# Quantum Technologies: a new frontier in cyber-security

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# Summary

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1 Quantum Key Distribution
- Introduction to QKD
- Our recent achievements

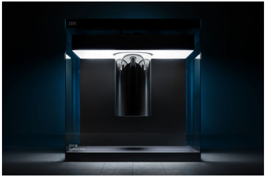
2 Quantum Random Number Generators

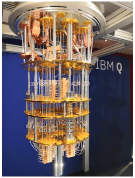
3 Conclusions

# Summary

# Possible issues with classical cryptography

- Classical cryptography is based on (currently) hard computational problems
- Breakthrough in classical algorithm can broke security
- Quantum computer will broke some classical cryptograpic scheme (RSA)






- Post-Quantum crypto

# QKD: quantum key distribution

- A novel approach for unconditionally secure communications: Security based on physics and not on **computational complexity**

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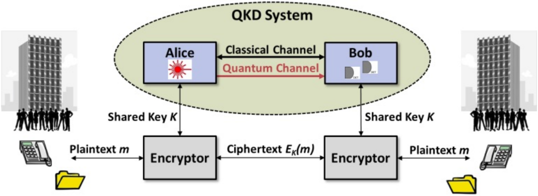
# QKD: quantum key distribution

- A novel approach for unconditionally secure communications: Security based on physics and not on **computational complexity**
- Exploit quantum mechanics laws for establishing secure keys
- Single photon transmission to create keys and classical channel for send encrypted message



# OpenQKD


- Develop an experimental testbed based on QKD and to test the interoperability of equipments
- Preparation of the future pan-European QKD infrastructure
- Over 25 use-case trials already been determined and will be complimented by open calls.

# One time pad

The best method to encrypt a message is the One-Time-Pad (OTP) protocol: for a $n$-bit message, a $n$-bit secure key is needed

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| message | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |

$$\oplus$$

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| random key | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 |

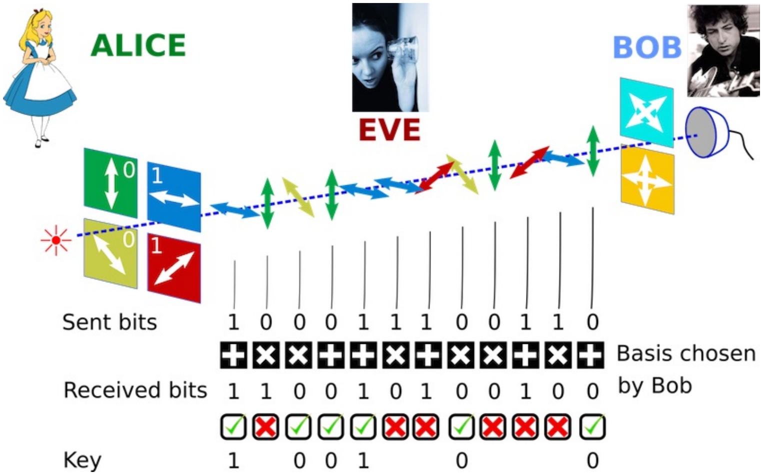
$$=$$

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| encrypted message | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |

Quantum key distribution (QKD) allows two users to exchange random and secret keys

# QKD in a nutshell

BB84 protocol



# Secret key rate

QKD can achieve unconditional security



V. Scarani, *et al.*, *The security of practical quantum key distribution*, **Rev. Mod. Phys. 81, 1301 (2009)**

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$$\left.\begin{array}{l}\text{▶ two non-commuting basis}\\ \text{▶ no-cloning theorem}\\ \text{▶ any measurement (generally) perturbs the systems}\end{array}\right\} \Rightarrow \text{Eve detection!}$$



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Secret key rate related to **Quantum Bit Error Rate** $Q$:

$$\boxed{r = 1 - 2h_2(Q)}$$

with

$$h_2(Q) = -Q\log_2(Q) - (1-Q)\log_2(1-Q)$$



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If Eve is gaining information on the key, the key is discarded: no information on the secret message



V. Scarani, *et al.*, *The security of practical quantum key distribution*, **Rev. Mod. Phys. 81, 1301 (2009)**

# Real life implementation: decoy state

Are true single photon sources necessary?



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- Use a classical laser attenuated to the single photon level.

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# Real life implementation: decoy state

Are true single photon sources necessary?
NO, if the decoy state method is implemented

- Use a classical laser attenuated to the single photon level.
- Modulate the intensity and


choose randomly between three possible values of the pulse mean photon number $\mu$ of the laser:

1. $\mu_1 = 0.5$
2. $\mu_2 = 0.1$
3. $\mu_3 = 0$

 V. Scarani, *et al.*, *The security of practical quantum key distribution*, **Rev. Mod. Phys. 81, 1301 (2009)**

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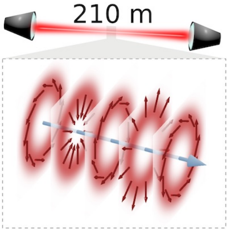
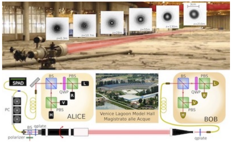
V. Scarani, *et al.*, *The security of practical quantum key distribution*, **Rev. Mod. Phys. 81, 1301 (2009)**

# Long distance free-space quantum communication

**Phys. Rev. Lett. 113, 060503 (2014)**

Rotation invariant QKD by OAM



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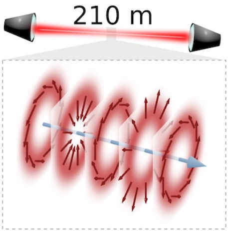


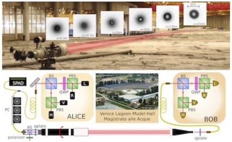


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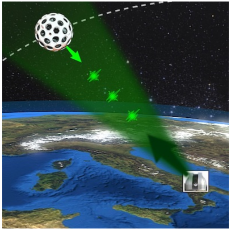
Experimental satellite quantum communication



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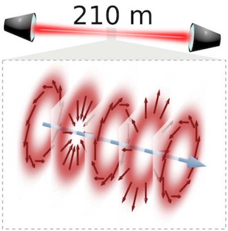


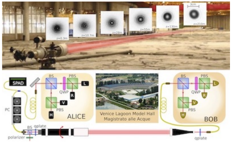


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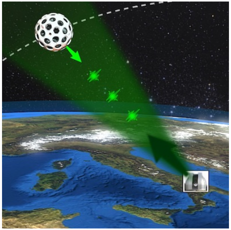
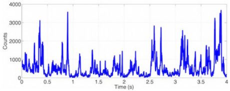
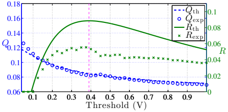


**Phys. Rev. A 91, 042320 (2015)**

Mitigating turbulence in free-space QKD

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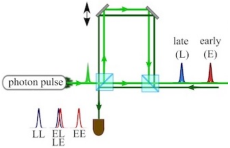
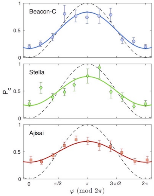
Single photon interference in space channels



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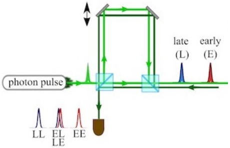
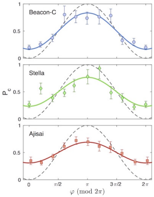
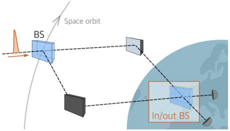
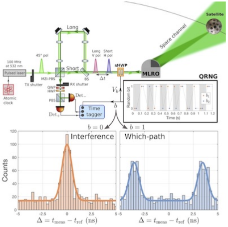



**Science Advances 3, e1701180 (2017)**

Wheeler's delayed choice in space



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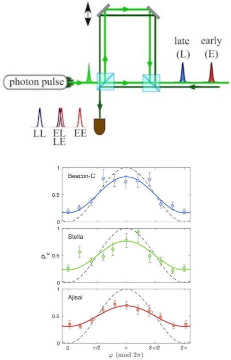


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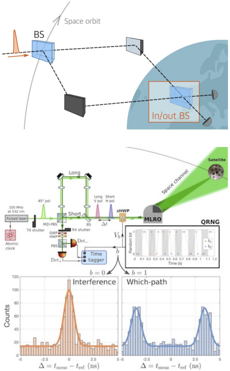
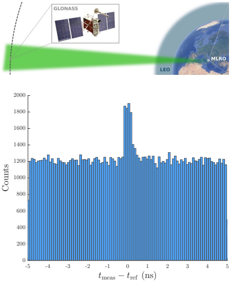


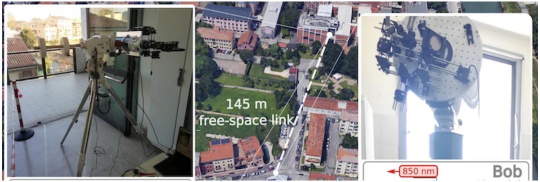

**Quantum Science and Tech. 4, 015012 (2019)**

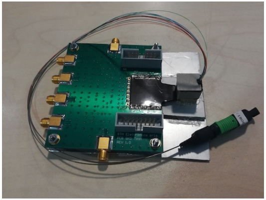
Single-photon exchange with GNSS satellite (20000 km)

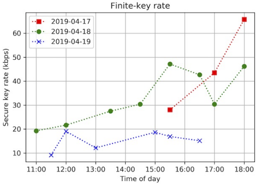


# Daylight operation of free-space QKD

M. Avesani, *et. al.*, **[arXiv:1907.10039]**



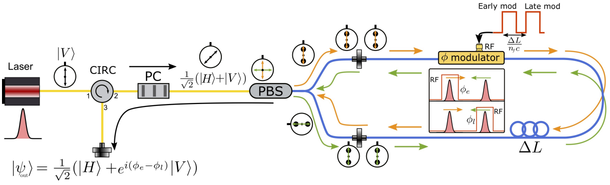



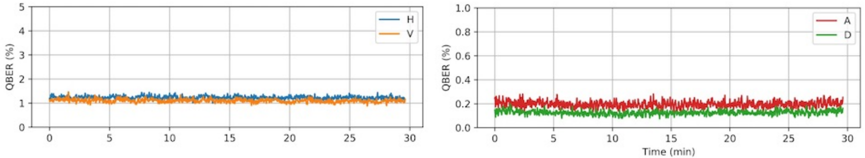


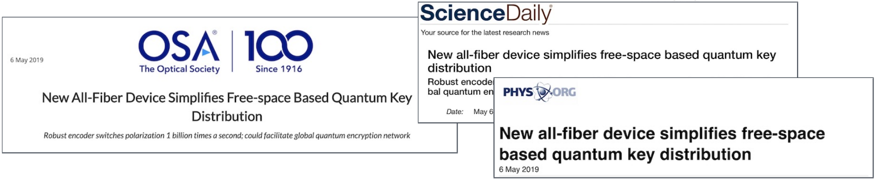

- QKD from 11:00 to 18:00. Full daylight
- Photonic integrated chip source

# Quantum state encoder

## POGNAC = POlarization saGNAC



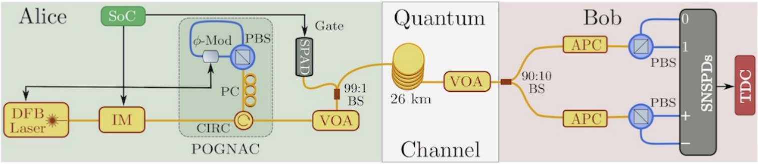



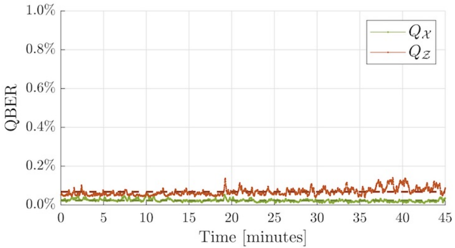



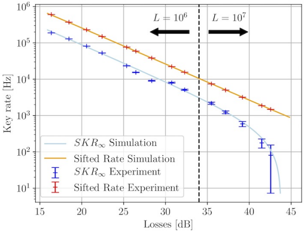



C. Agnesi, *et. al.* **Optics Letters 44, 2398 (2019)**

# Test with fiber-link



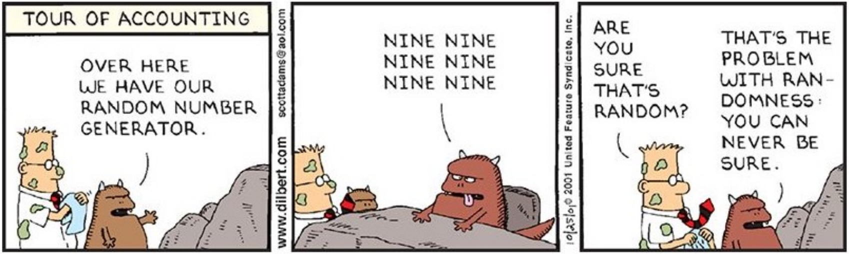

- Lowest intrinsic QBER ever reported (<0.07%)


C. Agnesi, *et. al.* **[arXiv: 1909.12703]**

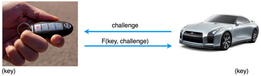
# Summary

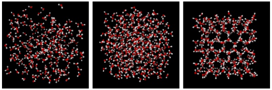
# What is a random number

A random number is a number generated by an unpredictable process



# Why random numbers?

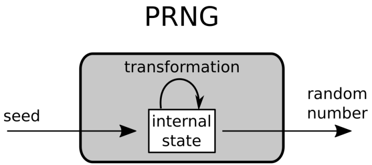



Random numbers are crucial in several applications:

1. Information technology and security (also QKD)
2. Scientific simulation (meteorology, biology, physics...)
3. Lottery/gaming

# Pseudo Random Number Generators




Pseudo-random numbers are generated by a deterministic algorithm that produces a sequence that "resemble" a random sequence

## PROS

- simple
- fast

## CONS

- period
- not-uniformity
- correlations

# but....

## Von Neumann (1903-1957)

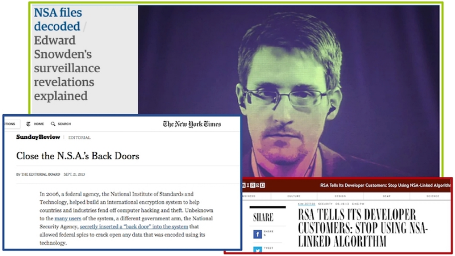
(among the father of information theory

*"Anyone who attempts to generate random numbers by deterministic means is, of course, living in a state of sin"*

# Flaws in PRNG!

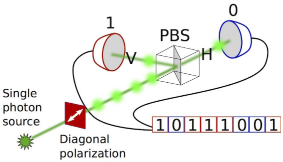
## NSA (National Security Agency) scandal

NSA inserted a “backdoor" in the generator Dual_EC_DRBG certified by NIST




Dual_EC_DRBG was used in several RSA products. In 2013, RSA officially discouraged his clients to use their products with Dual_EC_DRBG.

# Why QRNG?




- RANDOM NUMBERS are needed to encrypt all digital communications (email, social networks) and are essential for QKD

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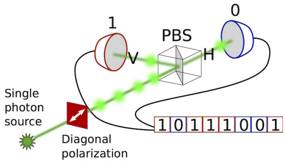


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What QRNG offer:

- intrinsic randomness of quantum measurements

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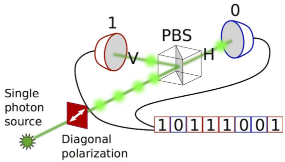


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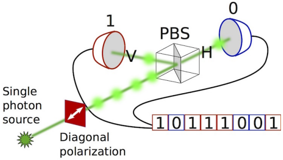


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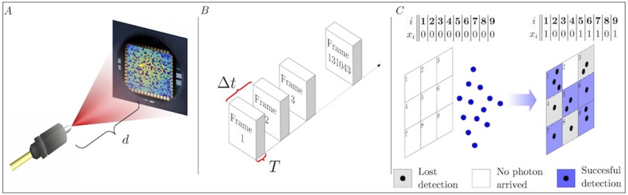
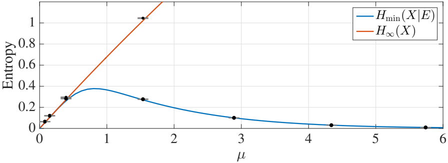
What QRNG offer:

- intrinsic randomness of quantum measurements
- outputs not predictable even if the initial state is known
- randomness is not due to ignorance on the initial conditions (like coin tossing)

# Photon position: single-photon camera QRNG



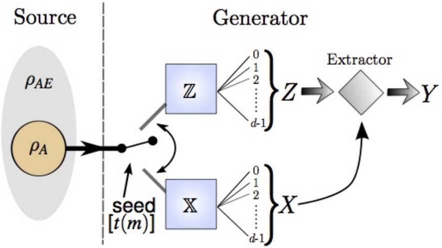

- The eavesdropper knows the number of photons emitted by the source
- Detection inefficiency modeled by perfect detectors activated, with probability $\eta$, by the eavesdropper





D.G. Marangon, GV, U. Zanforlin, P. Villoresi, **Quantum Sci. Technol. 1, 015005 (2016)**

# QRNG certified




- $Z$ is the random sequence
- $X$ is the sequence used to evaluate the randomness in $Z$.
- $Y$ is the final random sequence

$$H_{\min}(Z|E) \geq \log_2 d - \log_2 [\sum_x \sqrt{p_x}]^2$$

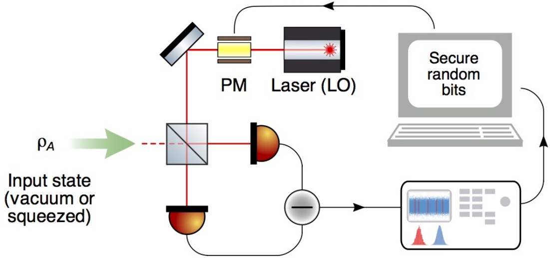
$$\Downarrow$$

$$P_{\text{guess}}(Z) \leq \frac{1}{d} (\sum_x \sqrt{p_x})^2$$



GV, D. Marangon, M. Tomasin, P. Villoresi, **Phys. Rev. A 90, 052327 (2014)**

# Source-device-independent QRNG with CV




Switch between two conjugate quadratures $\hat{p}$ and $\hat{q}$



D. G. Marangon, GV, P. Villoresi, **Phys. Rev. Lett. 118, 060503 (2017)**

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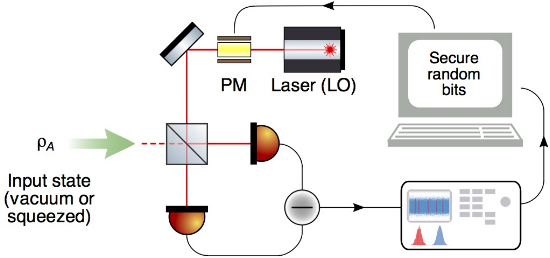
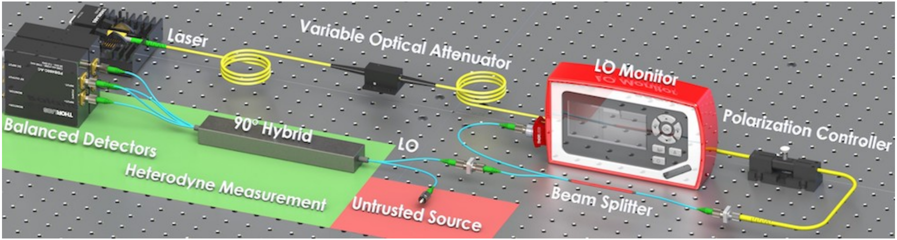



Switch between two conjugate quadratures $\hat{p}$ and $\hat{q}$

Secure bit generation rate of approximately 1.76 Gbit/s


D. G. Marangon, GV, P. Villoresi, **Phys. Rev. Lett. 118, 060503 (2017)**

# QRNG based on heterodyne




Secure heterodyne-based QRNG at 17 Gbps


M. Avesani, D. G. Marangon, G. Vallone, P. Villoresi, **Nature Communications 9, 5365 (2018)**

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- QKD is able to generate unconditional secure keys between two users
- QKD guarantees forward security: protect critical infrastructure for long time in the future
- QRNGs guarantees unpredictability of the generated numbers by physical laws
- QKD and QRNG could be employed in all classical security algorithm (xoring technique)

# The group

## FACULTY


P. Villoresi


G. Vallone

## POST-DOC


F. Vedovato

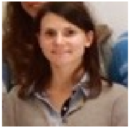

L. Calderaro


A. Stanco

## PHD

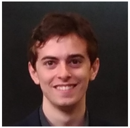

C. Agnesi


M. Avesani


A. Scriminich


H. Tebyanian


L. Zahidy


G. Foletto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THANK YOU FOR
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QuantumFuture
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