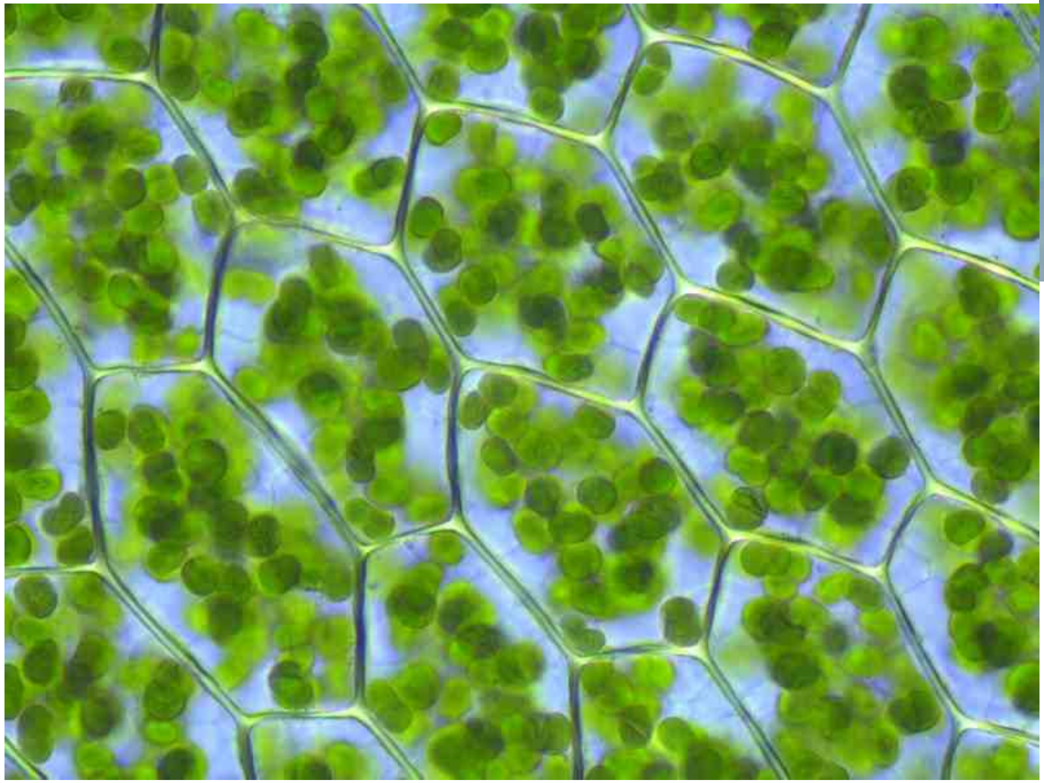
2 Solar systems

2.1. photosynthesis
2.2. solar heat
2.3. photovoltaics



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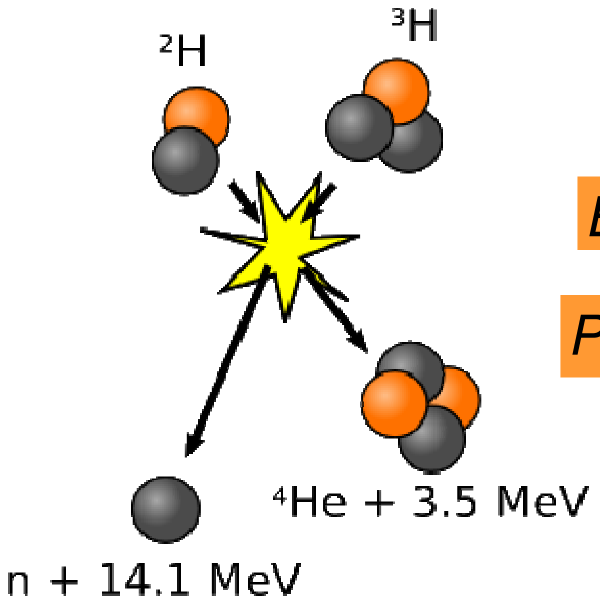
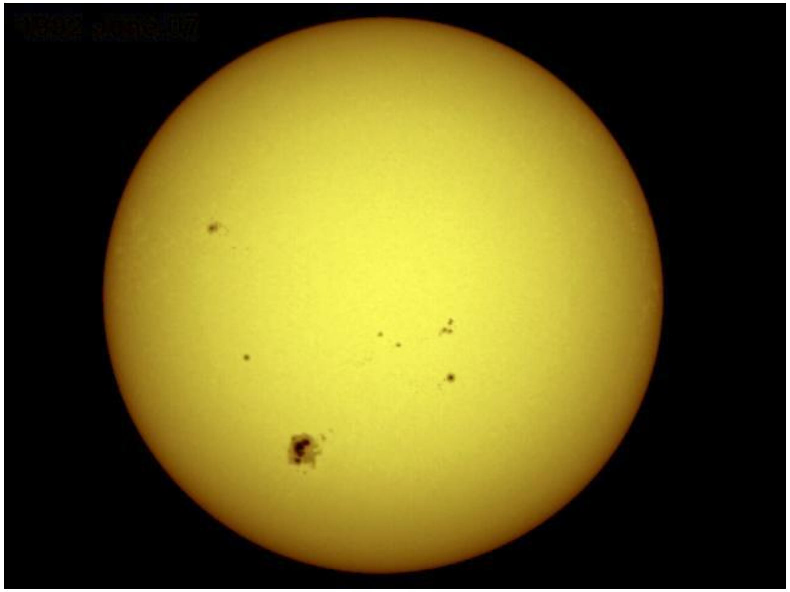
Solar systems

Where does the solar energy come from?



$$E = \Delta mc^2$$

$$P = \Delta mc^2 / t$$



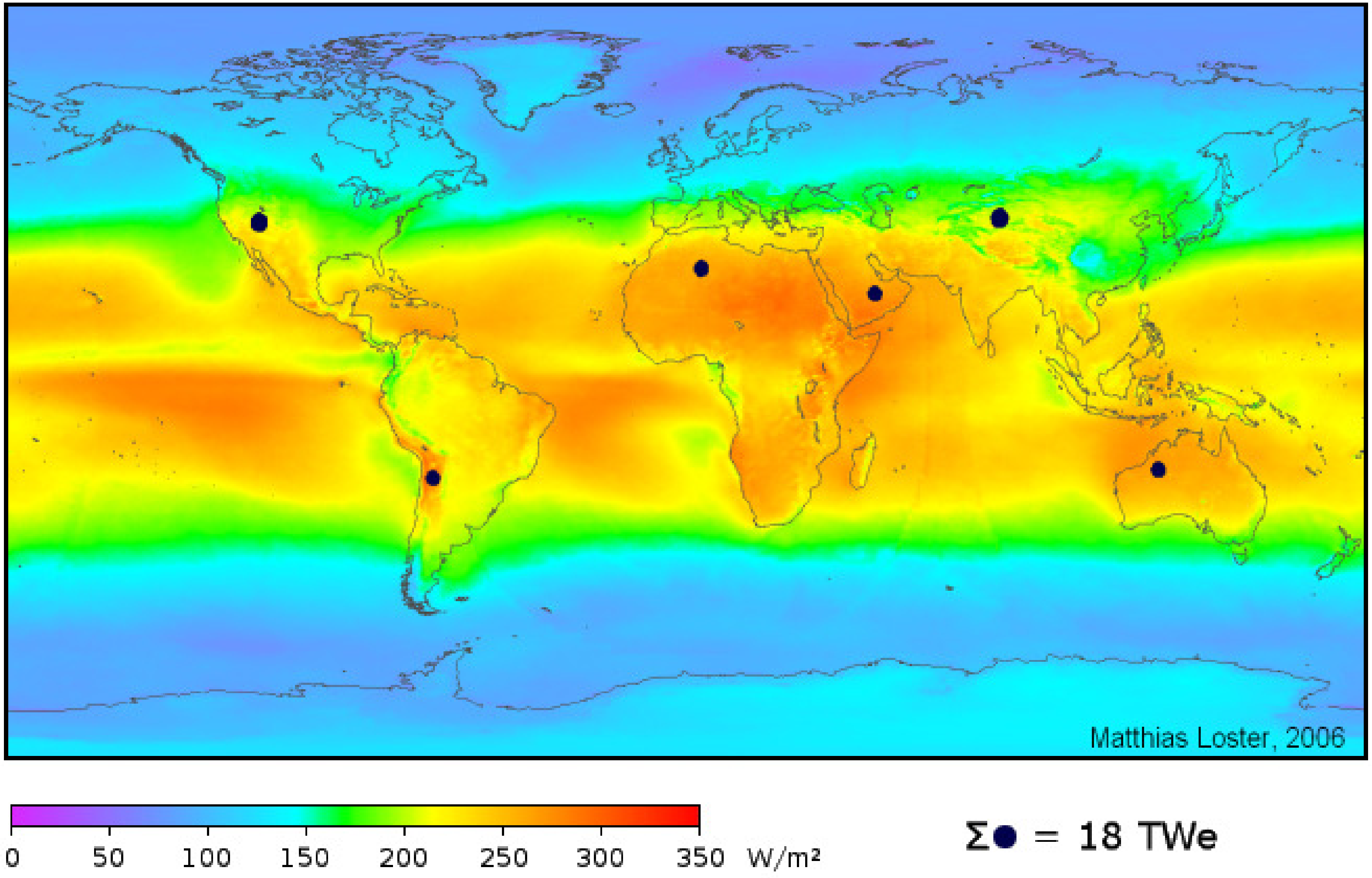
- Nuclear fusion generates heat
- Heat leads to thermal radiation
- Emitted radiation power (energy per time) (radiant power Φ or P):

$$\Phi = P = 3.846 \cdot 10^{26}\,\mathrm{W}$$

Comparison: mean power consumption per capita in Germany is about 5kW

Solar systems

Global average solar power density



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Solar systems

Emitted solar radiation per area - irradiance

$$\frac{\Phi}{A} = 63.11 \frac{\text{MW}}{\text{m}^2}$$

Fraction of the radiation, that hits the earth

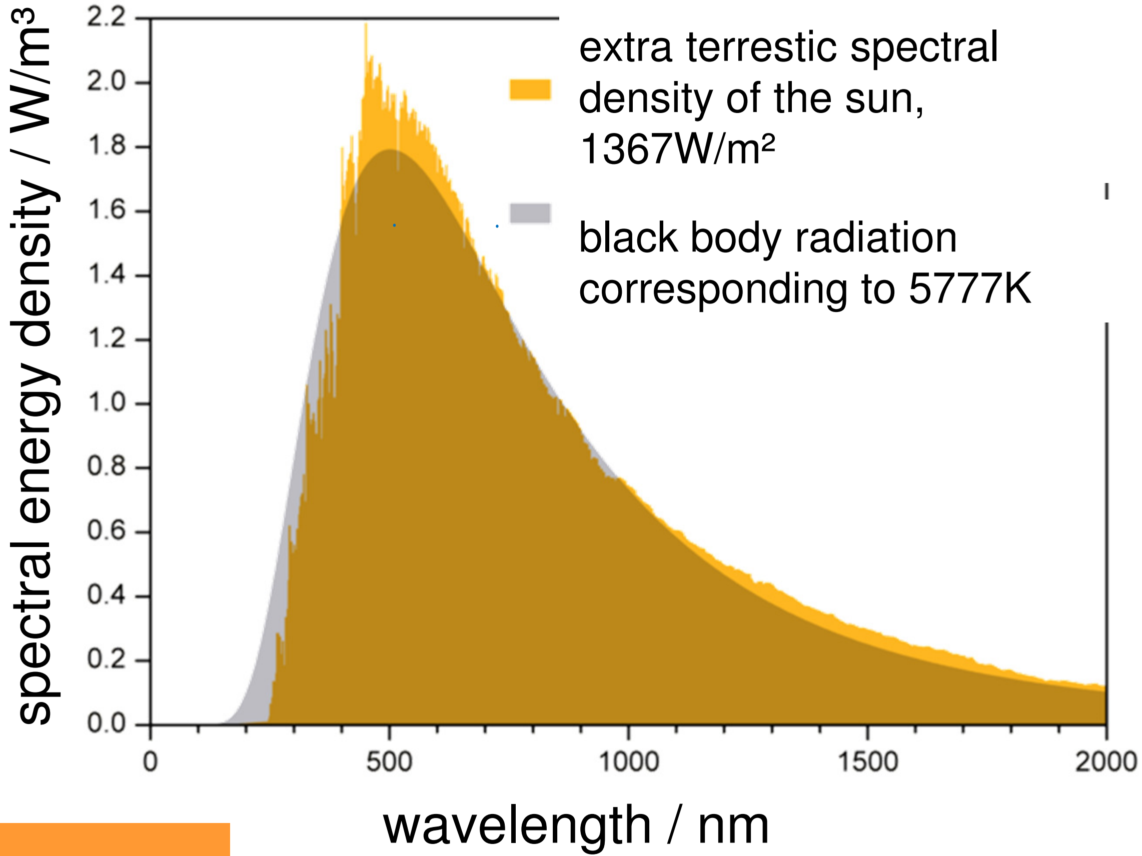
$$\frac{\Phi}{A} = E_0 = 1367 \frac{\text{W}}{\text{m}^2}$$ Extraterrestric solar constant

Solar systems

Emitted solar radiation per area - irradiance

$$\frac{\Phi}{A} = 63.11 \frac{\text{MW}}{\text{m}^2}$$

black body radiation?



Radiation power emitted by a surface element dA in the wavelength range between λ and λ + dλ

$$M(\lambda, T)\, dA d\lambda = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\left(\frac{hc}{\lambda kT}\right)} - 1} dA d\lambda$$

Planck's law

Solar systems

Facts about black body radiation

The spectrum of black body radiation was a proof of the existence of single photons forming electromagnetic waves

Energy can be transferred as electromagnetic waves

The total emitted solar energy consists of a number of photons differing in wavelength, i.e. photon energy

$$E = h \cdot f$$

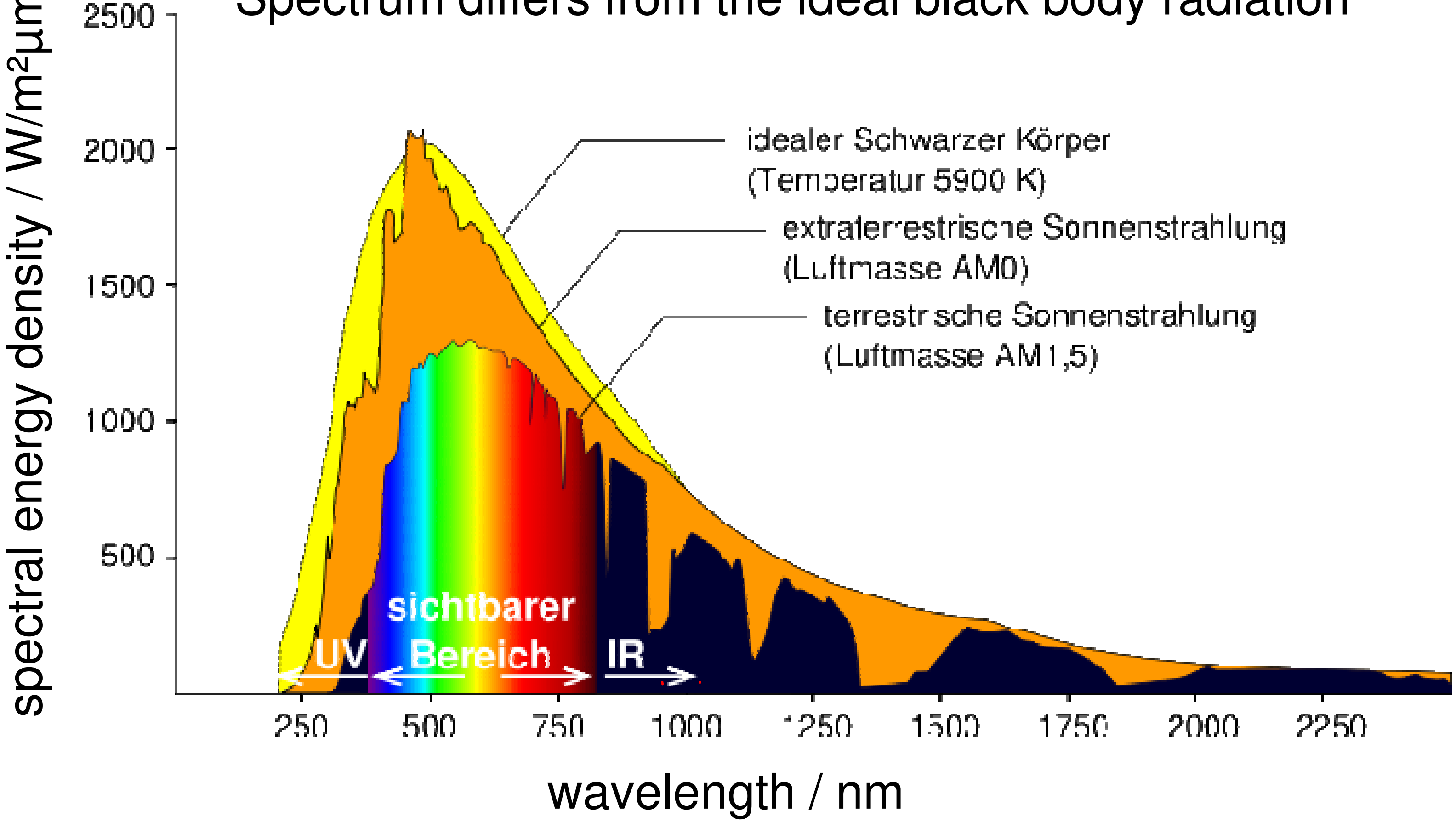
$$E_{tot} = \sum_i n_i \cdot h \cdot f_i$$

$$c = \lambda \cdot f$$

Solar systems

What happens to the photons on the flight from the sun to the earth?

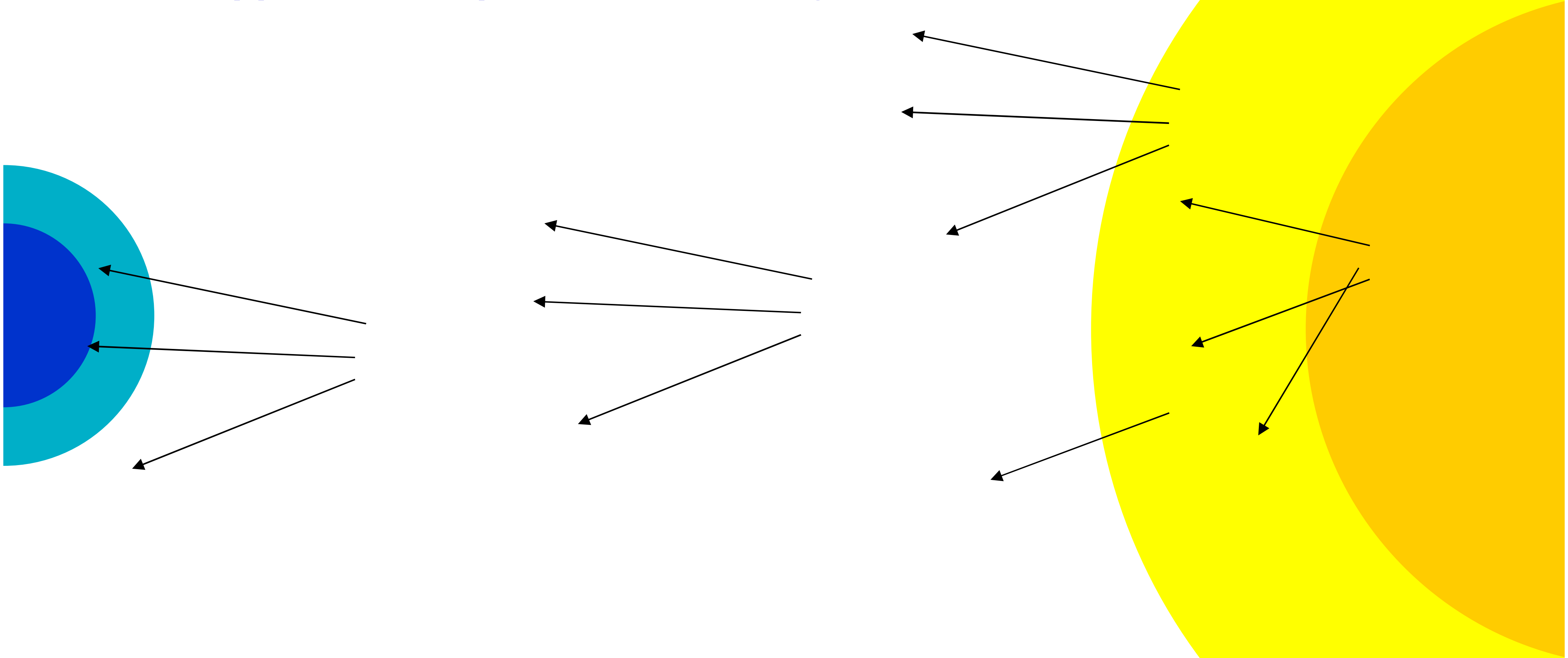
Spectrum differs from the ideal black body radiation



Attention: Spectrum versus wavelength leads to maximum at 500 nm, displayed versus photon energy the maximum is around 1.41 eV, i.e. 900 nm)

Solar systems

What happens to the photons on the flight?



- Emission of thermal radiation
- Absorption and scattering close to the sun
- Absorption and scattering close to the earth

wavelength dependent

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Solar systems

Absorption at the sun

Missing wavelengths correspond to the atomic resonances of the chemical elements in the vicinity of the sun

Absorption at the earth's atmosphere

Ozone absorbs high energetic radiation (except in Australia), (almost) no wavelengths below 300 nm hit the earth's surface

Different molecules: absorbing at single lines in the IR

All molecules: Rayleigh-Scattering (dimensions smaller than the wavelength)

$\sigma \propto f^4$

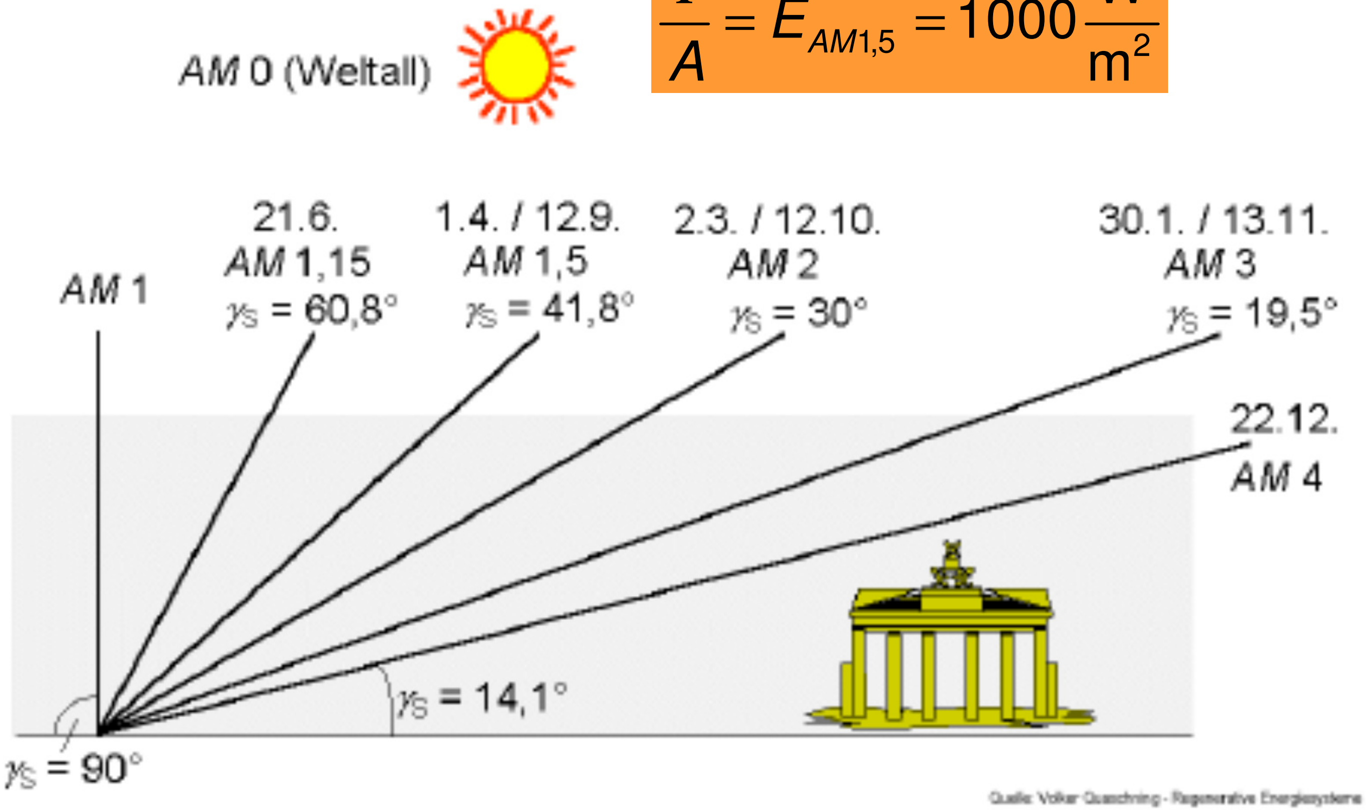
Dust, fog, Mie-scattering (object larger than the wavelength)

Solar cells and photosynthesis on the ground operates with a number of photons differing in **wavelength**, **number** and **direction**

Solar systems

Fraction of the radiation, that hit the surface

$$\frac{\Phi}{A} = E_{AM1,5} = 1000\,\frac{\mathrm{W}}{\mathrm{m}^2}$$



Air Mass Factor (AM) takes into account the impact of a propagation through an effectively thicker atmosphere

$$AM = \frac{1}{\sin \gamma_s}$$

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Solar systems

Typical values depending on the total losses

γ_S	AM	Absorption	Rayleigh-Streuung	Mie-Streuung	Gesamt-schwächung
90°	1,00	8,7 %	9,4 %	0 ... 25,6 %	17,3 ... 38,5 %
60°	1,15	9,2 %	10,5 %	0,7 ... 29,5 %	19,4 ... 42,8 %
30°	2,00	11,2 %	16,3 %	4,1 ... 44,9 %	28,8 ... 59,1 %
10°	5,76	16,2 %	31,9 %	15,4 ... 74,3 %	51,8 ... 85,4 %
5°	11,5	19,5 %	42,5 %	24,6 ... 86,5 %	65,1 ... 93,8 %

Difference of direct and indirect radiation

Tabelle 2.7 Tägl. Direkt- und Diffusstrahlung im Monatsmittel (1966-75) in Berlin [Pal96]

kWh/(m² d)	Jan	Feb	Mär	Apr	Mai	Juni	Juli	Aug	Sep	Okt	Nov	Dez	Jahr
direkt	0,17	0,40	1,03	1,42	2,13	2,58	2,29	2,05	1,38	0,54	0,22	0,10	1,20
diffus	0,44	0,74	1,41	2,07	2,64	2,86	2,97	2,53	1,67	1,05	0,54	0,35	1,61

Plants or technical systems can direct towards maximum (direct) radiation

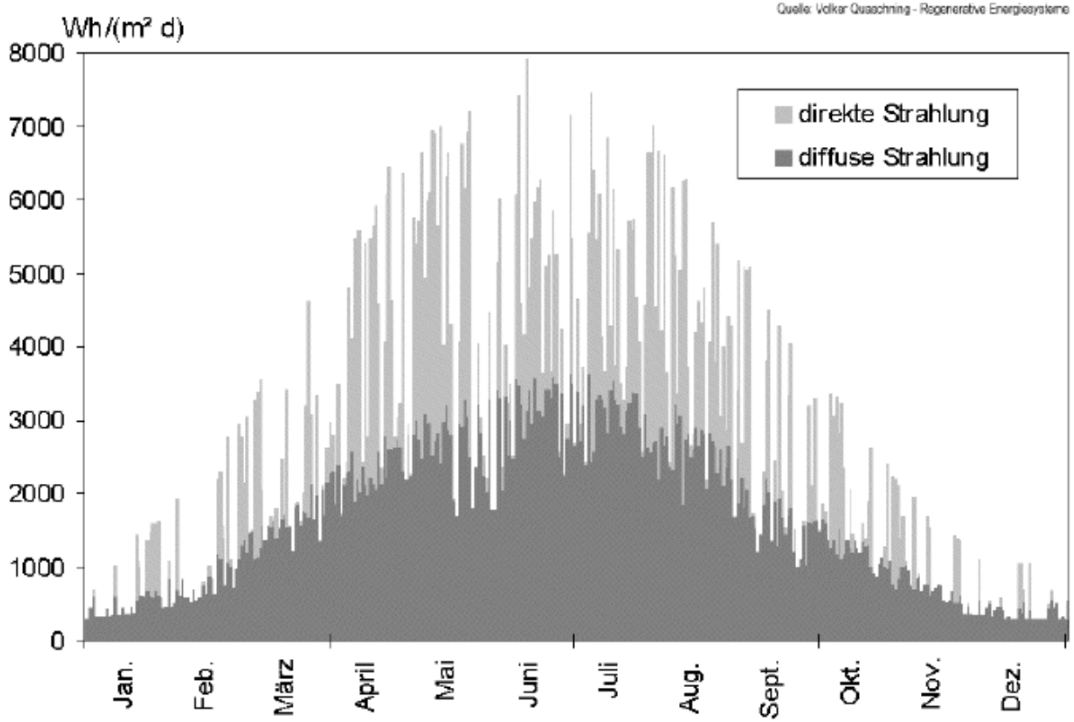
Solar systems

Difference of direct and indirect radiation

Tabelle 2.8 Jahresmittelwerte (1966-75) der täglichen Direkt- und Diffusstrahlung [Pal96]

kWh/ (m² d)	Bergen	Stock-holm	Berlin	London	Wien	Nizza	Rom	Lissabon	Athen
direkt	0,86	1,41	1,20	0,99	1,40	2,59	2,41	3,06	2,67
diffus	1,29	1,42	1,61	1,47	1,63	1,66	1,78	1,67	1,66

Quelle: Volker Quaschning - Regenerative Energiesysteme



Large differences in the composition

- long term
- short term
- spatially

Local vegetation!

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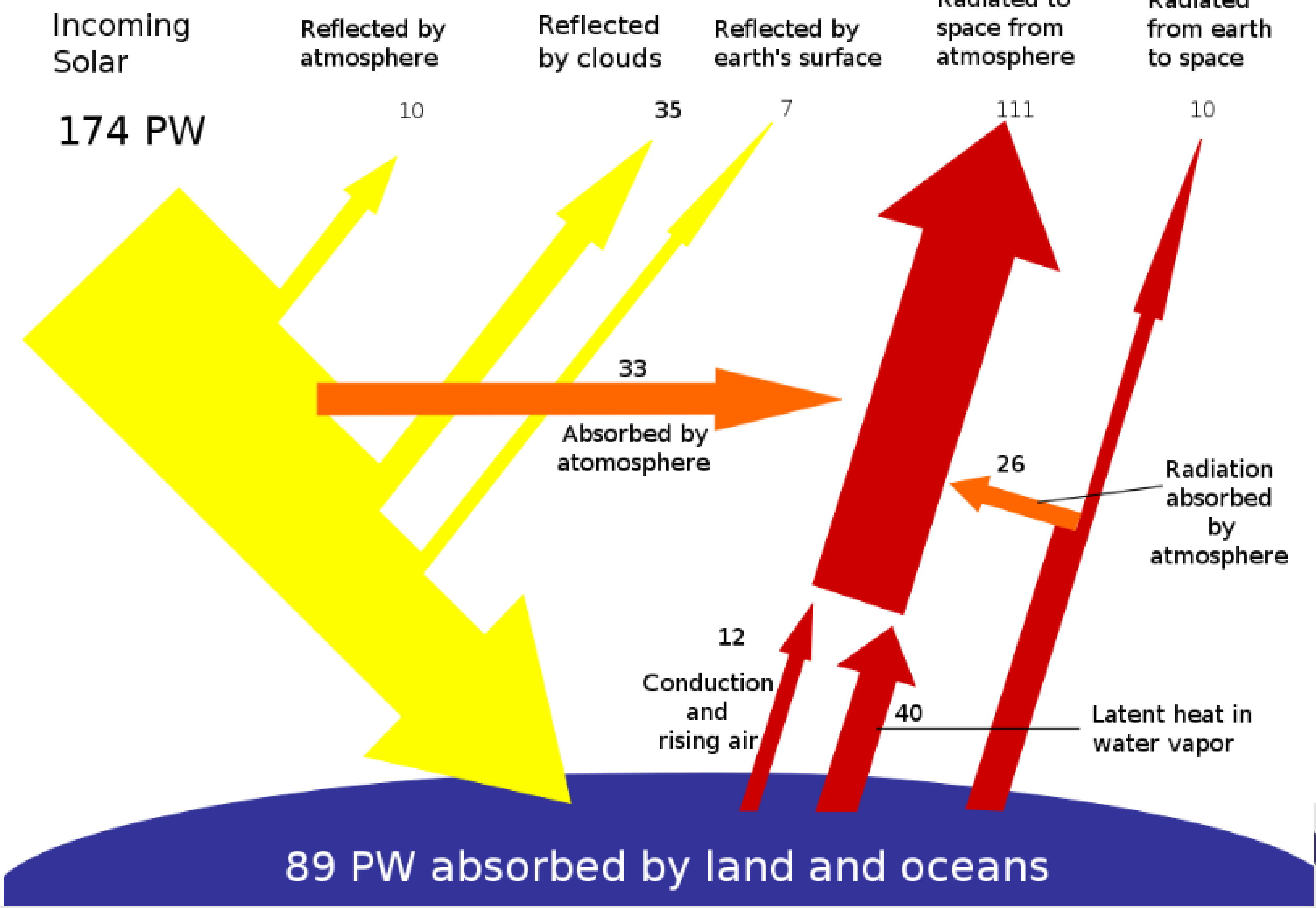
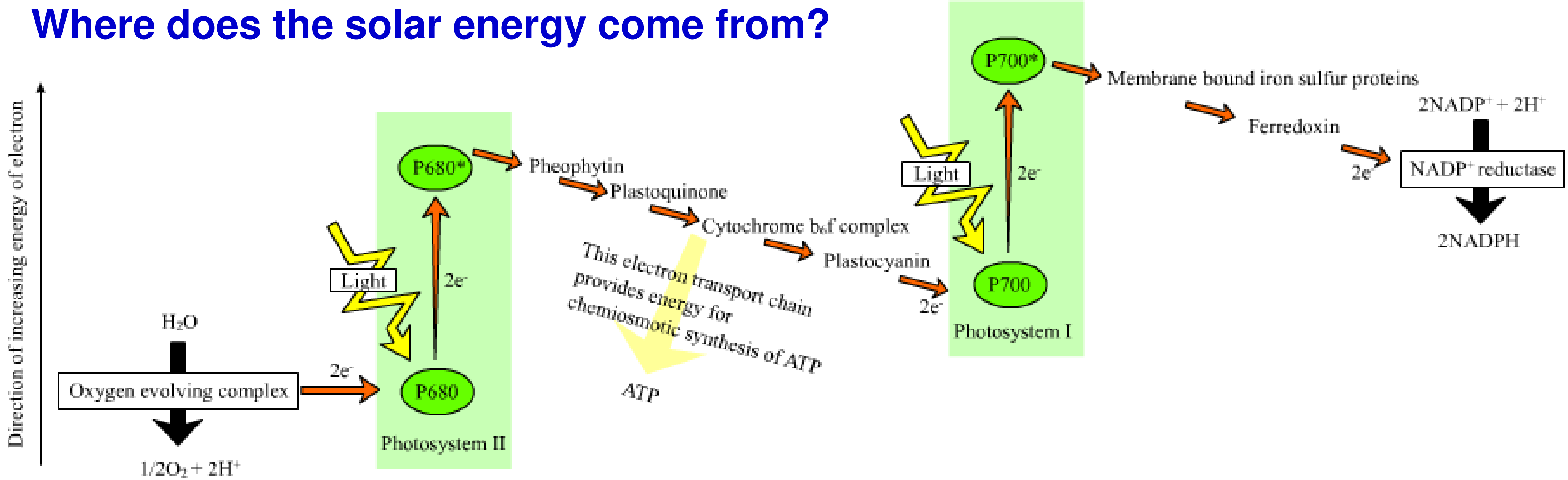
Solar systems

Energy balance



Photosynthesis

Where does the solar energy come from?



$$6H_2O + 6CO_2 \xrightarrow{\text{photons ' energy}} C_6H_{12}O_6 + 6O_2$$

$\Delta G = 2875\,kJ/mol = 1.8 \cdot 10^{25}\,eV/mol$

$\Rightarrow \underline{30\,eV}$ ≙ 10 blue photons

20 red "

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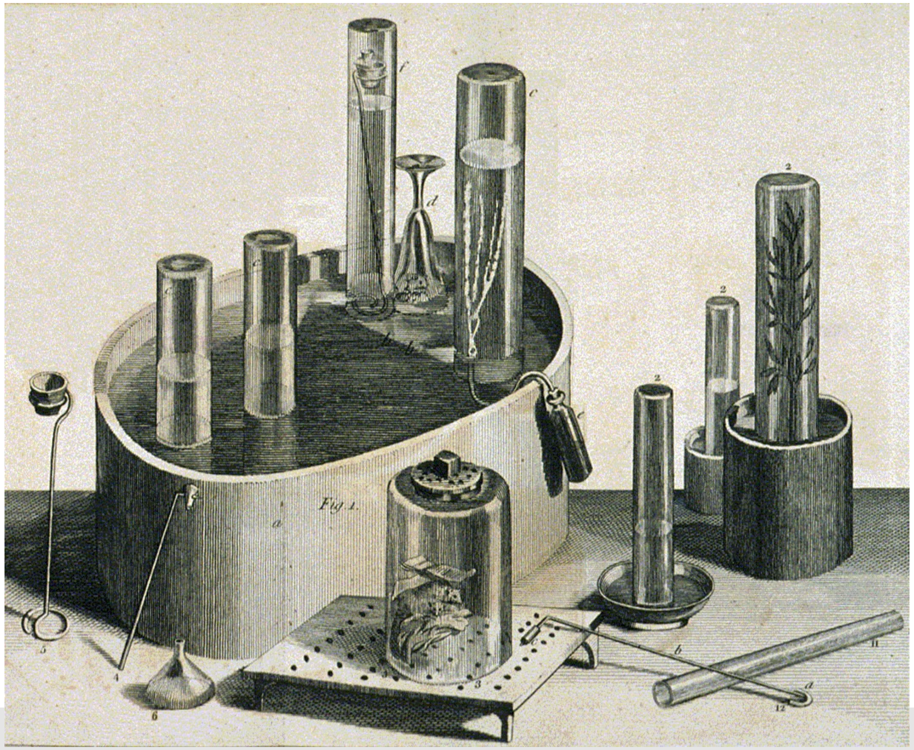
Photosynthesis

Historic experiment

Joseph Priestley discovered:

- candles burn by the help of oxygen
- oxygen concentration can be increased with the help of plants

Photosynthesis can convert CO_2 into O_2 with the help of sunlight



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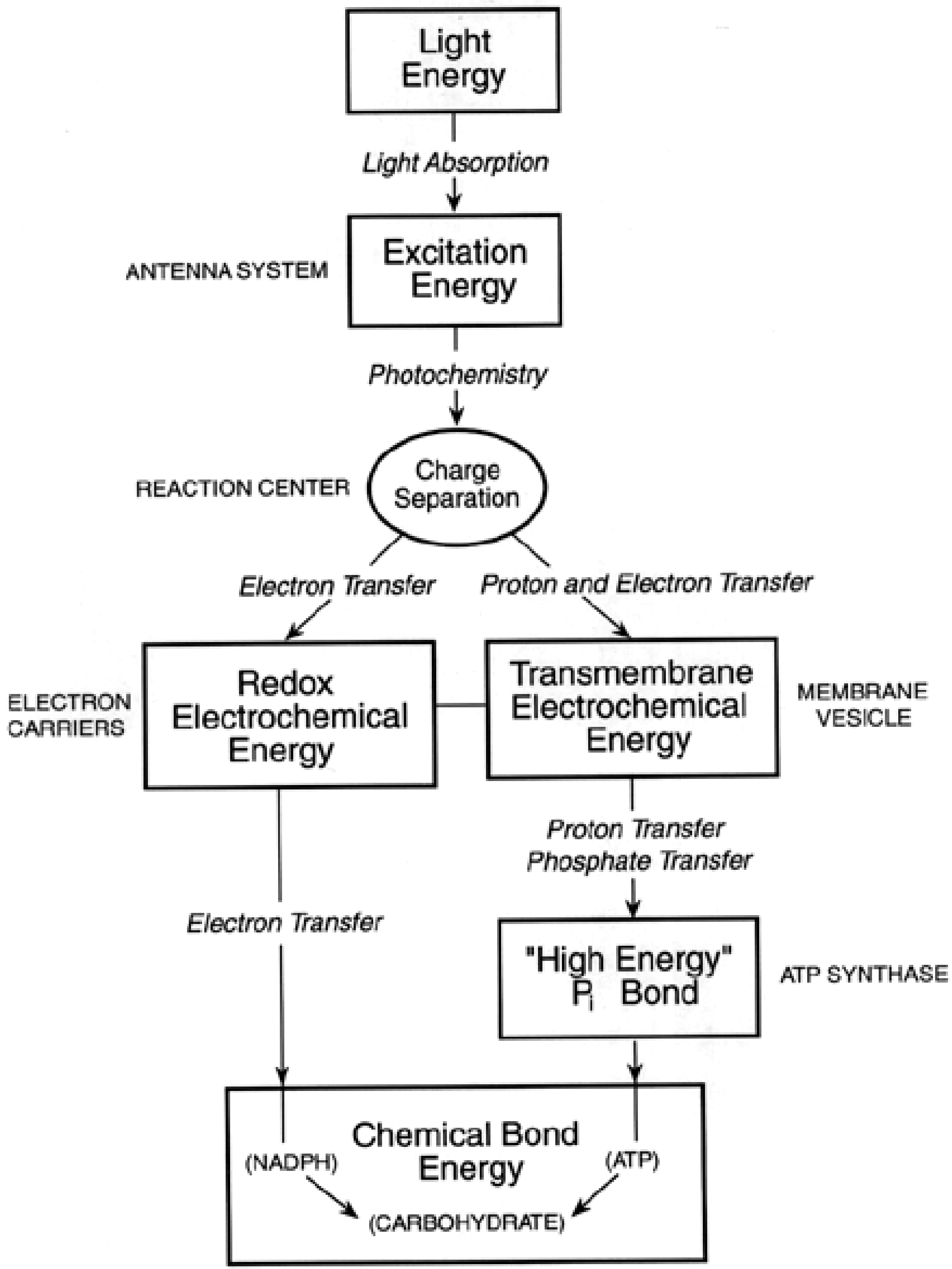
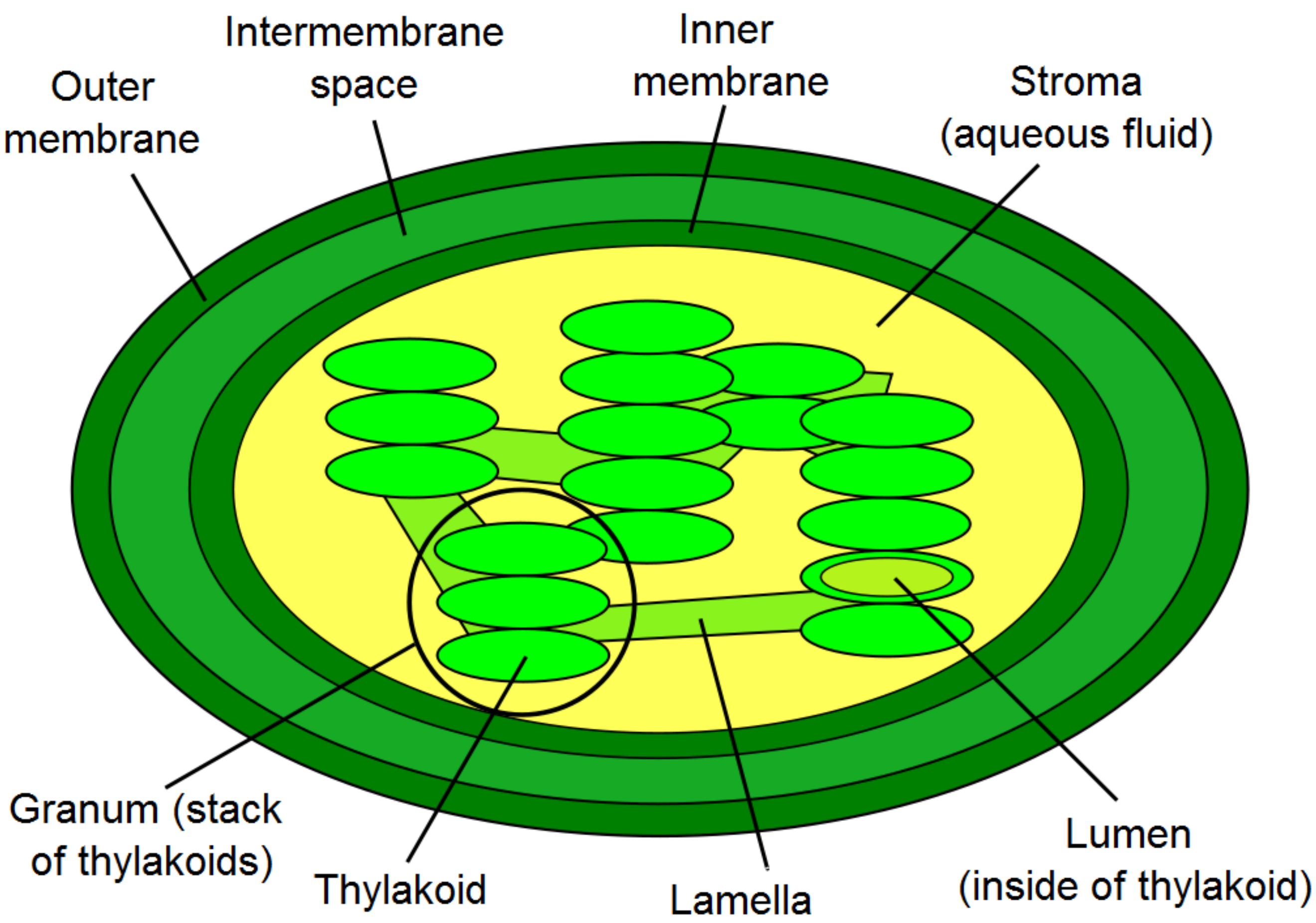
Energy Transformation in Photosynthesis

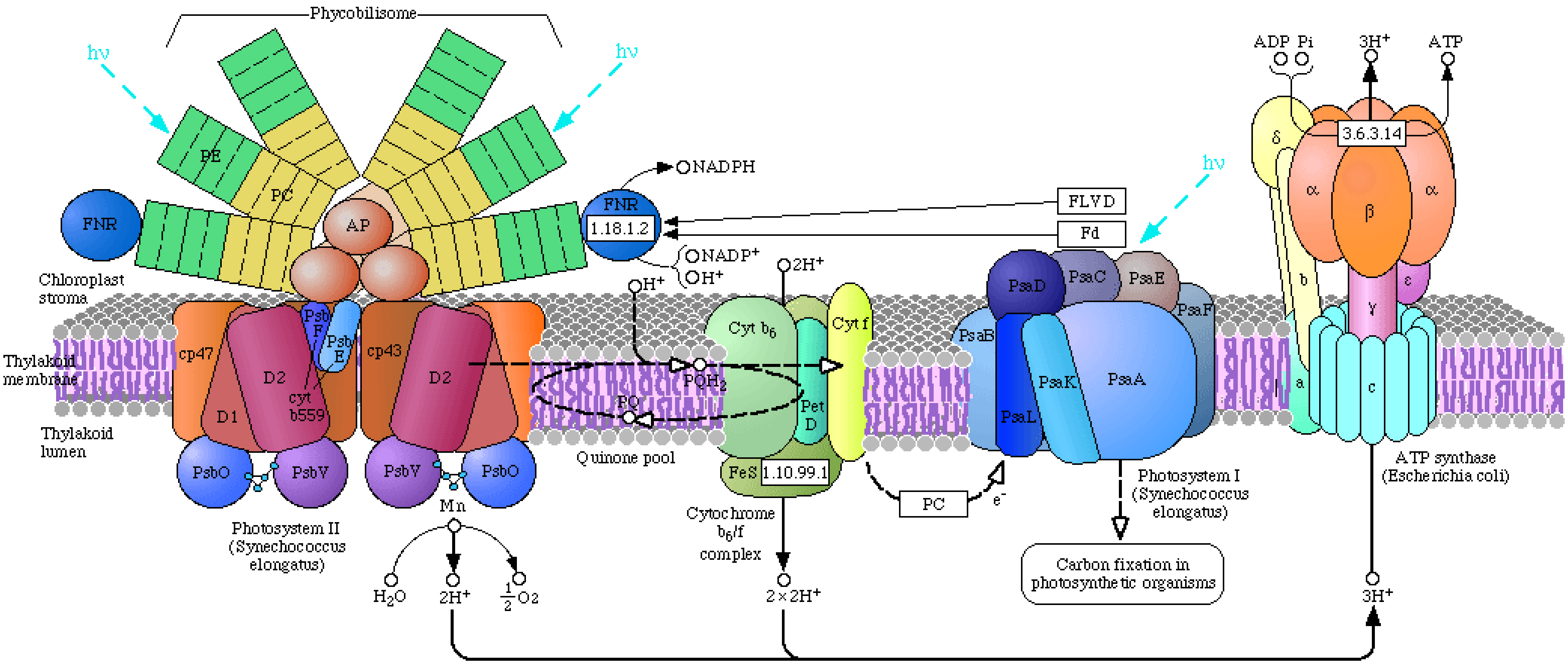


Photosynthesis

Setup of a chromoplast



Photosynthesis



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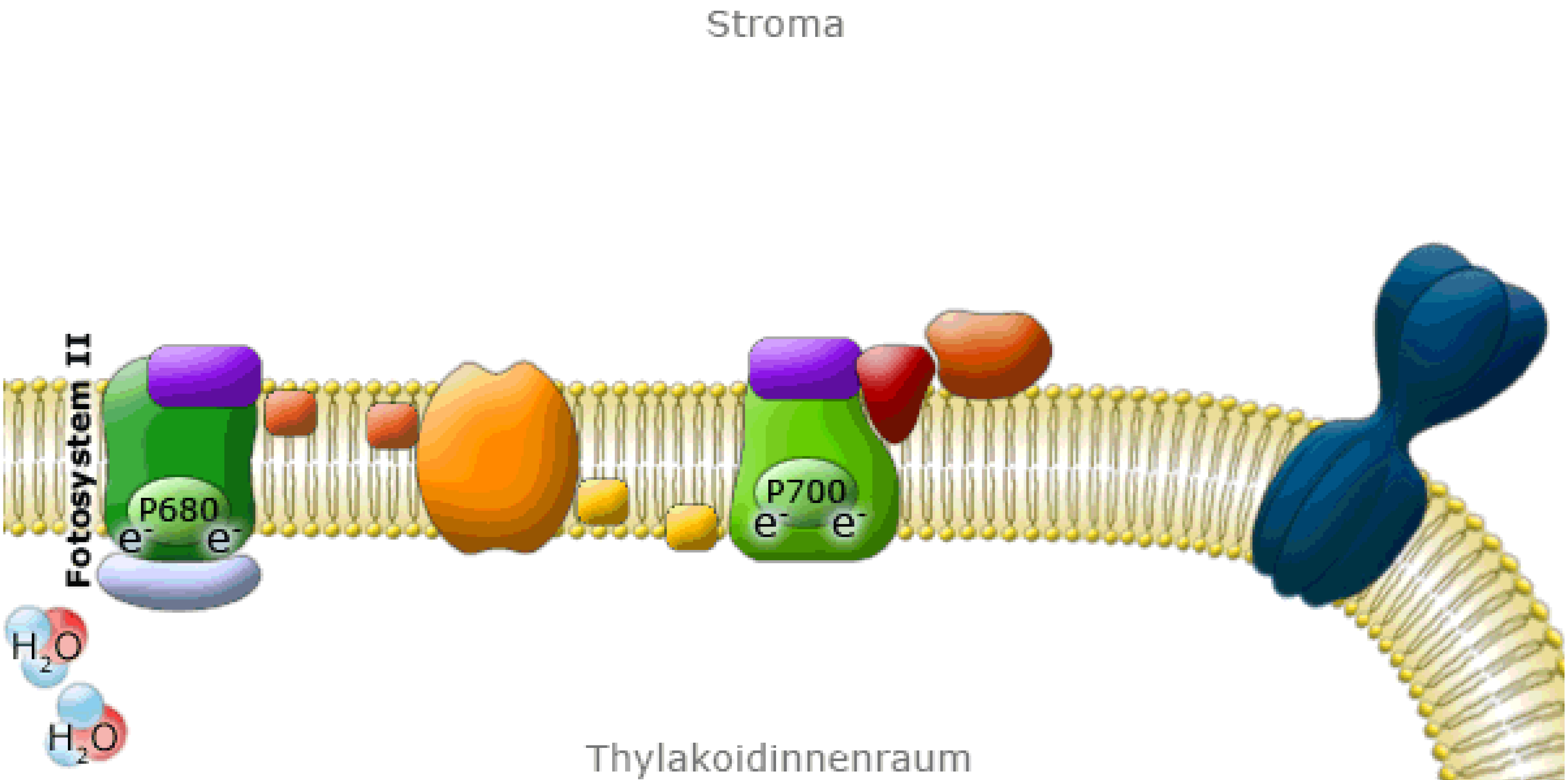
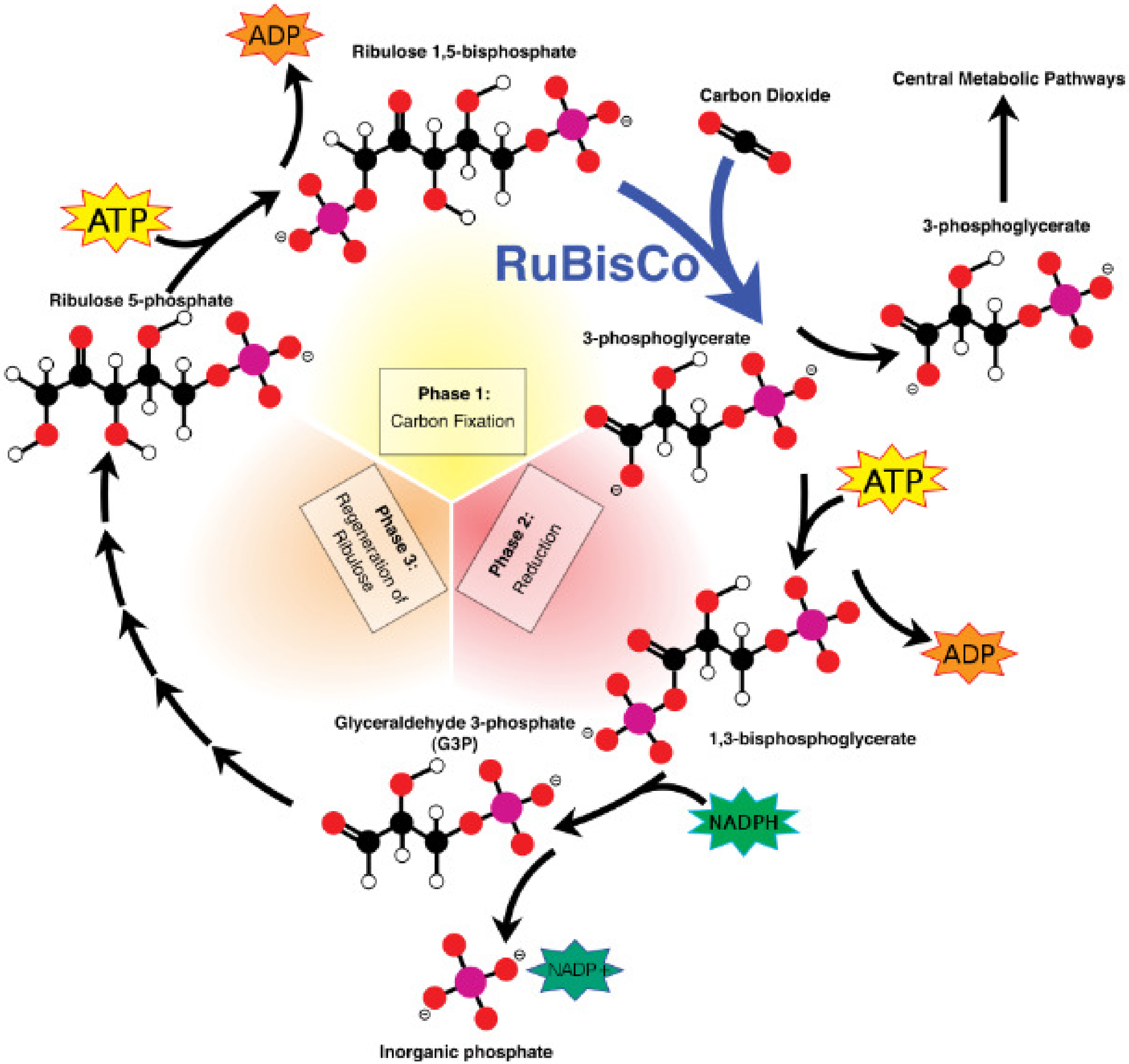
Photosynthesis



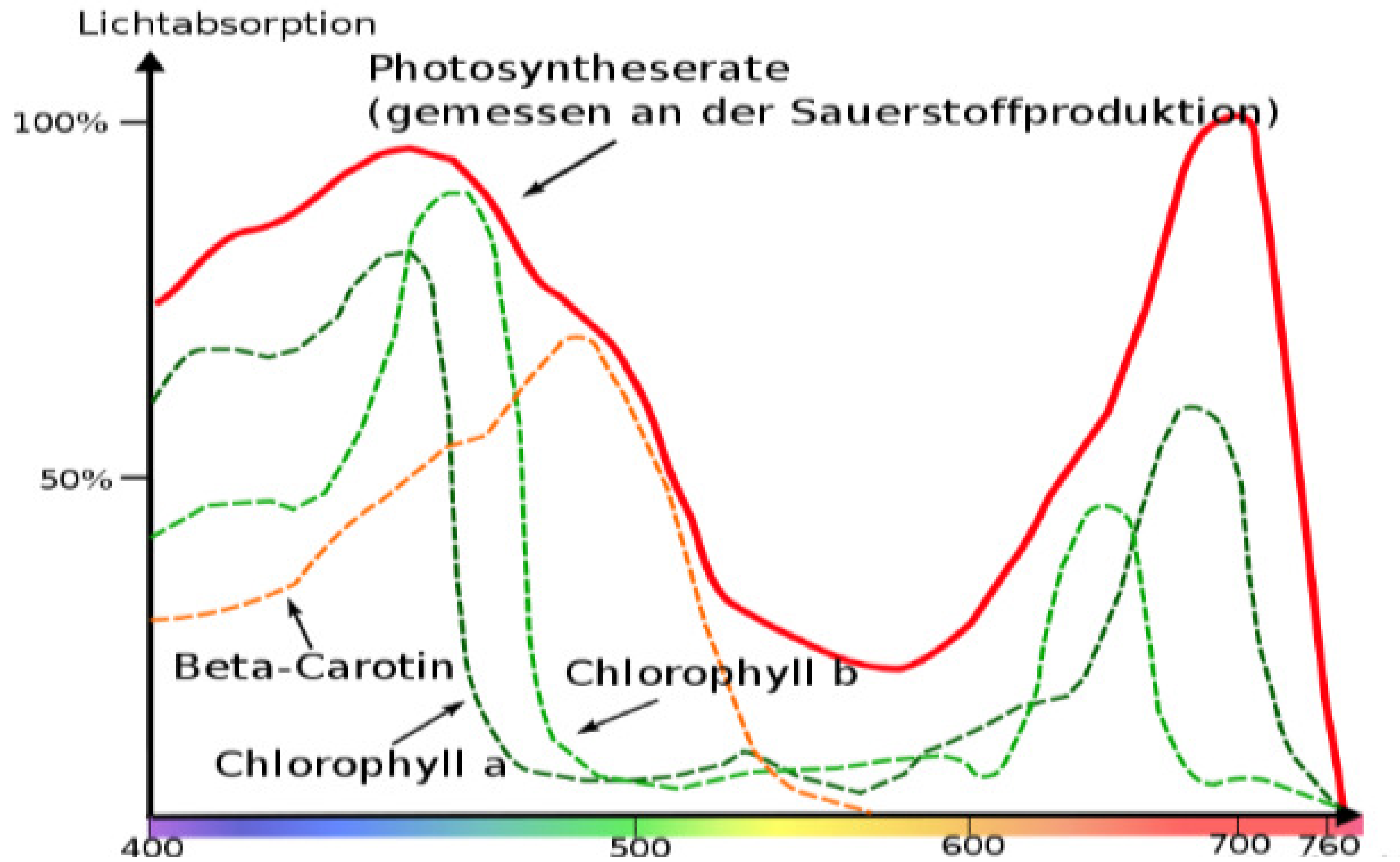
Photosynthesis



Calvin-Benson cycle:
Formation of glucoses-like molecules

Photosynthesis

Sensitivity of chlorophyll



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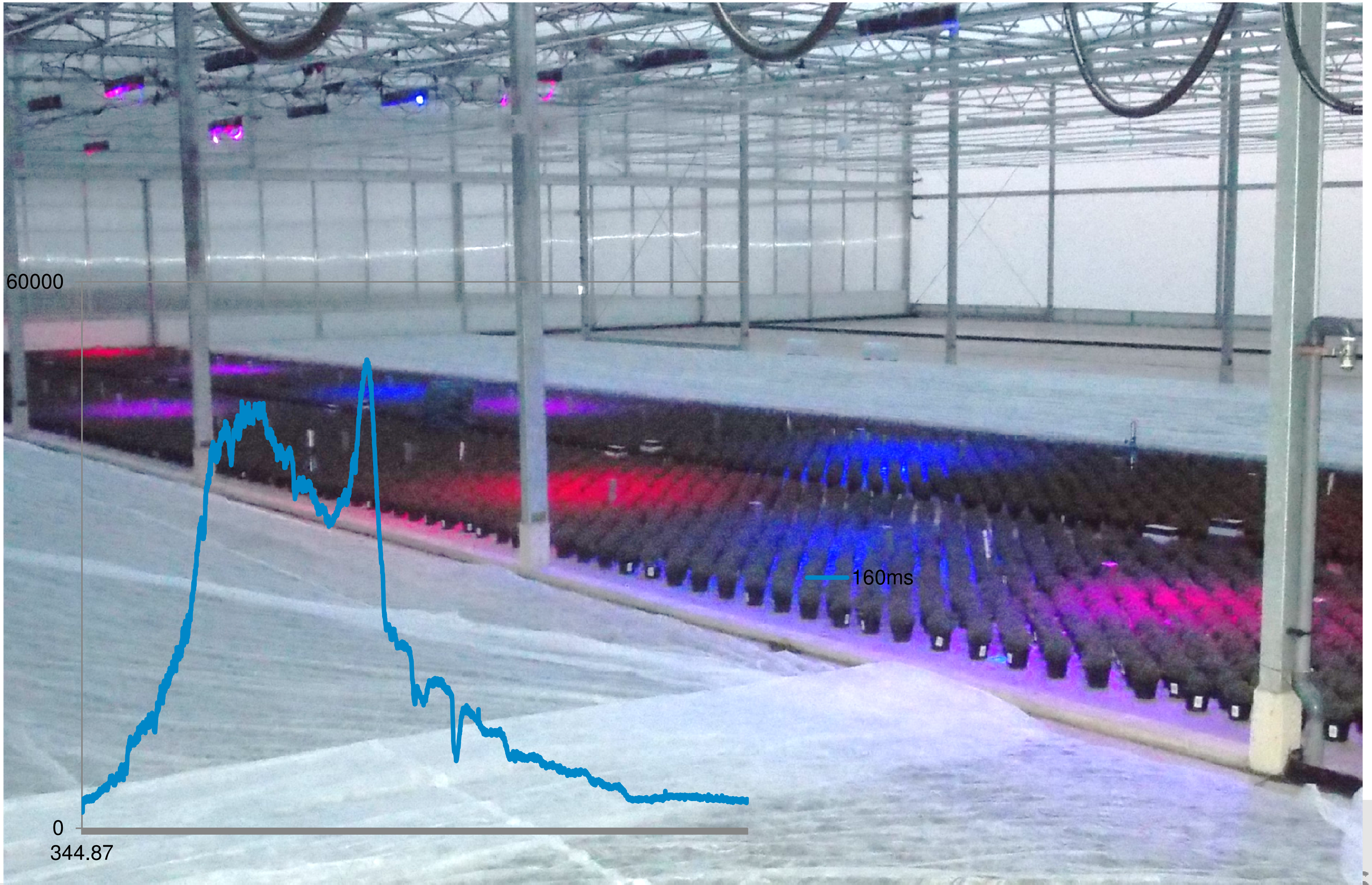
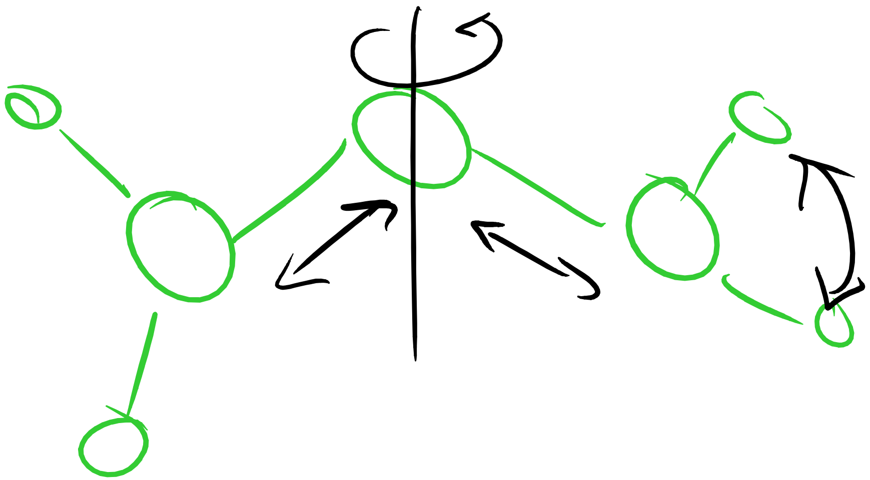
Photosynthesis

Artificial illumination



Photosynthesis

Molecule spectra and excitations



- Electrons (standing waves) form discrete energy levels
- Energy can be stored in the rotation of a molecule (in the gas phase)
- Energy can be stored in the vibration of a molecule

$$E = h \cdot f = E_n + E_{rot} + E_{vib}$$

Photosynthesis

Molecule spectra and excitations

$$E_{rot} = \frac{1}{2} I \omega^2 = \frac{L^2}{2I}$$

Quantization of angular momentum

$$L^2 = J(J+1)\hbar^2$$

$$J = 0, 1, 2, \ldots$$

Rotation quantum number

$$E_{vib} = \left(\mathrm{v} + \frac{1}{2}\right) h \cdot \nu$$

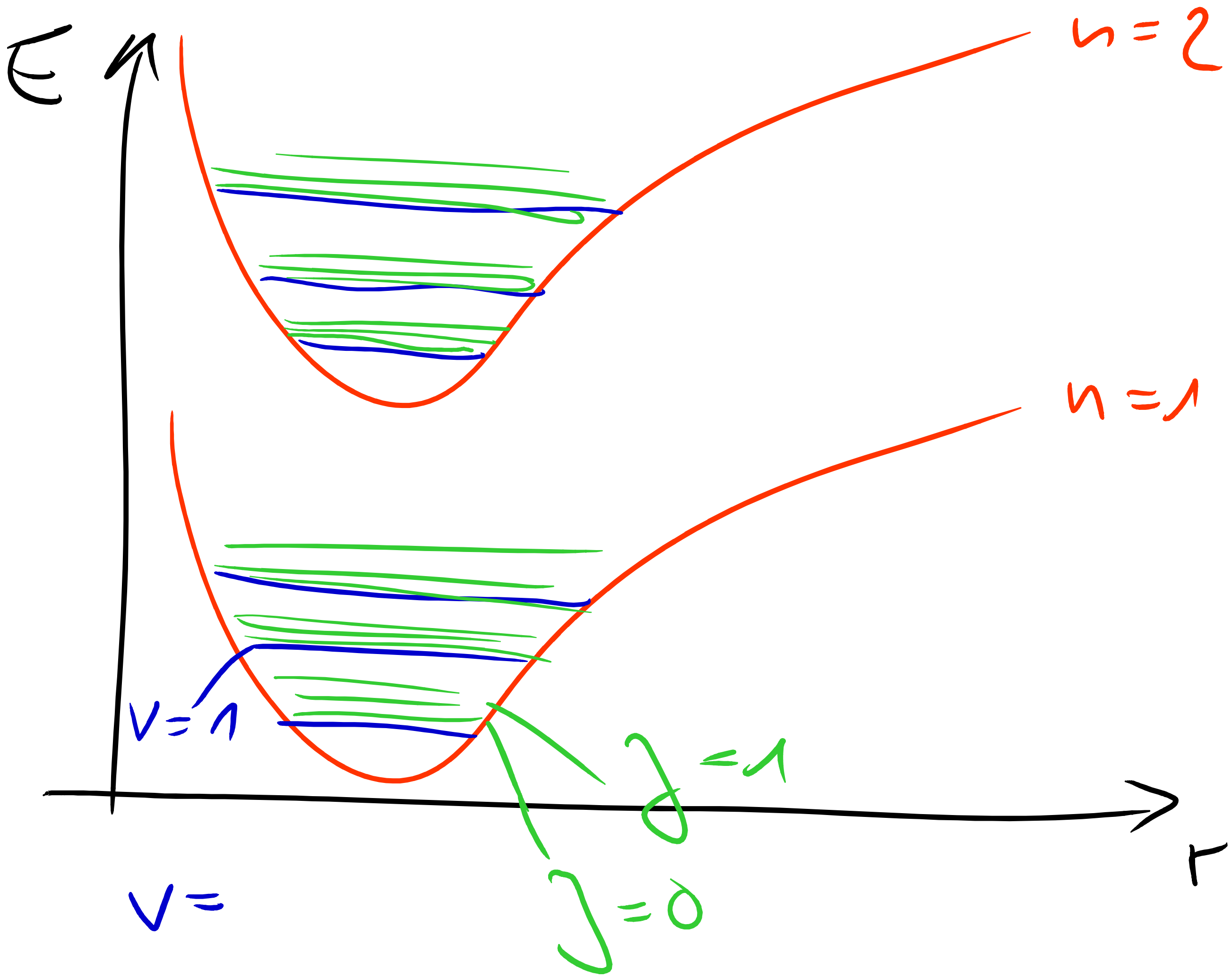
oscillation frequency

oscillation quantum number

Similar to classical mechanical spring plus quantum mechanics

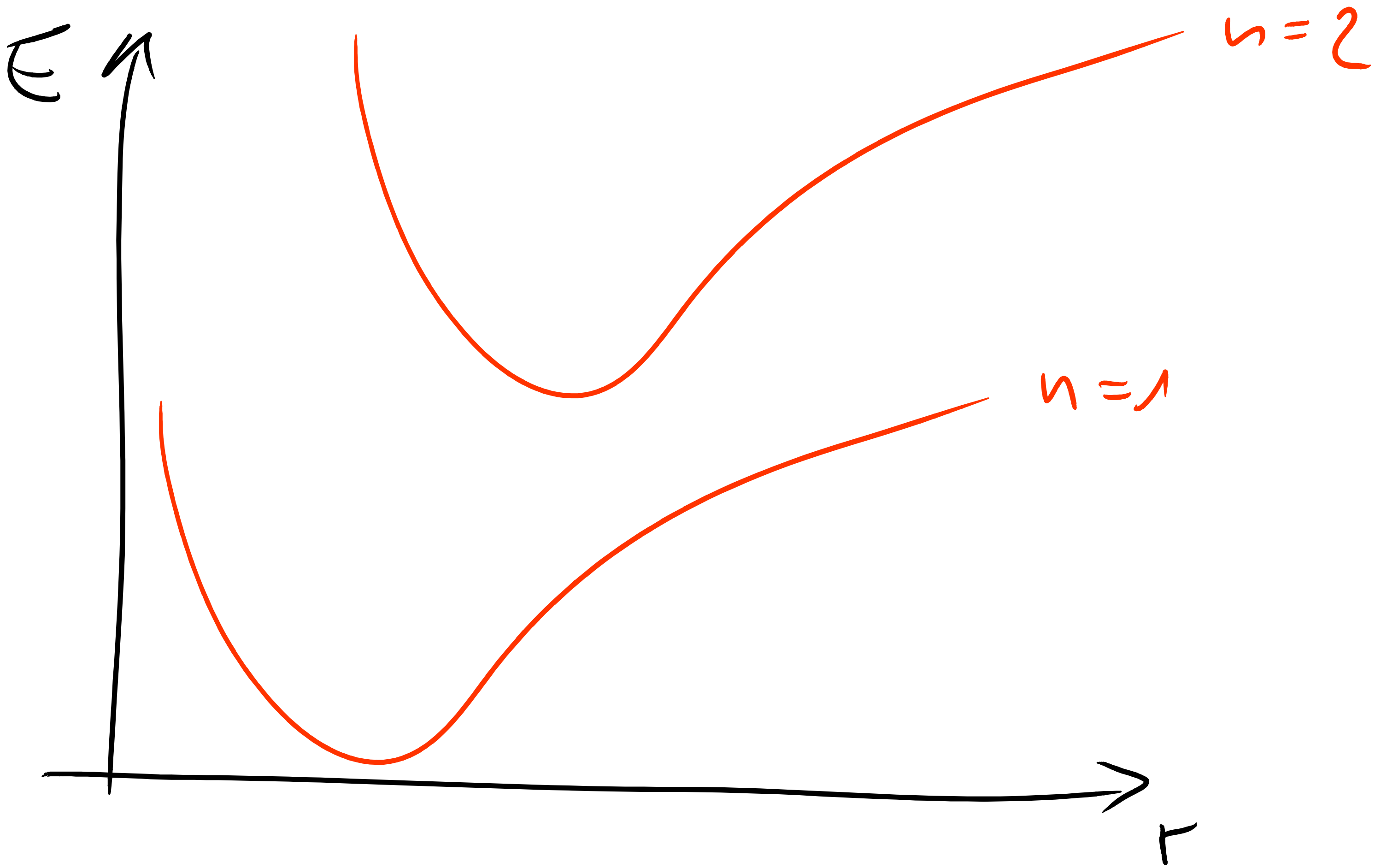
Photosynthesis

Molecule spectra and excitations



Photosynthesis

Molecule spectra and excitations



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Photosynthesis

Efficiency

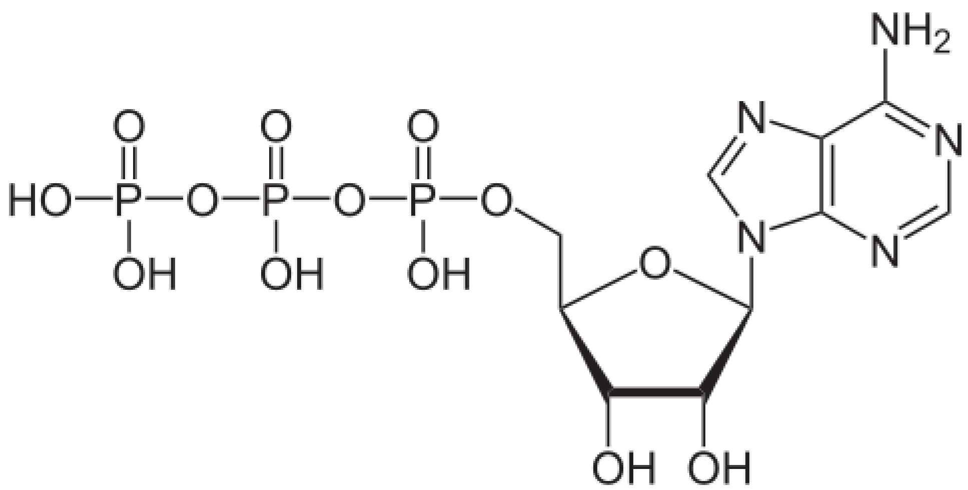
Photon absorption: close to 100%

Primary photochemical reaction: 40%

Total photochemical process: 3-4%

Main benefit of photosynthesis is the combined energy storage in carbon hydrate

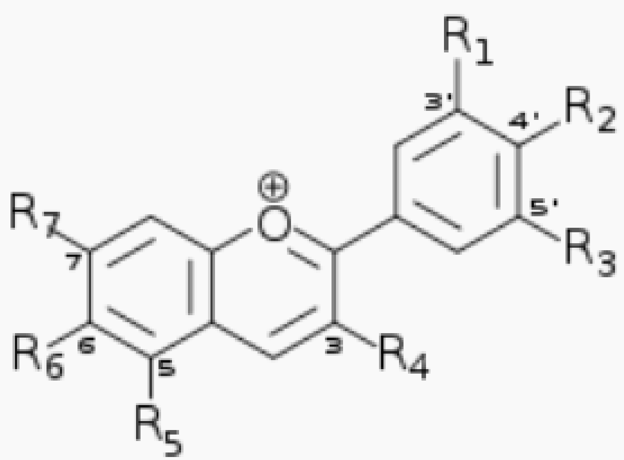
ADP and P is converted to ATP by light:

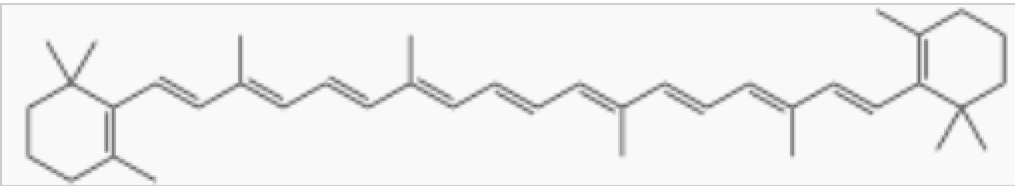


Photosynthesis

Other chemical compounds in addition to chlorophyll

Selected anthocyanidins and their substitutions

Anthocyanidin	Basic structure	R_1	R_2	R_3	R_4	R_5	R_6	R_7
Aurantinidin		−H	−OH	−H	−OH	−OH	−OH	−OH
Cyanidin		−OH	−OH	−H	−OH	−OH	−H	−OH
Delphinidin		−OH	−OH	−OH	−OH	−OH	−H	−OH
Europinidin		$-OCH_3$	−OH	−OH	−OH	$-OCH_3$	−H	−OH
Luteolinidin		−OH	−OH	−H	−H	−OH	−H	−OH
Pelargonidin		−H	−OH	−H	−OH	−OH	−H	−OH
Malvidin		$-OCH_3$	−OH	$-OCH_3$	−OH	−OH	−H	−OH
Peonidin		$-OCH_3$	−OH	−H	−OH	−OH	−H	−OH
Petunidin		−OH	−OH	$-OCH_3$	−OH	−OH	−H	−OH
Rosinidin		$-OCH_3$	−OH	−H	−OH	−OH	−H	$-OCH_3$



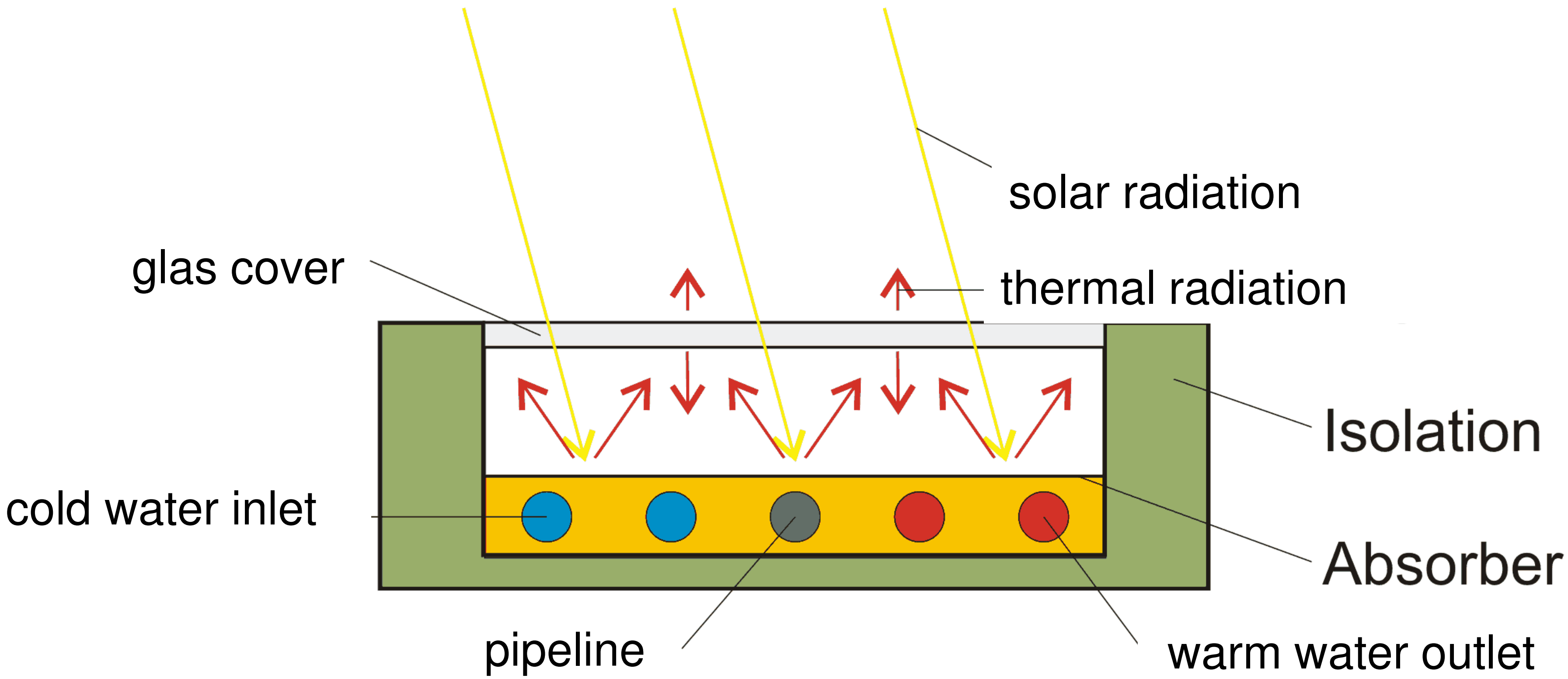
β-Carotin

Solar thermal systems

Flat solar thermal collector

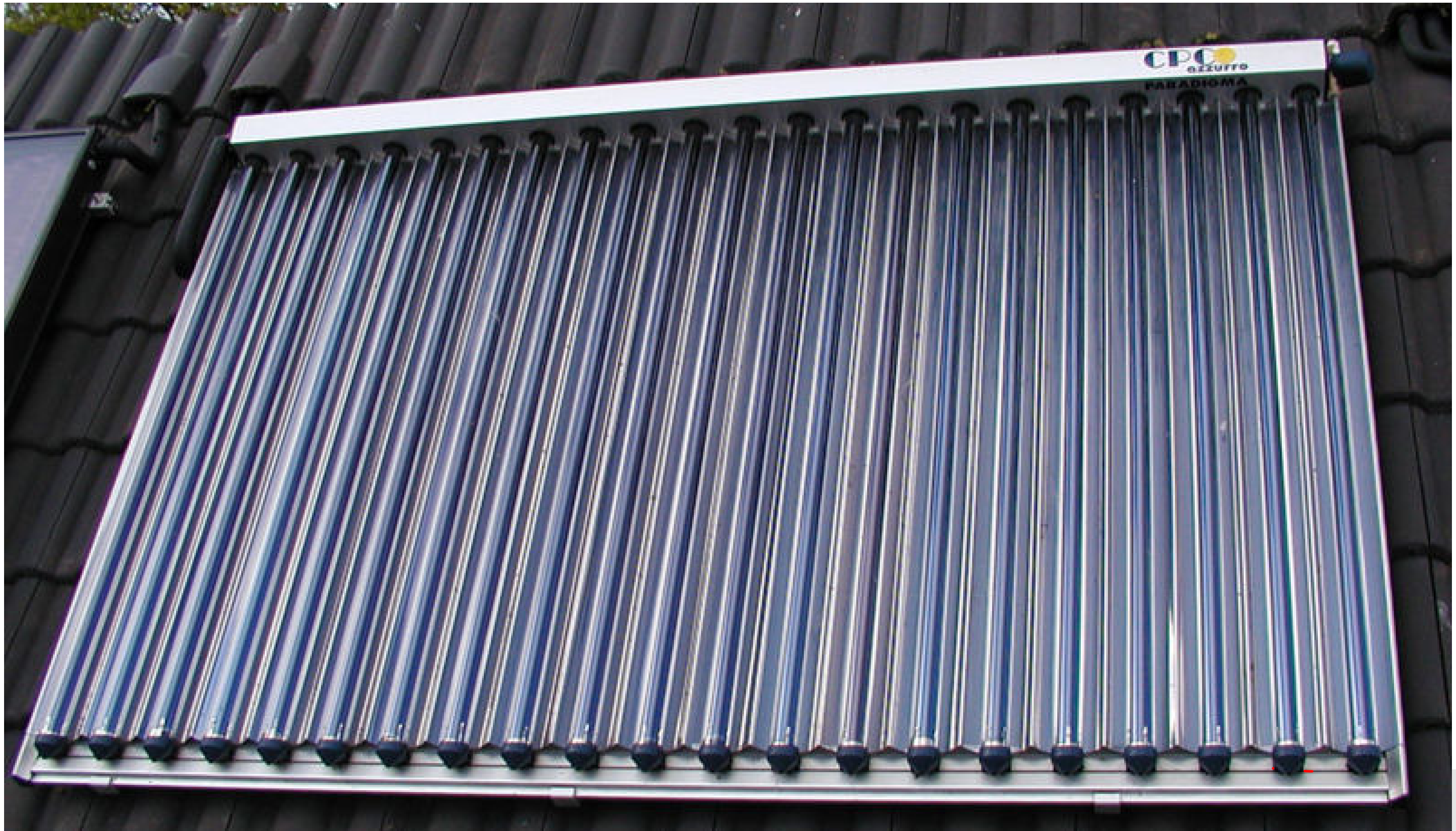
Solar thermal systems

Flat solar thermal collector



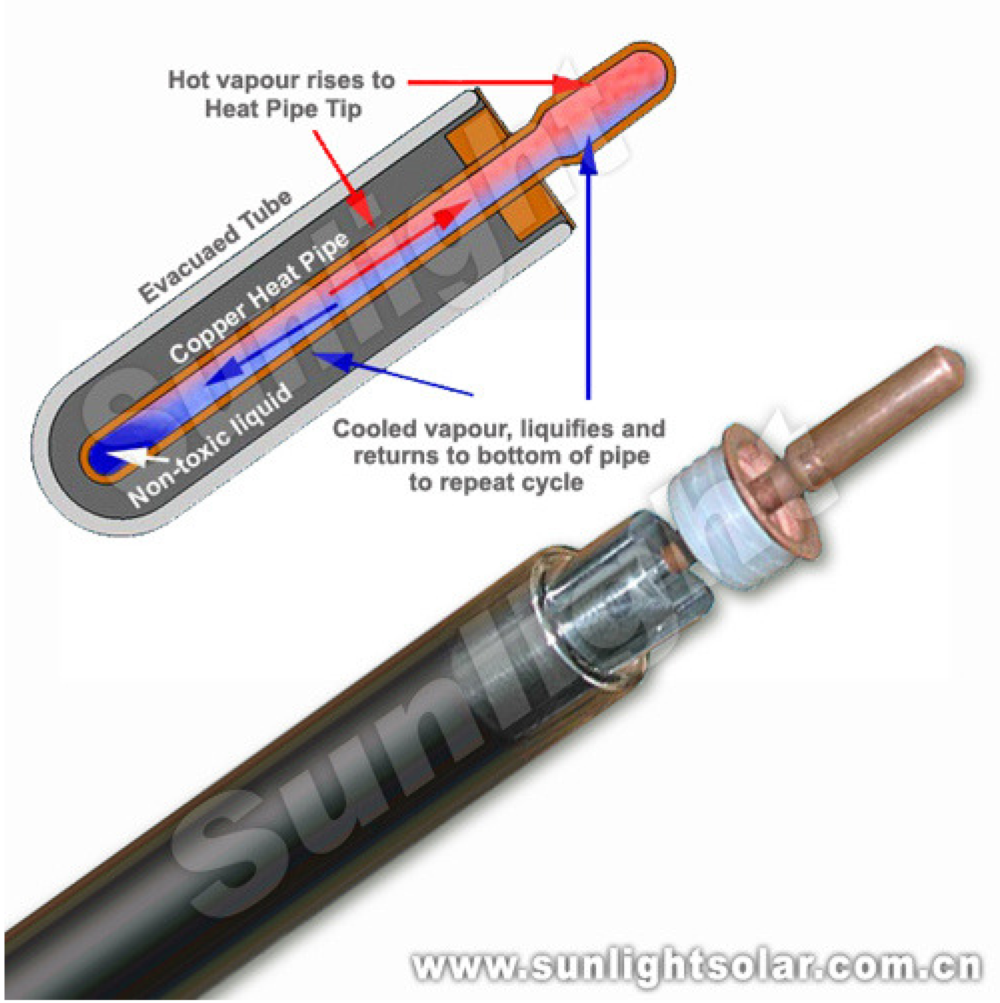
Solar thermal systems

Vacuum solar collector



Solar thermal systems

Vacuum solar collector



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Solar thermal systems

Parabolic 1D and 2D

Solar thermal systems

Maximum performance is governed by

- the ability to concentrate the light
- smart ways to guide the heat
- avoid thermal radiation of the system
- reduce losses due to convection
- smart heat storage systems

Maximum benefit is governed by

- the production costs
- the annual absorbed energy
- ways to simply adjust the system to follow the direct sunlight
- the maximum temperature achieved

Solar thermal systems