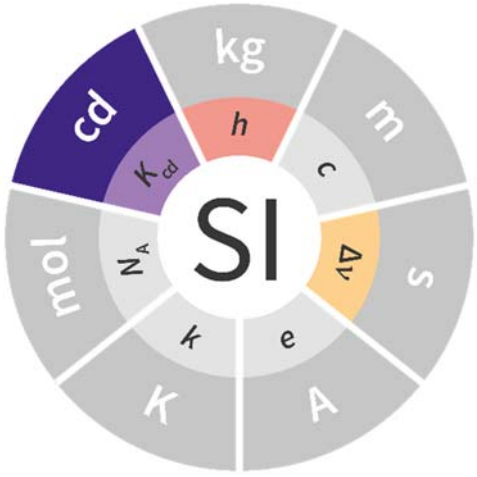
What next with the candela

20th Meeting of the NMI Directors

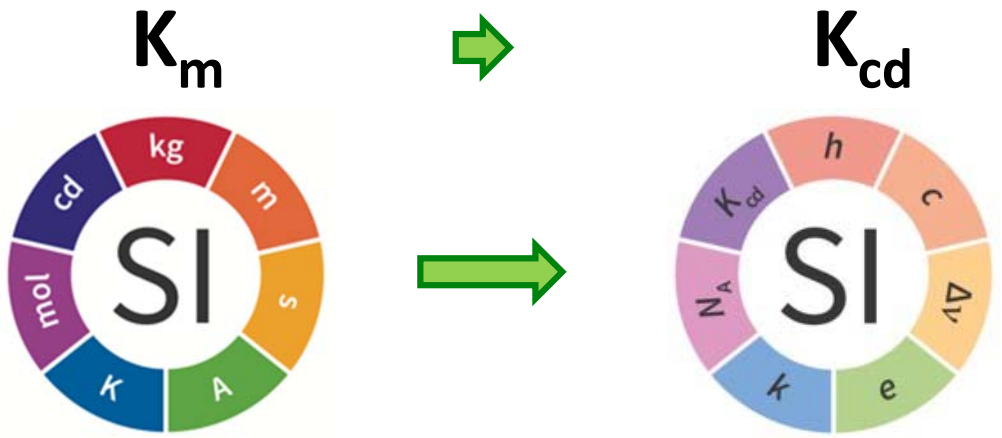
Bureau International des Poids et Mesures

- Introduction of **defining constant** for photometry, K_{cd} ***luminous* efficacy** of monochromatic radiation of frequency 540×10^{12} Hz
- **Reformulation** of definition of the candela
  - (not a redefinition), to bring it in **explicit constant** form:



THE CANDELA

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 540×10^{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 $\Delta\nu_{Cs}$.



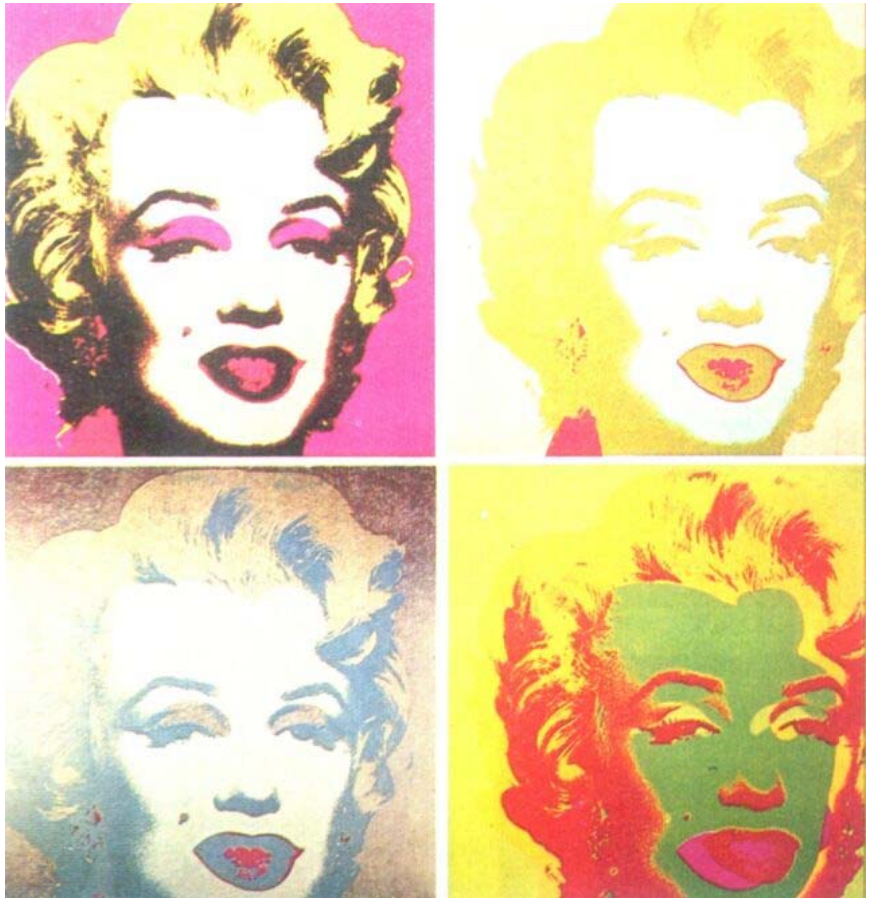
The luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, is 683 lm/W.

- K_{cd} makes a direct link between photometric and radiometric quantities for monochromatic radiation of frequency 540 THz

flux	illuminance	intensity	luminance
$\mathrm{lm} \leftrightarrow \mathrm{W}$	$\mathrm{lx} \leftrightarrow \mathrm{W \cdot m^{-2}}$	$\mathrm{cd} \leftrightarrow \mathrm{W \cdot sr^{-1}}$	$\mathrm{cd \cdot m^{-2}} \leftrightarrow \mathrm{W \cdot sr^{-1} \cdot m^{-2}}$
K_{cd}	K_{cd}	K_{cd}	K_{cd}

- *Mise en pratique* for the definition of the candela in the SI (20 May 2019)
- BIPM report 05/2019: Principles governing photometry (20 May 2019)
- Appendix 3 Units for photochemical and photobiological quantities (20 May 2019)

Photometry



Warhol, *Marilyn* Monroe(1967)

Photometry

Photometry is the science of the measurement of light, in terms of its perceived brightness to the human eye.

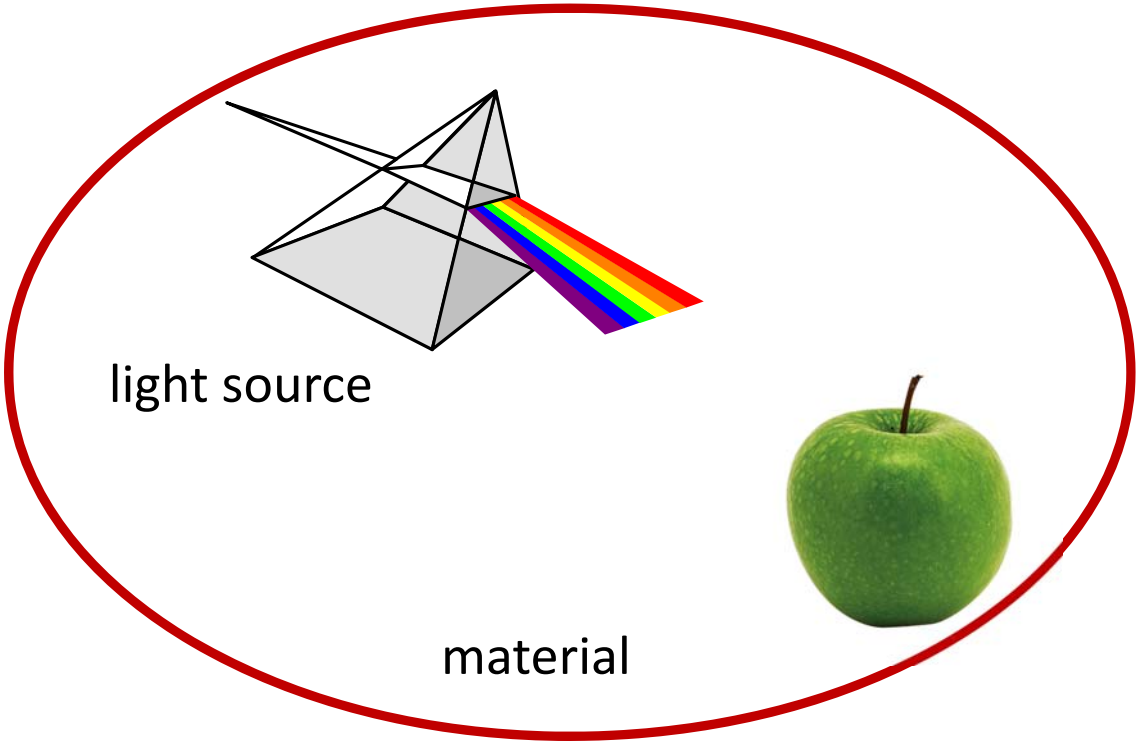
To do photometry, you need :

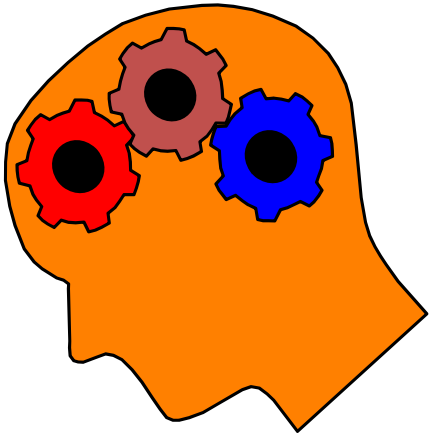
light stimulus

eyes

brain

Photometry





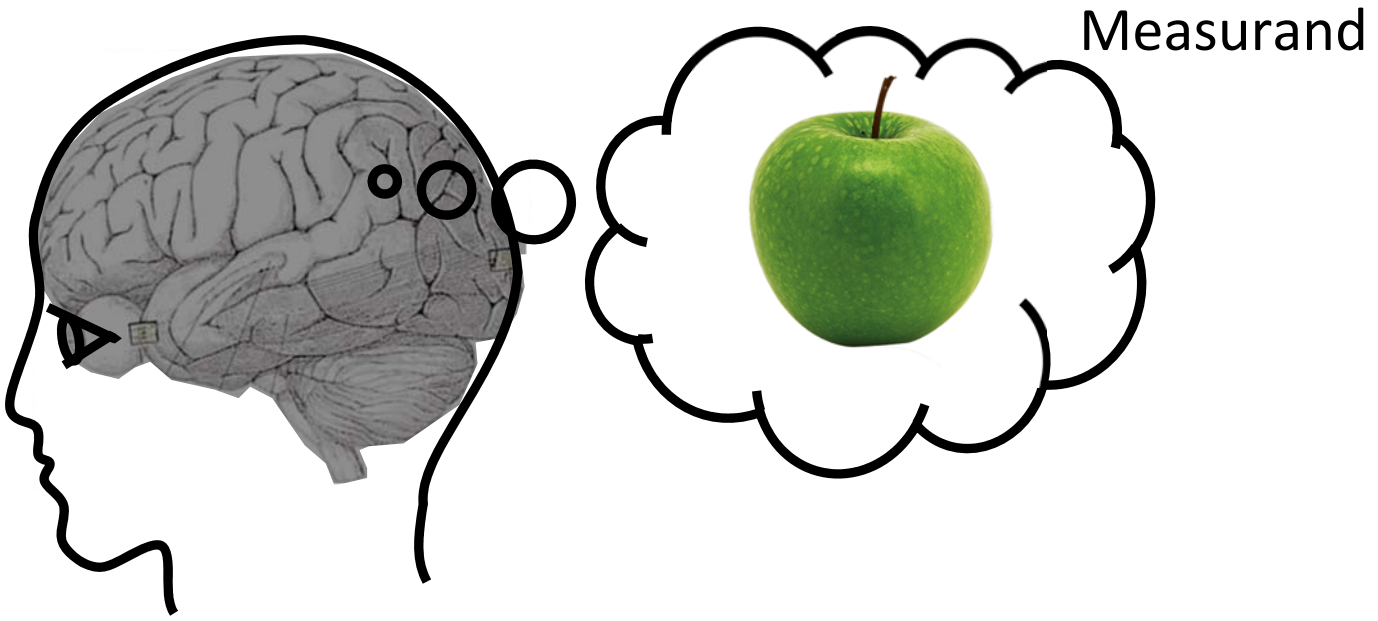
light
stimulus

Measurement of perceptive quantities

Challenge

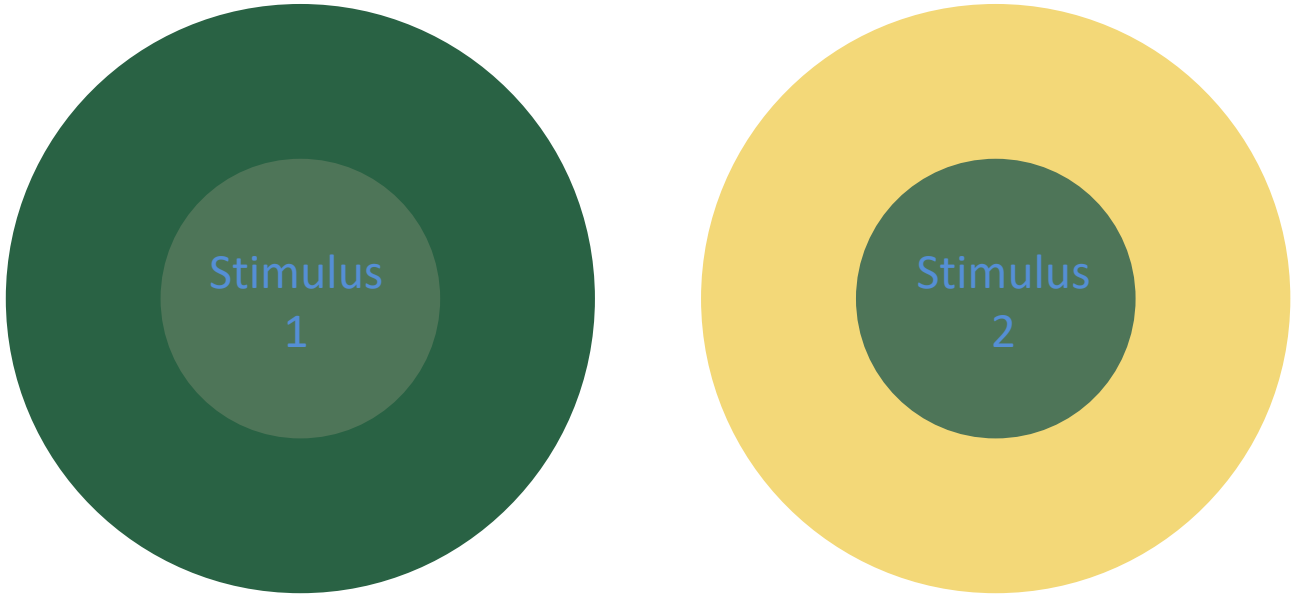
The measurand is not accessible by the measuring instrument

Object



Measurement of perceptive quantities

Is stimulus 1 = stimulus 2 ?



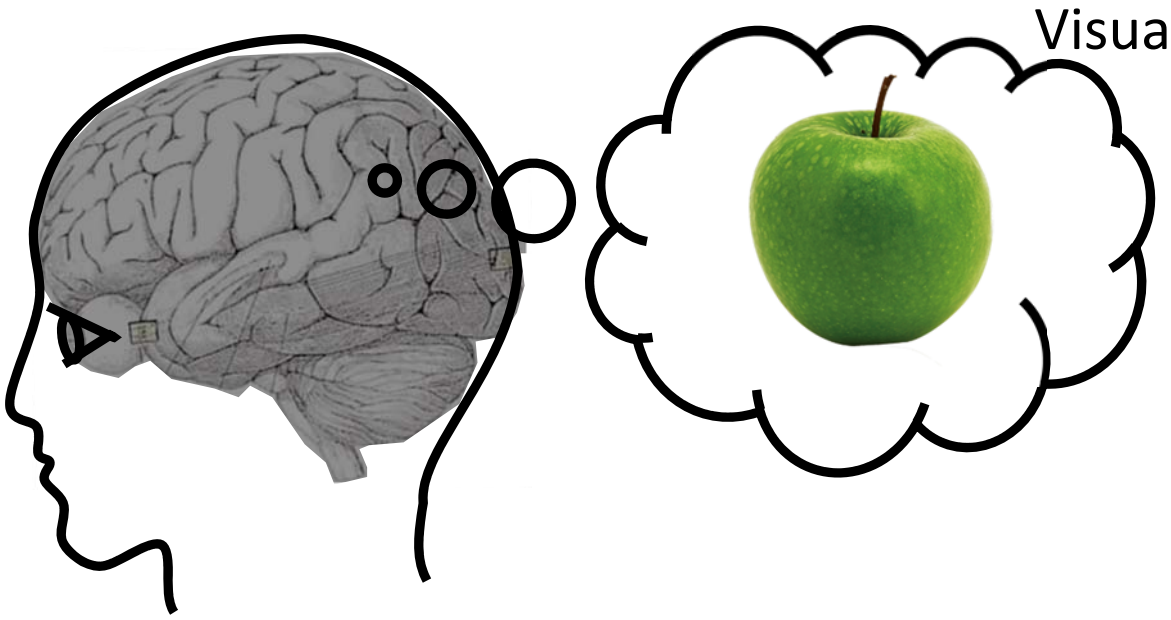
Measurement of visual quantities

Photometry deals with visual quantities.

The measurand is not accessible by the measuring instrument

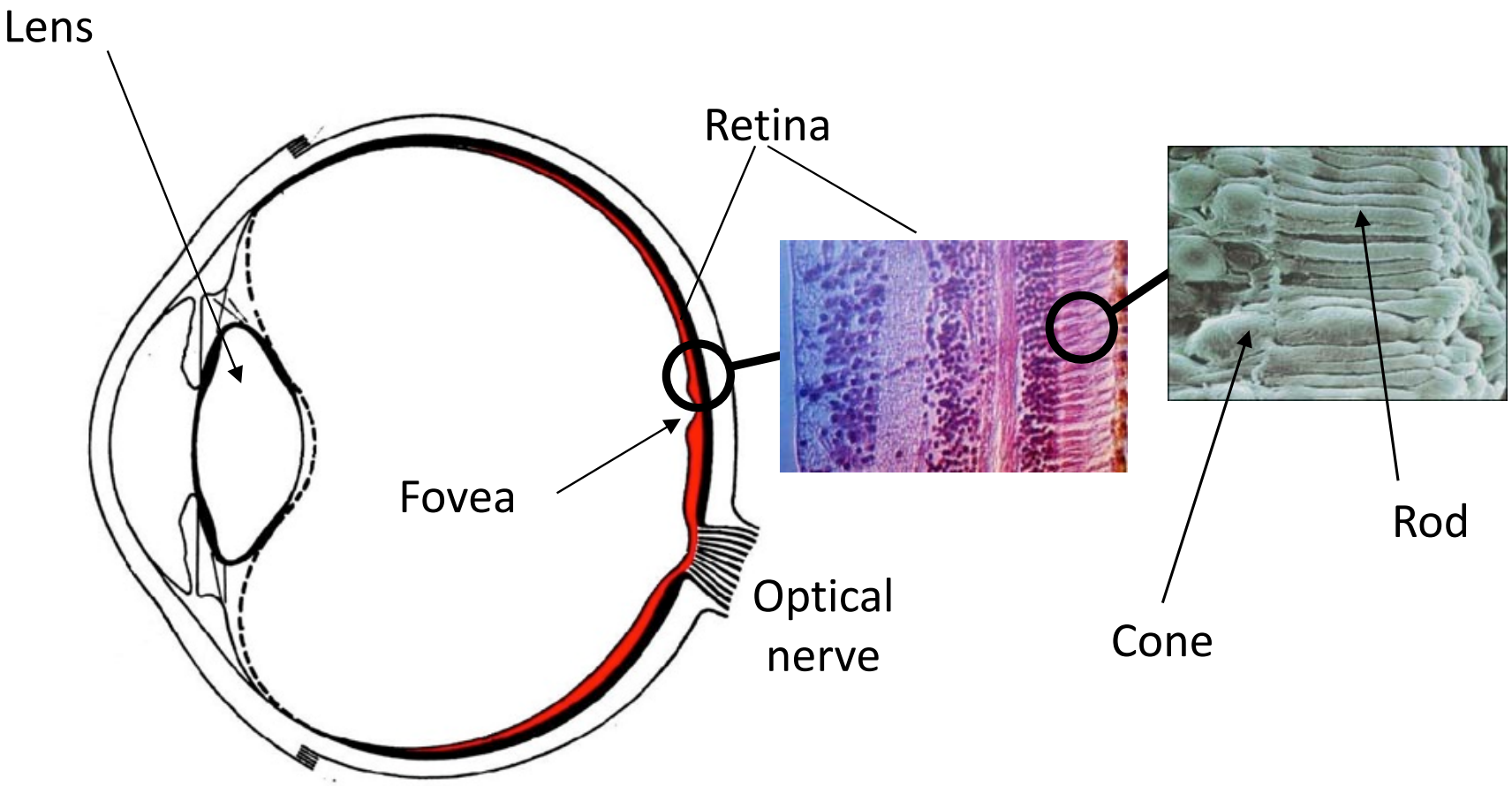
The measurand may vary from an observer to another

Object



Vision and V(λ) curve

Human eye

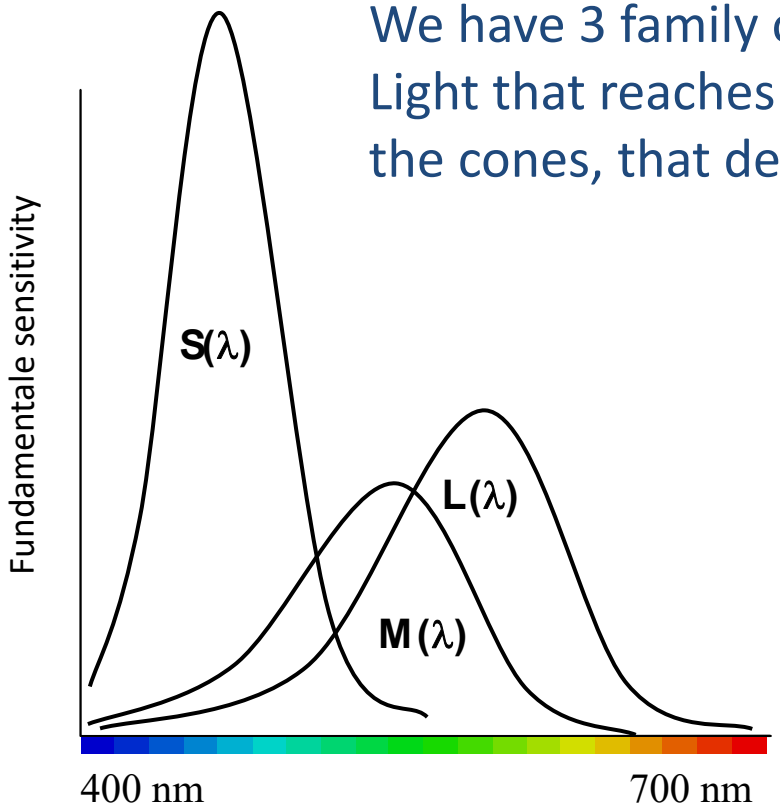


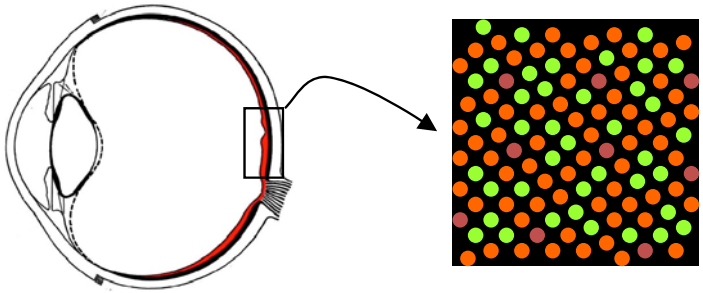
Source : ???

Vision and V(λ) curve

Cones (L M S)

We have 3 family of cones.
Light that reaches the retina generates 3 signals in the cones, that depend upon the wavelength





S(λ) $\lambda_{max} \cong$ **440 nm**

M(λ) $\lambda_{max} \cong$ **540 nm**

L(λ) $\lambda_{max} \cong$ **570 nm**

Vision and V(λ) curve

Individual variations

- We don't have the same repartition of cones, but the visual system adjusts the sensitivity by adapting the gain

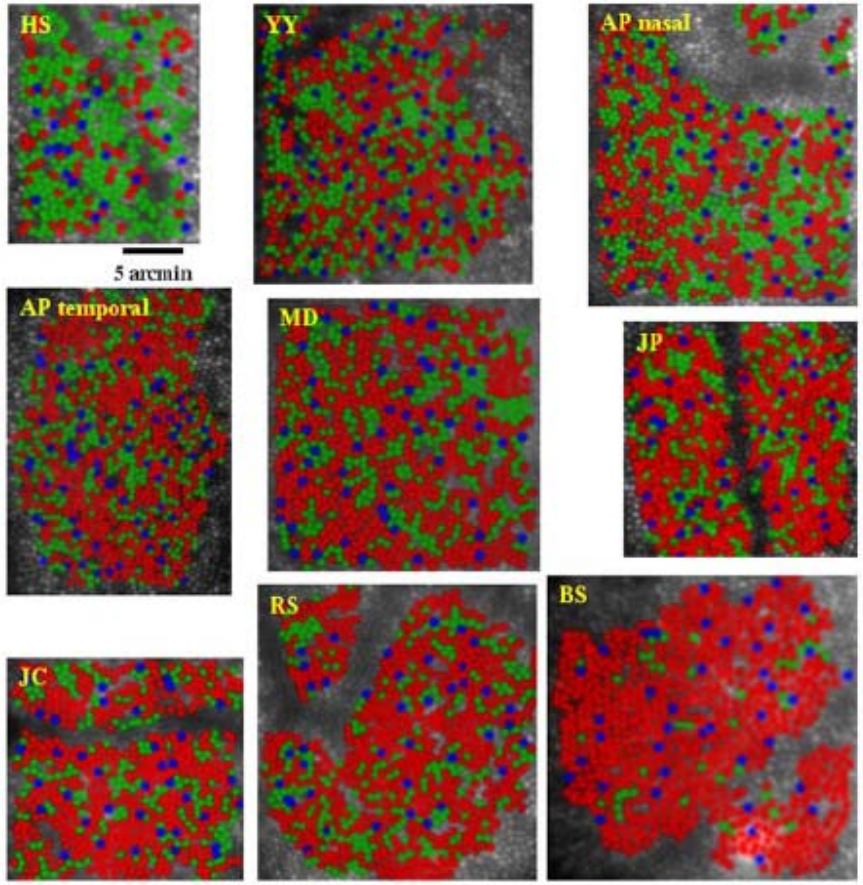


Figure 4. False color images showing the arrangement of L (red), M (green), and S (blue) cones in the retinas of different human subjects. All images are shown to the same scale.

Hofer, Carroll, Neitz, Neitz, Williams, JNeuroscience 2005

Vision and V(λ) curve

CIE Photometric strandard observer

6th session of CIE, Geneva, 1924

K. S. Gibson :
Visibility function

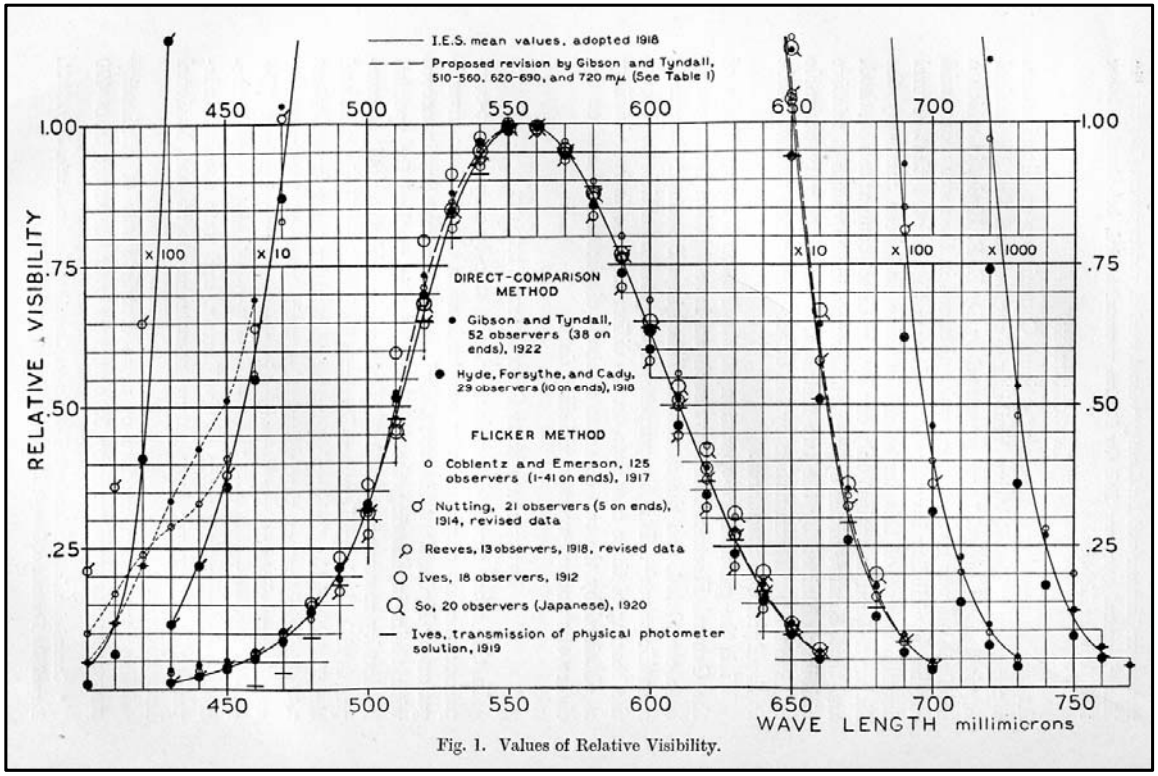
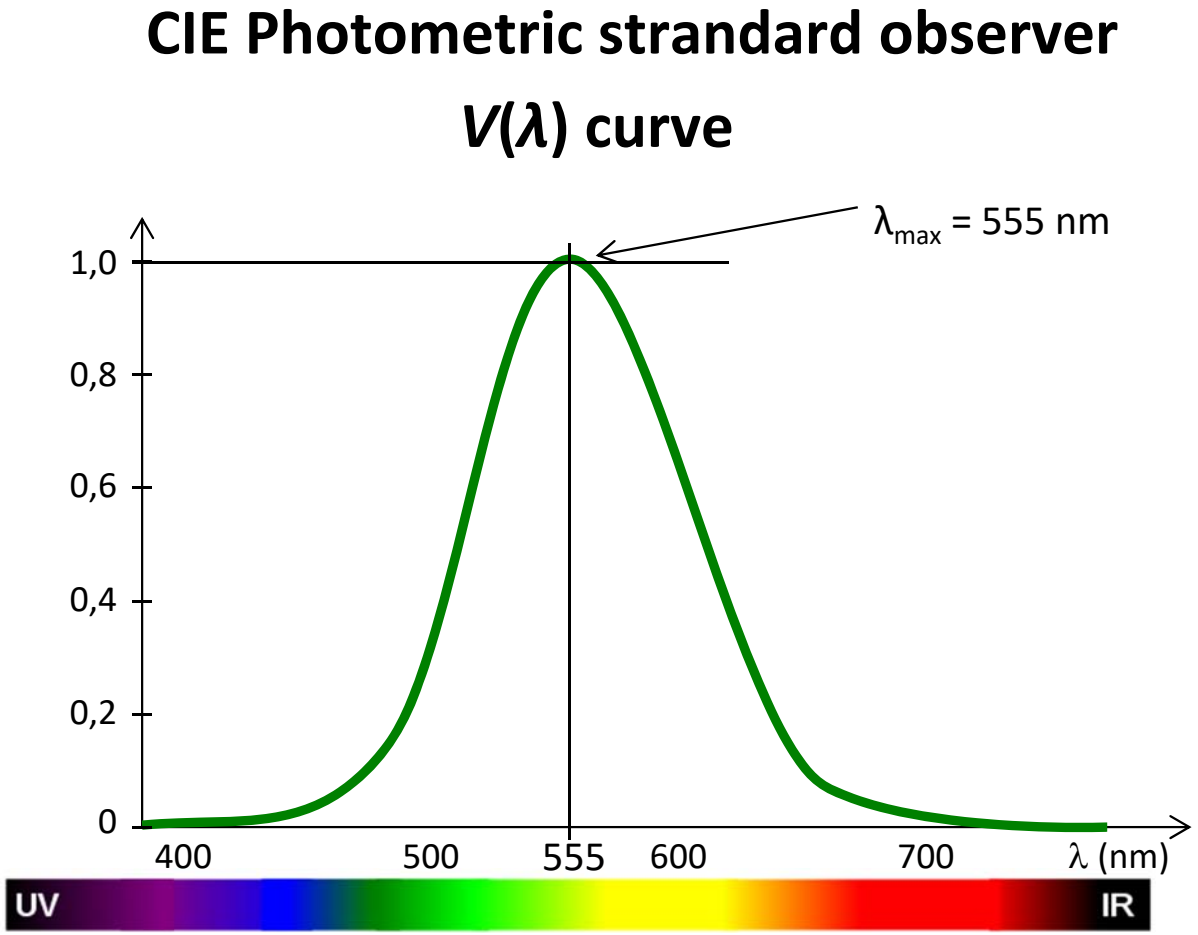


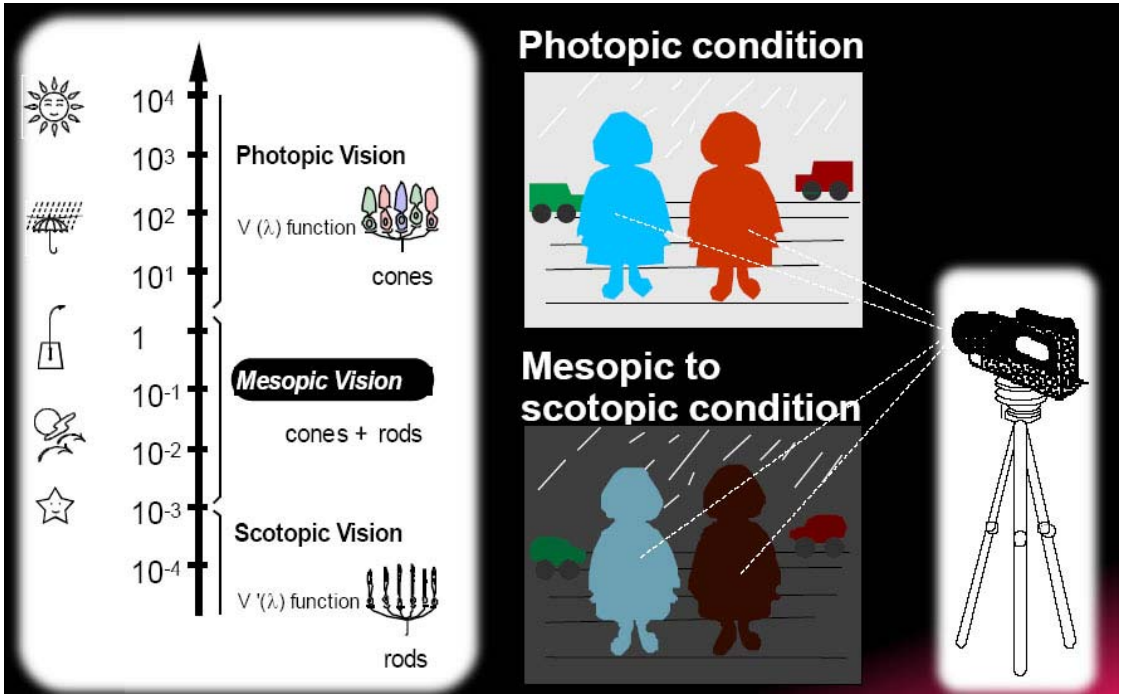
Fig. 1. Values of Relative Visibility.

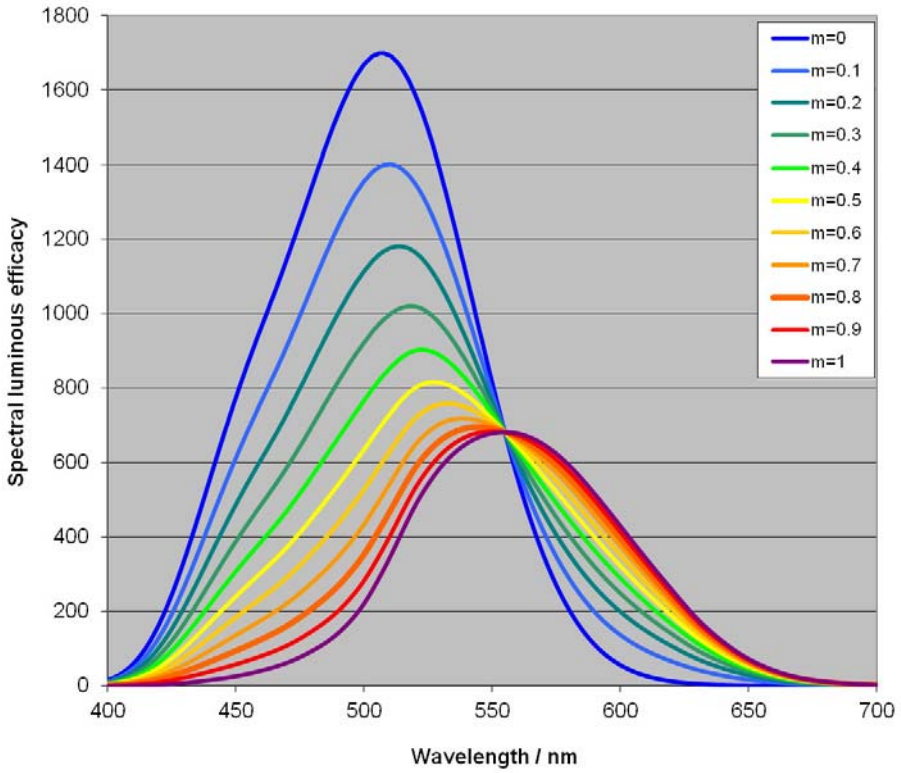
272 observers (UK, Japan, US)

Vision and V(λ) curve



Many agreed **human visual response function** (**mesopic & 10°**)





Observers

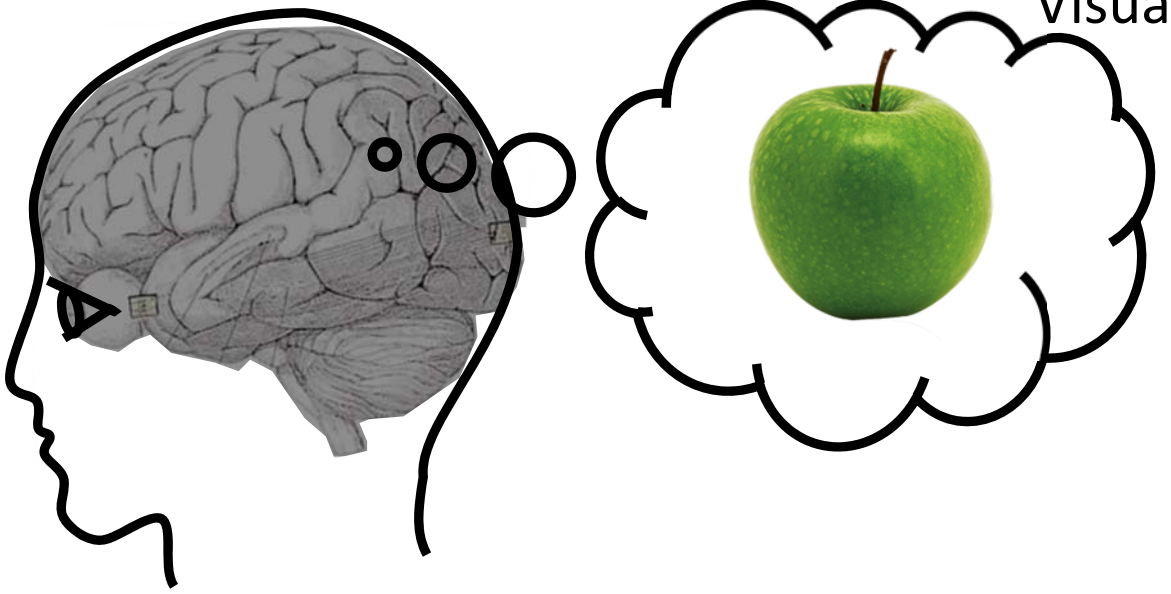
- ✓ Female / Male
- ✓ Young / Old
- ✓ Naïve / Expert
- ✓ Colour blind?
- ✓ Vision corrected
- ✓ Morning / Afternoon
- ✓ …..

Photometry deals with visual quantities.

The measurand is not accessible by the measuring instrument

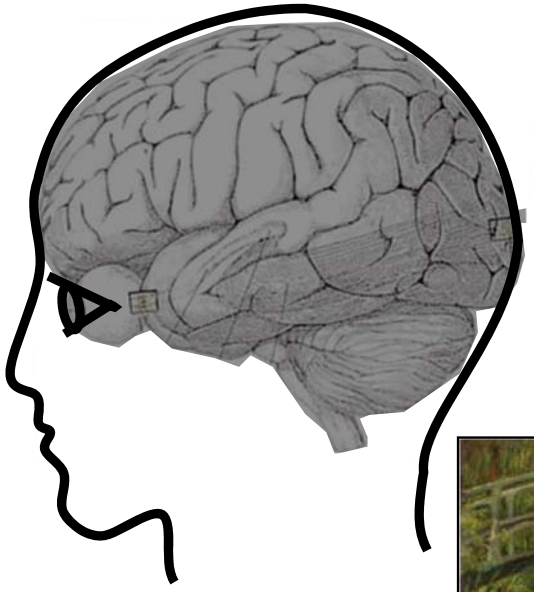
The measurand may vary from an observer to another

Object



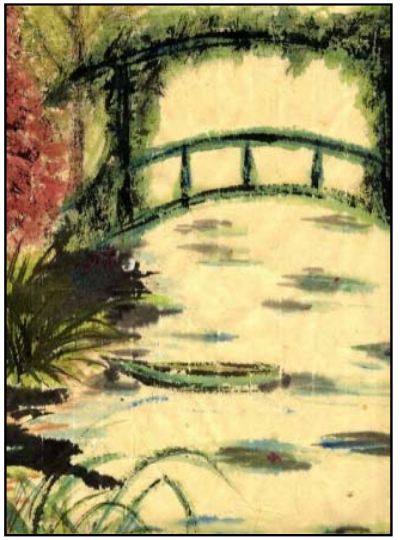
Visual quantity

The measurand may vary from an observer to an other



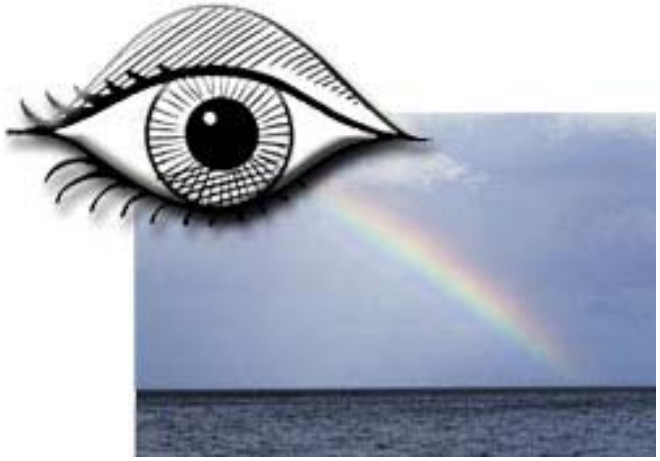
Elaine Moynihan Lisle

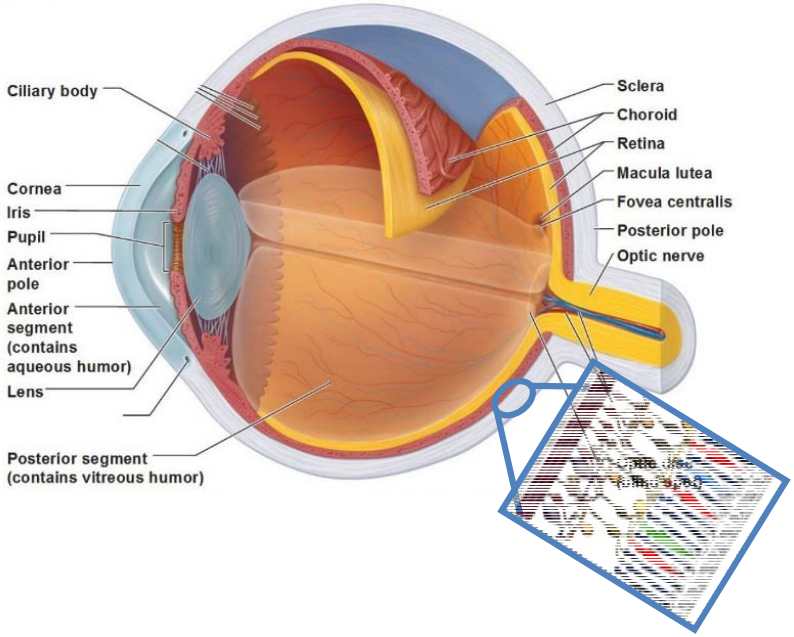
Monet



Miraï

Photometry describes the effects of visible light on the human eye, in terms of brightness and colour





Towards the candela

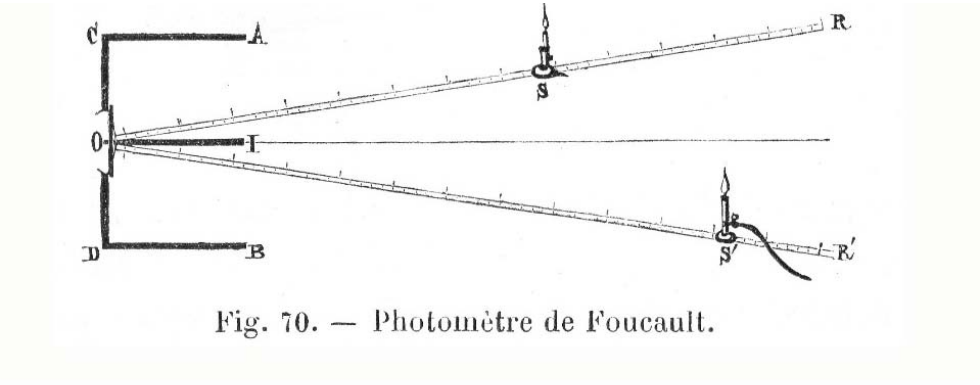


Fig. 70. — Photomètre de Foucault.

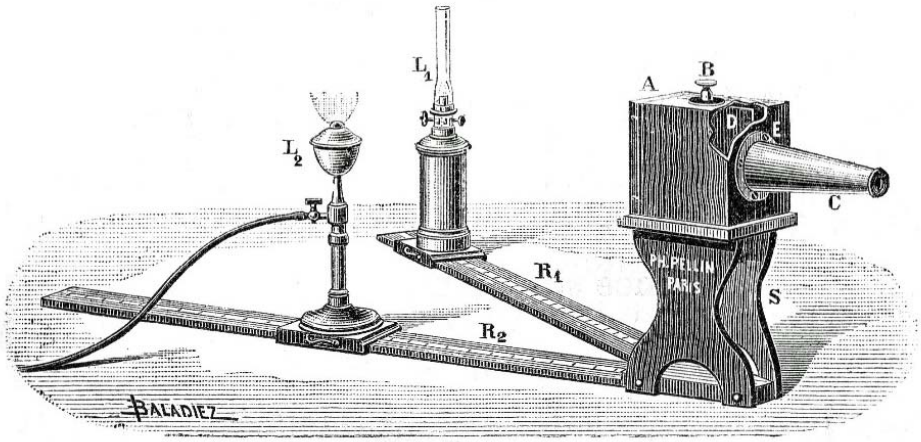


Fig. 71. — Photomètre de Foucault.

Visual comparisons

What is the reference?

UK Parliamentary Candle (1860)

Extracted from “manipulation de physique”
A. Leduc, 1895

1854

Towards the candela

First standard

Standard lamps

© Cnam - Musée

© PTB

© NIST

1890

1900 : the « black body », the ideal standard

Radiance from the black body depends only of its temperature

$$L_\lambda(\lambda,T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda kT)} - 1}$$

with :
λ, wavelength of the radiation
T, black body temperature
c, speed of light
h, Planck constant
k, Boltzmann constant

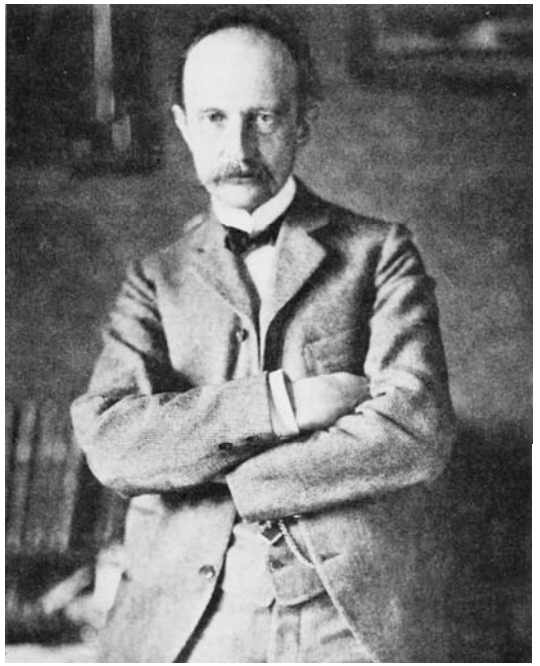


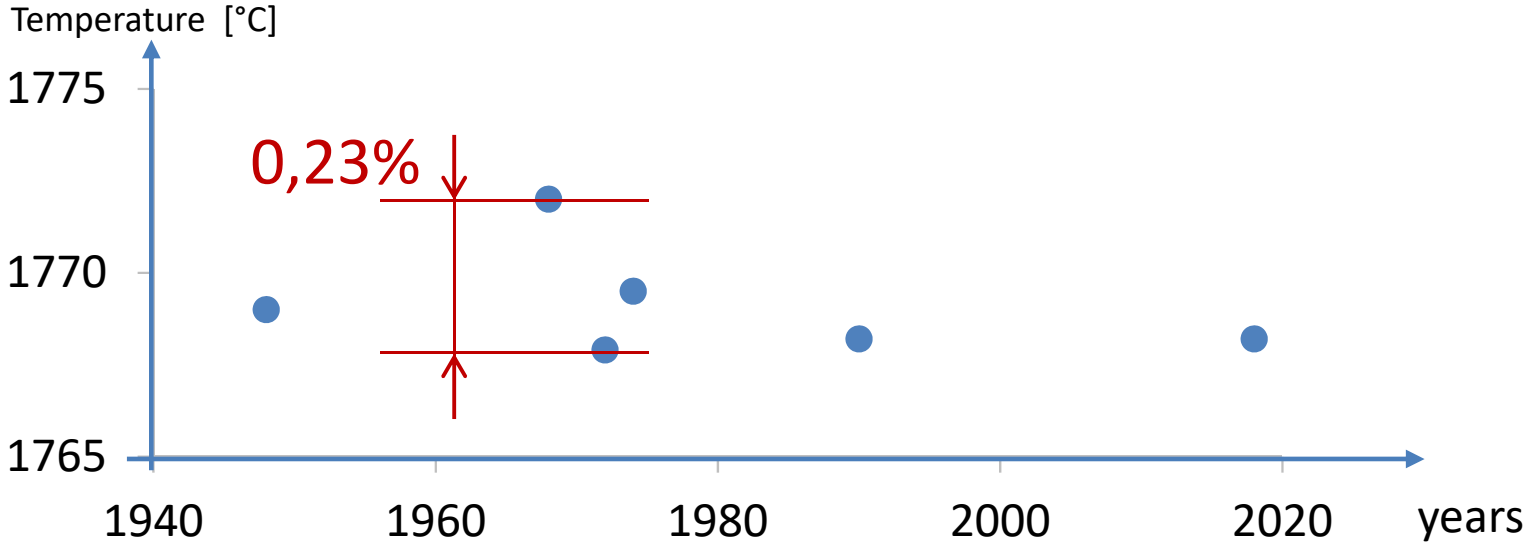
Photo collection particulière D. J. Lovell

Max Planck

Freezing temperature of Platinium

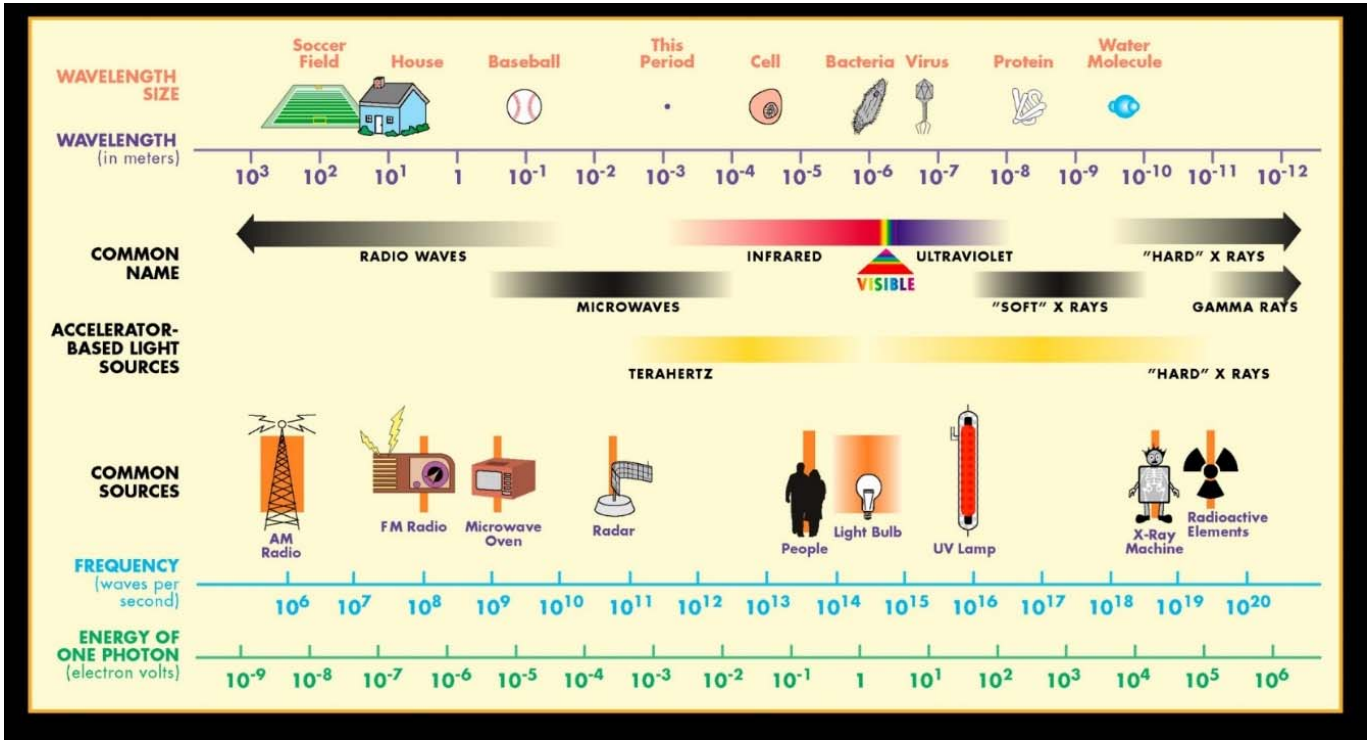
«“The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre.”» **XIII^{ème} CGPM, 1968**

If the feezing platinum temperature varies, the radiation emitted by the black body varies and the candela varies !!



Radiometry to rescue photometry

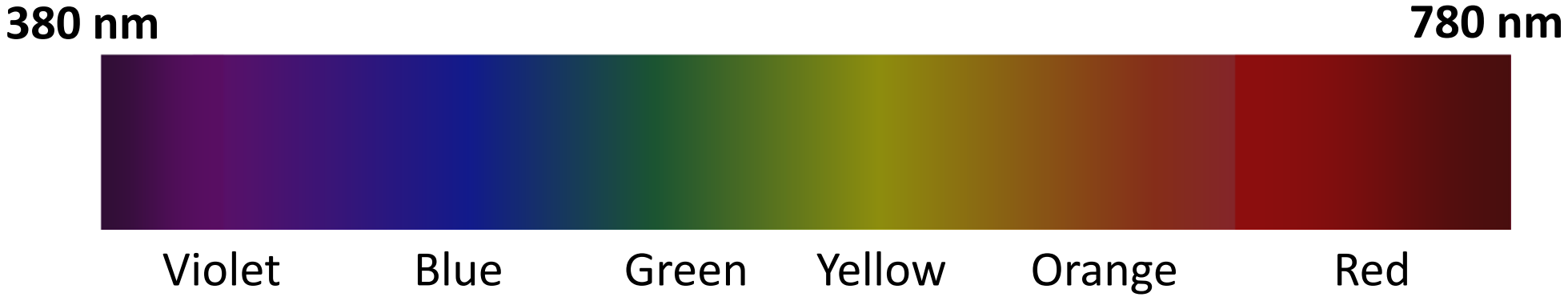
Radiometry is the science of measurement of radiant energy (including light) in terms of absolute power. Radiometric techniques characterize the distribution of the radiant power according to the wavelength.



Radiometry, a new way for the candela

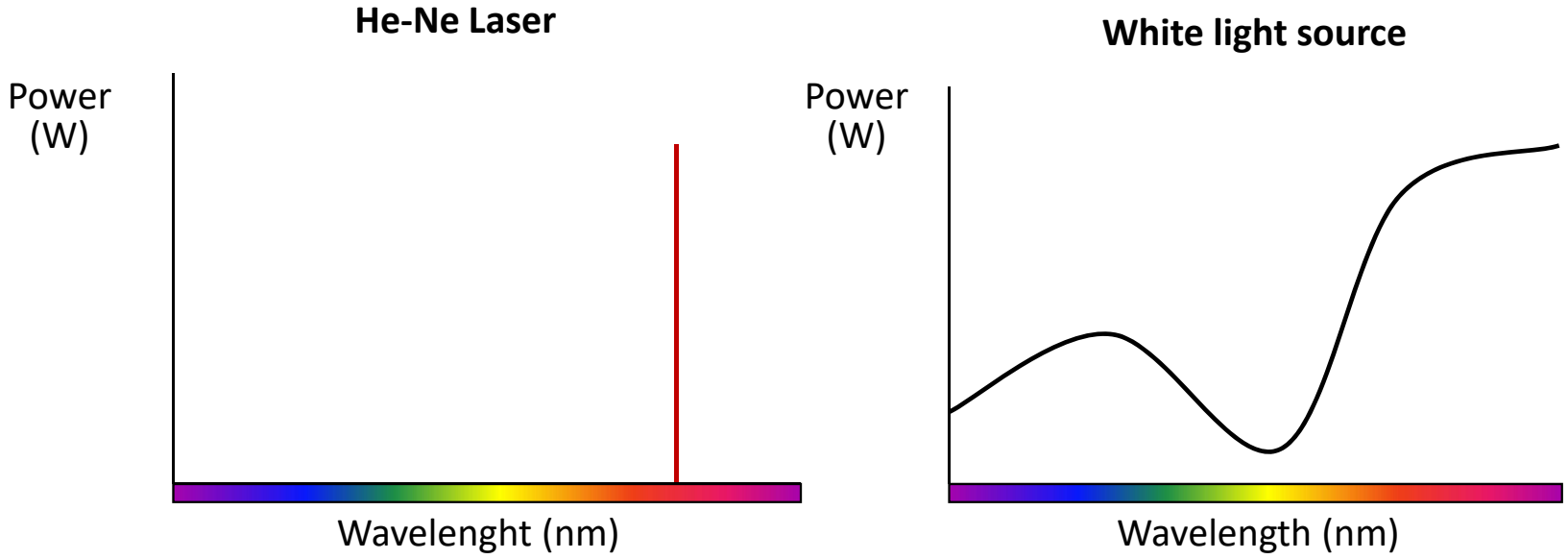
LIGHT

Electromagnetic waves with a wavelength between 380 nm and 780 nm

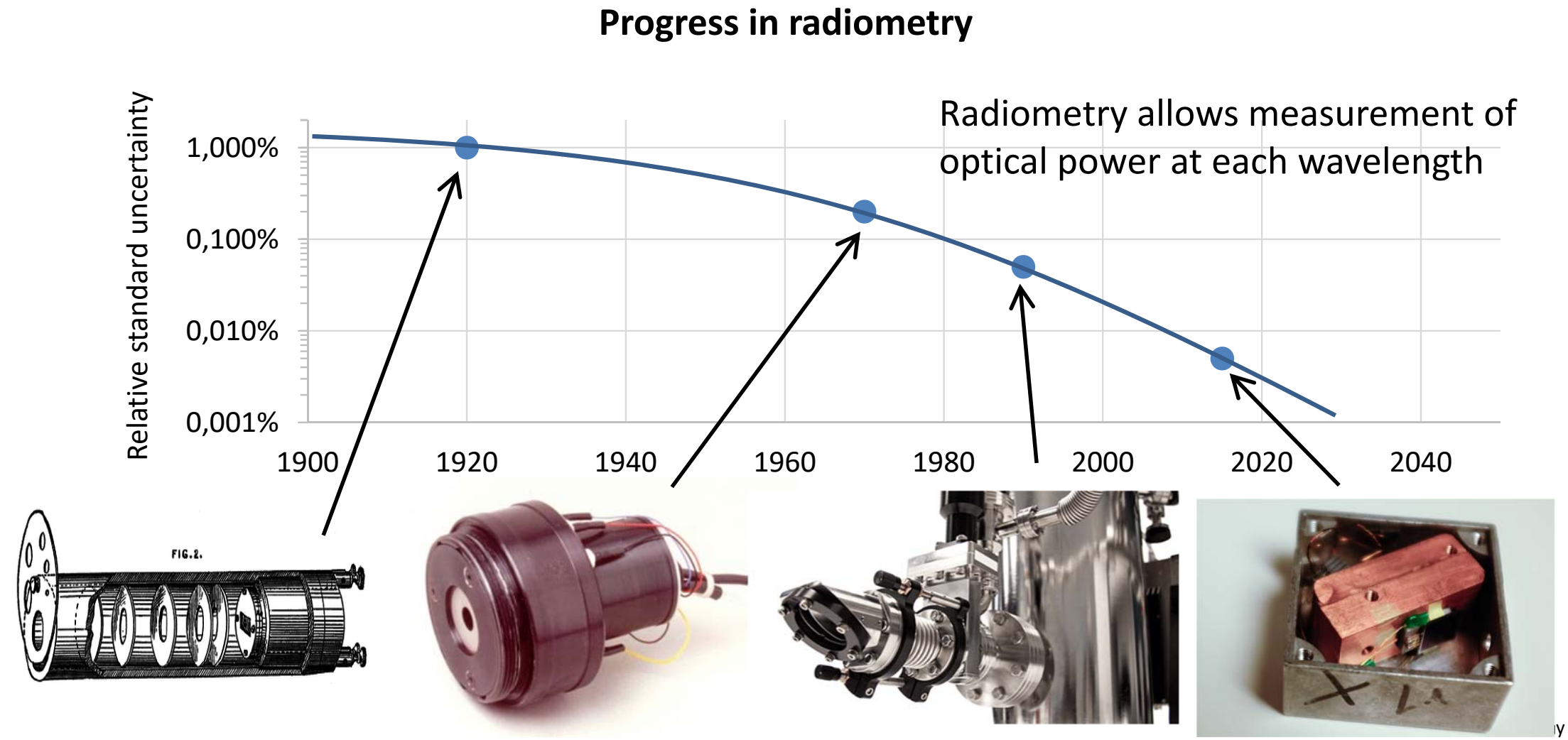


Spectral power distribution of light sources

Spectral power distribution describes the light spectrum of a light source
It shows which radiations are present, at which wavelength, in which proportion.

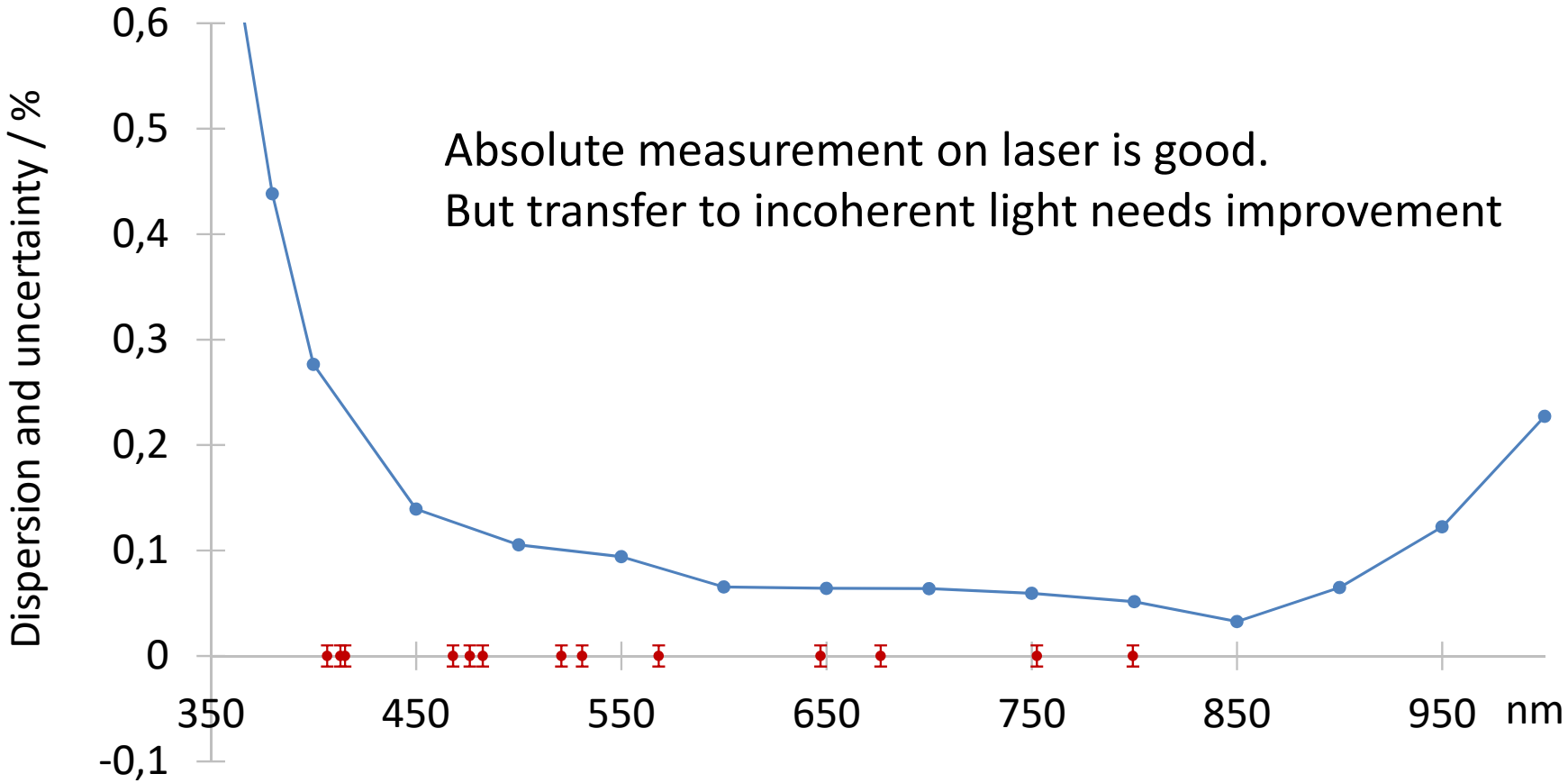


Radiometry, a new way for the candela



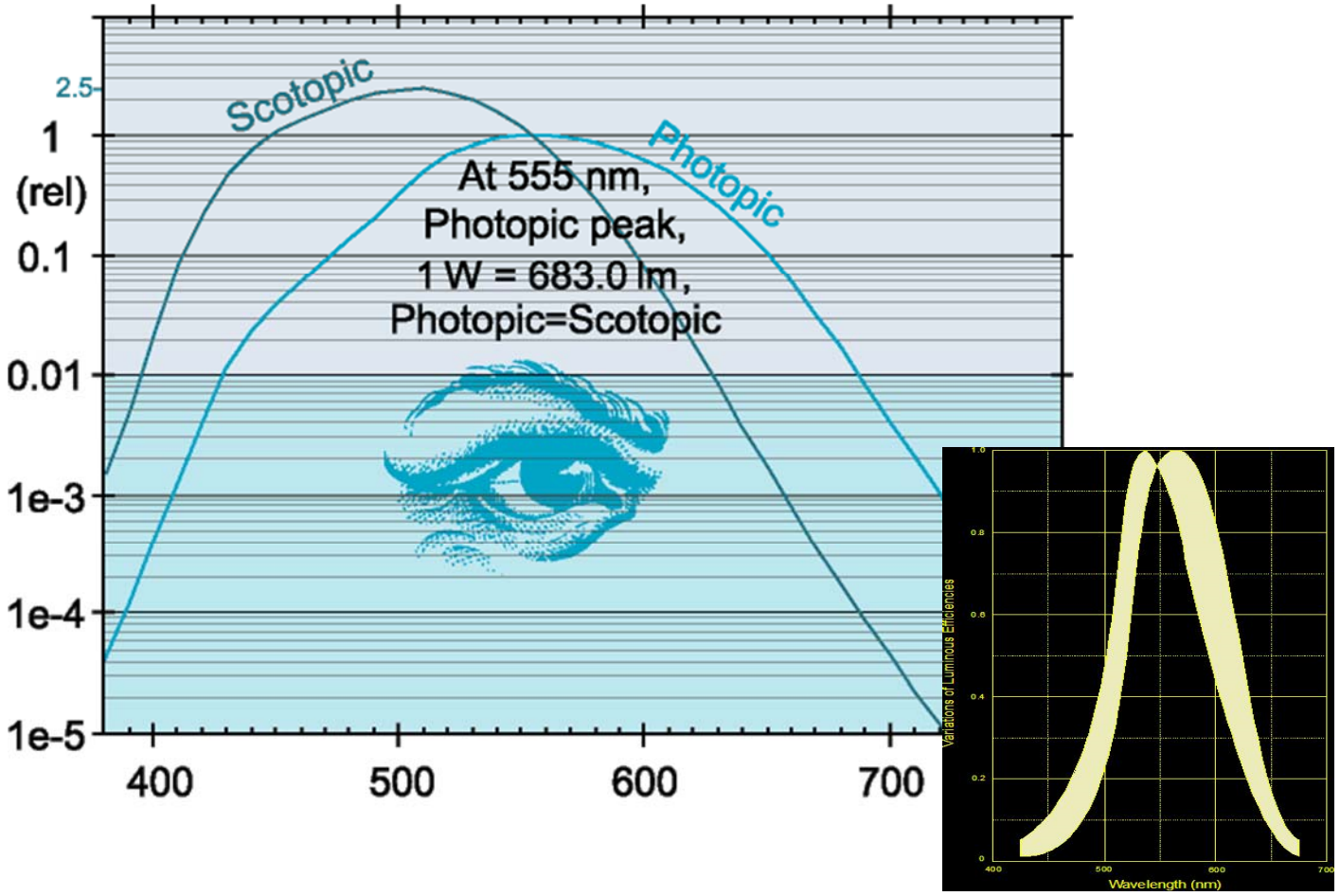
Radiometry, a new way for the candela

cryogenic radiometer



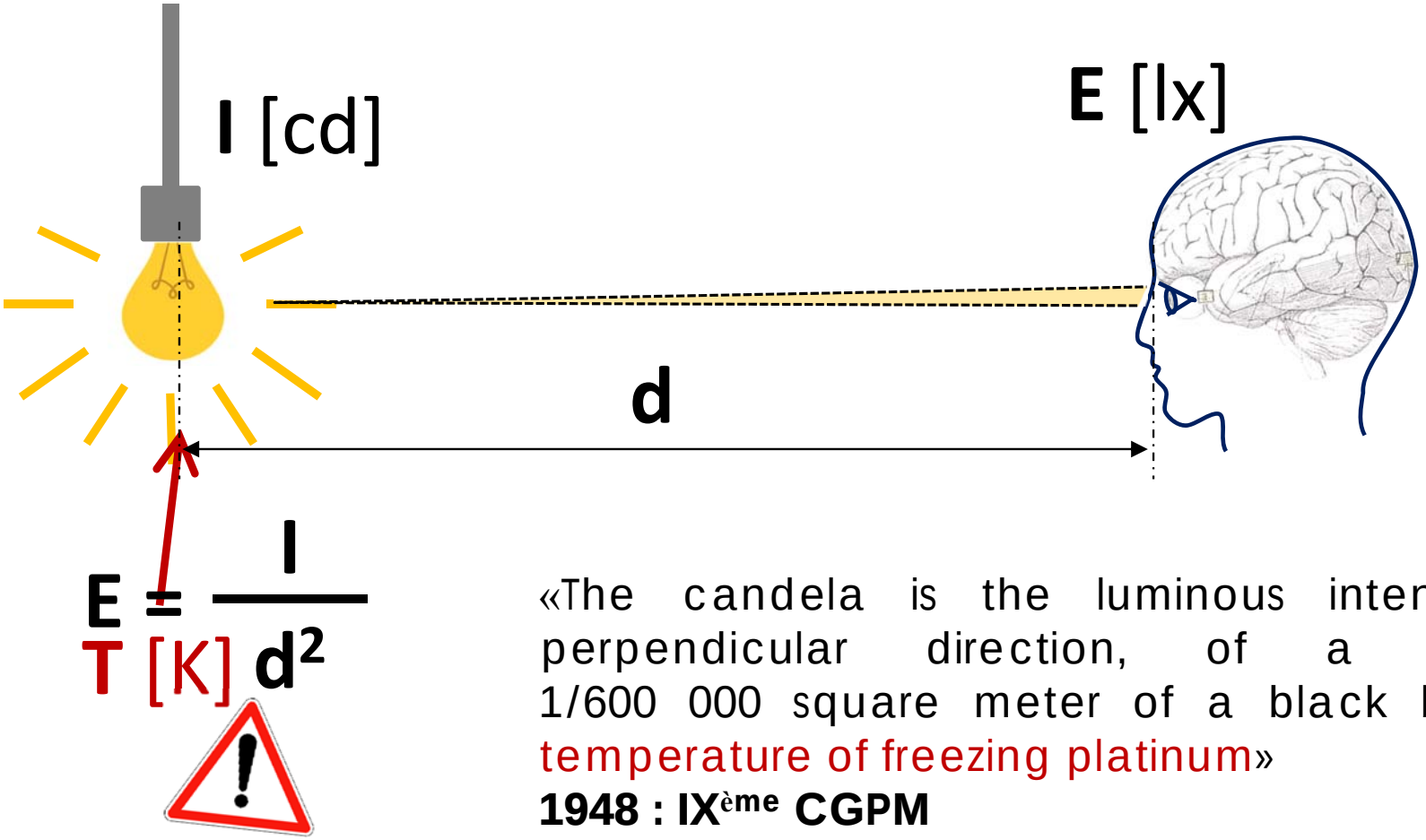
Absolute measurement on laser is good.
But transfer to incoherent light needs improvement

Sensitivity curve of human eye



Radiometry, a new way for the candela

the new way…

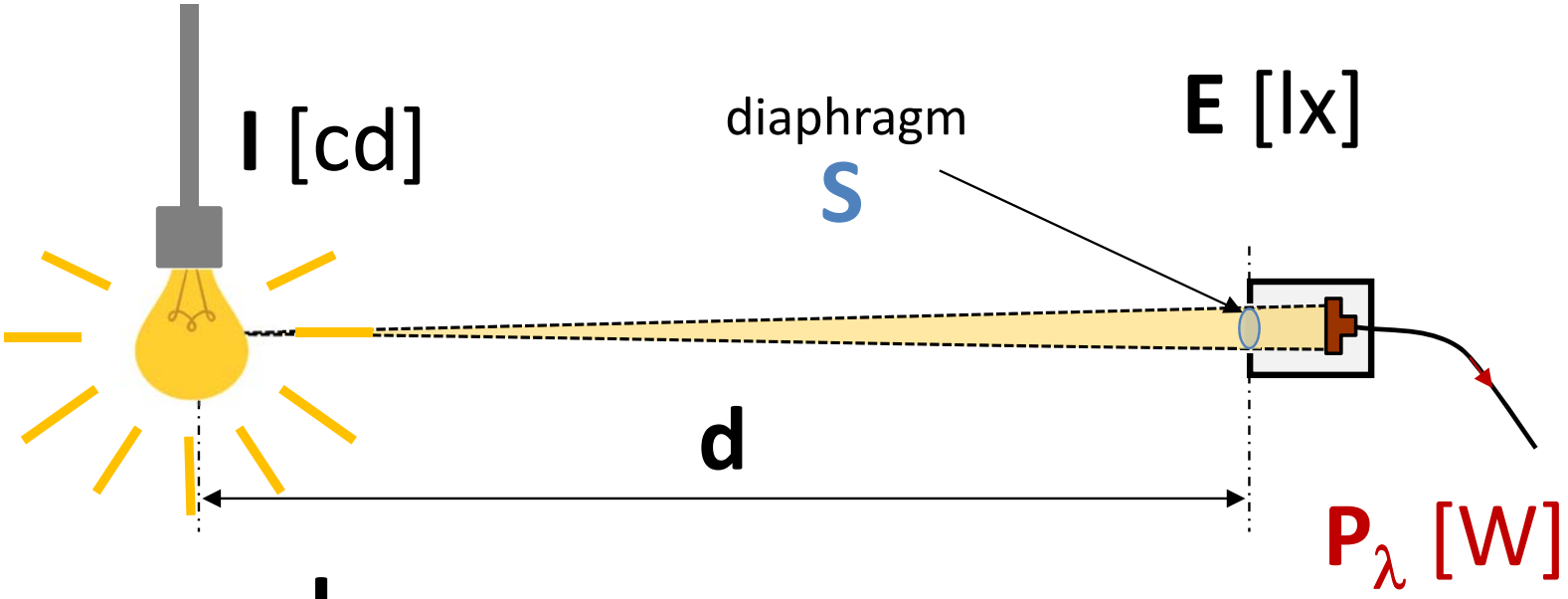


«The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square meter of a black body at the temperature of freezing platinum»

1948 : IX^{ème} CGPM

Radiometry, a new way for the candela

the new way…

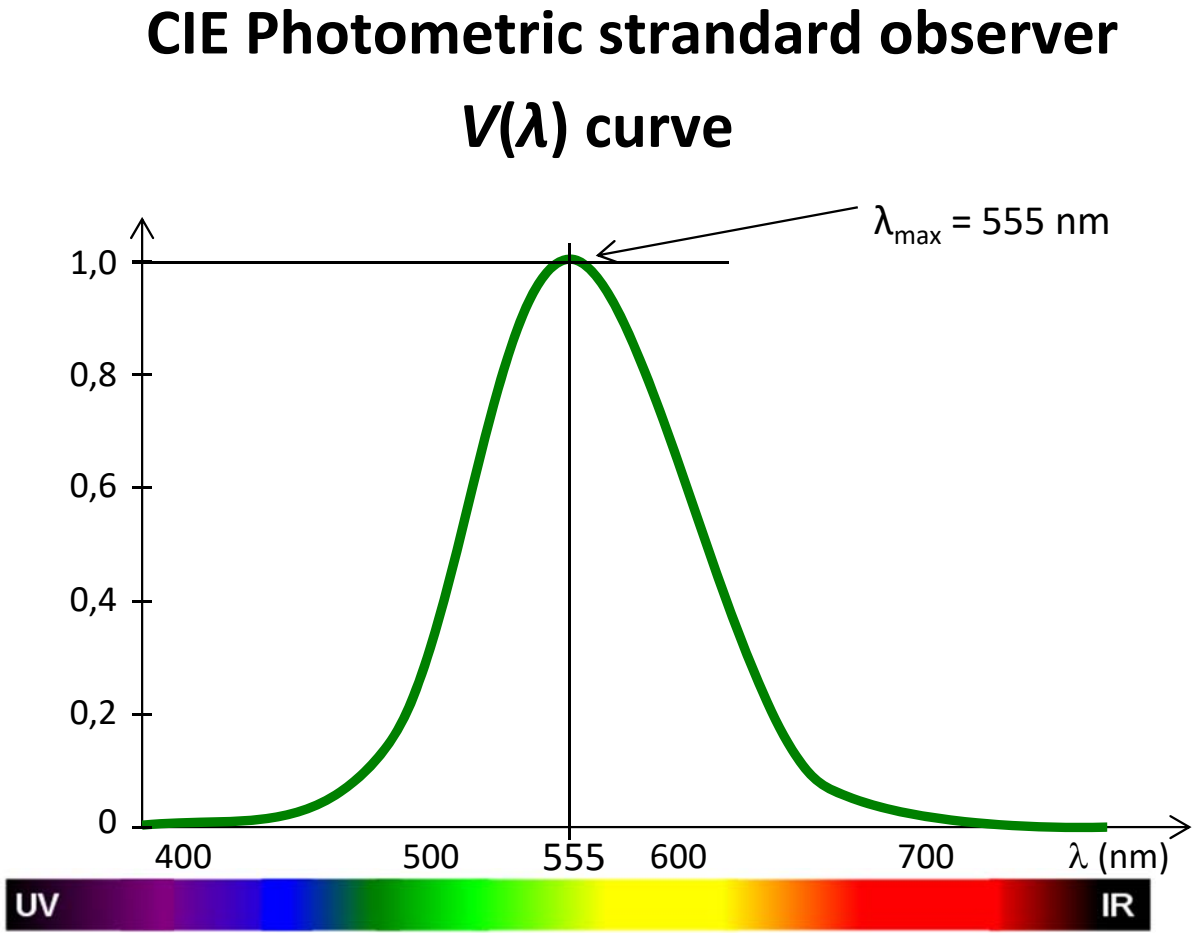


$$E = \frac{I}{d^2}$$

«The candela is the luminous intensity, in the perpendicular direction, *of a light source that generates an illuminance of 1 lx at 1m distance, that is accessed by radiometry*

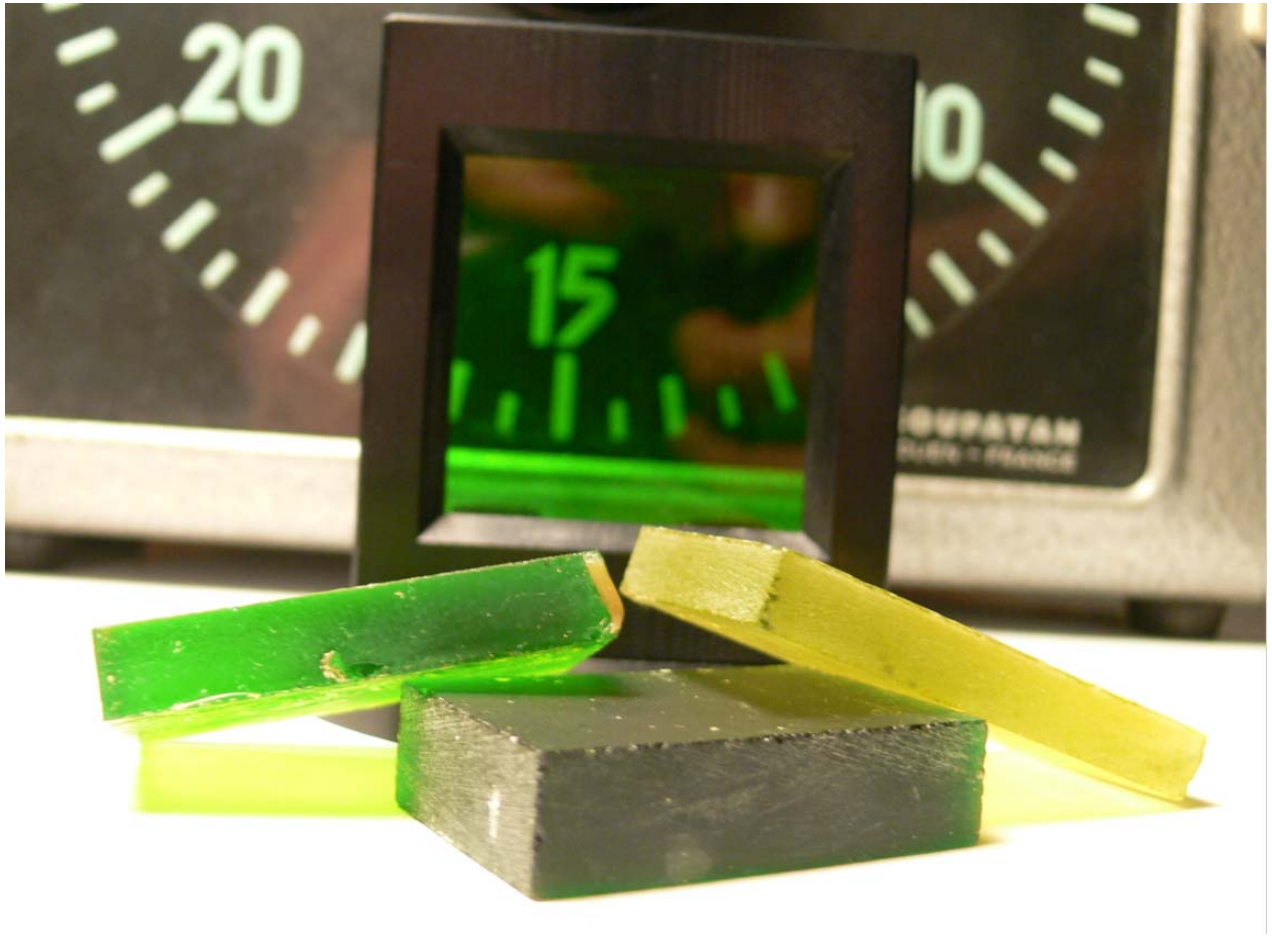
xxx : xxx^{ème} CGPM

Vision and V(λ) curve

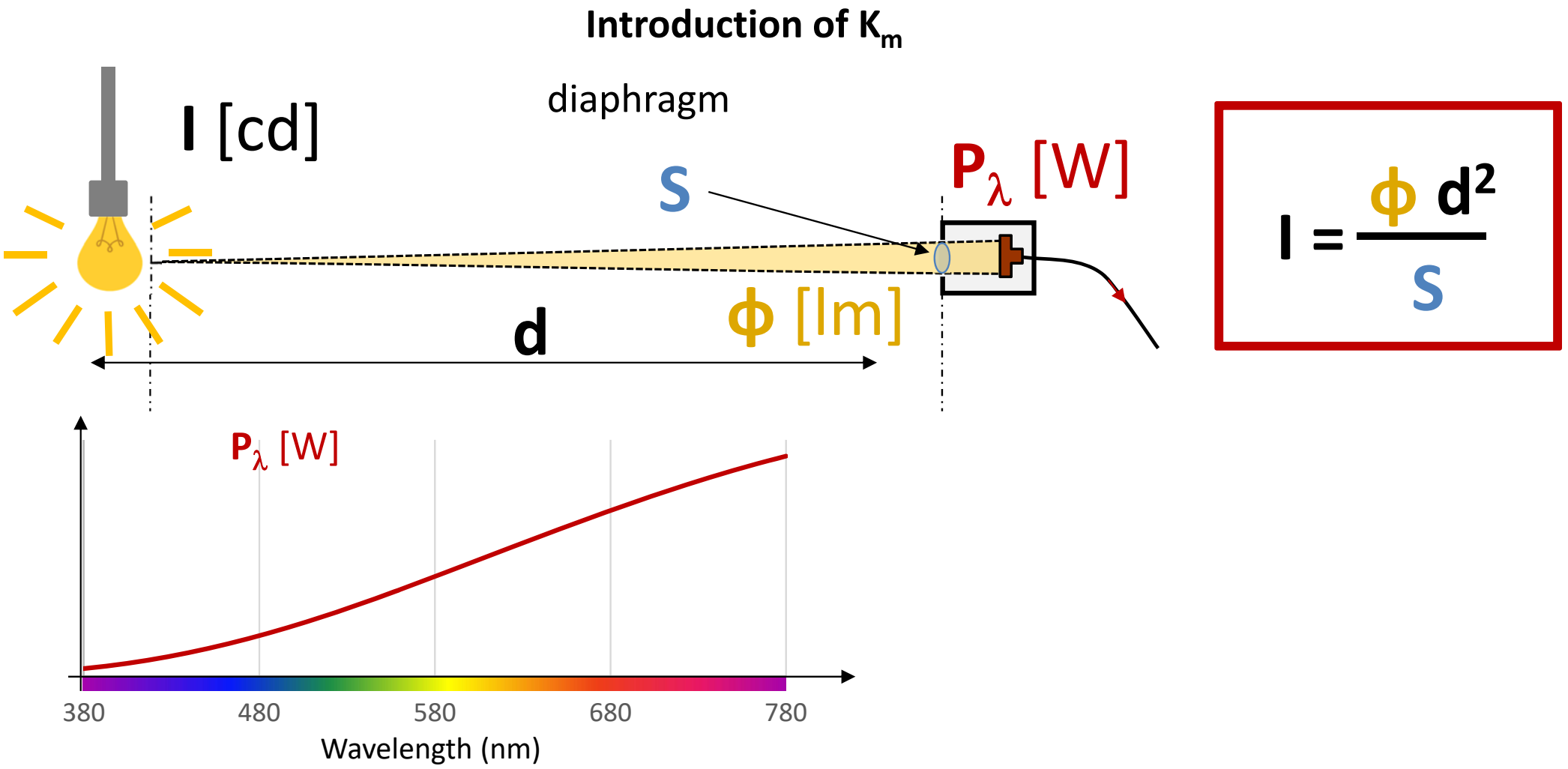


Vision and V(λ) curve

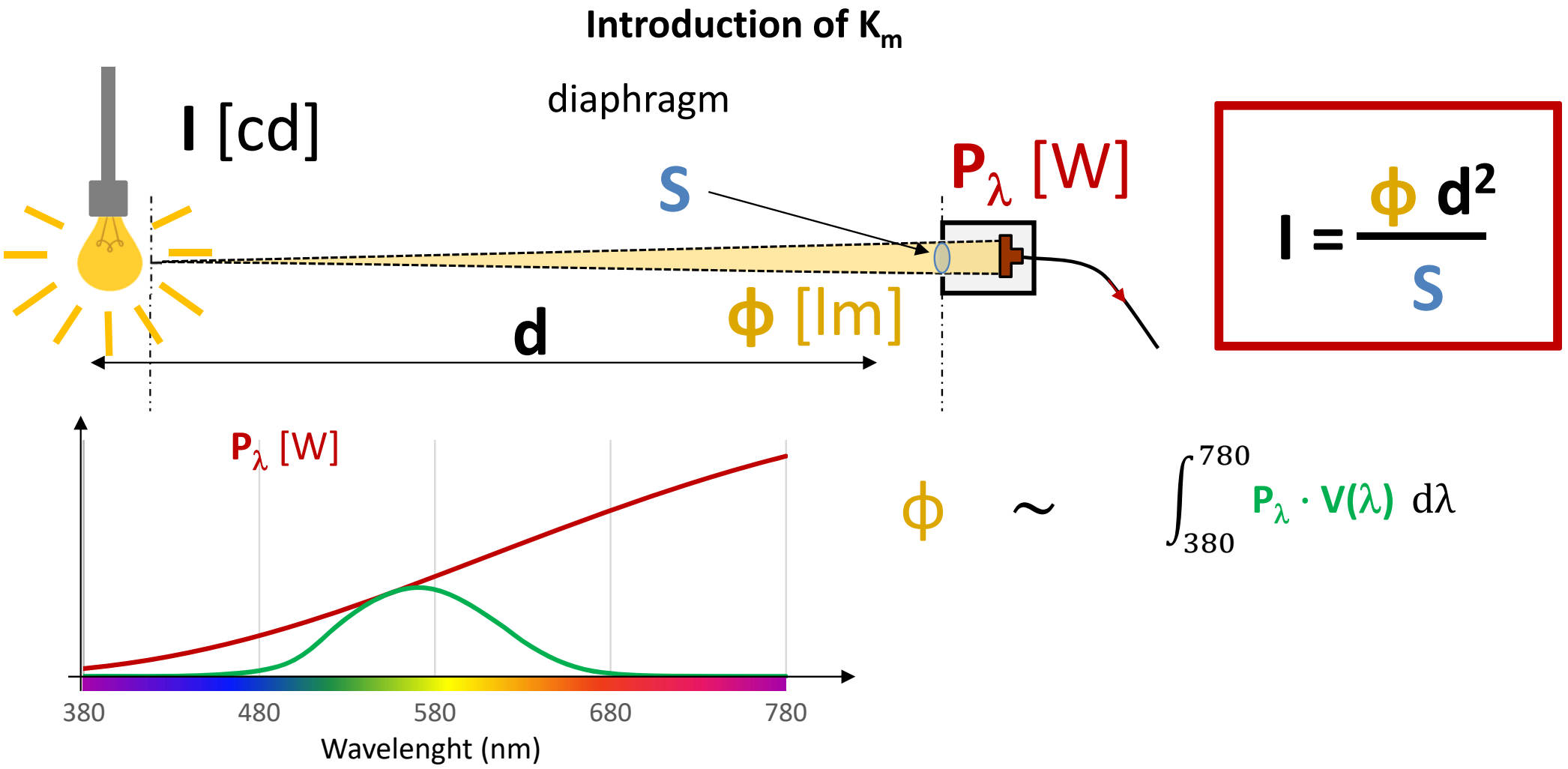
V(λ) filter



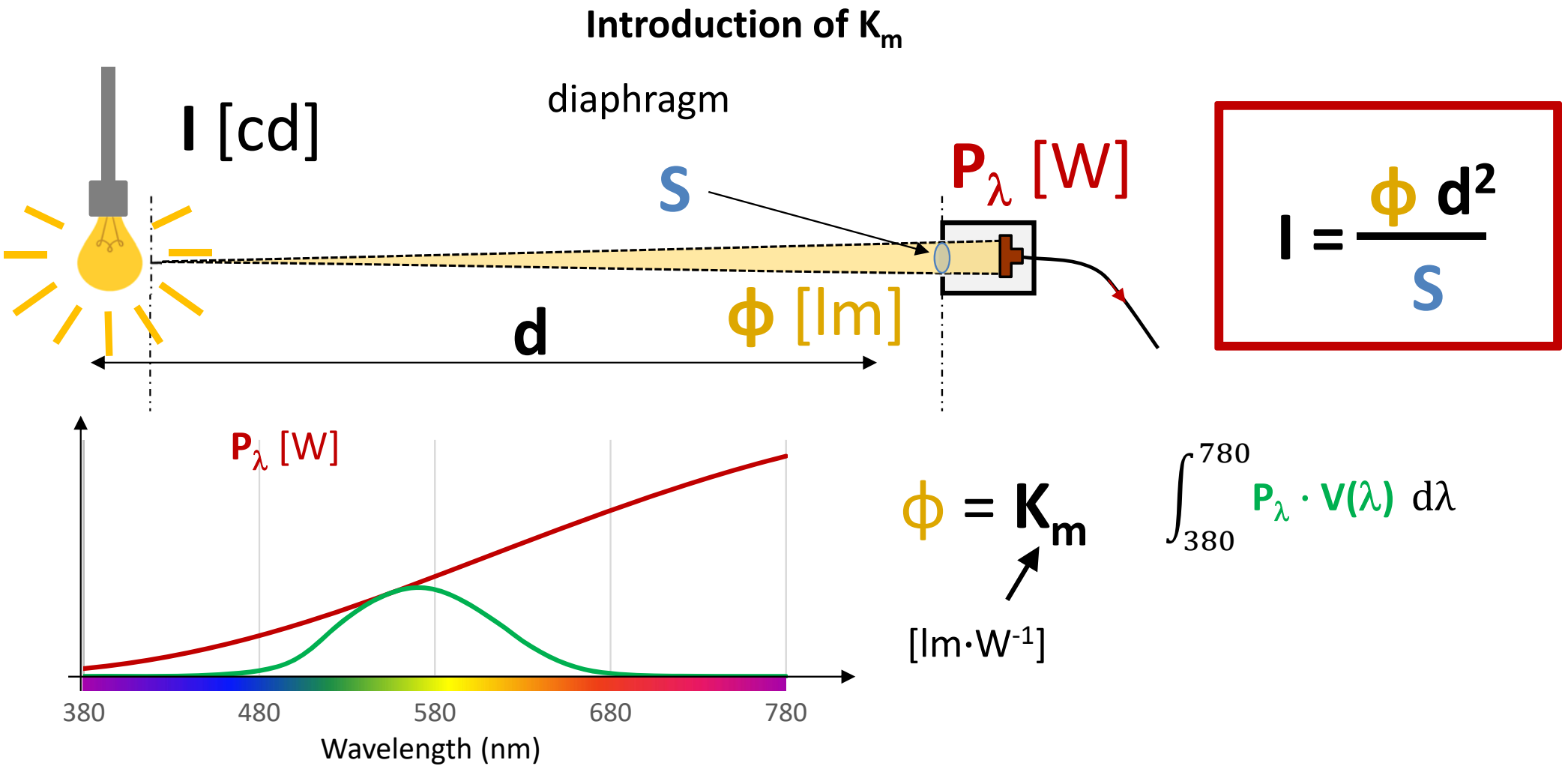
1979, new definition and introduction of K_m



1979, new definition and introduction of K_m

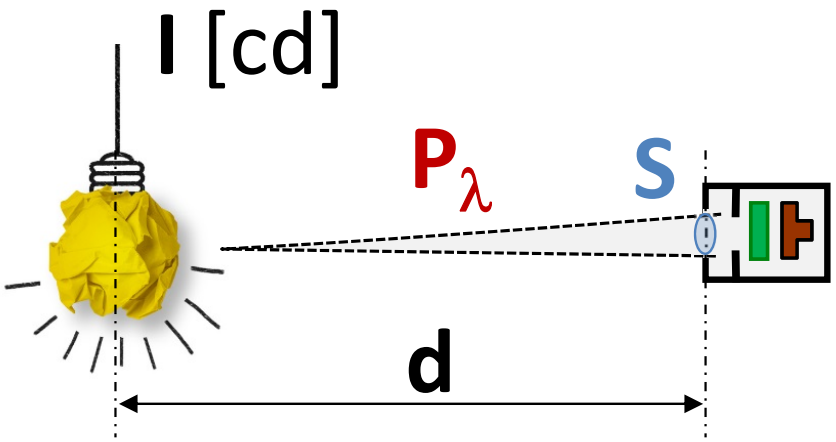


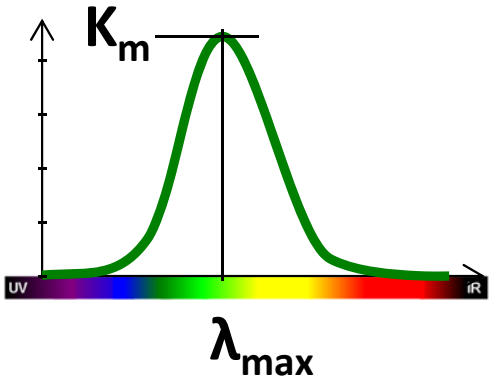
1979, new definition and introduction of K_m



1979, new definition and introduction of K_m

Definition of the *candela*

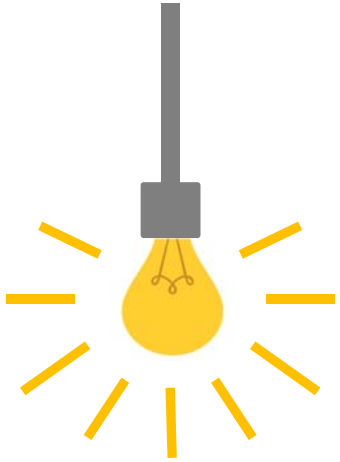




«The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 THz and that has a radiant intensity in that direction of 1/683 watt per steradian»

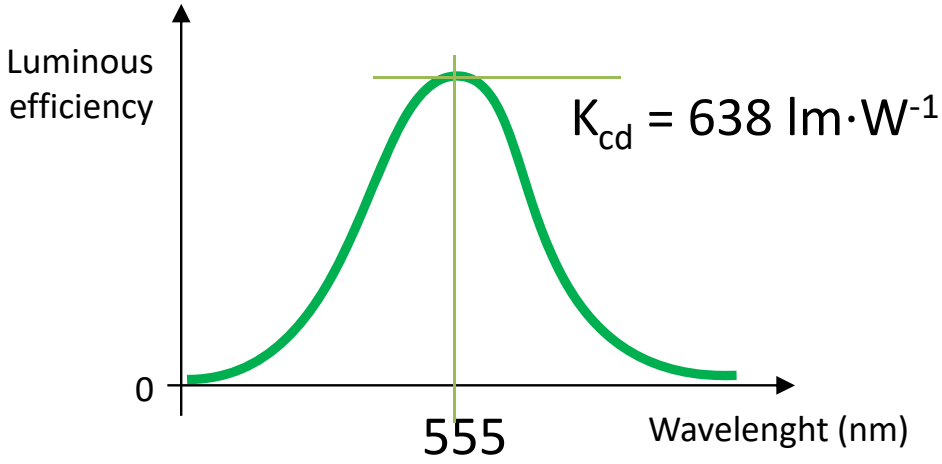
1979 : XVI^{ème} CGPM

Success story : Photometry



Luminous intensity
(visual)

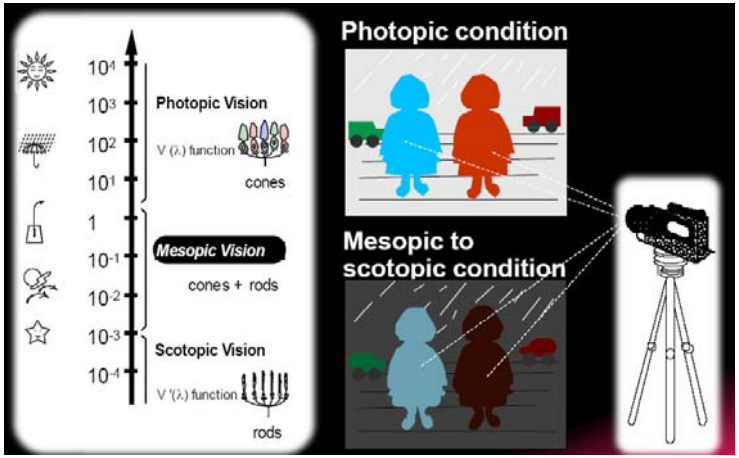
Standard Photopic observer
(CIE 1924)

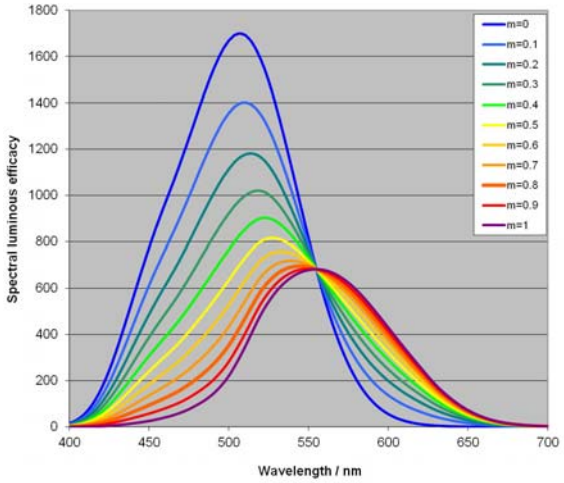


SI brochure
Principle governing photometry

What is missing

New agreed **human visual response function** (**mesopic and 10°**)

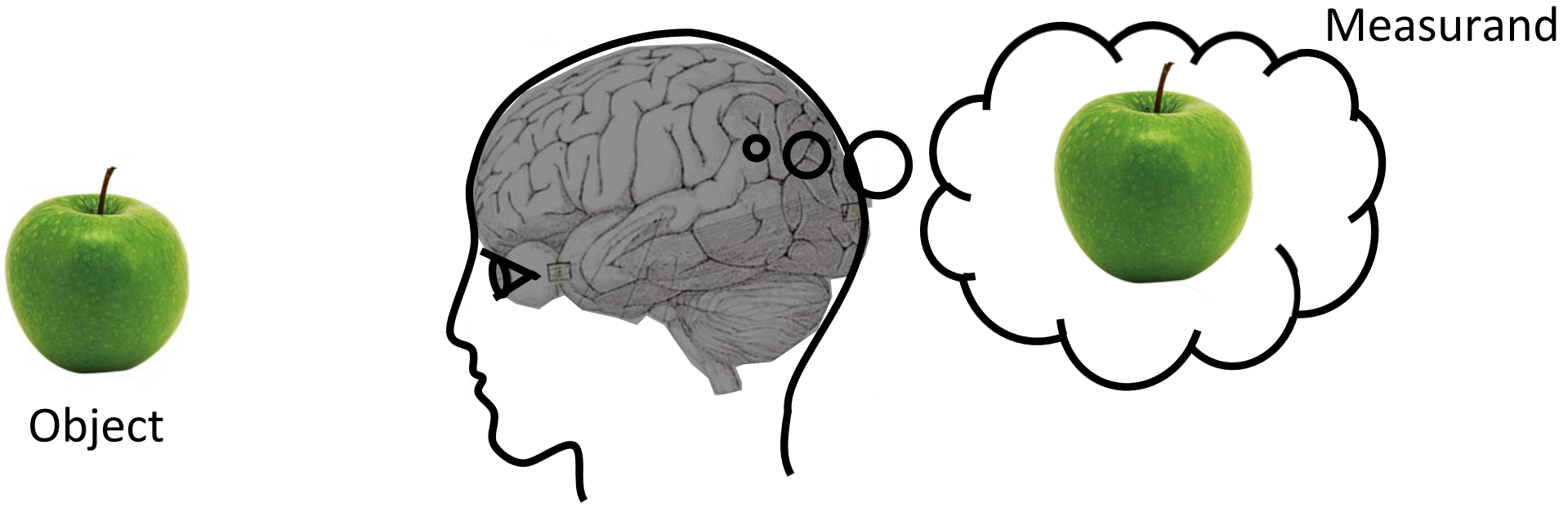




What is missing

Challenge (1/2)

The measurand is not accessible by the measuring instrument

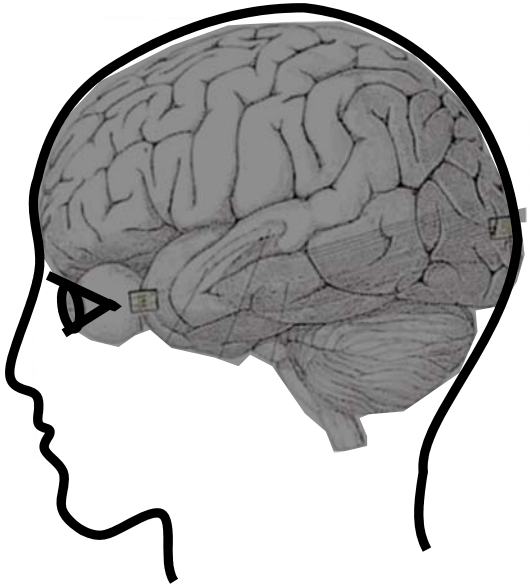


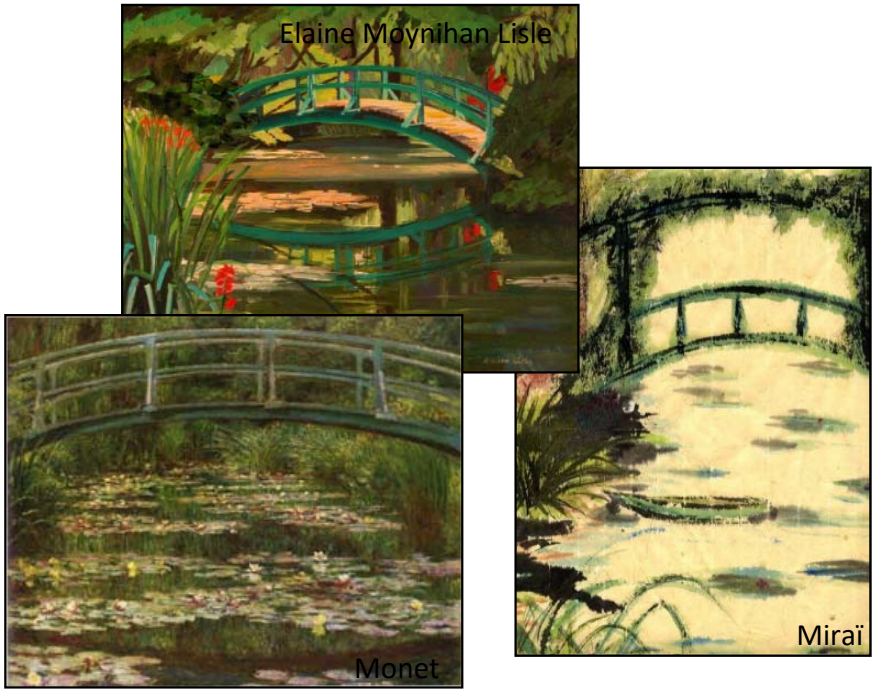
What is missing

Challenge (2/2)

The measurand may vary from one observer to an other

Le pont japonais, Giverny



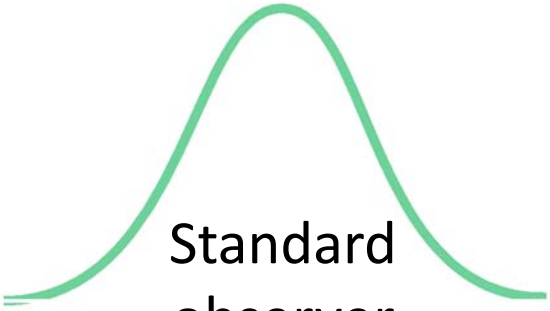


Measurement of perceptive quantities

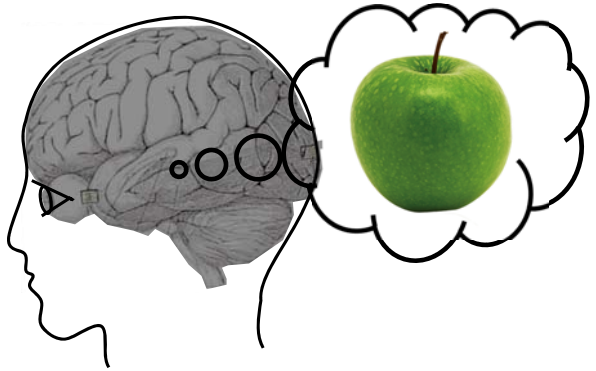
Current method

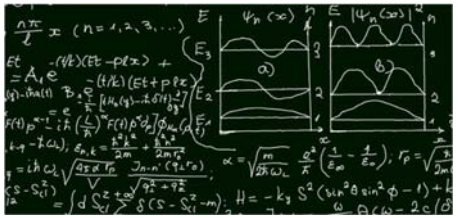
Radiometry & spectrophotometry

Psychophysic experiments



Standard observer

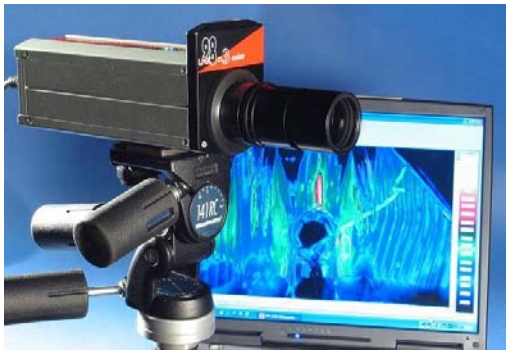




Perception model $\int_{380}^{780} P_\lambda \cdot V(\lambda)\ d\lambda$

Normalization activity

Measurement of perceptive quantities



Future method

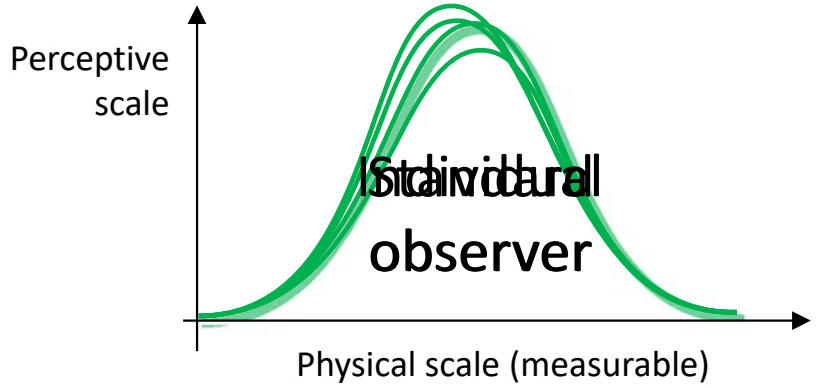
Radiometry

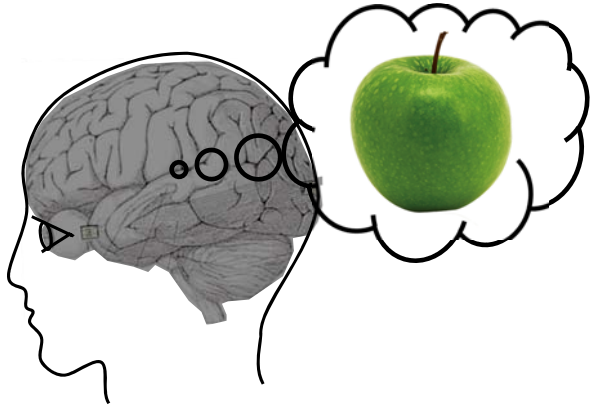
Image-based photometry

Spectrophotometry

Psychophysic experiments

Machine learning



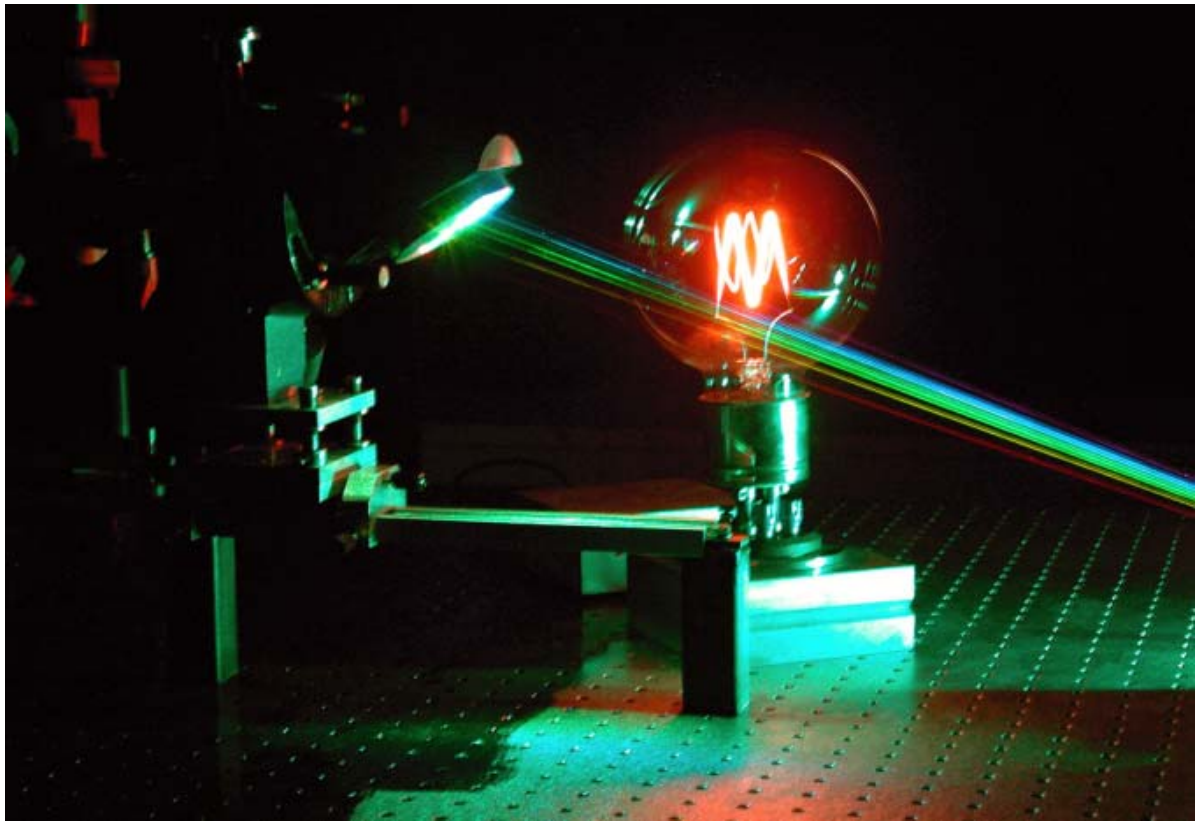


Artificial intelligence

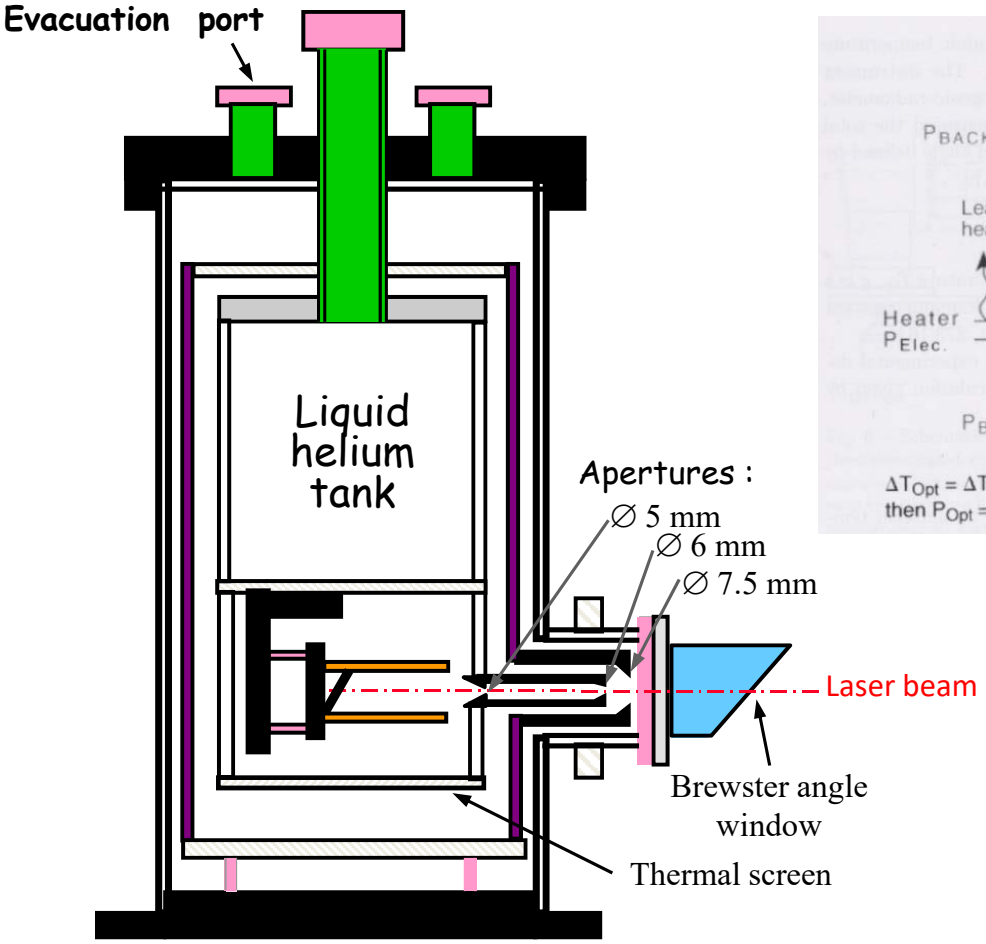
Perception models

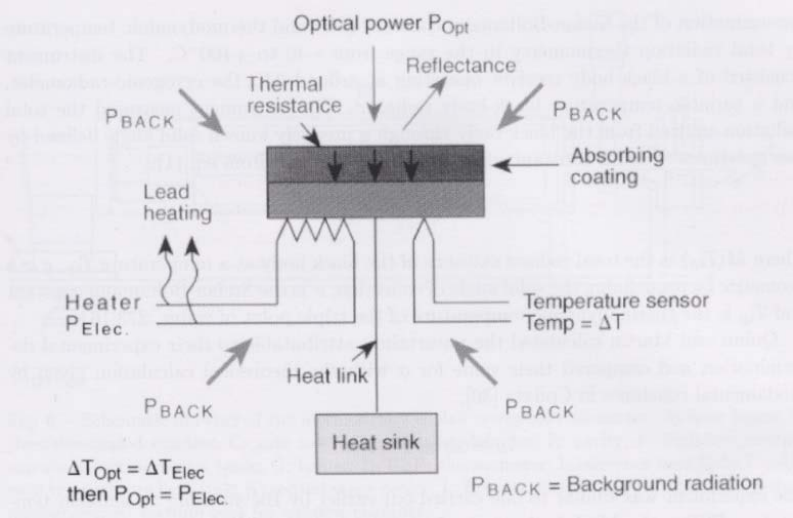
Normalization activity

The laser

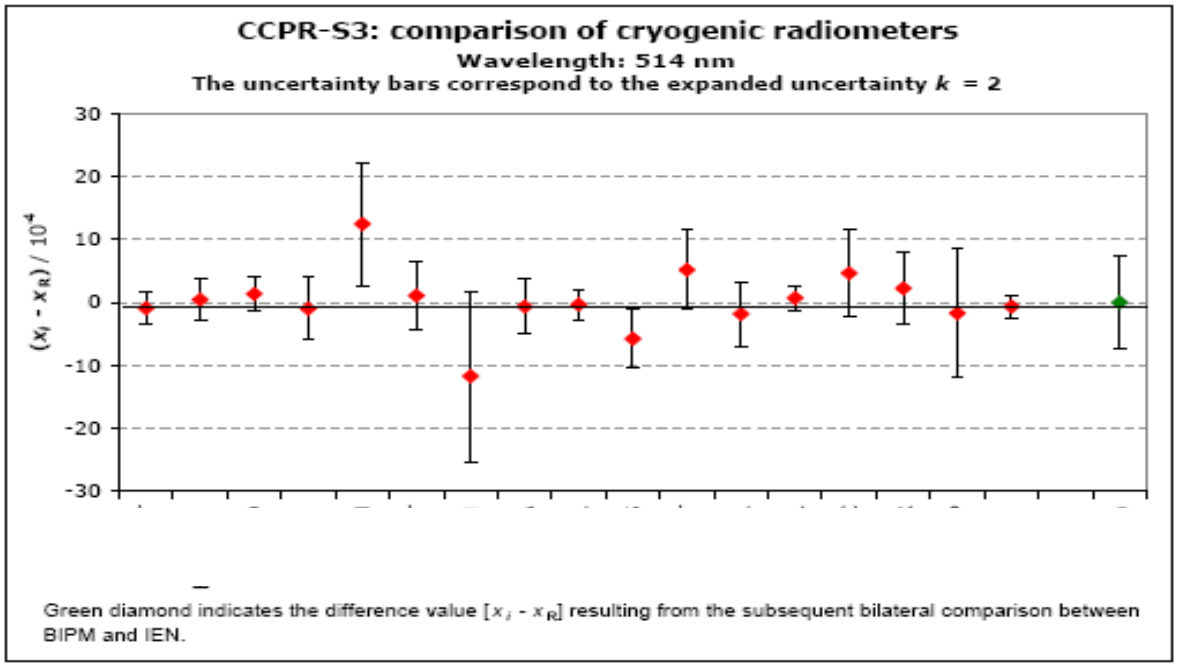


Cryogenic Radiometer

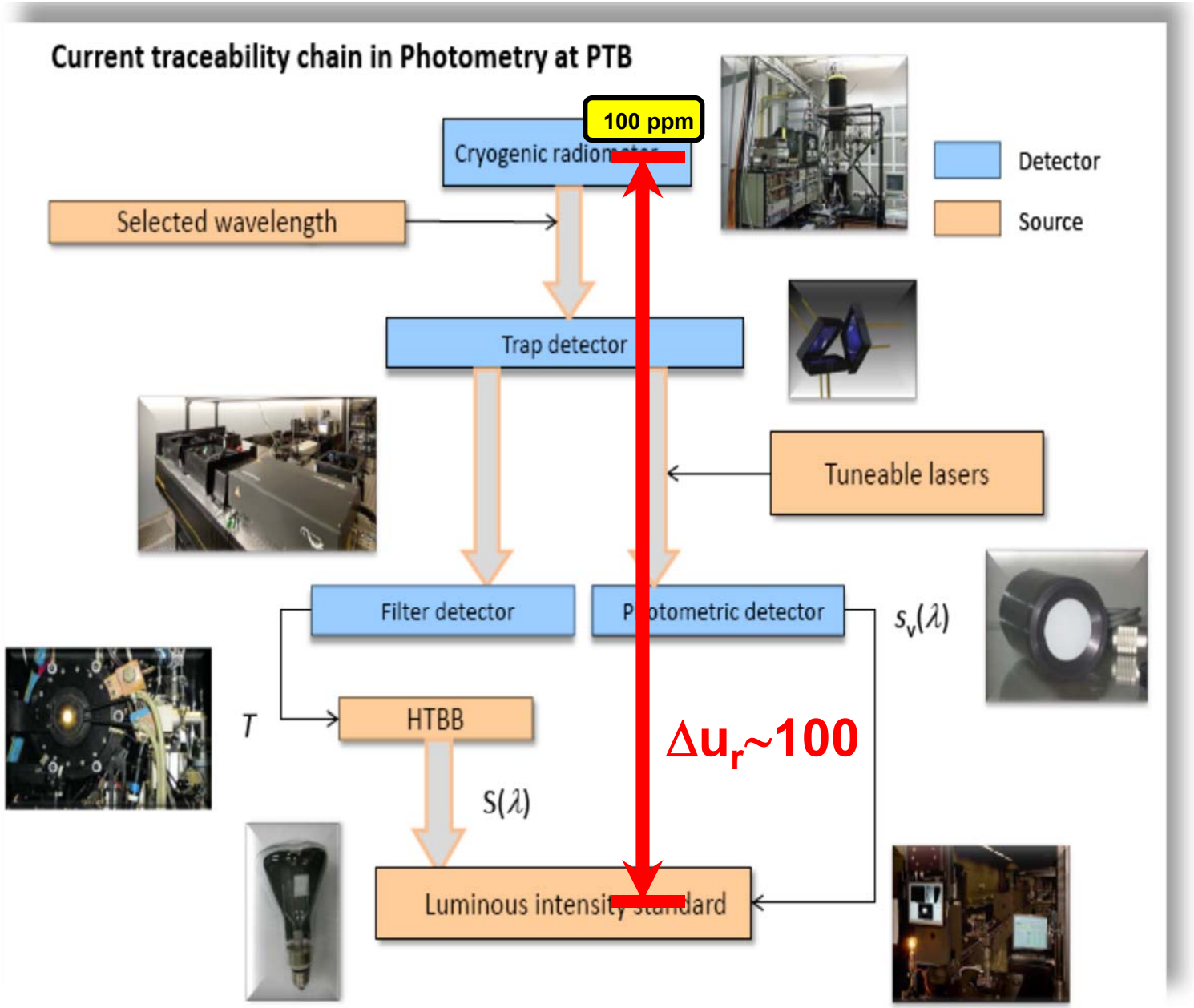




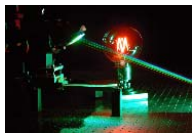
International agreement and consistency



Accuracy to SI <~0.01 %



Kind courtesy of Armin Sperling, PTB



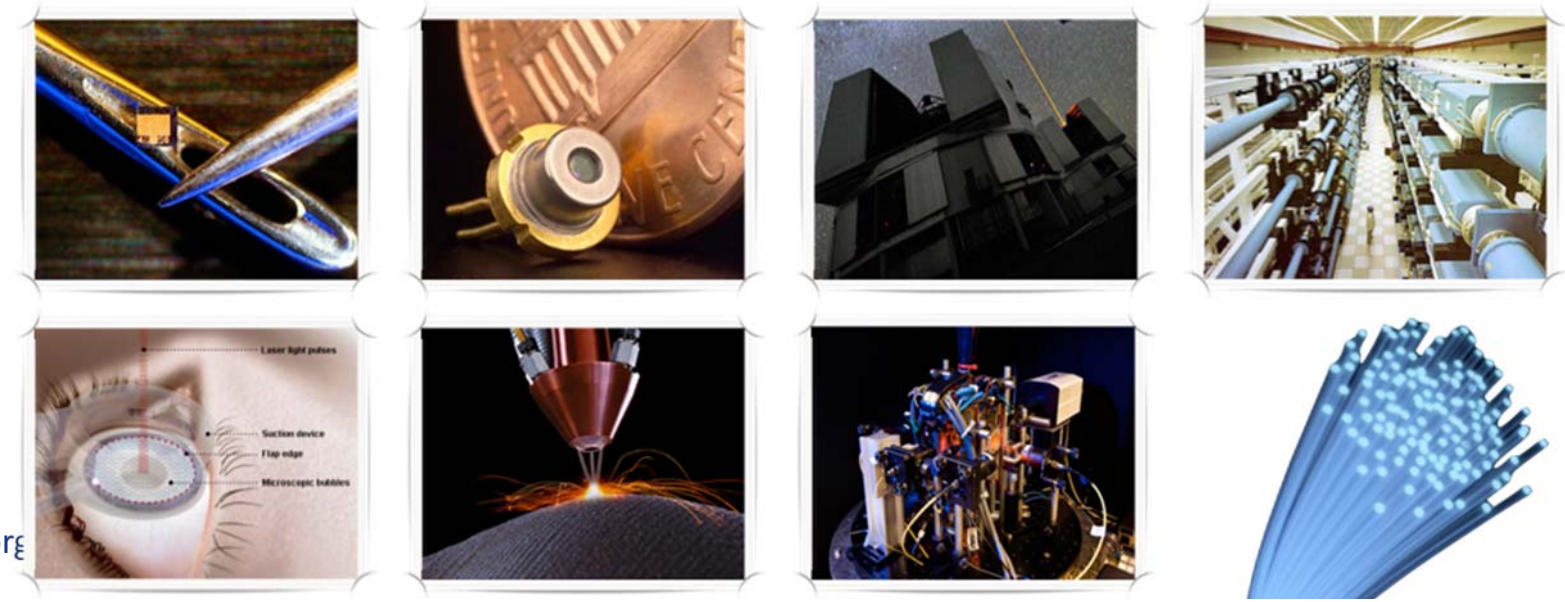
Transformative technology

Invented in 60s in the USSR and the US

Nobel prize to Basov, Prokhorov, Townes

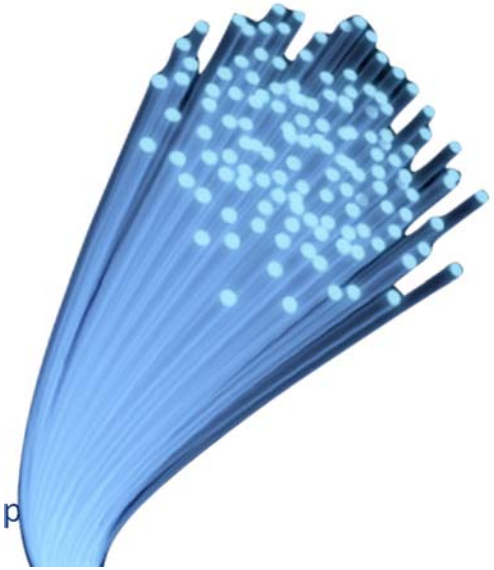
Was recognized as an amazing discovery “from science fiction”

Was thought to be a useless “science toy”: “a solution looking for problem”

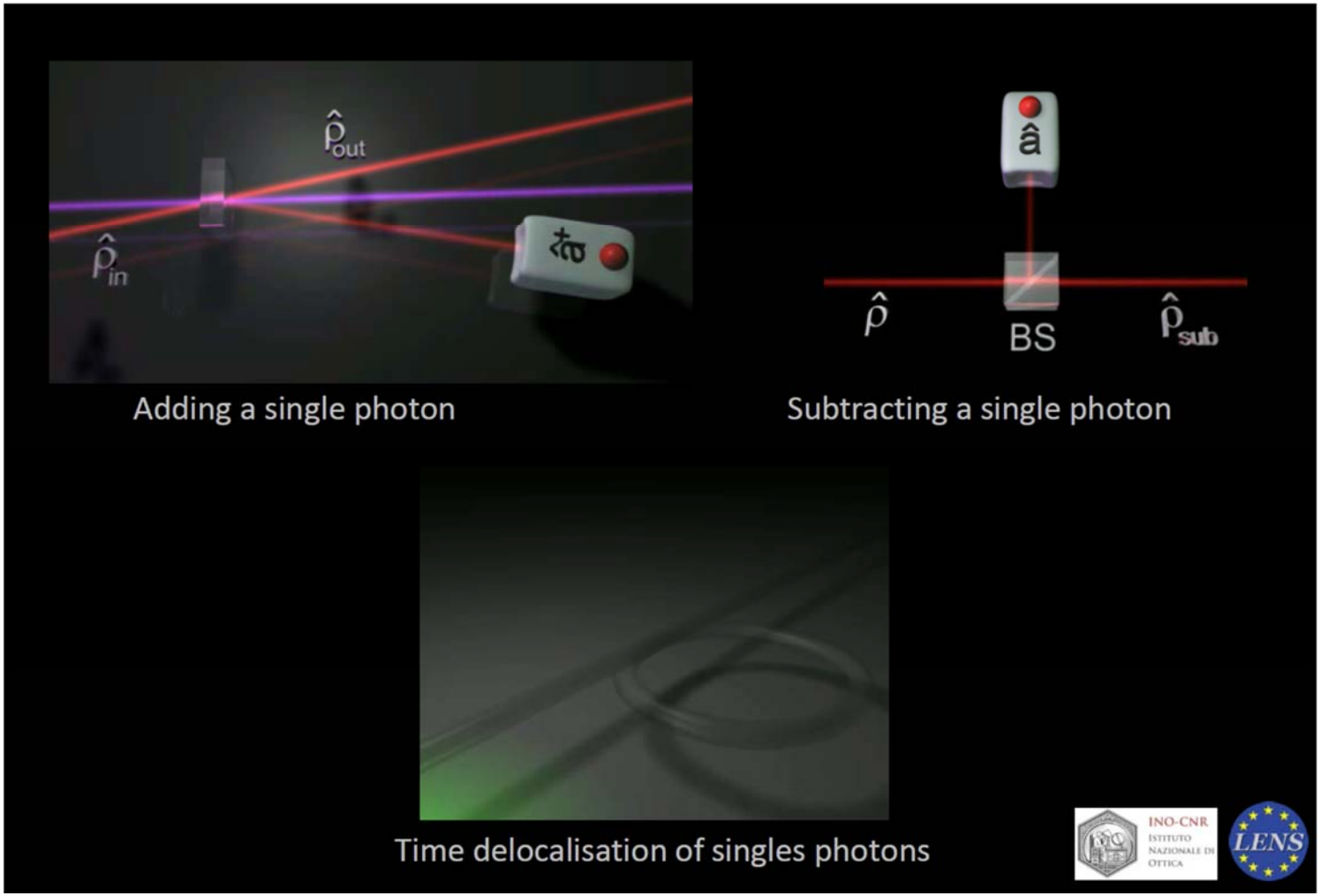


From laser to WEB 2.0

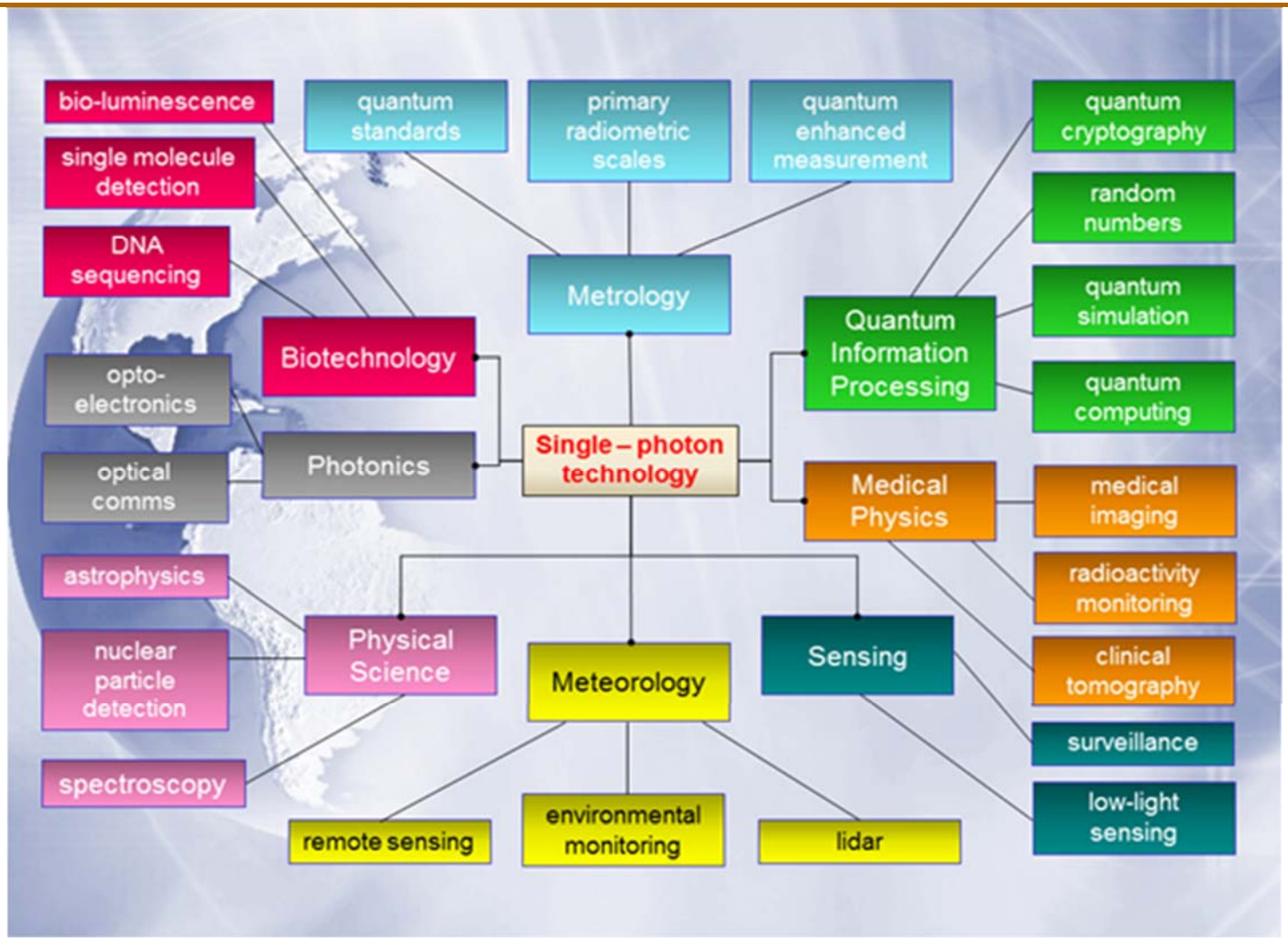
- Broad-band data transmission is enabled by fiber-optical communication
- Laser is a key component
- Dramatic impact on modern society in the past decade



Manipulating single photons

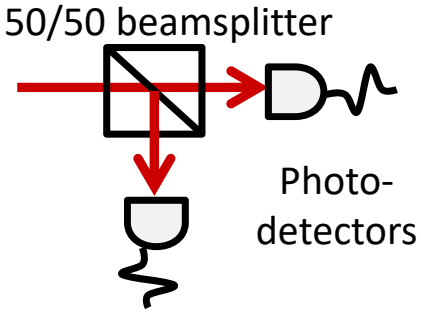


Second Quantum Revolution



Light sources

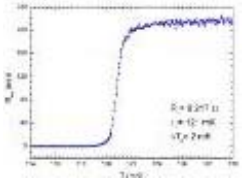
Correlation functions



$g^{(2)}(0)=1$: **random**, no correlation, ex. poissonian (laser) light

$g^{(2)}(0)>1$: **bunching**, photons tend to arrive together, ex.: thermal light

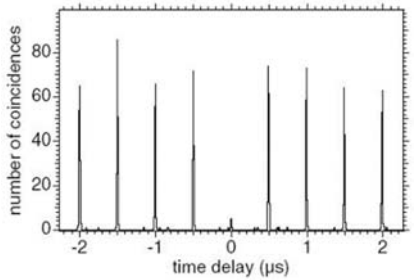
$g^{(2)}(0)<1$: **anti-bunching**, violates classical inequality, ex.: Fock states



Single-Photon Sources for practical quantum applications

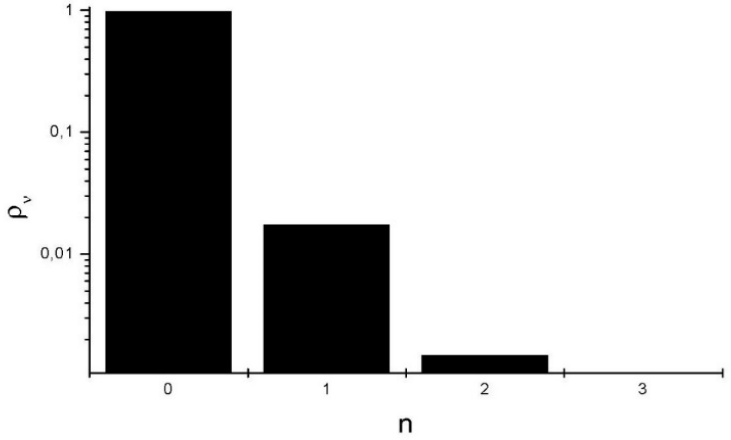
- On demand

- No multiphoton states

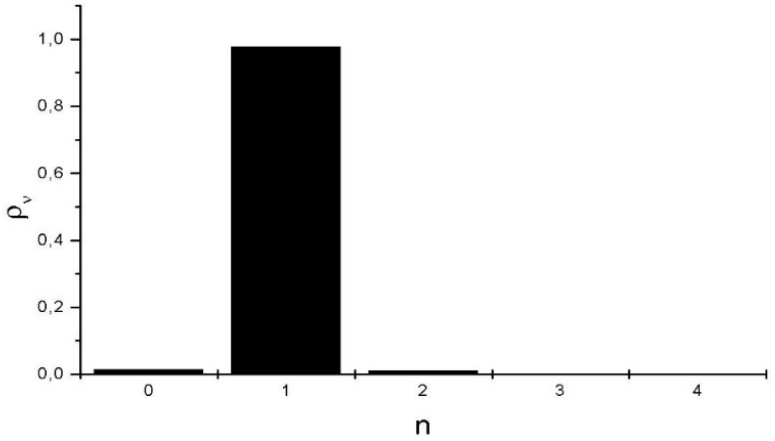


- Indistinguishability

Statistical recostruction of quantum optical states

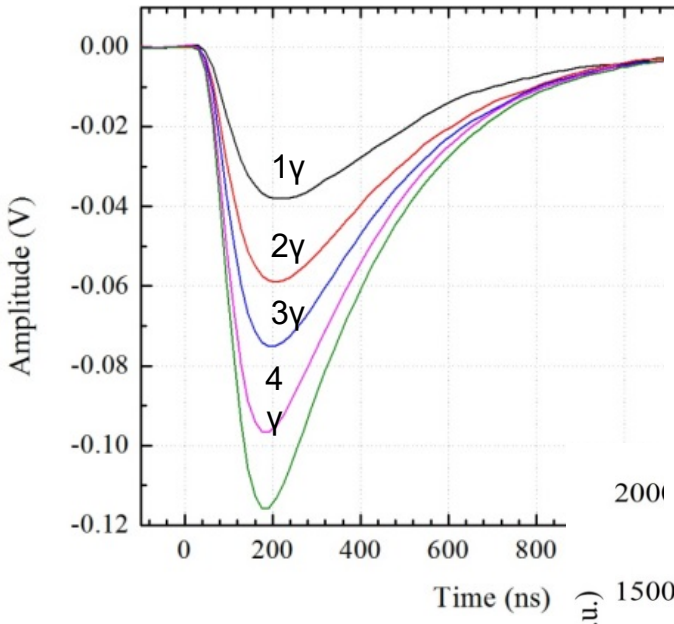


Coherent state
(attenuated He-Ne laser)

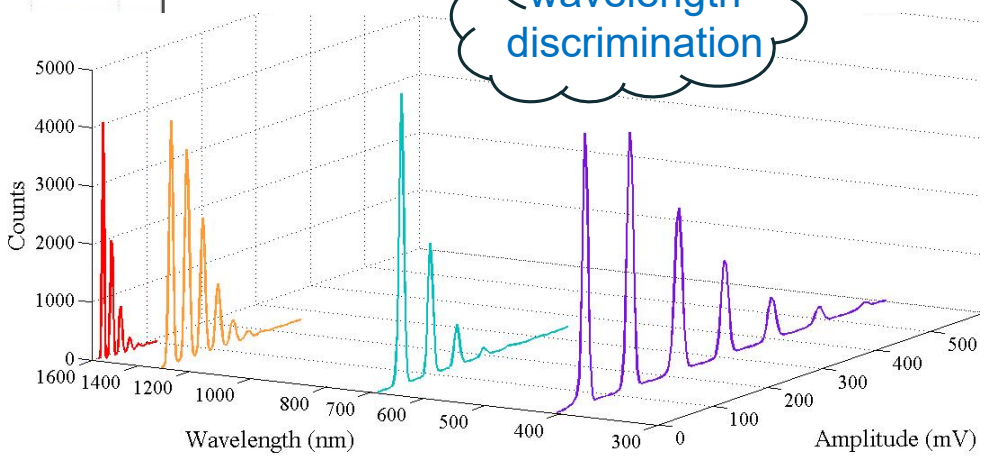


Single photon states

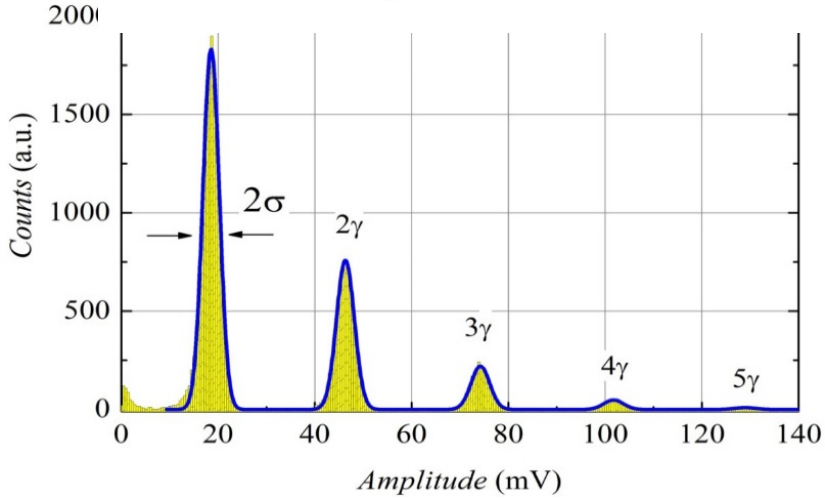
Photon Number Resolving Detectors

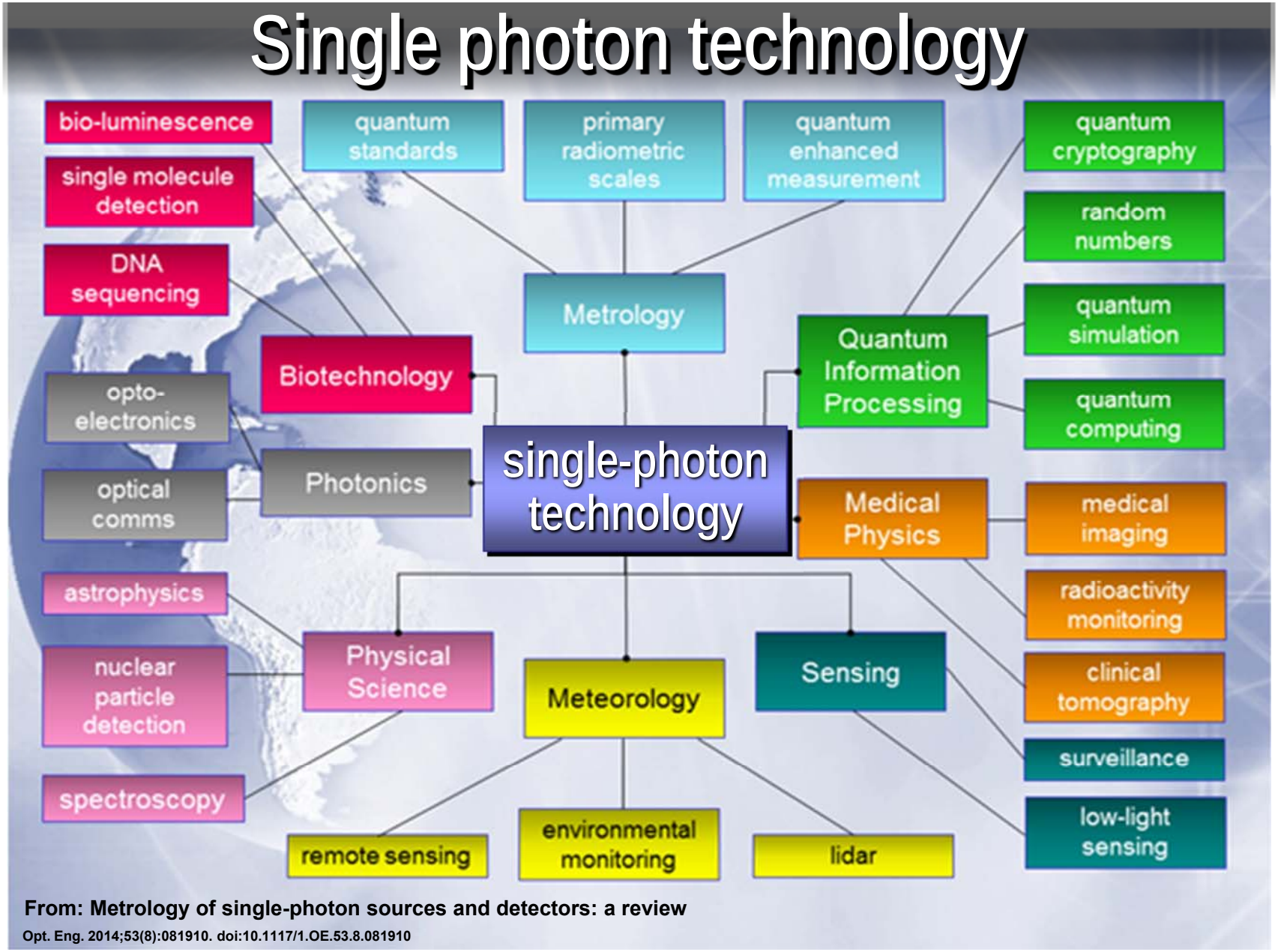


wavelength discrimination



discrimination of single and multiple incident photons



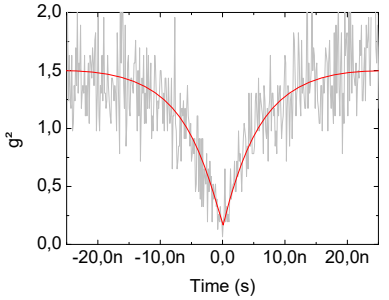


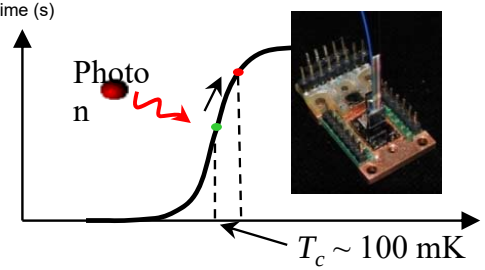
From: Metrology of single-photon sources and detectors: a review

Opt. Eng. 2014;53(8):081910. doi:10.1117/1.OE.53.8.081910

Quantum Radiometry

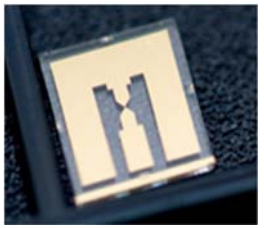
TARGETS





- Develop suitable metrics for
  - single photon sources
  - photon counting detectors

- Develop methods and measurement facilities for characterising non-classical properties of light:
  - antibunching
  - indistinguishability
  - entanglement
  - quantumness



Quantum Sensors

- The most widespread single-photon detectors ?

Bureau International des Poids et Mesures

Quantum Sensors

❑ The most widespread single-photon detectors

✓ **The human eye:**

NATURE COMMUNICATIONS | ARTICLE OPEN

Direct detection of a single photon by humans

Jonathan N. Tinsley, Maxim I. Molodtsov, Robert Prevedel, David Wartmann, Jofre Espigulé-Pons, Mattias Lauwers & Alipasha Vaziri

Affiliations | Contributions | Corresponding author

Nature Communications 7, Article number: 12172 | doi:10.1038/ncomms12172
Received 15 January 2016 | Accepted 07 June 2016 | Published 19 July 2016

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✓ **… but also the frog eye:**

Interaction of Fixed Number of Photons with Retinal Rod Cells

Nam Mai Phan, Mei Fun Cheng, Dmitri A. Bessarab, and Leonid A. Krivitsky
Phys. Rev. Lett. **112**, 213601 – Published 29 May 2014

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Quantum Sensors

Quantum Sensors (not only) in Italy:

❑ The most widespread single-photon detectors

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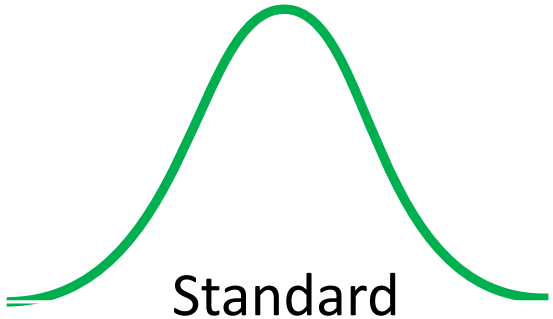
Measurement of perceptive quantities

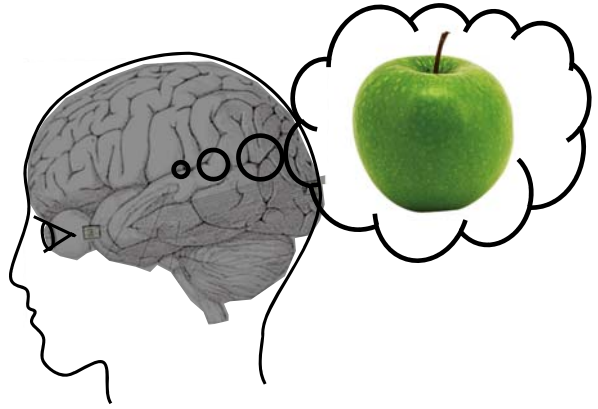
Scotopic vision

Light stimulus
(physical)



Standard
observer
for scotopic
vision

Measurand
(perceptive)



$$\int_{380}^{780} P_\lambda \cdot V(\lambda)\ d\lambda$$

This is just the starting point …

Thank you

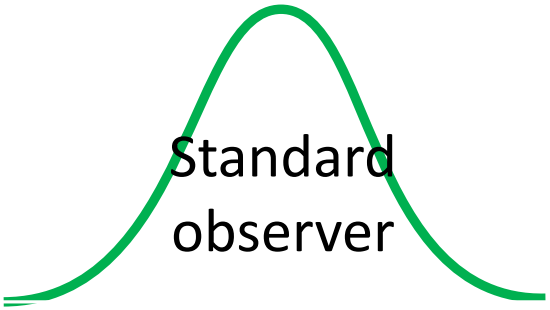
Bureau International des Poids et Mesures

www.bipm.org

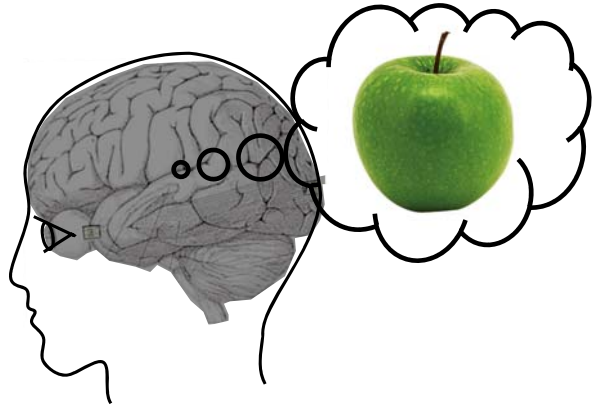
Measurement of perceptive quantities

Current method

Light stimulus
(physical)



Measurand
(perceptive)



$$\int_{380}^{780} P_\lambda \cdot V(\lambda)\ d\lambda$$