Solar Photovoltaics & Energy Systems

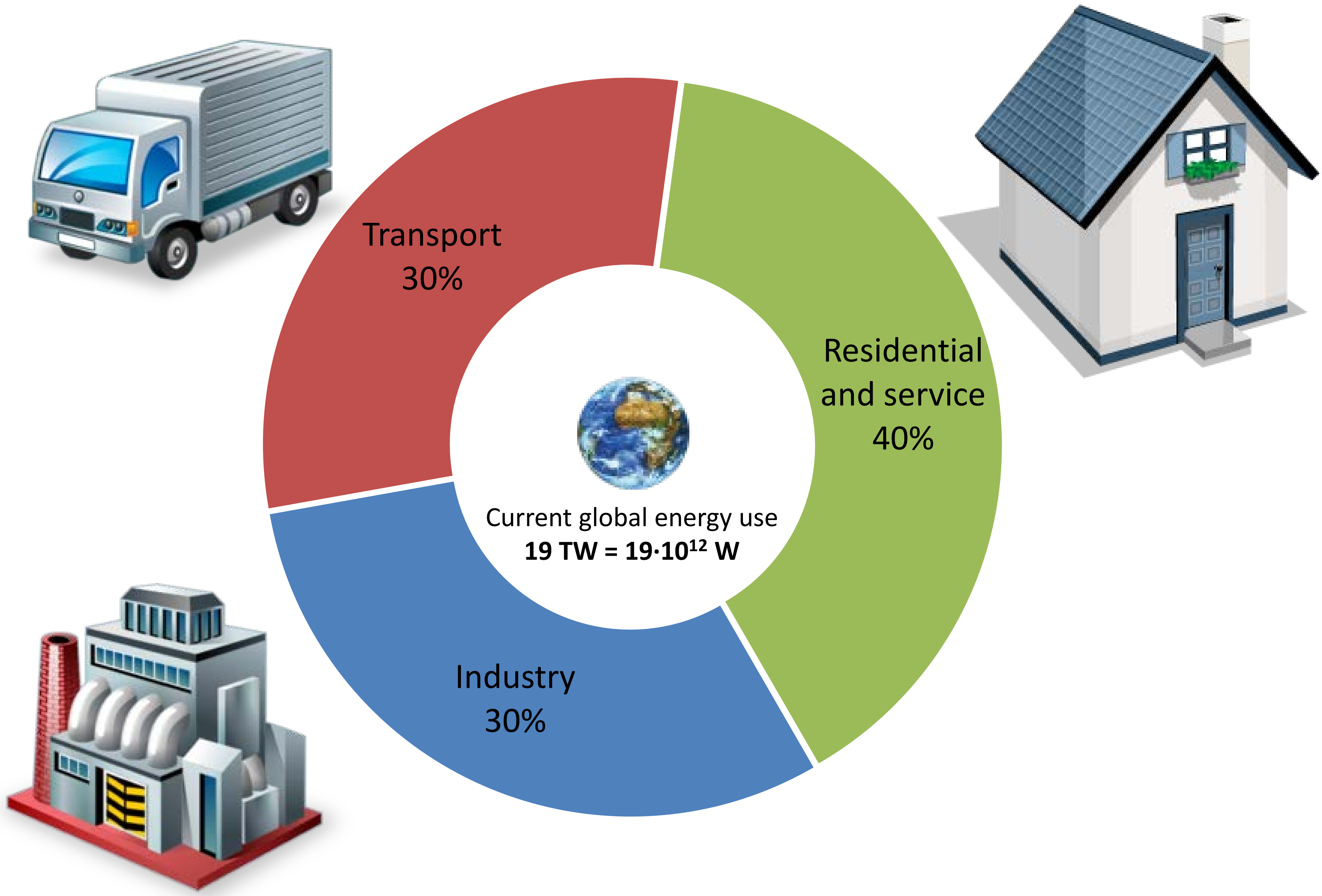
Lecture 1 – The nature of Solar irradiation, thermodynamics of solar energy conversion, solar thermal limitations

ChE-600

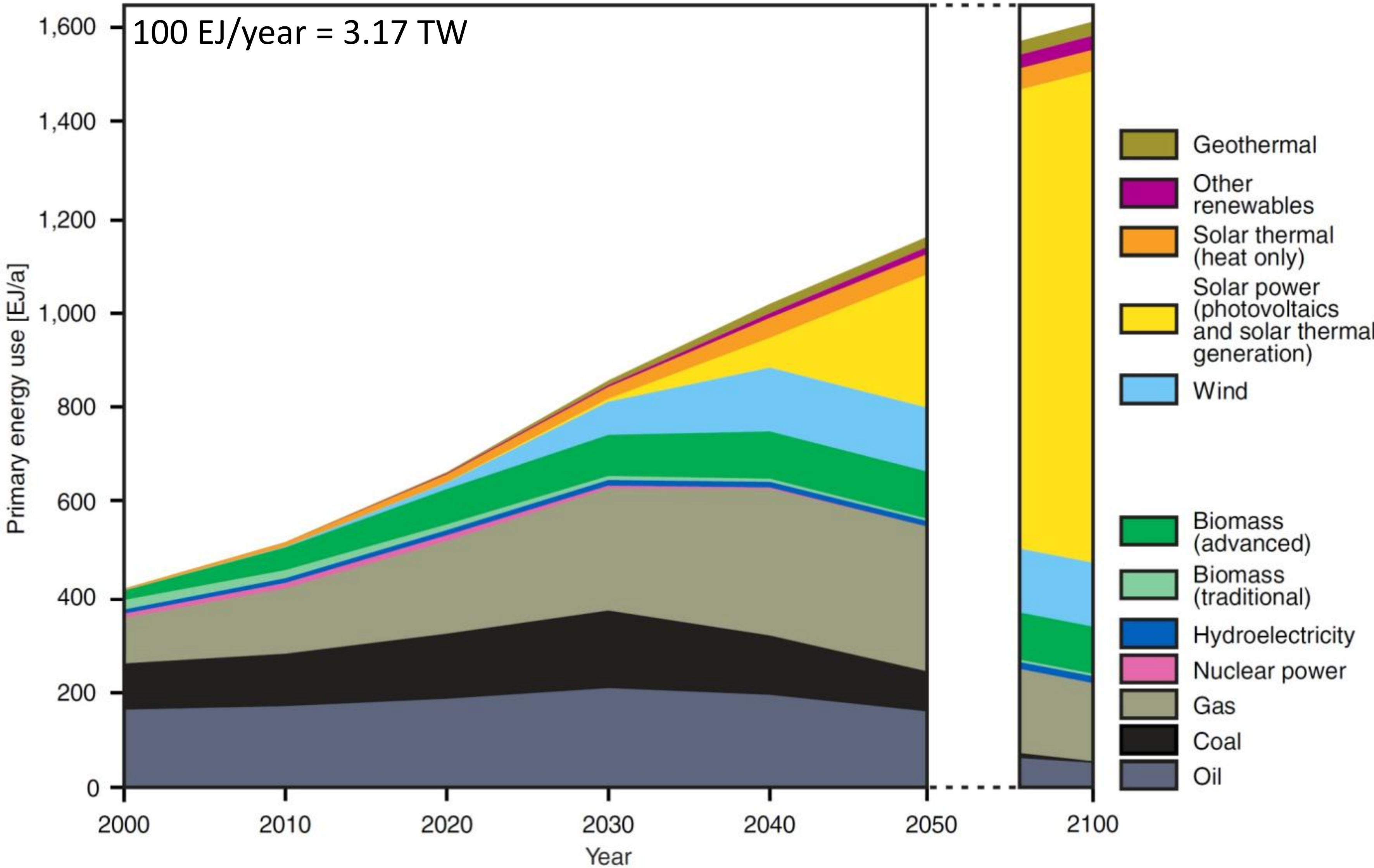
Kevin Sivula, Spring 2018

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Energy use today and in the future

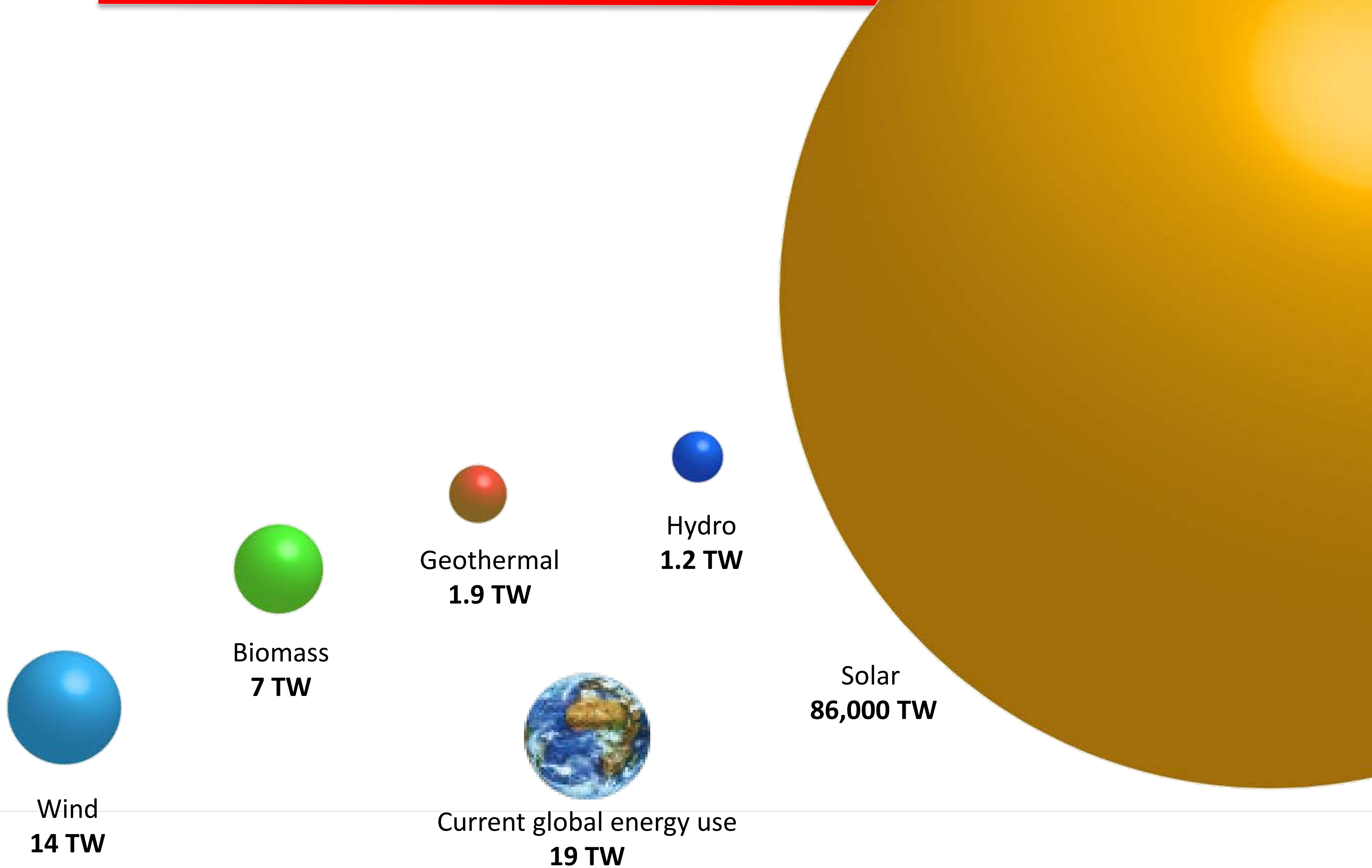


Energy use today and in the future



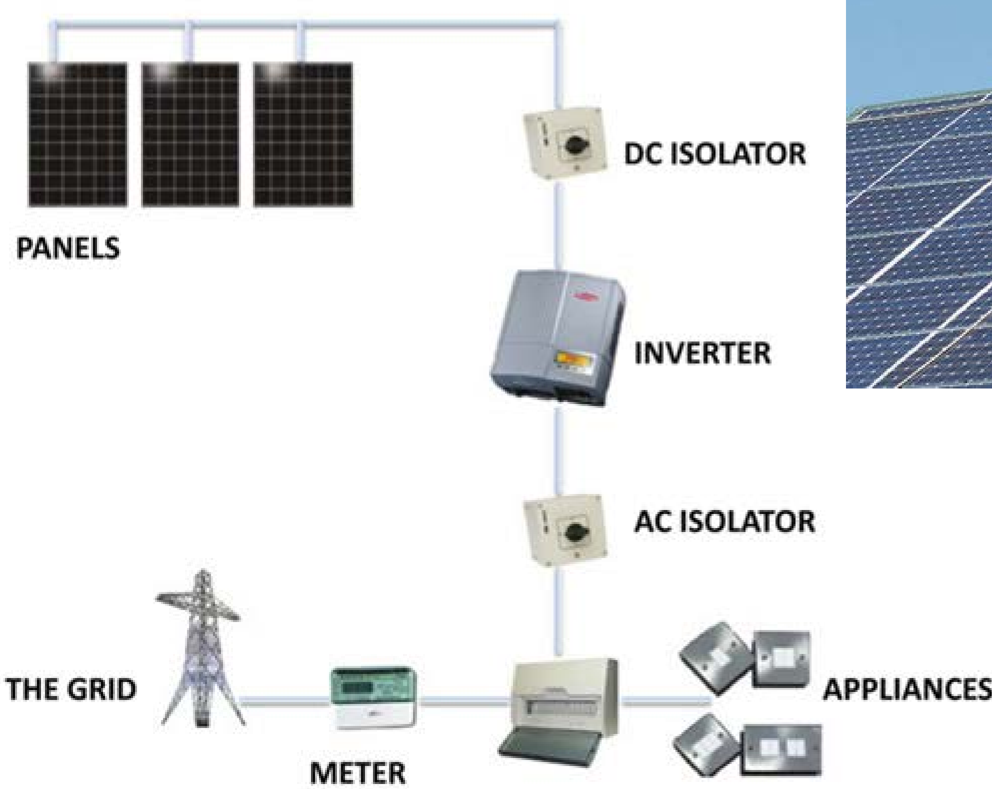
German Advisory Council on Global Change, ISBN 1-85383-882-9

Energy use today and in the future



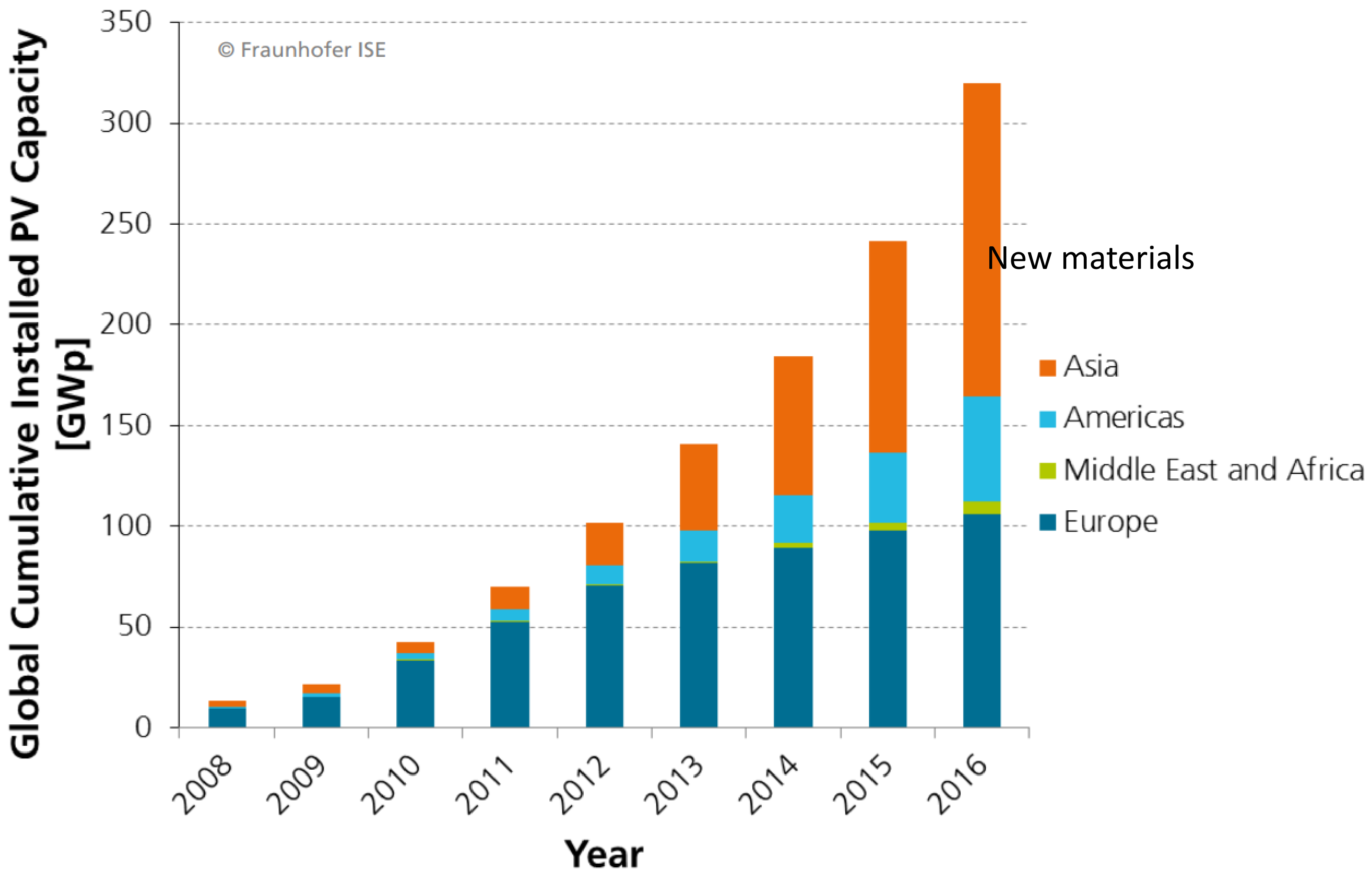
WEA **2000** and Lewis and Nocera *PNAS* **2006**, 103, 15729.

Modern Si photovoltaic installations



7.7MW in Rion-des-Landes

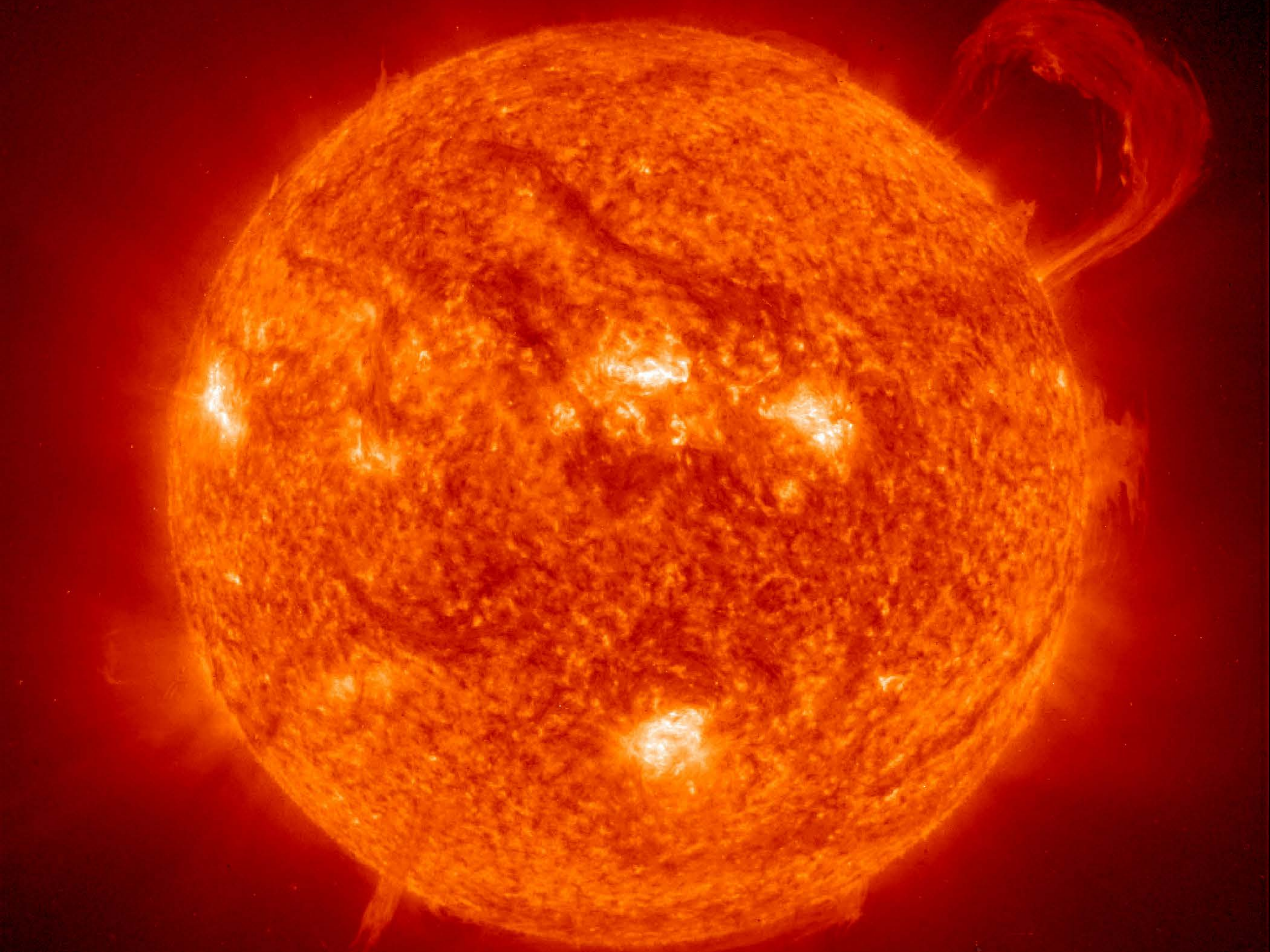
Growth of photovoltaic installations



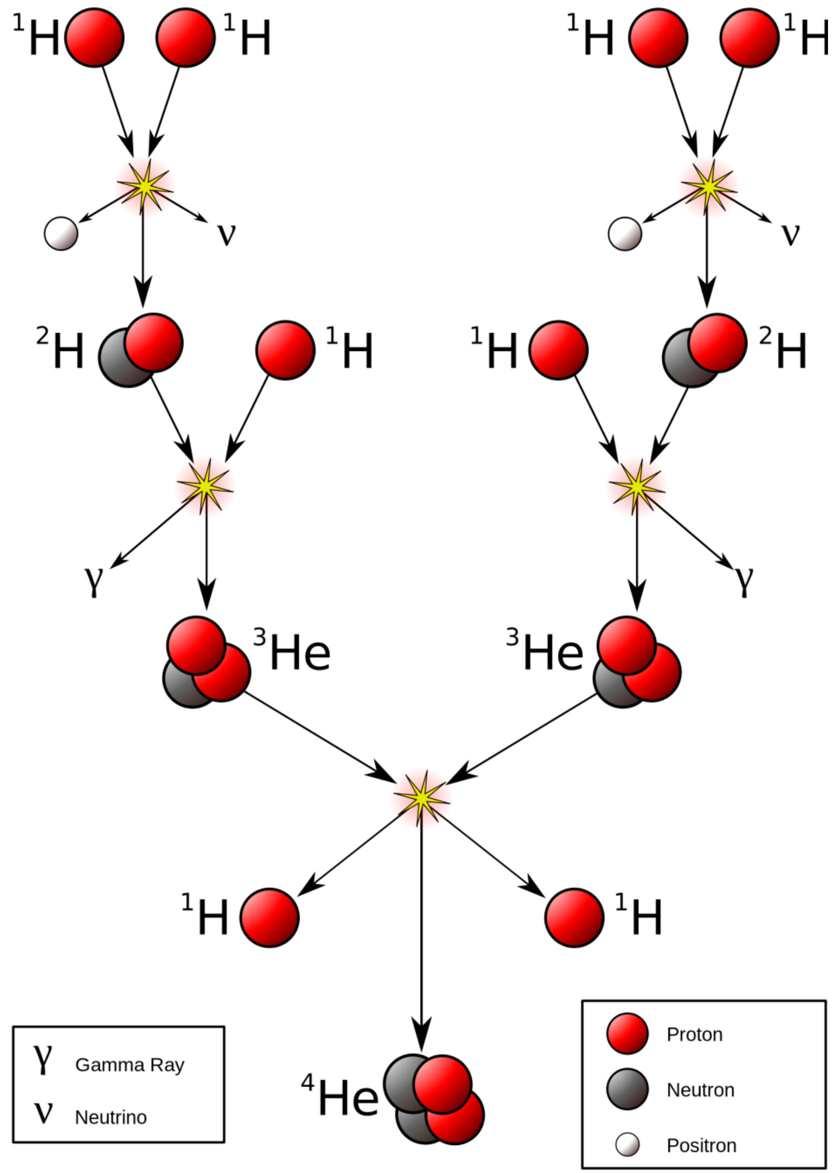
Course Schedule

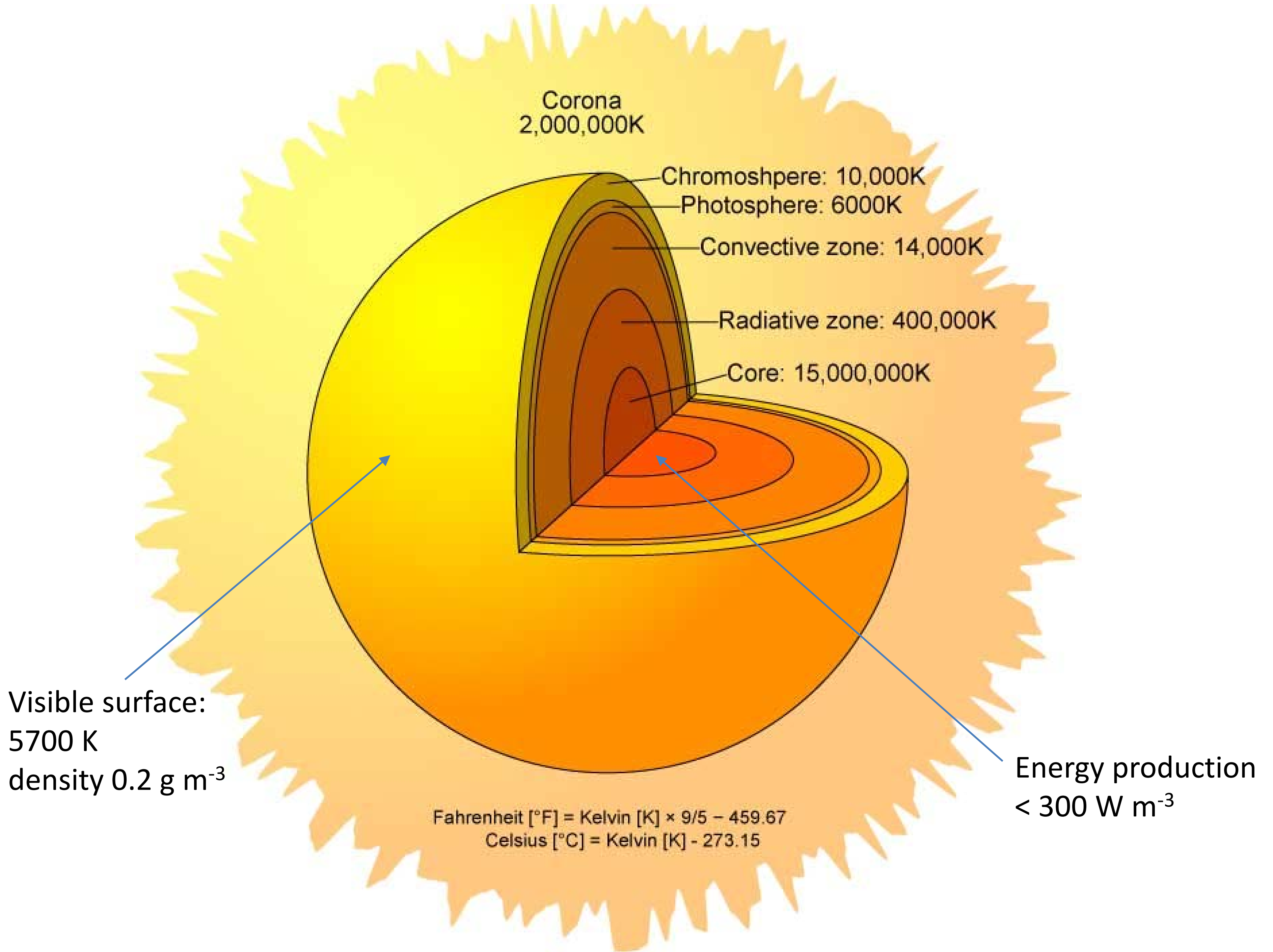
Date	Lecturer	Topic
27-02-18	Kevin Sivula	The nature of Solar irradiation, thermodynamics of solar energy conversion, solar thermal approaches
01-03-18	Kevin Sivula	Thermodynamics of band-gap based solar energy conversion, the SQ limit
06-03-18	Wolfgang Tress	pn Junctions, Silicon Solar Cells, and III-V materials
08-03-18	Wolfgang Tress	Heterojunction, Organic and Dye Sensitized Solar Cells
13-03-18	Wolfgang Tress	Perovskite and Third Generation Solar Cells
15-03-18	Néstor Guijarro	Solar-to-fuel conversion, motivation and approaches
20-03-18	Néstor Guijarro	Direct solar to fuel with photoelectrochemical and photocatalytic systems
22-03-18	Student presentations	Advanced strategies and materials (Literature Project)
27-03-18	Student presentations	Advanced strategies and materials (Literature Project)
29-03-18	Student presentations	Advanced strategies and materials (Literature Project)

URL: https://go.epfl.ch/ChE_600_2018



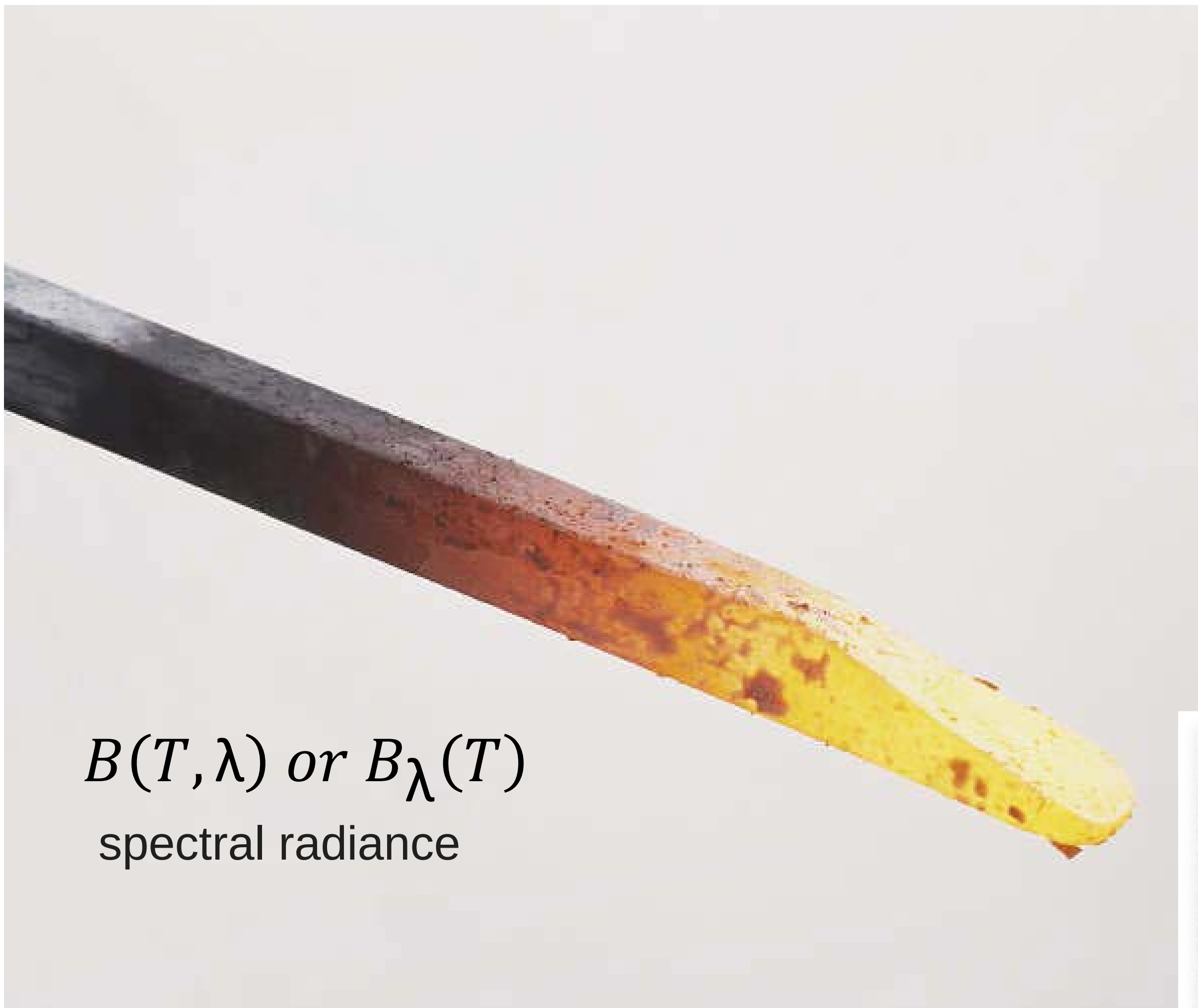
Why do stars "shine"?





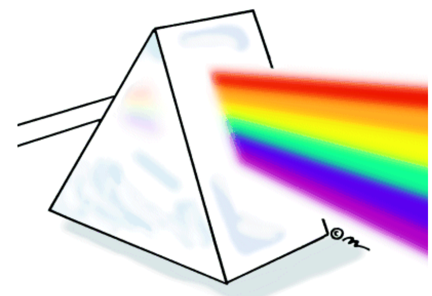
Corona
2,000,000K
Chromoshpere: 10,000K
Photosphere: 6000K
Convective zone: 14,000K
Radiative zone: 400,000K
Core: 15,000,000K
Visible surface:
5700 K
density 0.2 g m^{-3}
Energy production
< 300 W m^{-3}
Fahrenheit [°F] = Kelvin [K] × 9/5 − 459.67
Celsius [°C] = Kelvin [K] - 273.15

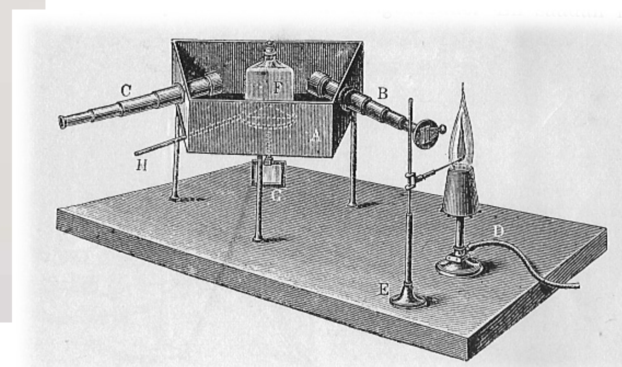
Blackbody radiation



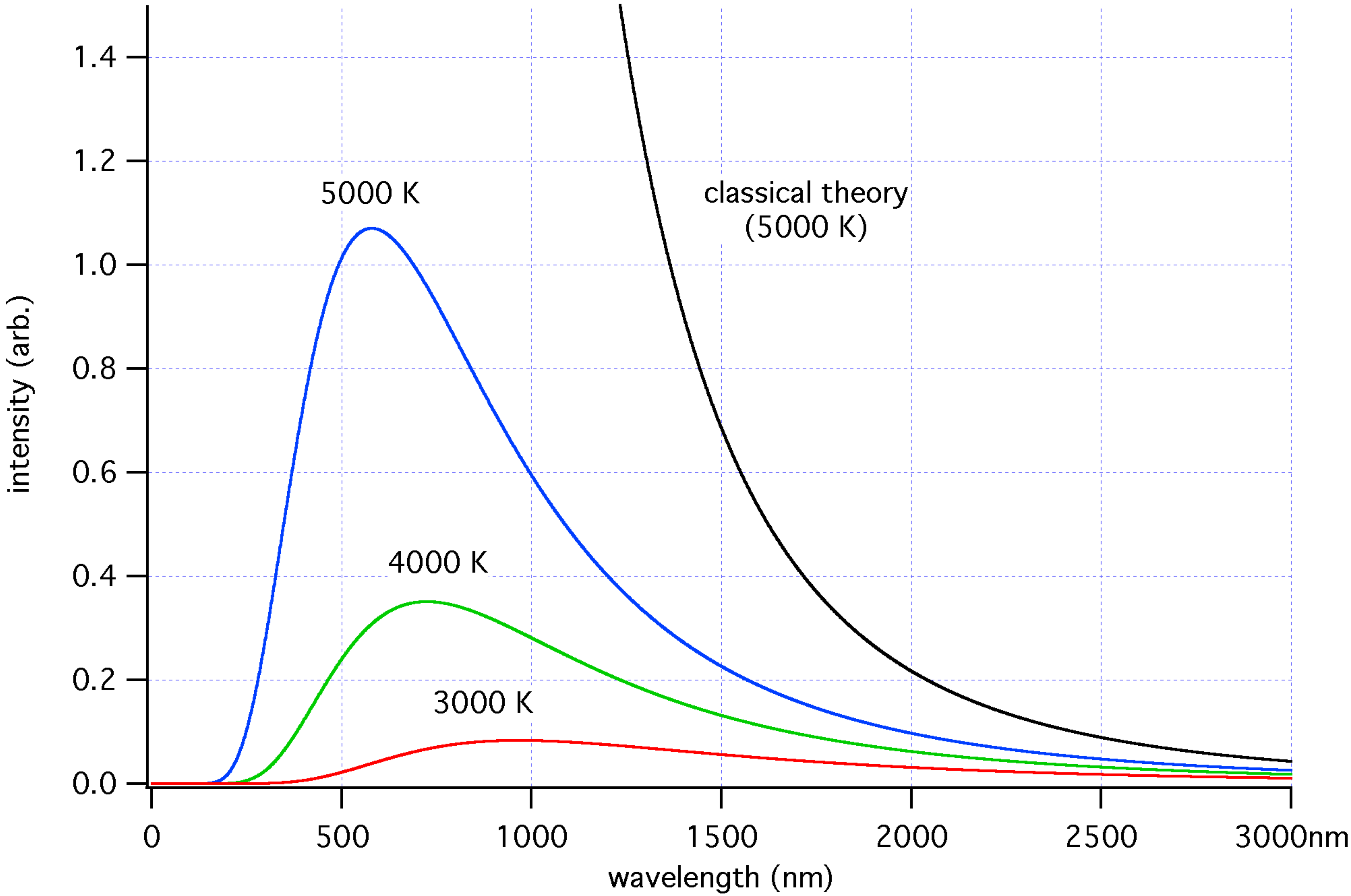
$B(T,\lambda)$ *or* $B_\lambda(T)$

spectral radiance

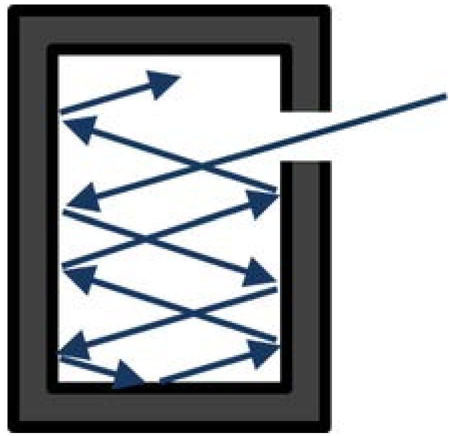


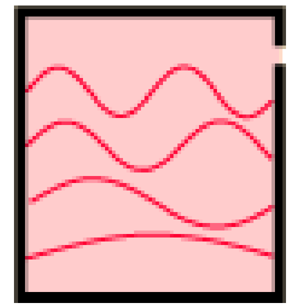


Classical theory vs. experimental results



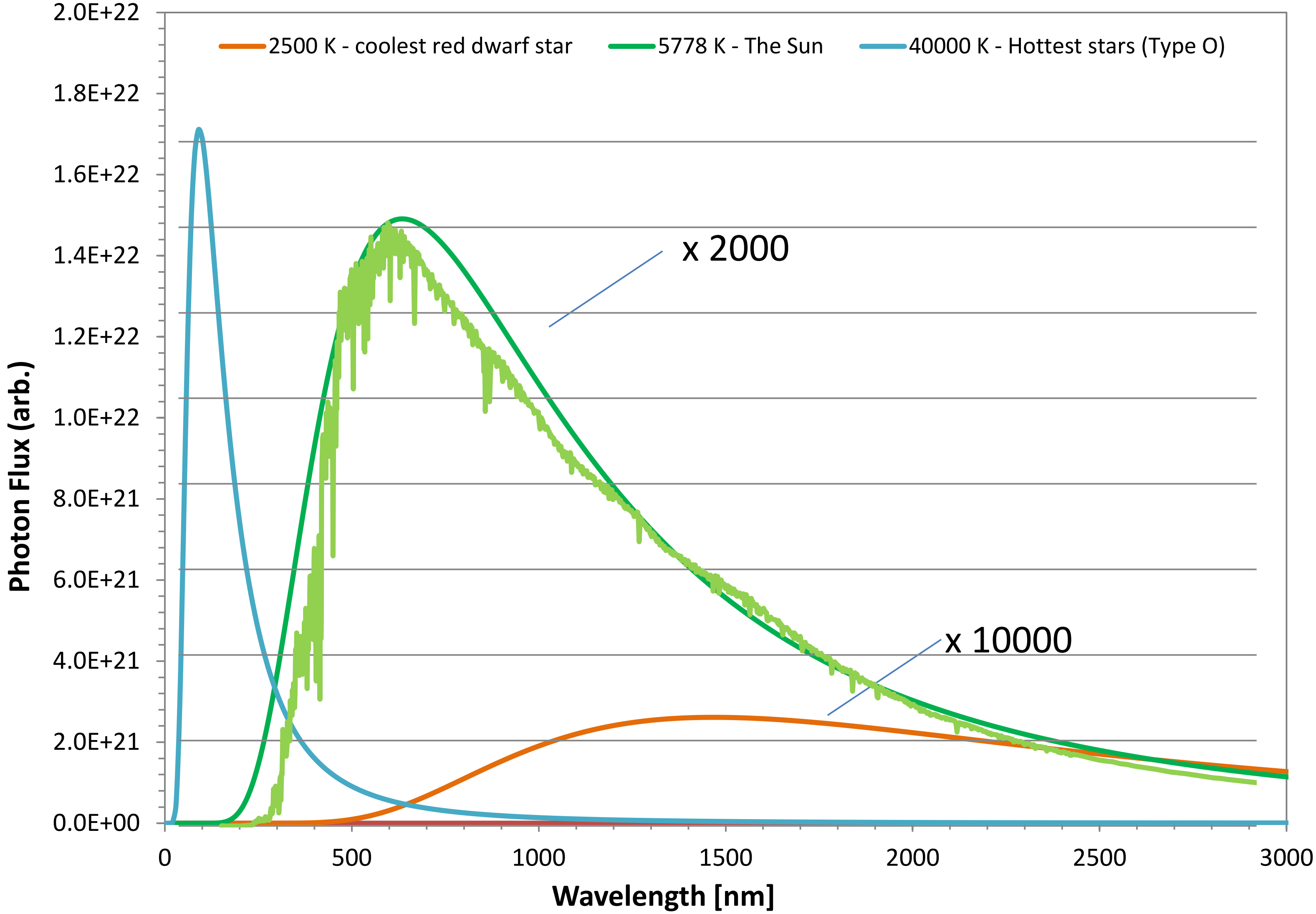
Blackbody radiation





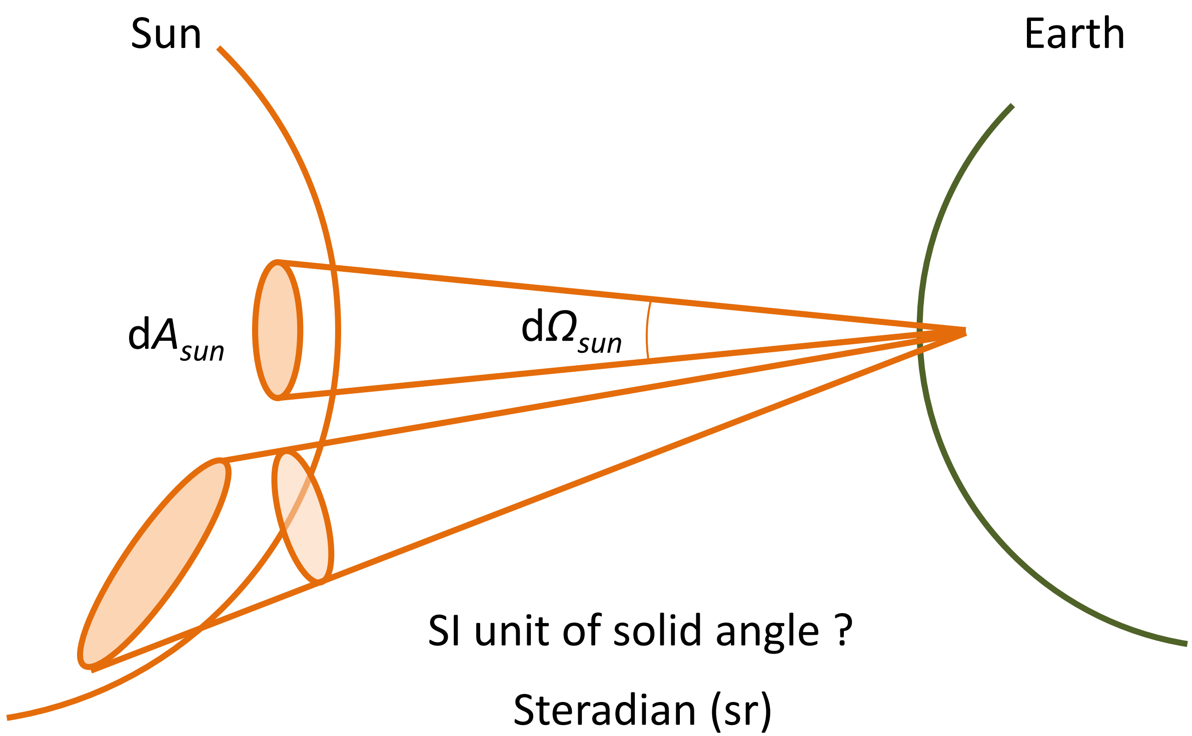
	$\frac{\text{N}^\text{o}\text{ of modes}}{\text{unit volume}}$	**Probability of occupying modes**	**Average energy per mode**	**Prediction**
Classical	$\frac{8\pi}{c\lambda^2}$	Equal for all modes	$\frac{1}{2}k_B T$	$B_\lambda(T) = \frac{2ck_B T}{\lambda^4}$
Quantum	$\frac{8\pi}{c\lambda^2}$	Quantized modes: need hν to excite, higher modes less probable	$\frac{\frac{hc}{\lambda}}{e^{\frac{hc}{\lambda k_B T}} - 1}$	$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$

Blackbody radiation



Flux of photons from a blackbody

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1} [=] \frac{Energy\ carried\ by\ photons}{time \cdot projected\ surface\ area \cdot wavelength \cdot solid\ angle}$$



SI unit of solid angle ?

Steradian (sr)

4π sr in a sphere

Total solid angle of the sun from the viewpoint of the earth is Ω_{se} = 6.8 x 10^{-5} sr

Flux of photons from the sun

$$B_{600\text{nm}}(5778\text{K})\Omega_{se} = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1}\Omega_{se} = 153169\,\frac{\text{mW}}{\text{cm}^2\ \text{sr nm}}\frac{1}{e^{4.15}-1}\Omega_{se}$$

$$= 2453\,\frac{\text{mW}}{\text{cm}^2\ \text{sr nm}}\left(\frac{6.2415 \times 10^{15}\ \text{eV}}{\text{mW}\cdot\text{s}}\right)\left(\frac{\text{photon}}{2.067\ \text{eV}}\right)\Omega_{se}$$

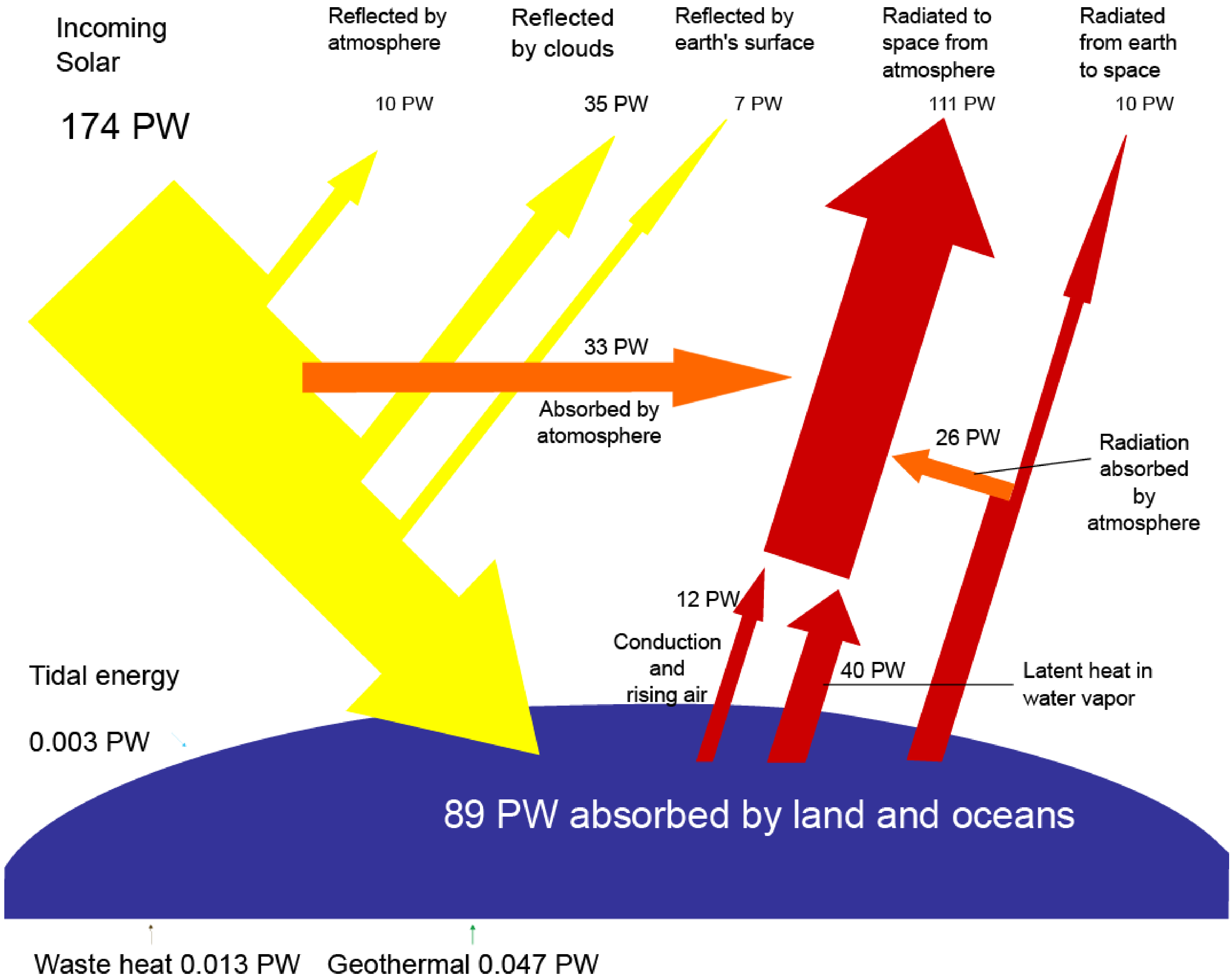
$$= 7.405 \times 10^{18}\ \frac{\text{photons}}{\text{cm}^2\ \text{s sr nm}}(6.8 \times 10^{-5}\ \text{sr})$$

$$= 5.03 \times 10^{14}\ \frac{\text{photons}}{\text{cm}^2\ \text{s nm}} \qquad \text{measured value} = 5.34 \times 10^{14}\ \frac{\text{photons}}{\text{cm}^2\ \text{s nm}}$$

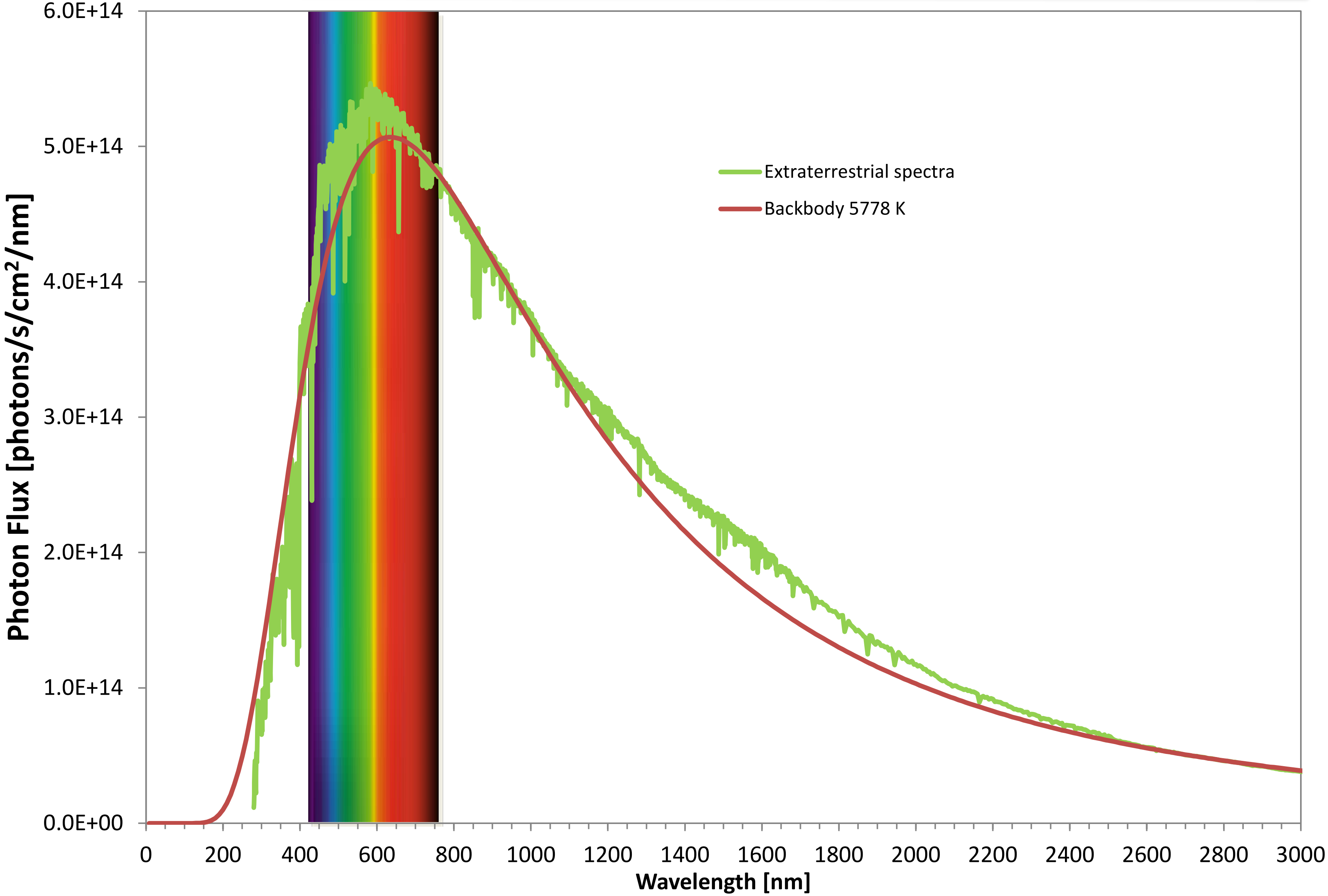
The solar constant:

$$\int_{\lambda=0}^{\infty} B_\lambda(5778K)\Omega_{se}\,d\lambda = 136.8\,\frac{\text{mW}}{\text{cm}^2} \qquad \text{measured value} = 136.1 - 136.2\,\frac{\text{mW}}{\text{cm}^2}$$

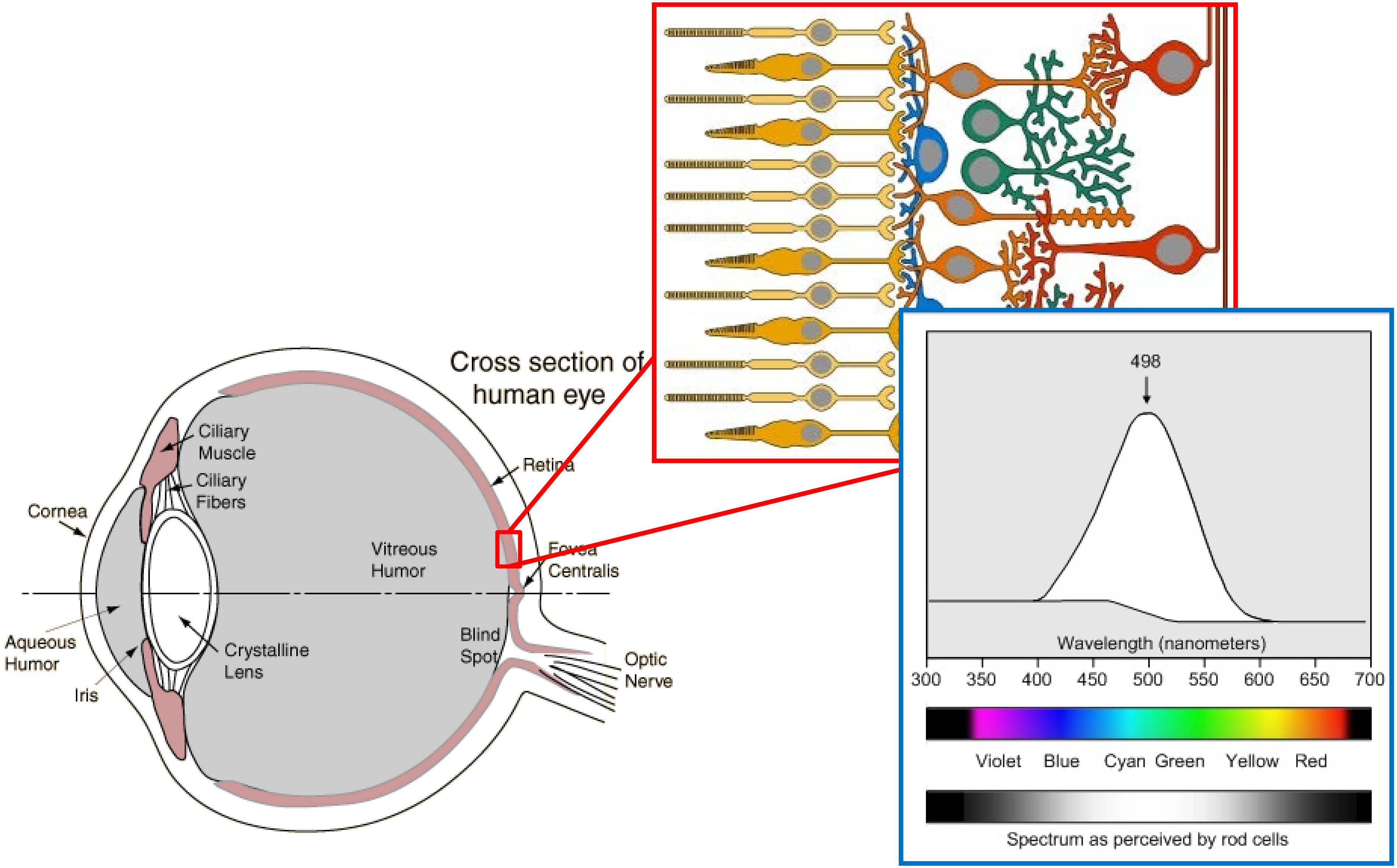
$$136.8\,\frac{\text{mW}}{\text{cm}^2}(1.27 \times 10^8\ \text{km}^2) = 174\ \text{PW}$$


Incoming Solar
174 PW
Reflected by atmosphere
10 PW
Reflected by clouds
35 PW
Reflected by earth's surface
7 PW
Radiated to space from atmosphere
111 PW
Radiated from earth to space
10 PW
33 PW
Absorbed by atomosphere
26 PW
Radiation absorbed by atmosphere
12 PW
Conduction and rising air
40 PW
Latent heat in water vapor
Tidal energy
0.003 PW
89 PW absorbed by land and oceans
Waste heat 0.013 PW
Geothermal 0.047 PW

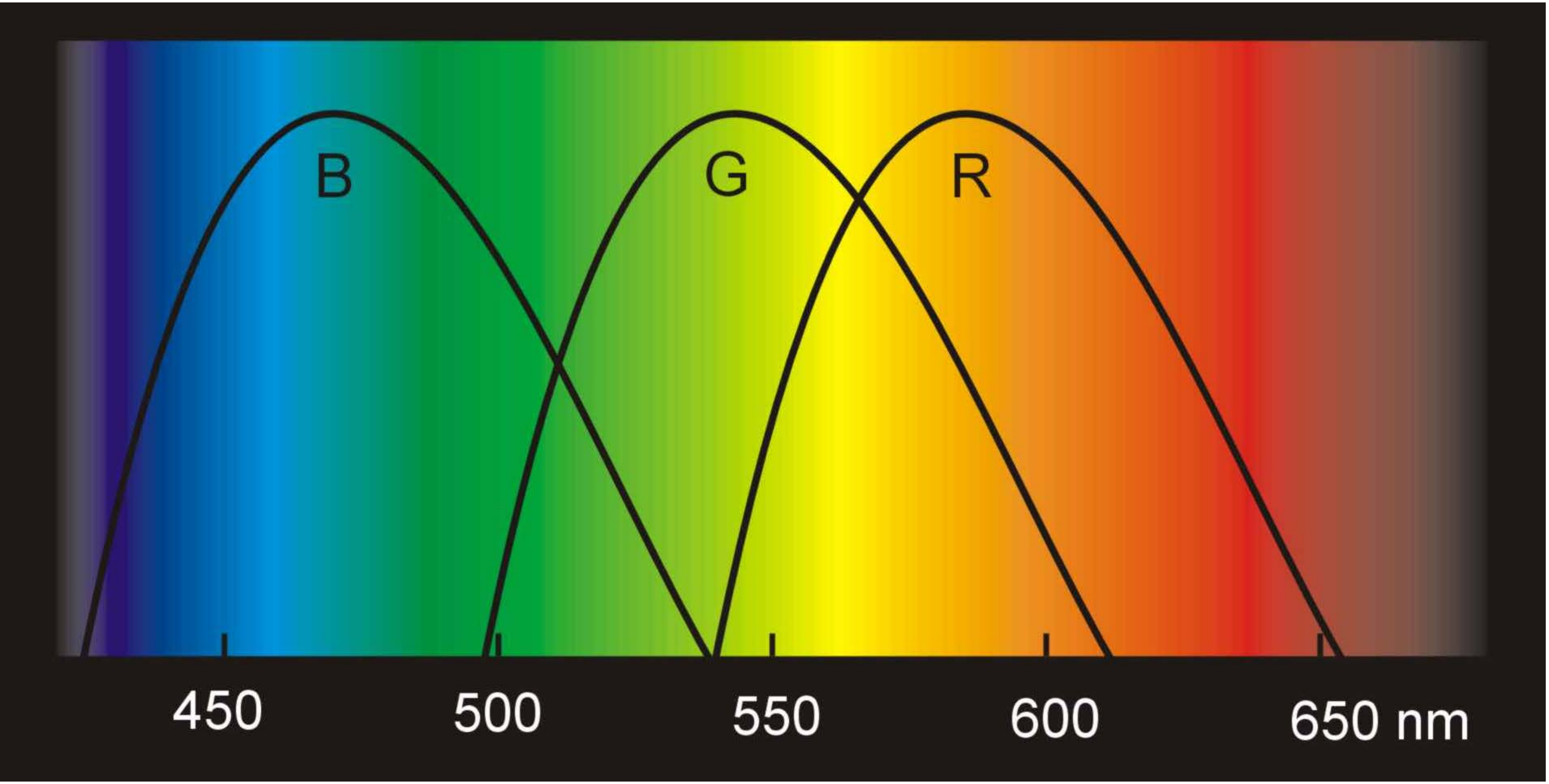
Blackbody radiation



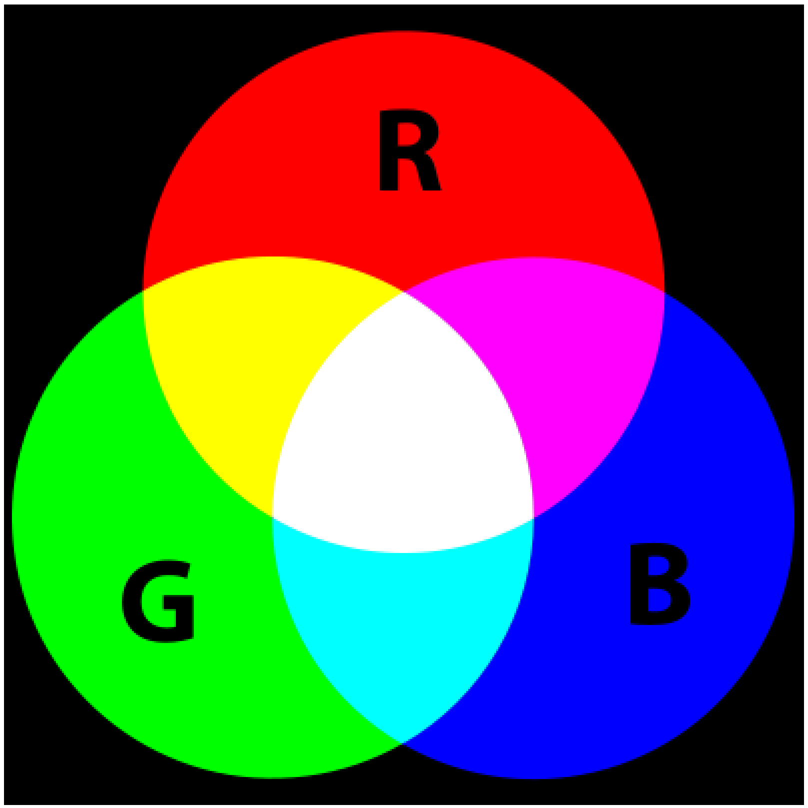
Solar energy conversion by the human eye

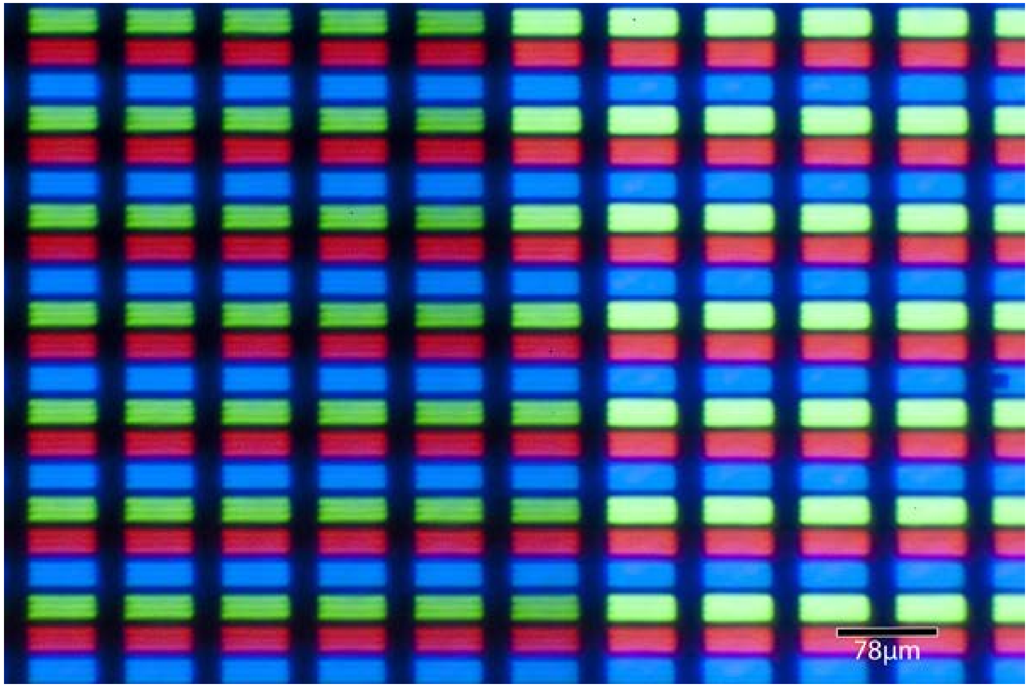


Spectral sensitivities of human cone cells



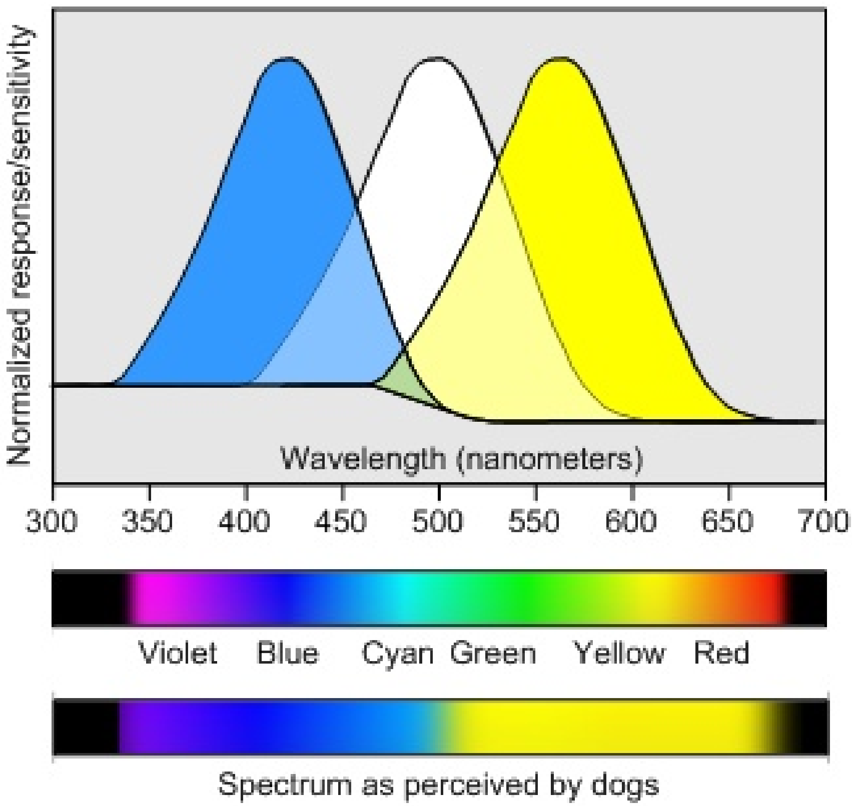
Trichromatic vision





iphone 4 display

Dichromatic vision



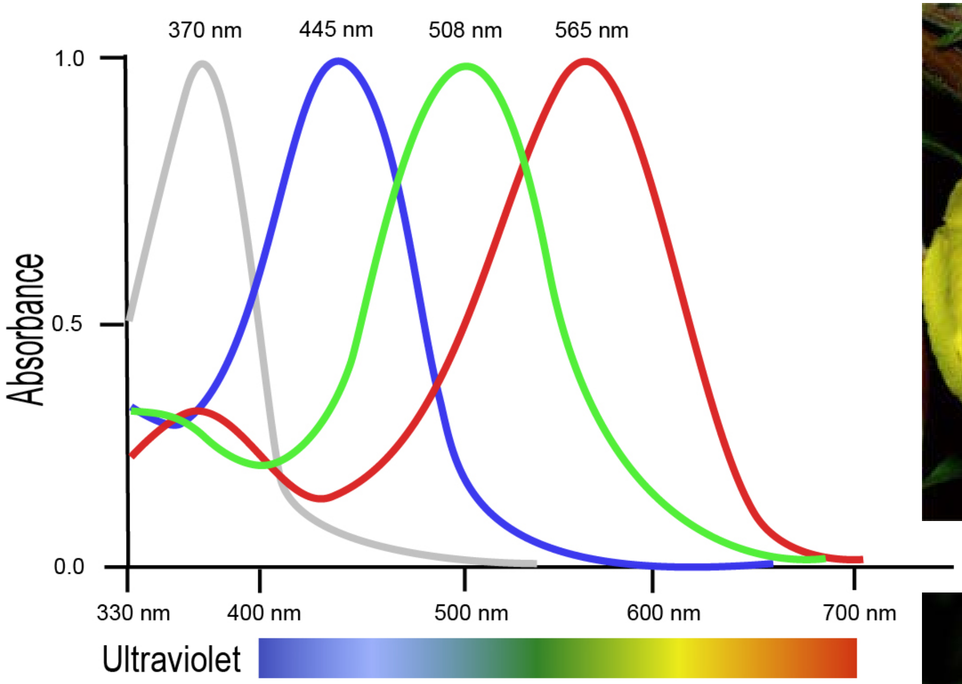
Dogs are dichromats
(two color cone/pigment types – blue and yellow)


The way a mammalian trichromat (three cones) would see a scene

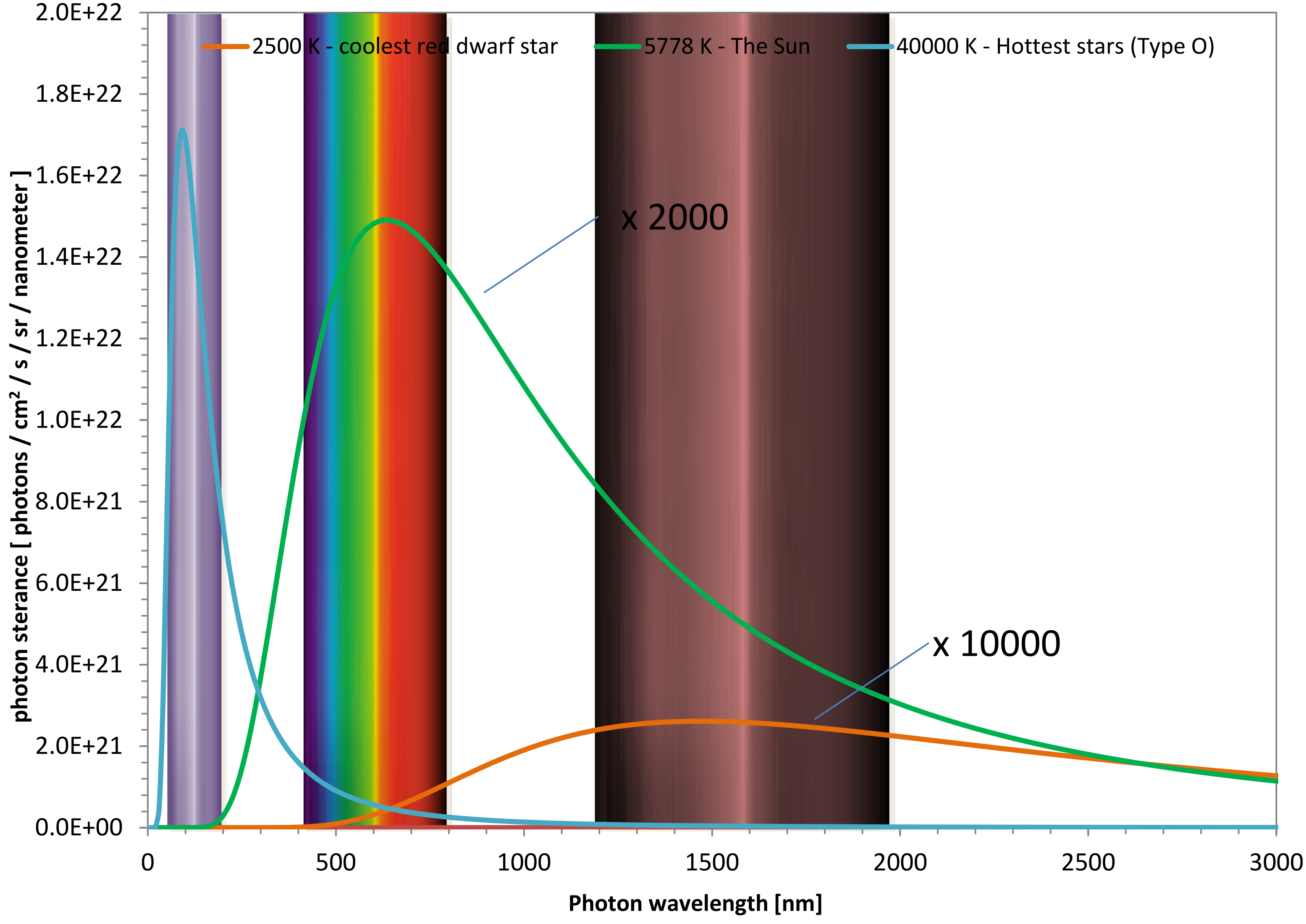

The way a mammalian dichromat (two cones) would see the same scene

http://www.diycalculator.com/sp-cvision.shtml

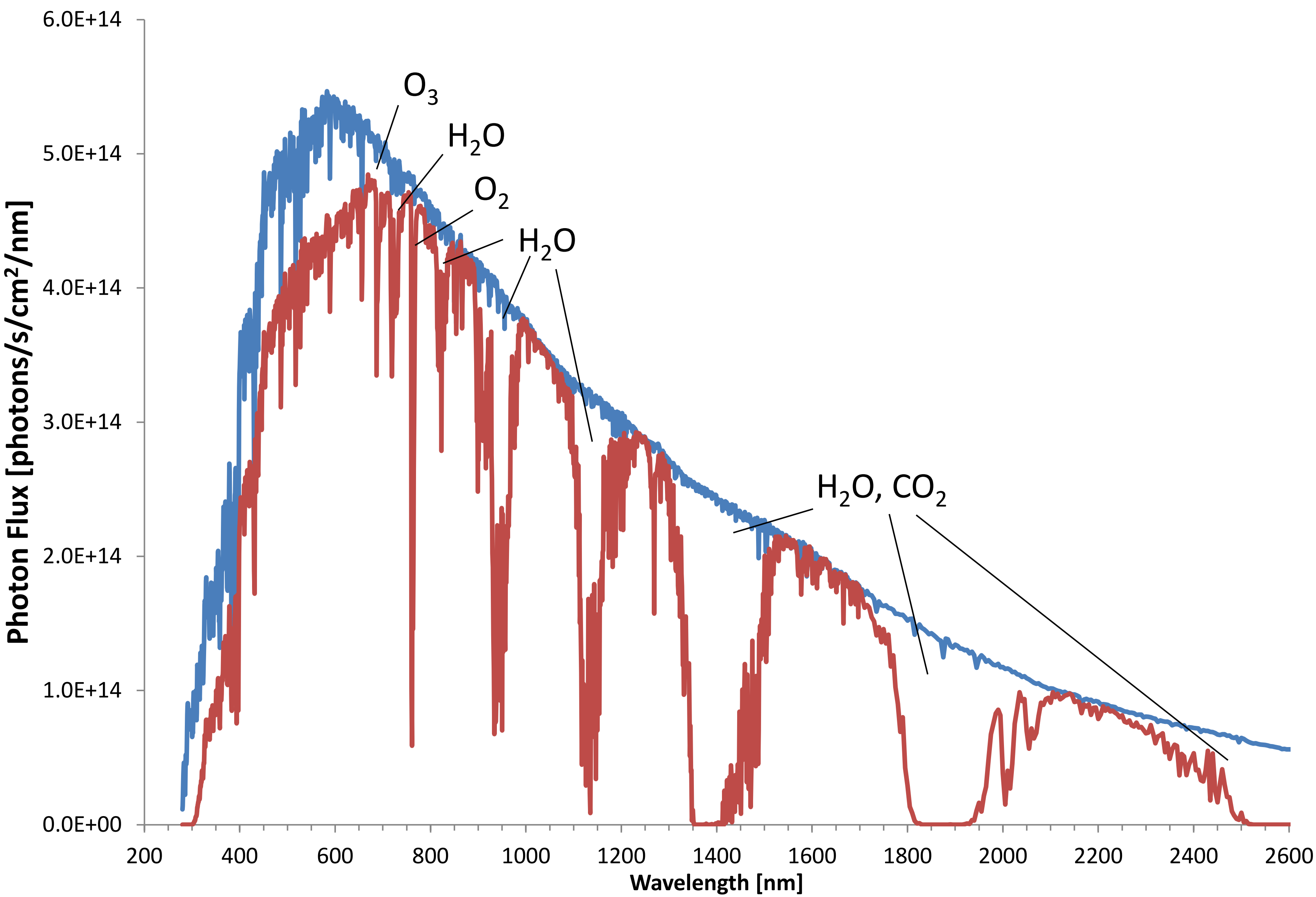
Tetrachromatic vision



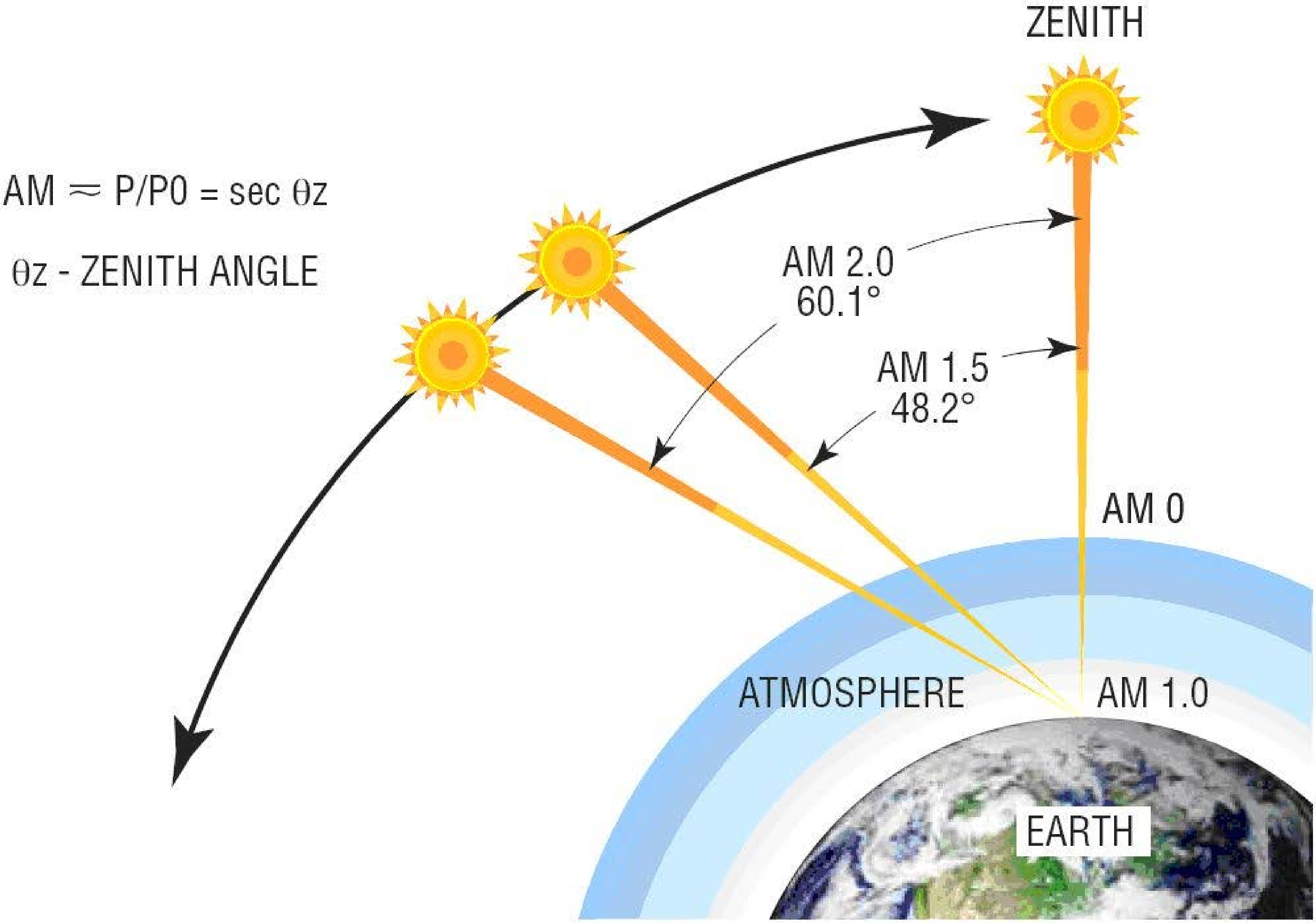
Another digression



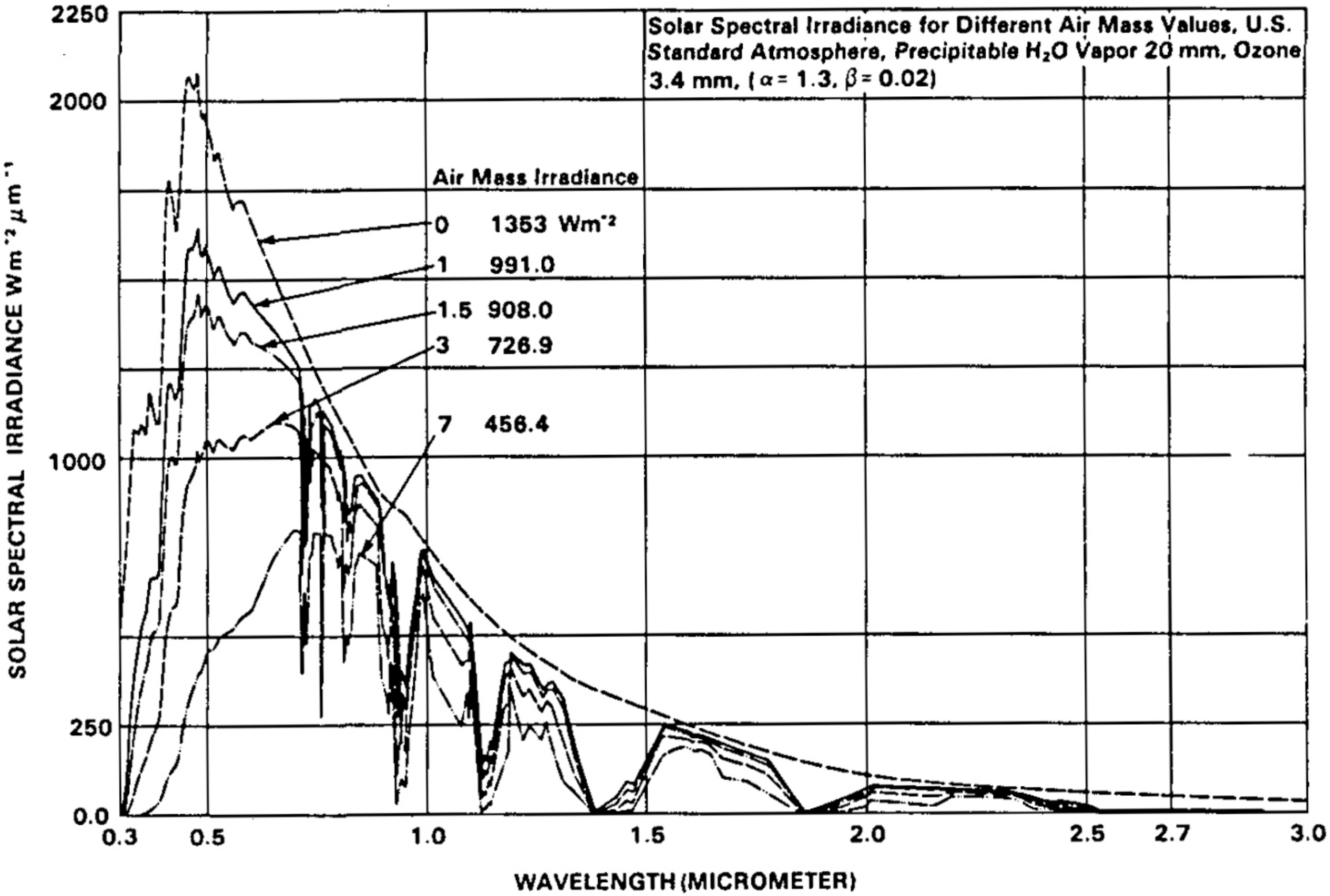
Solar Spectra



Atmospheric effects

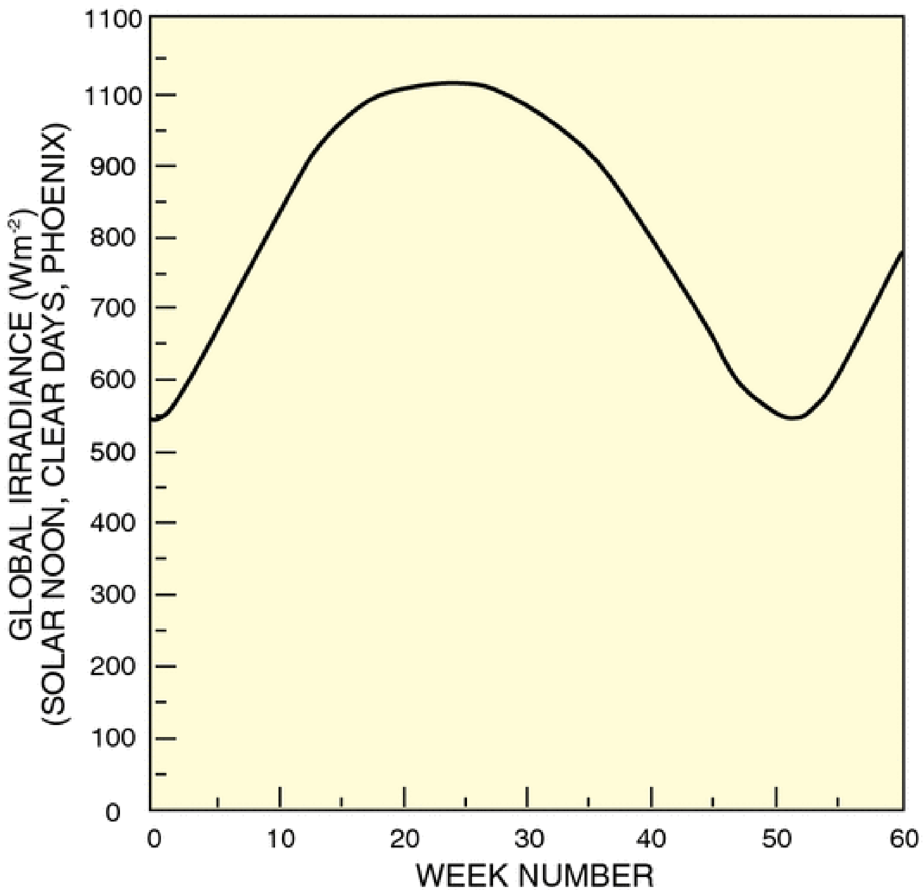


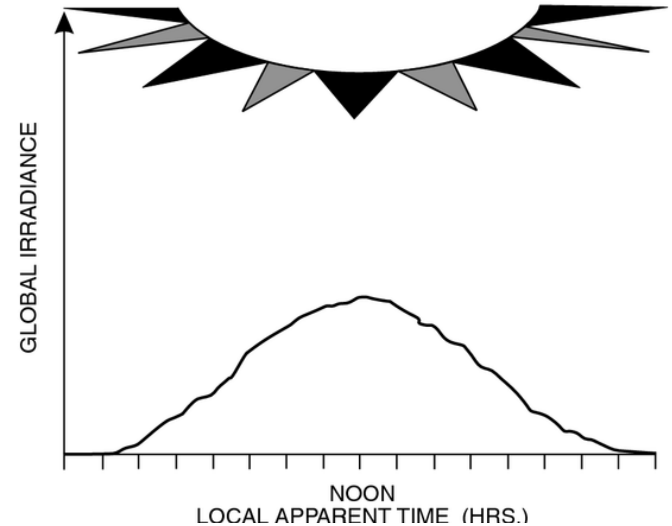
Solar Spectra

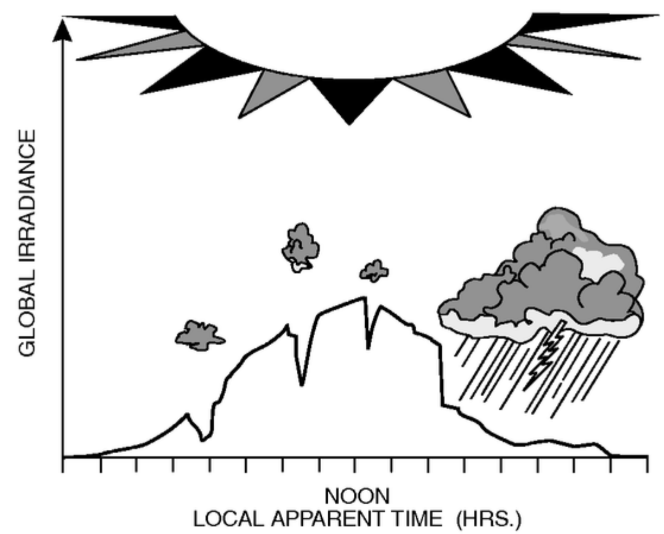


Mecherikunnel et al., *Applied Optics* **1983**, 22, 1534

Variations in solar irradiance

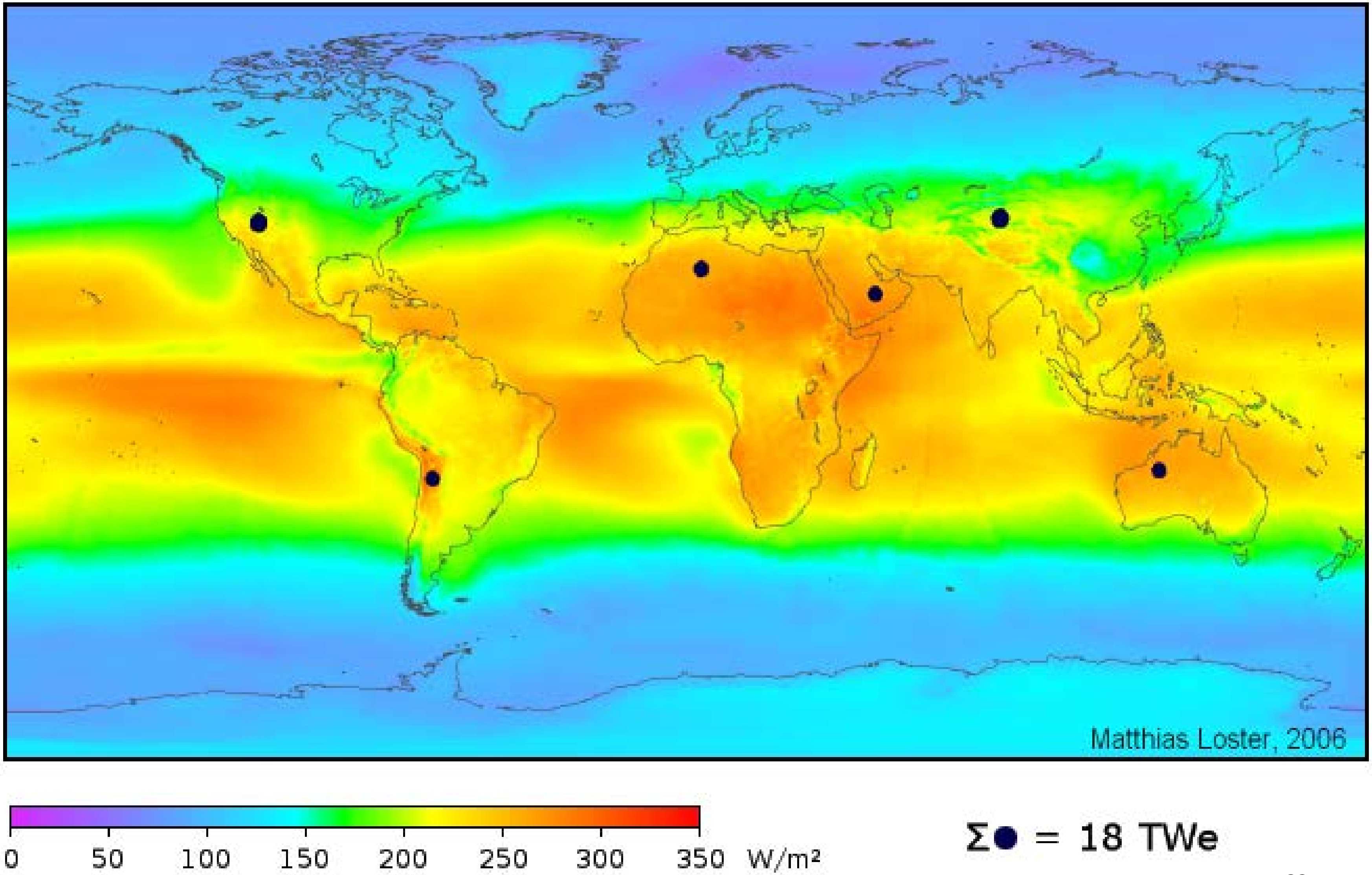






http://www.newport.com/Introduction-to-Solar-Radiation

Averaged Solar Radiation 1990-2004

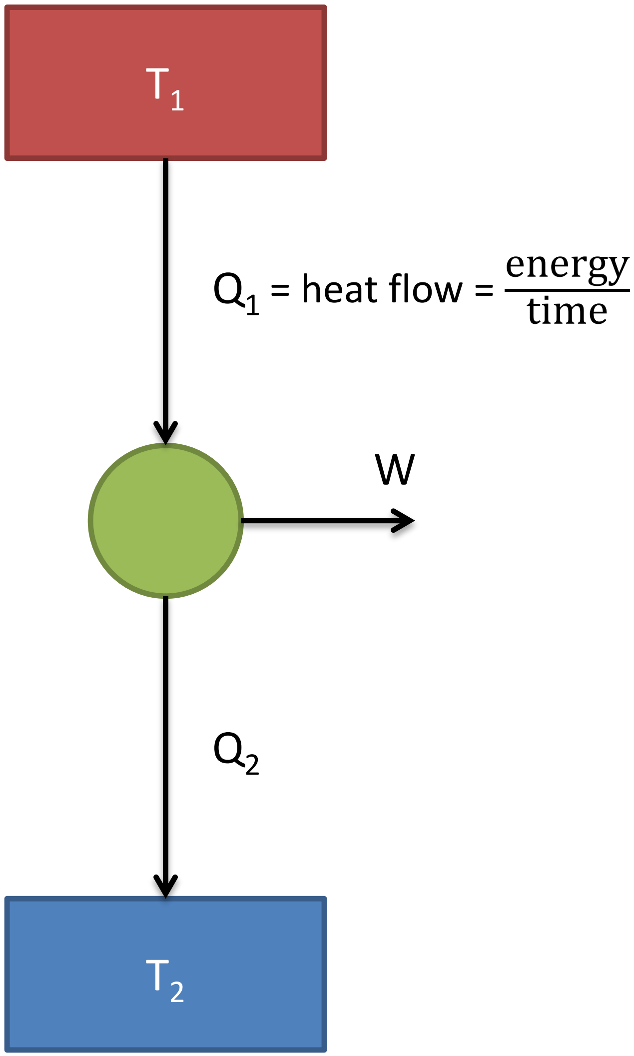


Σ● = 18 TWe

Assuming 8% energy conversion efficiency

Energy conversion thermodynamics

- How can we understand the limits of solar energy conversion?
  - Let's start with a simple thermodynamic model (Carnot Engine)
  - Add linear (conduction) heat transfer (Curzon-Ahlborn Engine)
  - Add radiative heat transfer (The Stefan-Boltzmann Engine)
  - Include a Sun-planet model (The Müser Engine)
  - Include a "band gap" to derive the Shockley–Queisser limit



Reference: Thermodynamics of Solar Energy Conversion by Alexis De Vos **ISBN: 978-3-527-40841-2**

Thermodynamics: The Carnot engine

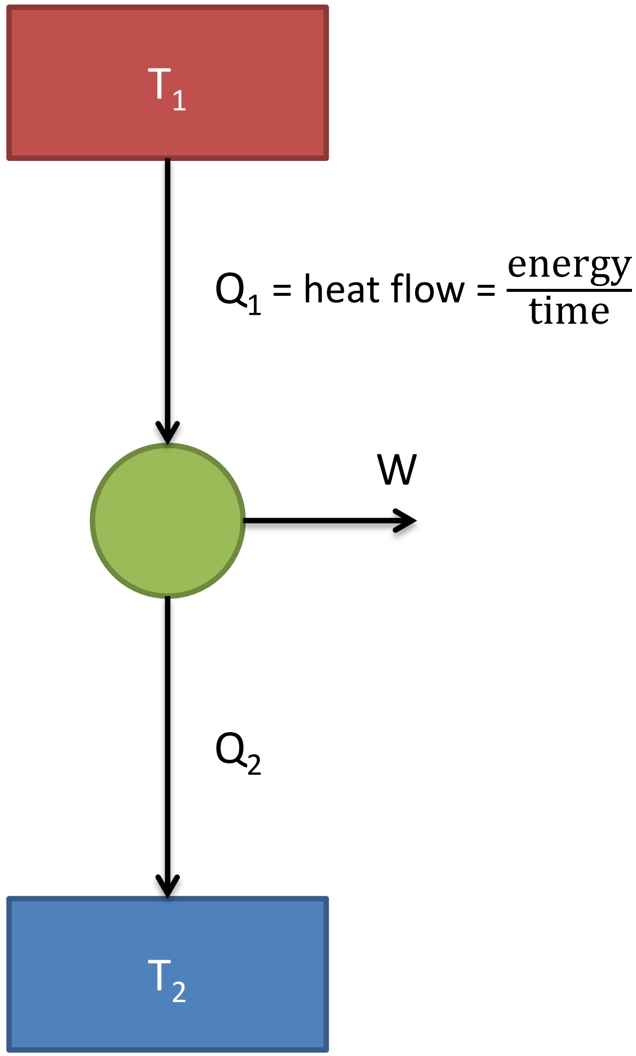
- The Carnot Engine
  - Normally $T_1 > T_2$
- Axiom 1 (first law)
  - $\Sigma Q + \Sigma W = dU = 0$
- Axiom 2 (second law)
  - $\Sigma S = 0$ (for reversible processes)
- Postulate: heat flow is accompanied by an entropy flow Q/T, and work flow is accompanied by an entropy flow of 0, then
  - $\Sigma(Q/T) = 0$
- It follows:
  - $Q_1 = W + Q_2$ and $Q_1/T_1 = Q_2/T_2$
- Introduce "efficiency"
  - $W = \eta_C Q_1$

- $\eta_C = 1 - T_2/T_1$

If W>0: positive work flow, "heat engine"

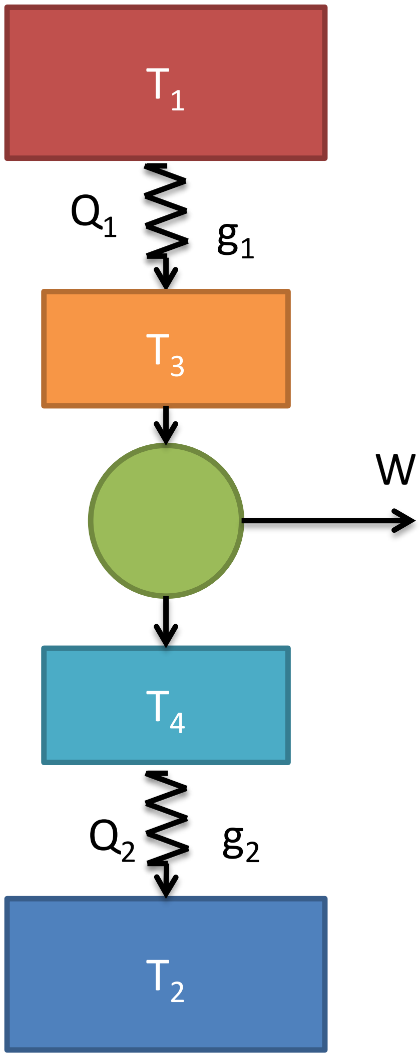
If W<0: negative work flow, two subcases:

1) $T_1 > T_2$ this is a "heat pump" with $\eta_C > 0$
2) $T_2 > T_1$ this is a "refrigerator" with $\eta_C < 0$



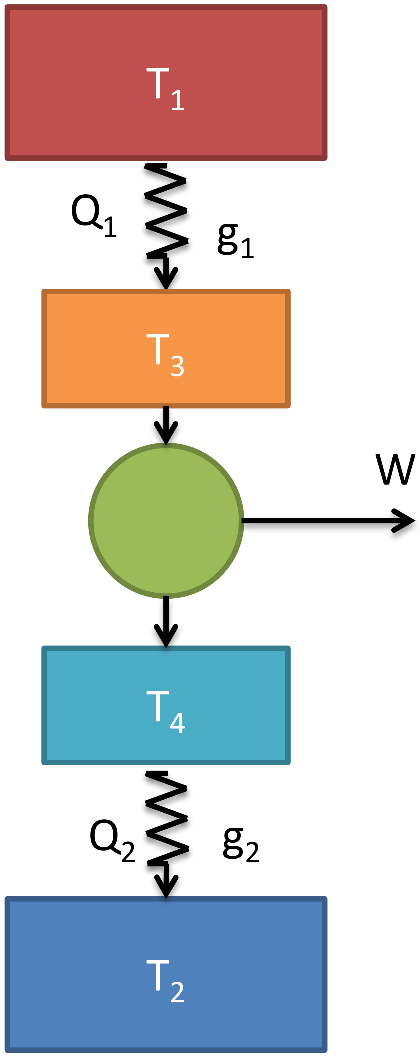
The Carnot engine with linear conduction

- The Curzon-Ahlborn Engine
  - Normally $T_1 > T_2$ as in Carnot
  - Two irreversible components
  - Reversible Carnot engine between T_3 and T_4
- Axiom 1 (first law)
  - $\Sigma Q + \Sigma W = 0 \Longrightarrow Q_1 = W + Q_2$
- Axiom 2 (second law)
  - $\Sigma(Q/T) = 0 \Longrightarrow Q_1/T_3 = Q_2/T_4$
- $\eta_{CA} = 1 - T_4/T_3$
- Fourier's law:
- $Q = -\lambda_{th} \nabla T$ (assume linear conduction, λ_{th} thermal conductivity)
  - $Q = g\,\Delta T$ ($g = \lambda_{th}/L$)
    - $Q_1 = g_1(T_1 - T_3)$
    - $Q_2 = g_2(T_4 - T_2)$



Curzon-Ahlborn Engine

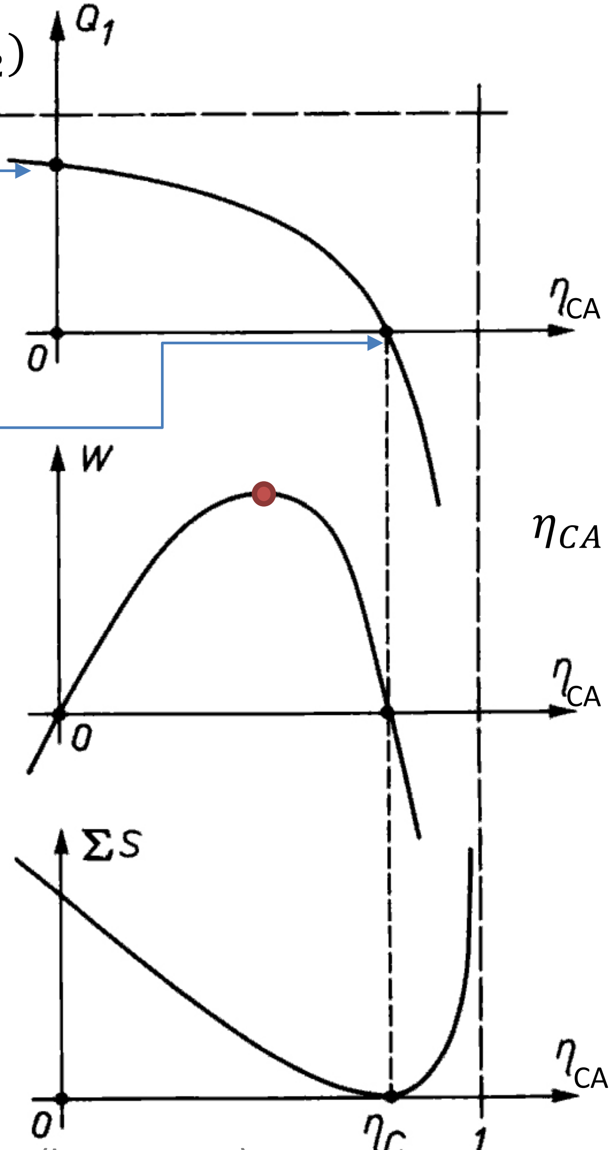
- $Q_1 = g_t \frac{T_1 - T_2 - T_1\eta_{CA}}{1-\eta_{CA}}, \ g_t = \frac{g_1 g_2}{g_1 + g_2}$
- $W = g_t \frac{\eta_{CA}(T_1 - T_2 - T_1\eta_{CA})}{1-\eta_{CA}}$
- $\Sigma S = g_t \frac{(T_1 - T_2 - T_1\eta_{CA})^2}{T_1 T_2 (1-\eta_{CA})}$



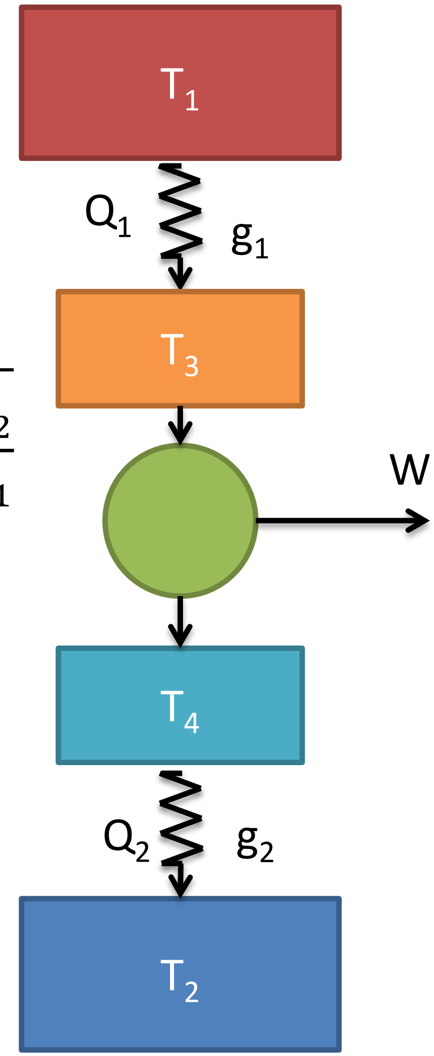
Curzon-Ahlborn Engine

$$Q_{1,sc} = g_t\,(T_1 - T_2)$$

$$\eta_{CA,oc} = 1 - \frac{T_1}{T_2}$$



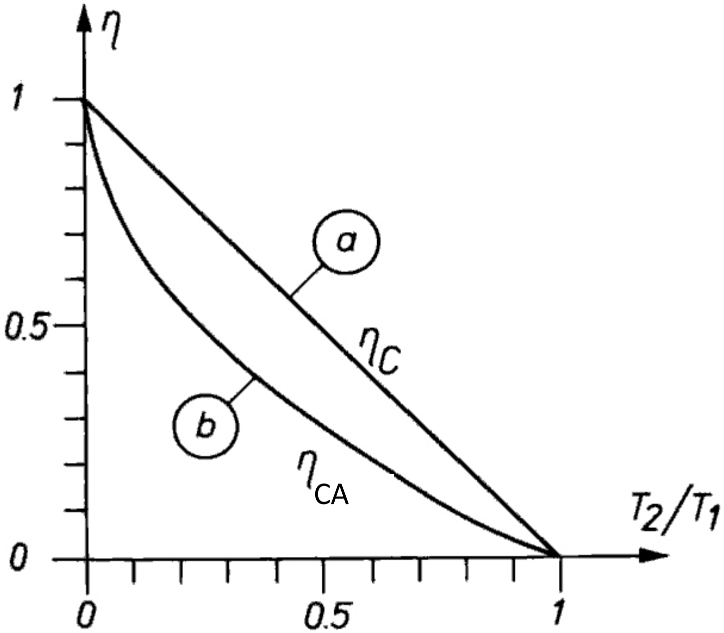
$$\eta_{CA} = 1 - \sqrt{\frac{T_2}{T_1}}$$



For $\eta_{CA} > \eta_C$ $T_3 > T_1 > T_2 > T_4$ (heat pump)

For $-\infty < \eta_{CA} < 0$, $T_1 > T_3$, $T_4 > T_3$, $T_4 > T_2$ (refrigerator)

Curzon-Ahlborn Engine

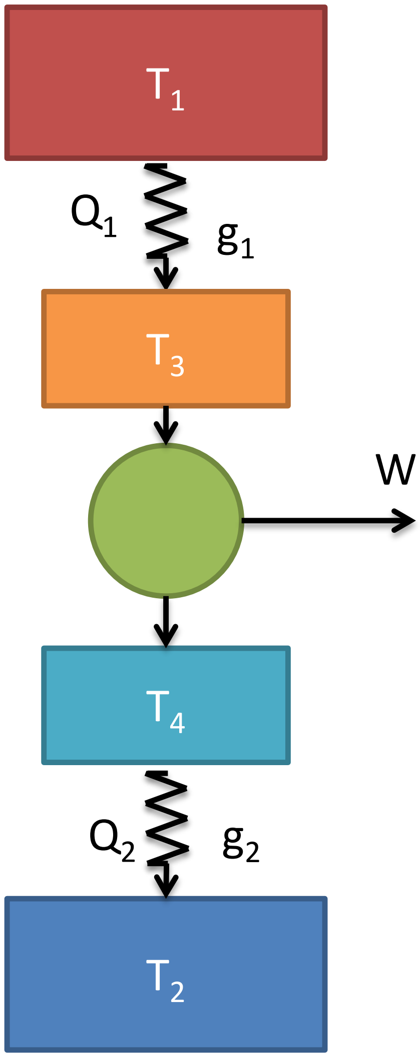


$$Q_1 = g\sqrt{T_1}\left(\sqrt{T_1} - \sqrt{T_2}\right), \qquad g = \frac{g_1 g_2}{g_1 + g_2}$$

$$W = g\left(\sqrt{T_1} - \sqrt{T_2}\right)^2$$

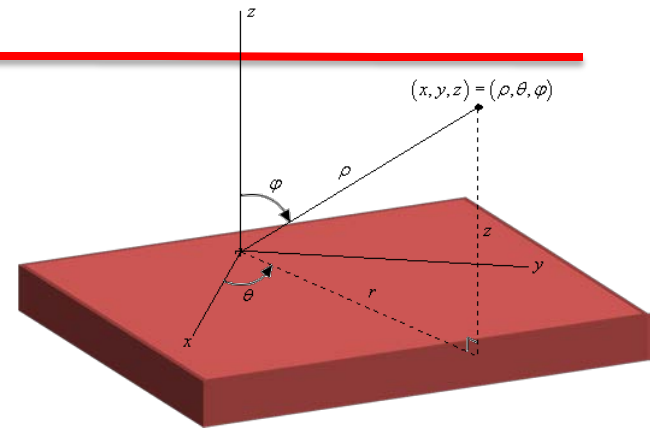
$$\Sigma S = g\frac{\left(\sqrt{T_1} - \sqrt{T_2}\right)^2}{\sqrt{T_1 T_2}}$$

$$\eta_{CA} = 1 - \sqrt{\frac{T_2}{T_1}}$$



Heat transfer by Radiation

The maximum hear transfer from the surface of a blackbody can be calculated from the spectral distribution:



$$\frac{Q}{A} = q = \int_{\lambda=0}^{\infty} B_{\lambda}(T)d\lambda \int_{\theta=0}^{2\pi} d\theta \int_{\varphi=0}^{\pi/2} \cos\varphi \sin\varphi \; d\varphi$$

$$= \pi \int_{\lambda=0}^{\infty} B_{\lambda}(T)d\lambda = \int_{\lambda=0}^{\infty} \frac{2\pi h c^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} d\lambda \;\; = \sigma T^4$$

$$\zeta(s) = \frac{1}{\Gamma(s)} \int_0^{\infty} \frac{x^{s-1}}{e^x - 1} \mathrm{d}x$$

Stefan-Boltzmann law:

$$\sigma = \frac{2\pi^5 k_B^4}{15 c^2 h^3}$$

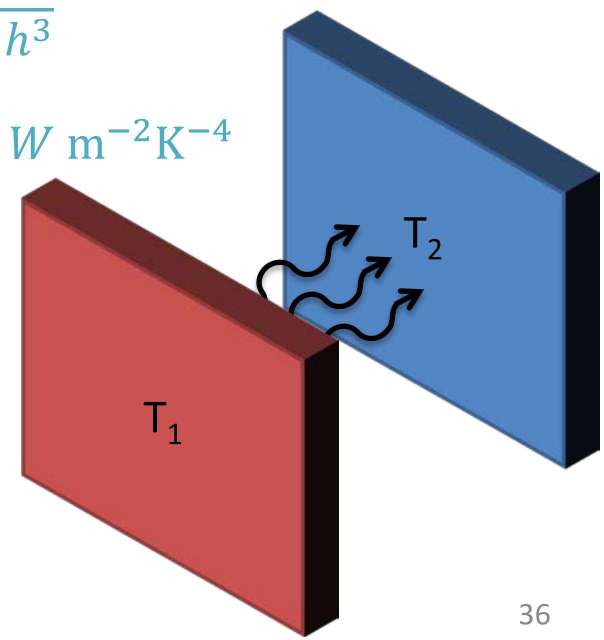
$$Q/A = \varepsilon\sigma T^4$$

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

E = emissivity of the material (ε=1 for a blackbody)

(grey body, $\alpha(\lambda) \; = \varepsilon(\lambda)$)

For two (infinite) parallel plates of the same area and same material :



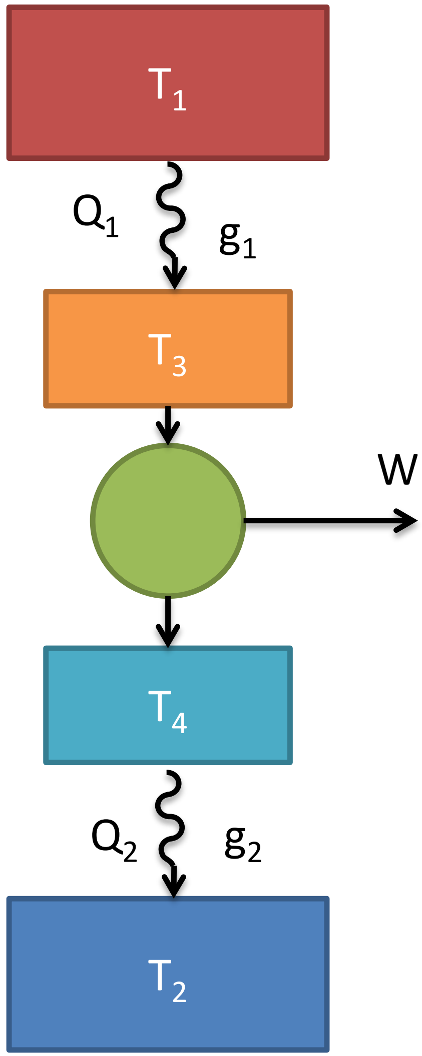
$$Q = \varepsilon\sigma(T_1^4 - T_2^4)$$

5.1 Heat transfer by Radiation

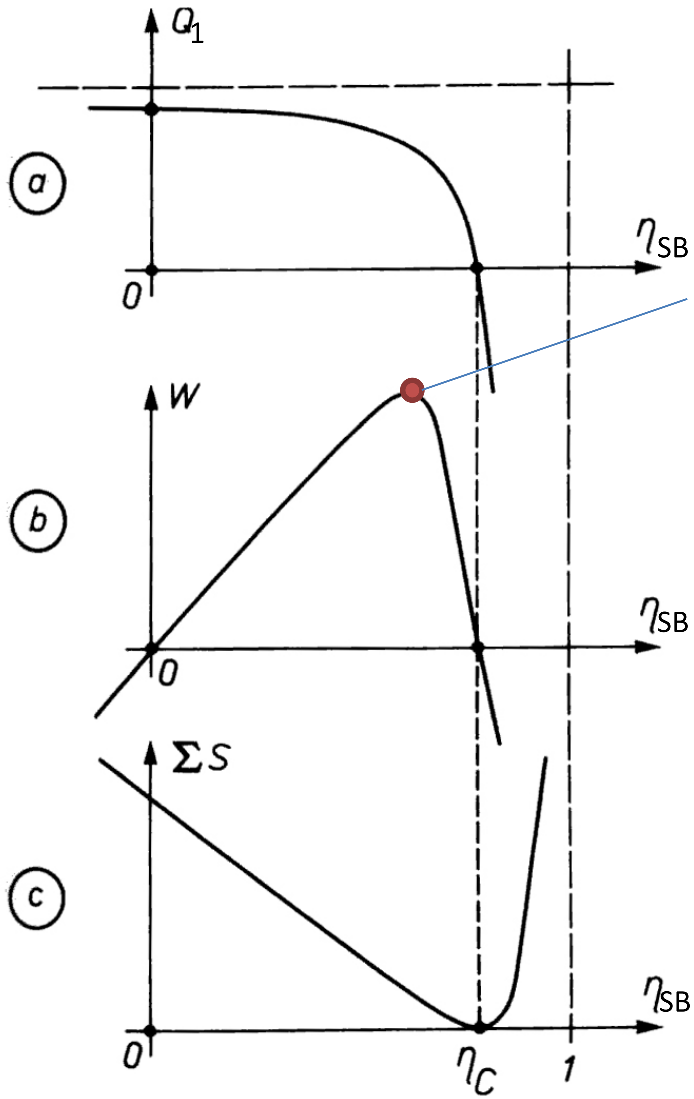
Material	Average Emissivity
Aluminum foil	0.03
Aluminum, anodized	0.9
Asphalt	0.88
Brick	0.90
Concrete, rough	0.91
Copper, polished	0.04
Copper, oxidized	0.87
Glass, smooth (uncoated)	0.95
Ice	0.97
Limestone	0.92
Marble (polished)	0.89 to 0.92
Paint (including white)	0.9
Paper, roofing or white	0.88 to 0.86
Plaster, rough	0.89
Silver, polished	0.02
Silver, oxidized	0.04
Snow	0.8 to 0.9
Water, pure	0.96

The Stefan-Boltzmann Engine

- $Q = \sigma\varepsilon A T^4$ (assume radiative heat transfer)
  - $Q_1 = g_1\,(T_1^4 - T_3^4)$
  - $Q_2 = g_2\,(T_4^4 - T_2^4)$
  - $\eta_{SB} = 1 - T_4/T_3$
- $Q_1 = g_1 g_2 \frac{(1-\eta_{SB})^4 T_1^4 - T_2^4}{g_1(1-\eta_{SB}) + g_2(1-\eta_{SB})^4}$
- $W = g_1 g_2 \eta_{SB} \frac{(1-\eta_{SB})^4 T_1^4 - T_2^4}{g_1(1-\eta_{SB}) + g_2(1-\eta_{SB})^4}$
- $\Sigma S = \frac{g_1 g_2}{T_1 T_2} \frac{((1-\eta_{SB})T_1 - T_2)((1-\eta_{SB})^4 T_1^4 - T_2^4)}{g_1(1-\eta_{SB}) + g_2(1-\eta_{SB})^4}$



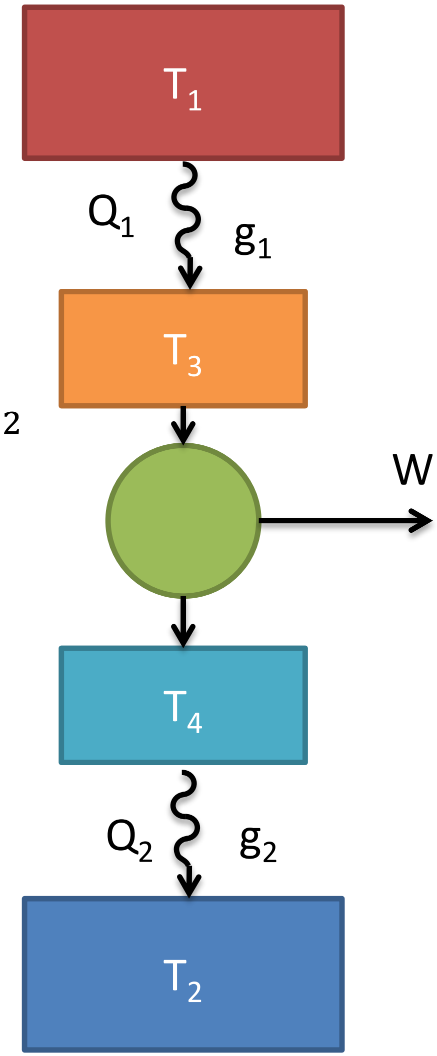
The Stefan-Boltzmann Engine



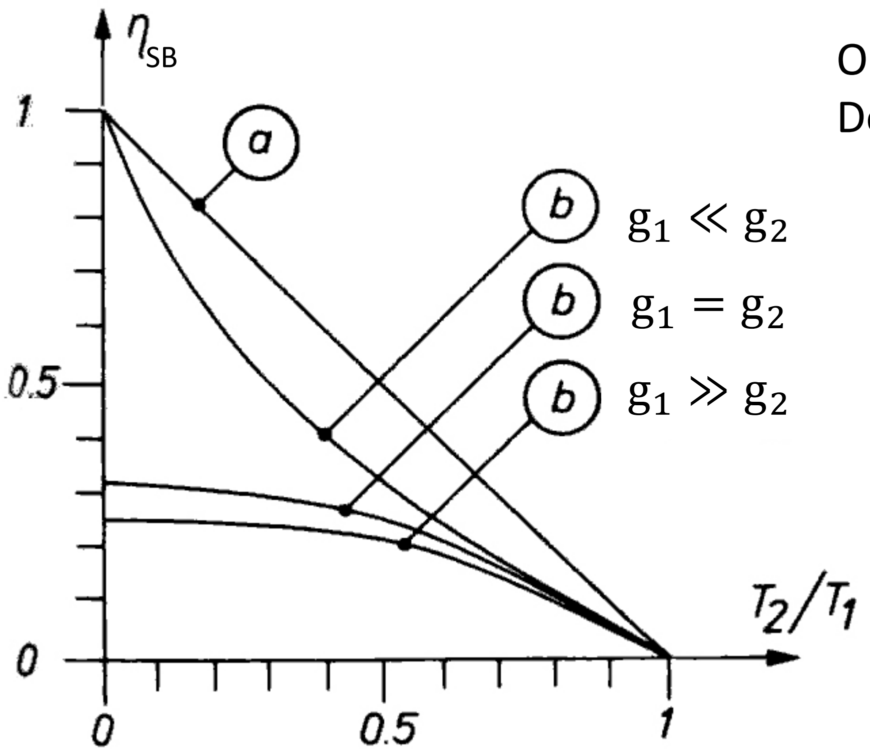
For $\frac{dW}{d\eta_{SB}} = 0$

Order 8 in η_{SB}

Depends on g_1/g_2



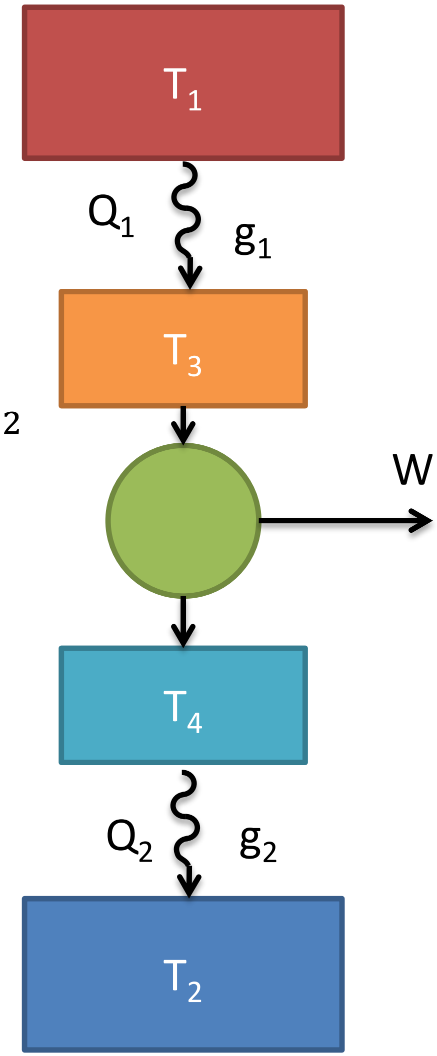
The Stefan-Boltzmann Engine



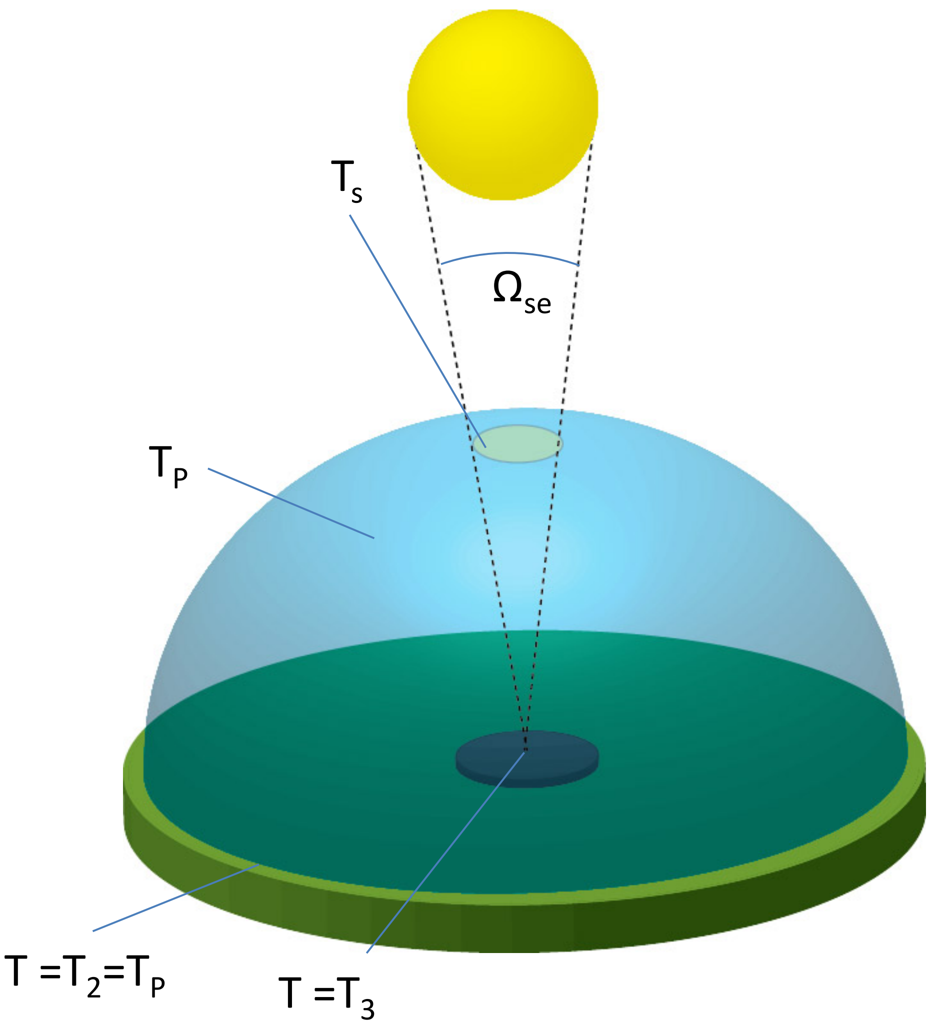
For $\frac{dW}{d\eta_{SB}} = 0$

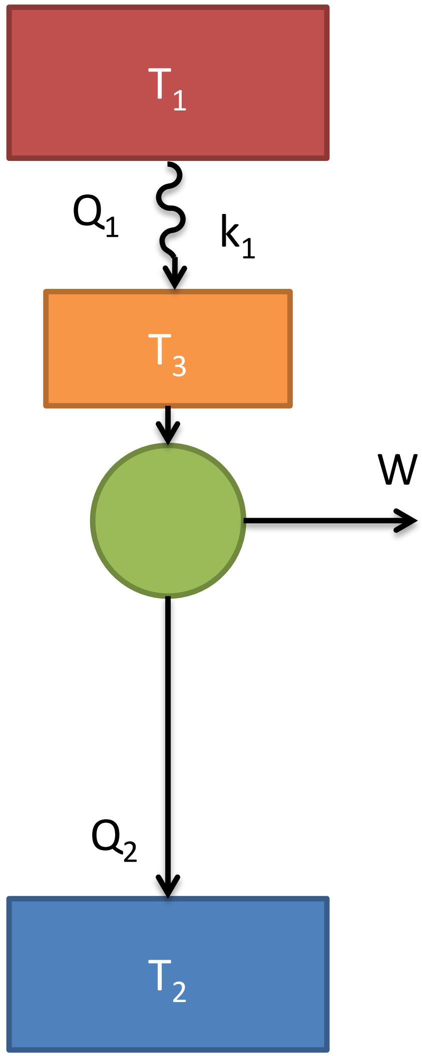
Order 8 in η_{SB}

Depends on g_1/g_2

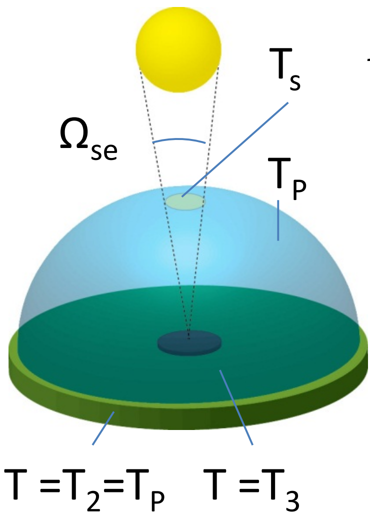


The Müser Engine





The Müser Engine

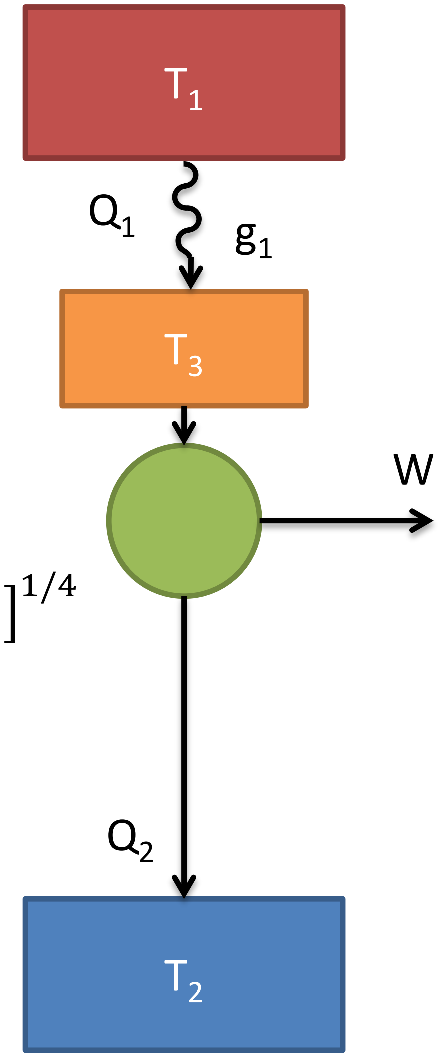


$$f = \frac{apparent\ area\ subtended\ by\ sun}{apparent\ area\ of\ the\ hemisphere}$$

$$= \frac{\iint_{\Omega} \cos\theta\, d\Omega}{\iint_{2\pi} \cos\theta\, d\Omega} \approx \frac{\Omega_{se}}{\pi}$$

$$= \frac{6.8 \times 10^{-5}}{\pi} = 2.16 \times 10^{-5}$$

$$Q_{sun\text{-}earth} = f\sigma T_s^4$$



$$Q_1 = f\sigma T_s^4 + (1-f)\sigma T_p^4 - \sigma T_3^4$$
$$= \sigma\left[fT_s^4 + (1-f)T_p^4 - T_3^4\right]$$

$$T_1 = \left[fT_s^4 + (1-f)T_p^4\right]^{1/4}$$
$$g_1 = \sigma$$

$$Q_1 = g_1\,(T_1^4 - T_3^4)$$

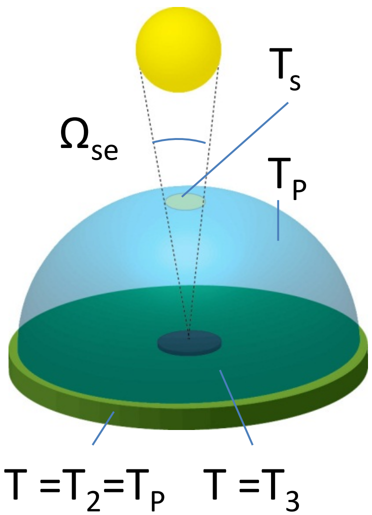
The Müser engine efficiency:

$$W = \eta_M Q_1$$

Solar energy efficiency:

$$W = \eta_{solar} f \sigma T_s^4$$

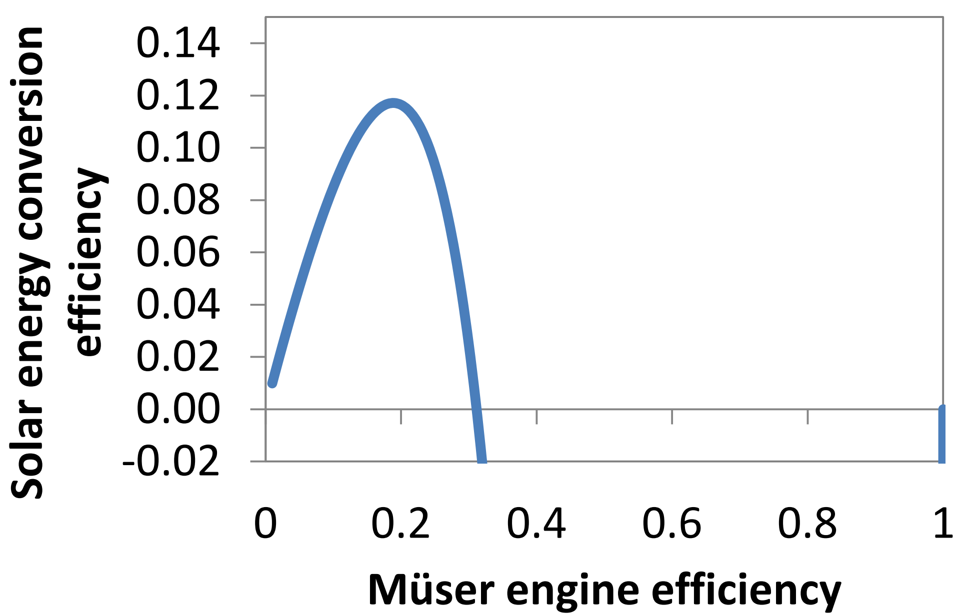
The Müser Engine

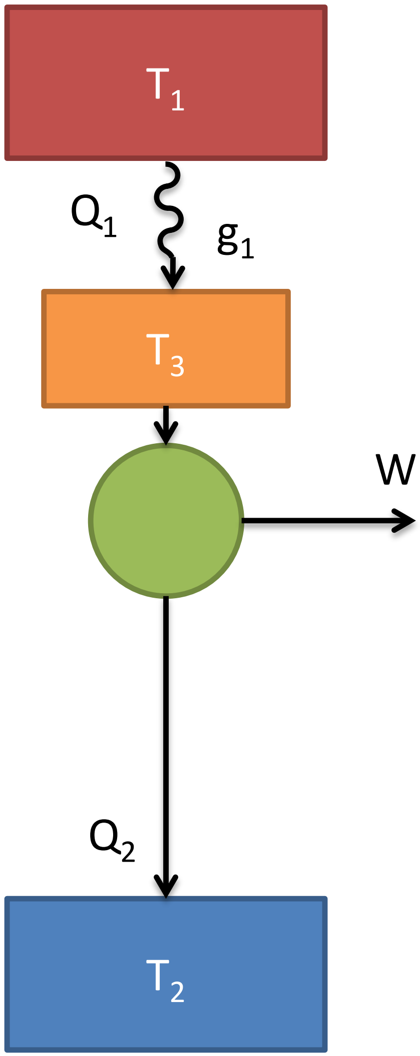


$$T_3 = \frac{T_p}{1-\eta_M}$$

$$W = \eta_M \left[f\sigma T_s^4 + \left(1 - f - \frac{1}{(1-\eta_M)^4}\right)\sigma T_p^4 \right]$$

$$\eta_{solar} = \eta_M \left[1 + \frac{(1-f)(1-\eta_M)^4 - 1}{(1-\eta_M)^4} \frac{T_p^4}{f T_s^4} \right]$$





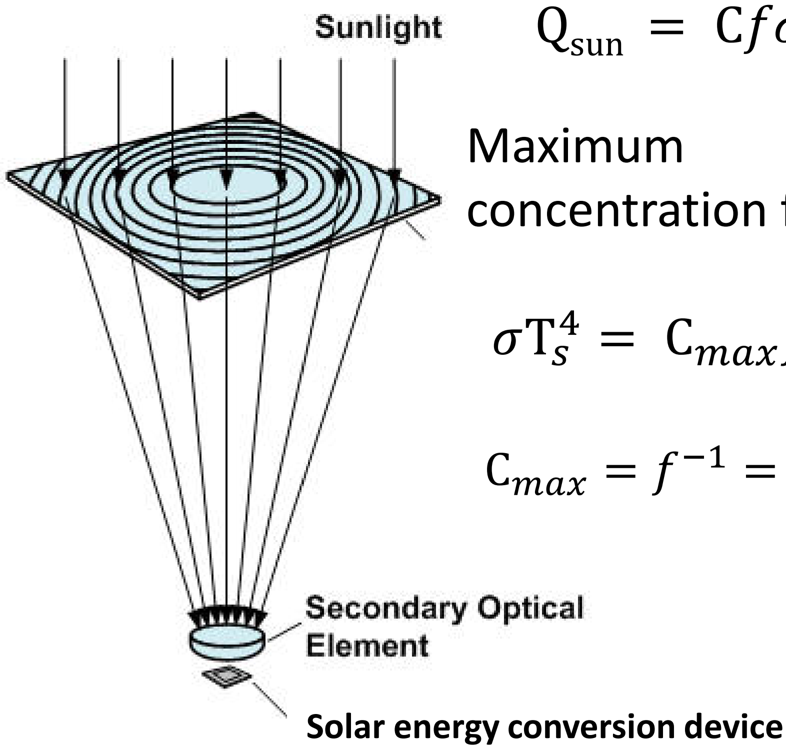
The Müser Engine on other planets

$$\eta_{solar} = \eta_M \left[1 + \frac{(1-f)(1-\eta_M)^4 - 1}{(1-\eta_M)^4} \frac{T_p^4}{f T_s^4} \right]$$

A first approximation:
$T_p^4 = \frac{f}{4} T_s^4$

Planet	Avg. distance (Gm)	f	S (W m^{-2})	T_p (K)	Max. η_{solar}(%)
Mercury	57	1.48×10^{-4}	9228	440	13.5
Venus	108	4.14×10^{-5}	2586	733	0.95
Earth	150	2.16×10^{-5}	1353	288	11.8
Mars	227	9.37×10^{-6}	586	220	13.6
Jupiter	778	8.01×10^{-7}	50	124	12.3
Saturn	1426	2.38×10^{-7}	15	95	11.3
Uranus	2868	5.89×10^{-8}	4	59	15.2
Neptune	4497	2.40×10^{-8}	2	59	8.75

Concentrating solar irradiation



Concentration factor:

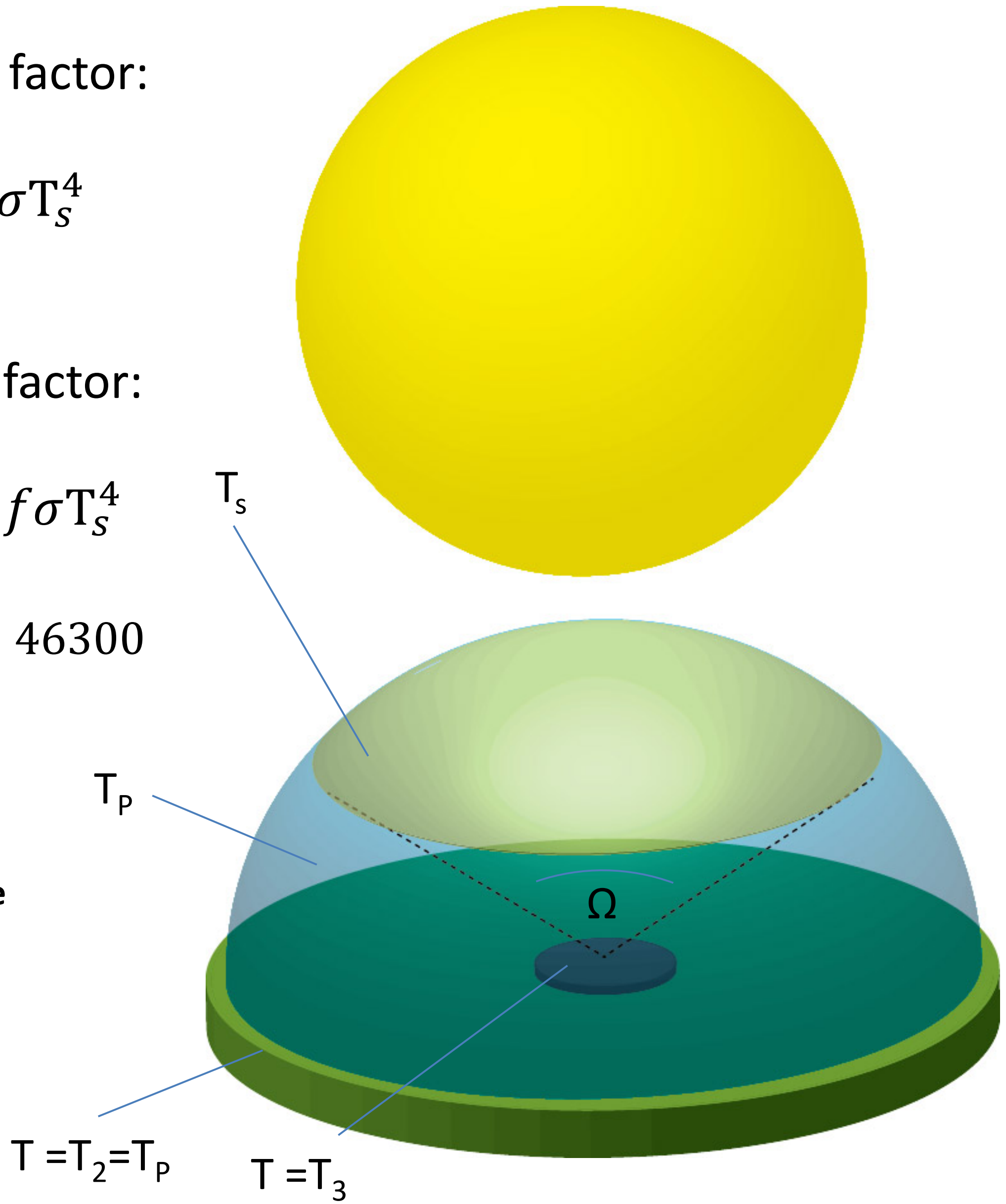
$$C > 1$$

$$Q_{sun} = C f \sigma T_s^4$$

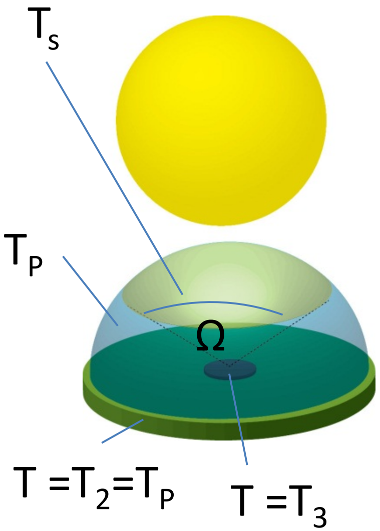
Maximum concentration factor:

$$\sigma T_s^4 = C_{max} f \sigma T_s^4$$

$$C_{max} = f^{-1} = 46300$$



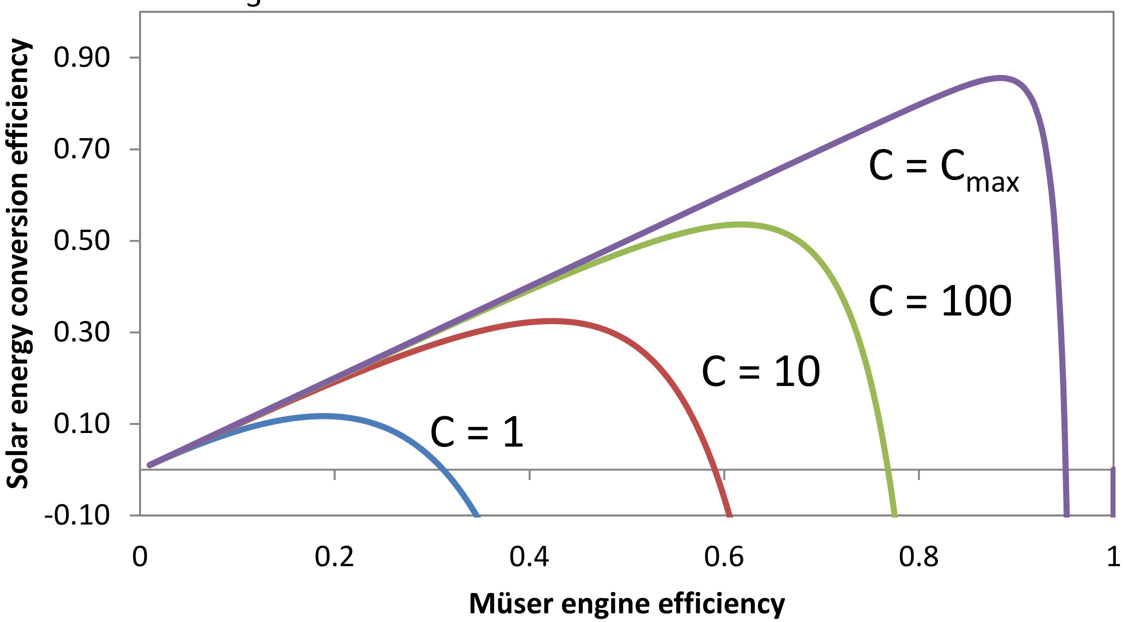
The Müser Engine with a concentrator

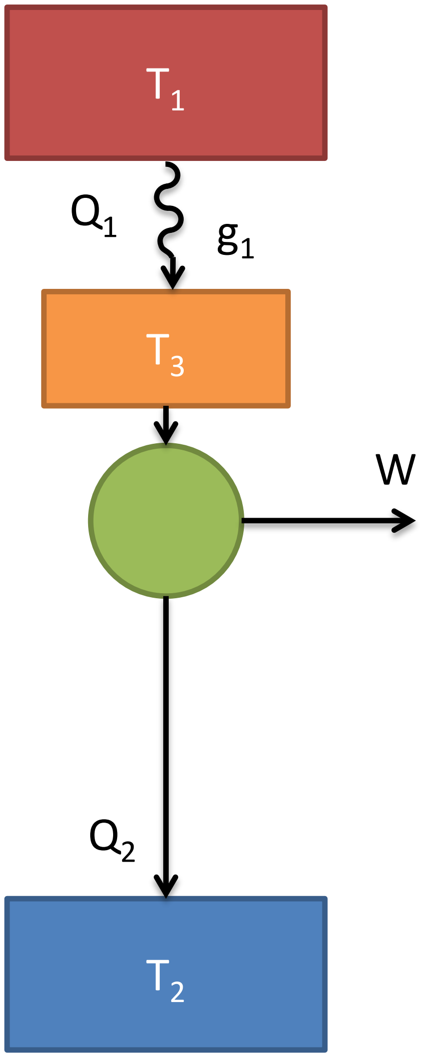


$$Q_1 = \sigma\left[Cf T_s^4 + (1 - Cf) T_p^4 - T_3^4\right]$$

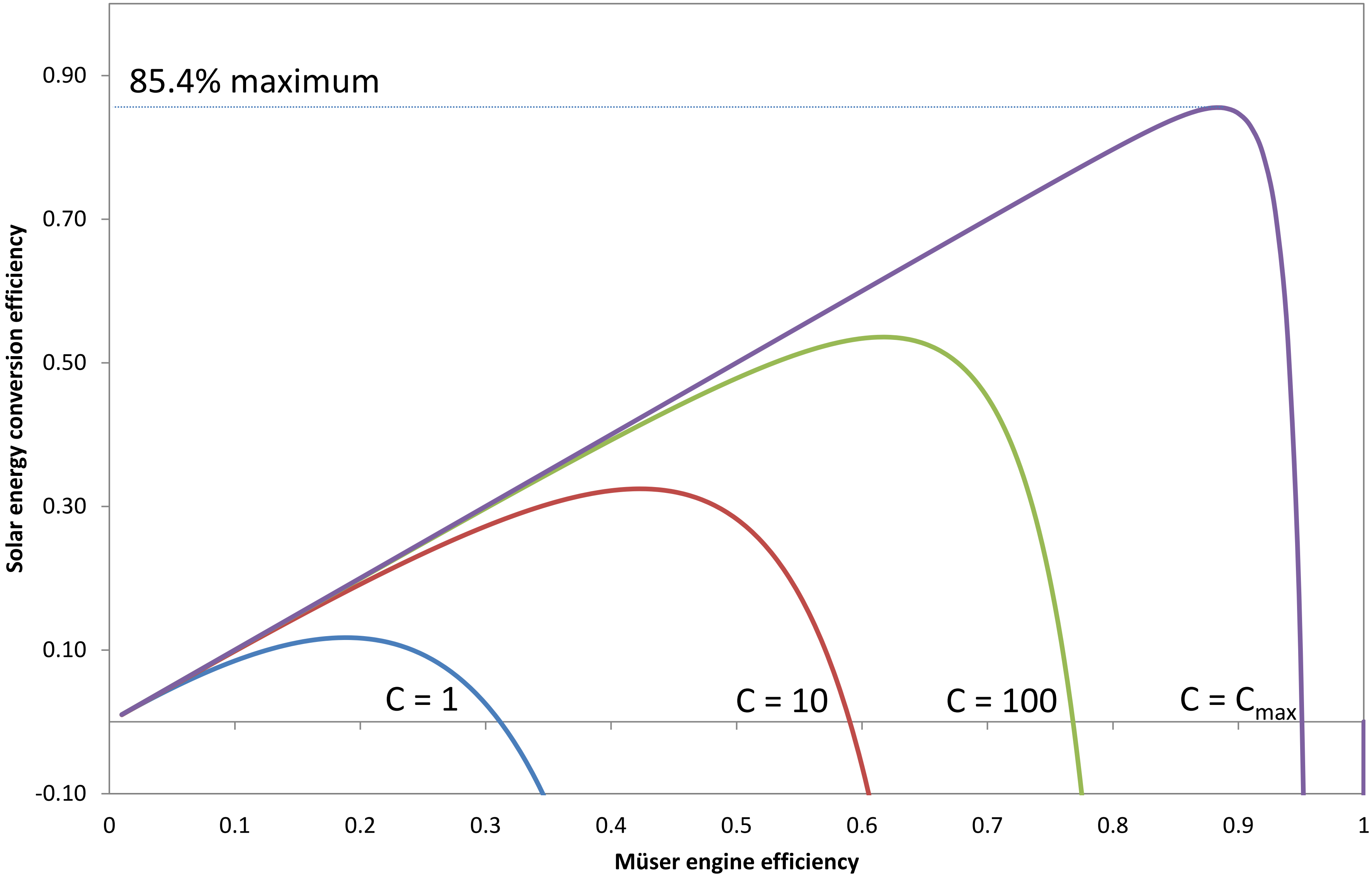
Solar energy efficiency:

$$W = \eta_{solar} C f \sigma T_s^4$$

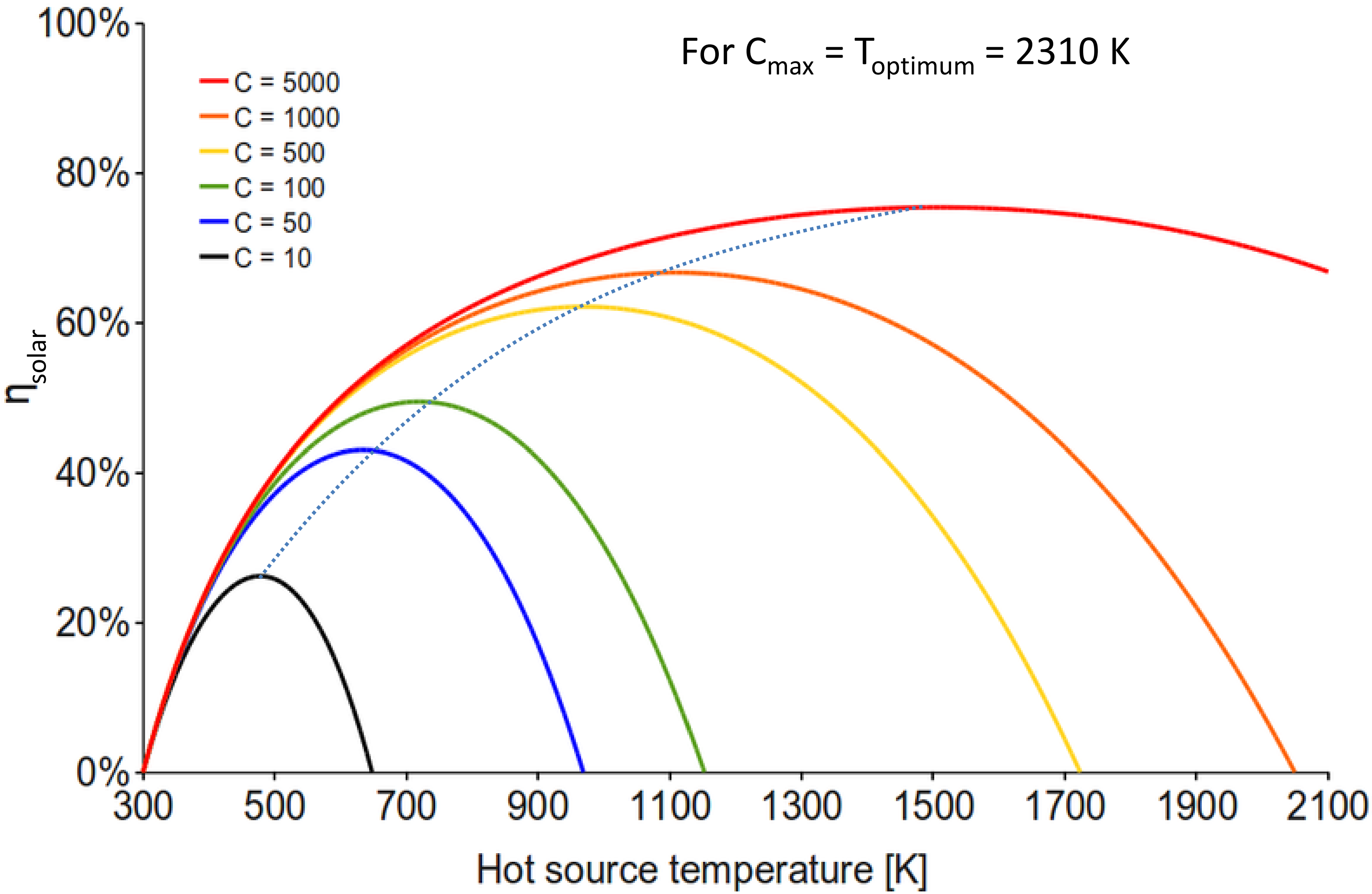




The Müser Engine with a concentrator



$\eta_{solar}(T_3)$ for different C



The Müser Engine with concentrator on other planets

Planet	Avg. distance (Gm)	f	S ($W\ m^{-2}$)	T_p (K)	Max. η_{solar}(%) With conc.
Mercury	57	1.48×10^{-4}	9228	440	79.7
Venus	108	4.14×10^{-5}	2586	733	75.0
Earth	150	2.16×10^{-5}	1353	288	85.4
Mars	227	9.37×10^{-6}	586	220	88.1
Jupiter	778	8.01×10^{-7}	50	124	92.5
Saturn	1426	2.38×10^{-7}	15	95	93.9
Uranus	2868	5.89×10^{-8}	4	59	95.6
Neptune	4497	2.40×10^{-8}	2	59	95.7
Pluto	5874	1.18×10^{-8}	2	44	96.6

Summary

- The Curzon-Ahlborn engine provides the framework for energy conversion with heat transfer
- The Stefan-Boltzmann engine uses radiative heat transfer and shows that the highest efficiency can be gained if the thermal transfer to the cold sink is infinitely good
- The Müser engine approximates this and reveals that only about 12% solar energy conversion efficiency is possible even with a Carnot cycle.
- Concentration allows the maximum efficiency of 85.4%