Photovoltaics & Thermoelectrics

Prof Douglas J. Paul
School of Engineering
University of Glasgow

Douglas.Paul@glasgow.ac.uk

What You will Learn Today

- An overview of some applications needing energy harvesting
- How to convert thermal energy into electricity through thermoelectric generation
- The amount of energy available from the sun at different points on the planet
- How photovoltaic solar cells generate electricity
- What is the optimum absorption wavelength
- How can we maximise PV electricity generation efficiency

Energy Harvesting Applications

Cars: replace alternator

Solar powered road signs

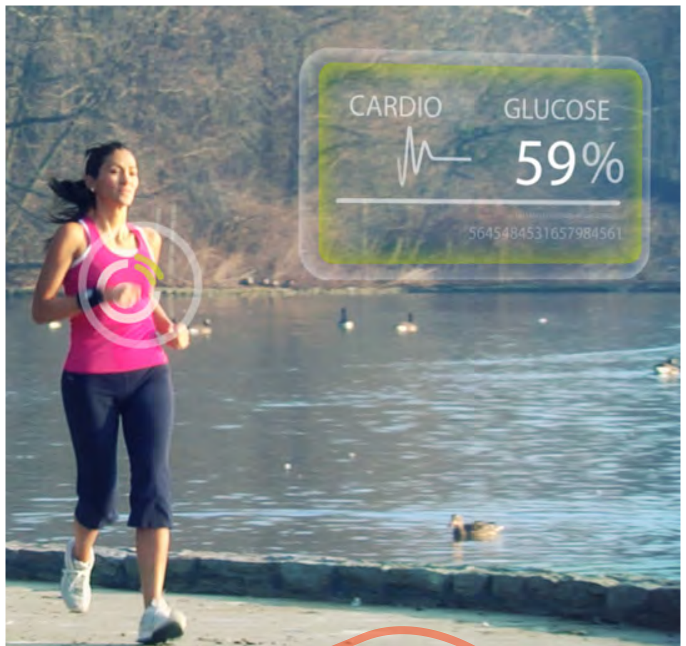
Trains: Vibrations powering sensors

Temperature control for CO_2 sequestration

Battery free autonomous sensors: ECG, blood pressure, etc.

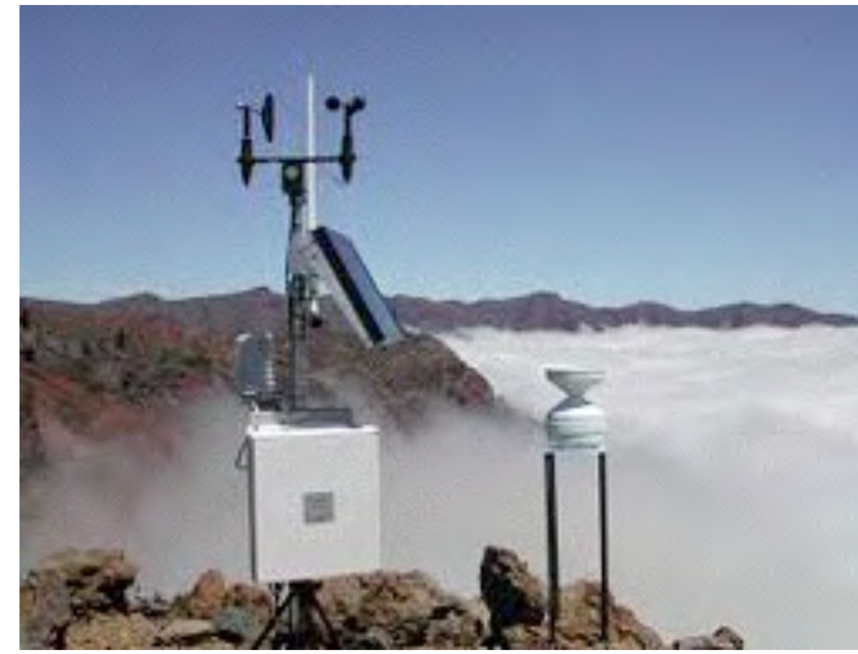
Energy Harvesting for Remote Sensing

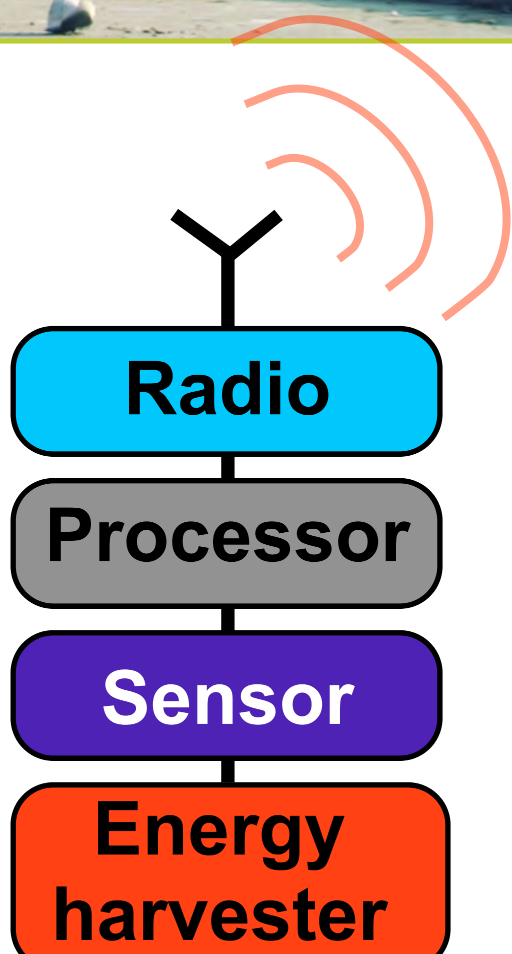
Sports performance sensors

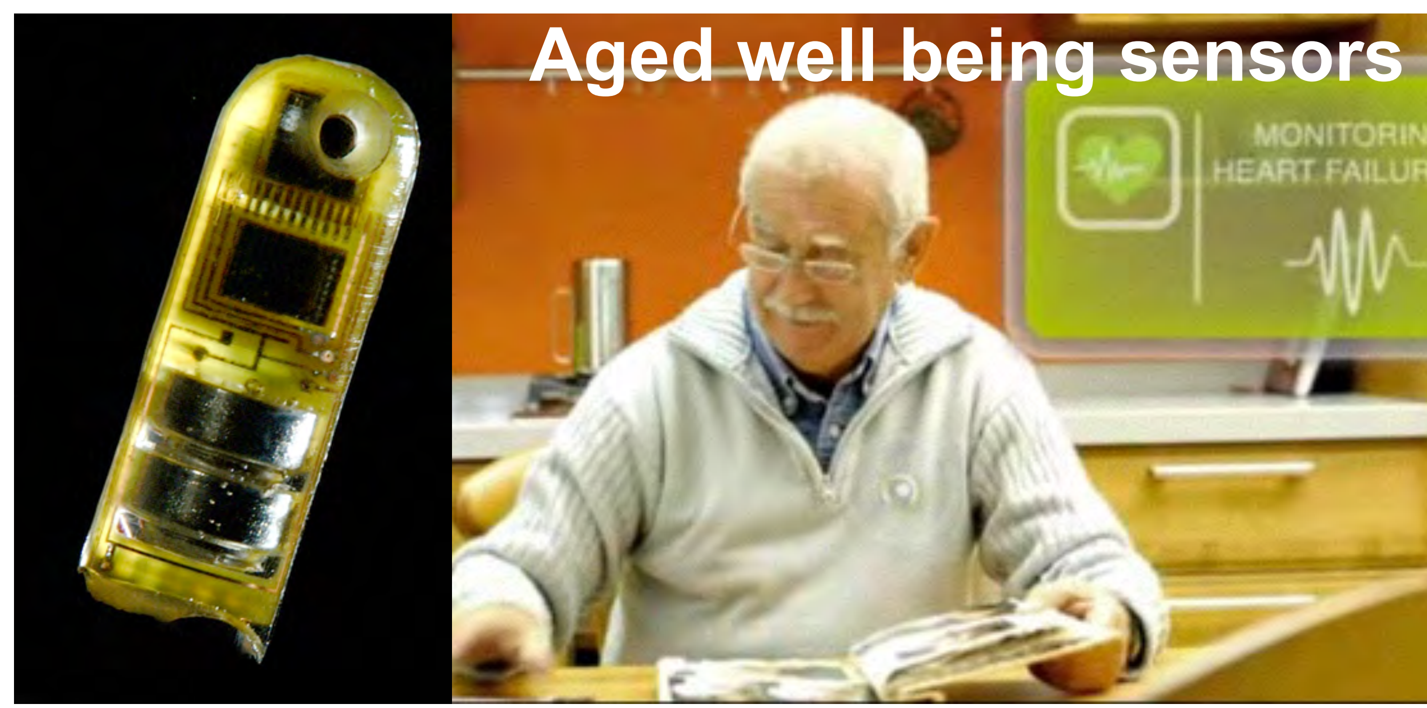


Flood sensors

Weather monitoring

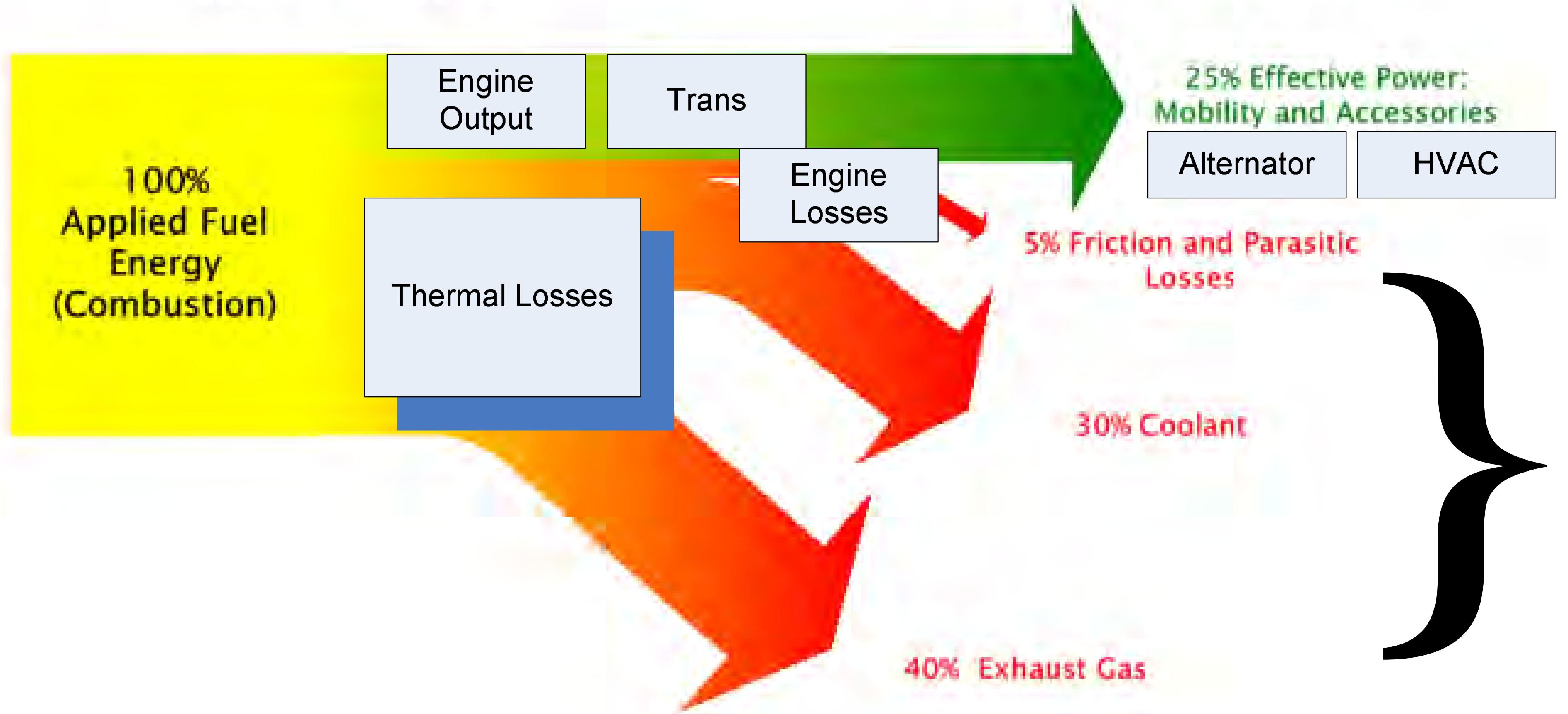






Battery free autonomous sensors: ECG, blood pressure, etc.

Thermoelectric Energy Harvesting in Cars



75% of waste = heat!

Fuel consumption $\propto$ $\eta_{powertrain}$ (kinetic energy + amenities energy)

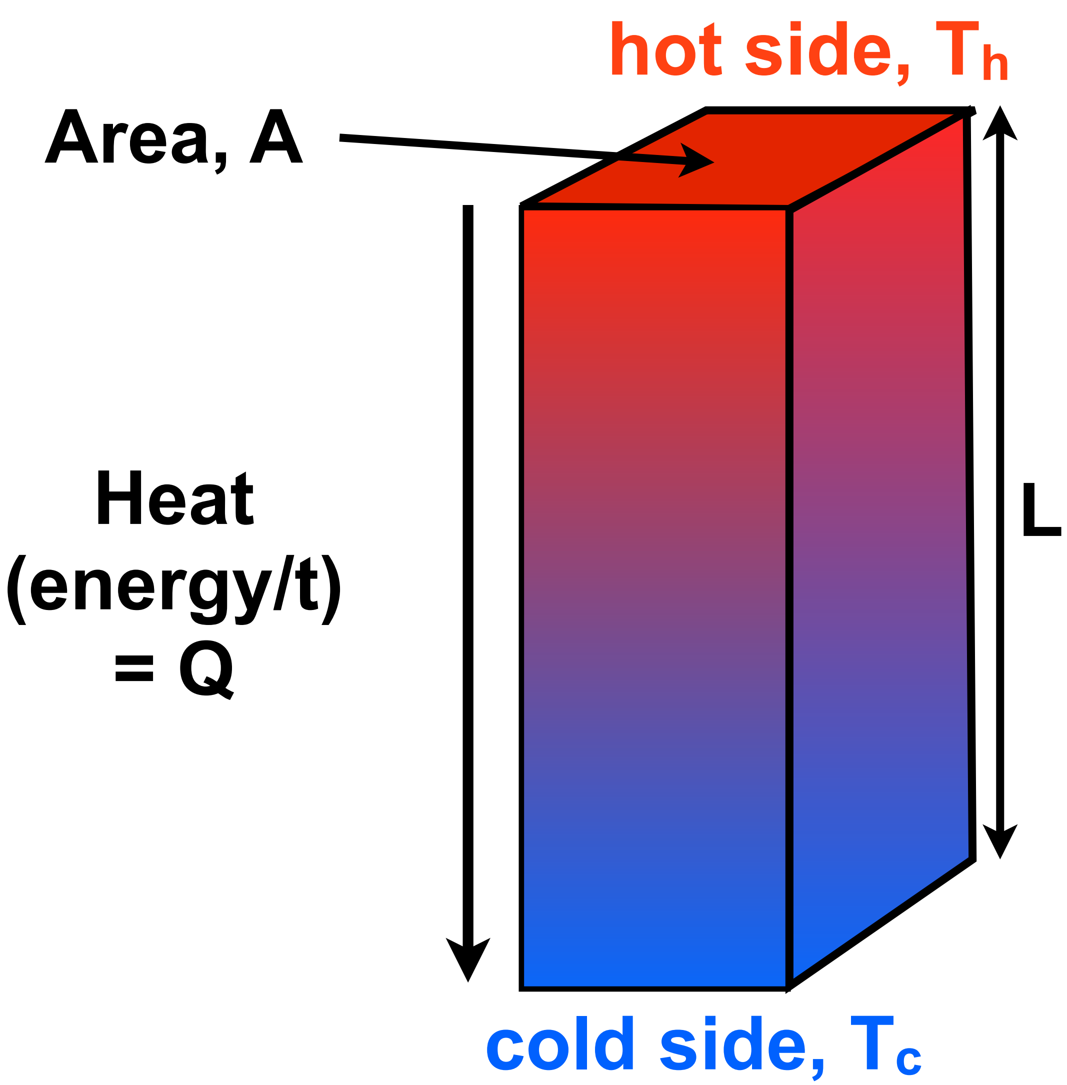
Thermoelectrics in Cars:

- **Use waste heat energy (45% of fuel!)**
- **Can reduce fuel consumption ≤ 5%**
- **Provide efficient local cooling**

Background Thermal Physics

Fourier thermal transport

$$Q = -\kappa A \nabla T$$

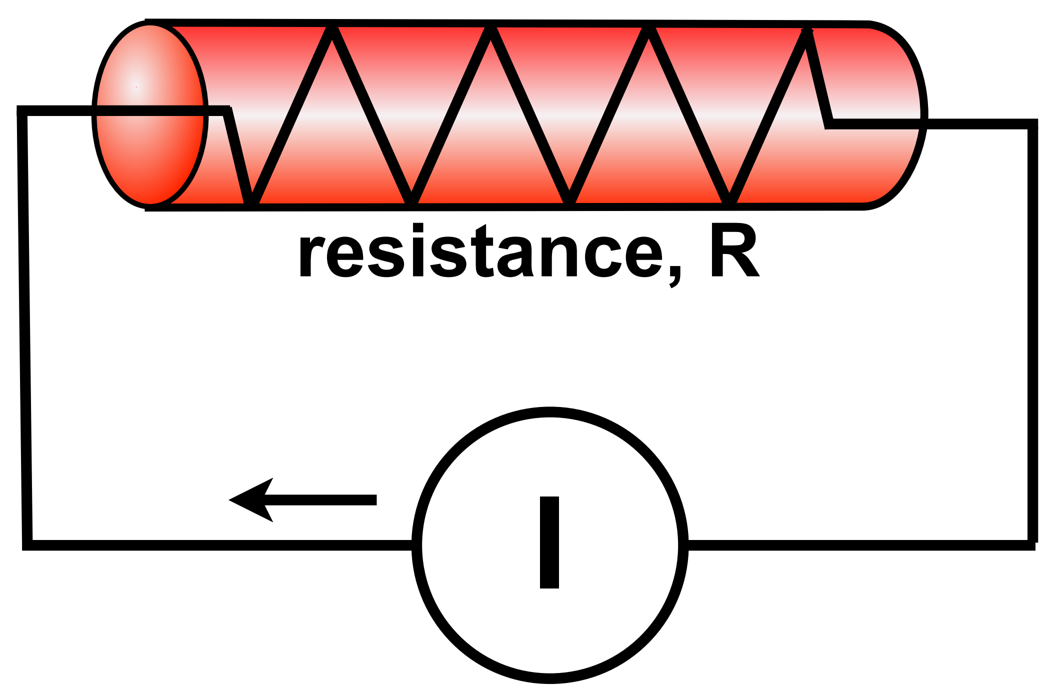


$$Q = -\kappa A \frac{T_c - T_h}{L}$$

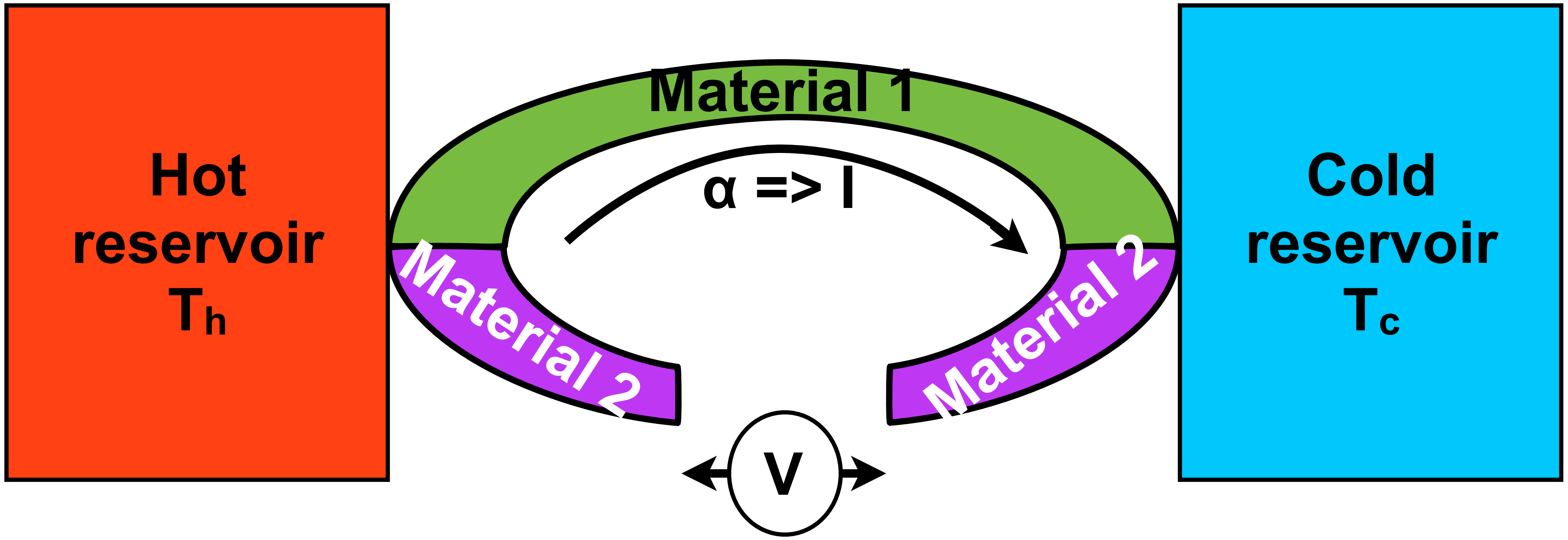
Joule heating

$$Q = I^2 R$$

Q = heat (power i.e energy / time)



The Seebeck Effect



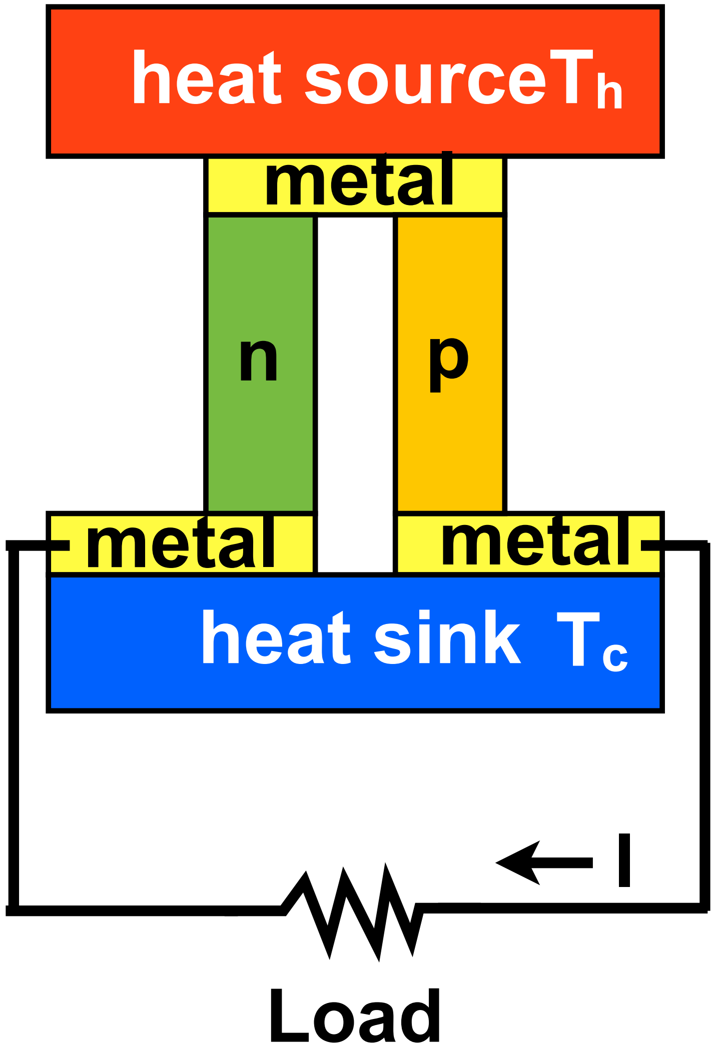
- Open circuit voltage, $V = \alpha (T_h - T_c) = \alpha \Delta T$

Seebeck coefficient, $\alpha = \frac{dV}{dT}$

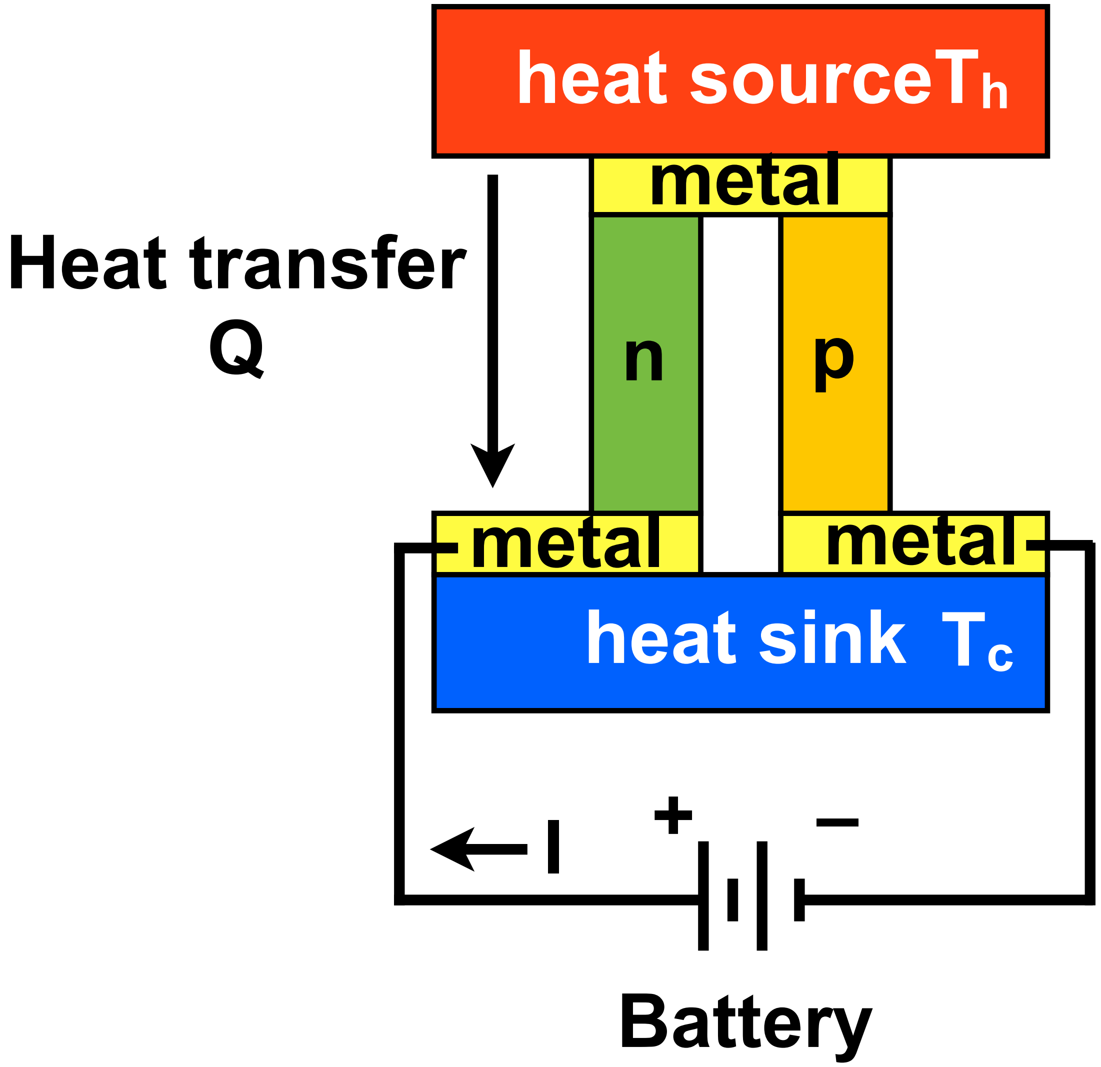
units: V/K

- Seebeck coefficient = $\frac{1}{q}$ x entropy $\left(\frac{Q}{T}\right)$ transported with electron

Seebeck effect: electricity generation

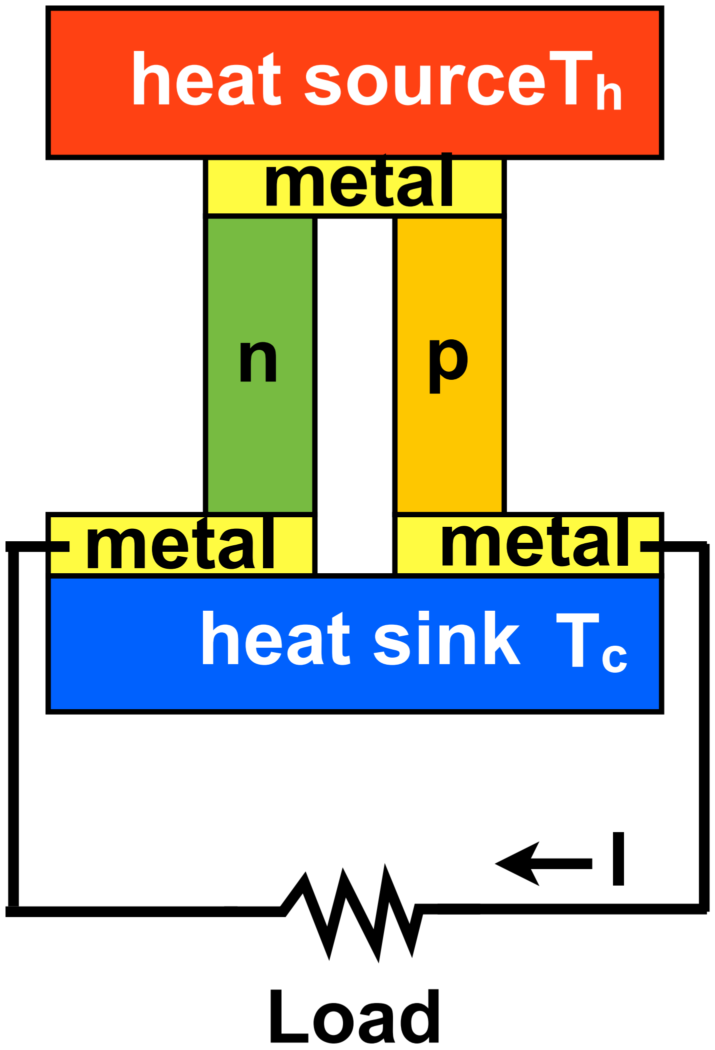


Peltier effect: electrical cooling i.e. heat pump



Thermoelectric Power Generating Efficiency

$$\eta = \frac{\Delta T}{T_h} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}}$$



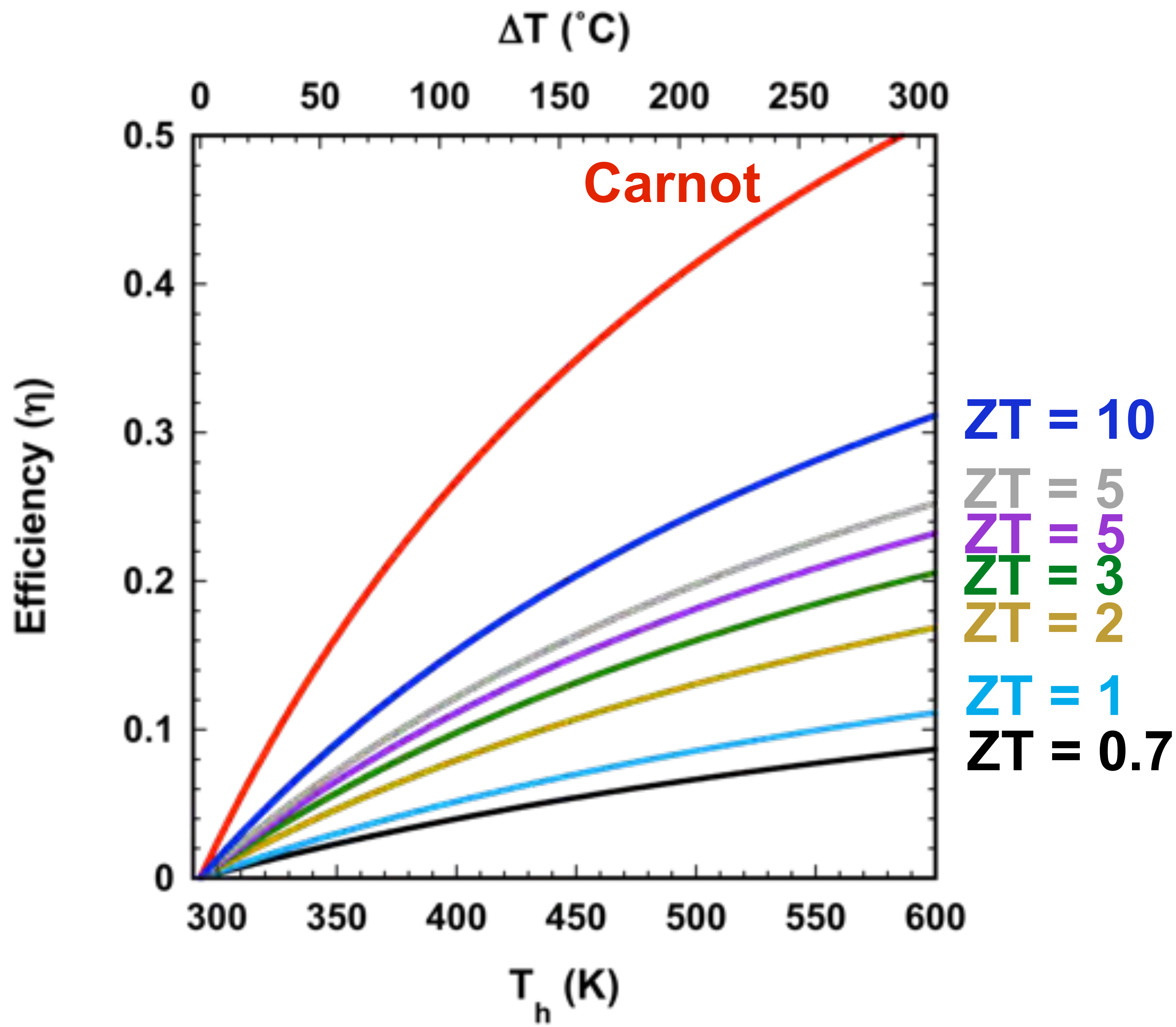
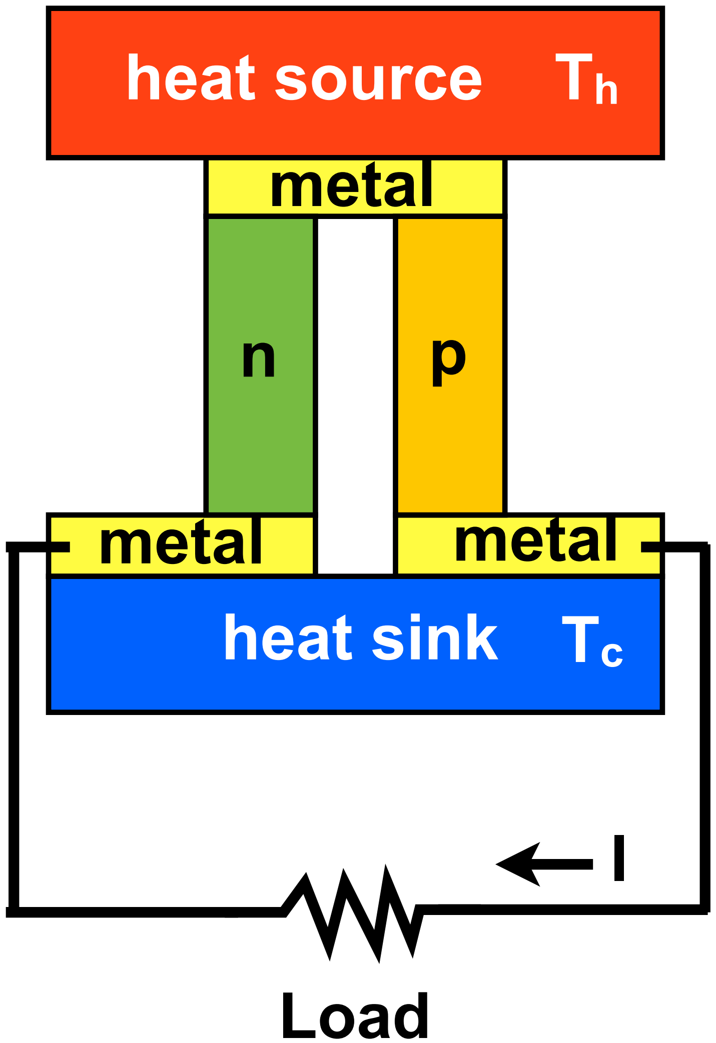


Figure of merit

$$ZT = \frac{\alpha^2 \sigma}{\kappa} T$$

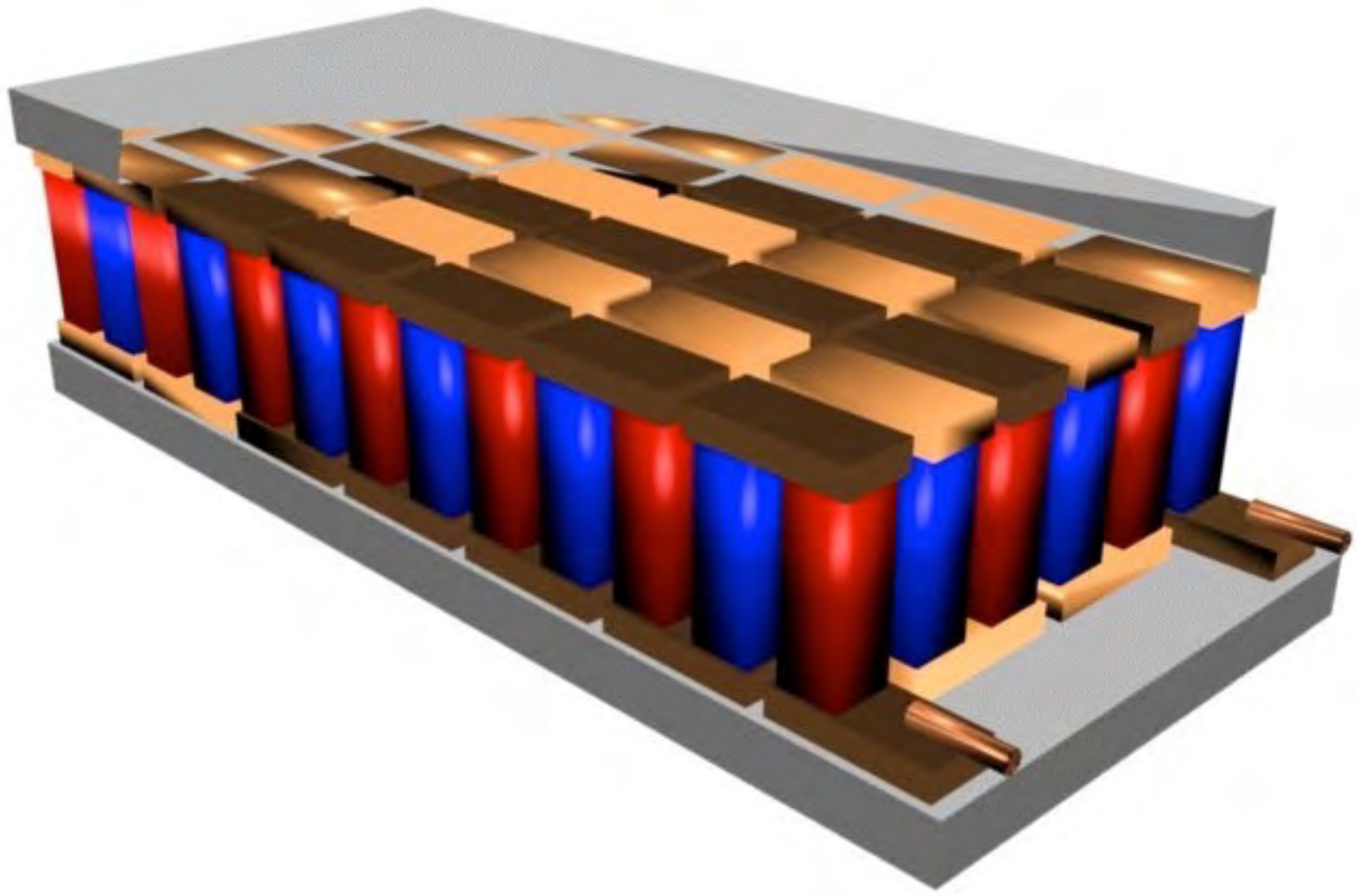
Thermoelectric Generators

Module



~ 0.2 mV

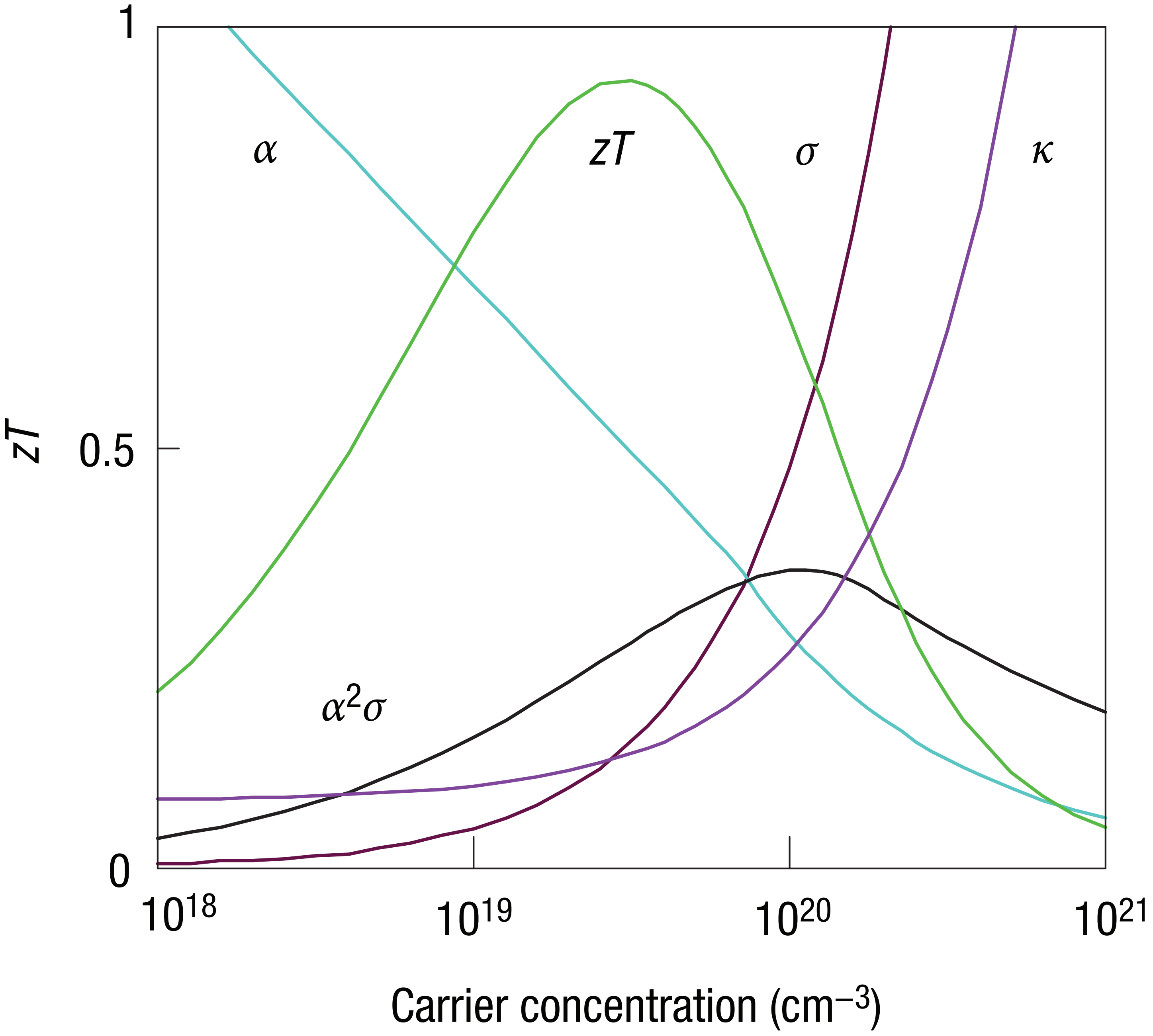
Generator



> 1 V

- **Modules stacked electrically in series, thermally in parallel to get useful I & V**

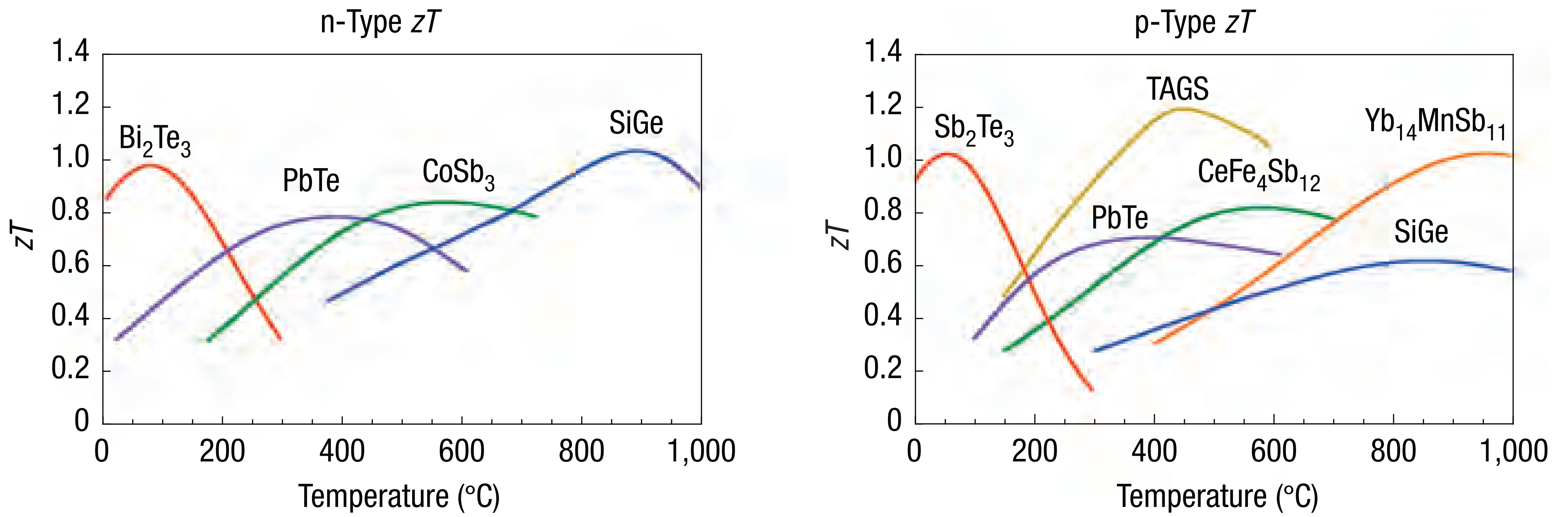
Bi_2Te_3 ZT Optimisation Through Doping



- Maximum ZT requires compromises with α, σ & κ
- Limited by Wiedemann-Franz Law
- Maximum ZT ~ 1 at ~100 ˚C

G.J. Snyder et al., Nature Mat. 7, 105 (2008)

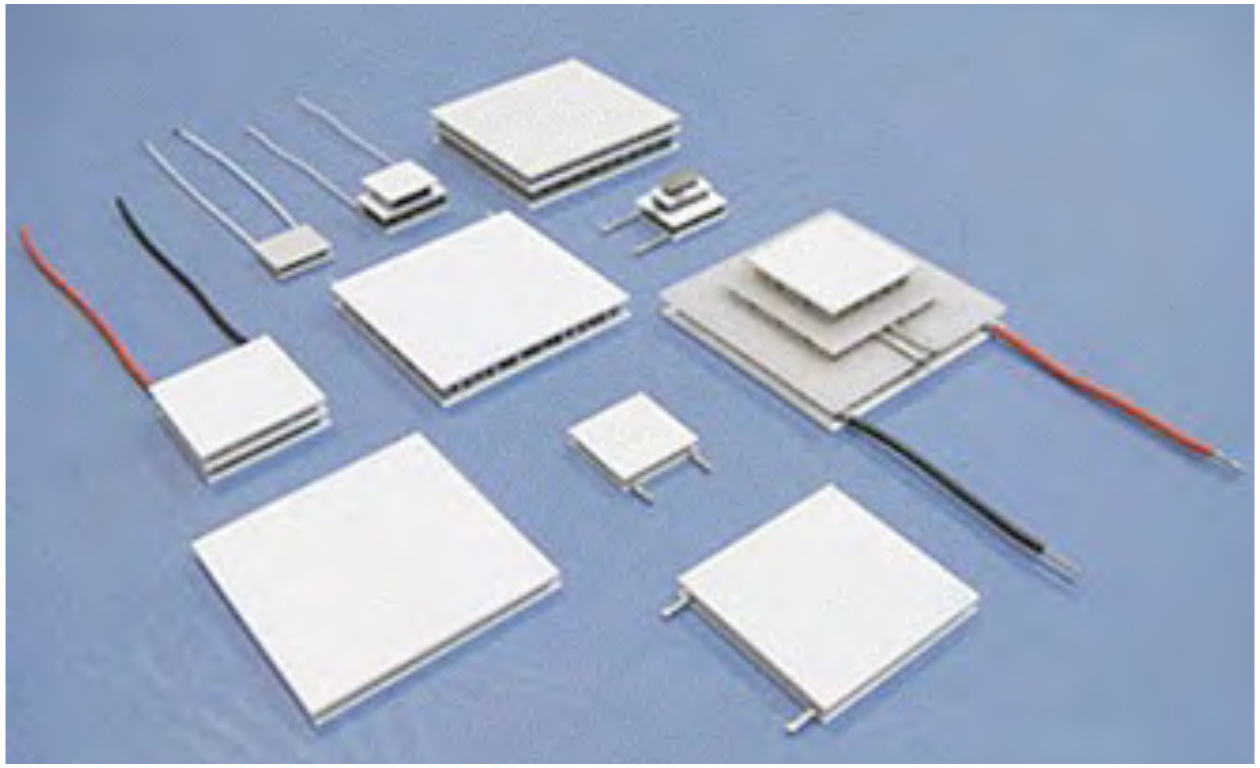
Bulk Thermoelectric Materials Performance



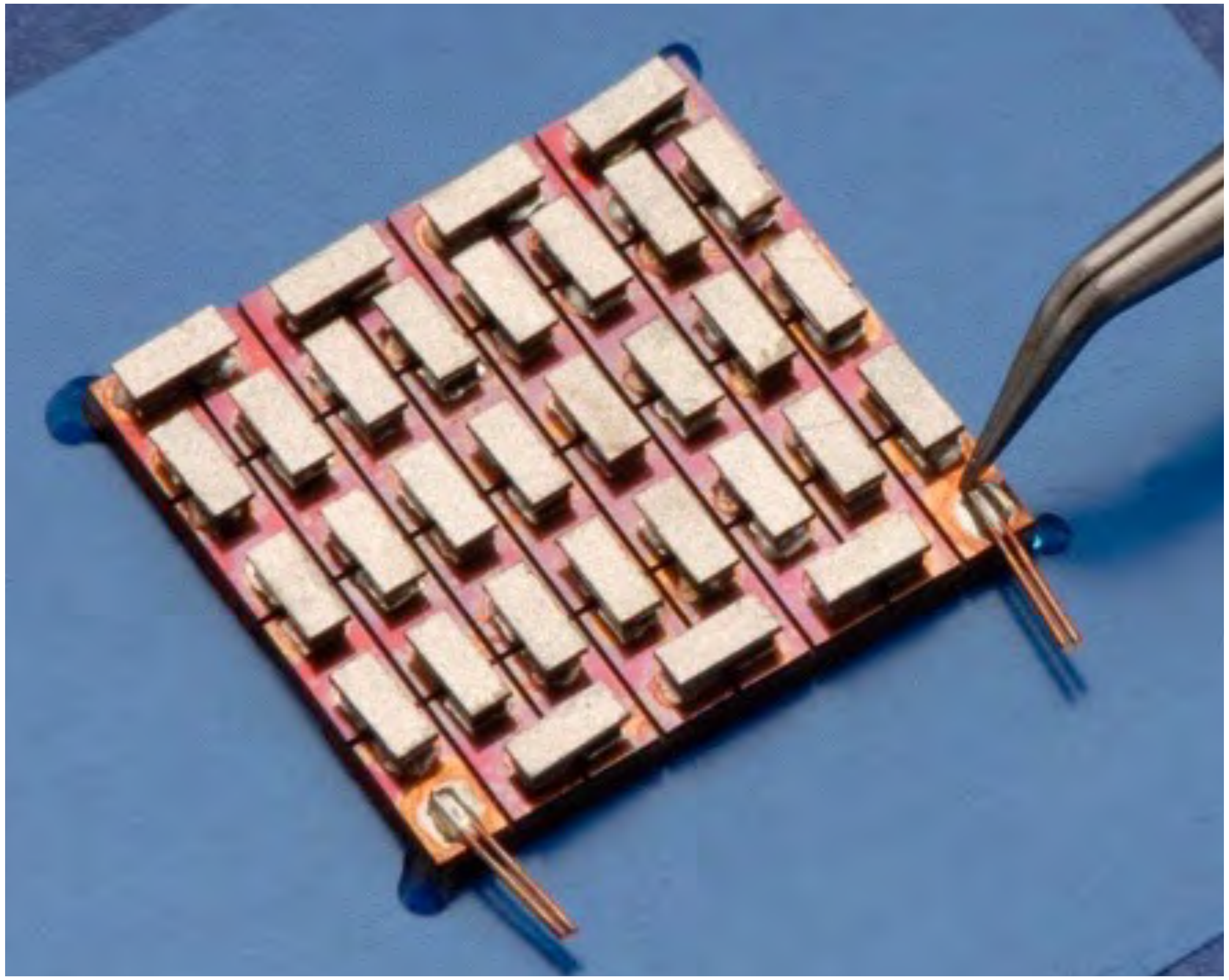
Nature Materials 7, 105 (2008)

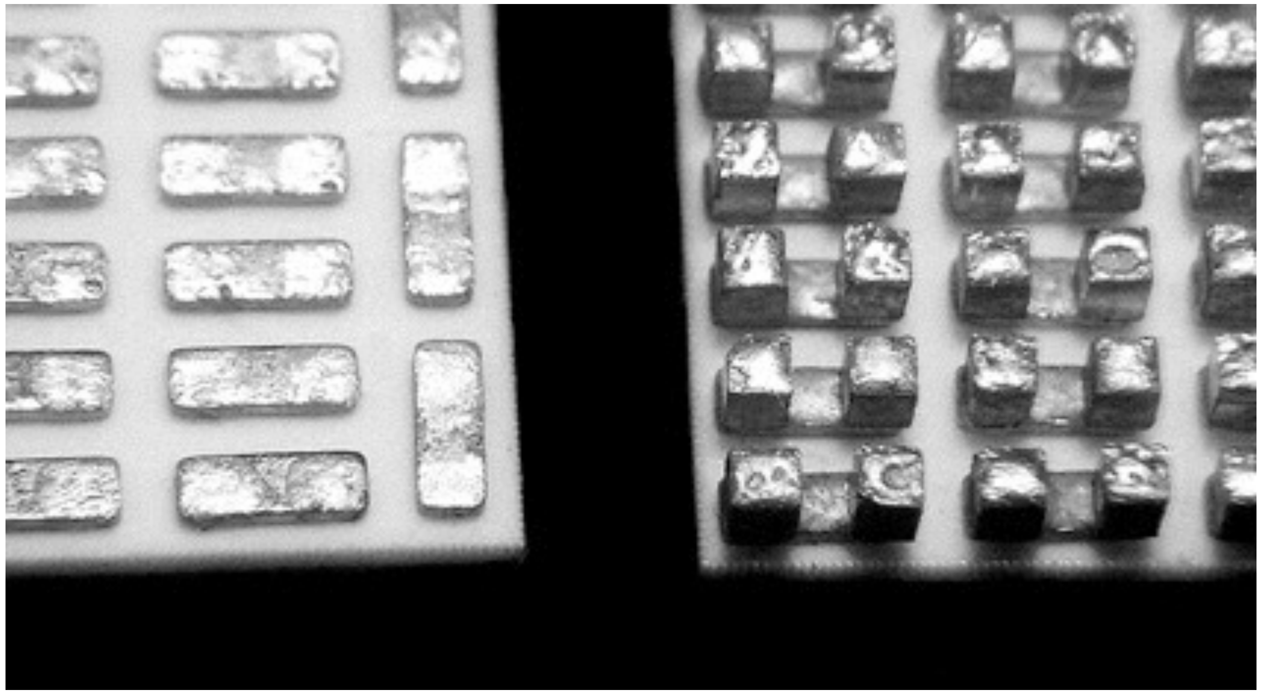
- **Bulk n-Bi_2Te_3 and p-Sb_2Te_3 used in most commercial thermoelectrics & Peltier coolers**
- **But tellurium is 8^{th} rarest element on earth !!!**
- **Bulk $Si_{1-x}Ge_x$ (x~0.2 to 0.3) used for high temperature satellite applications**

Thermoelectric Generators / Peltier Coolers

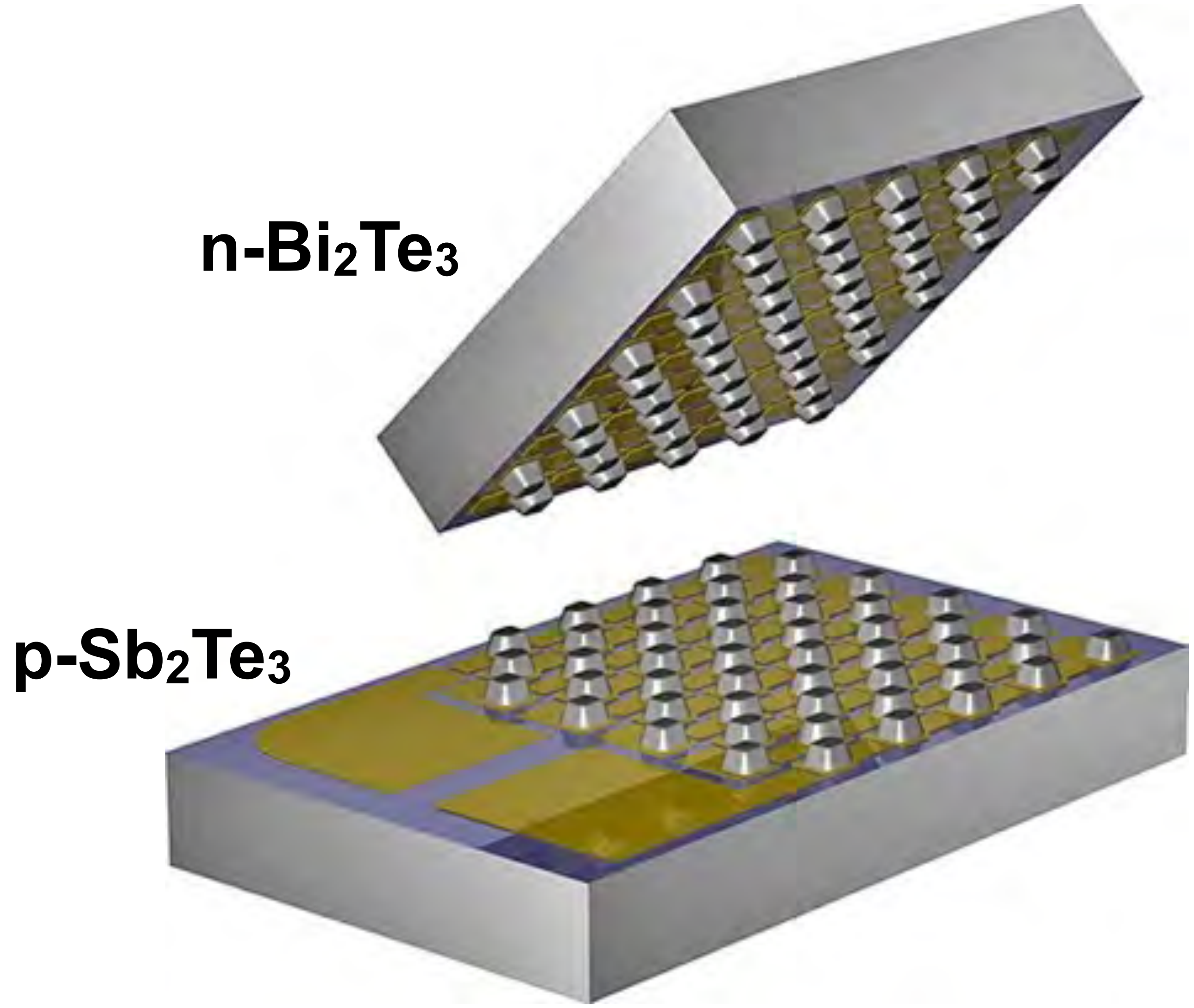


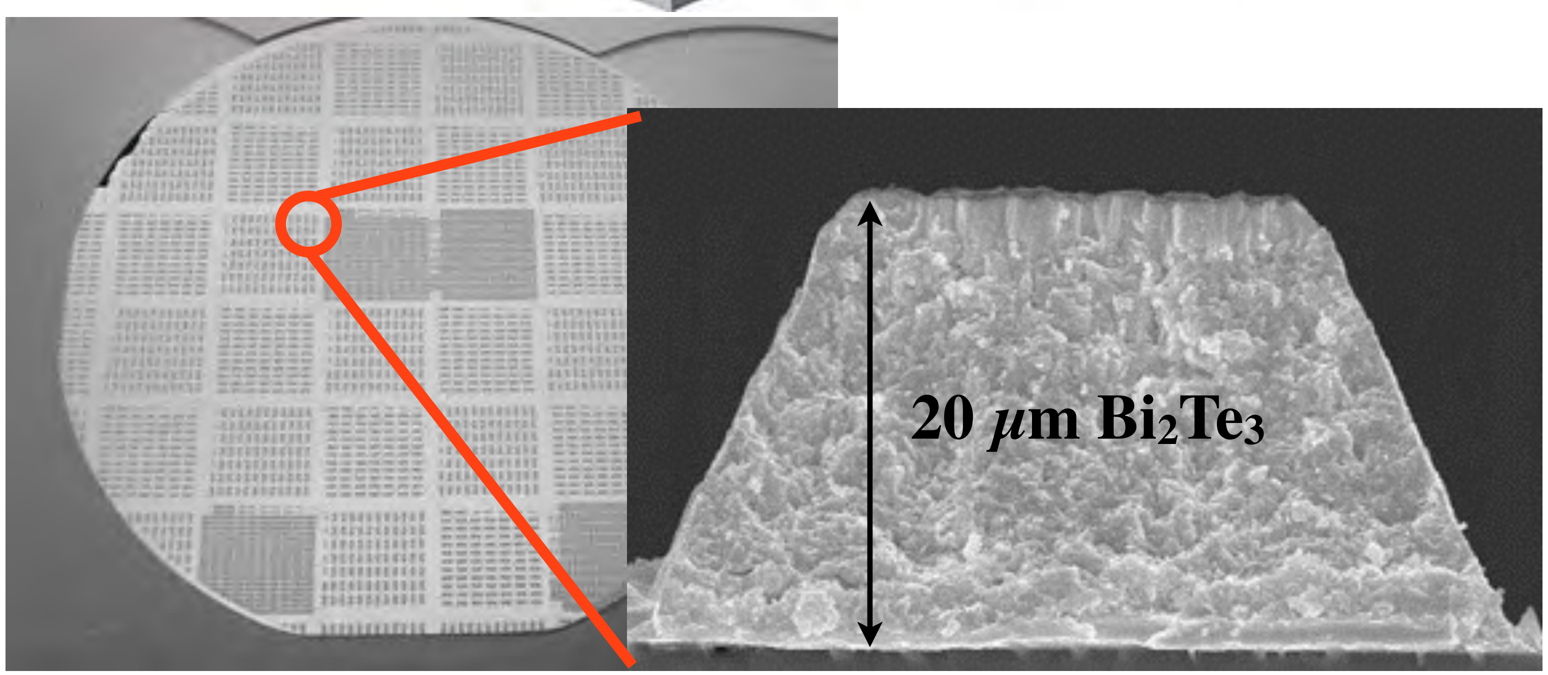
Bulk n-Bi_2Te_3 and p-Sb_2Te_3 devices



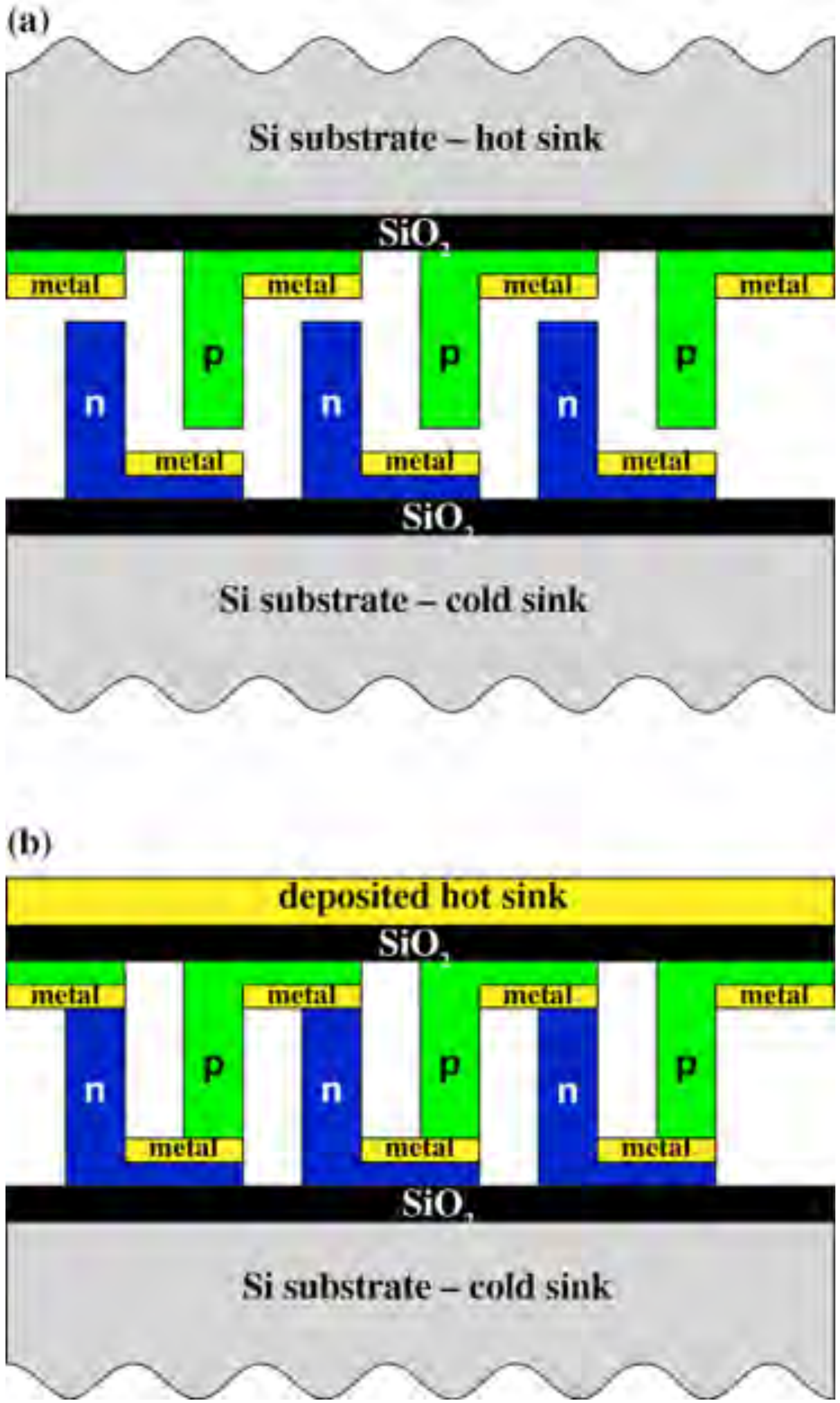


Wafer Scale Microfabrication of Generators



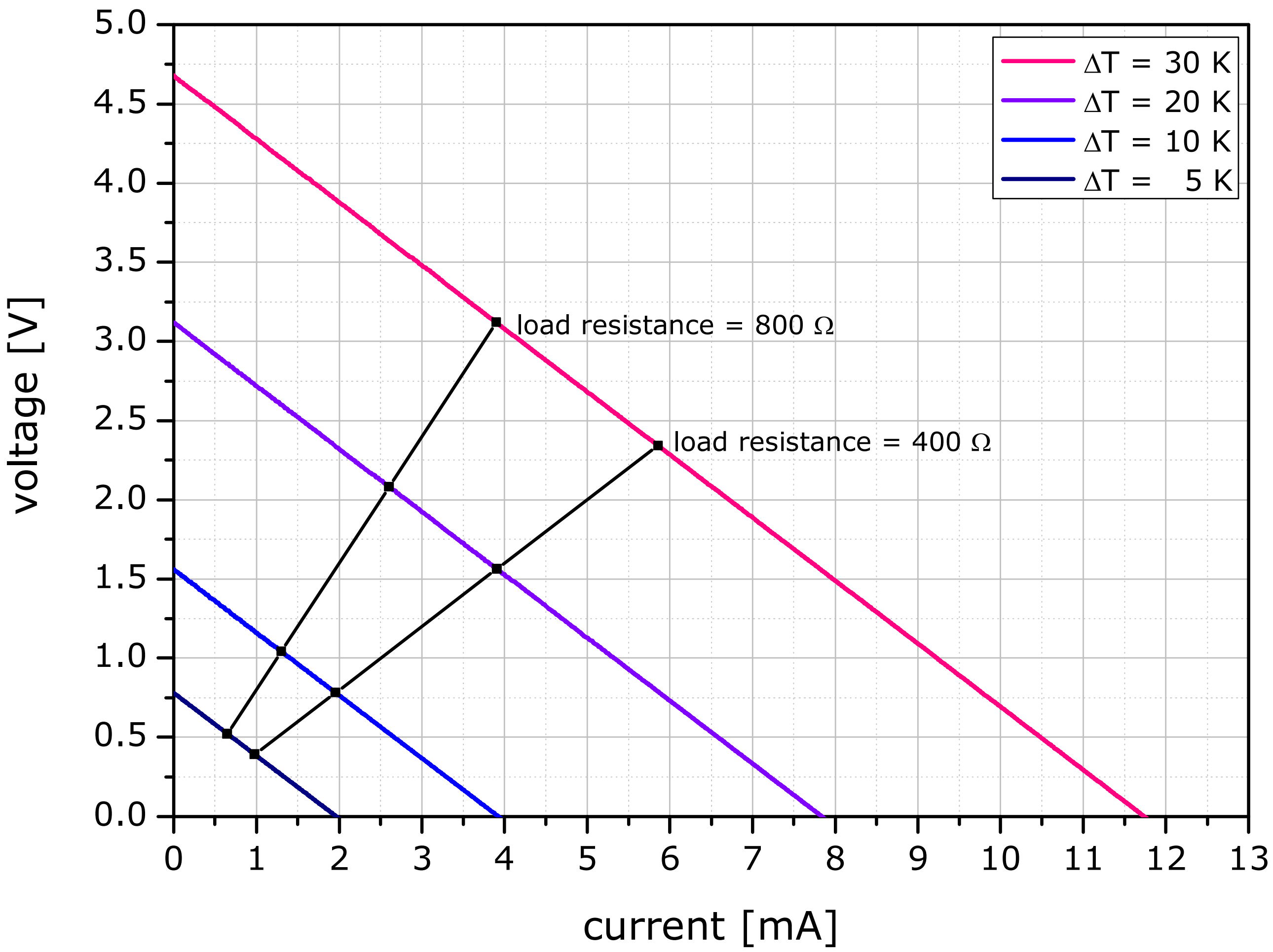


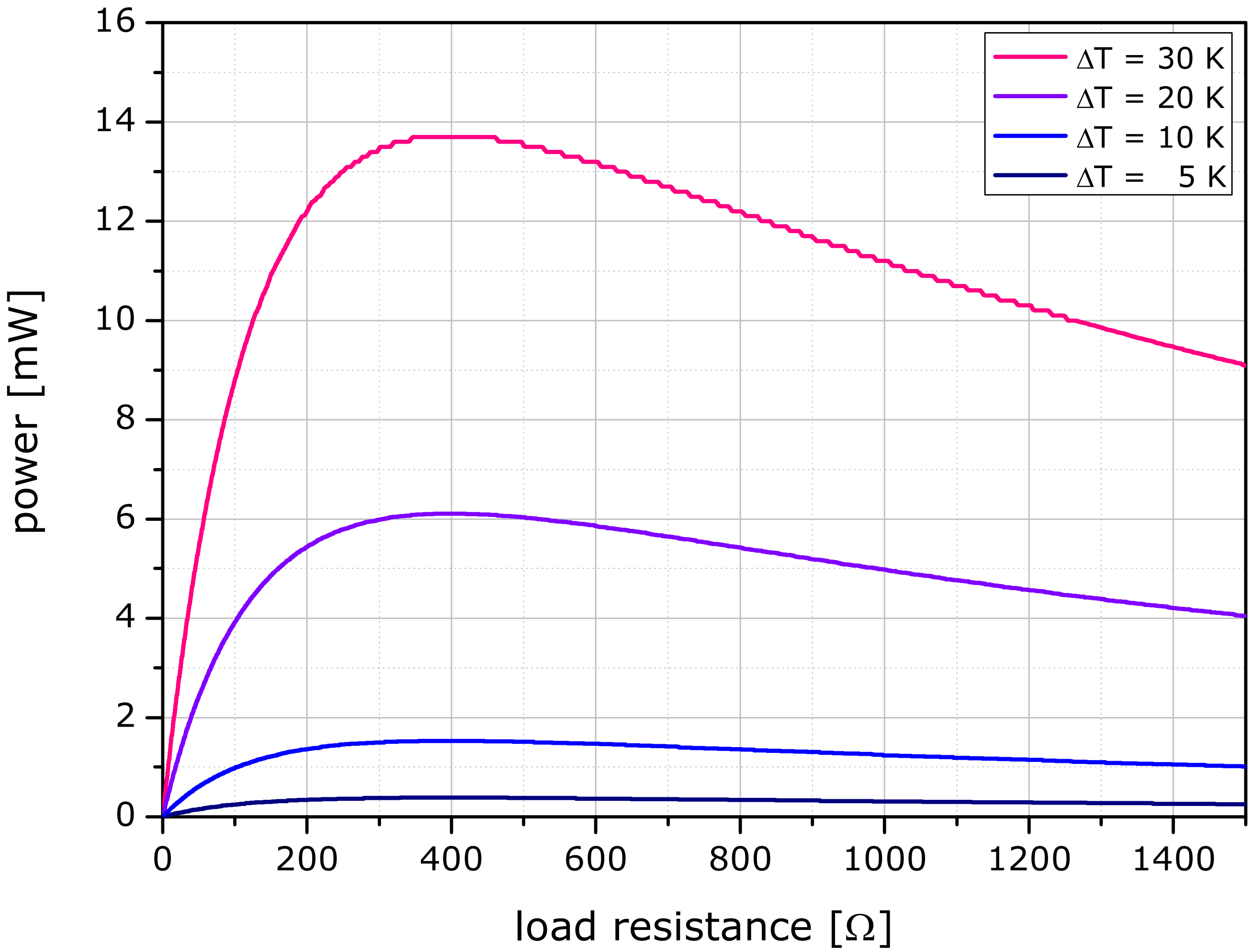
Vertical Generator

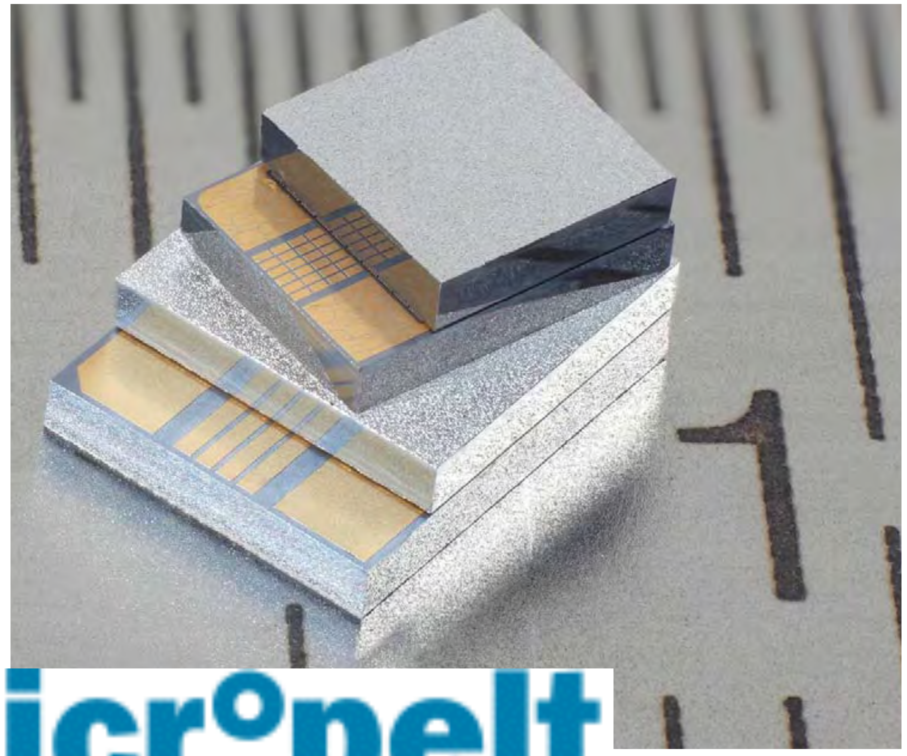


http://www.micropelt.com/

Micropelt MPG-D751 TEG Modules

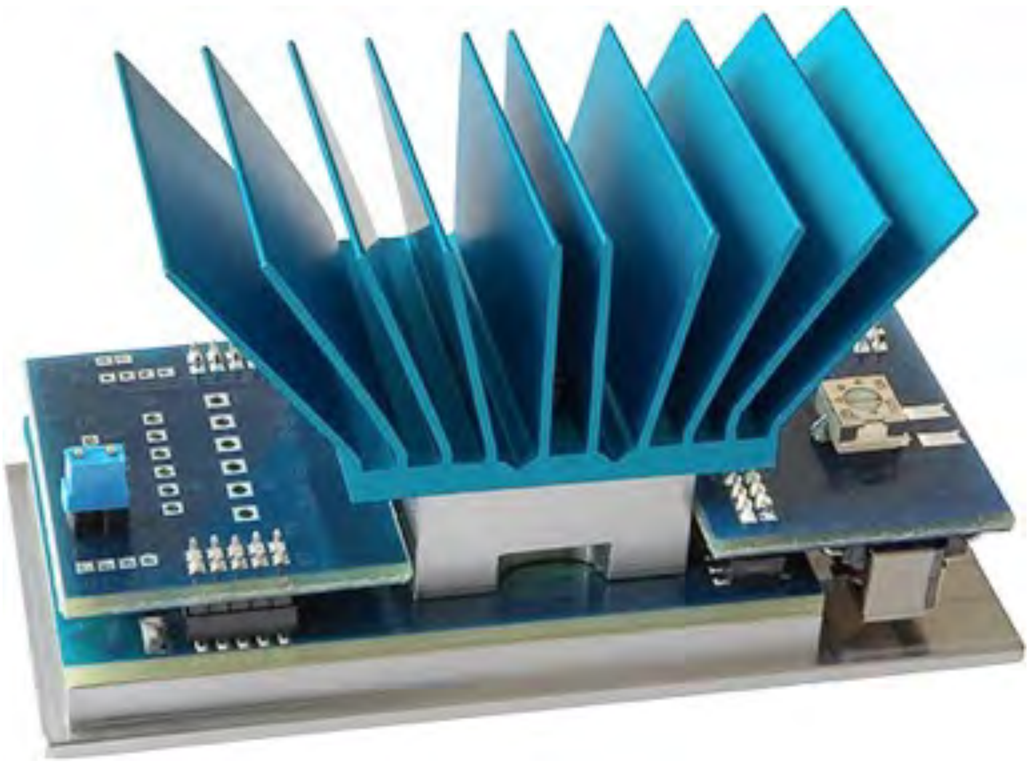






micropelt

3.4 x 3.4 mm



Solar Energy: Photovoltaic Cells

- The sun is an abundant source of "clean" energy
- Photovoltaic cells absorb photons and convert them into dc electricity through the creation of electron-hole pairs

Questions:

- How much solar energy is available to use?
- What is the optimum absorption wavelength?
- How can we maximise the electricity generation efficiency?
- Can we make photovoltaic cells which are economically competitive with other energy sources?

The Black-Body Emission Properties

- A black body emits photons with a distribution of energies = hν determined by the objects characteristic temperature T

h = Planck's constant, ν = frequency, λ = wavelength

$$\mathbf{E} = \mathbf{h}\nu \qquad \lambda = \frac{\mathbf{c}}{\nu} \qquad \mathbf{E} = \frac{\mathbf{hc}}{\lambda}$$

- Equilibrium photon energy density (i.e. per unit volume)

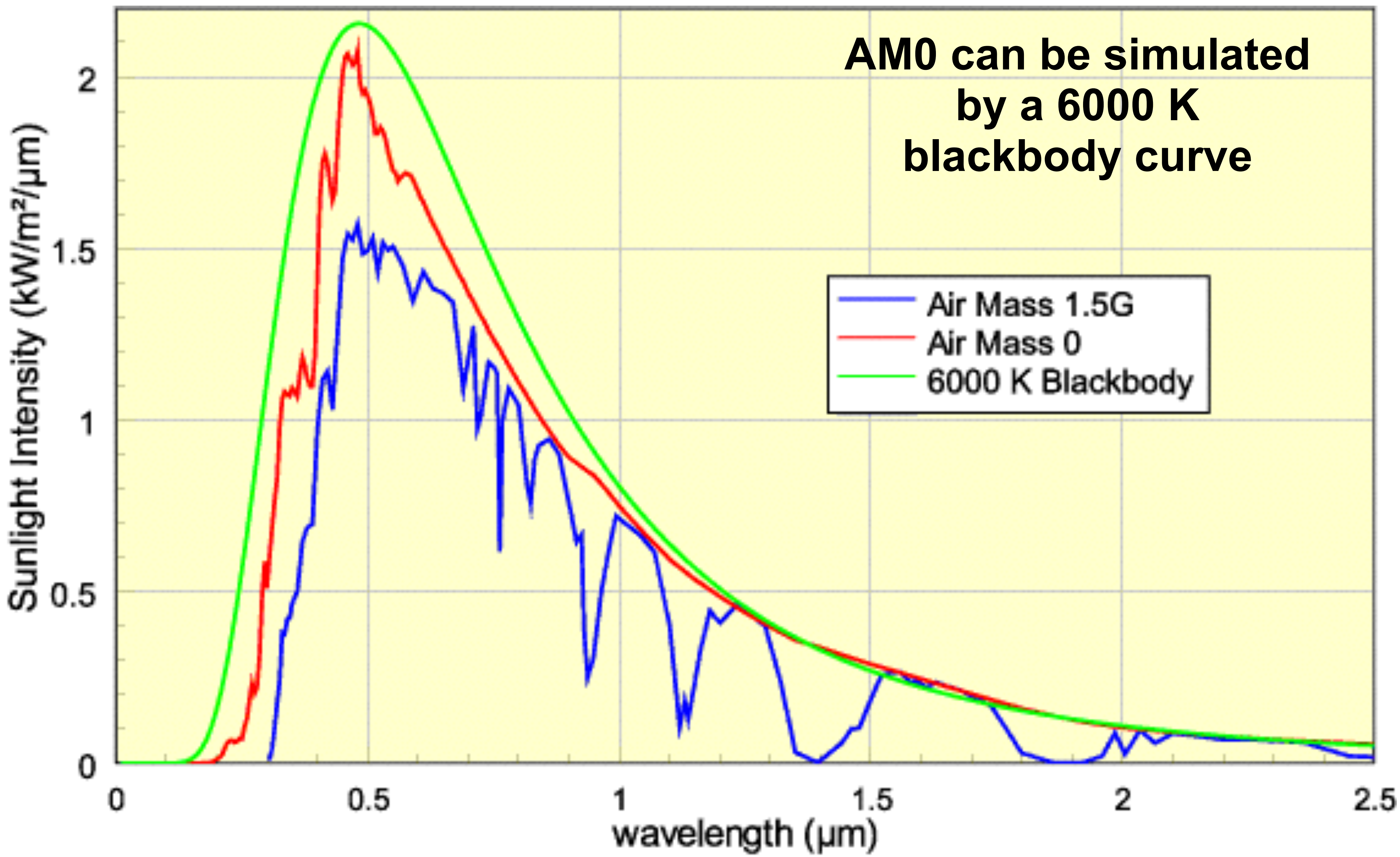
$$\rho(\mathbf{h}\nu) = \frac{\mathbf{8}\pi\mathbf{h}\nu^{\mathbf{3}}}{\mathbf{c^3}[\exp(\frac{\mathbf{h}\nu}{\mathbf{k_B T}}) - \mathbf{1}]}$$

- The particle or energy flux emitted by a blackbody per unit surface area of a hemisphere over energy range E_1 to E_2 is

$$\mathbf{N(E)} = \frac{\mathbf{2}\pi}{\mathbf{h^3 c}} \int_{\mathbf{E_1}}^{\mathbf{E_2}} \frac{\mathbf{E^2}}{[\exp(\frac{\mathbf{E}}{\mathbf{k_B T}}) - \mathbf{1}]} \mathbf{dE}$$

The Spectrum of Sunlight

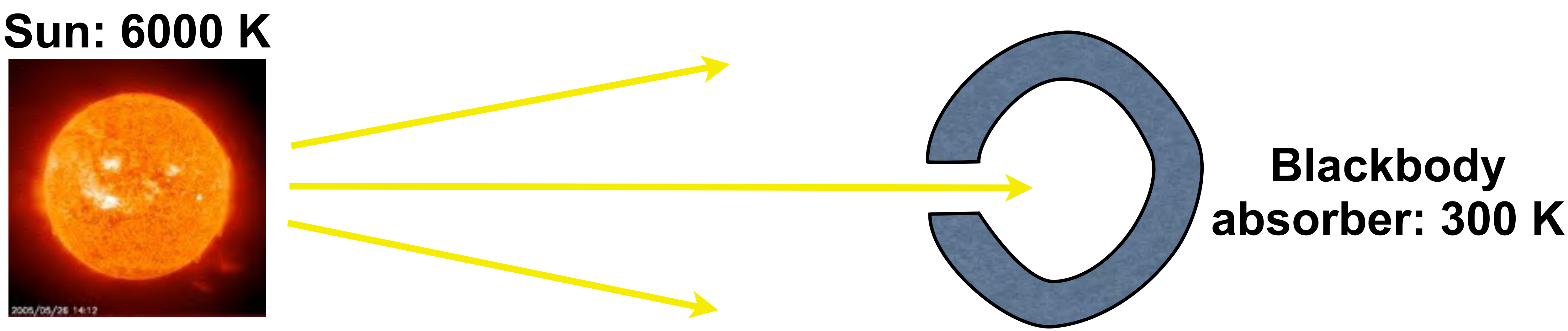
- "Air Mass Zero" (AM0) is the solar spectrum at the equator before it enters the atmosphere



University of Glasgow

Carnot Limit for Radiative Absorption

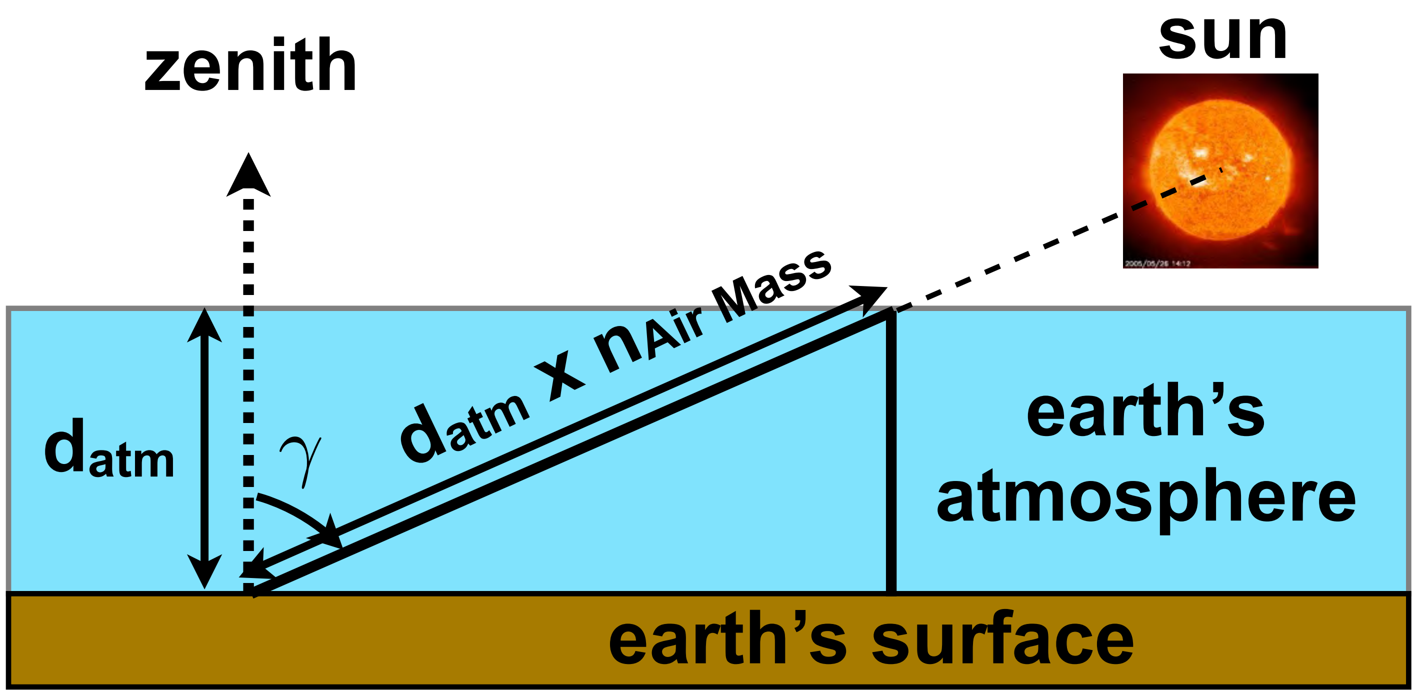
- Thermal limit i.e. heating for the sun as a 6000 K black body emitter with a 300 K solar cell black body absorber



- Maximum Carnot efficiency is 85% for absorber at 2470 K:
  all photons absorbed
  maximum heat from every photon
  zero thermal dissipation from absorber

- Actual efficiencies for a room temperature absorber are < 85%

Atmospheric Attenuation: Air Mass Index



$$\cos\gamma = \frac{d_{atm}}{d_{atm} \times n_{\text{Air Mass}}}$$

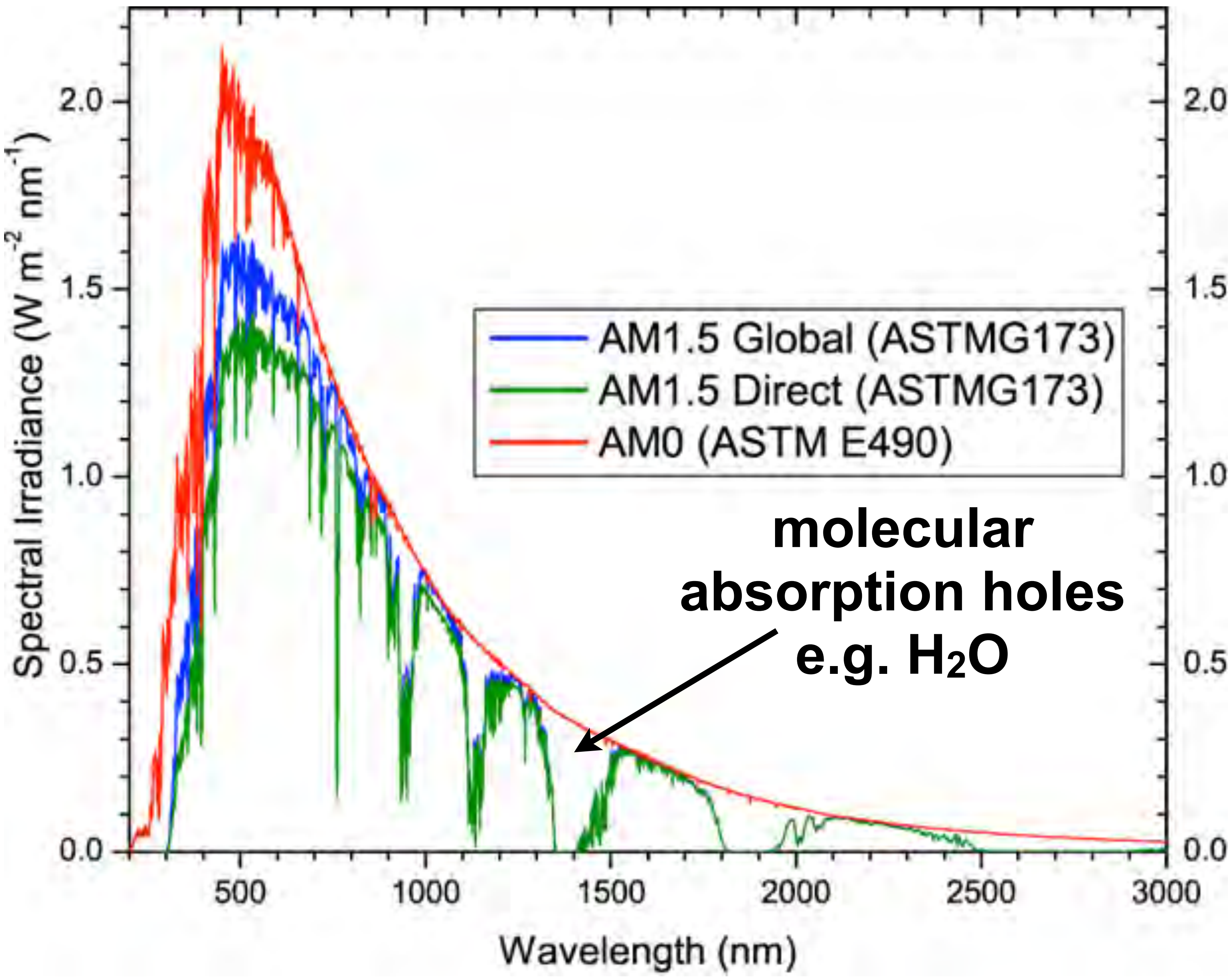
$$\mathbf{n}_{\text{Air Mass}} = \frac{\text{optical path length to sun}}{\text{optical path length if sun directly overhead}}$$

$$= \frac{\mathbf{1}}{\mathbf{cos}\gamma}$$

- **To allow comparison between solar cell technology all cells compared at AM1.5**

How Much Solar Energy and What Wavelength?

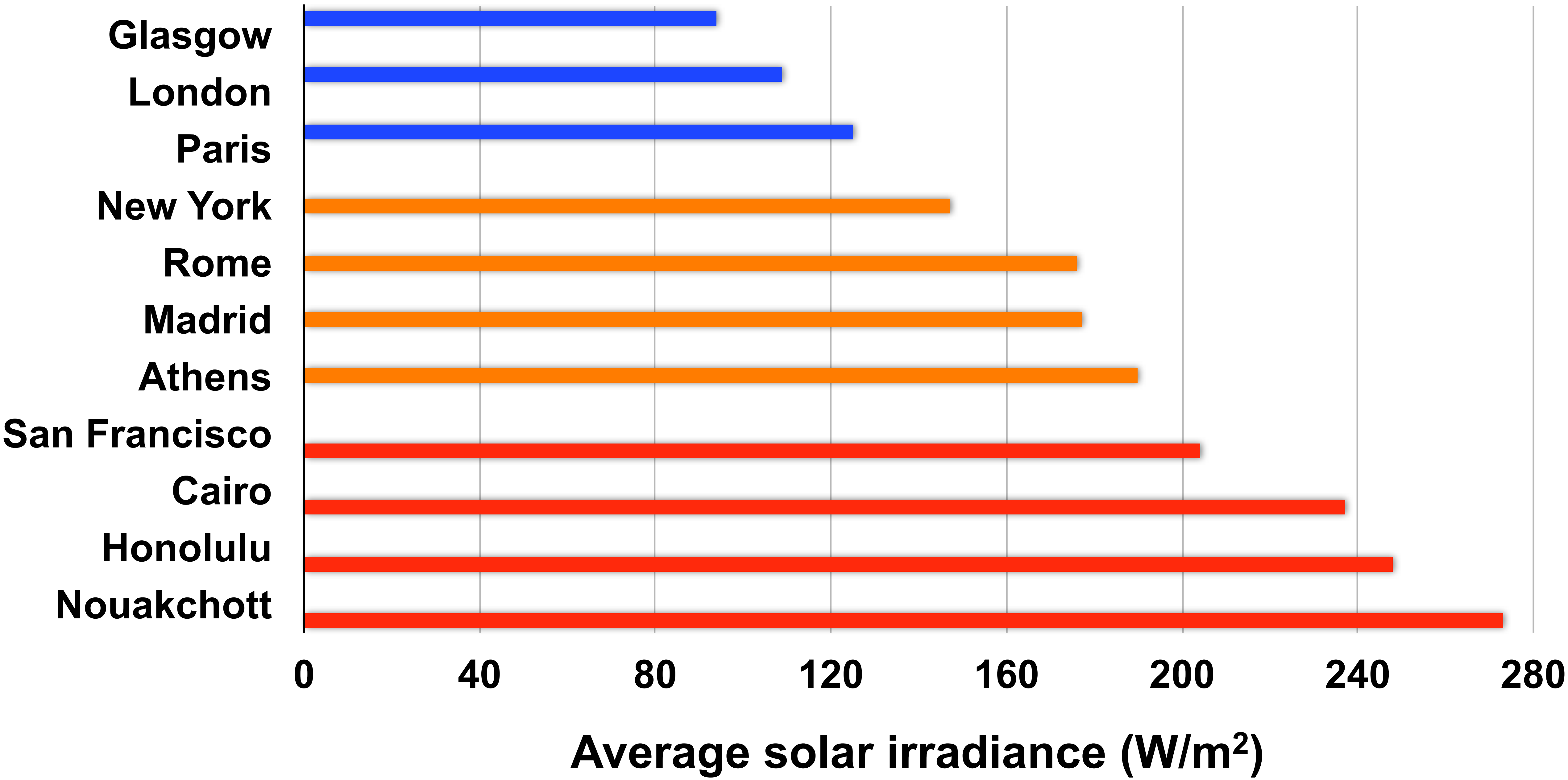
- "Air Mass Zero" (AM0) is the solar spectrum at the equator before it enters the atmosphere



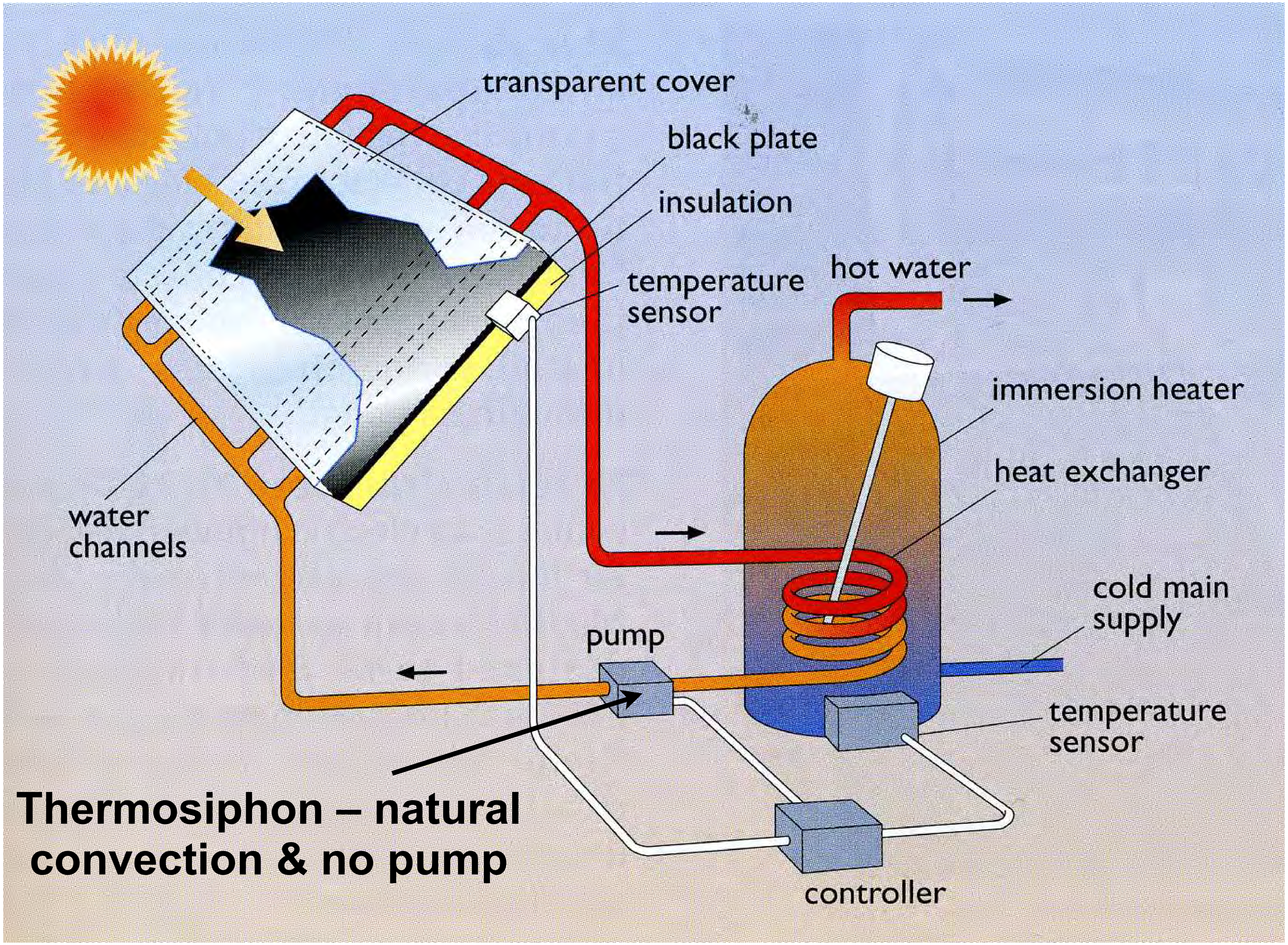
- **Maximum AM0 power is ~1353 W/m^2 over all wavelengths**
- **Molecular absorption produces "holes"**
- **AM1.5 power is ~1000 W/m^2 over all wavelengths**

How Much Continuous Solar Energy?

- Due to clouds, day/night & seasons, average energy << peak energy
- Available energy needs to be averaged over 365 days and 24 hours



Solar Thermal Water Heating System

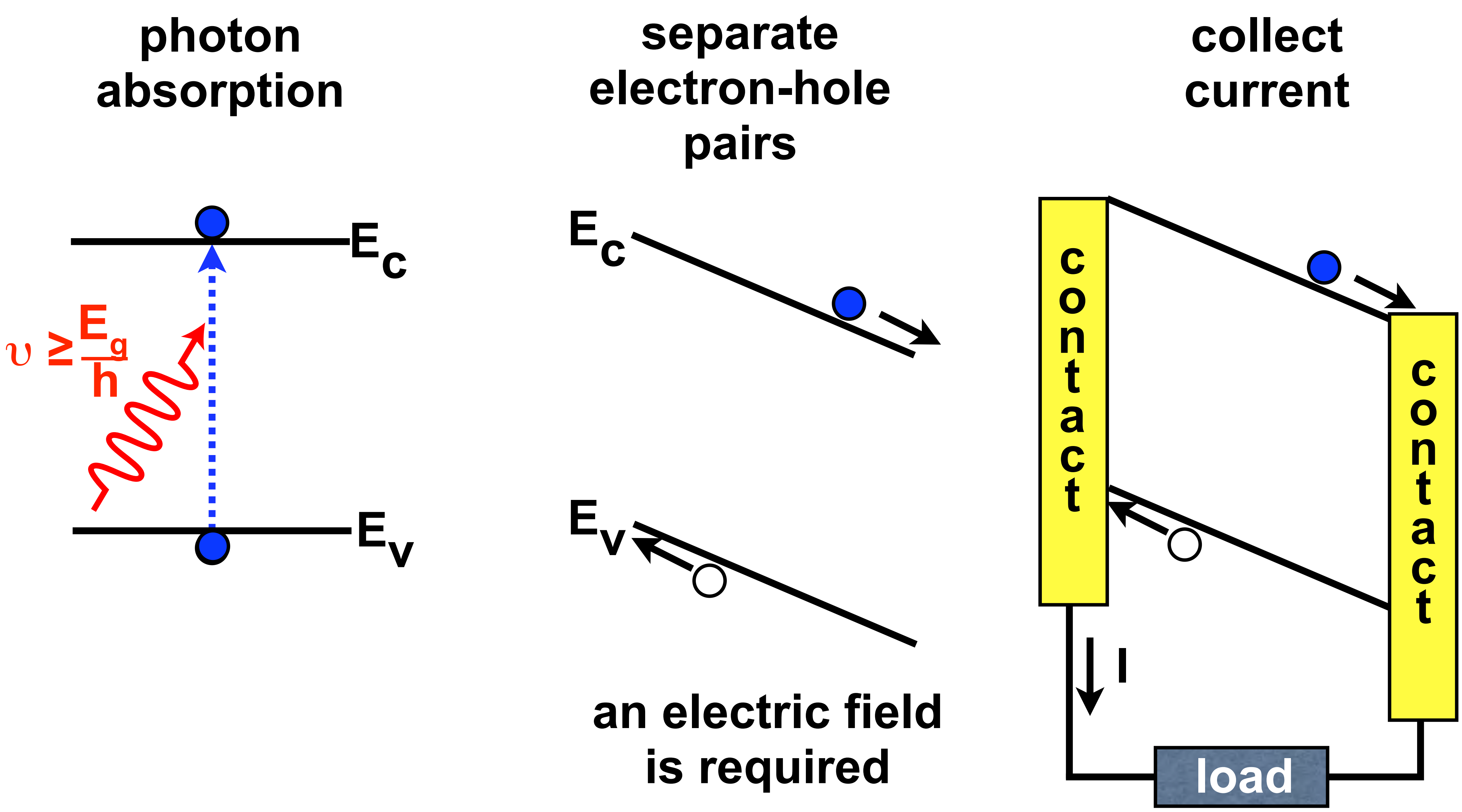


- **Typically efficiencies up to 70% for generating hot water in homes**

Photovoltaic Solar Cells

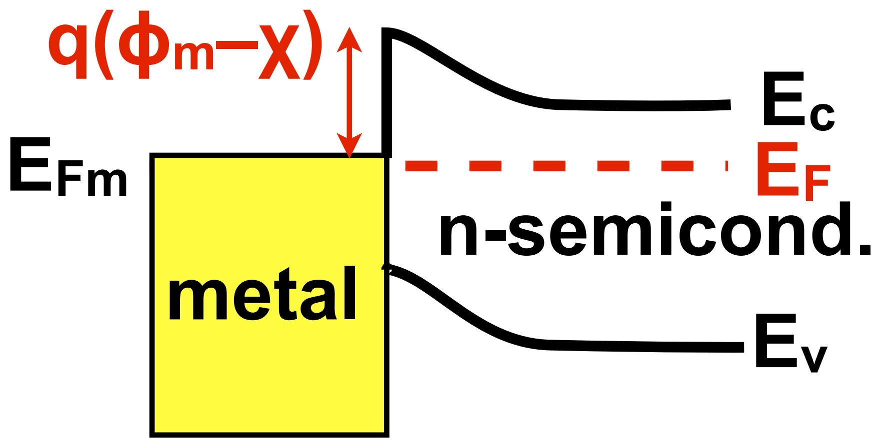
Serpa, Portugal 11 MW from 52,000 photovoltaic modules

Basic Requirements of Photovoltaic Cell



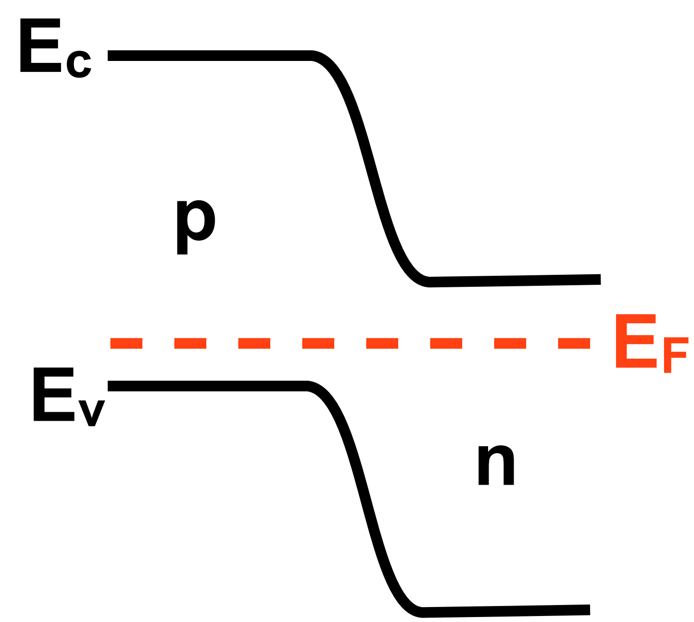
Options for Photovoltaic Solar Cells

Schottky diode

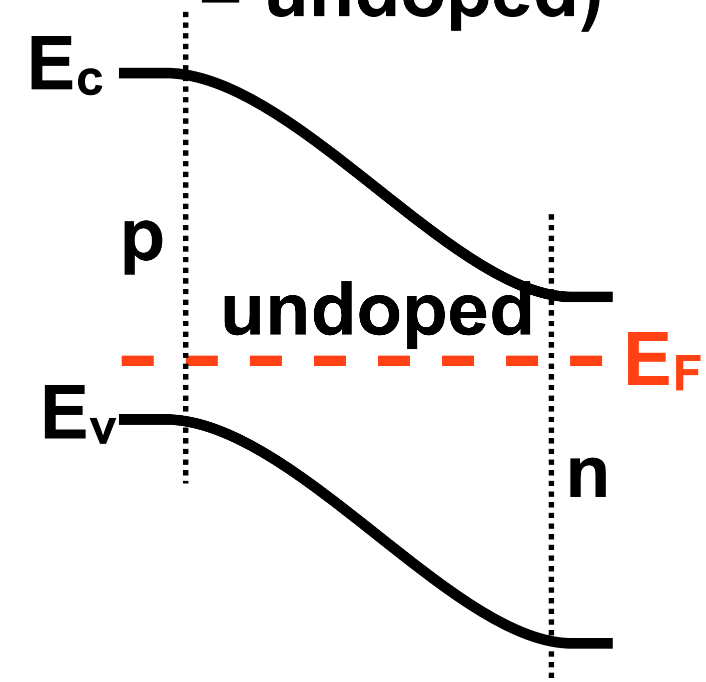


- N.B. only a few metals are transparent at visible wavelengths
- Schottky diodes not used for PV

p-n junction

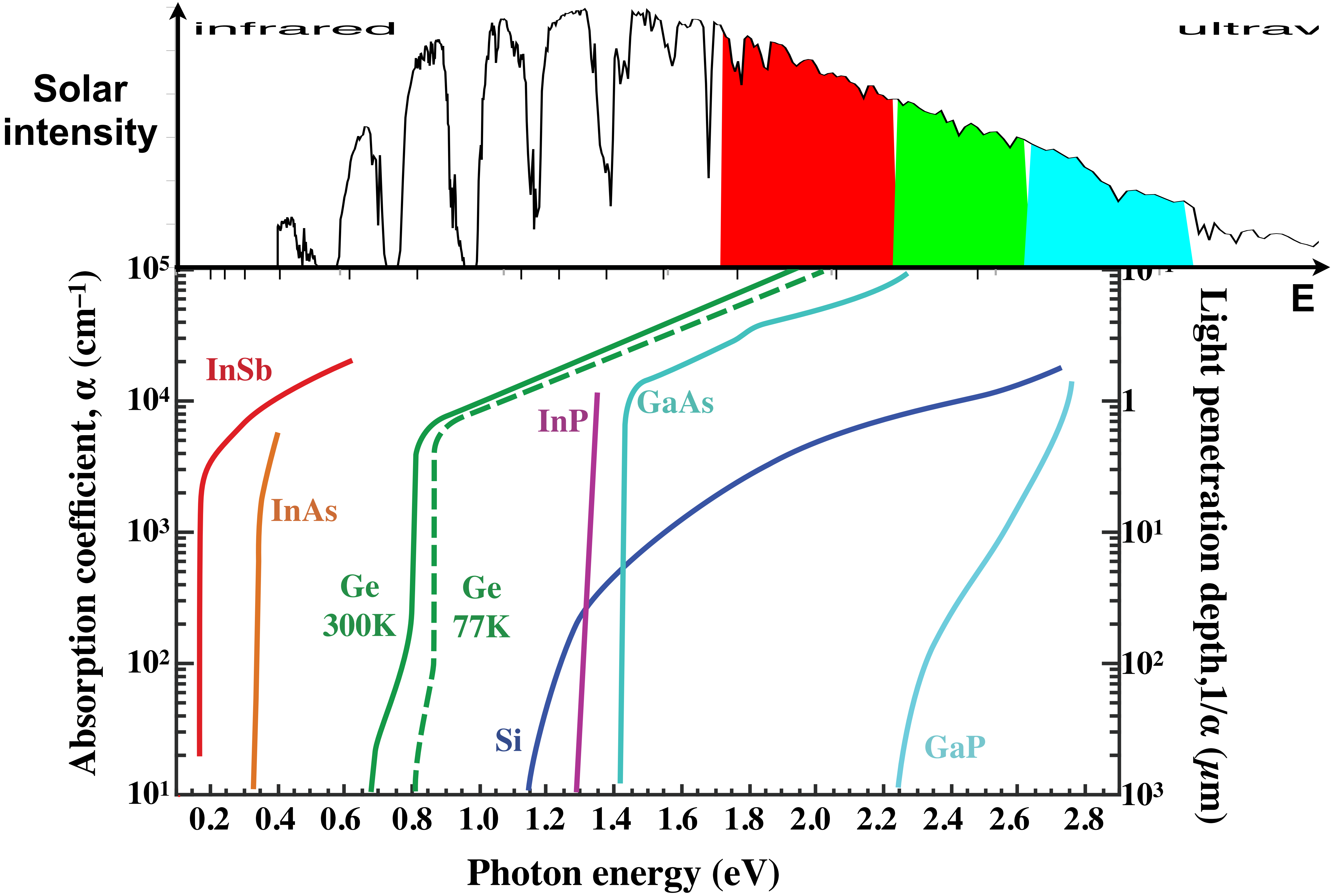


p-i-n junction (i = insulating = undoped)



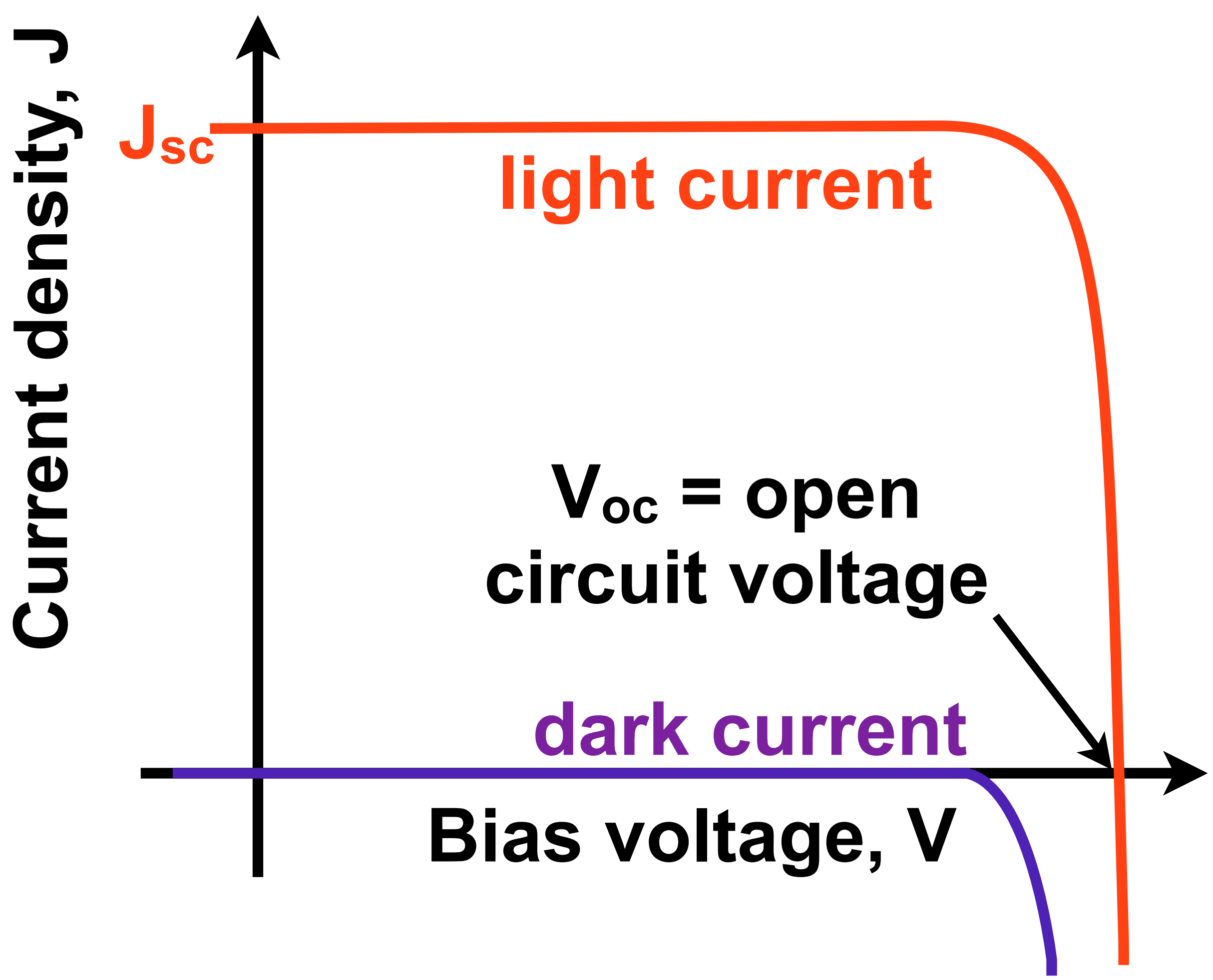
- Expands region over which absorption + separation occurs
- Same IV equations as p-n junction

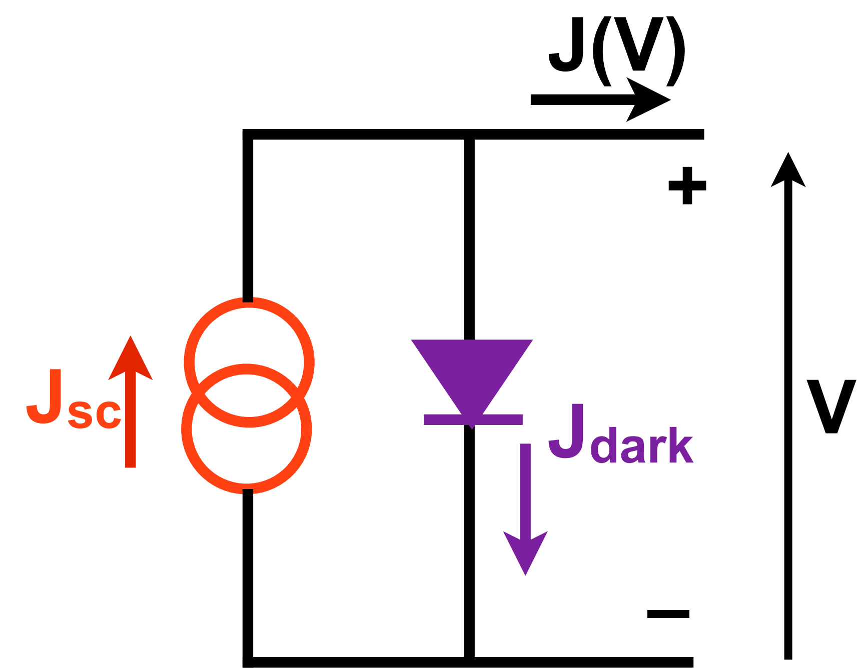
Absorption Coefficient of Semiconductors



The Superposition Approximation

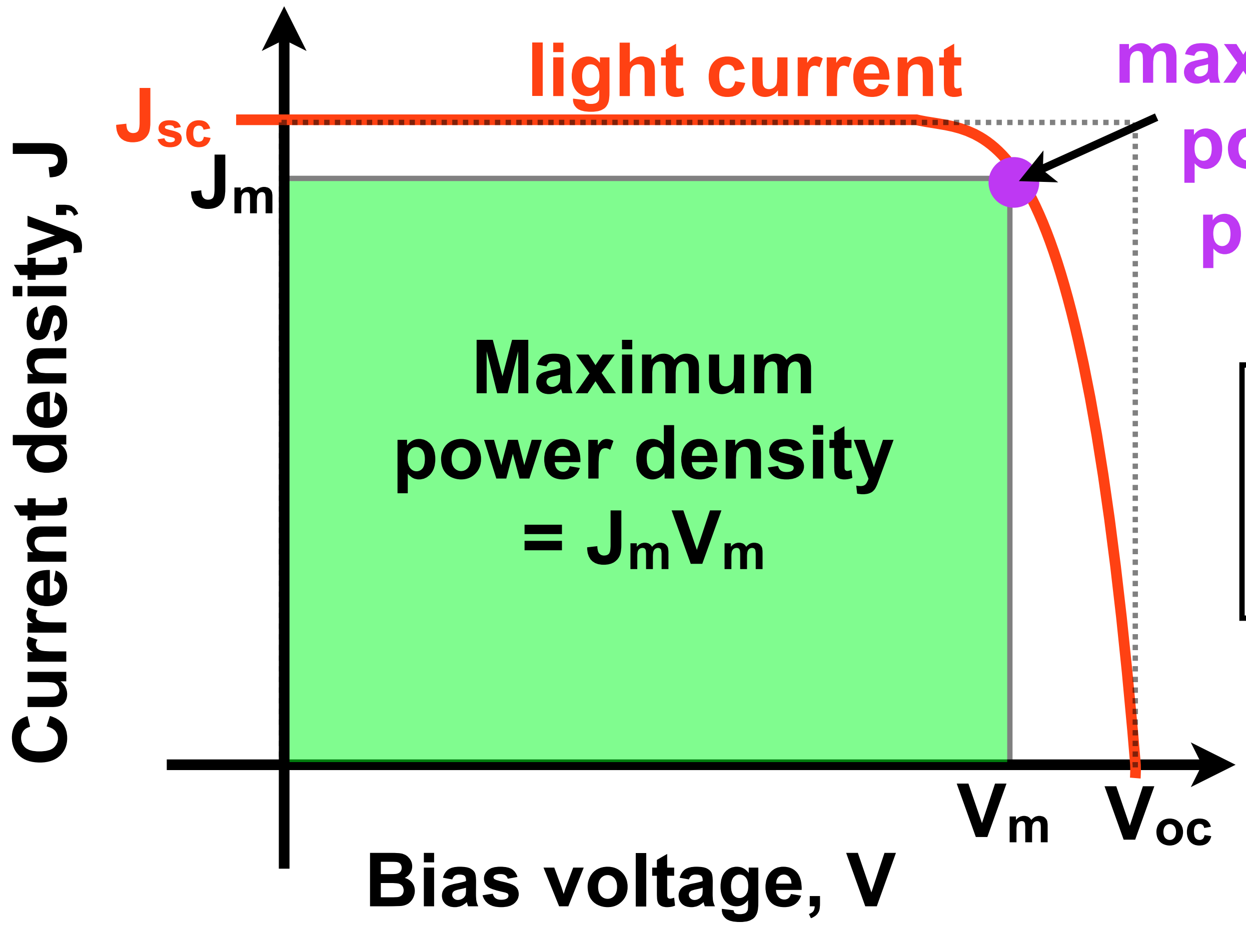
- For solar cell, current-voltage can be approximated by the sum of short circuit photocurrent + dark current
- Current convention: photocurrent is positive (this is the opposite to normal current !)





$$J(V) = J_{sc} - J_{dark}(V)$$

Photovoltaic Efficiency



- power density = P = JV

efficiency = electrical power out / optical power in

$$\eta = \frac{P_{max}}{P_{opt}} = \frac{J_m V_m}{P_{opt}}$$

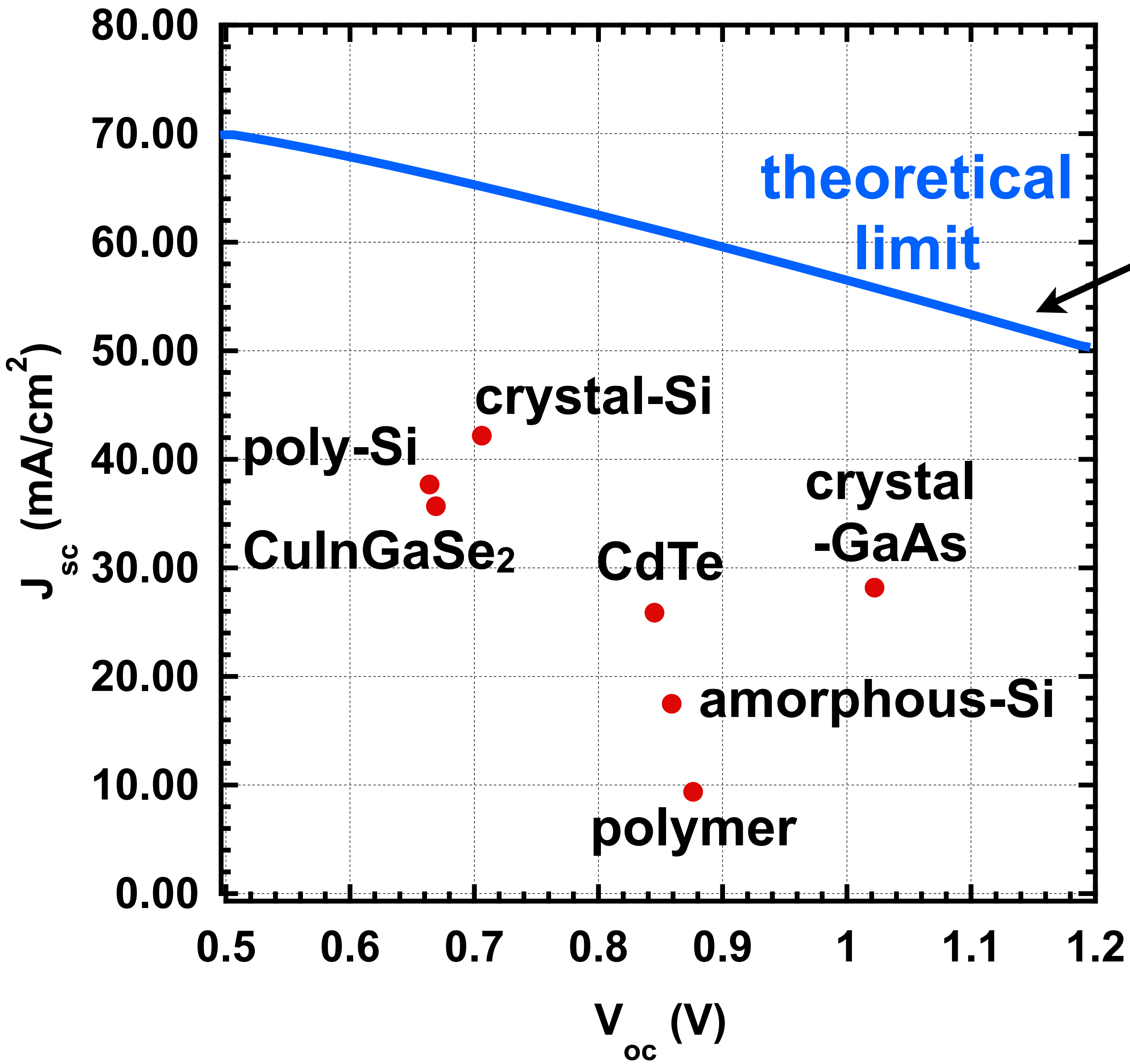
- The efficiency is related to J_{sc} and V_{oc} using the fill factor, FF

$$\eta = \frac{J_{sc} V_{oc} FF}{P_{opt}}$$

or

$$FF = \frac{J_m V_m}{J_{sc} V_{oc}}$$

Photovoltaic Current and Voltages



Maximum theoretical output power

- $J_{sc}V_{oc} \propto$ constant = $f(E_g)$
- i.e. high J_{sc} –> low V_{oc} and vice-versa
- N.B. All voltages too low for most appliances and applications: requires stacking

Comparison of Single Cell Technologies

- **Best results quoted from the literature – not commercial devices**

Type	η (%)	V_{oc} (V)	J_{sc} (mA/cm²)	FF (%)
crystalline silicon	25.0 ± 0.5	0.706	42.7	82.8
crystalline GaAs	28.3 ± 0.8	1.107	29.5	86.7
polycrystalline silicon	20.4 ± 0.5	0.664	38	80.9
amorphous Si	10.1 ± 0.3	0.886	16.8	67
CdTe	16.5 ± 0.5	0.845	25.9	75.5
organic polymer	10.0 ± 0.3	0.889	16.8	66.1

Prog. Photovoltaics: Res. Appl. 20, 12 (2012)

- **Standard test conditions: 1000 W/m² illumination (i.e. 1 sun - no concentration) with AM1.5 spectra at 25 ˚C**

- **η decay over time due to x-ray absorption from sun / space**

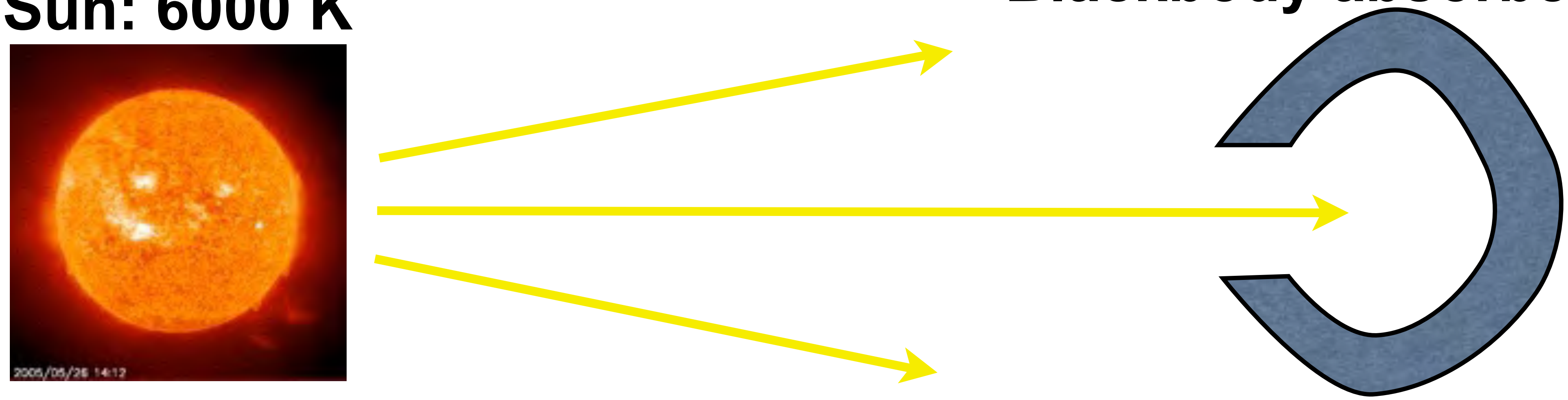
University of Glasgow

Carnot Efficiency

- **Thermal limit i.e. heating for the sun as a 6000 K black body emitter with a 300 K solar cell black body absorber**

Sun: 6000 K

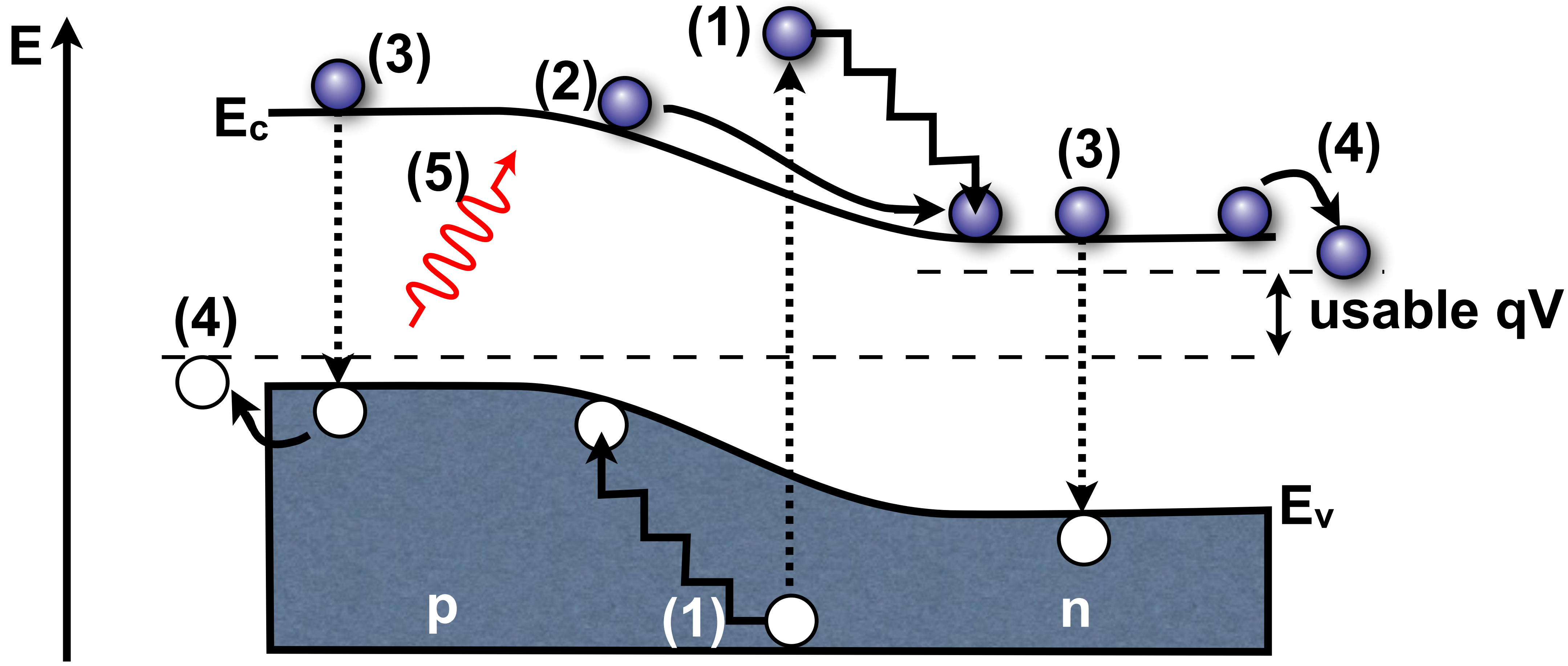
Blackbody absorber: 300 K



- **Maximum Carnot efficiency is 85% for absorber at 2470 K:**
  all photons absorbed
  maximum heat from every photon
  zero thermal dissipation from absorber

- **Why are real PV cells significantly smaller than is efficiency?**

Single-Junction Loss Processes



Energy conversion loss processes in single-junction solar cell:

(1) Lattice thermalisation loss

(2) Junction loss

(3) recombination loss

(4) contact loss

(5) no absorption from photons with energy < E_g

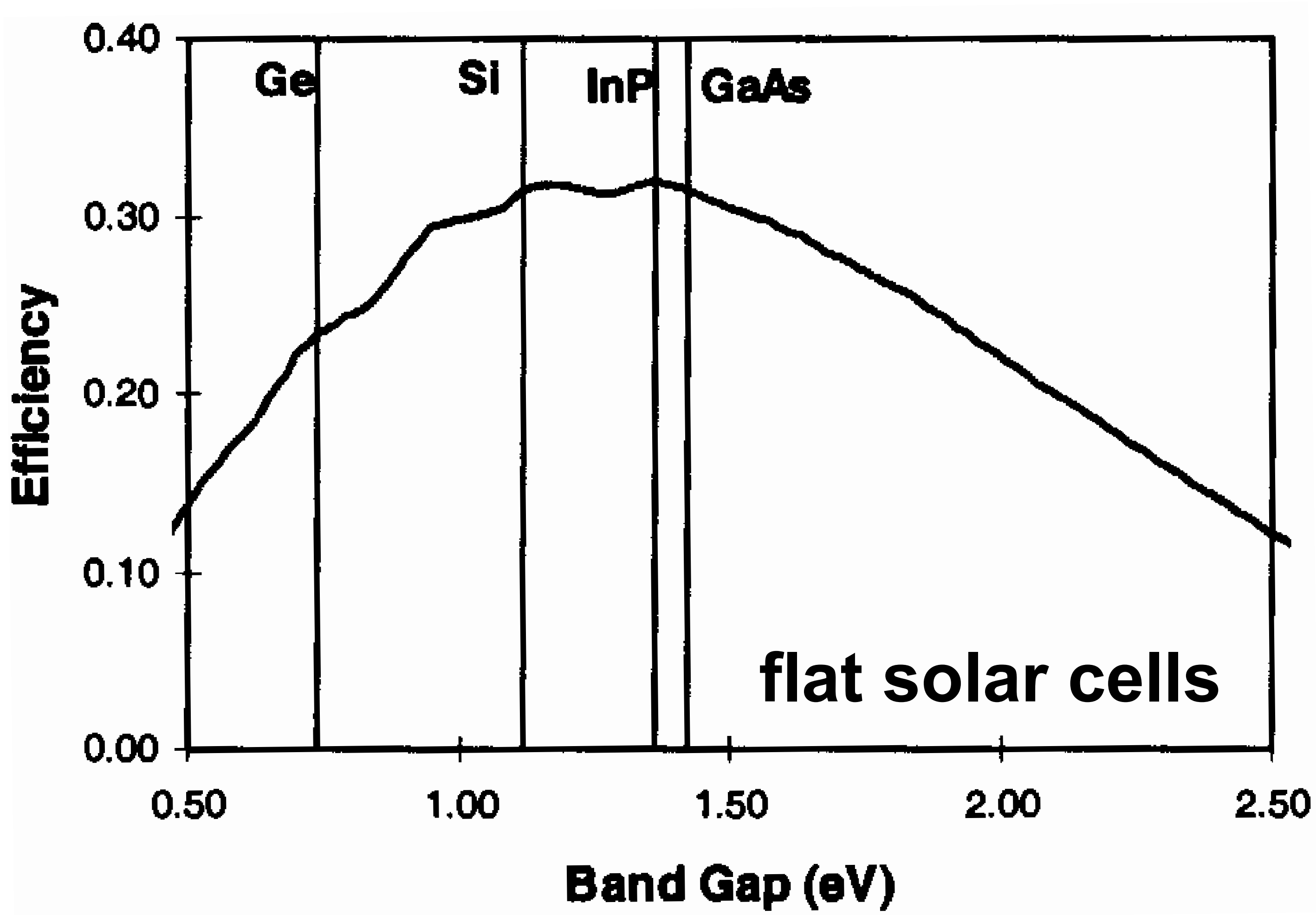
Shockley-Queisser Efficiency Limit Predictions

For **Si** cells: T_s = 6000 K, T_c = 300 K, E_g = 1.1 eV

- **Maximum η = 30%**

For **GaAs** cells: T_s = 6000 K, T_c = 300 K, E_g = 1.46 eV

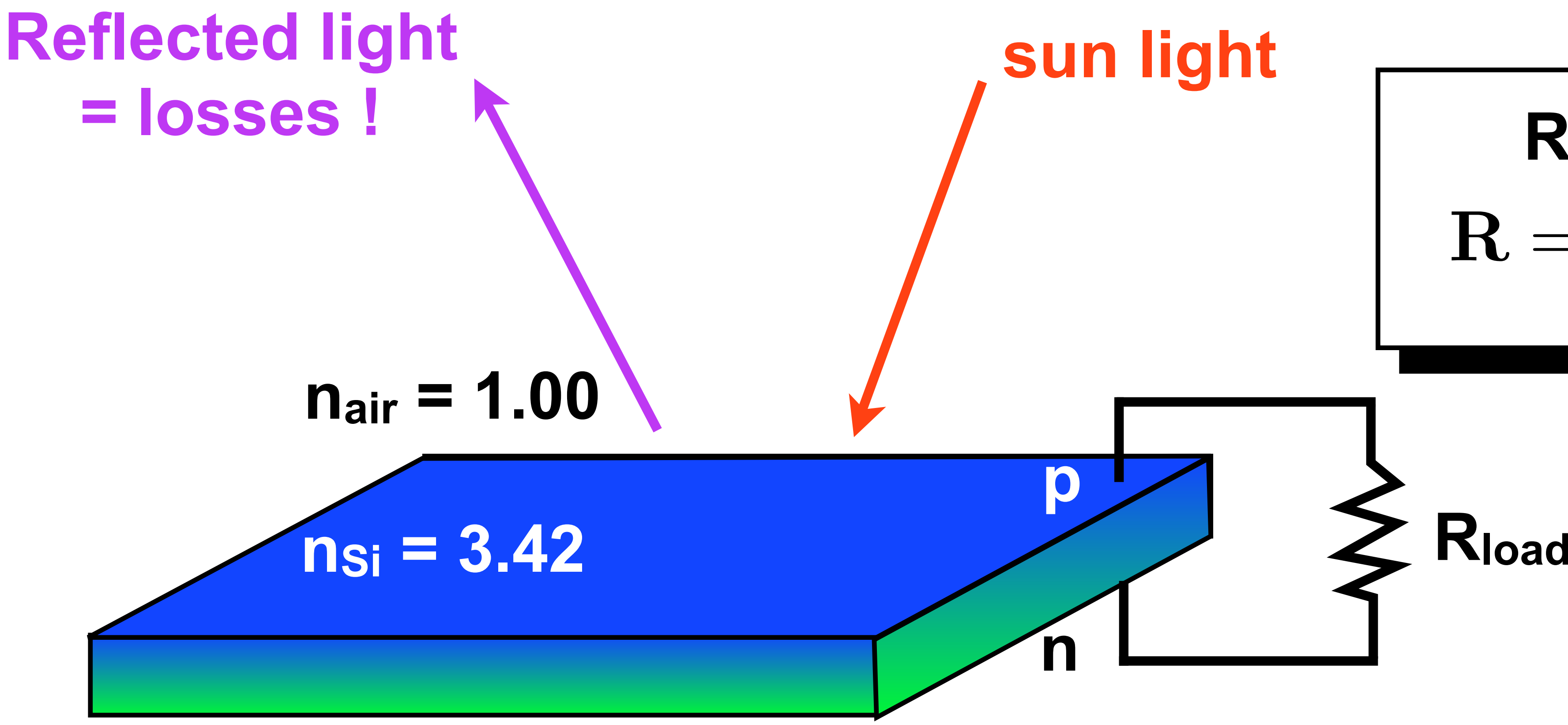
- **Maximum η = 31%**



- Quite low efficiencies for single junction cells
- Variation with E_g related to black-body curve
- What can be done to improve efficiency?

University of Glasgow

Basic η of Silicon pn Junction without Optimisation

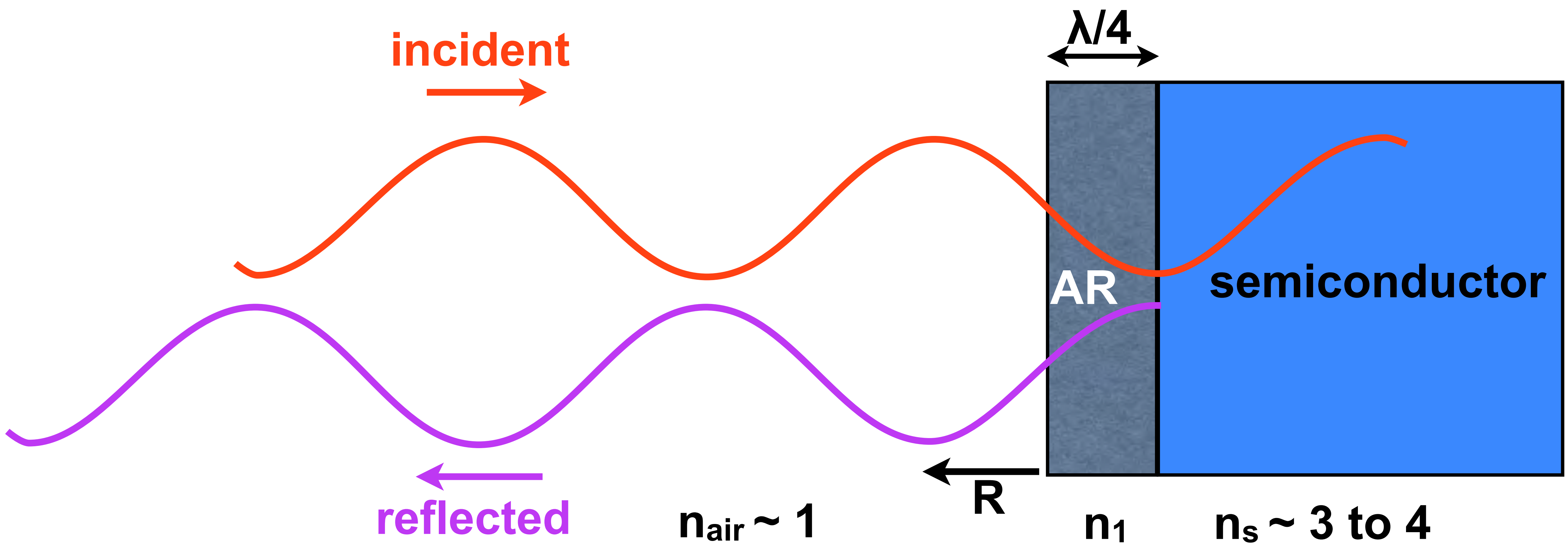


Reflected light =

$$R = \left(\frac{n_{Si} - n_{air}}{n_{Si} + n_{air}}\right)^2 = 30\%$$

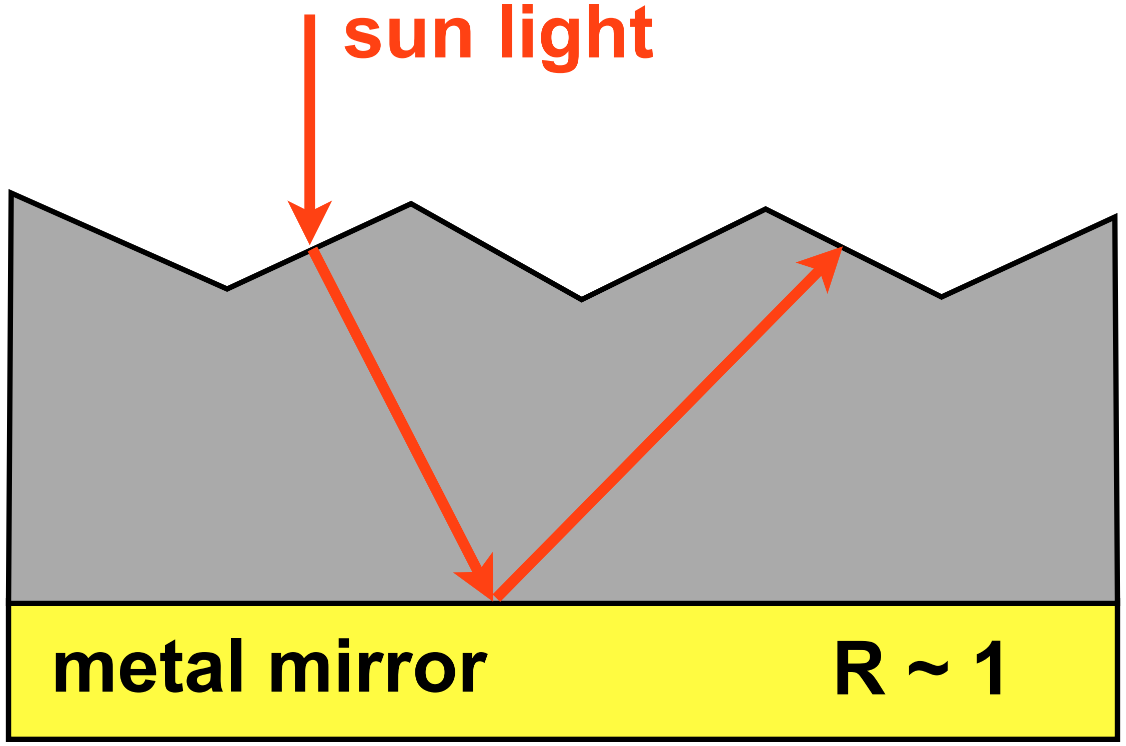
- **Efficiency for standard flat Si wafer = 13% since many photons are not absorbed**
- **Need to reduce all surface reflections**
- **Also need longer path length for absorption: can we trap the light?**

Anti-reflection (AR) Coatings



- R vanishes for $n_1 = \sqrt{n_{air} n_s} \sim \sqrt{n_s}$ with a thickness of $\lambda/4$
- For this condition, incident and reflect waves are out of phase & interfere destructively so R –> 0
- ∴ η increases since more light is trapped and can be absorbed

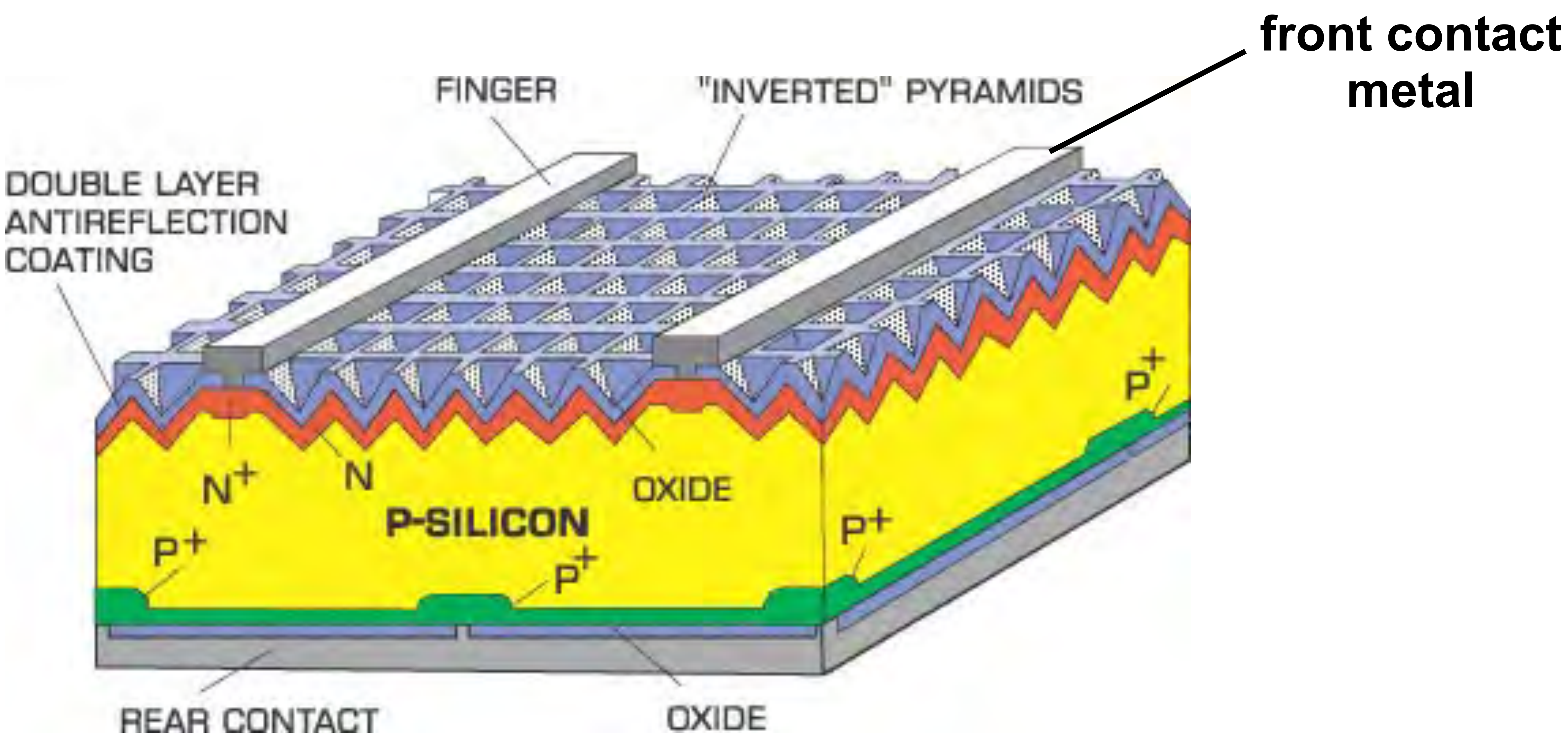
Trapping Light: Textured Surfaces and Mirrors



Also electrical contact metal

- Path length of light doubled
- Higher probability of absorption
- Asymmetrical patterning can produce x4 or greater path length
- Texturing can be combined with anti-reflection coating

Passivated Emitter Rear Totally diffused (PERT)

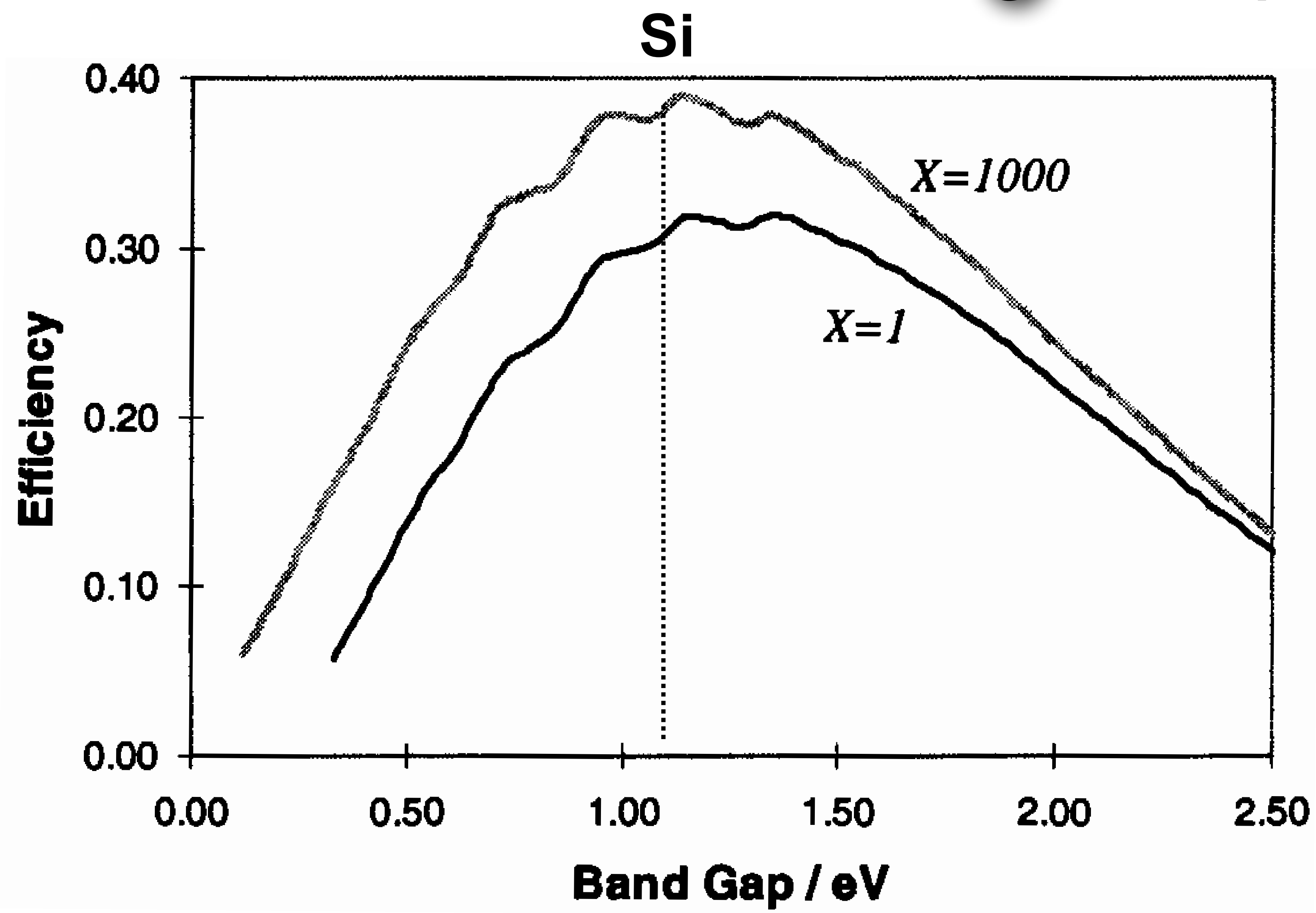


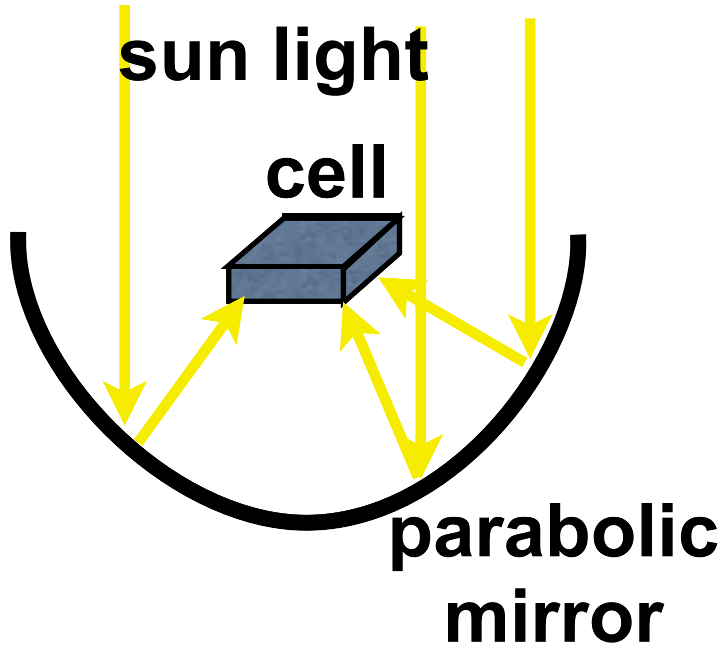
- **Highest performance silicon solar cell: 25.0% efficiency**
- **Anti-reflective coatings, textured surface, bottom mirror**

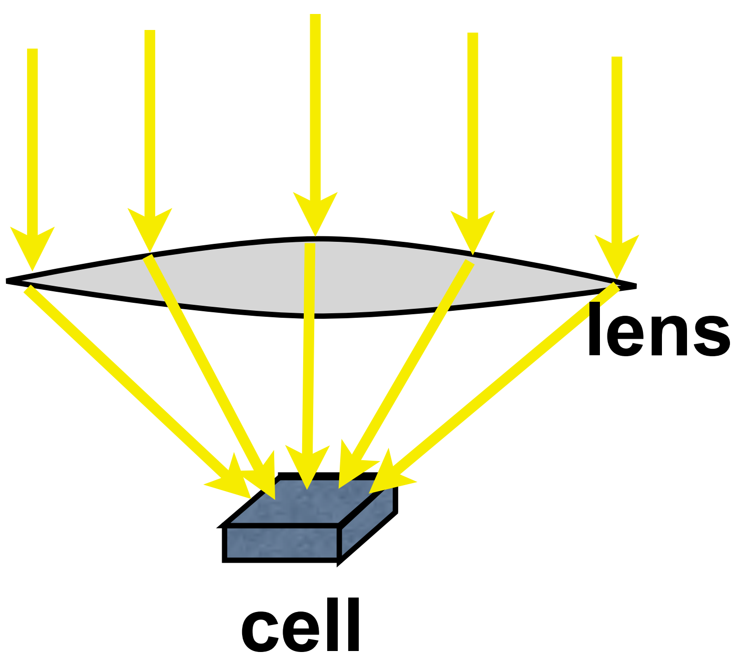
Solar Cell Efficiency with Concentrator

- Increase f_s = solar intercept fraction by concentrating light into cell

- Examples:





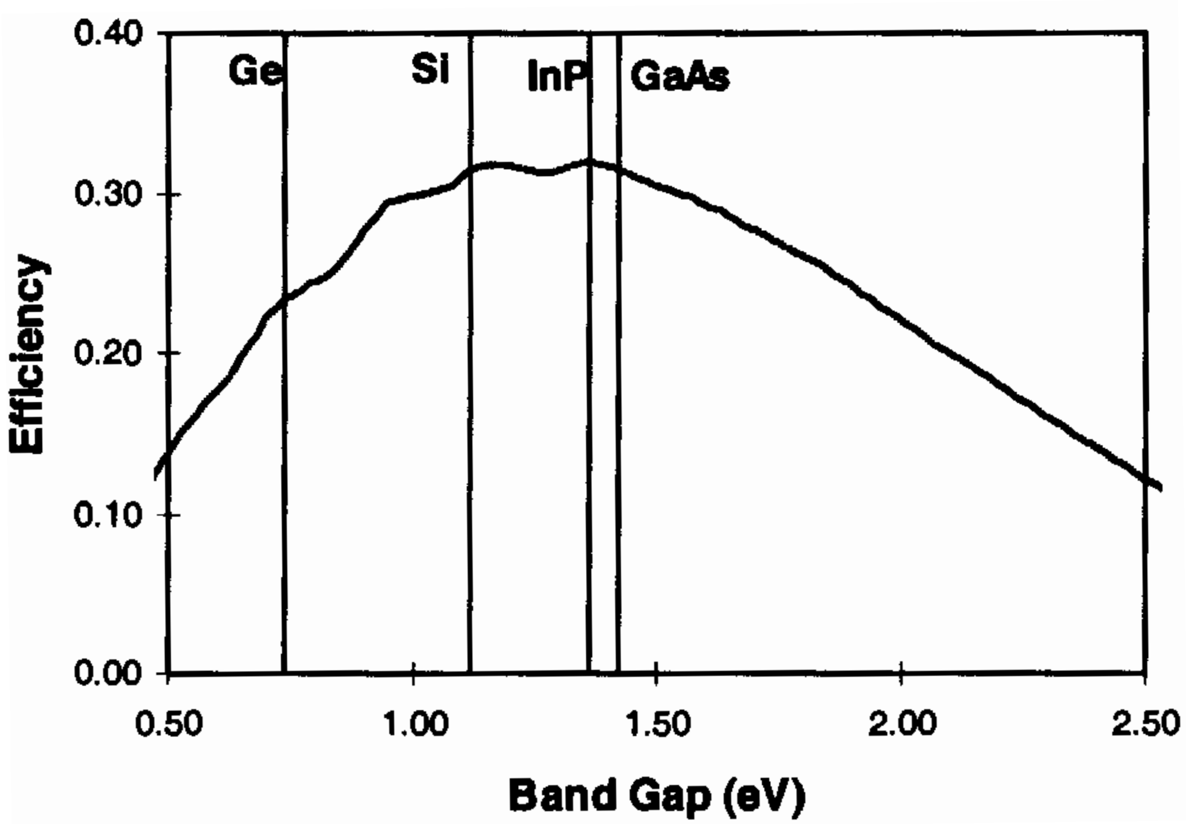


More light captured –> Schockley-Queisser limit increases

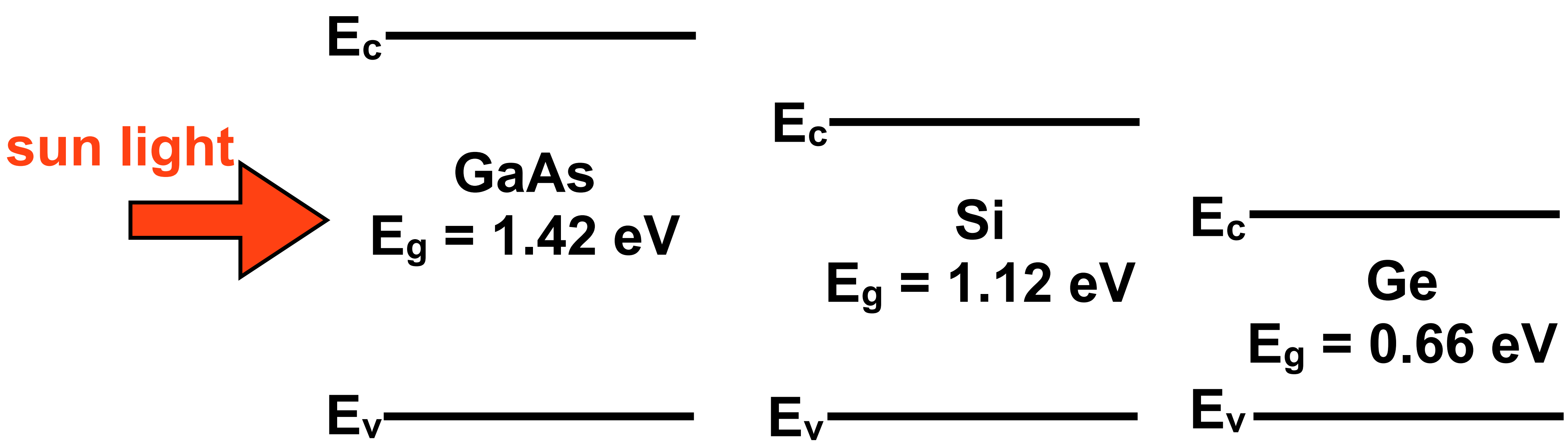
Tracking Systems

- The sun moves from the east to the west through a day
- A tracking system can be used so that the solar cell is always pointing at the sun
- Tracking systems give 40% more energy compared to stationary systems – but at higher system cost
- For many concentration designs, tracking systems are essential

Multiple Bandgap Cells

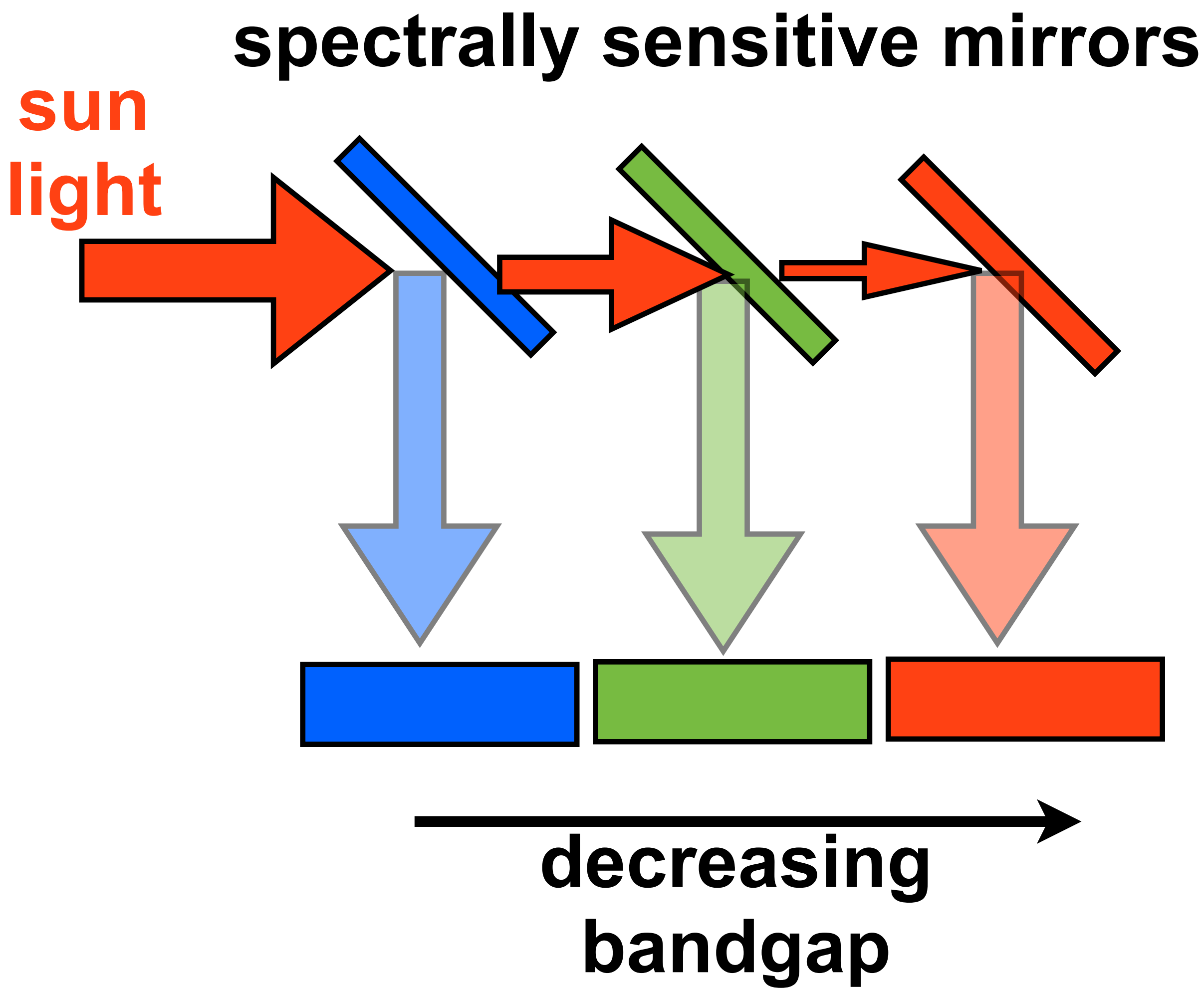


- Choose 2 or 3 materials with different bandgaps
- Need to have largest bandgap as front cell due to absorption
- Example: GaAs, Si and Ge cells



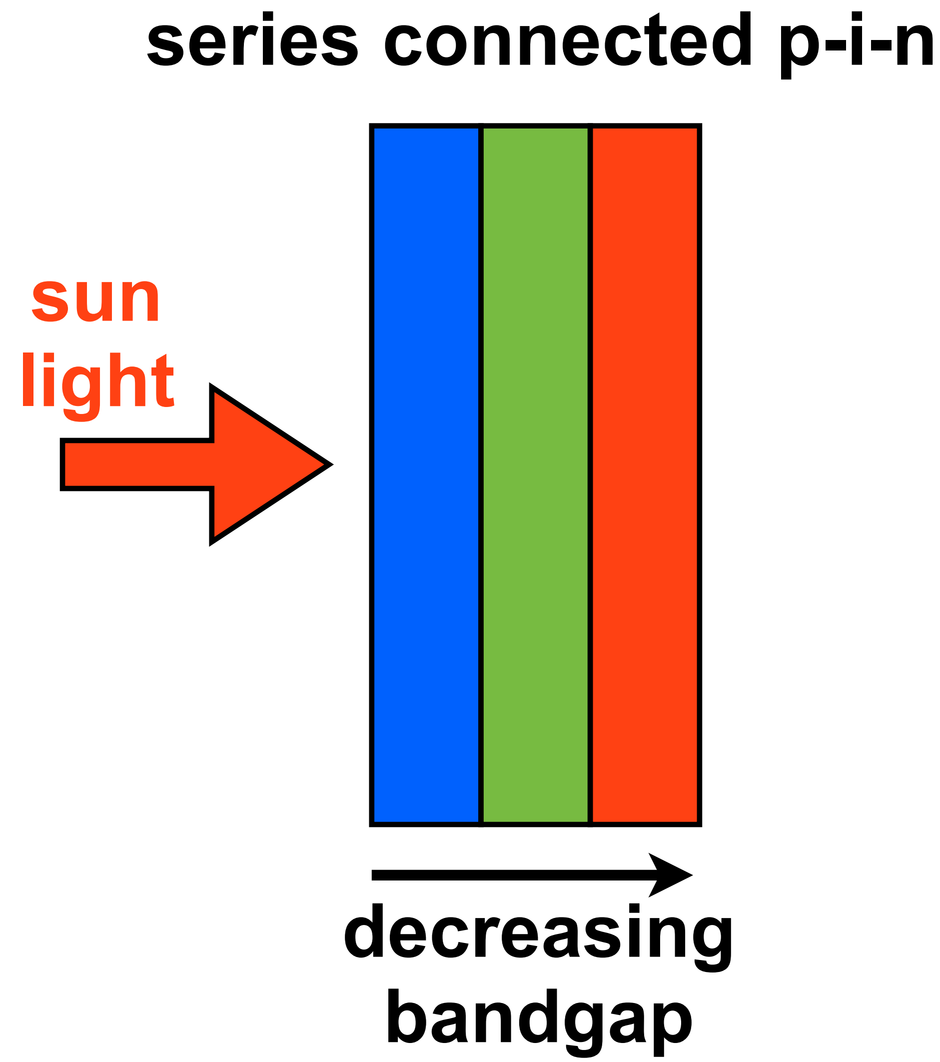
Tandem Cell Concepts

- **Spectrum splitting**



higher cost

- **Cell stacking**



lower cost

Multiple Cell Efficiencies

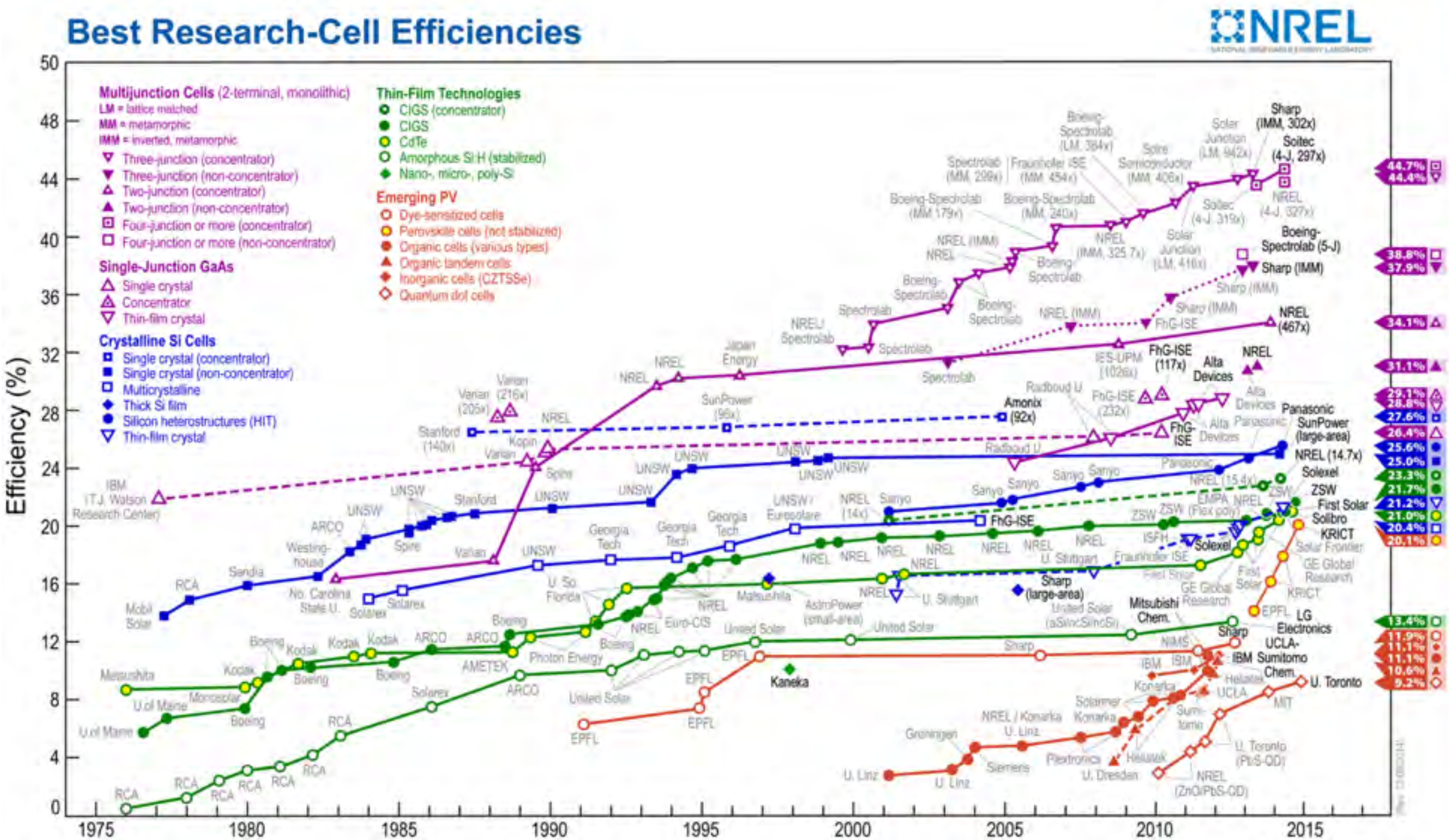
- All values at 1 sun AM1.5 without concentration

No. of cells	Description	Optimal bandgaps (eV)						Max. η (%)
		E_1	E_2	E_3	E_4	E_5	E_6	
1	diffuse series	1.31						31
2	diffuse series	0.97	1.7					42.5
3	diffuse series	0.82	1.3	1.95				48.6
4	diffuse series	0.72	1.1	1.53	2.14			52.5
5	diffuse series	0.66	0.97	1.3	1.7	2.29		55.1
6	diffuse series	0.61	0.89	1.16	1.46	1.84	2.41	57
∞	diffuse series							68.2

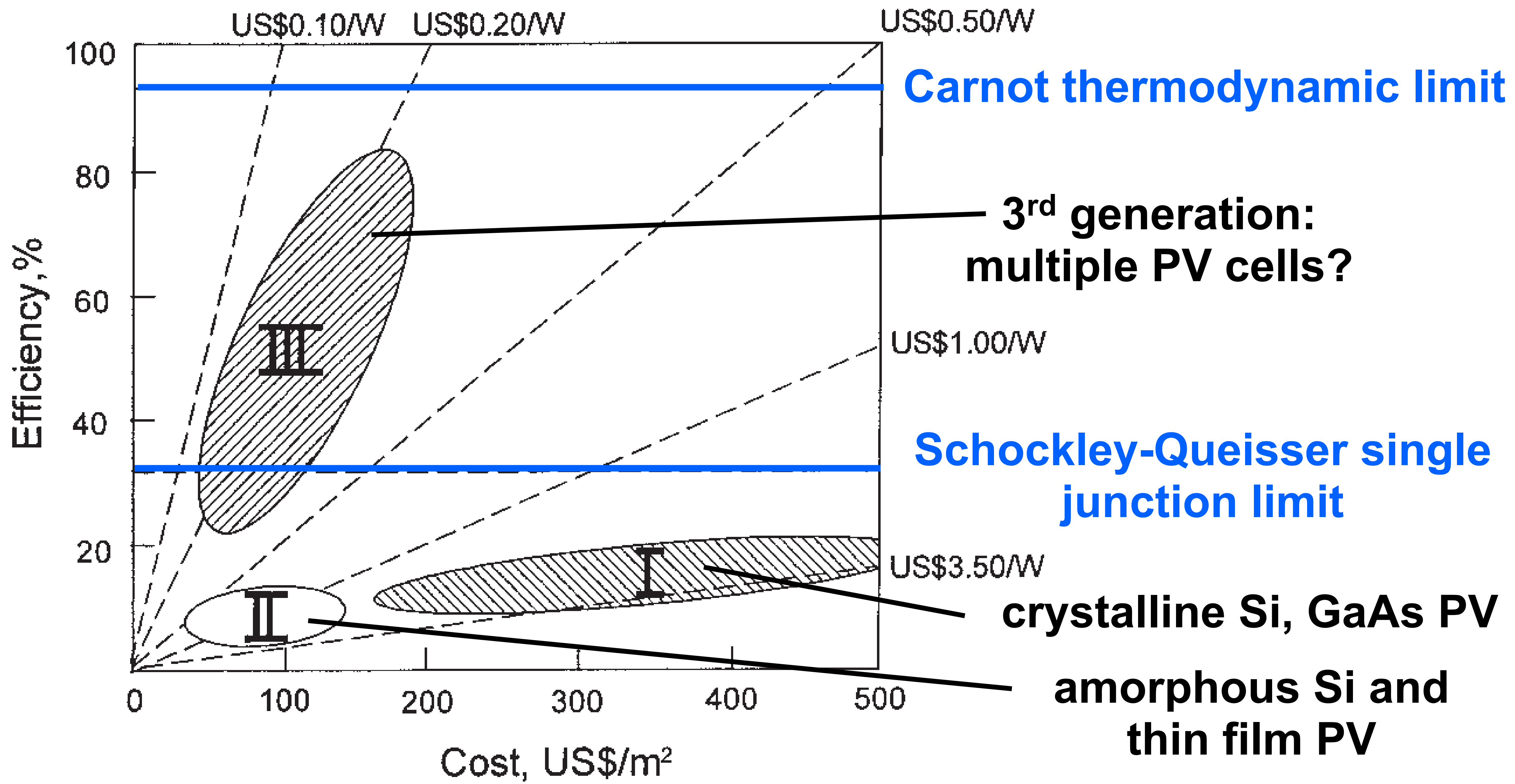
M.A. Green "Third Generation Photovoltaics" Springer (2003)

- Best demonstrated 3 bandgap cell has η = 37.9% for 1 sun !

PV Efficiencies 2014



Market Penetration: Low Cost versus High η



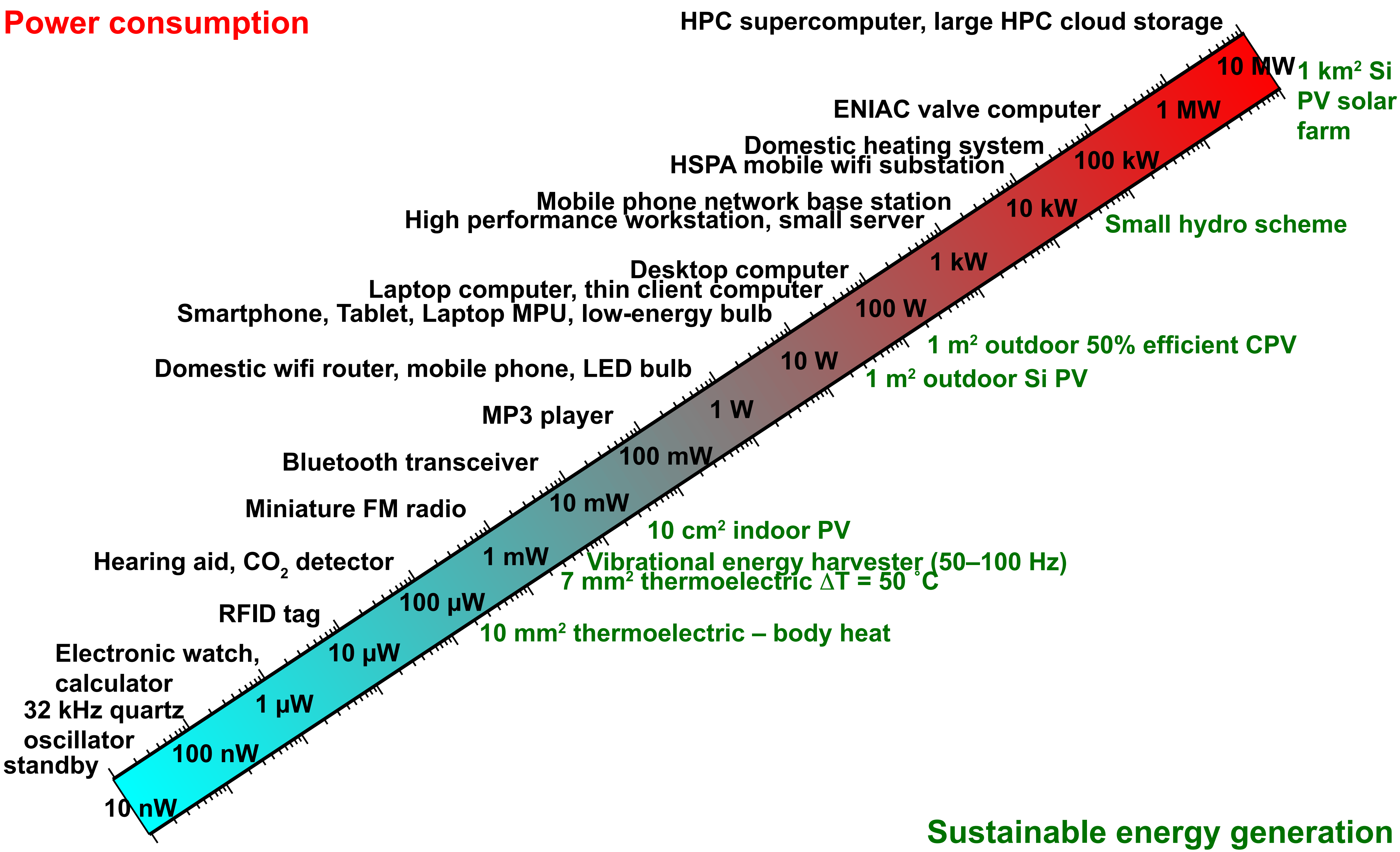
- The market is driven by cost per Watt generated
- Smaller area is cheaper so higher efficiency is a stronger driver

Energy Quality

Highest Quality
Electromagnetic
Mechanical (kinetic)
Photon (light)
Chemical
Heat (thermal)
Lowest Quality

- First proposed as availability by Kelvin in 1851 refined by Ohta
- Energy quality describes the ease (i.e. η) with which energy can be transformed
- A transition down the table will be more efficient than moving up the table
- Therefore solar heating is more efficient than photovoltaic electrical generation
- Expanded version from chemistry developed by Odum

ICT Energy Harveting Requirements



University of Glasgow

Summary

- The available spectrum of solar energy varies around the globe
- Carnot efficiency limit 85% for solar energy
- Thermal heating most efficient use of solar energy $\eta < 75\%$
- PV Shockley-Queisser maximum $\eta \sim 31\%$ for single cell
- Trapping light important. Multi-junction & concentration offer higher η potential up to ~70%
- Low cost per Watt essential for large market penetration