Interdisciplinary postgraduate program «Optics and Vision»

Foundations of Modern Optics

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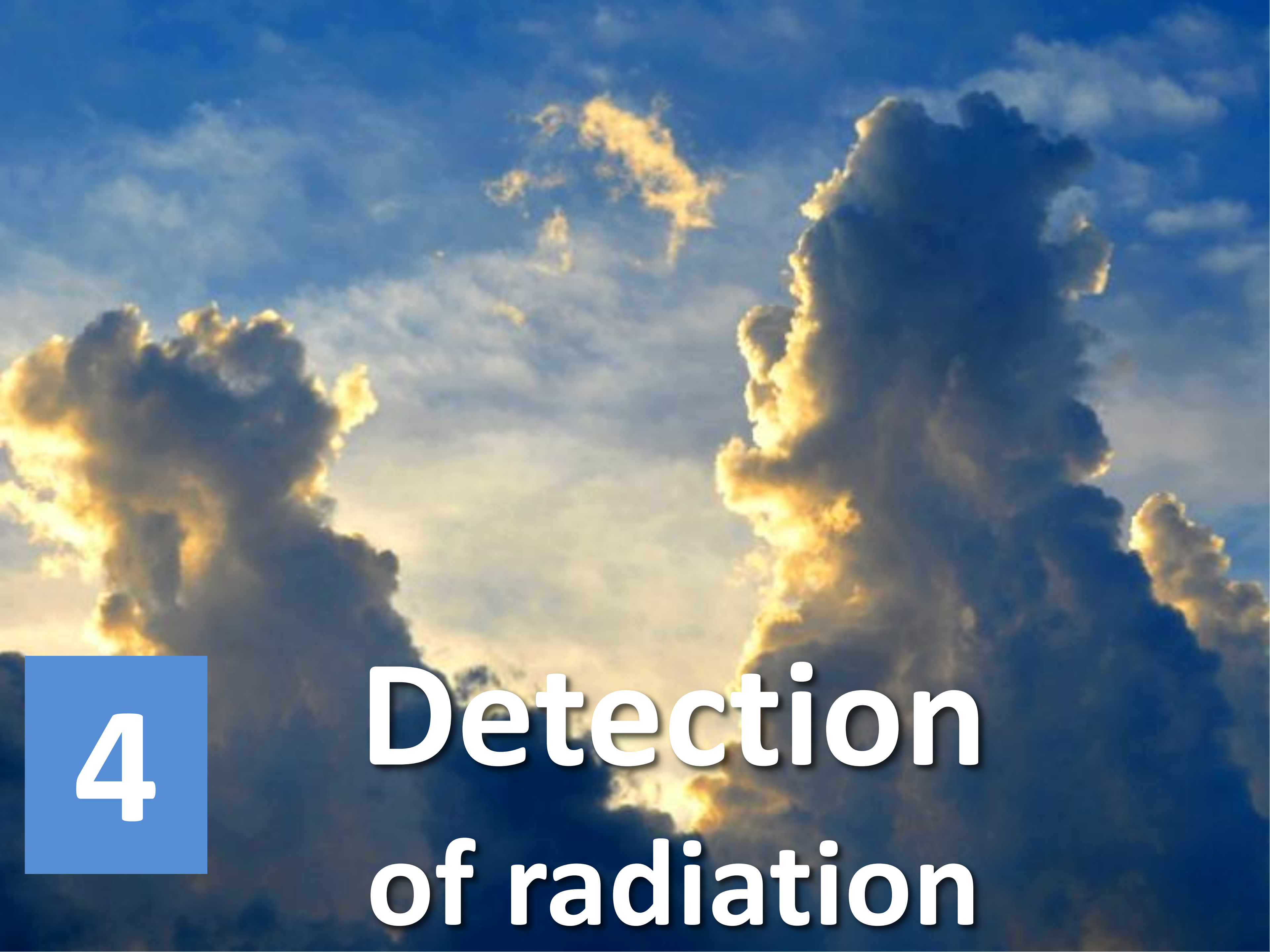
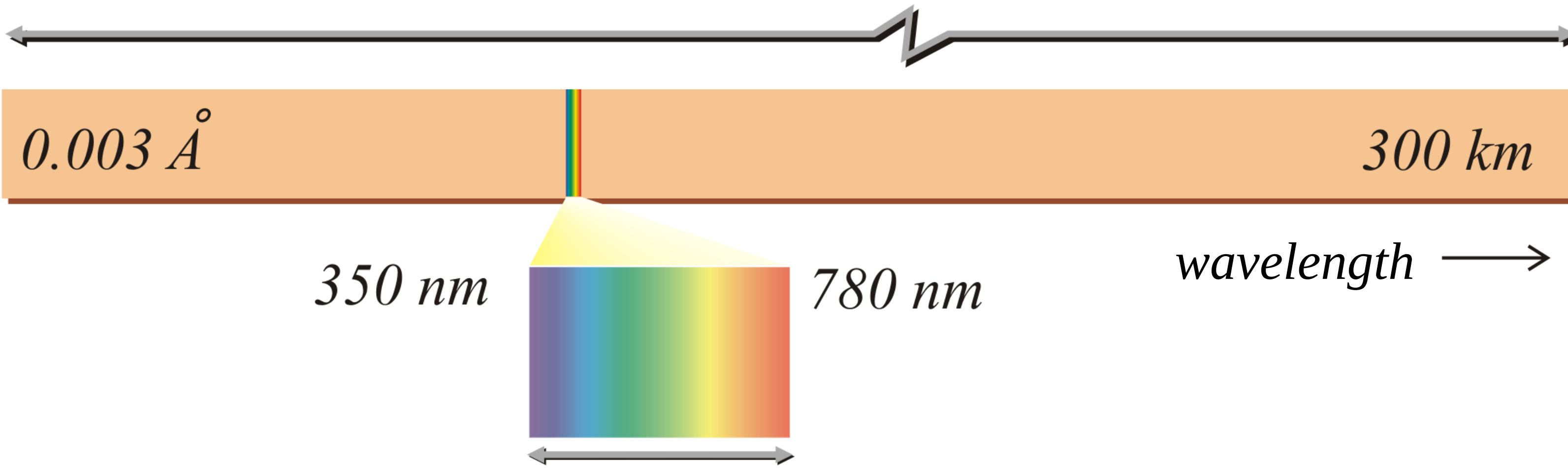


4 Detection of radiation

4.1 Photometry - Radiometry

Photometry - Radiometry

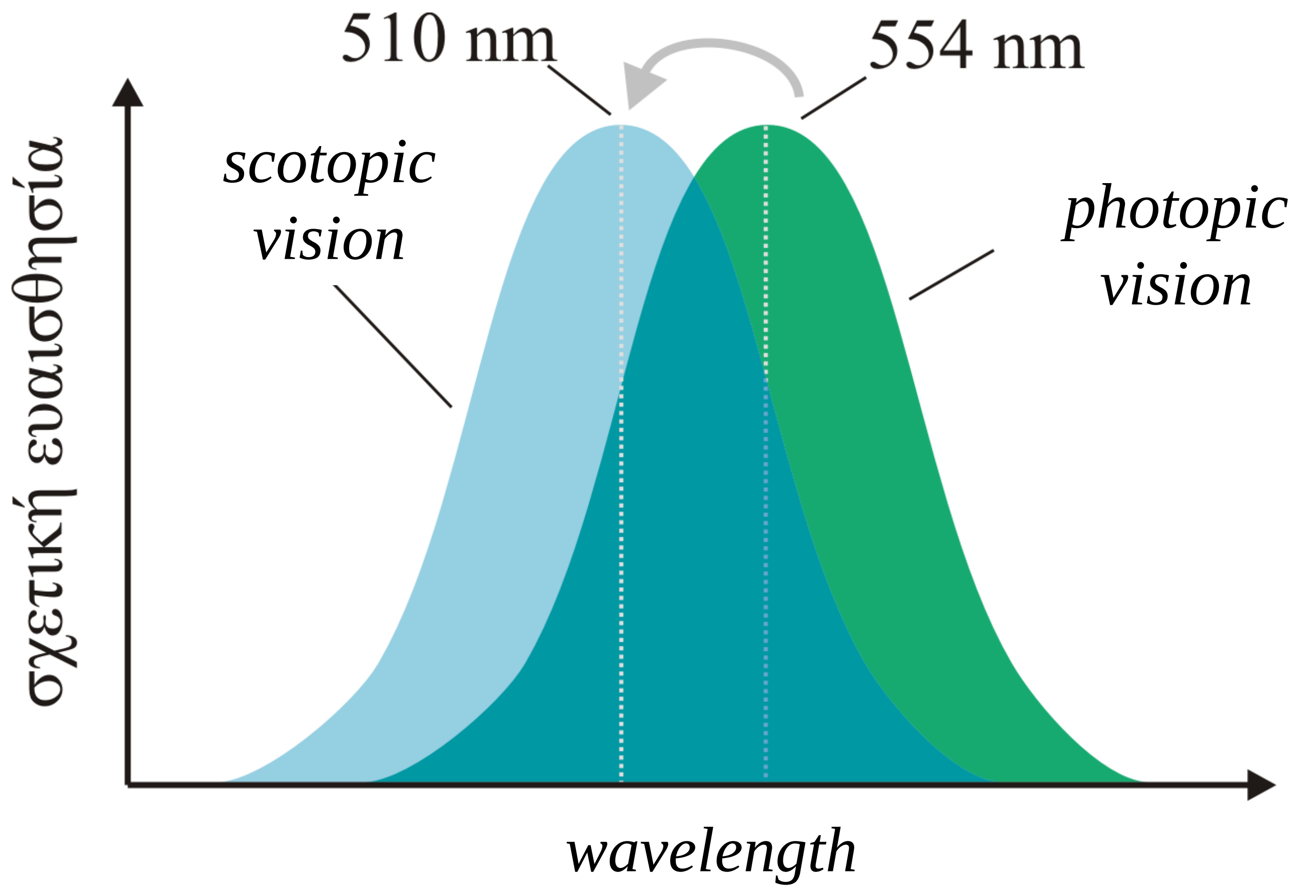
Radiometry:
refers to the whole electromagnetic spectrum



Photometry:
refers only to the visible spectrum

In photometry the reference photodetector
is the ***human eye***

Spectral sensitivity of the human vision



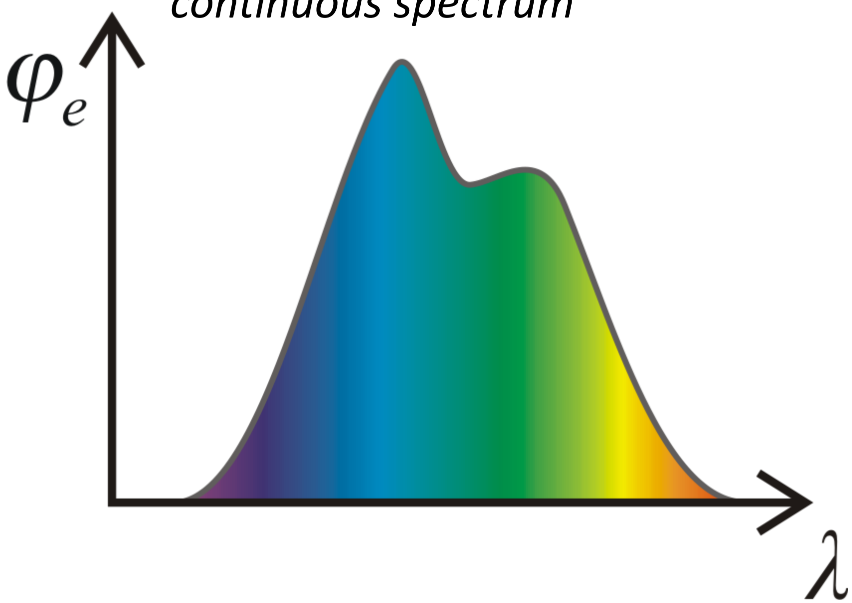
relative spectral sensitivity of the human eye

The relative spectral sensitivity of the **photopic vision** is used as a reference for the calibration of photometric detectors

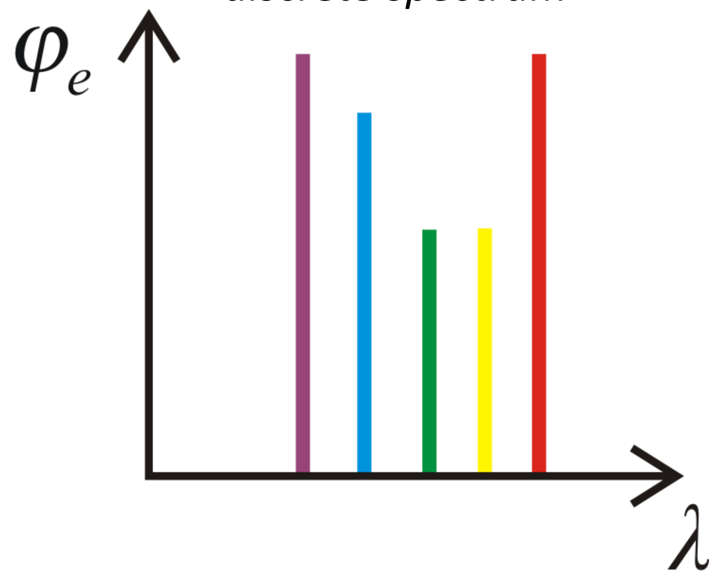
Typical emission spectra

A light source can emit a continuous or a discrete spectrum

continuous spectrum



discrete spectrum



$$\Phi_e = \int_{\lambda_1}^{\lambda_2} \varphi_e(\lambda)\, d\lambda$$

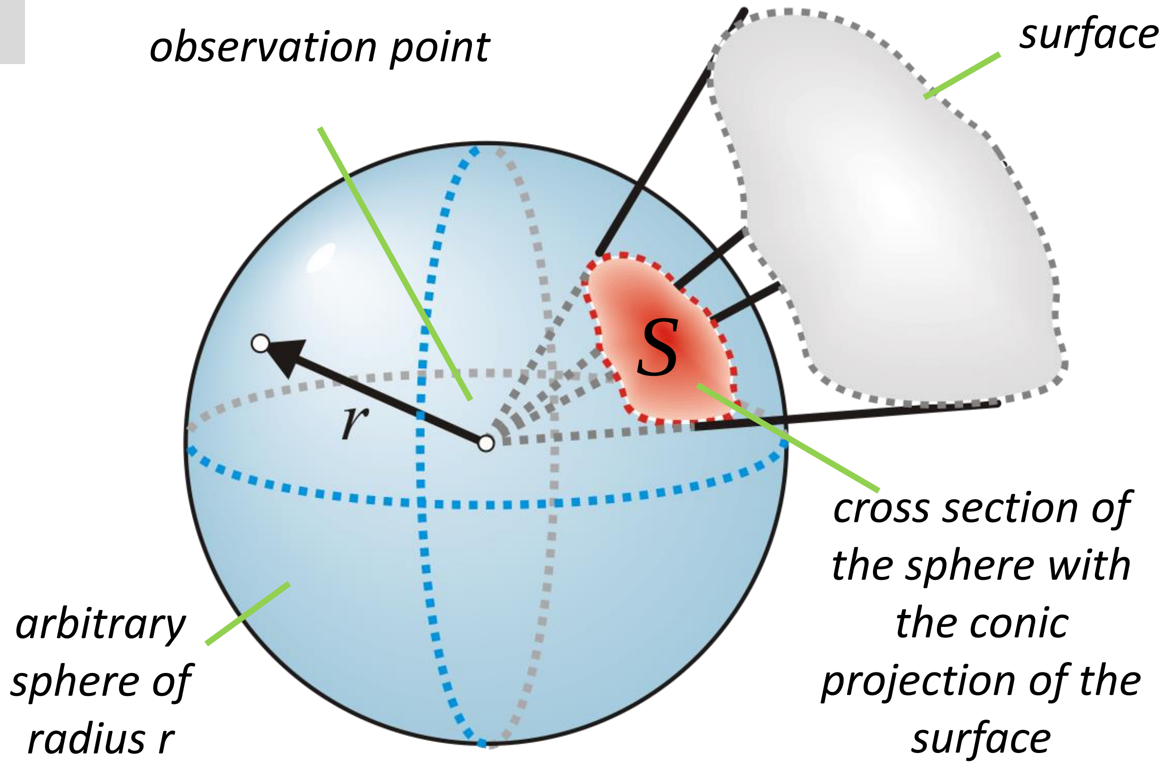
emitted power

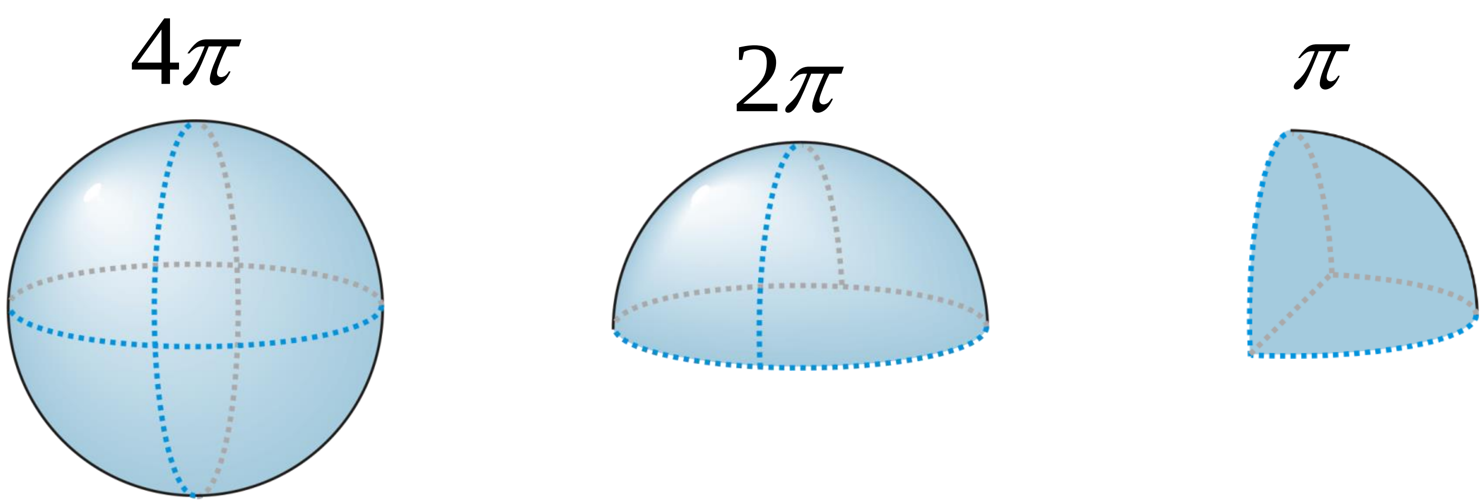
spectral distribution of the emitted power

Solid angle

$$\Omega \equiv \frac{S}{r^2}$$

units 1 *sr* (*steradian*)





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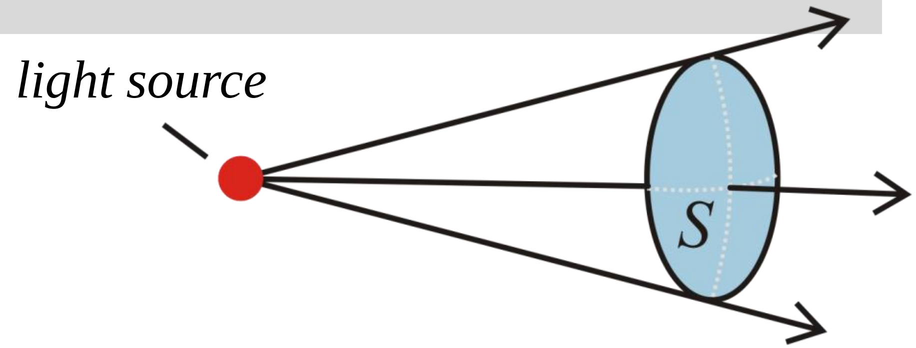
Flux

expresses the **flow of energy per time unit** through a surface *S*



Photometric units

Luminus flux

$$\Phi = \frac{dQ}{dt}$$

lm (lumen)

Radiometric units

Radiant flux

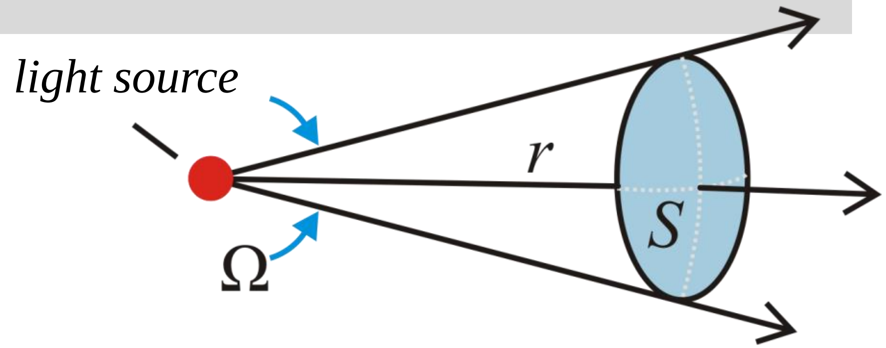
$$\Phi_e = \frac{dQ_e}{dt}$$

W (Watt)

Radiant flux of 1 W of monochromatic radiation at the peak of the eye sensitivity (554 nm) is equivalent to 680 lm

Intensity

it expresses the ratio of the **radiant flux** through a surface *S* **per solid angle**



Photometric units

Luminus intensity

$$I = \frac{d\Phi}{d\Omega}$$

cd (candela)

Radiometric units

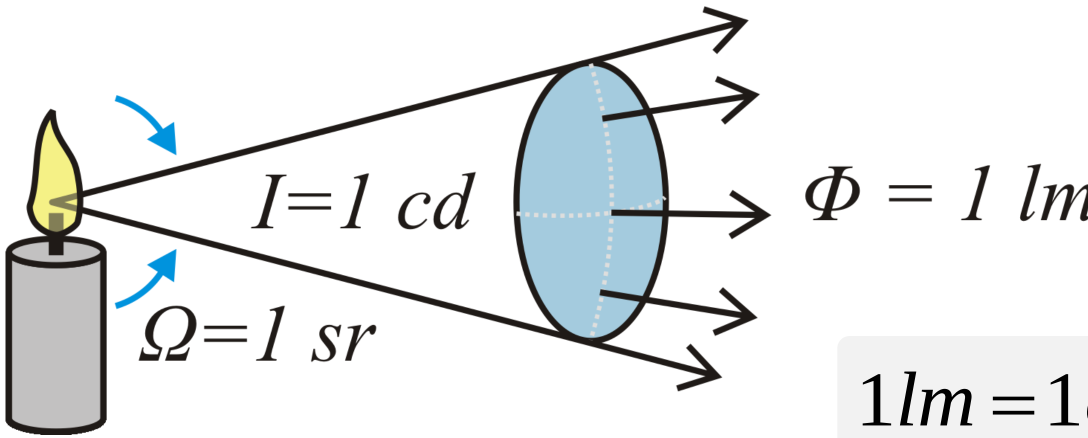
Radiant intensity

$$I_e = \frac{d\Phi_e}{d\Omega}$$

W/sr

1 cd is defined as the 1/60 of the optical power emitted from a 1 cm² surface of Pt at melting temperature

Relation between candelas and lumens

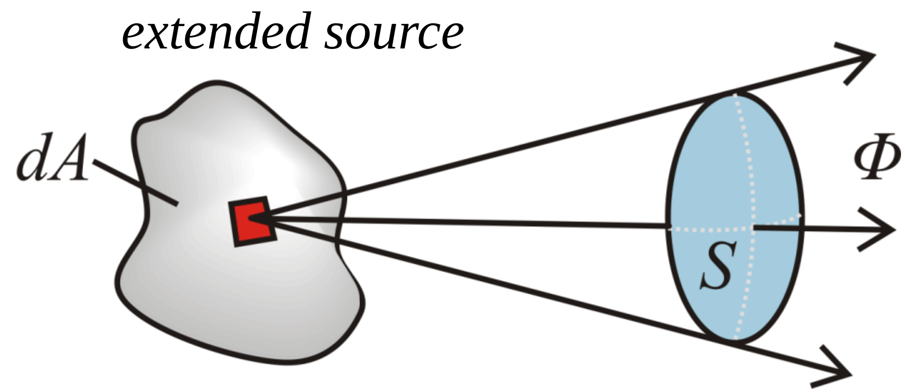


$$1lm = 1cd \cdot 1sr$$

Typical Luminus intensity values	
candle	~ 1 cd
Incandescent lamp 40 W	40 cd
Incandescent lamp 100 W	130 cd
arc lamp	2000 cd

Emittance

expresses the flow of **radiation per surface area** of the source



Photometric units

Luminus emittance

$$M = \frac{d\Phi}{dA}$$

lm/m²

Radiometric units

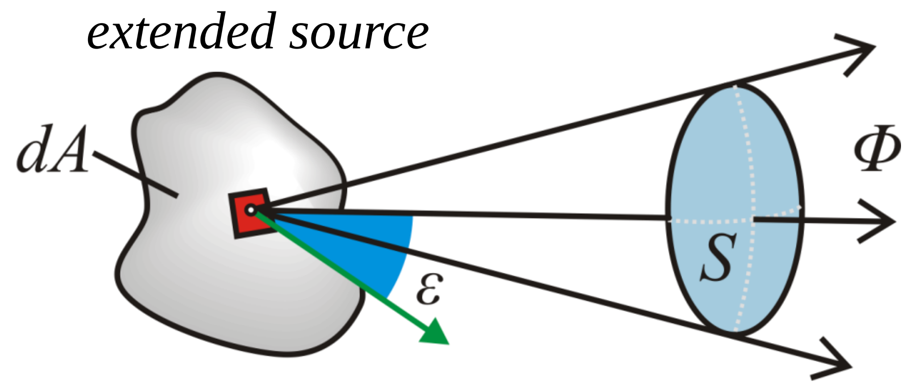
Radiant emittance

$$M_e = \frac{d\Phi_e}{dA}$$

W/m²

Radiance

expresses the **intensity of the light source per surface area** for a **specific angle to the surface normal**



Photometric units

Luminance

$$L = \frac{dI}{dA\cos\varepsilon}$$

cd/m²

Radiometric units

Radiance

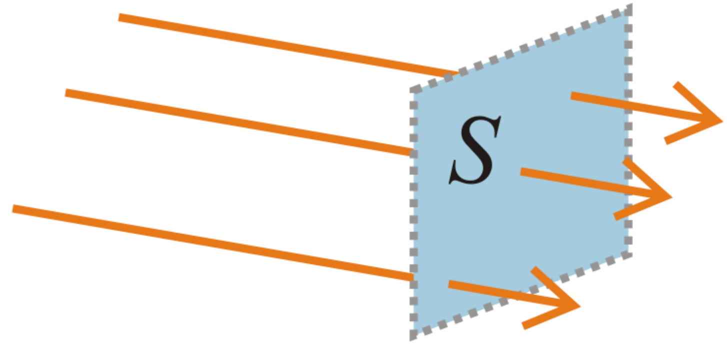
$$L_e = \frac{dI_e}{dA\cos\varepsilon}$$

W/(sr·m²)

A perfectly diffusing surface emitter exhibits constant Luminance and is called ***Lambertian***

Illumination

expresses the flow of **radiation through a surface** S **per surface area**



Photometric units

Illumination

$$E = \frac{d\Phi}{dS}$$

lx (lux)

$$1 lux = 1 lumen / m^2$$

Photometer

By Thomas Wydra
[CC BY-SA 3.0 de], Wikimedia Commons

Radiometric units

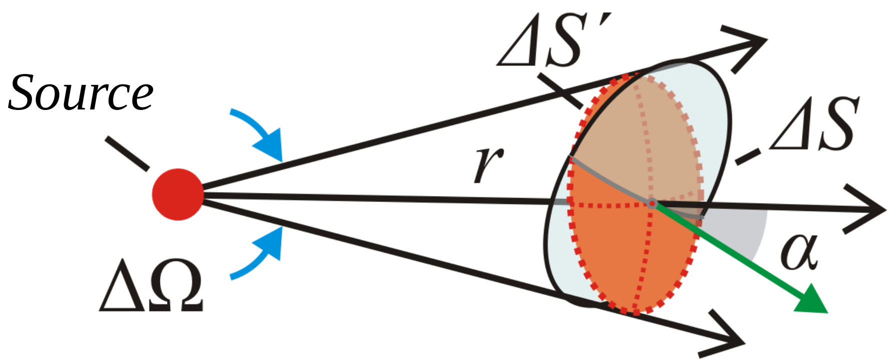
Irradiance

$$I = \frac{d\Phi_e}{dS}$$

W/m²

Typical illumination values	
Illumination from the stars	~ 10^{-4} *lx*
Illumination from the full moon	0.2 *lx*
Illumination of a street at night	20 *lx*
Typical room illumination	*100 lx*
Illumination for reading	500 *lx*
Illumination for fine work	2000 - 5000 *lx*
Typical shiny day	~ 10^{4} *lx*
Direct solar illumination	~ 10^{5} *lx*

Basic principles of photometry



light source intensity

$$E \equiv \frac{\Delta\Phi}{\Delta S} = \frac{I\,\Delta\Omega}{\Delta S}$$

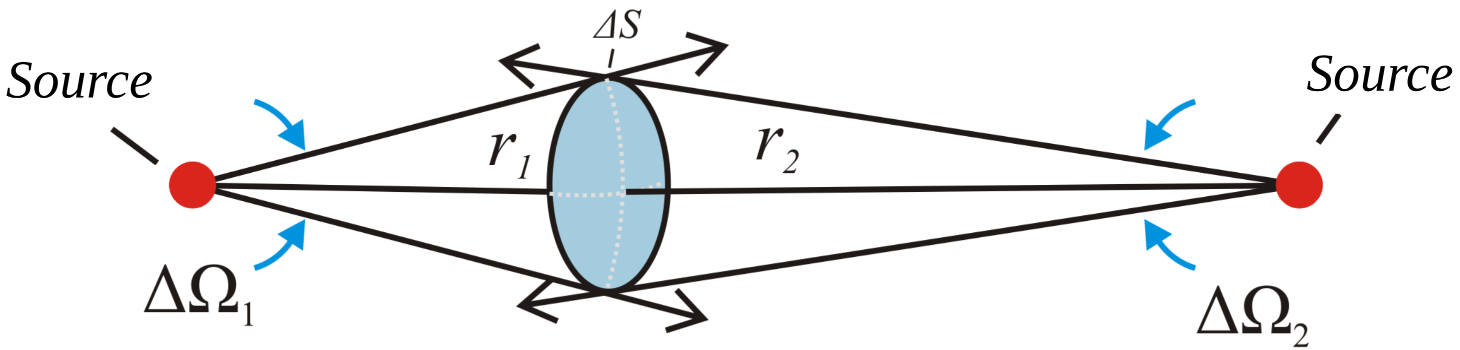
Illumination

$$\Delta\Omega \equiv \frac{\Delta S'}{r^2} = \frac{\Delta S\cos\alpha}{r^2}$$

solid angle

$$\left.\begin{array}{l} E \equiv \dfrac{\Delta\Phi}{\Delta S} = \dfrac{I\,\Delta\Omega}{\Delta S} \\ \Delta\Omega \equiv \dfrac{\Delta S'}{r^2} = \dfrac{\Delta S\cos\alpha}{r^2} \end{array}\right\} \Rightarrow \boxed{E = \frac{I\cos\alpha}{r^2}}$$

law of illumination



$$E_1 = E_2 \Leftrightarrow \frac{I_1}{I_2} = \frac{r_1^2}{r_2^2}$$

condition for equal illumination

By using this condition we can measure the intensity of an unknown light source by comparing it to the intensity of a candle

$$I_x = I_{candle} \cdot \frac{r_x^2}{r_{candle}^2} \cong 1cd \cdot \frac{r_x^2}{r_{candle}^2}$$

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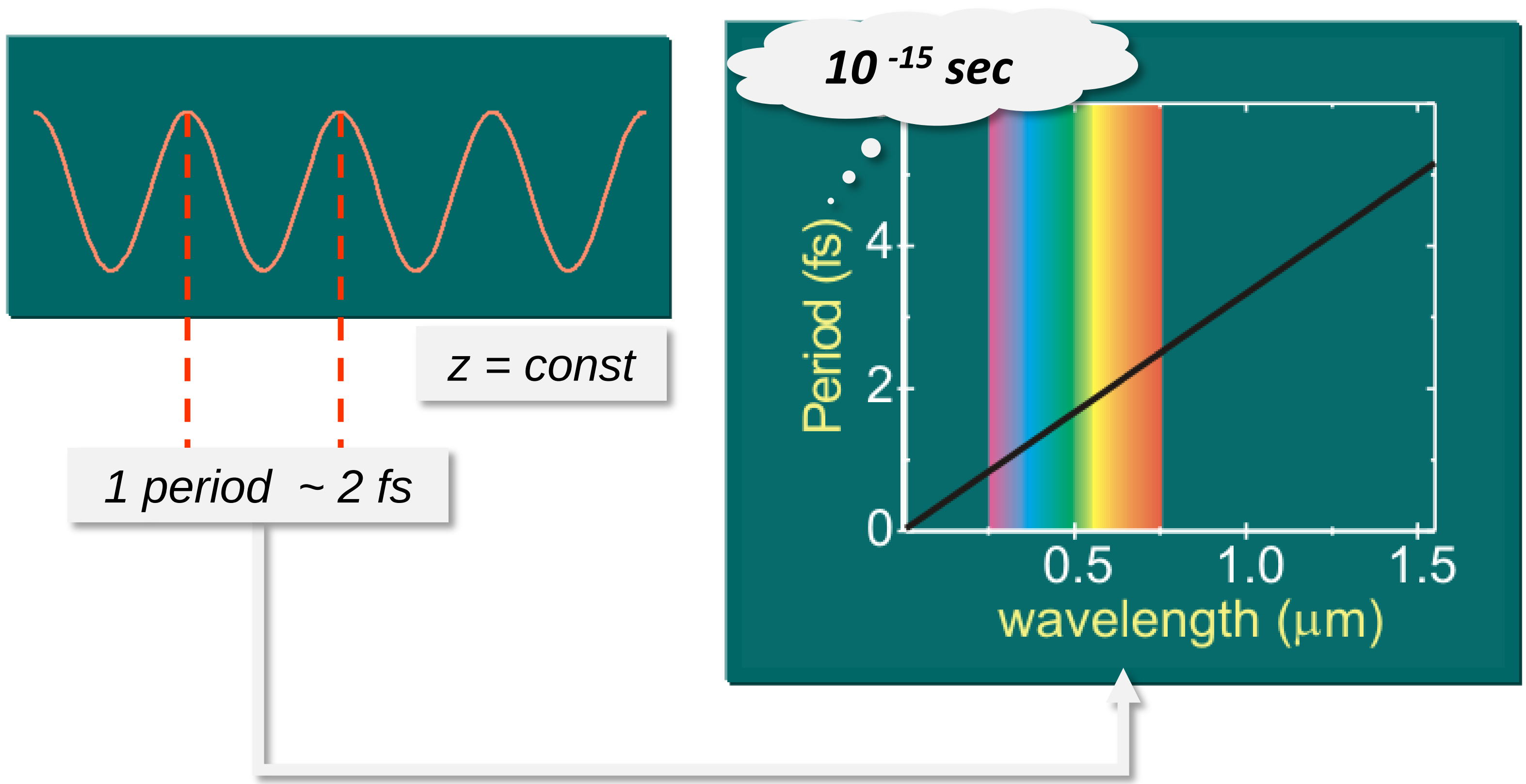
4.2 Detectors

How fast is light's oscillation ?

The oscillation of the light field is much faster from our detector's response time !



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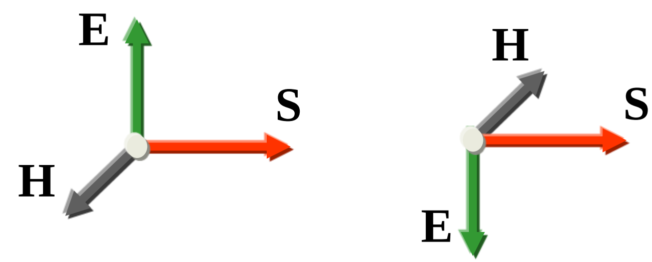
The averaging action

The energy transferred by the field
is expressed by the **Poynting vector**

$$\mathbf{S} = \mathbf{E} \times \mathbf{H}$$



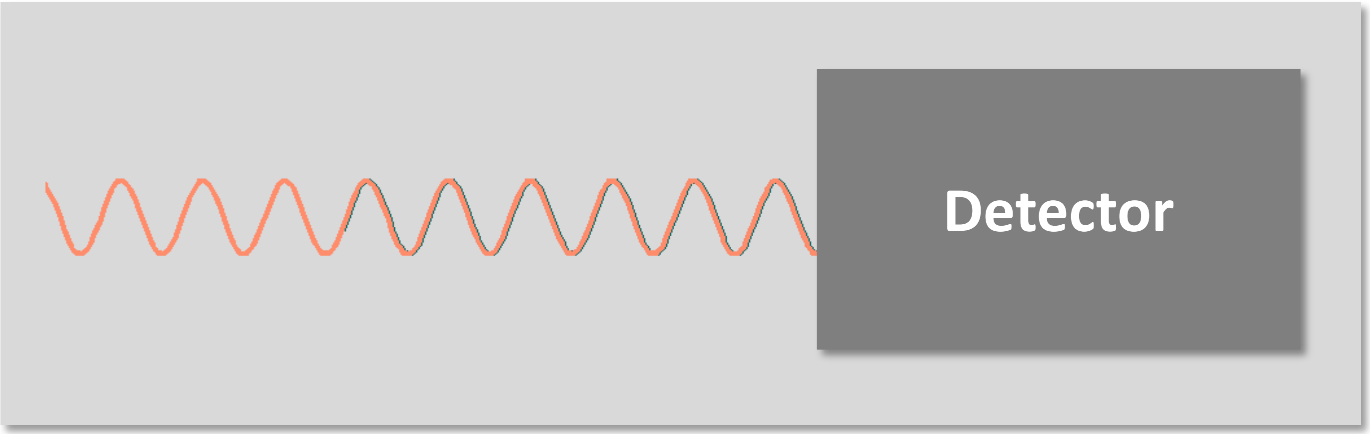
S oscillates from zero to maximum
at **twice the frequency** of the light field !

$$I \equiv \left\langle \left| \mathbf{S} \right| \right\rangle_t = n\,\varepsilon_o\,c \left\langle \left| \mathbf{E} \right|^2 \right\rangle_t$$

(*W/m*²)

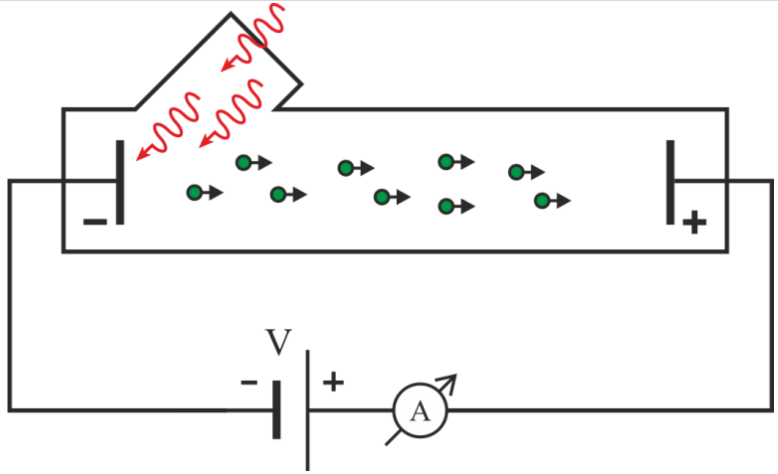
Intensity

Detecting H/M radiation



By direct measurement we are actually detecting the **average energy** transferred from the light field **over many oscillation periods**

Photoelectric effect



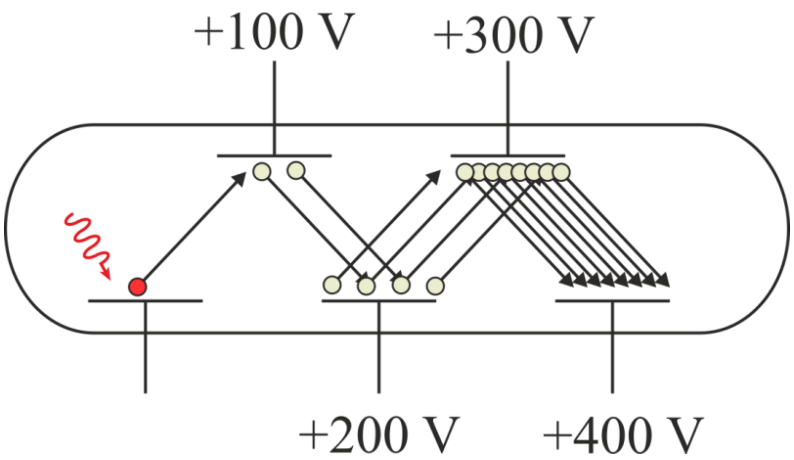
No photoelectrons are emitted,
for a given metal, **below a minimum frequency *f*** of incident radiation.

The **time lag** between the incidence of radiation and the emission of a photoelectron **is very small**, much less than a *nsec*.

The maximum kinetic energy of the photoelectrons emitted **depends on the frequency** and is **independent of the intensity** of the incident light.

light consists of particles of energy $h\,f$

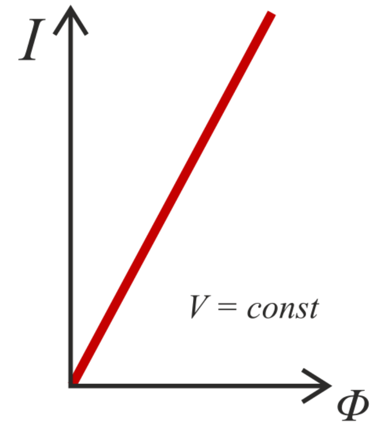
Typical light detectors: Photomultipliers



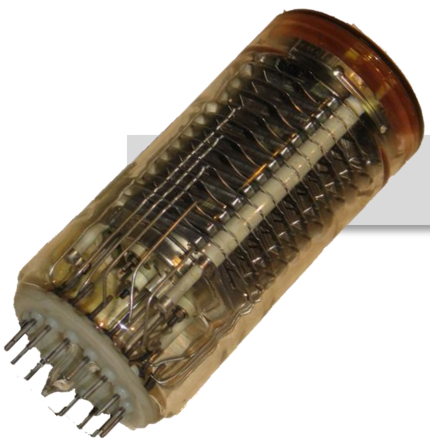
Sensitivity ~ 100 mA/W

Current amplification ~ 10^6

Operation at UV and VIS



The most sensitive light detectors !



Photomultiplier

By Poil
[CC BY], Wikimedia Commons

photomultiplier
HAMAMATSU R446

By ScAvenger
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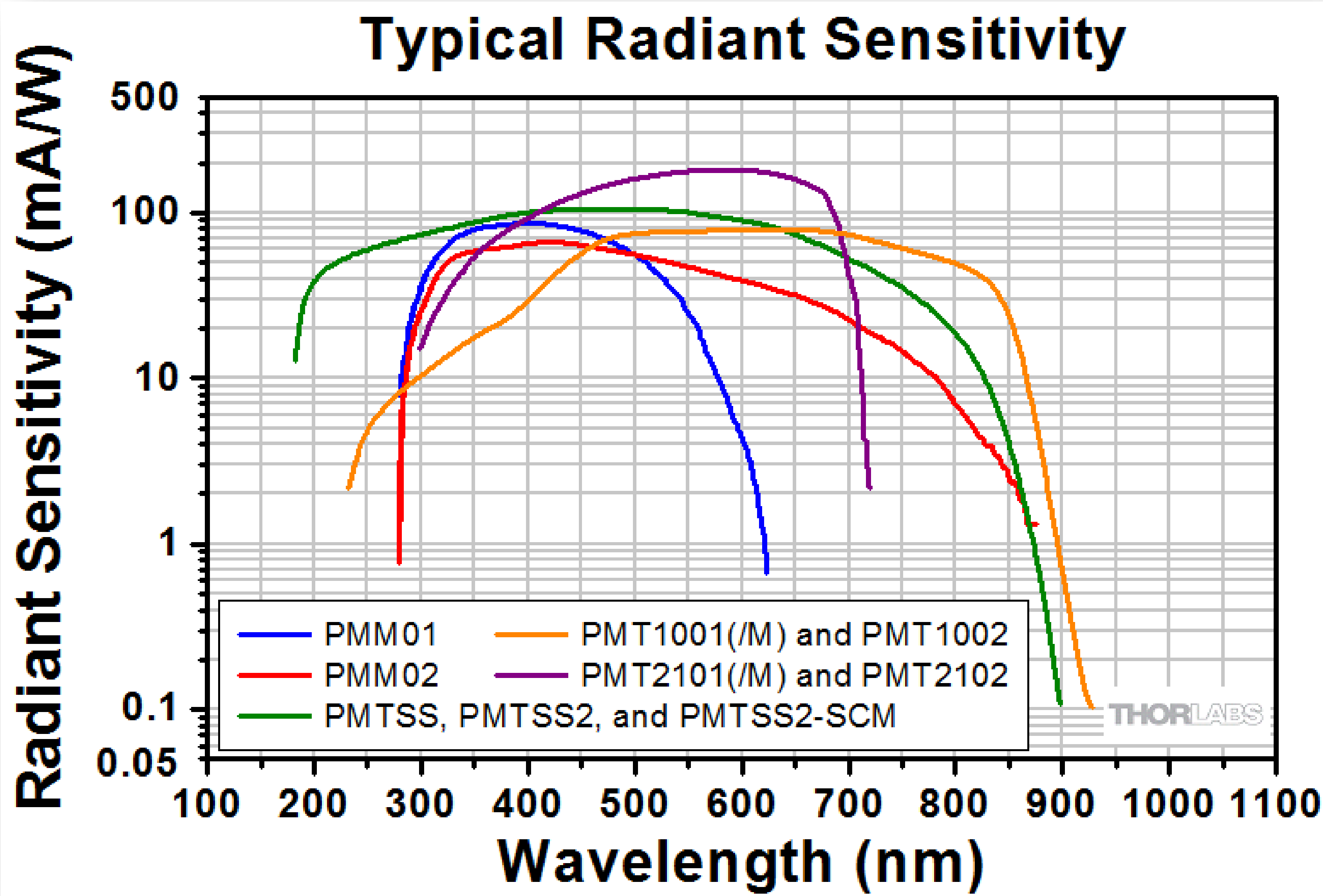


photomultiplier spectral response

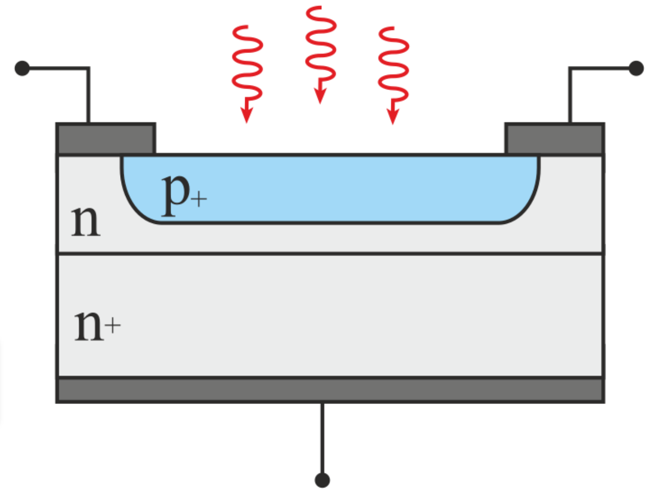
Thorlabs (www.tohrlabs.com)

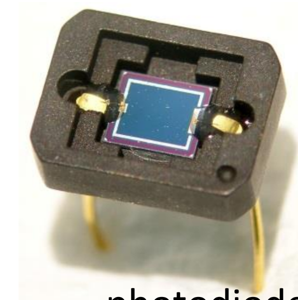
Typical light detectors: Photodiodes

Sensitivity ~ 100 μA/W

Operation at UV, VIS and IR

Pulsed operation up to 10 GHz



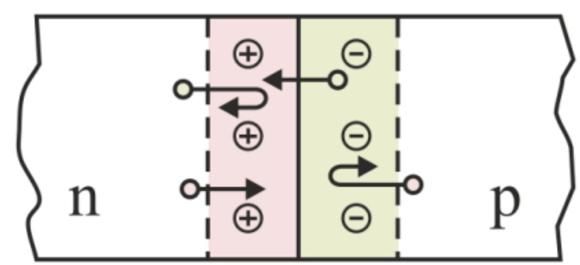


photodiode

Photodiodes are based on the operation of **p-n semiconductor junctions**.

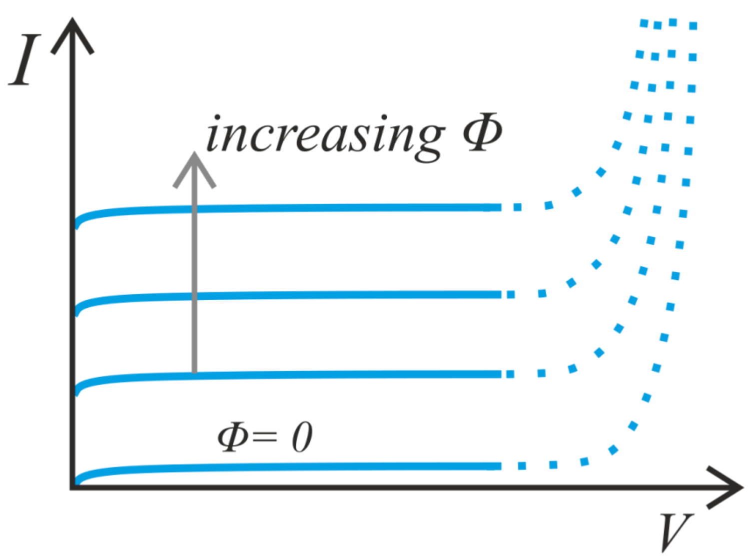
When a photon of sufficient energy strikes the diode, it creates an **electron-hole pair**.

In the depletion region electron and holes move in opposite directions and a photocurrent is produced.

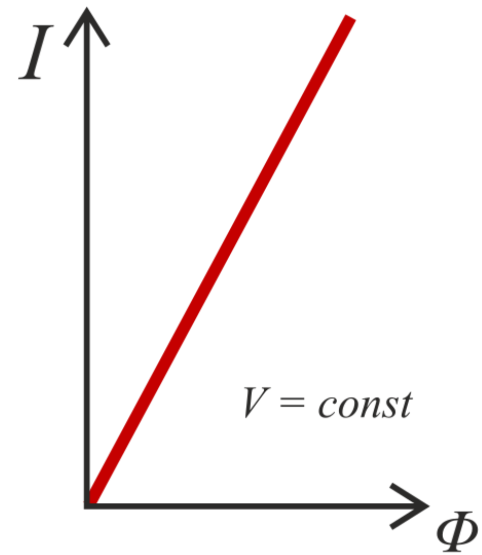


photodiode operation principle

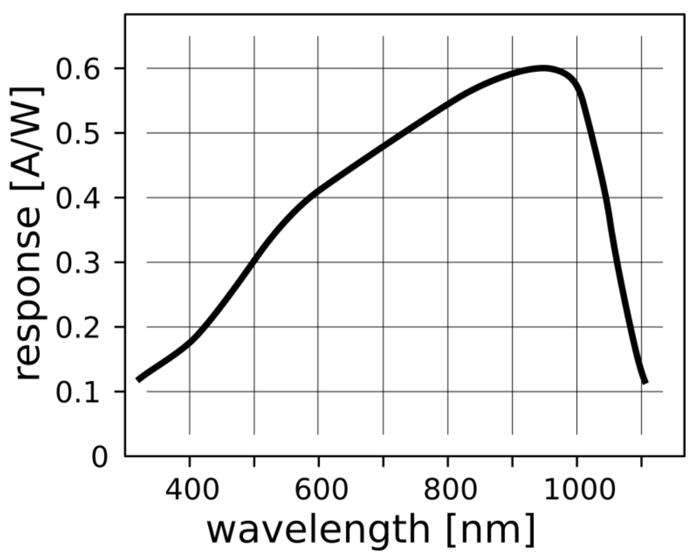
Commonly used, low cost and fast!



I-V characteristic of a photodiode



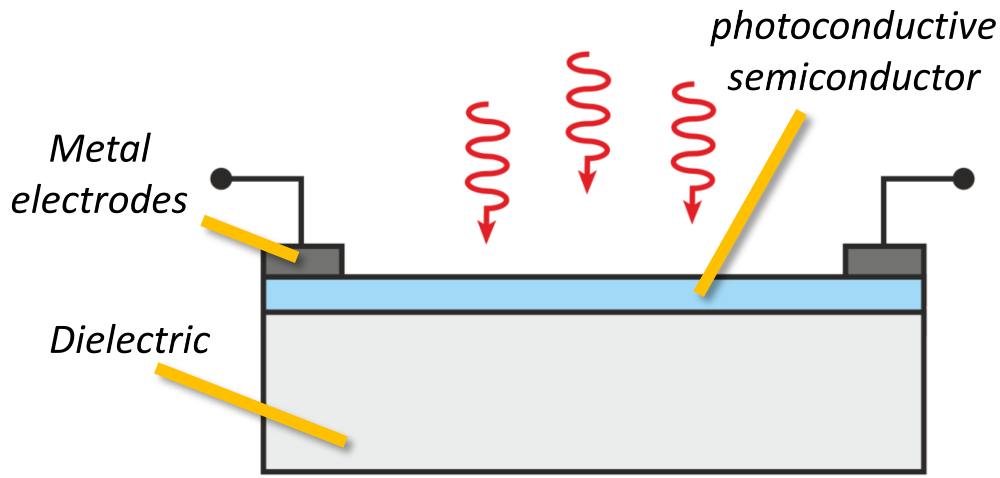
I-Φ characteristic of a photodiode

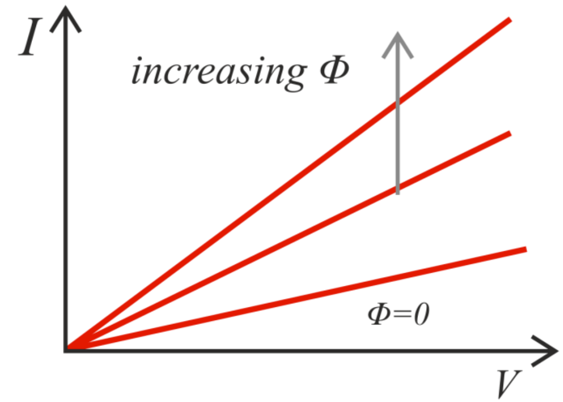


Spectral Response
of a silicon photodiode

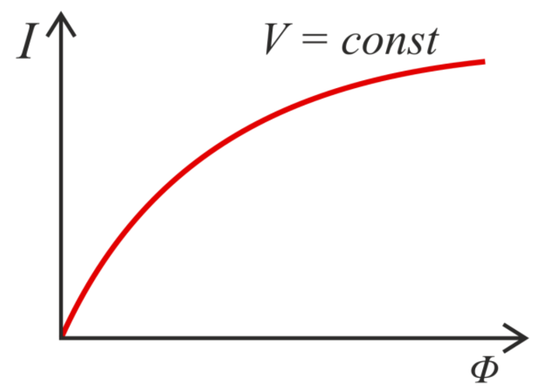
By KaiMartin

Typical light detectors: Photoresistors





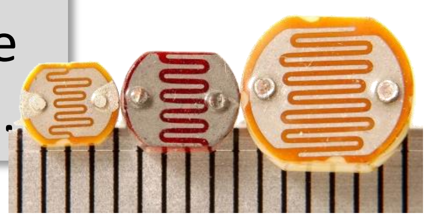
I-V characteristic of a photoresistor



I-Φ characteristic of a photoresistor

Photoresistors are composed of high resistance semiconductors.

In the dark, their resistance is **several MΩ**, while in the light, it drops **bellow 1 kΩ**.

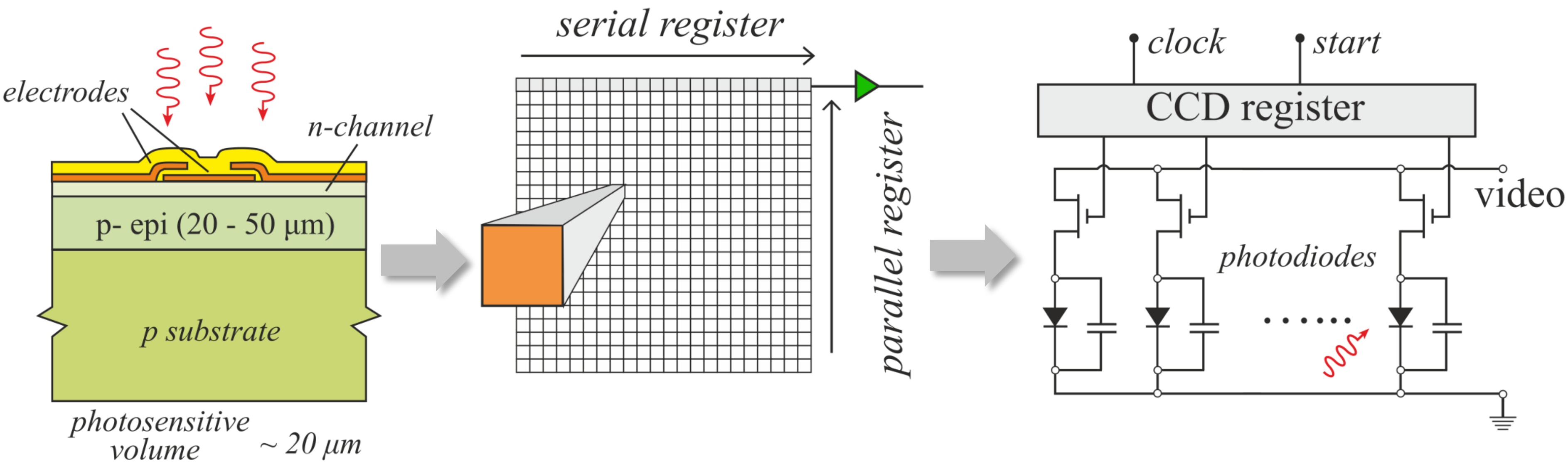


photoresistors

By Junkyardsparkle, [CC0], Wikimedia Commons

Very low cost, and slow.

Typical light detectors: Charge-coupled devices (CCDs)



CCDs are composed of a **photosensitive region** (array of photodiodes) , and a **transmission region** made out of a shift register.

Parallel processing

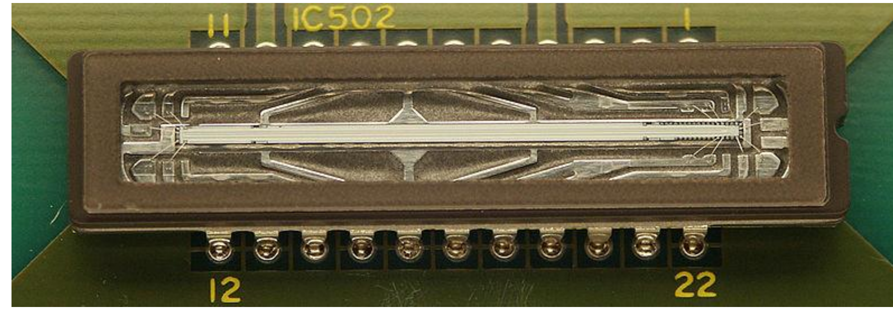
Operation up to 100 kHz

Operation at VIS and NIR

Can provide 2D image sampling !

CCD SONY
ICX493AQA
10.14 Mpixels
APS-C 1.8"

By Andrzej w k 2
[CC BY-SA 4.0], Wikimedia Commons



CCD line sensor in a ceramic dual in-line package, soldered on a printed circuit board.

By Stefan506
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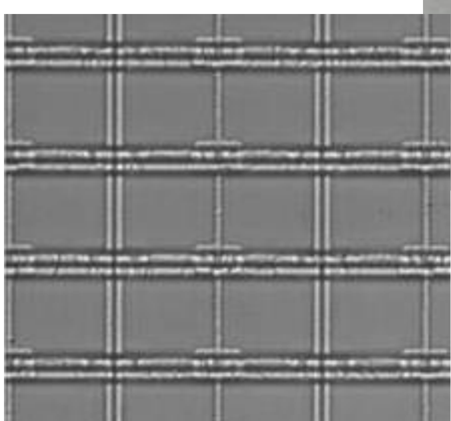
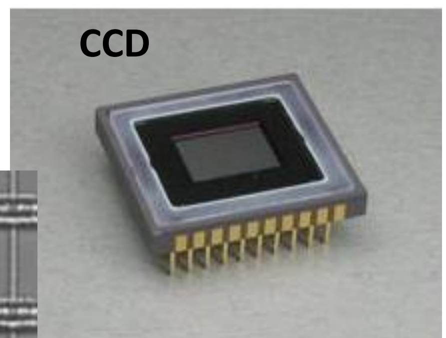
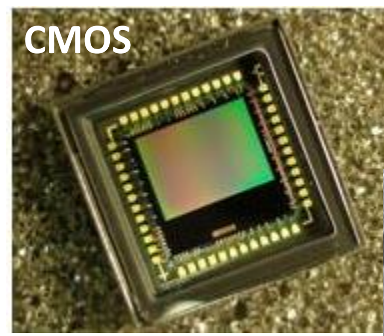
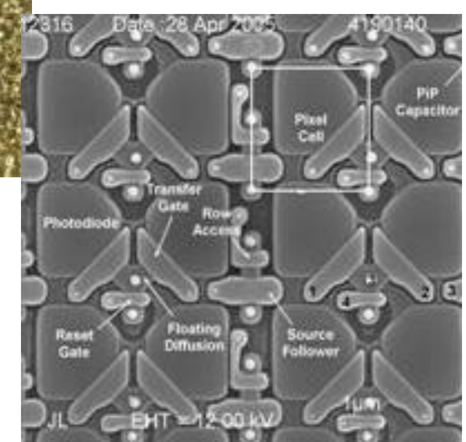
SEM image







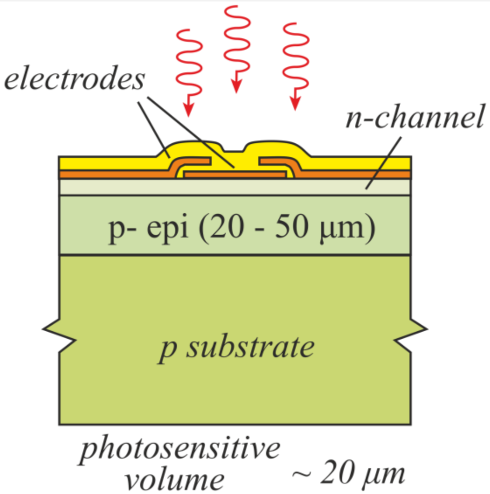
SEM image



CCD vs. CMOS sensors

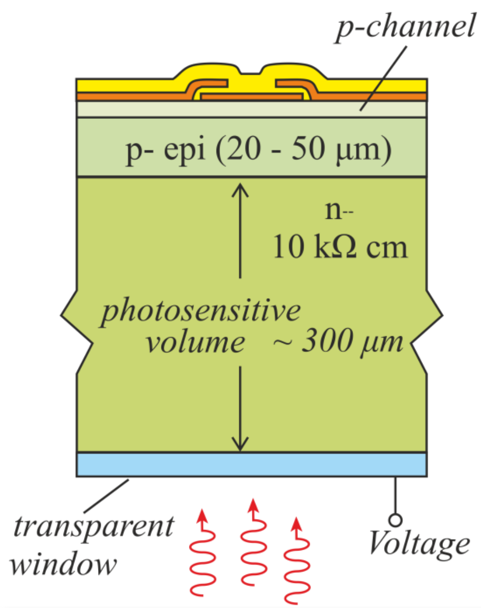
adapted work from image created by Master dpo
[CC BY-SA 3.0], Wikimedia Commons

typical CCD pixel



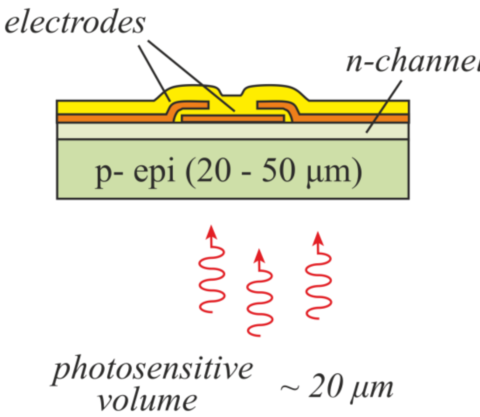
- low response in blue due to absorption from the gate electrodes
- low response in IR due to the low thickness of the epitaxial layer
- fringes due to the gate structure

Back illuminated



- low cost (we avoid thinning)
- good response in IR (up to 1 μm)
- transparent window with antireflective coating for good response in the blue

Thinned, back illuminated



- thinning is expensive
- low response in IR due to the low thickness of the epitaxial layer
- fringes due to the gate structure

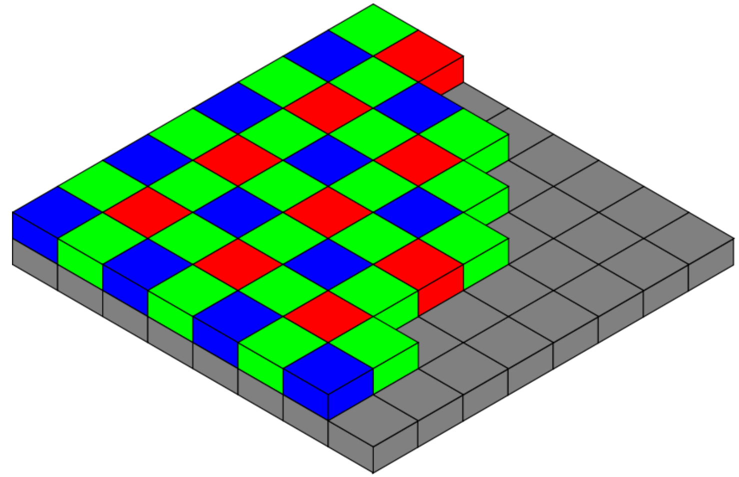
Color CCD sensors

Color CCD sensors usually use a **Bayer mask** over the CCD.

For each 2x2 square of pixels one is filtered red, one blue, and two green

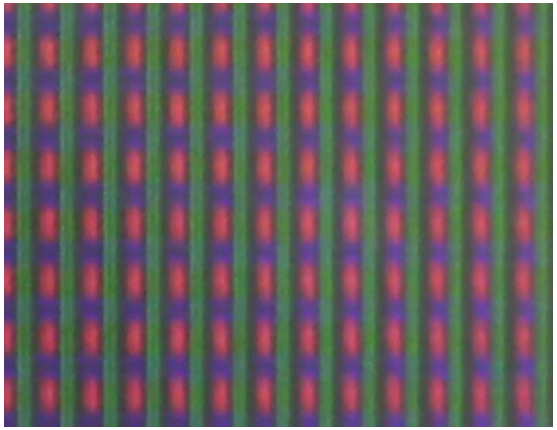
Luminance information is collected at every pixel.

Color resolution is 4 times lower than the luminance resolution.



A Bayer filter on a CCD sensor

By Cburnett



A x80 microscope view of the RGGB Bayer color filter on a 1980's 240 line resolution Sony PAL Camcorder CCD

By Binarysequence


x 4
x 16
color pixel level
x 64

Digital Cameras

A digital camera produces still, single-frame images that can be stored in digital memory, displayed on a screen and printed on physical media.

Its is comprised of:

- **an optical imaging system**
- **an image sensor (CCD or CMOS)**
- **a storage device**
- **a display**

Digital camera Sony DSC-H2.

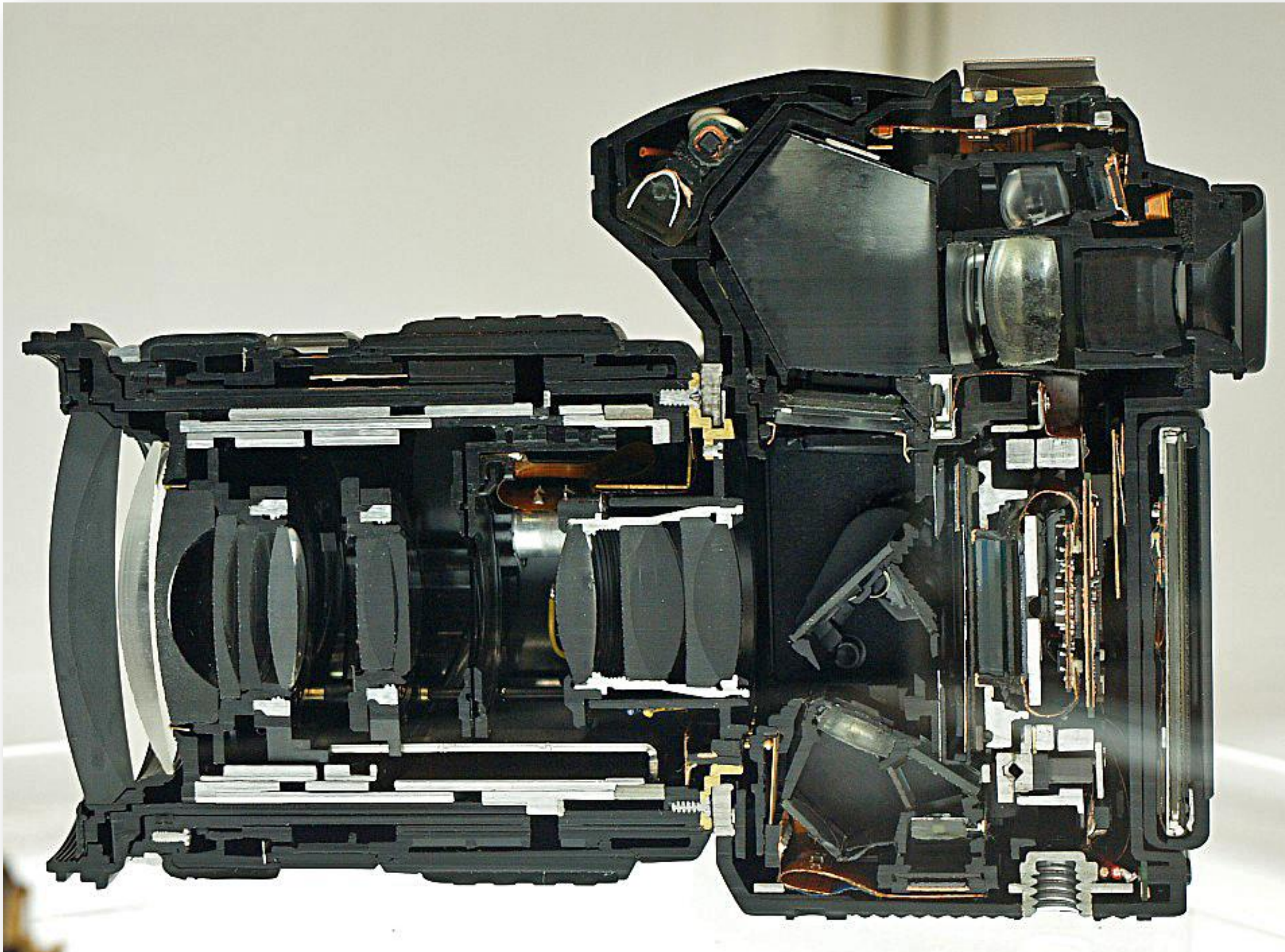
By Christian Jansky (User:Tschaensky) – Self-photographed, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3161095

Canon Powershot A95 compact digital camera

By Fir0002 (composite version by Matt57) - Own work, GFDL 1.2, https://commons.wikimedia.org/w/index.php?curid=5159773

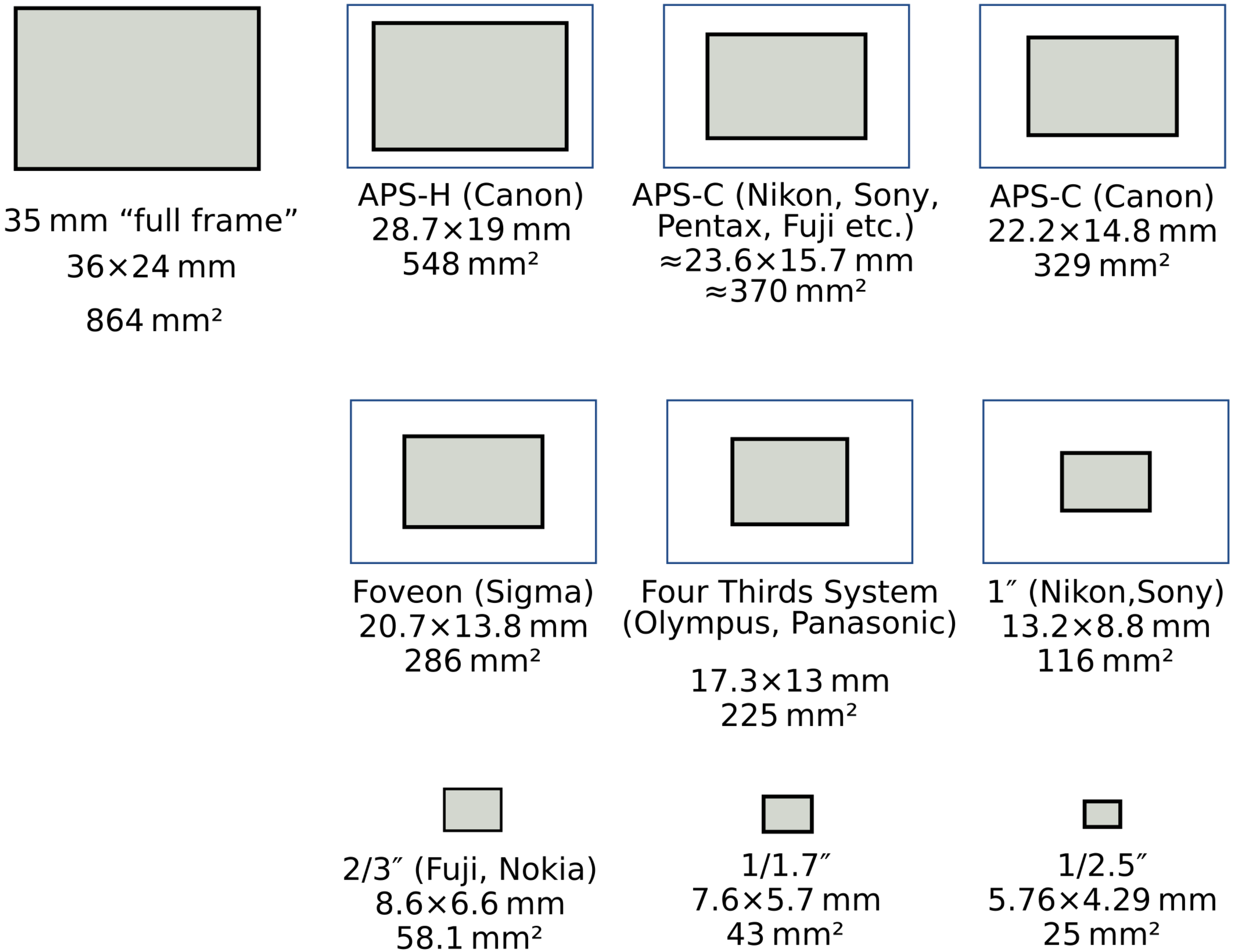
A CompactFlash (CF) card, used to store digital photographs

By Motorrad-67 https://commons.wikimedia.org/w/index.php?curid=2845628



A cutaway of an Olympus E-30 DSLR Camera with Zuiko Digital ED 14-54mm F2.8-3.5 II lens.

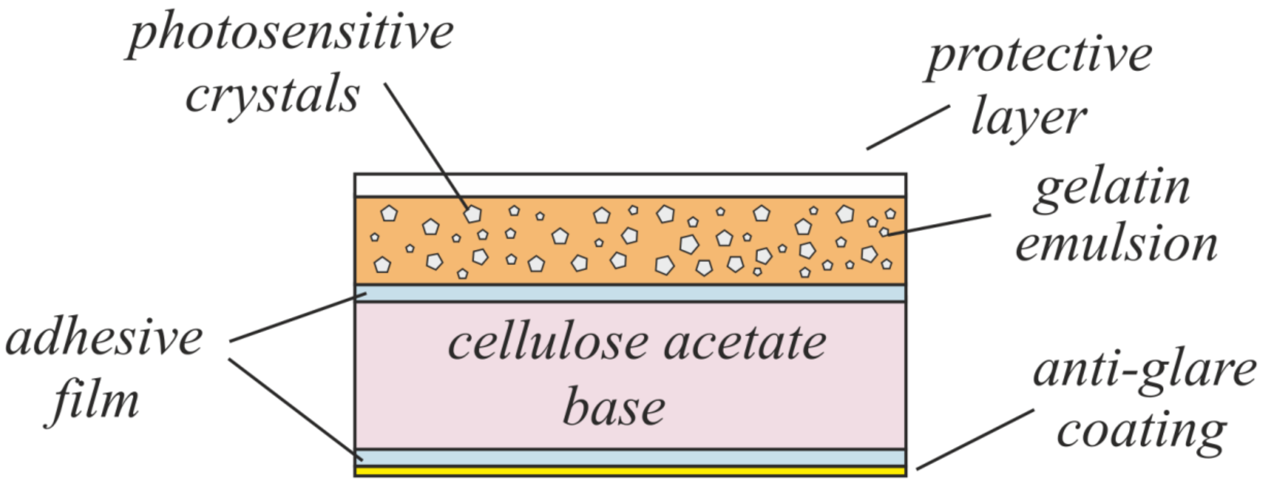
By Hanabi123, [CC BY-SA 3.0], Wikimedia Commons



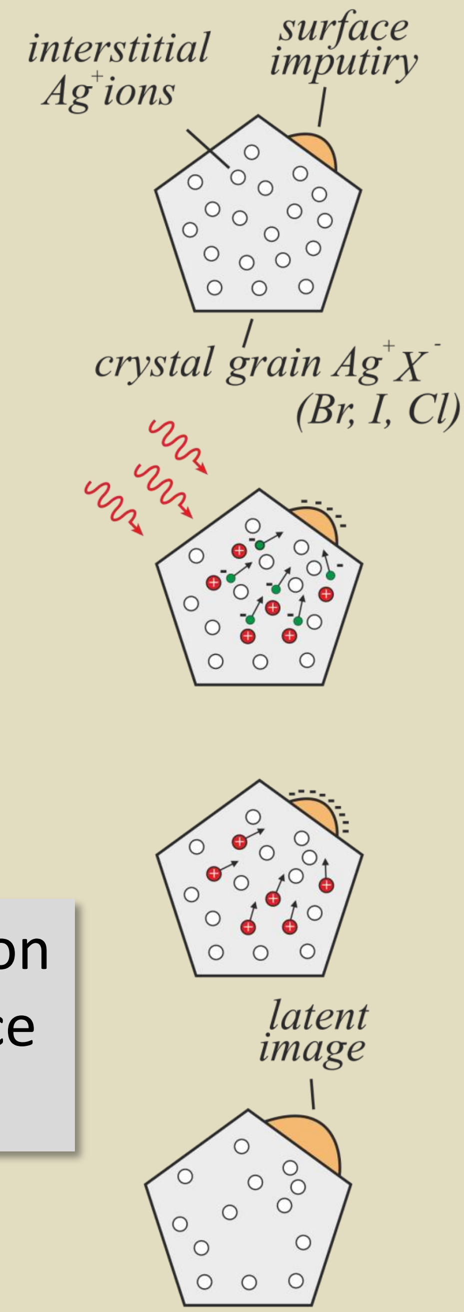
Comparison of digital camera image sensor sizes

By RenniePet , [PD], Wikimedia Commons

Typical light detectors: Photographic film



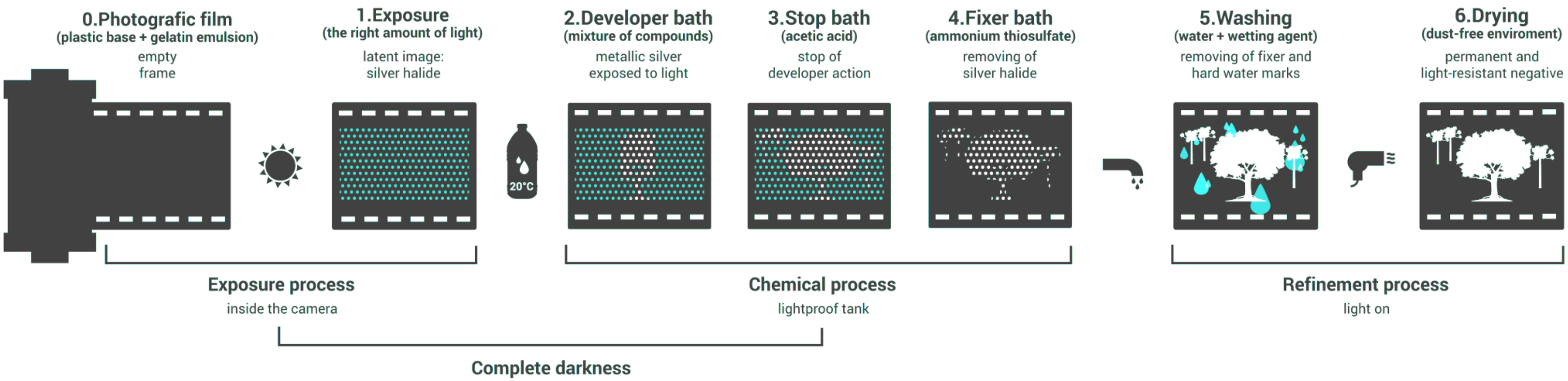
Photographic film structure



through a complex photochemical reaction metallic Ag is concentrated on the surface impurities of the Ag^+X^- crystal grains.

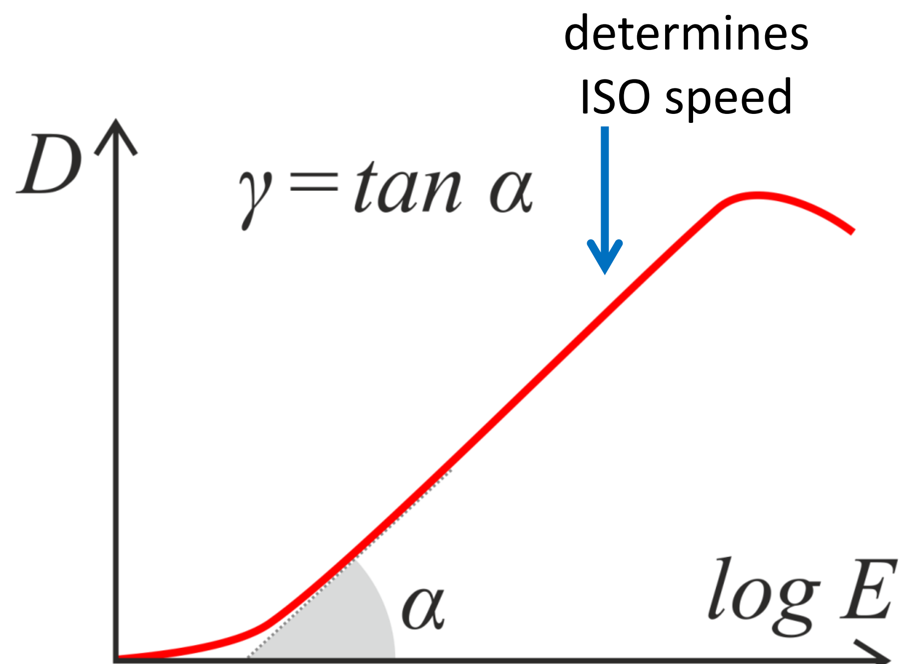
Operation: X-Rays to NIR

Photographic film processing



$$D = -\log(I_{out} / I_{in})$$

Optical density

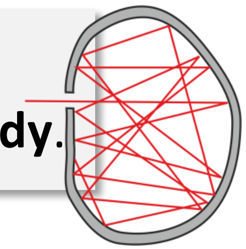


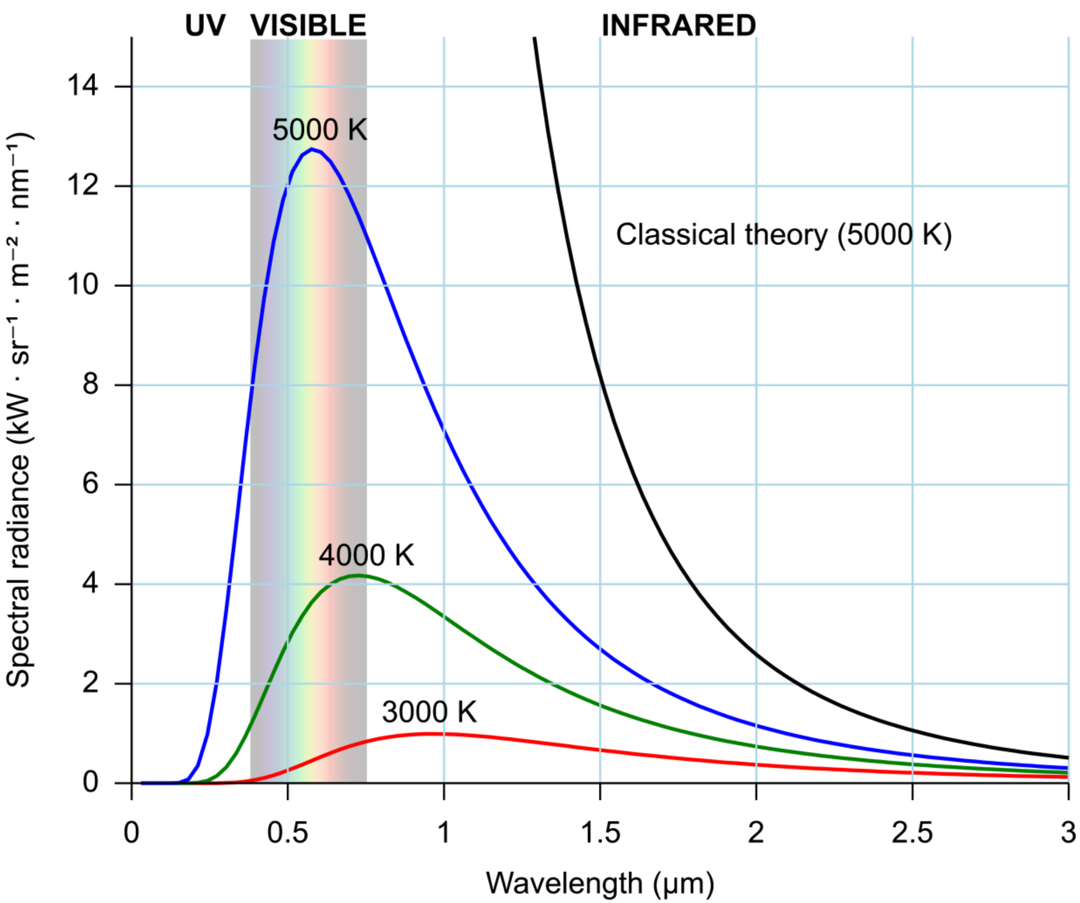
H-D curve

4.3 Sources

Black Body radiation

An idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence is called **black body**.





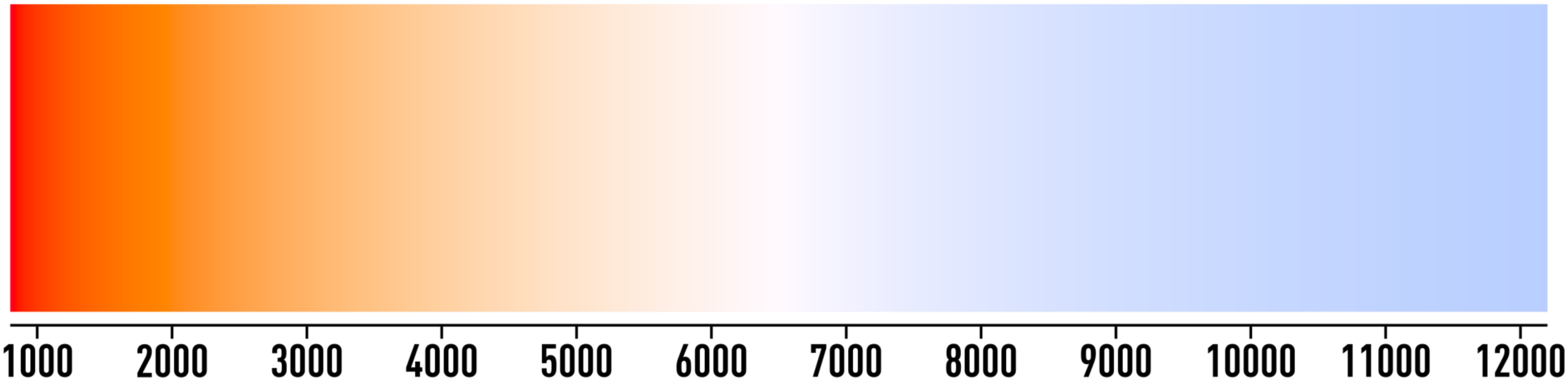
By Darth Kule , [PD], Wikimedia Commons

Black-body radiation has a characteristic, continuous frequency spectrum that depends only on the body's temperature.

$$\lambda_{\max} = \frac{2898}{T}\,\frac{K}{\mu m}$$

Wien law

Color of a black body from 800 K to 12200 K.



By Bhutajata - Own work, CC BY-SA 4.0,
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radiant emittance

$$I_e = \sigma T^4$$

Stefan–Boltzmann law

$$\sigma \cong 57 \frac{nW}{m^2 K^4}$$

Lava (Kilauea Hawaii 2003)

By Hawaii Volcano Observatory (DAS) , [PD], Wikimedia Commons

Typical light Sources

Incandescent lamps

A **tungsten filament** is **heated** at high temperature up at by passing an electric current through it. It is protected from oxidation with a glass or fused quartz bulb that is filled with inert gas or evacuated.

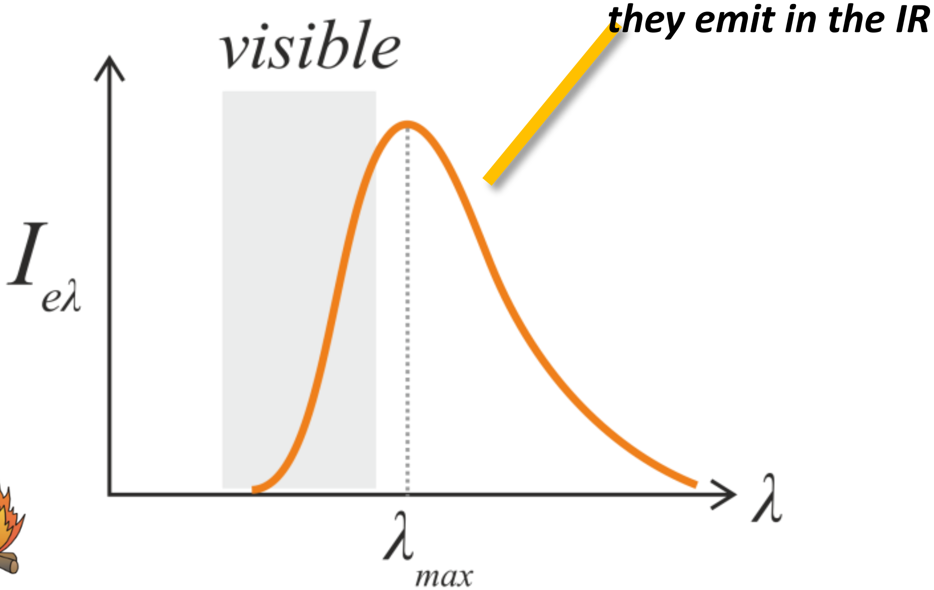
Continuous spectrum

Temperature ~ 2500 K

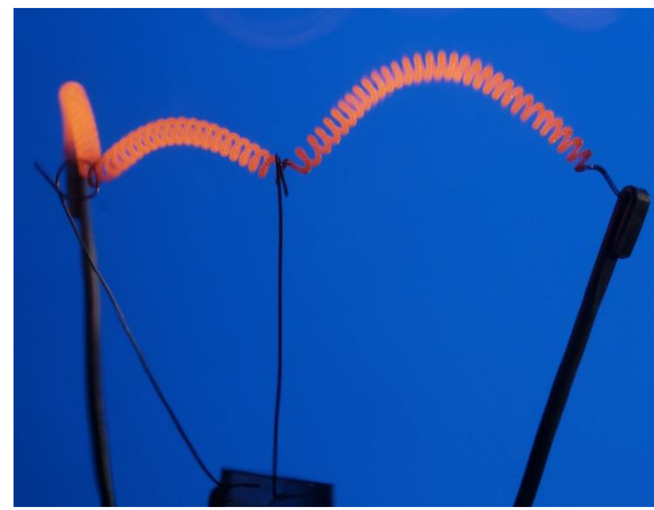
Improved version: Halogen Lamps

Incandescent lamp

By KMJ CC BY-SA 3.0, Wikimedia Commons



"Hot" source



Bulb filament at reduced voltage

By Arnoldius CC-BY-SA-3.0 Wikimedia Commons

Arc lamps

In an arc lamp, the electrodes are **carbon rods** in free air.

The rods are first touched together, allowing a relatively low voltage to strike the arc. Then the rods are slowly drawn apart, and electric current heats and maintains an arc across the gap

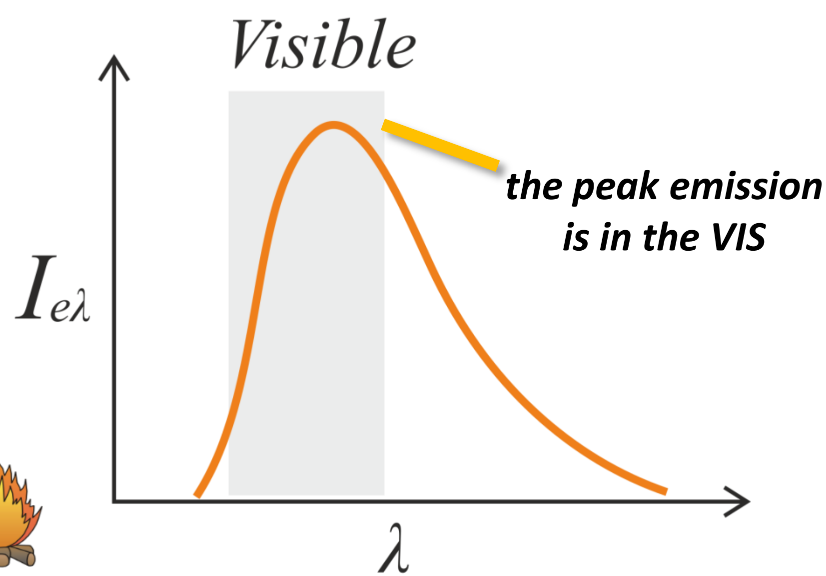
Continuous spectrum

Temperature ~ 4000 K

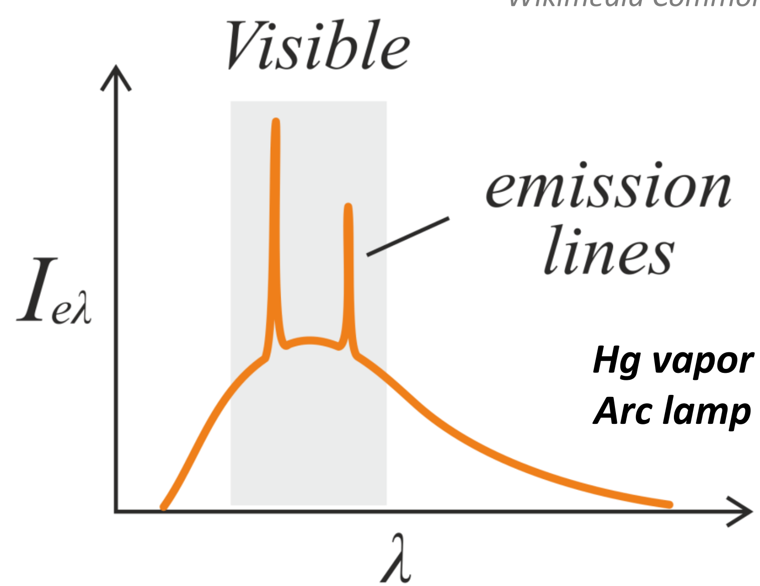
Excellent white light sources

An arc lamp for IMAX

By Atlant, CC BY 2.5, Wikimedia Commons



“Hot” source

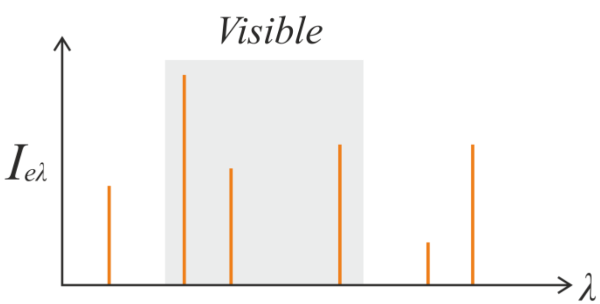


Low pressure Gas discharge lamps

In gas discharge lamps light is generated by sending an electric discharge through an ionized gas. Typically, they use a noble gas (Ar, Ne, Kr, Xe) or a mixture of these gases. Some include additional substances, like Hg, Na, and metal halides, which are vaporized during startup to become part of the gas mixture.

- Discrete spectrum
- Atomic line emission
- Useful in spectroscopy

Gas discharge lamp



λ (nm)	color	element	λ (nm)	color	element
365.0	UV	Hg	546.07	G	Hg
404.66	V	Hg	587.56	Y	He
435.83		Hg	589.29		Na
479.99	B	Cd	643.85		Cd
486.13		H	656.27	R	H
			706.52		He

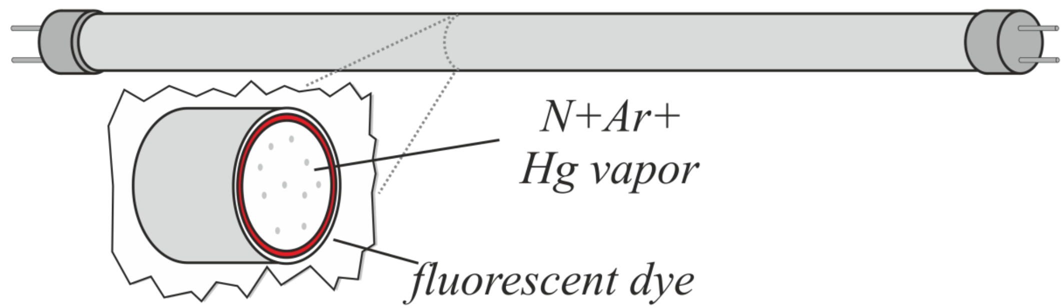
“Cold” source

Fluorescent Lamps

A fluorescent lamp is a **low-pressure mercury-vapor gas-discharge** lamp that uses fluorescence to produce visible light.

Mercury vapor excited by an electric current in the gas, produces **UV light** that then causes a **fluorescent dye** (phosphor) coating to glow.

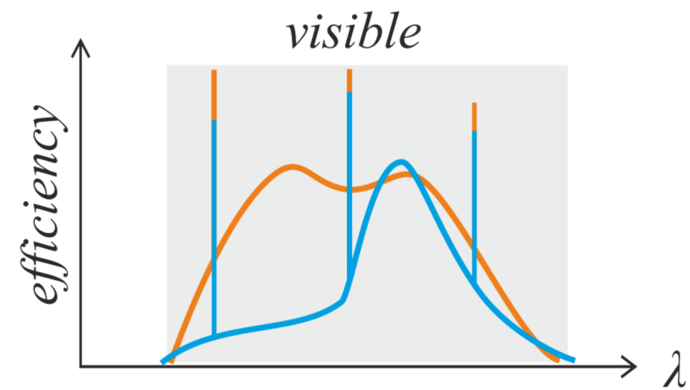
Fluorescent lamp



Continuous Spectrum

Broad spectrum

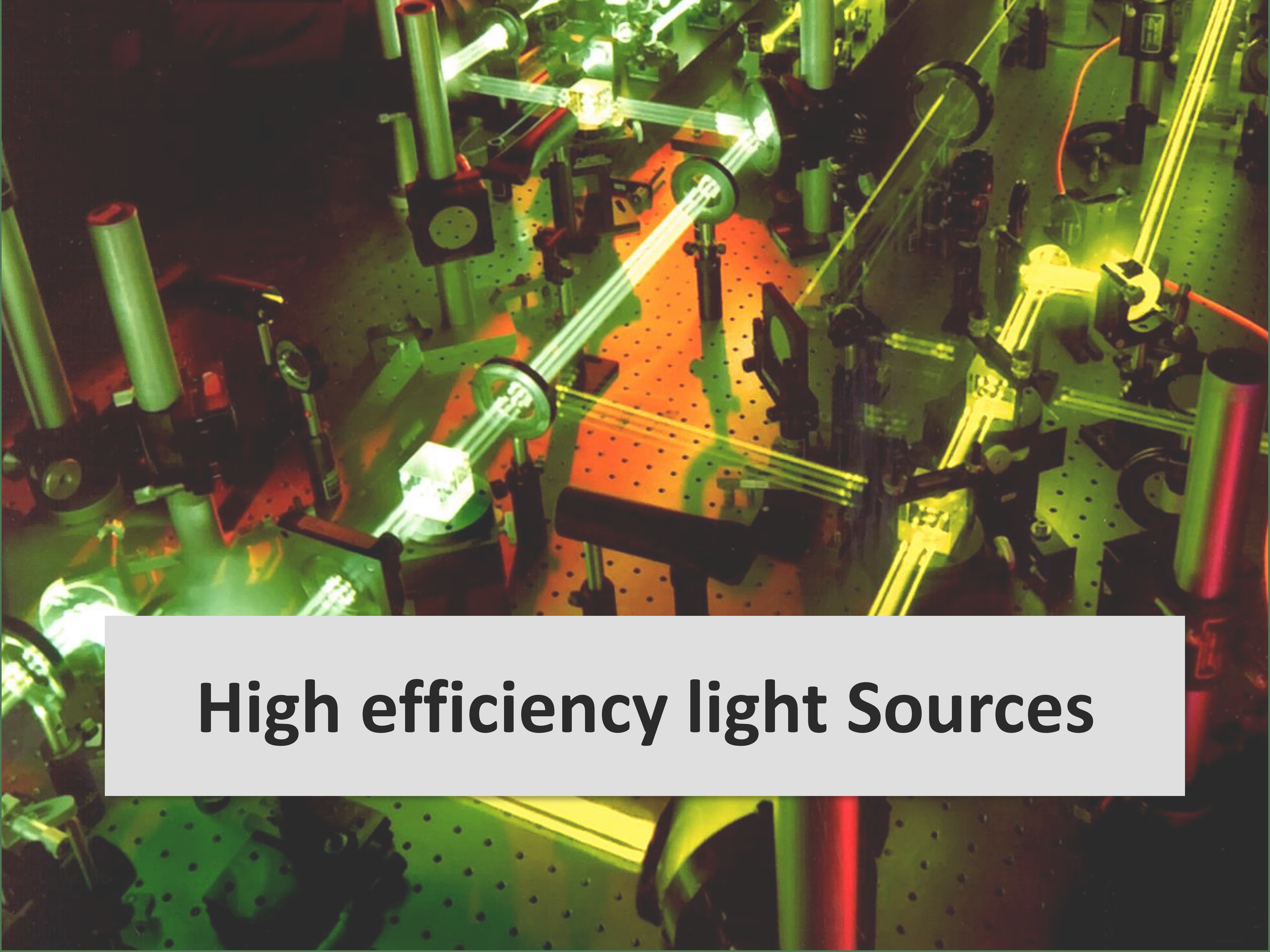
High efficiency



compact fluorescent lamp

By Lovelac7 [PD], Wikimedia Commons

"Cold" source



High efficiency light Sources

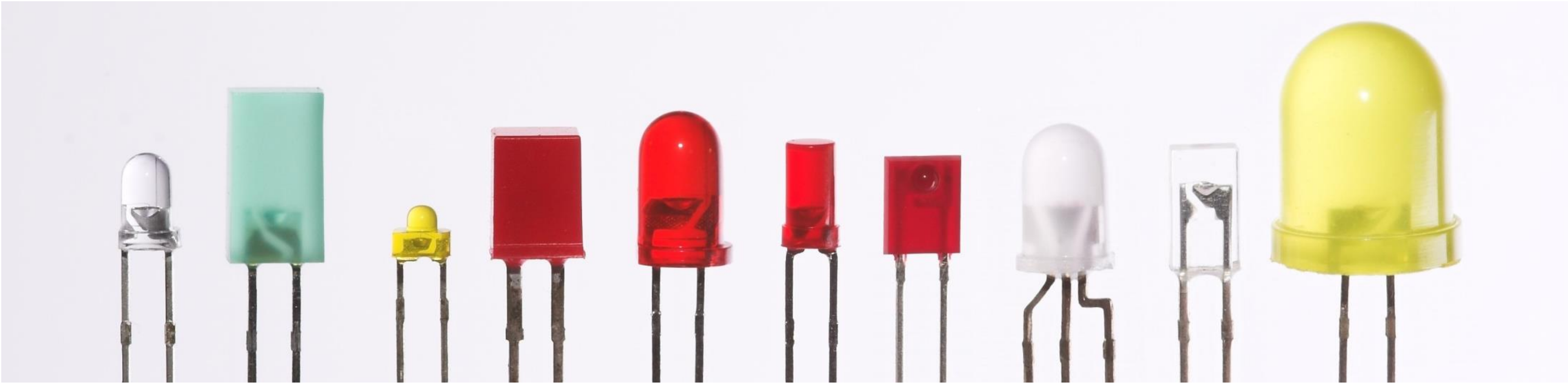
Light Emitting Diode (LED)

LEDs are **semiconductor light sources**. They consist of a **p–n junction** diode that emits light when activated. When a suitable voltage is applied to the leads, electrons and holes recombine, releasing energy in the form of photons.

- Narrow spectrum
- Quantum Mechanical
- High efficiency
- Color tuned by the band gap

Red, Green, Blue LEDs

By PiccoloNamek CC BY-SA 3.0, Wikimedia Commons

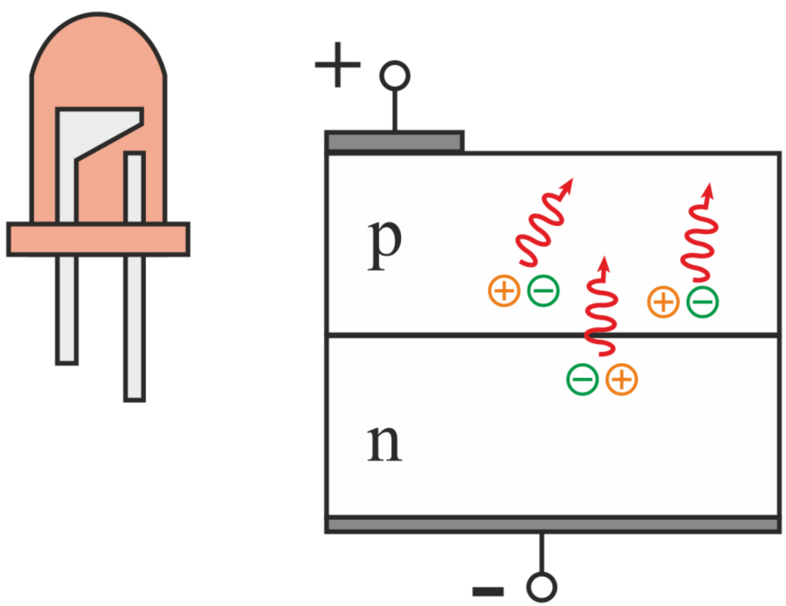


LEDs are produced in a variety of shapes and sizes

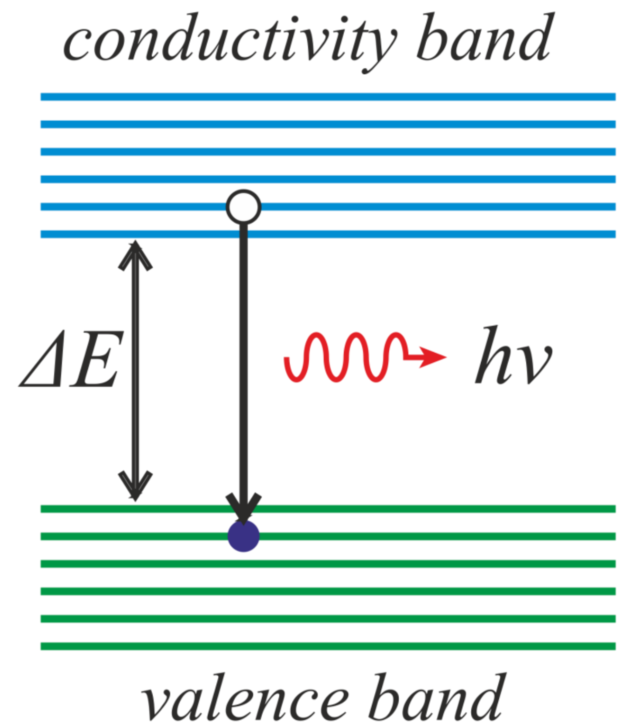
By Afrank99 , CC BY-SA 2.0,, Wikimedia Commons

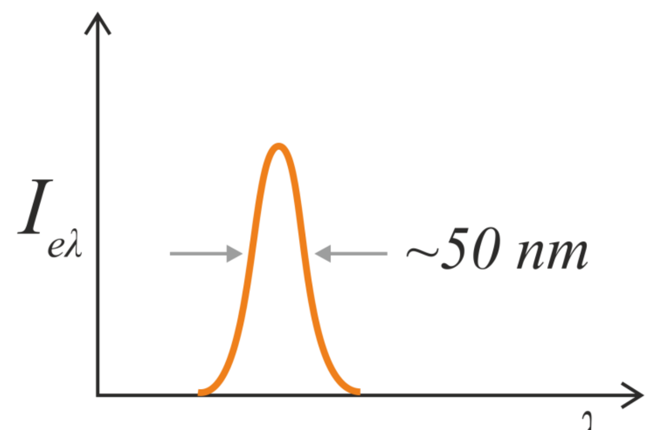
“Cold” source

modulated source



LED Operation principle

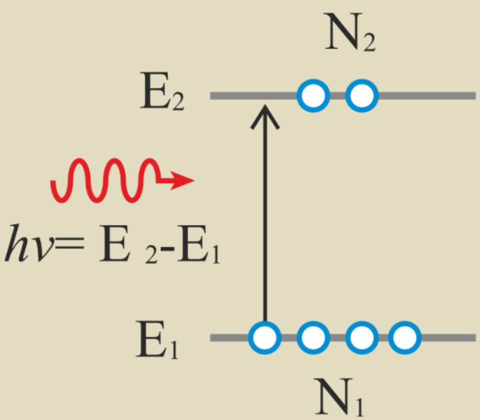




Typical LED emission

Light Amplification by Stimulated Emission of Radiation (LASER)

Absorption

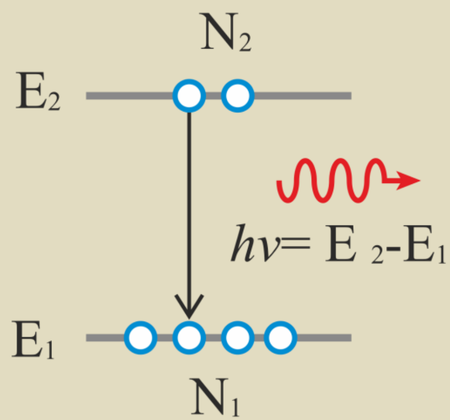


Transition probability: ***B_{12}***

$$\frac{dN_2}{dt} = B_{12} \cdot \rho_v \cdot N_1$$

$$\rho_v = D_v \cdot h \cdot v$$

Spontaneous emission

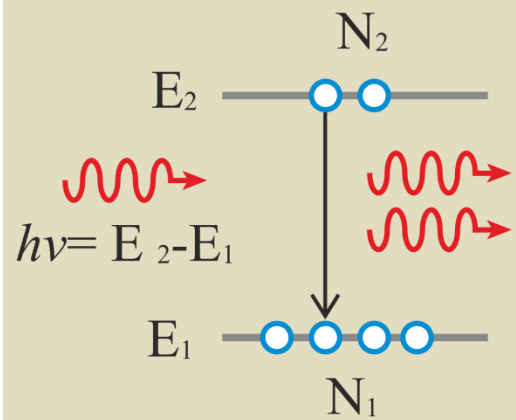


Transition probability: ***A_{12}***

$$\frac{dN_2}{dt} = A_{12} \cdot N_2$$

identical frequency, random phase and direction

Stimulated emission



Transition probability: ***B_{21}***

$$\frac{dN_2}{dt} = -B_{21} \cdot \rho_v \cdot N_1$$

identical frequency, phase and direction

Light amplification

The case of thermal equilibrium

$$\frac{A_{21}}{B_{21}} = \frac{8\pi \cdot h \cdot \nu^5}{c^3} \Leftrightarrow B_{21} = B_{12}$$

Application to a thermal source

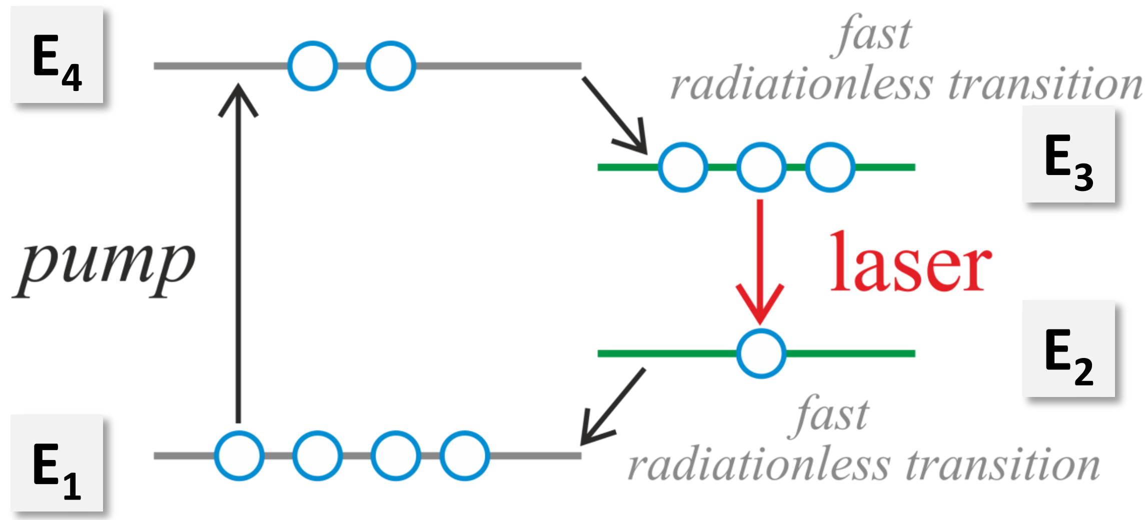
$$T = 2000K,\ \ \nu = 500\,THz \ \Rightarrow \frac{\rho_\nu B_{21}}{A_{21}} = 6.6 \cdot 10^{-6}$$

In a typical thermal source the ratio of the stimulated to the spontaneous emission rates is very low!

It is **not possible** to achieve **amplification** when we are **at thermal equilibrium**.

Beyond equilibrium: Inversion of Population

Population inversion occurs when **more members** of a system are in **higher, excited states** than in lower, unexcited energy states



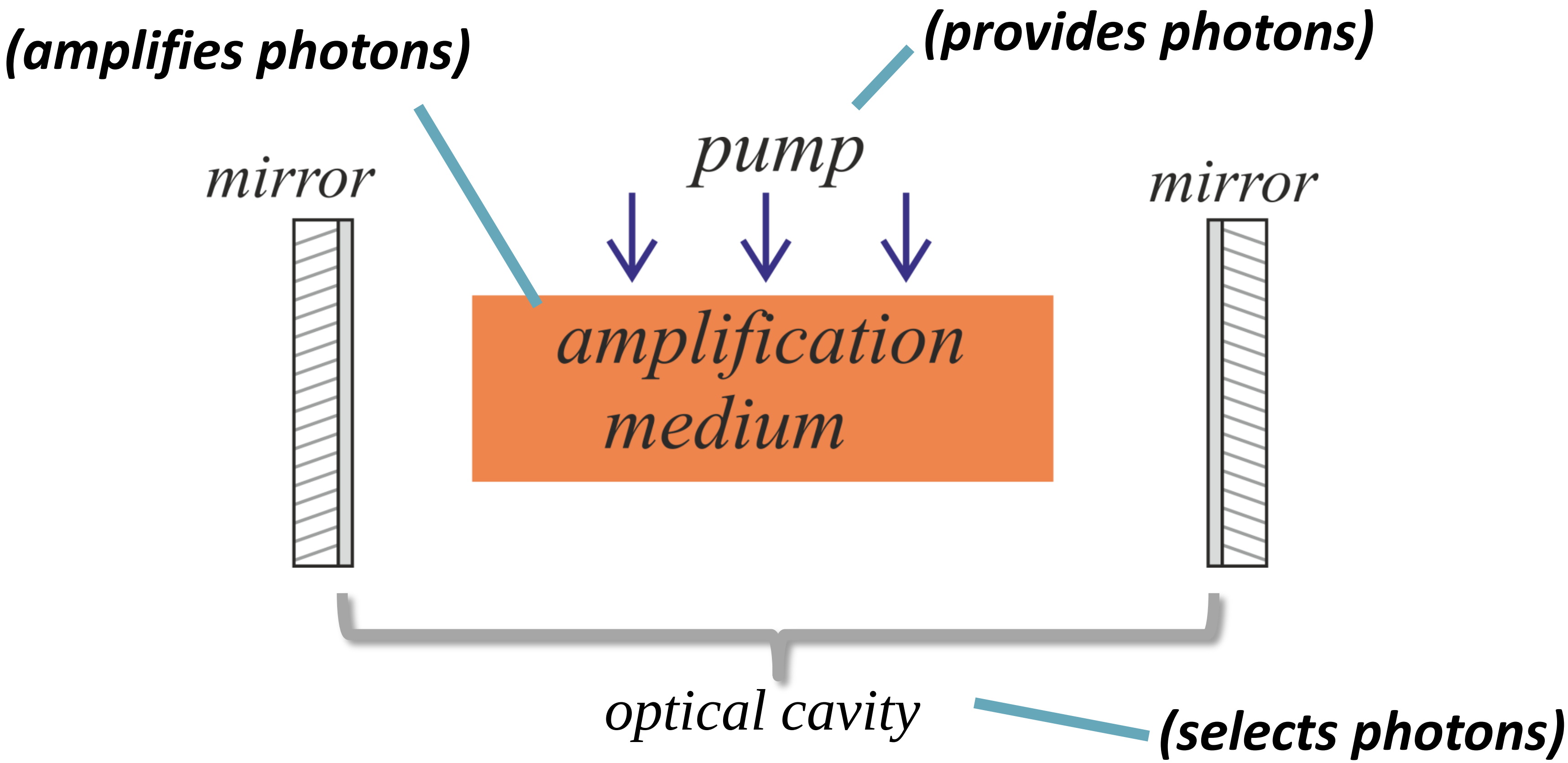
4 Level Laser system

Pumping excites the atoms in the ground state E_1 into E_4.

From there the atoms decay by a fast, non-radiative transition into the level E_3. Since the lifetime of the $E_3 \rightarrow E_2$ transition is long compared to that of $E_4 \rightarrow E_3$, a population accumulates in level E_3 (the upper laser level).

into level E_2 (the lower laser level). This level likewise has a fast, non-radiative decay into the ground state.

LASER sources

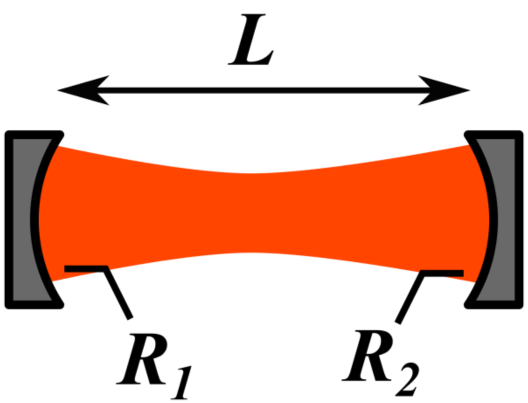


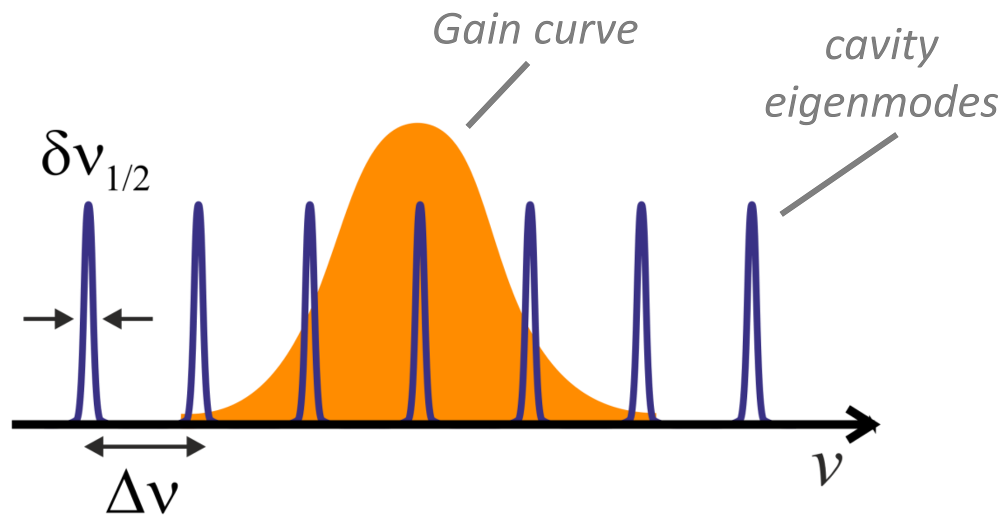
The Pump **provides** the photons

The amplification medium amplifies these photons

The optical cavity **selects** which photons will be **repeatedly amplified** thus determines the LASER output

Optical cavity





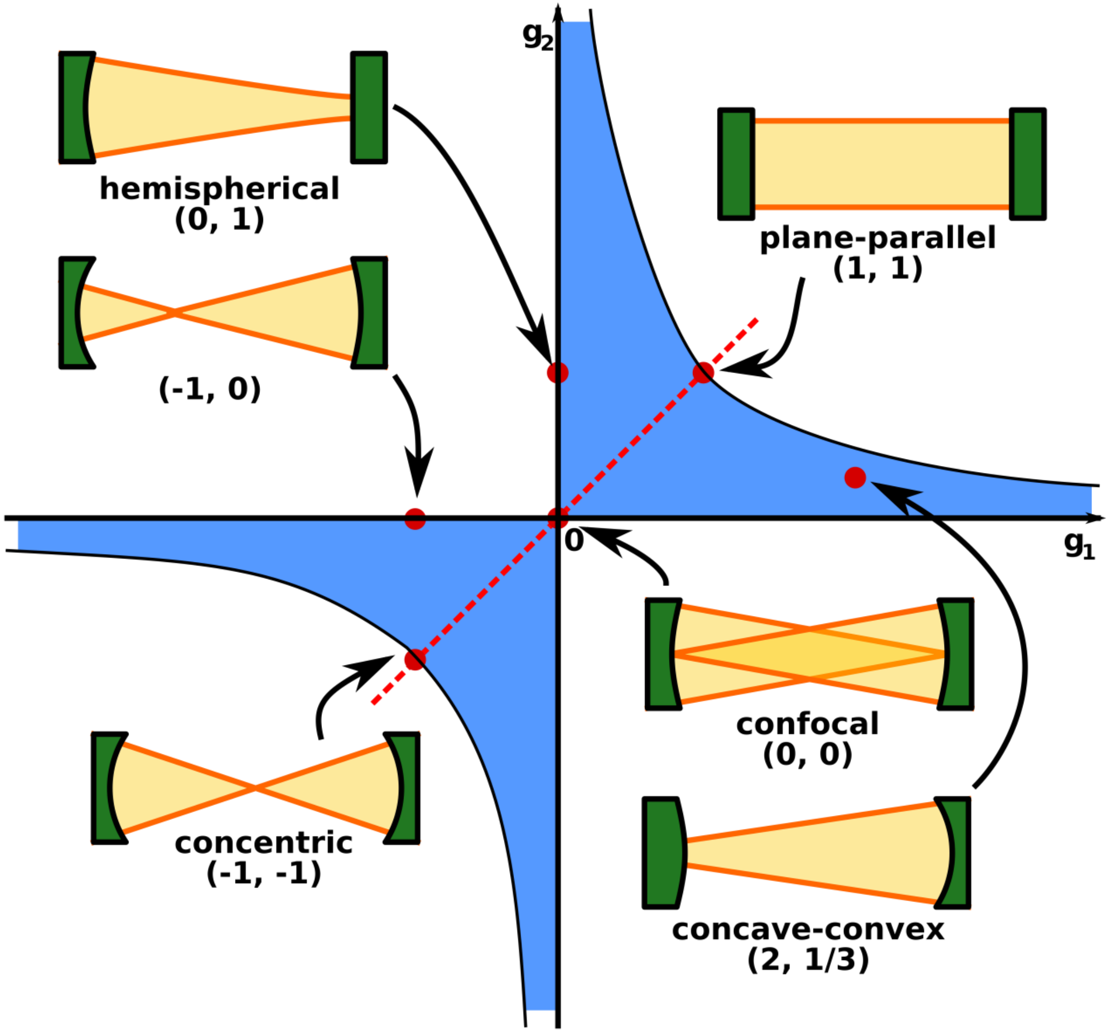
Light confined in a cavity will reflect multiple times, and due to of **interference**, only certain patterns and frequencies, the **eigenmodes of the cavity**, will be sustained.

$$\Delta\nu = \frac{c}{2L}$$

$$\Delta\nu_{1/2} = \frac{\Delta\nu}{\pi\sqrt{2F}}$$

$$F \equiv \left(\frac{2r}{1-r^2}\right)^2$$

finesse

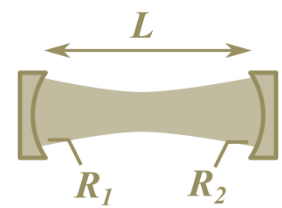


Stability of an optical resonator

By FDominec, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3017470

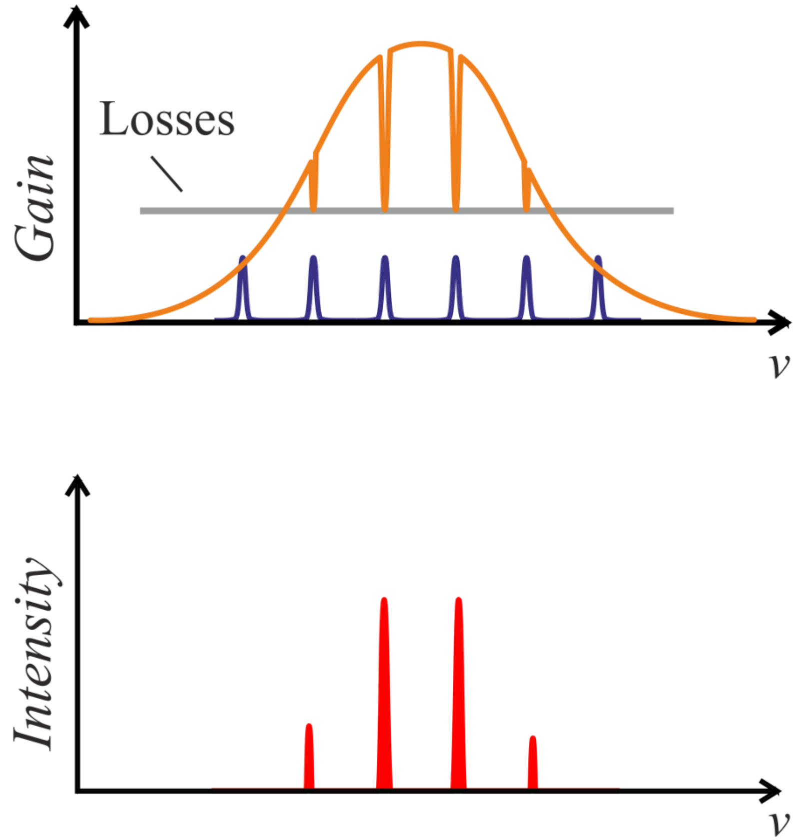
$$g_1 = 1 - \frac{L}{R_1}$$

$$g_2 = 1 - \frac{L}{R_2}$$

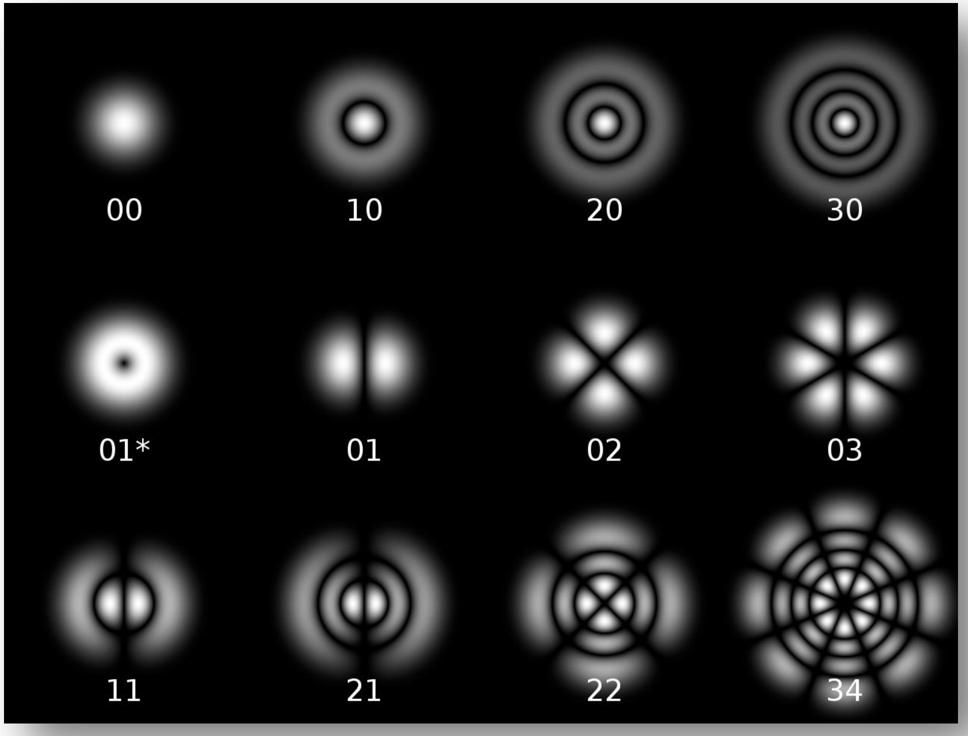


Only certain ranges of values for R_1, R_2, and L produce stable resonators in which periodic refocusing of the intracavity beam is produced

Longitudinal and transverse cavity modes



Longitudinal cavity modes

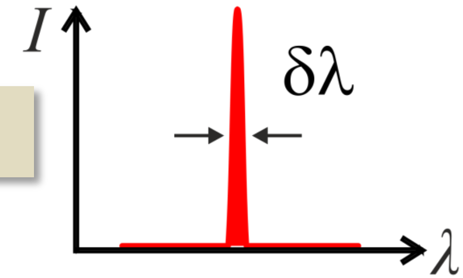


Transverse cavity modes (Laguerre-Gaussian)

Laser beam properties

Monochromaticity

$$\frac{\delta\lambda}{\lambda} \propto \frac{\lambda}{L}\sqrt{\frac{2}{F}} < 10^{-5}$$



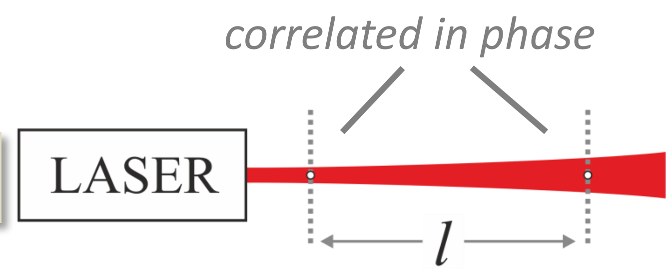
Directionality

$$\theta \cong \frac{\lambda}{2d} \ll 1 mrad$$

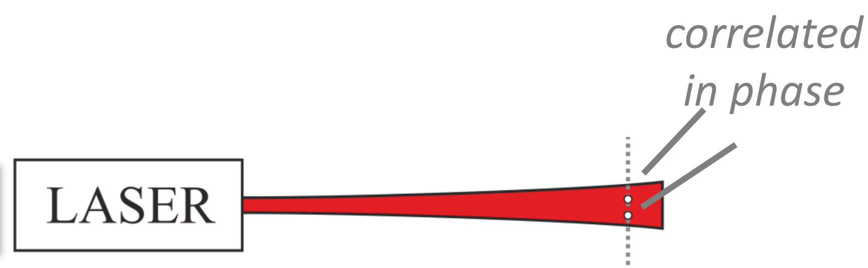
Coherence

$$l \cong \frac{c}{\Delta\nu} > 30\,cm$$

Temporal



Spatial



These properties result from the cavity and not the amplification!

They are not unique to lasers

Dimitris Papazoglou, *dpapa@materials.uoc.gr*

The **amplification** in combination to the cavity results extremely high values of **spectral brightness**
(power per surface area per solid angle per frequency unit)

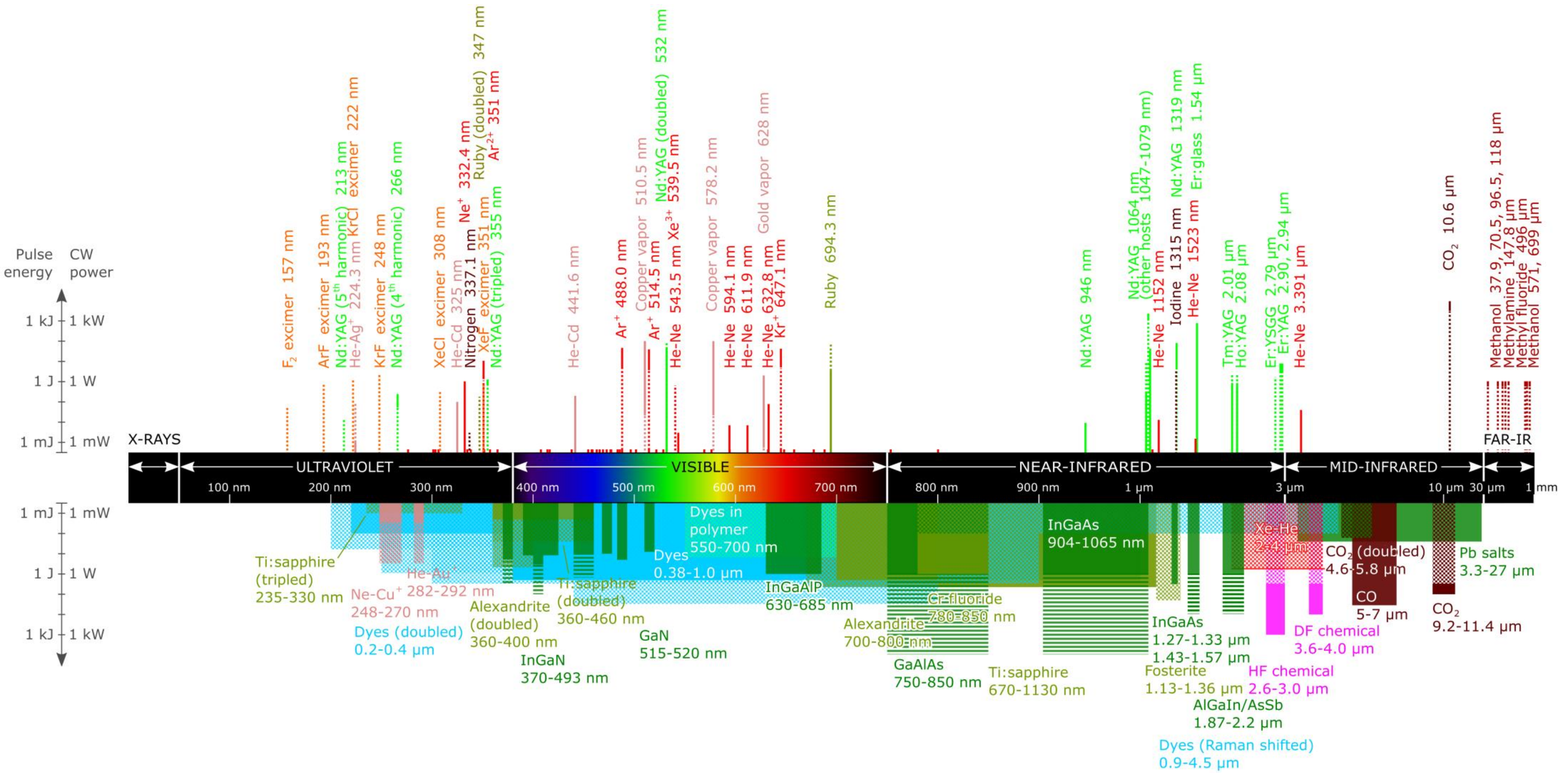
Spectral Brightness

$$\beta_\nu = \frac{P_\nu}{A \cdot \Delta\Omega \cdot \Delta\nu}$$

$$\frac{W}{cm^2 sr\ Hz}$$

Typical values

Sun	**$1.5 \cdot 10^{-12}$**
He-Ne (1 mW)	**25**
Nd:glass (10 GW)	**$2 \cdot 10^{8}$**



Wavelengths of commercially available lasers.

By Danh - Own work.
Uses File:Linear visible spectrum.svg↑ Weber, Marvin J. Handbook of laser wavelengths, CRC Press, 1999. ISBN 0849335086, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=8187485

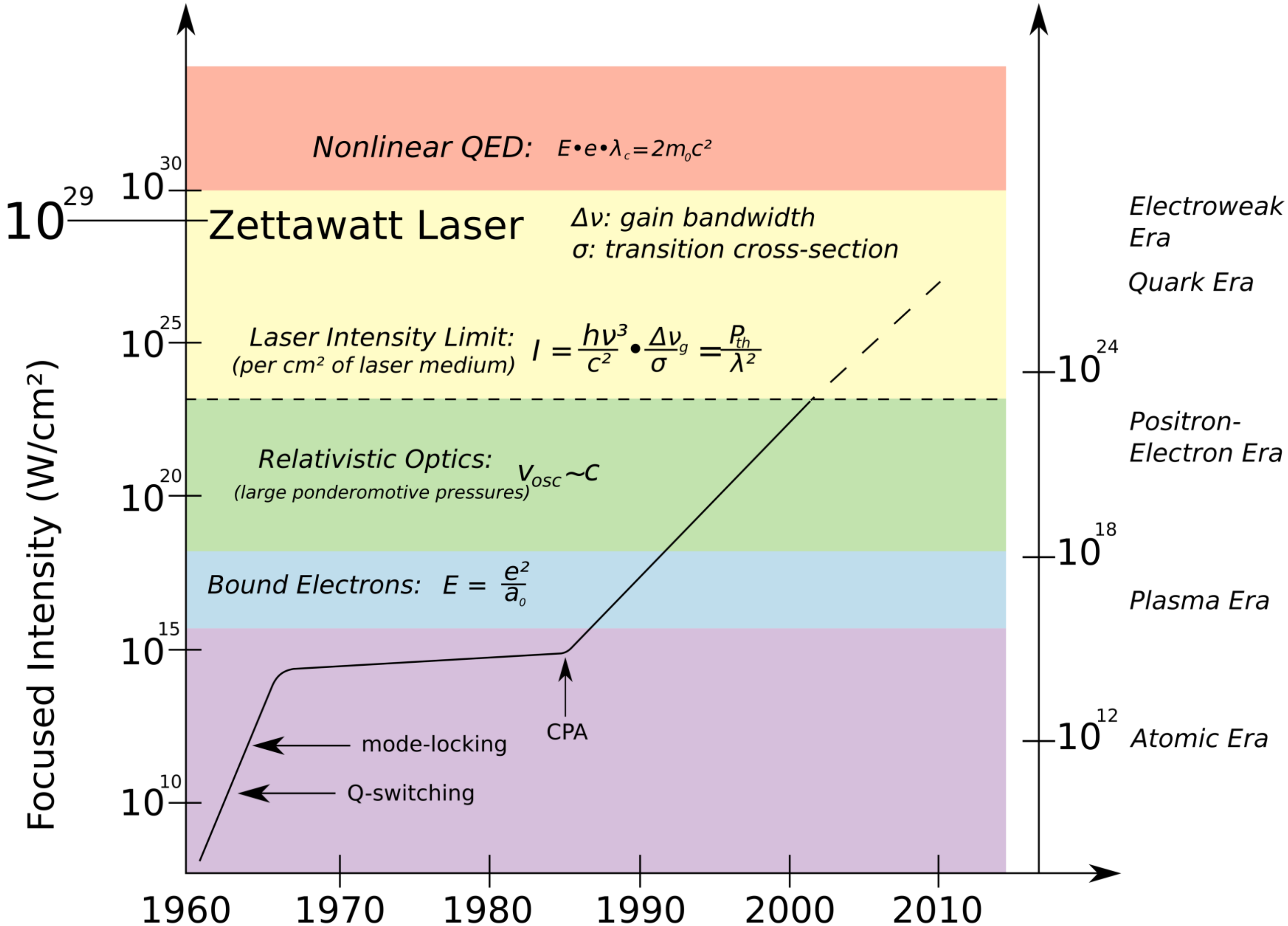
Wavelength ranges from IR to UV

Continuous wave lasers (CW)

Pulsed lasers

Pulse duration: μsec down to few fs

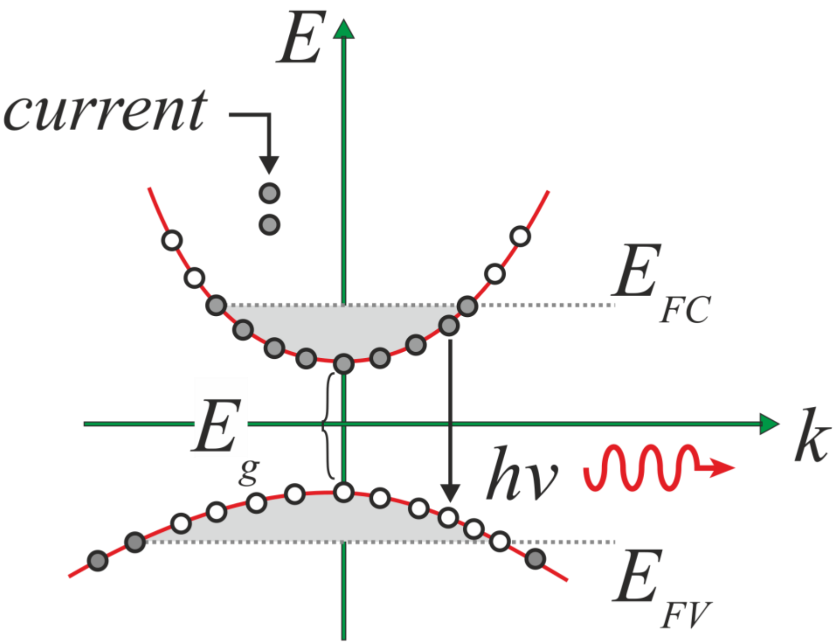
Repetition rate: MHz down to few Hz

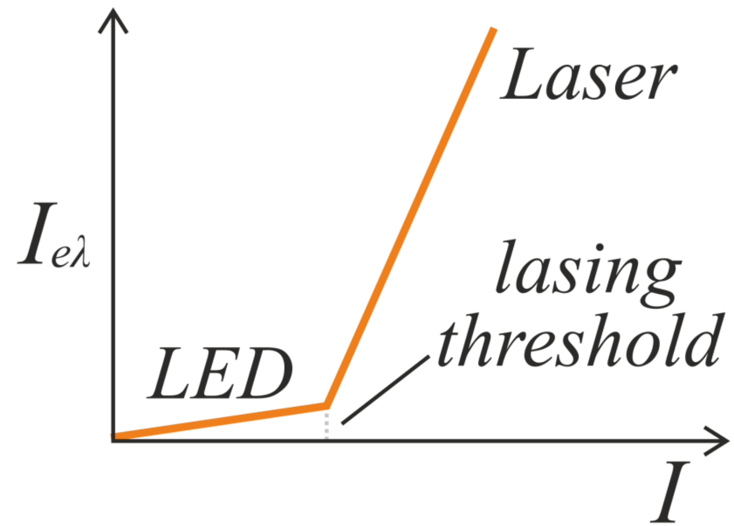


Graph showing the history of maximum laser pulse intensity throughout the past 40 years

[PD] Wikimedia Commons

LASER Diodes





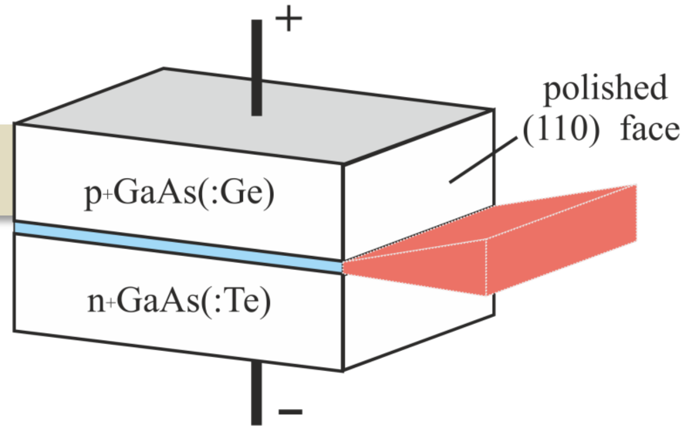
Large carrier density

+

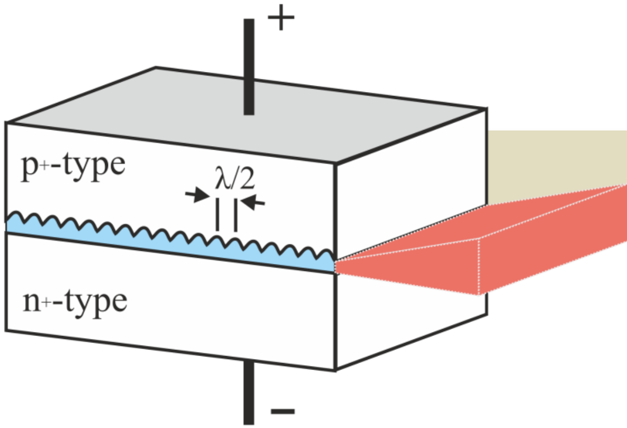
High current density

→ **Population inversion** → **Stimulated electron – hole recombination** → **Lasing**

Simple Diode laser cavity



Distributed feedback Diode laser



packaged laser diode shown with a penny for scale

By Jet Propulsion Laboratory ,
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Semiconductor lasers (520nm, 445nm, 635nm)

By 彭家杰 - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=31615648