# Quantum hacking

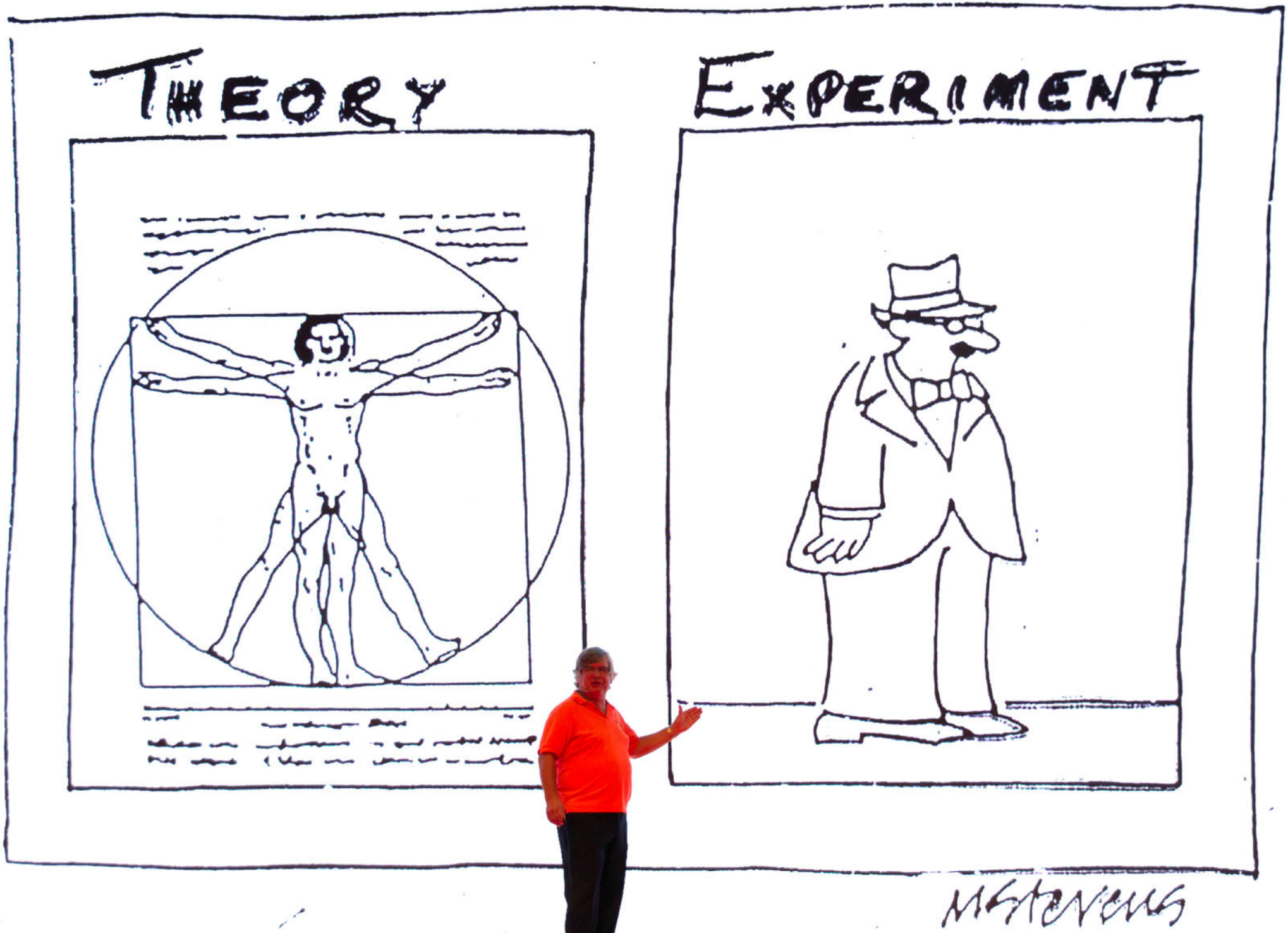
Vadim Makarov

RQC MISIS

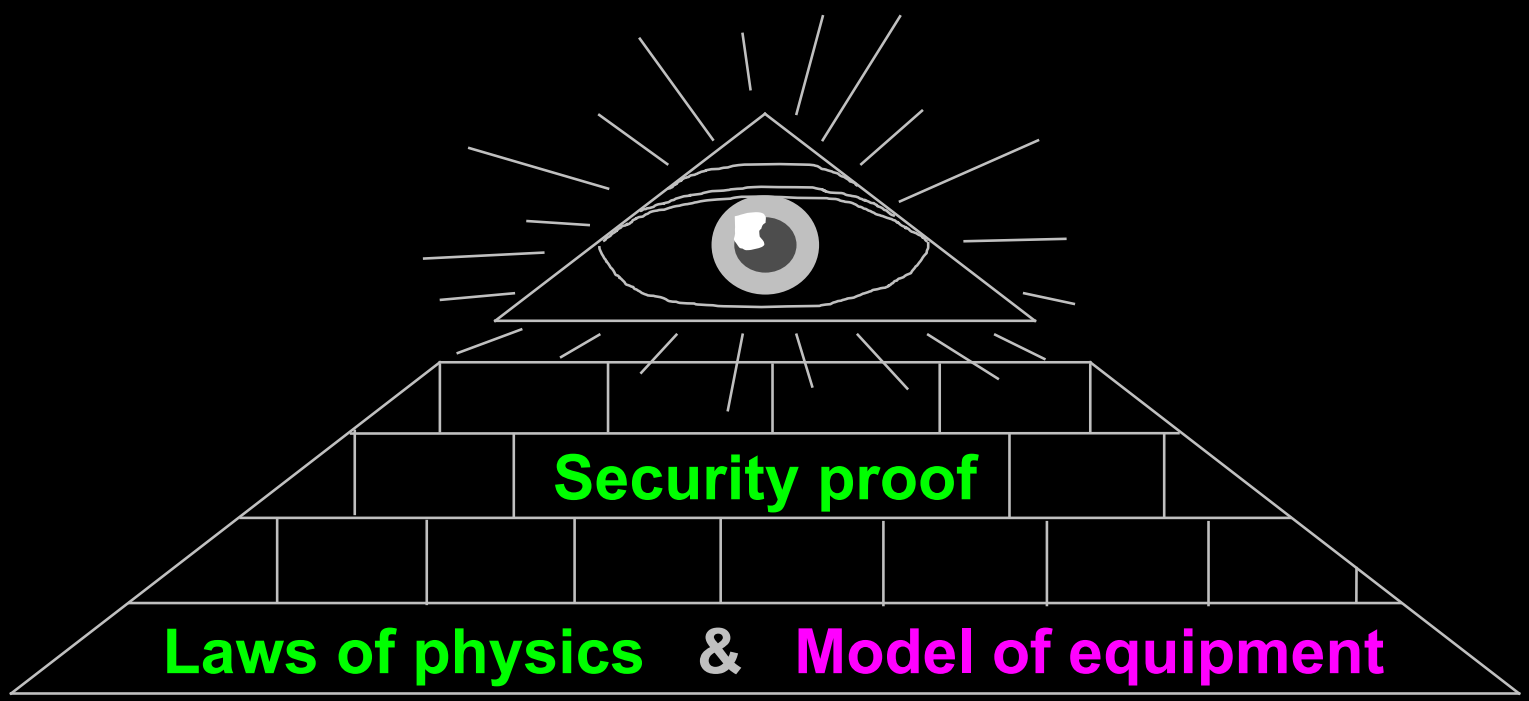
vad1.com/lab

# A (very) brief history of cryptography

| | | Broken? |
|---|---|---|
| **Monoalphabetic cipher** | invented ~50 BC (J. Caesar) | ~850 (Al-Kindi) |
| **Nomenclators (code books)** | ~1400 – ~1800 | ✓ |
| **Polyalphabetic (Vigenère)** | 1553 – ~1900 | 1863 (F. W. Kasiski) |
| … | | |
| **One-time pad** | invented 1918 (G. Vernam) | **impossible** (C. Shannon 1949) |
| **Polyalphabetic electromechanical (Enigma, Purple, etc.)** | 1920s – 1970s | ✓ |
| … | | |
| **DES** | 1977 – 2005 | 1998: 56 h (EFF) |
| **Public-key crypto (RSA, elliptic-curve)** | 1977 – | will be once we have q. computer (P. Shor 1994) |
| **AES** | 2001 – | ? |
| **Quantum cryptography** | invented 1984, in development | **impossible*** |
| **Public-key crypto ('quantum-safe')** | in development | ? |


THEORY
EXPERIMENT
MSTEVENS

# Implementation security of quantum communications

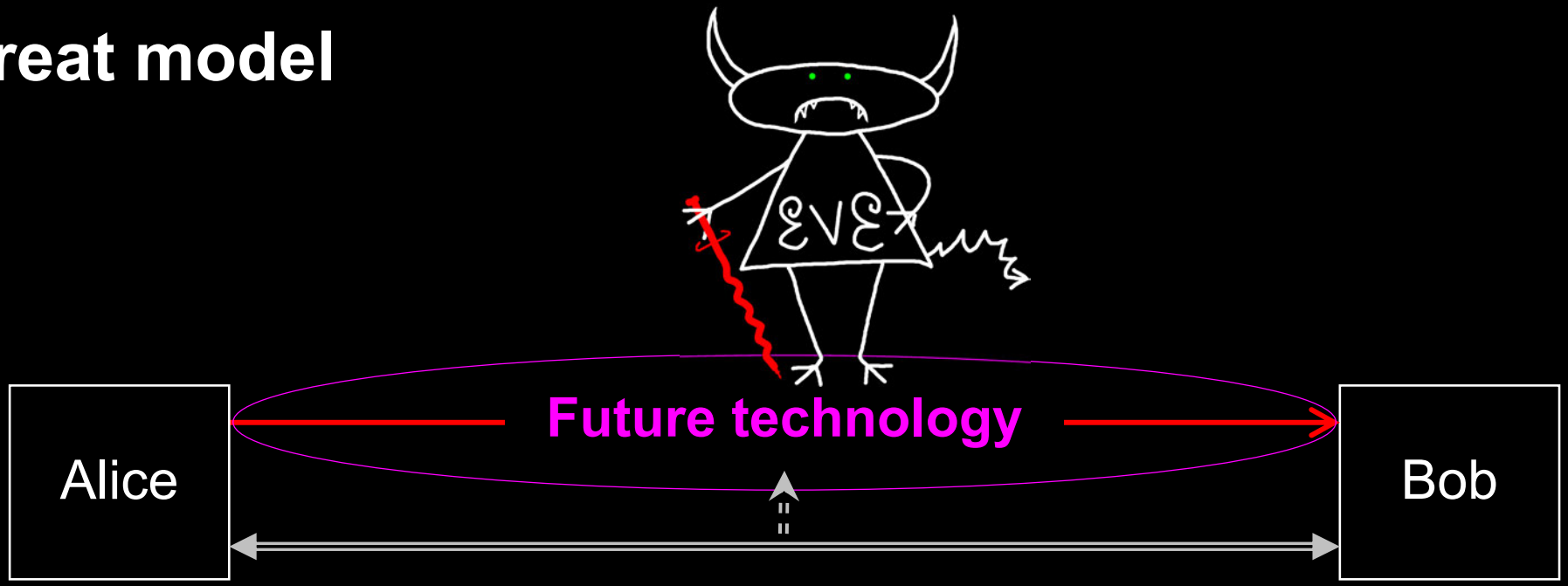



Hack

Integrate imperfection into security model

**Formal certification: we need standards and labs ecosystem**

# Threat model




**physically secure,**
**characteristics known**

**physically secure,**
**characteristics known**

**Kerckhoffs' principle:**

**Il faut qu'il n'exige pas le secret, et qu'il puisse sans inconvénient tomber entre les mains de l'ennemi**

A. Kerckhoffs, J. des Sciences Militaires **9**, 5 (1883)

**Everything about the system that is not explicitly secret is known to the enemy**

| Attack | Target component | Tested system |
|---|---|---|
| **Induced photorefraction**<br>P. Ye *et al.,* Phys. Rev. Appl. **19**, 054052 (2023); F.-Y. Lu *et al.,* Optica **10**, 520 (2023); L. Han *et al.,* arXiv:2303.14683 | modulators in Alice | 7 components, research |
| **Uncertainty of state preparation**<br>A. Huang *et al.,* Phys. Rev. Appl. **19**, 014048 (2023) | Alice | 2 commercial systems |
| **Laser seeding**<br>A. Huang *et al.,* Phys. Rev. Appl. **12**, 064043 (2019); X.-L. Pang et al., Phys. Rev. Appl. **13**, 034008 (2020) | laser in Alice | 3 components |
| **Distinguishability of decoy states**<br>A. Huang *et al.,* Phys. Rev. A **98**, 012330 (2018) | laser in Alice | 3 research systems |
| **Intersymbol interference**<br>K. Yoshino *et al.,* npj Quantum Inf. **4**, 8 (2018); F. Grünenfelder *et al.,* Appl. Phys. Lett. **117**, 144003 (2020) | modulators in Alice | 2 research systems |
| **Laser damage**<br>V. Makarov *et al.,* Phys. Rev. A **94**, 030302 (2016); A. Huang *et al.,* Phys. Rev. Appl. **13**, 034017 (2020). | any | 5 commercial systems |
| **Spatial efficiency mismatch**<br>M. Rau *et al.,* IEEE J. Sel. Top. Quantum Electron. **21**, 6600905 (2015); S. Sajeed *et al.,* Phys. Rev. A **91**, 062301 (2015) | receiver optics | 2 research systems |
| **Pulse energy calibration**<br>S. Sajeed *et al.,* Phys. Rev. A **91**, 032326 (2015) | classical watchdog detector | ID Quantique |
| **Trojan-horse**<br>I. Khan *et al.,* presentation at QCrypt (2014) | phase modulator in Alice | SeQureNet |
| **Trojan-horse**<br>N. Jain *et al.,* New J. Phys. **16**, 123030 (2014); S. Sajeed *et al.,* Sci. Rep. **7**, 8403 (2017) | phase modulator in Bob | ID Quantique |
| **Detector saturation**<br>H. Qin, R. Kumar, R. Alleaume, Proc. SPIE 88990N (2013) | homodyne detector | SeQureNet |
| **Shot-noise calibration**<br>P. Jouguet, S. Kunz-Jacques, E. Diamanti, Phys. Rev. A **87**, 062313 (2013) | classical sync detector | SeQureNet |
| **Wavelength-selected PNS**<br>M.-S. Jiang, S.-H. Sun, C.-Y. Li, L.-M. Liang, Phys. Rev. A **86**, 032310 (2012) | intensity modulator | (theory) |
| **Multi-wavelength**<br>H.-W. Li *et al.,* Phys. Rev. A **84**, 062308 (2011) | beamsplitter | research system |
| **Deadtime**<br>H. Weier *et al.,* New J. Phys. **13**, 073024 (2011) | single-photon detector | research system |
| **Channel calibration** | single-photon detector | ID Quantique |

| Attack | Target component | Tested system |
|---|---|---|
| H. Weier *et al.,* New J. Phys. **13**, 073024 (2011) | | |
| **Channel calibration**<br>N. Jain *et al.,* Phys. Rev. Lett. **107**, 110501 (2011) | single-photon detector | ID Quantique |
| **Faraday-mirror**<br>S.-H. Sun, M.-S. Jiang, L.-M. Liang, Phys. Rev. A **83**, 062331 (2011) | Faraday mirror | (theory) |
| **Detector control**<br>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 systems |
| **Phase-remapping**<br>F. Xu, B. Qi, H.-K. Lo, New J. Phys. **12**, 113026 (2010) | phase modulator in Alice | ID Quantique |
| **Time-shift**<br>Y. Zhao *et al.,* Phys. Rev. A **78**, 042333 (2008) | single-photon detector | ID Quantique |
| **Efficiency mismatch**<br>V. Makarov, A. Anisimov, J. Skaar, Phys. Rev. A **74**, 022313 (2006) | single-photon detector | 2 components |
| **Avalanche backflash**<br>C. Kurtsiefer *et al.,* J. Mod. Opt. **48**, 2039 (2001); A. Meda et al., Light Sci. Appl. 6, e16261 (2017); P. Pinheiro *et al.,* Opt. Express 26, 21020 (2018); | single-photon detector | 3 components, research |
| **Photon-number splitting**<br>C. Bennett *et al.,* J. Cryptology **5**, 3 (1992); G. Brassard *et al.,* Phys. Rev. Lett. **85**, 1330 (2000) | laser in Alice | (theory) |

# Example of vulnerability and countermeasures

## Photon-number-splitting attack

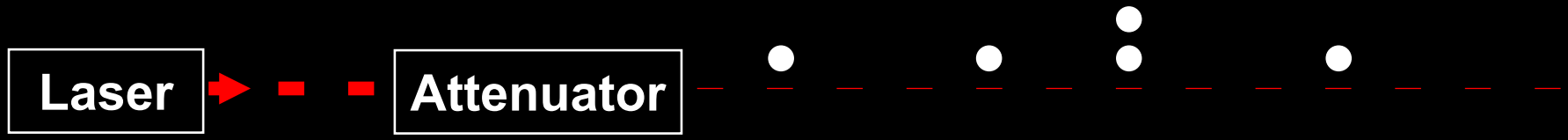
C. Bennett, F. Bessette, G. Brassard, L. Salvail, J. Smolin, J. Cryptology **5**, 3 (1992)

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)

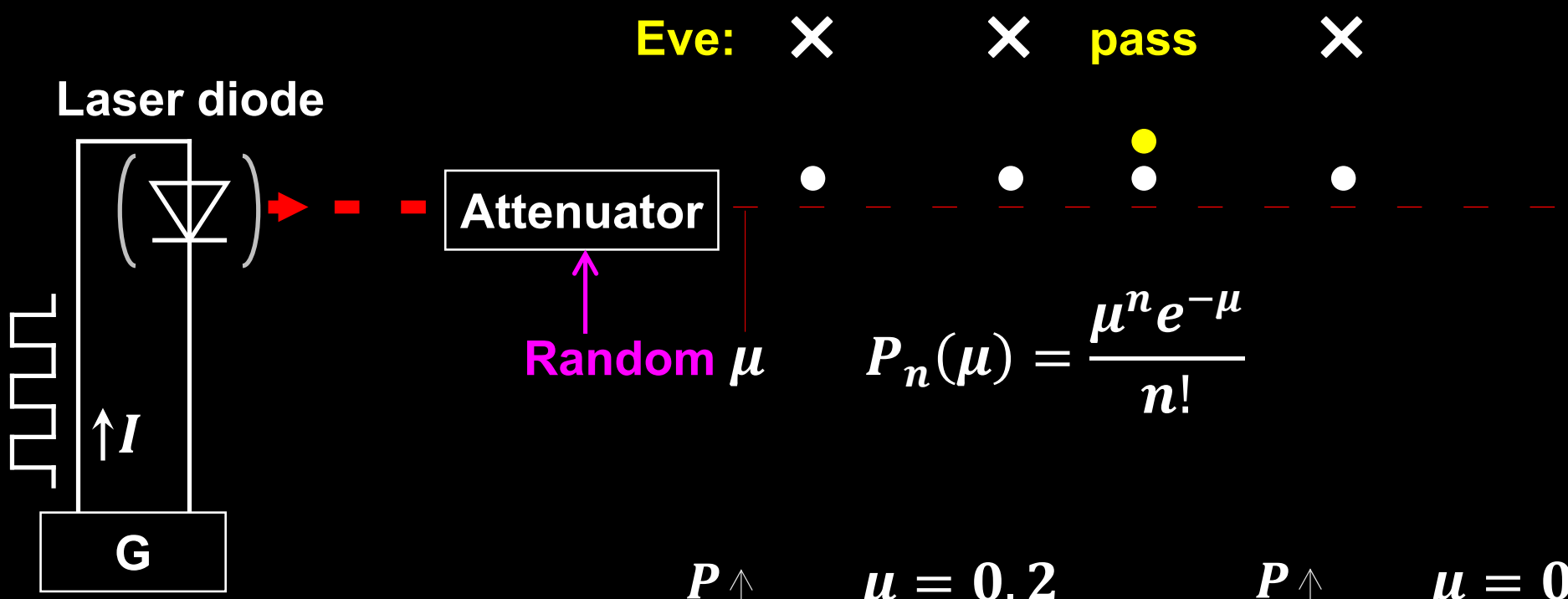
## ★ Distributed-phase-reference protocols

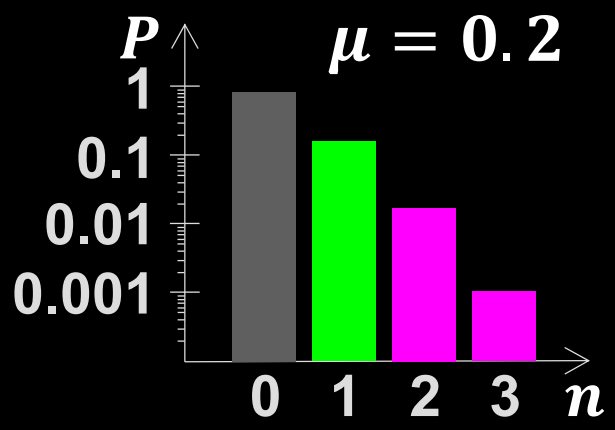
K. Inoue, E. Waks, Y. Yamamoto, Phys. Rev. Lett. **89**, 037902 (2002)

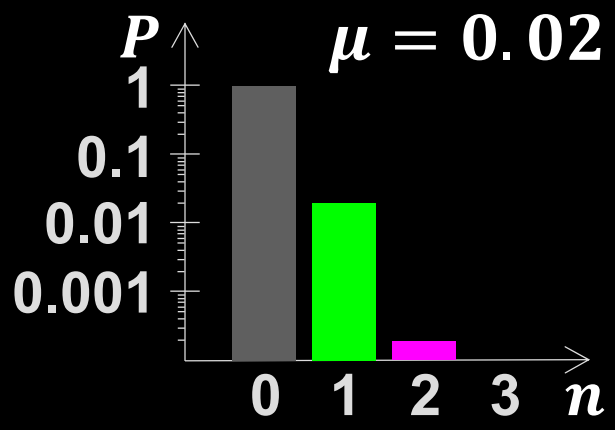
K. Inoue, E. Waks, Y. Yamamoto, Phys. Rev. A. **68**, 022317 (2003)

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

# Decoy-state protocol




Eve: blocks less

blocks more

S. J. van Enk, C. A. Fuchs, arXiv:quant-ph/0111157; W.-Y. Hwang, Phys. Rev. Lett. 91, 057901 (2003)

# Commercial QKD

1st generation (circa 2008)
ID Quantique *Cerberis* system

**Classical encryptors:**

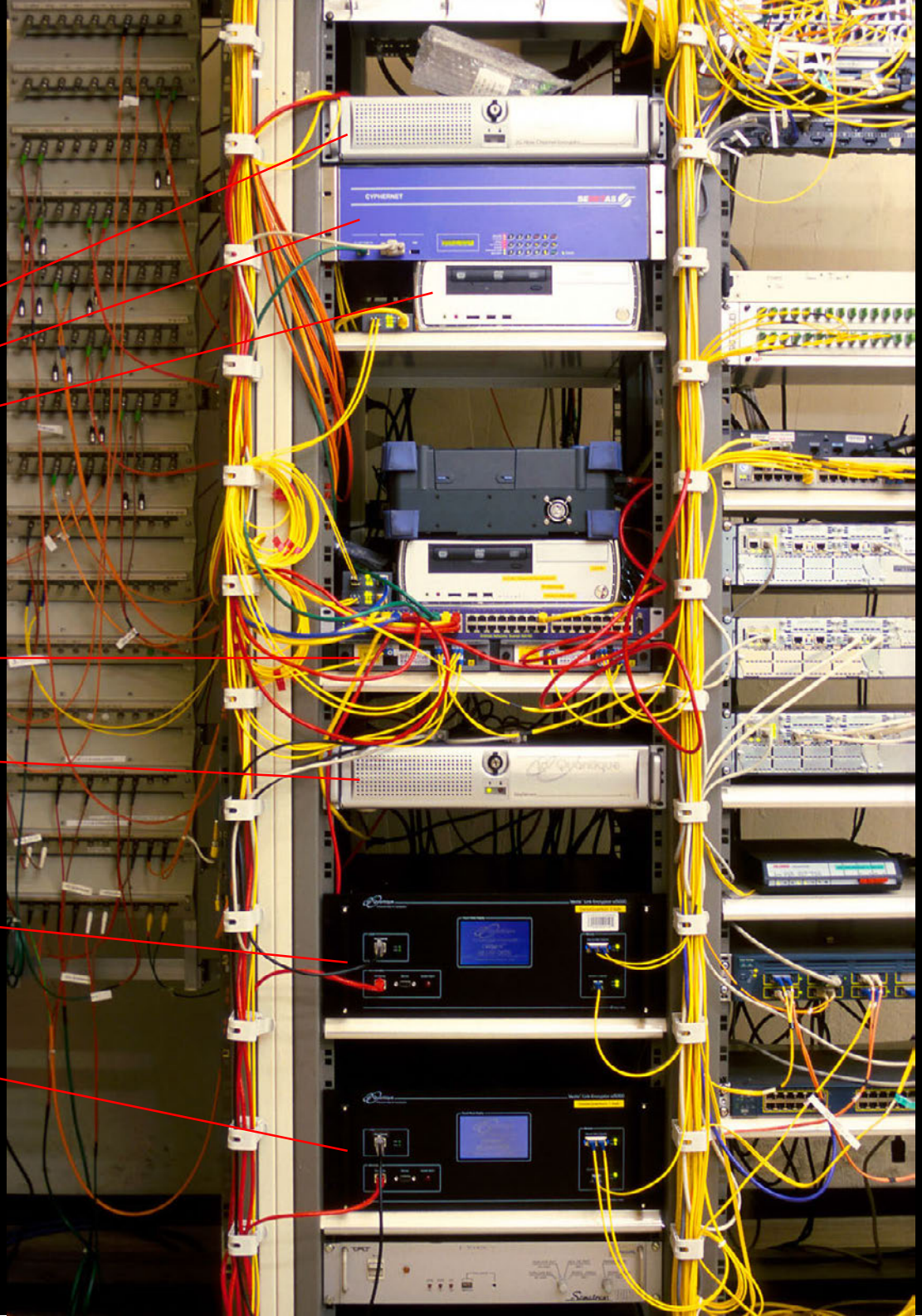
L2, 2 Gbit/s
L2, 10 Gbit/s
L3 VPN, 100 Mbit/s

**WDMs**

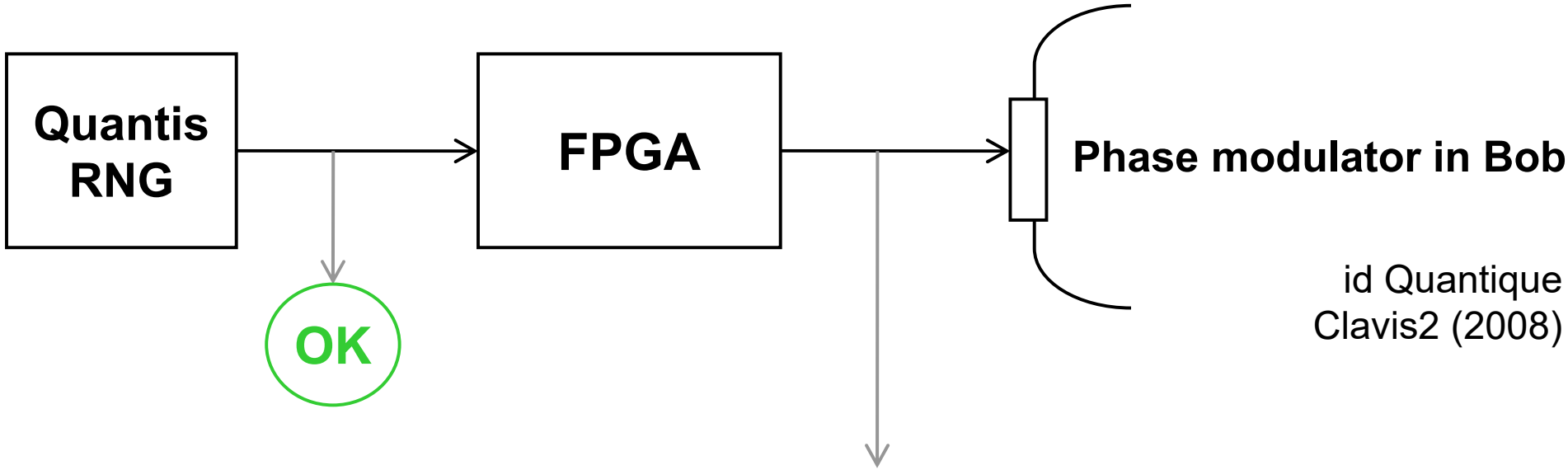
**Key manager**

**QKD** to another node (4 km)

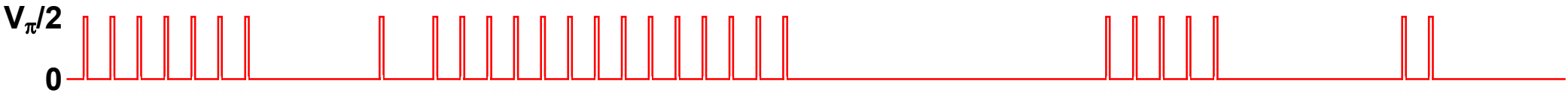
**QKD** to another node (14 km)



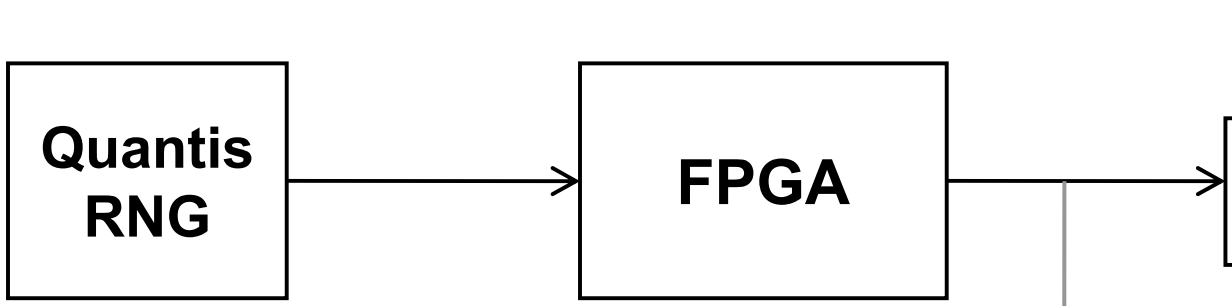
# True randomness?



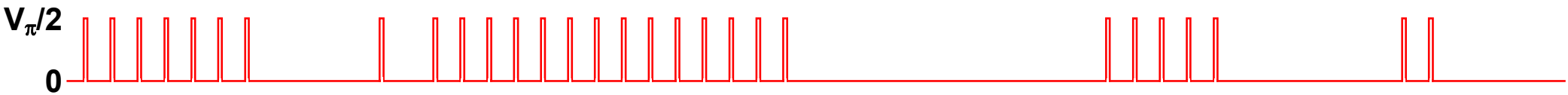

id Quantique
Clavis2 (2008)



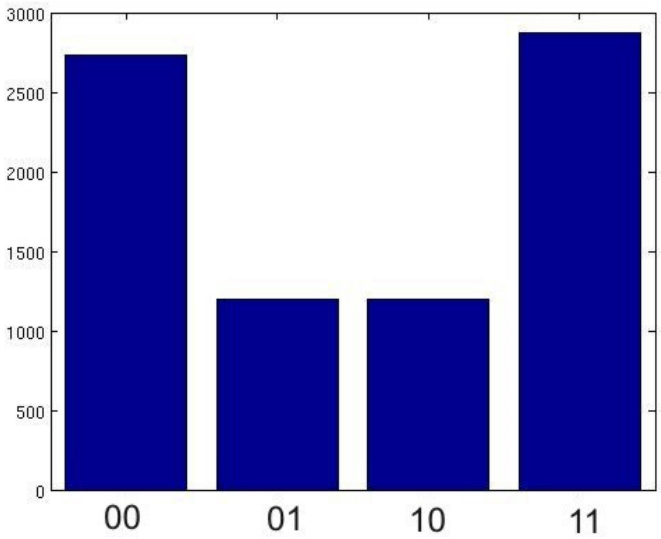

# True randomness?



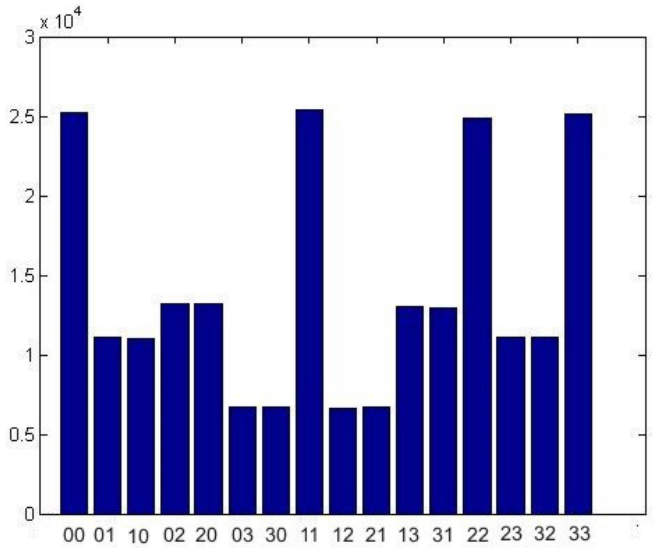

id Quantique
Clavis2 (2008)




**Bob:**



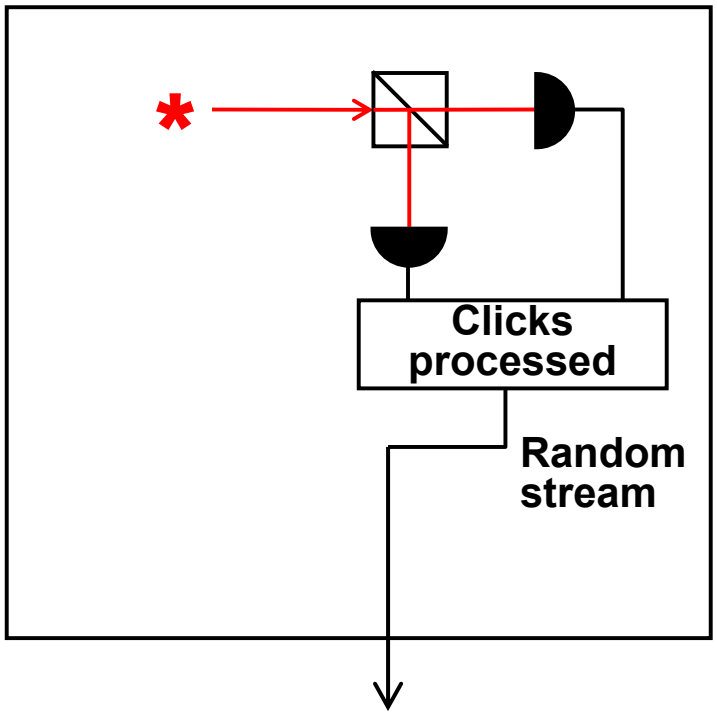

**Alice:**



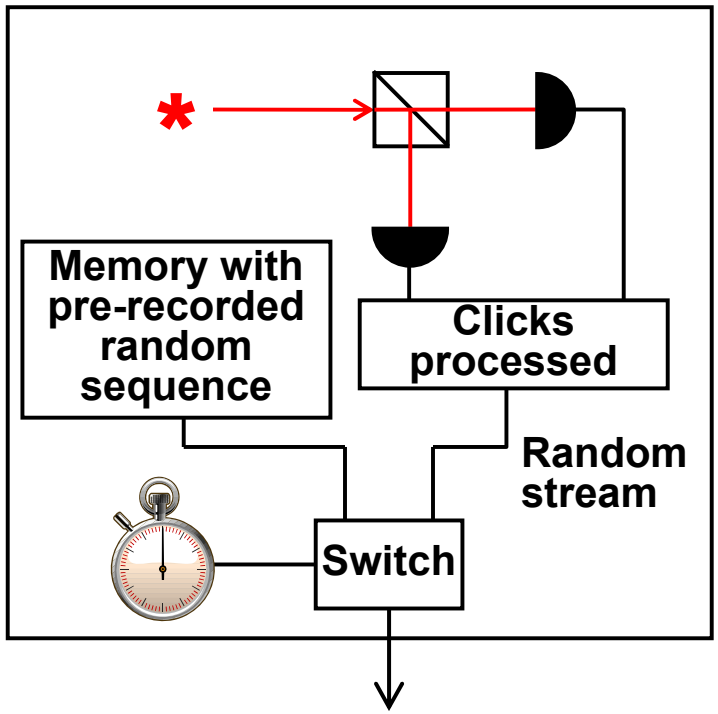

**Issue reported patched in 2010**

# Do we trust the manufacturer?

Quantis RNG



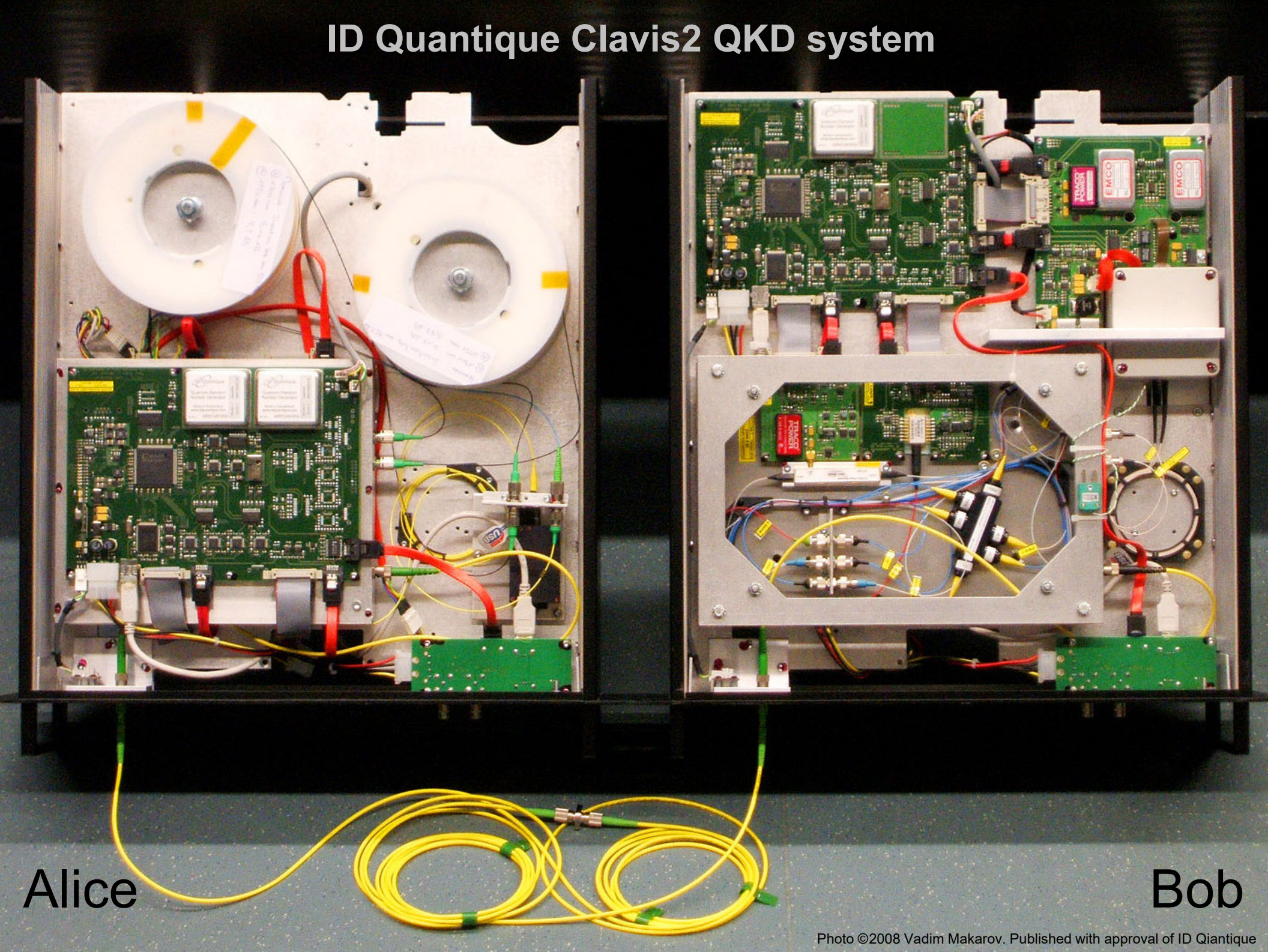

Quantis RNG, Trojan-horsed :)




**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

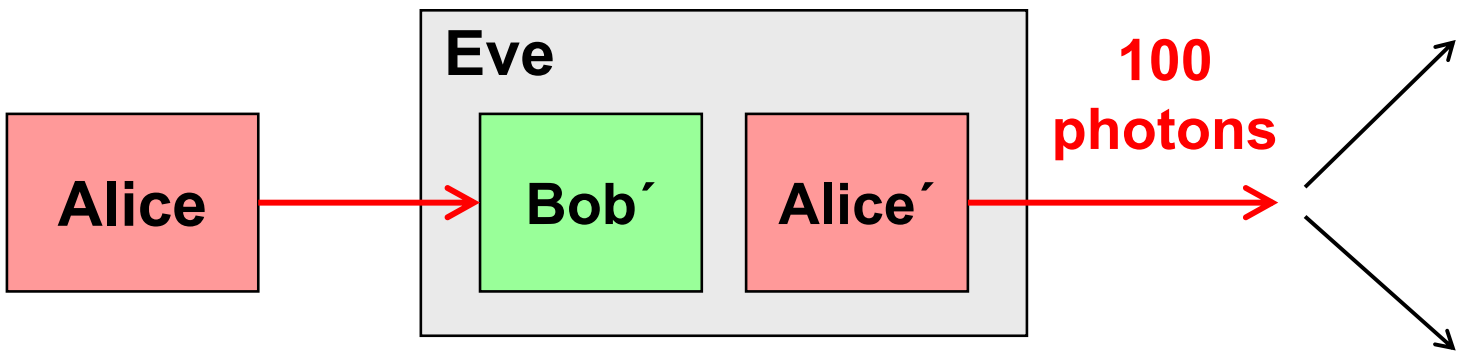


# Double clicks

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

Discard them?

Intercept-resend attack... with a twist:




**Bob:**

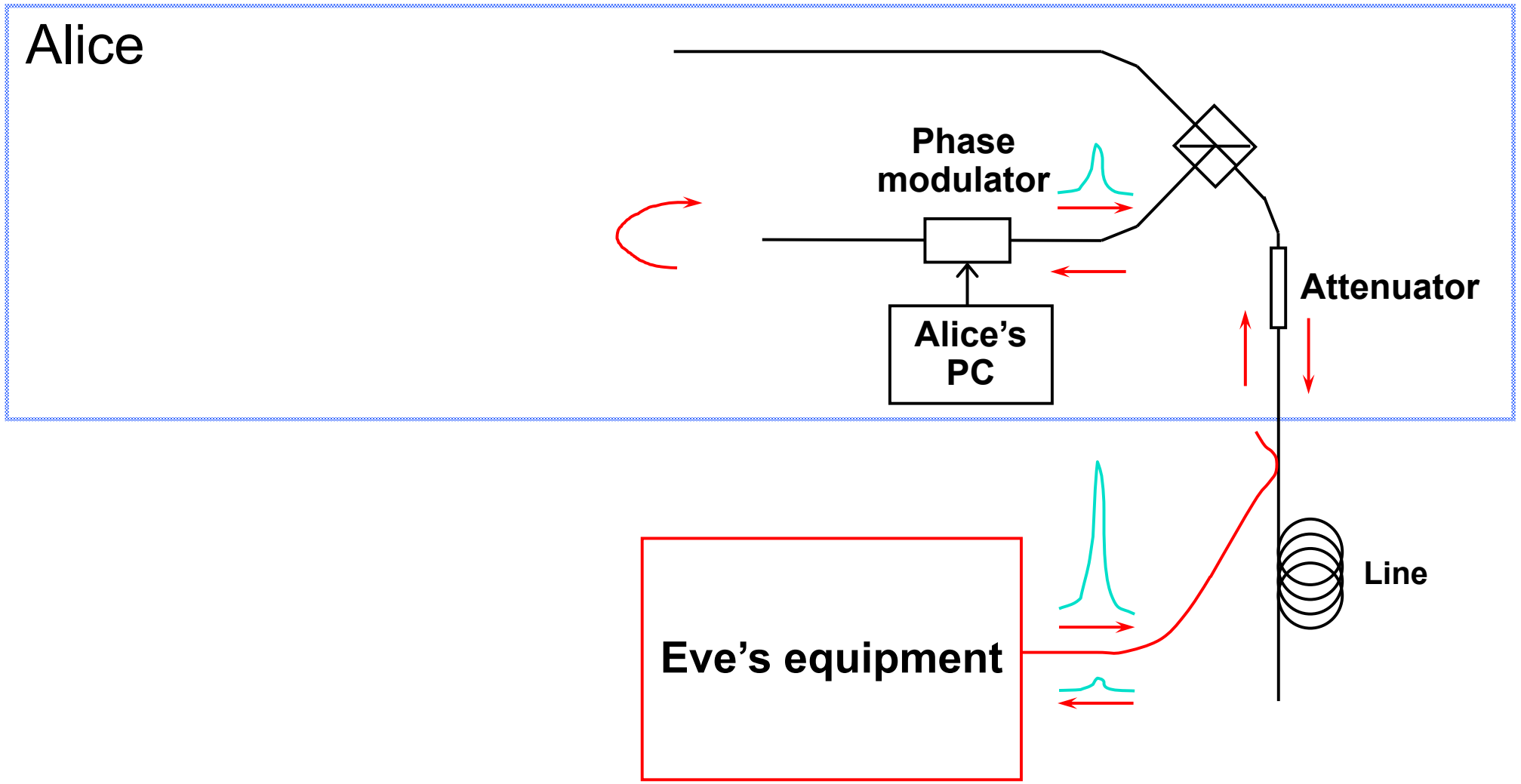
Detects in Eve's basis: single click

Detects in conjugate basis: double click, discarded

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

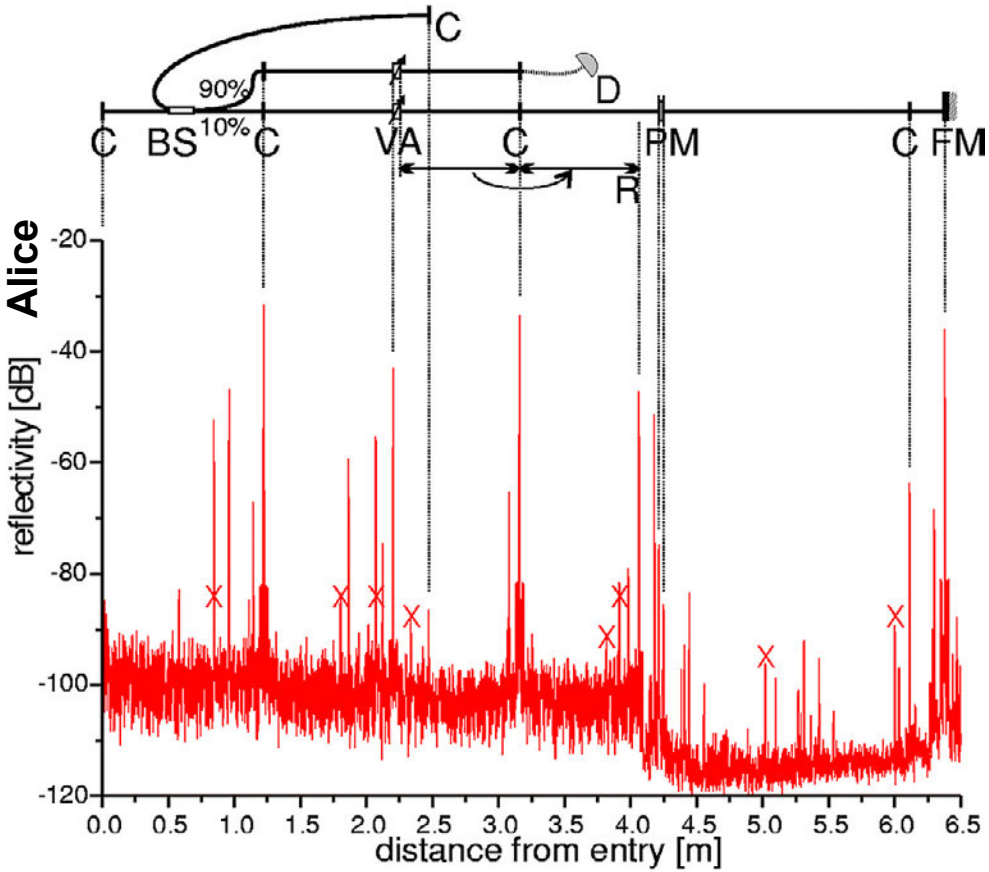
N. Lütkenhaus, Phys. Rev. A **59**, 3301 (1999)
T. Tsurumaru & K. Tamaki, Phys. Rev. A **78**, 032302 (2008)

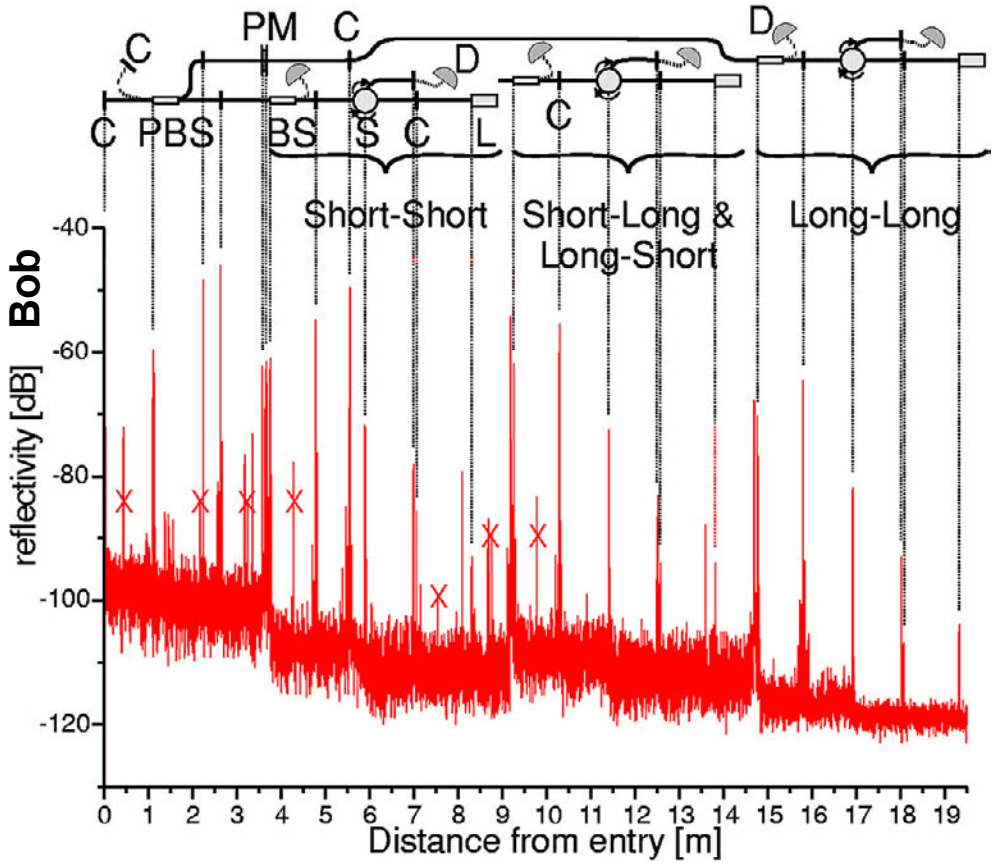
# Trojan-horse attack




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

# Trojan-horse attack for plug-and-play system

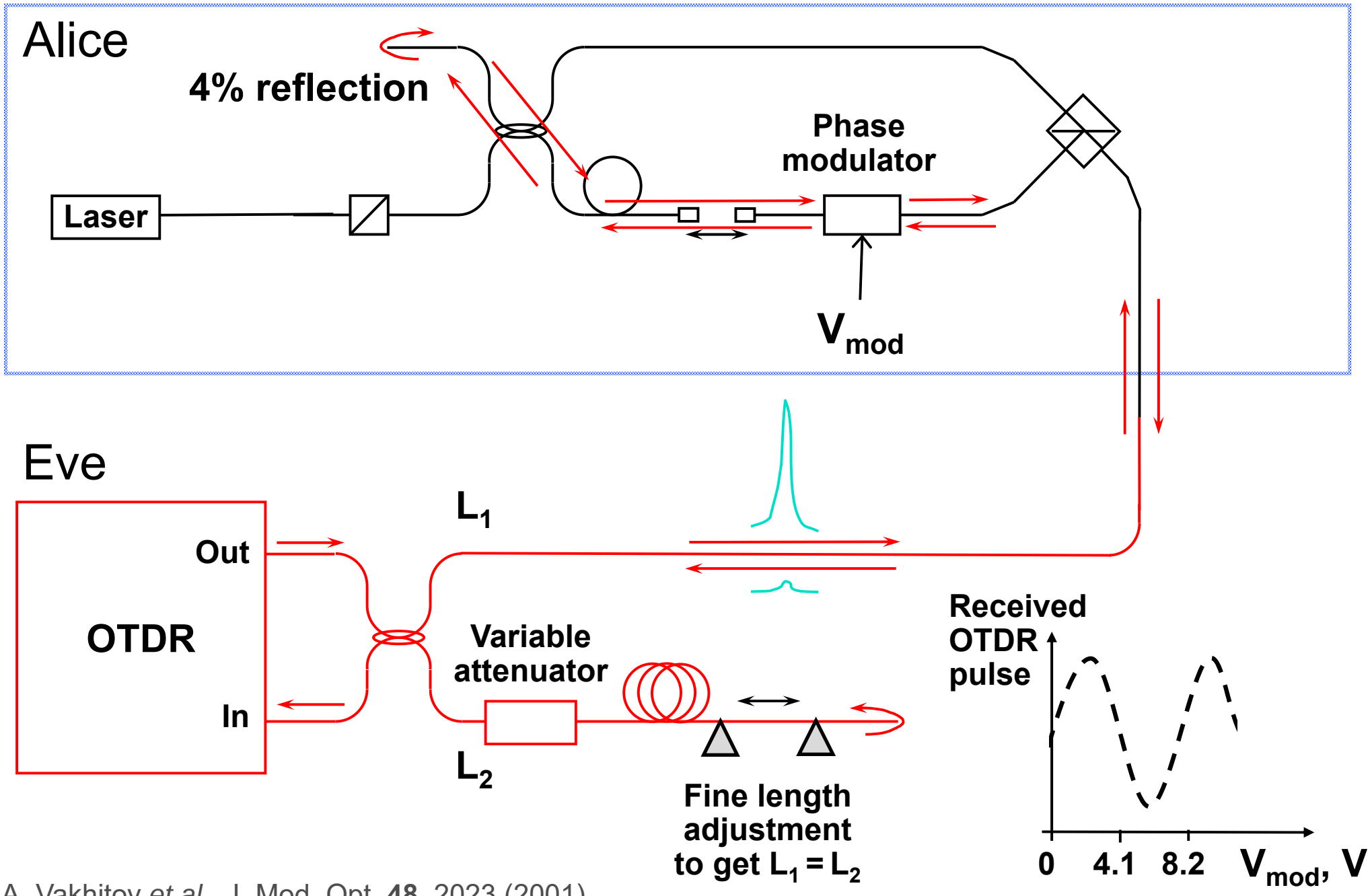



**Eve gets back one photon → in principle, extracts 100% information**

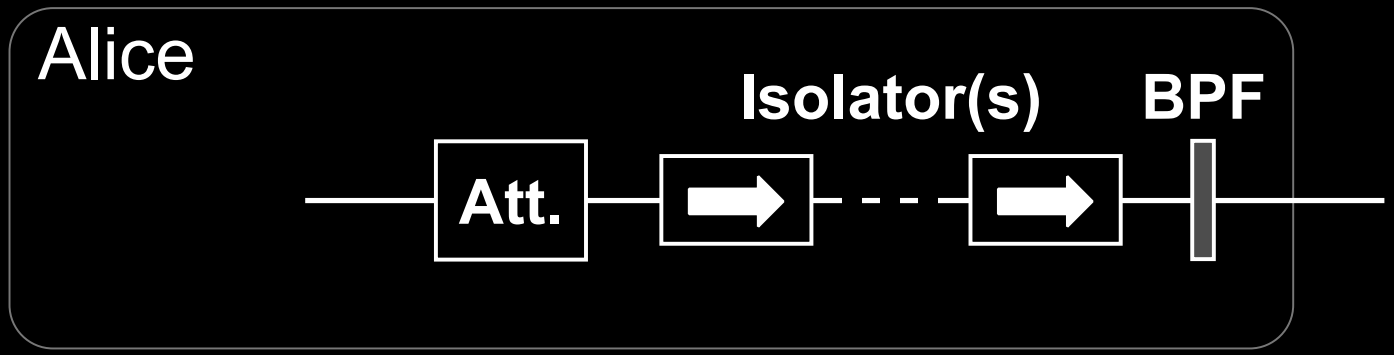
N. Gisin *et al.*, Phys. Rev. A **73**, 022320 (2006)

# Trojan-horse attack experiment




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

# Draft security standard @ ETSI: Trojan-horse in one-way system




M. Lucamarini *et al.*, Phys. Rev. X **5**, 031030 (2015)