EURAMET

EURAMET European Metrology Network for Quantum Technologies: Quantum Metrology and Single Photon Detector calibration

Ivo Pietro DEGIOVANNI

EMN-Q Chair & INRIM

QUANTUM TECHNOLOGIES

ISSW 2022

The International SPAD Sensor Workshop

Outline

Quantum metrology

- … as **quantum enhanced measurements**

- … according to **metrologists**

- … for **quantum technologies**

Paradigmatic example:

Single-photon Detectors calibration

A coherent European effort: ***EMN-Quantum***

QUANTUM TECHNOLOGIES

Quantum Enhanced Measurement

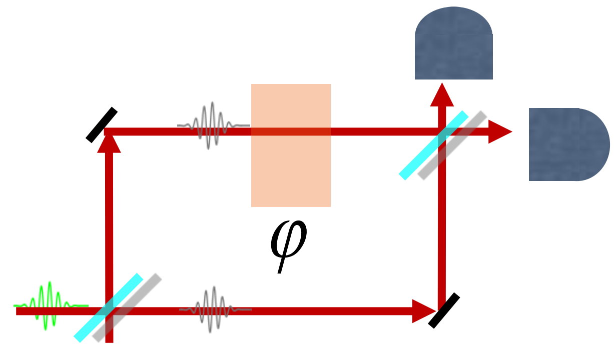
Quantum Metrology, Imaging and Sensing with photons

The Shot-Noise Limit

- **phase**

-Interferometry

-GW detectors

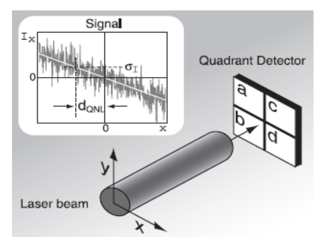


$$\Delta\varphi_{min} \approx \frac{1}{\sqrt{N}}$$

- **Displacement:**

-lithography

-beams, particles tracking



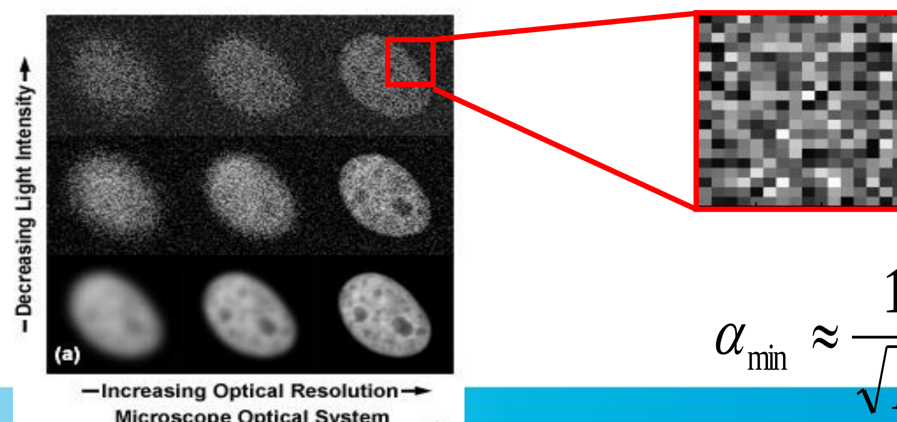
$$X_R \approx \lambda \frac{f}{D} \qquad \Delta x_{min} \approx \frac{X_R}{\sqrt{N}}$$

- **Absorption/reflection:**

-Imaging

-microscopy

-Target recognition



$$\alpha_{min} \approx \frac{1}{\sqrt{N}}$$

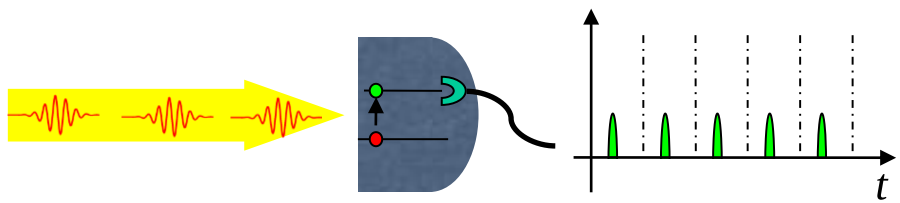
Quantum Enhanced Measurement

Quantum Metrology, Imaging and Sensing with photons

However quantum mechanics predicts existence of quantum states of light which allow to beat the shot-noise limit

Fock state $|N\rangle$

Single photon source : $|1\rangle$

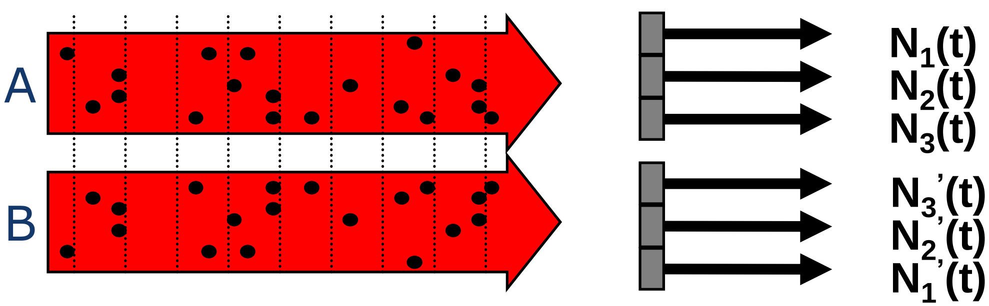


$$\Delta N \approx 0!!!$$

non-classical correlation and entanglement :

Twin beam:

$$\left|\Psi_{AB}^{(TWB)}\right\rangle = \prod_{\mathbf{k}} \left[\sum_{n} C_{\mathbf{k}}(n)\, |n_{\mathbf{k}}\rangle_A |n_{-\mathbf{k}}\rangle_B \right]$$



$$\sigma = \frac{Var(N_i - N'_i)}{\langle N_i + N'_i \rangle} < 1$$

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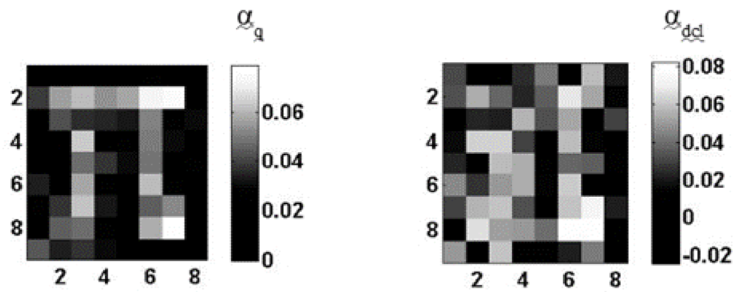
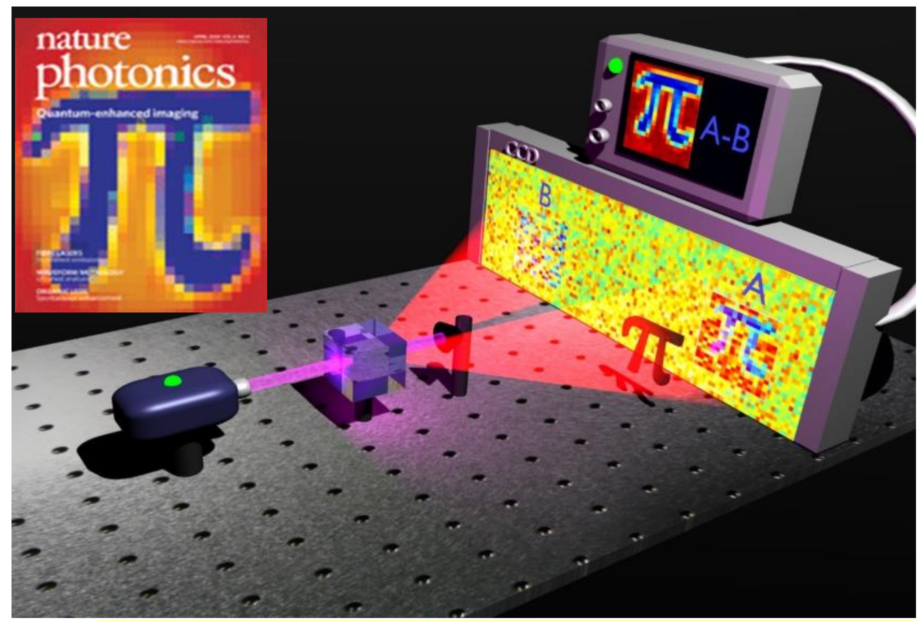
Quantum Enhanced Measurement

Quantum Metrology, Imaging and Sensing with photons

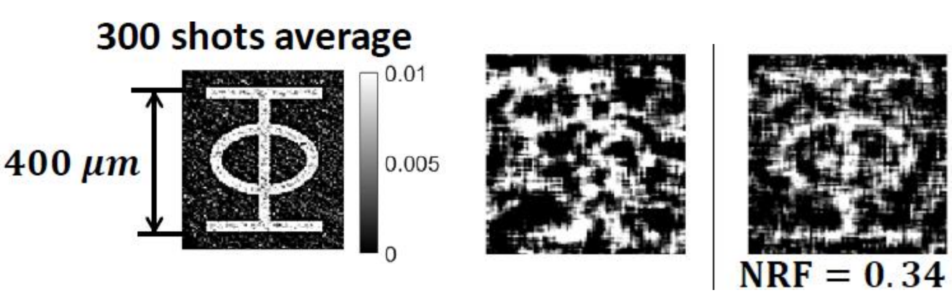
Sub-Shot Noise Imaging

Beating the shot-noise with quantum light





Wide-Field Sub-Shot Noise Microscope



5 μm resolution

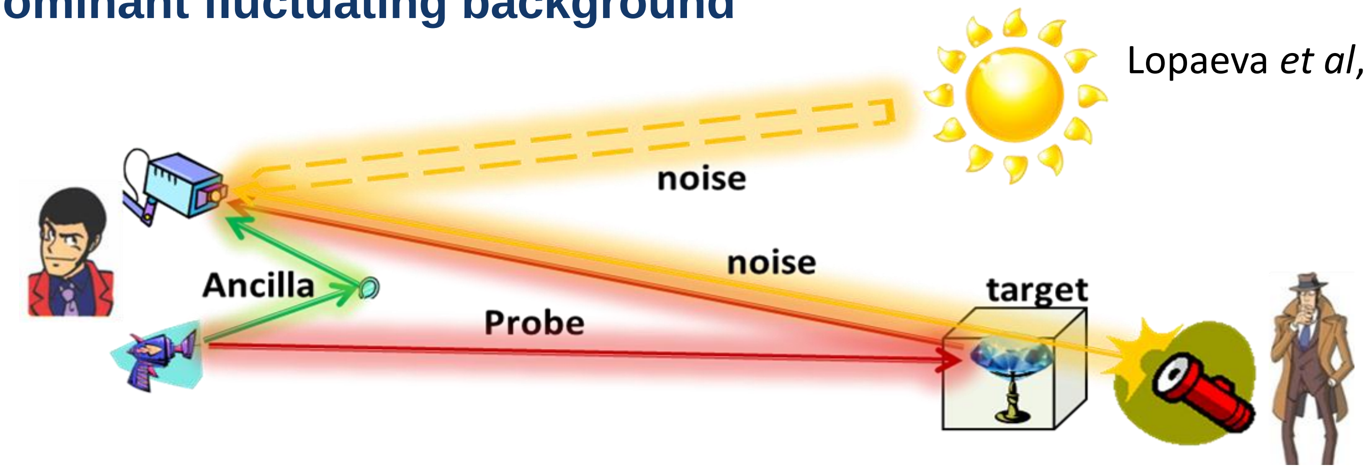
Light S&A 6, e17005 (2017)

Quantum Enhanced Measurement

Quantum Metrology, Imaging and Sensing with photons

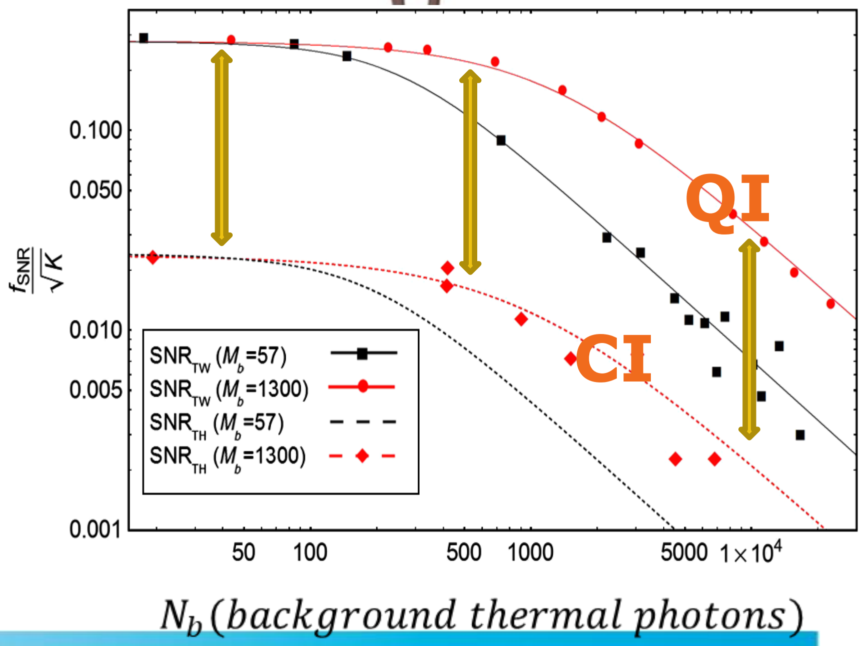
Problem: detection of a partially reflecting target which is immersed in a dominant fluctuating background

Lopaeva *et al*, PRL 110, 153603 (2013)



Quantum illumination takes advantage of an ancillary beam, quantum correlated /entangled with the probe, by a joint measurement of the two.

- ✓ **Large quantum enhancement!**
- ✓ **Independent of noise and losses!**
- ✓ **Non-classical signature does not survive the noise**



Quantum Metrology... according to metrologists

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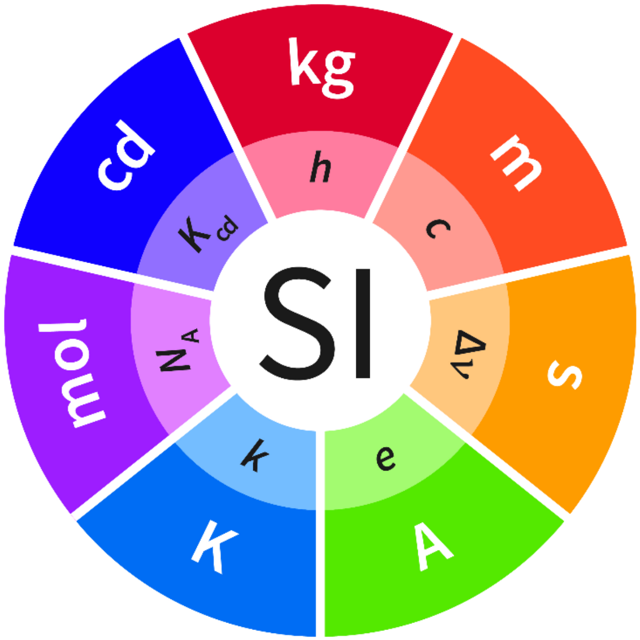
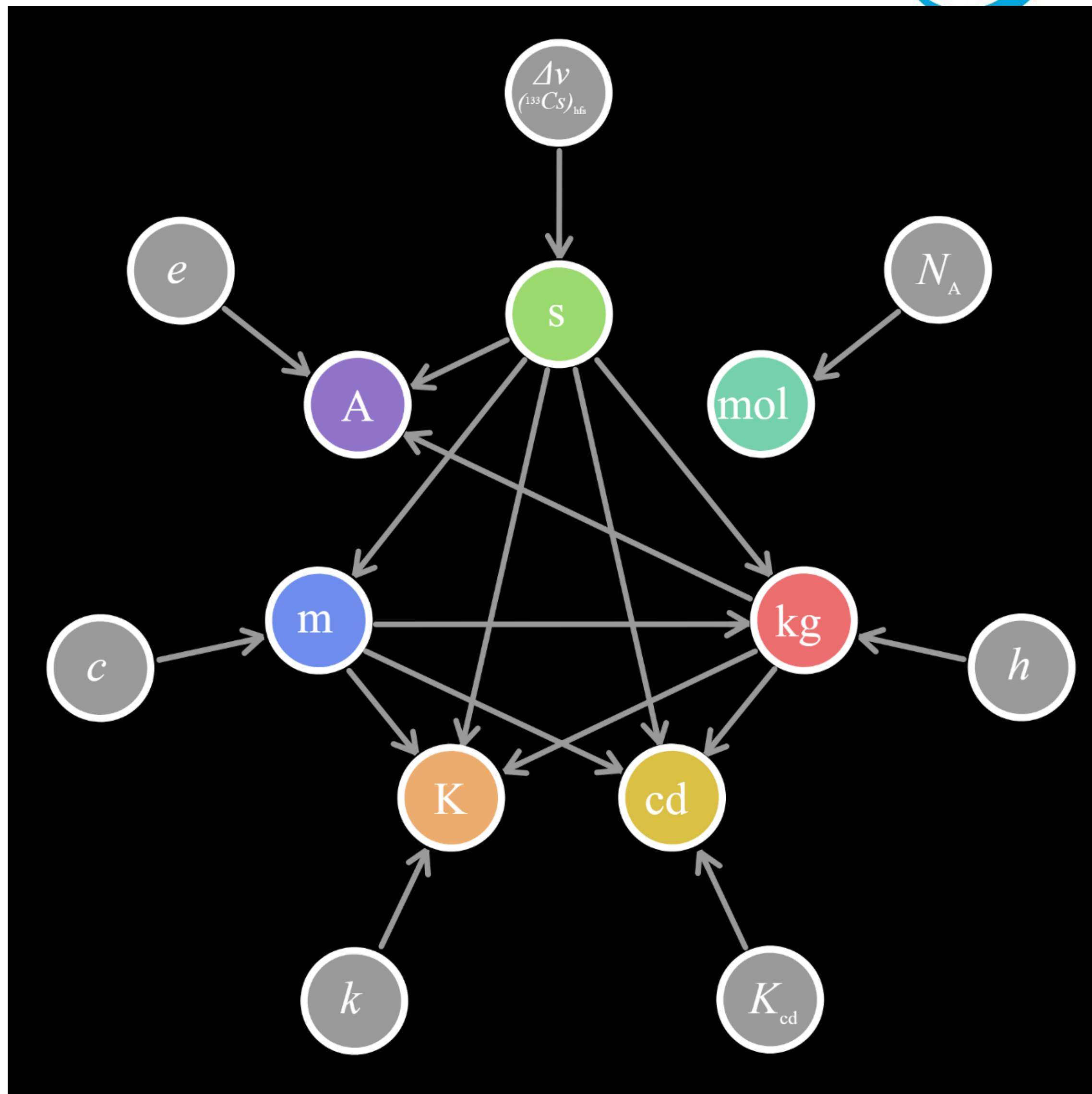
The New SI ...



November 2018

26th General Conference on Weights and Measures (CGPM)



Quantum Metrology… according to metrologists

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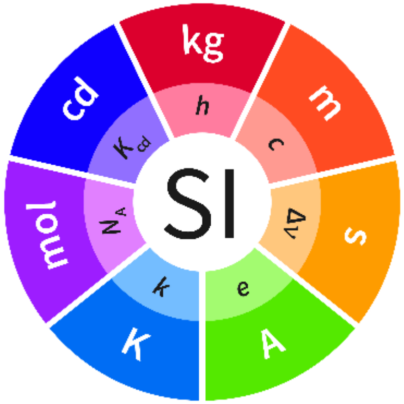
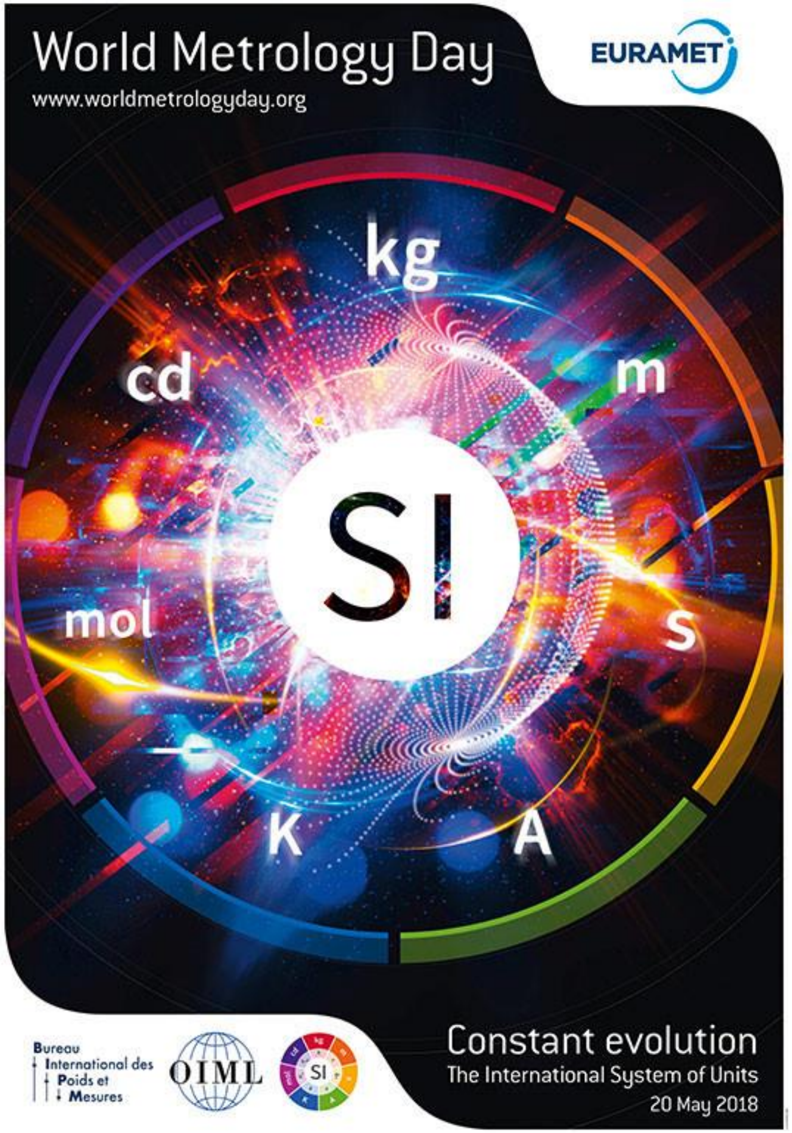
*The **SI** and **its defined units** are not static.*

*The progress in science, in particular in the area of laser physics, quantum optics, solid-state physics, and nanotechnology, has now paved the way for an upcoming fundamental **revision of the SI**.*

*The physics and technology behind the **new SI** definitions and their realization is (mostly) **quantum**.*



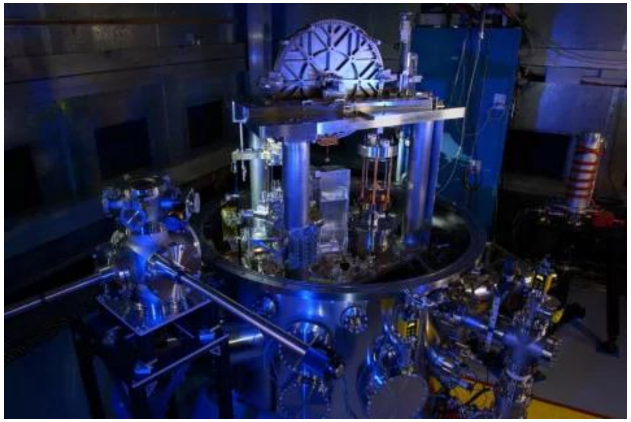


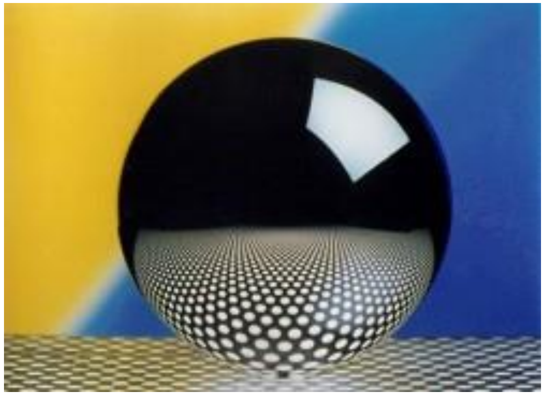
INRIM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

Quantum Metrology... according to metrologists

The kilogram* is defined in terms of the *Planck constant

Kibble balance used to calculate Planck's constant.

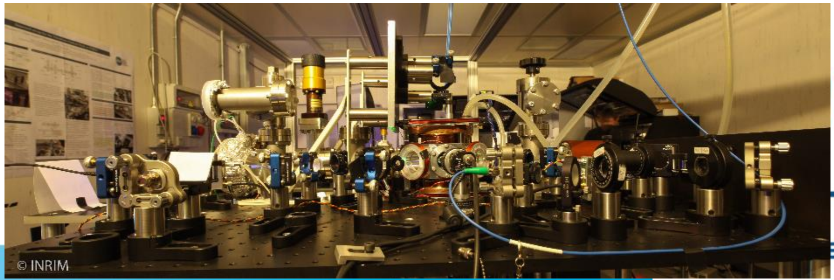




Avogadro sphere (X-ray crystal density) used to estimate the Plank's constant

***The second* *is* defined in terms of the hyperfine transition frequency of the caesium 133 atom**

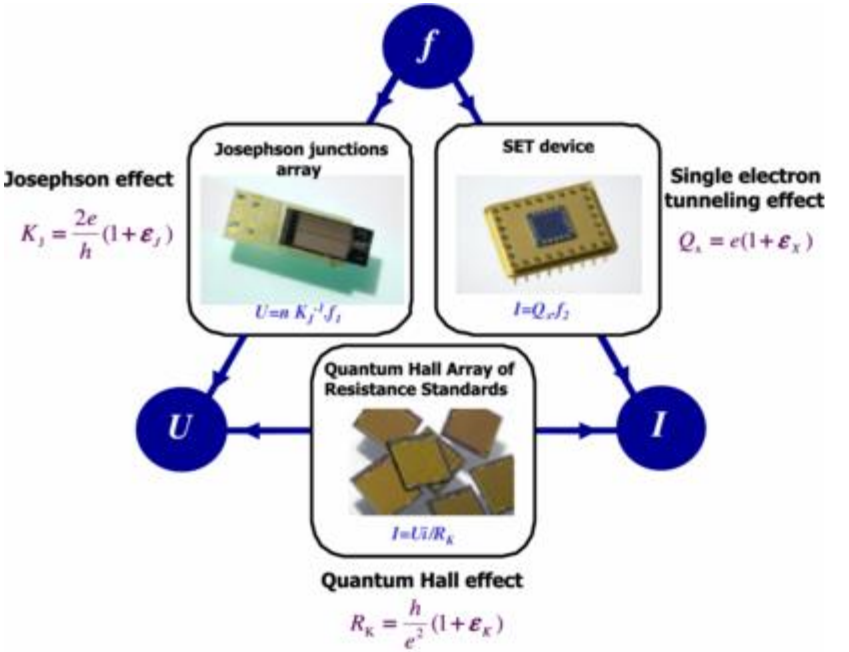
Optical Atomic clock



Quantum Metrology... according to metrologists

The Ampere* is defined in terms of the *electron charge

***Quantum metrological triangle**: Ohm's law with the three quantum electrical effects: the Josephson effect (JE), the quantum Hall effect (QHE) and the single-electron tunnelling effect (SET)*



***The Mole* is defined in terms of NA**

***The Kelvin* is be defined in terms of Boltzmann's constant**

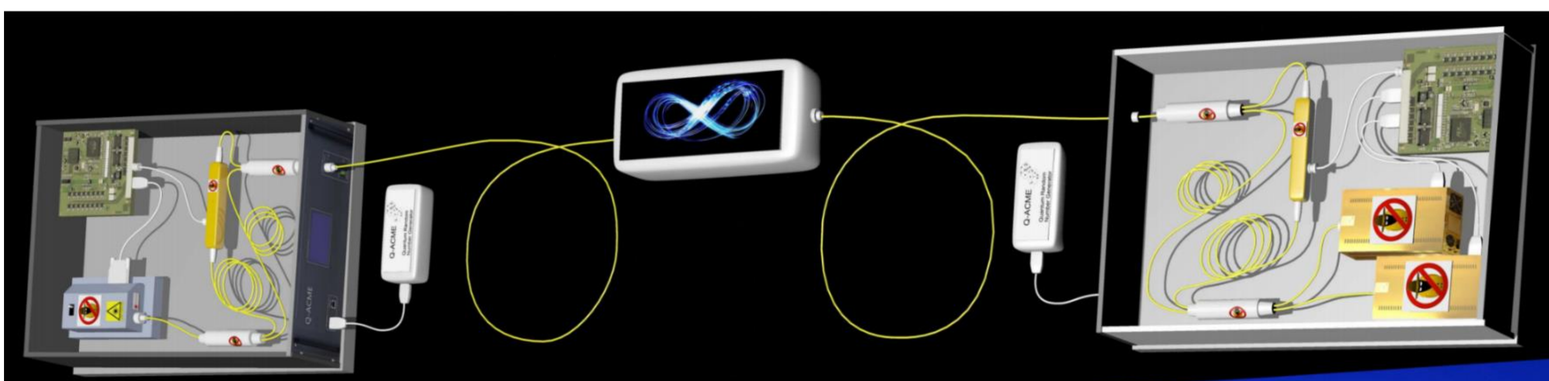
***The Candela** is* defined in terms of K_{cd} constant

QUANTUM TECHNOLOGIES

Q-Metrology for Q-Communication

An Industry Specification Group (ISG) of the European Telecommunications Standards Institute (ETSI) has been installed from October 2008 to address standardization issues in QKD, to support the commercialization of QKD devices on various levels and stages.

Quantum Radiometry is **necessary** to the standardization framework for providing traceable characterization techniques at single-photon level.



Q-Metrology for Q-Communication

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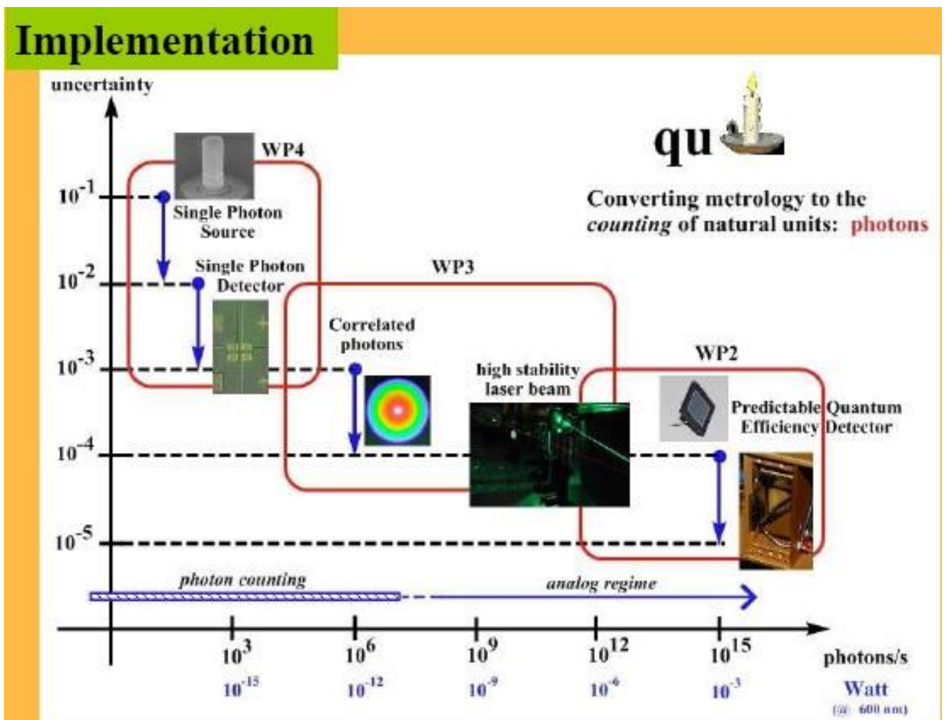
Quantum Radiometry: Effort to create a linkage between the typical optical power measurement regime of conventional radiometry and the single-photon counting regime



NPL National Physical Laboratory

PTB

CMI

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

MIKES

Justervesenet

METROSERT

EURAMET European Association of National Metrology Institutes

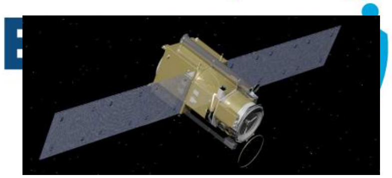
iMERA PLUS

EMRP European Metrology Research Programme
Programme of EURAMET

QUANTUM TECHNOLOGIES

Q-Metrology for Q-Communication

Projects on single-photon metrology

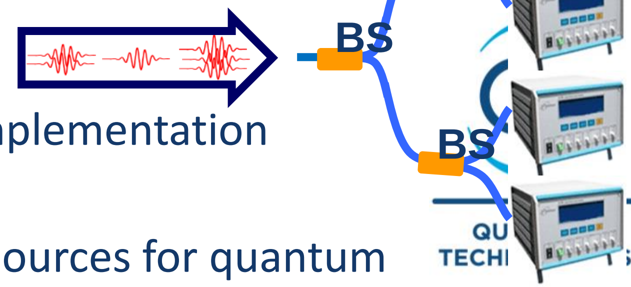


Project Coordinator: **INRIM**
Quantum Candela: radiometric measurements in the natural units, the number of photons

SIQUTE
Project Coordinator: **PTB**
Deterministic and efficient single-photon sources for quantum metrology

Project Coordinator: **INRIM**
Metrology for Quantum Key Distribution (QKD) in fiber

Project Coordinator: **INRIM**
Metrology for free-space QKD and Anti-"Quantum-Hacking"



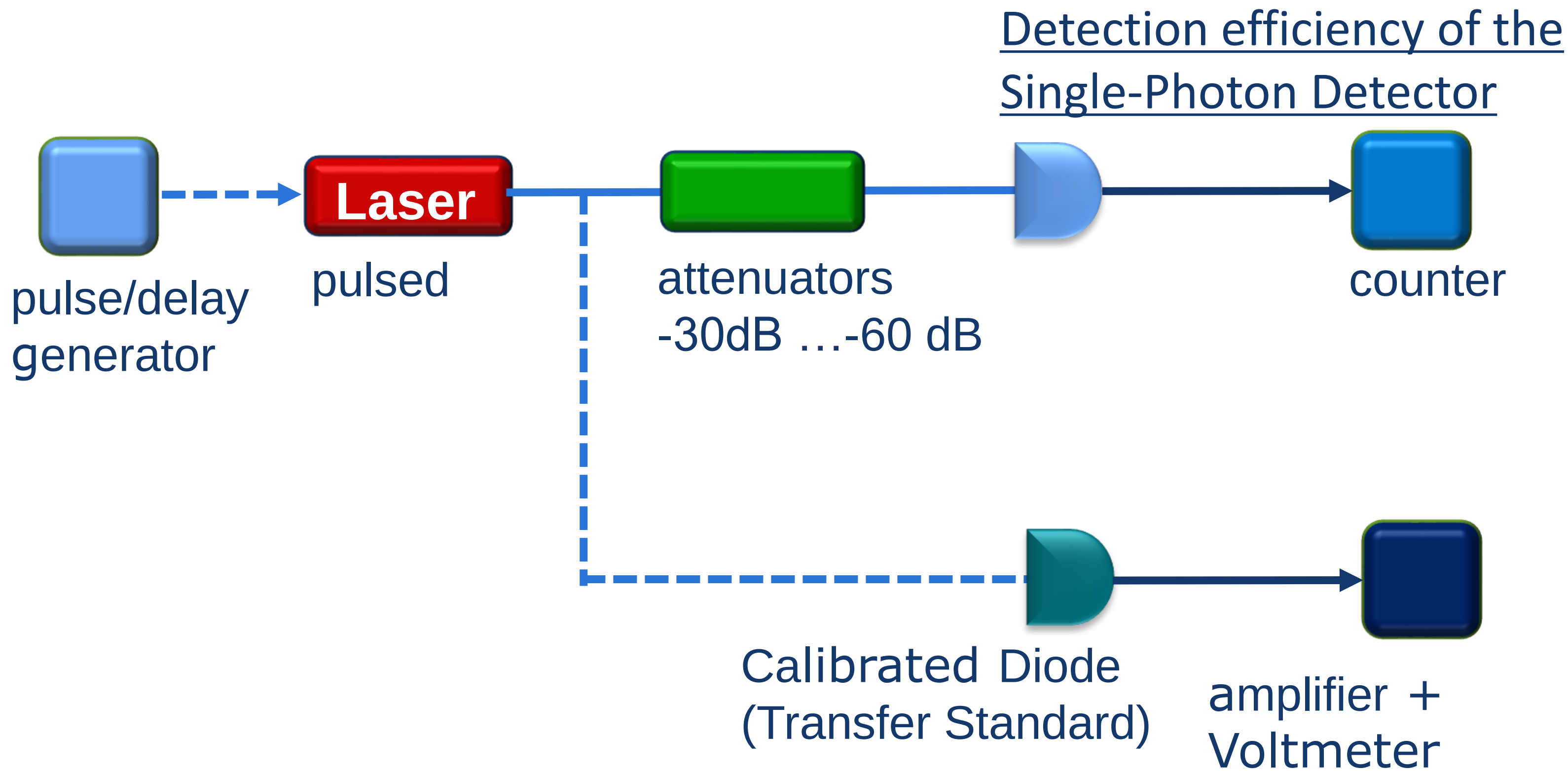
Project Coordinator: **INRIM**
Metrology for Testing the Implementation Security of QKD Hardware

SIQUST
SEQUME
Efficient single-photon sources for quantum technologies and quantum metrology

Project Coordinator: **PTB**

Detection Probability measurement: Substitution Method

Single-Photon Detection Probability



Issues

- Attenuators Calibration From CW to pulsed source
- Nonlinearity & Deadtimes
- From CW to pulsed source
- …

Detection Probability measurement: Substitution Method

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Optical power traceability chain (SI)

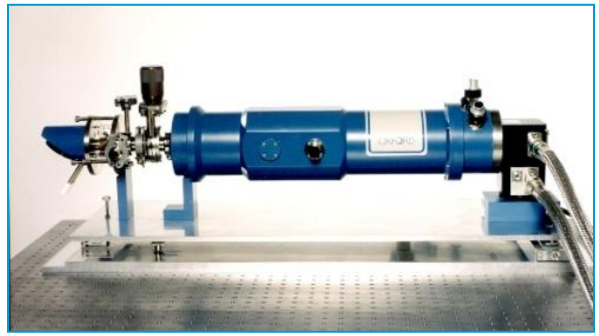
Primary standard
Cryogenic radiometry

↓

NMI reference detectors

↓

Low power reference detector



0.005 % uncertainty

visible wavelengths,
0.5 mW,
collimated,
free-space laser radiation

1% uncertainty or less (k = 2)

100 pW,
output from optical fibre

QUANTUM TECHNOLOGIES

Detection Probability measurement: Substitution Method

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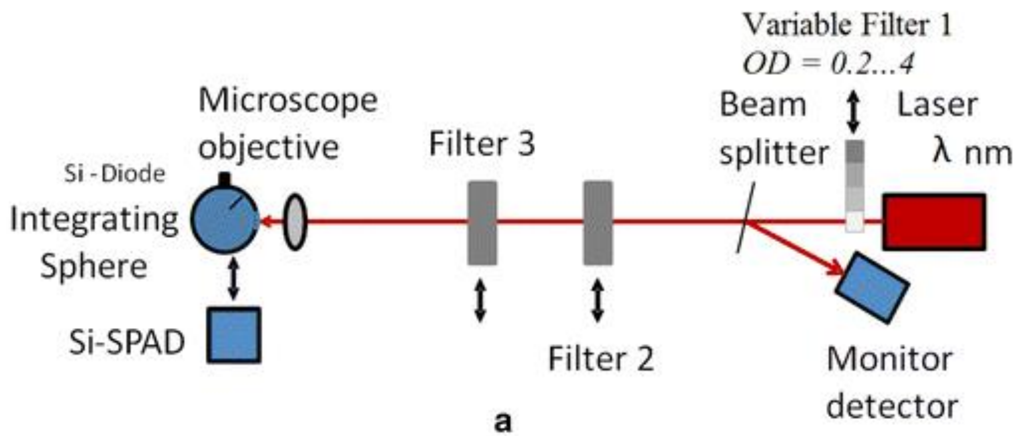
EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Pilot comparison on the detection efficiency meas. of single-photon detectors @850nm and @1550nm

Le Système international d'unités
The International System of Units
SI

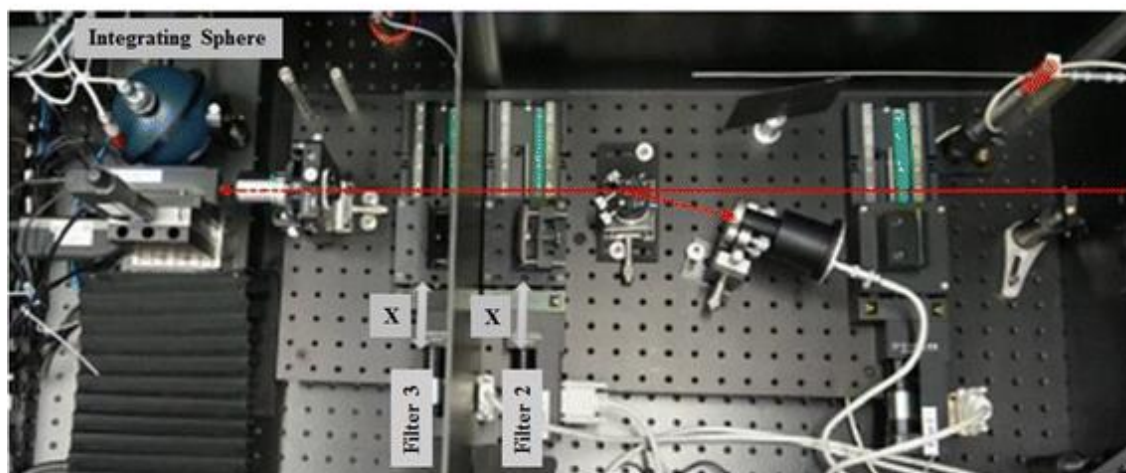


a

@850 nm
11 NMIs: EU, Asia and America

@1550 nm
Study in MIQC2
4 NMI: INRIM, PTB, NPL and CMI

MIQC2



b

EPJ-QT **7**, 14 (2020)
APL **118**, 174002 (2021)

Detection Probability measurement: Substitution Method

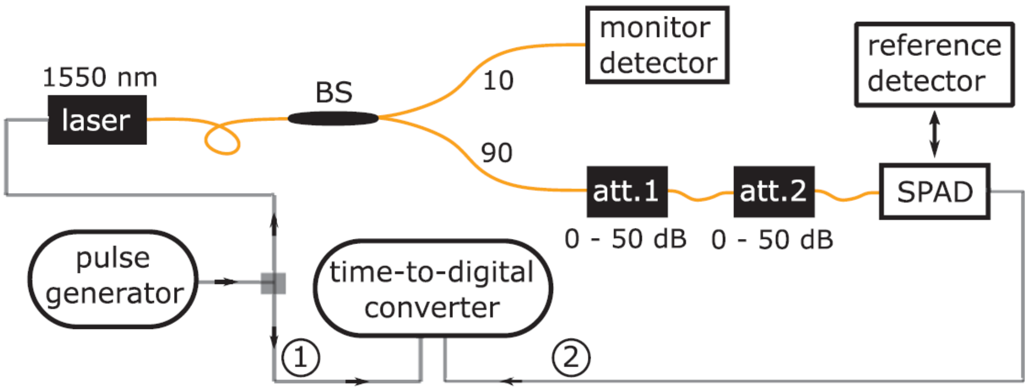
EURAMET

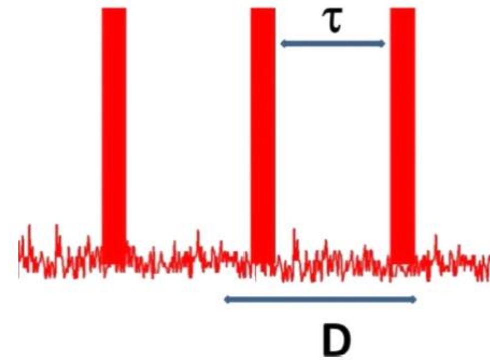
EMPIR

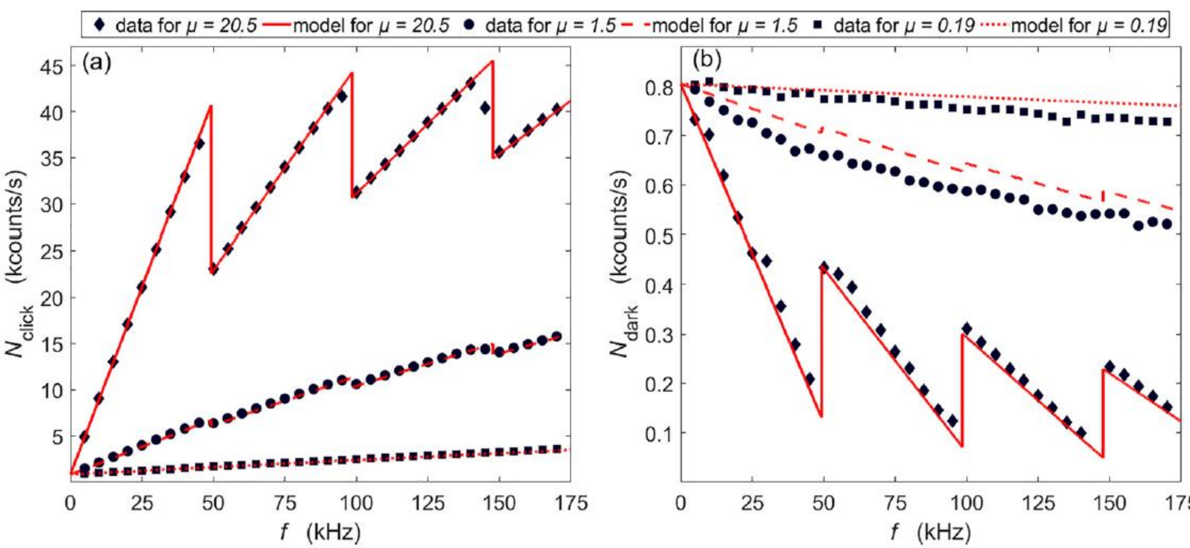
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

MIQC2

Comparison on the detection efficiency meas. of *free-running* single-photon detectors @1550nm with *pulsed* laser source







EPJ-QT **7**, 14 (2020)

APL **118**, 174002 (2021)

QUANTUM TECHNOLOGIES

Detection Probability measurement: Substitution Method

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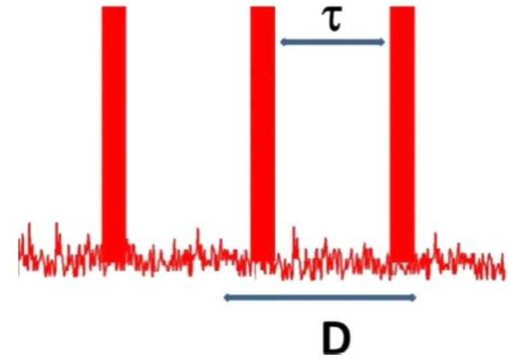
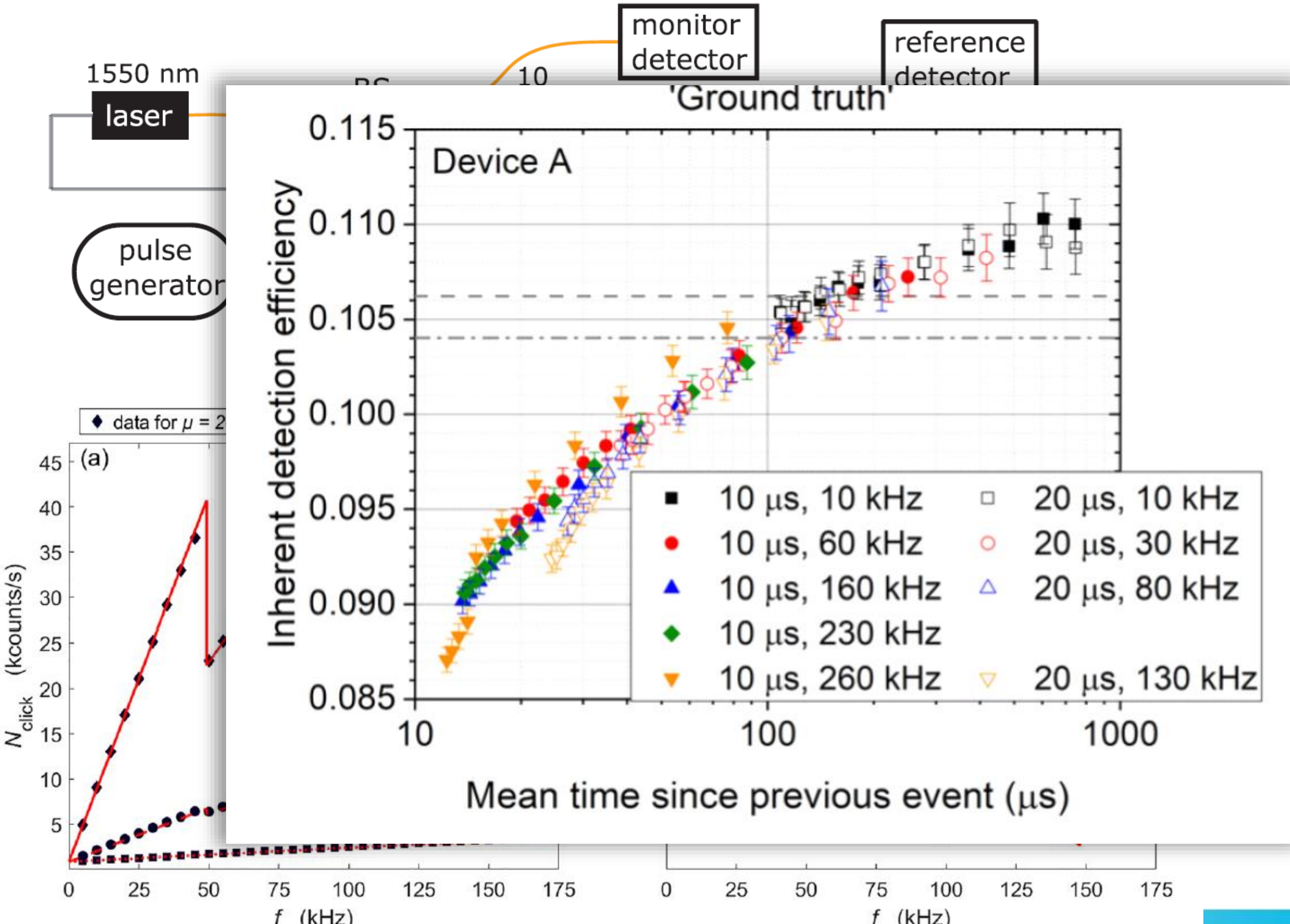


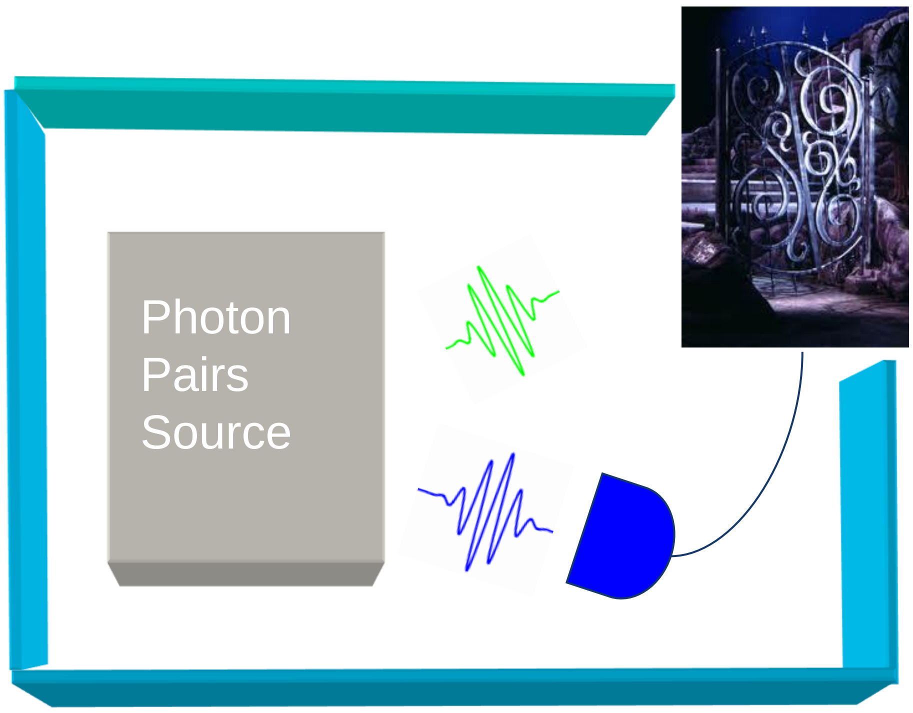


EPJ-QT **7**, 14 (2020)
APL **118**, 174002 (2021)
PRA **105**, 042615 (2022)

QUANTUM TECHNOLOGIES

Detection Probability measurement: Klishko's technique

Detector's quantum efficiency (η) measurement



Heralded Photon Source:

photon timing ➔ known

wavelength ➔ known

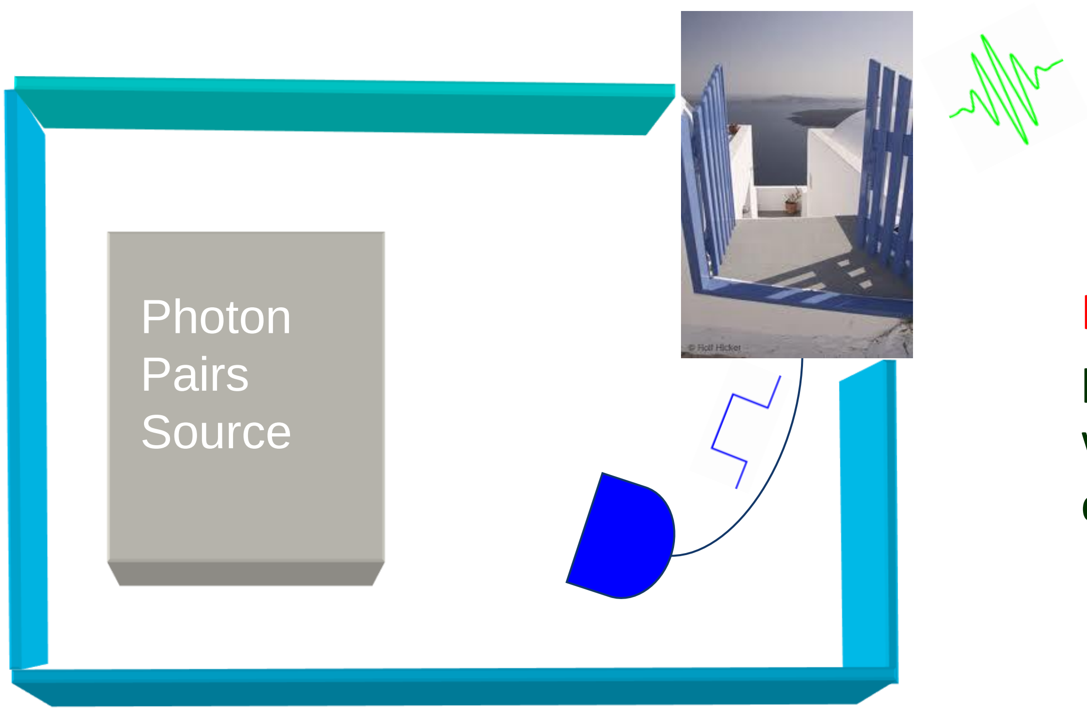
direction ➔ known

η prob. of detecting the heralded photon

[Zeldovich & Klychko, Sov. Phys. JETP Lett. 9, 40 (1969)]

Detection Probability measurement: Klishko's technique

Detector's quantum efficiency (η) measurement



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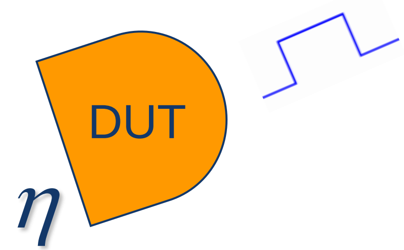
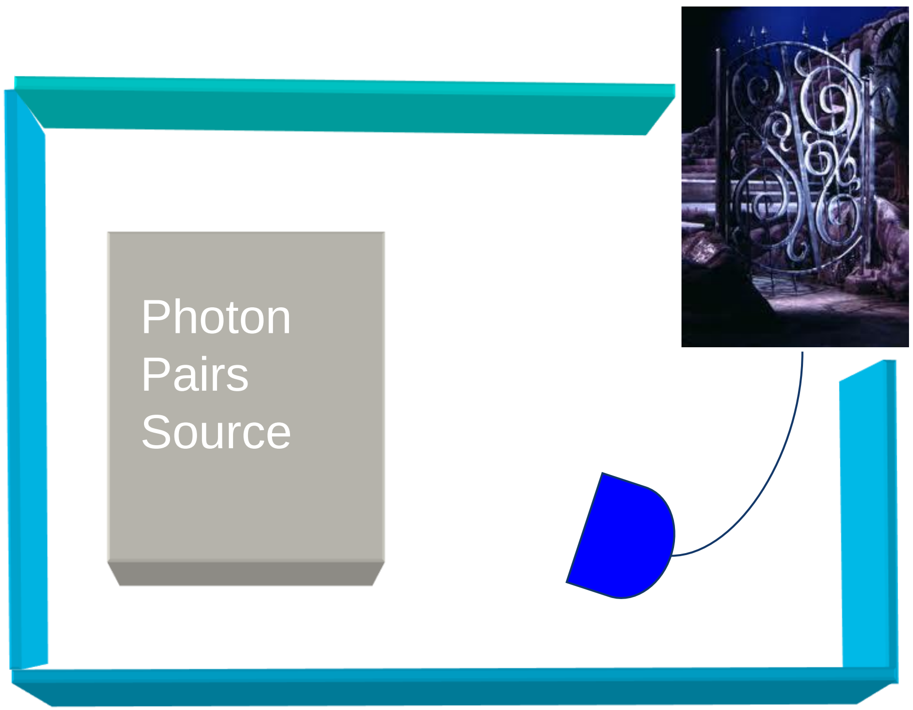
Detection Probability measurement: Klishko’s technique

Detector’s quantum efficiency (η) measurement





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η prob. of detecting the heralded photon

[Zeldovich & Klychko, Sov. Phys. JETP Lett. 9, 40 (1969)]

QUANTUM TECHNOLOGIES

Detection Probability measurement: Klishko's technique

- First experimental implementation (PDC)

  [Burnham & Weinberg, PRL **25**, 84 (1970)]

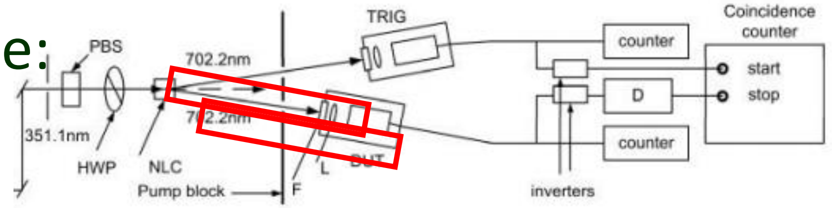
- International research effort:

  [Malygin *et al.,* Sov. J. Quantum Electron. **11** 939 (1981); Rarity et. al., Appl. Opt. **26**, 4616 (1987); Penin, *et al.,* Appl. Opt. **30** 3582 (1991); Ginzburg *et. al.,* Opt. Eng. **32**, 2911 (1993); Kwait *et al.,* Appl. Opt. **33**, 1844 (1994)...]

- First research effort in the metrological community

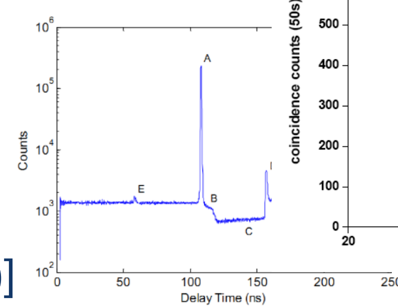
  [Migdall et al., Metrologia **32**, 479 (1996)]

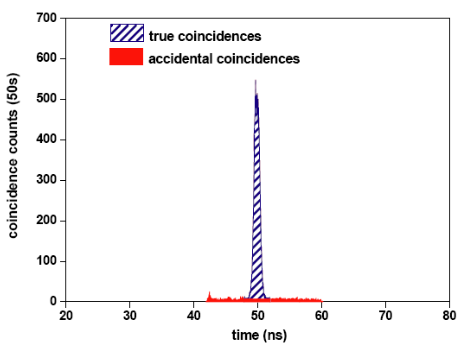
Kt… as a reliable radiometric technique:



Non-idealities to be accounted for

- Optical losses DUT channel
- Accidental coincidences
- Detectors non-linearity, dark counts, after-pulses
- …



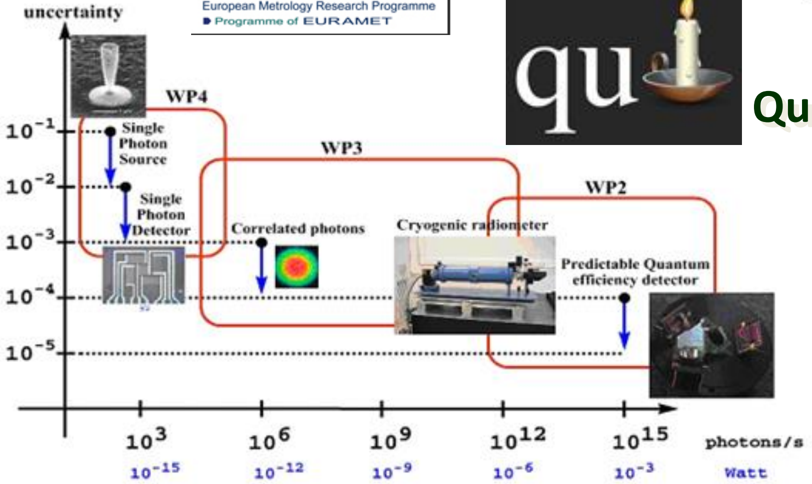


[Polyakov & Migdall, JMO **56**, 1045 (2009)]

QUANTUM TECHNOLOGIES

Detection Probability measurement: Klishko's technique

... already well established radiometric technique



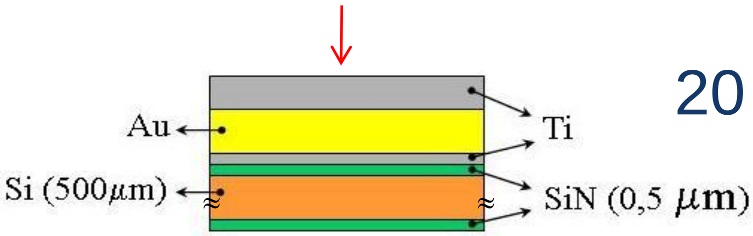
Qu.Candela project

Lowest relative uncertainties achieved so far: ~0.2%
(comparison with a classical technique traceable to a primary standard)
[Polyakov & Migdall, Optics Express **15**, 1391 (2007)]

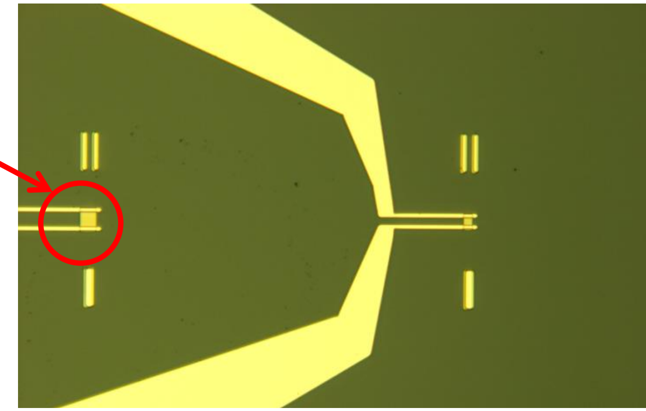
Results confirmed by the Qu-Candela consortium
(New low-optical power reference detector)
[Cheung et al., Optics Express **19**, 20347 (2011)]

Detection Probability measurement: Klishko's technique: Extension 1

TES - Transition Edge Sensor

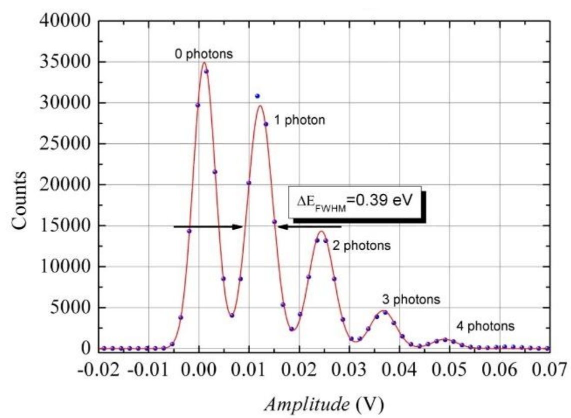


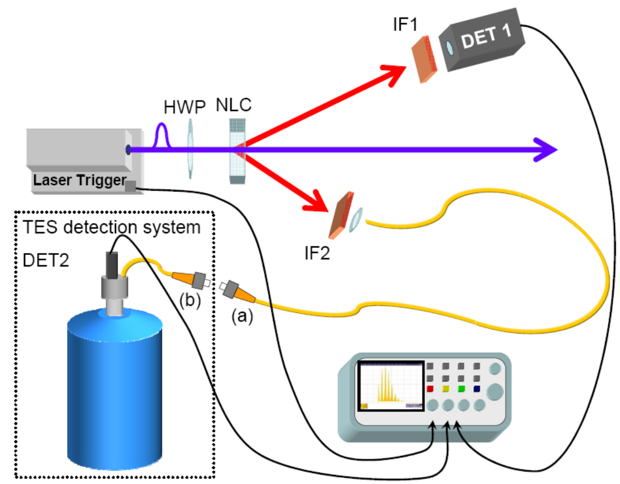
20 μm x 20 μm



TESs are based on a superconducting thin film working as a very sensitive microcalorimeter

PNR detector





[Optics Express **19**, 23249 (2011)]:

Absolute technique for measuring quantum efficiency:

- based on an heralded single photon source
- exploiting the PNR ability of the detector

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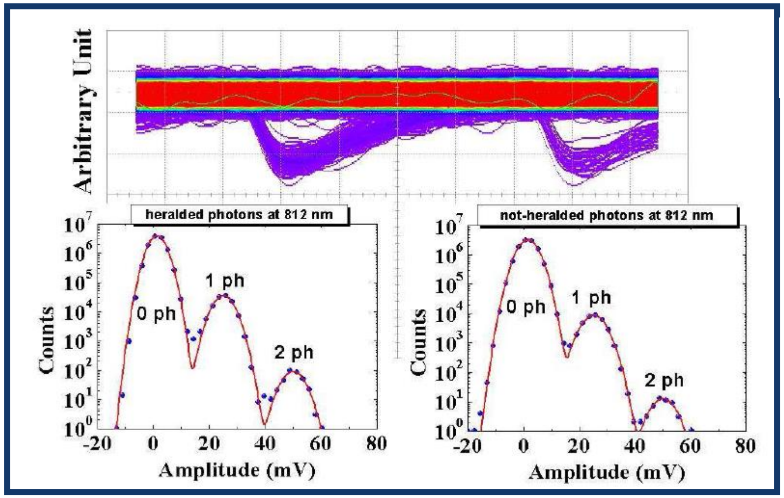
QUANTUM TECHNOLOGIES

Detection Probability measurement: Klishko's technique: Extension 1



$P(i)$($\mathcal{P}(i)$) Probability of observing i photons per heralding count in the presence/absence of the heralded photon (i.e. of observing (i-1)/i "accidental" counts)

From each $P(i)$ a value of "Total" Quantum Efficiency can be estimated (*Consistency Test*)

From the prob. of *0:*

$$\gamma_0 = \frac{\mathcal{P}(0) - P(0)}{\xi \mathcal{P}(0)}$$

From the prob. of *i:*

$$\gamma_i = \frac{P(i) - \mathcal{P}(i)}{\xi(\mathcal{P}(i-1) - \mathcal{P}(i))}$$

Detection Probability measurement: Klishko's technique: Extension 2

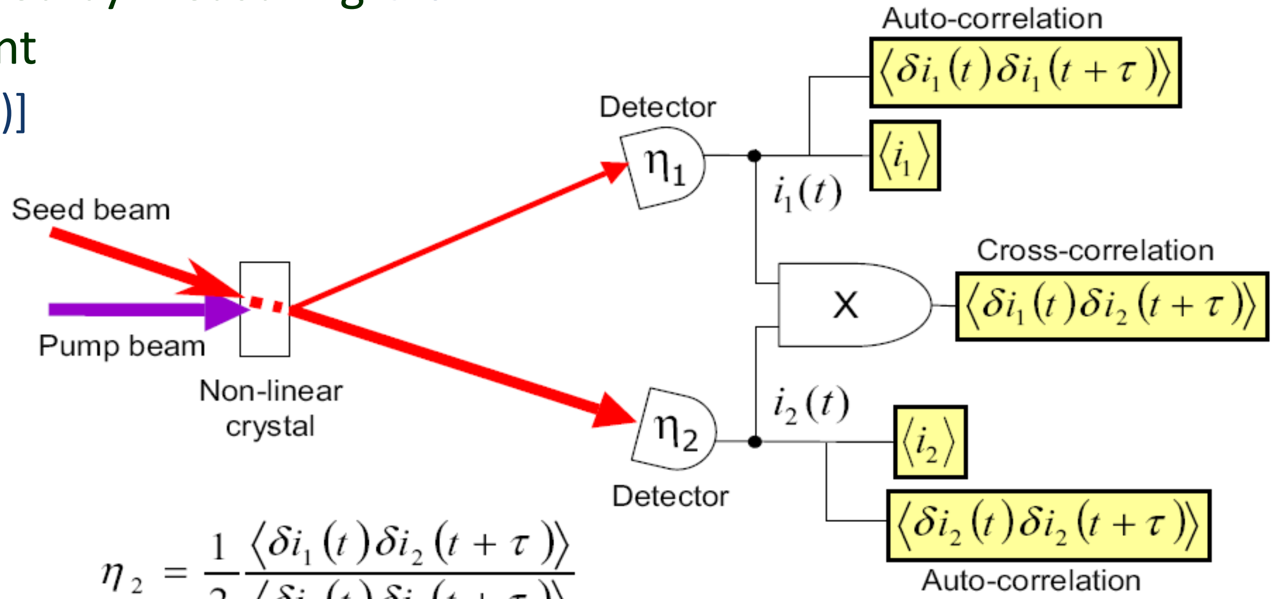
Extension of the KT to the calibration of analog (i.e. not operating at single photon level) detector exploiting twin beam (only in low gain regime)

[JOSAB **23**, 2185 (2006)]

Solution: Seeded Twin Beam

Quantum efficiency obtained by measuring C-c and A-c of the photocurrent

[Optics Expr. **16**, 12551 (2008)]



$$\eta_2 = \frac{1}{2}\frac{\langle \delta i_1(t)\delta i_2(t+\tau)\rangle}{\langle \delta i_1(t)\delta i_1(t+\tau)\rangle}$$

Implementation exploiting a 4 WM in Rb hot vapor

[Marino & Lett, JMO **56**, 401 (2009)]

Detection Probability measurement: Klishko's technique: Extension 3

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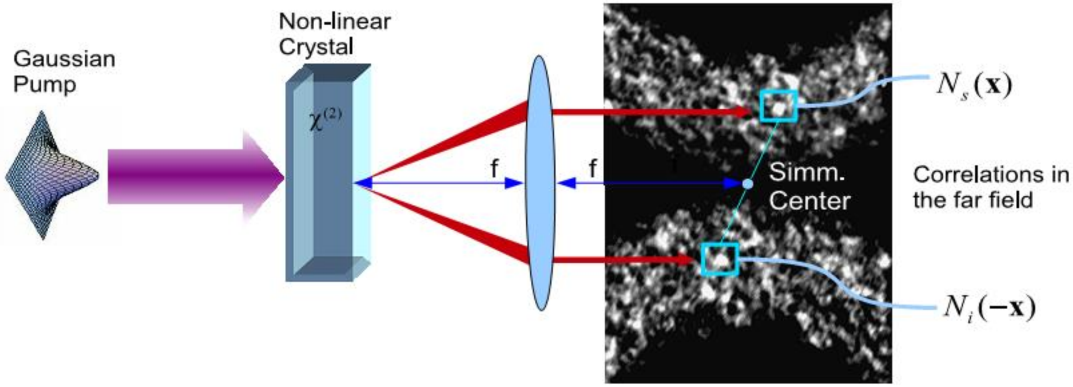
[Optics Expr. **18**, 20572 (2010); APL **105**, 10113 (2014); Opt. Lett. **41**, 1841 (2016)]

Bright Multimode Twin-Beams used to calibrate scientific CCD camera

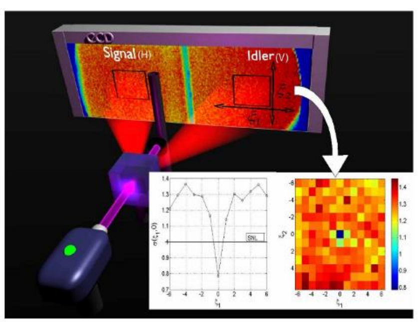


$$|\psi(\mathbf{q})\rangle = \sum_n C_{\mathbf{q}}(n)|n\rangle_{i,\mathbf{q}}|n\rangle_{s,-\mathbf{q}}$$

NRF: $$\sigma \equiv \frac{\langle \delta^2 N_- \rangle}{\langle N_i + N_s \rangle}$$

$$\langle \delta^2 N_- \rangle \equiv \langle \delta^2 N_s \rangle + \langle \delta^2 N_i \rangle - 2\langle \delta N_i \delta N_s \rangle$$

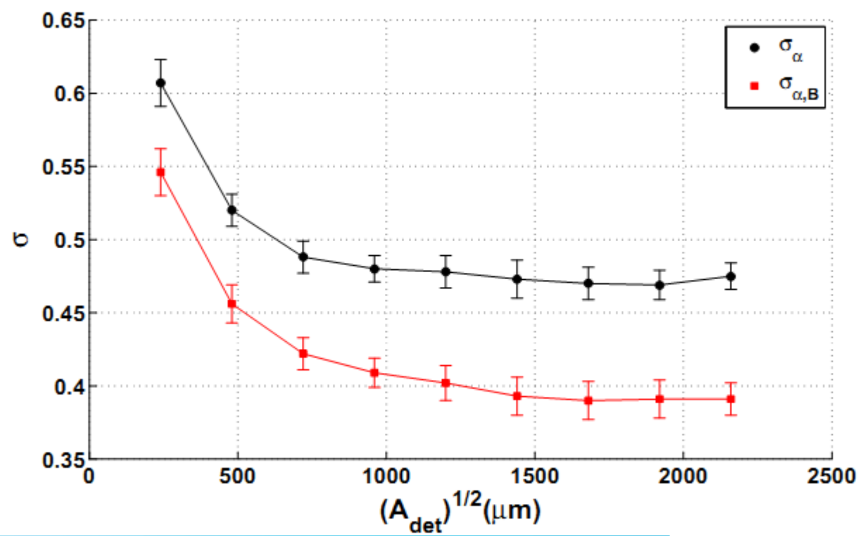
(**Sub-Shot Noise Imaging** [Nat.Phot.(2010)**4**,227], **Quantum Illumination** [PRL(2013)**110**,153603])



Corrected NRF

$$\sigma_\alpha \equiv \frac{\langle \delta^2 (N_s - \alpha N_i) \rangle}{2\langle N_s \rangle} = \frac{1}{2}(1+\alpha) - \eta_s$$

$$\alpha = \langle N_s \rangle / \langle N_i \rangle$$



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Detector’s POVM tomography

POVM Π_n provides the description of the measurement process

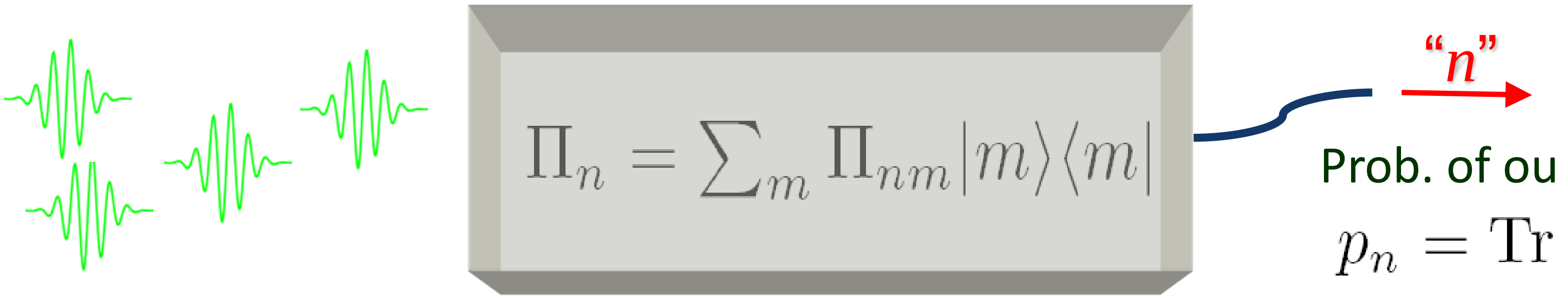
“*n*”

Prob. of output “*n*”

$$p_n = \mathrm{Tr}\left[\varrho\,\Pi_n\right]$$

Detector's POVM tomography

POVM Π_n provides the description of the measurement process

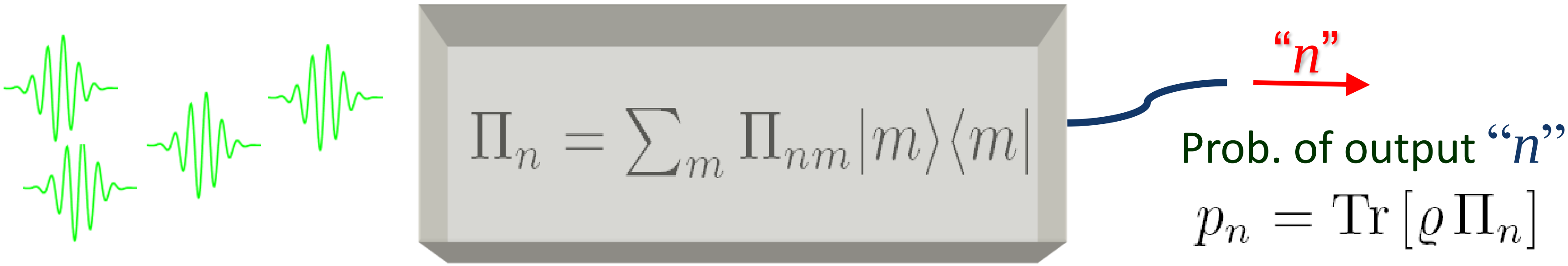


Prob. of output "n"

$$p_n = \mathrm{Tr}\left[\varrho \, \Pi_n\right]$$

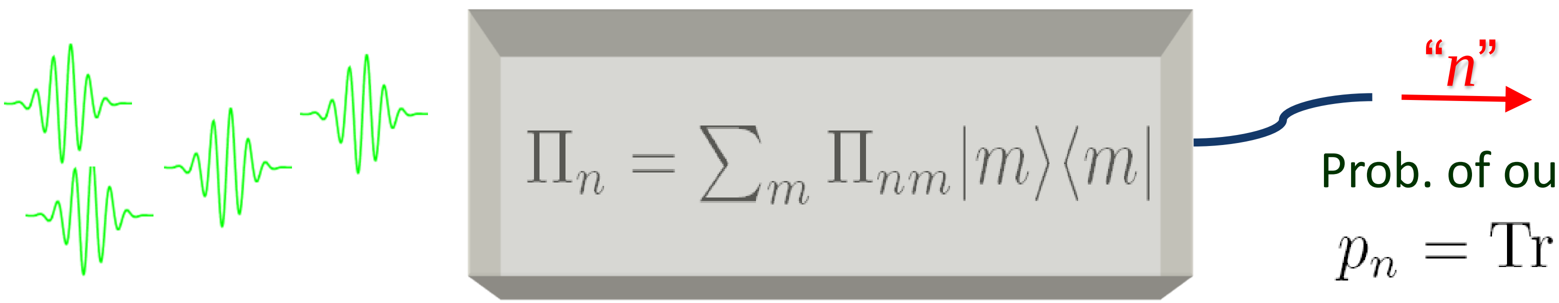
Detector's POVM tomography

POVM Π_n provides the description of the measurement process



Detector’s POVM tomography

POVM Π_n provides the description of the measurement process



“n”

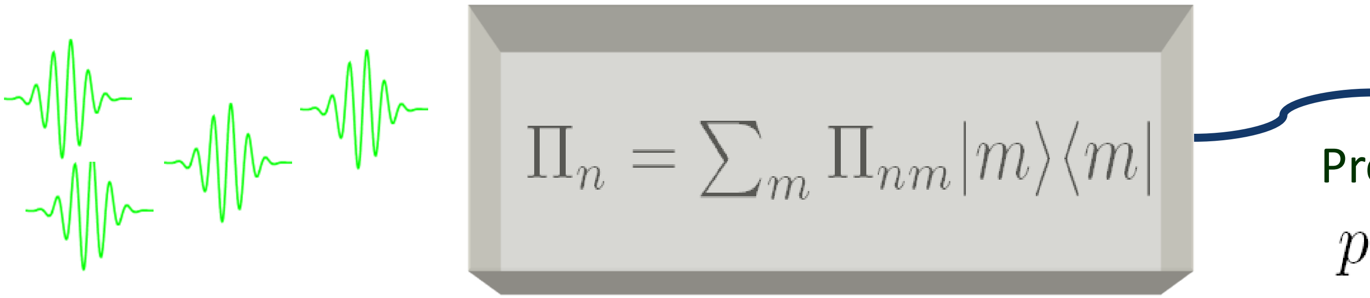
Prob. of output “n”

$$p_n = \mathrm{Tr}\left[\varrho\, \Pi_n\right]$$

Π_{nm} : Prob. of having output “n” with m photons as input

Detector’s POVM tomography

POVM Π_n provides the description of the measurement process



“n”

Prob. of output “n”

$$p_n = \mathrm{Tr}\left[\varrho\,\Pi_n\right]$$

Π_{nm} : Prob. of having output “n” with m photons as input

- Quorum of states

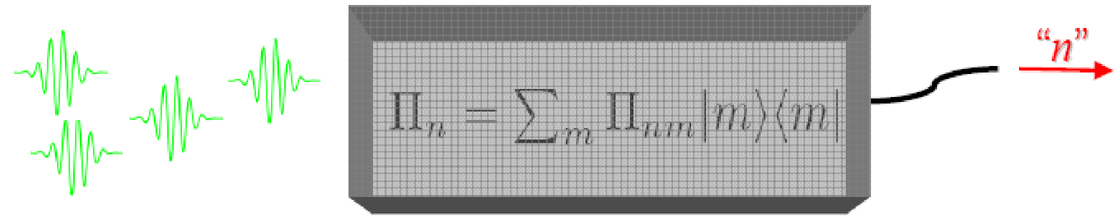
- Ancilla assisted

Detector’s POVM tomography

Simplest Solution:

Fock state source

$|m\rangle\langle m|$



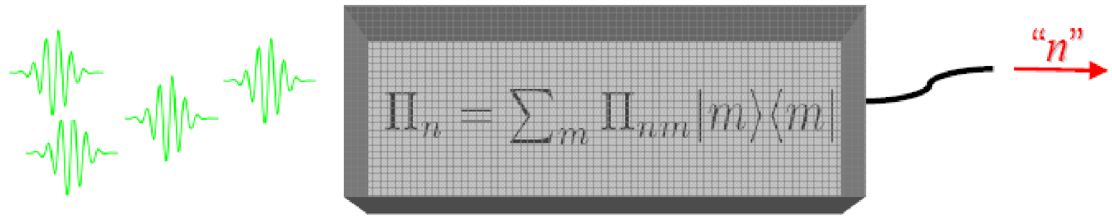
$$p_n = \langle m | \Pi_n | m \rangle = \Pi_{nm}$$

Detector's POVM tomography

Simplest Solution:

Fock state source

$|m\rangle\langle m|$



$$p_n = \langle m|\Pi_n|m\rangle = \Pi_{nm}$$

Detector's POVM tomography

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Fock state source

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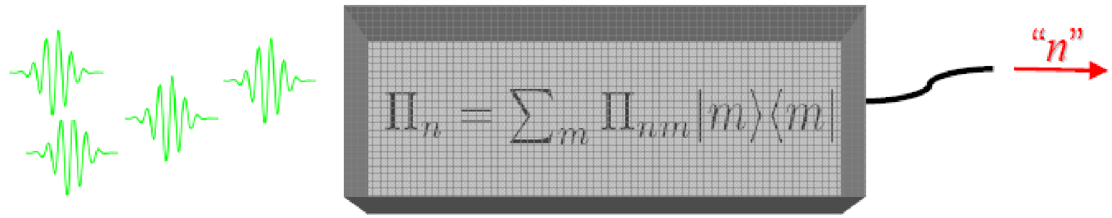


$$p_n = \langle m|\Pi_n|m\rangle = \Pi_{nm}$$

Affordable Solution: **Coherent source**

[Lundeen et al., Nat. Phys **5**, 27 (2009)]

$|\alpha_j\rangle,\ j = 1, \ldots, K$

$$p_{nj} = \mathrm{Tr}[|\alpha_j\rangle\langle\alpha_j|\Pi_n] = \sum_m \Pi_{nm}\, q_{mj}$$

$$q_{mj} = \exp(-\mu_j)\mu_j^m/m!$$

$$\mu_j = |\alpha_j|^2$$

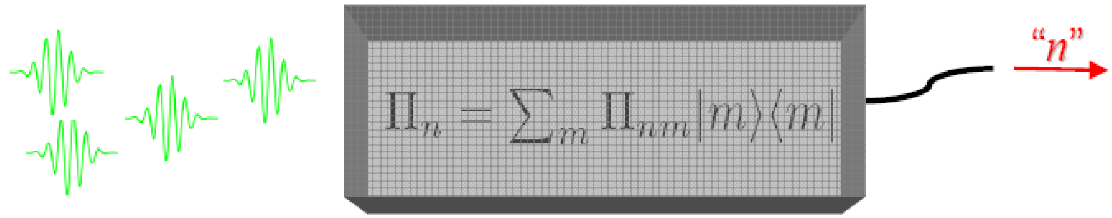
QUANTUM TECHNOLOGIES

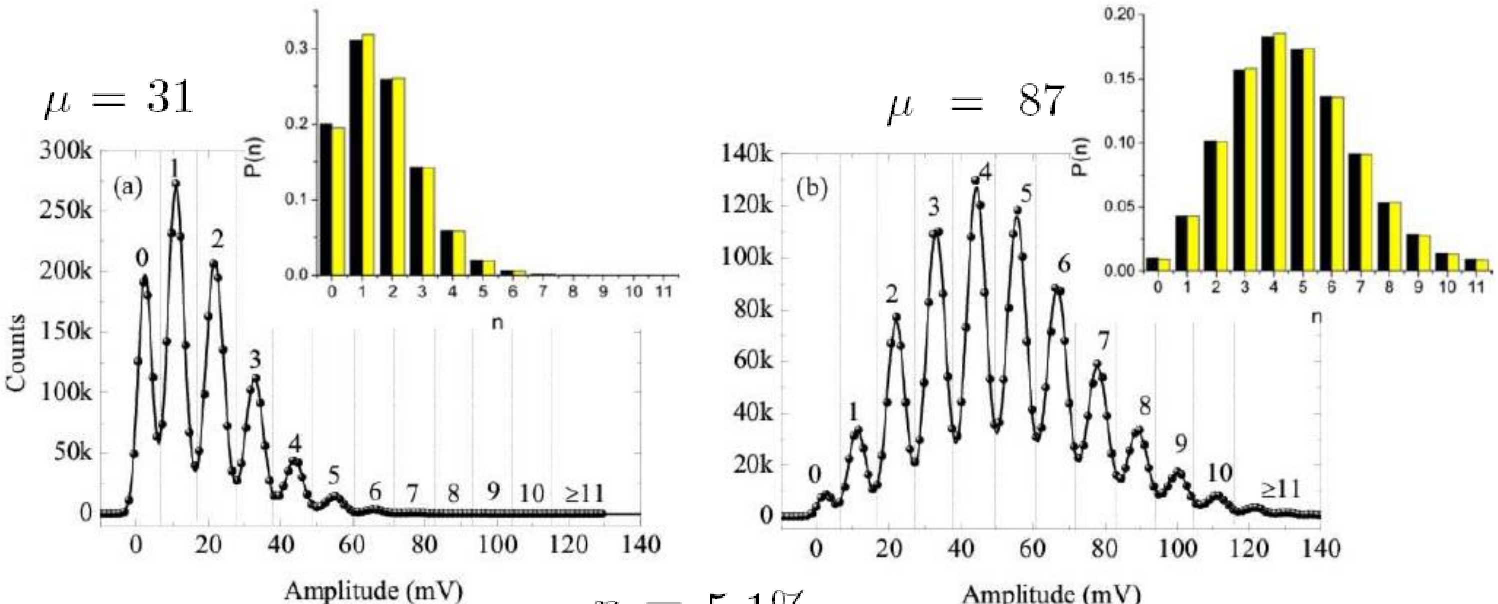
Detector’s POVM tomography

Coherent source

Pulsed laser source

Experiment with a TES



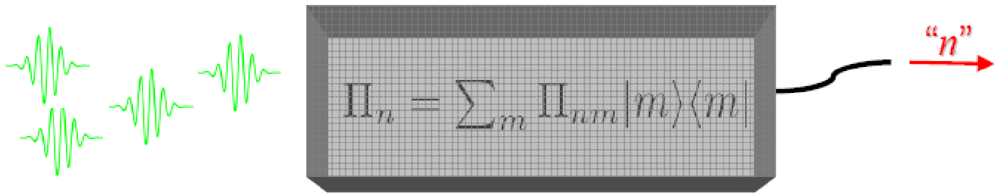


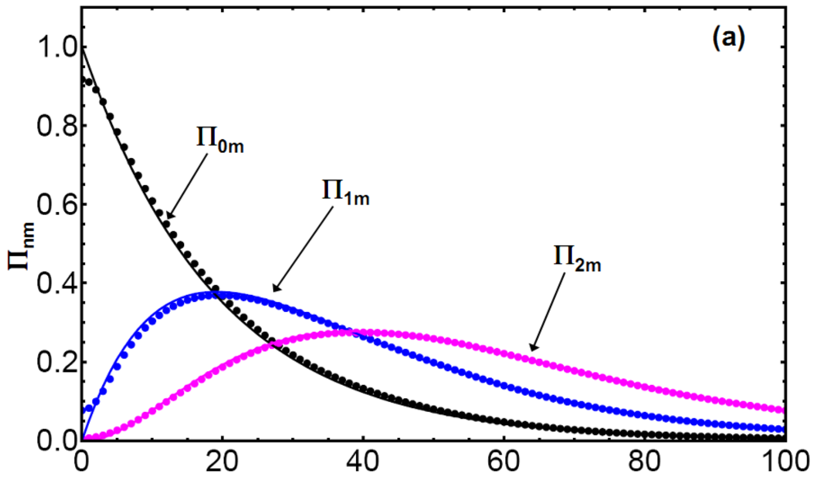
$$\eta = 5.1\%$$

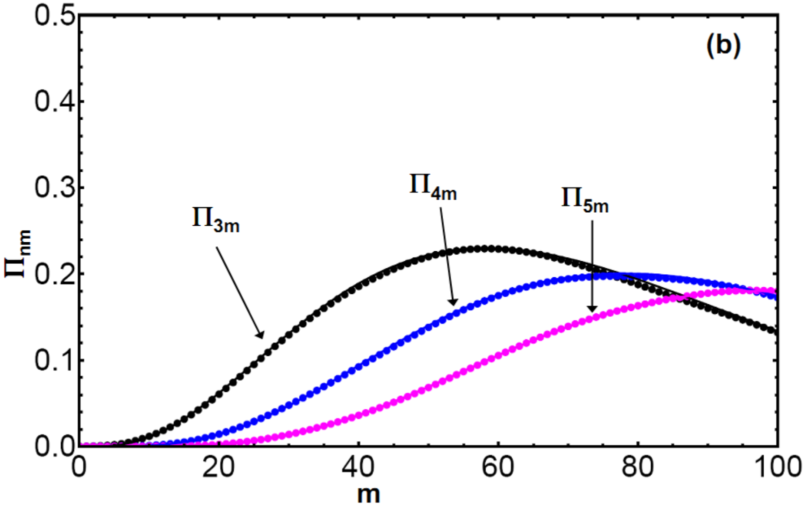
[NJP **14**, 085001 (2012)]

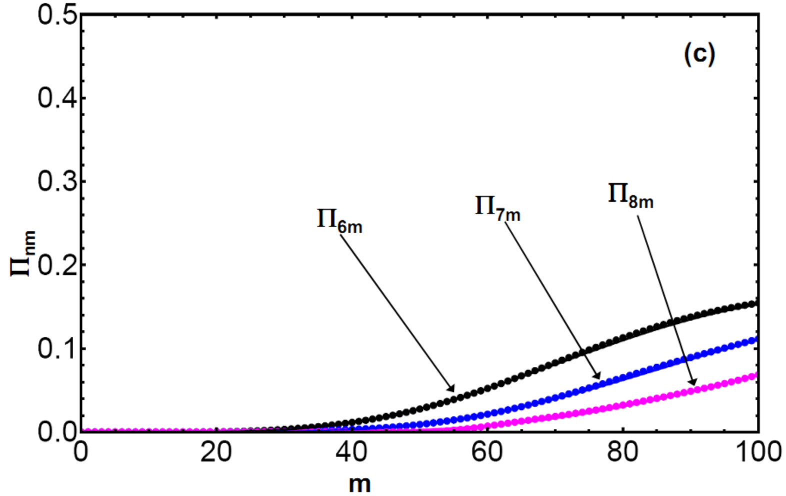
Detector's POVM tomography

Coherent source









Linear detection model

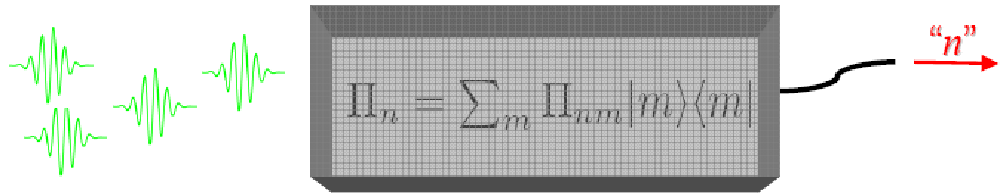
$$\Pi_n = \sum_{m=n}^{\infty} B_{nm} |m\rangle\langle m|$$

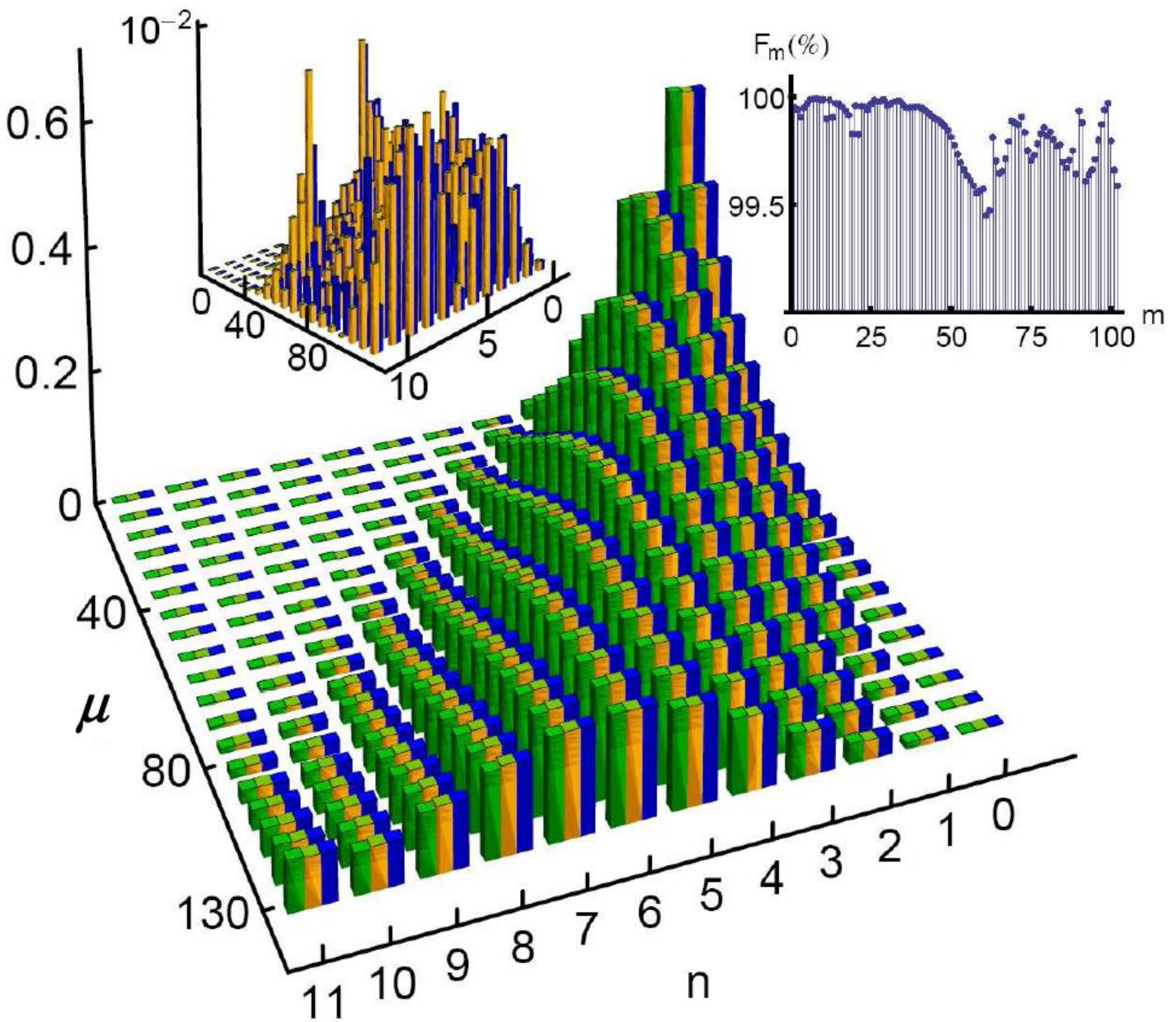
$$B_{nm} = \binom{m}{n} \eta^n (1-\eta)^{m-n}$$

[NJP **14**, 085001 (2012)]

Detector's POVM tomography

Coherent source





$$\Pi_n = \sum_{m=n}^{\infty} B_{nm}|m\rangle\langle m|$$

$$B_{nm} = \binom{m}{n} \eta^n (1-\eta)^{m-n}$$

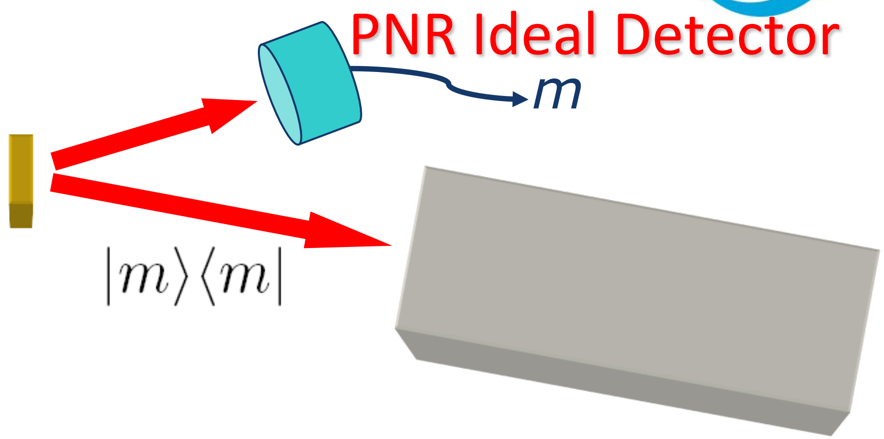
[NJP **14**, 085001 (2012)]

Detector's POVM tomography

Simplest Solution:

Heralded Fock state source

$$|R\rangle\rangle = \sum_m R_m |m\rangle |m\rangle$$

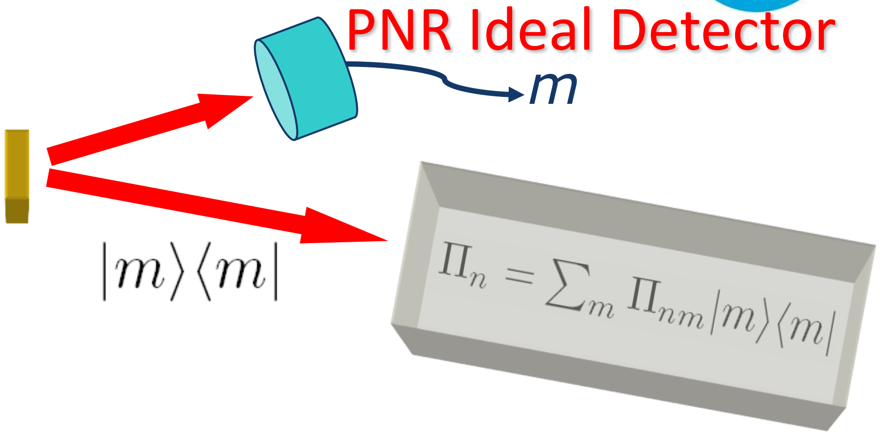


Detector's POVM tomography

Simplest Solution:

Heralded Fock state source

$$|R\rangle\rangle = \sum_m R_m |m\rangle|m\rangle$$



QUANTUM TECHNOLOGIES

Detector's POVM tomography

Simplest Solution:

Heralded Fock state source

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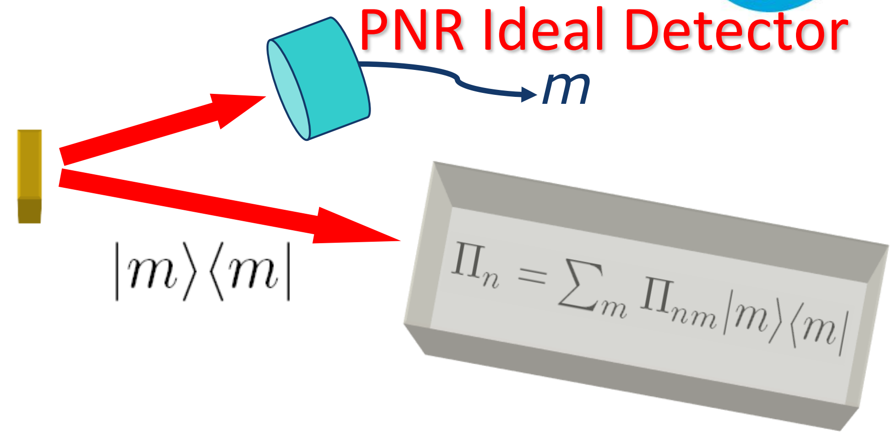
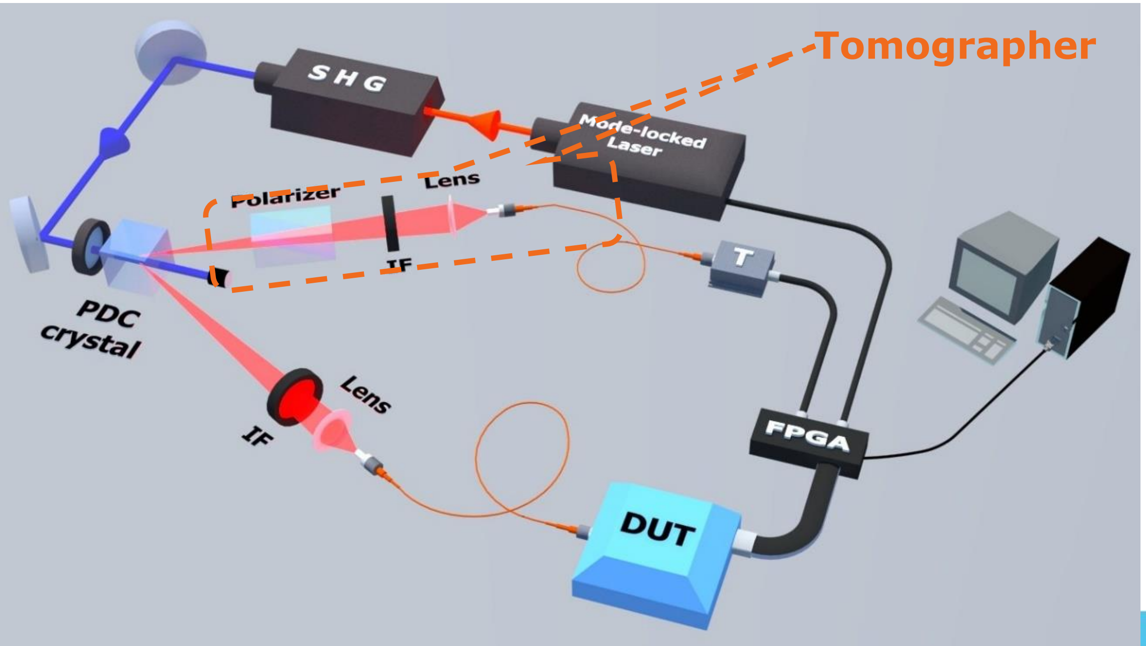


Affordable Solution: **Tomographer on the ancilla arm**

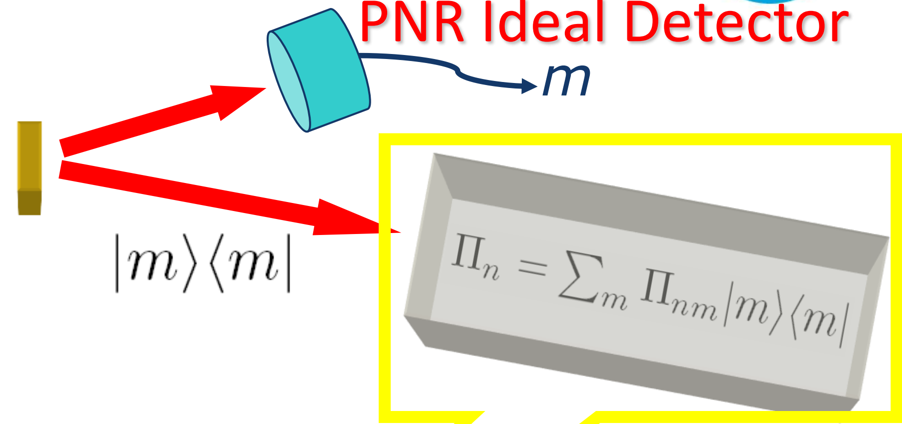


Detector's POVM tomography

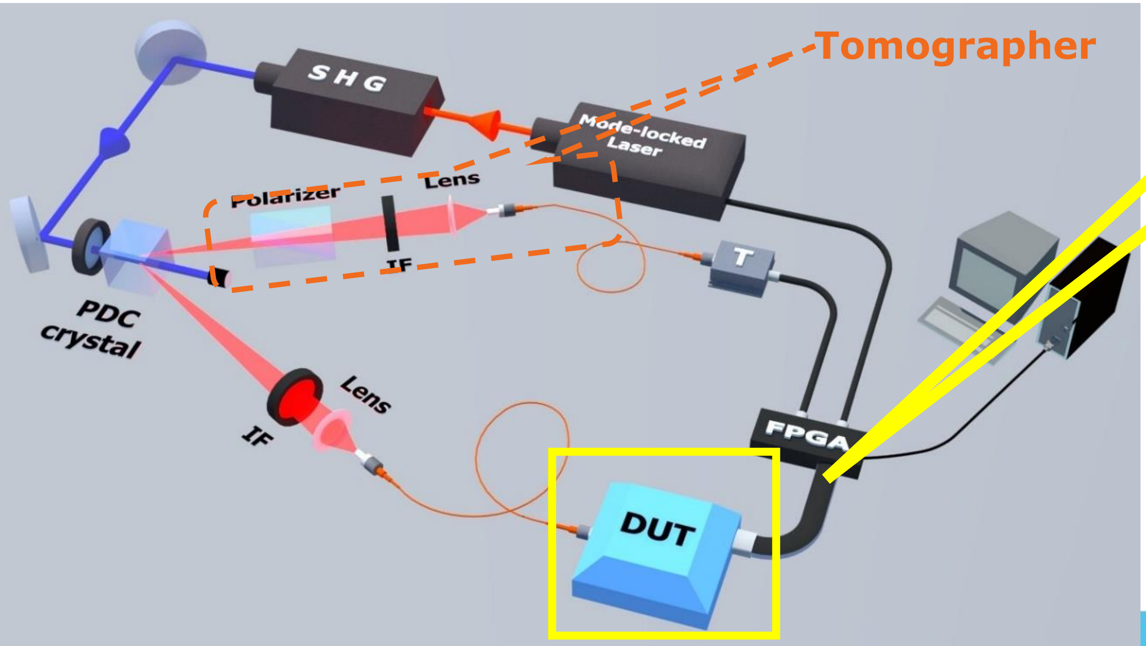
Simplest Solution:

Heralded Fock state source

$$|R\rangle\rangle = \sum_m R_m |m\rangle|m\rangle$$



Affordable Solution: **Tomographer on the ancilla arm**



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QUANTUM TECHNOLOGIES

Detector's POVM tomography

Simplest Solution:

Heralded Fock state source

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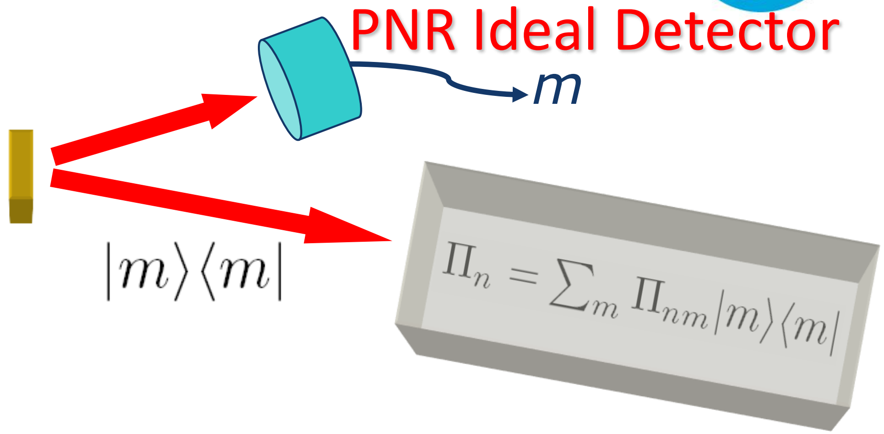

Affordable Solution: **Tomographer on the ancilla arm**

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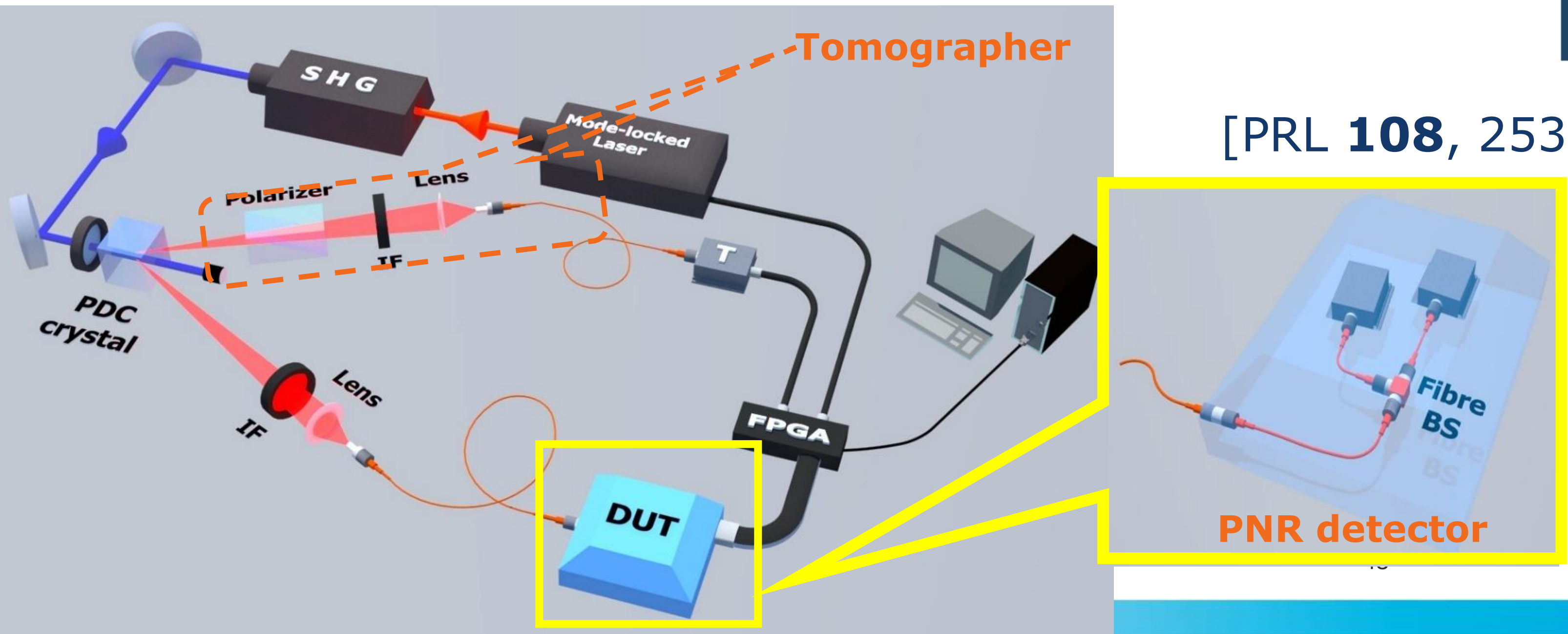
[PRL **108**, 253601 (2012)]



QUANTUM TECHNOLOGIES

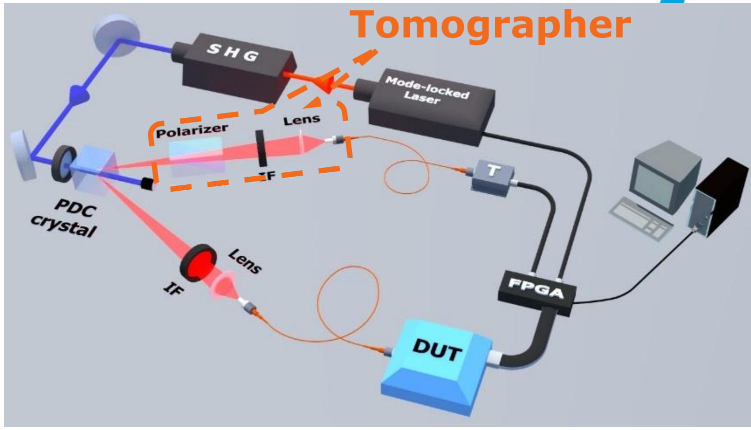
Detector's POVM tomography

$$|R\rangle\rangle = \sum_m R_m |m\rangle|m\rangle$$

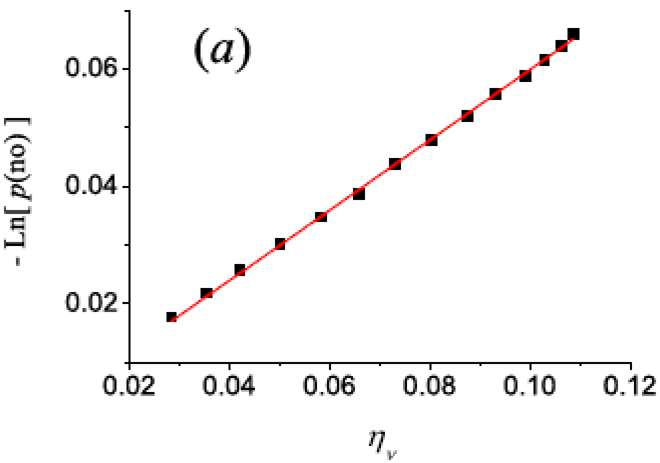
Tomographer on the ancilla arm

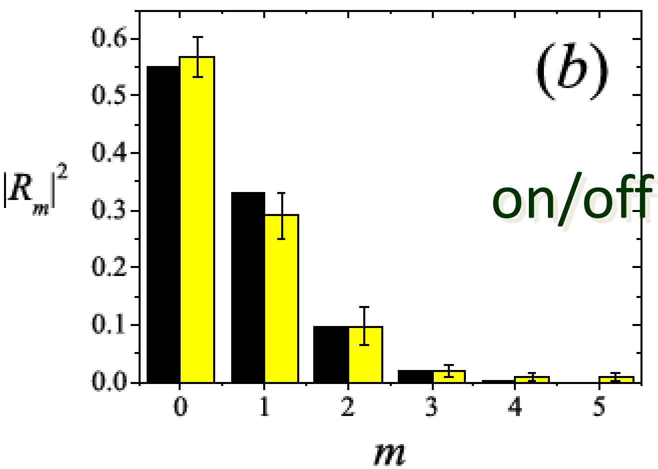
$$p(n, \text{yes}) = \sum_m \Pi_{nm} |R_m|^2 [1 - (1-\eta)^m]$$

$$p(n, \text{no}) = \sum_m \Pi_{nm} |R_m|^2 (1-\eta)^m$$



[PRL **108**, 253601 (2012)]

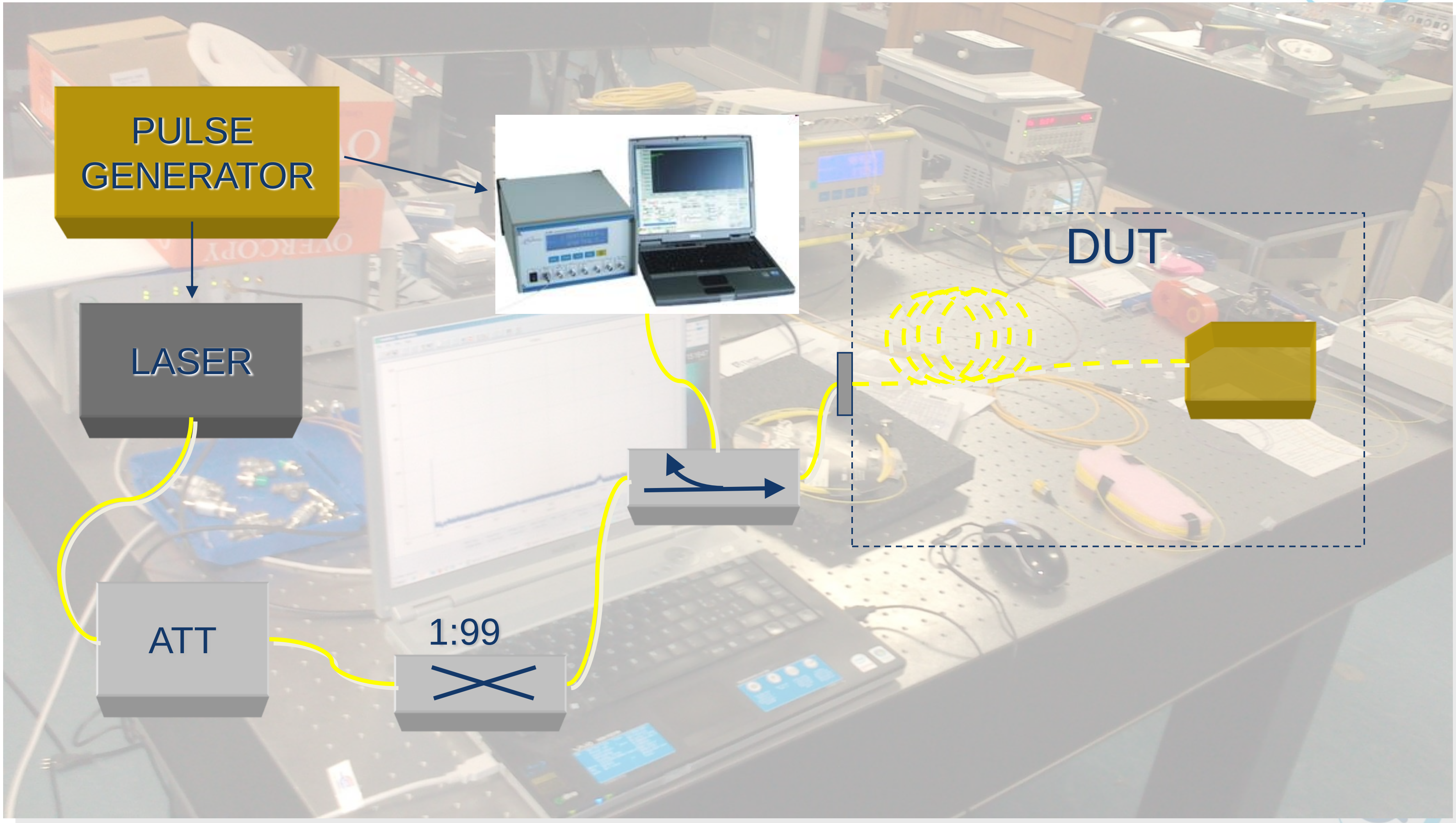




on/off reconstruction

[PRA **70**, 055801 (2004); J. Řeháček et al., PRA **67**, 061801 (2003)]

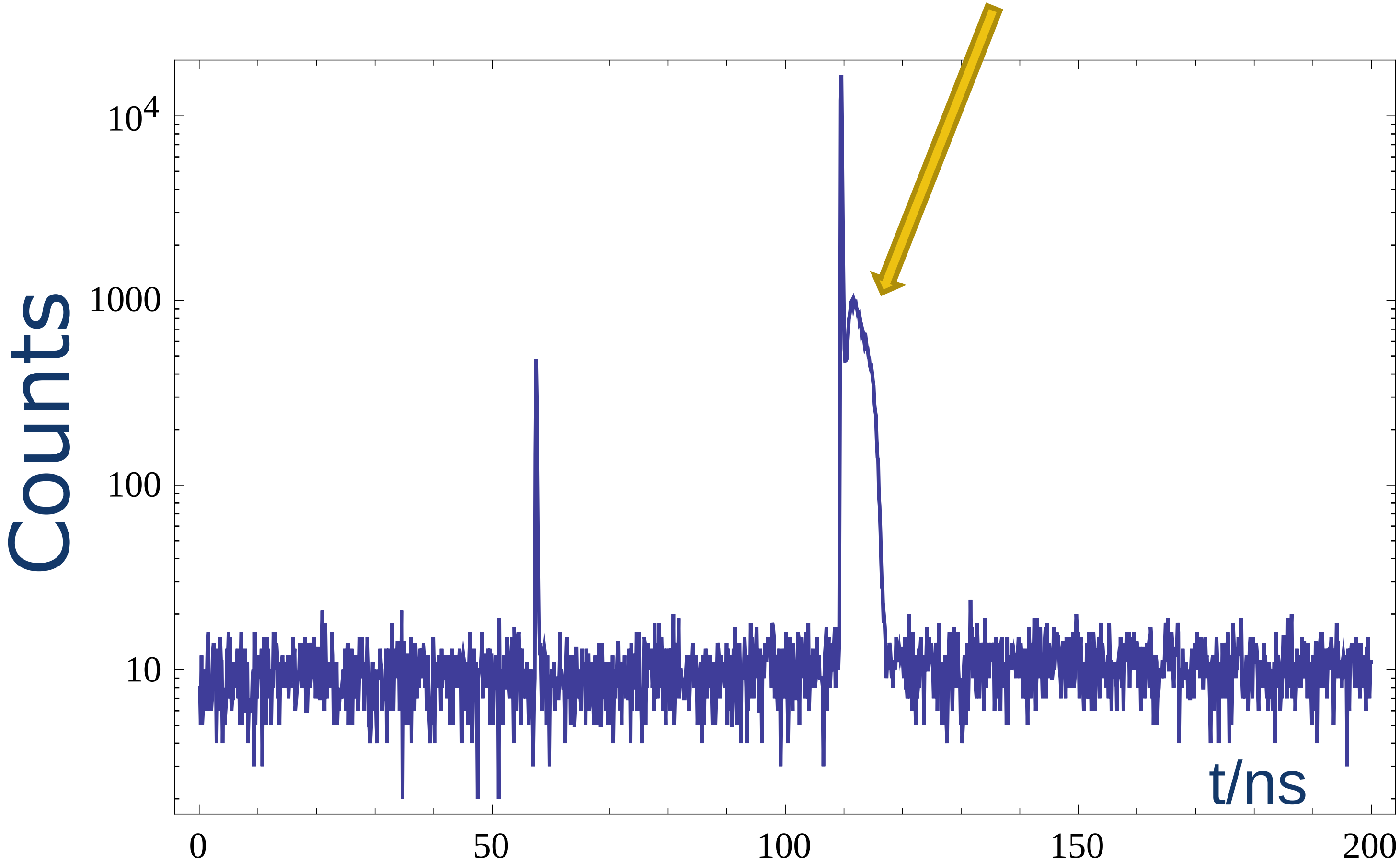
Detectors' Backflash Emission: a security threat



OTDR operating at single-photon level

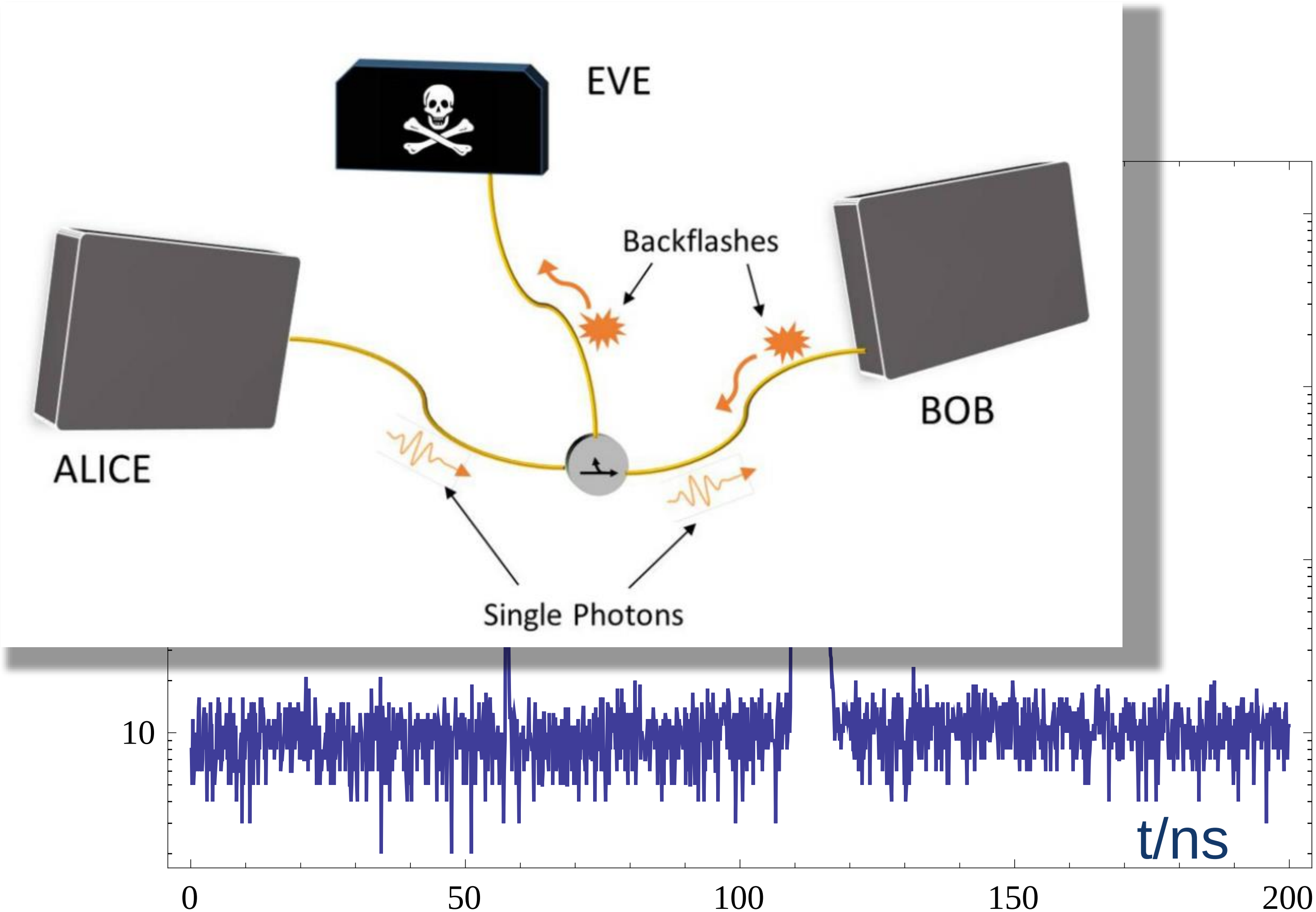
Detectors’ Backflash Emission: a security threat

Single-photon-detector Back-Flashes



Light: S&A 6, e16261 (2017)

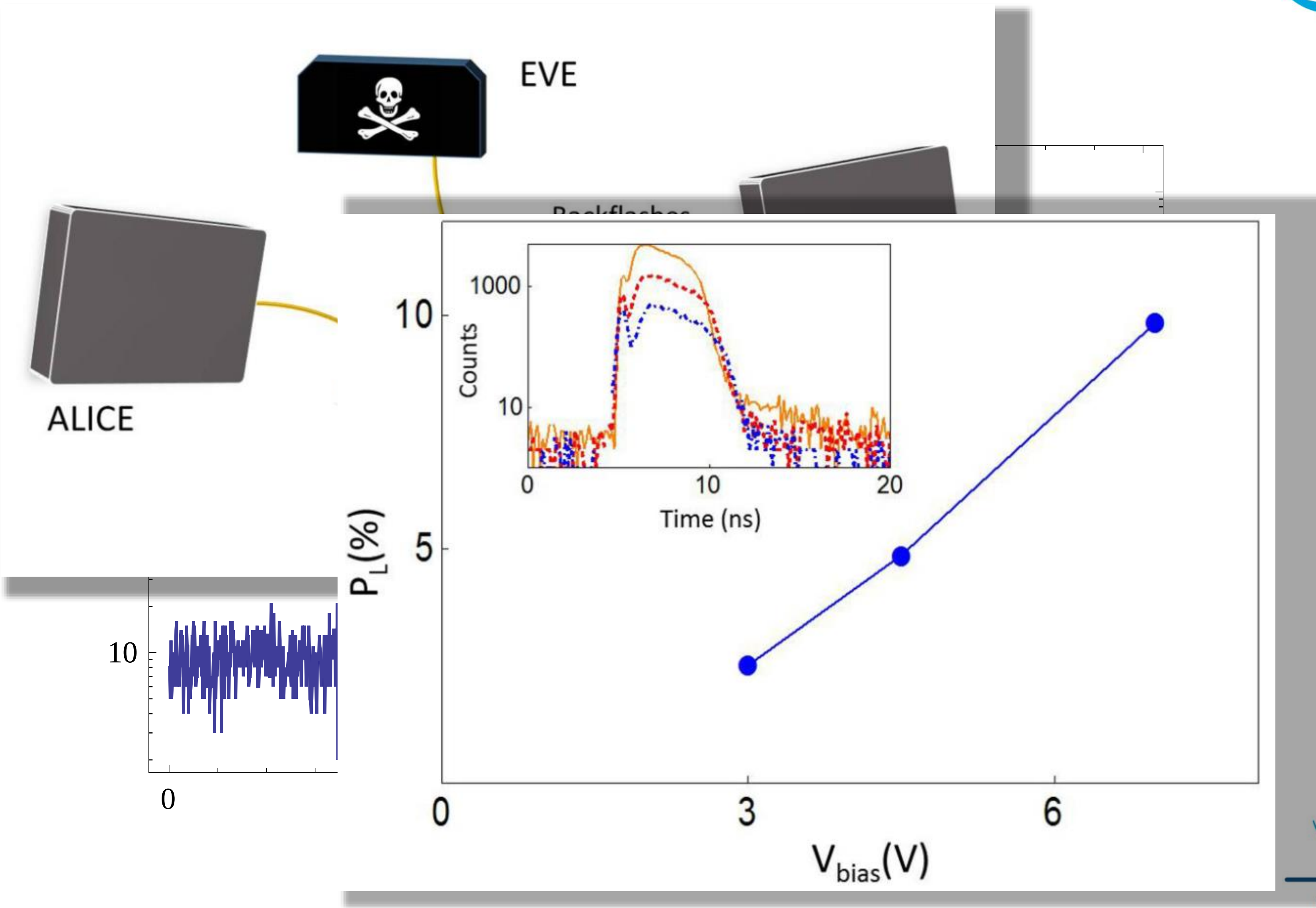
Detectors’ Backflash Emission: a security threat



Light: S&A 6, e16261 (2017)

Detectors' Backflash Emission: a security threat

EURAMET



Light: S&A 6, e16261 (2017)

QUANTUM TECHNOLOGIES

EURAMET

EURAMET is the Regional Metrology Organisation (RMO) of Europe.

- Cooperation of National Metrology Institutes (NMI) in Europe in research in metrology, traceability of measurements, international recognition of Calibration and Measurement Capabilities (CMC);

- Knowledge Transfer and cooperation among EURAMET members EURAMET facilitates the development of the metrology infrastructures;

- European Metrology Research Programmes (EMRP and EMPIR) designed to encourage collaboration between European National Metrology Institutes (NMIs) and partners in industry or academia.

QUANTUM TECHNOLOGIES

European Metrology Networks (EMN)

EURAMET

Objective: To create sustainable structures in areas of strategic importance for the future of European metrology.

The Networks…

- cover an area of major strategic importance, with a **European dimension**;
- establish close links with a wider **stakeholder community**; including cooperation with other partnerships;
- strive for **scientific excellence**;
- develop and coordinate a **common metrology strategy & infrastructure** to support innovation, public policy, & regulation.

EMN for Quantum Technologies: EMN-Q

Commitment:

- To become the **unique contact point to stakeholders** interested in metrology for quantum technologies (QT)
- To contribute to **standardisation and certification** of QT
- To promote the **take-up of metrology** in the development of QT
- To promote the use of **quantum measurement techniques** where advantageous for "classical" technical areas
- To support **industrial needs** in synergy with the objectives of the **EC Quantum Flagship** and **national QT programs**

EMN-Q Contact Group

EMN for Quantum Technologies: EMN-Q

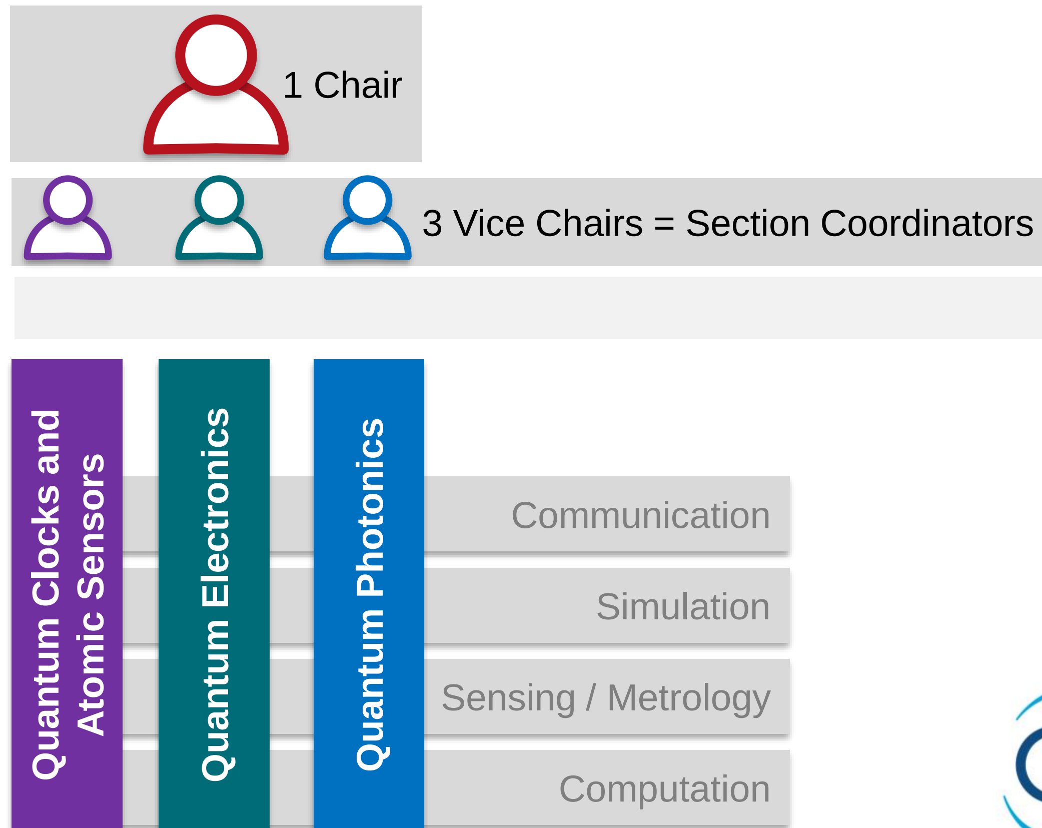
By 20 May 2021,
18 EURAMET Members and Partners
signed the MoU of EMN-Q

Aalto	FI
Metrosert	EE
CEM	SP
CMI	CZ
DFM	DK
GUM	PL
INRIM	IT
IPQ	PT
JV	NO
LNE	FR
LNE-LCM/CNAM	FR
LNE-SYRTE	FR
METAS	CH
VTT-MIKES	FI
NPL	UK
PTB	DE
RISE	SE
UME	TR

https://www.euramet.org/european-metrology-networks/quantum-technologies/quantum-technologies-member-institutes/

EMN-Q: Structure and Organisation

EMN-Q: Structure and Organisation



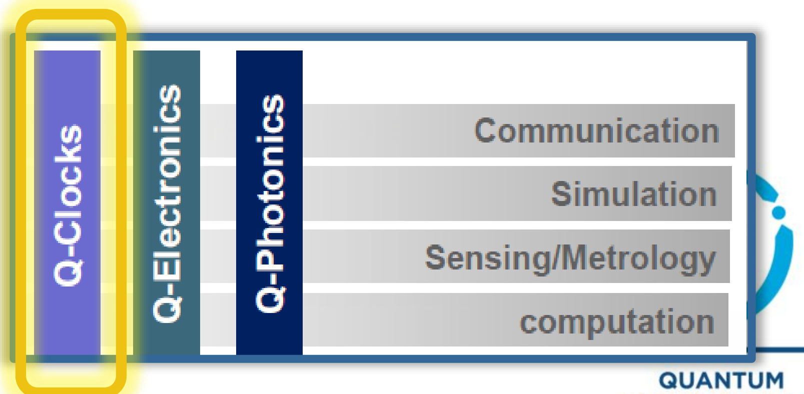
EMN-Q (3 sections)

EMN-Q

EURAMET

Quantum Clocks and Atomic Sensors

- **New optical clocks** and **quantum-enhanced** techniques (e.g. QND, entanglement-based)
- **EU frequency distribution** fiber network, space network
- **Certified time** and time stamping distribution
- **Atomic sensors**: gravimeters, gyroscopes, …
- …

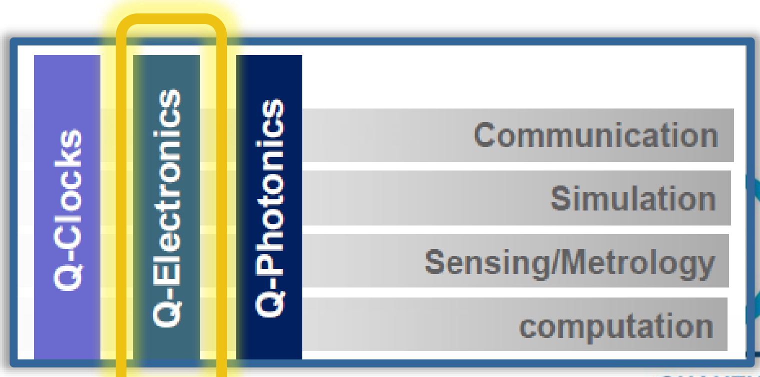


QUANTUM TECHNOLOGIES

EMN-Q

Quantum Electronics

- **Commercial quantum electrical standards** with graphene
- **Topological insulators**
- **Novel quantum devices** based on, e.g., superconducting nanostructures or semiconducting quantum dots for **electrical metrology and sensing**
- …

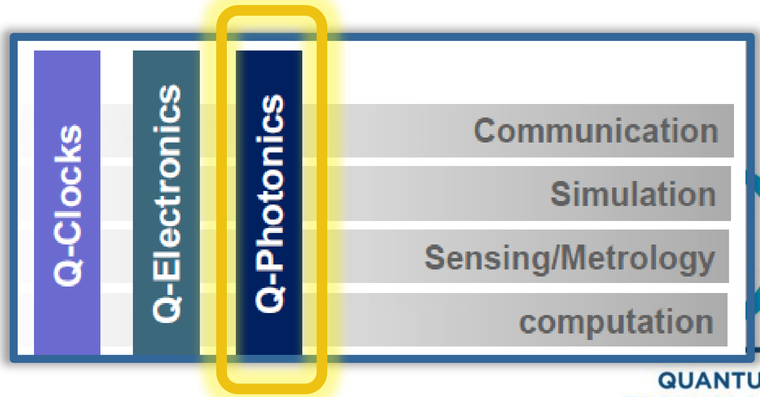


QUANTUM TECHNOLOGIES

EMN-Q

Quantum Photonics

- Traceability of measurement at **single photon level**
- **Metrology for QKD** in fiber and QKD testbeds, metrology for QKD in space
- **Quantum imaging**: metrology but also R&D
- **Quantum** (magnetic, pressure, temperature) **sensors** based on colour centers
- …



QUANTUM TECHNOLOGIES

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19NET02 «EMN-Quantum»
EMPIR
EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

EURAMET

Thanks for your attention!

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EMPIR EURAMET

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