Proposal:
Photon-based candela

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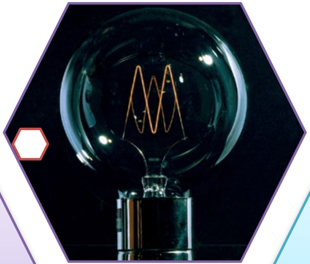
Bureau International des Poids et Mesures

Overview

1 cd ≙ 4.09… × 10^{15} ph/(s sr)

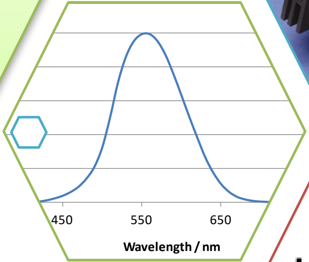
SI base unit: candela (cd)

The candela in numbers



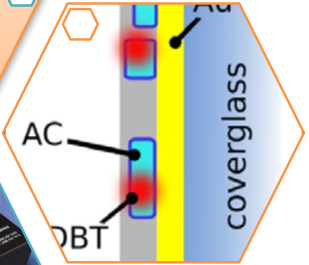
Photometric units vs. Radiometric units

How to measure single photons



How to generate single photons

152.83 µmol/s/m^2 (PPFD)



Photons and mole?

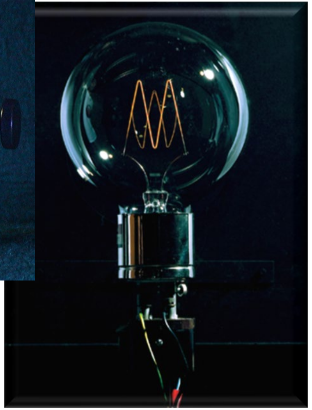
SI base unit: candela (cd)

The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540 x 10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or cd sr kg^{-1} m^{-2} s^3, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

https://www.bipm.org/en/si-base-units/candela

The candela is the ***luminous intensity***, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

$\Rightarrow$ The candela corresponds to a ***radiant intensity*** of 1/683 watt per steradian for monochromatic radiation of frequency 540 x 10^{12} hertz.



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The candela (cd) in numbers

A radiant intensity of 1/683 W per steradian for photons with a frequency of 540×10^{12} Hz corresponds to 1/683 W/(hν) photons per second per steradian:

$\Rightarrow$ N/s = 1/683 W/(hν) = 1 Js^{-1} /(683 × 6.626 070 15 × 10^{-34} Js × 540 × 10^{12} s^{-1})

$\Rightarrow$ N/s = 4.091942356… × 10^{15} s^{-1}

Simple rewording of the definition!

I.e.,:

- **the candela corresponds to 4.091942356… × 10^{15} photons per second per steradian with photons at a frequency of 540 × 10^{12}.**
- **a nanocandela corresponds to 4.091942356… × 10^{6} photons per second per steradian with photons at a frequency of 540 × 10^{12}.**

Measurable (countable) with single-photon detectors!

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SI base unit: candela (cd)

The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540 x 10^{12} Hz, $K_{cd,n}$, **to be 4.091942356… × 10^{15} when expressed in the unit lm s photons^{-1}, which is equal to cd sr s photons^{-1}, where the second is defined in terms of $\Delta\nu_{Cs}$ and photons are given as a number.**

The candela is the ***luminous intensity***, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of **4.091942356… × 10^{15} photons per second** per steradian.

⇒ The candela corresponds to a ***radiant intensity*** of 1/683 watt per steradian for monochromatic radiation of frequency 540 x 10^{12} hertz.

Photometry and radiometry based on counting

Number of photons

Radiant Flux
Power

$$\Phi = \frac{n}{t}\frac{hc}{\lambda}$$

Time

Photon energy
- **Constants of nature**
- **Wavelength**

Note:
Candela is the unit for luminous intensity, thus involving the steradian

Counting with sources and detectors

Pulse to single photon converter

PULSED LASER f_{rep} → **SPS** → **Single-Photon Detector**

$n/t = f_{rep}$

$$\Phi = f_{rep} \frac{hc}{\lambda}$$

$$\Phi = \frac{n}{t} \frac{hc}{\lambda}$$

Internal Quantum Efficiency < 100 %
Photon Collection Efficiency < 100 %

Absolute, predictable Single-Photon Source

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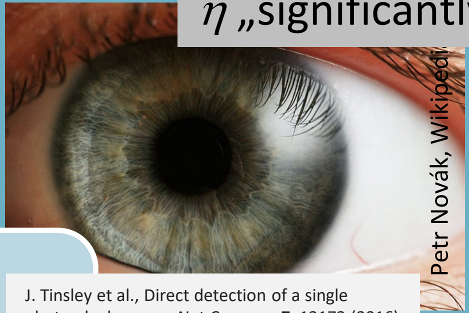
How to measure single-photons?

Single Photon Avalanche Diode (SPAD)

$\eta \approx 80\ \%$

Human Eye!

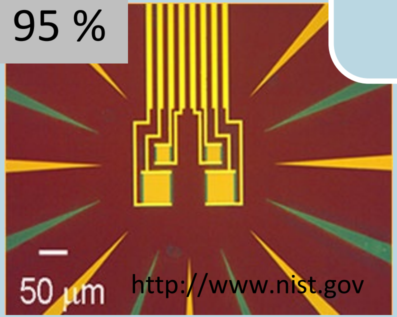
η „significantly above chance“



J. Tinsley et al., Direct detection of a single photon by humans. *Nat Commun* **7**, 12172 (2016)

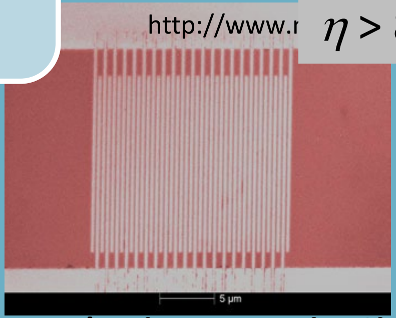
Single-photon detectors

$\eta > 95\ \%$



Transition Edge Sensor (TES)

$\eta > 85\ \%$



Superconducting Nanowire Single-Photon Detector (SNSPD)

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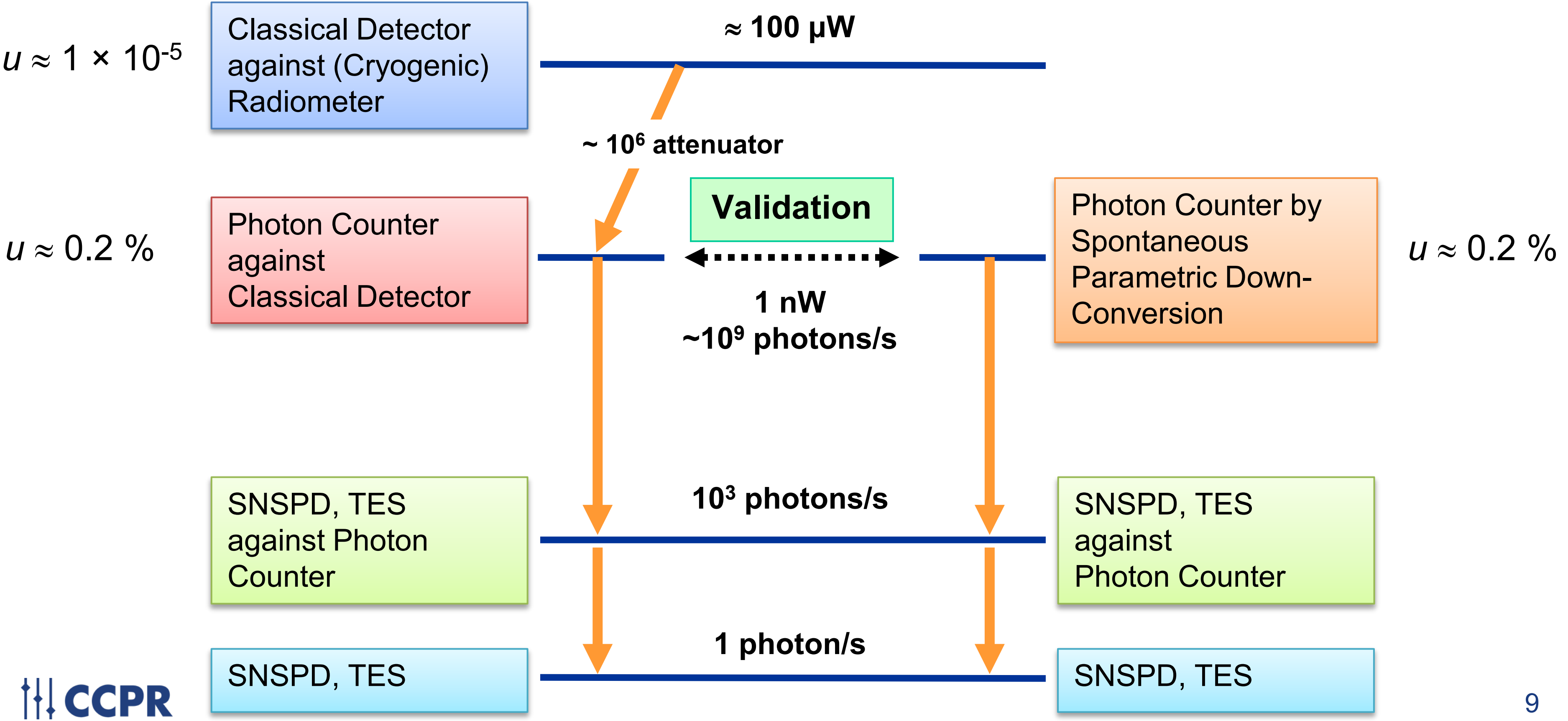
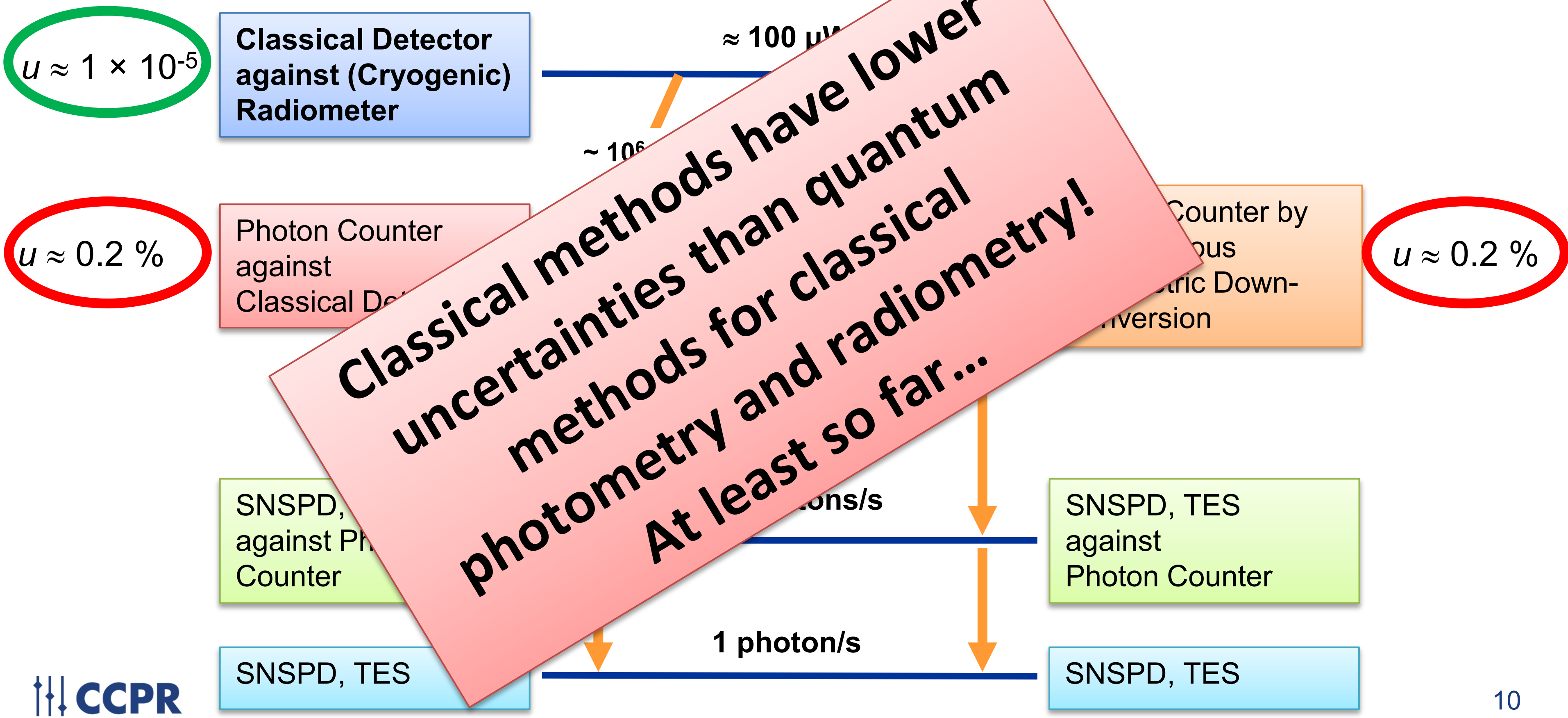
Standard detector – Traceability

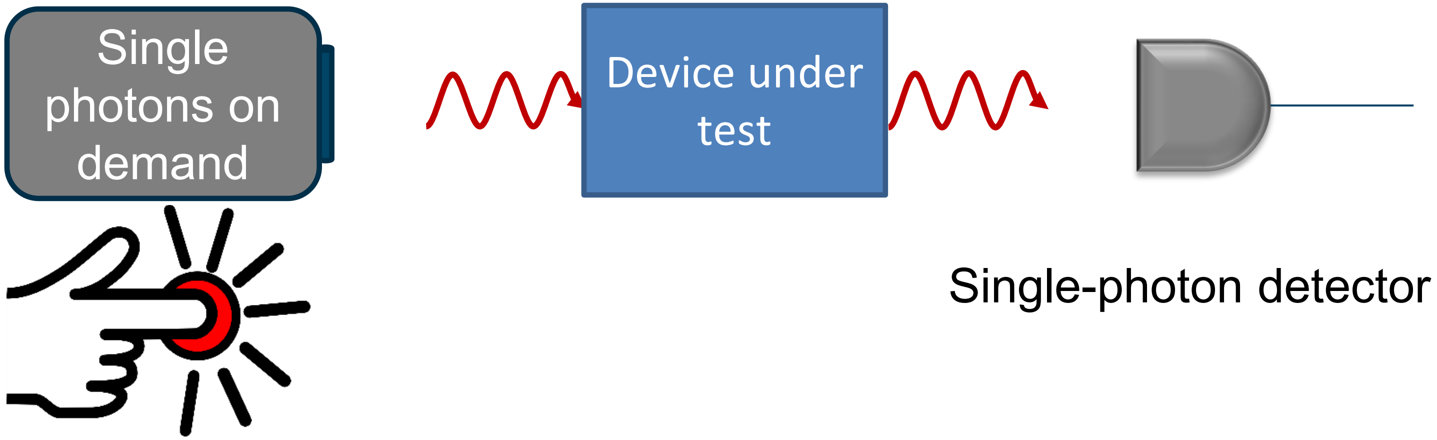


Standard detector – Traceability



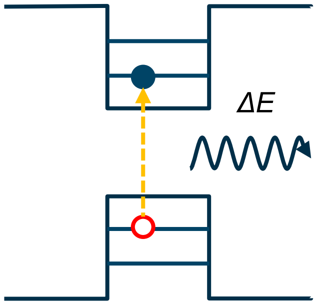
Classical methods have lower uncertainties than quantum methods for classical photometry and radiometry! At least so far…

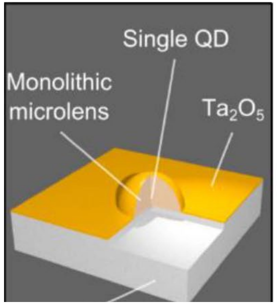
What about single-photon sources?



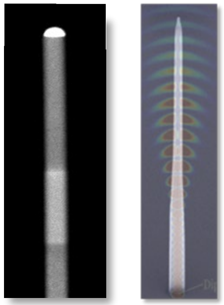
Deterministic single-photon sources

Quantum dots





InP
InAs
InP

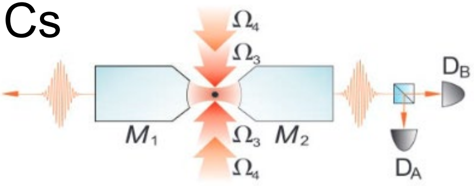


berlin

NRC·CNRC

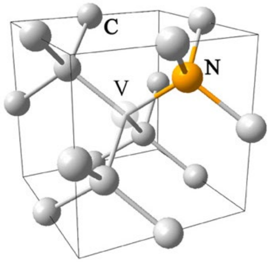
Single atoms

Cs



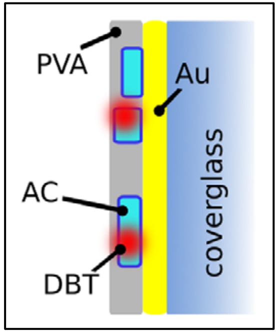
Science 303, 1992 (2004)

Defect centres in diamond



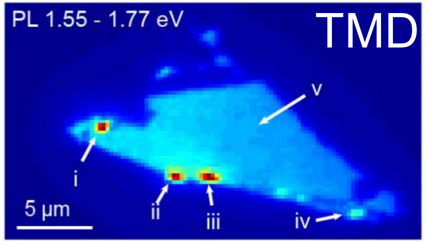
Rep. Prog. Phys. 74 076501 (2011)

Single molecules



CNR-INO

Defect in 2D materials



Optica 2, 347 (2015)

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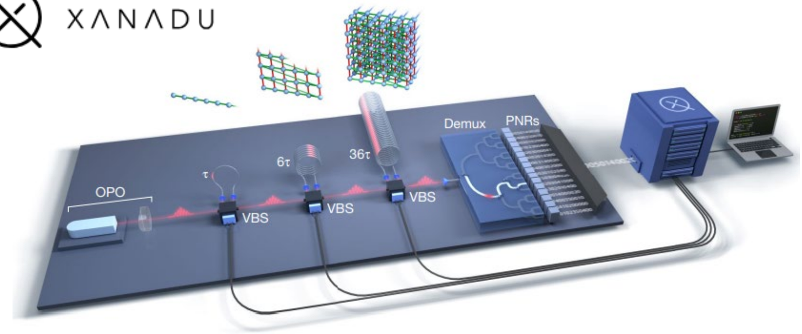
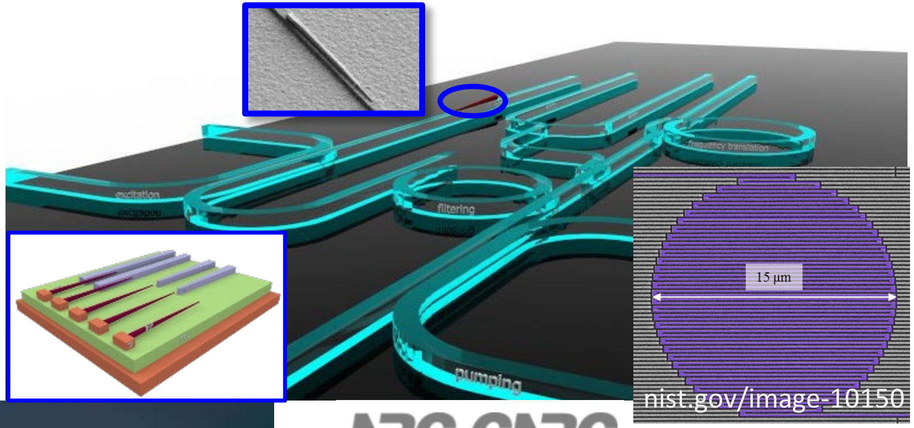
Integrated single-photon technologies

Photonic integrated circuits for quantum computing & quantum networks

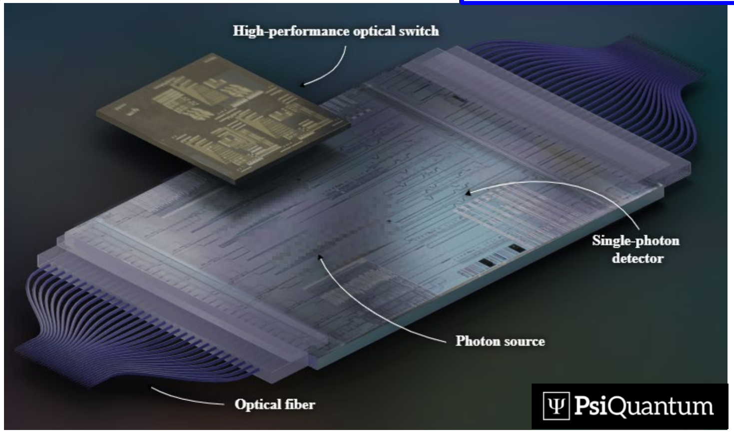
XANADU



Madsen et. al. Nature 606, 75 (2022)



NRC·CNRC



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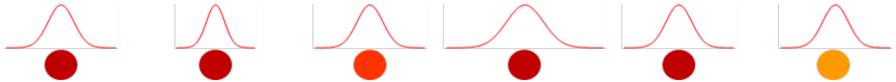
Single-photon source characteristics

Photon purity: produces single-photons with 100 % probability 

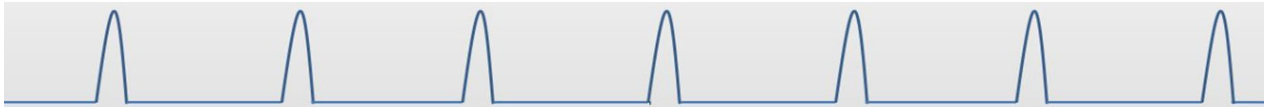
Indistinguishability: spectral, spatial, temporal and polarization properties



Efficiency: photon generation and collection efficacy

→ Optical fibre vs free space optics

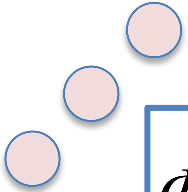
Repetition rate: GHz rates for quantum information applications



Motivation for single-photon sources in metrology

Quantum Radiometry

- Reduction of measurement uncertainty
- Standard source
- Realization of photon-number-based candela



"N_{cd}"

$$\Phi = f_{rep} \frac{hc}{\lambda}$$

Sub-shot noise metrology

Ideal SPS has no noise!
Noise-reduced measurements:

- e. g. transmission measurement

$$\frac{\Delta T_{SP}^2}{\Delta T_C^2} = 1 - 2\eta \frac{T}{1+T}$$

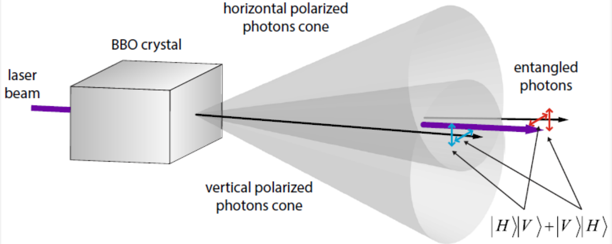
ΔT variance in transmission
T transmission
η total efficiency of setup

B. Lounis, M. Orrit, Rep. Prog. Phys. **68** 1129 (2004)

Photon-photon entanglement

Applications, e.g.:

- Quantum information
- Imaging, Spectroscopy
- Quantum physics fundamentals



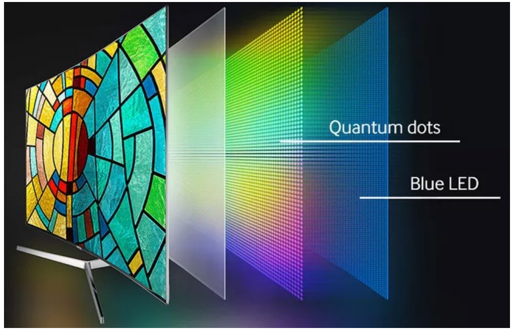
Opt. Quant. Electron. **48**, 363 (2016)

Applications beyond “metrology“

Quantum dot emitters:

- Used in display and other light emitting technologies

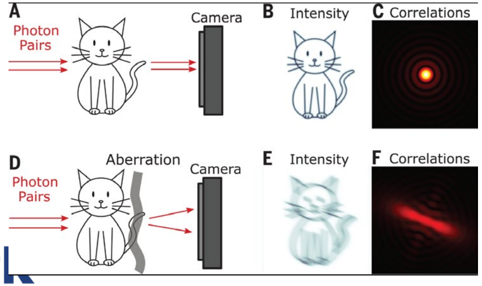
  → Control over aesthetics and ambiance

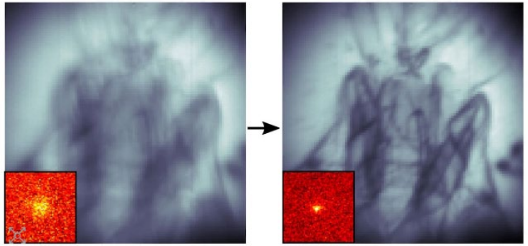


www.lifewire.com/quantum-dots-enhance-lcd-tv-performance

Photon counting in Medical technologies

- Computerized tomography (PCCT) minimized patient exposure to x-ray radiation and increases image resolution
- Microscopy for biological imaging



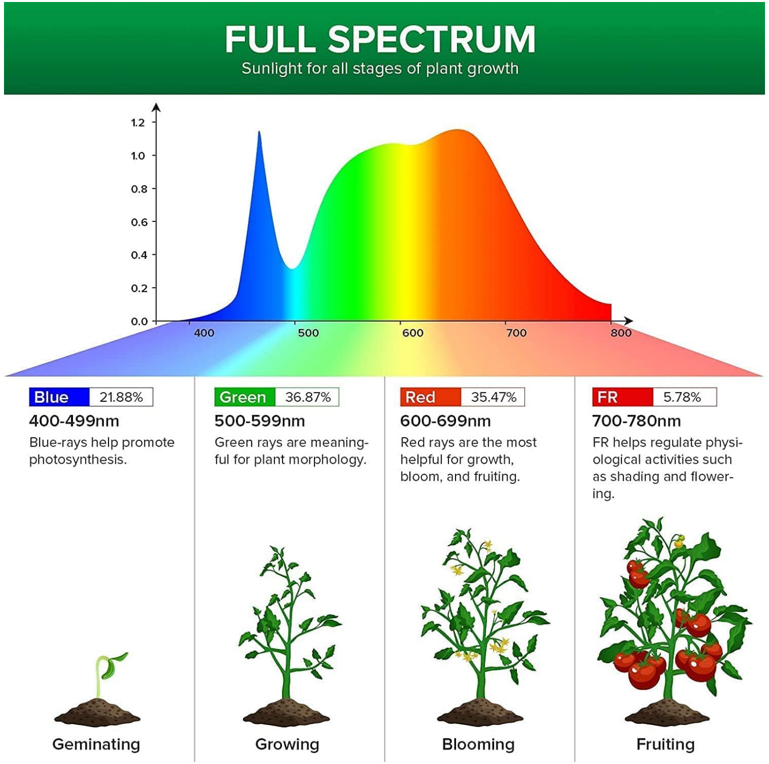


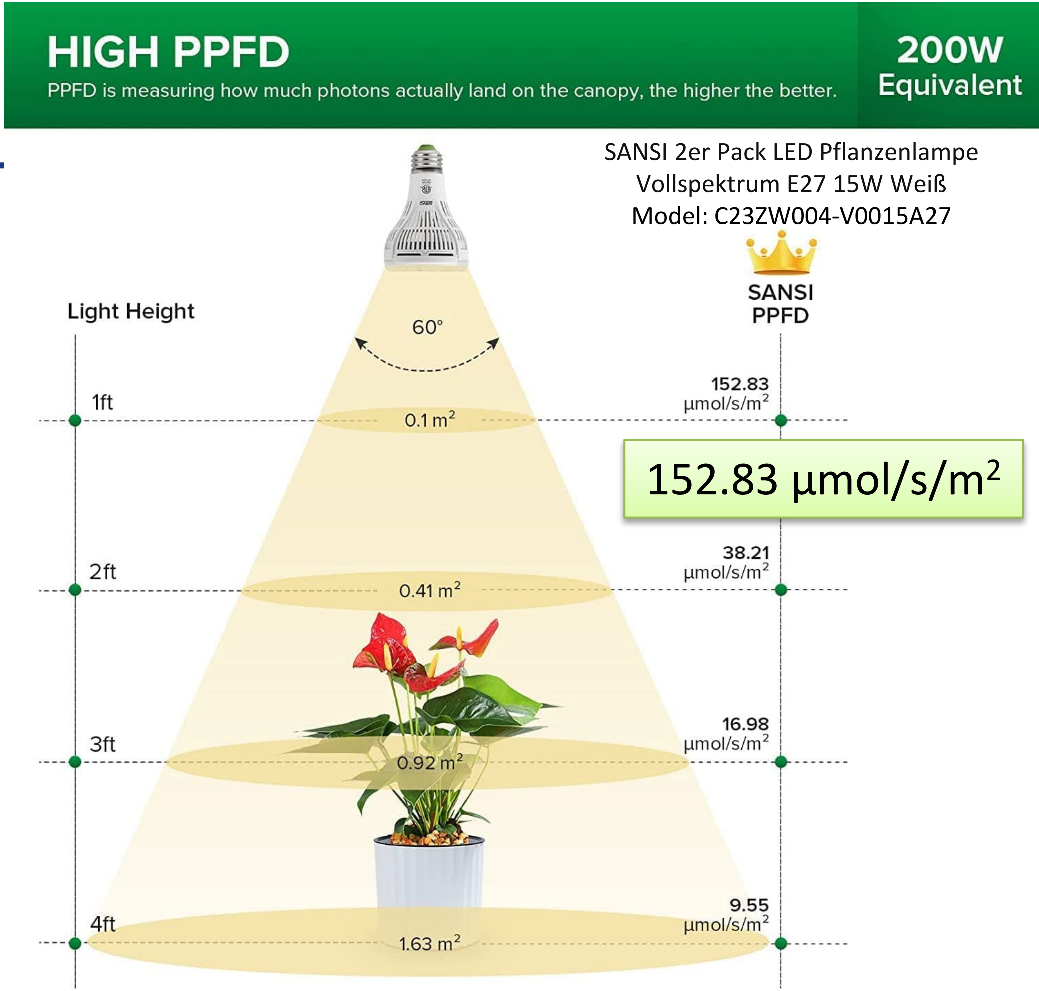
Science **383** 1142 (2024)

https://physicsworld.com/a/entangled-photons-enhance-adaptive-optical-imaging/

https://physicsworld.com/a/photon-counting-ct-promises-a-new-era-of-medical-imaging/

Counting photons in botany





SANSI 2er Pack LED Pflanzenlampe Vollspektrum E27 15W Weiß
Model: C23ZW004-V0015A27

152.83 µmol/s/m²

PPFD: Photosynthetic Photon Flux Density

Take home messages

Candela – by counting photons?

Pros: Potential unified framework for quantifying light

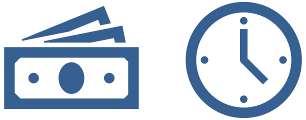
Photons for photonics & photometry

Useful for many applications:

- Quantum information
- Low flux radiometry / Quantum radiometry
- Medical, biological, display and light emitting technologies

Cons:

- Higher measurement uncertainties (at least for now)
- Financial and time costs of changing measurement practices in the lighting industry



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