

Detection efficiency characterization for free-space single-photon detectors

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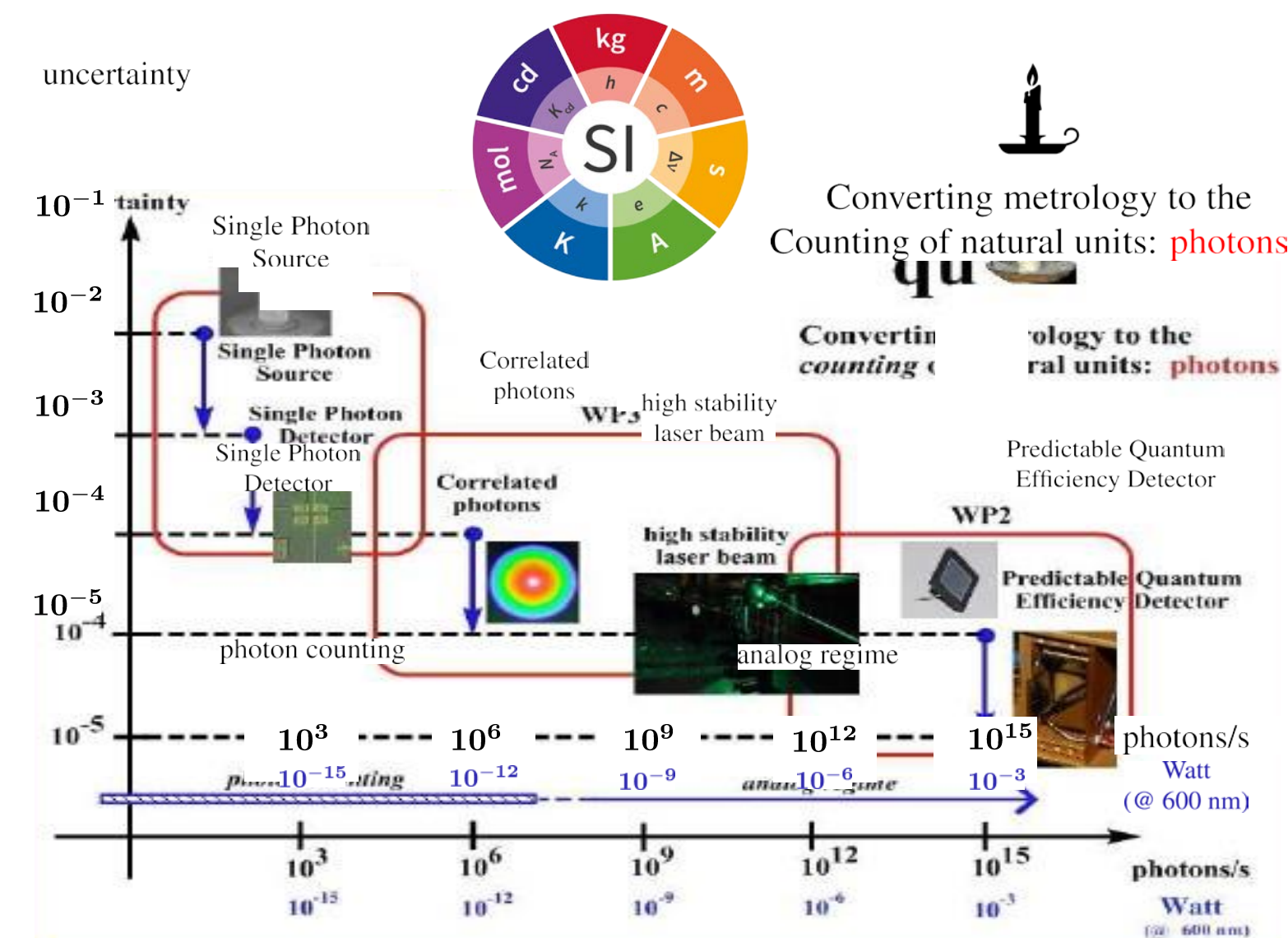
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Introduction

Single-photon detectors (SPDs) are essential for photon-based Quantum Technologies as Quantum Key Distribution (QKD).

The calibration of the **detection efficiency** of SPDs is of paramount importance for QKD security

Unlike detectors calibrated using classical radiometric techniques, there is currently **no established standard** for calibrating the detection efficiency of SPDs based on the measured counts



Quantum Radiometry: link between typical optical power measurement regime of conventional radiometry and photon counting regime.

Si-SPADs are SPDs operating in Geiger mode. They find huge application for free-space QKD wherein the employed wavelength is often around 850 nm



Spectral characterization

Etaloning effect of the two surfaces of the optical window of the SPAD packaging. For a window with thickness L and refractive index n , the transmissivity depends on the wavelength λ through the parameter Γ :

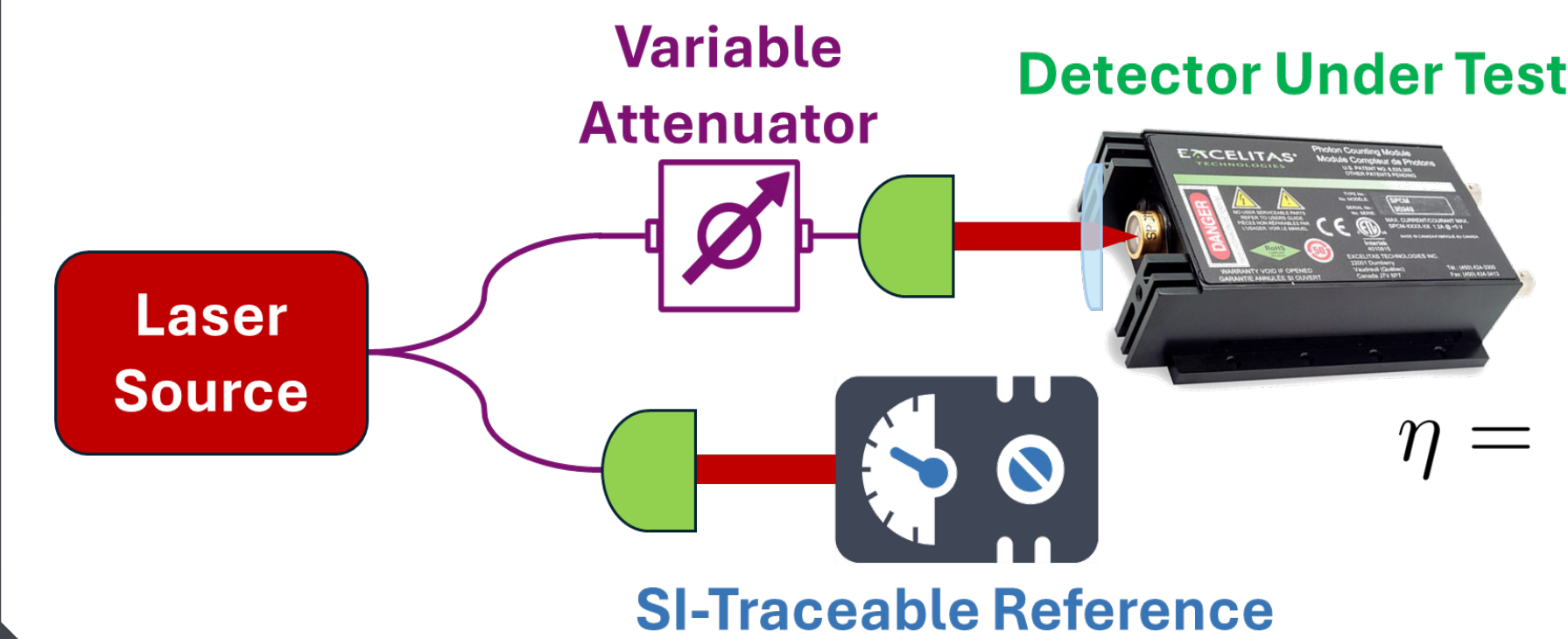
$$\Gamma(\lambda, n, L) = \frac{\gamma \left(1 - \exp \left[-2i \frac{2\pi}{\lambda} nL \right] \right)}{1 - \gamma^2 \exp \left[-2i \frac{2\pi}{\lambda} nL \right]}$$

with $\gamma = (n - n_a) / (n + n_a)$

The blue dots represent the experimental results with their associated standard measurement uncertainties, while the red line corresponds to the **fitted model**:

$$\eta_i(\lambda, n, L) = \eta_i(\lambda) (1 - |\Gamma(\lambda, n, L)|^2)$$

Substitution method



Detection efficiency:

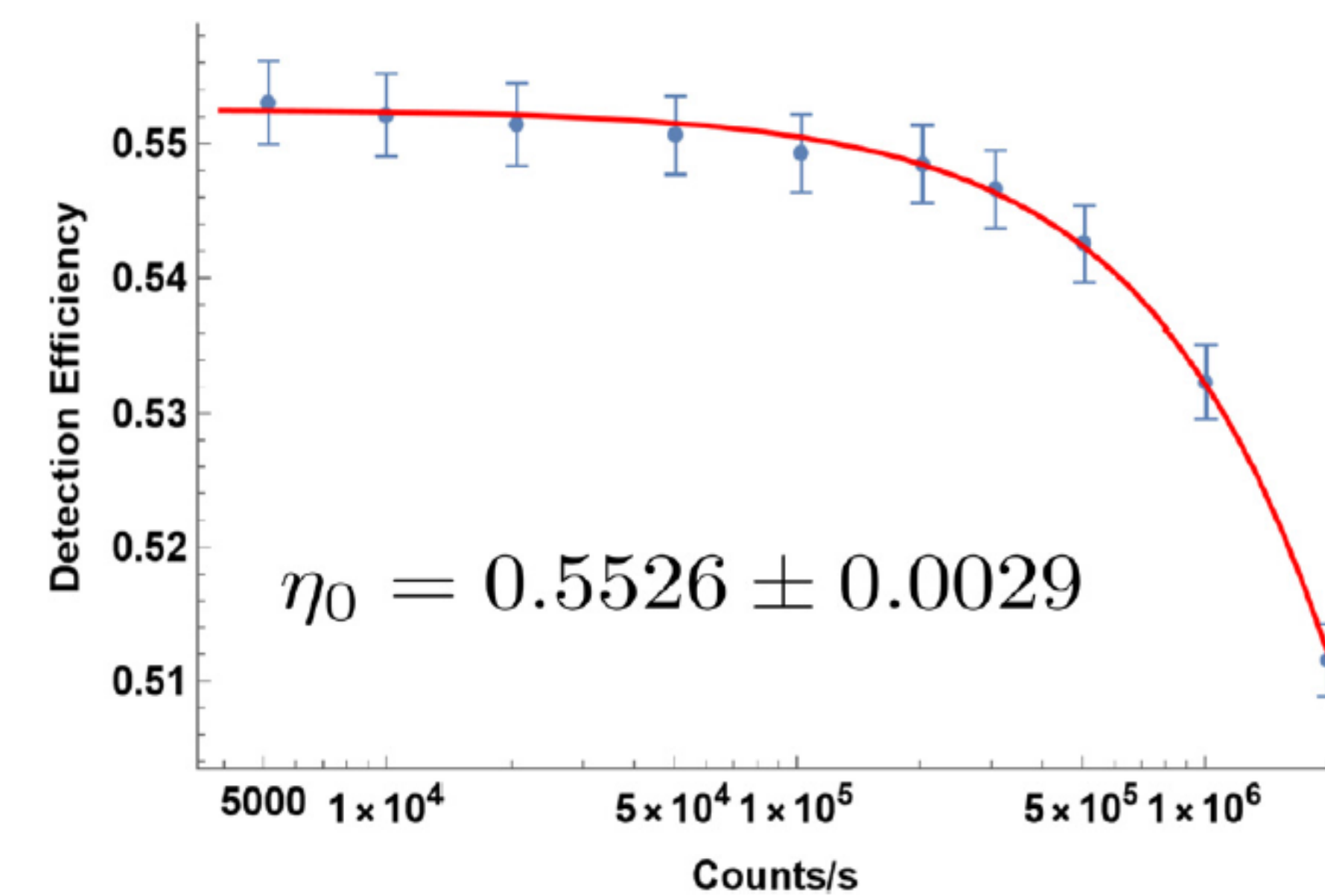
probability of a SPAD producing a measurable signal in response to one incident photon

The **substitution method** [1, 2] compares the signal measured by a **SI-traceable** detector with respect to the one measured from an SPD after a proper attenuation

$$\eta = \frac{hc}{\lambda} \frac{\mathcal{R}}{\tau \mathcal{P}}$$

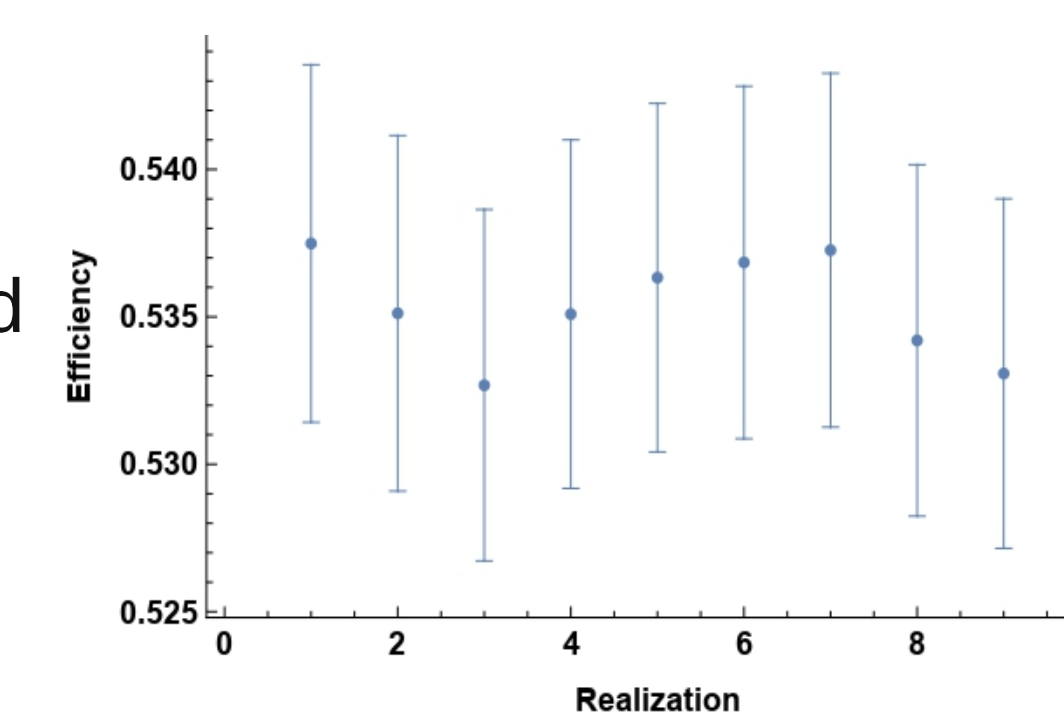
Results

To remove the arbitrary dependence on the count rate, the **zero-flux efficiency** η_0 , i.e. the detection efficiency extrapolated to the zero-flux level, whose value is not affected by the presence of the SPD dead time, is estimated.



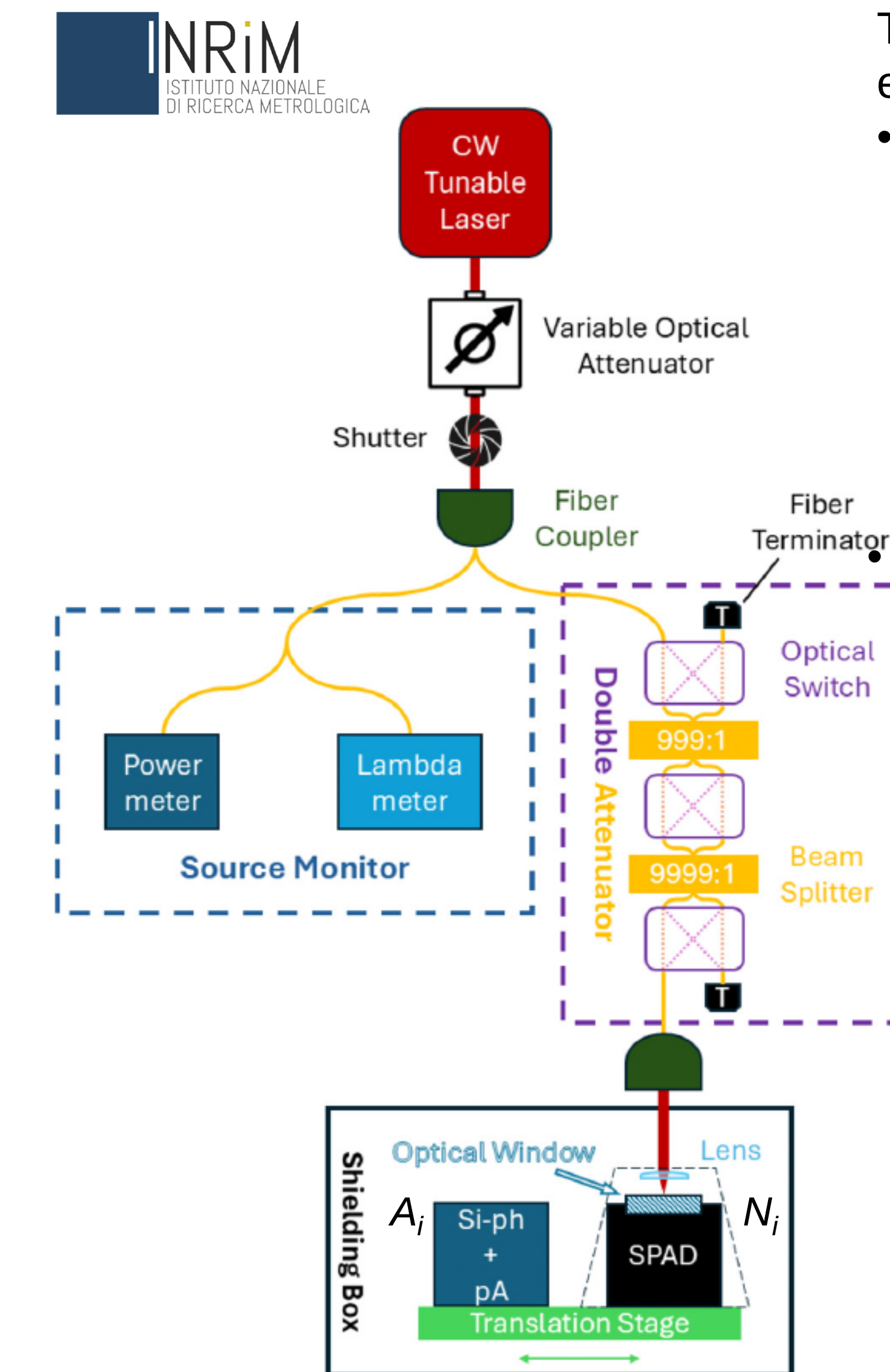
Si-SPAD detection efficiencies at η_0 obtained from **ten independent estimations** with related standard measurement uncertainties.

Coefficient	Value	Uncertainty	% Contribution
N_i'	20655	27	5.47
N_i^{env}	28	1	0.012
A_i'	1.92807×10^{-8} A	4.9×10^{-12} A	0.06
A_i^{env}	4.88×10^{-14} A	1.3×10^{-15} A	1.5×10^{-8}
τ	2.1601×10^{-7} s	7.0×10^{-10} s	33.83
ϵ	1.0148	1.4×10^{-3}	5.70
s	0.4766 W/A	1.9×10^{-3} W/A	51.55
C	1.000023	1.0×10^{-5}	3.2×10^{-4}
T	0.985000	3.0×10^{-5}	3.0×10^{-3}
λ	8.50711×10^{-7} m	6×10^{-12} m	1.6×10^{-4}
t	1.0000 s	1.0×10^{-3} s	3.22
$\langle \eta(N', \lambda) \rangle$	0.5514	0.0031	



An example of **uncertainty budget** for a fixed count rate. Uncertainties are propagated from the model considering both statistical and non-statistical contributions.

Experimental setup and model



The model for the detection efficiency estimation [3]:

- accounts for dark counts and background photons as well as for the dark current

$$\eta_i(\lambda) = \frac{hc}{\lambda t} \frac{s(N_i - N_i^{env})}{\tau C(A_i - A_i^{env})T}$$

corrects the measured N_i and A_i with respect to the source fluctuations:

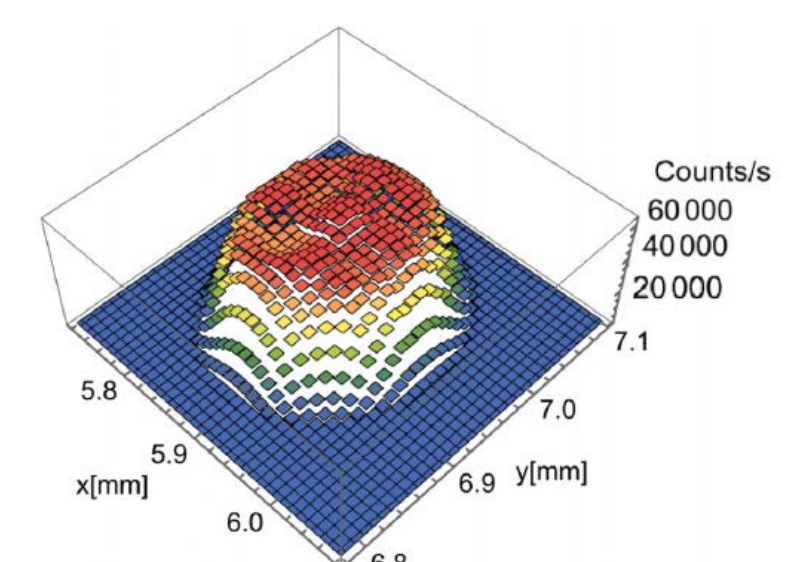
$$N_i \rightarrow N_i' = N_i \rho_i^{\text{DUT}}$$

$$A_i \rightarrow A_i' = \epsilon A_i \rho_i^{\text{Si-ph}}$$

with

$$\rho_i^{\text{DUT}} = \langle p_i^{\text{DUT}} \rangle / \langle p_i^{\text{DUT}} \rangle$$

$$\epsilon = \langle p_i^{\text{DUT}} \rangle / \langle p_i^{\text{Si-ph}} \rangle$$



(300×300) μm^2 scan of the Si-SPAD's active area obtained by probing with a focused beam with waist around 40 μm

Conclusions

- INRiM developed a facility for **traceable measurement of detection efficiency η_0** of commercial free-space Si-SPADs
- An innovative automated setup to estimate detection efficiency at a fixed wavelength with standard uncertainty less than 1 %, exploiting the double attenuator technique, was realized and tested
- The effect induced by the quartz window on the DUT efficiency was explored

References

- [1] M. López, H. Hofer & S. Kück, Detection efficiency calibration of single-photon silicon avalanche photodiodes traceable using double attenuator technique, *Journal of Modern Optics* **62**, 1732-1738 (2015)
- [2] M. López, A. Meda, *et al.*, A study to develop a robust method for measuring the detection efficiency of free-running InGaAs/InP single-photon detectors, *EPJ Quantum Technol.* **7**, 14 (2020)
- [3] S. Virzi, A. Meda, *et al.*, Detection efficiency characterization for free-space single-photon detectors: Measurement facility and wavelength-dependence investigation, *Appl. Phys. Lett.* **125**, 221108 (2024)