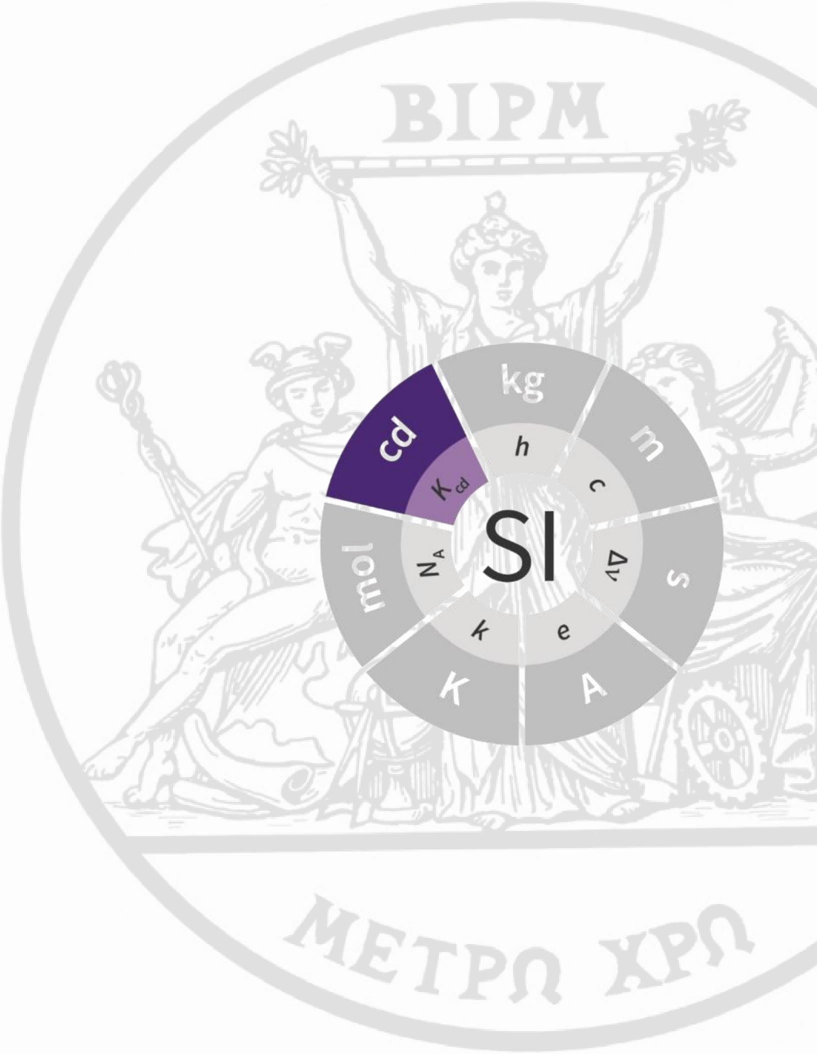
2023 CCU/CCQM workshop on: The metrology of quantities which can be counted

Stefan Kück, PTB
Report at the CCPR WG-SP
2023-09-09

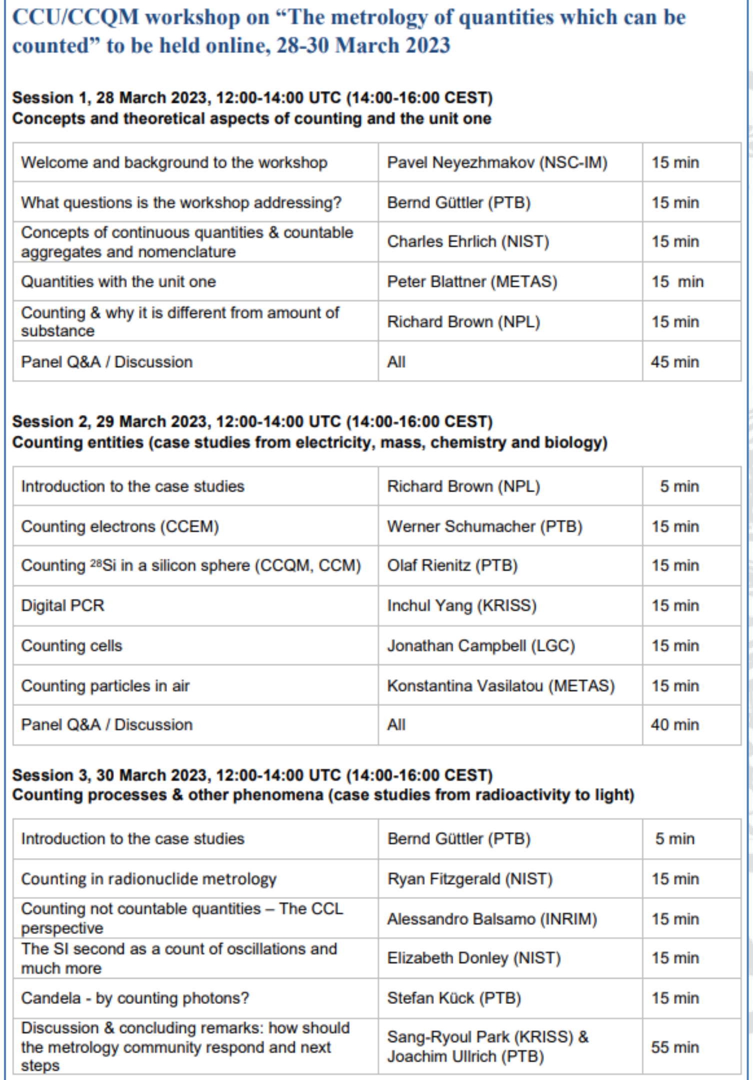


Bureau
International des
Poids et
Mesures

2023 CCU/CCQM workshop on: The metrology of quantities which can be counted

Stefan Kück, PTB
Report at the CCPR WG-SP
2023-09-09

Bureau
International des
Poids et
Mesures



CCU/CCQM workshop on "The metrology of quantities which can be counted" to be held online, 28-30 March 2023

Session 1, 28 March 2023, 12:00-14:00 UTC (14:00-16:00 CEST)
Concepts and theoretical aspects of counting and the unit one

Welcome and background to the workshop	Pavel Neyezhmakov (NSC-IM)	15 min
What questions is the workshop addressing?	Bernd Güttler (PTB)	15 min
Concepts of continuous quantities & countable aggregates and nomenclature	Charles Ehrlich (NIST)	15 min
Quantities with the unit one	Peter Blattner (METAS)	15 min
Counting & why it is different from amount of substance	Richard Brown (NPL)	15 min
Panel Q&A / Discussion	All	45 min

Session 2, 29 March 2023, 12:00-14:00 UTC (14:00-16:00 CEST)
Counting entities (case studies from electricity, mass, chemistry and biology)

Introduction to the case studies	Richard Brown (NPL)	5 min
Counting electrons (CCEM)	Werner Schumacher (PTB)	15 min
Counting ^{28}Si in a silicon sphere (CCQM, CCM)	Olaf Rienitz (PTB)	15 min
Digital PCR	Inchul Yang (KRISS)	15 min
Counting cells	Jonathan Campbell (LGC)	15 min
Counting particles in air	Konstantina Vasilatou (METAS)	15 min
Panel Q&A / Discussion	All	40 min

Session 3, 30 March 2023, 12:00-14:00 UTC (14:00-16:00 CEST)
Counting processes & other phenomena (case studies from radioactivity to light)

Introduction to the case studies	Bernd Güttler (PTB)	5 min
Counting in radionuclide metrology	Ryan Fitzgerald (NIST)	15 min
Counting not countable quantities – The CCL perspective	Alessandro Balsamo (INRIM)	15 min
The SI second as a count of oscillations and much more	Elizabeth Donley (NIST)	15 min
Candela - by counting photons?	Stefan Kück (PTB)	15 min
Discussion & concluding remarks: how should the metrology community respond and next steps	Sang-Ryoul Park (KRISS) & Joachim Ullrich (PTB)	55 min

2023 CCU/CCQM workshop on
The metrology of quantities which can be counted

Candela - by counting photons?

CCPR, Stefan Kück

In consultation with:
- Maria Luisa Rastello
- Maria Nadal

Lecture, in excerpts

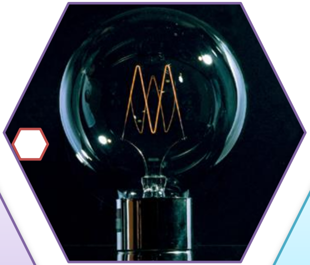
Bureau
International des
Poids et
Mesures

Overview

$$1\ \text{cd} \triangleq 4.09\ldots \times 10^{15}\ \text{ph/(s sr)}$$

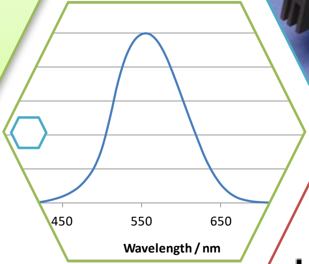
SI base unit: candela (cd)

The candela in numbers



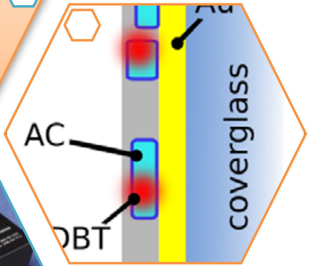
Photometric units vs. Radiometric units

How to measure single photons



How to generate single photons

152.83 μmol/s/m^2 (PPFD)



Photons and mole?

Photometric Units vs. Radiometric Units

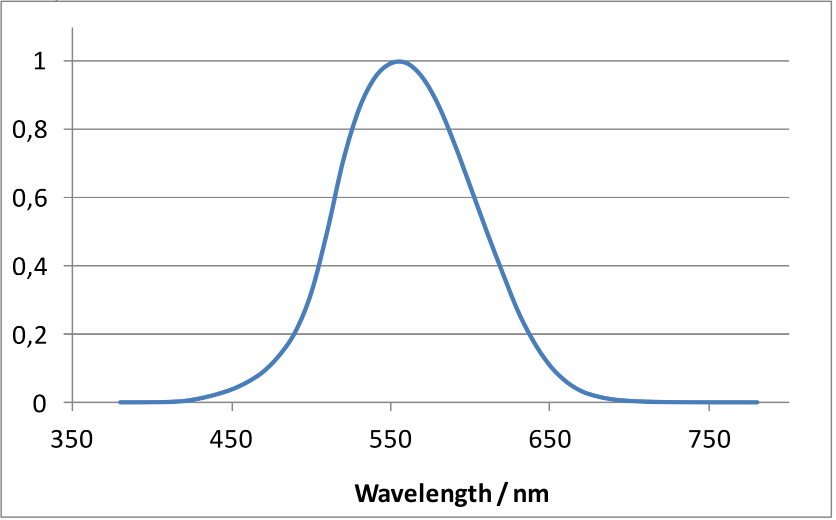
To consider:

Measured quantities in photometry are spectrally integrated quantities!

$$X_{\mathrm{v,x}} = \frac{K_{\mathrm{cd}}}{V_{\mathrm{x}}(\lambda_a)} \int_\lambda X_{\mathrm{e},\lambda}(\lambda) V_{\mathrm{x}}(\lambda) \mathrm{d}\lambda$$

The most important of these visual functions is the photopic luminous efficiency function for the light-adapted eye, *V*(*λ*), which is defined by the CIE over the wavelength range 360 nm to 830 nm at 1 nm intervals.

CCPR-WG-SP-TG16:
Cone Fundamentals



Nonetheless: 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) = $1\ \mathrm{Js}^{-1} / (683 \times 6.626\ 070\ 15 \times 10^{-34}\ \mathrm{Js} \times 540 \times 10^{12}\ \mathrm{s}^{-1})$

$\Rightarrow$ N/s = $4.091942356\ldots \times 10^{15}\ \mathrm{s}^{-1}$

I.e.,:

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

Measurable (countable) with single-photon detectors!

How to measure single-photons?

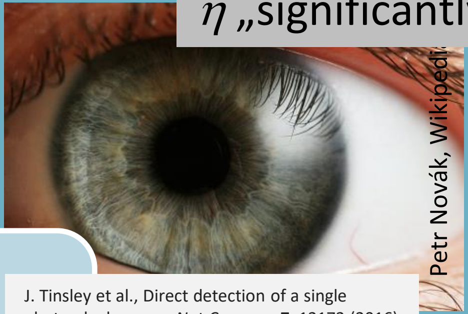
Single Photon Avalanche Diode (SPAD)

$\eta \approx 80\ \%$


nsor-ic.com/

Human Eye!

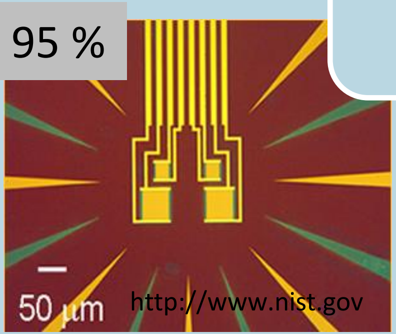
η „significantly above chance“


Petr Novák, Wikipedi

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

Single-photon detectors

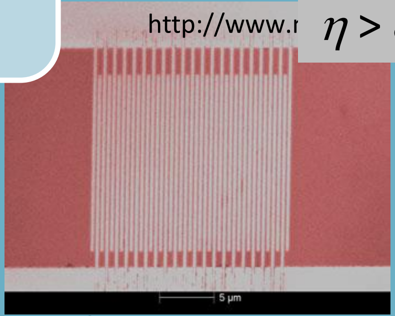
$\eta > 95\ \%$



http://www.nist.gov

Transition Edge Sensor (TES)

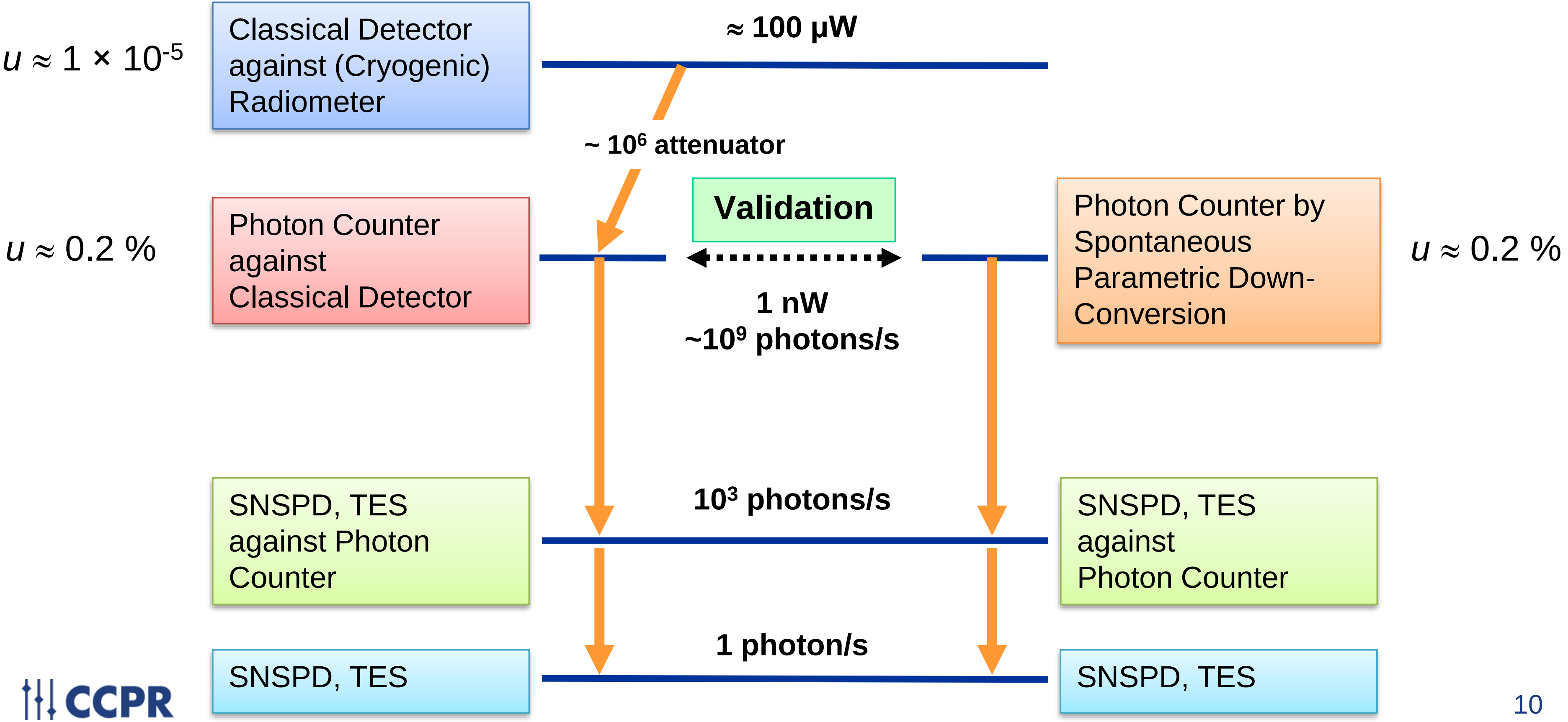
$\eta > 85\ \%$



http://www.r

Superconducting Nanowire Single-Photon Detector (SNSPD)

Standard detector – Traceability



$u \approx 1 \times 10^{-5}$

Classical Detector against (Cryogenic) Radiometer

≈ 100 µW

~ 10^6 attenuator

$u \approx 0.2\ \%$

Photon Counter against Classical Detector

Validation

1 nW
~10^9 photons/s

Photon Counter by Spontaneous Parametric Down-Conversion

$u \approx 0.2\ \%$

10^3 photons/s

SNSPD, TES against Photon Counter

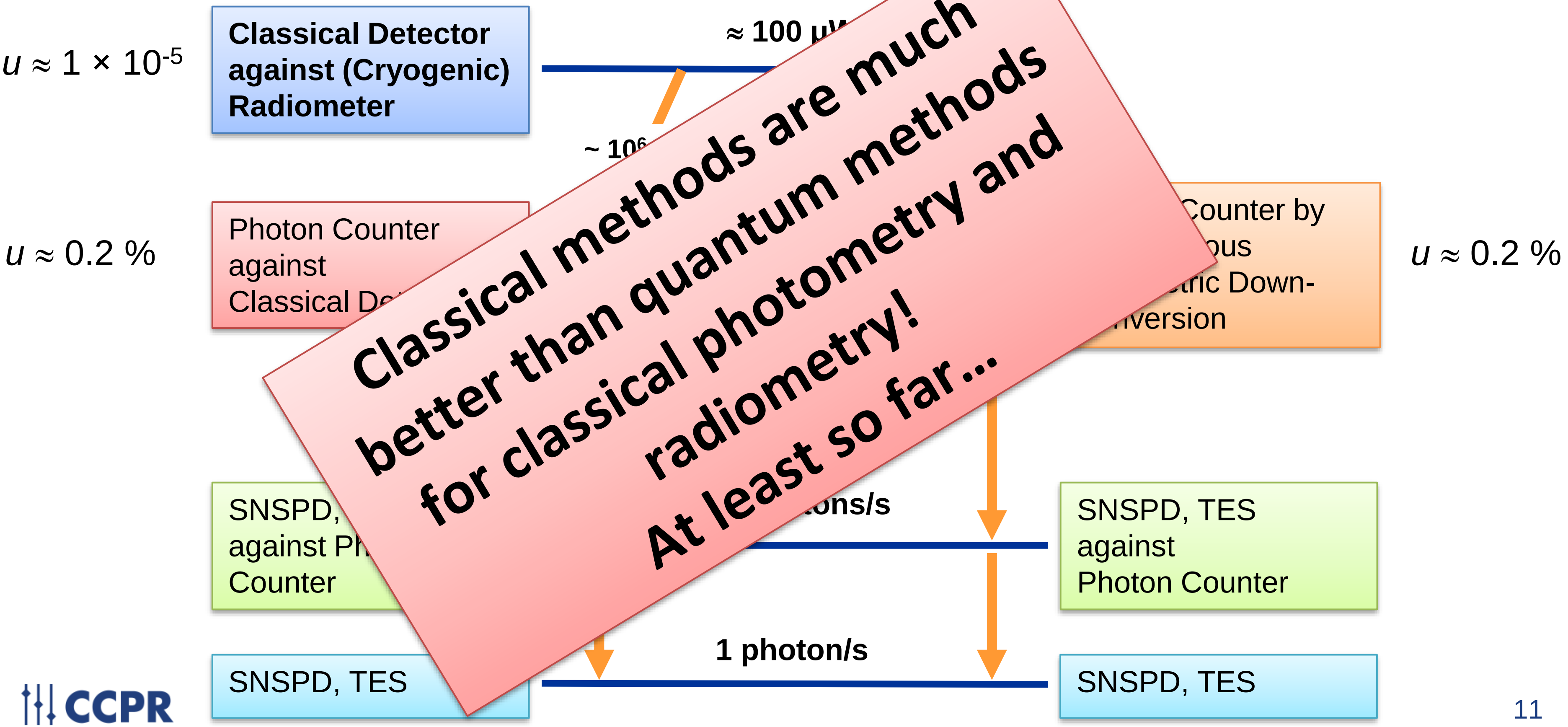
SNSPD, TES against Photon Counter

1 photon/s

SNSPD, TES

SNSPD, TES

Standard detector – Traceability



$u \approx 1 \times 10^{-5}$

Classical Detector against (Cryogenic) Radiometer

≈ 100 µW

~ 10^6

$u \approx 0.2$ %

Photon Counter against Classical De

Counter by ous tric Down- nversion

$u \approx 0.2$ %

Classical methods are much better than quantum methods for classical photometry and radiometry!

At least so far…

SNSPD, against Ph Counter

ons/s

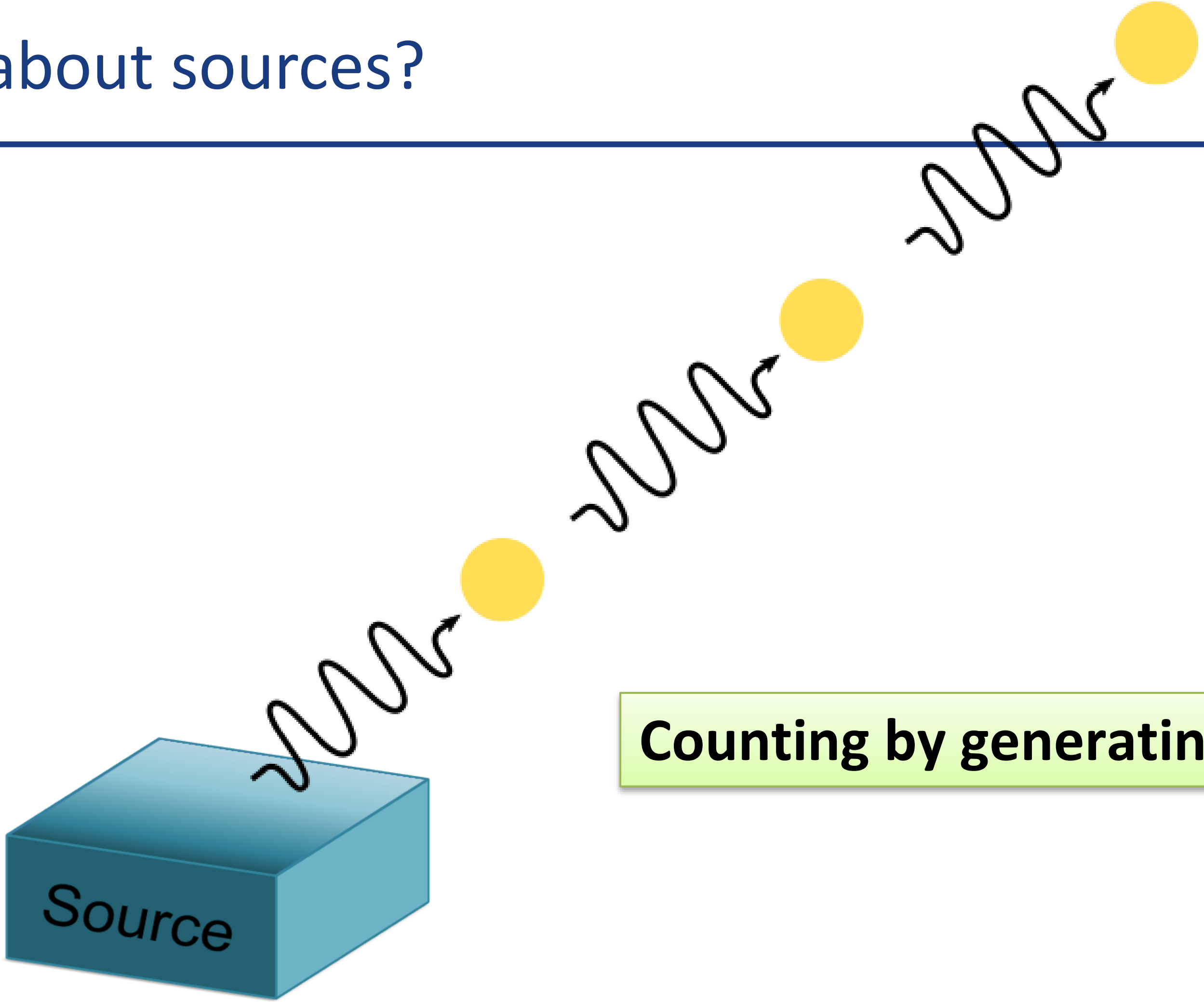
SNSPD, TES against Photon Counter

1 photon/s

SNSPD, TES

SNSPD, TES

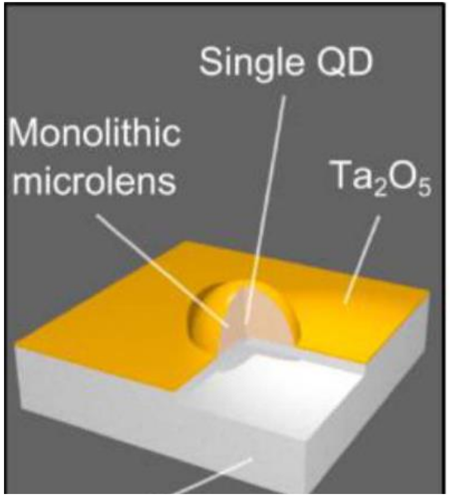
What about sources?



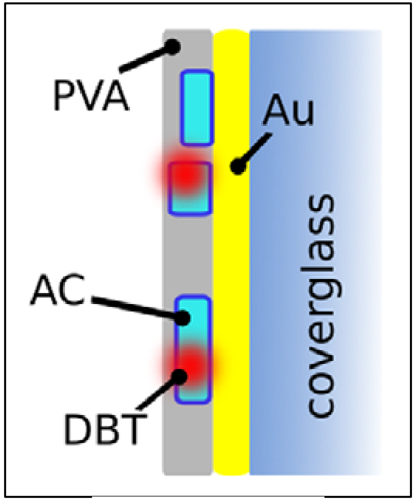
Counting by generating!?

Single photon sources – how to?

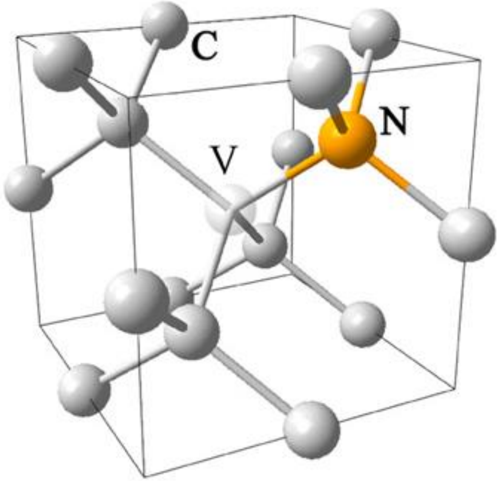
Semiconductor quantum dots



Single molecules

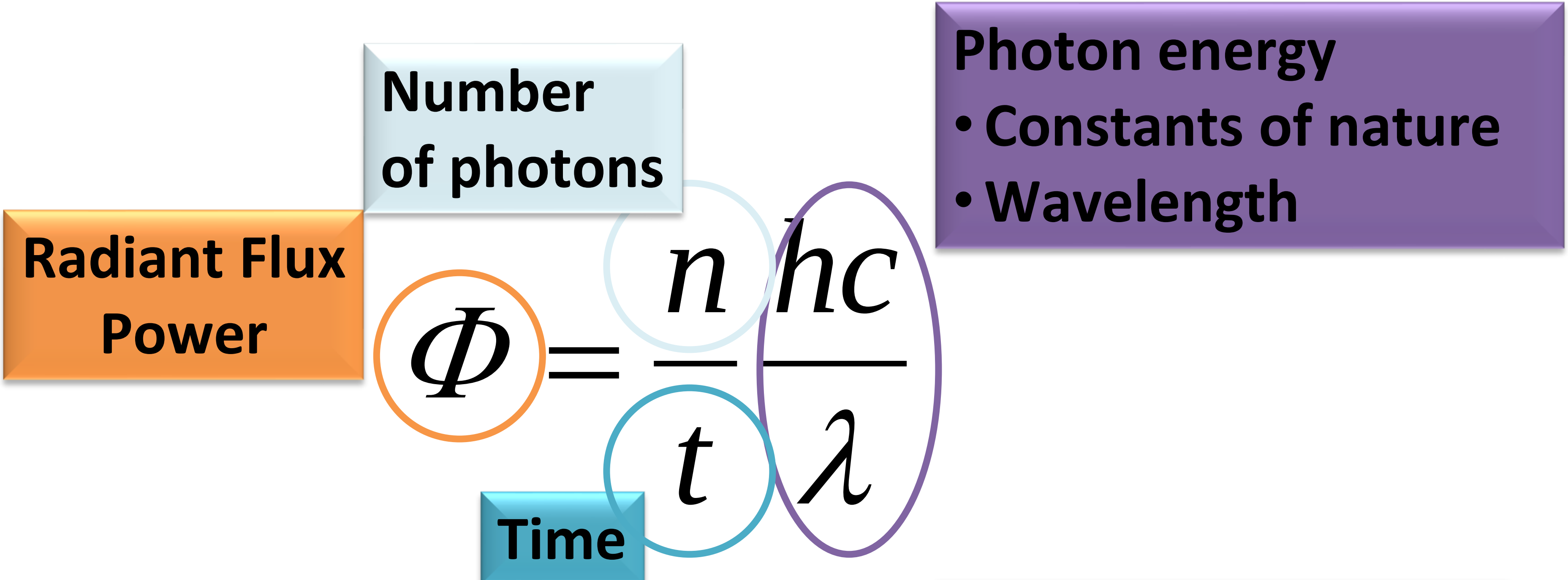


Colour centres in diamond



I. Aharonovich et al.,
Rep. Prog. Phys. 74 076501 (2011)

My dream…



Radiant Flux
Power

Number of photons

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

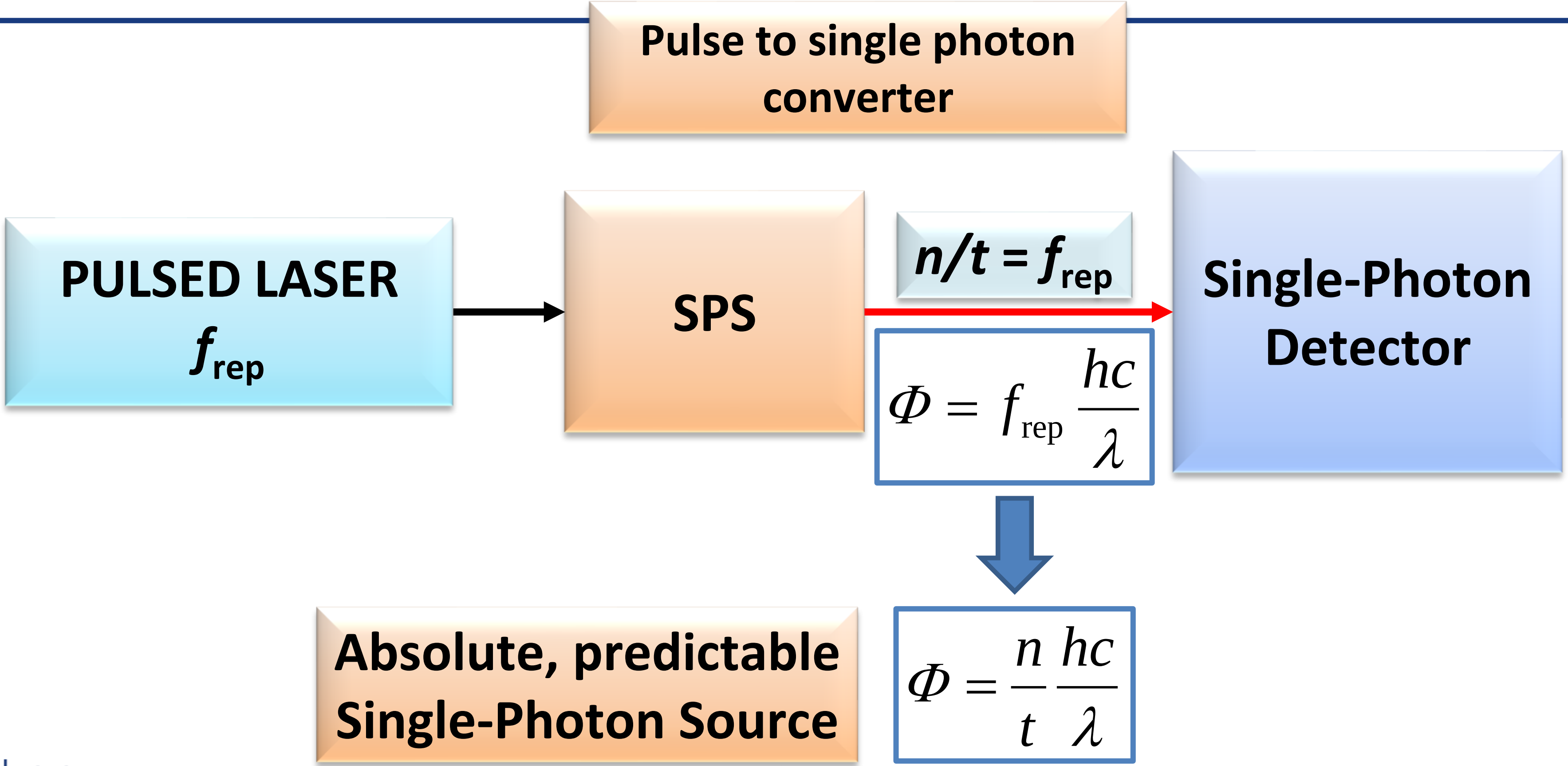
Time

Photon energy

- **Constants of nature**
- **Wavelength**

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

My dream… comes true!



Pulse to single photon converter

PULSED LASER
f**rep**

SPS

n/t* = *f**rep**

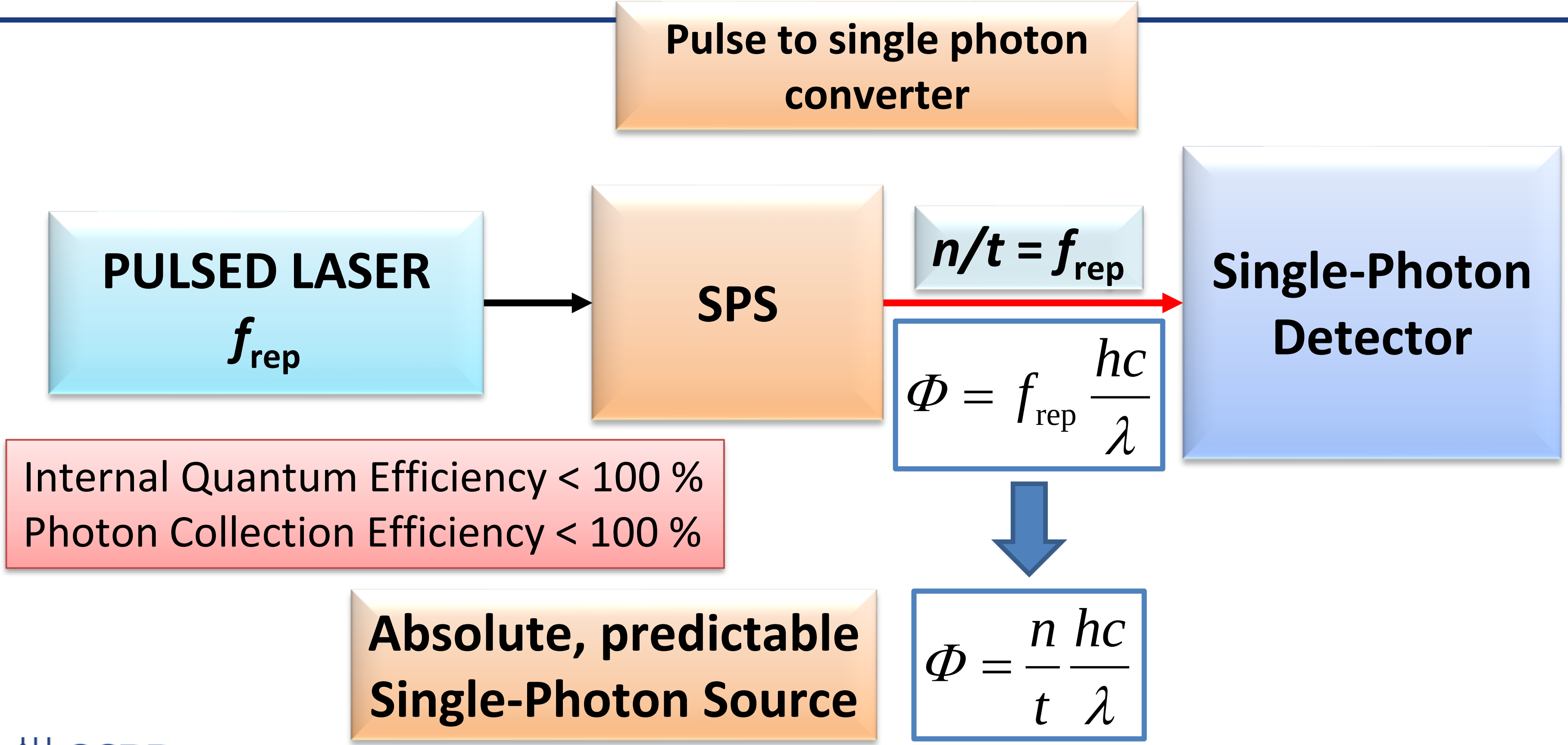
$$\Phi = f_{\text{rep}} \frac{hc}{\lambda}$$

Single-Photon Detector

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

Absolute, predictable Single-Photon Source

Waking up is hard...!



Pulse to single photon converter

PULSED LASER
f_{rep}

SPS

$n/t = f_{\mathrm{rep}}$

Single-Photon Detector

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

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

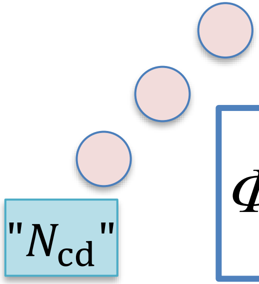
Absolute, predictable Single-Photon Source

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

Motivation for single-photon sources in metrology

Quantum Radiometry

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



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

Sub-shot noise metrology

Ideal SPS has no noise!
Noise-reduced measurements:

- e. g. transmission measurement

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

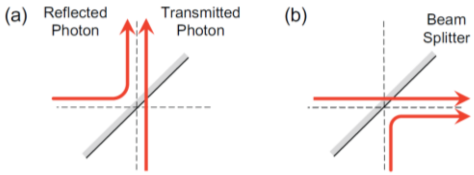
ΔT	variance in transmission
T	transmission
η	total efficiency of setup

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

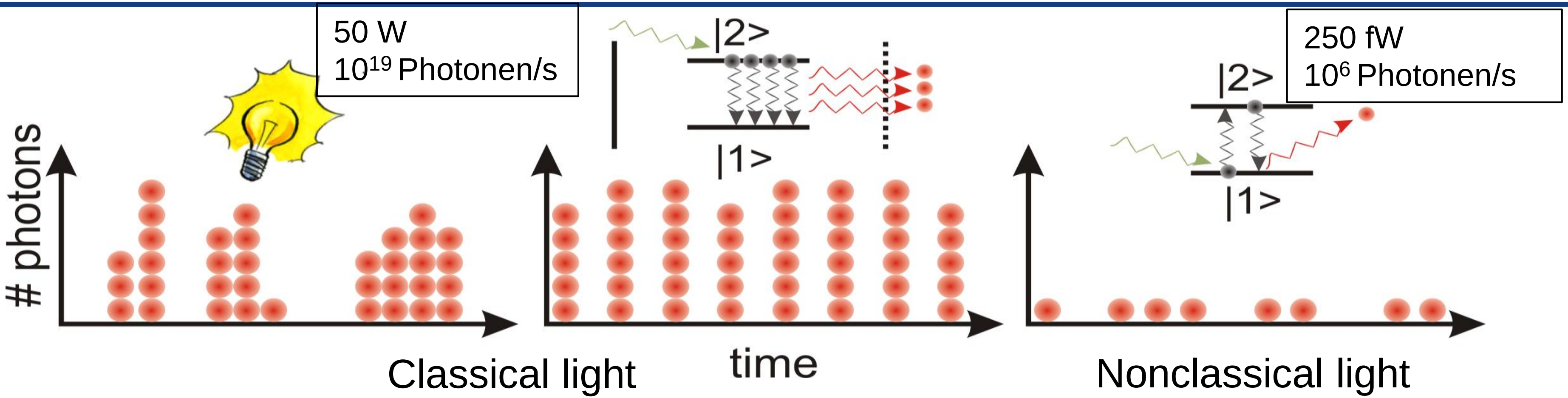
Photon-photon entanglement

Applications, e.g.:

- quantum cryptography
- quantum repeater
- quantum computing



Photon statistics



50 W
10^{19} Photonen/s

250 fW
10^{6} Photonen/s

Classical light

Nonclassical light

Thermal light

Coherent (Laser) light

Super-Poissonian-Distribution
bunching effect

Poissonian-Distribution

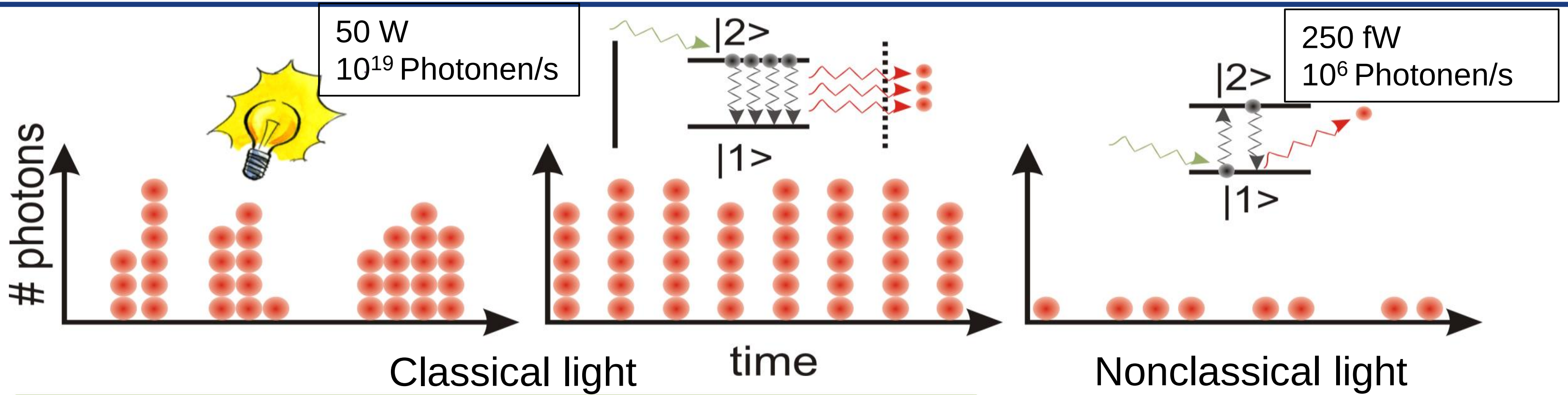
Sub-Poissonian-Distribution
anti-bunching effect

$$P_{h\nu}^{therm.}(n) = \frac{\langle n\rangle^n}{(\langle n\rangle + 1)^{n+1}}$$

$$P_{h\nu}^{Laser}(n) = \frac{\langle n\rangle^n e^{-\langle n\rangle}}{n!}$$

$$P_{h\nu}^{\text{Fock m}}(n) = \delta_{n,m}$$

Photon statistics



50 W
10^{19} Photonen/s

250 fW
10^{6} Photonen/s

Classical light

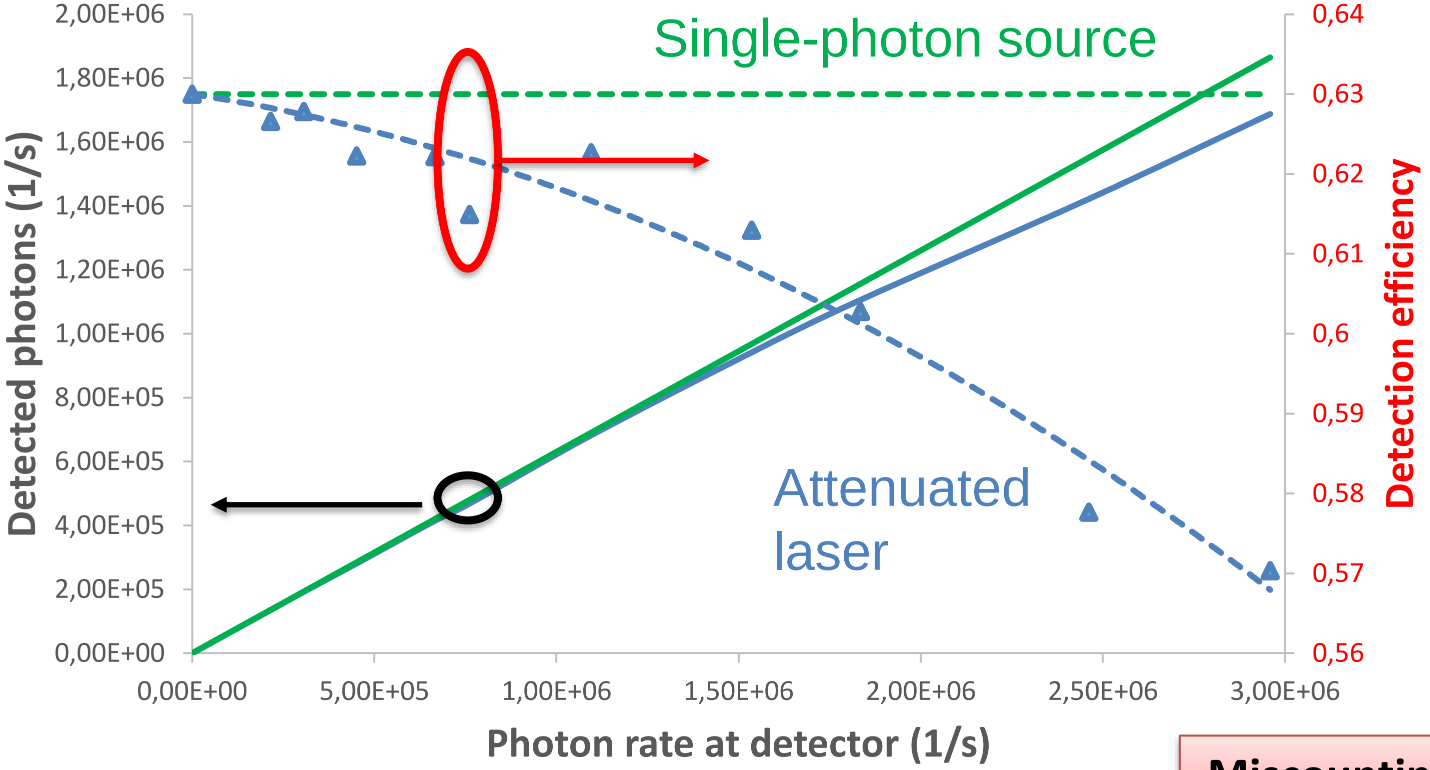
Nonclassical light

With thermal or with laser light, there will always be - with a specific probability - more than one photon within a time slot!

Sub-Poissonian-Distribution
anti-bunching effect

$$P_{h\nu}^{\text{Fock m}}(n) = \delta_{n,m}$$

Influence on measurement



Miscounting!

Finally: the candela and the mole?

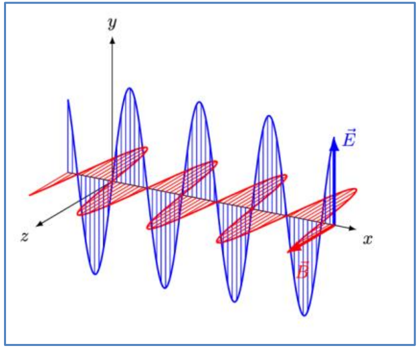
$$4.091942356\ldots \times 10^{15}\ \text{photons}/(\text{s sr})$$

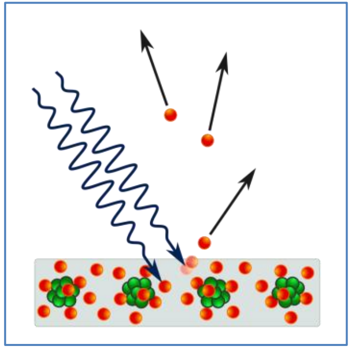
$$=$$

$$6.794830142\ldots \times 10^{-9}\ \text{mol}/(\text{s sr})$$

Note:
The mole is the unit of amount of substance
Photons sometimes are / behave like particles

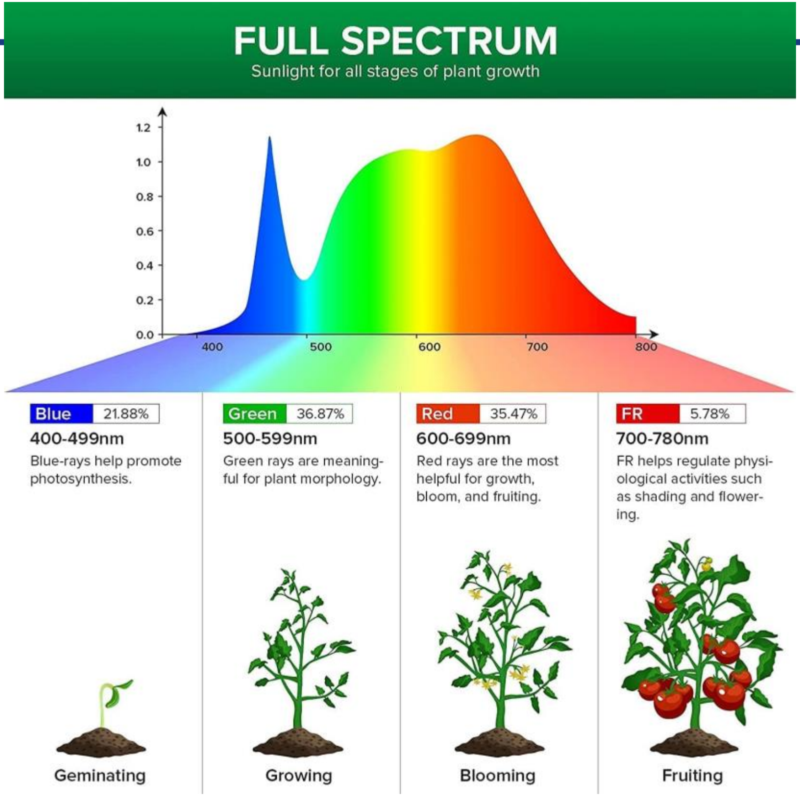
Von And1mu - Eigenes Werk, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=49759107



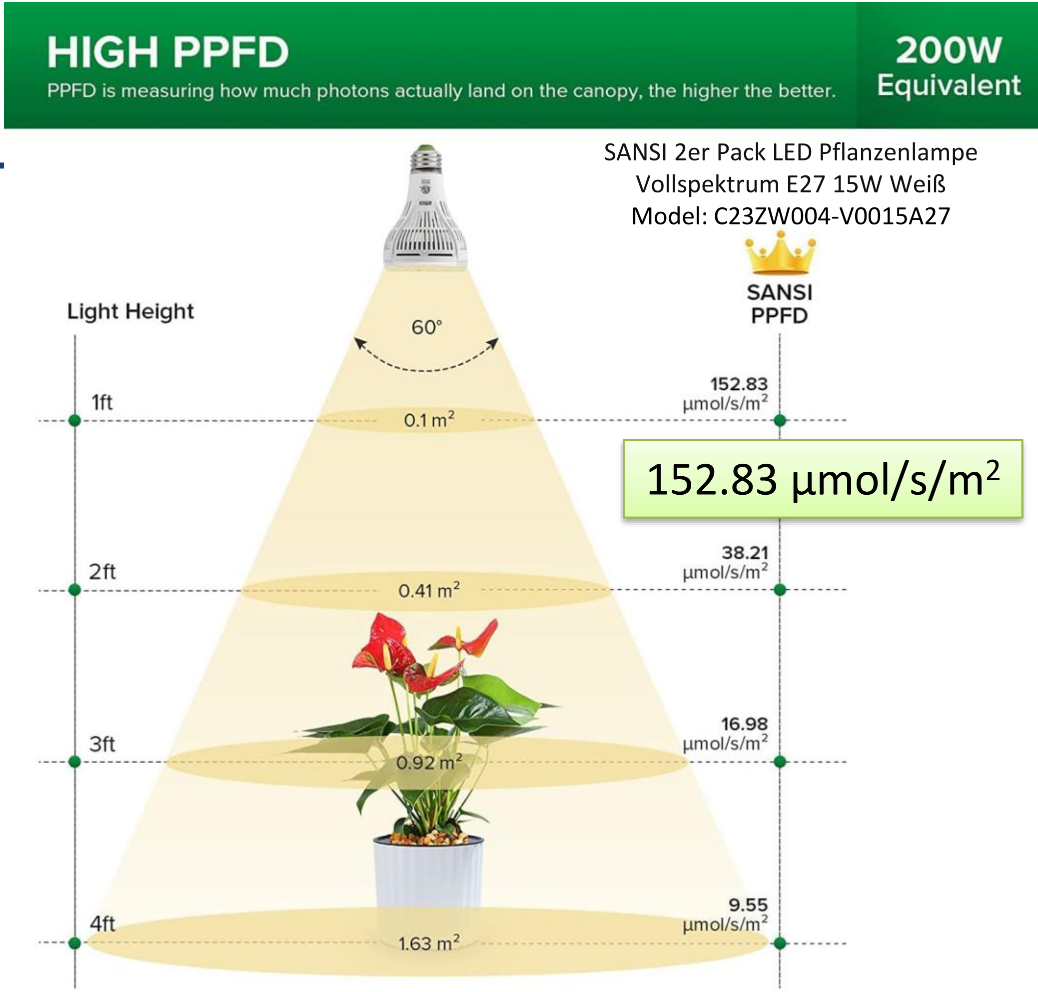


Von Ponor - Eigenes Werk, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=92684859

Photons and mole?



Blue 21.88%	**Green** 36.87%	**Red** 35.47%	**FR** 5.78%
400-499nm	**500-599nm**	**600-699nm**	**700-780nm**
Blue-rays help promote photosynthesis.	Green rays are meaningful for plant morphology.	Red rays are the most helpful for growth, bloom, and fruiting.	FR helps regulate physiological activities such as shading and flowering.
Geminating	Growing	Blooming	Fruiting



PPFD is measuring how much photons actually land on the canopy, the higher the better.

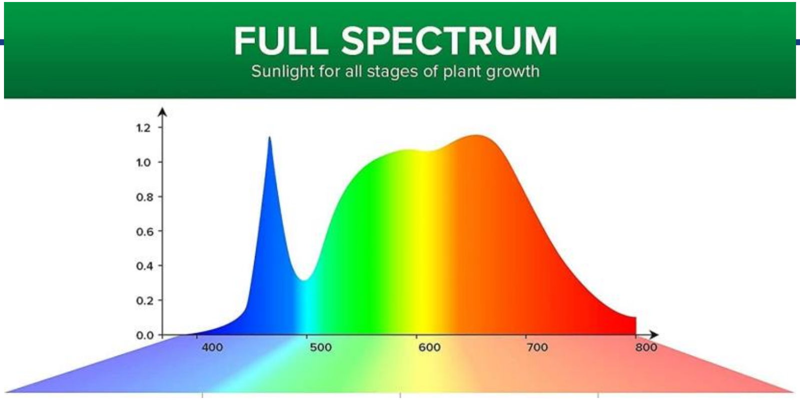
SANSI 2er Pack LED Pflanzenlampe
Vollspektrum E27 15W Weiß
Model: C23ZW004-V0015A27

Light Height		SANSI PPFD
1ft	0.1 m²	152.83 µmol/s/m²
2ft	0.41 m²	38.21 µmol/s/m²
3ft	0.92 m²	16.98 µmol/s/m²
4ft	1.63 m²	9.55 µmol/s/m²

152.83 µmol/s/m²

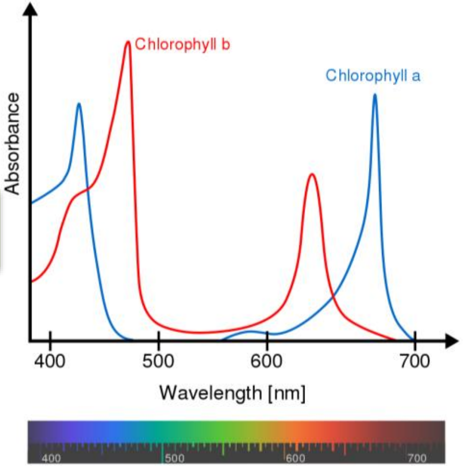
PPFD: Photosynthetic Photon Flux Density

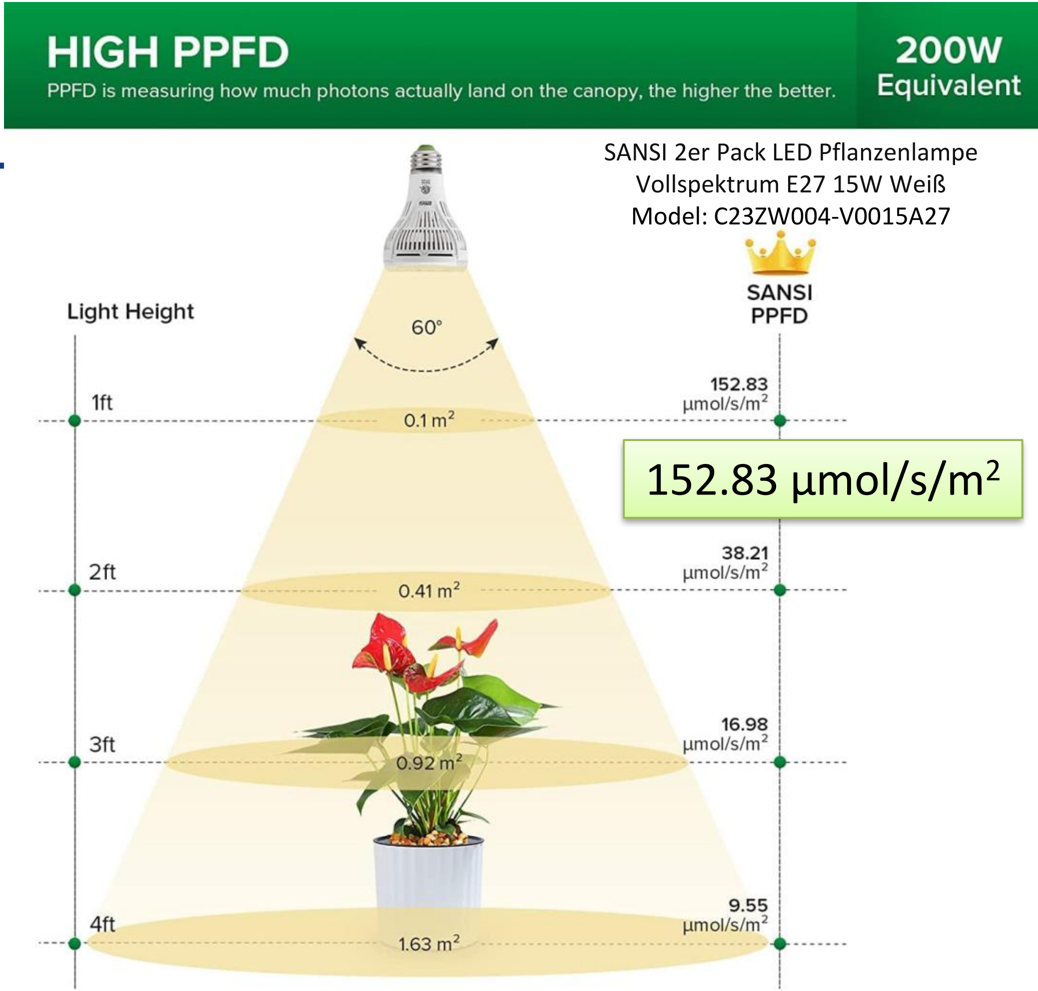
Photons and mole?



Action spectrum

By Original: Daniele Pugliesi
Vector: M0tty - This file was derived from: Chlorophyll ab spectra2.PNG:, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=20509583





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?

- No, at least not yet

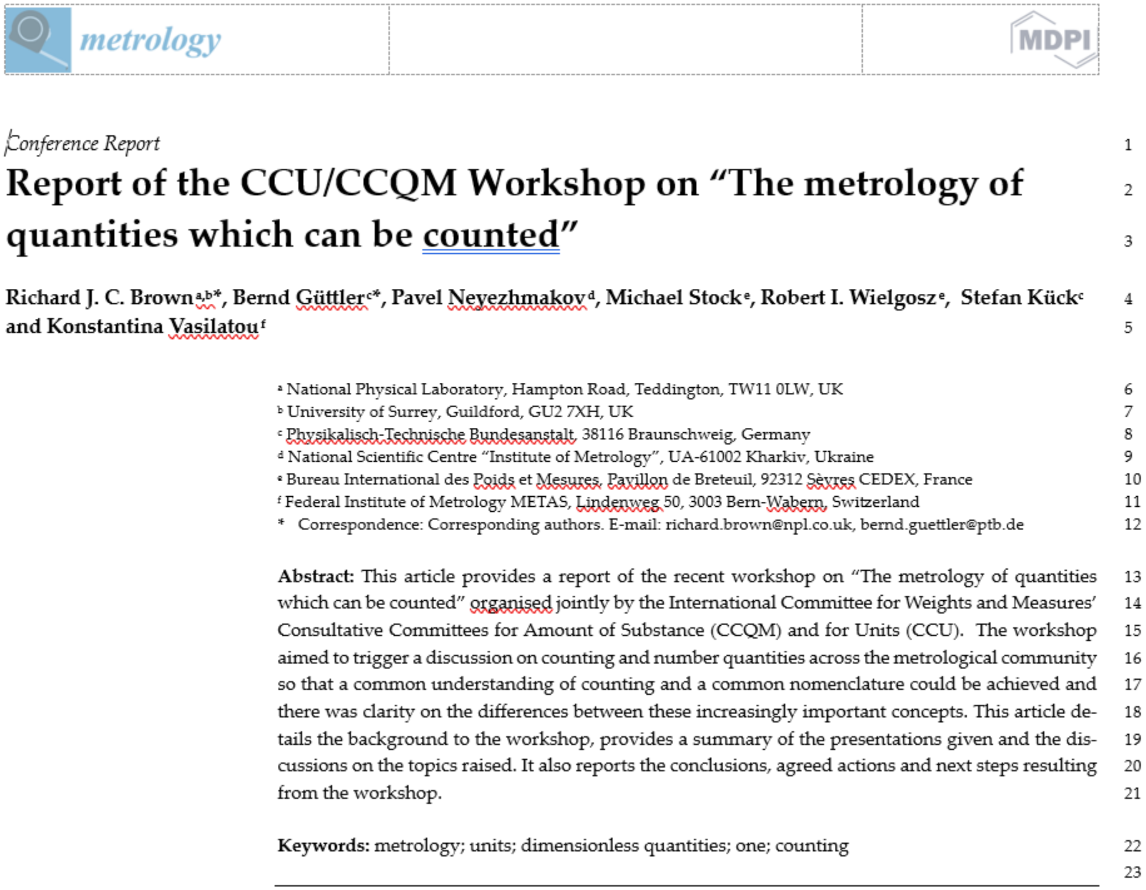
Nonetheless, **counting photons** is useful for many applications, e.g.:

- Quantum communication
- Quantum computing
- Low flux radiometry / Quantum radiometry

Photons and mol:

- PPFD: µmol/s/m^2
- Are photons „entities“ or an „amount of substance“, i.e., are they like Ni-atoms or like fish?

Submitted publication



metrology MDPI

Conference Report

Report of the CCU/CCQM Workshop on "The metrology of quantities which can be counted"

Richard J. C. Brown[a,b]*, Bernd Güttler[c]*, Pavel Neyezhmakov[d], Michael Stock[e], Robert I. Wielgosz[e], Stefan Kück[c] and Konstantina Vasilatou[f]

[a] National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK
[b] University of Surrey, Guildford, GU2 7XH, UK
[c] Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
[d] National Scientific Centre "Institute of Metrology", UA-61002 Kharkiv, Ukraine
[e] Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres CEDEX, France
[f] Federal Institute of Metrology METAS, Lindenweg 50, 3003 Bern-Wabern, Switzerland
* Correspondence: Corresponding authors. E-mail: richard.brown@npl.co.uk, bernd.guettler@ptb.de

Abstract: This article provides a report of the recent workshop on "The metrology of quantities which can be counted" organised jointly by the International Committee for Weights and Measures' Consultative Committees for Amount of Substance (CCQM) and for Units (CCU). The workshop aimed to trigger a discussion on counting and number quantities across the metrological community so that a common understanding of counting and a common nomenclature could be achieved and there was clarity on the differences between these increasingly important concepts. This article details the background to the workshop, provides a summary of the presentations given and the discussions on the topics raised. It also reports the conclusions, agreed actions and next steps resulting from the workshop.

Keywords: metrology; units; dimensionless quantities; one; counting

Accepted:
25.08.23

Submitted publication - 2.3.4. “Candela – by counting photons?” Stefan Kück (PTB, Germany)

The presentation “Candela – by counting photons?” offered an overview of the SI unit candela and its measurement.

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 $\Delta\nu_{Cs}$. This means, that the candela corresponds to a *radiant intensity* of 1/683 watt per steradian for monochromatic radiation of frequency 540 x 10^{12} hertz. Measured quantities in photometry must be considered as spectrally integrated quantities, where the integration is carried out over the product of the radiometric quantity and a luminous efficiency function. The most important of these functions is the photopic luminous efficiency function for the light-adapted eye, $V(\lambda)$, which is defined by the CIE over the wavelength range 360 nm to 830 nm at 1 nm intervals.

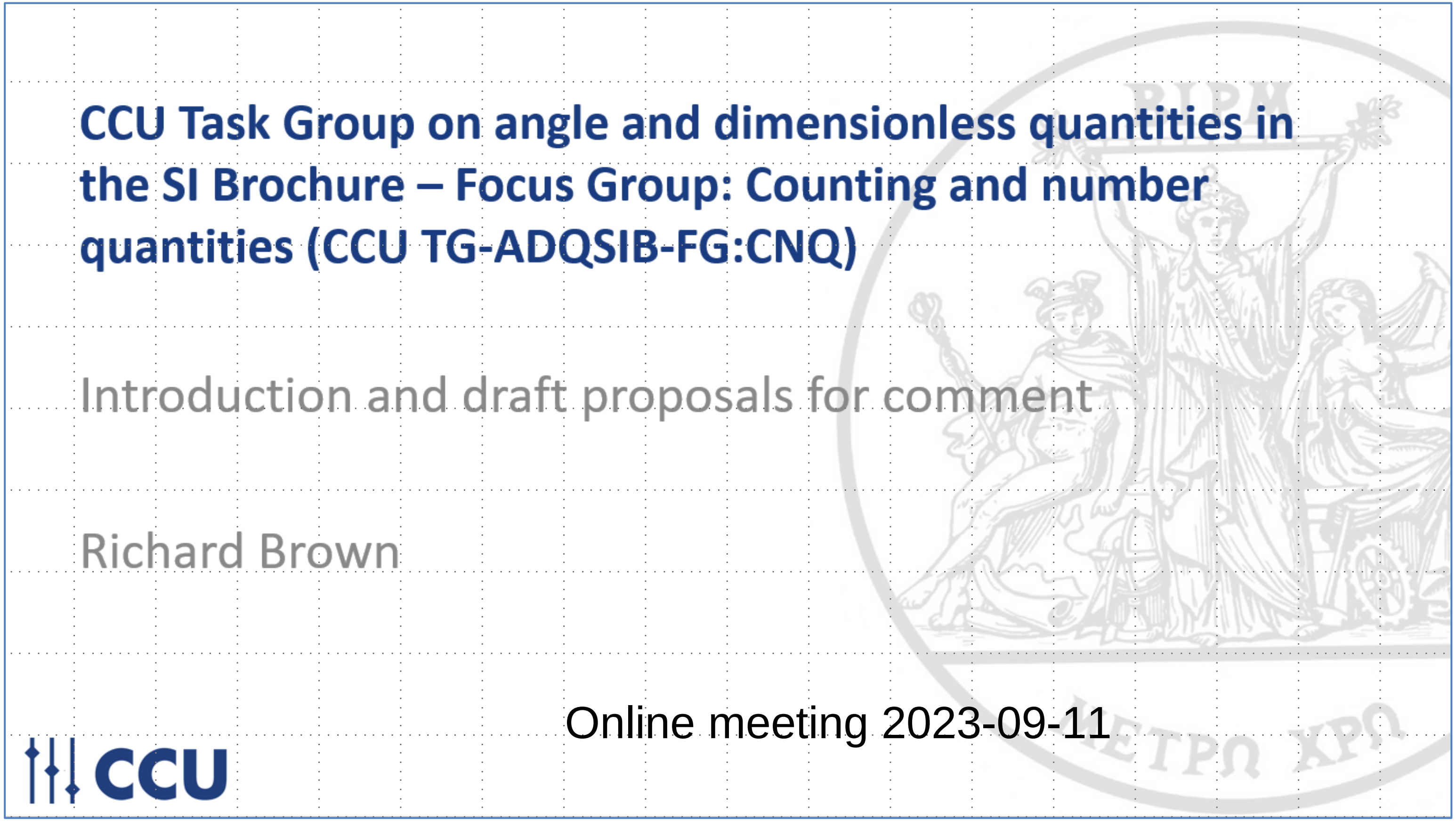
Expressing the candela numerically, a radiant intensity of 1/683 W/sr corresponds to 4.091942356... x 10^{15} photons/(sr s) at a frequency of 540 x 10^{12} Hz. Single photon detectors, like Si single-photon avalanche diode (SPAD) detectors, can measure lower radiant intensities, e.g., 4.091942356… x 10^6 (photons/(sr s), which corresponds to 1 nCd, however, traceability to classical radiometric methods is currently more accurate than to quantum-based approaches. Generating single photons is another promising method in the realm of photon techniques, utilizing sources like semiconductor quantum dots, single molecules, or colour centres in diamond. However, the accuracy of measurement is influenced by internal quantum efficiency and photon collection efficiencies. It is important to emphasize that the candela is a unit for luminous intensity, so it must include the steradian, which is sometimes omitted in these considerations. Realizing the candela by counting or producing single photons is currently not as accurate as the classical method of using a cryogenic radiometer.

Despite limitations, single-photon sources find uses in quantum metrology, in particular quantum radiometry and sub-shot noise metrology. They offer sub-Poissonian photon statistics and exhibit the anti-bunching effect, which classical light sources or lasers cannot achieve. Single photon sources are particularly valuable when paired with digital detectors like SPAD detectors.

The presentation also explored the relation between the candela and the mole. In principle, the mole can replace the number of photons, expressing the candela as 6.794830142... x 10^{-9} (mol/sr)/s at 540 x 10^{12} Hz. Notably, the mole is the unit of amount of substance, and photons sometimes behave like particles. In horticulture, photons and the mole are combined in units like PPFD (photosynthetic photon flux density) with (µmol/m^2)/s. However, merely knowing the number of photons is insufficient: understanding the spectrum of photons and the receiver's action spectrum is also essential.

To summarize, although counting photons is valuable in various applications, realizing the candela through photon counting is currently suboptimal. Emerging fields like horticulture lighting emphasize the significance of combining photons and the mole. The question of whether photons numbers can be described as amount of substance remains open for discussion.

New task group: CCU TG-ADQSIB-FG:CNQ



CCU Task Group on angle and dimensionless quantities in the SI Brochure – Focus Group: Counting and number quantities (CCU TG-ADQSIB-FG:CNQ)

Introduction and draft proposals for comment

Richard Brown

Online meeting 2023-09-11