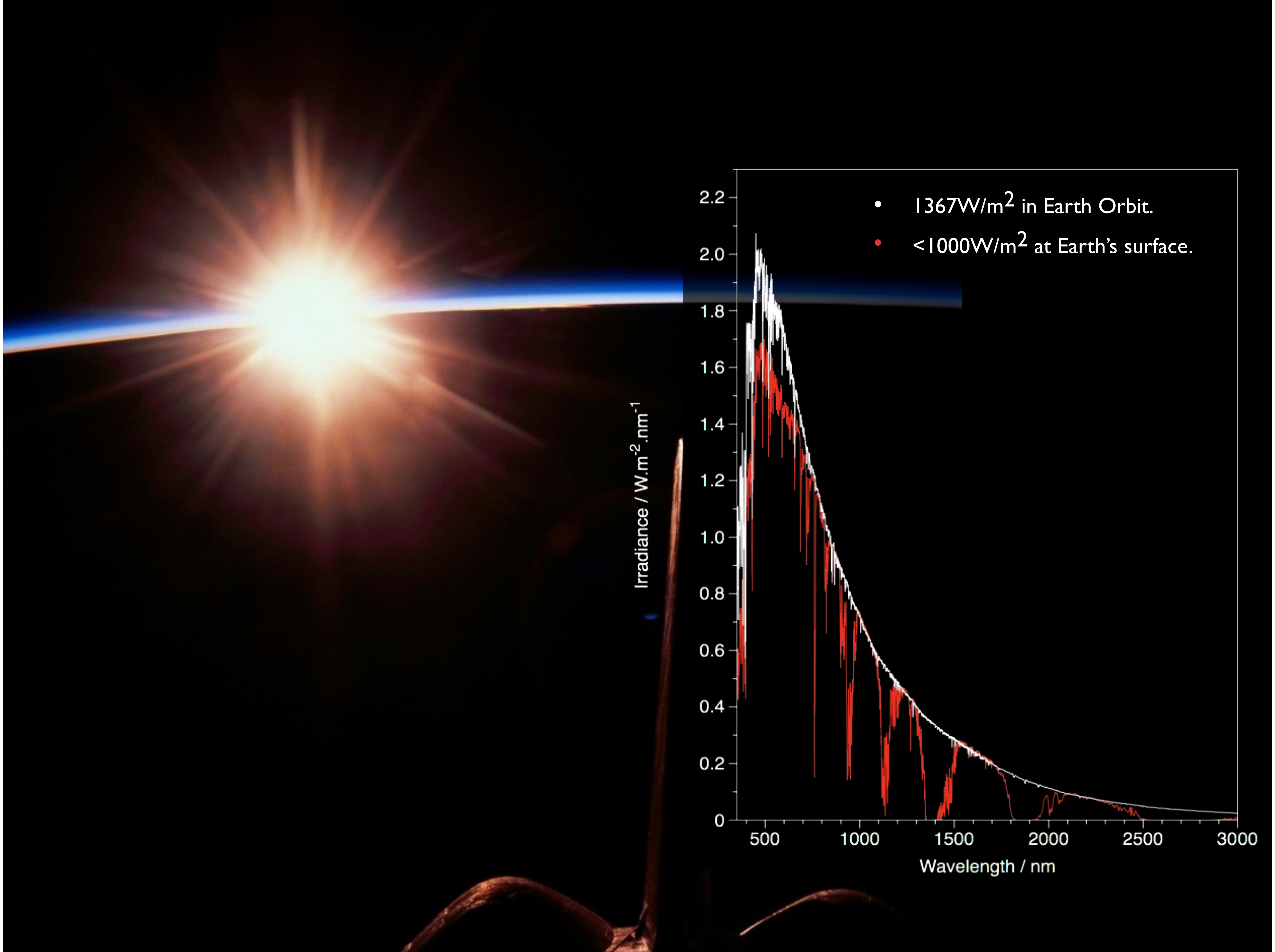
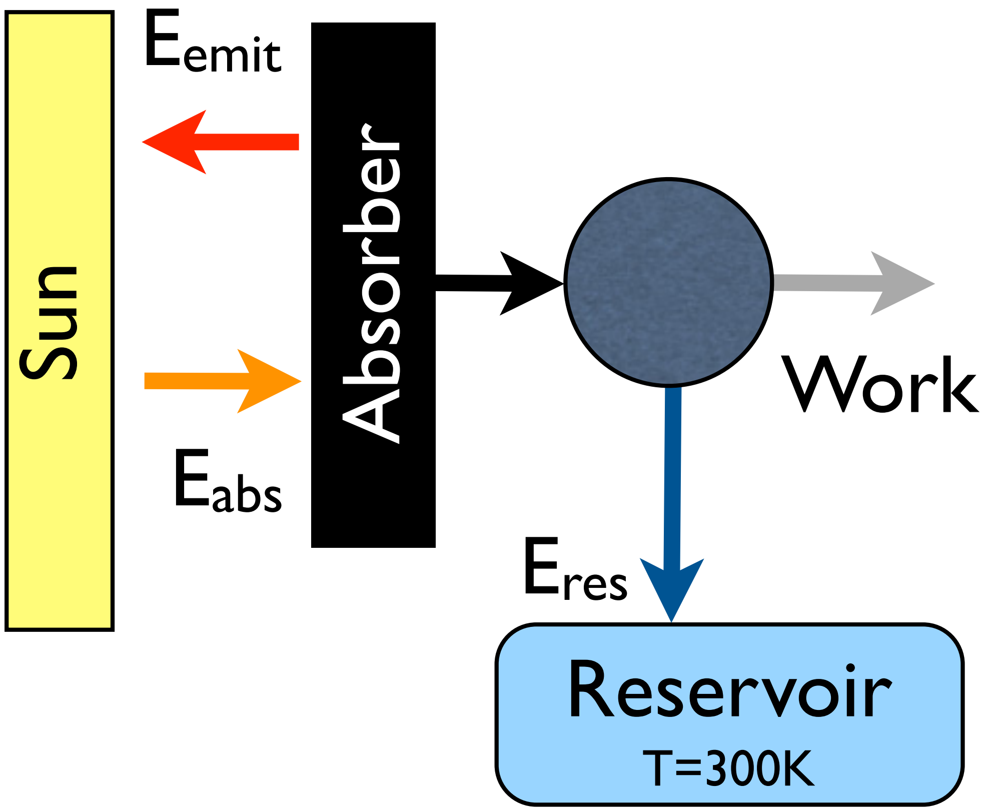
# Solar Power Conversion Efficiency Above 40%
# Short and Long Term Options

Imperial College London

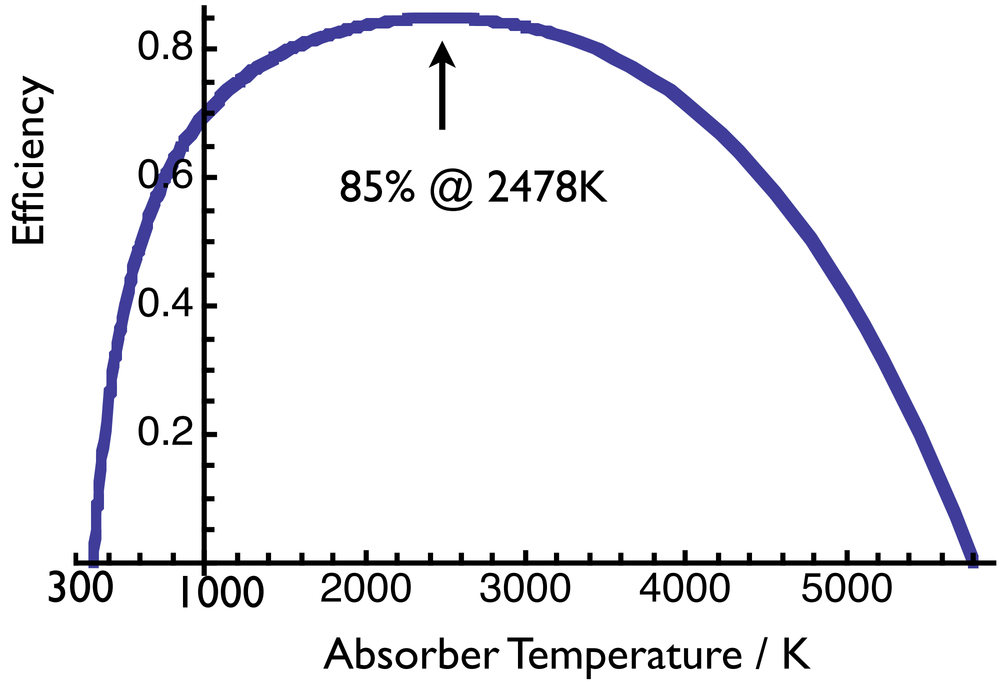
**N.J. Ekins-Daukes,**
**D.Alonso-Alvarez, A.Braun, J.Dimmock, N.Hylton, A.Mellor, P.Pearce, C.Phillips, A.Pusch, T.Wilson, A.Vaquero, M.Yoshida**
www.imperial.ac.uk/qpv

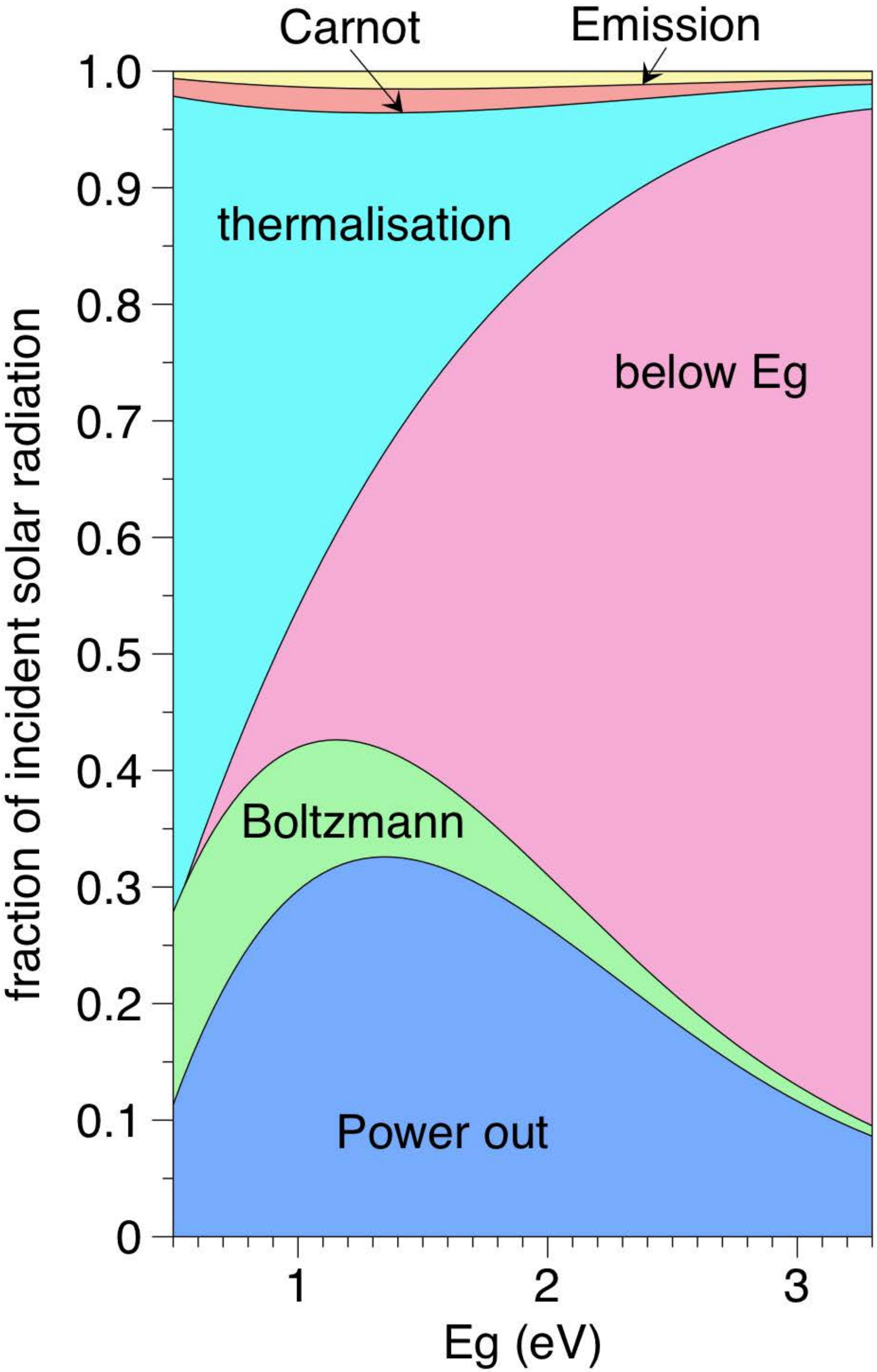

1367W/m2 in Earth Orbit.
<1000W/m2 at Earth’s surface.
Irradiance / W.m-2.nm-1
Wavelength / nm
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
500
1000
1500
2000
2500
3000

# General Solar Collector

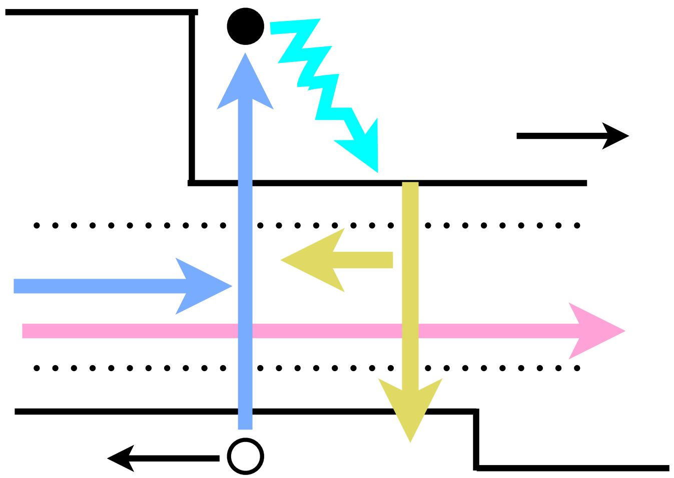


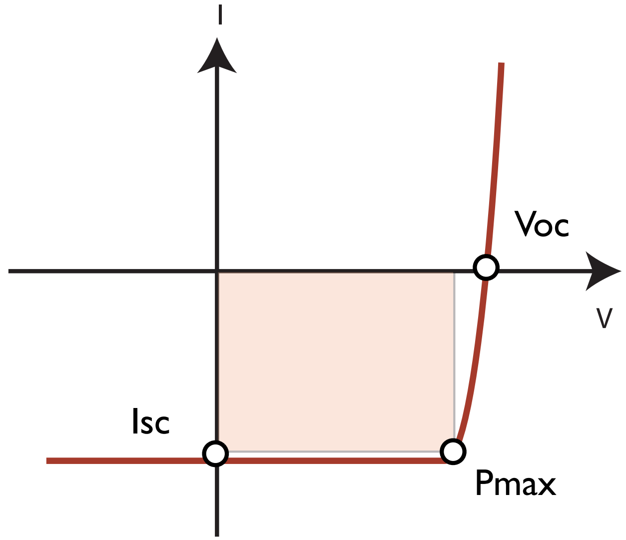

SEGS - Mojave Desert, California



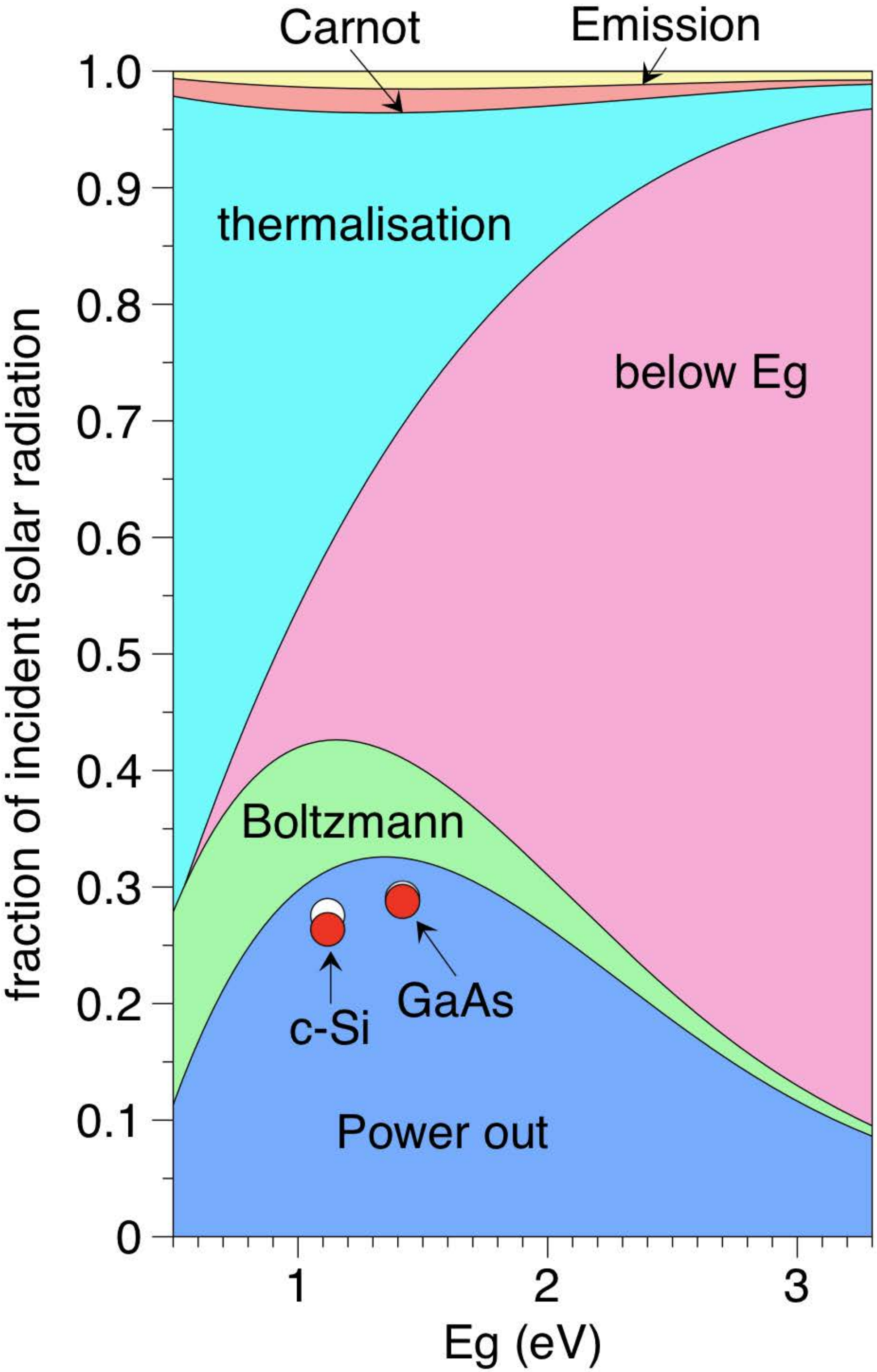


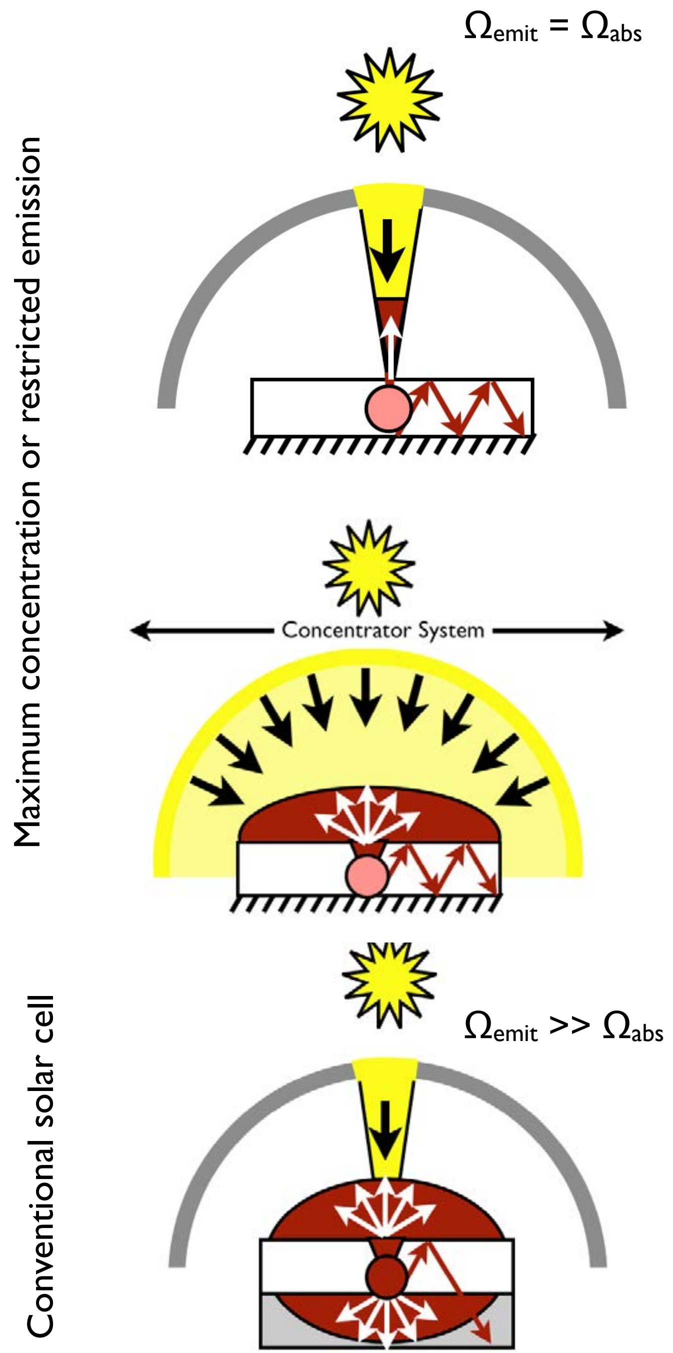

# The Shockley-Queisser Efficiency limit.





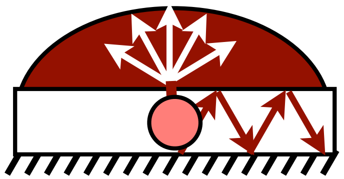

Louise Hirst & N.J.Ekins-Daukes,
"Fundamental Losses in Solar Cells"
Progress in Photovoltaics, (2011) 19: p286



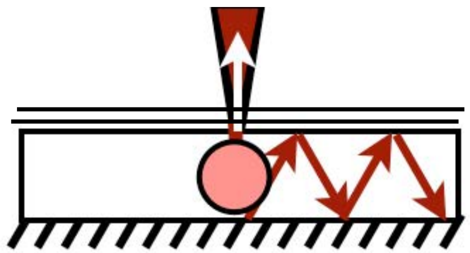




Louise Hirst & N.J.Ekins-Daukes,
"Fundamental Losses in Solar Cells"
Progress in Photovoltaics, (2011) 19: p286

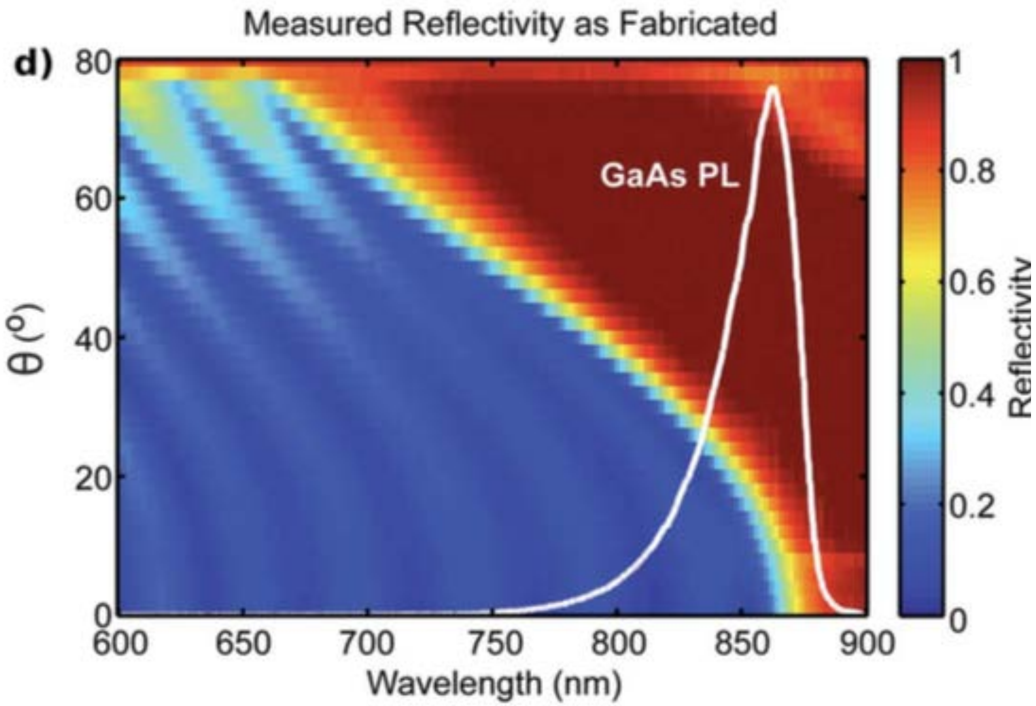
# Controlling Radiative (Boltzmann) Loss using Front Surface Filters.

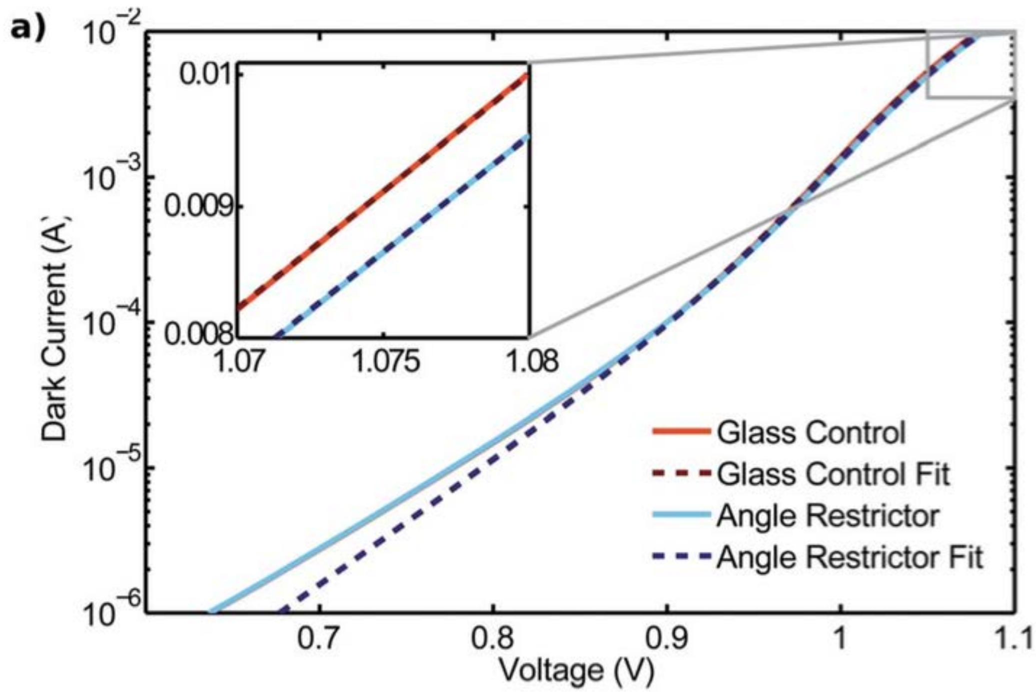


Control device



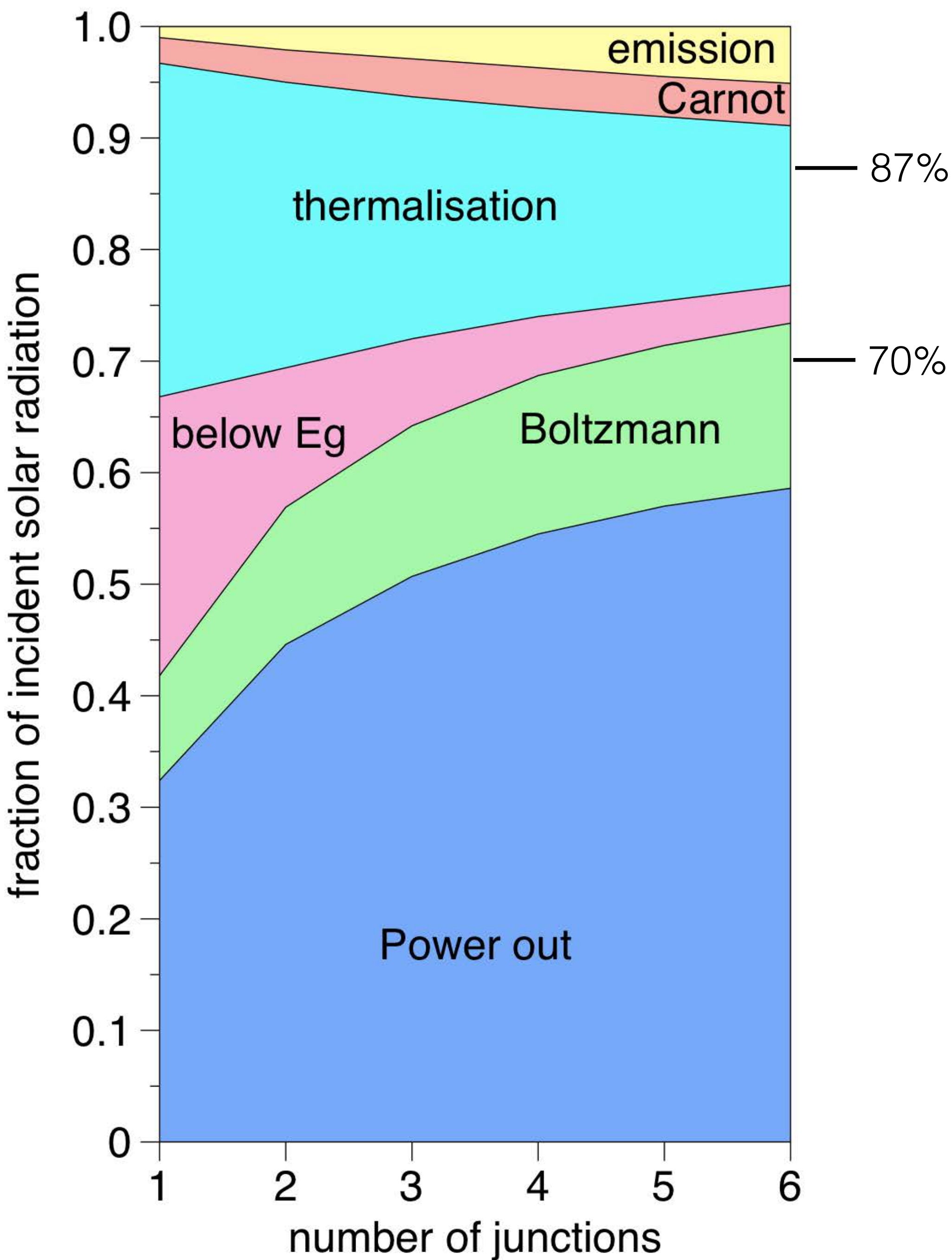
Front surface filter

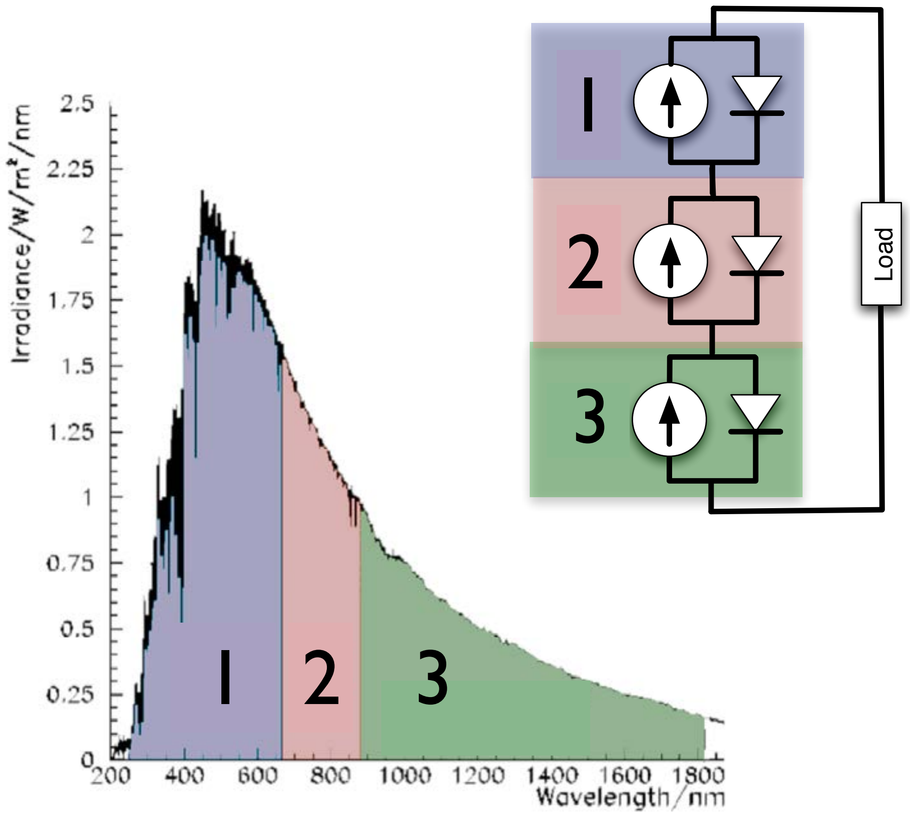



Kosten, E.D. et al, Energy & Environmental Science, 7(6), pp.1907–1912 (2014).

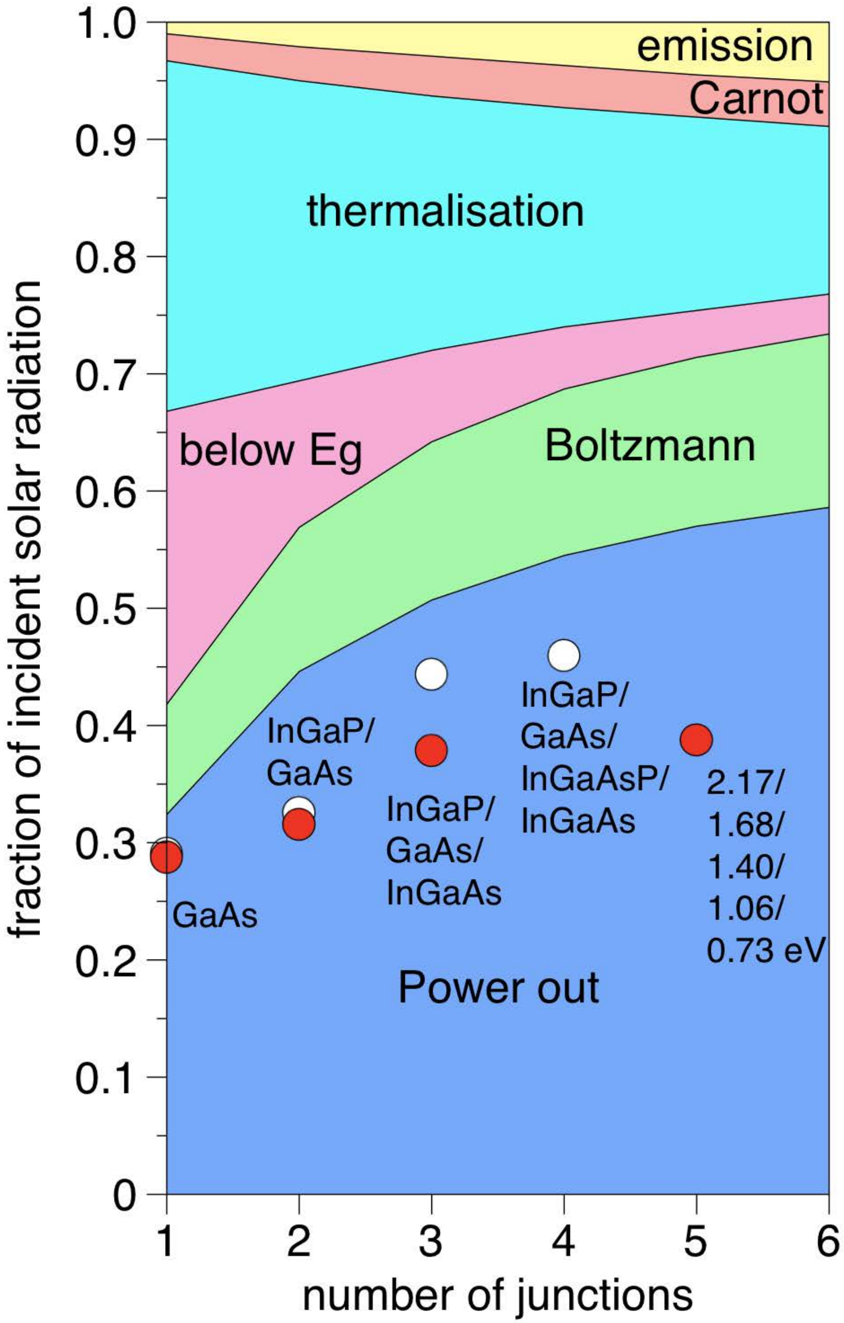
# Multi-Junction Cell Limiting Efficiency

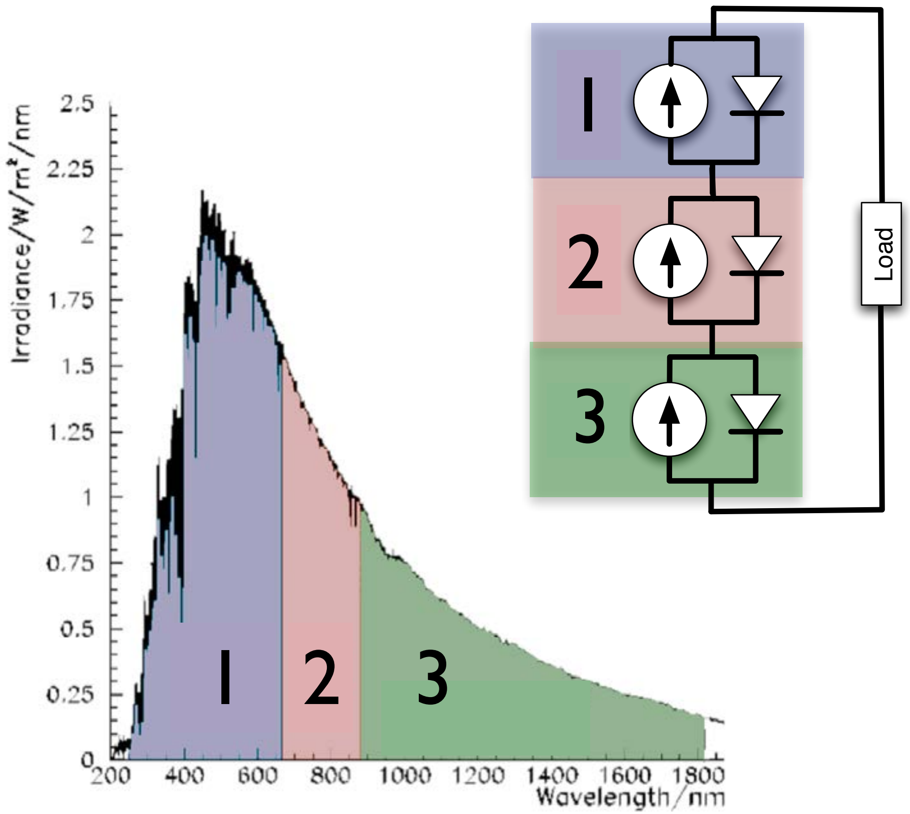



Louise Hirst & N.J.Ekins-Daukes,
"Fundamental Losses in Solar Cells"
Progress in Photovoltaics, (2011) 19: p286

# Multi-Junction Cell Summary




Louise Hirst & N.J.Ekins-Daukes,
"Fundamental Losses in Solar Cells"
Progress in Photovoltaics, (2011) 19: p286

# Lattice Matched MJ Cells

InGaP/InGaAs/Ge 3J

| |
|---|
| 1.9eV InGaP |
| 1.4eV $In_{0.01}GaAs$ |
| 0.66eV Ge substrate |

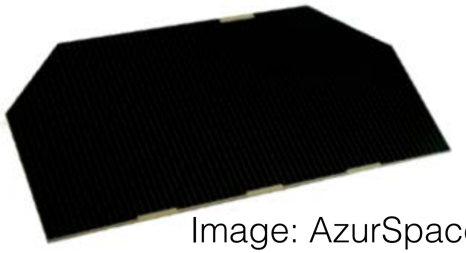
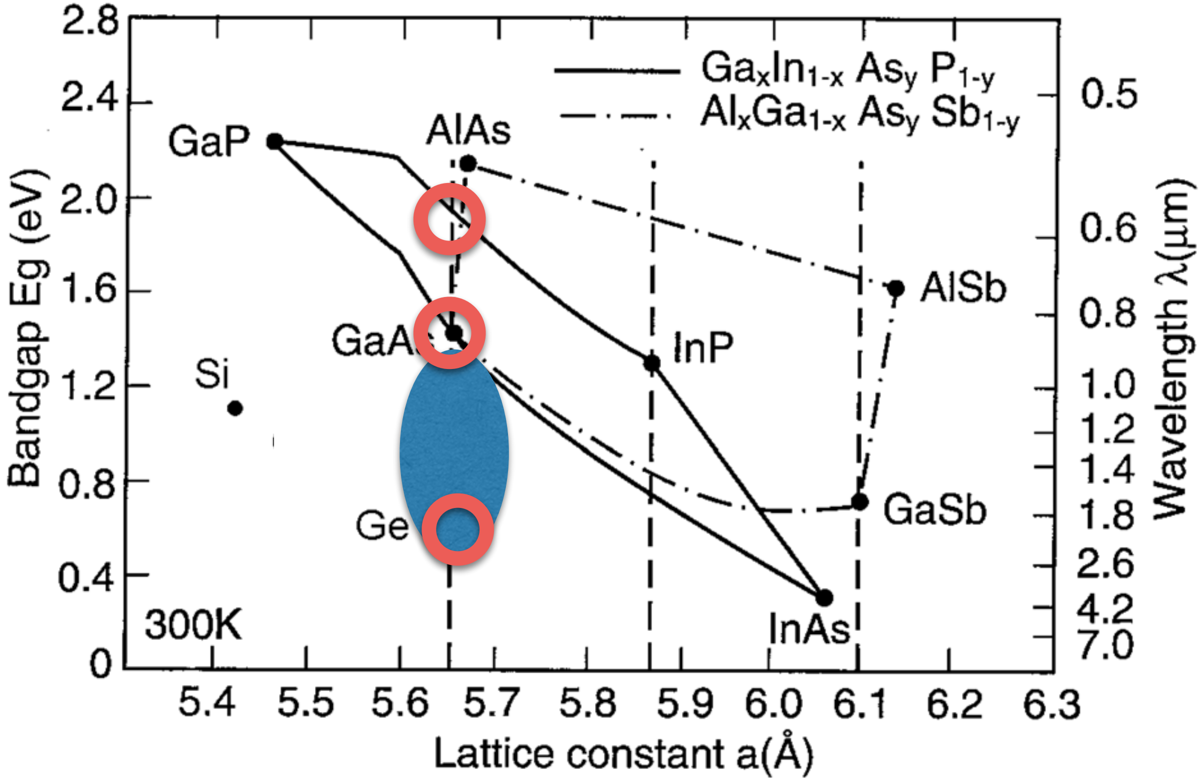


Image: AzurSpace.

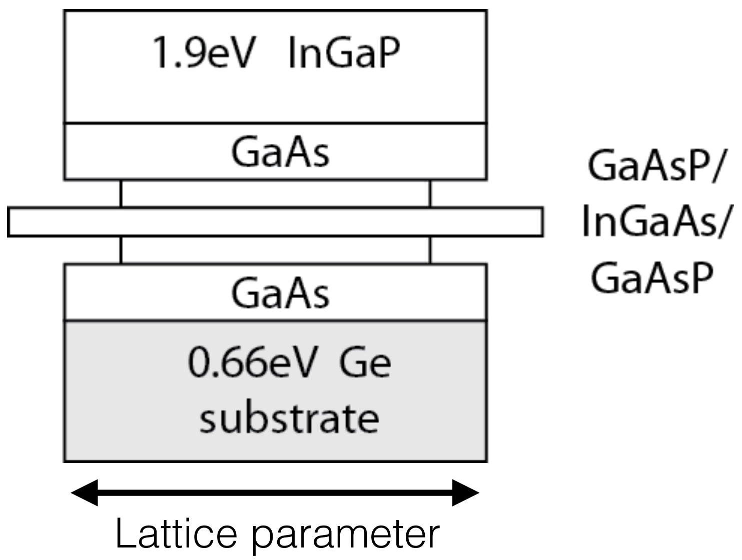
CPV ~40% (AM1.5d)

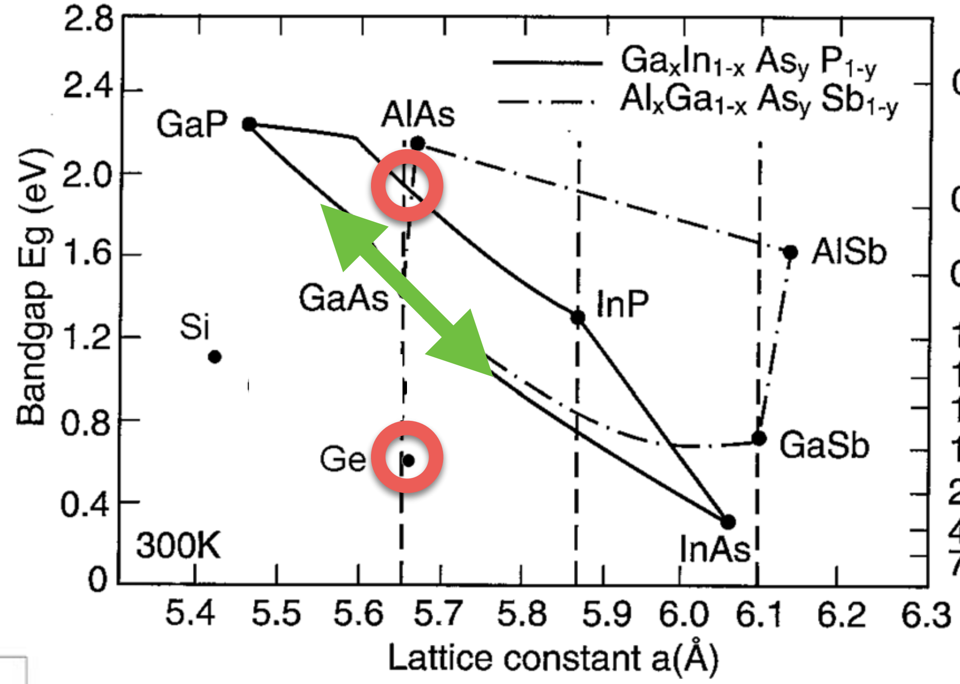
Space ~30% (AM 0)

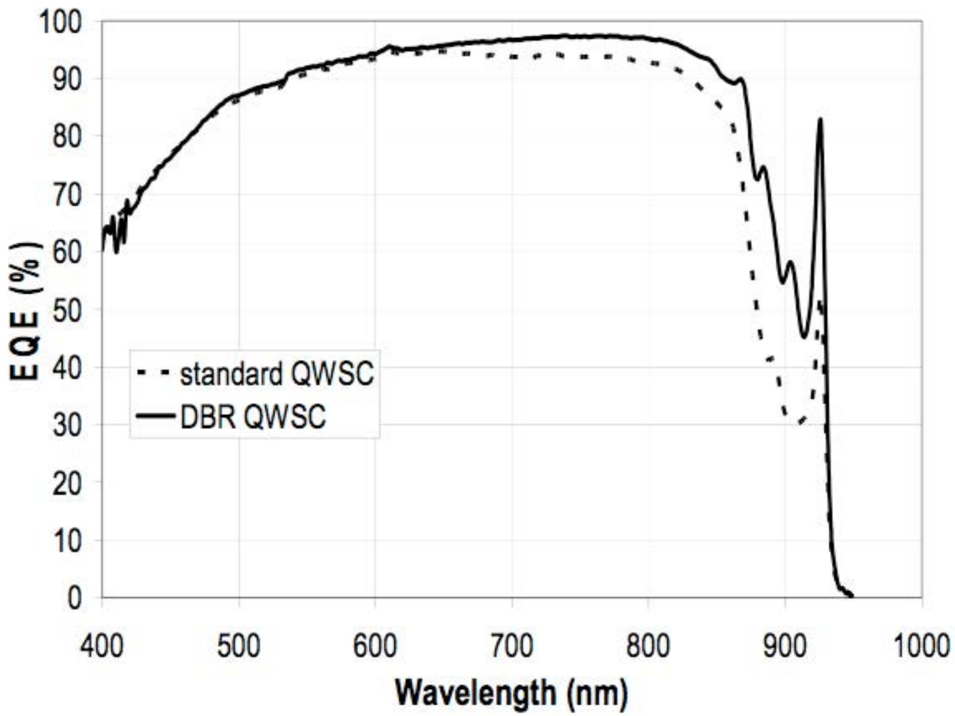


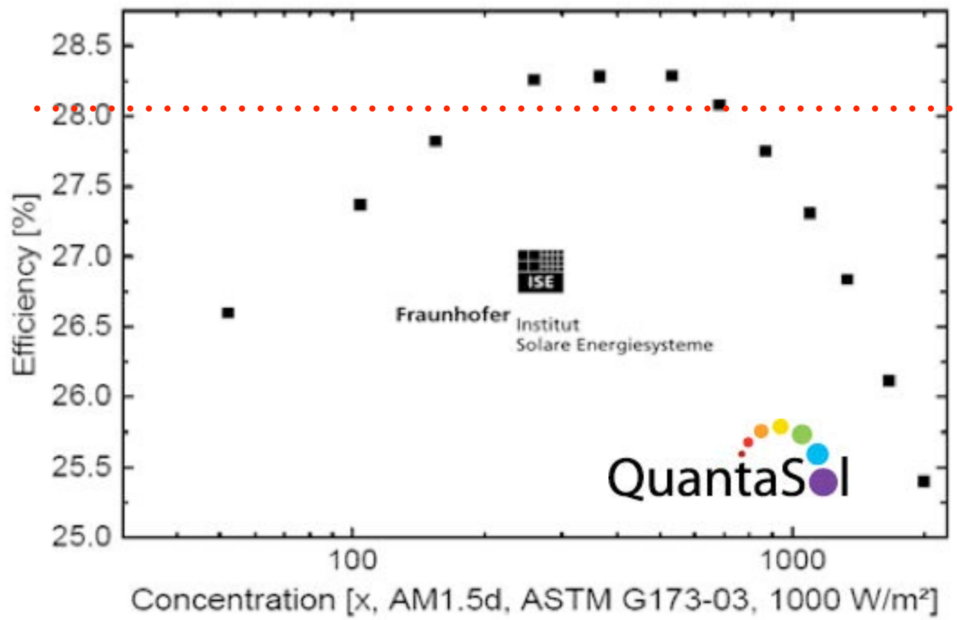

- InGaP/InGaAs/Ge 3J (40.1% @135X) R.R.King, App.Phys.Lett, 90 183516, (2007)
- Dilute nitride InGaP/GaAs/**InGaAsSbN** 3J (44.0% @ 942X) , V.Sabnis, Proc. CPV-7, 2012
- InGaP/GaAs/**SiGeSn** 3J, R.Rouka et al, IEEE-JPV,6(4) p1025 (2016)

# Strain-Balanced MJ Solar Cells



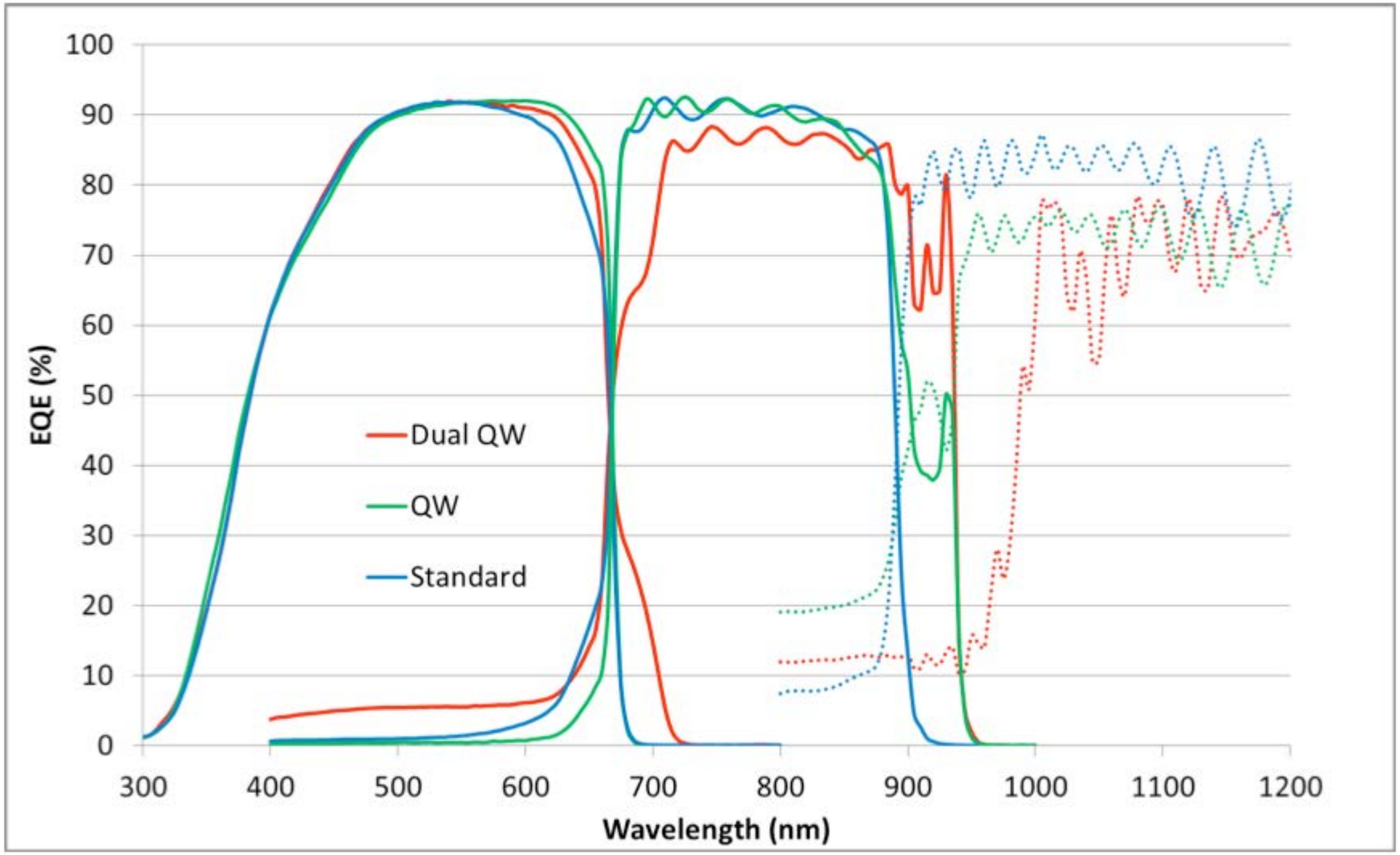



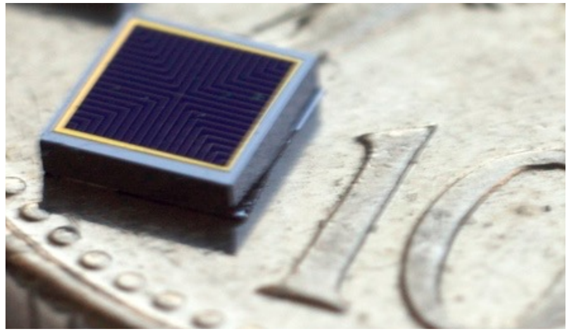




N.J. Ekins-Daukes, App.Phys.Lett. , 75(26), pp.4195 (1999)

# 42.5% Dual (InGaP/InGaAsP)/(GaAsP/InGaAs)/Ge MQW 3J solar cell



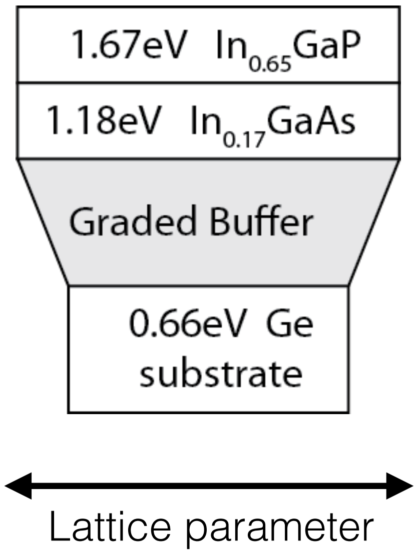



Browne, B. et al., 2013. Triple-junction quantum-well solar cells in commercial production. In 9th International Conference on Concentrator Photovoltaic Systems: CPV-9. AIP, pp. 3–5. (2013)

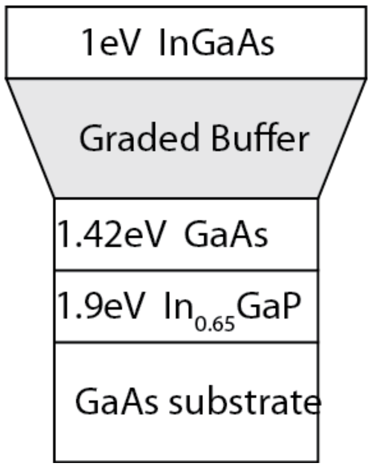
JDSU

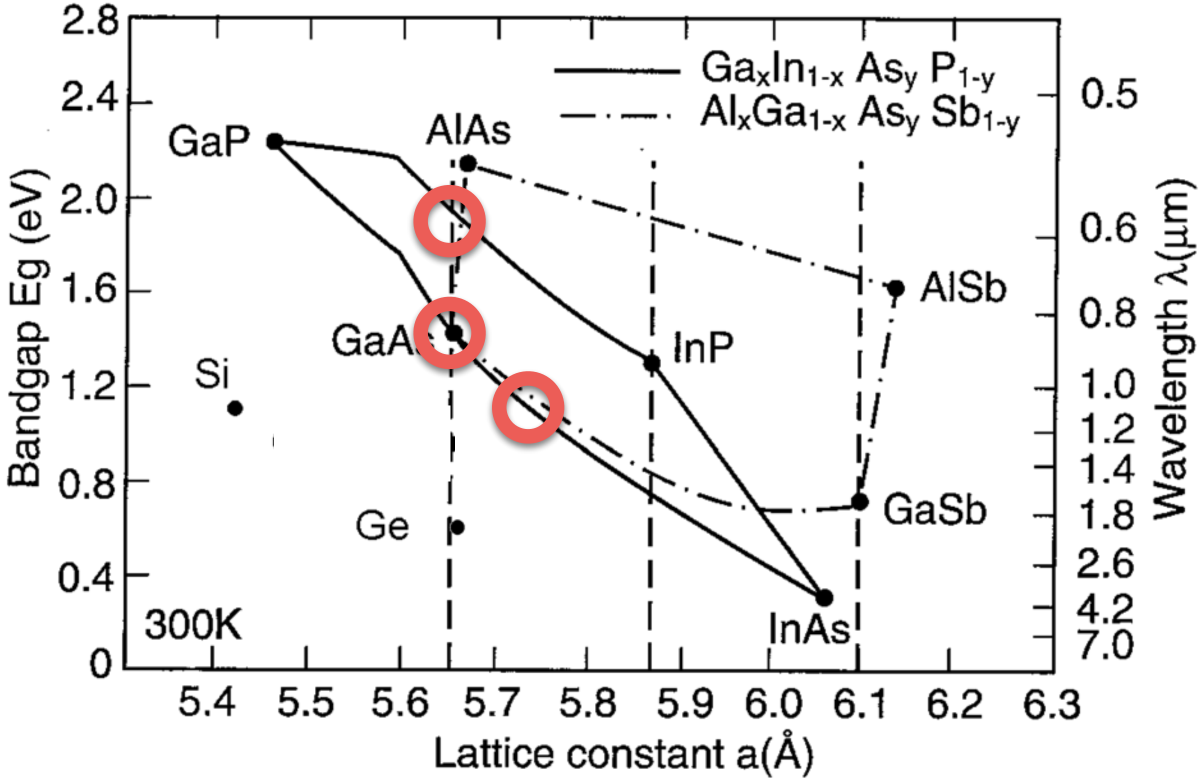
# Metamorphic MJ Cells

Upright




Inverted



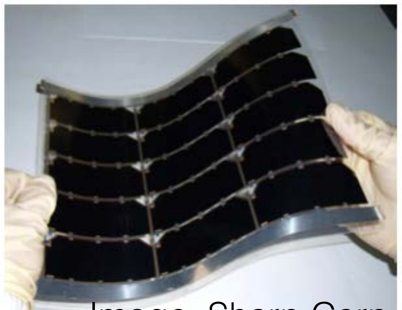
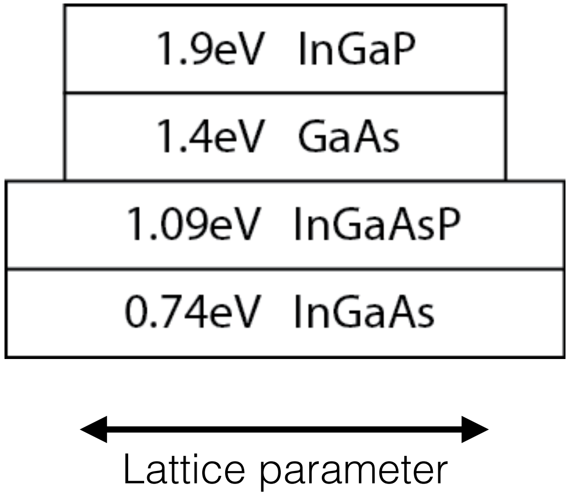
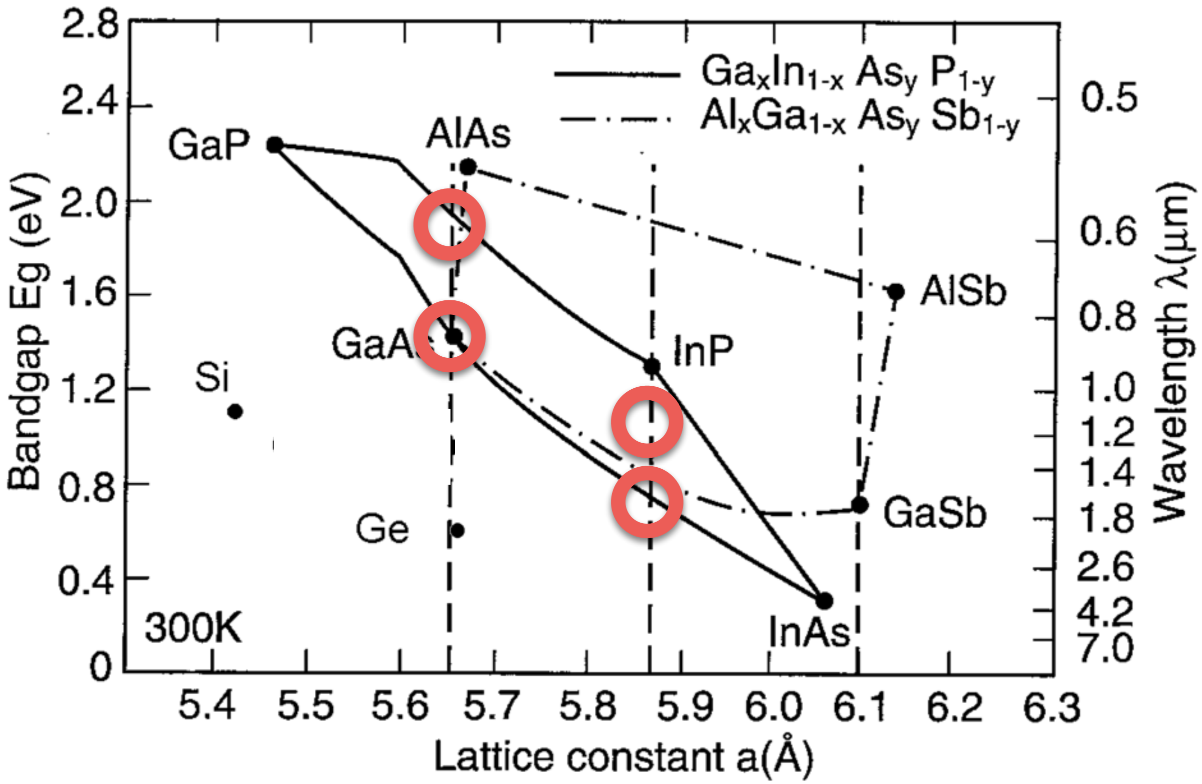



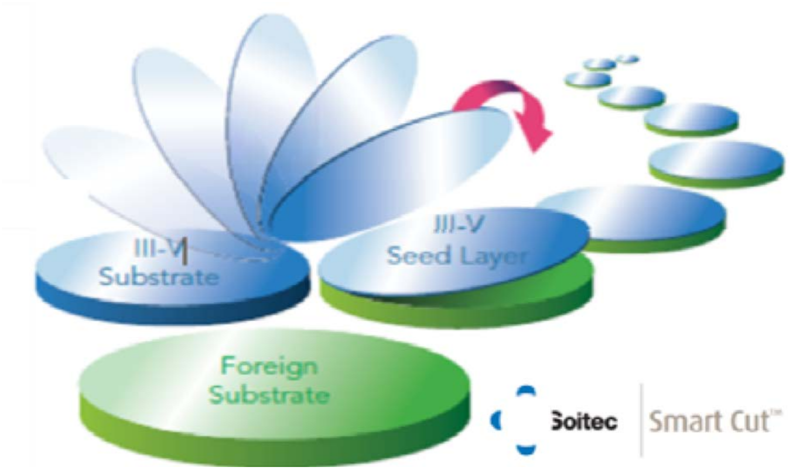
Image: Sharp Corp.

- Upright : W. Guter, Appl. Phys. Lett. 94 (2009) 223504.
- Inverted : T. Takamoto et al. Proc. 35th IEEE PVSC (2010) p.412.

# Wafer Bonded Solar Cells

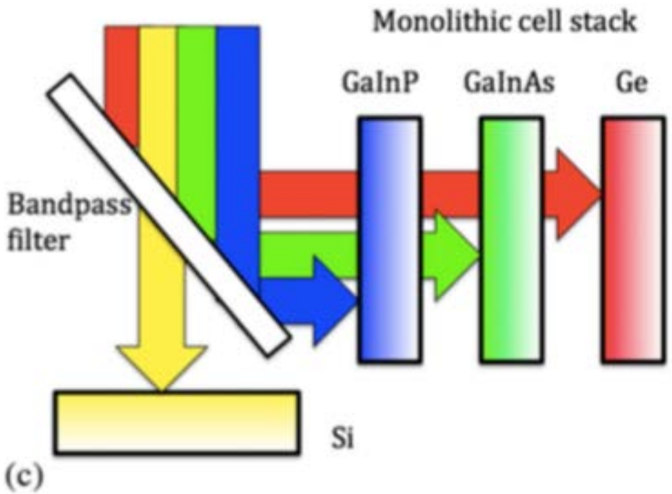


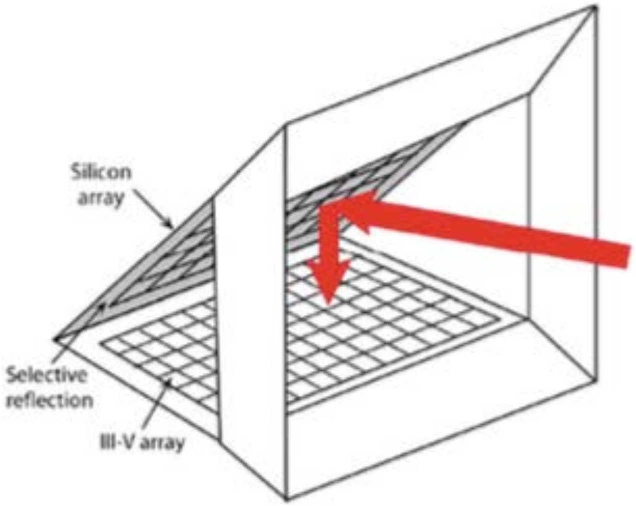



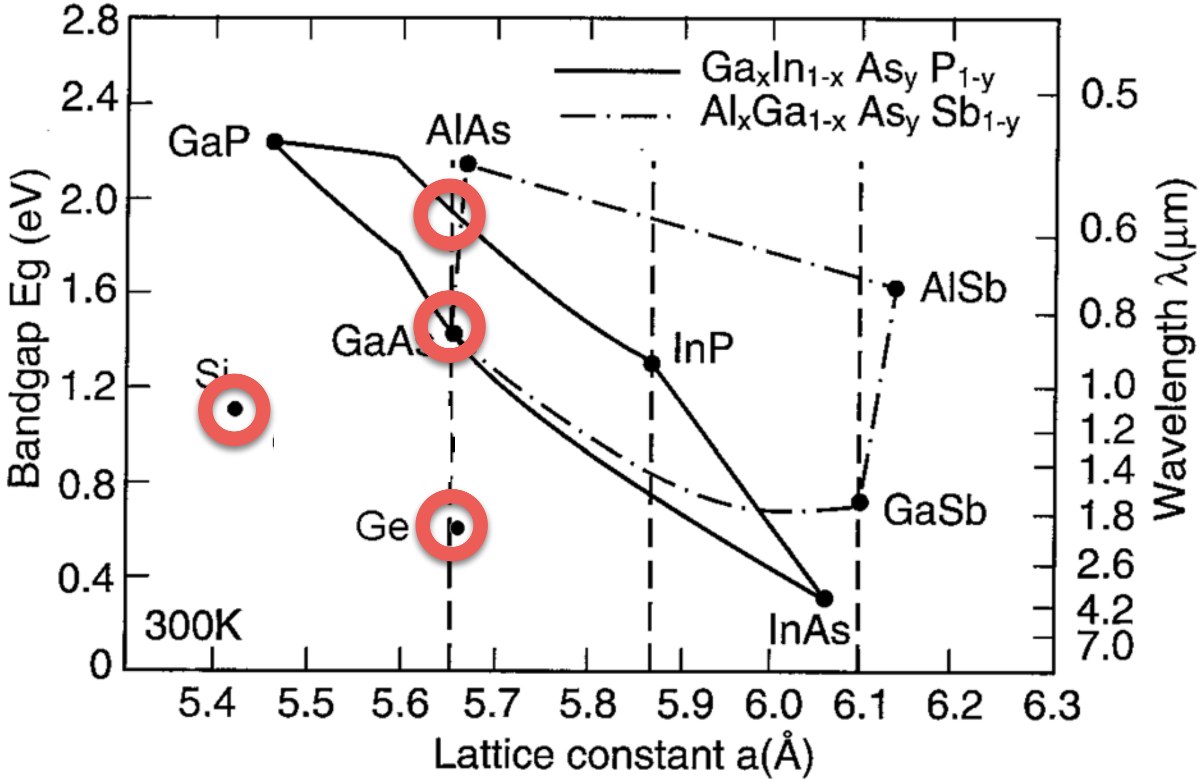




- 508X AM1.5D 46.5% T.Tibbits, et al. Proc. EU PVSEC, (2014)
- AM1.5G 5J 38.8% Chiu PT, et al., Proc. 40th IEEE PVSC (2014) 11–13.

# Spectral Splitting Systems

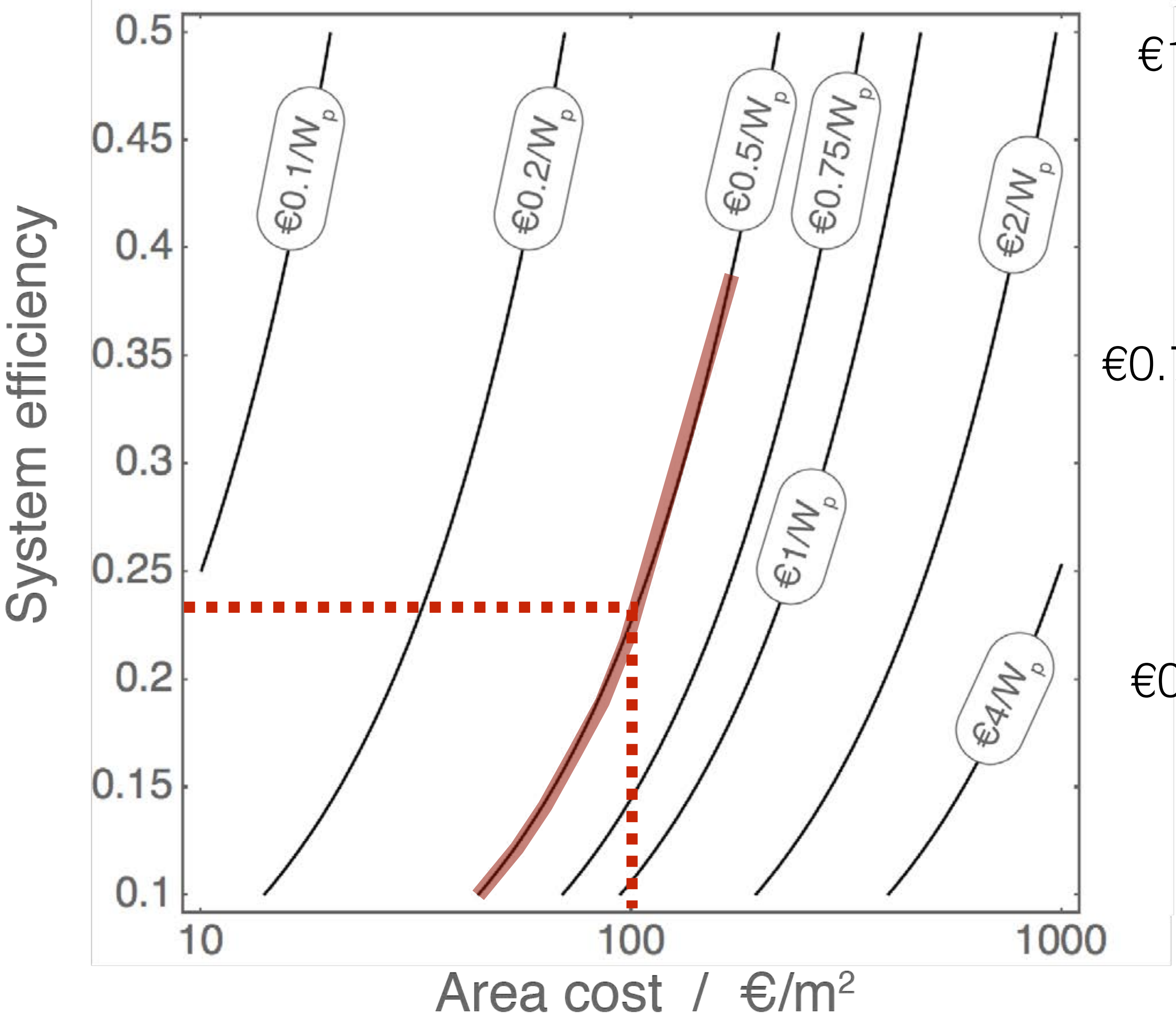



- 40% efficient power conversion achieved outdoors, M.A.Green, et al., Prog. Photovolt: Res. Appl. 23:685–691 (2015)

# c-Si system cost




€1/Wp c-Si system cost (2015):

- 15% system efficiency
- €135/m² area cost

€0.75/Wp c-Si system cost (2020):

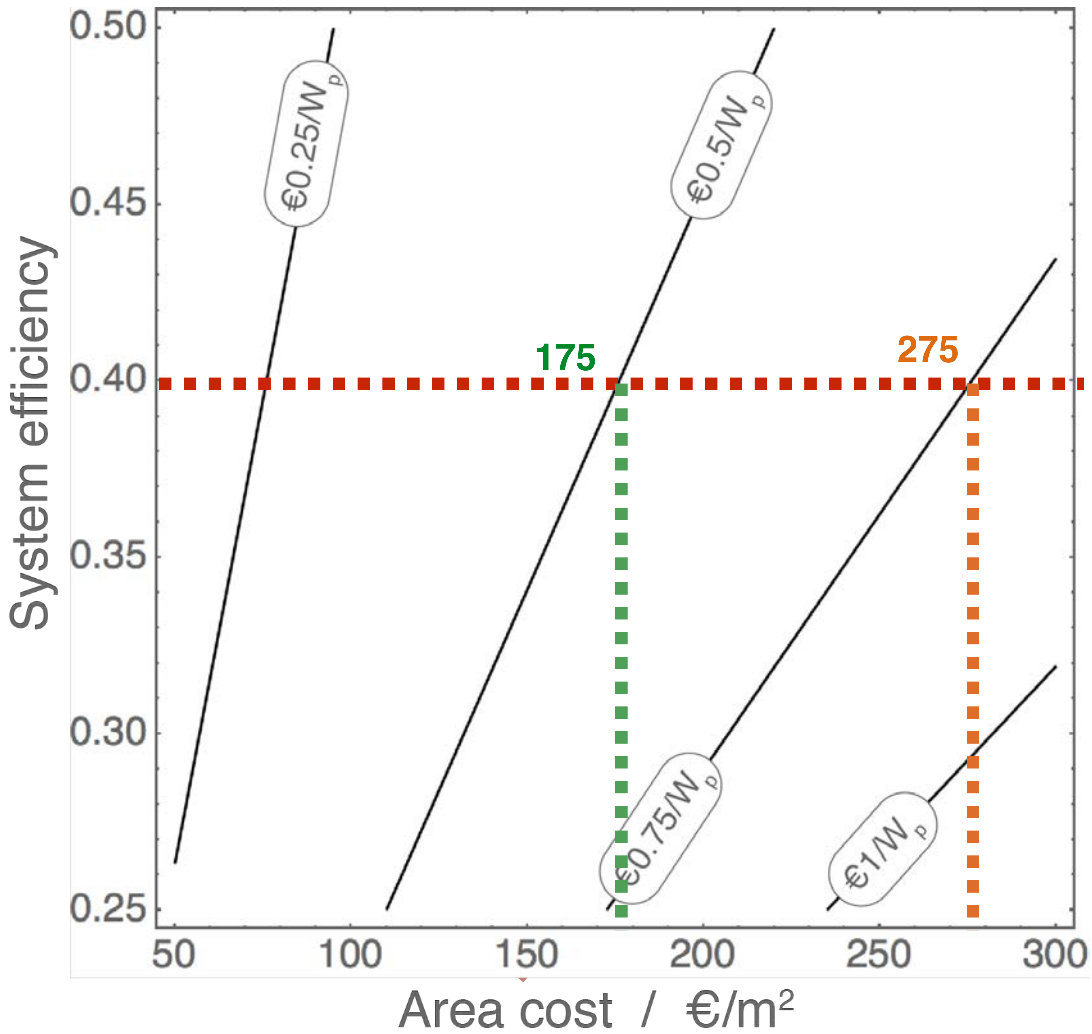
- 17% system efficiency
- €120/m² area cost

€0.5/Wp c-Si system cost ( ?? ):

- 23% system efficiency
- €100/m² area cost

$$\text{System cost}[€/W_p] = \frac{\text{Area cost}[€/m^2]}{\text{Std. Irradiance}[W/m^2] \times \text{System Efficiency}} + \text{BOS cost}[€/W_p]$$

# CPV system cost




30% system efficiency (2015):

- €1/Wp implies €275/m$^2$ (match c-Si today)
- €0.75/Wp implies €210/m$^2$ (match c-Si in 2020)
- €0.5/Wp implies €130/m$^2$

40% system efficiency:

- €0.75/Wp implies €275/m$^2$ (match c-Si in 2020)
- €0.5/Wp implies €175/m$^2$

$$\text{System cost}[€/W_p] = \frac{\text{Area cost}[€/m^2]}{\text{Std. Irradiance}[W/m^2] \times \text{System Efficiency}} + \text{BOS cost}[€/W_p]$$

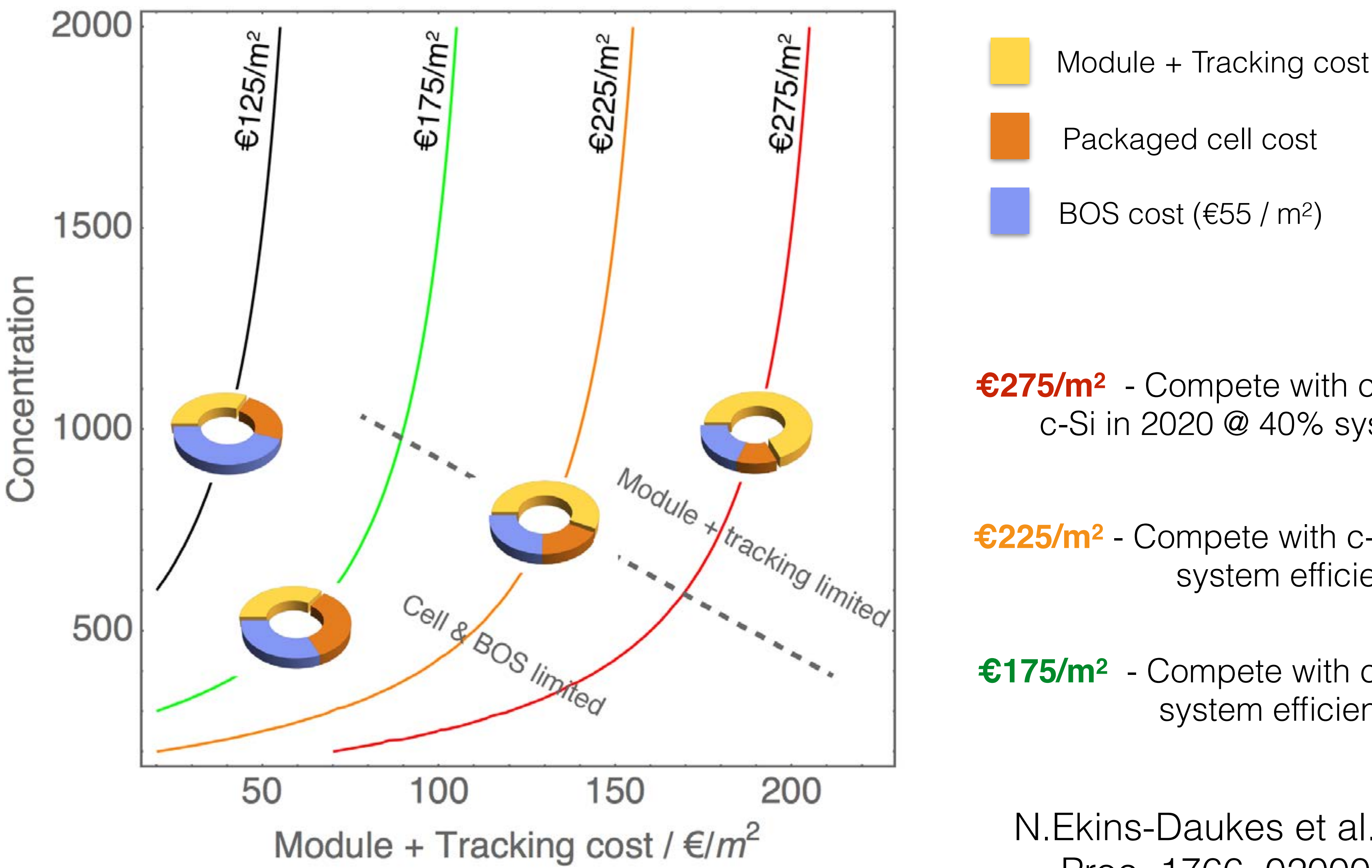
N.Ekins-Daukes et al., AIP Conf. Proc. 1766, 020004 (2016)

# Module & Tracking Costs

$$\text{Area cost}[€/m^2] = \frac{\text{Cell cost}[€/m^2]}{Concentration} + \text{Module cost}[€/m^2] + \text{Tracking cost}[€/m^2] + \text{BOS cost}[€/m^2]$$

( €55 /m²)

Packaged cell cost = €3/cm²



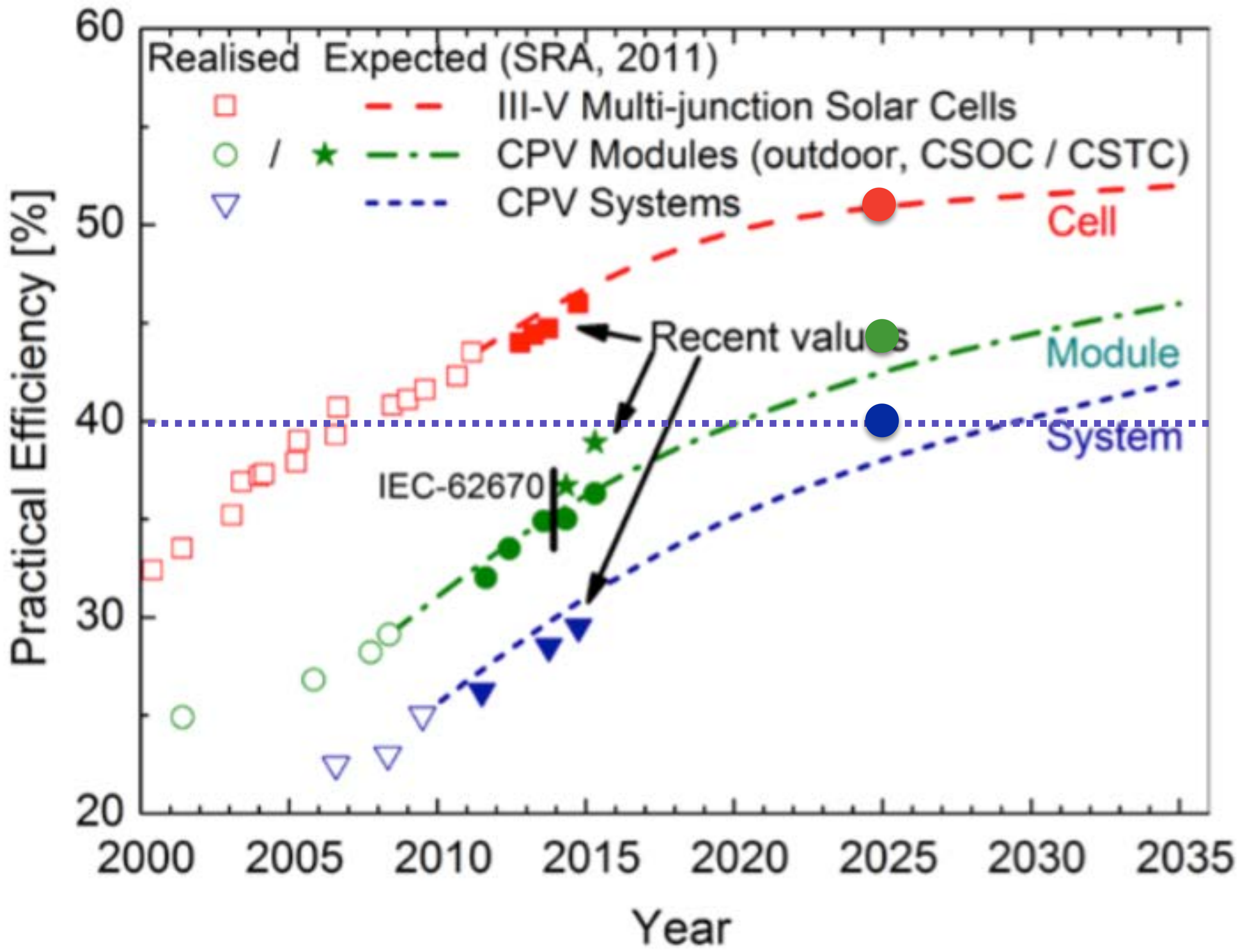

**€275/m²** - Compete with c-Si today @ 30% or c-Si in 2020 @ 40% system efficiency

**€225/m²** - Compete with c-Si in 2020 @ 30% system efficiency

**€175/m²** - Compete with c-Si limit @ 40% system efficiency

N.Ekins-Daukes et al., AIP Conf. Proc. 1766, 020004 (2016)

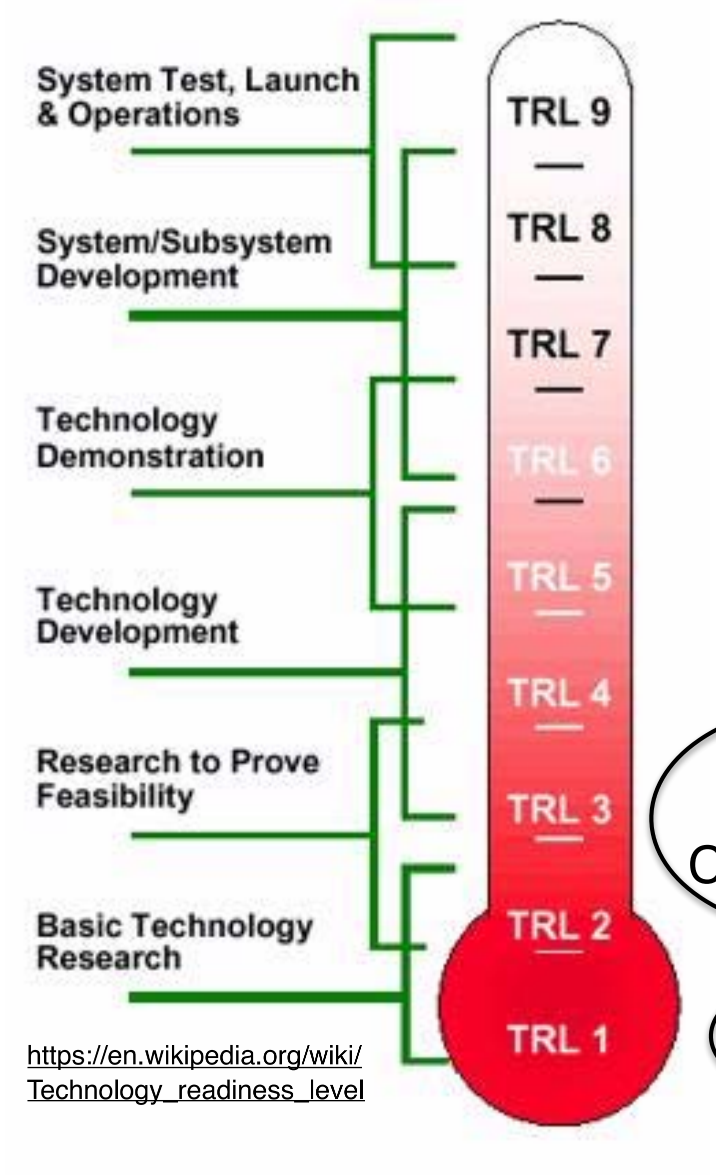
# 40% system efficiency

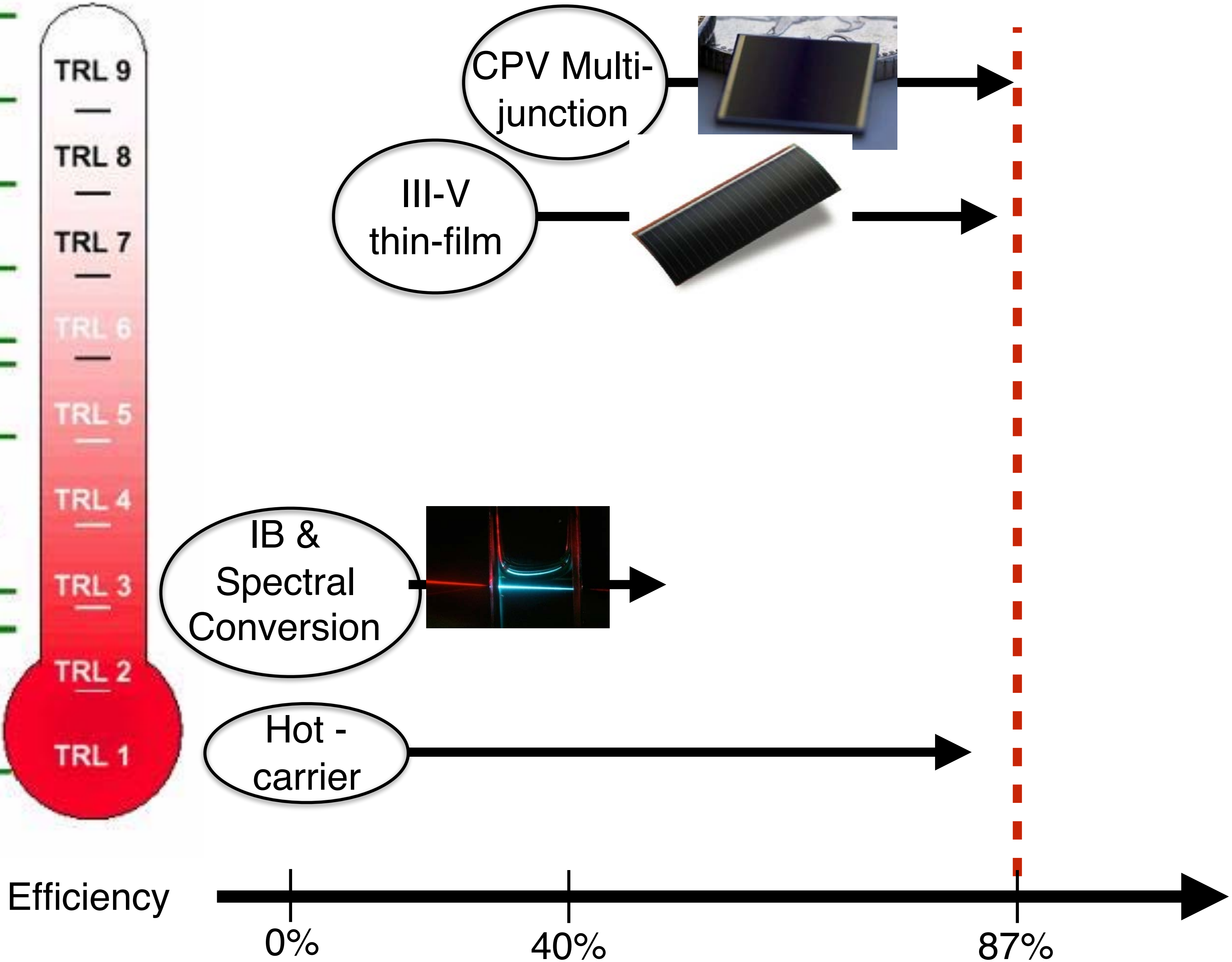



Philipps, S.P. et al., 2016. Current Status of Concentrator Photovoltaic (CPV) Technology TP-6A20-63916

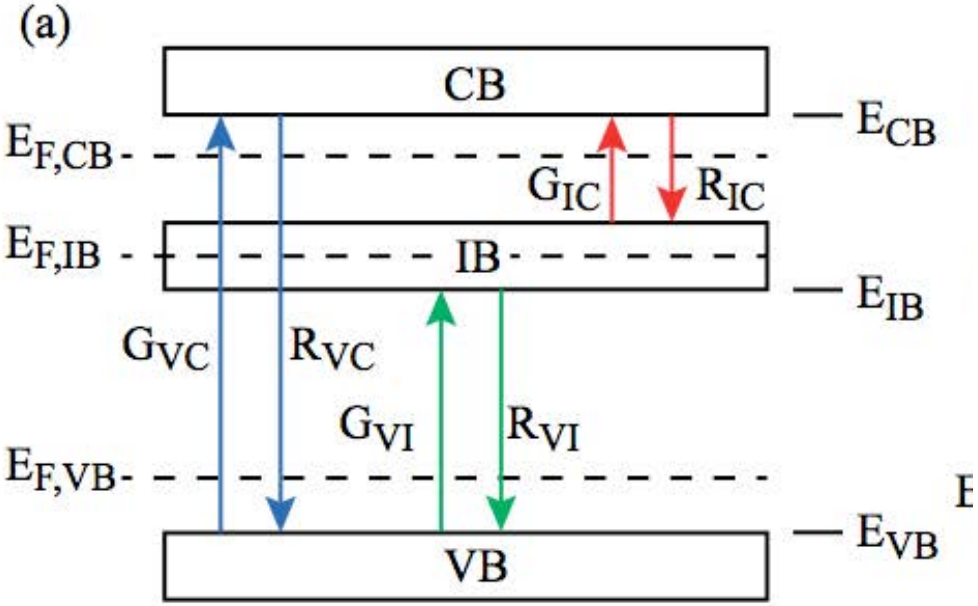
# High efficiency solar cell concepts

Technology readiness level:

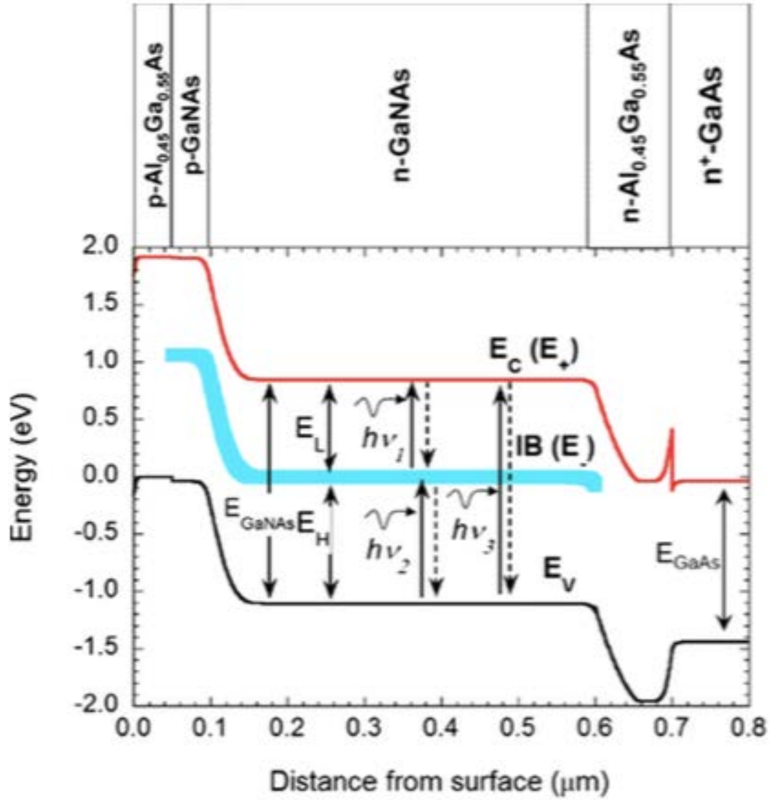


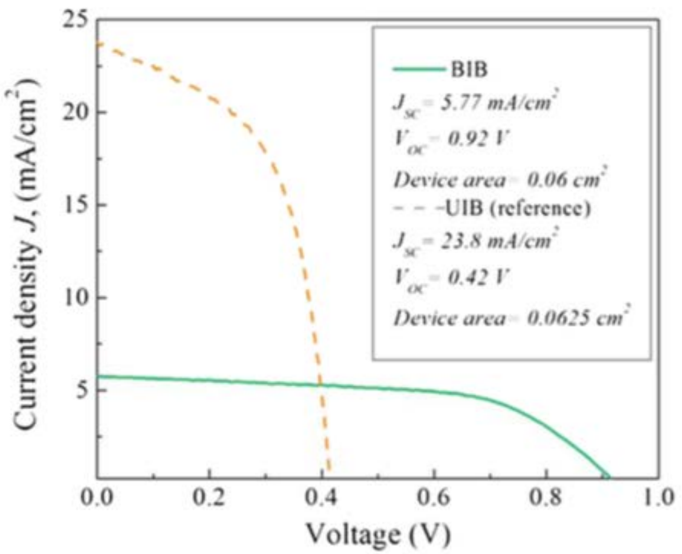



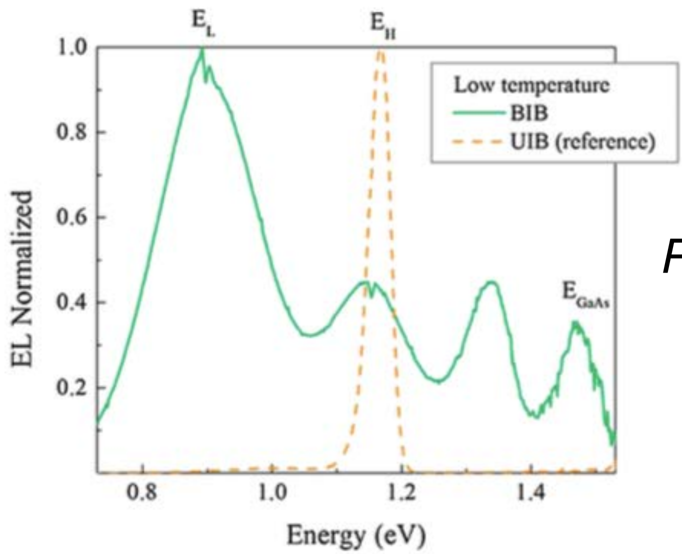
# Intermediate Band Solar Cell




A.Luque, A.Marti,
Physical Review Letters, 78, 5014 (1997).



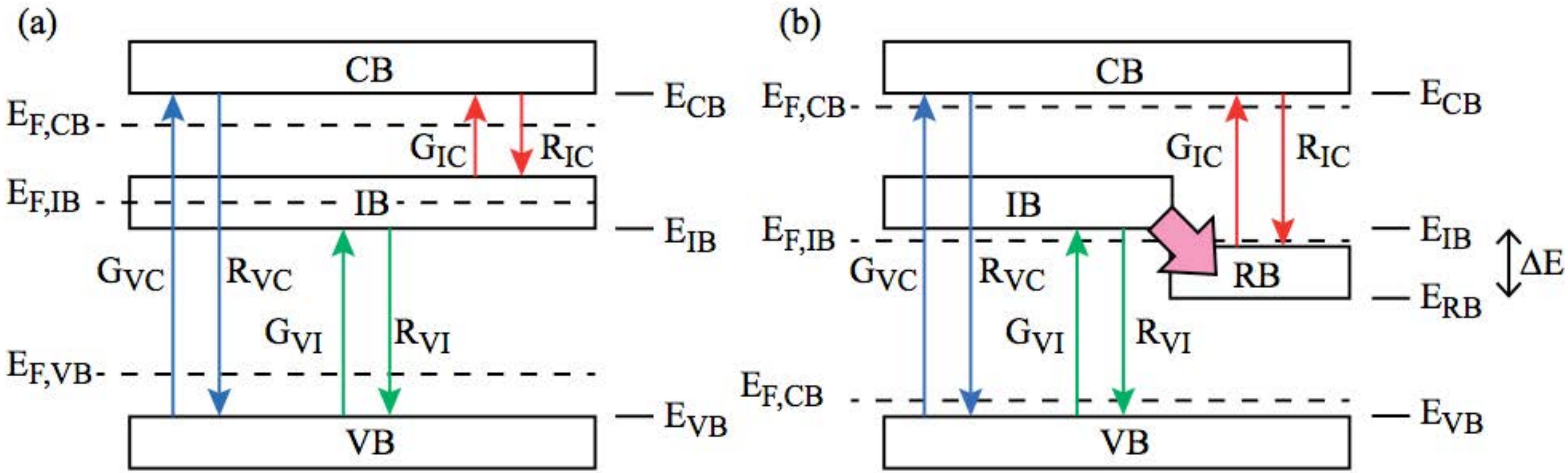



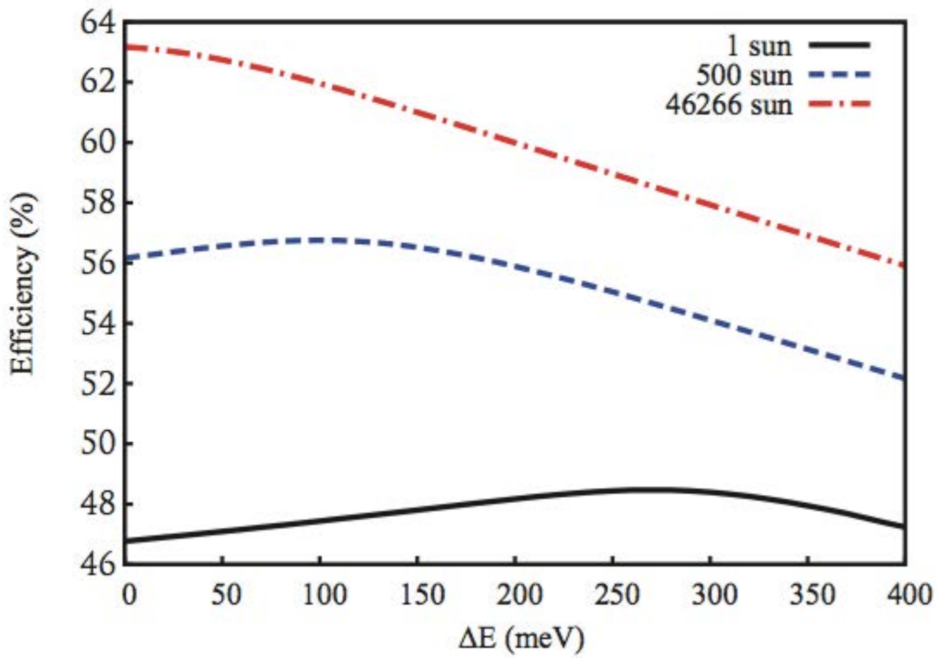

N. López,et al.,

*Physical Review Letters*, 106(2), p.028701 (2011)

Review paper: Y. Okada, et al., Applied Physics Reviews, 2(2), p.021302 (2015)

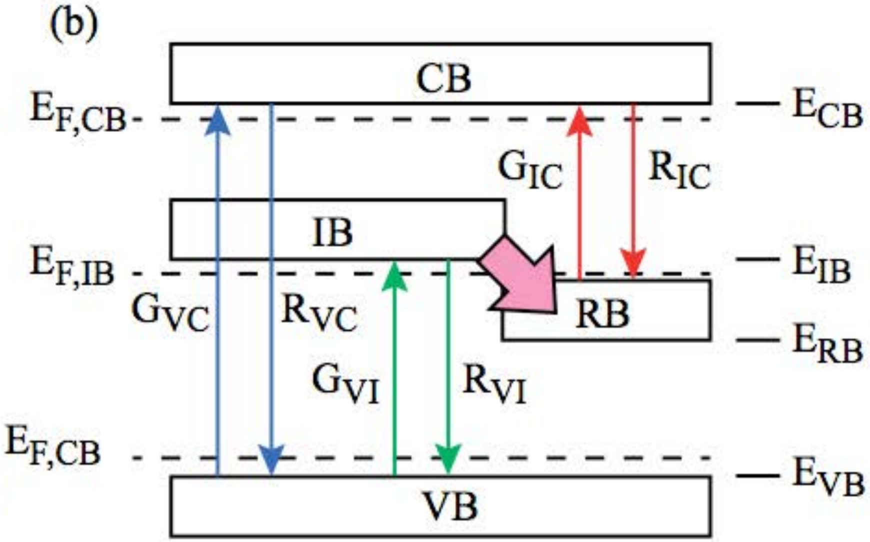
# Sequential Absorption via a 'Photon Ratchet'

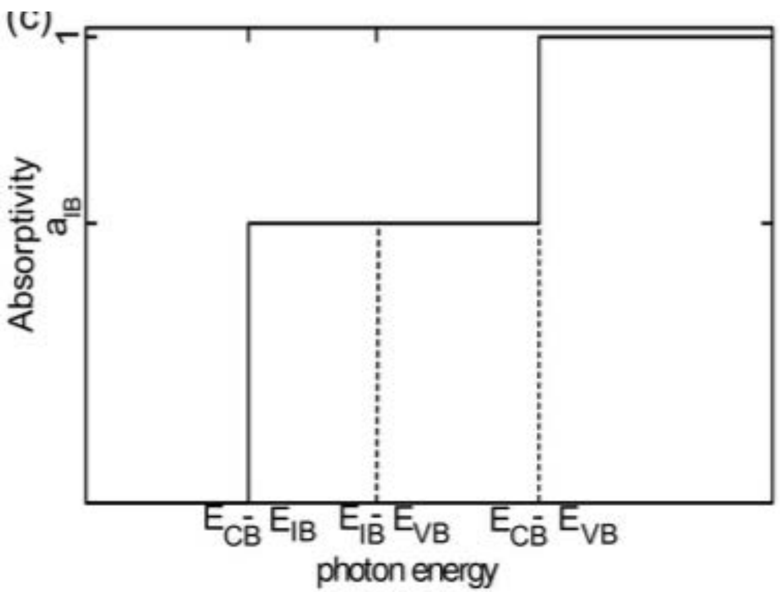


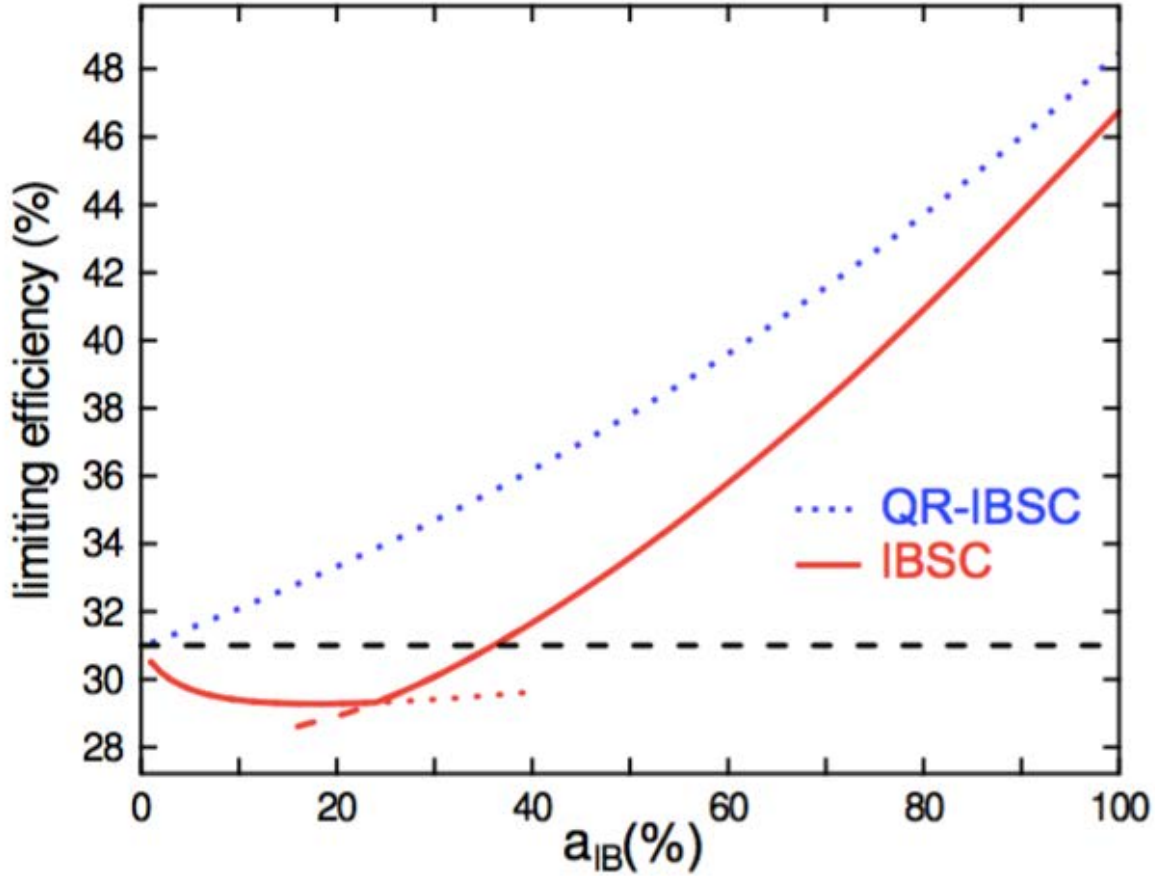




M. Yoshida, et al., Applied Physics Letters 100, 263902 (2012).

# The need for absorption and/or relaxation in an IBSC



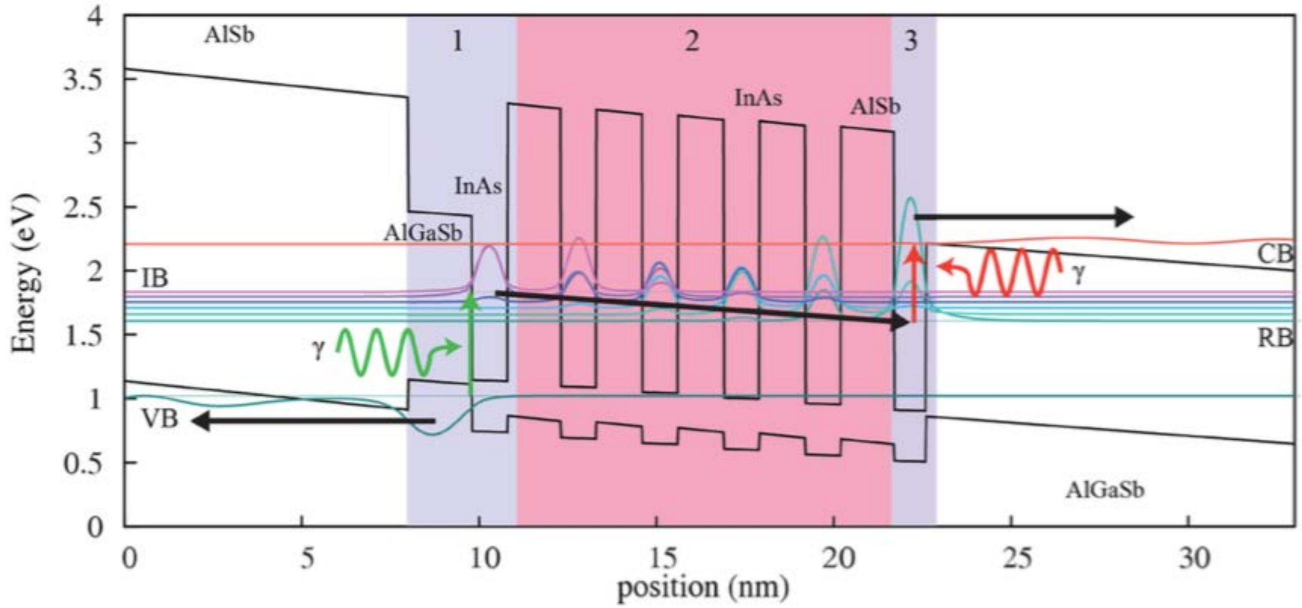




Pusch, A. et al., Progress in Photovoltaics, 24(5), pp.656 (2016).

# Examples of two ratchet types:

## Spatial Ratchet

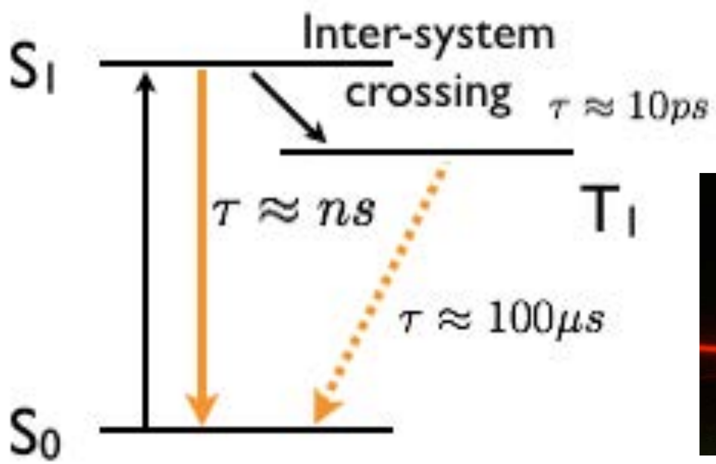


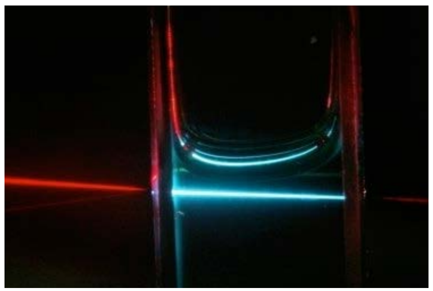

O.J. Curtin, et al., Photovoltaics, IEEE - JPV 6(3), p.673 (2016).

T. Kada, et al., Phys. Rev. B, 91(20), p.201303. (2015)

M.Sugiyama et al., IEEE- JPV, 2(3) p298 (2012)

## Spin Ratchet

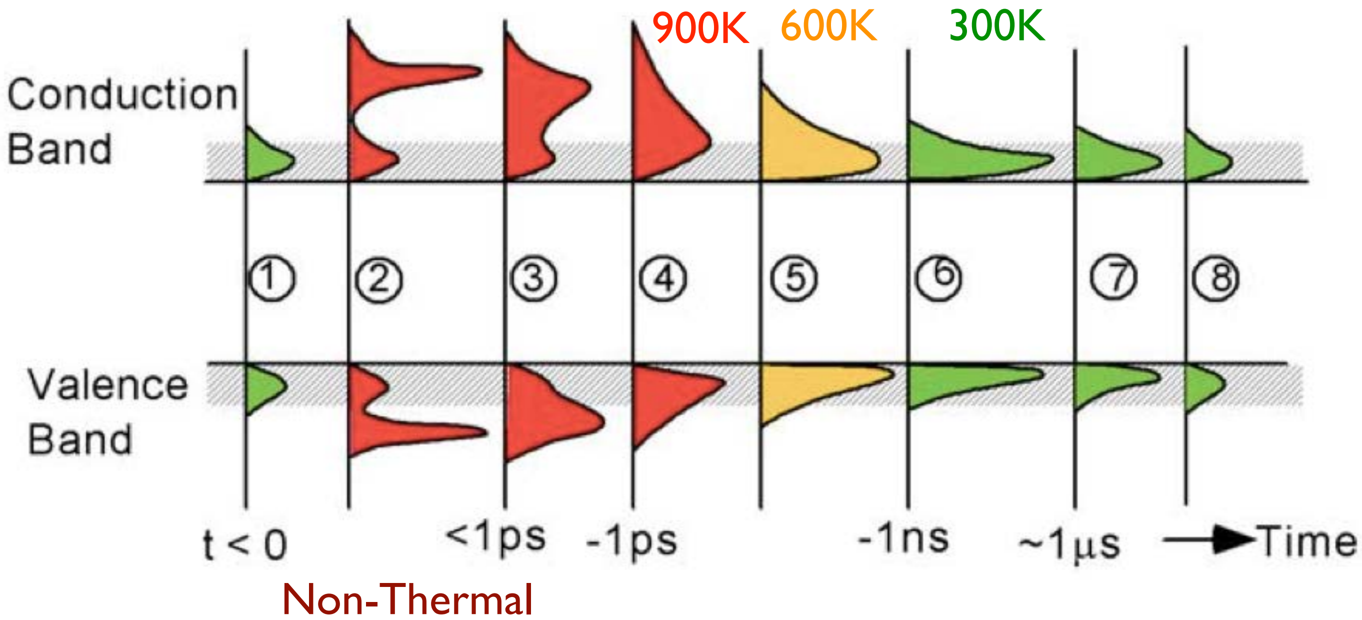


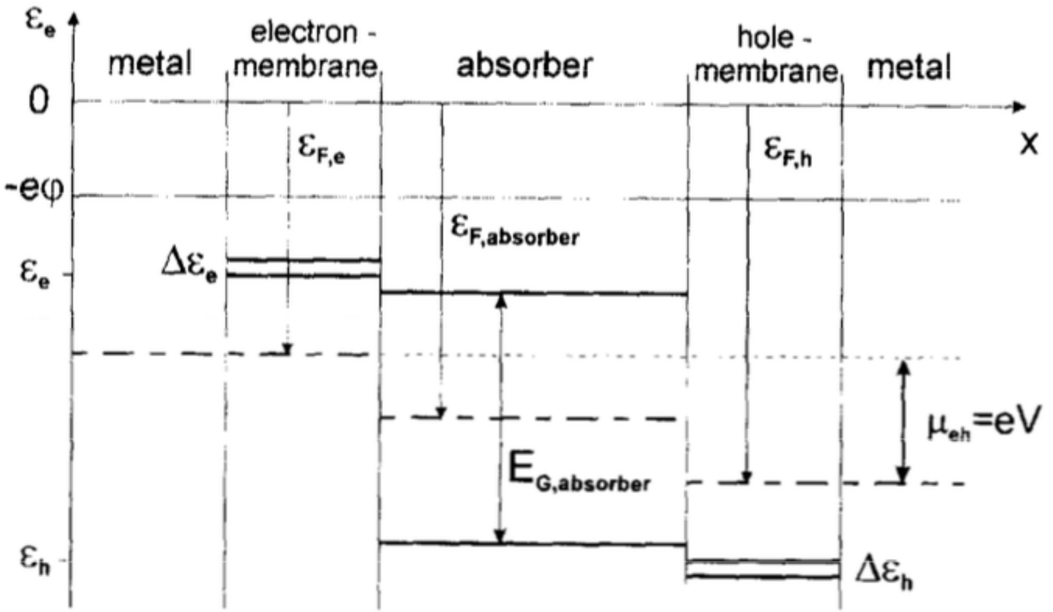
P. Olsson et al., Phys.Rev.Lett 102(22), 227204 (2009)

T.F. Schulze, & T.W. Schmidt, Energy Environ. Sci., 8, 103 (2015)

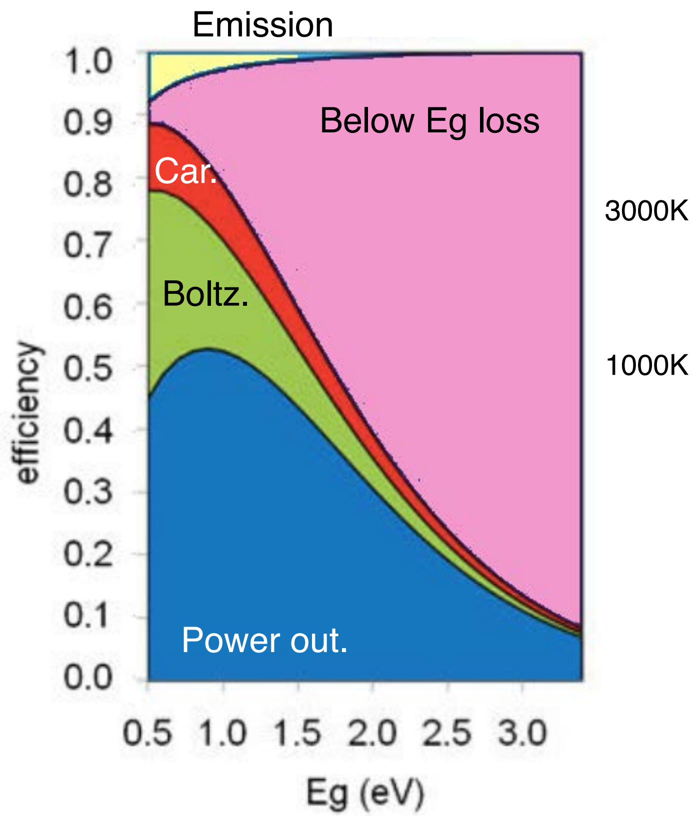
# Hot Carrier Solar Cell




Green, M.A., Third Generation Photovoltaics, Springer 2003

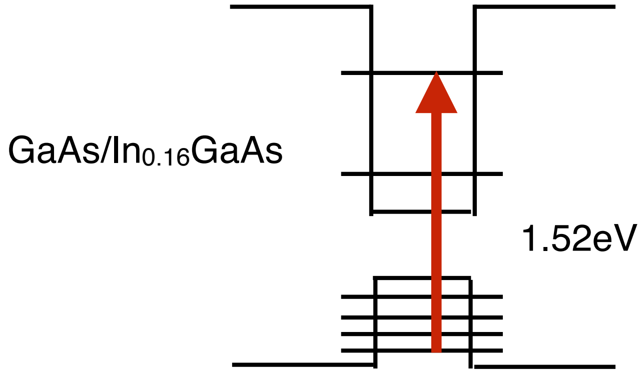


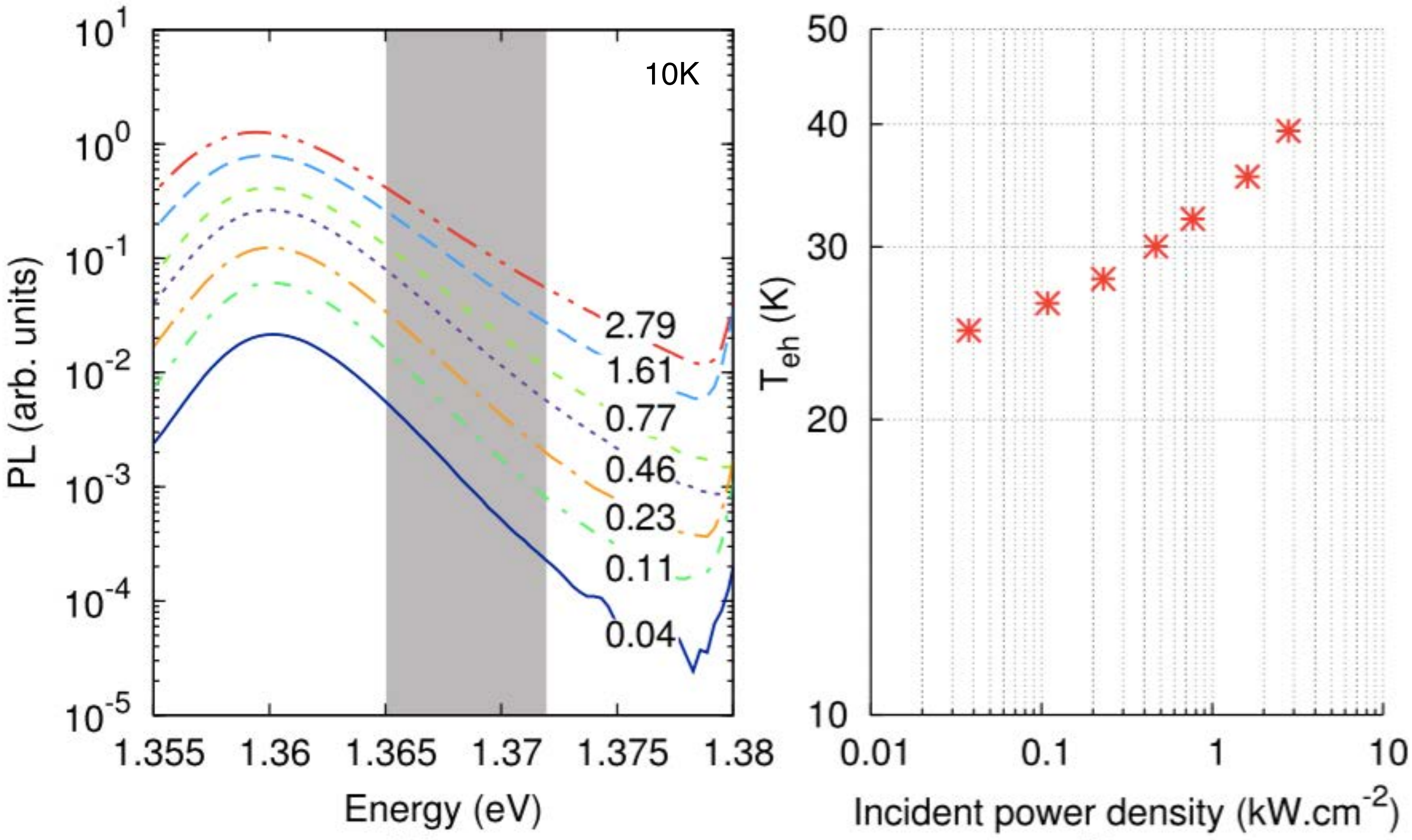

Wurfel, P., *Solar Energy Materials And Solar Cells*, 46(1), pp.43–52. (1997)




Hirst, L.C. et al.,. Proc. 37th IEEE Photovoltaic Specalists Conf.. p. 3302. (2011)

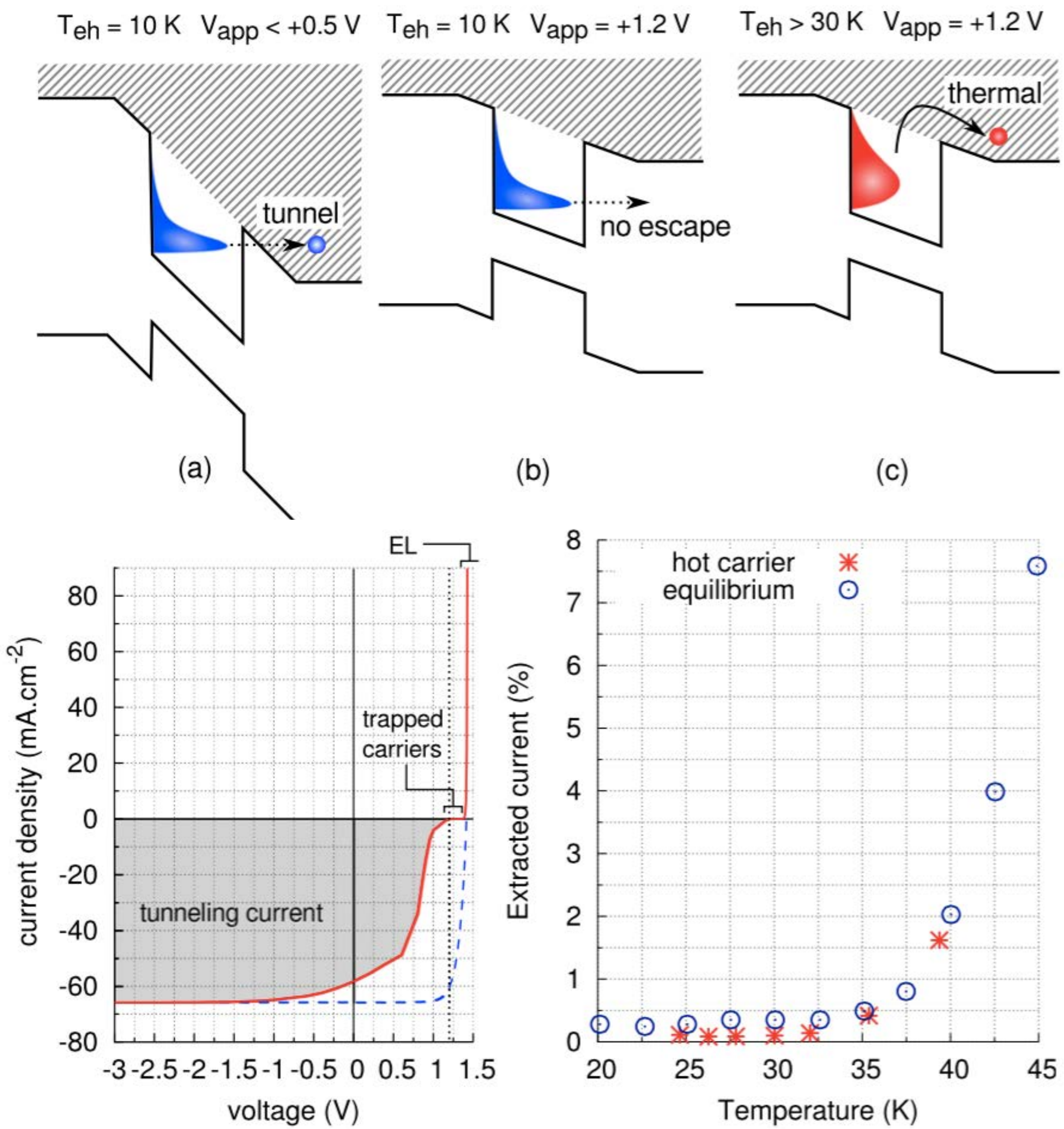
# QW Hot-Carrier PV Cell



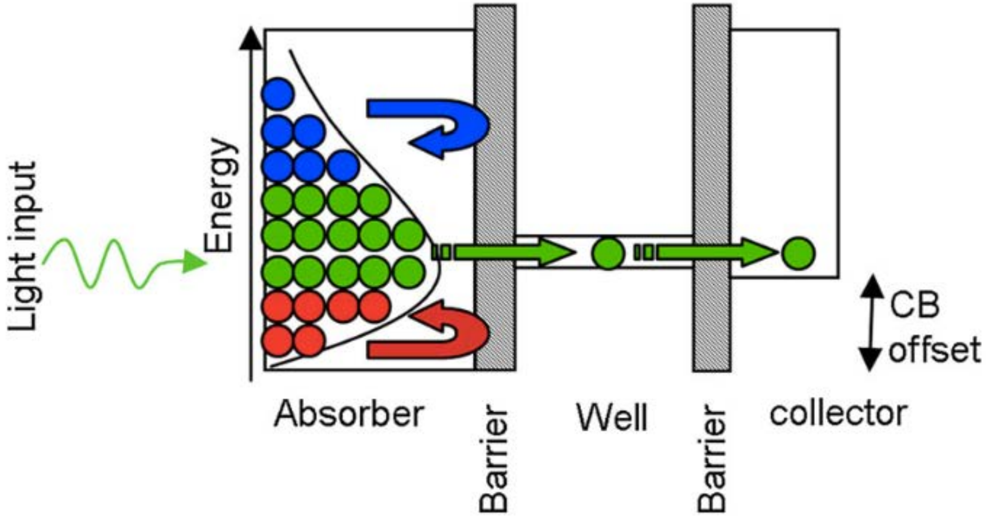

Hirst, L.C. et al. *Applied Physics Letters*, 104(23), p.231115. (2014)

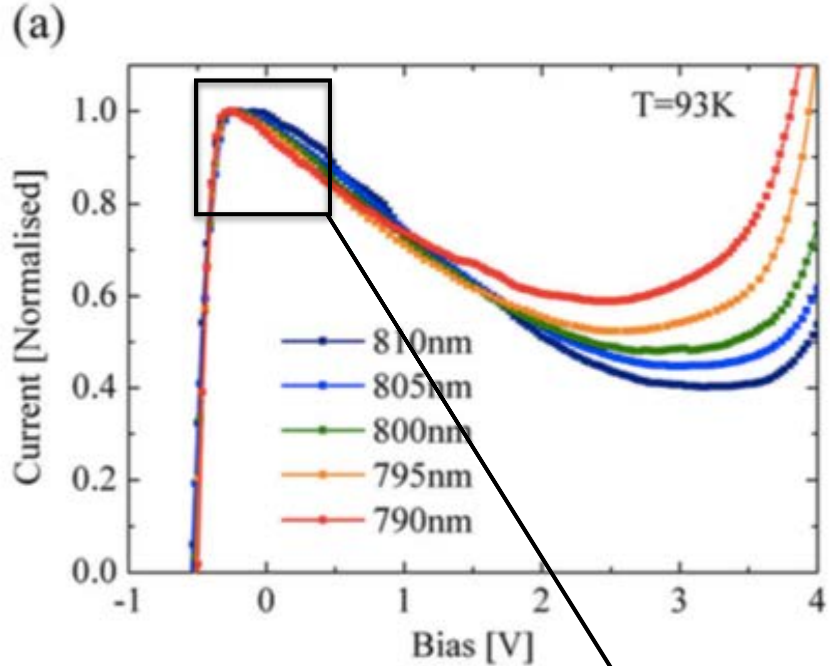
# QW Hot-Carrier PV Cell

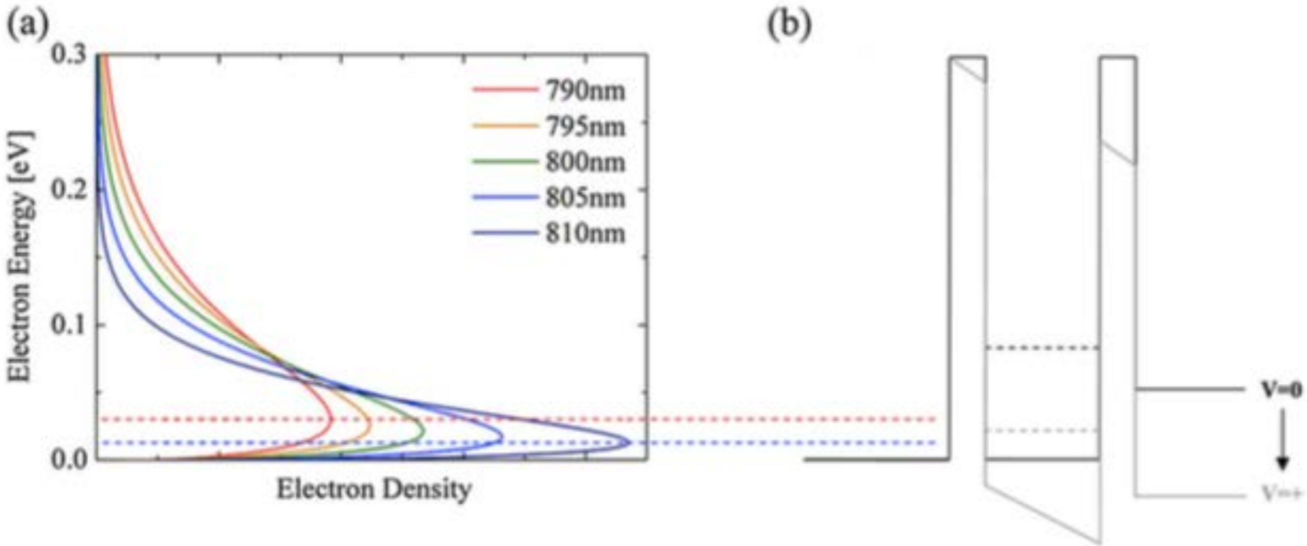


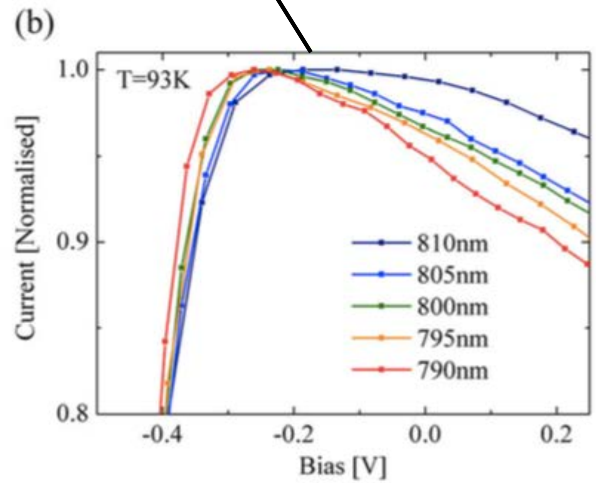

Hirst, L.C. et al. *Applied Physics Letters*, 104(23), p.231115. (2014)

# Resonant Tunnel Hot Carrier Solar Cell



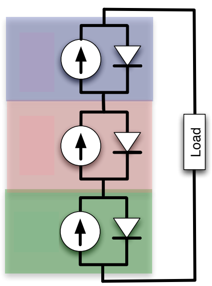



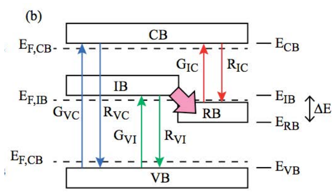

Dimmock, J.A.R. et al., *Progress In Photovoltaics*, 22(2), pp.151–160 (2014).

# Conclusions

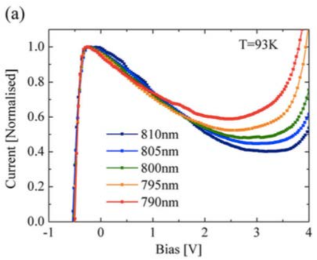



Single junction solar cells now operate close to the Shockley-Queisser limit.

Multi-junction solar cells offer efficiencies >40% today with 50% likely by 2020.




Up-Conversion and the intermediate band solar cell require strong sequential absorption. A carrier relaxation stage to form a 'ratchet' is likely to aid this process.




Hot carrier solar cells have been demonstrated, under intense, monochromatic illumination at cryogenic temperature.

EPSRC Engineering and Physical Sciences Research Council
esa
THE ROYAL SOCIETY
Royal Commission Exhibition of 1851