

Welcome to the course “Energy Conversion by Semiconductor Devices”

Jun-Ho YUM

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No lecture on 15. Oct. 2024

Break on 22. Oct. 2024

15 min Presentation exam on 10. and 17. Dec. 2024

Oral exam:

5 – 7 questions and answers

20 min preparation and 20 min answer

Presentation must cover following aspects:

1. Background:

- A short summary of the previous main results in that field
- A motivation and hypothesis established and tested in the work.

2. A description of the key methodology and key results

3. Criticism:

- Significance of the result and impact on that field
- Any misconception, any missing scientific results, any inconsistency or flaw in the hypothesis and results.

4. Outlook

Please, send the title of your selected paper to junho.yum@epfl.ch and by 29th
November 2024

Selection of papers

Research articles published in 2024 but **no review articles**

Topics: Nanomaterials, Solar energy, Photoelectrochemistry, Photocatalysis, Water splitting or H₂ production, CO₂ reduction, Solar-driven NH₃ production, Solar Cells, Optoelectronic applications, etc.

Journal recommendation: Nature and Nature family (Nature Mater., Nature Chem., Nature Photonics, Nature Energy, Nature Commun.), Science, RSC journals (Energy Environ. Sci., J. Mater. Chem.), ACS journals (JACS, ACS Nano, Nano Lett., ACS Energy Lett.), Wiley (Adv. Mater., Adv. Funct. Mater., Adv. Energy Mater., Angewandte), Cell Press (Joule, Matter)

**Exam will be
scheduled
alphabetically
(Family name).**

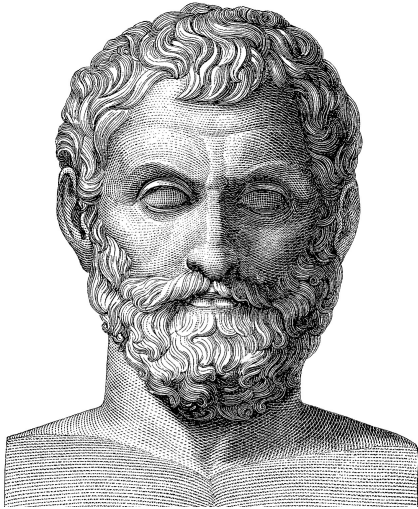
15/15 Name First Name

1	Bergonzi Clara Lisa
2	Bouchez Arthur Eliot
3	Collignon Sybille
4	Diercks Nicolas Johannes
5	Ducruet Lou-Anne Juliette
6	Foltzer-De Cian Louise Marie
7	Guillosso Coline
9	Kakavas Nikolaos
10	Kim Dayon
11	Raboud Loïc Emile
12	Rey Doina Damaris
13	Tang Vidale Marc
14	Tracol Gavard Axel Pierre
15	Watanabe Rin

- 1. The solar energy**
- 2. Light-Matter interaction**
- 3. The basic of semiconductors and junctions**
- 4. The basic of solar energy conversion and solar cells**
- 5. Solar cell technologies, pn junction solar cell, third generation solar cells**
- 6. The basic in electrochemistry in water splitting**
- 7. Green water splitting by photoelectrochemistry**
- 8. Green water splitting by photocatalysis**

Thales

(BC 626 – BC 548)

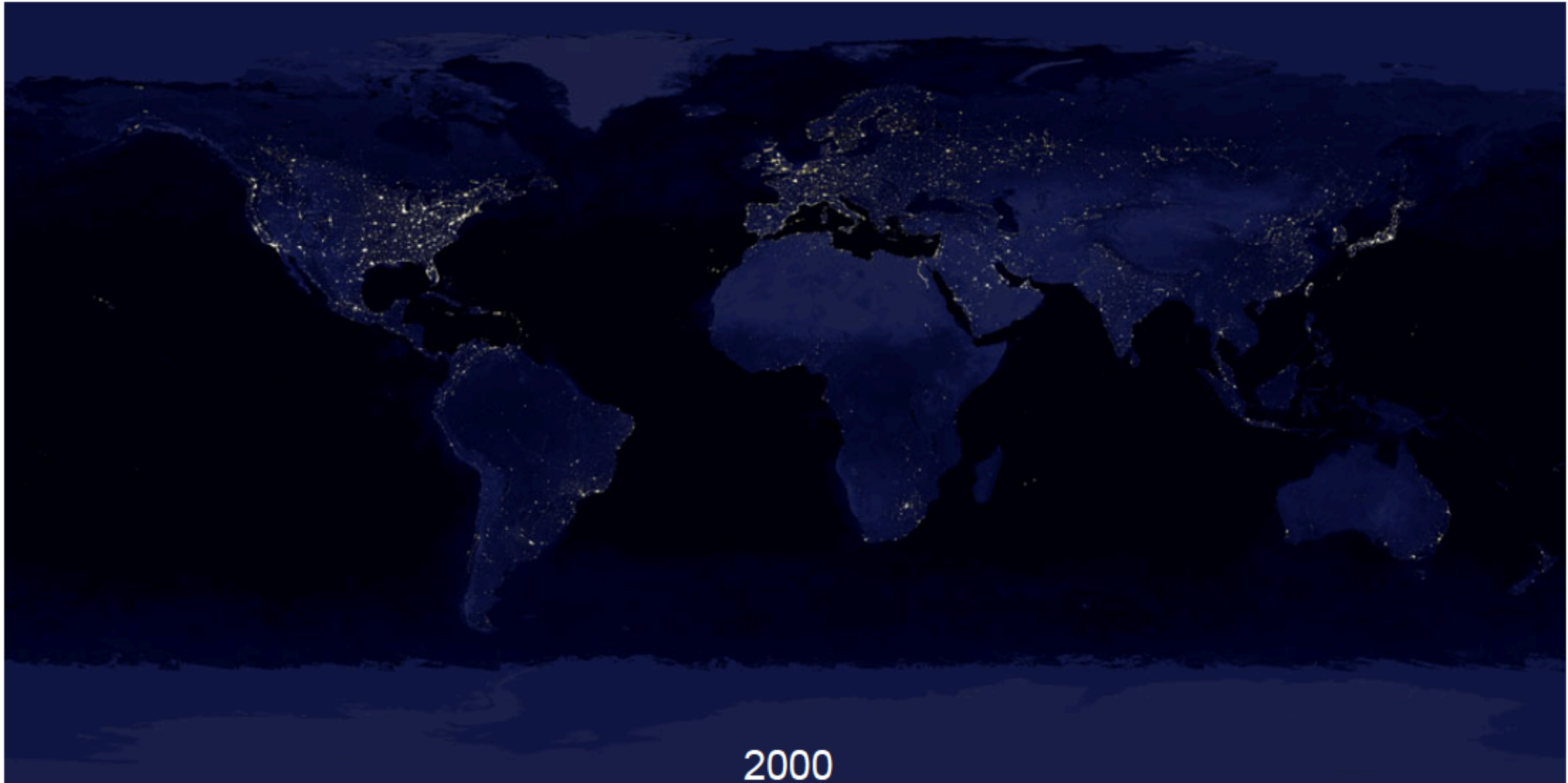


William Gilbert

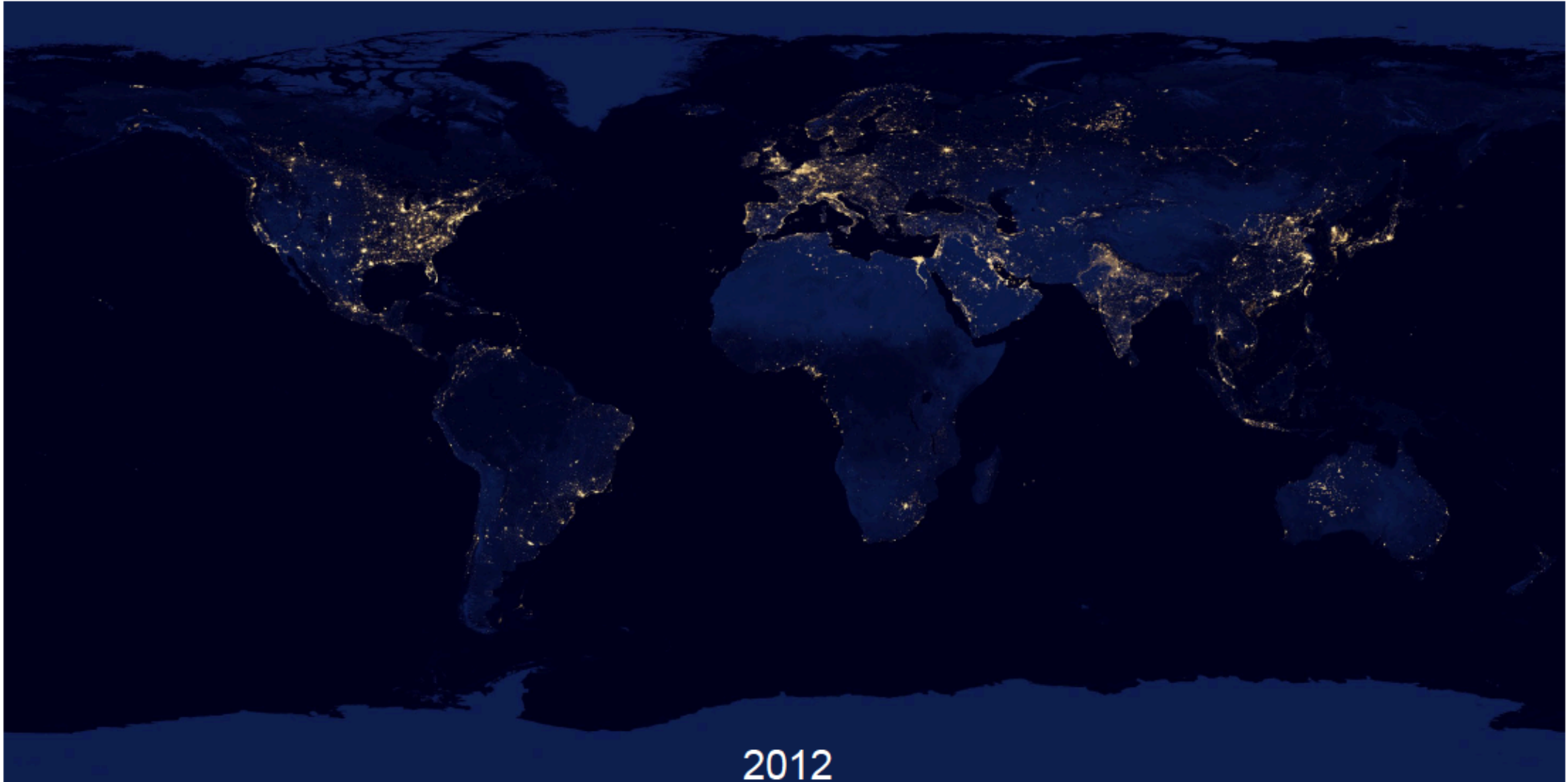
(1544 – 1603)



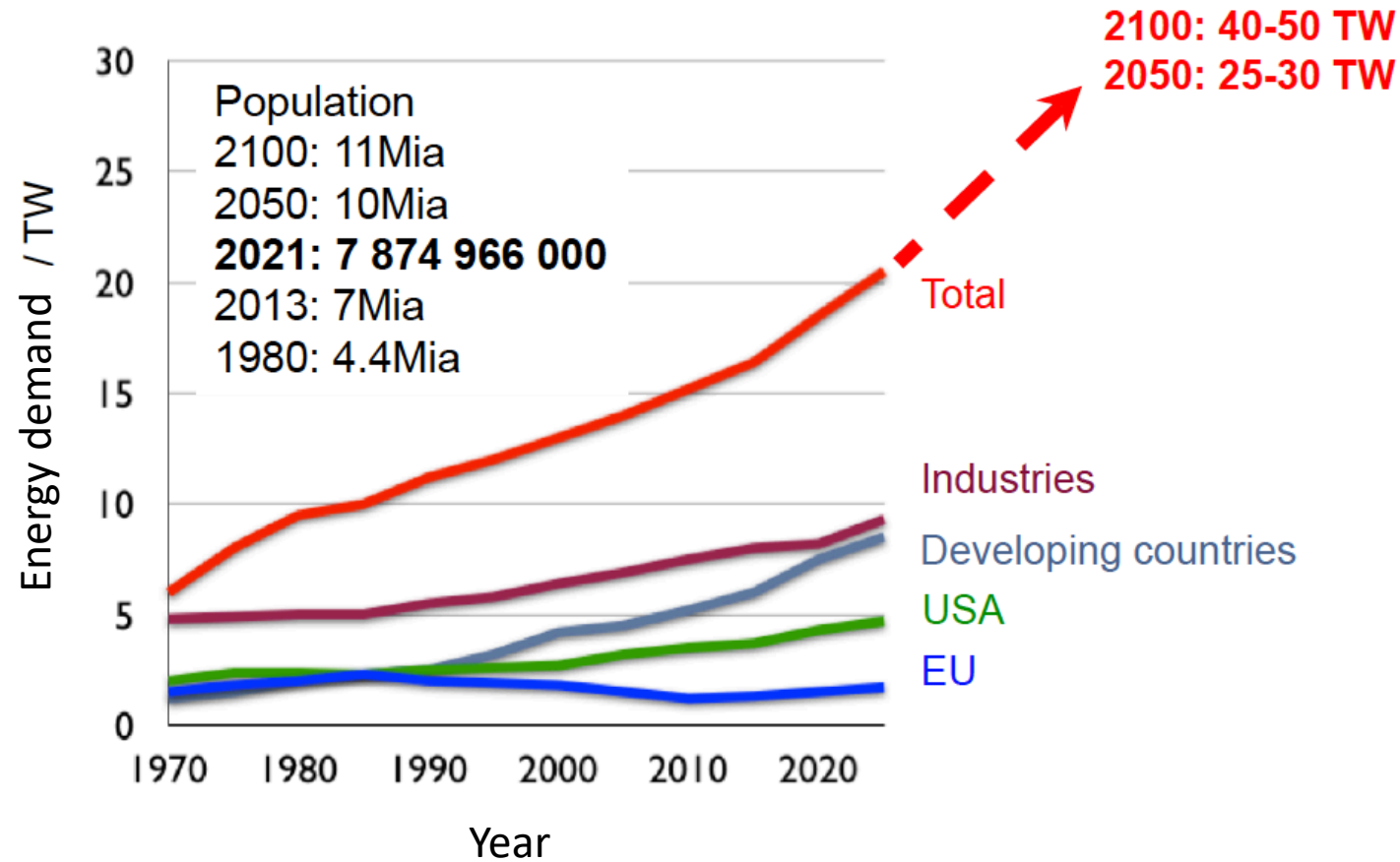
- The early Greek word for the Sun: ‘hlector’ (pronounced ‘elector’).
- In many ancient Greek writings that describe Thales’ work and ideas, amber is called “electron”.
- This was also used to describe the material amber because its colour reminded people of the Sun.
- William Gilbert was the first person to use the word “electricity”.



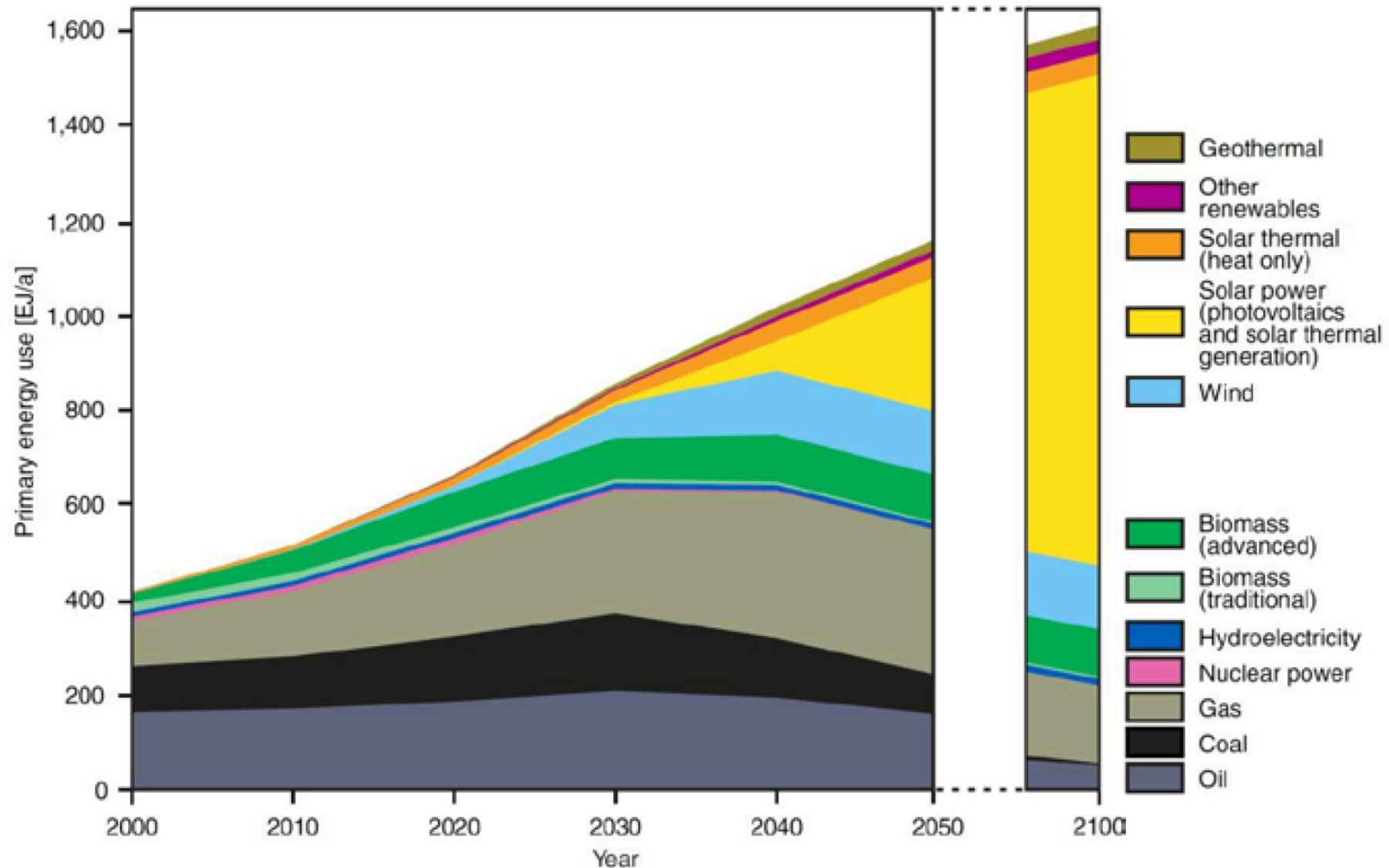
Source: <https://earthobservatory.nasa.gov/images/event/79869/earth-at-night>



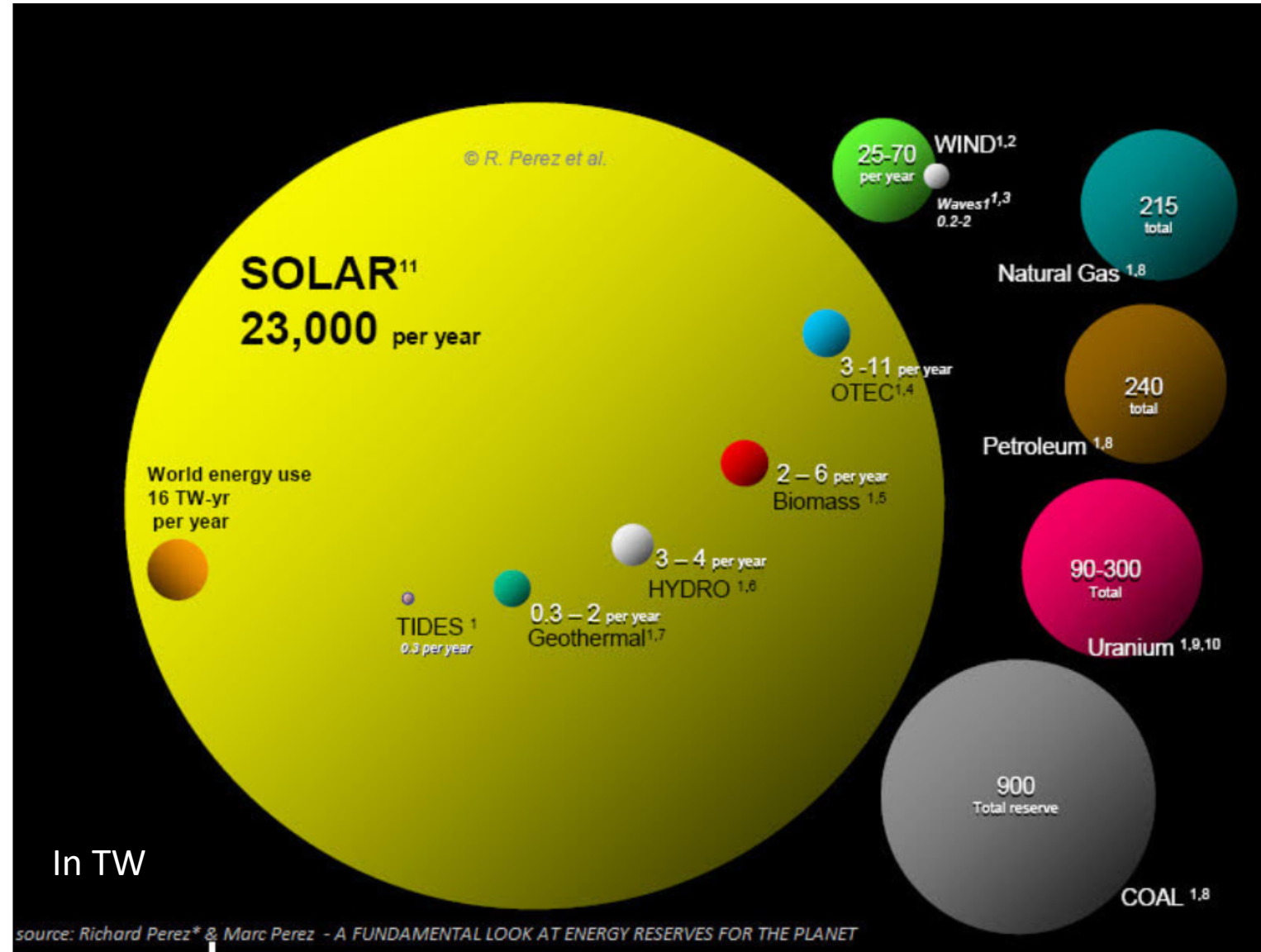
Source: <https://earthobservatory.nasa.gov/images/event/79869/earth-at-night>



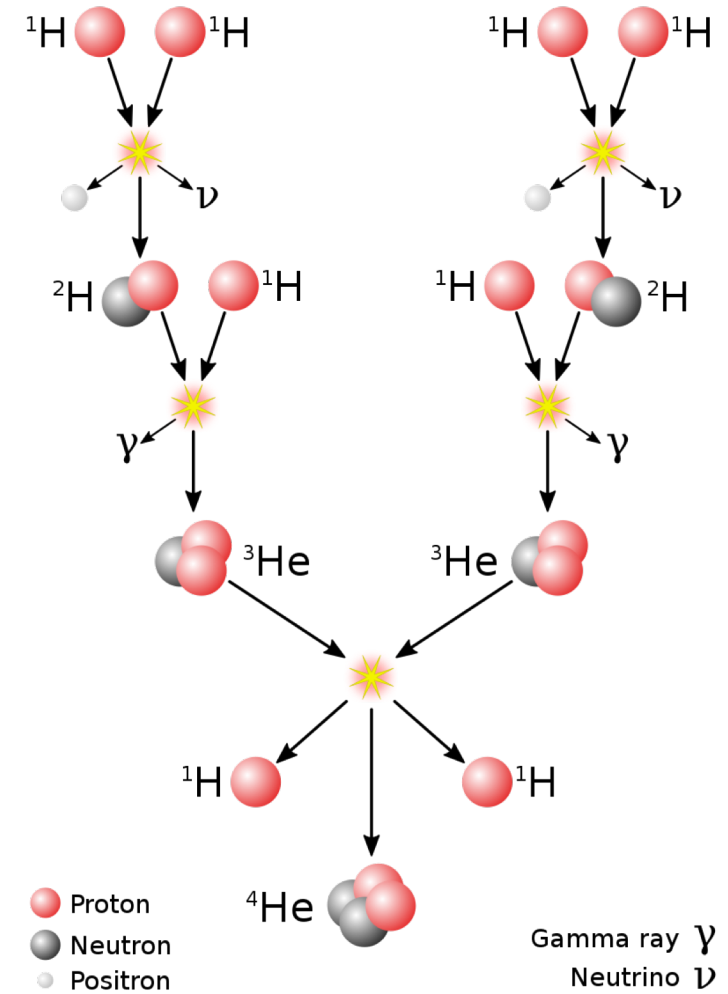
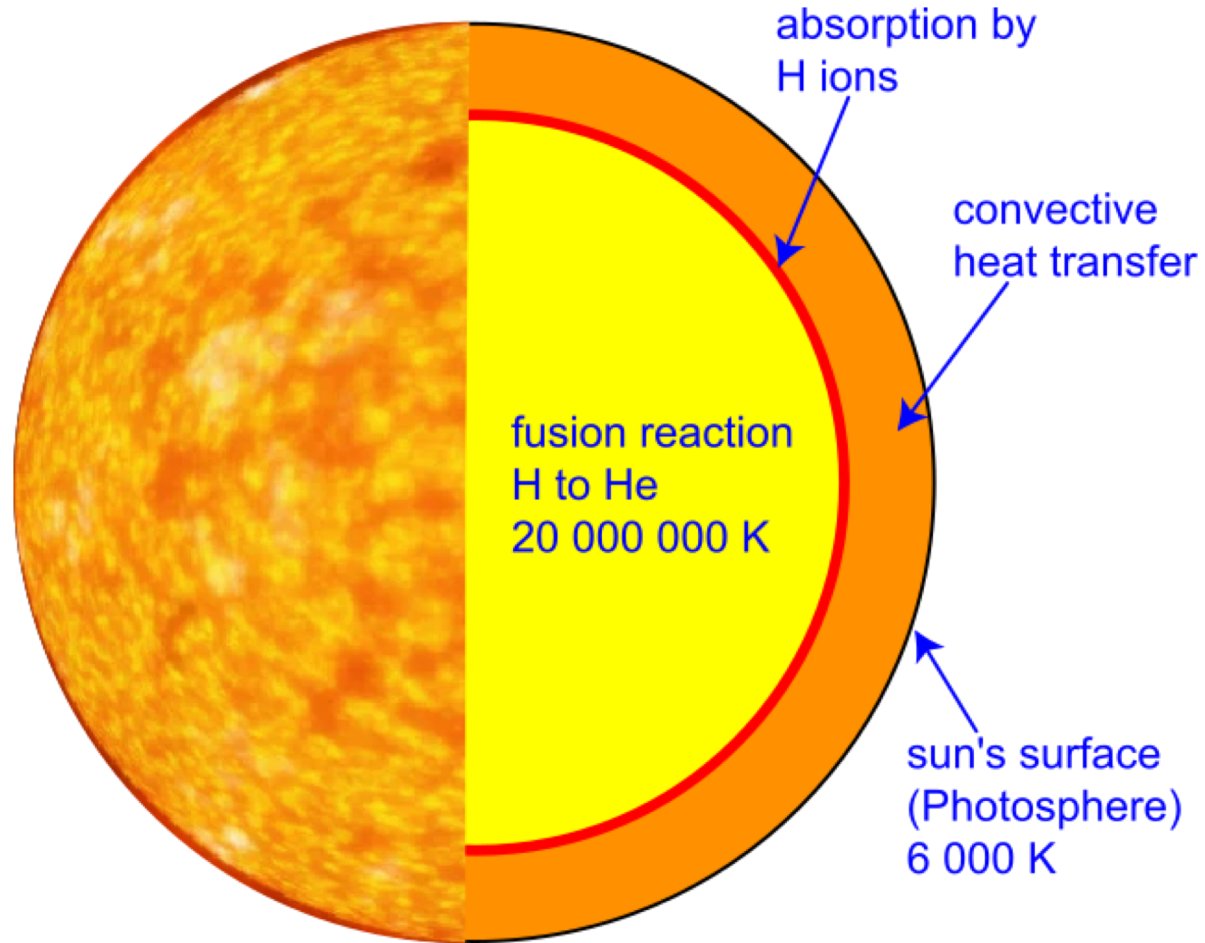
Source: <https://www.lifegate.com/greater-aletsch-glacier>

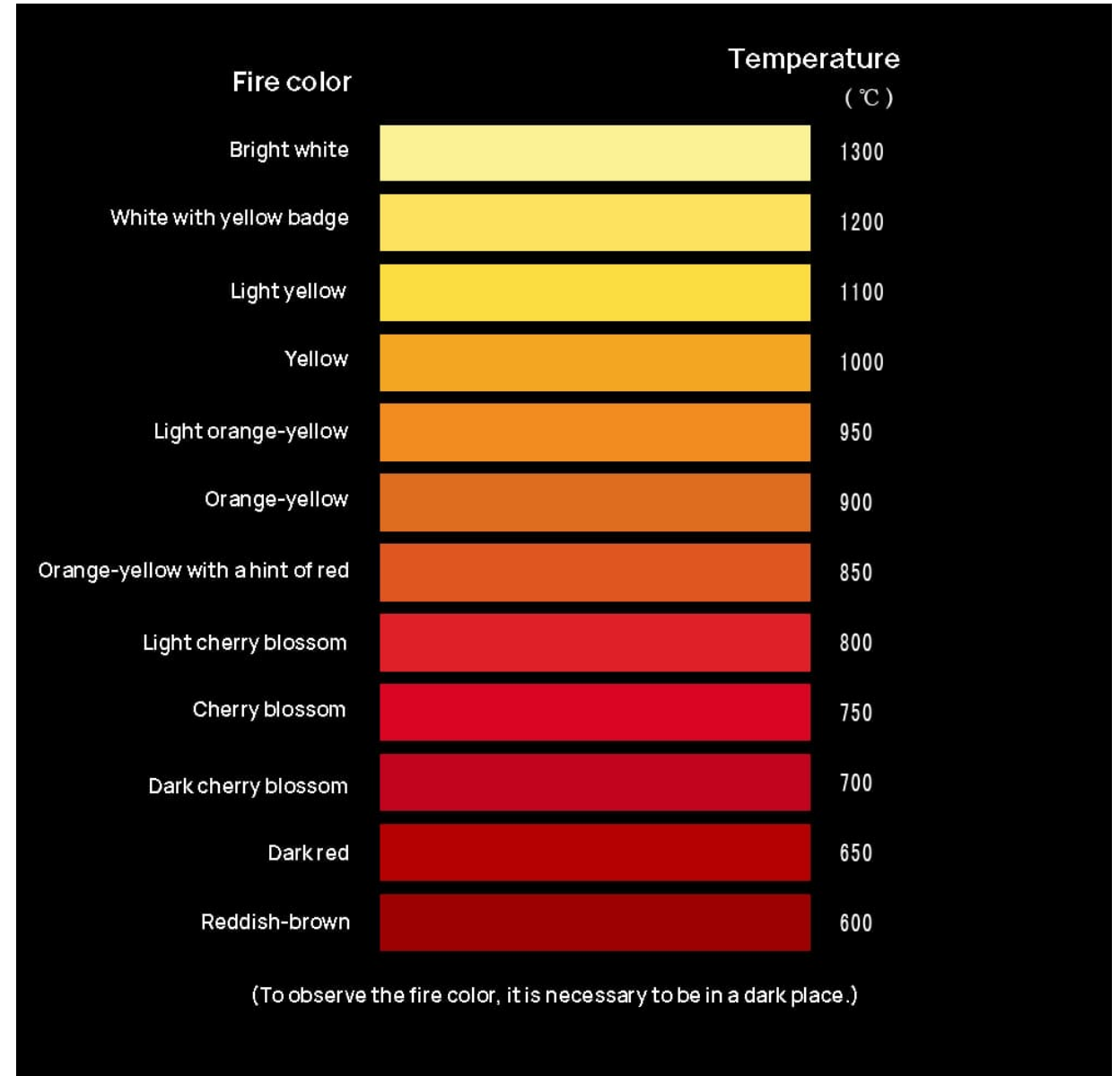
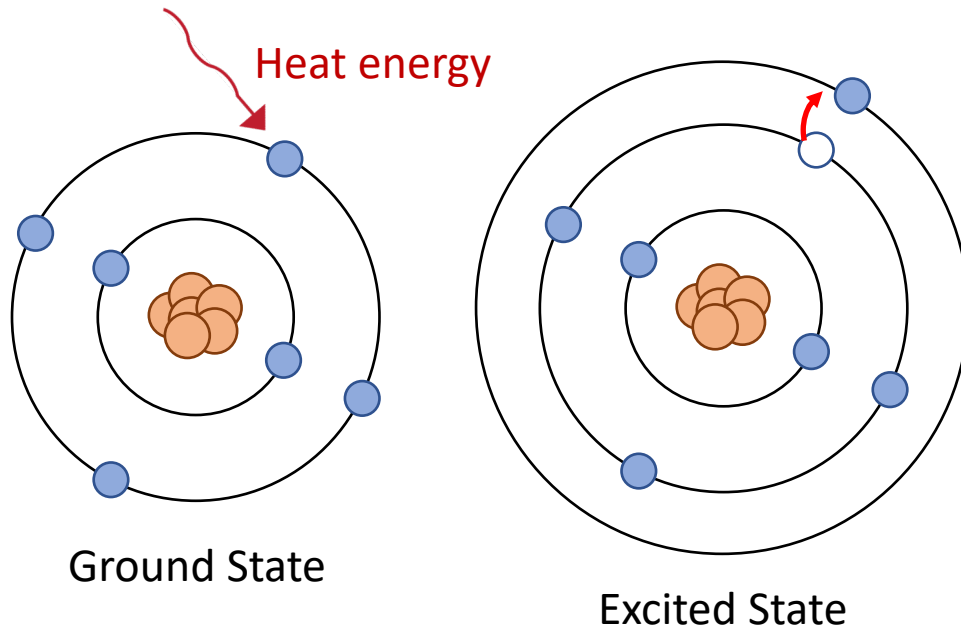


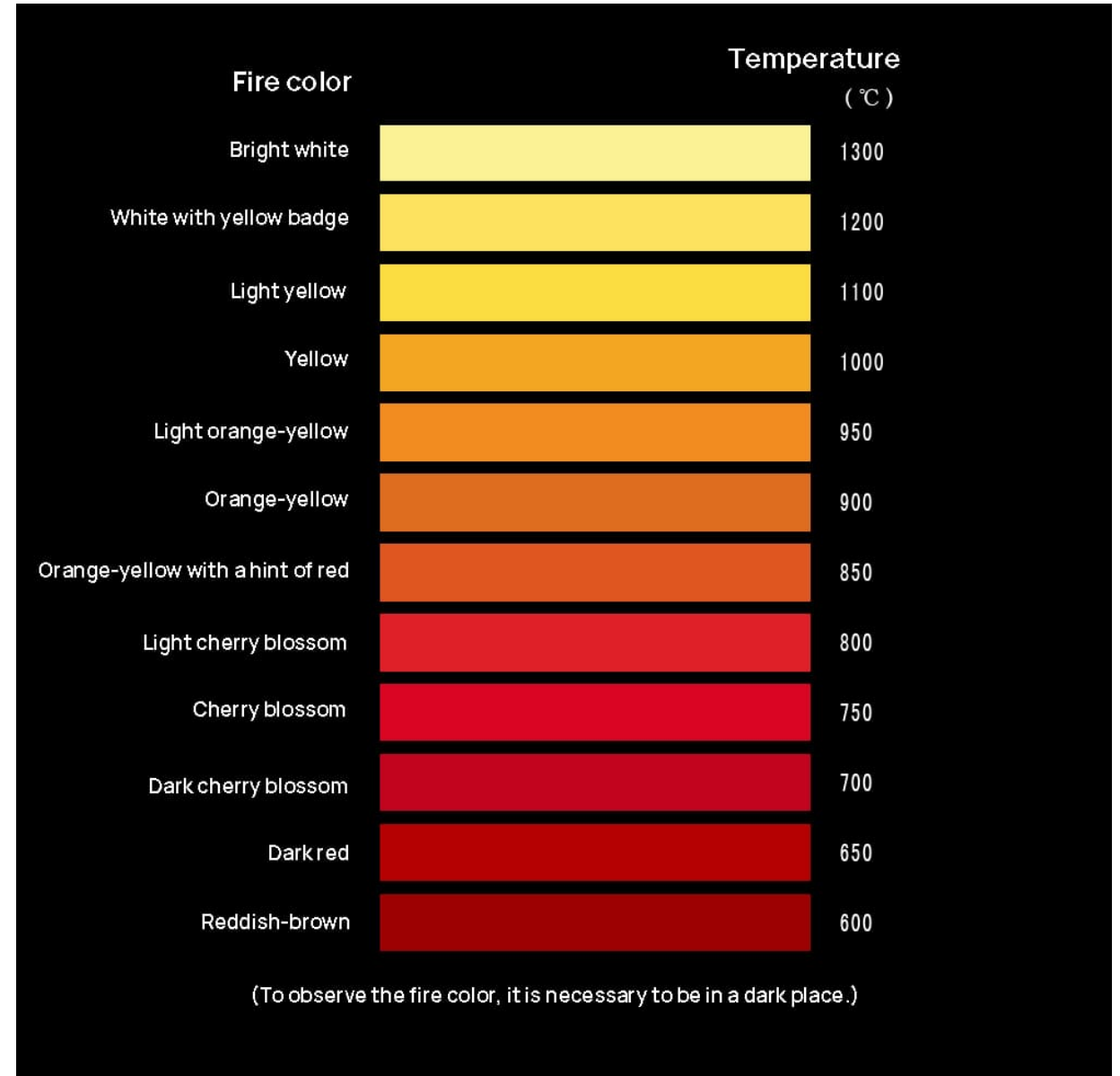
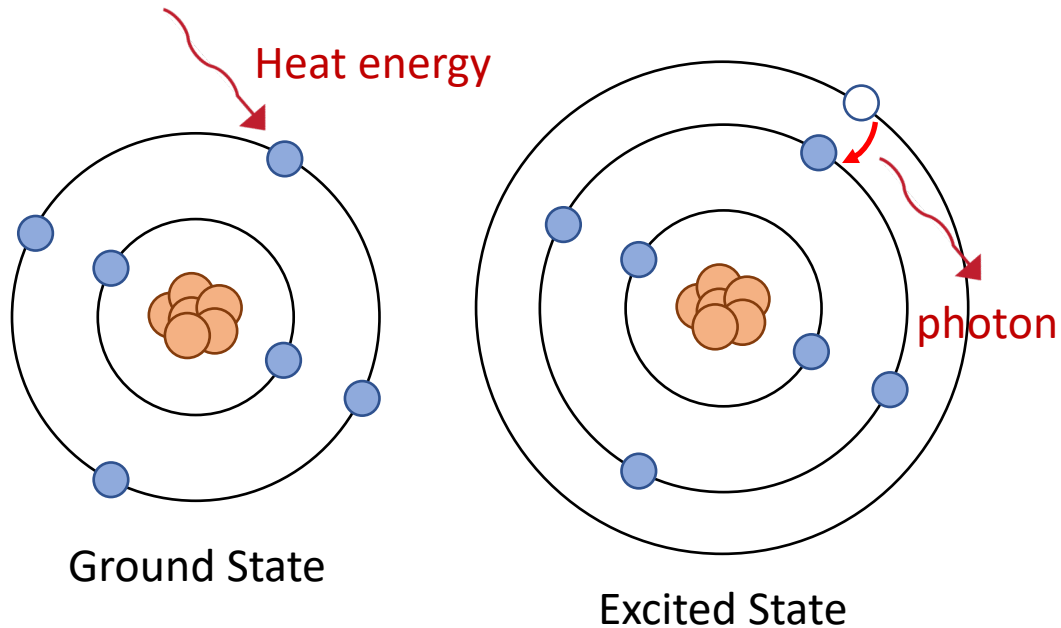
German Advisory Council on Global Change, ISBN 1-85383-882-9



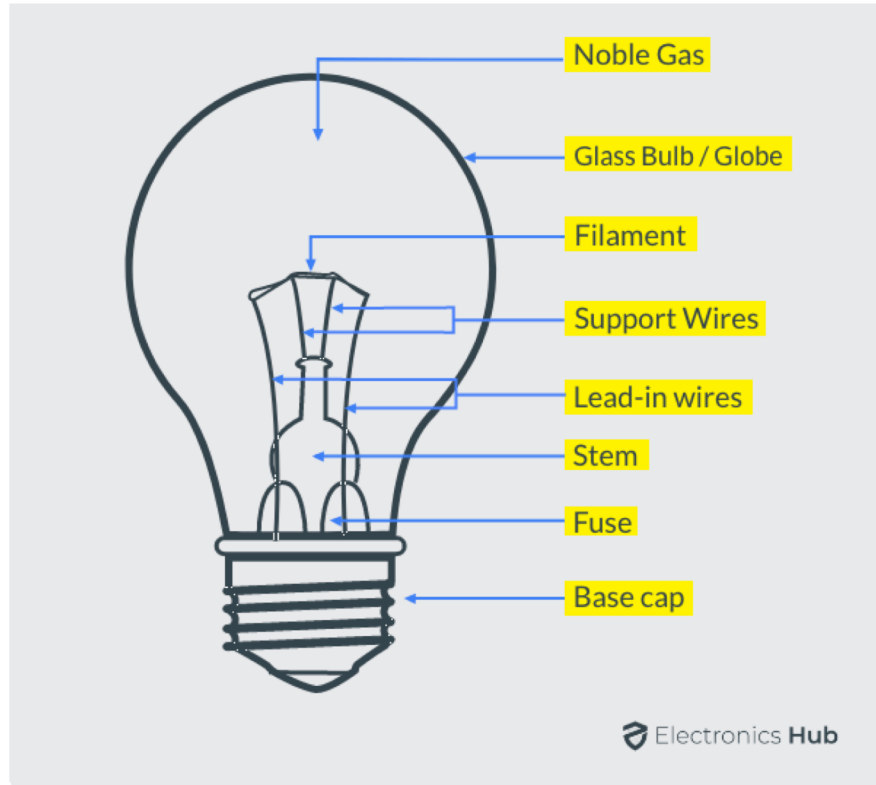
Perez, R. and M. Perez, (2009): A fundamental look at energy reserves for the planet. The International Energy Agency SHC Programme Solar Update, Volume 50, pp. 2-3, April 2009







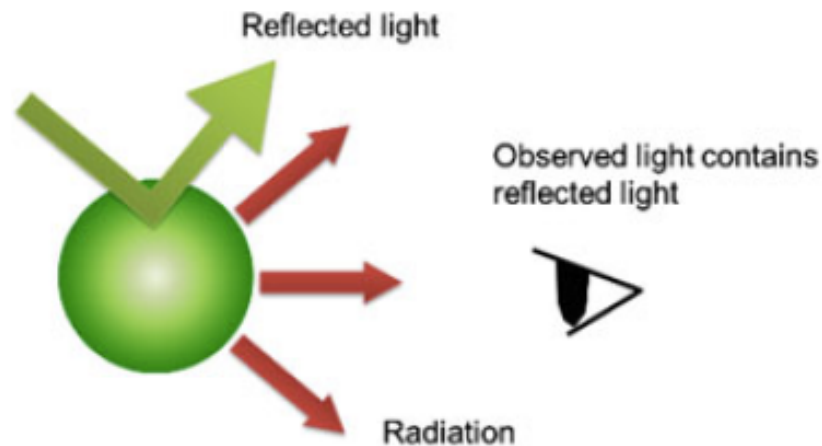
EPFL Hot Object Emits Light!



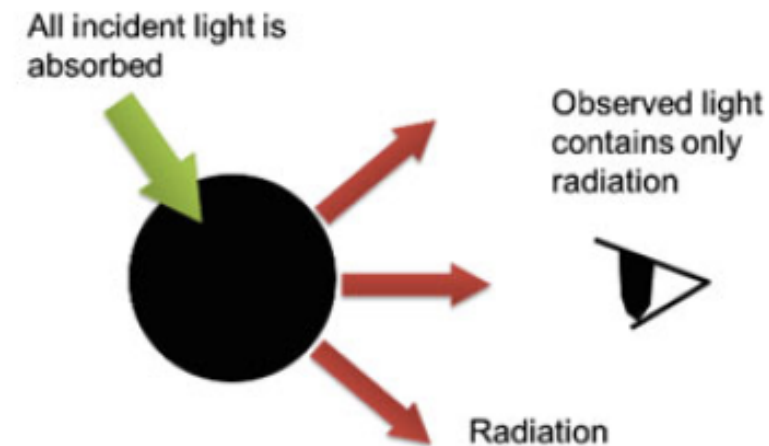
<https://www.usgs.gov/media/images/what-minerals-produce-colors-fireworks>

EPFL Black Body Radiation

Many commonly encountered light sources, including the sun, are closely modelled as "blackbody" emitters. A blackbody absorbs all radiation incident on its surface and emits radiation based on its temperature. Blackbodies derive their name from the fact that, if they do not emit radiation in the visible range, they appear black due to the complete absorption of all wavelengths.



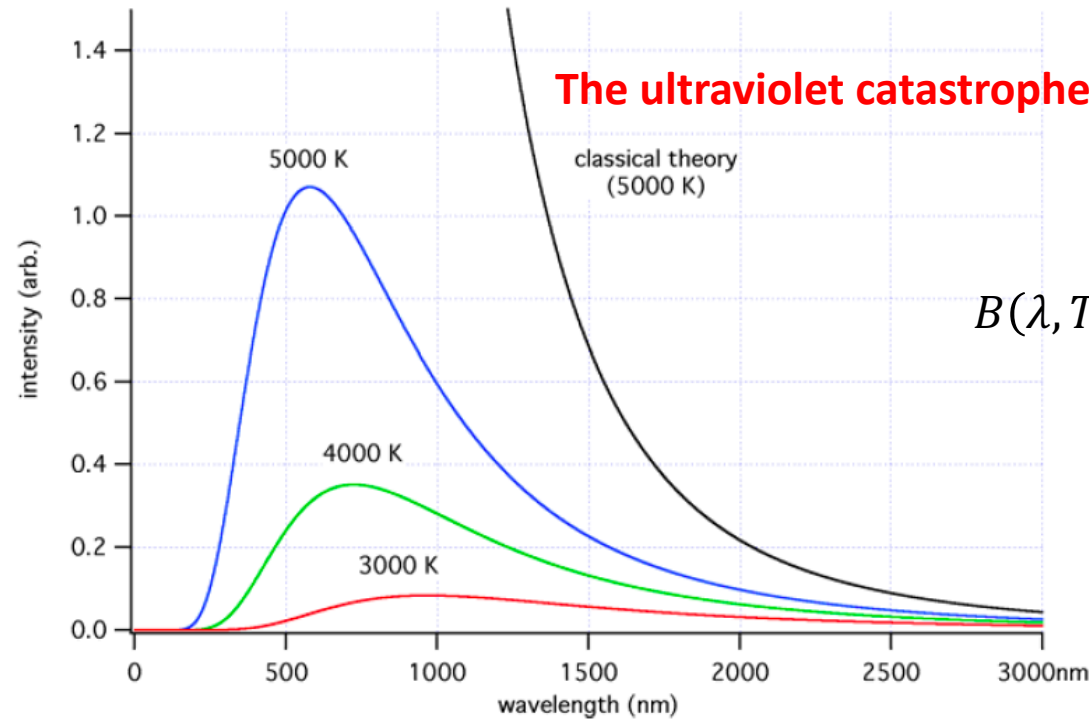
(a) General radiation



(b) Black-body radiation

EPFL Black Body Radiation

Many commonly encountered light sources, including the sun, are closely modelled as "blackbody" emitters. A blackbody absorbs all radiation incident on its surface and emits radiation based on its temperature. Blackbodies derive their name from the fact that, if they do not emit radiation in the visible range, they appear black due to the complete absorption of all wavelengths.

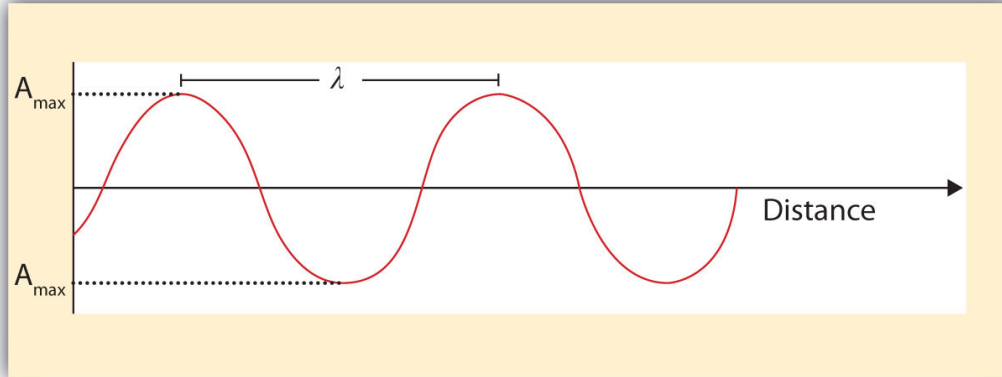


$$B(\lambda, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{k_B T}} - 1} = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

energy of a quantum (photon) = (a calibration constant) x (frequency of vibration)

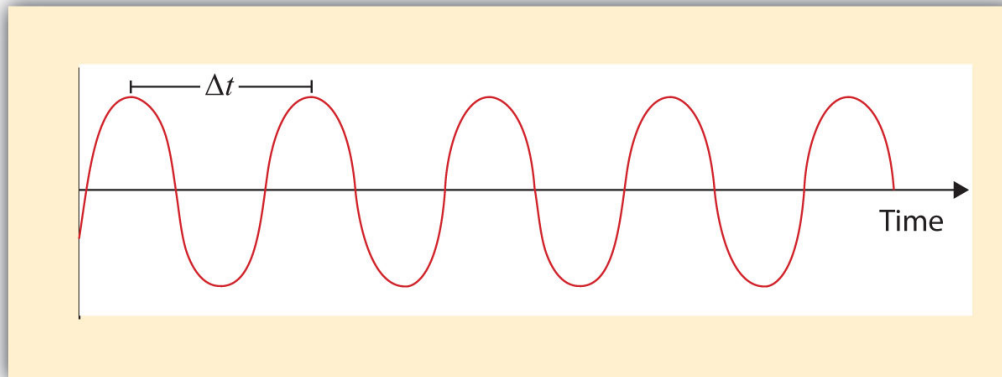
$$E = h\nu = hc/\lambda$$

EPFL Wavelength and Frequency



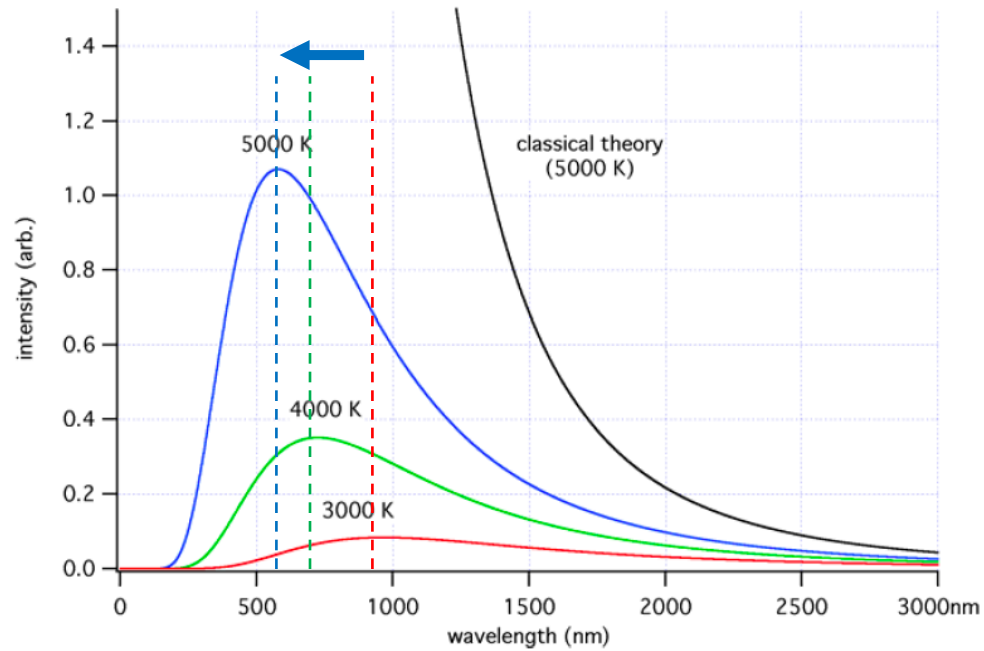
Wavelength (λ): the distance in the line of advance of a wave from any one point to the next point of corresponding phase.

$$v = c/\lambda$$



Frequency (ν): the number of cycles of light that pass a given point in one second.

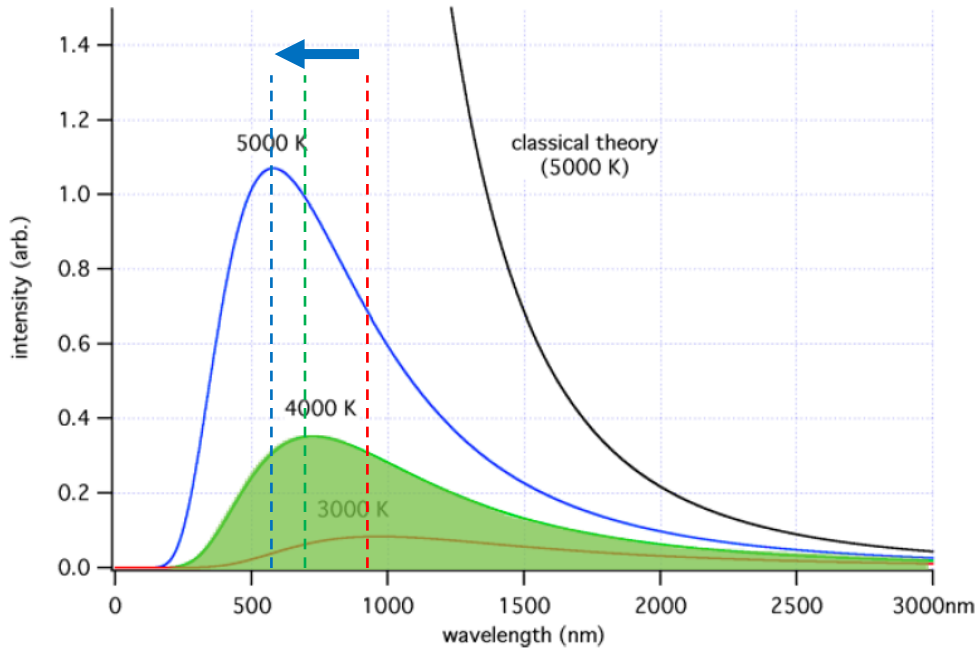
EPFL Black Body Radiation



Wien's displacement law: $\lambda_{peak} = \frac{b}{T}$

$$b = 2.898 \times 10^{-3} \text{ m} \cdot \text{K} \text{ or } 2898 \mu\text{m} \cdot \text{K}$$

EPFL Black Body Radiation



The relationship given by Planck's radiation law shows that **with increasing temperature, the total radiated energy of a body increases and the peak of the emitted spectrum shifts to shorter wavelength.**

Wien's displacement law: $\lambda_{peak} = \frac{b}{T}$

$$b = 2.898 \times 10^{-3} \text{ m} \cdot \text{K} \text{ or } 2898 \mu\text{m} \cdot \text{K}$$

Stefan-Boltzmann law: $E = \sigma T^4$ *E is the energy radiated per unit area per unit time from the body*

$$\sigma = 5.670 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$$

Planck's Law (Planck's radiation law)

$$B(\lambda, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{k_B T}} - 1} = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

$B(\lambda, T)$ is the spectral radiance of a body for wavelength λ at T
 = the power emitted per unit area of the body, per unit solid angle that the radiation is measured over, per unit λ (or ν)

ν is Frequency

k_B is Boltzmann Constant

h is Planck's Constant

c is speed of light in vacuum

EPFL Different forms in Planck's Law

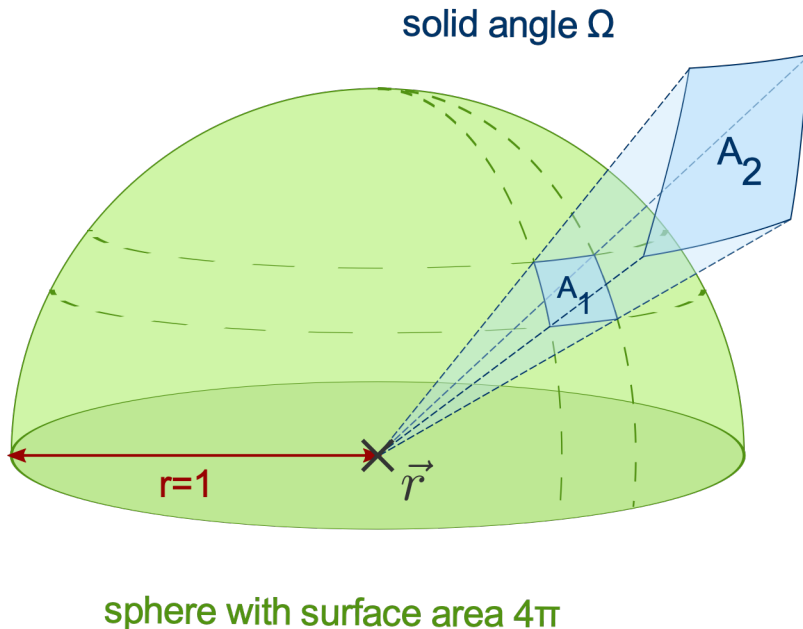
$$B(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{k_B T}} - 1}$$

The SI units are $W \cdot sr^{-1} \cdot m^{-2} \cdot Hz^{-1}$

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

The SI units are $W \cdot sr^{-1} \cdot m^{-2} \cdot \mu m^{-1}$

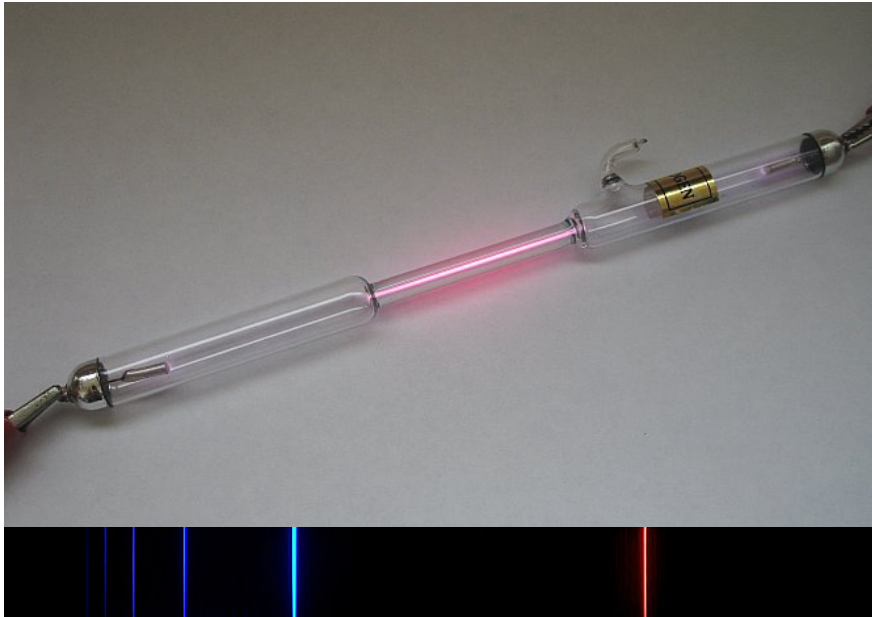
$$\begin{aligned} \text{using } \lambda &= \frac{c}{\nu} \\ \Rightarrow \frac{d\lambda}{d\nu} &= -\frac{c}{\nu^2} \\ \Rightarrow \left| \frac{d\lambda}{d\nu} \right| &= \frac{c}{\nu^2} \end{aligned}$$



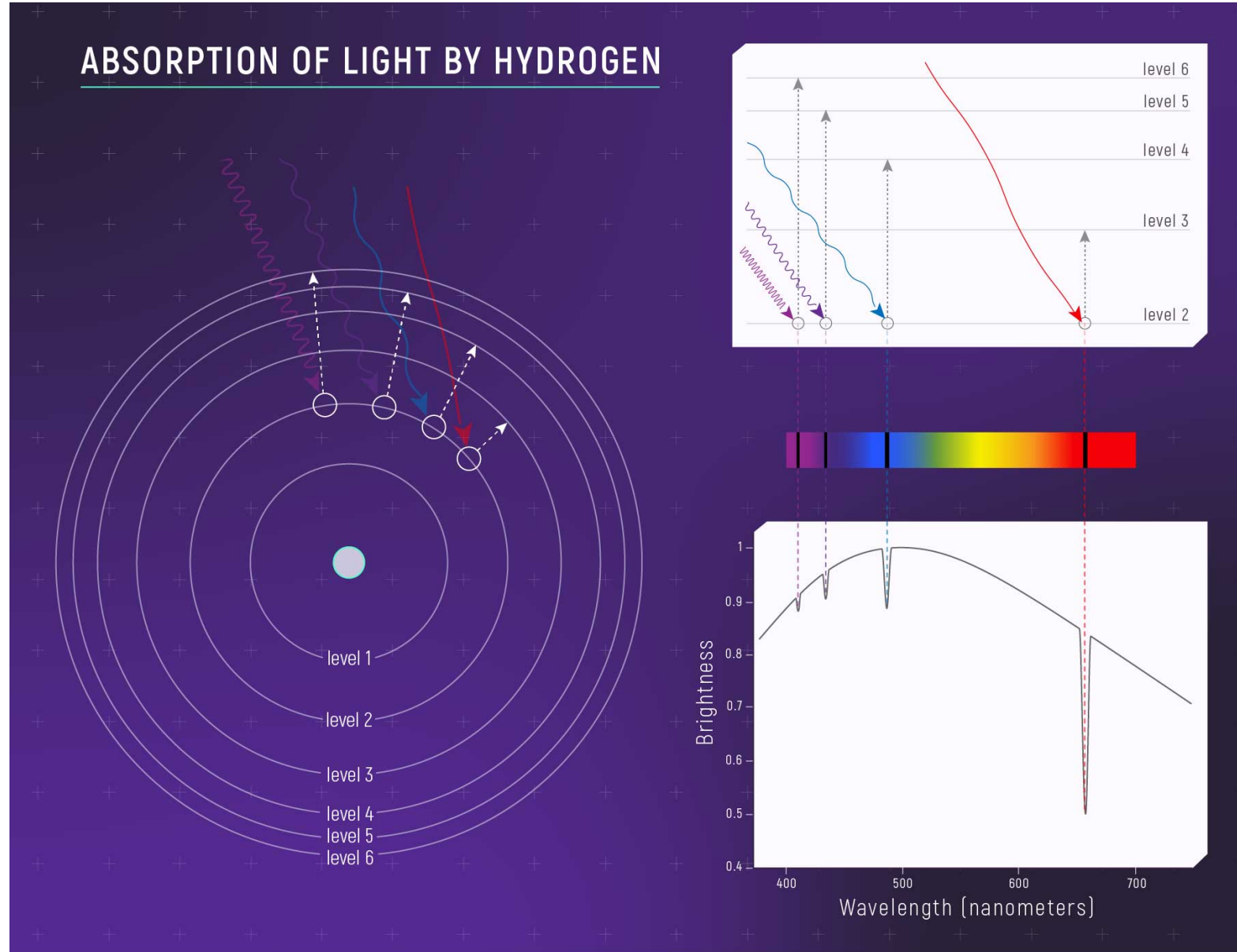
- The **solid angle** is 2D angle but in a 3D space and is represented by **steradians (sr)**.
- The solid angle is used to calculate how much of an object is in the field of view of another object.

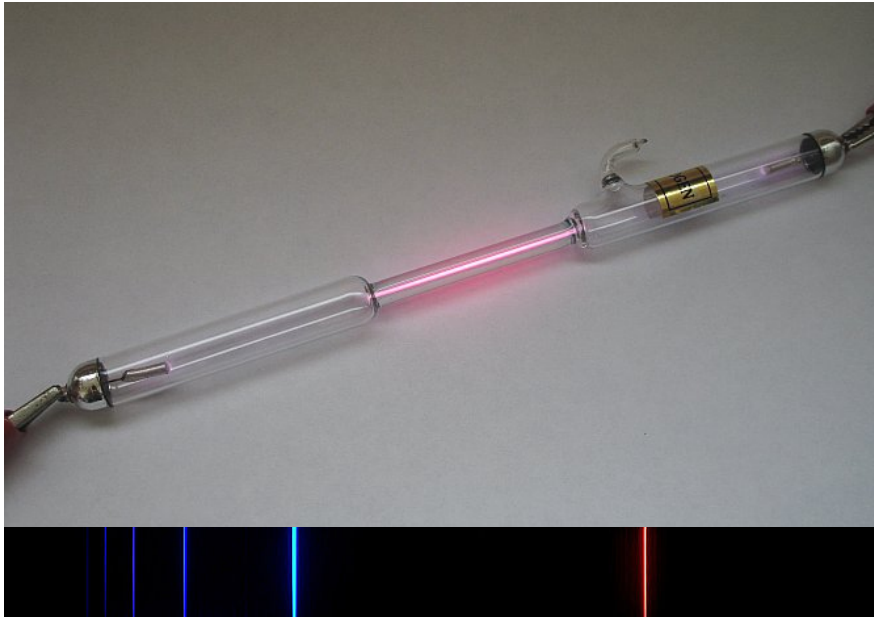
$$\Omega = \frac{A}{r^2}$$

A = the projection area of the object (the area normal to radial lines at the distance d)
 r = the distance

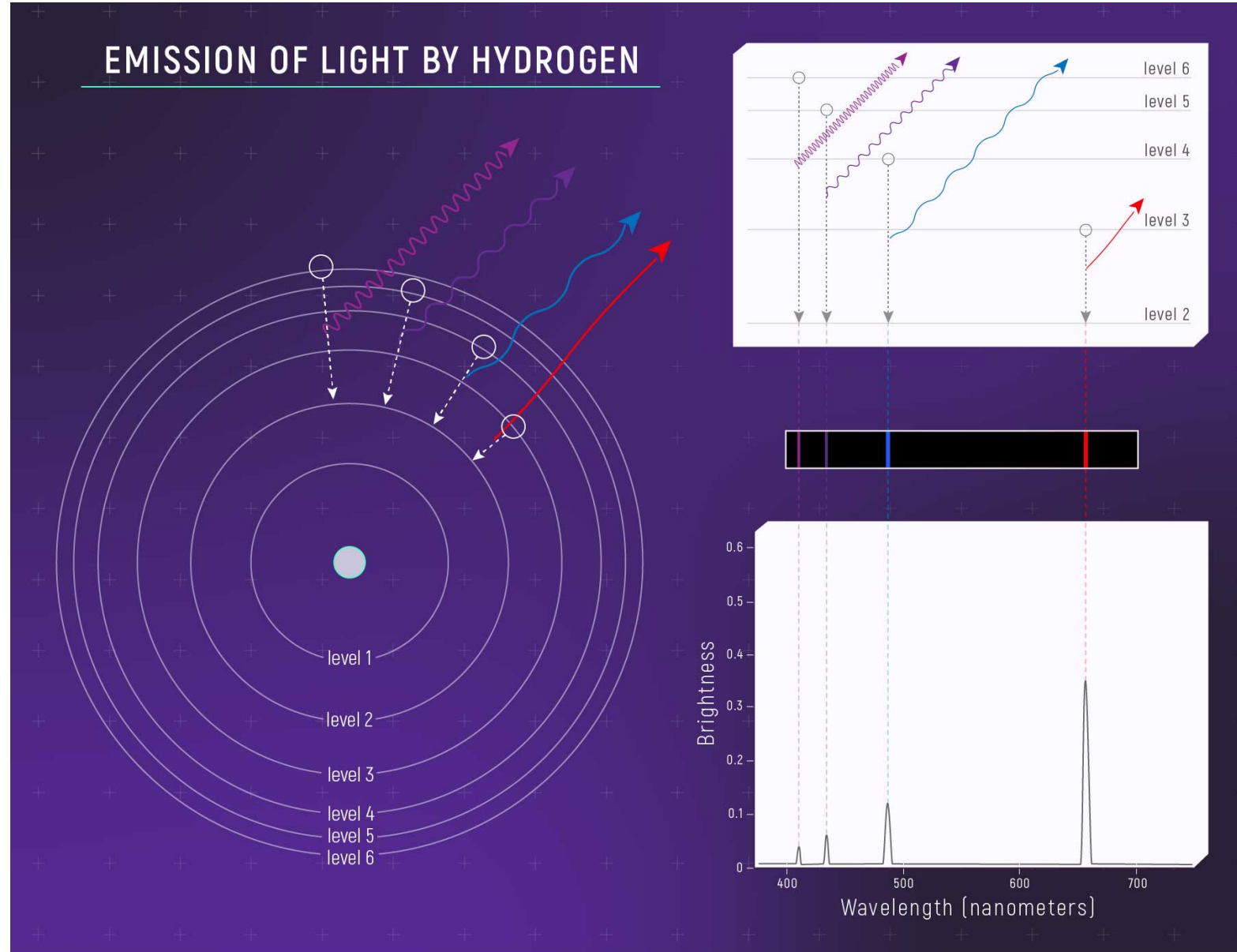


Emission by Hydrogen





Emission by Hydrogen



EPFL Line Spectra

John Balmer (1825 – 1898): the frequencies of the lines observed in the visible region of the spectrum of hydrogen fit a simple equation as follows

$$u = \text{constant} \left(\frac{1}{2^2} - \frac{1}{n^2} \right)$$

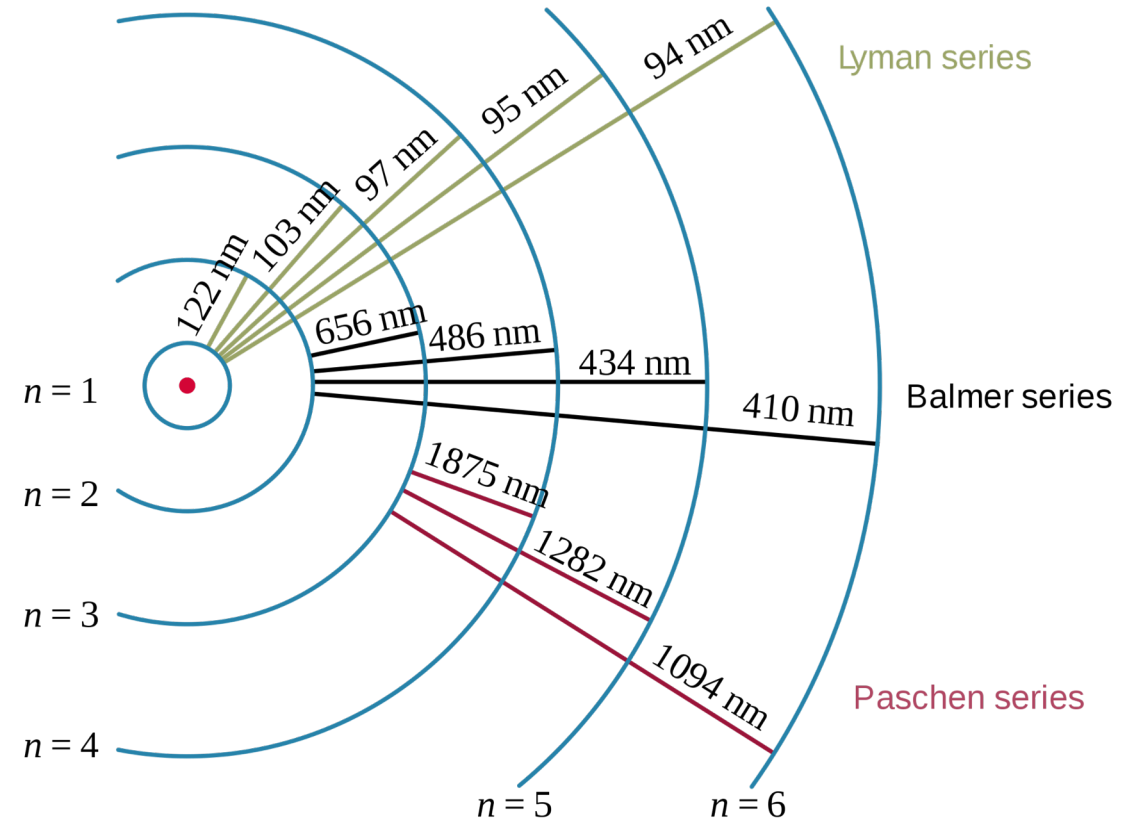
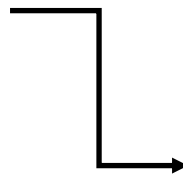
Johannes Rydberg (1854 – 1919) expanded Balmer's result in the Rydberg equation:

$$\frac{1}{\lambda} = -R \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$$

Rydberg constant (R): $1.09737 \times 10^7 \text{ m}^{-1}$

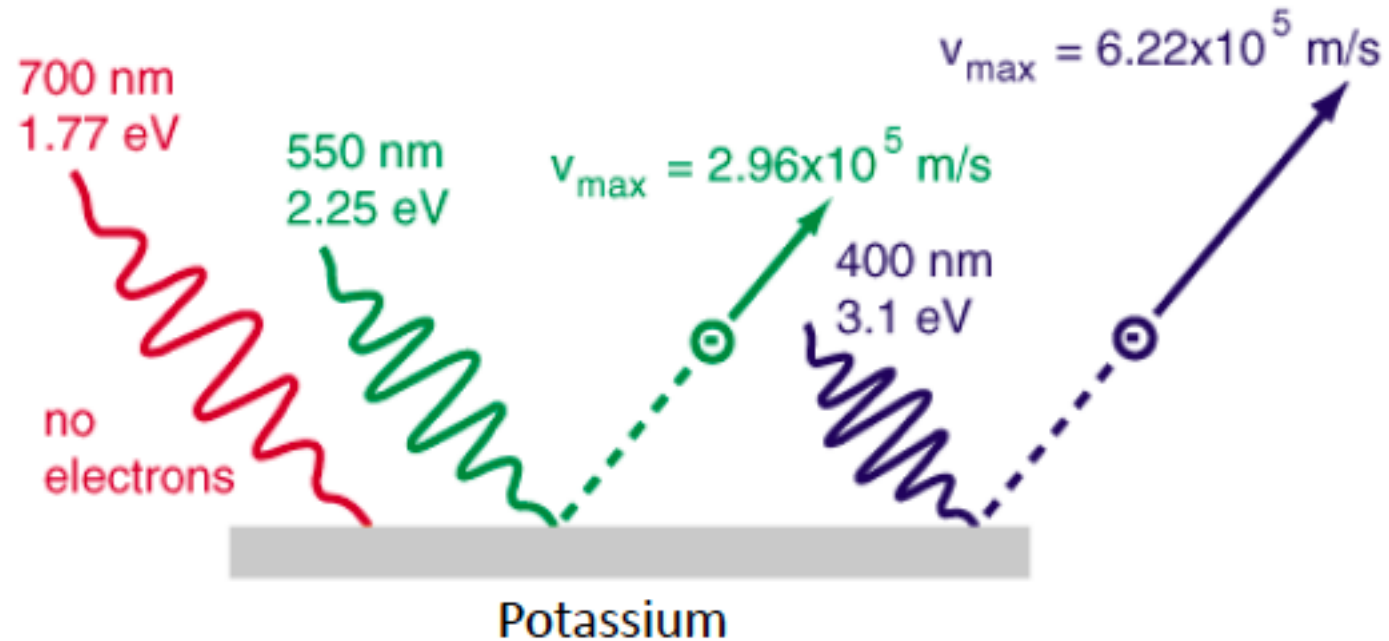
Niels Bohr (1885 – 1962, Nobel prize in Physics, 1922) proposed a model for the hydrogen atom:

$$E_n = -\frac{Rhc}{n^2}$$



$$\Delta E = E_{\text{final}} - E_{\text{initial}}$$

The electron moves around the nucleus in circular orbits that can have only certain allowed radii.



$$KE_{\max} = h\nu - W, \quad W = \text{work function of metal}$$

When light shines on the surface of a metallic substance, electrons in the metal absorb the energy of the light and they can escape from the metal's surface. This is called the **photoelectric effect**. Electrons emitted in this manner are called photoelectrons.

Phenomenon

Wave explanation

Particle explanation

Reflection



Refraction



Interference



Diffraction



Polarization



Photoelectric effect



Wavelength $\longrightarrow \lambda = \frac{h}{p}$

$\longleftarrow$ Planck's constant

$\longleftarrow$ Momentum = mass x velocity



Louis de Broglie (1892 – 1987)
Nobel Prize in Physics 1929

$$\text{Wavelength} \longrightarrow \lambda = \frac{h}{p} \quad \begin{array}{l} \longleftarrow \text{Planck's constant} \\ \longleftarrow \text{Momentum = mass x velocity} \end{array}$$



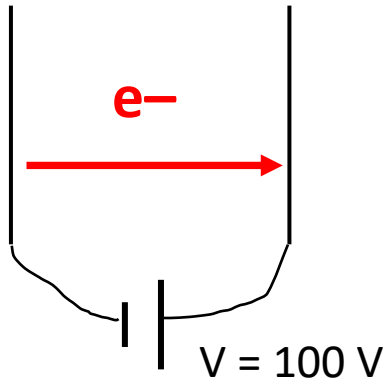
De Broglie wavelength of a football

v: 210 km/h by Ronny Heberson but for simple calculation, 144 km/h (= 40 m/s)
m: 0.45 kg

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{0.45 \text{ kg} \times 40 \text{ m/s}} = 3.68 \times 10^{-35} \text{ m}$$

Too small and the wave nature is not detectable!

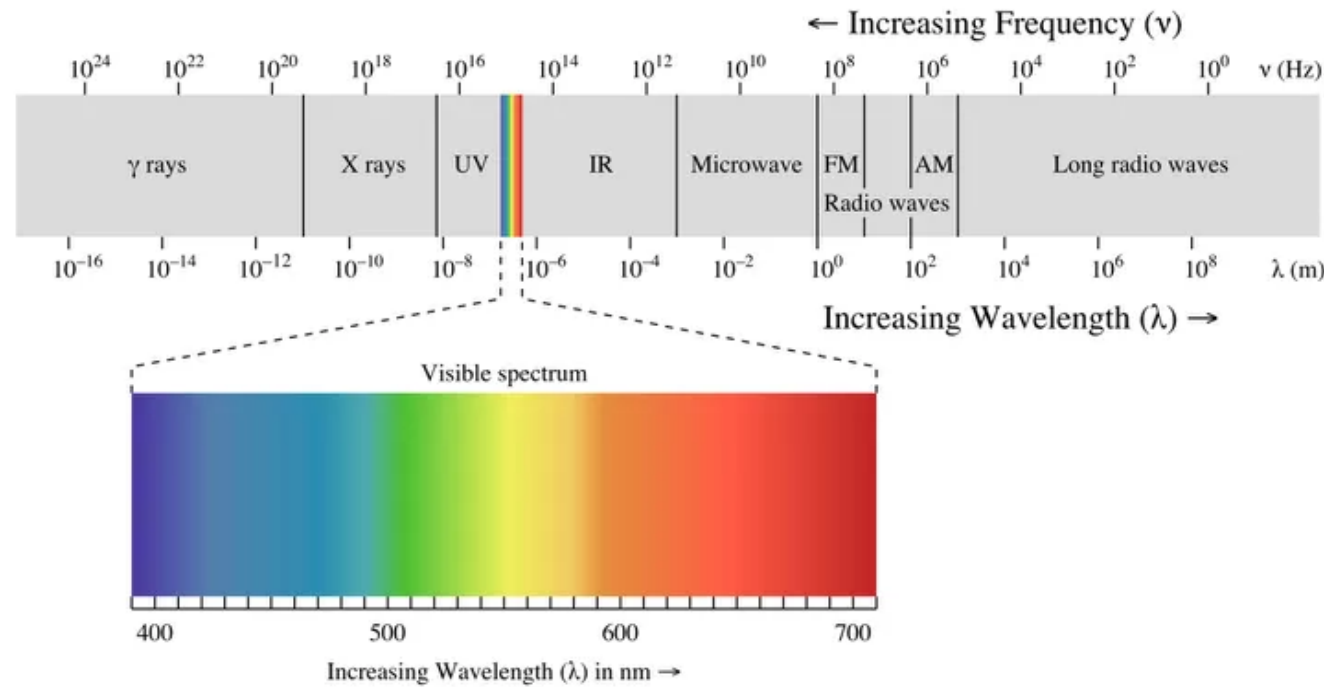
De Broglie wavelength of an electron



v: $5.9 \times 10^6 \text{ m/s}$ at a 100 V
m: $9.1 \times 10^{-31} \text{ kg}$

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{9.11 \times 10^{-31} \text{ kg} \times 5.9 \times 10^6 \text{ m/s}} = 1.2 \times 10^{-10} \text{ m} (1.2 \text{ \AA})$$

Photons are packets of energy!
behave as particles and waves!
have no mass!



$$E = h\nu = hc/\lambda$$

Increasing Energy



A photon is characterized by either a frequency, denoted by ν or equivalently an energy, denoted by E . There is an inverse relationship between the energy of a photon (E) and the wavelength of the light (λ) given by the equation:

$$E = h\nu = hc/\lambda$$

where h is Planck's constant and c is the speed of light: $h = 6.626 \times 10^{-34}$ J·s and $c = 2.998 \times 10^8$ m/s

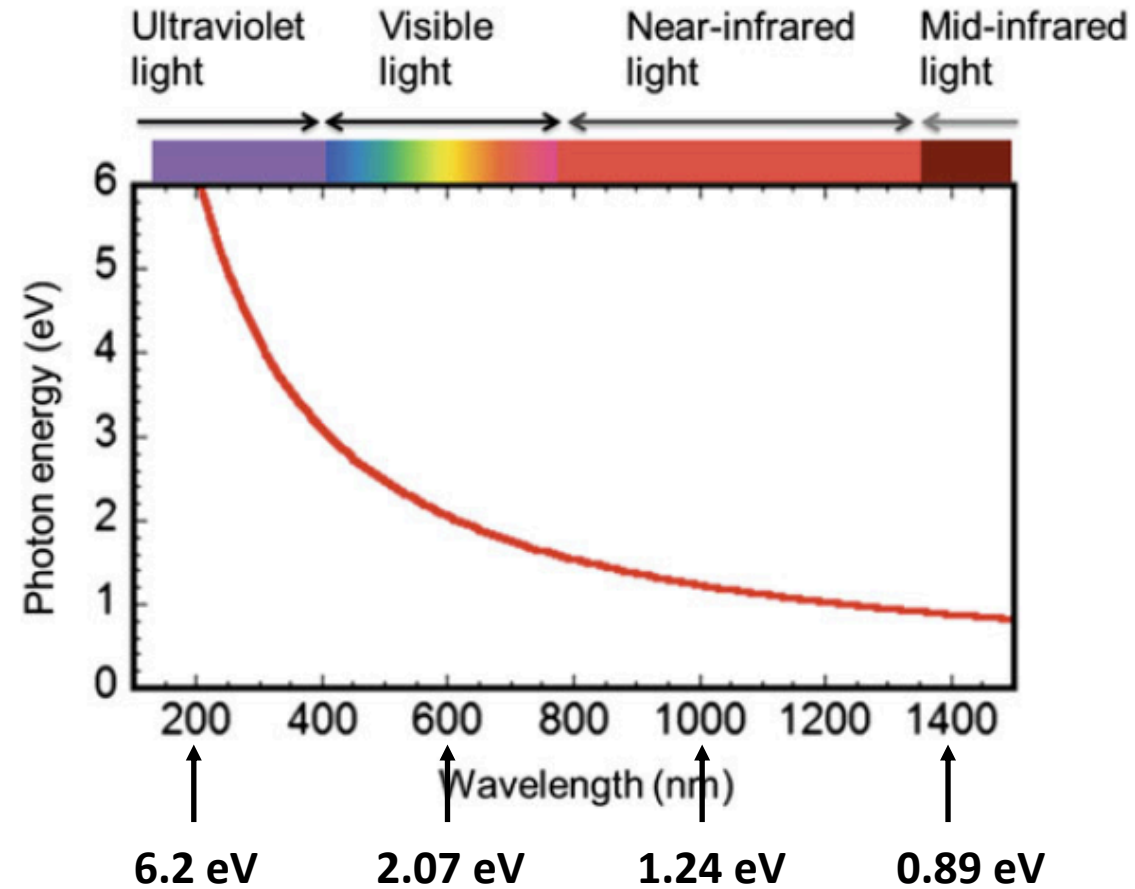
When dealing with "particles" such as **photons** or electrons, a commonly used unit of energy is the electron-volt (eV) rather than the joule (J).

An electron volt is the energy required to raise an electron through 1 volt: $1 \text{ eV} = 1.602 \times 10^{-19}$ J.

Therefore, we can rewrite the above constant for hc in terms of eV: $hc = (1.99 \times 10^{-25} \text{ J}\cdot\text{m}) \times (1 \text{ eV}/1.602 \times 10^{-19} \text{ J}) = 1.24 \times 10^{-6} \text{ eV}\cdot\text{m} = 1.24 \text{ eV}\cdot\mu\text{m} = 1240 \text{ eV}\cdot\text{nm}$

$$E(\text{eV}) = \frac{1240}{\lambda (\text{nm})}$$

$$E(\text{eV}) = \frac{1240}{\lambda (\text{nm})}$$



EPFL Photon Flux and Power Density

The photon flux is defined as the number of photons per second per unit area:

$$\phi = \frac{\text{number of photons}}{m^2 \cdot sec}$$

The photon flux is important in determining the number of electrons which are generated from a solar energy conversion system.

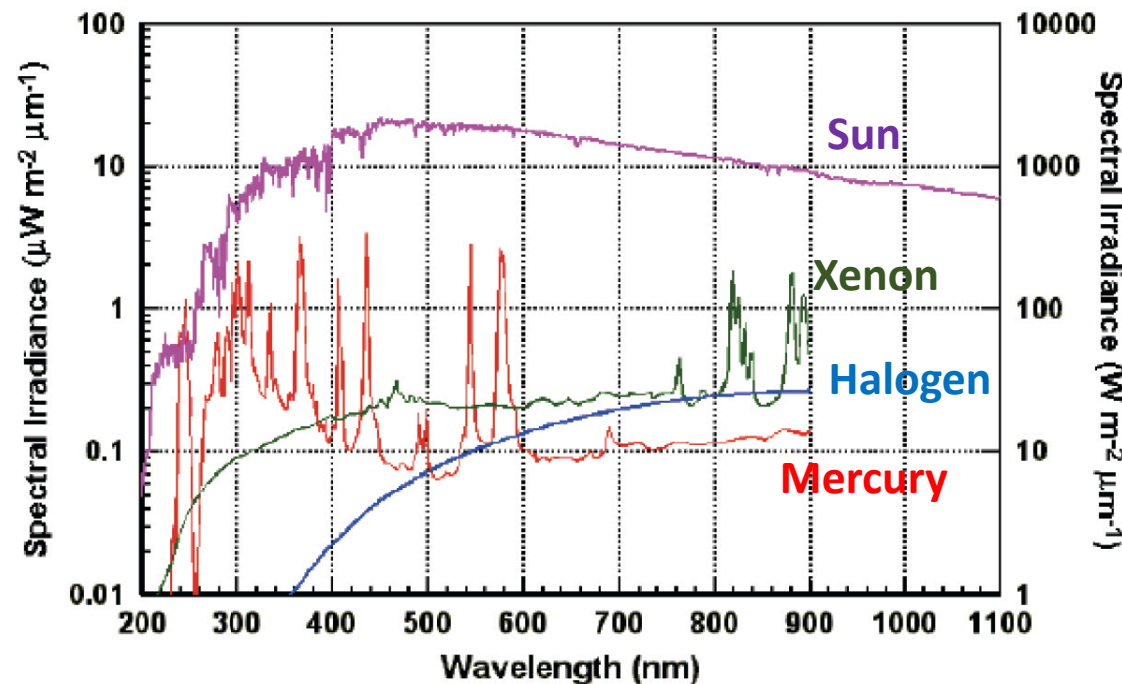
Since the photon flux gives the number of photons striking a surface in a given time, multiplying by the energy of the photons comprising the photon flux gives the energy striking a surface per unit time, which is equivalent to a power density.

$$\begin{aligned} H \left(\frac{W}{m^2} \right) &= \phi \times h\nu && \text{For frequency} \\ &= \phi \times q \frac{1240}{\lambda \text{ (nm)}} && \text{For wavelength in nm} \\ &= \phi \times qE \text{ (eV)} && \text{For energy in eV} \end{aligned}$$

Photon flux = $1E^{21} \text{ m}^{-2}\text{s}^{-1}$ with photon energy of 1.77 eV (700 nm) $\rightarrow$ 283 W/m²

The spectral irradiance as a function of photon wavelength (or energy), denoted by F , is the most common way of characterizing a light source. It gives the power density at a particular wavelength. The units of spectral irradiance are in $\text{Wm}^{-2}\mu\text{m}^{-1}$.

$$F(\lambda) = \phi \times q \frac{1240}{\lambda \text{ (nm)}} \times \frac{1}{\Delta\lambda} = H \times \frac{1}{\Delta\lambda}$$



The spectral irradiance of artificial light sources (left axis) compared to the spectral irradiance from the sun (right axis).

Elsarrag, E. et al. *Renew. Wind. Water Solar*, 2(16), (2015)

EPFL Solar Energy to The Earth

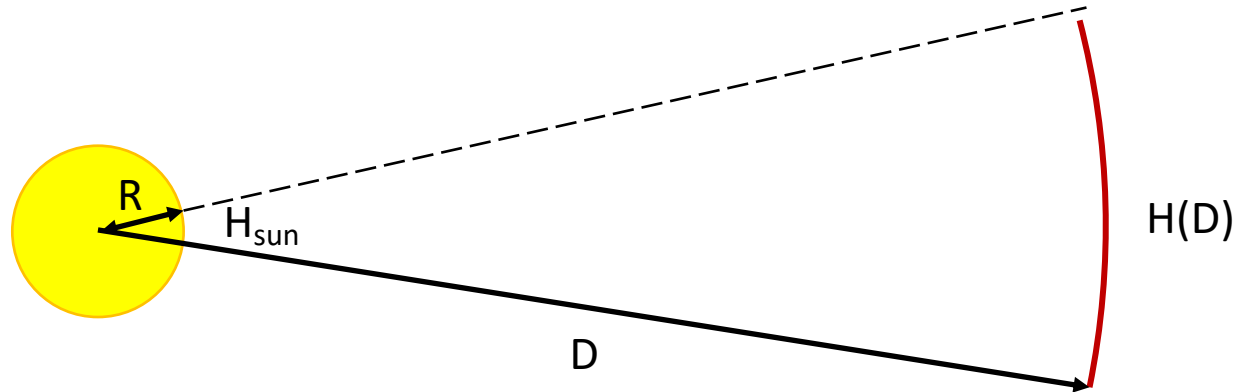
The solar energy on an object some distance D from the sun is found by dividing the total power emitted from the sun by the surface area over which the sunlight falls.

$$H(D) = \frac{4\pi R_{sun}^2}{4\pi D^2} H_{sun} = \frac{R_{sun}^2}{D^2} H_{sun}, H_{sun} \text{ by Stefan Boltzman equation } (\sigma T_s^4) \text{ and } \mathbf{H_{Earth} = 1366 W/m^2}$$

$$\sigma = 5.670 \times 10^{-8} W m^{-2} K^{-4}$$

$$E_{Earth} = 1366 \times \pi R_{Earth}^2 = 1366 \times 1.275 \times 10^8 km^2 = 174 PW$$

$$\text{measured value} = 1361 - 1362 W/m^2$$



Solar Constant: the rate at which solar energy arrives at the top of the atmosphere = the amount of energy received in unit time on a unit area perpendicular to the sun's direction at the mean distance of the earth from the sun

Planet	Distance (x 10 ⁹ m)	Solar Constant (W/m ²)	Radius (m)	Solar Radiation (PW)
Mercury	58	9087	2440	170
Venus	108	2620	6050	302
Earth	150	1366	6370	174
Mars	228	588	3390	21

Solar Constant: the rate at which solar energy arrives at the top of the atmosphere = the amount of energy received in unit time on a unit area perpendicular to the sun's direction at the mean distance of the earth from the sun

Planck's law:

$$B(\lambda, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1} = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} = \left[\frac{\text{Energy carried by photons}}{\text{time} \cdot \text{wavelength} \cdot \text{projected surface area} \cdot \text{solid angle}} \right]$$

$$E_{Earth} = \int_0^\infty B_\lambda(5778K) \Omega_{se} d\lambda$$

The solar constant:

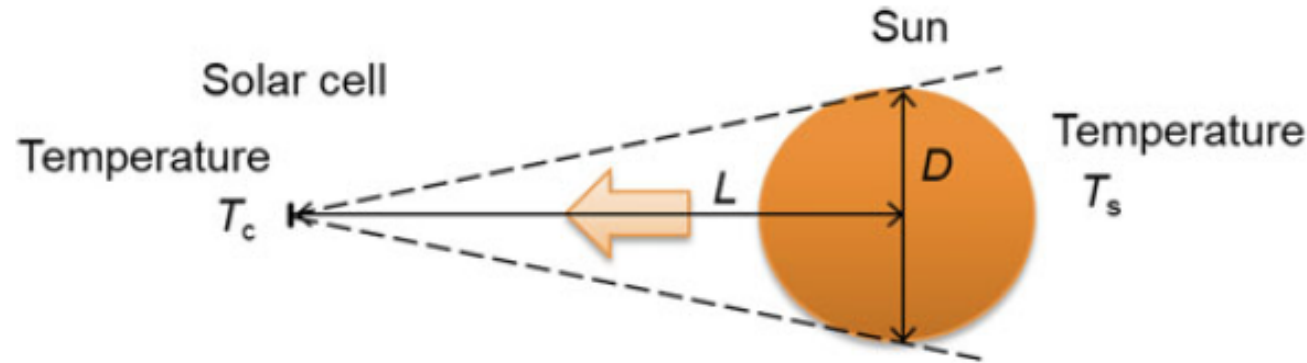
$$\int_{\lambda=0}^\infty B_\lambda(5778K) \Omega_{se} d\lambda = 1368 \text{ W/m}^2 \quad \text{measured value} = 1361 - 1362 \text{ W/m}^2$$

$$E_{Earth} = 1368 \times \pi R_{Earth}^2 = 1368 \times 1.275 \times 10^8 \text{ km}^2 = 174 \text{ PW}$$

EPFL Solid Angle of The Sun

- The solid angle is 2D angle but in a 3D space and is represented by steradians.
- The solid angle is used to calculate how much of an object is in the field of view of another object.

The solid angle of the sun Ω_{se} = **Total solid angle of the sun from the viewpoint of the earth**
 = $\frac{\text{the area of the sun projected onto a plane normal to the vector pointing from the Earth to the sun}}{(\text{the distance from the earth to the sun})^2}$



Sun and Earth: $D_{sun} = 1.39 \times 10^9 \text{ m}$ and $L = 1.49 \times 10^{11} \text{ m}$

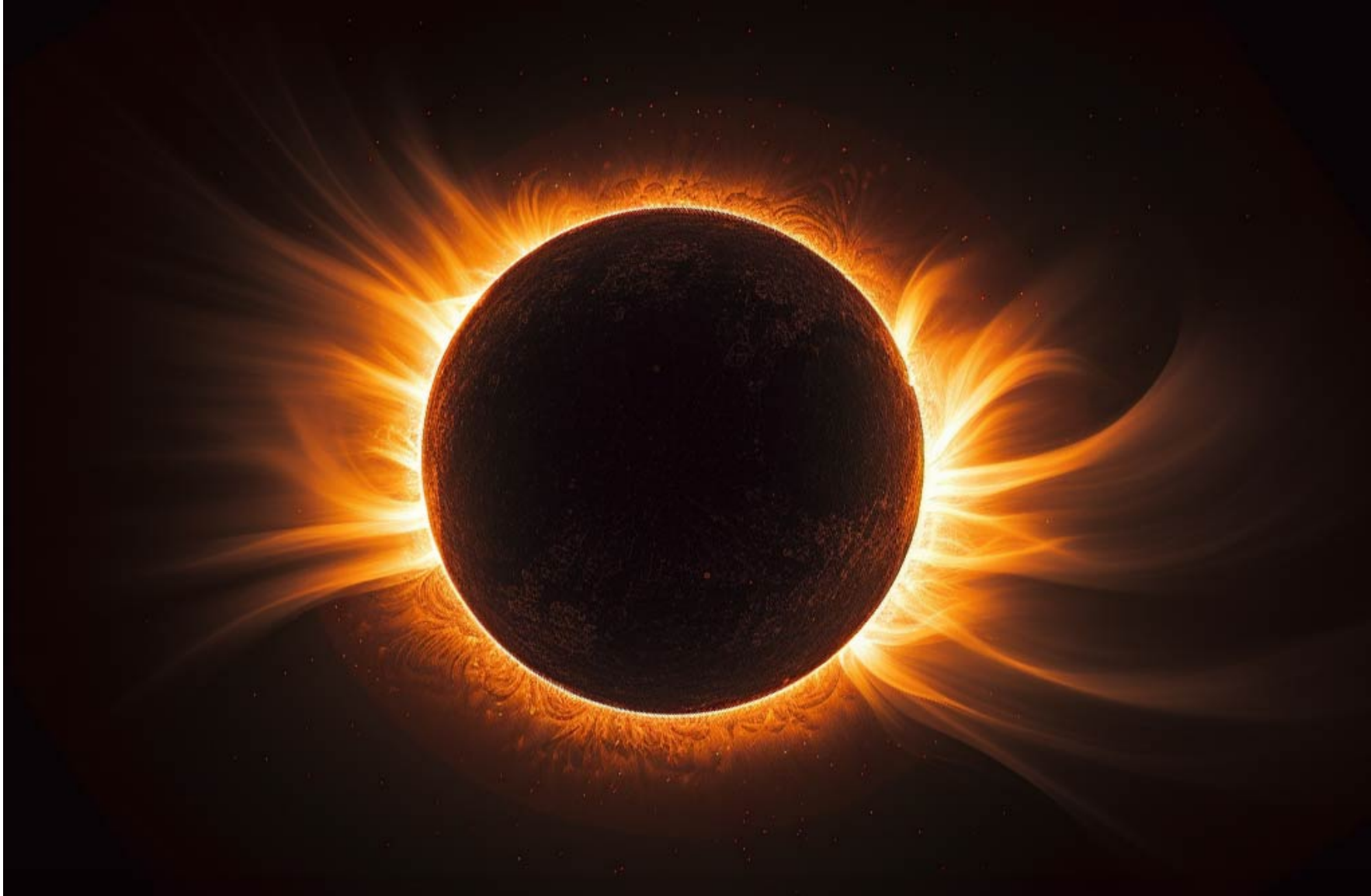
Moon and Earth: $D_{moon} = 3.47 \times 10^6 \text{ m}$ and $L = 3.84 \times 10^8 \text{ m}$

$$\Omega_{se} = \frac{\pi \left(\frac{D}{2}\right)^2}{L^2} = \pi \times (2.18 \times 10^{-5}) = 6.84 \times 10^{-5} \text{ sr}$$

f_ω (Geometrical factor)
↓

$$\Omega_{me} = 6.43 \times 10^{-5} \text{ sr}$$

The Sun and Moon appear approximately the same size when viewed from the Earth.



EPFL Solar Energy to The Earth

The solar energy on an object in some distance D from the sun is found by dividing the total power emitted from the sun by the surface area over which the sunlight falls.

$$H(D) = \frac{4\pi R_{sun}^2}{4\pi D^2} H_{sun} = \frac{R_{sun}^2}{D^2} H_{sun}, H_{sun} \text{ by Stefan Boltzman equation } (\sigma T_s^4) \text{ and } H_{Earth} = 1366 \text{ W/m}^2$$

Example) Each photon carries on the average 1.48 eV. Calculate the photon flux.

Solution)

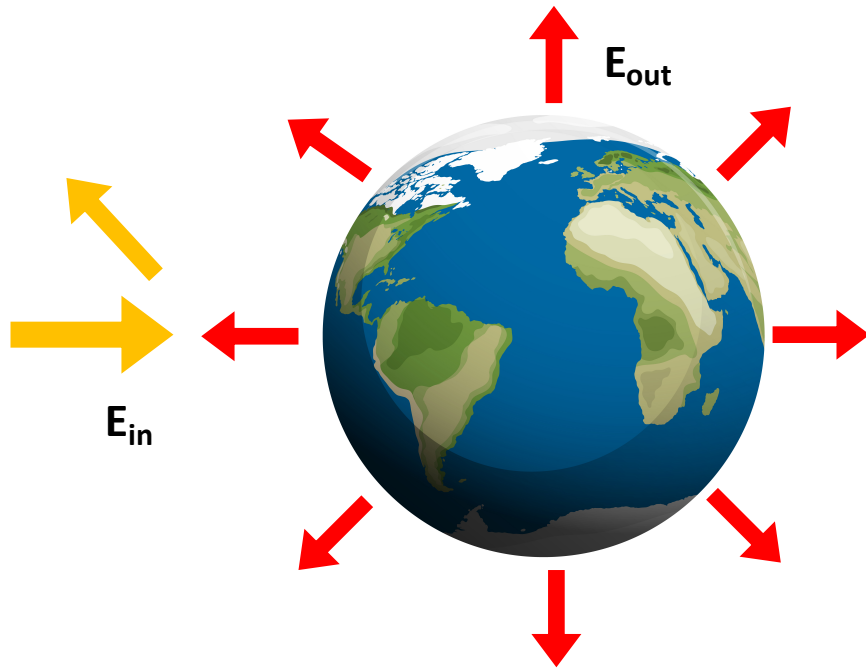
$$\begin{aligned} H \left(\frac{W}{m^2} \right) &= \phi \times h\nu \\ &= \phi \times q \frac{1240}{\lambda \text{ (nm)}} \\ &= \phi \times qE \text{ (eV)} \end{aligned}$$

$$\phi = \frac{1366 \text{ W/m}^2}{1.48 \text{ eV}} \times \frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} = 5.8 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1} = 5.8 \times 10^{17} \text{ cm}^{-2} \text{ s}^{-1}$$

with $J = W \times sec$

AM	Comments	Solar constant (W/cm ²)	$h\nu_{av}$ (eV)	N_{ph} (cm ⁻² sec ⁻¹)
0	Outside atmosphere	0.135	1.48	5.8×10^{17}
1	Sea level, sun at zenith	0.106	1.32	5.0×10^{17}
2	Sea level, sun at 60 degree from zenith	0.088	1.28	4.3×10^{17}
3	Sea level, sun at 70.5 degree from zenith	0.075	1.21	3.9×10^{17}
1	Cloudy weather	0.012	1.44	5.2×10^{16}

Energy Balance, $E_{in} = E_{out}$



$$E_{Earth} = 1366 \times \pi R_{Earth}^2 = 1366 \times 1.275 \times 10^8 \text{ km}^2 = 174 \text{ PW}$$

$$E_{in} = E_{Earth} \times (1 - A)$$

A (Albedo) = the fraction of light that a surface reflects = 0.33

$$E_{out} = \sigma T_{earth}^4 \times (4\pi R_{Earth}^2)$$

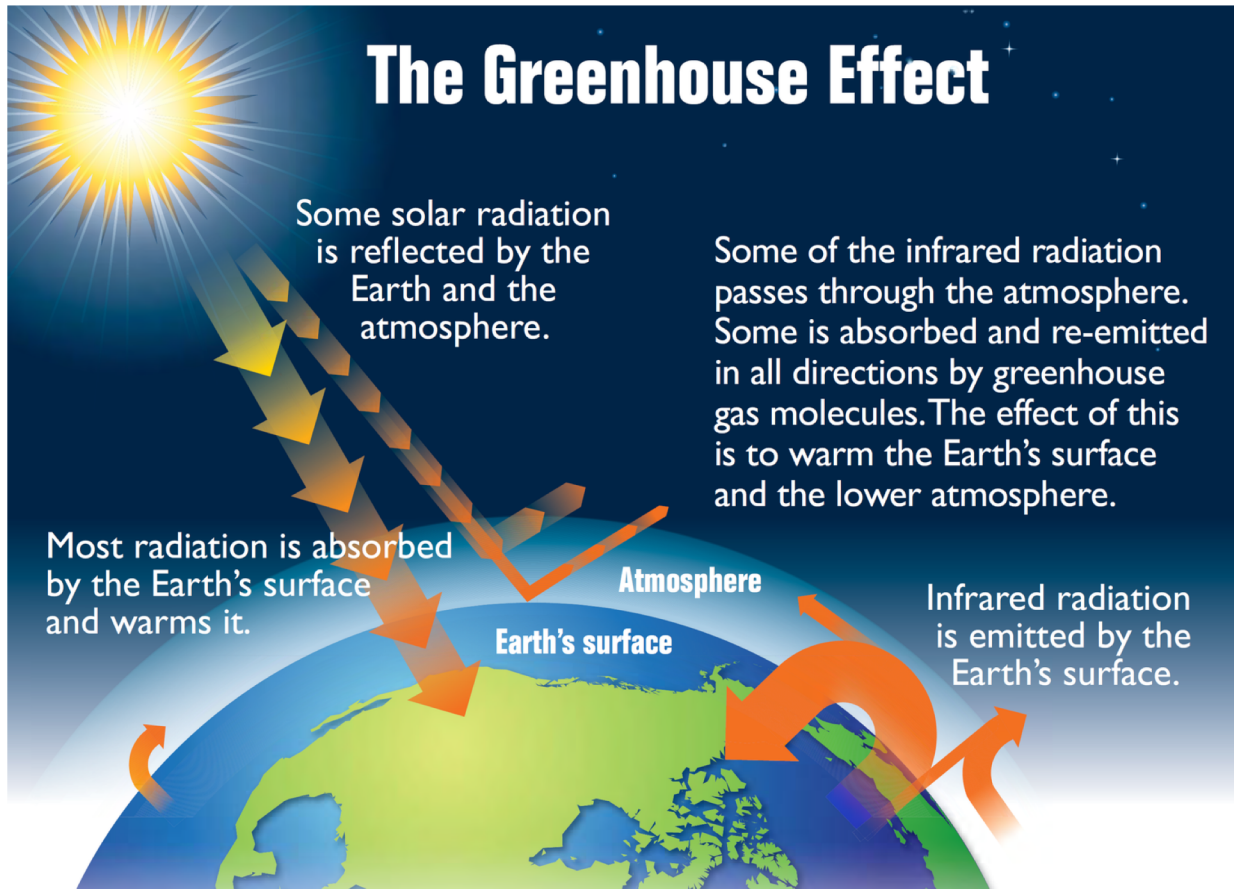
$$1366 \times \pi R_{Earth}^2 \times (1 - A) = \sigma T_{earth}^4 \times (4\pi R_{Earth}^2)$$

$$T_{earth} = \left[\frac{1366 \text{ W/m}^2 \times (1 - A)}{4\sigma \text{ Wm}^{-2}\text{K}^{-4}} \right]^{1/4}$$

$$T_{earth} = 252 \text{ K} = -21^\circ\text{C}$$

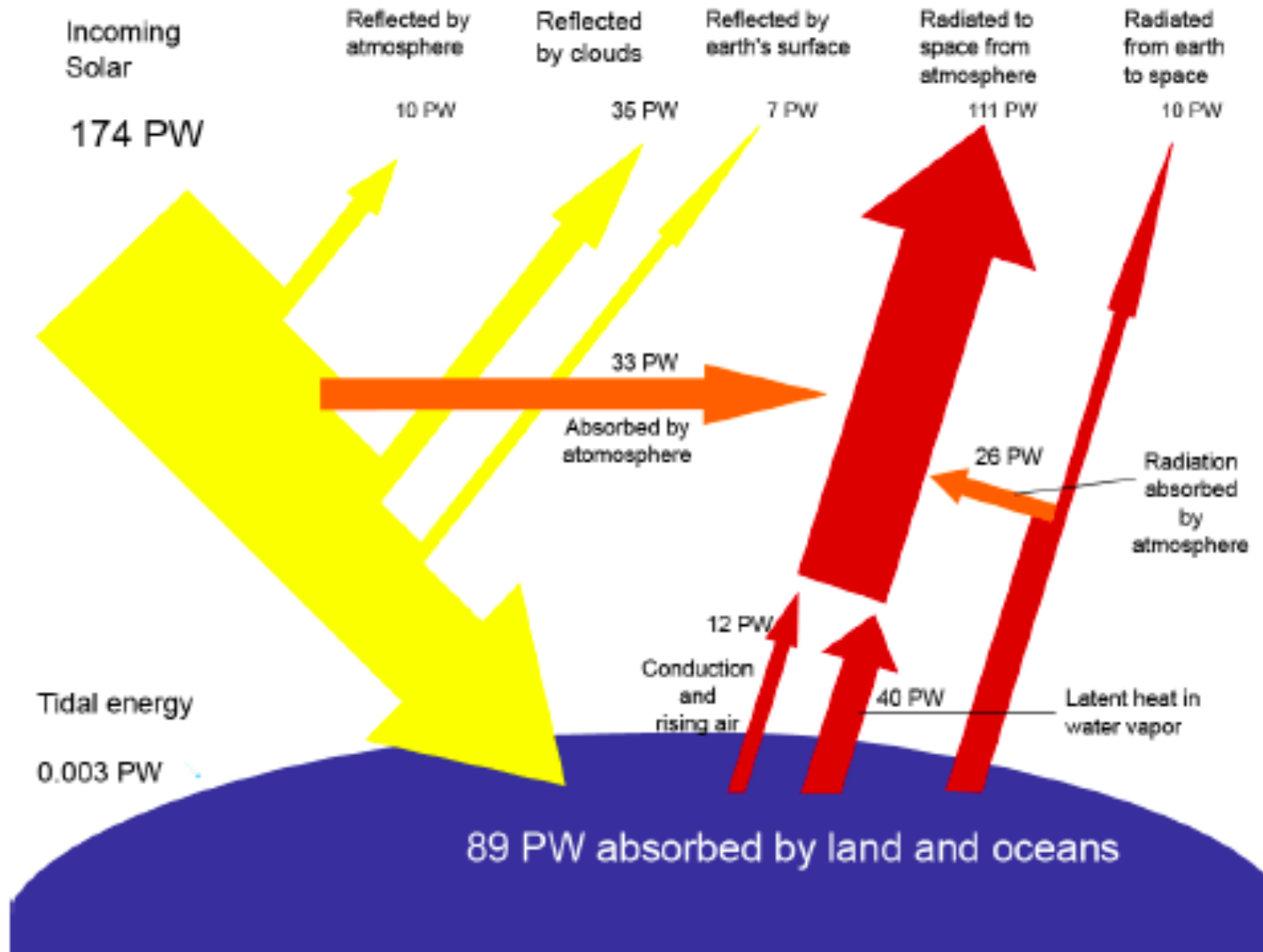


The observed ground temperature is 15°C



- The Earth is 33 °C warmer than expected based on black body calculations and the known input of solar energy.
- This extra warmth is what we call the **greenhouse effect**.
- It is a result of warming of the Earth's surface by the absorption and re-emission of IR radiation by molecules in the atmosphere.
- The greenhouse gases for the earth: methane, carbon dioxide, water vapour.
- The atmosphere is warm at the surface (15 °C), cold in the middle (-4 °C), and extremely cold near the top (-100 °C).

EPFL Solar Energy

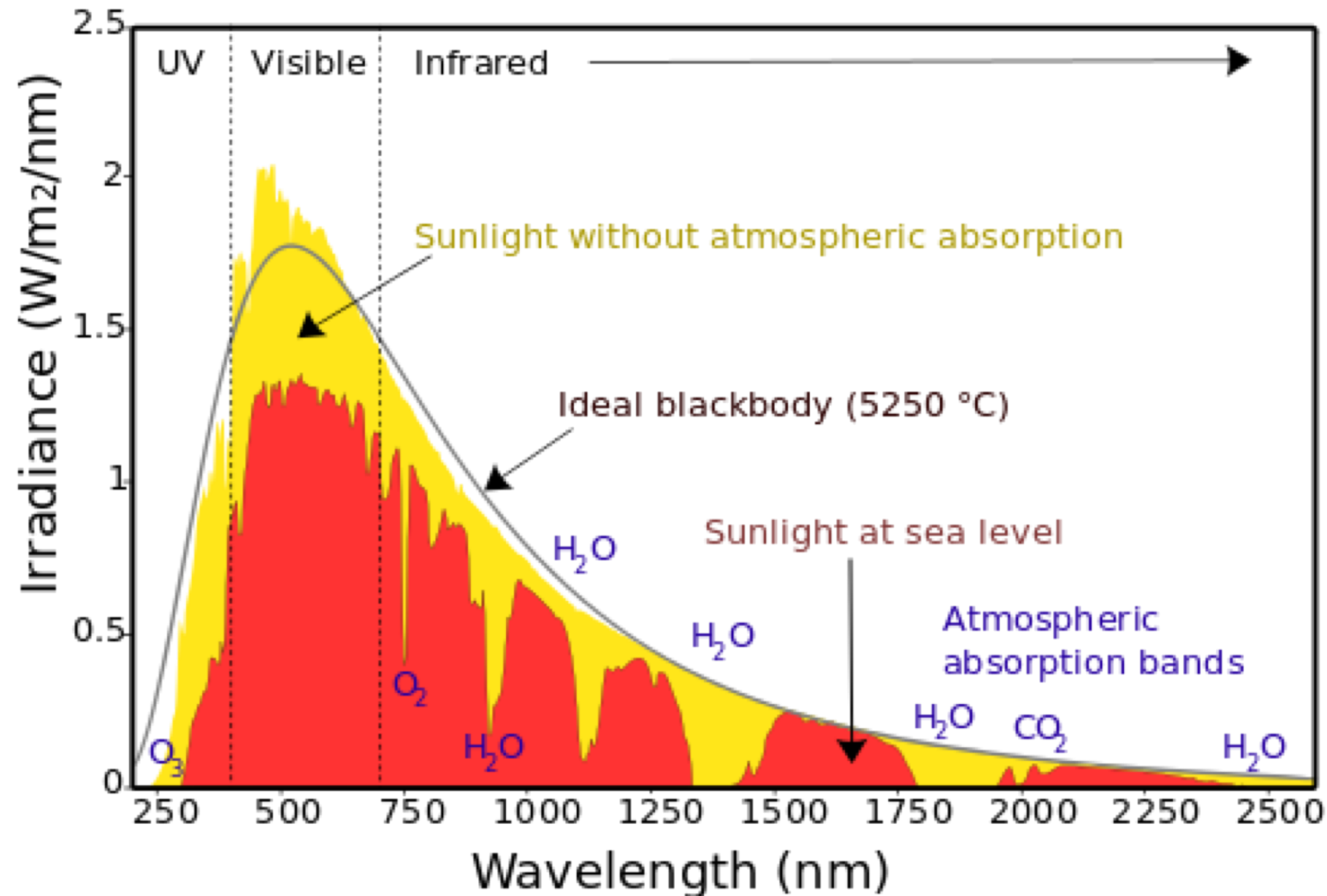


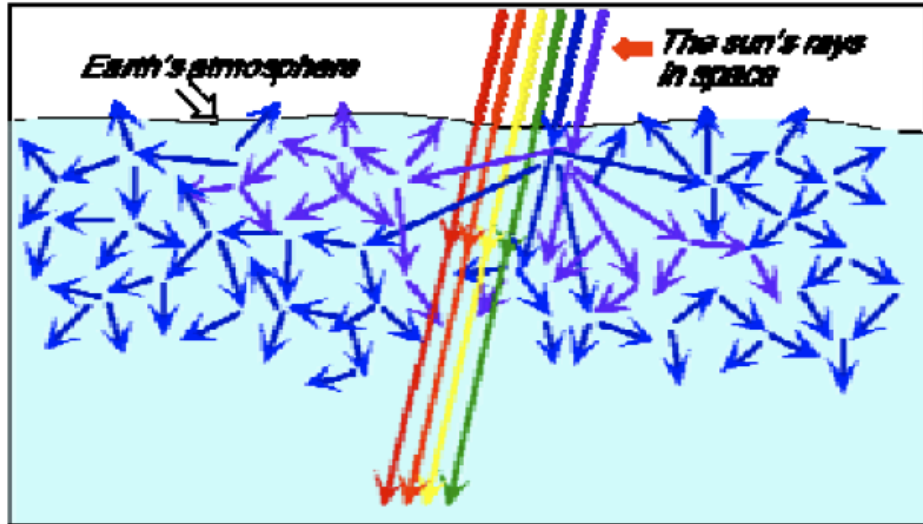
Atmospheric effect

- Absorption, scattering, reflection in the atmosphere.
- A reduction in the power of the solar radiation.
- A change in the spectral content.
- Diffuse component into the solar spectrum.
- Local variations (clouds, sun hours).

Global energy consumption = 0.02 PW

Spectrum of Solar Radiation (Earth)

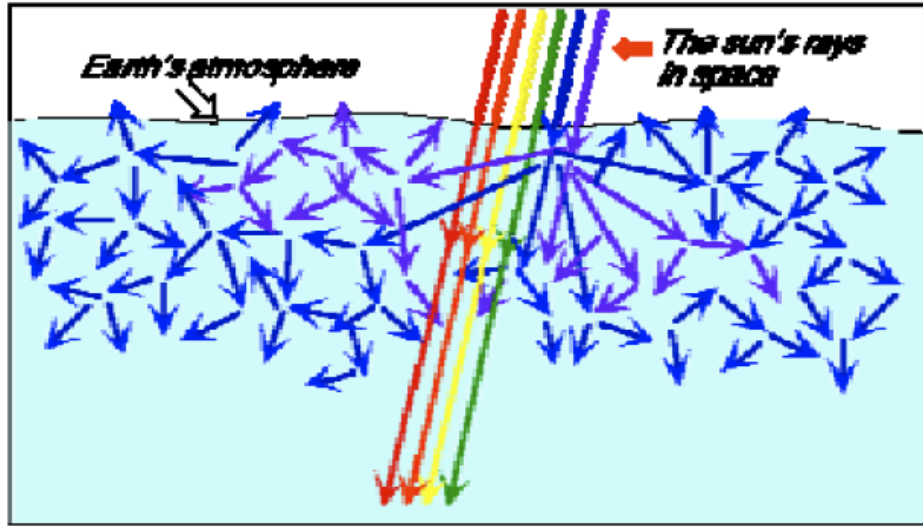




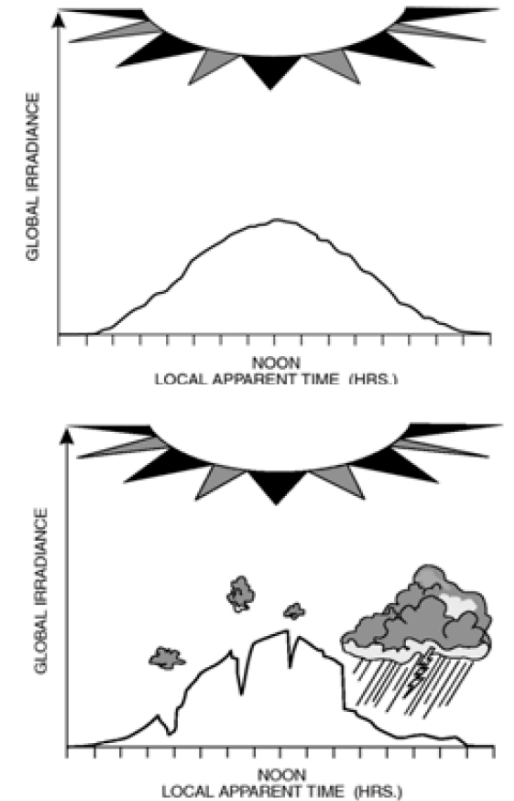
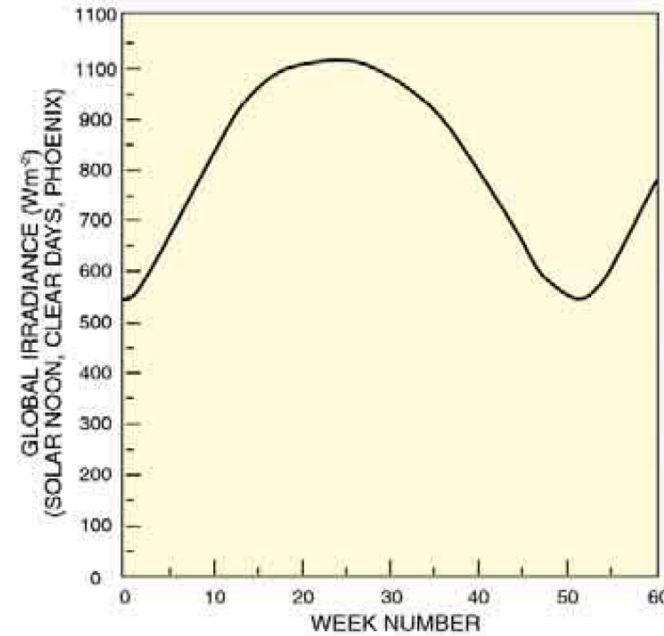
- Rayleigh scattering by molecules, $I \propto 1/\lambda^4$
- Mie Scattering by dust and aerosols



EPFL Solar Energy: Scattering and Variations



- Rayleigh scattering by molecules, $I \propto 1/\lambda^4$
- Mie Scattering by dust and aerosols



- Total terrestrial irradiance depends on location (north, south ..), hours/days of sun, cloud coverage, etc.
- When averaged over one day: Clear $\sim 590 - 1000 \text{ W/m}^2$
Cloudy days $\sim 120 \text{ W/m}^2$