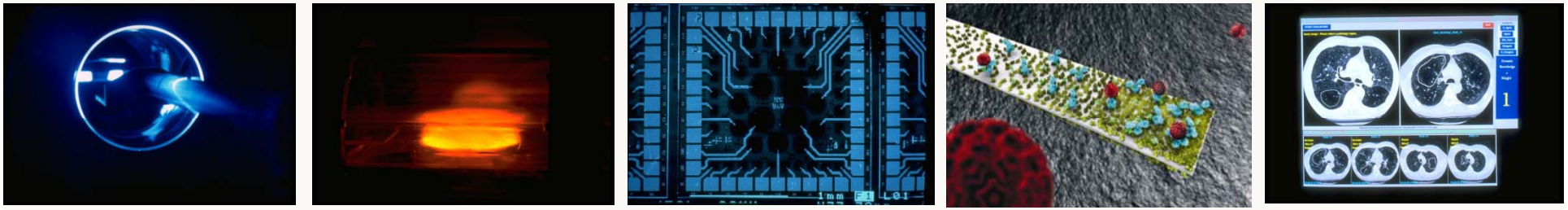

PURDUE UNIVERSITY

School of Electrical and Computer Engineering

# Theoretical Efficiency of Solar Cells at Very High Temperatures


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**Acknowledgements**

John Wilcox (Purdue) Howard Branz (ARPA-E)

# Objective

Predict the efficiency of a single junction solar cell operating at very high temperatures

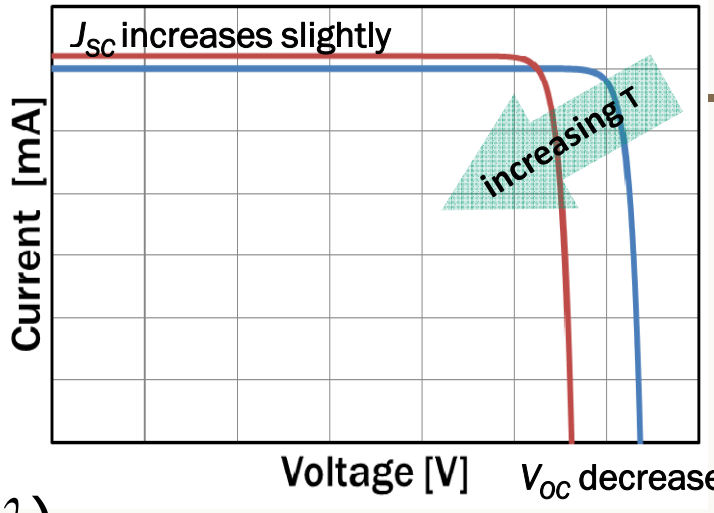
- 25 °C to 800 °C (298 K to 1073 K)
- Find the semiconductor band gap ($E_G$) that generates the highest efficiency at a given T
- Include effects of
  - Radiative Recombination
  - Auger Recombination
  - SHR (single level trap) Recombination (upper bound)

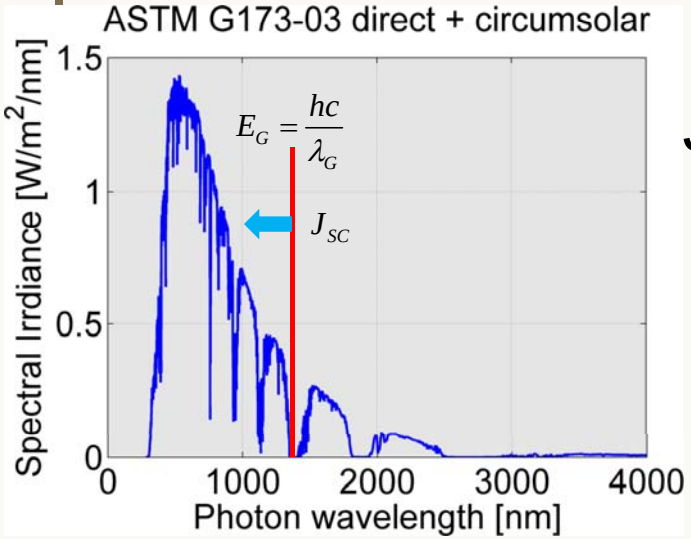


# Basic Principles

$$\eta = \frac{P_{out}}{P_{in}} = \frac{FFV_{OC}J_{SC}}{X \times P_{in}\left(1\,Sun \square 100mW/cm^2\right)}$$

Solar conc. (Suns)



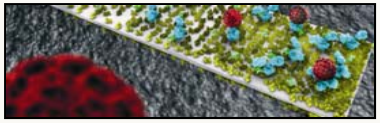
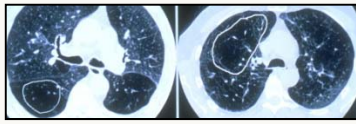

$$J_{SC} = q\int_{\lambda_G}^{0} \frac{\Phi(\lambda)}{hc/\lambda}\,d\lambda$$

$$V_{OC}(T) = \frac{nkT}{q}\ln\left(\frac{J_{SC}(T)}{J_O(T)} + 1\right)$$

$$FF = \frac{qV_{OC} - nkT\ln\left(qV_{OC}/nkT + 0.72\right)}{qV_{OC} + nkT}$$





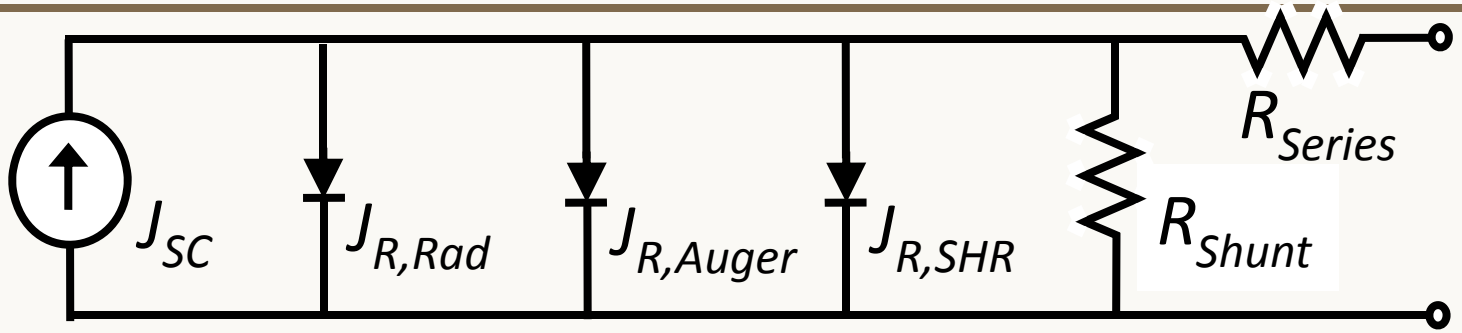




# Basic Principles - Summary

- The bandgap decreases with temperature
  - Open-circuit voltage decreases with temperature (through increase in dark current) by about - 2mV/K
  - Fill factor (FF) decreases with temperature
  - Short-circuit current increases slightly with temperature
- Efficiency projections provided here will be as a function of the operating temperature bandgap, and ***not*** converted to a room temperature bandgap



# Approach – diode model



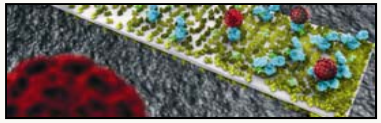
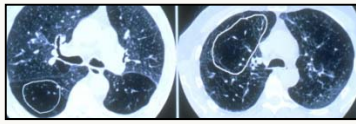

$$J = J_{SC} - J_{R,Rad} - J_{R,Auger} - J_{R,SHR} - \frac{V + JR_{Series}}{R_{Shunt}}$$

- Series and shut resistance will be neglected

$$J_R = \sum_{m=Rad,Auger,SHR} J_{O,m}\left(exp\left[\frac{V}{n_m kT}\right] - 1\right)$$





# Approach - $J_O$ T Dependence (high level injection)

- Radiative recombination $n$ =1 (will assume B indep. of T)

$$J_{O,Rad} \propto BT^3 exp\left[\frac{-E_G}{kT}\right]$$

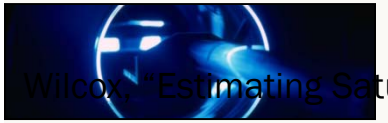
- Auger recombination $n$ =2/3 (will assume C independent of T)

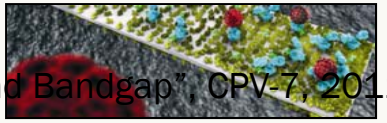
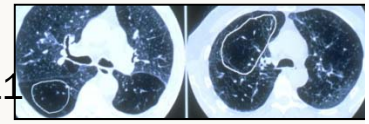
$$J_{O,Auger} \propto \left(C_n + C_p\right)T^{9/2} exp\left[\frac{-E_G}{\frac{2}{3}kT}\right]$$

- SHR and surface recombination $n$ =2 ($\tau \propto v_{th}^{-1} \propto T^{-1/2}$ )

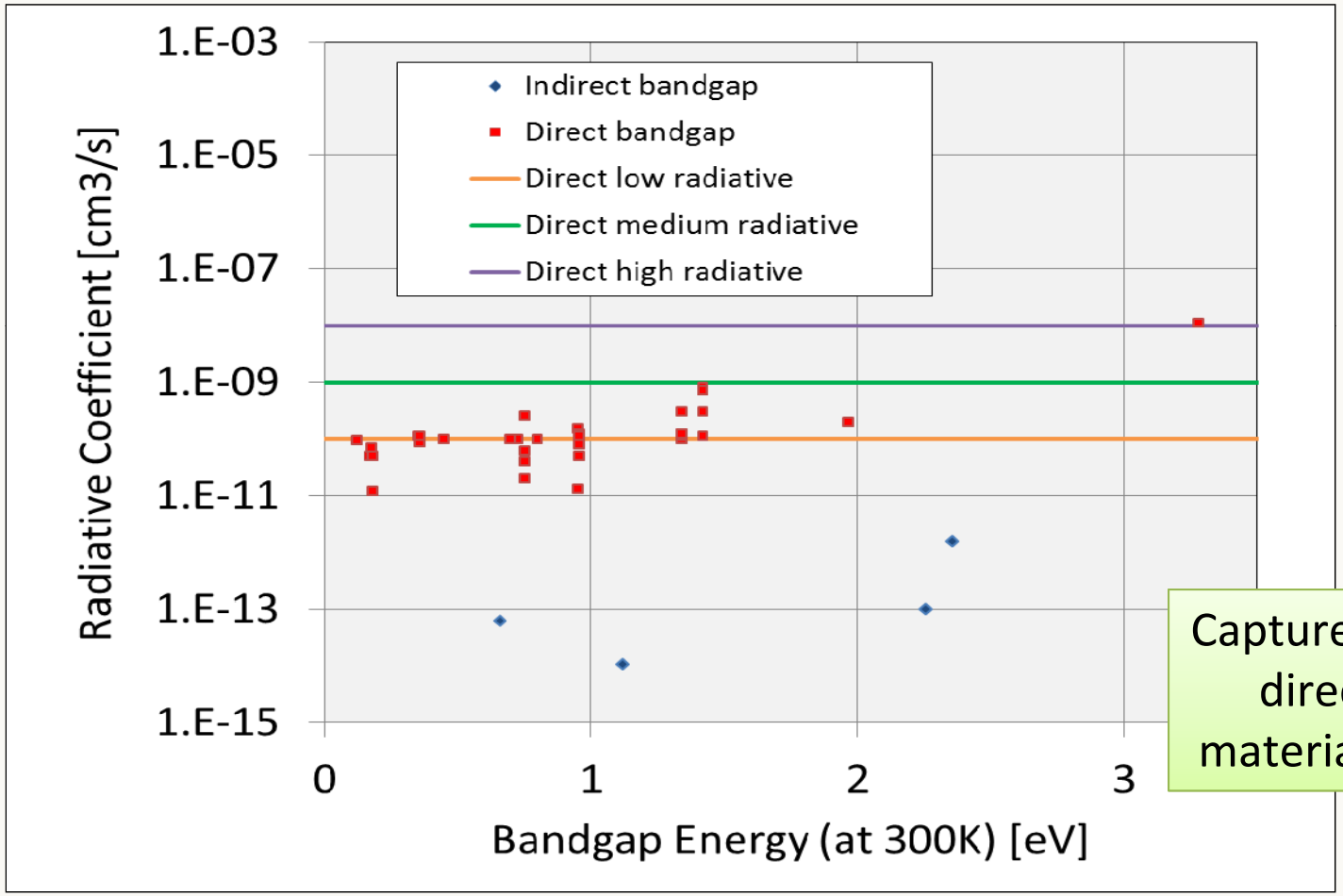
$$J_{O,SHR} \propto \frac{1}{\tau_n + \tau_p} T^{3/2} exp\left[\frac{-E_G}{2kT}\right]$$





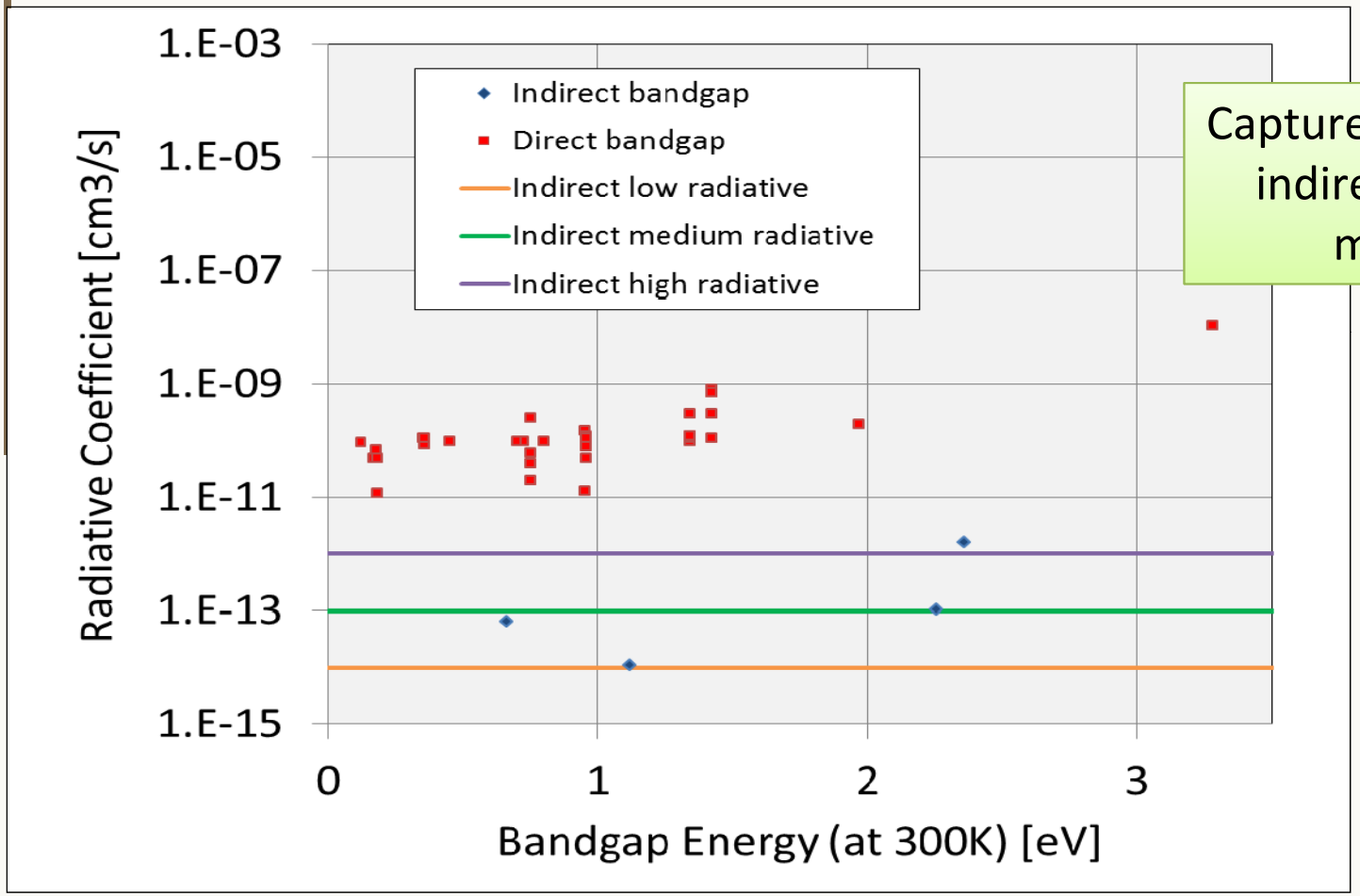
# Approach – Radiative (B) Coefficient




Captures the range of direct bandgap materials above 1 eV



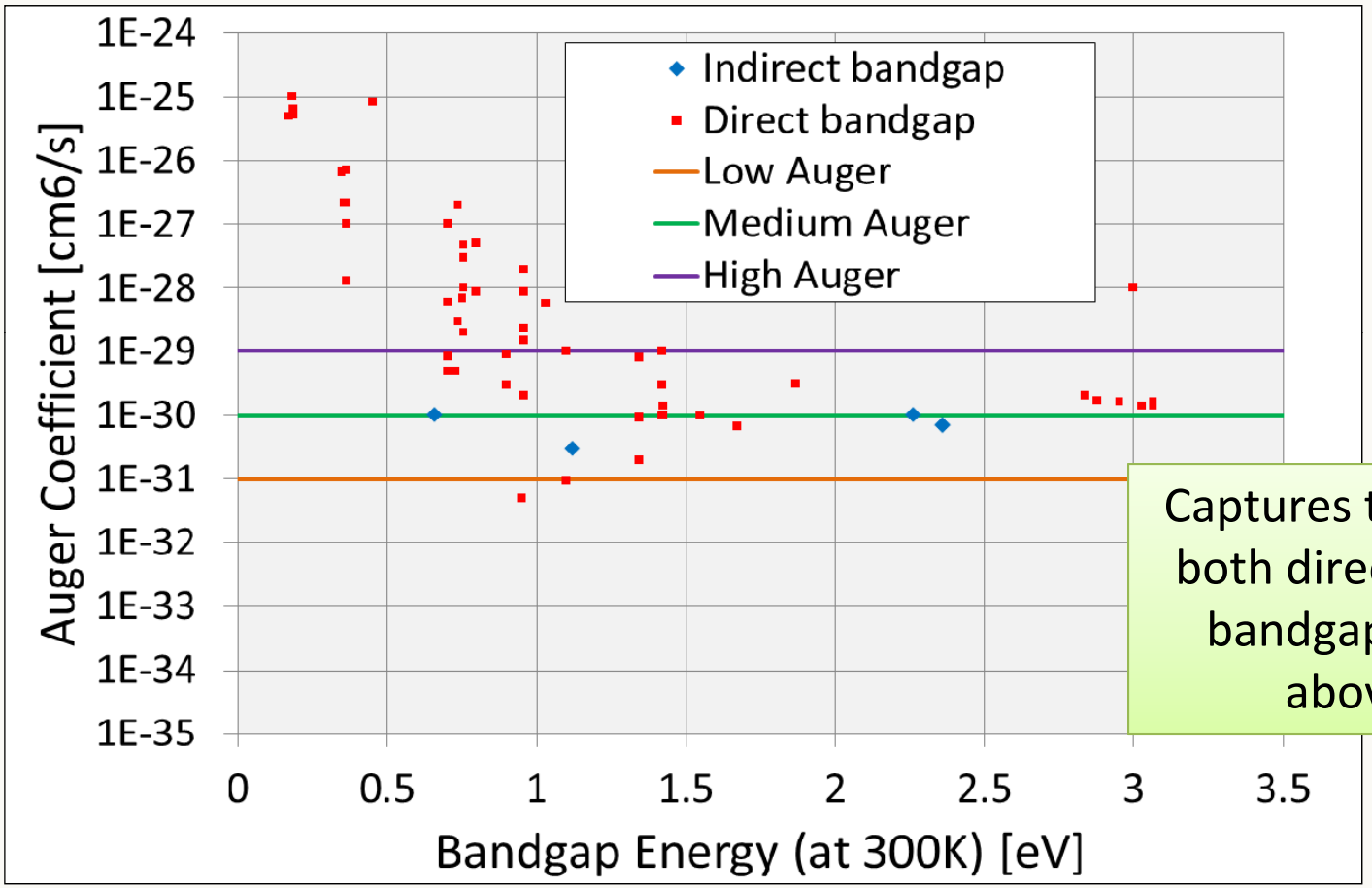
# Approach – Radiative (B) Coefficient




Captures the range of indirect bandgap materials



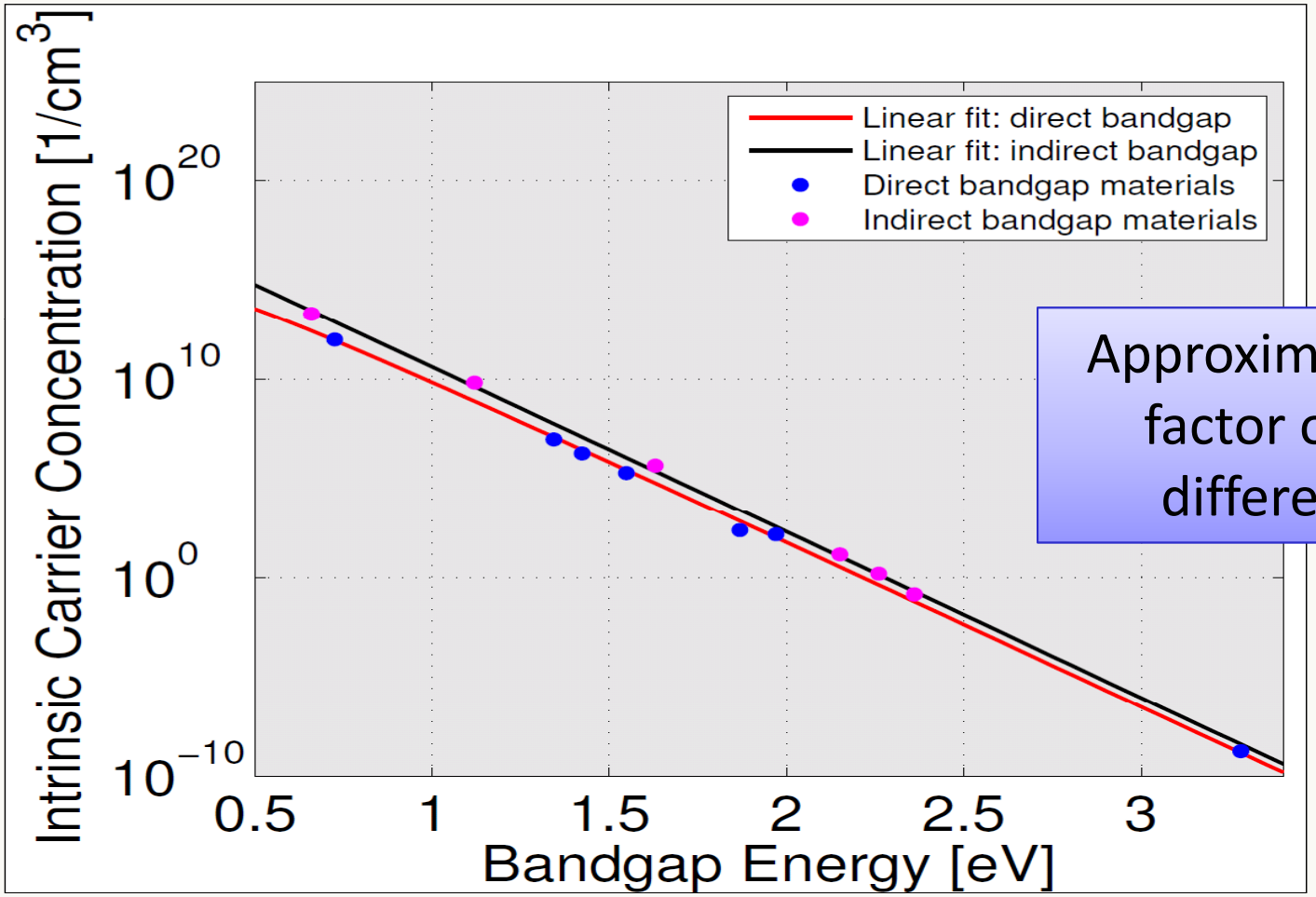
# Approach – Auger (C) Coefficient




Captures the range for both direct & indirect bandgap materials above 1 eV



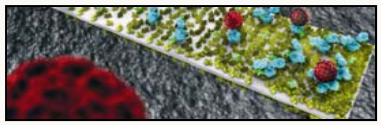
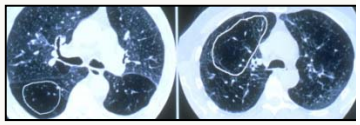
# Approach- Intrinsic Carrier Conc.




Approximately a factor of 10 difference





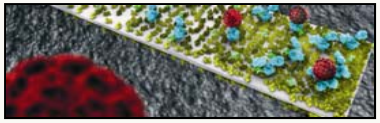
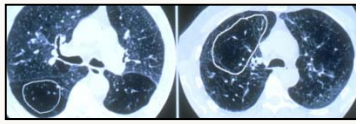




# Results

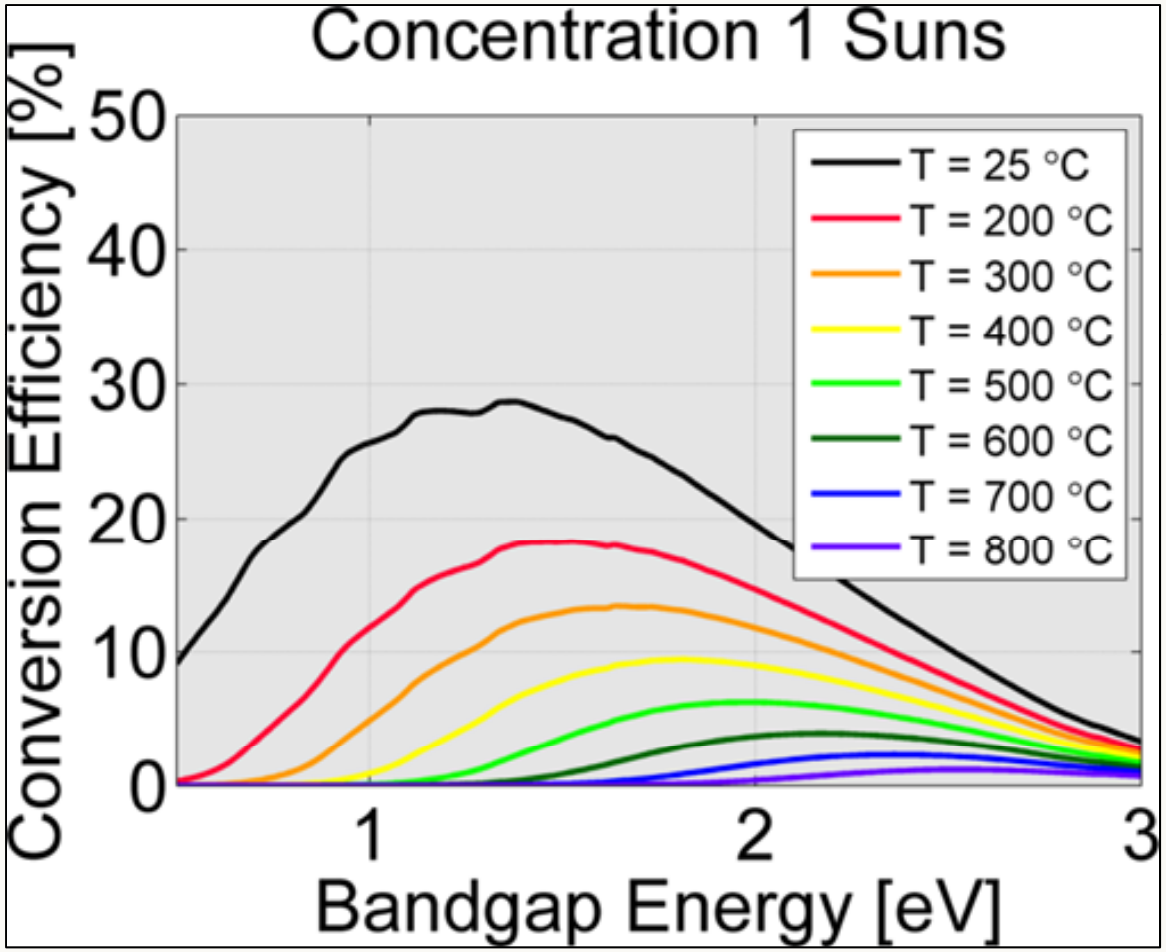
- AM1.5D spectrum
- Use appropriate $n_i(E_G)$ for direct/indirect
- Cell thickness assumption
  - Direct: 1 micron
  - Indirect: 100 microns
  - Confirm that short-base diode approx. holds
- Assume T independent B, C (low, med., high)
  - Use appropriate B range for direct/indirect
  - Use same C range for both direct/indirect
- SHR assumed negligible





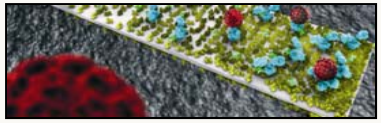
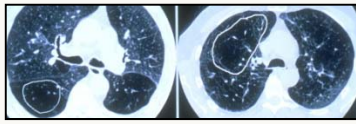
# Results – direct, *hli*, medium B, C





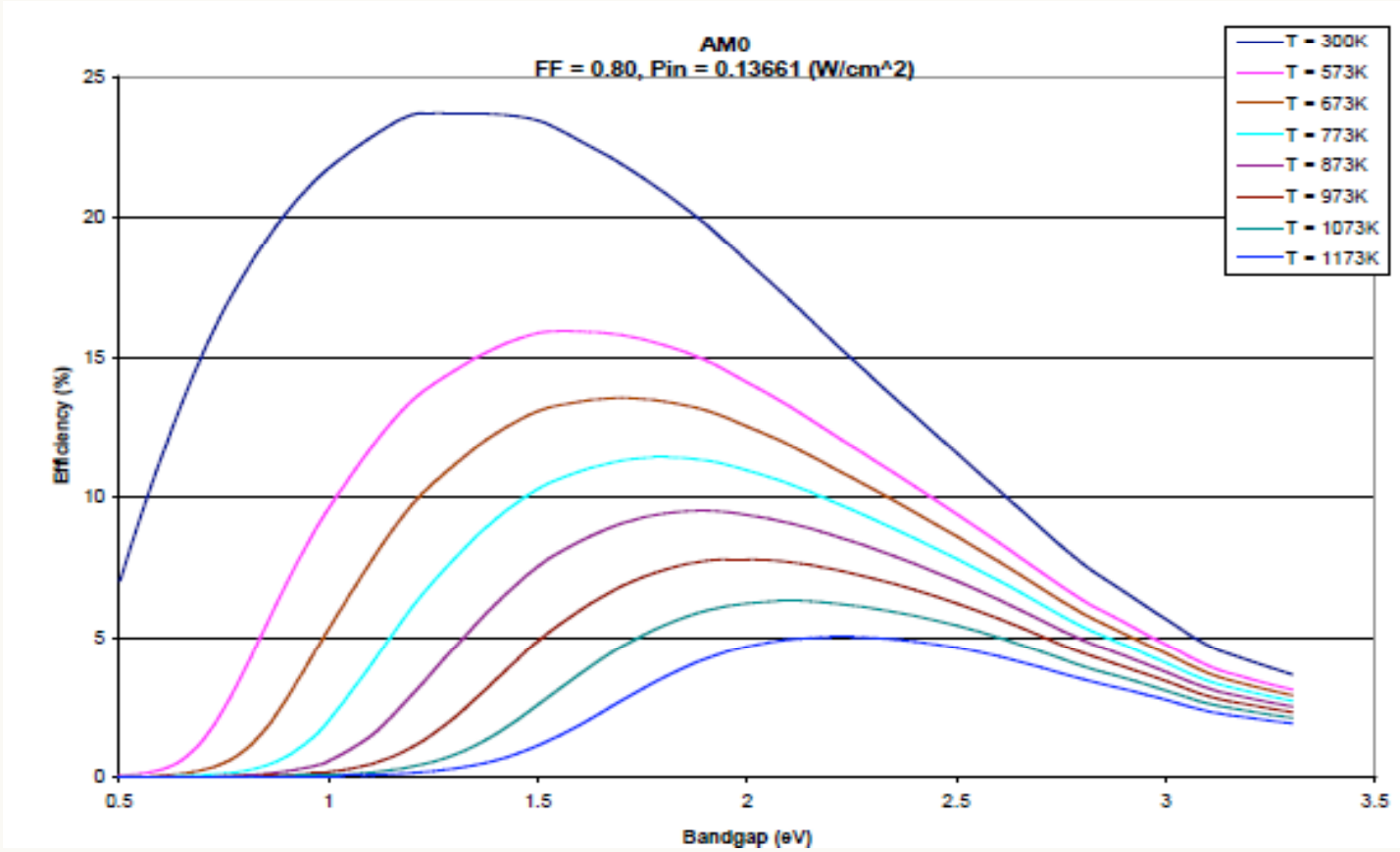




# Compare to Landis Model (NASA)

Landis, “High Temperature Solar Cell Development,” NASA report 2005-213431



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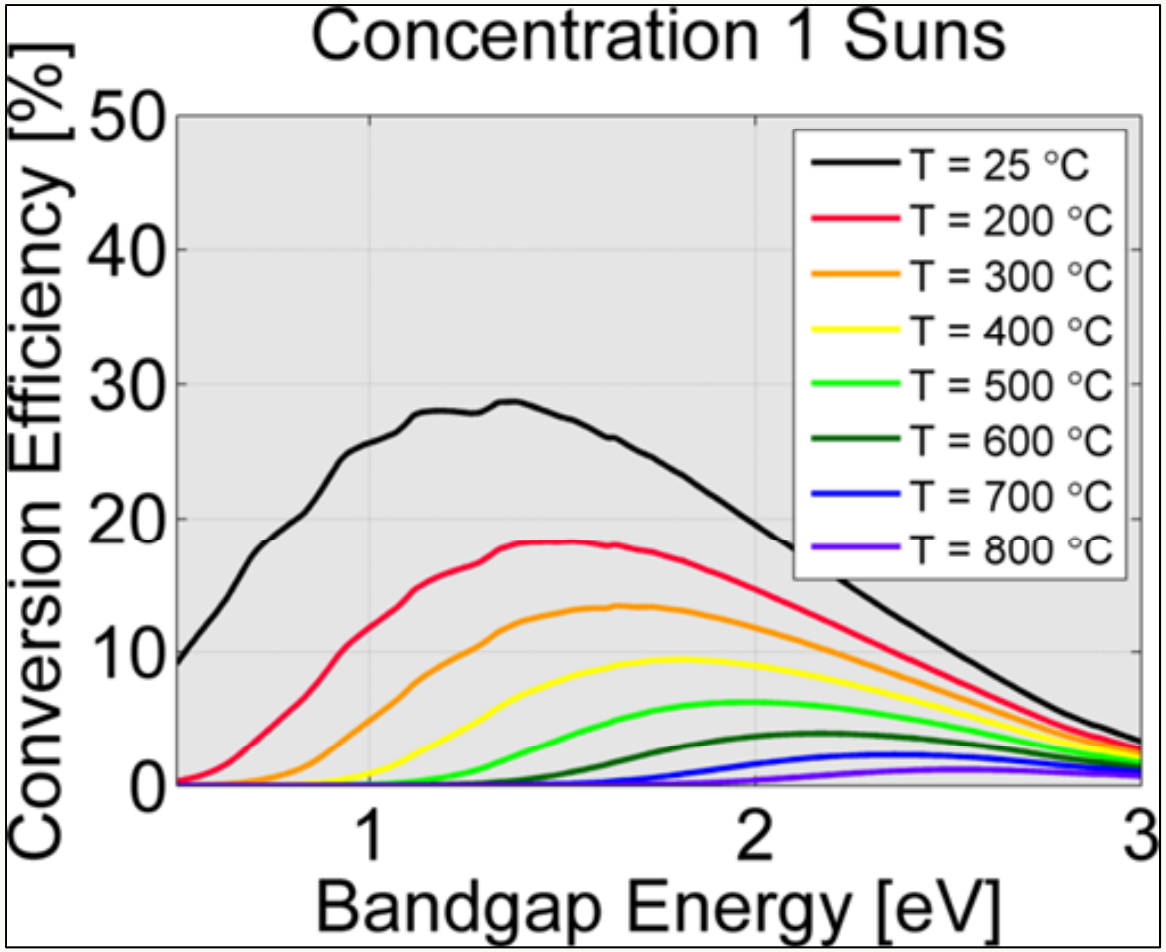







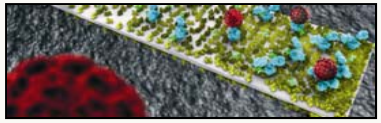
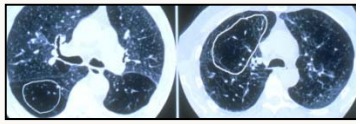

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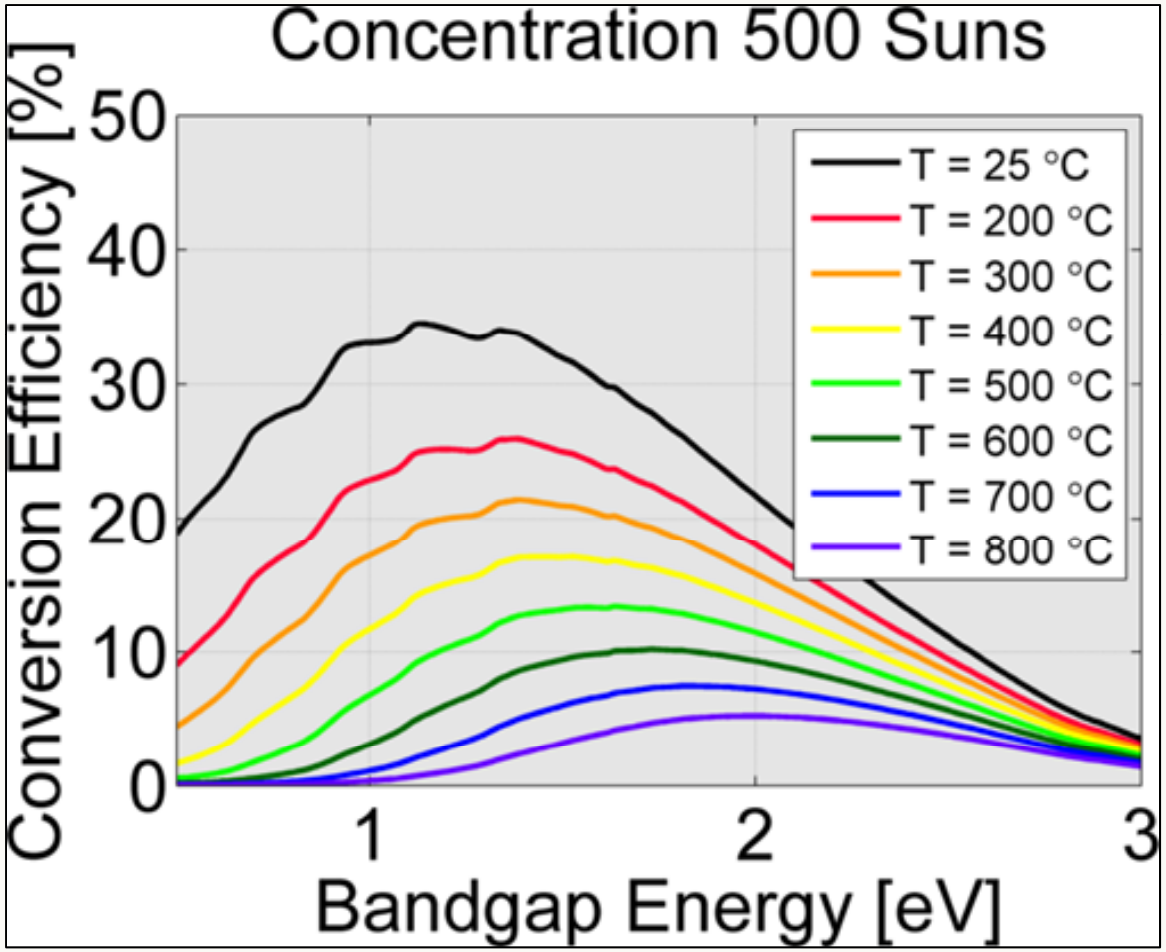







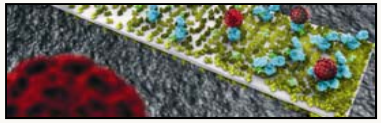
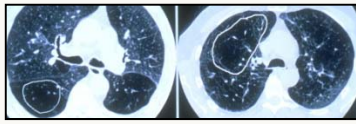

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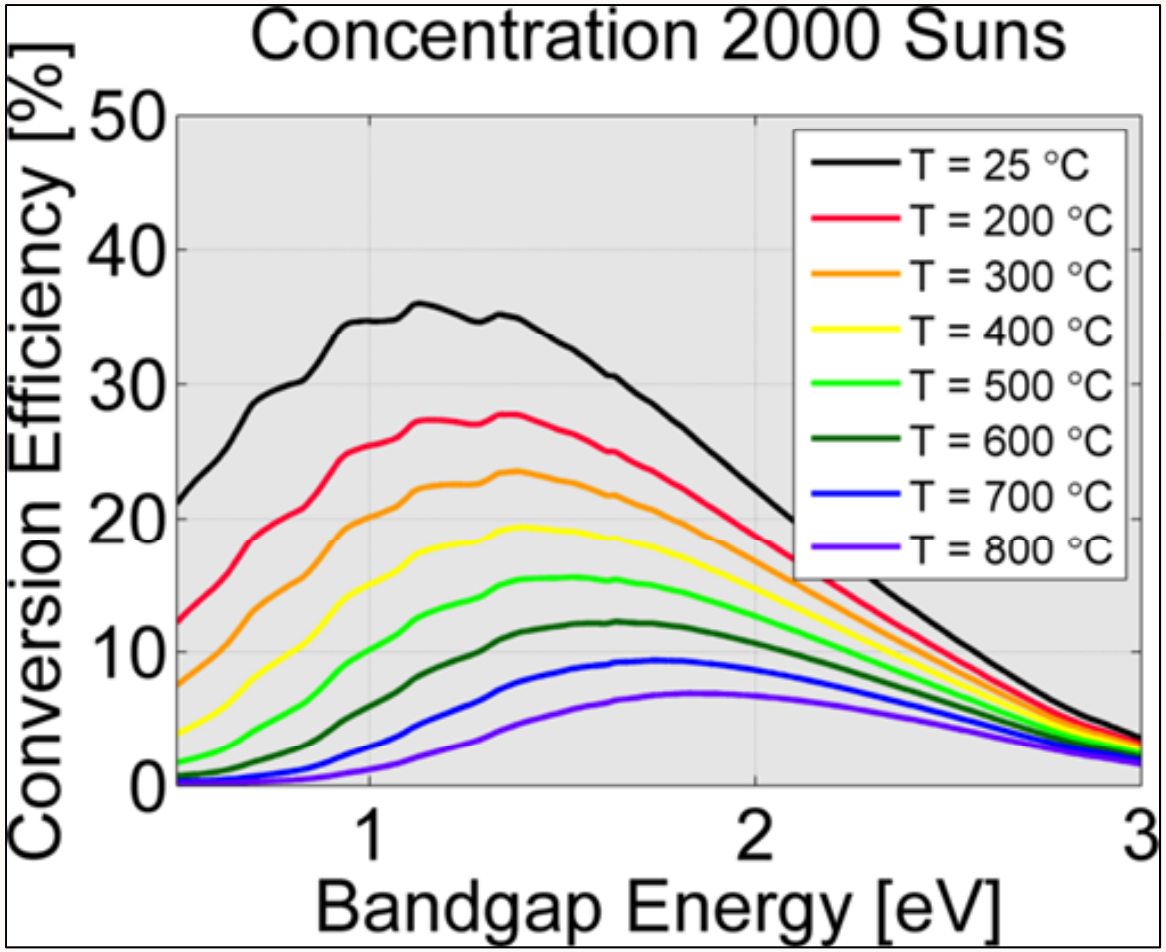
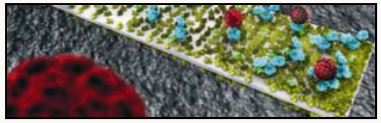
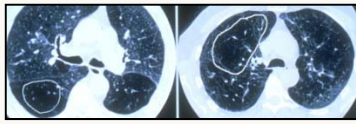


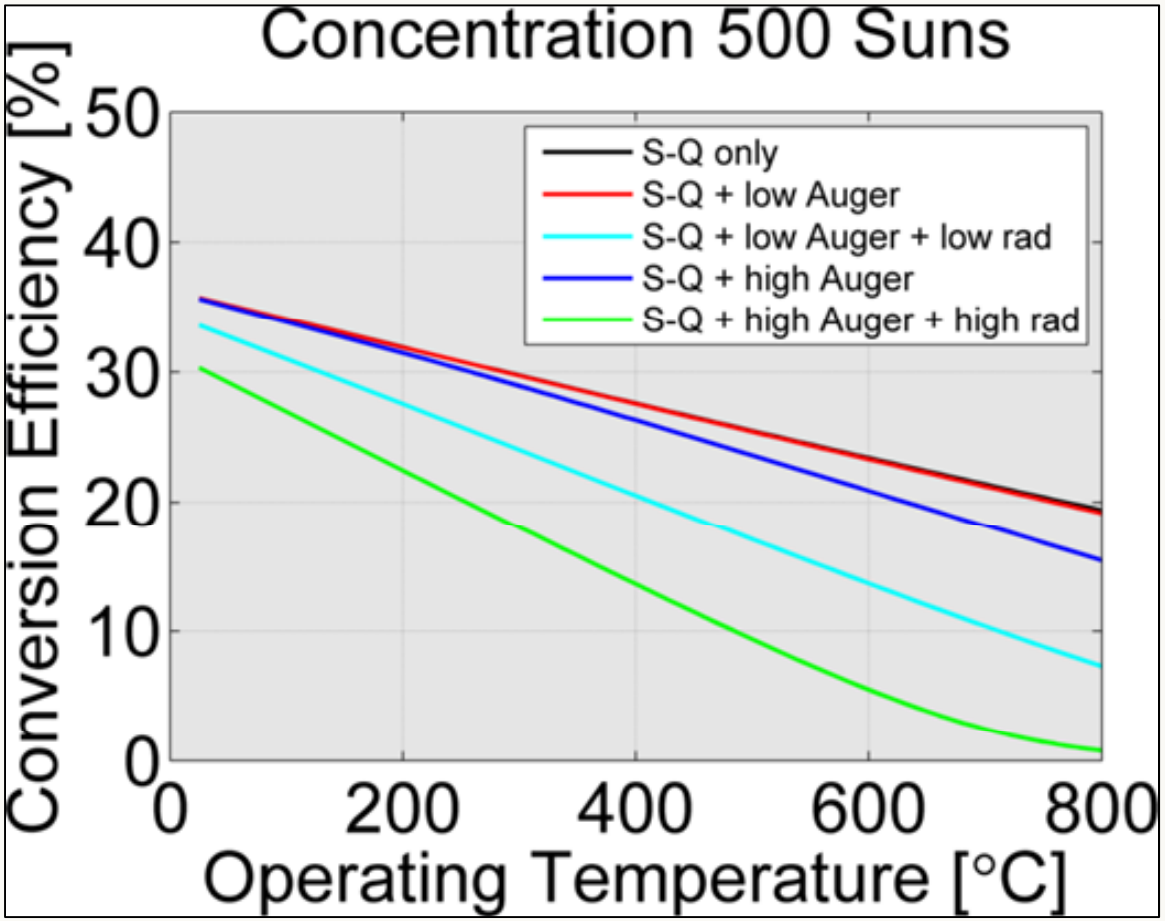






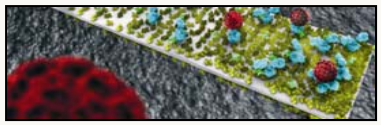
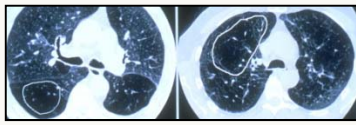
# Results – 1.5 eV bandgap, direct



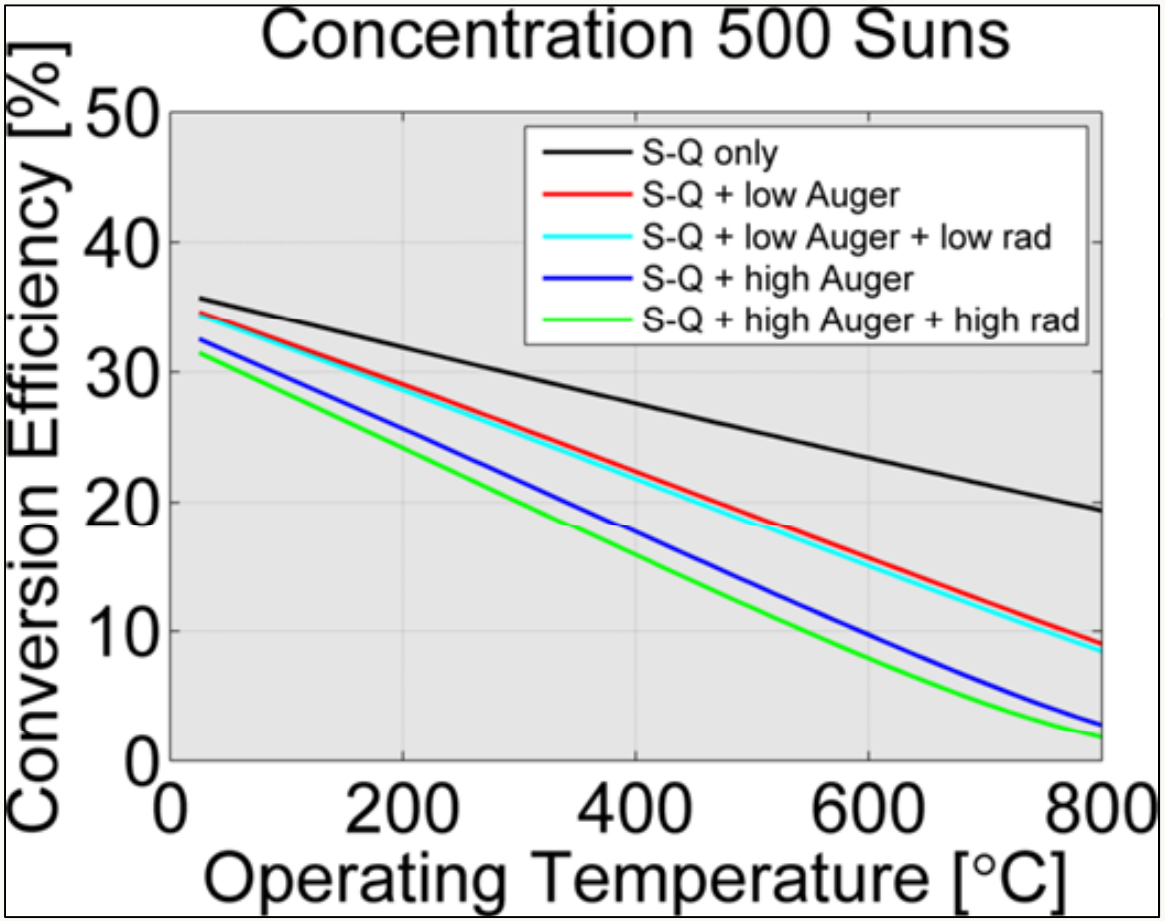






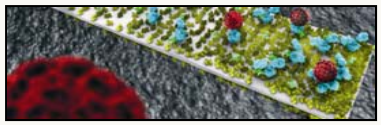
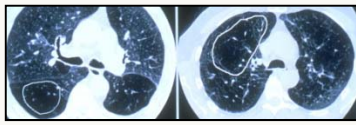
# Results – 1.5 eV bandgap, indirect









# Conclusions

- Optimum bandgap (@ $T_{op}$) increases with temp and decreases with solar concentration
- Solar cell bandgap should be selected based on operating temperature/solar conc.
- Efficiency of direct bandgap cells is mainly limited by radiative recombination
- Efficiency of indirect bandgap cells is mainly limited by Auger recombination
- Rel. few measurements at high T's available



# Thank You

Questions?