Low Temperature Characterization of Space Photovoltaics

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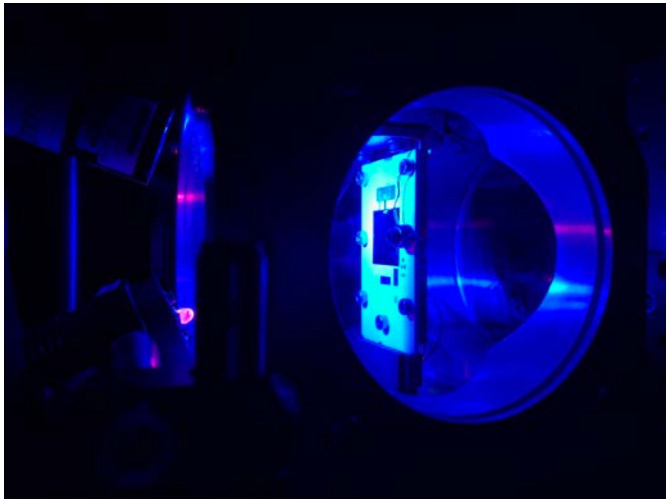
Why Low Temperature Characterization

X-Ray by Measurement

- LIV
  - *Power at lower temperatures for deep space missions such as Juno and when coming out of eclipse in earth based orbits*
- QE
  - *Current mismatch is affected by temperature*
  - *Band edges shift as a function of temperature which in turn affects how much of the solar spectrum is absorbed by each junction*



- Subcell IV
  - *Subcell open circuit voltage*
  - *Subcell diode properties*
  - *Quantify midgap defect energy*
- EL
  - *Identify junction quality*
  - *Identify energy level of defects*
- Hopefully provide more accurate data and develop models to improve on orbit performance of solar cells

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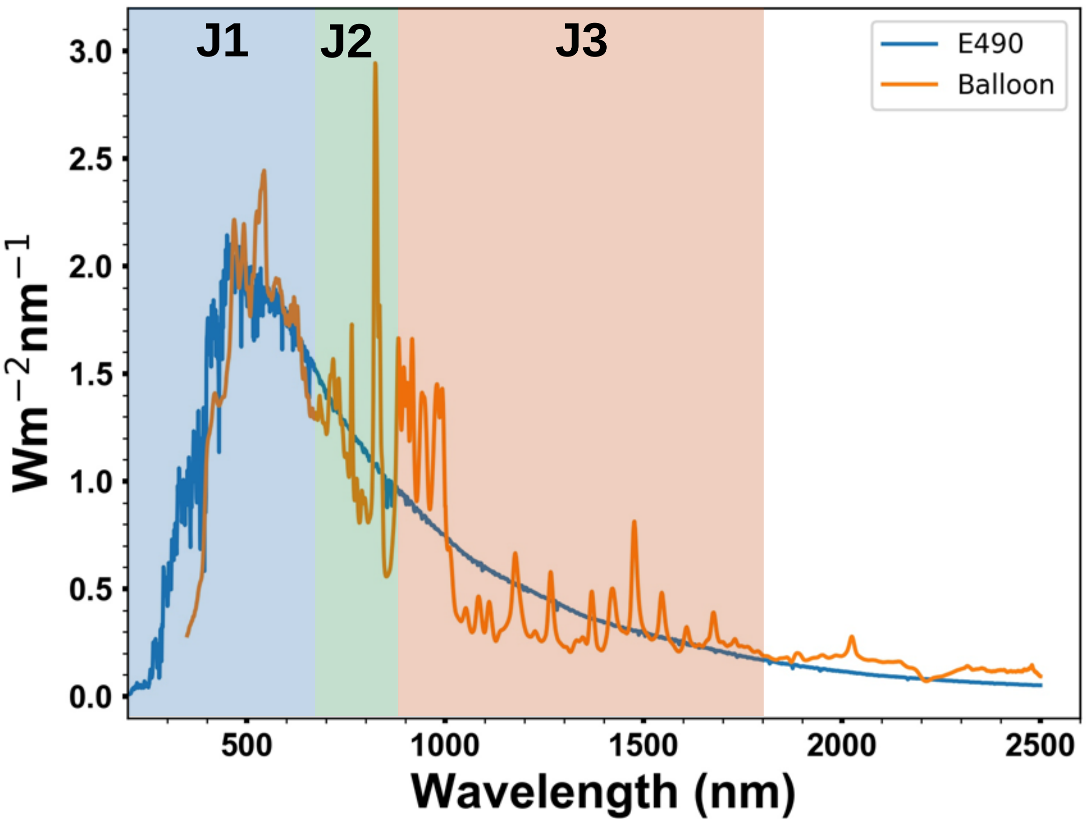
Temperature Dependent LIV

Why Radiometric Calibration

- Standard method: Calibrate simulator using solar cell isotypes of a given technology at 28°C. Next, vary the temperature of the solar cell and measure LIV data
  - *Historically calibration standards of multijunction junction solar cells are made from high altitude flights and their calibration values are set to be at 28C.*
- Problems with Standard method:
  - *The simulator is not a good "Constant". The spectrum of the lab looks very different than AM0*
  - *As the absorption properties of the solar cell change, how much light they see from a simulator changes as well. Because the simulator spectrum is not a good match to AM0 this can introduce error*
- By using radiometric calibration we can alleviate this problem



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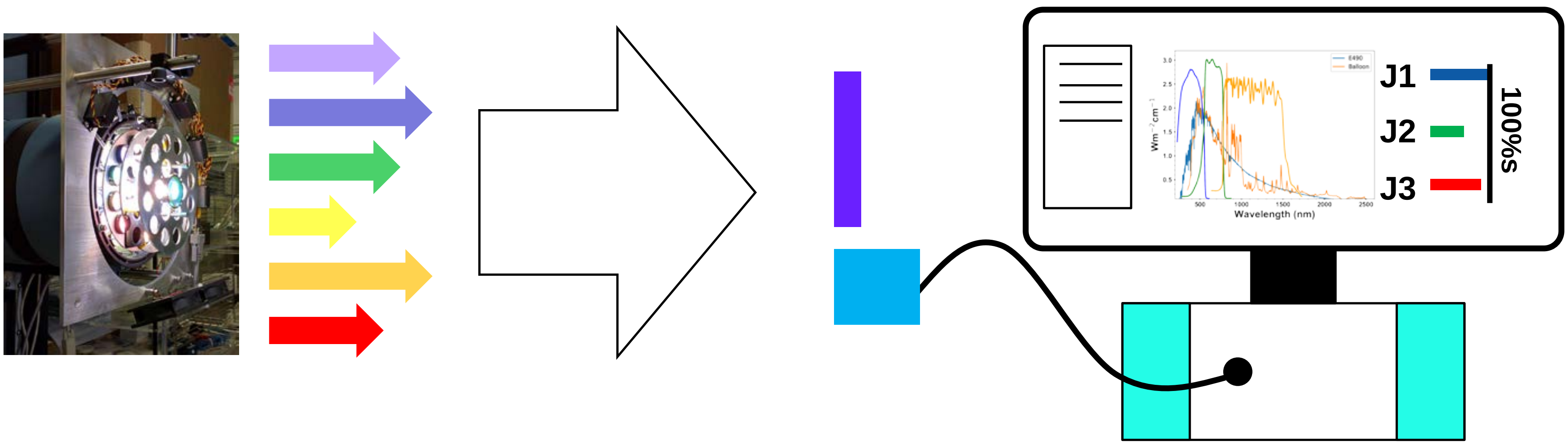
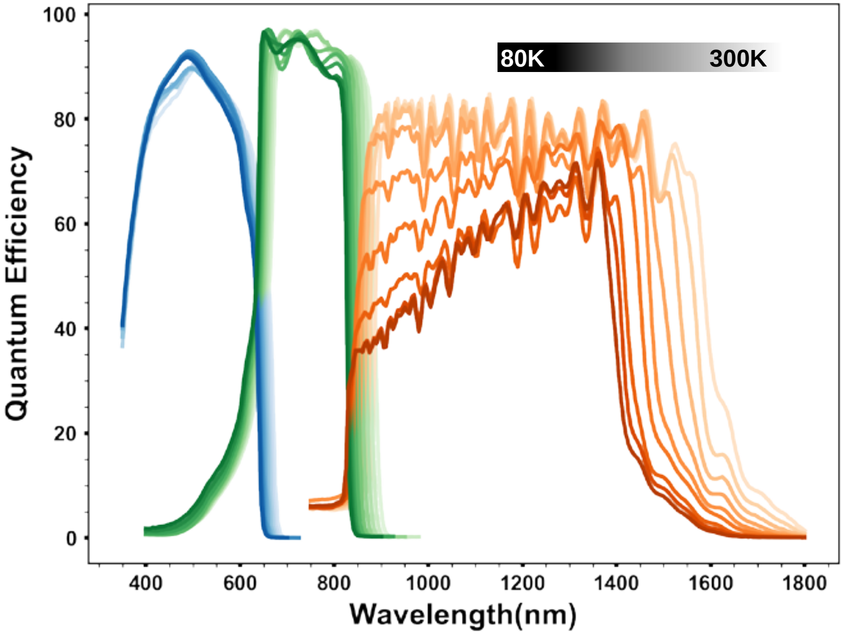
Radiometric Calibration

- Radiometric calibration uses a spectroradiometer to measure the spectrum of the simulator
- Quantum efficiency measurements of monolithic multijunction solar cells are used to tune the spectrum of the simulator instead of isotypes
  - *Effectively mimics isotypes without the need of isotypes*
- A set of filters to tune the color spectrum of the lamp and iris to tune the intensity allow for the ability to tune up to 6 zones on our X-25 solar simulator

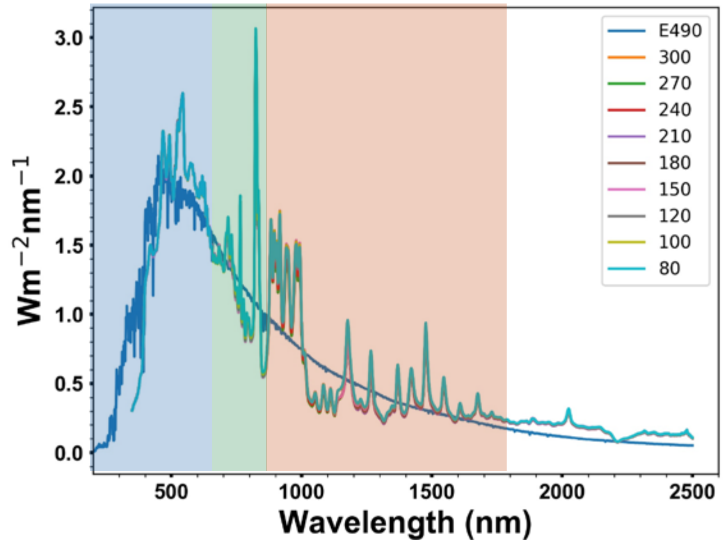


Tuning for Temperatures

Tuning Radiometrically



Radiometric Tuning



- Solar simulator was tuned for each temperature as referenced to E490 AM0
- Results in a different solar simulator spectrum for each temperature

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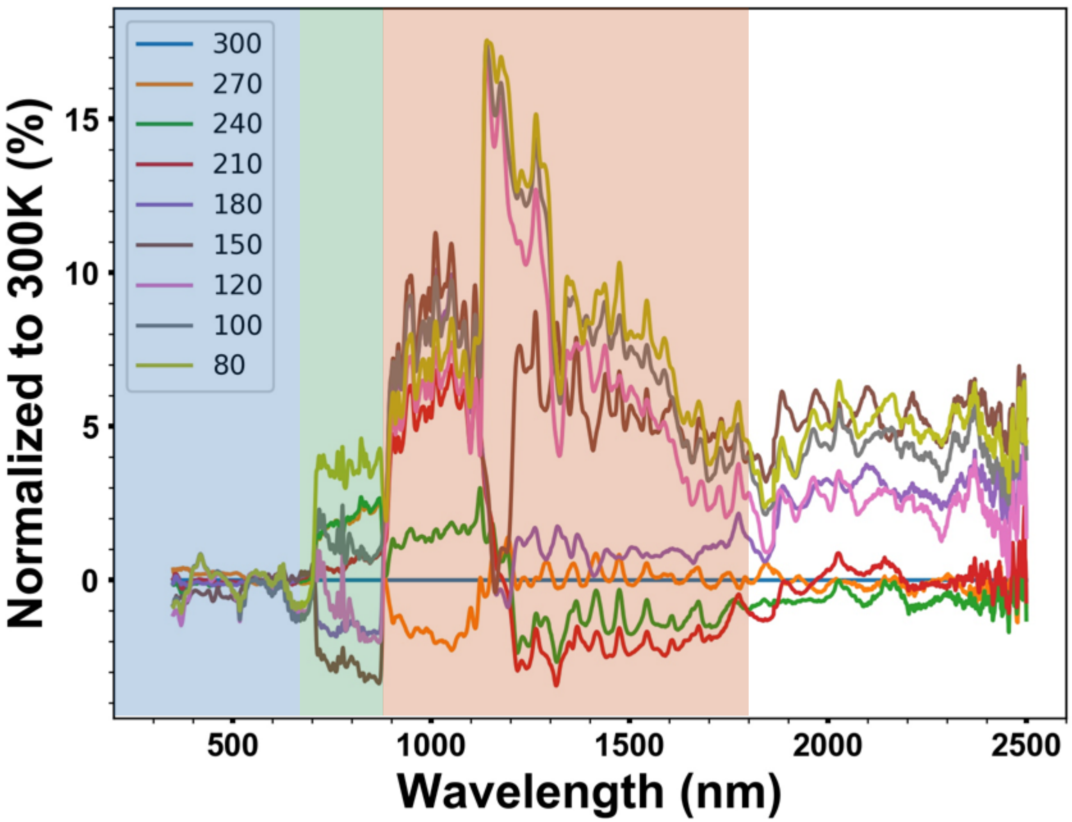
Difference between each Simulator Spectrum



- All simulator spectra were normalized to the 300K tune
- Most of the spectral differences are in the J2 and J3
- Spectrum can be up to 15% off

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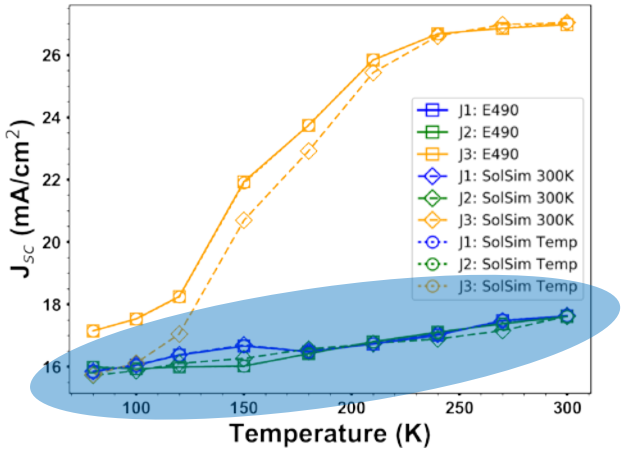
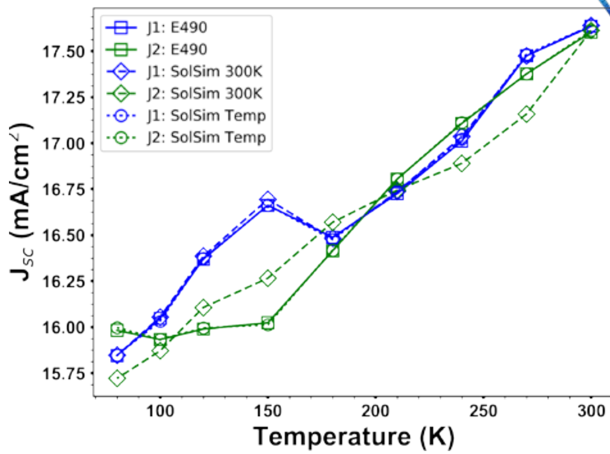
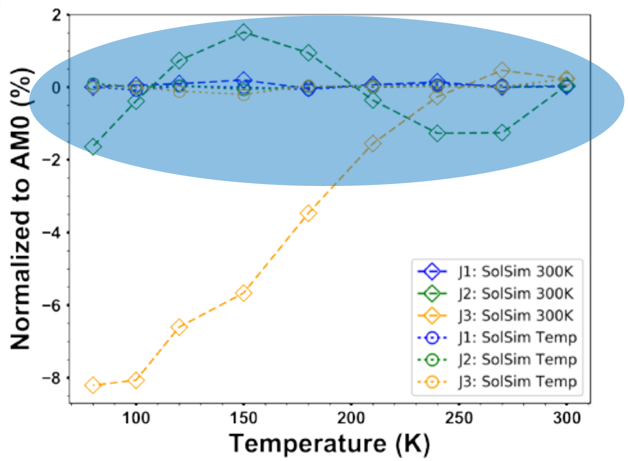
How well does radiometric match AM0?

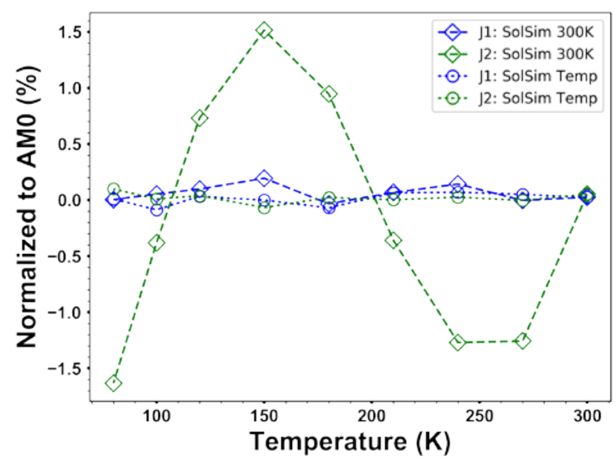
- Pretty well….better than not tuning radiometrically
- Tuning for each temperature allows almost a near perfect match to E490
- If you only tune for one temperature (300K in this case), the cell ends up being J3 limited at 80K
- J1 was a close match to AM0 regardless of method
- This is the case with our simulator and represents potential lab-to-lab differences





Normalized to AM0





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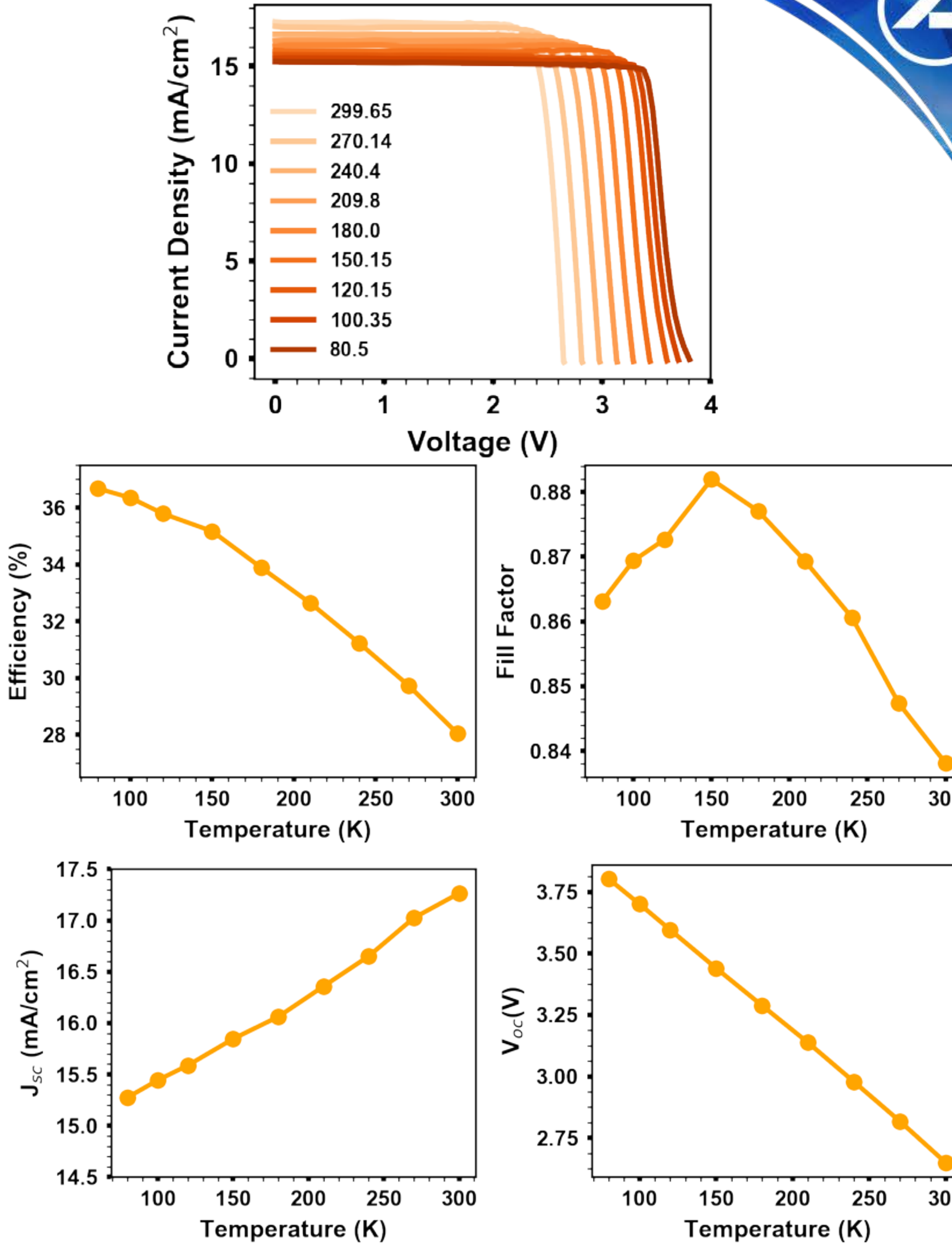
LIV

- Current decreases and voltage increases with decreasing temperatures…as expected

- Fill Factor rises, maxing out at 150K and begins to decrease

- Efficiency reaches a maximum of > 36% at 80K from 28% at 300K



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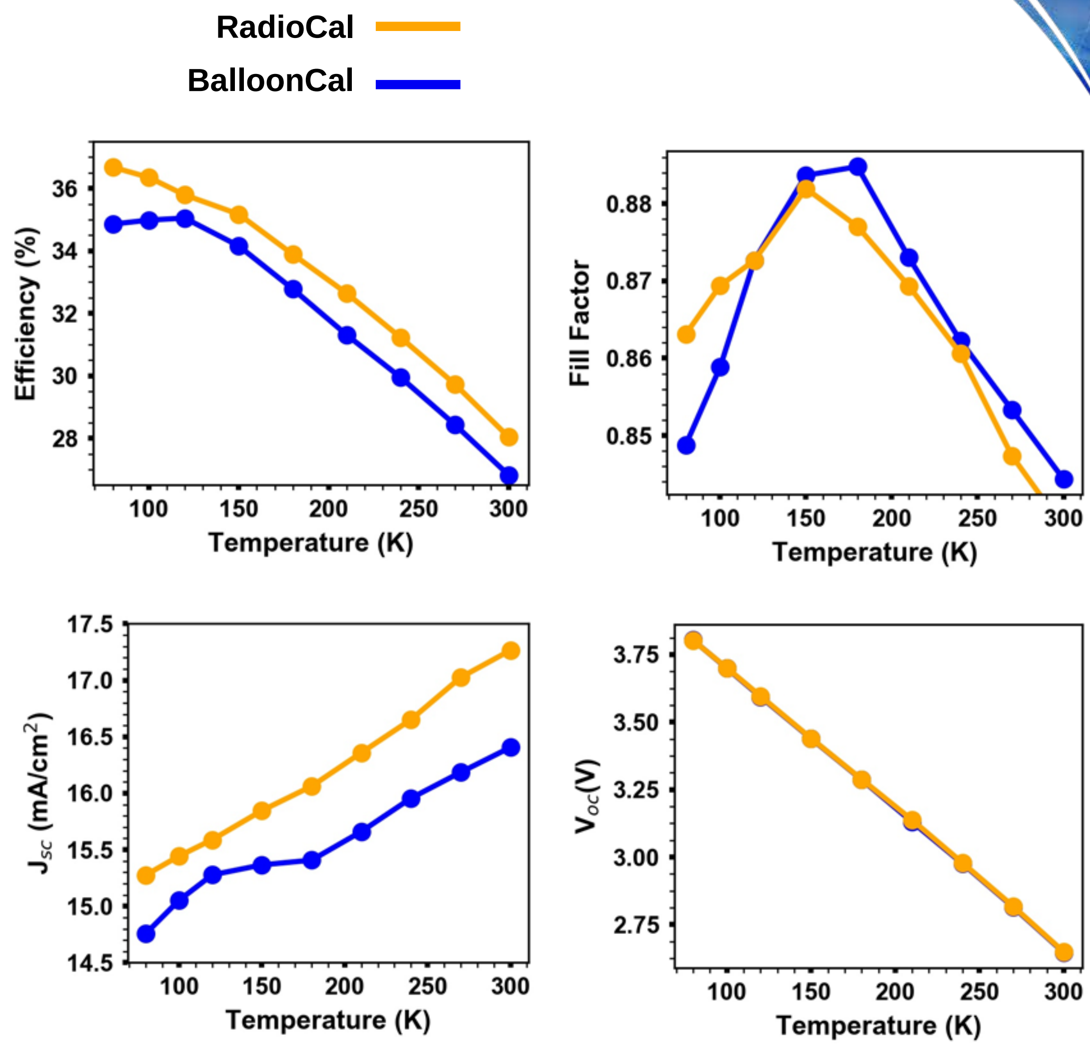
Balloon Calibration vs Radiometric Calibration

- Radiometric tuning allows for an accurate determination of efficiency at lower temperatures
- If we tune using the standard method the efficiency actually goes down at lower temperatures
- Also the short circuit current produced from the standard method and radiometric is very different. The balloon calibration tune yields lower currents
  - *Still investigating the cause for this*



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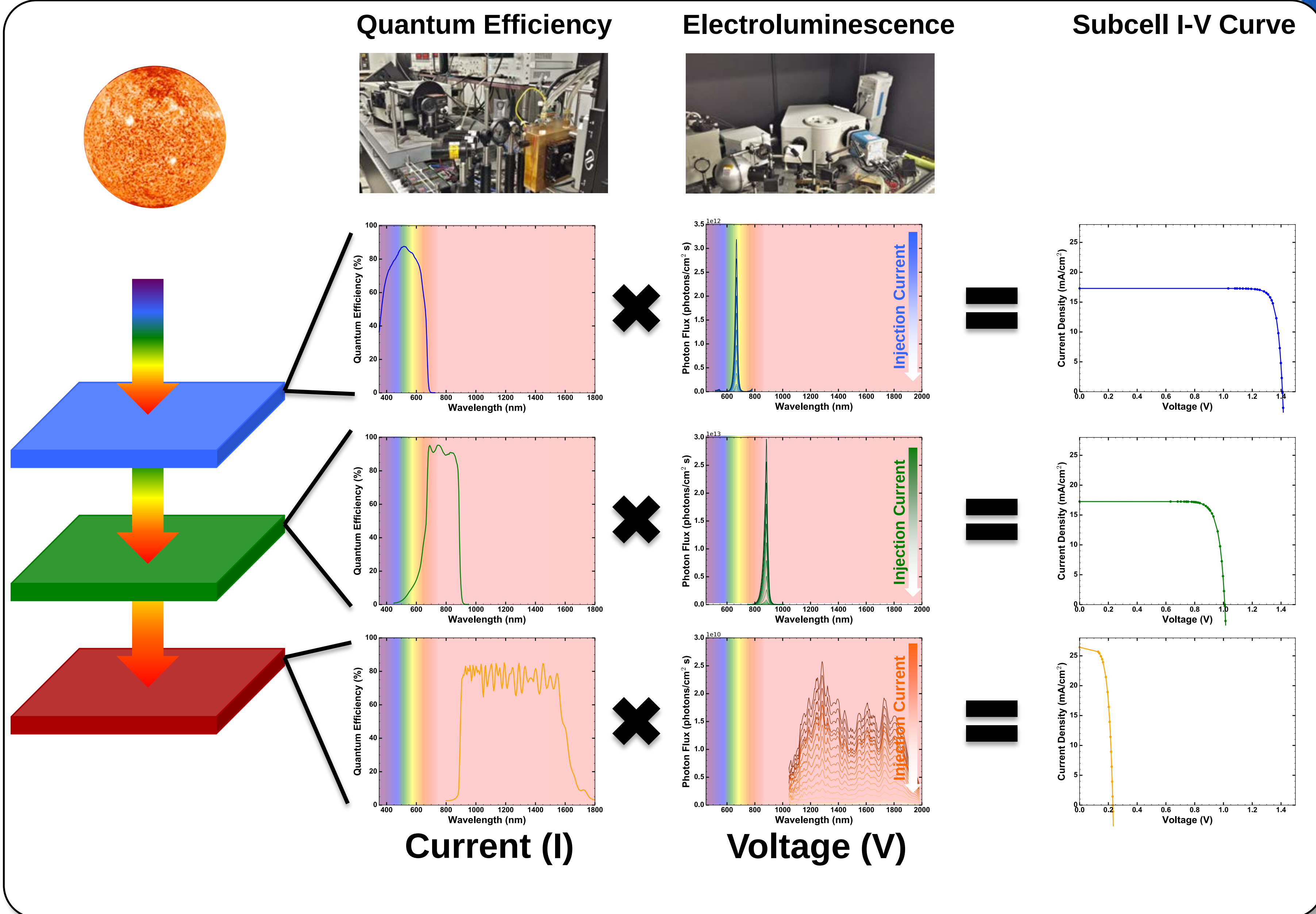
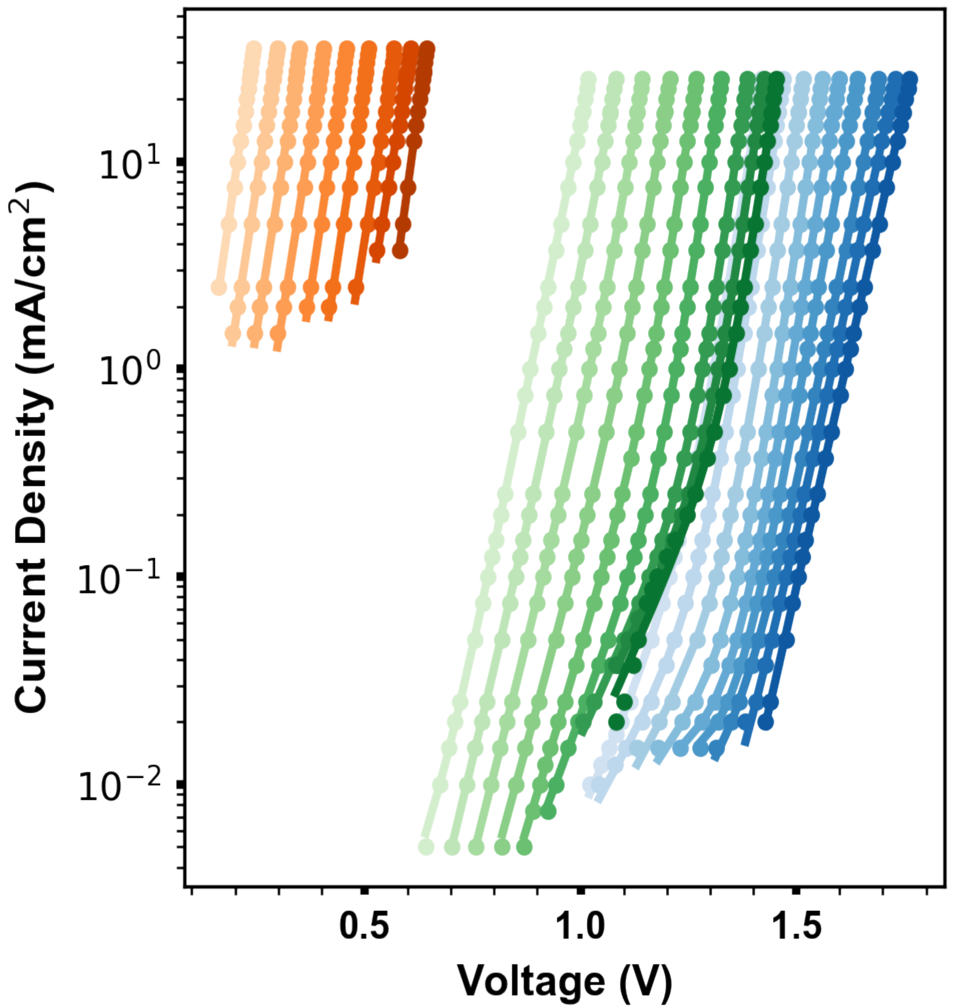
Subcell Characterization



Low Temperatures Subcell I-V

- As seen in the LIV the subcell I-V shifts to higher voltage at lower temperatures
- A tunnel defect appears to show up at lower temperatures for J1 and J2
- Lines through points represents fits to diode equation
- Future analysis will look into the midgap energy and change in ideality with temperature and compared to post radiation testing



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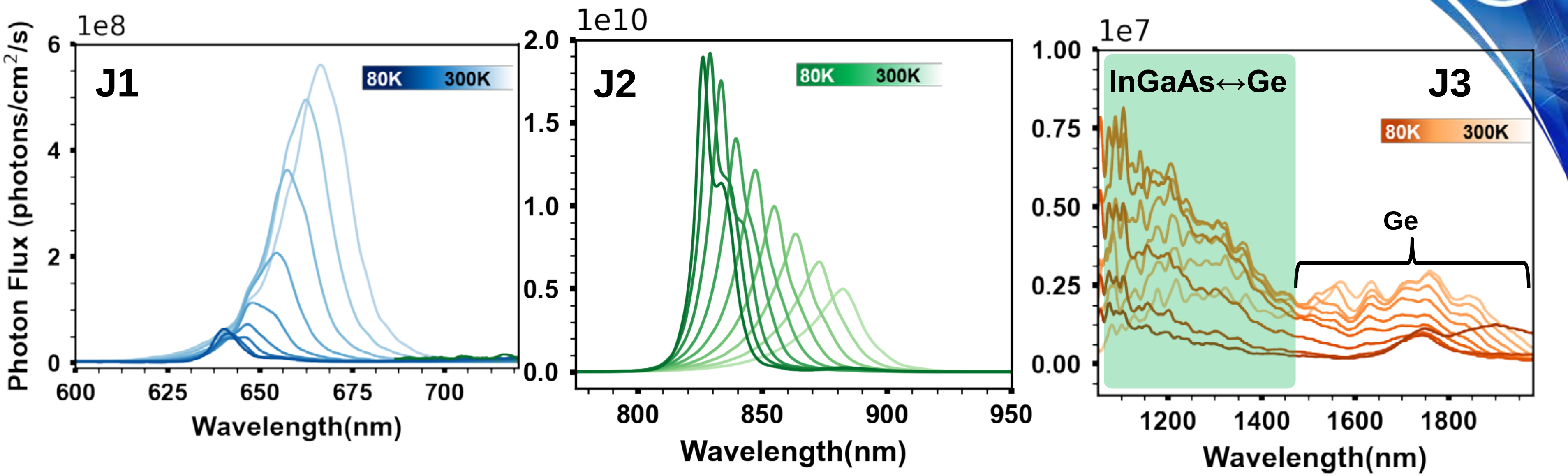
Low Temperature Electroluminescence



- The top cell EL intensity behaves contrary to typical III-V direct and indirect materials.
  - *Luminescence intensity decreases with decreasing temperatures.*
  - *The peak band energy blue shifts as expected.*
  - *At temperatures below 120K the luminescence intensity begins to increase and low energy shoulder begins to appear.*
  - *Behavior has been observed in higher bandgap InGaP materials with a large Ga content [1]*
  - *A possible reason for the EL behavior could be due to ordered and disordered layers in the InGaP top layers [2]*
- Middle cell behaves exactly as expected
  - *At lower temperatures a low energy defects begins to appear*
  - *Intensity increase stabilizes*
- Bottom cell intensity behaves similar to the top cell due to its indirect nature
  - *Broad band emission is due to diffusion of Ge and dopants between the middle and Ge bottom cell [3]*

[1] C. Wang, B. Wang, R. I. Made, S.-F. Yoon, and J. Michel, "Direct bandgap photoluminescence from n-type indirect GaInP alloys," *Photonics Res.*, vol. 5, pp. 239–244, 2017

[2] L. Bhusal *et al.*, "Ordering induced direct-indirect transformation in unstrained Ordering induced direct-indirect transformation in unstrained GaxIn1−xP for 0.76 ≤ x ≤ 0.78," vol. 114909, pp. 1–4, 2009

[3] G. Brammertz *et al.*, "Low-temperature photoluminescence study of thin epitaxial GaAs films on Ge substrates," *J. Appl. Phys.*, vol. 99, no. 9, 2006

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Lots more to do

- Conclusions
  - *Radiometric calibration allows for accurate low temperatures LIV measurements that match well to AM0*
  - *Obtained low temperature quantum efficiency of multijunction solar cells*
  - *Demonstrated measurement of low temperature subcell current-voltage curves*
  - *Identified potential disorder in top cell as well as finally figured out the origin of the broadband luminescence in the IR luminescence*
- Next Step
  - *Perform defect energy analysis using luminescence, DIV, and subcell I-V data*
  - *Irradiate solar cell and see what happens*
    - We know the ideality changes but now we want to see what defects show up in EL and energy of those defects
  - *Perform annealing studies to see how the defects stay or go away*
  - *Ultimately relate this to some model to better predict radiation degradation in solar cells*