al.,* Phys. Rev. Lett. **107**, 110501 (2011)	single-photon detector	ID Quantique
Faraday-mirror S.-H. Sun, M.-S. Jiang, L.-M. Liang, Phys. Rev. A **83**, 062331 (2011)	Faraday mirror	(theory)
Detector control I. Gerhardt *et al.,* Nat. Commun. **2**, 349 (2011); L. Lydersen *et al.,* Nat. Photonics **4**, 686 (2010)	single-photon detector	ID Quantique, MagiQ, research system
Phase-remapping F. Xu, B. Qi, H.-K. Lo, New J. Phys. **12**, 113026 (2010)	phase modulator in Alice	ID Quantique*

* Attack did not break security of the tested system, but may be applicable to a different implementation.

Example 1: academic

Photon-number-splitting attack

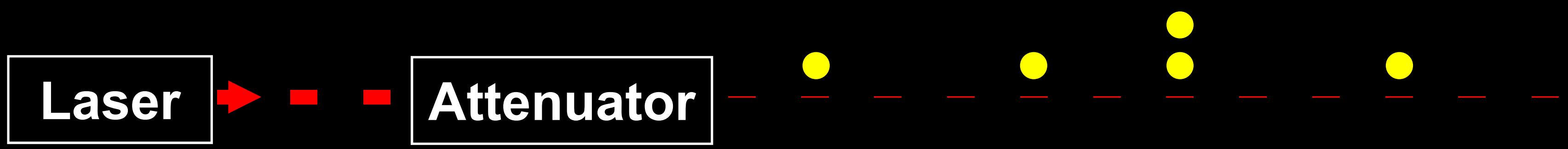
C. Bennett, F. Bessette, G. Brassard, L. Salvail, J. Smolin, J. Cryptology **5**, 3 (1992)

G. Brassard, N. Lütkenhaus, T. Mor, B. C. Sanders, Phys. Rev. Lett. **85**, 1330 (2000)

N. Lütkenhaus, Phys. Rev. A **61**, 052304 (2000)

S. Félix, N. Gisin, A. Stefanov, H. Zbinden, J. Mod. Opt. **48**, 2009 (2001)

N. Lütkenhaus, M. Jahma, New J. Phys. **4**, 44 (2002)



Decoy-state protocol

W.-Y. Hwang, Phys. Rev. Lett. **91**, 057901 (2003)

SARG04 protocol

V. Scarani, A. Acín, G. Ribordy, N. Gisin, Phys. Rev. Lett. **92**, 057901 (2004)

Distributed-phase-reference protocols

K. Inoue, E. Waks, Y. Yamamoto, Phys. Rev. Lett. **89**, 037902 (2002)

K. Inoue, E. Waks, Y. Yamamoto, Phys. Rev. A. **68**, 022317 (2003)

N. Gisin, G. Ribordy, H. Zbinden, D. Stucki, N. Brunner, V. Scarani, arXiv:quant-ph/0411022v1 (2004)


1 2
3 4
5 6
7 8
9 0
* #

Commercial QKD

ID Quantique *Cerberis* system

Classical encryptors:

L2, 2 Gbit/s

L2, 10 Gbit/s

L3 VPN, 100 Mbit/s

WDMs

Key manager

QKD to another node (4 km)

QKD to another node (14 km)

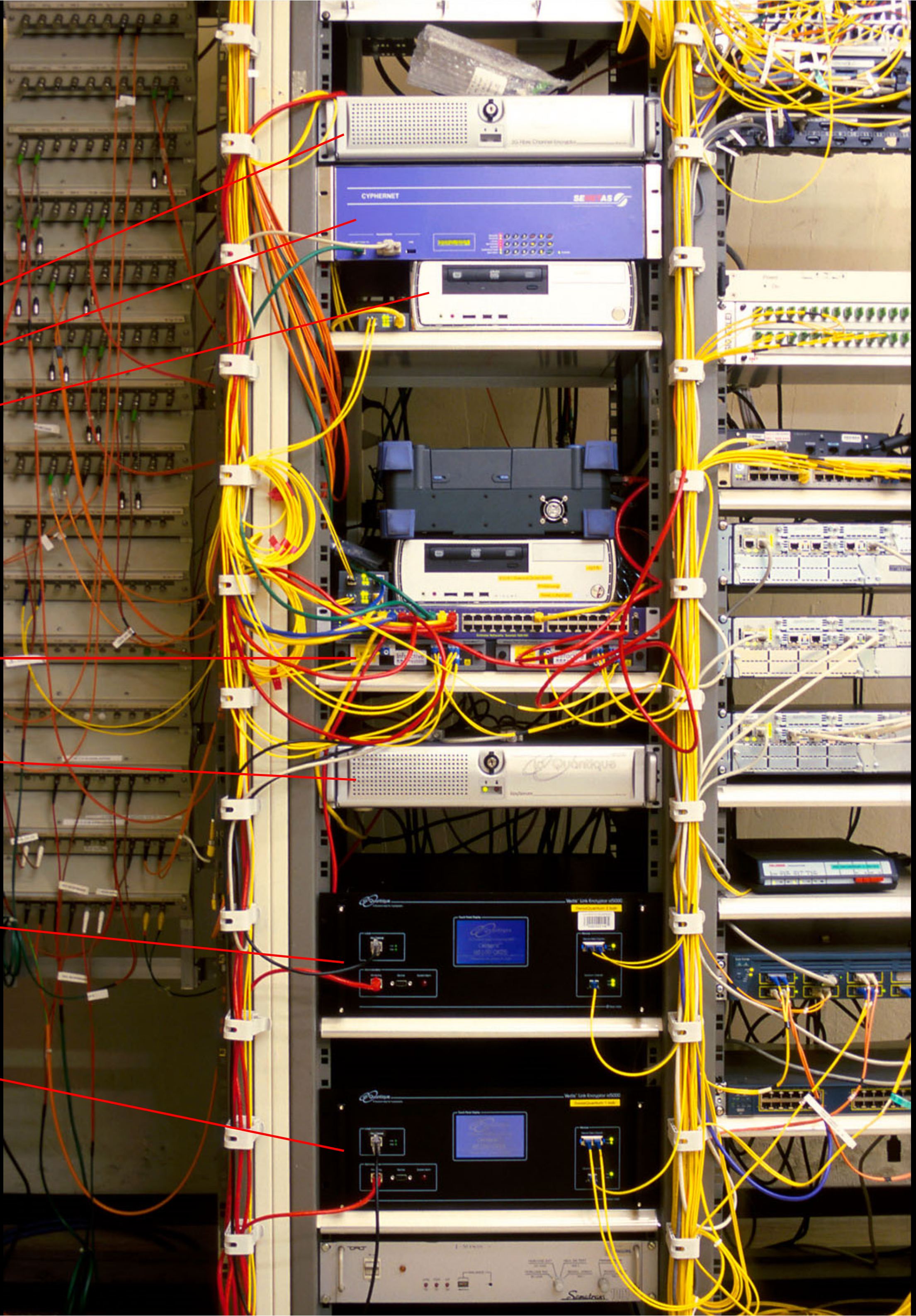
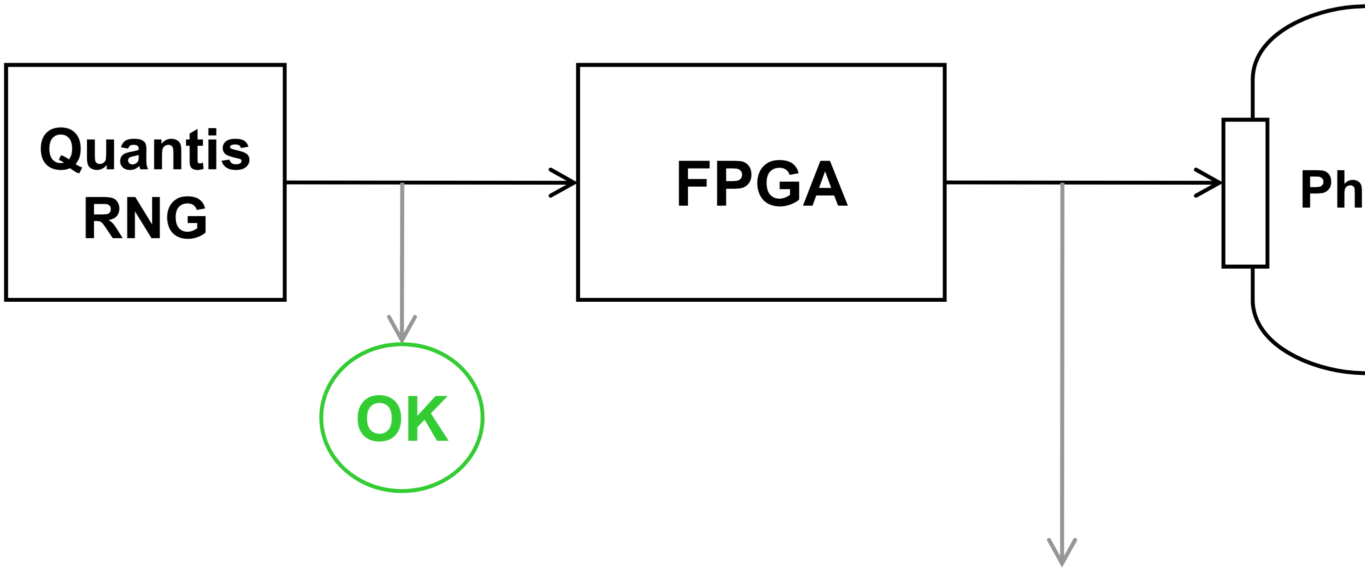


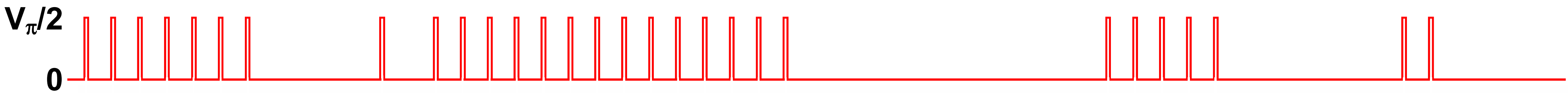
Photo ©2010 Vadim Makarov

www.swissquantum.com

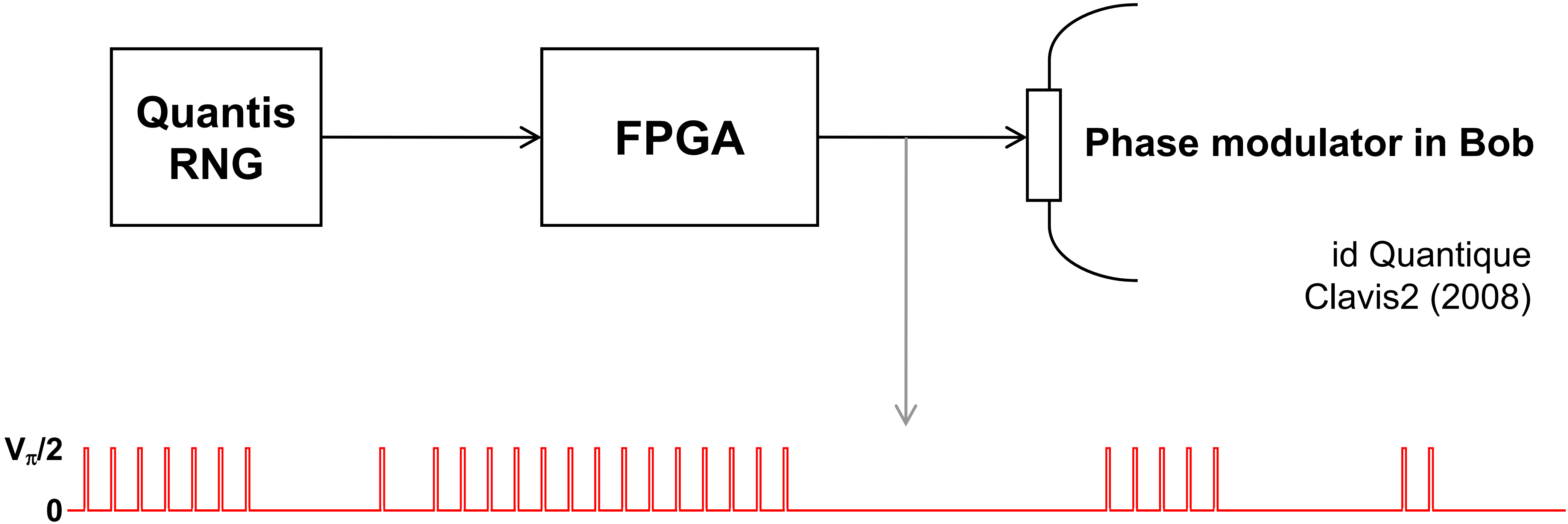
True randomness?



id Quantique
Clavis2 (2008)

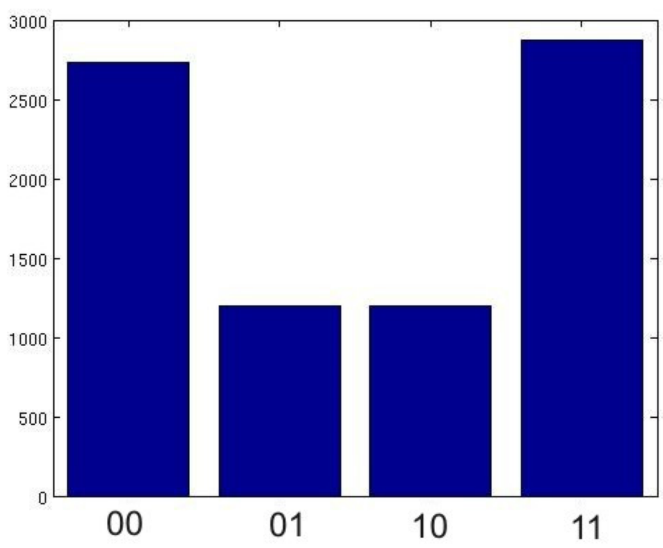


True randomness?

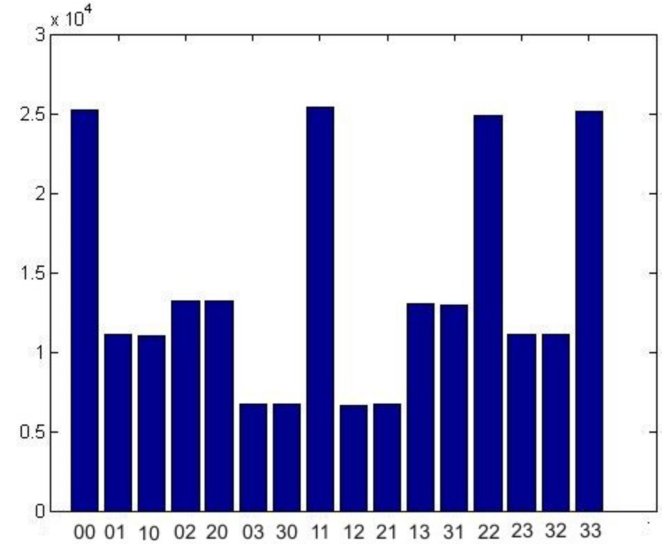


id Quantique
Clavis2 (2008)

Bob:

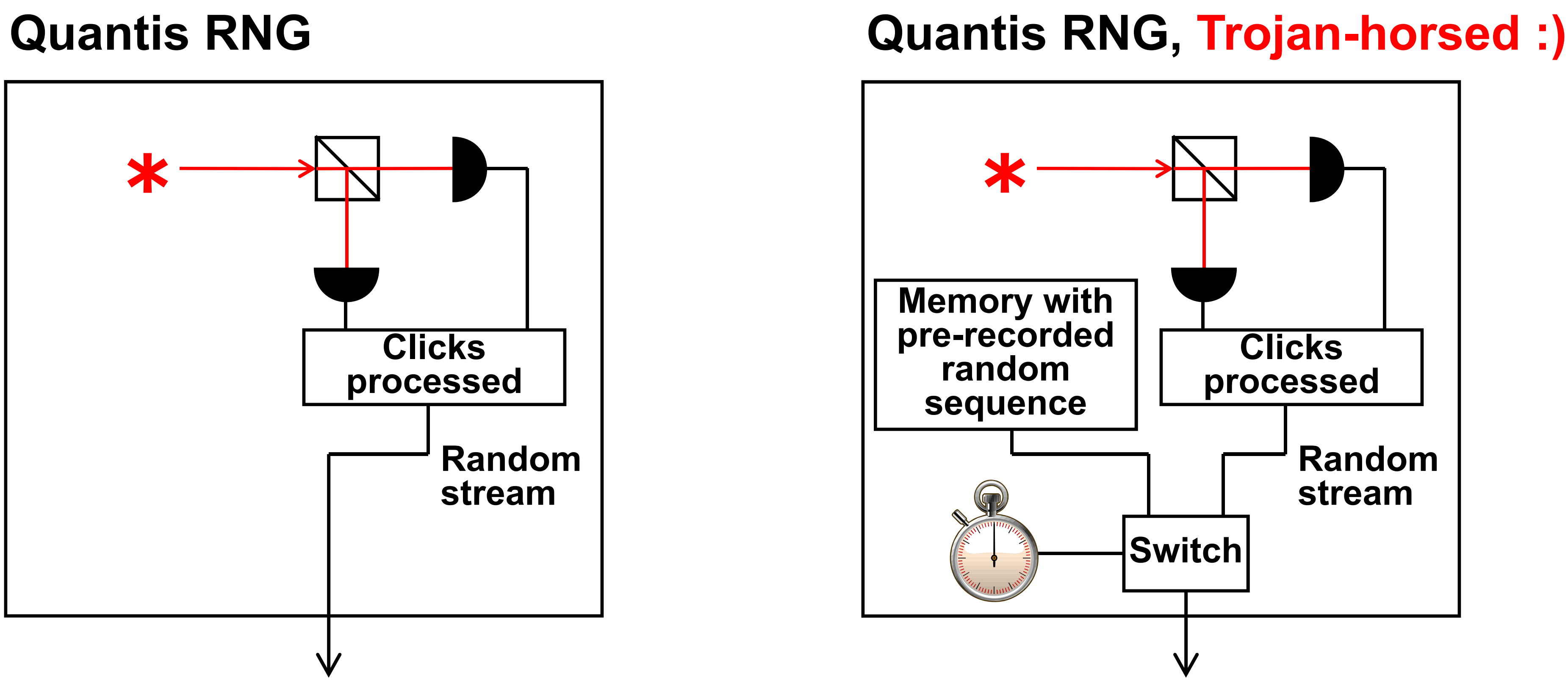


Alice:



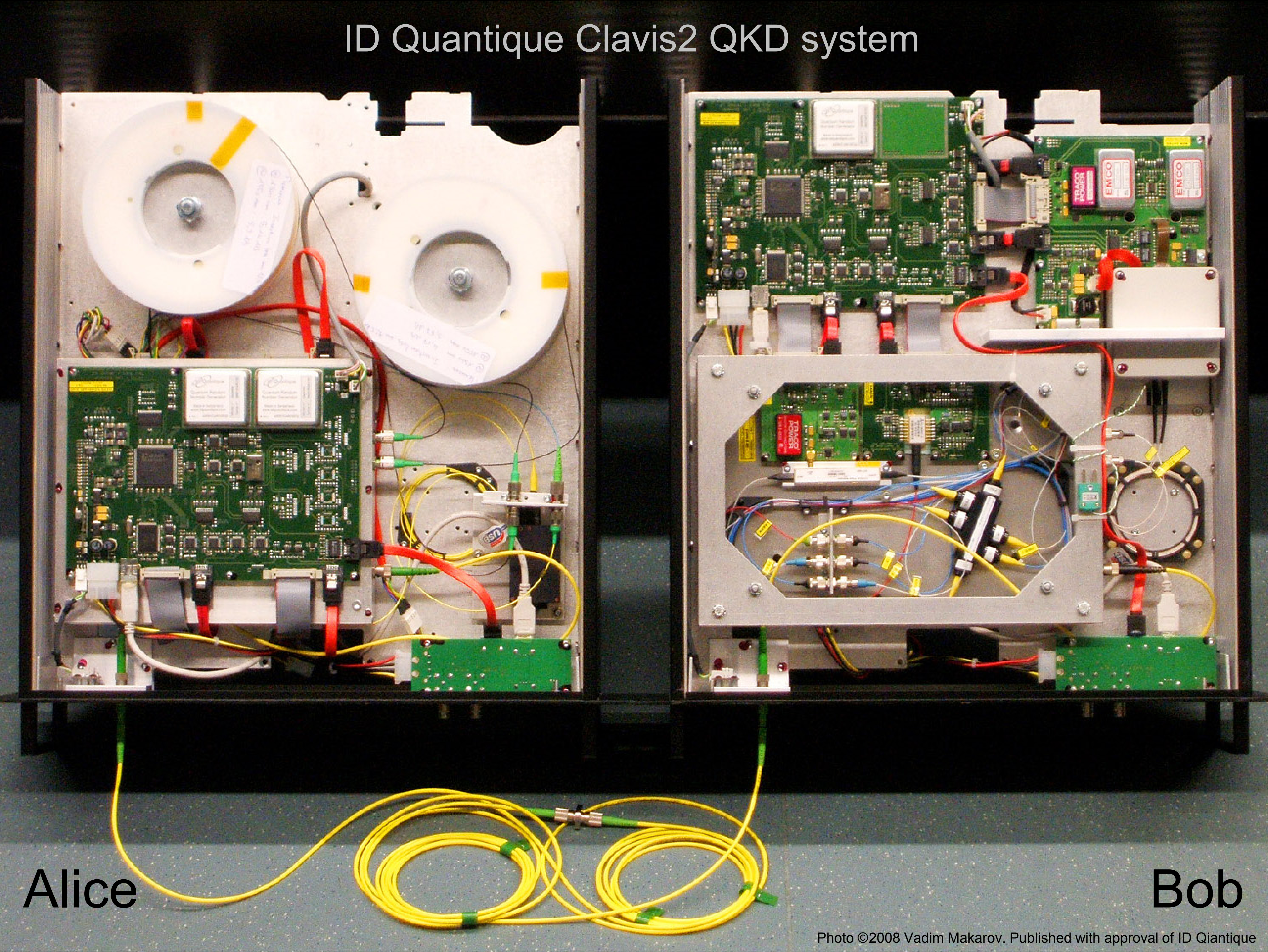
Issue reported patched, as of January 2010

Do we trust the manufacturer?

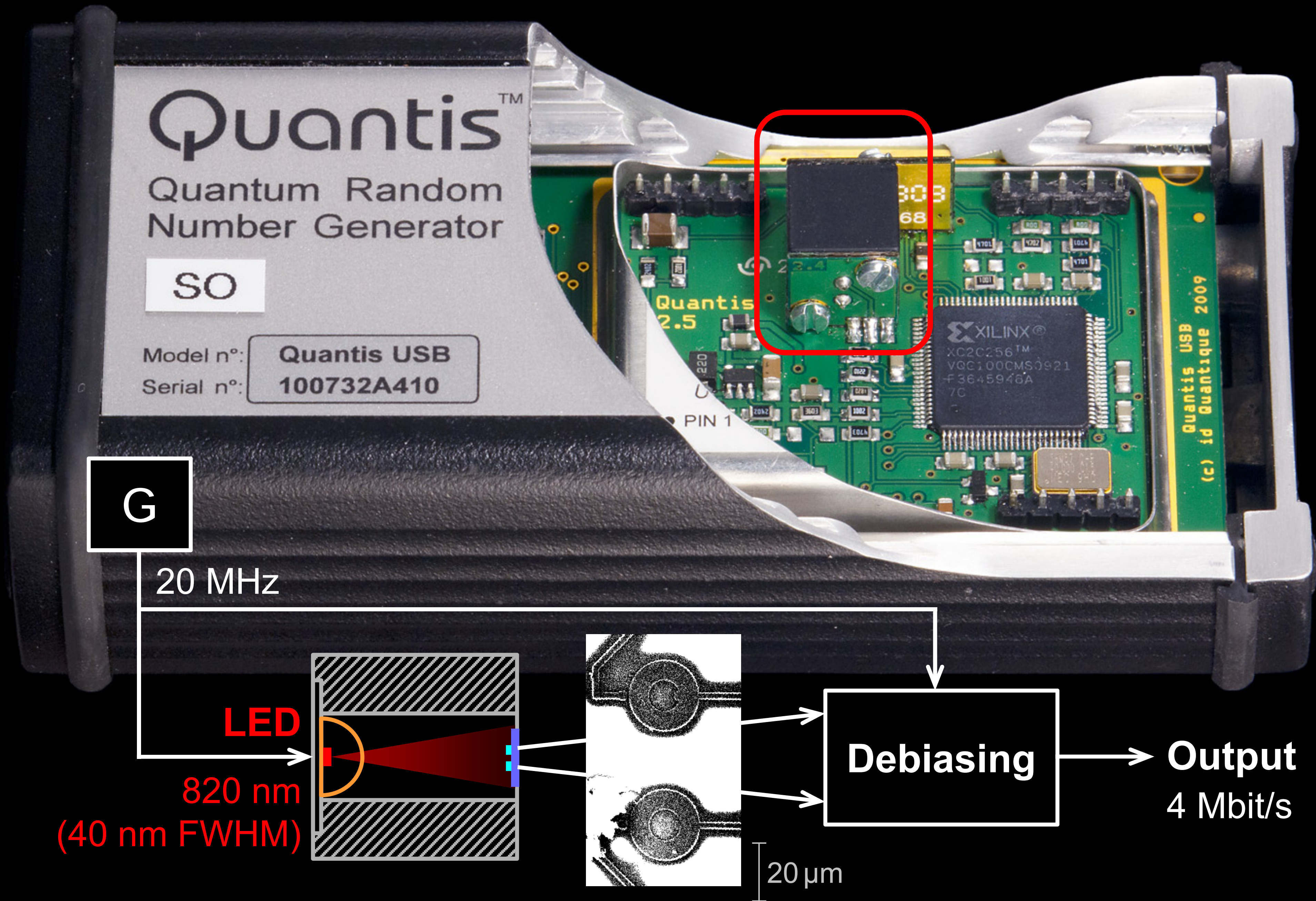


Many components in QKD system can be Trojan-horsed:

– access to secret information
– electrical power
– way to communicate outside or compromise security


ID Quantique Clavis2 QKD system
TRACO POWER
EMCO
EMCO
USB
Alice
Bob
Photo ©2008 Vadim Makarov. Published with approval of ID Qiantique

Quantis RNG: what's inside?



G. Ribordy, O. Guinnard, US patent appl. US 2007/0127718 A1 (filed in 2006)

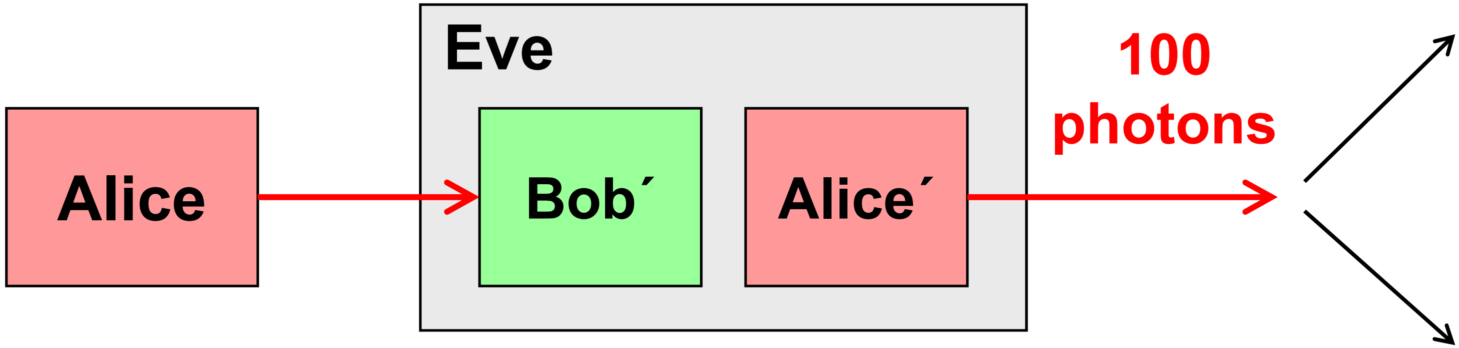
I. Radchenko *et al.*, unpublished

Double clicks

– occur naturally because of detector dark counts, multi-photon pulses...

Discard them?

Intercept-resend attack... with a twist:



Bob:

Detects in Eve's basis: single click

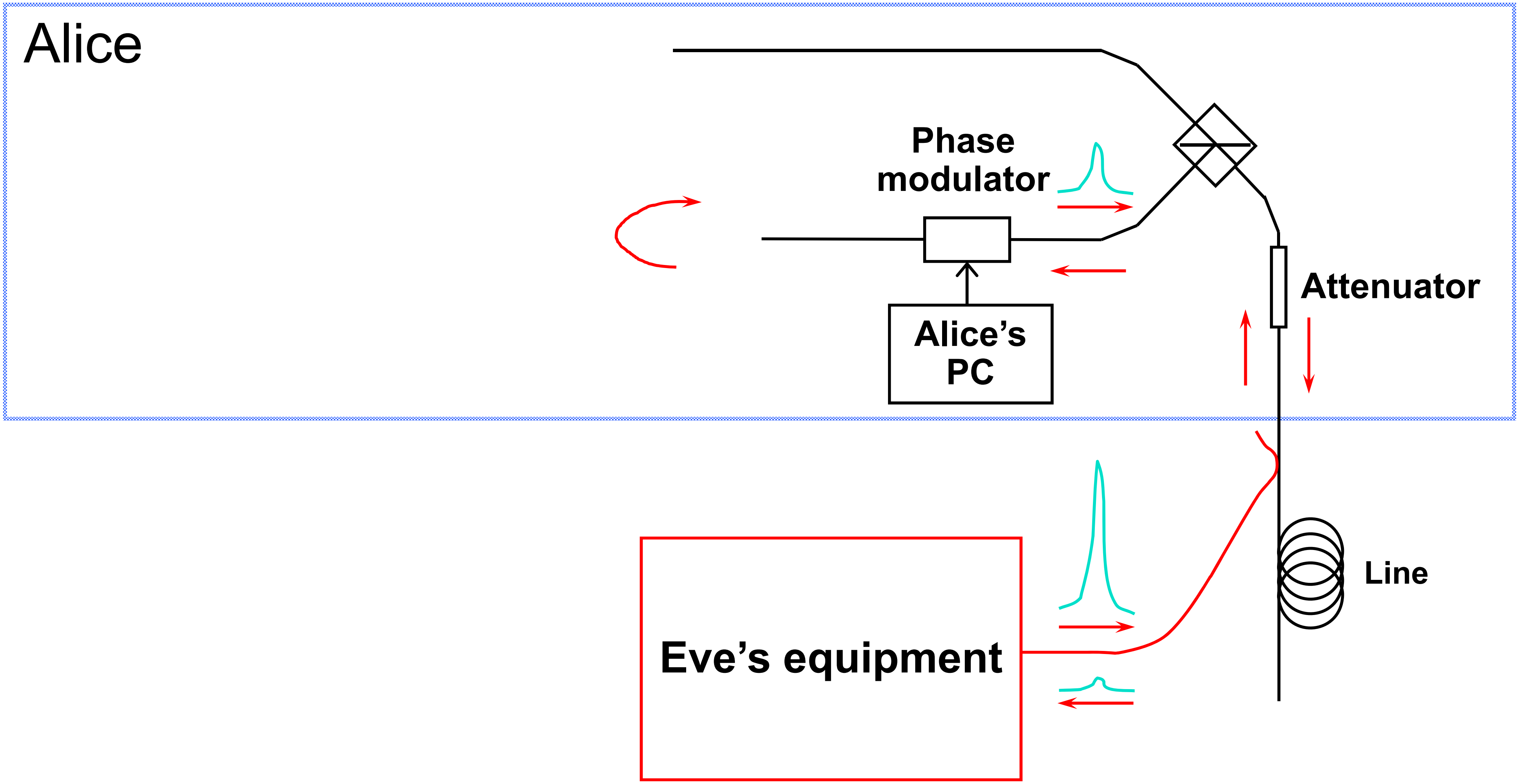
Detects in conjugate basis: double click, discarded

Proper treatment for double clicks: assign a random bit value.

N. Lütkenhaus, Phys. Rev. A **59**, 3301 (1999)
T. Tsurumaru & K. Tamaki, Phys. Rev. A **78**, 032302 (2008)

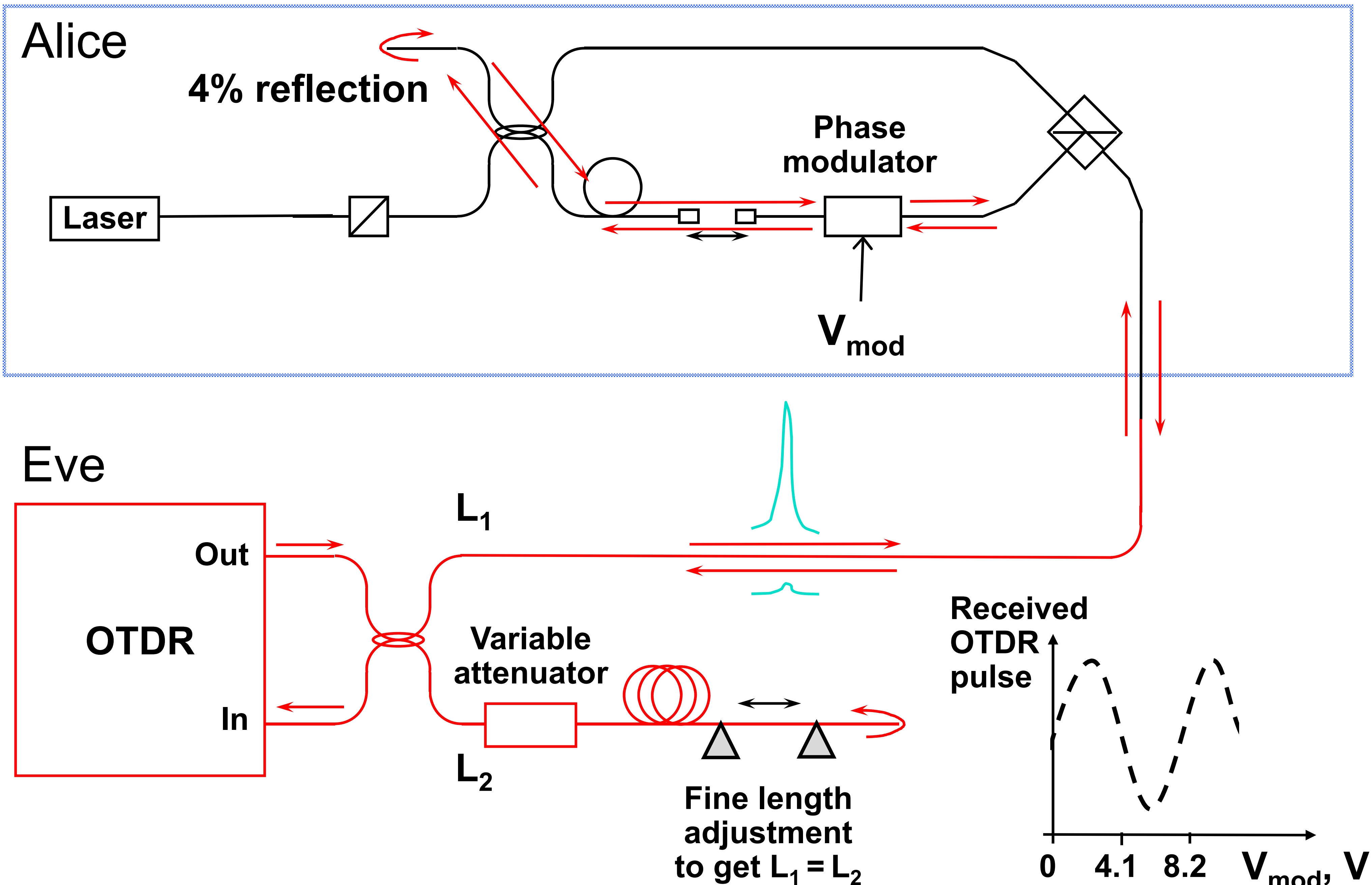
End of lecture 3

Trojan-horse attack

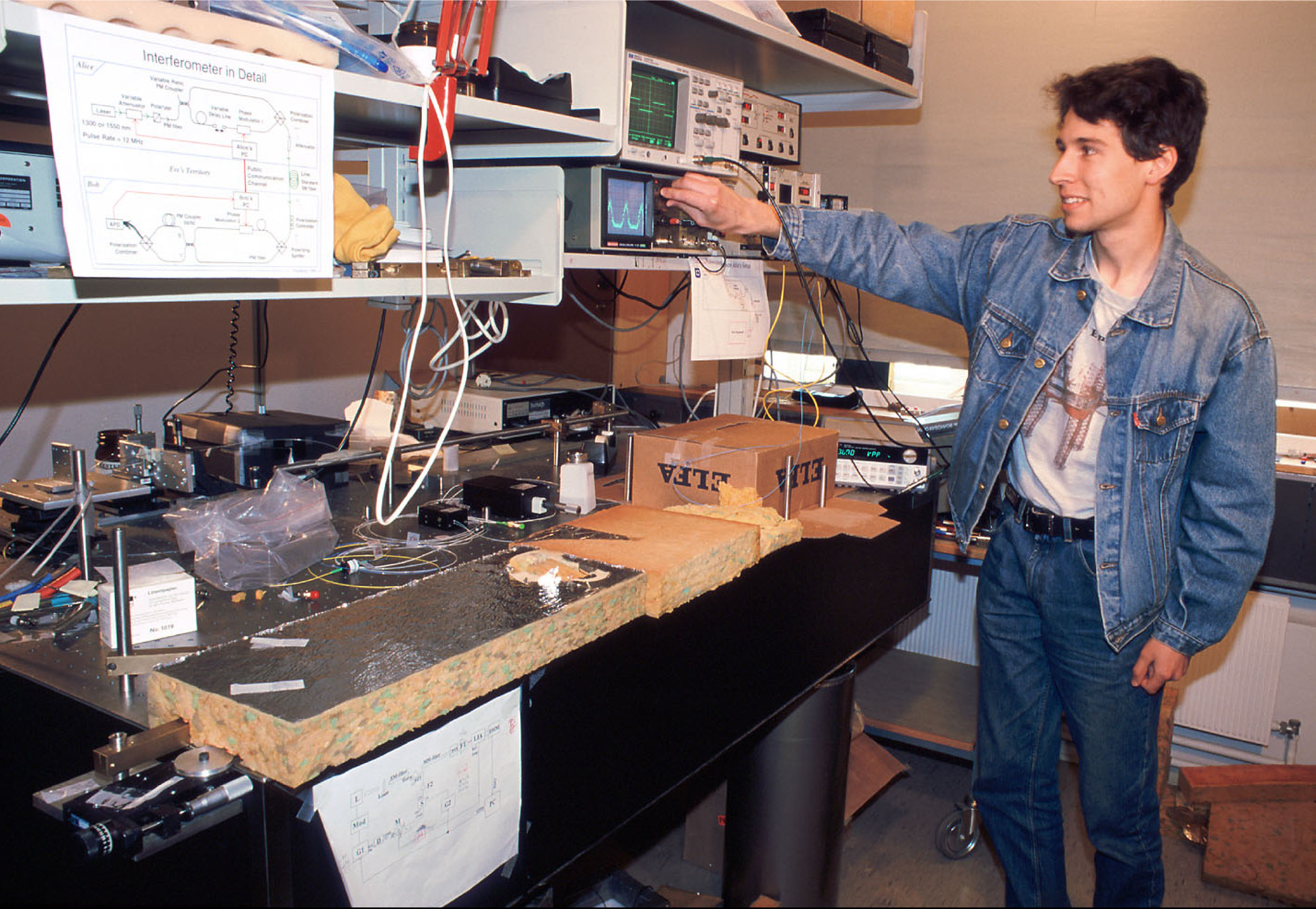


– interrogating Alice's phase modulator with powerful external pulses (can give Eve bit values directly)

Trojan-horse attack experiment

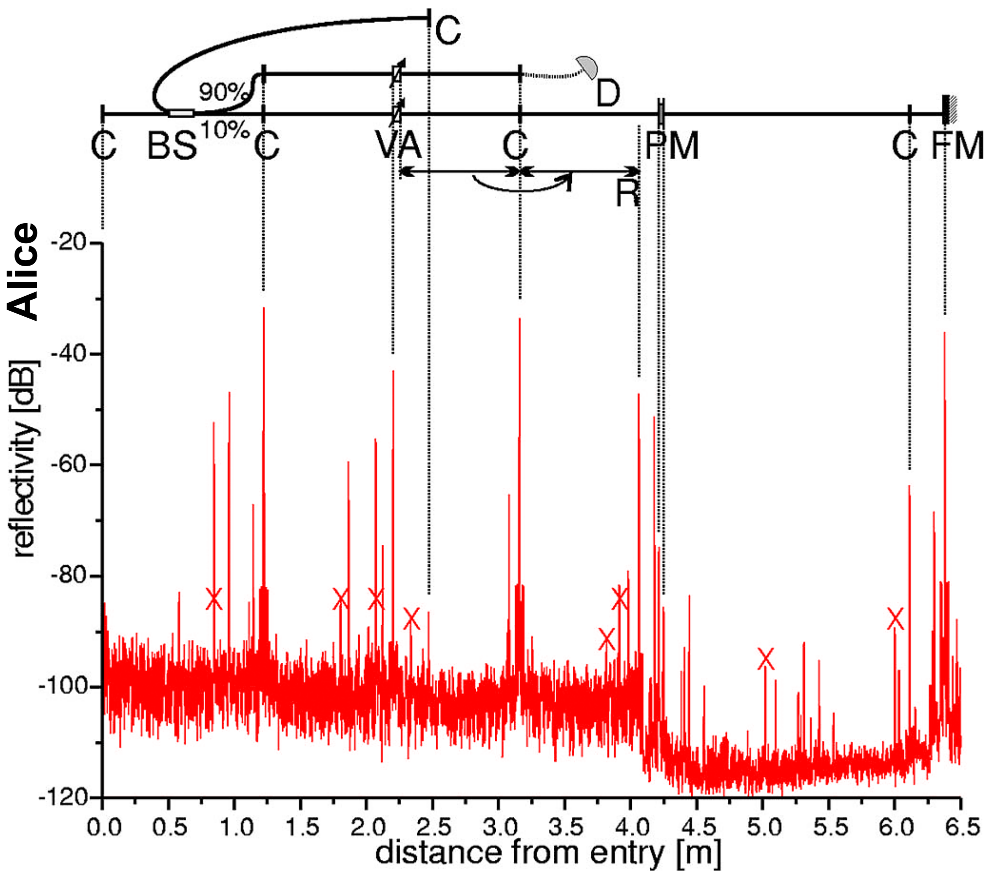


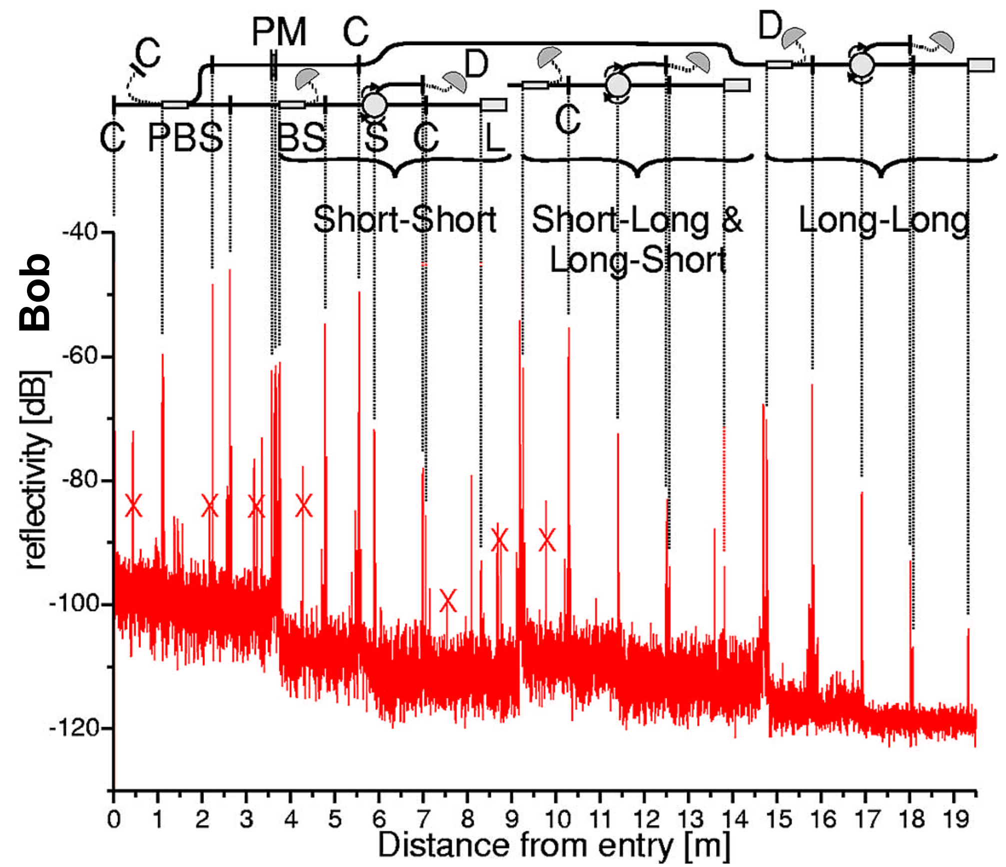
A. Vakhitov *et al.*, J. Mod. Opt. **48**, 2023 (2001)



Artem Vakhitov tunes up Eve's setup

Trojan-horse attack for plug-and-play system

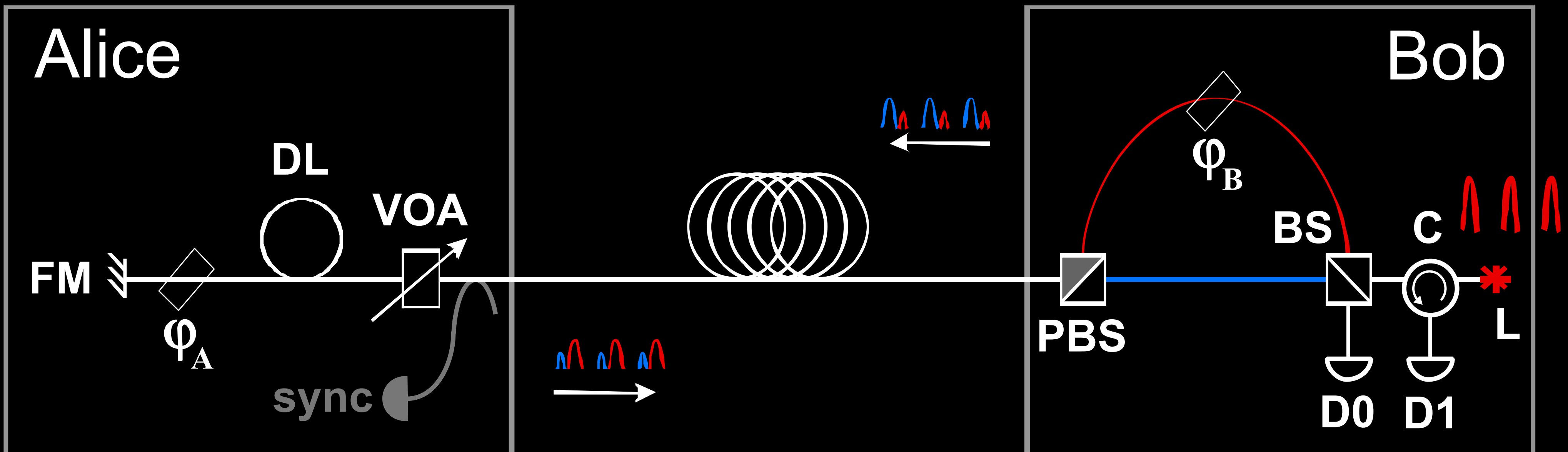




Eve gets back one photon $\rightarrow$ in principle, extracts 100% information

N. Gisin *et al.*, Phys. Rev. A **73**, 022320 (2006)

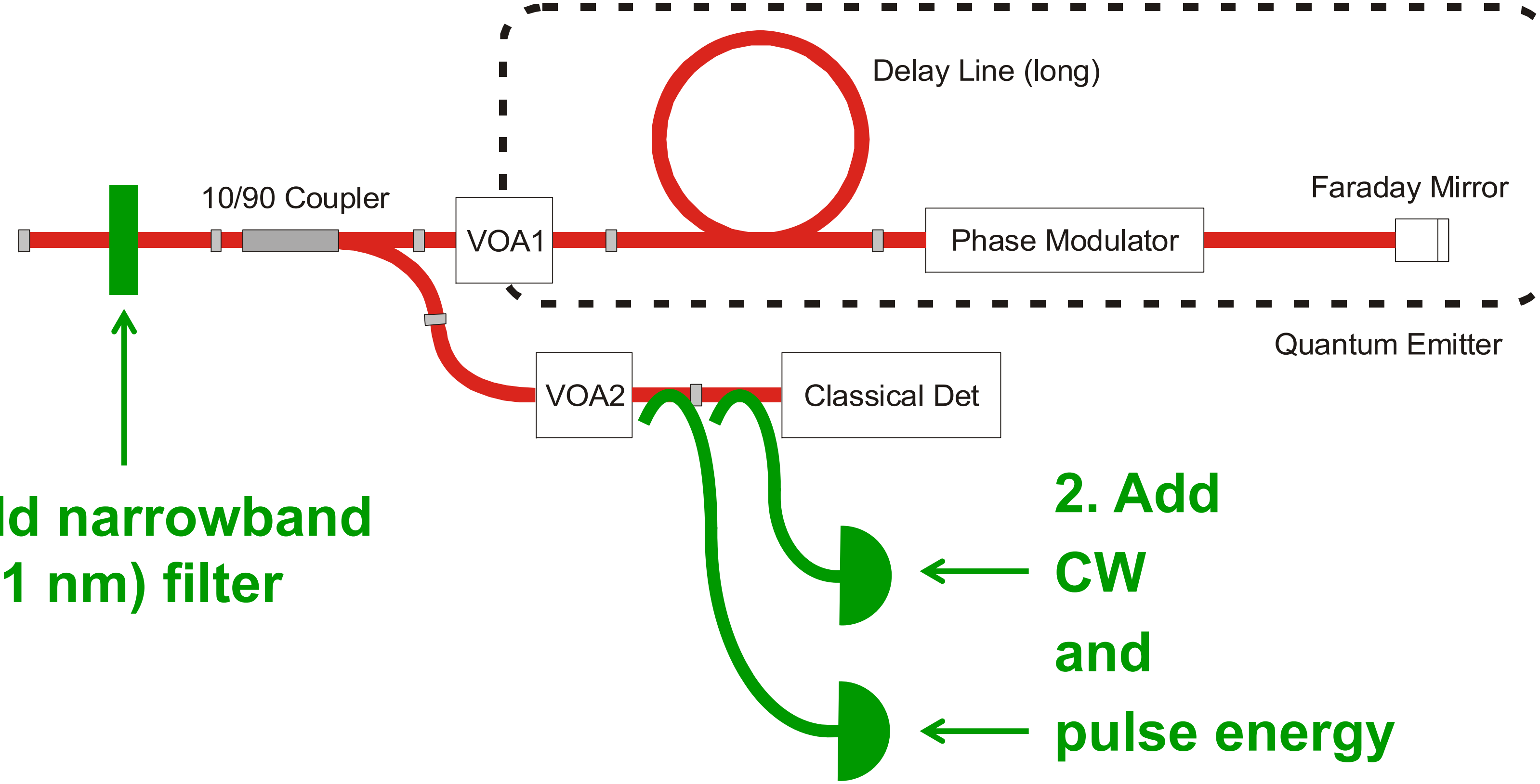
Countermeasures?



D. Stucki *et al.*, New J. Phys. **4**, 41 (2002)

Countermeasures for plug-and-play system

Alice:



1. Add narrowband (~1 nm) filter

2. Add CW and pulse energy monitoring detectors

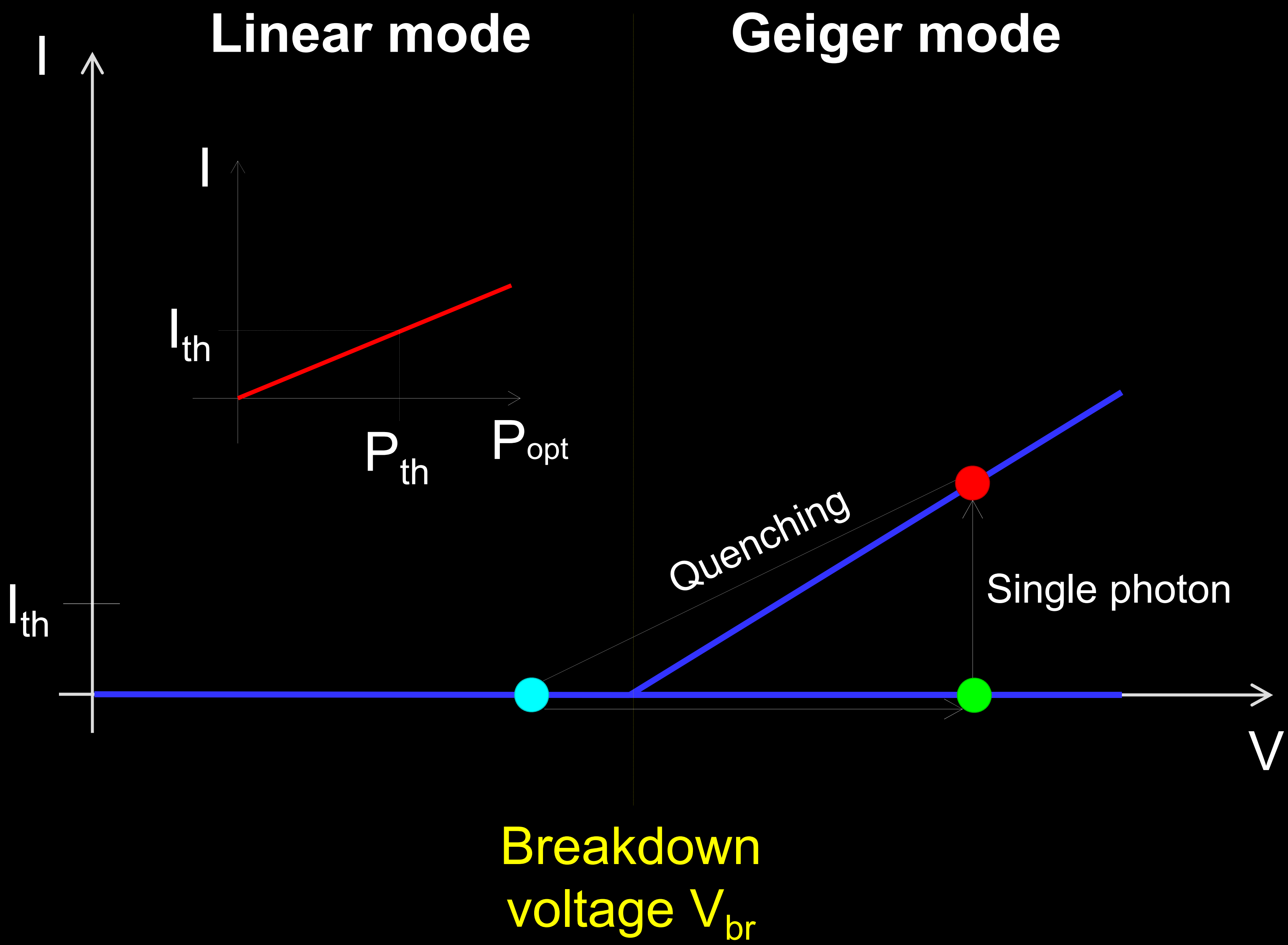
S. Sajeed *et al.*, Phys. Rev. A **91**, 032326 (2015)

Bob: none

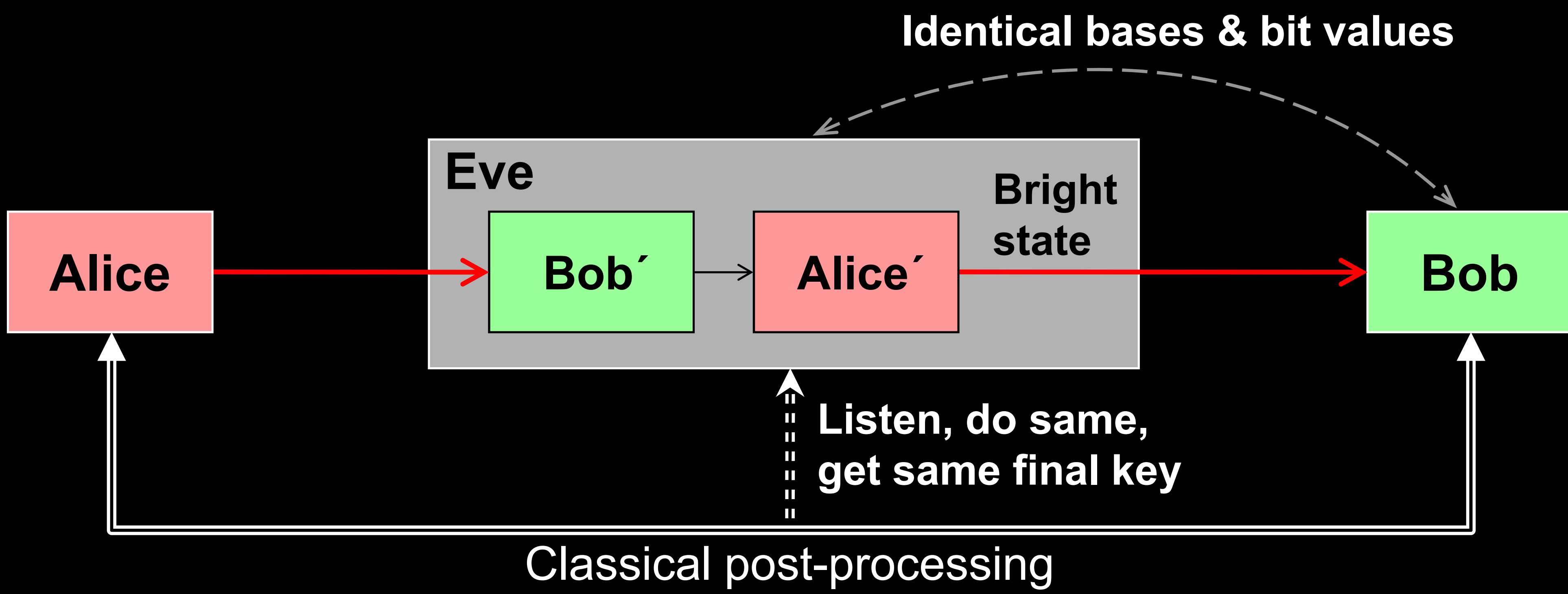
(one consequence: SARG protocol may be insecure)

N. Jain *et al.*, New J. Phys. **16**, 123030 (2014)

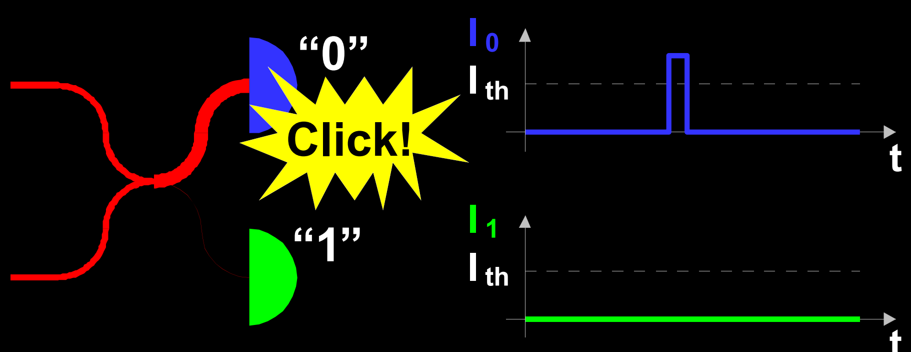
Attack example: avalanche photodetectors (APDs)



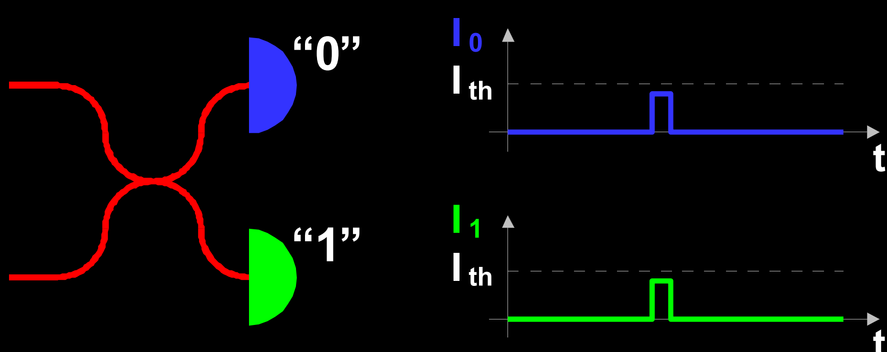
Faked-state attack in APD linear mode



Bob chooses same basis as Eve:

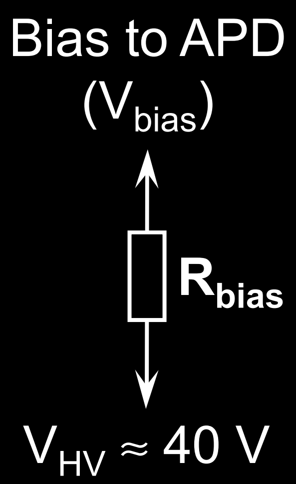


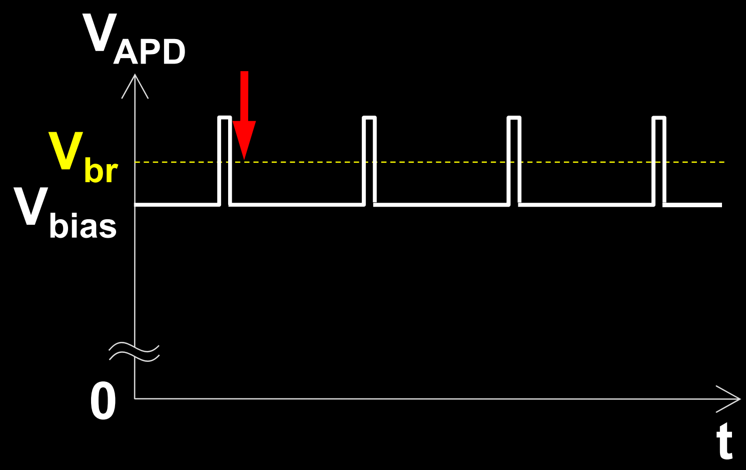
Bob chooses different basis:



L. Lydersen, C. Wiechers, C. Wittmann, D. Elser, J. Skaar, V. Makarov, Nat. Photonics **4**, 686 (2010)

Blinding APD with bright light

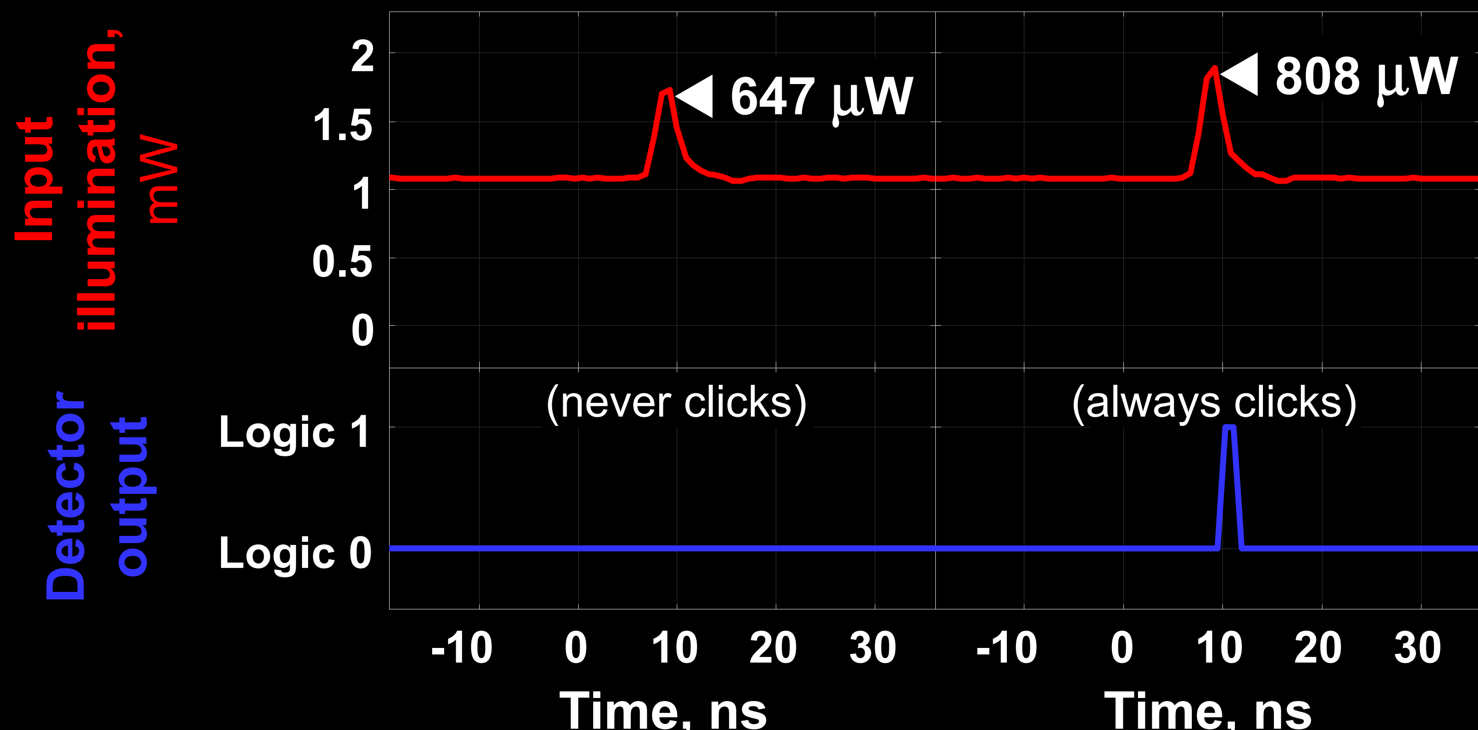




Eve applies CW light

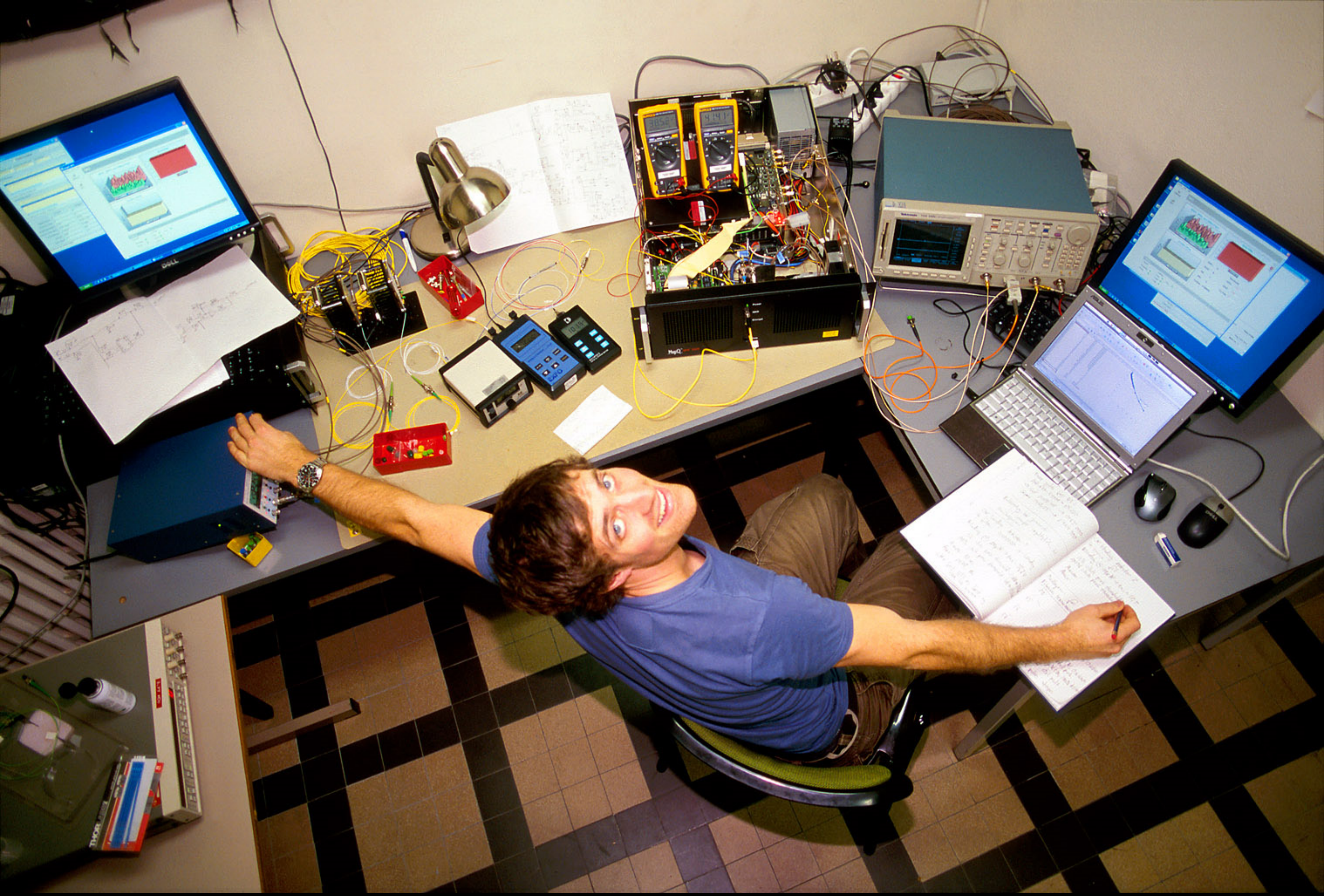
Detector blind!

Zero dark count rate



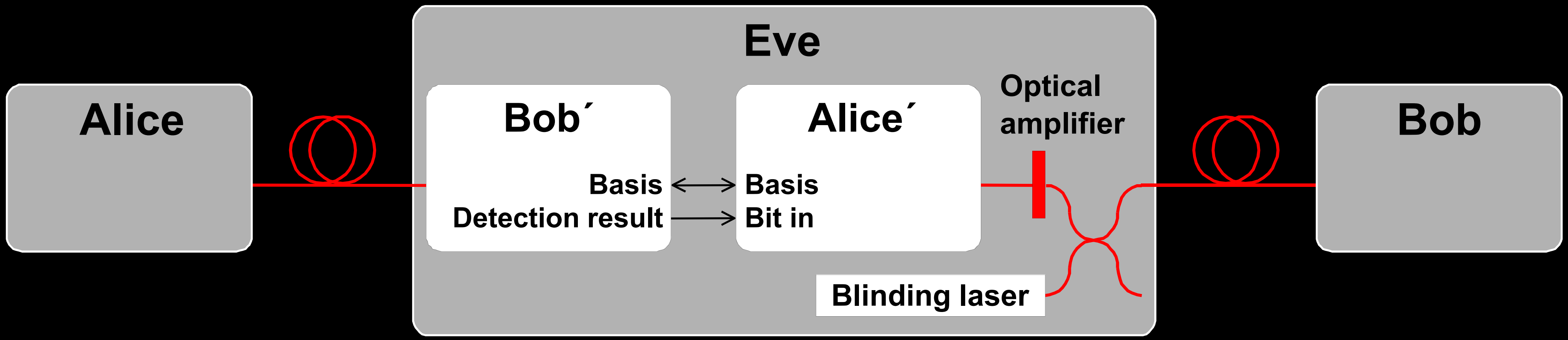
ID Quantique Clavis2

L. Lydersen, C. Wiechers, C. Wittmann, D. Elser, J. Skaar, V. Makarov, Nat. Photonics **4**, 686 (2010)



Lars Lydersen testing MagiQ Technologies QPN 5505

Proposed full eavesdropper

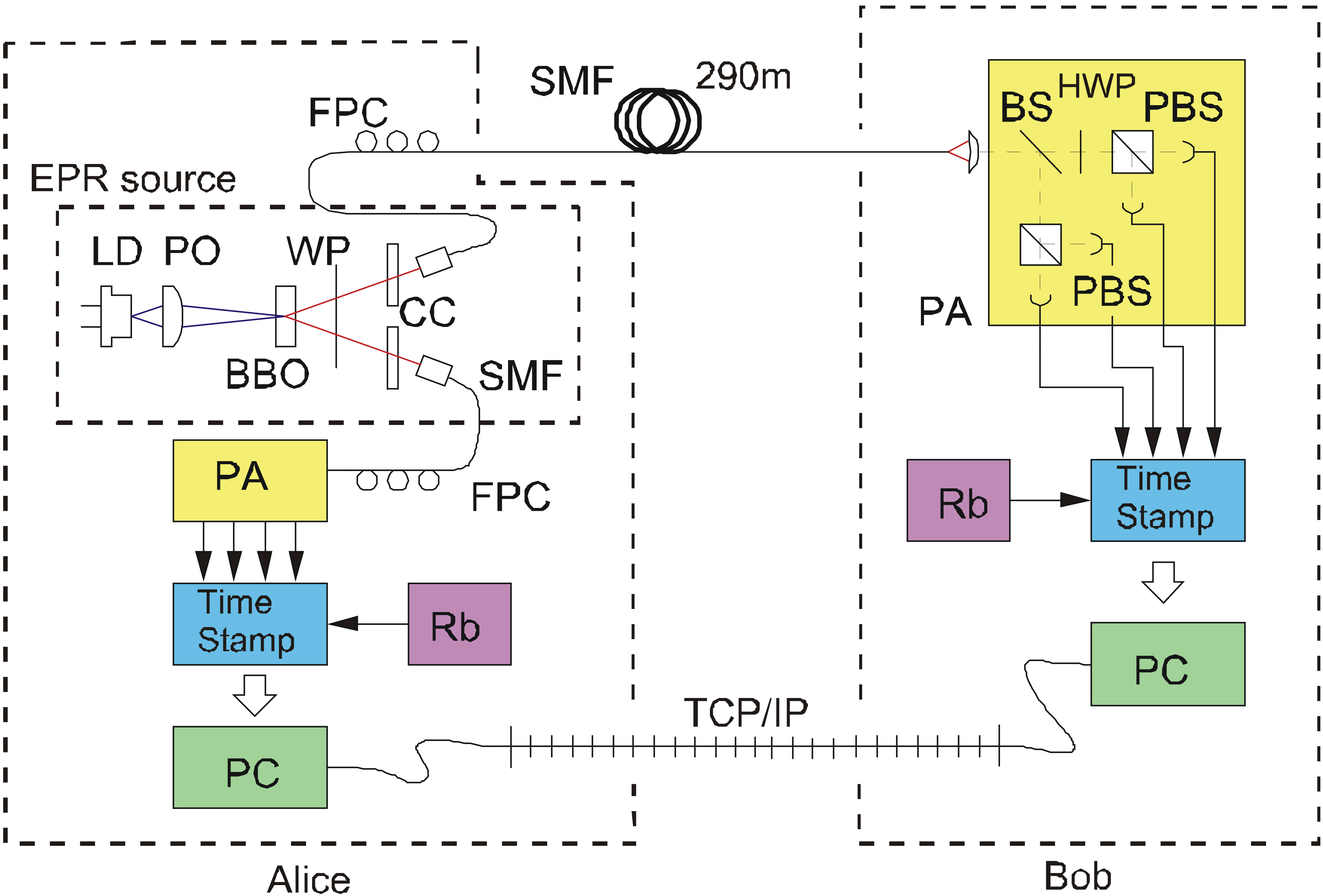


Eavesdropping 100% key on installed QKD line

on campus of the National University of Singapore, July 4–5, 2009

I. Gerhardt, Q. Liu *et al.*,
Nat. Commun. **2**, 349 (2011)

Entanglement-based QKD



M. P. Peloso *et al.*, New J. Phys. **11**, 045007 (2009)

Eavesdropping 100% key on installed QKD line

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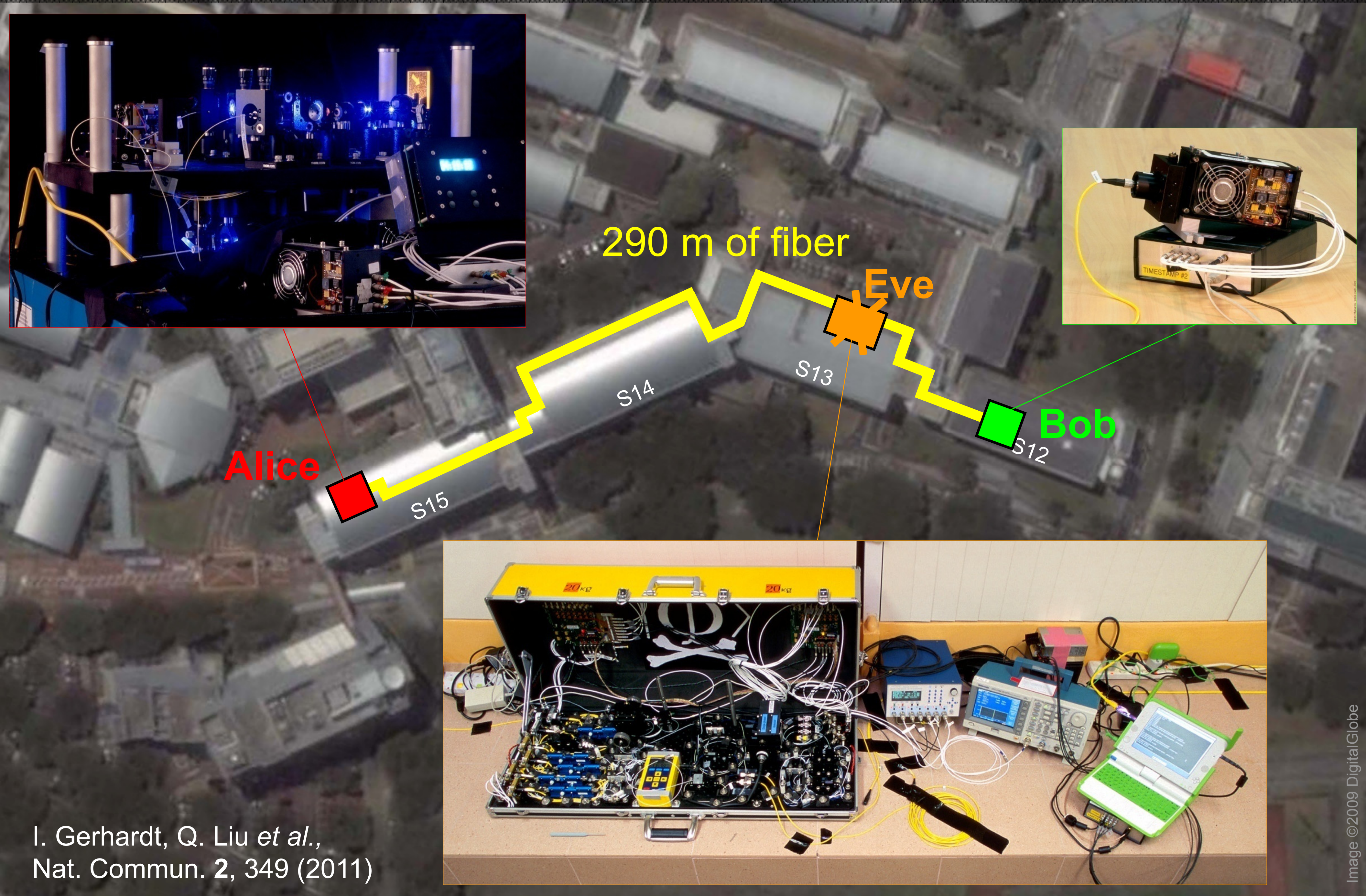


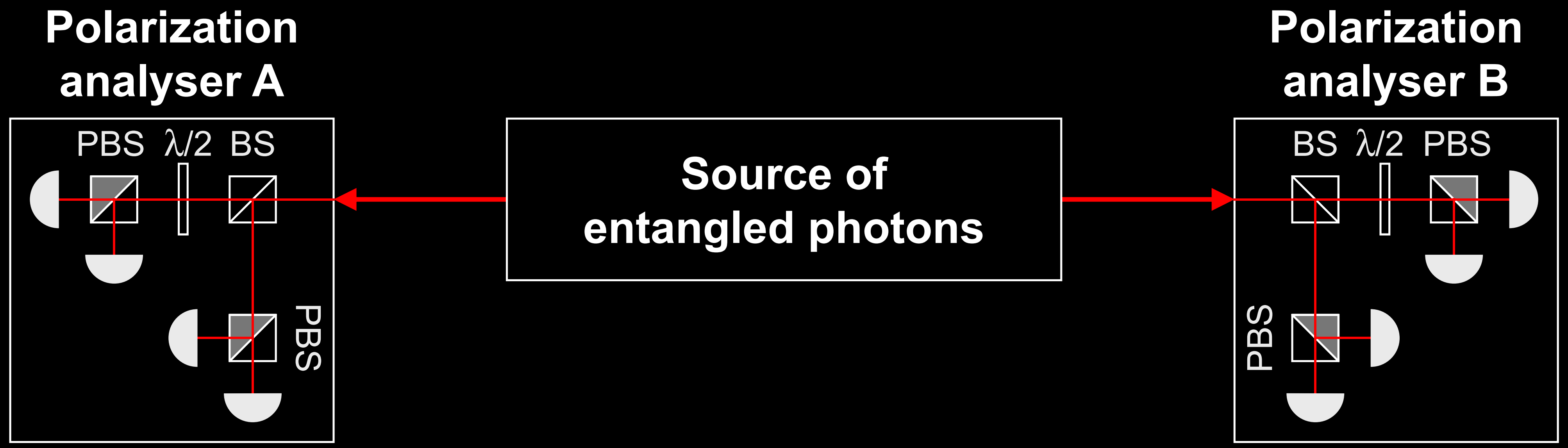
I. Gerhardt, Q. Liu *et al.*,
Nat. Commun. **2**, 349 (2011)

Faking violation of Bell inequality

CHSH inequality: $|S = E_{AB} + E_{A'B} + E_{AB'} - E_{A'B'}| \le 2$

$$E \in [-1, 1]$$

Entangled photons: $|S| \le 2\sqrt{2}$



I. Gerhardt, Q. Liu *et al.*, Phys. Rev. Lett. **107**, 170404 (2011); N. Sultana, V. Makarov, *unpublished*

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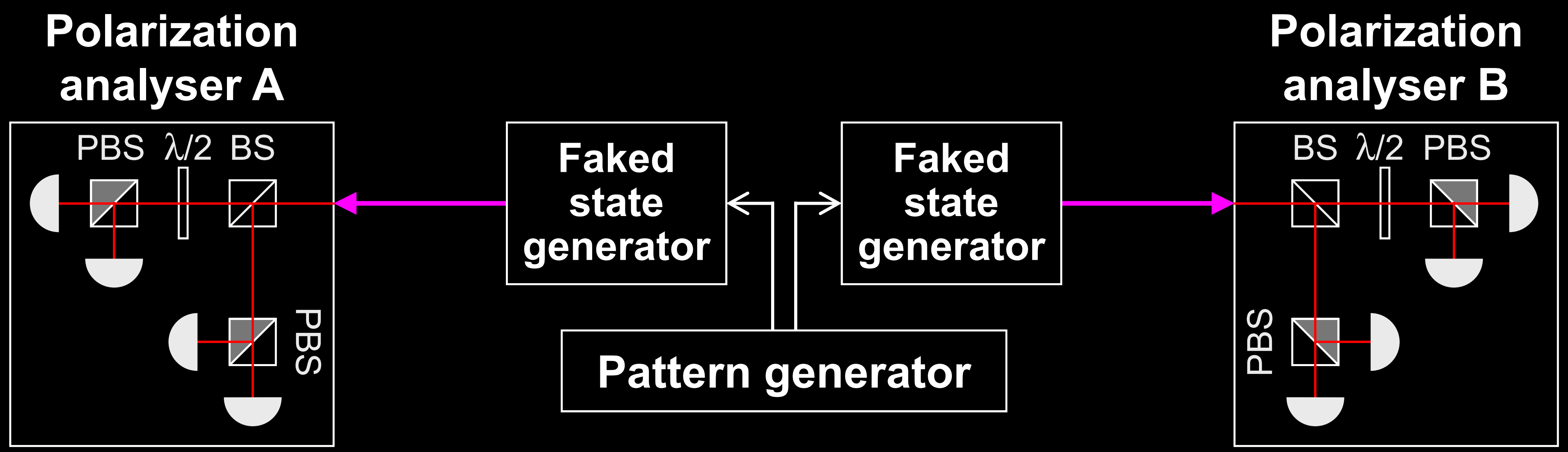

Passive basis choice: $|S| \leq 4$, click probability $= 100\%$

Active basis choice: $|S| \leq 4\ (2\sqrt{2})$, click probability $= 50\%\ (66.7\%)$

I. Gerhardt, Q. Liu *et al.*, Phys. Rev. Lett. **107**, 170404 (2011); S. Sajeed, N. Sultana *et al.*, unpublished

Countermeasures to detector attacks?

Industrial countermeasure (ID Quantique)

2004-11-10 First commercial Clavis1 system is shipped to a customer

2009-10-22 Report about detector blinding attack sent to company

2010-10-08 Company applies for a patent on randomization of detector efficiency as a countermeasure

2014-08-27 Lim *et al.* preprint about the countermeasure arXiv:1408.6398

2014-11-18 ★ Implementation of countermeasure delivered by company to our lab (firmware update for Clavis2)

2015-04-17 ? Countermeasure testing report sent to company

A. Huang *et al.*, unpublished

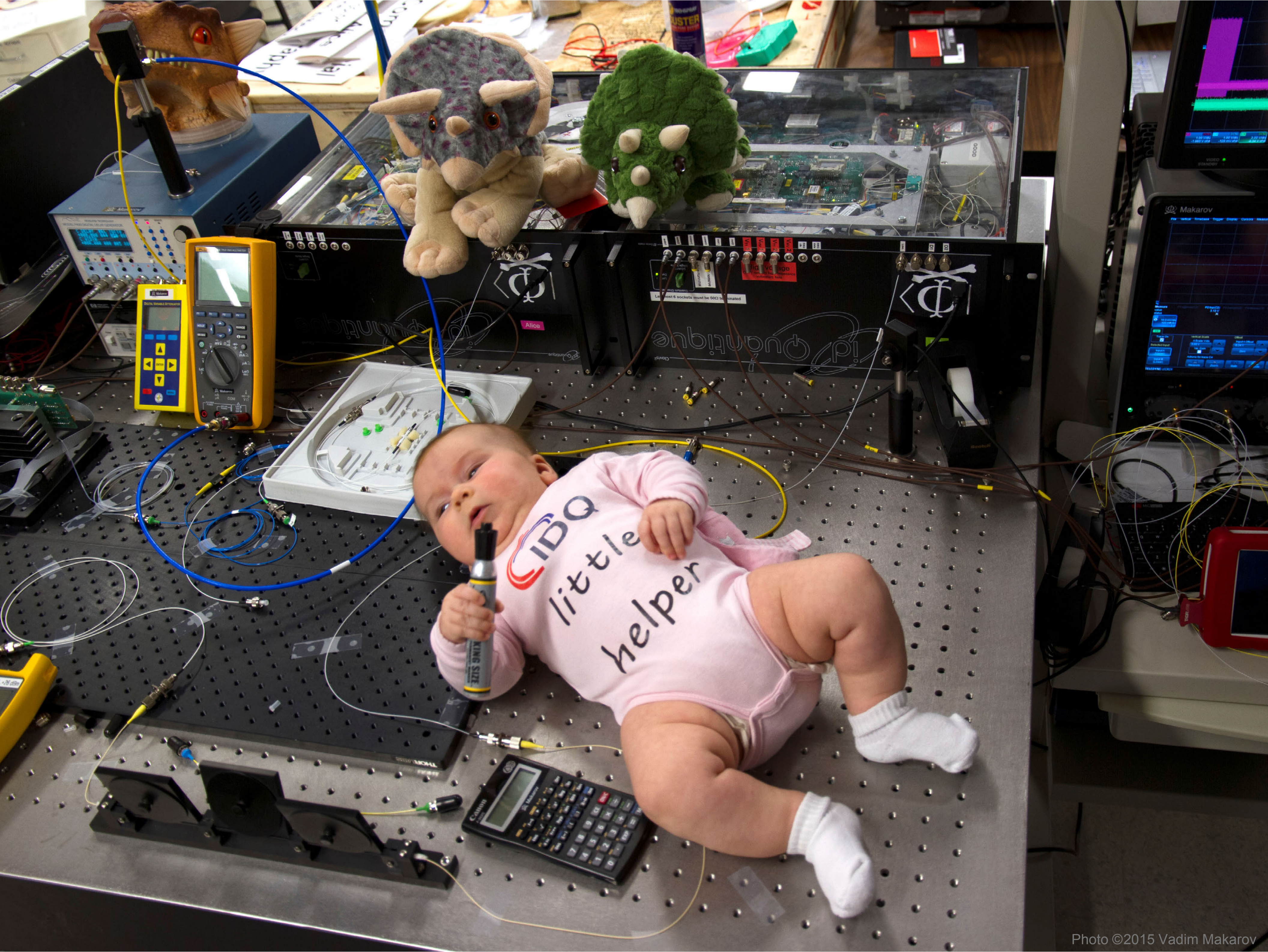
IDQ
little helper
Alice
Makarov
KING SIZE
Canon

Photo ©2014 Vadim Makarov, Scott McManus / IQC

IQC Institute *for* Quantum Computing

Quantum hacking lab

www.vad1.com/lab

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Quantum hacking lab

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