

# The candela, the most human of the SI base units



**Gaël Obein, LNE-CNAM**

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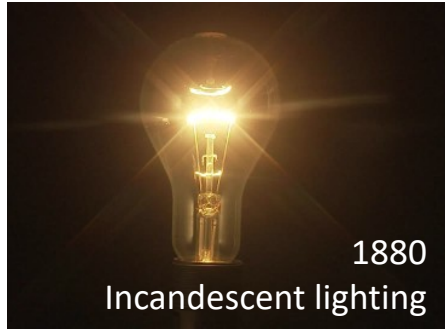


**Gaël Obein, LNE-CNAM**

## 5 sens



Humans feel their environment through their senses  
Vision is the most used in daytime situations.



Lighting has been an essential component of survival, security and well-being of the human species since the dawn of humanity.

# Photometry

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

*Wikipédia (June 28<sup>th</sup>, 2019)*

To do photometry, you need :



A light  
source



eyes



One brain  
(eventually)

# The candela, the most human of the SI base units

## Outlines

- Quantities and units in photometry
- First measurements
- Towards the candela, 6<sup>th</sup> SI unit
- Radiometry, a new way for the candela
- Vision and  $V(\lambda)$  curve
- 1979, new definition and introduction of  $K_m$
- Photometry widens to meet new societal needs
  - Luminous efficacy and energy saving
  - Non visual functions of the retina
- The candela, one of the 7 SI units... why?



# Quantities and units in photometry

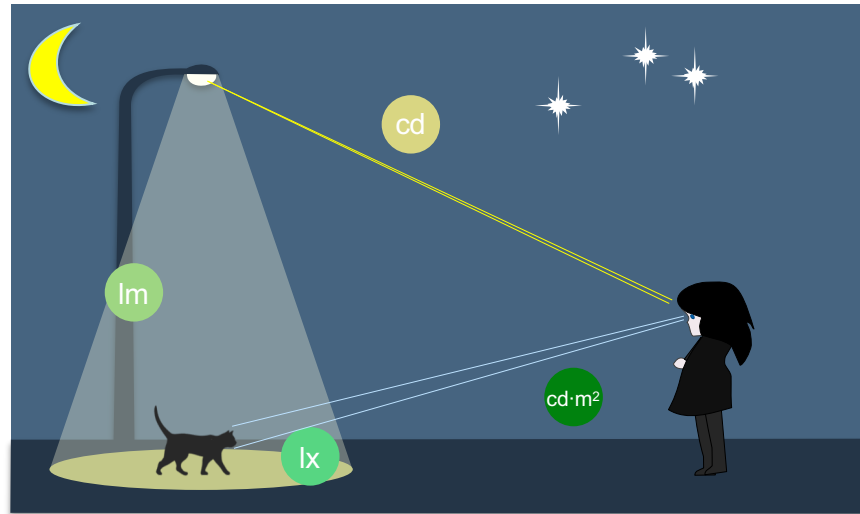
Photometric quantities are :

Flux, in lumen [lm],

Intensity, in candela [cd],

Illuminance, in lux [lx],

Luminance, in  $\text{cd}\cdot\text{m}^{-2}$ .



# First measurements

Until the XVII<sup>e</sup> century, no need



Jeune fille lisant une lettre à la bougie, J-B Santerre (1658–1717)



"Choeurs de lumière", Cathédrale de Lausanne, 2005



## At XVIII<sup>e</sup> century, invention of public gas lighting



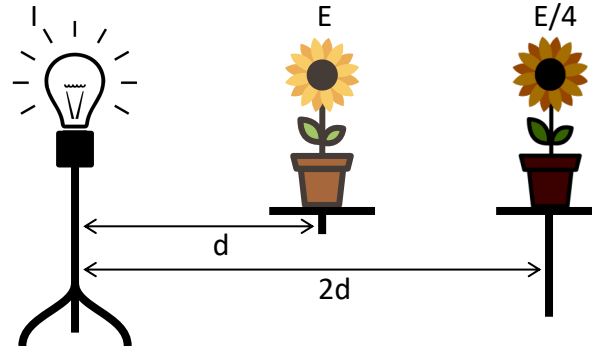
Flams haven't the same colour, notion of street lighting emerges, it is necessary to set up the metrology in order to ensure quality and efficiency of public lighting

# Theory

**Pierre Bouguer (1698-1758)**



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



## First photometers

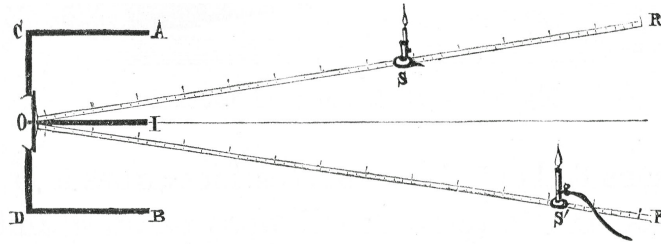


Fig. 70. — Photomètre de Foucault.

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

Visual comparisons

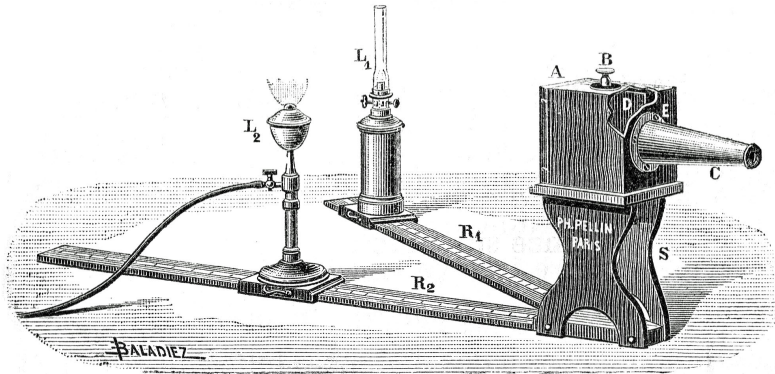
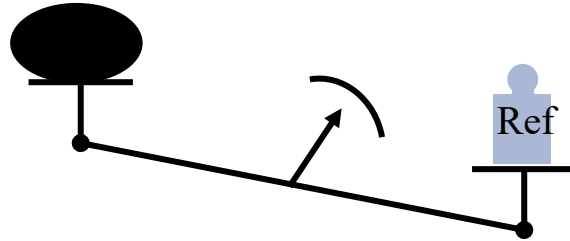


Fig. 71. — Photomètre de Foucault.

Extracted from "manipulation de physique"  
A. Leduc, 1895

1854

## Measure, it's compare



$$G = \{G\} [G]$$

Physical quantity

Numerical Value

Units

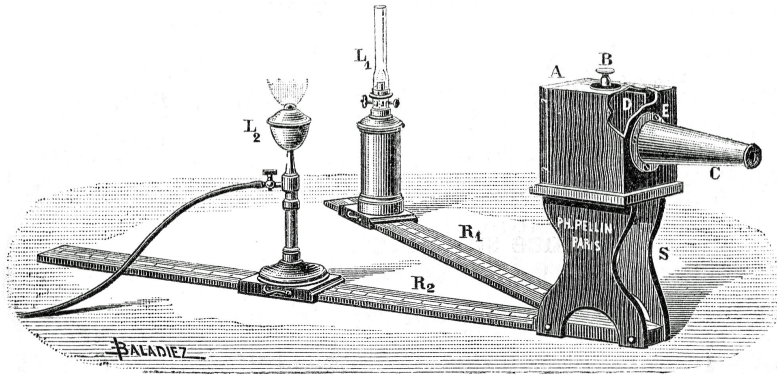


Fig. 71. — Photomètre de Foucault.

What is the reference?

## First standard

### Standard lamps



© Cham - Musée



© PTB

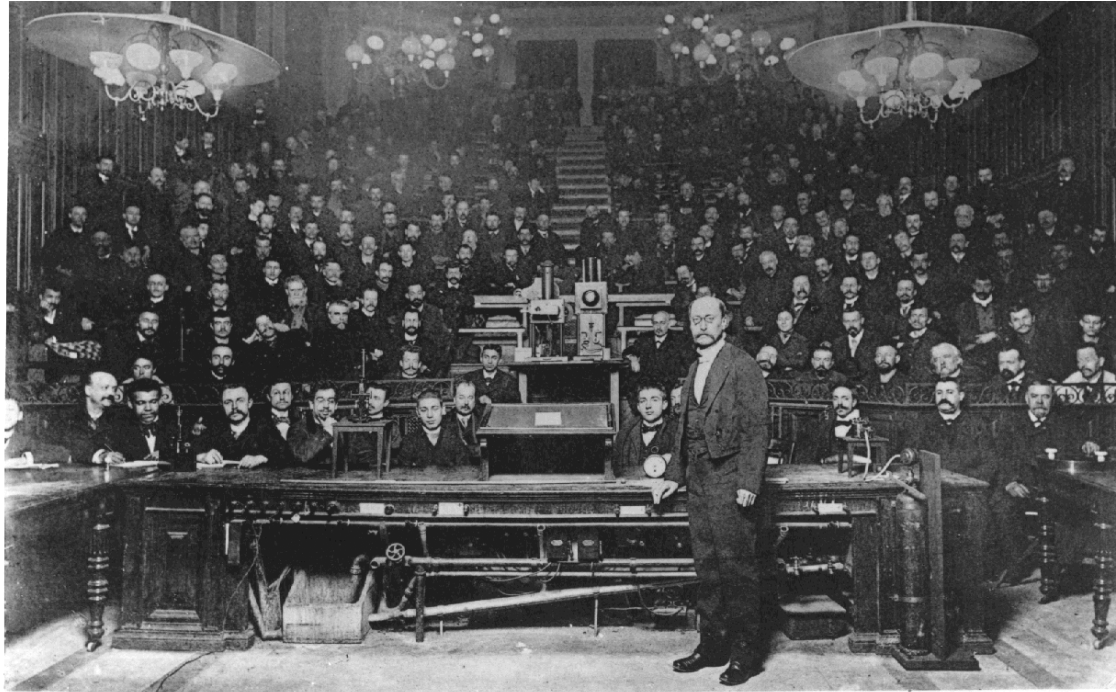


© NIST

1890

## ➤ Towards the candela, 6<sup>th</sup> SI unit

1881, new proposition from Louis Jules Gabriel Violle (1841-1923)



© Archives CNAM

## The violle and the « bougie décimale »

L. Violle proposes the use as standard of the amount of light emitted by 1 cm<sup>2</sup> of platinum at its freezing temperature (1 768 °C).

- ➡ Based on physical properties
- ➡ Independant of the properties of the light source
- ➡ Adopted en 1889 by the International congress of electrical measurement, that defines the « bougie décimale » as 1/20 of a violle.



## 1900 : the « black body », the ideal standard

Radiance from the black body  
depends only of its temperature

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

with :

$\lambda$ , wavelenght of the radiation

T, black body temperature

c, speed of light

h, Planck constant

k, Boltzmann constant

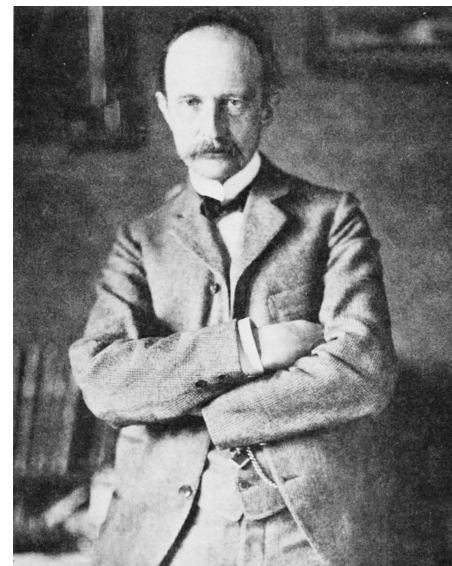


Photo collection particulière D. J. Lovell

Max Planck



## First definition of the *candela*

CIPM, 1946

### ■ Definitions of photometric units (PV, 20, 119-122)\*

#### Resolution

...

4. The photometric units may be defined as follows:

**New candle** (unit of luminous intensity). — The value of the new candle is such that the brightness of the full radiator at the temperature of solidification of platinum is 60 new candles per square centimetre.

**New lumen** (unit of luminous flux). — The new lumen is the luminous flux emitted in unit solid angle (steradian) by a uniform point source having a luminous intensity of 1 new candle.

5. ...

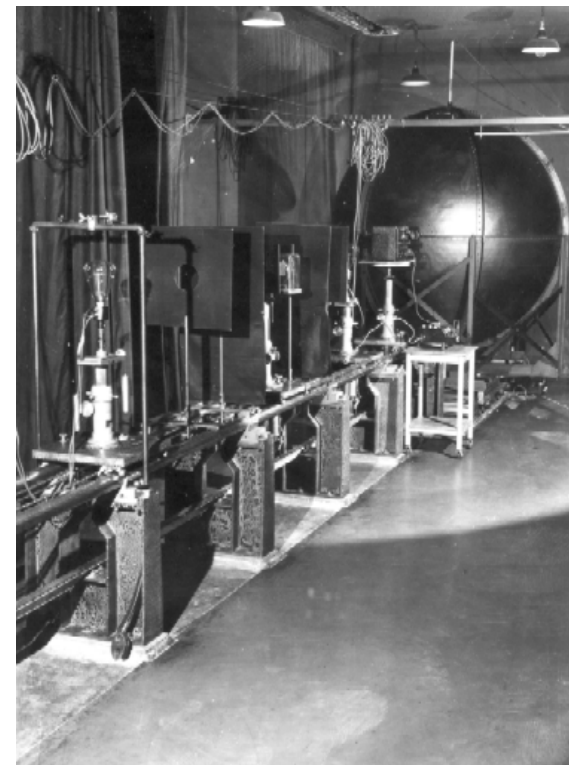
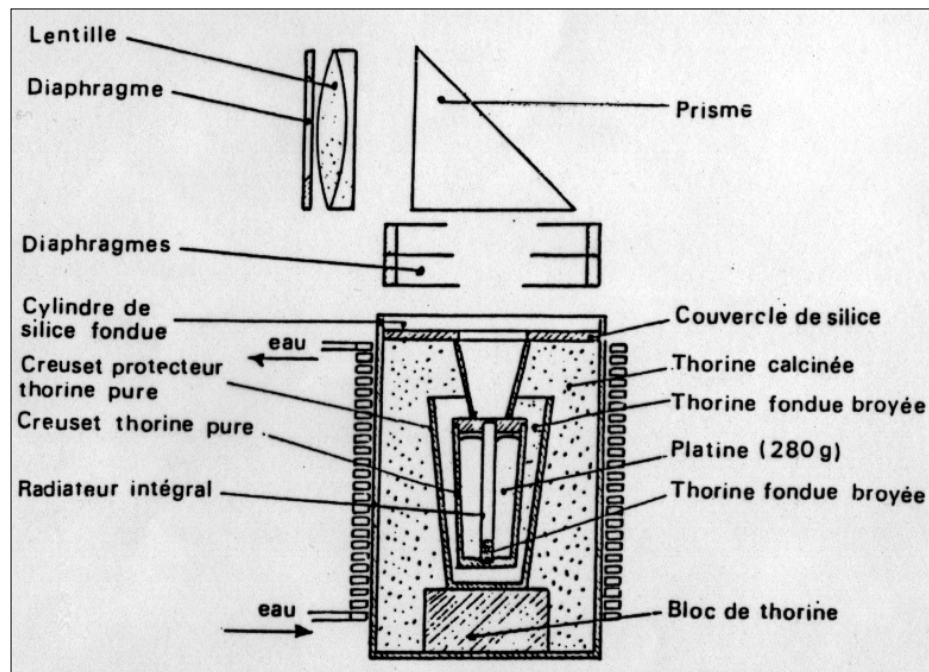


The 2 definitions were ratified in 1948 by the 9<sup>th</sup> CGPM, which gave the name **candela** to the « new candle » and lumen to the « new lumen »



## First mise en pratique of the *candela*

Black body at Platinum freezing temperature

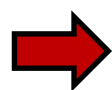


© Archives CNAM

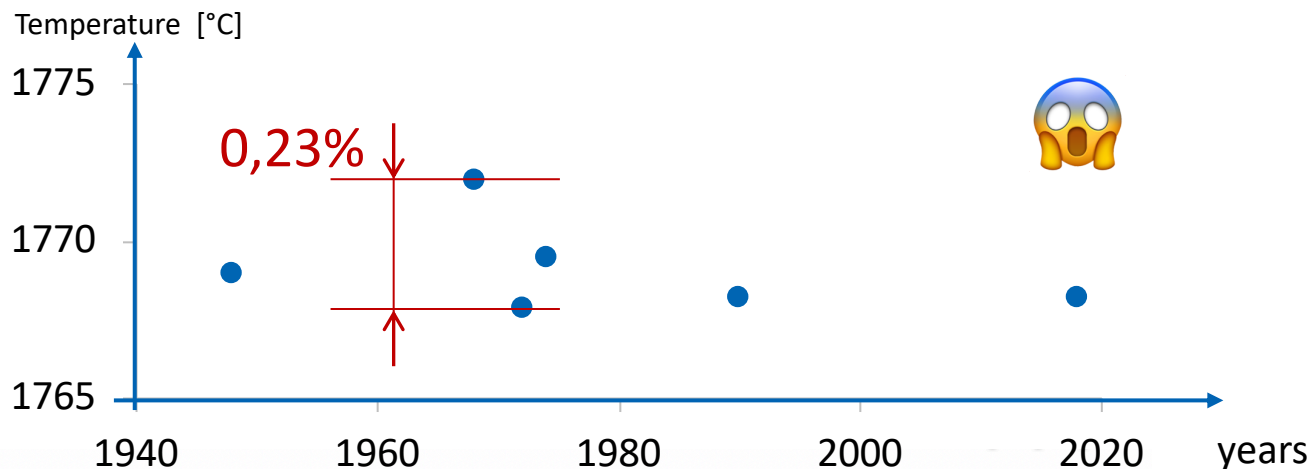
Debure M. et Leroy N. - Revue d'optique théorique et instrumentale 31, 12 (1952)

## Freezing temperature of Platinum

«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<sup>ème</sup> CGPM, 1968**



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



# The candela, the most human of the SI base units

## Outlines

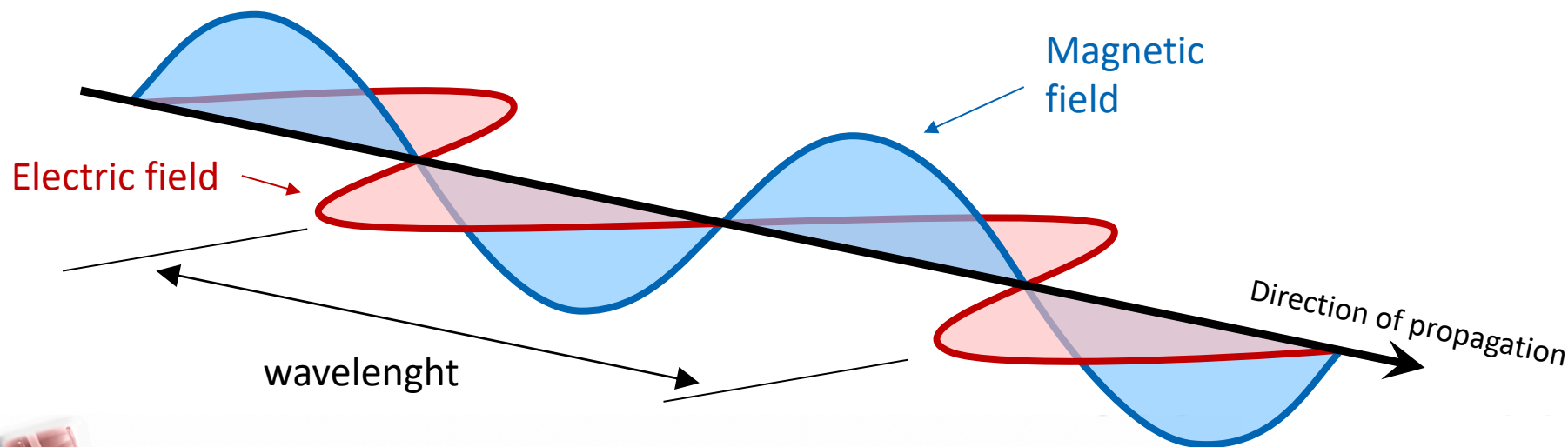
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## Radiometry to rescue photometry

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

Radiometry is distinct from quantum techniques such as photon counting.



## Visible

Electromagnetic waves with a wavelength between 380 nm and 780 nm are what we call the **visible light**

380 nm

780 nm



Violet

Blue

Green

Yellow

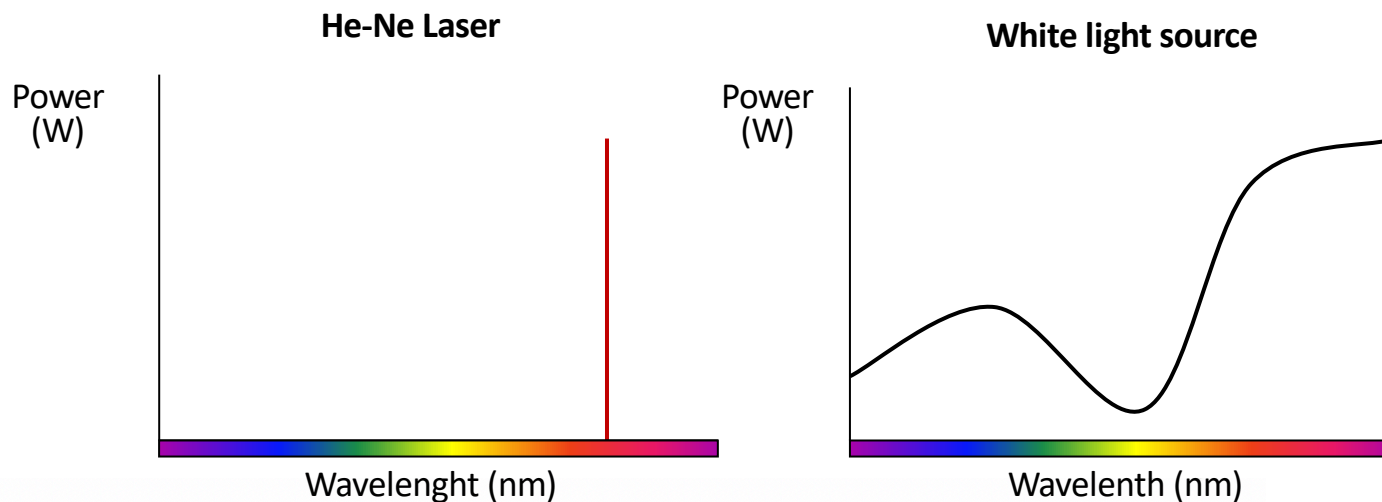
Orange

Red



## Spectral power distribution of light sources

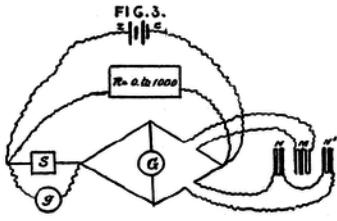
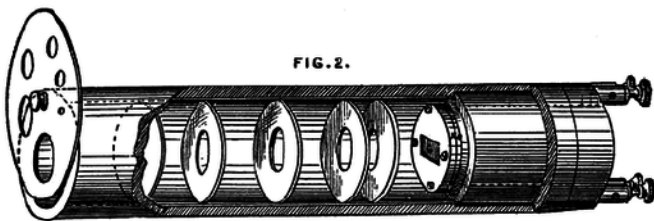
Spectral power distribution describes the light spectrum of a light source  
It shows which radiations are present, at which wavelength, in which proportion.



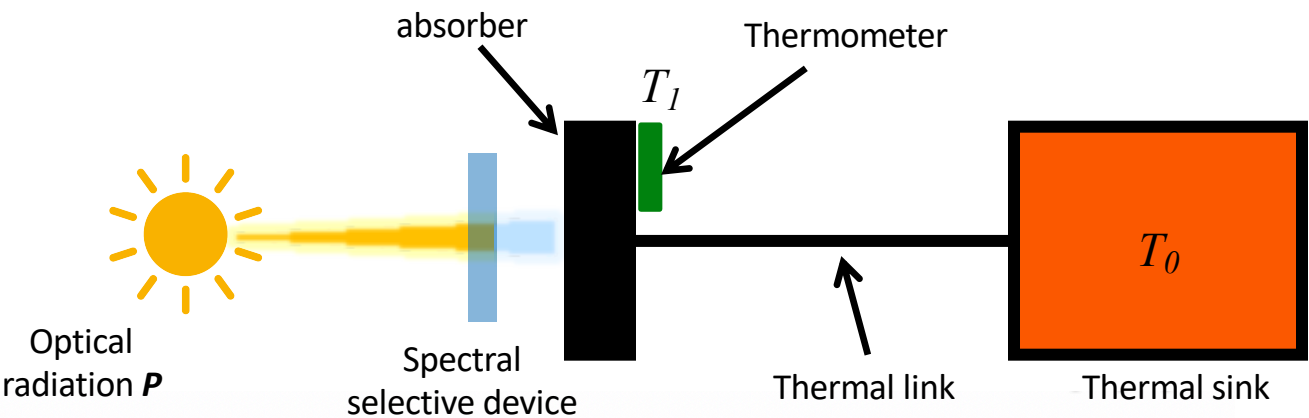


Samuel Langley

# First bolometer



S. Langley, "The Bolometer," *Nature*, **25**, p. 14, 1881.



Limited by  
thermodynamic  
knowledge

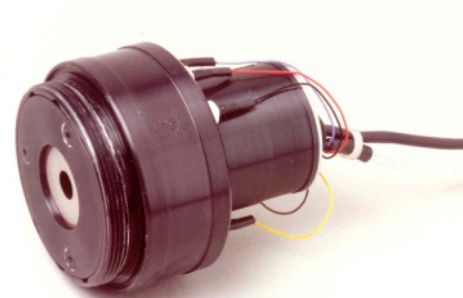
# Electrical substitution radiometer



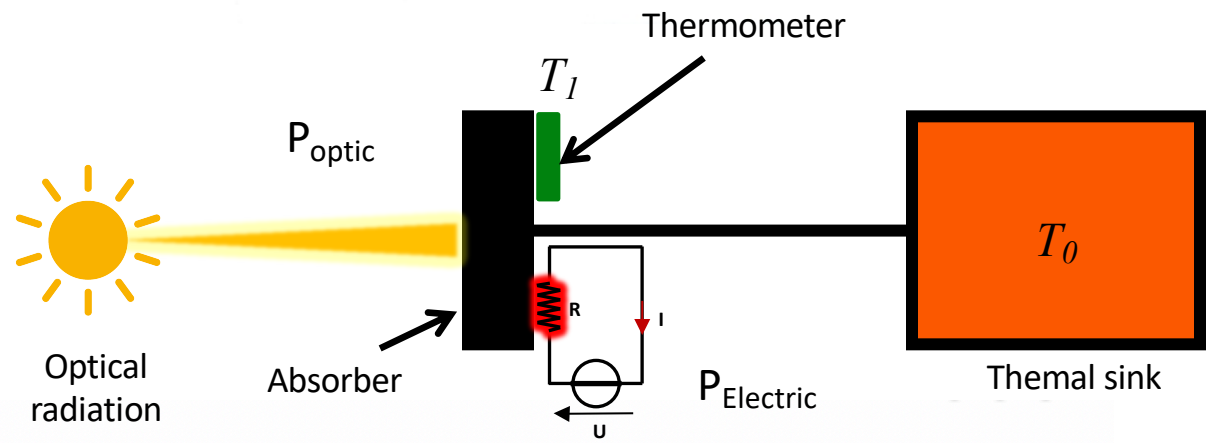
F. Kurlbaum



Angström



Correction	Coefficient	Rel Unc
Reflectance factor	0,9943	$5 \cdot 10^{-4}$
Spatial uniformity	1,0018	$1 \cdot 10^{-3}$
Pulsation	0,9986	$5 \cdot 10^{-4}$
Wire heat	1,0004	$2 \cdot 10^{-4}$
Thermal equivalence	0,9970	$1,5 \cdot 10^{-3}$
Total correction	0,9931	$2,0 \cdot 10^{-3}$



1980

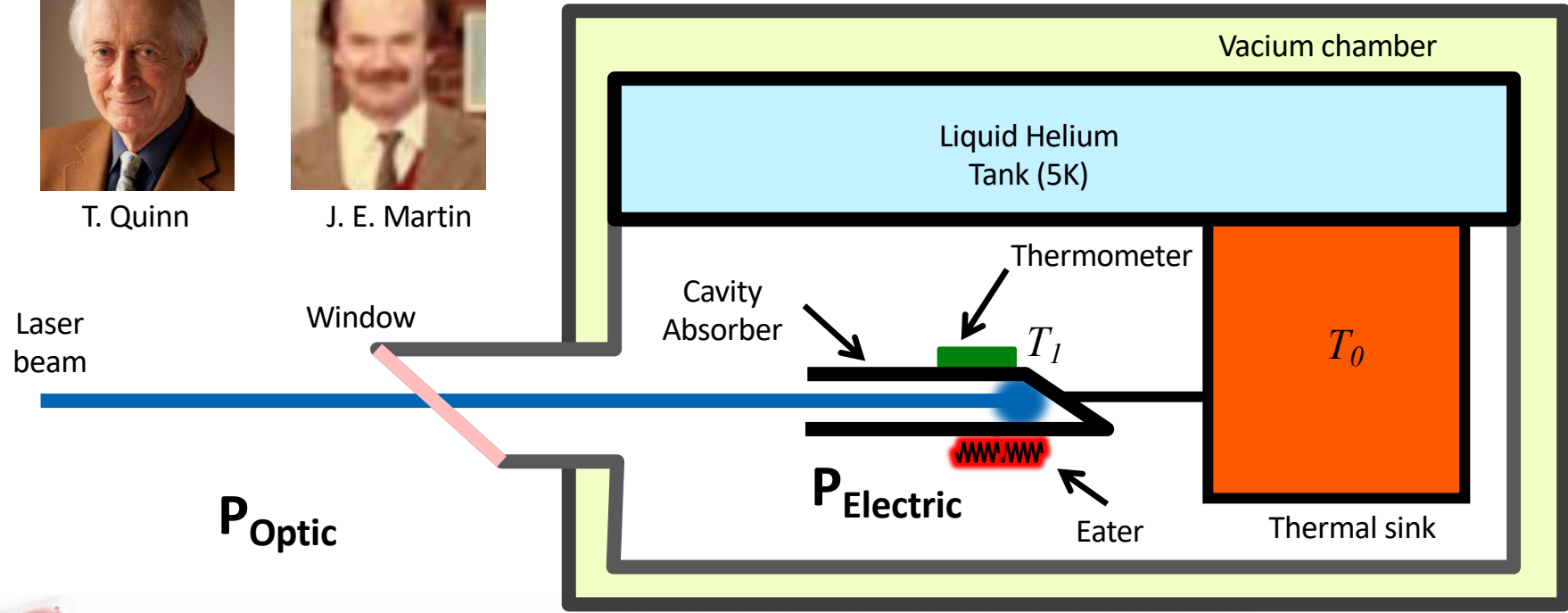
# Cryogenic radiometer



T. Quinn

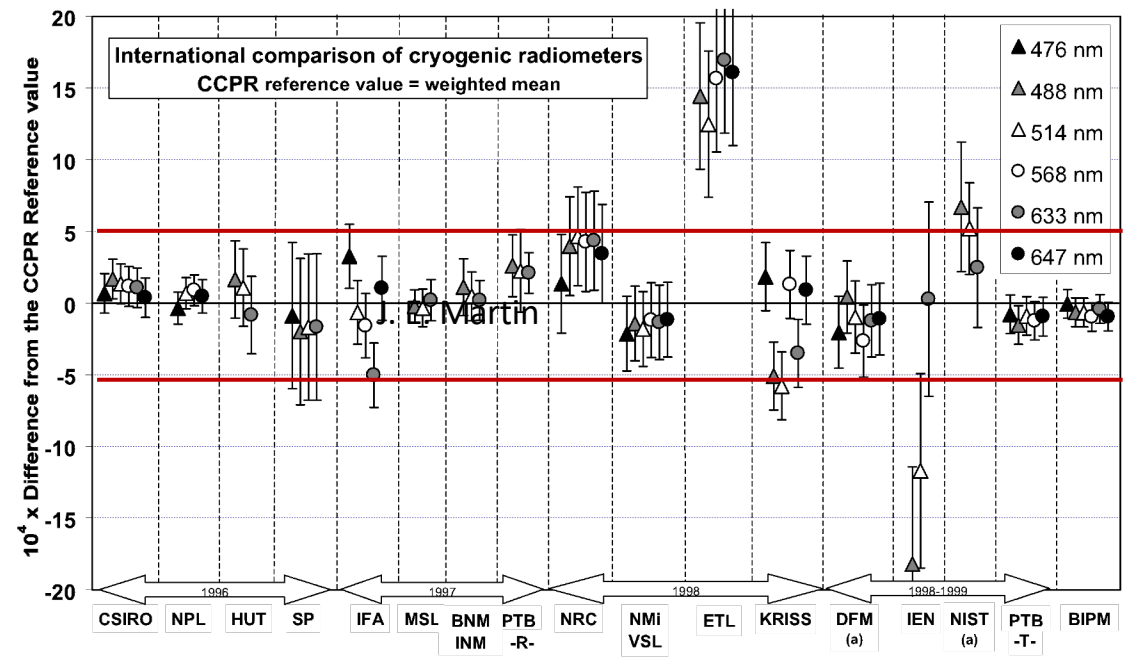


J. E. Martin



1985

# cryogenic radiometer



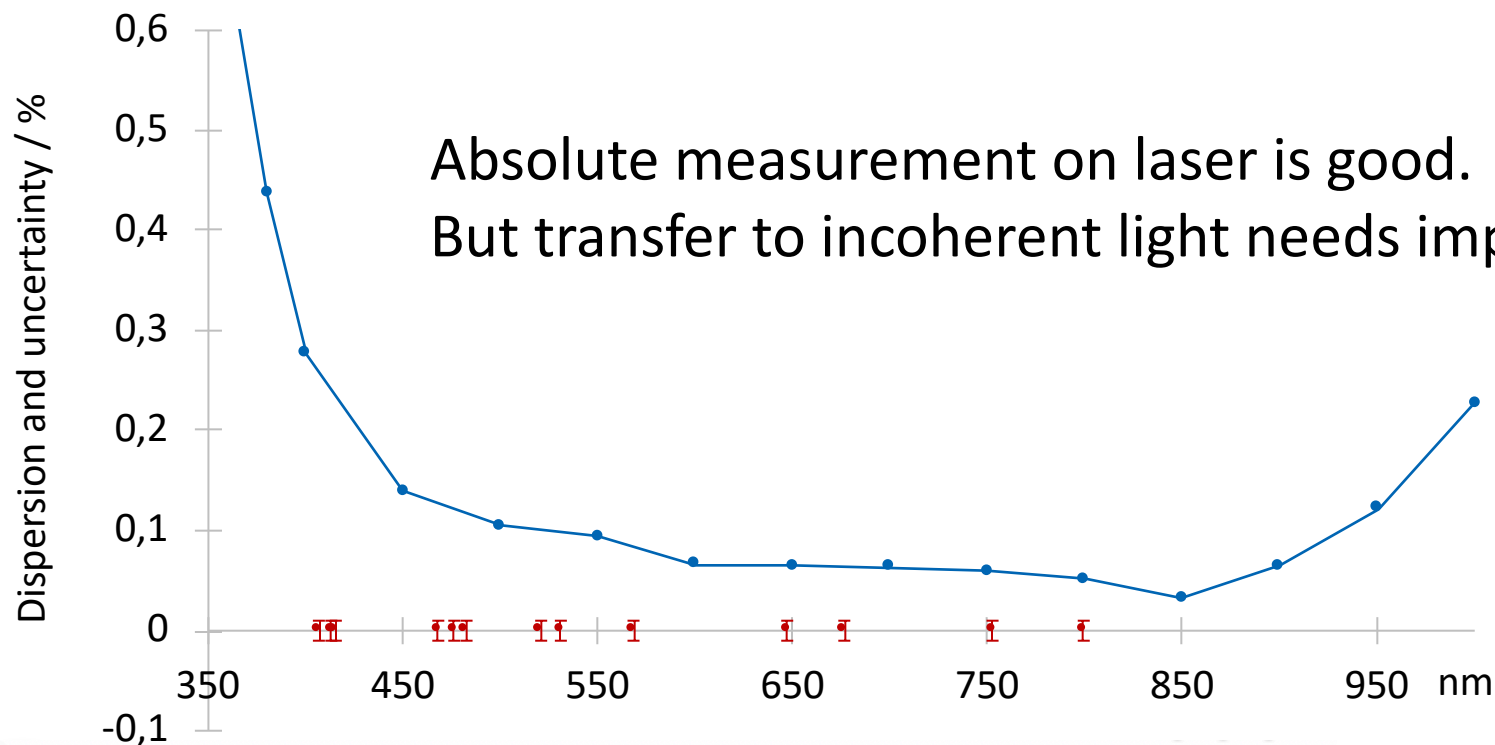
Relative agreement of  $\pm 5 \cdot 10^{-4}$  at NMI level



1985



## cryogenic radiometer



T. Hansen

32

# Predictable Quantum Efficient Detectors ( PQED)

INSTITUTE OF PHYSICS PUBLISHING  
Metrologia 40 (2003) S132-S135

METROLOGIA  
P11: S0026-1394(03)56910-9

## Prospects for improving the accuracy of silicon photodiode self-calibration with custom cryogenic photodiodes

Jon Geist<sup>1</sup>, Giorgio Brida<sup>2</sup> and Maria Luisa Rastello<sup>2</sup>

<sup>1</sup> Sequoyah Technology LLC, 4410 Winding Oak Drive, Olney, MD 20832, USA  
<sup>2</sup> Istituto Elettrotecnico Nazionale, strada della Cacce 91, 10135 Torino, Italy

E-mail: jon.geist@ieee.org

Published 7 February 2003  
Online at [stacks.iop.org/Met/40/S132](http://stacks.iop.org/Met/40/S132)

**Abstract**  
This paper considers the possibility of improving the accuracy of the predictable quantum efficiency method (self-calibration) by using custom photodiodes at cryogenic temperatures. The photodiode quantum deficiency is partitioned into nine terms associated with different phenomenological loss mechanisms. The size of each term is estimated for operation of the photodiode at 72 K and 16 V reverse bias. Requirements for high-accuracy self-calibration of the value and uncertainty of each of the quantum deficiency terms are discussed.

### 1. Introduction

The original self-calibration procedure [1] was not optimized

oxide-silicon interface,  $\delta_b$  is the fraction of the photogenerated carriers that recombine in the silicon substrate,  $\delta_w$  is the fractional contribution of the dark current to the photocurrent



2008-2011



2013-2016

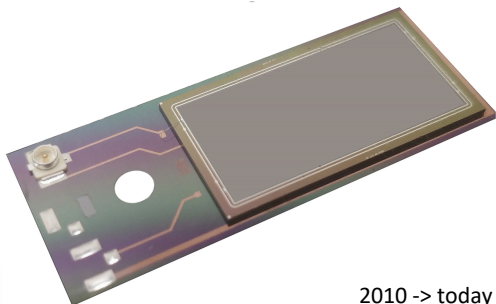


2019-2022



M. L. Rastello

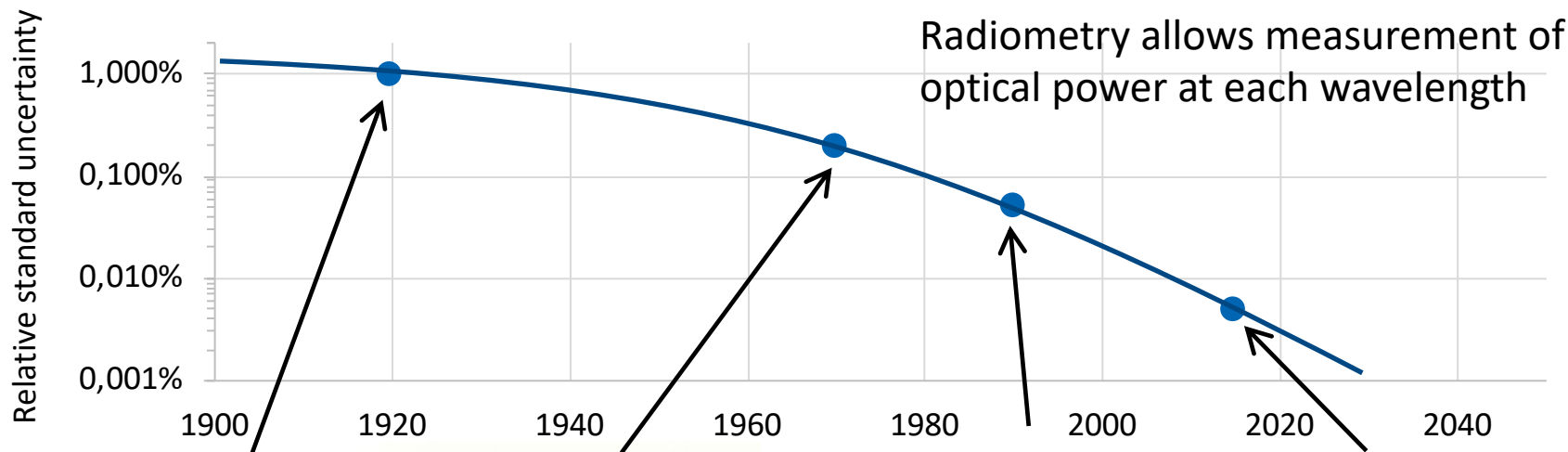
## Rel Unc of 5ppm



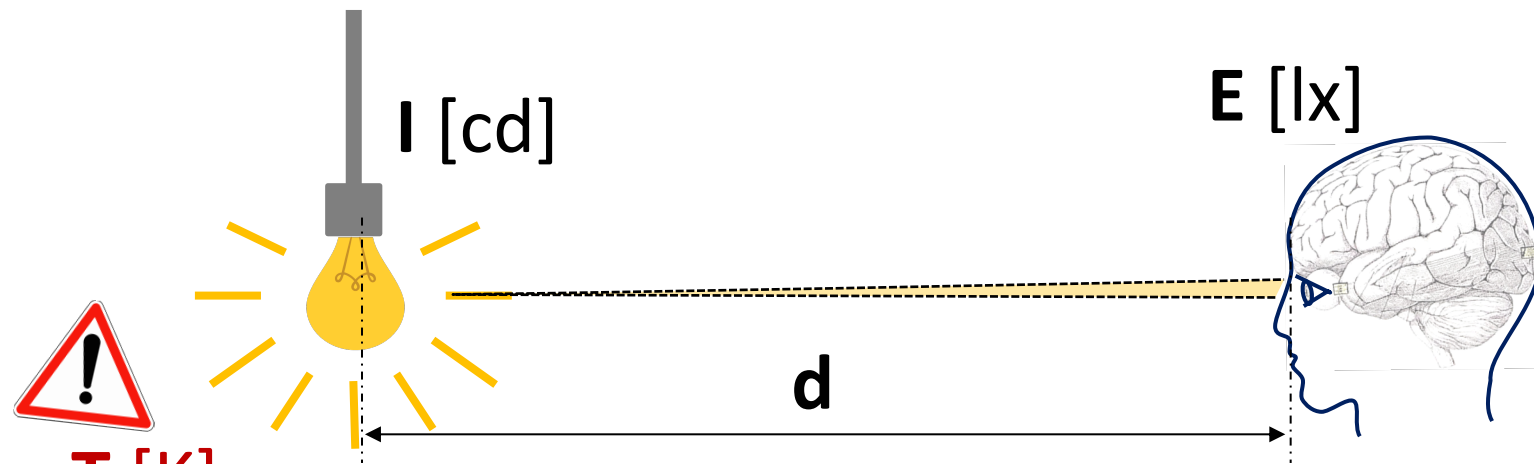
2010 -> today



# Progress in radiometry



## the new way...



**T [K]**

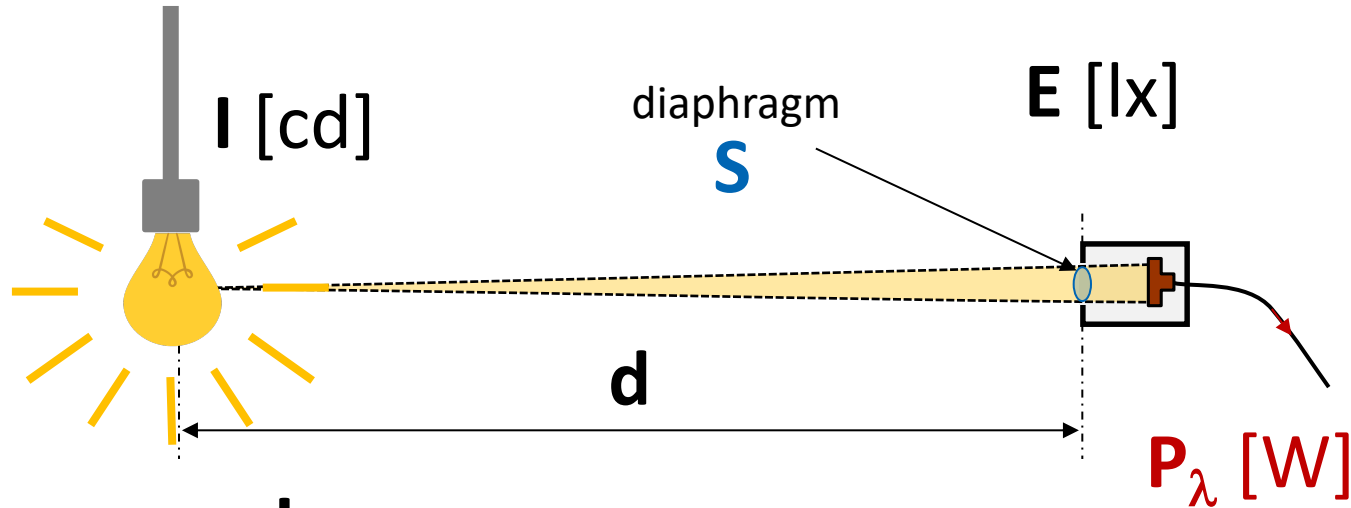
$$E = \frac{I}{d^2}$$

«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<sup>ème</sup> CGPM**



## the new way...

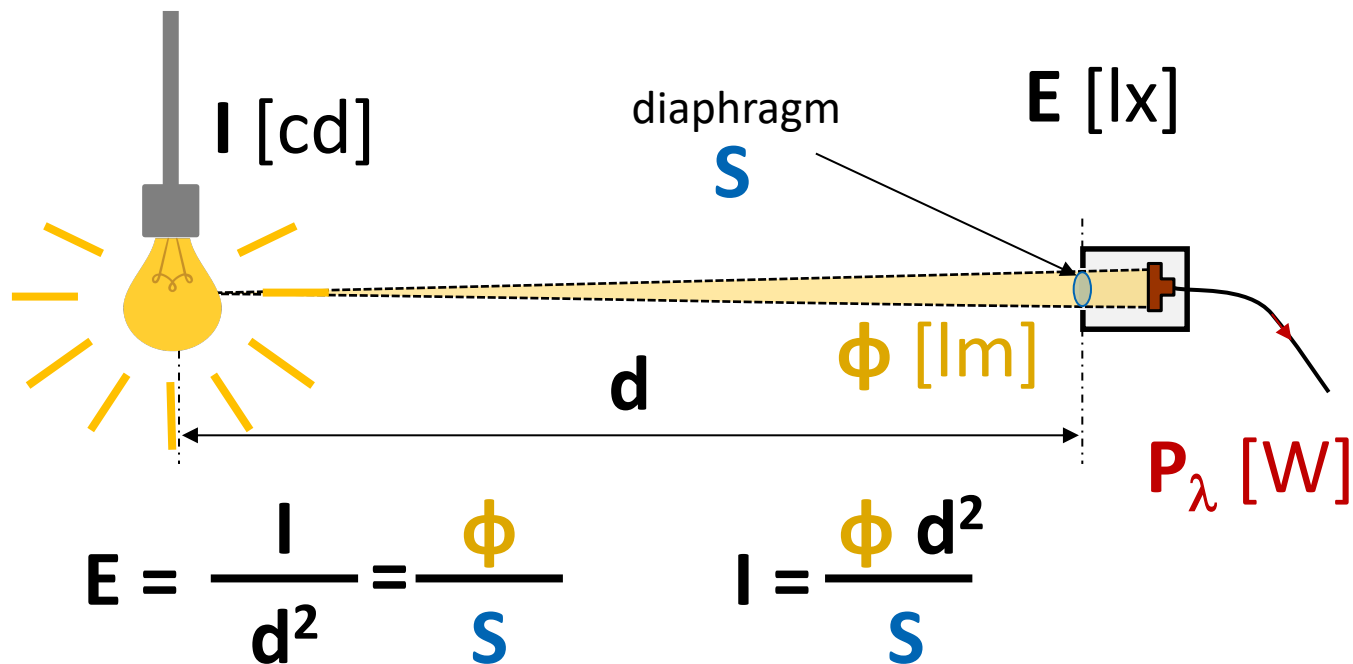


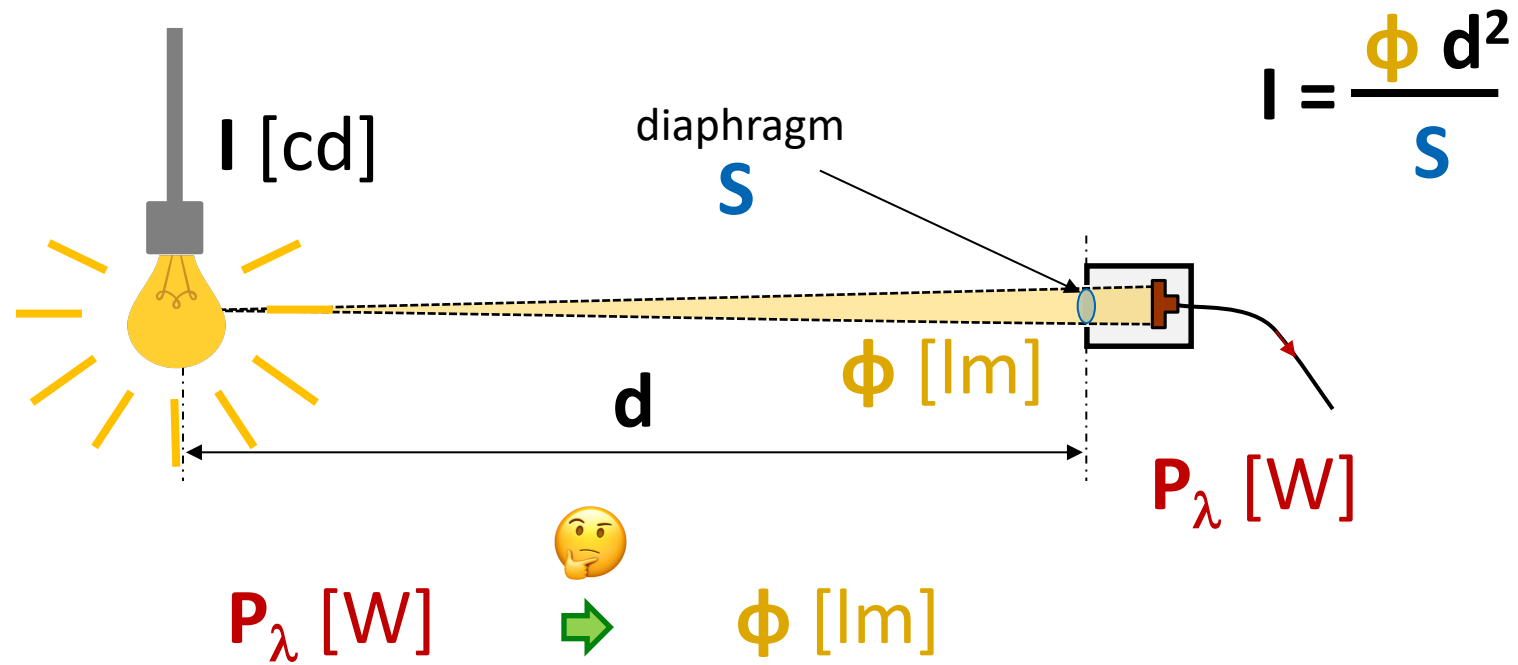
$$E = \frac{I}{d^2}$$

«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<sup>ème</sup> CGPM**

## the new way...





If we can establish the link between lumen and watt,  
we have the candela



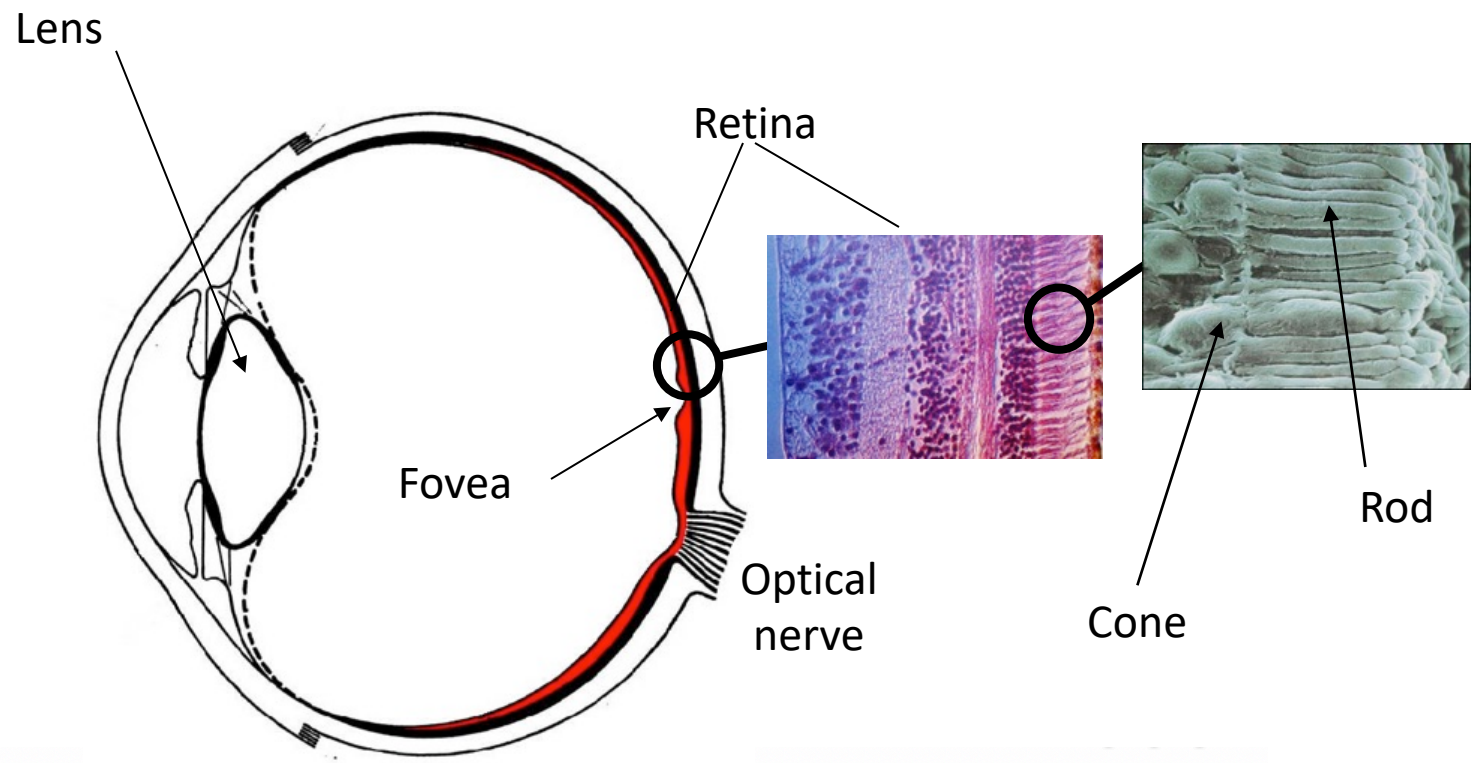
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# Human eye

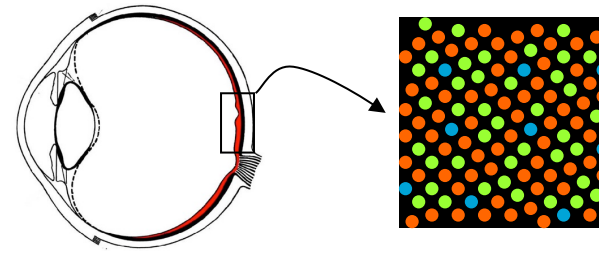
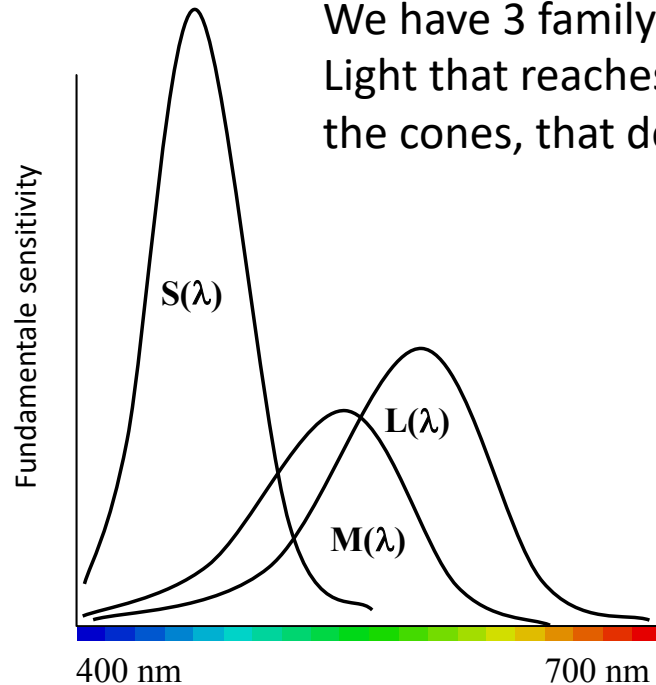


Source : ???

## 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



$S(\lambda)$   $\lambda_{\max} \cong 440 \text{ nm}$

$M(\lambda)$   $\lambda_{\max} \cong 540 \text{ nm}$

$L(\lambda)$   $\lambda_{\max} \cong 570 \text{ nm}$

## Individual variations

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

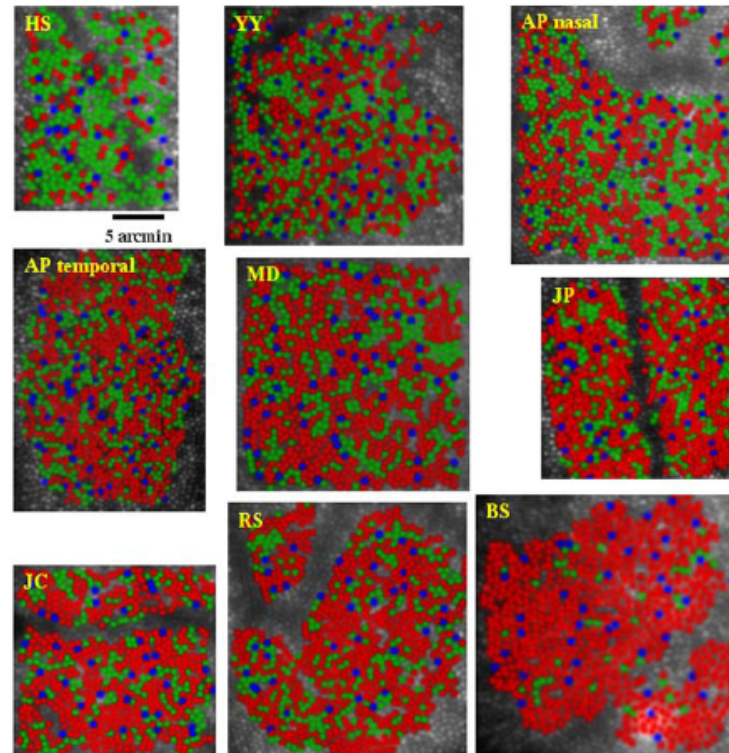


Figure 4. False color images showing the arrangement of L (red), M (green), and S (blue) cones in the retinas of different human subjects. All images are shown to the same scale.

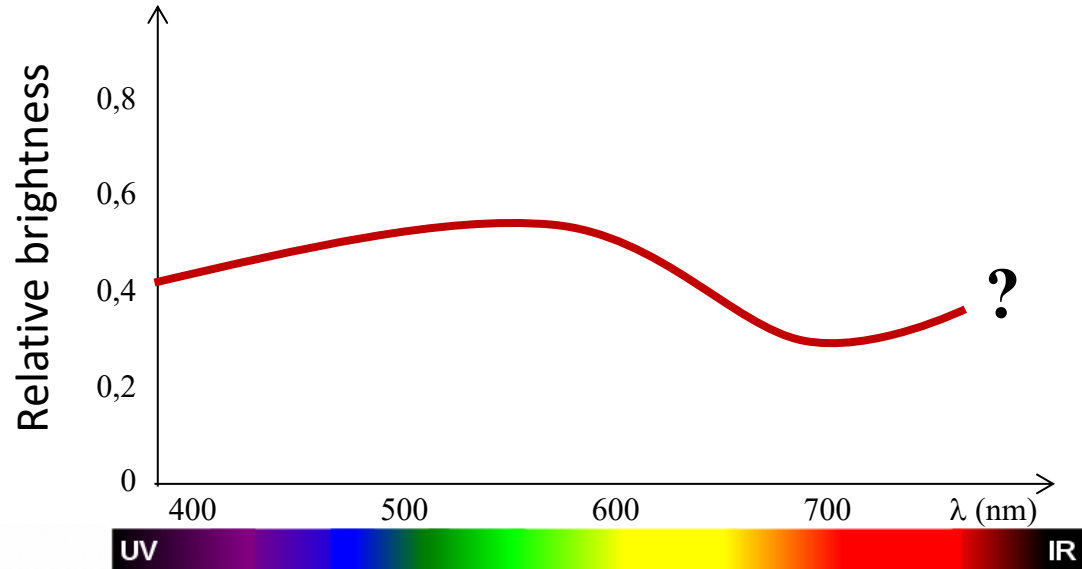
*Hofer, Carroll, Neitz, Neitz,  
Williams, JNeuroscience 2005*

# Effet of optical radiation on the visual system

$P_\lambda$  [W]

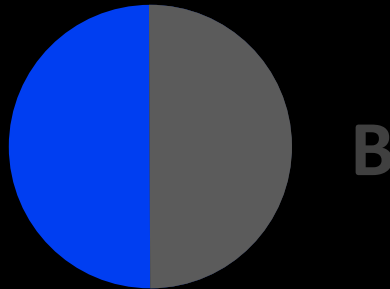


$\phi$  [lm]



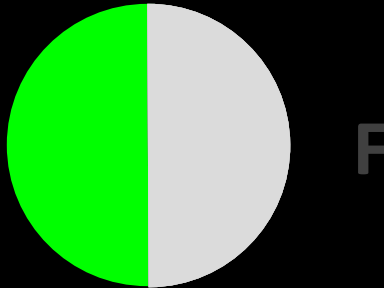
## Experience for the measurement of brightness of a monochromatic radiation

Method : Direct comparison



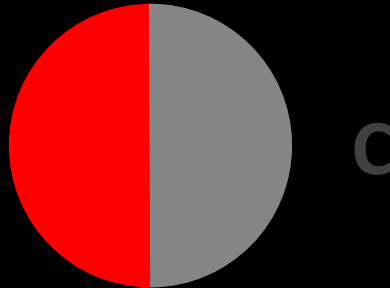
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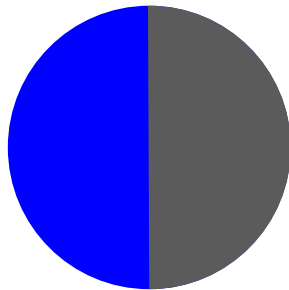
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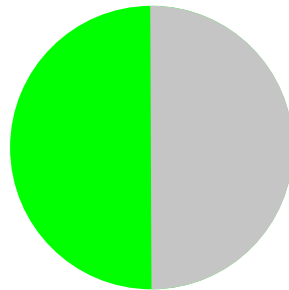


## Effet of optical radiation on the visual system

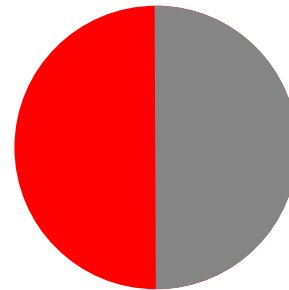
Result



**B**



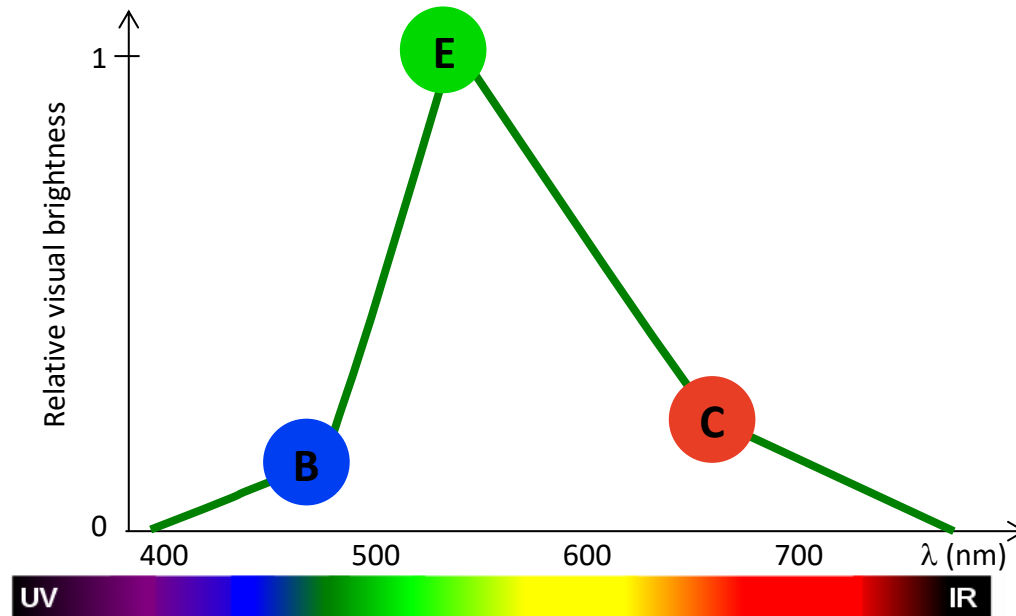
**E**



**C**



## Luminous efficacy of monochromatic light on the human visual system



# CIE Photometric standard observer

6<sup>th</sup> session of CIE, Geneva, 1924

K. S. Gibson :  
Visibility function

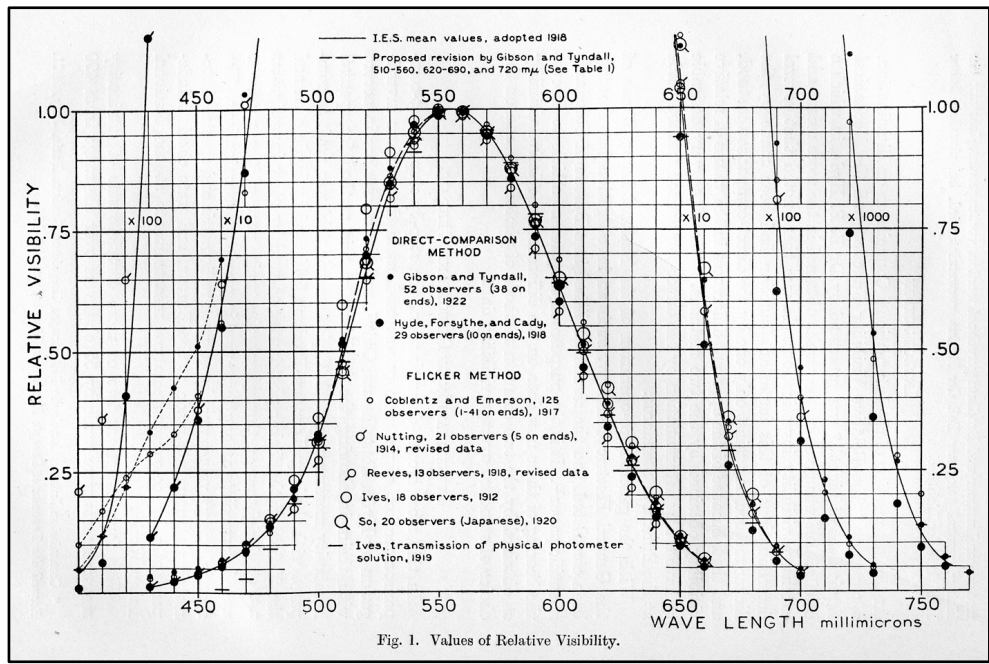
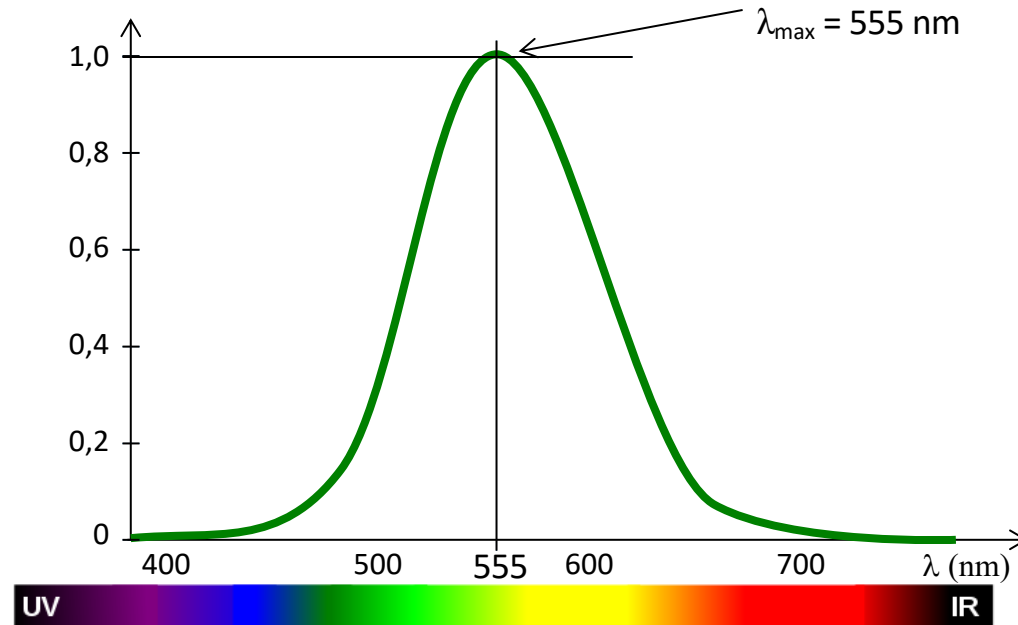


Fig. 1. Values of Relative Visibility.

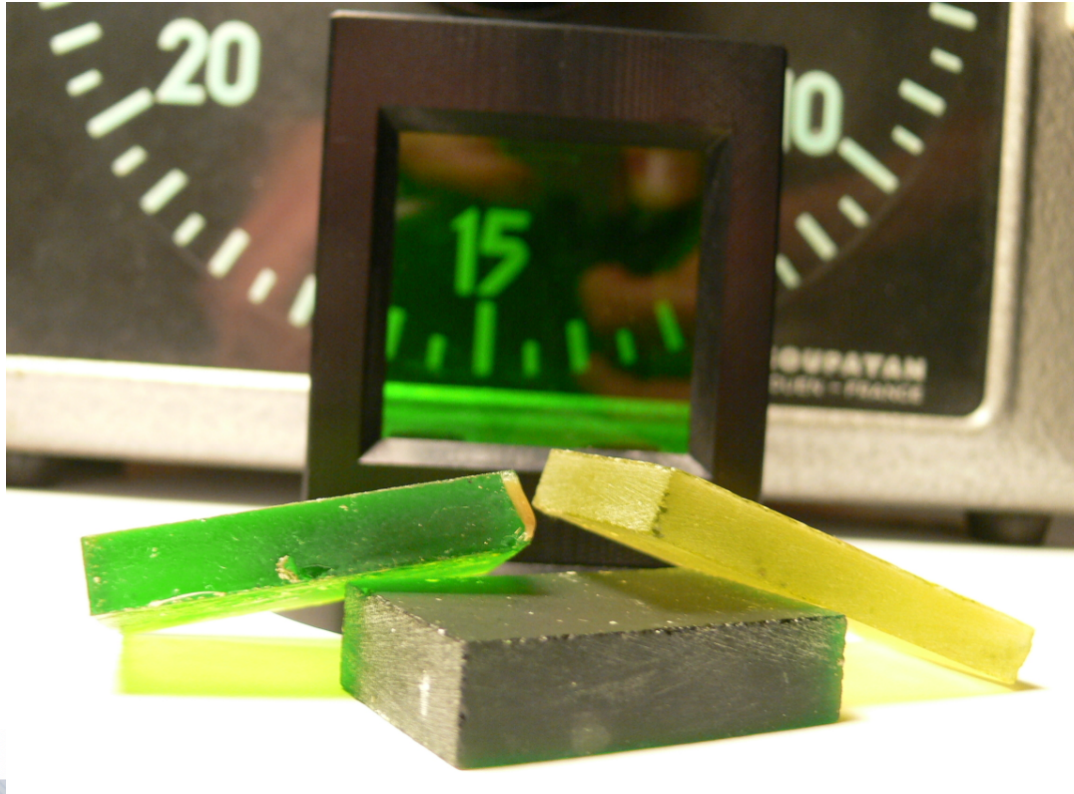
272 observers (UK, Japan, US)



## CIE Photometric standard observer $V(\lambda)$ curve

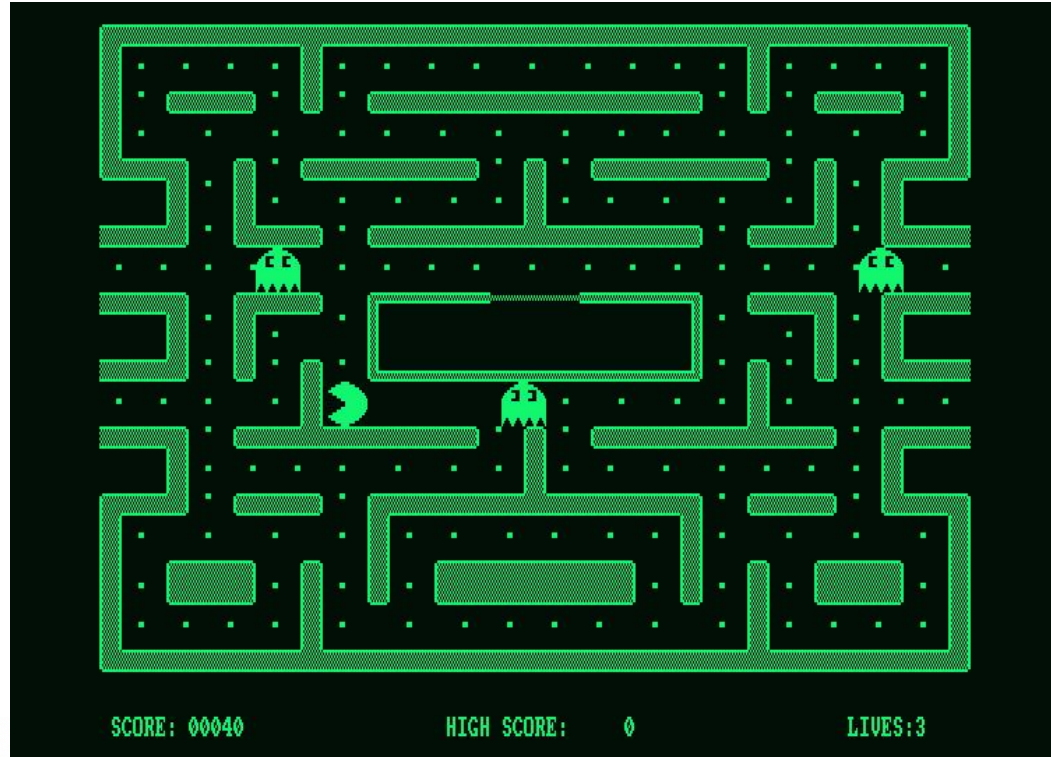


## $V(\lambda)$ filter



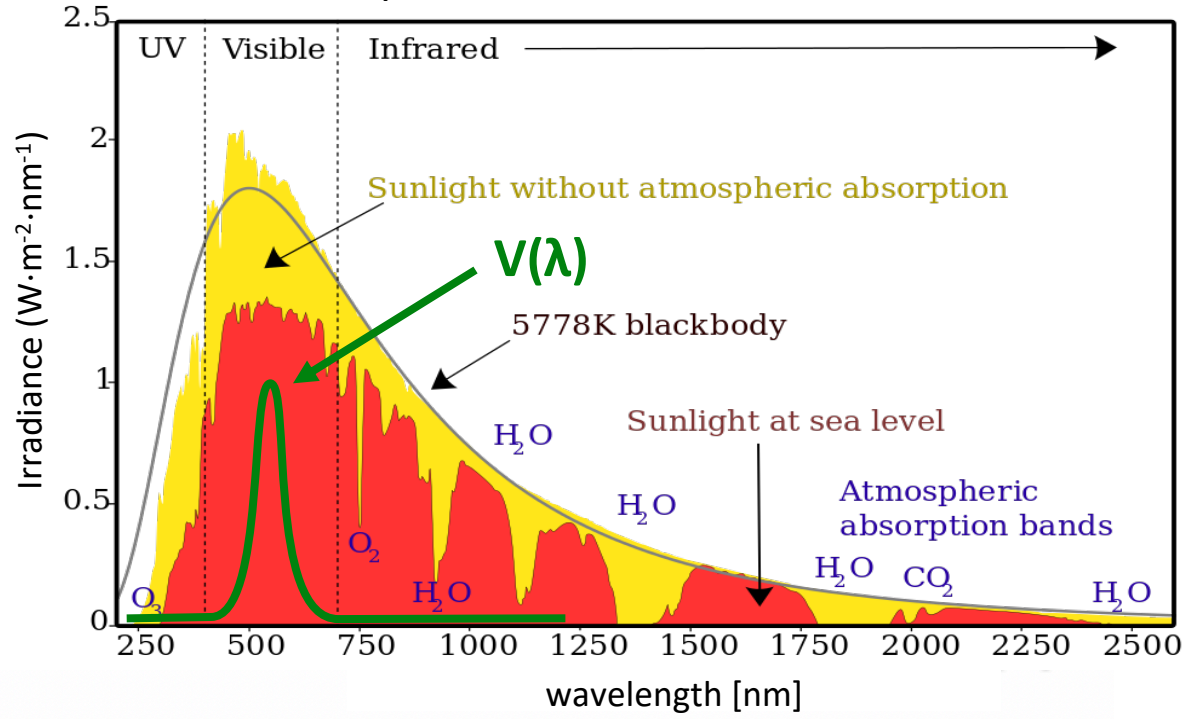
Remember ?....

$V(\lambda)$



$V(\lambda)$

Spectrum of solar radiation



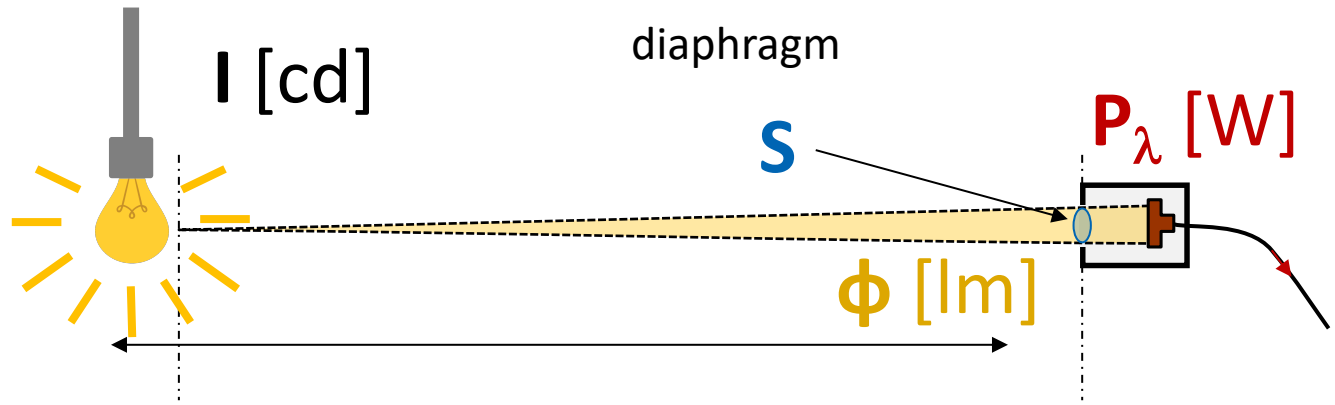
# The candela, the most human of the SI base units

## Outlines

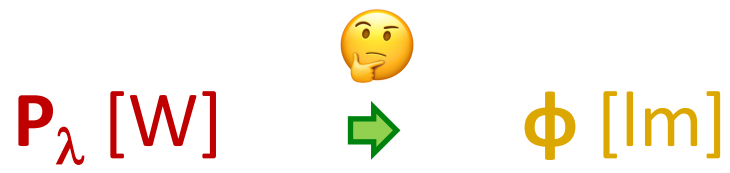
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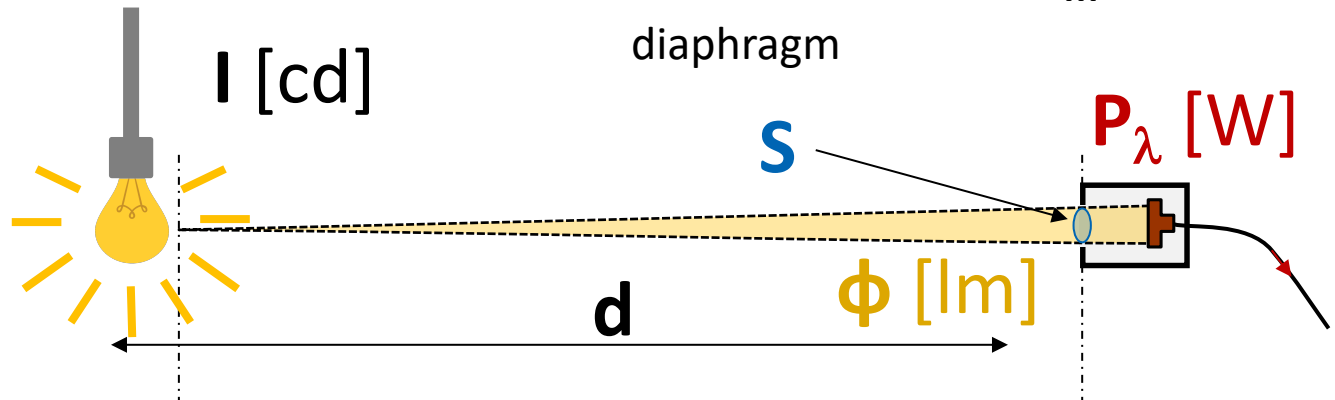
# Back on the candela



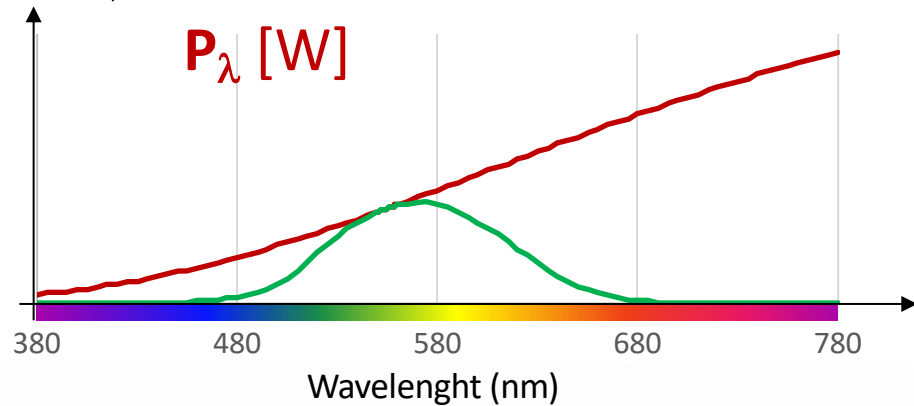
$$I = \frac{\Phi d^2}{S}$$



# Introduction of $K_m$



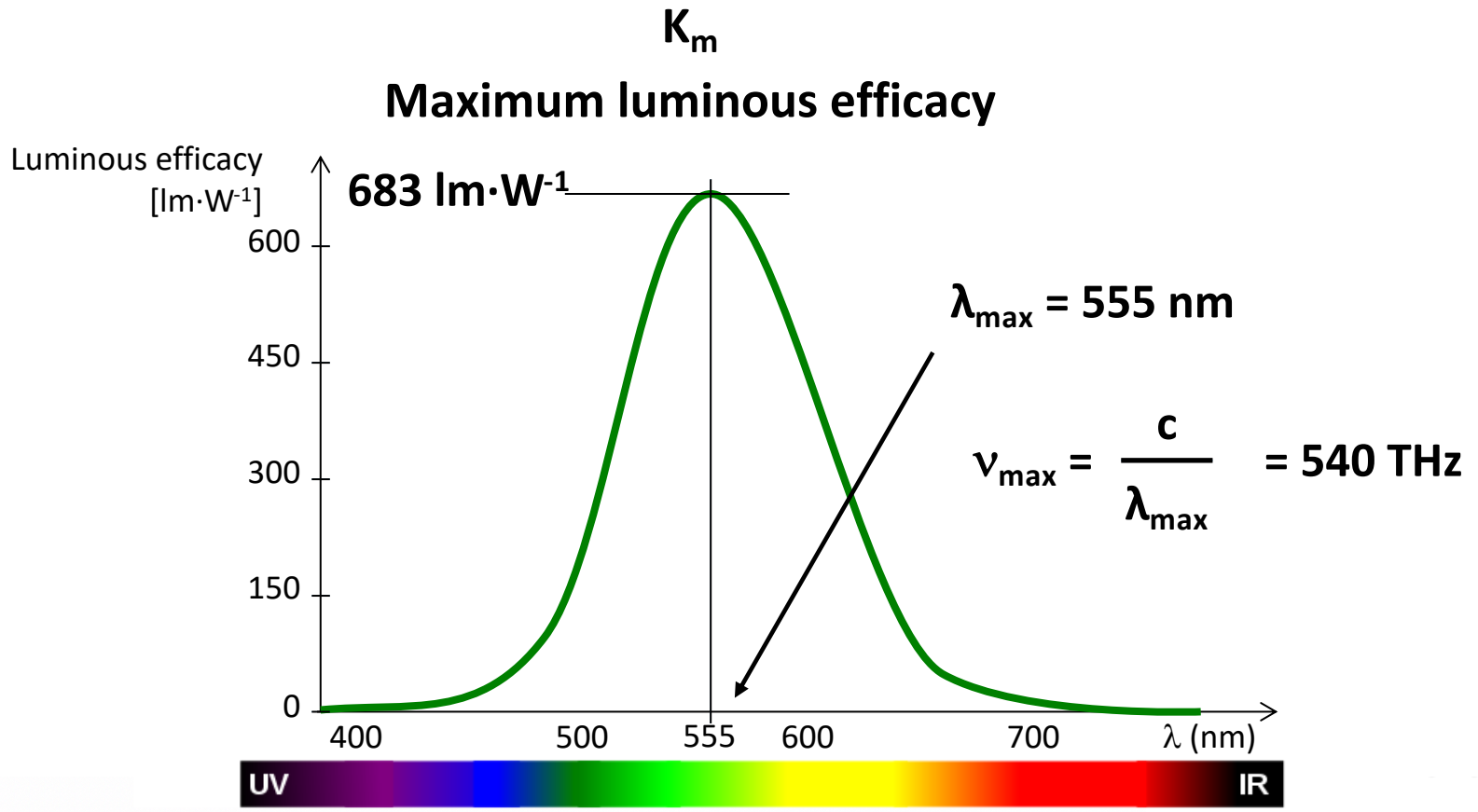
$$I = \frac{\phi d^2}{S}$$



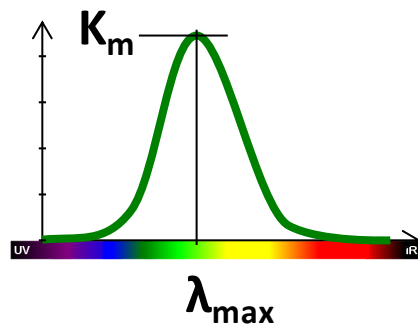
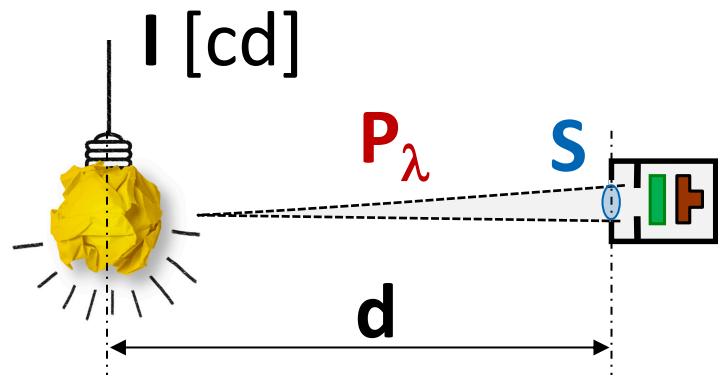
$$\phi = K_m \int_{380}^{780} P_\lambda \cdot V(\lambda) d\lambda$$

[lm·W<sup>-1</sup>]





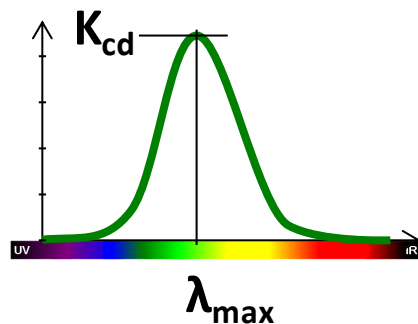
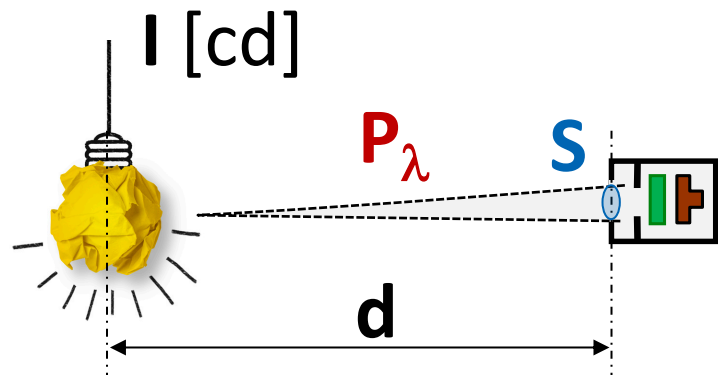
## Definition of the *candela*



«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<sup>ème</sup> CGPM**

## Definition of the *candela*

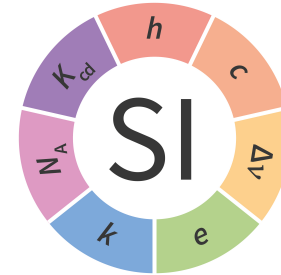


«The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540 THz,  $K_{cd}$ , to be 683 when expressed in the unit  $\text{lm} \cdot \text{W}^{-1}$ , which is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

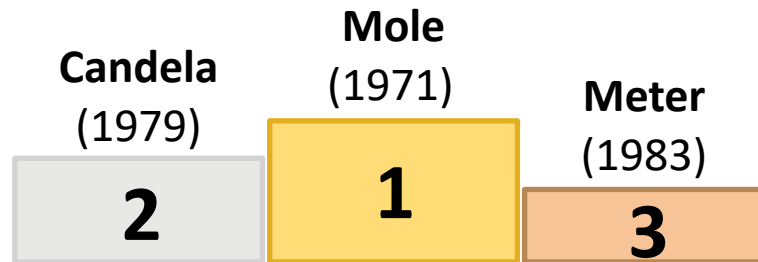
**2018 : XXVI<sup>ème</sup> CGPM**



**New SI**  
 $K_m \rightarrow K_{cd}$



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



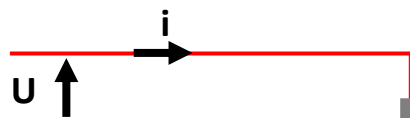
# The candela, the most human of the SI base units

## Outlines

- Quantities and units in photometry
- First measurements
- Towards the candela, 6<sup>th</sup> SI unit
- Radiometry, a new way for the candela
- Vision and  $V(\lambda)$  curve
- 1979, new definition and introduction of  $K_m$
- **Photometry widens to meet new societal needs**
  - Luminous efficacy and energy saving
  - Non visual functions of the retina
- The candela, one of the 7 SI units... why?



## Luminous efficacy of a light source [ $\text{lm}\cdot\text{W}^{-1}$ ]

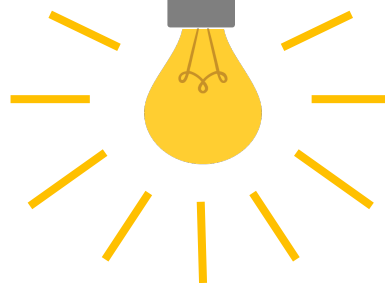


Electrical power

$$P_e = U \cdot I \text{ [W]}$$

Luminous  
efficacy

$$\eta = \frac{\Phi_v}{P_e}$$



Luminous flux  
 $\Phi$  [lm]

Luminous efficacy is crucial for energy saving



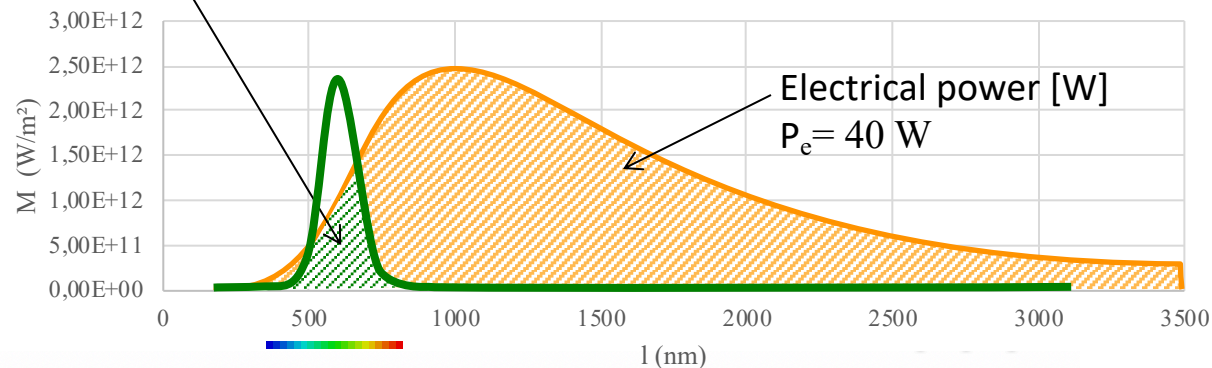
## Case of incandescent lamp

Luminous efficacy

$$\eta = \frac{\Phi_l}{P_e} = \frac{480}{40} = 12 \text{ lm} \cdot \text{W}^{-1}$$

Luminous flux [lm]

$\Phi_l = 480 \text{ lm}$



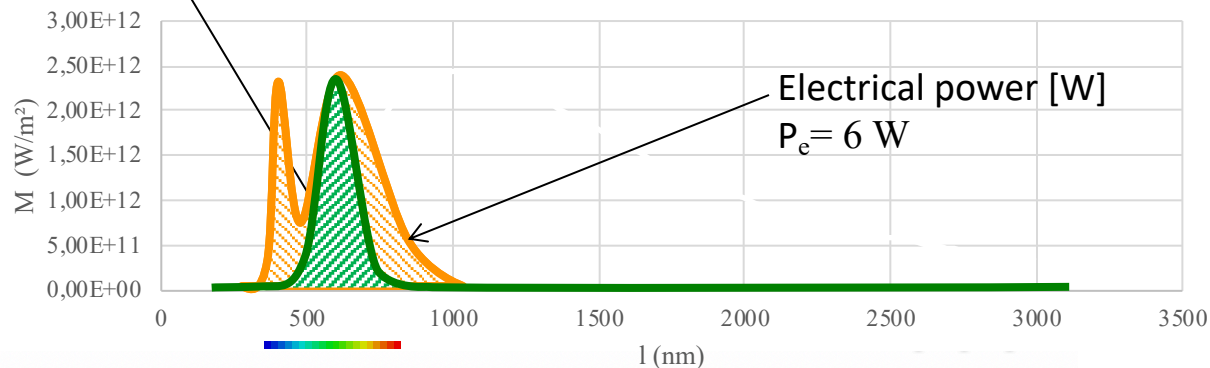
## Case of LED lamp (type UV-Blue)

Luminous efficacy

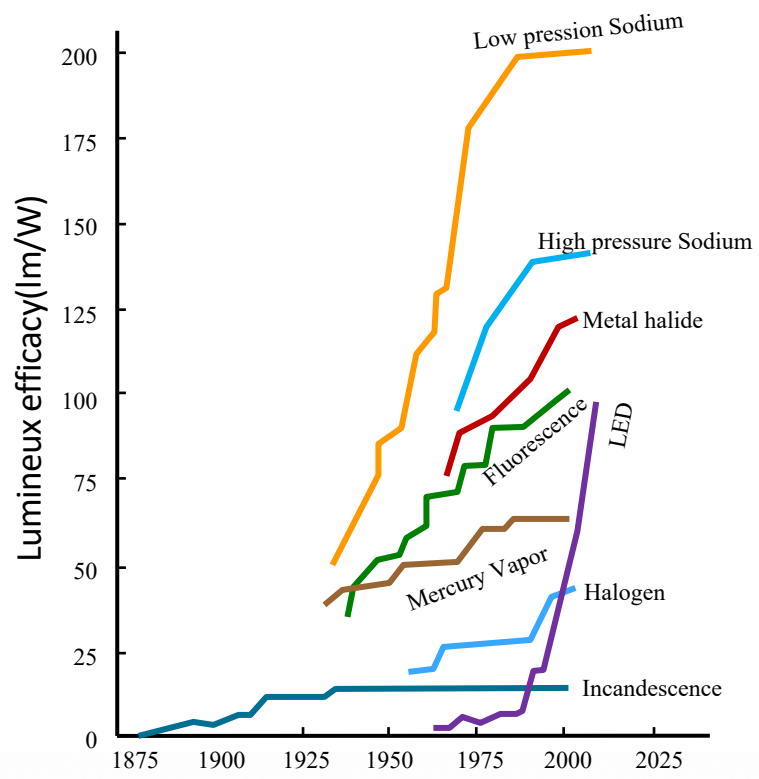
$$\eta = \frac{\Phi_l}{P_e} = \frac{470}{6} = 79 \text{ lm} \cdot \text{W}^{-1}$$

Luminous flux [lm]

$\Phi_l = 470 \text{ lm}$



# Luminous efficacy [lm·W<sup>-1</sup>]

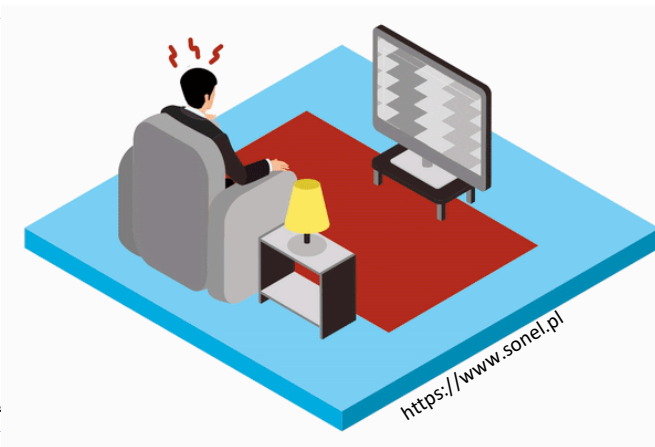
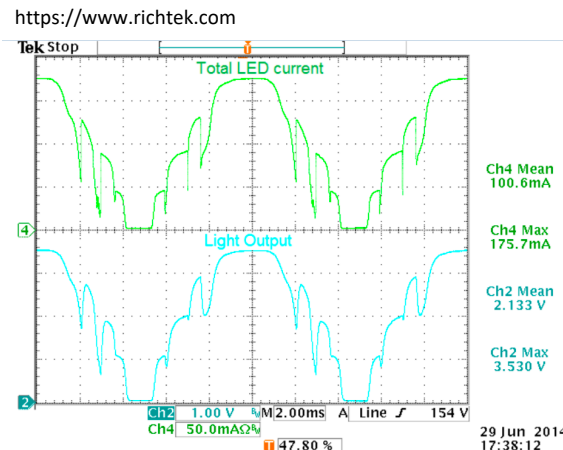
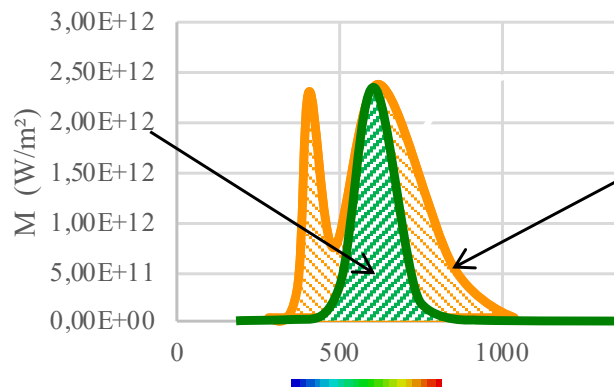


$$\eta = \frac{\Phi_l}{P_e}$$

in lm · W<sup>-1</sup>



## (LED - Luminous efficacy – Flicker) & metrology



### 3 CIE Technical Committees created over the last 5 years

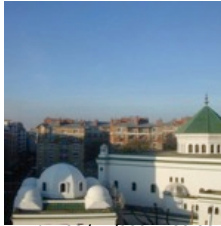
- 1-83 Visual Aspects of Time-Modulated Lighting Systems
- 2-76 Characterization of AC-driven LED products for SSL applications
- 2-89 Measurement of Temporal Light Modulation of Light Sources and Lighting Systems

## Going beyond lighting, the non visual functions of the retina

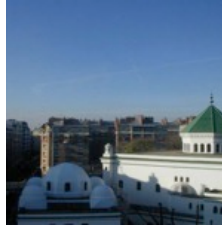


## Colour of sun

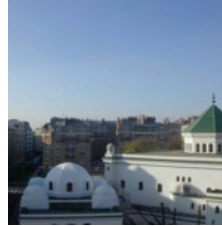
© F. Viénot



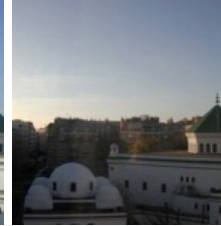
Paris - 23/11/2005 - 09:30



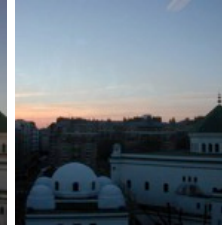
Paris - 23/11/2005 - 11:45



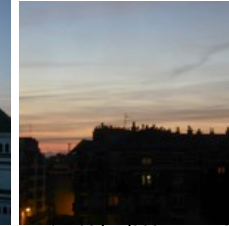
Paris - 23/11/2005 - 13:00



Paris - 23/11/2005 - 15:15



Paris - 23/11/2005 - 16:45



Paris - 23/11/2005 - 17:40

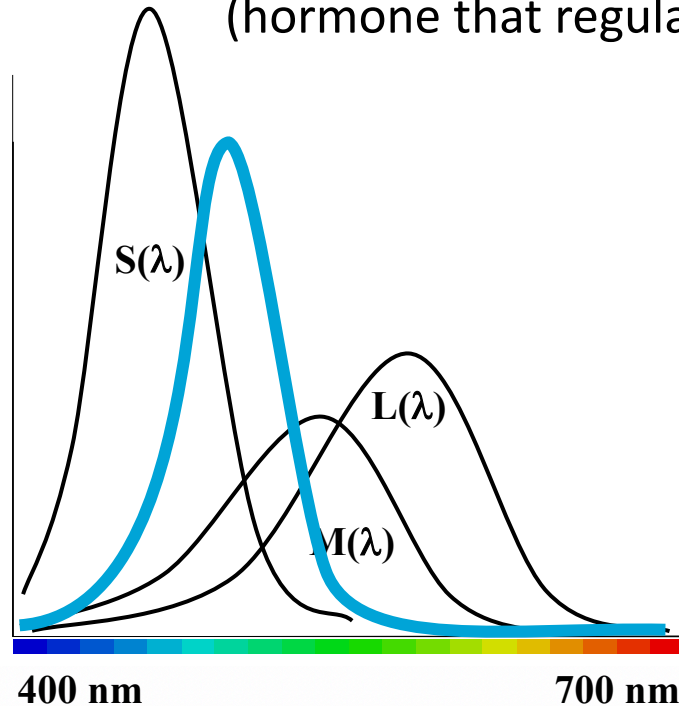
Along the daytime, sun colour evolves. It is orange in the morning, white at noon, yellow in the afternoon and red in evening.

This is our daily since the start of humanity.



## A 4<sup>th</sup> family of photosensitive function on the retina

Melanopsin, photopigment inhibitor of melatonin  
(hormone that regulates sleep–wake cycles)



**Mel(λ)**     $\lambda_{\max} \cong 470 \text{ nm}$

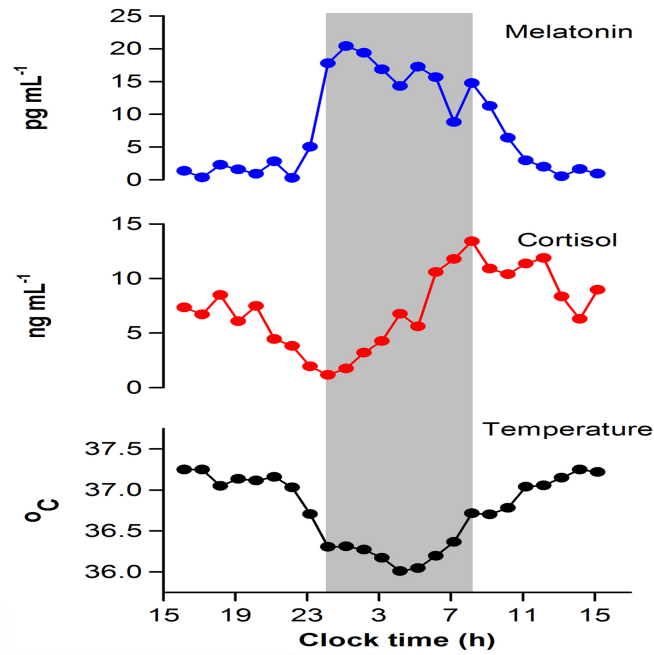
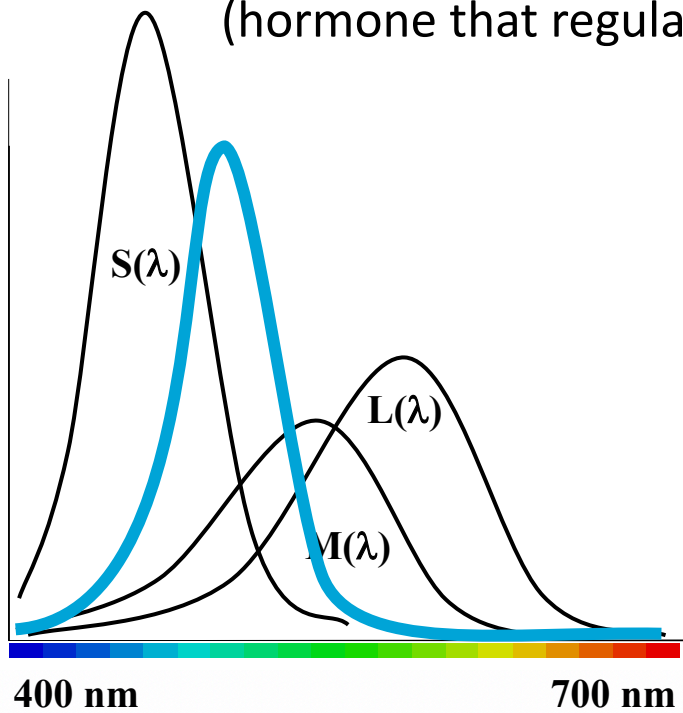
**S(λ)**     $\lambda_{\max} \cong 440 \text{ nm}$

**M(λ)**     $\lambda_{\max} \cong 540 \text{ nm}$

**L(λ)**     $\lambda_{\max} \cong 570 \text{ nm}$

# A 4<sup>th</sup> family of photosensitive function on the retina

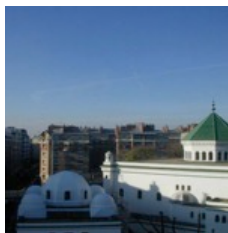
Melanopsin, photopigment inhibitor of melatonin  
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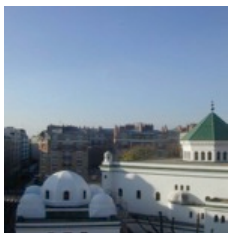
J. Gooley, Proc Nutrition Society, 75(4), 2019



# Spectral radiance of sun light



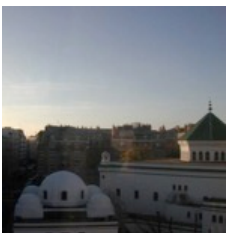
Paris - 23/11/2005 – 11:45



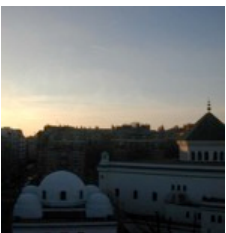
Paris - 23/11/2005 – 13:00



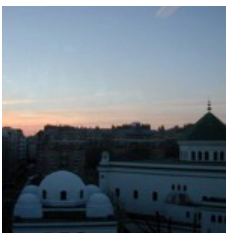
Paris - 23/11/2005 – 14:15



Paris - 23/11/2005 – 15:15



Paris - 23/11/2005 – 16:15



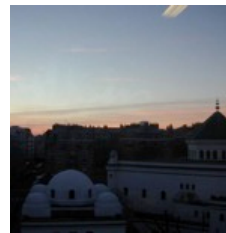
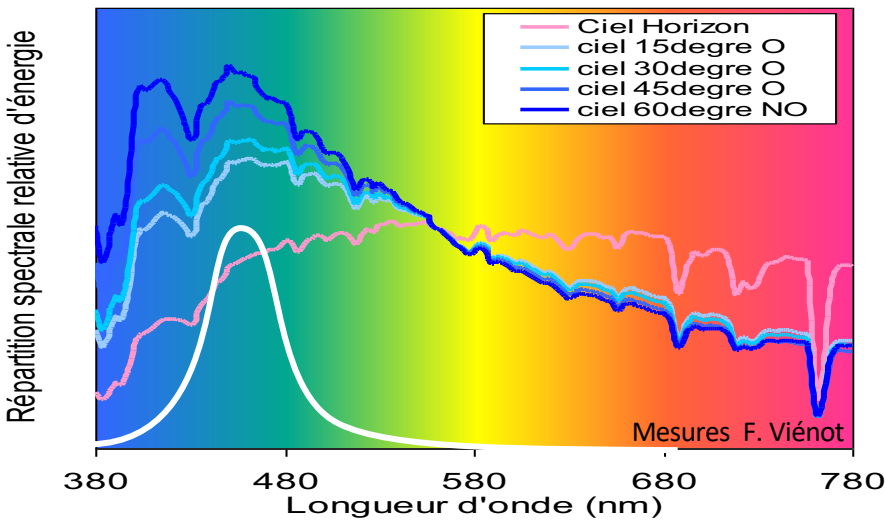
Paris - 23/11/2005 – 16:45



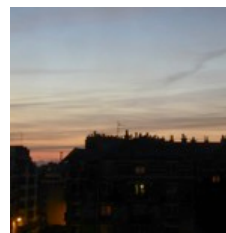
Paris - 23/11/2005 – 10:45



Paris - 23/11/2005 – 09:30

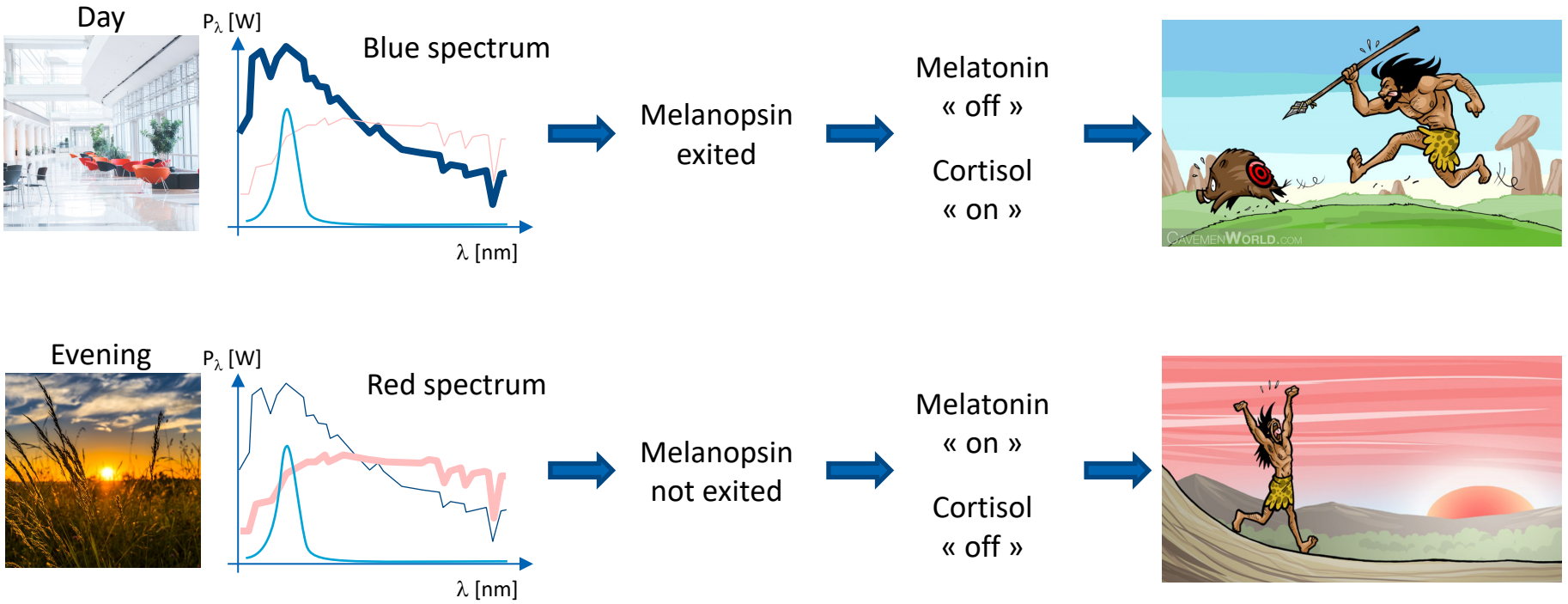


Paris - 23/11/2005 – 17:15

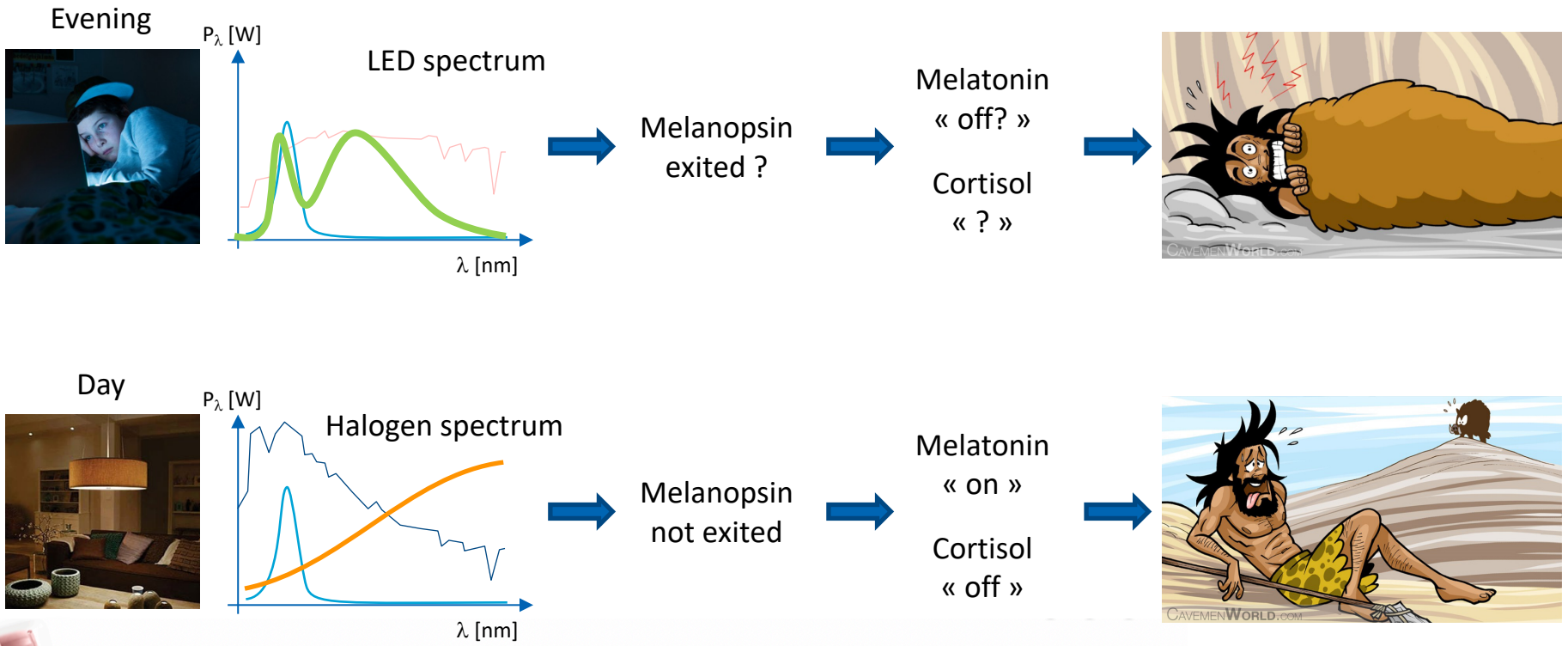


Paris - 23/11/2005 – 17:40

# Sunlight – Melanopsin – Circadian cycle



# Sunlight – Melanopsin – Circadian cycle



# Sunlight – Melanopsin – Circadian cycle

## Recommendations (1/3)



One hour of daylight per day at noon



# Sunlight – Melanopsin – Circadian cycle

## Recommendations (2/3)



Cold white,  $T_c = 6500$  K (morning)



Warm white,  $T_c = 2800$  K (evening)

## Match interior lighting with daylight



## Sunlight – Melanopsin – Circadian cycle

### Recommendations (3/3)



Avoid LED screen in evening



# Sunlight – Melanopsin – Circadian cycle

## Recommendations (4/3)



CIE S 026/E:2018

### CIE S 029/E:2018

CIE System for Metrology of Optical Radiation for ipRGC Responses to light

#### CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light

Système CIE de métrologie des rayonnements optiques dédié à la réponse à la lumière des cellules ganglionnaires photosensibles de la rétine (ipRGC)  
CIE-System für die Metrologie optischer Strahlung für ipRGC-beeinflusste Antworten auf Licht

**Use appendix 3 of SI brochure** when talking about sensitivity to light of Blue light, Circadian, Erythemal, L, M, S-cones, melanopic, rhodopic, etc...

# The candela, the most human of the SI base units

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## The candela, one of the 7 SI units... why?

Humans have created the International system of unit. As a reward, they must have a piece of themselves inside. This is the candela! The candela is the unit that represents the world of sensorial measurements.

