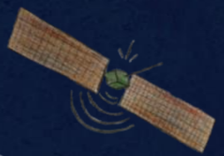
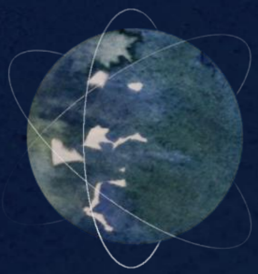
FREIGEIST

FELLOWSHIP DER VOLKSWAGENSTIFTUNG

Radiation Tolerant Electronics with Soft Halide Perovskites

From Single and Multijunction PV for Space and Earth to Medical Radiation Detectors



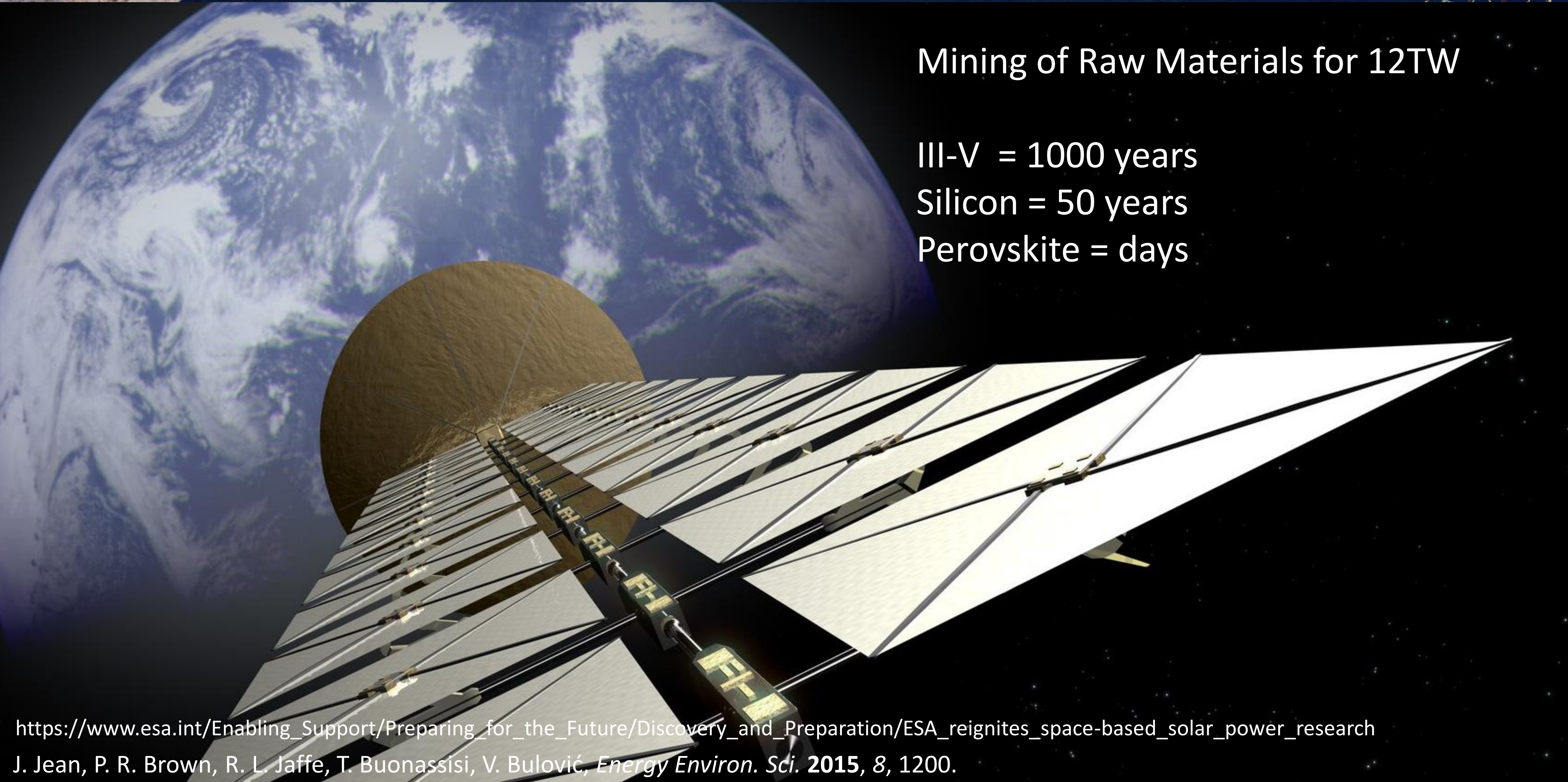


Universität Potsdam

Dr. Felix Lang,
ROSI Freigeist Group

Space Solar Cells on ISS: 215 kWatt Power

III-V upscalable to GW or TW?



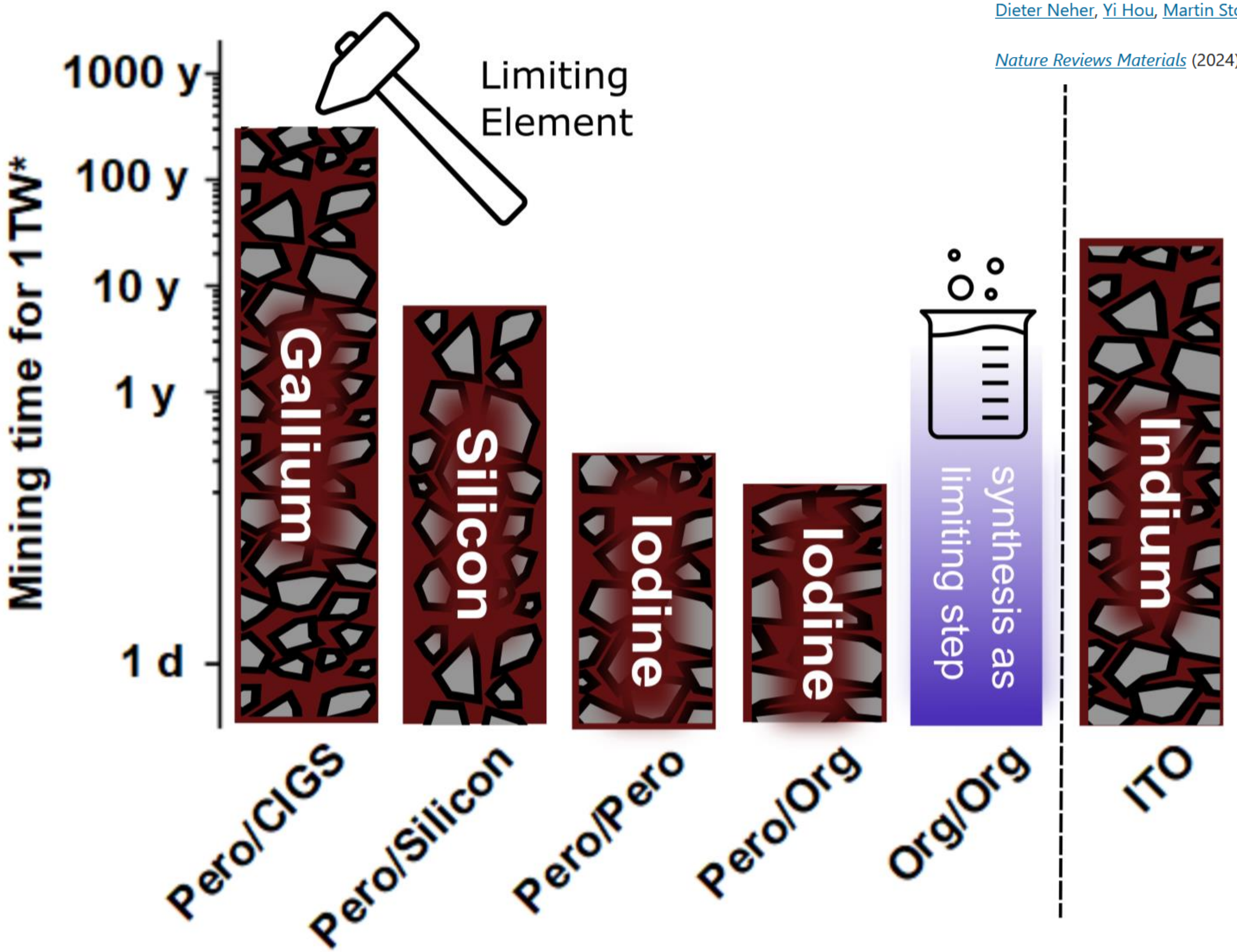
Mining of Raw Materials for 12TW

III-V = 1000 years
Silicon = 50 years
Perovskite = days

https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/ESA_reignites_space-based_solar_power_research

J. Jean, P. R. Brown, R. L. Jaffe, T. Buonassisi, V. Bulović, *Energy Environ. Sci.* **2015**, *8*, 1200.

Carbon Footprint and Ressource Availability

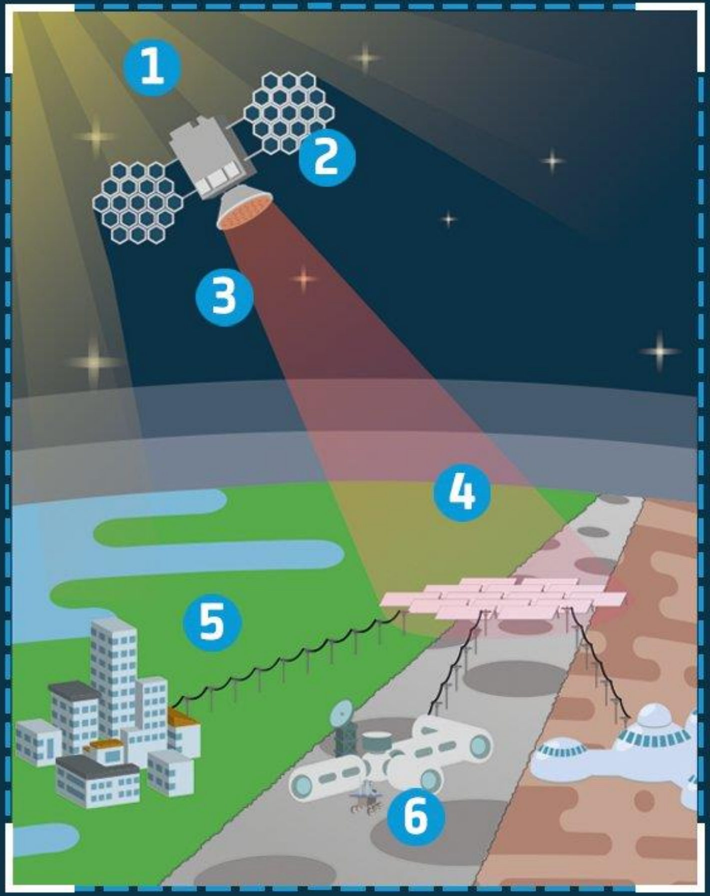


Perovskite–organic tandem solar cells

Kai O. Brinkmann, Pang Wang, Felix Lang, Wei Li, Xiao Guo, Florian Zimmermann, Selina Olthof, Dieter Neher, Yi Hou, Martin Stolterfoht, Tao Wang, Aleksandra B. Djurišić & Thomas Riedl

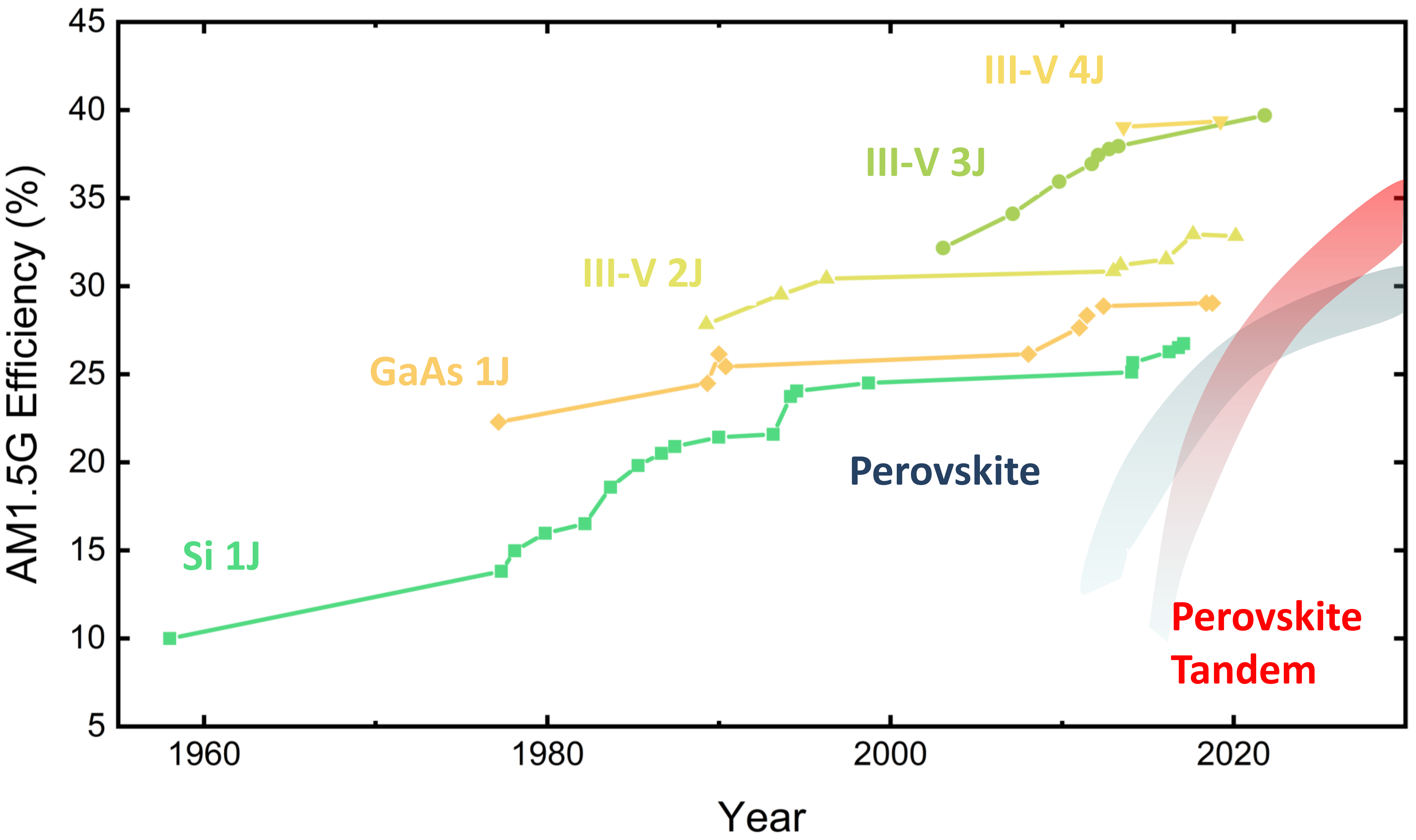
Nature Reviews Materials (2024) | Cite this article

SPACE-BASED SOLAR POWER

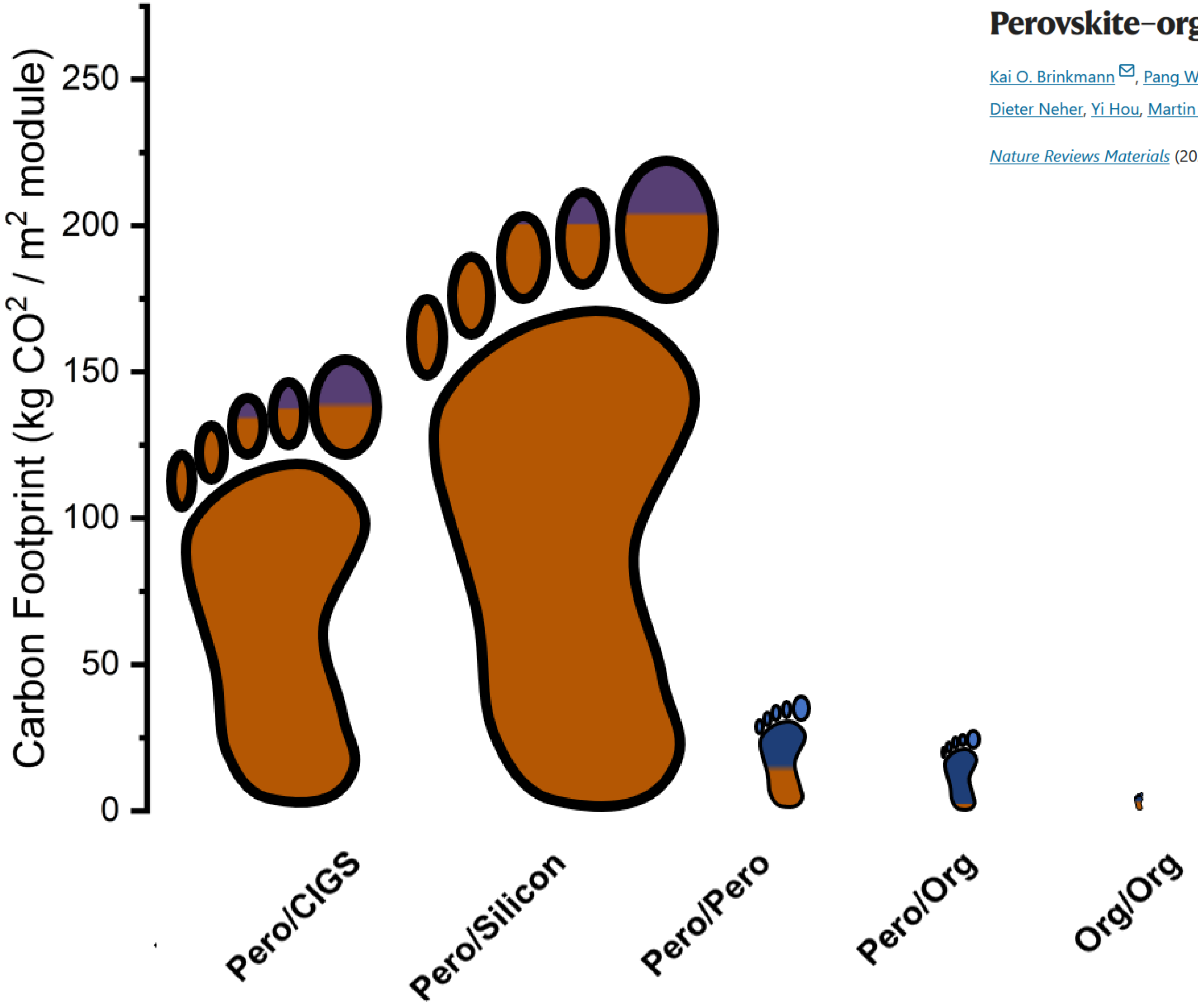


1. INCIDENT SOLAR RADIATION
2. SUNLIGHT CAPTURE AND ENERGY REGULATION
3. POWER BEAMING
4. BEAM CAPTURE AND ENERGY CONVERSION
5. POWER TRANSMISSION
6. ENERGY UTILISATION

Can we use Perovskite PV ??



Carbon Footprint and Ressource Availability



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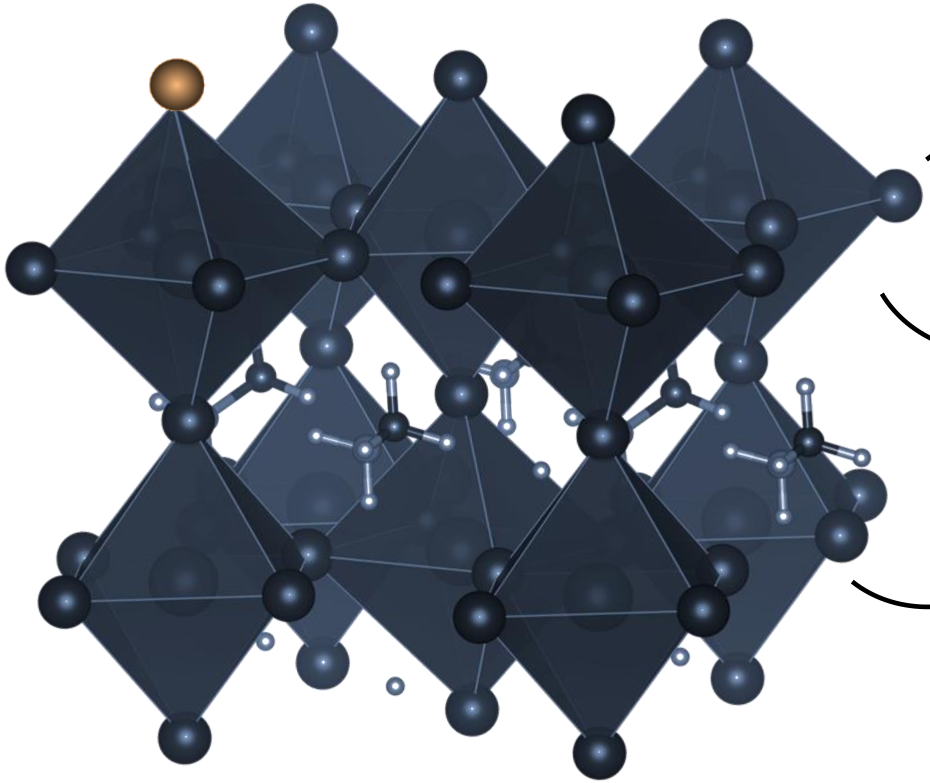
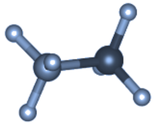
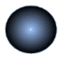
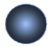
What are Halide Perovskites?

AMX_3



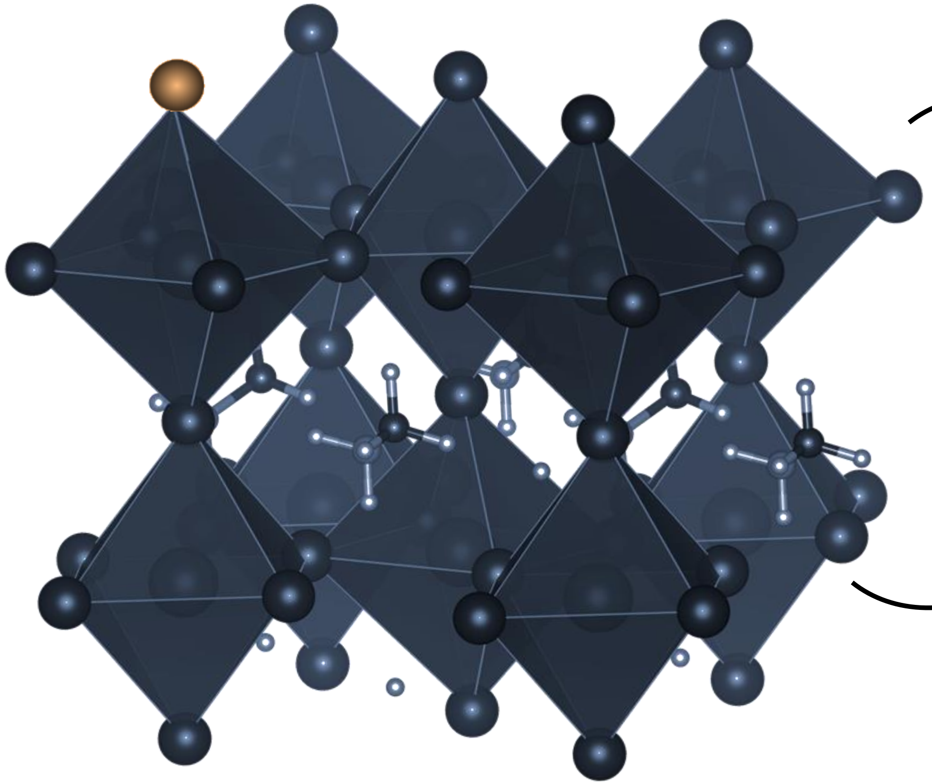
Perovskite = Name of the Crystal Structure

- **Good Optoelectronic Properties**
- **Ideal for Solar Cells**
- **Relatively Abundant Materials**

	AMX_3	
A		MA^+, FA^+, Cs^+…
M		Pb^{2+}, Sn^{2+}
X		Cl^-, I^-, Br^-

What are Halide Perovskites?

AMX_3



Tolerable “error” in
A, B, X_3
≈ 1-10%

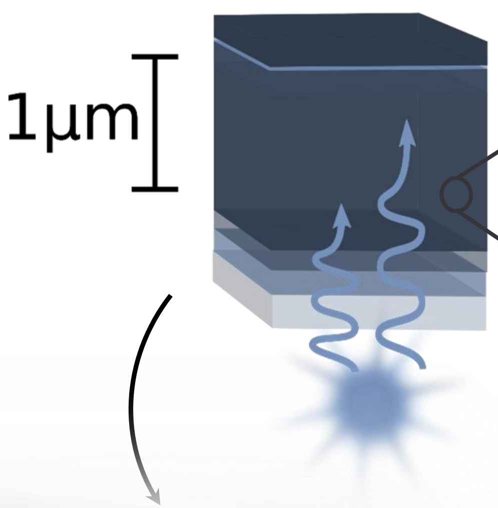
Even 1% Coffee !?
Wang et al., Joule 3, 1464–1477, 2019

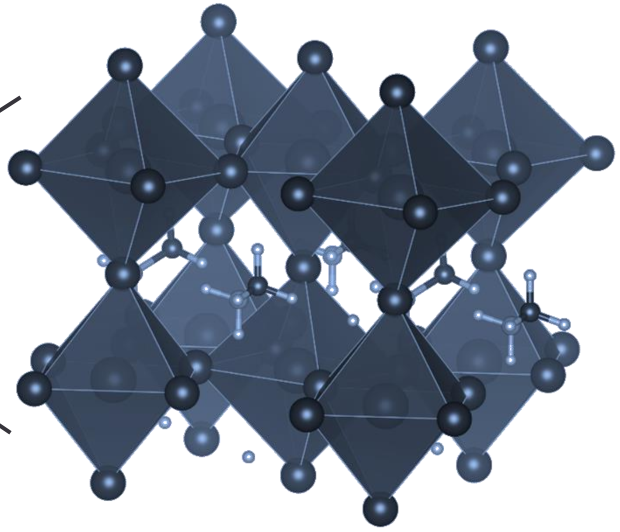
Perovskite = Name of the Crystal Structure

Silicon crystal

Impurity concentration
< < 10^{12} cm^{-3}
< < 1 ppb
(Carbon 1 ppm, Oxygen 10 ppm)

Perovskite based Photovoltaics





Ideal for Photovoltaics

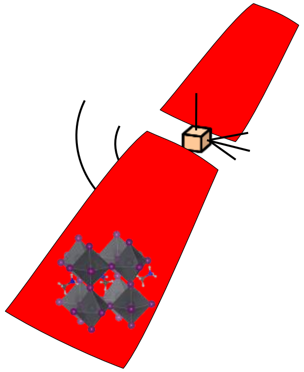
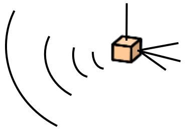
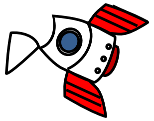
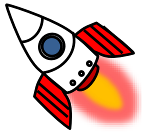
Efficiencies rival established technologies

Jean, J. et al. *Org. Electron.* **2016**, *31*, 120–126.

200 times thinner than the absorber in a typical silicon or III-V on Ge Solar Cell

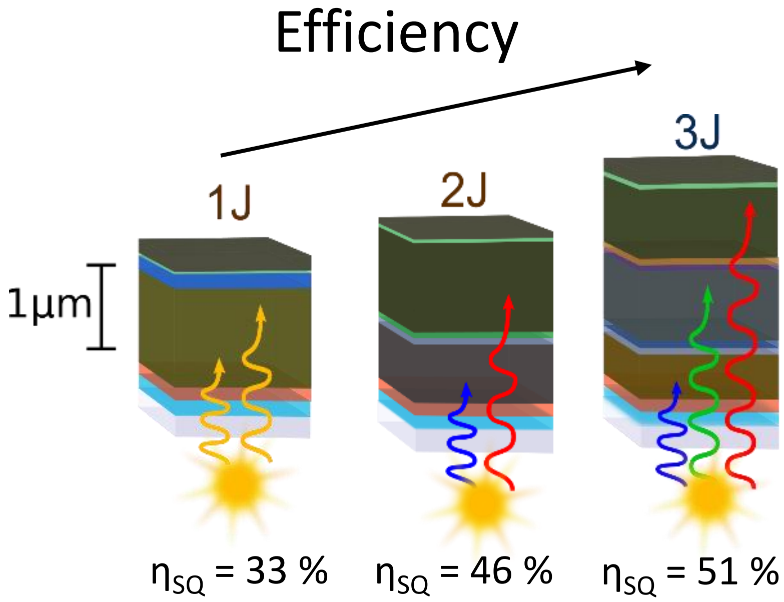
Photograph: Jeol Jean, https://news.mit.edu/2016/ultrathin-flexible-solar-cells-0226

Perovskite based multijunction space-PV

Ultrathin, lightweight & flexible solar foils for space

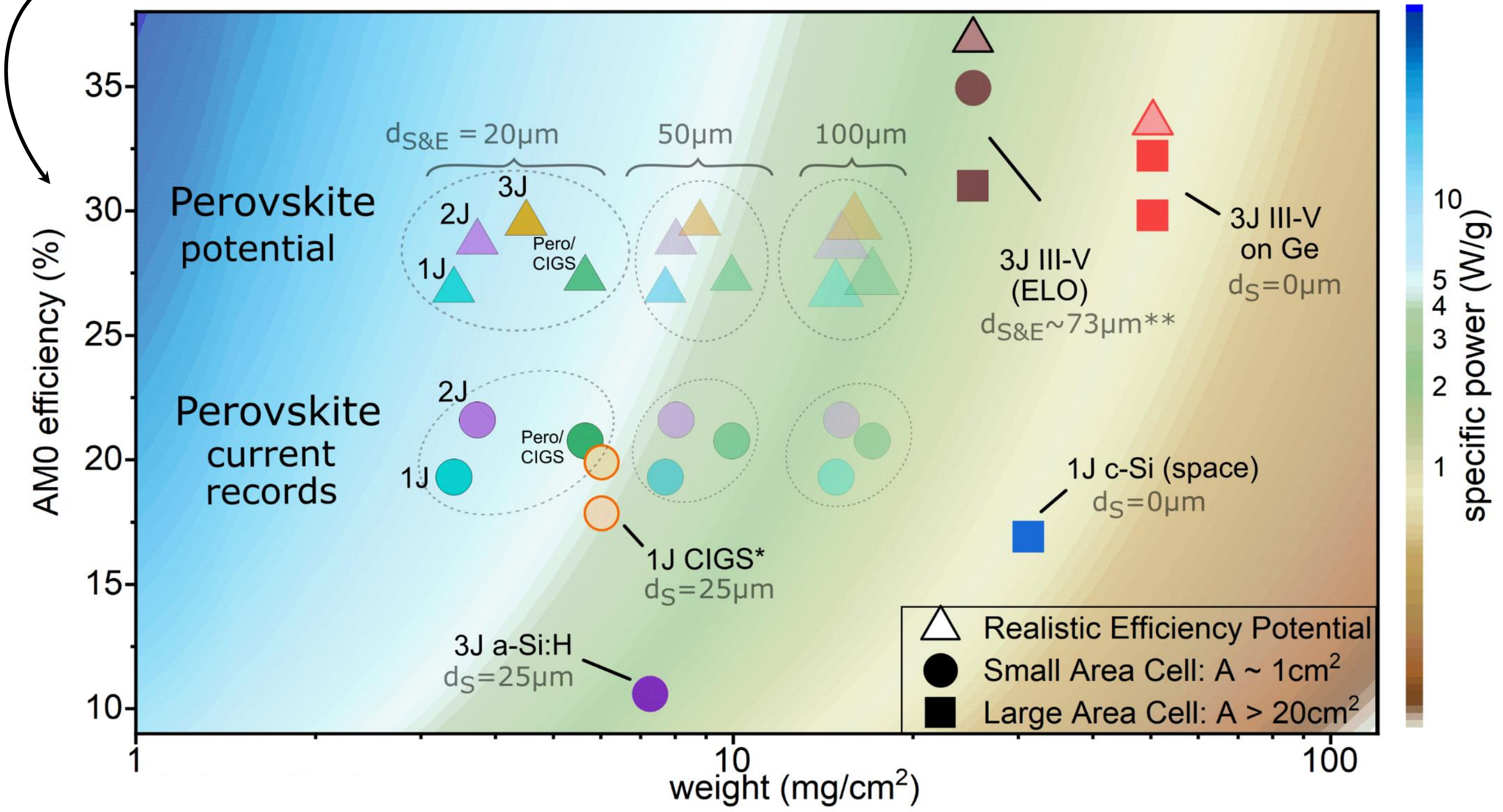
Jean, J. et al. *Org. Electron.* **2016**, *31*, 120–126.



Photograph: Jeol Jean, https://news.mit.edu/2016/ultrathin-flexible-solar-cells-0226

High Specific-Power Potential

Energy demanding satellites



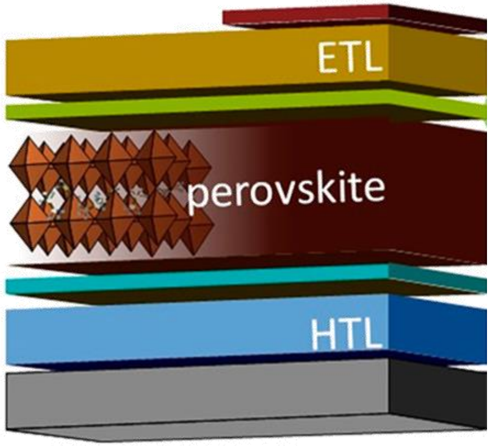
Satellite Launch Costs: 5000 $/kg

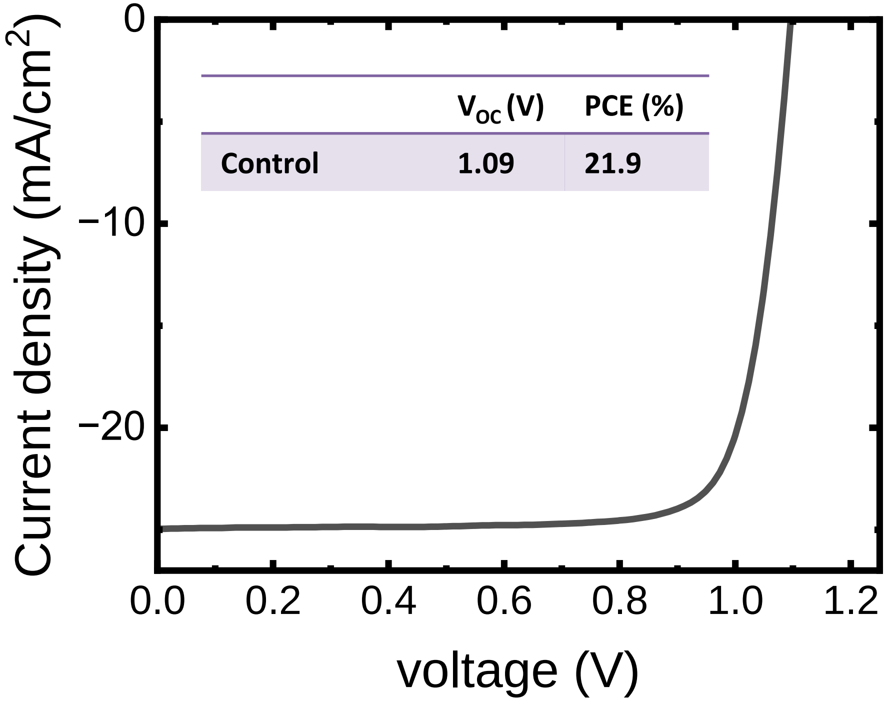
Lang, F., et al. Adv. Energy Mater. 2021, 11, 2102246.

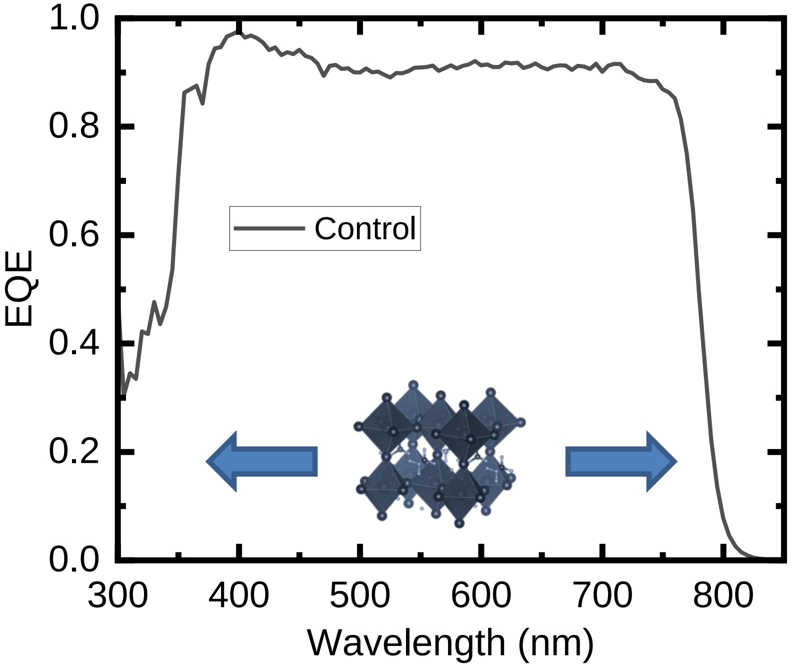
SINGLE JUNCTION SOLAR CELLS MADE IN POTSDAM

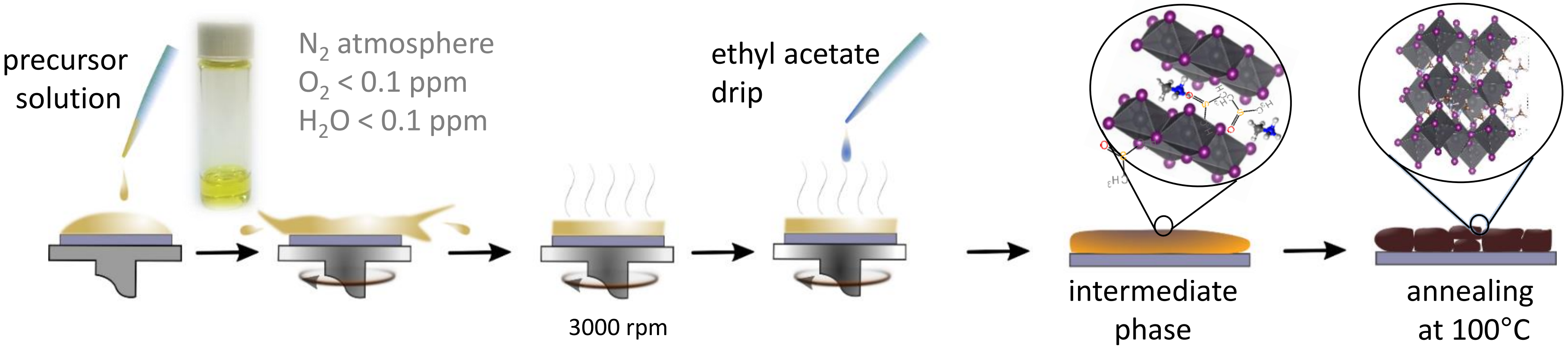
Ph.D. student
Biruk Alebachew

Triple Cation Triple HalidePerovskite $[Cs_{0.05}(MA_{0.05}FA_{0.95})_{0.95}]Pb(I_{0.95}Br_{0.05}Cl_{0.0X})_3$









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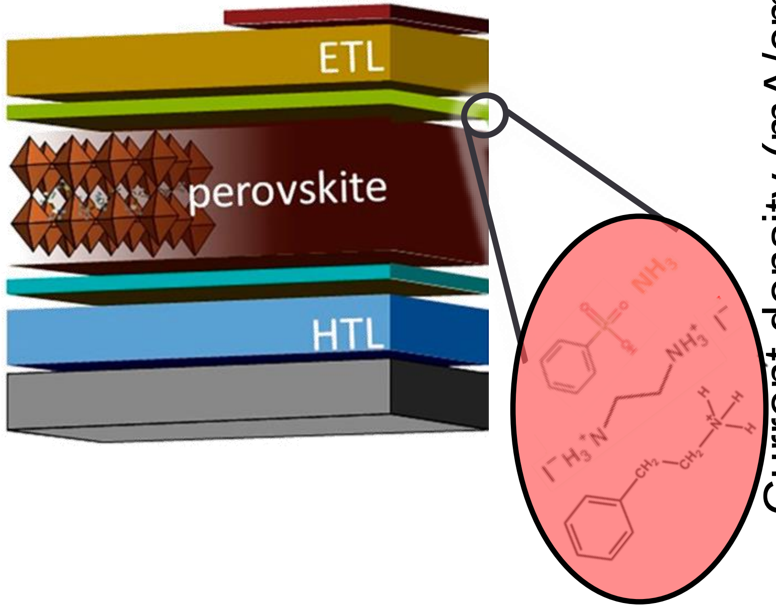
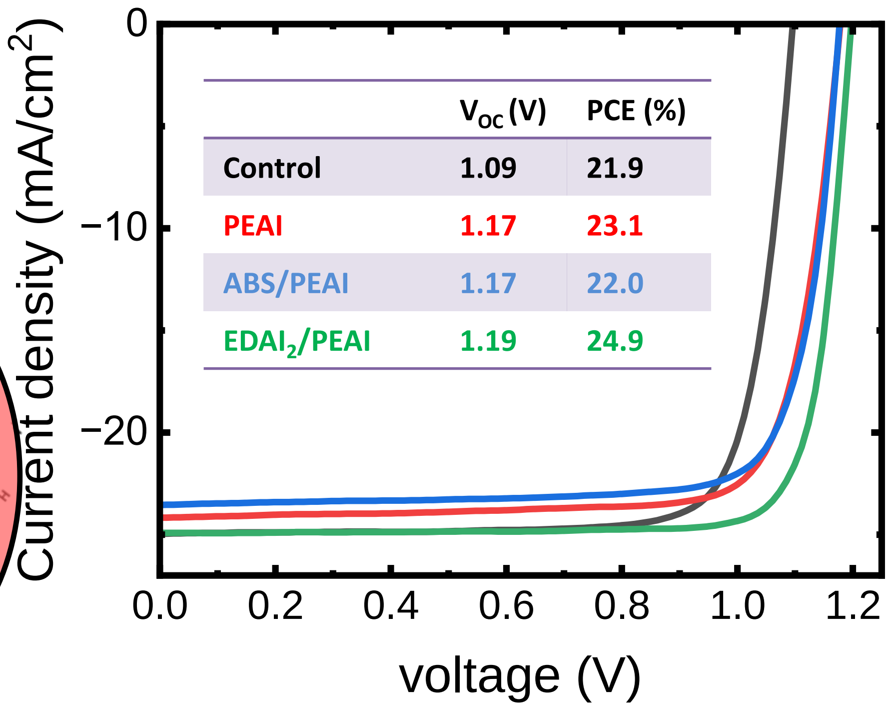
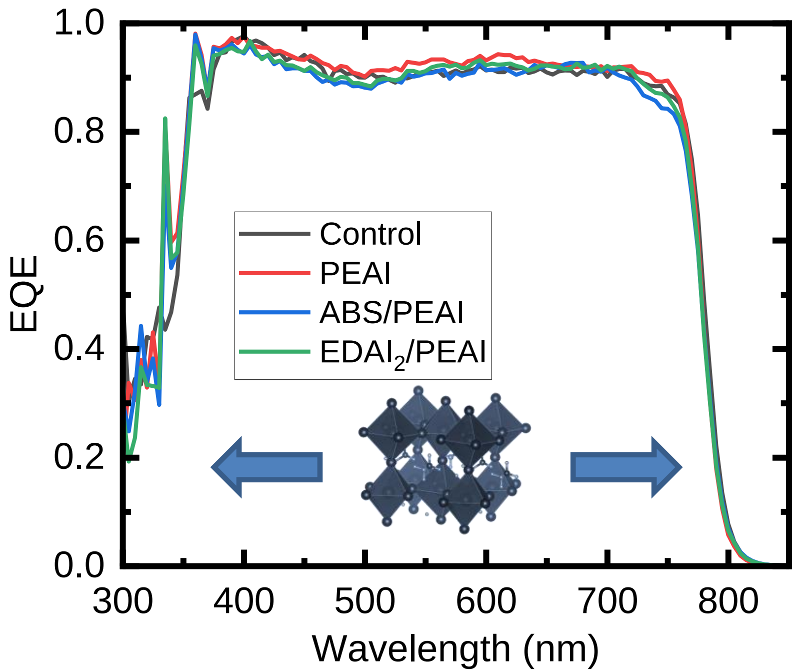
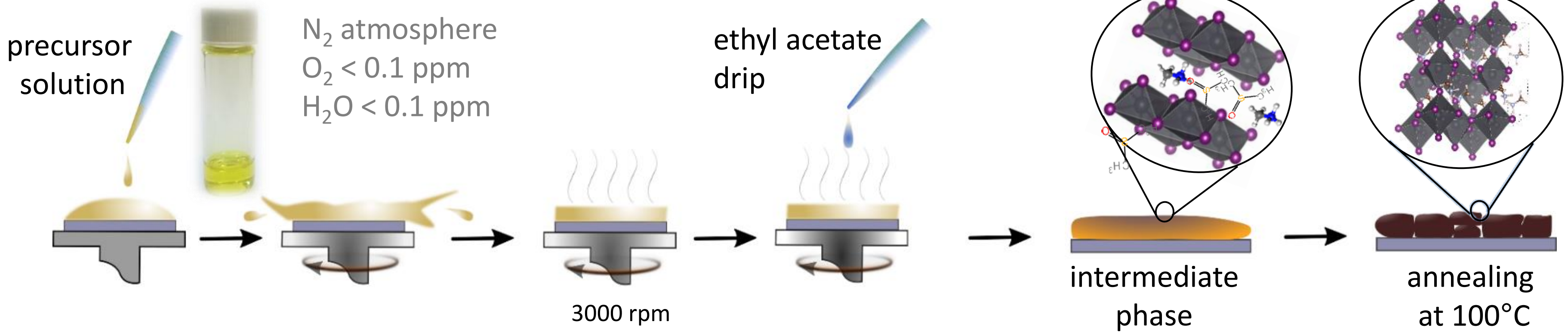


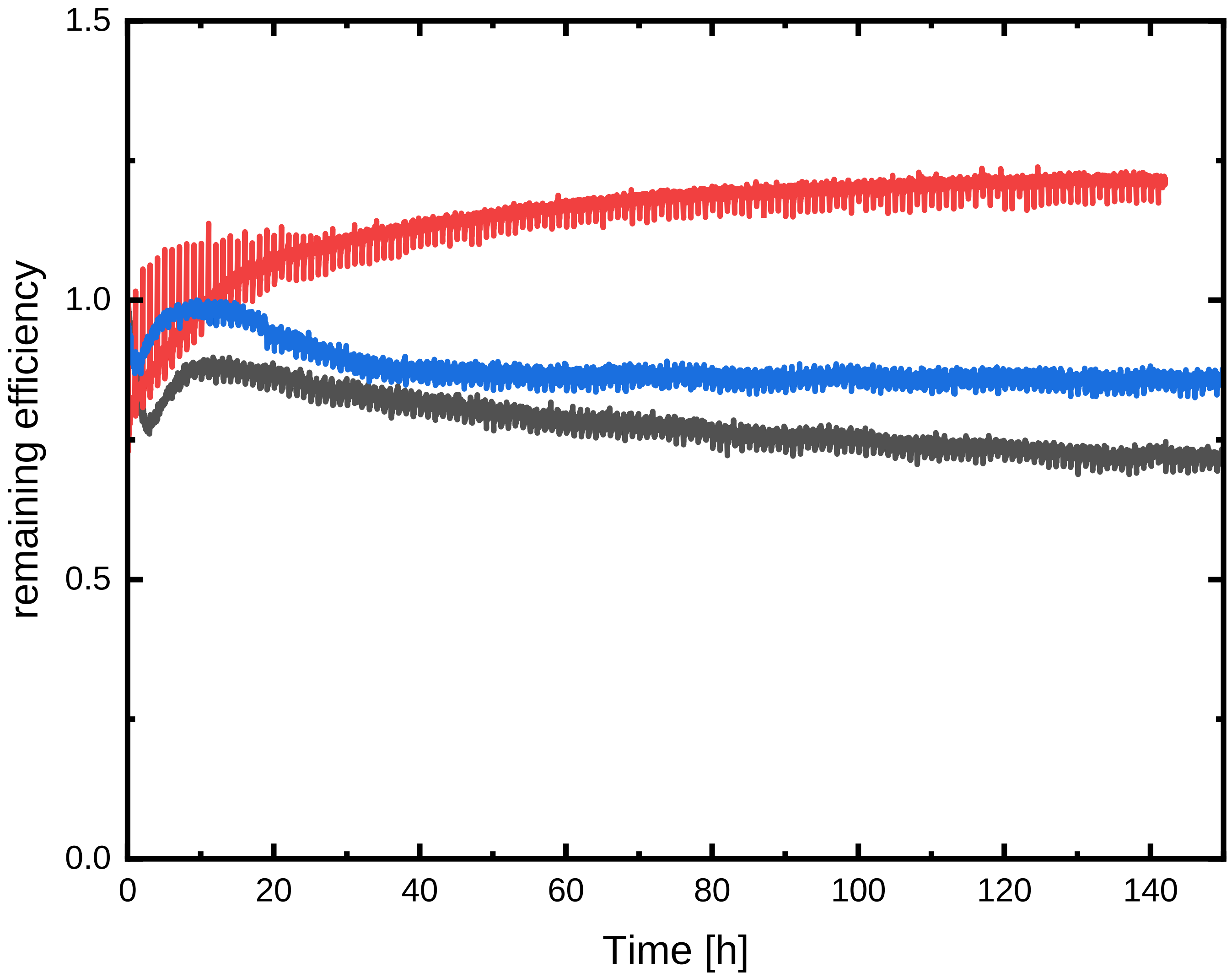


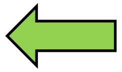
	V_{OC} (V)	PCE (%)
Control	1.09	21.9
PEAI	1.17	23.1
ABS/PEAI	1.17	22.0
$EDAI_2$/PEAI	1.19	24.9



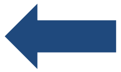


IMPROVING STABILITY



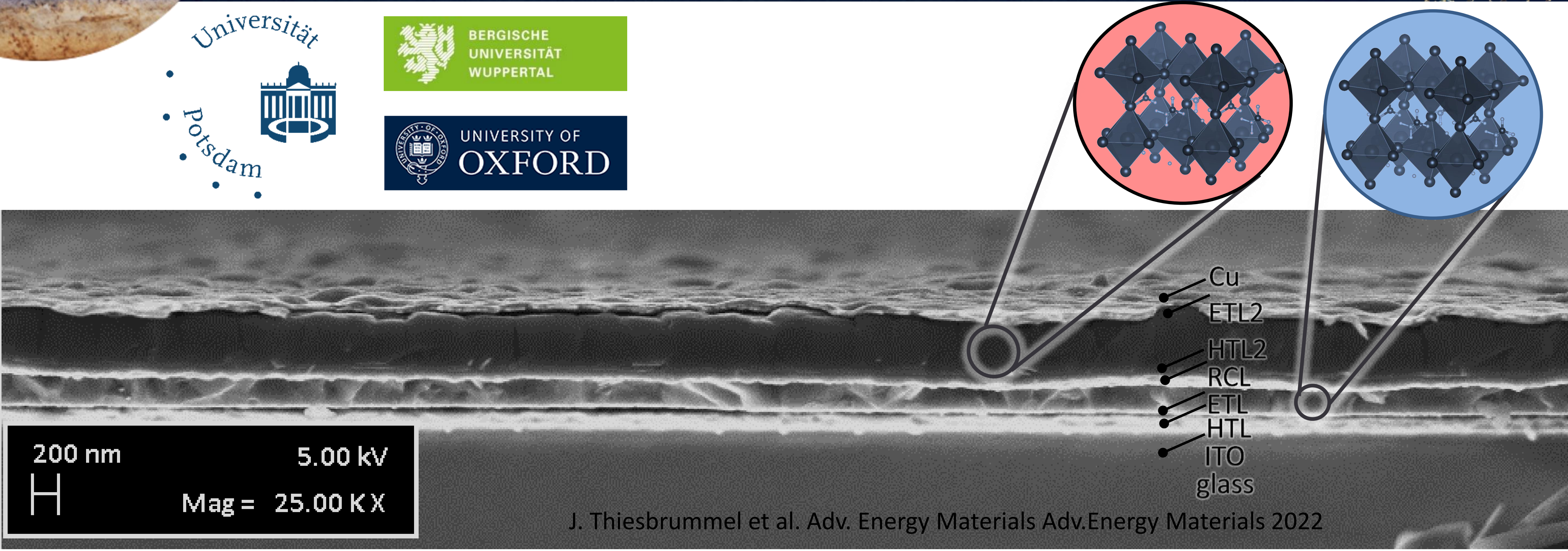


Europium Additive



Cr_2O_3/Cr/Cu Contact

All-Perovskite Tandems Made in Potsdam



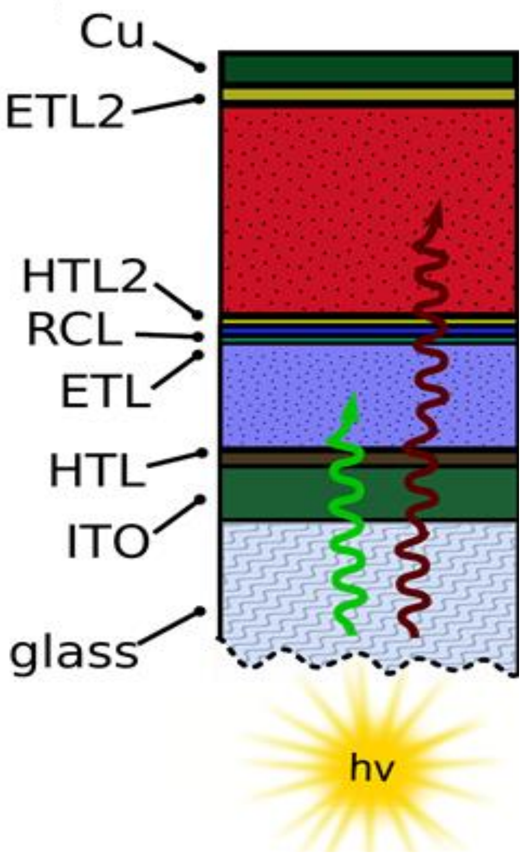

Jarla Thiesbrummel

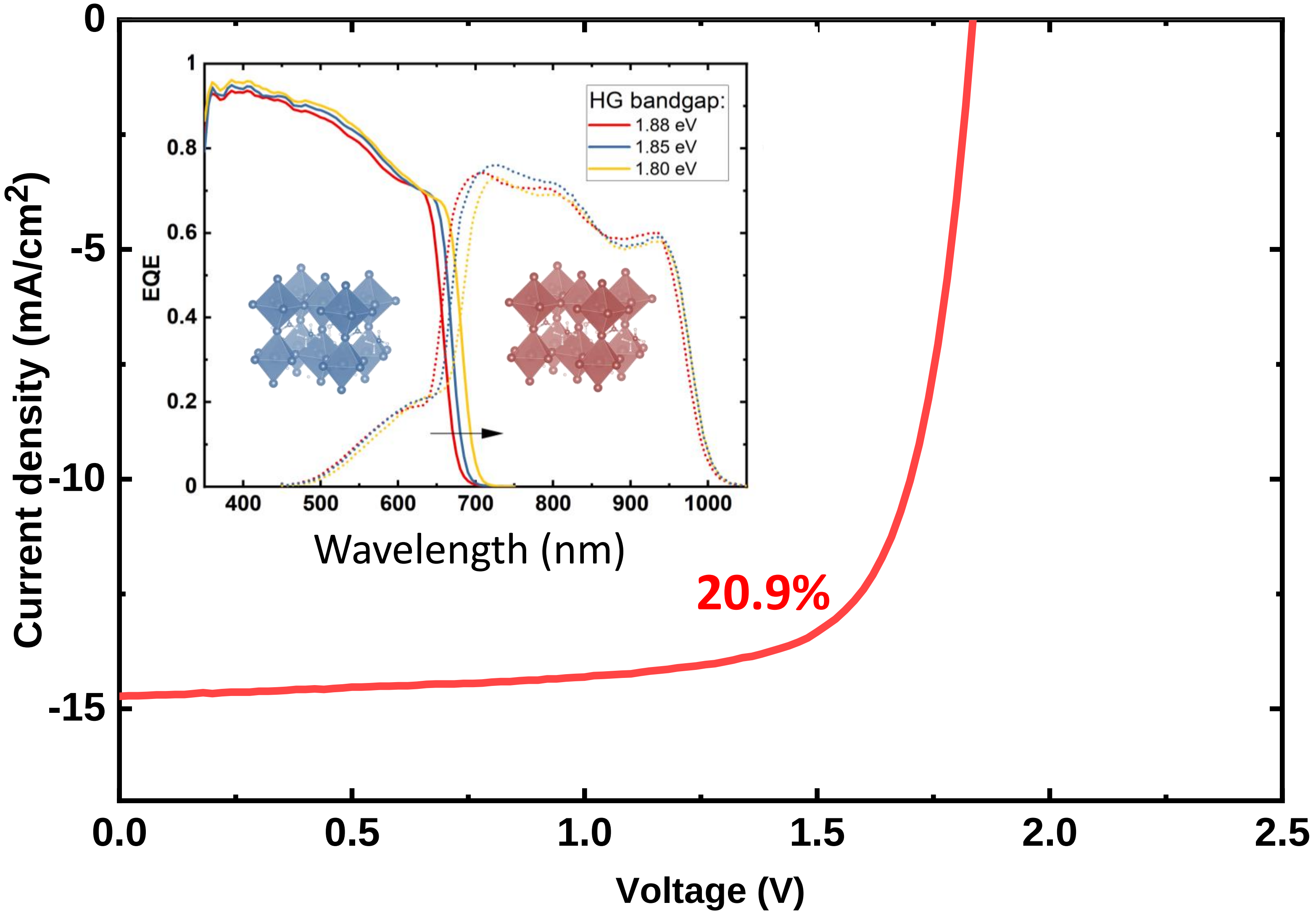

Francisco Peña-Camargo


Kai Brinkman


Dr. M. Stolterfoht

All-Perovskite Tandems Made in Potsdam





Jarla Thiesbrummel

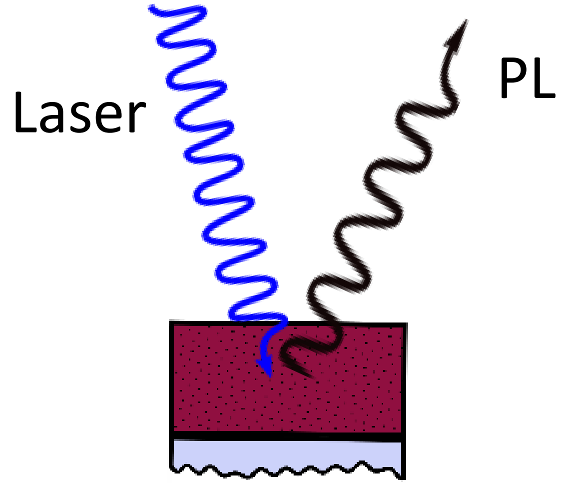
Francisco Peña-Camargo

Kai Brinkman

J. Thiesbrummel et al. Adv. Energy Materials Adv.Energy Materials 2022

High Gap Optimisation: Interfaces !!!

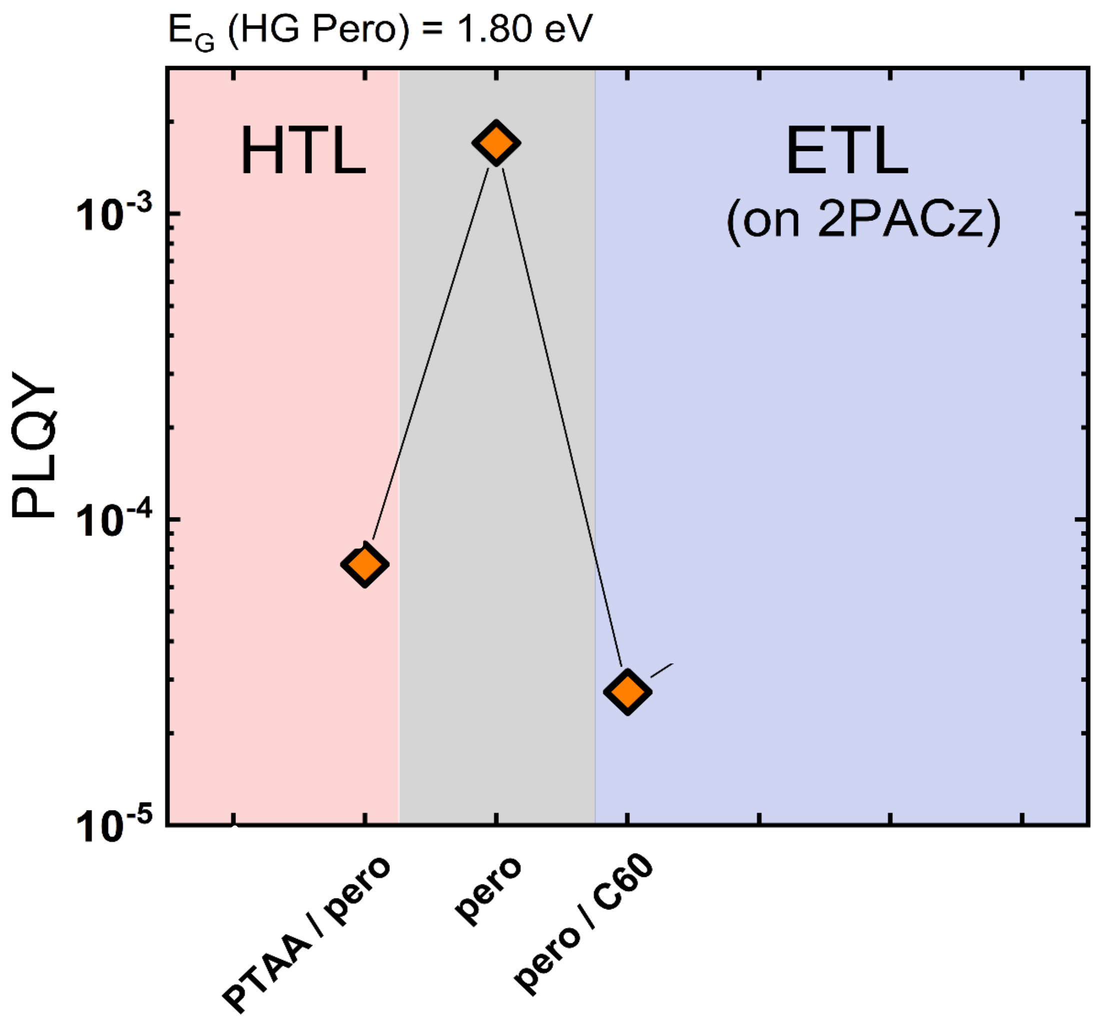
Photoluminescence Quantum Yield (PLQY)



$$PLQY = \frac{I_{PL}}{I_{abs}.Laser}$$

$$0 < PLQY < 1$$

bad perfect



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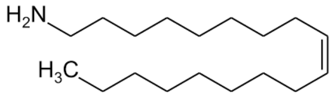
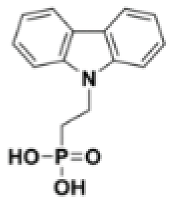
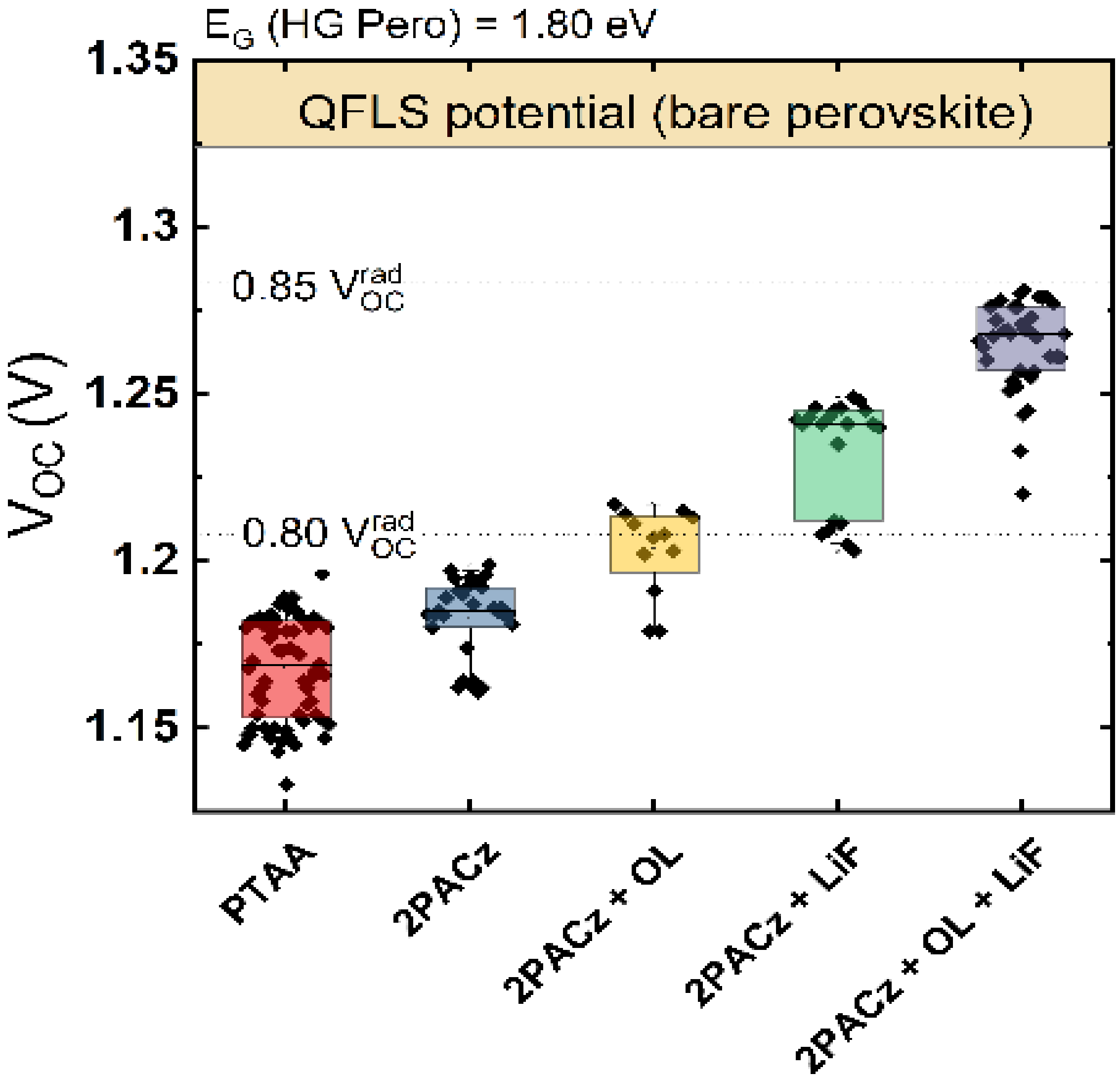
High Gap Optimisation: Interfaces !!!

Interface Optimization

+ SAM
+ OL
+LiF







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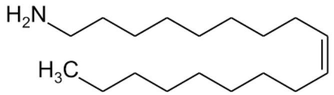
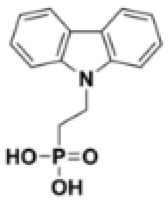
All-Perovskite Tandems Made in Potsdam

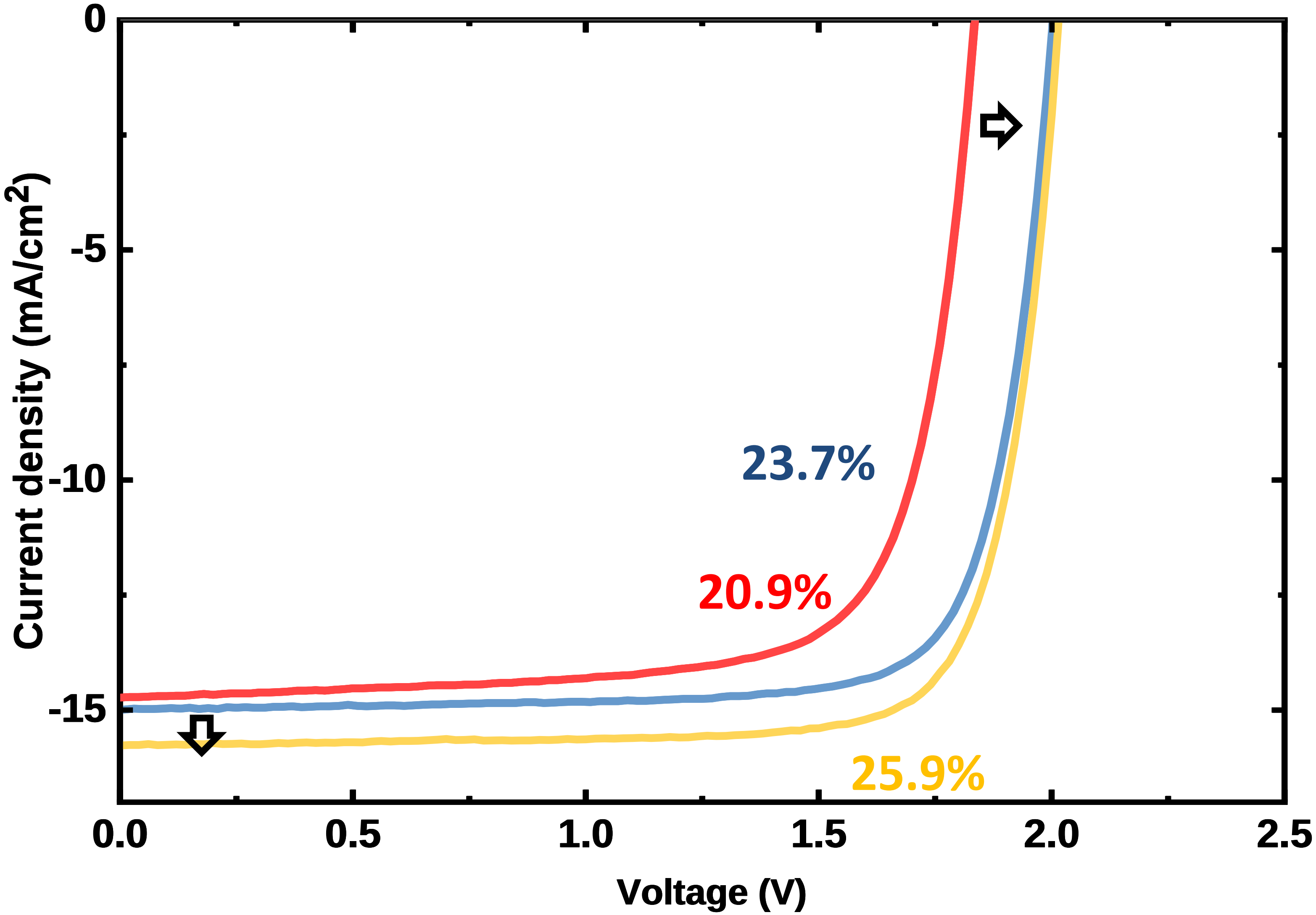
Interface Optimization

+ SAM
+ OL
+LiF





+
Thicker Low-Gap Perovskite



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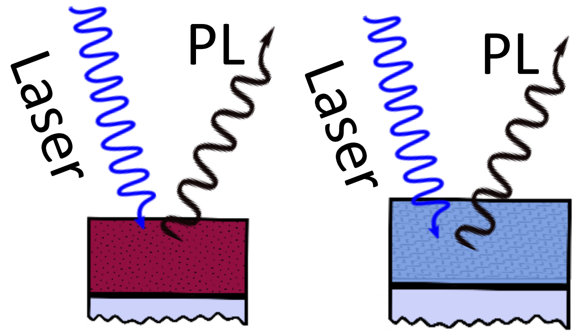
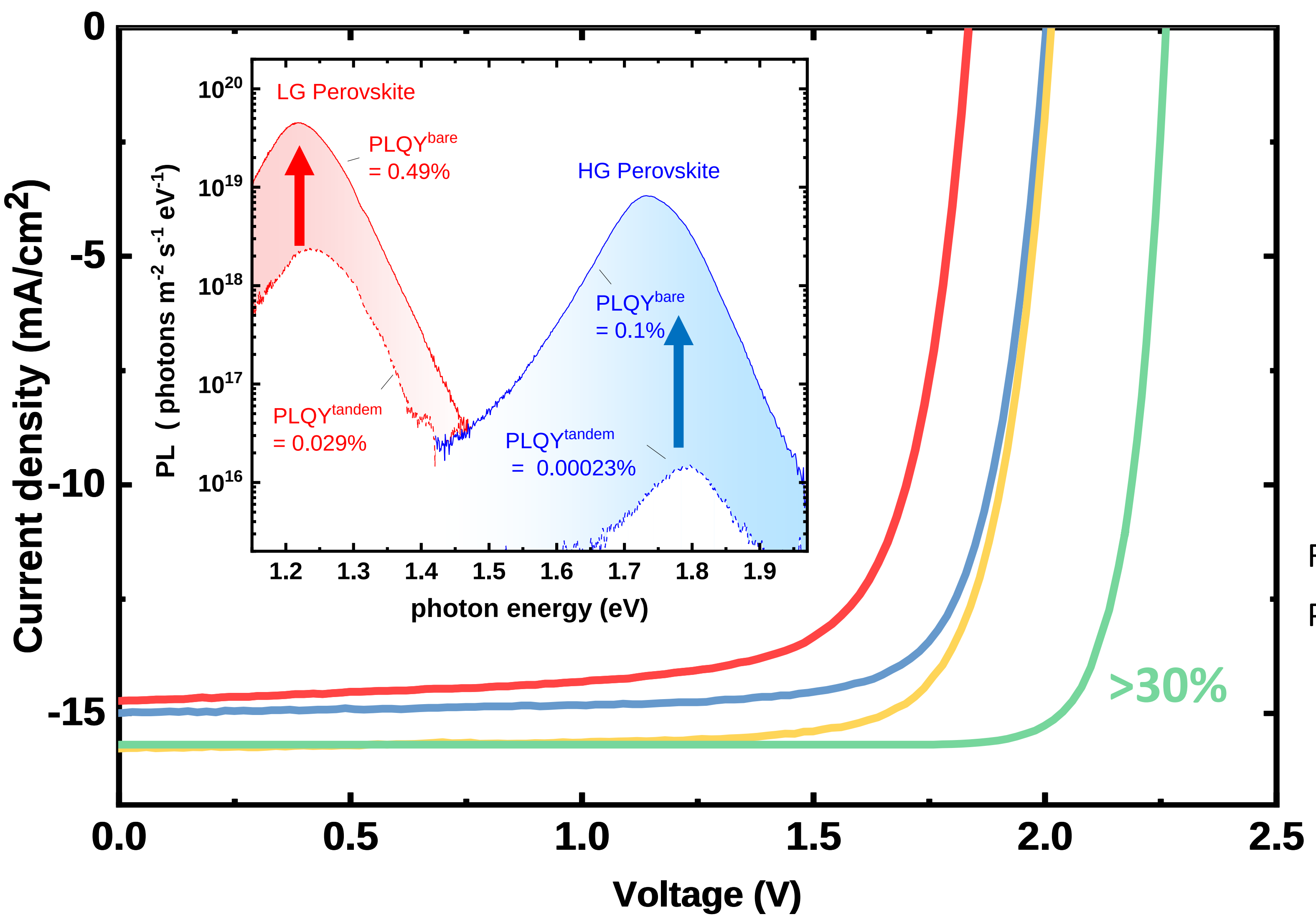
All-Perovskite Tandems Made in Potsdam

Efficiency Potential From Bare Perovskites >30%

(Measured Optically)





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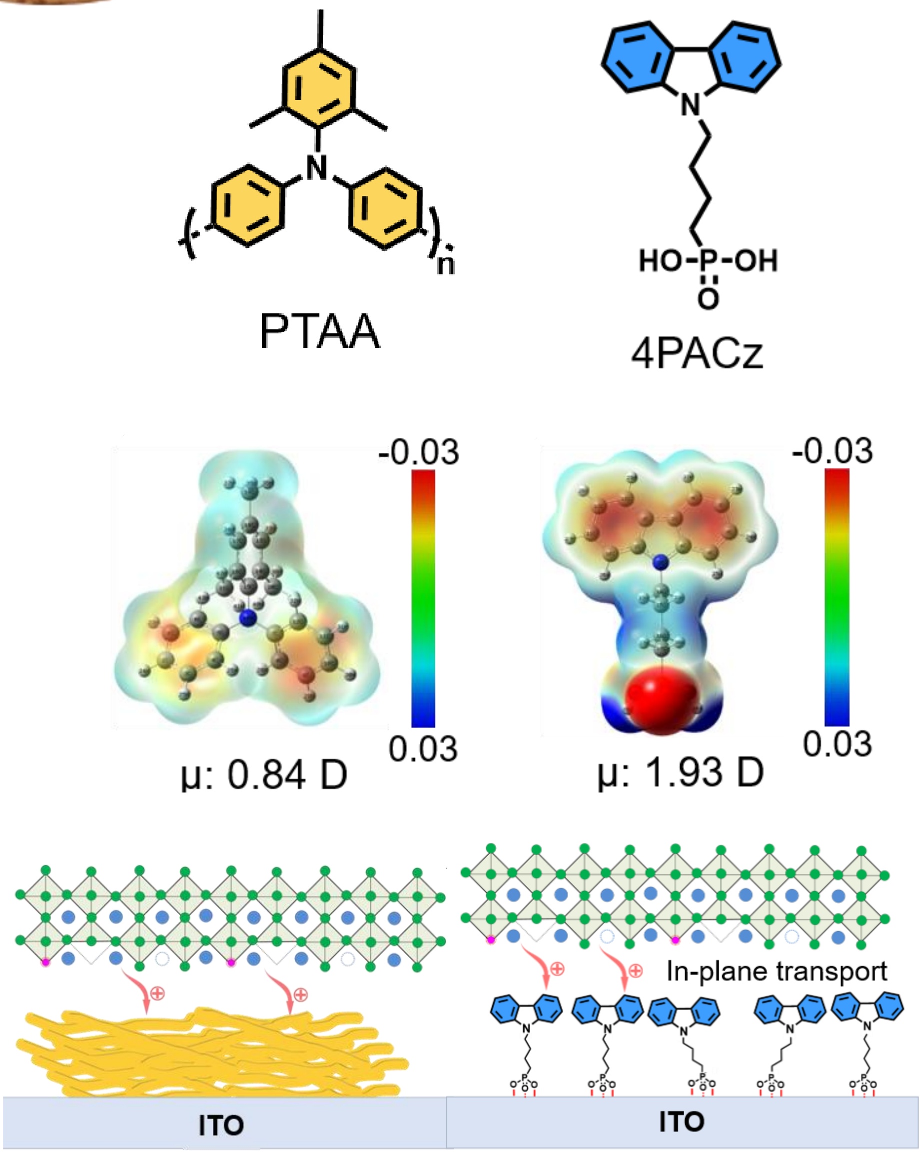
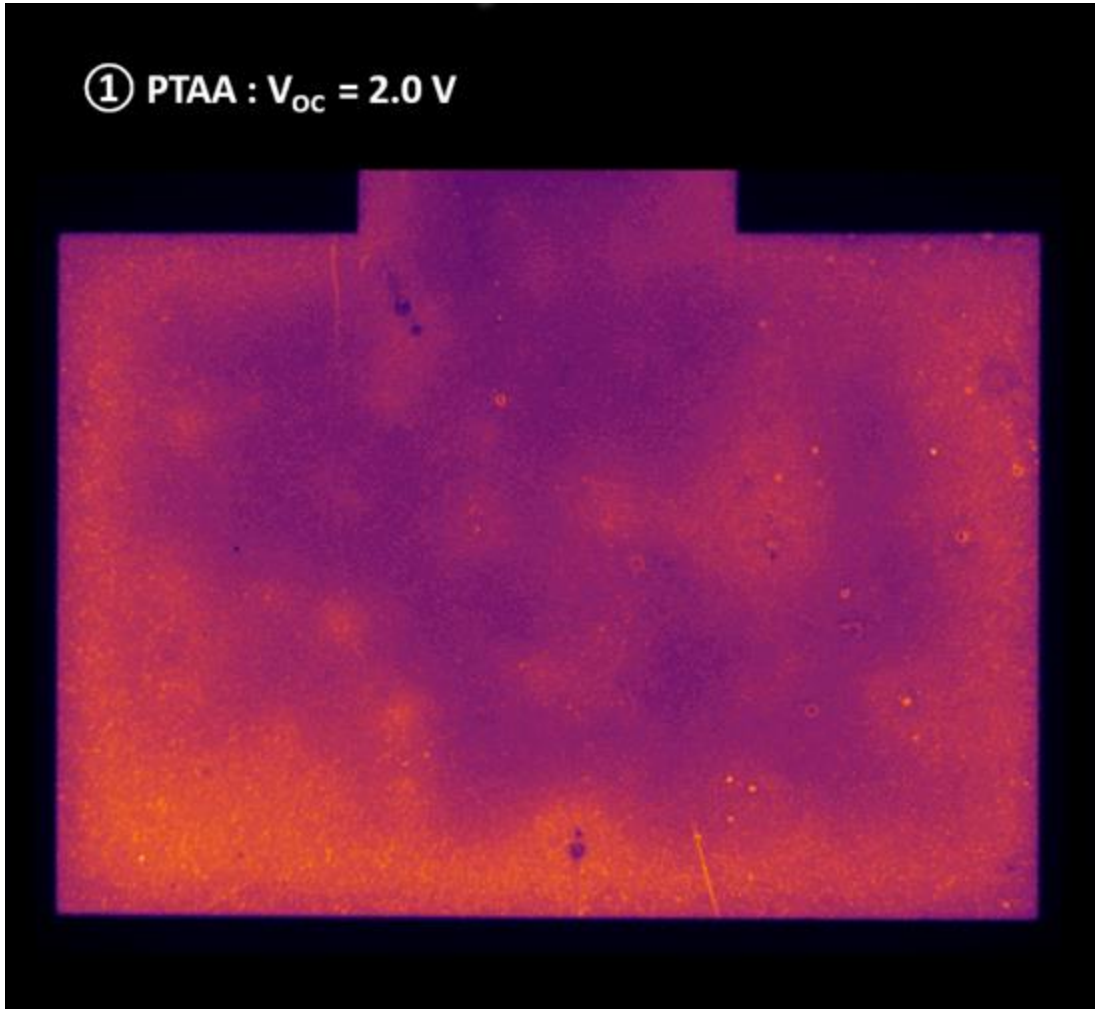
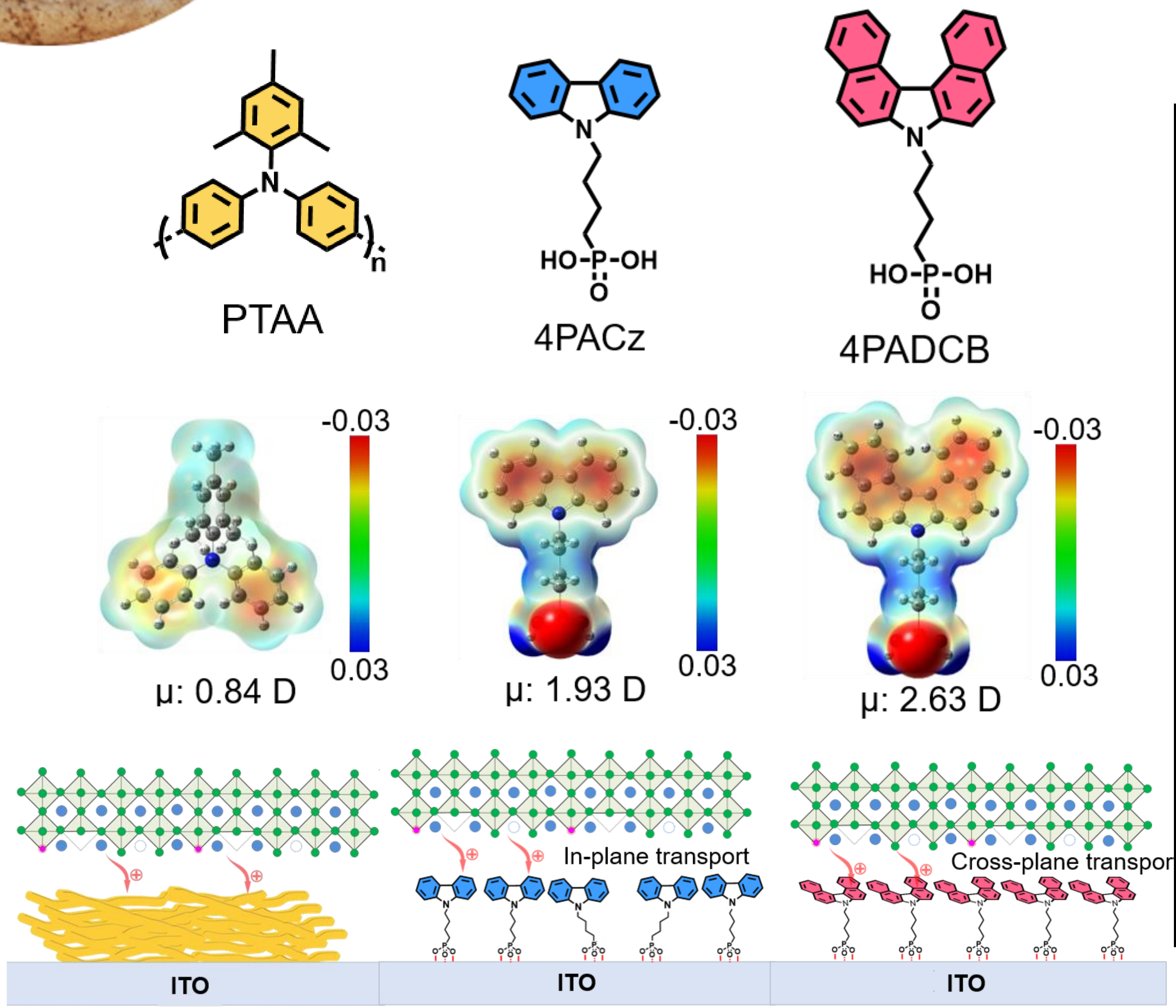
Challenge: Large Areas ($1cm^2$)

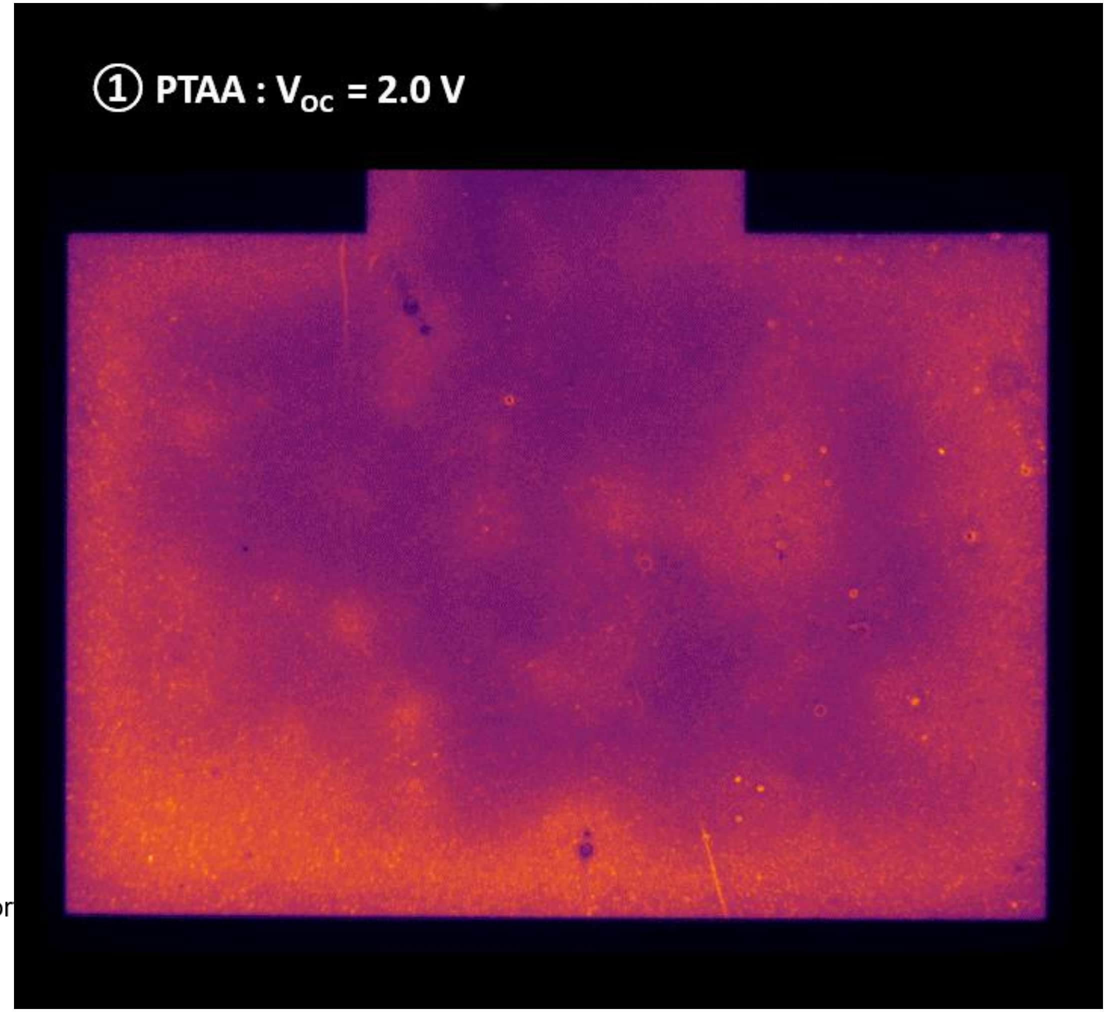




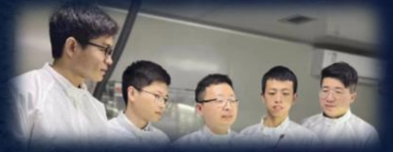
Challenge: Large Areas (1cm²)

Prof. Zhao & Team @ Sichuan University





1cm^2 Sized All-Perovskite Tandem PV



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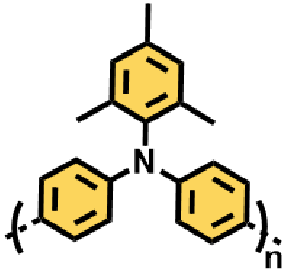
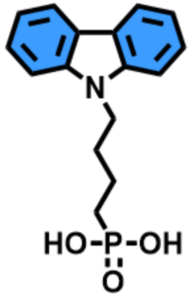
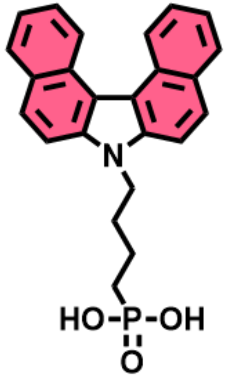


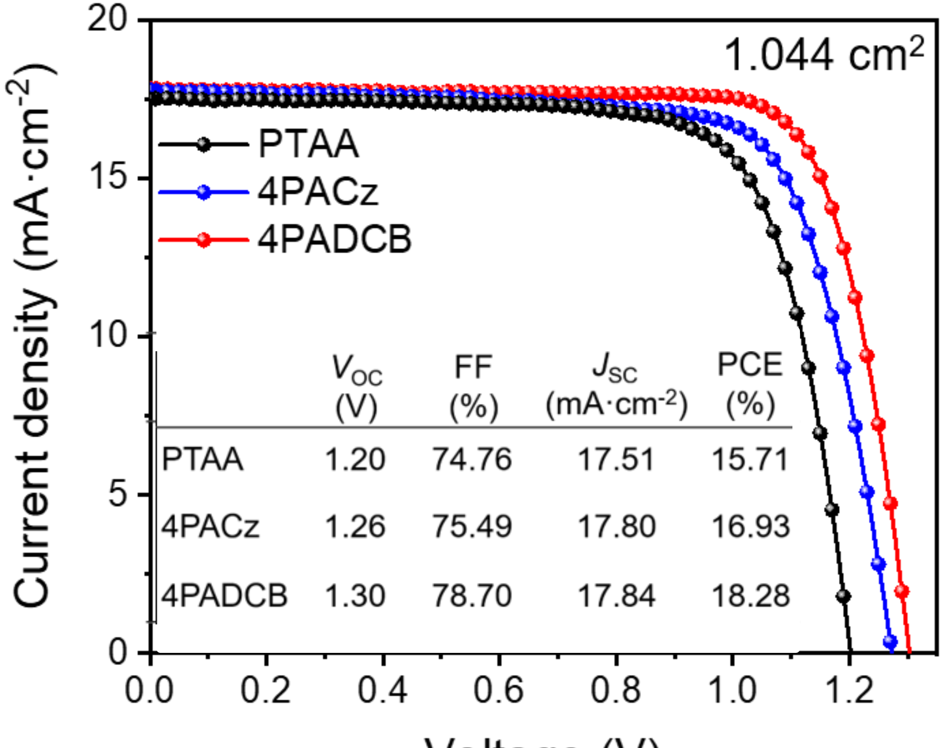
PTAA



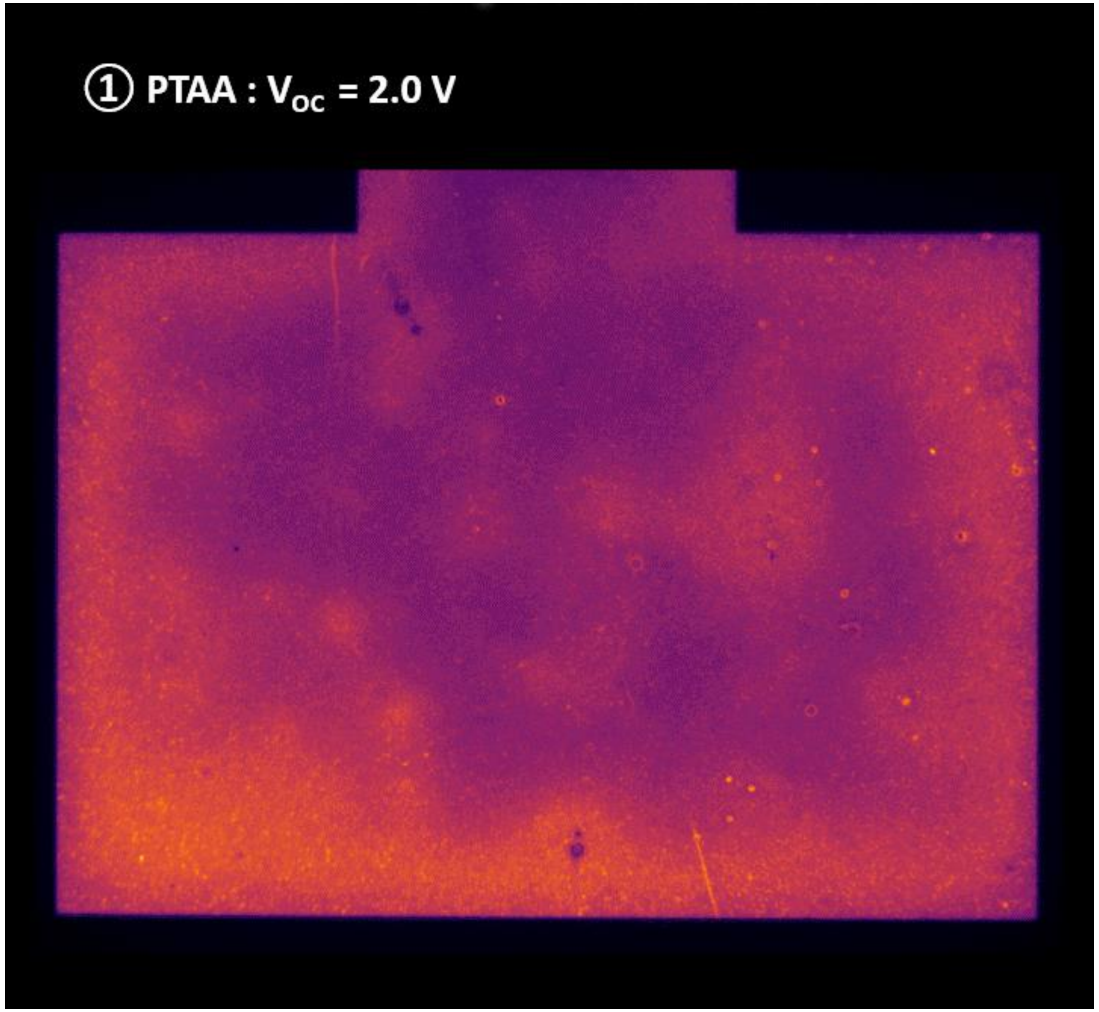
4PACz



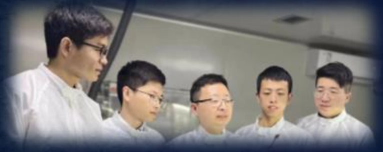
4PADCB

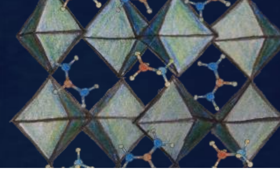


	V_{OC} (V)	FF (%)	J_{SC} (mA·cm^{-2})	PCE (%)
PTAA	1.20	74.76	17.51	15.71
4PACz	1.26	75.49	17.80	16.93
4PADCB	1.30	78.70	17.84	18.28

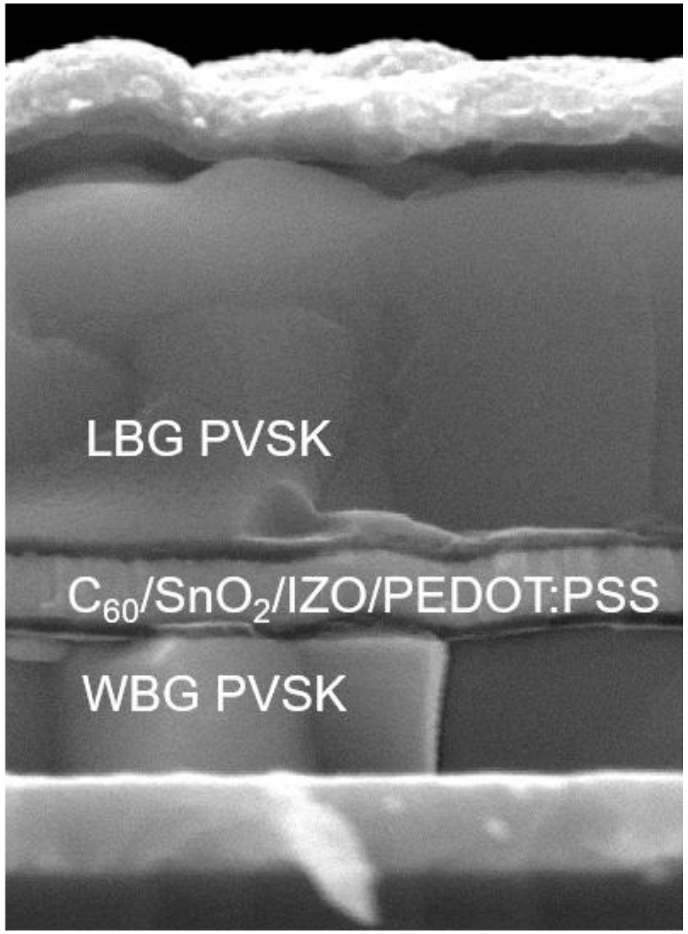


27% All-Perovskite Tandems





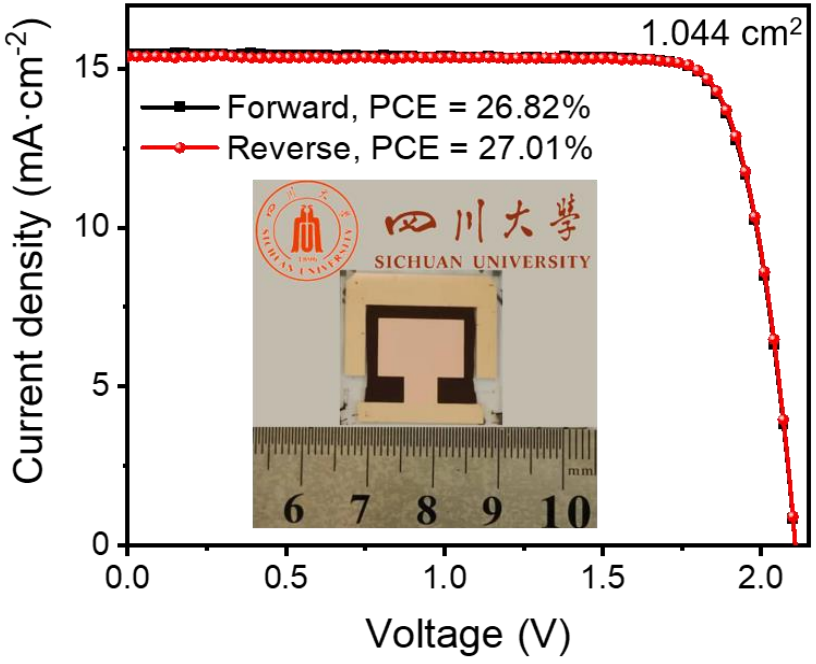
Prof. Zhao & Team @ Sichuan University

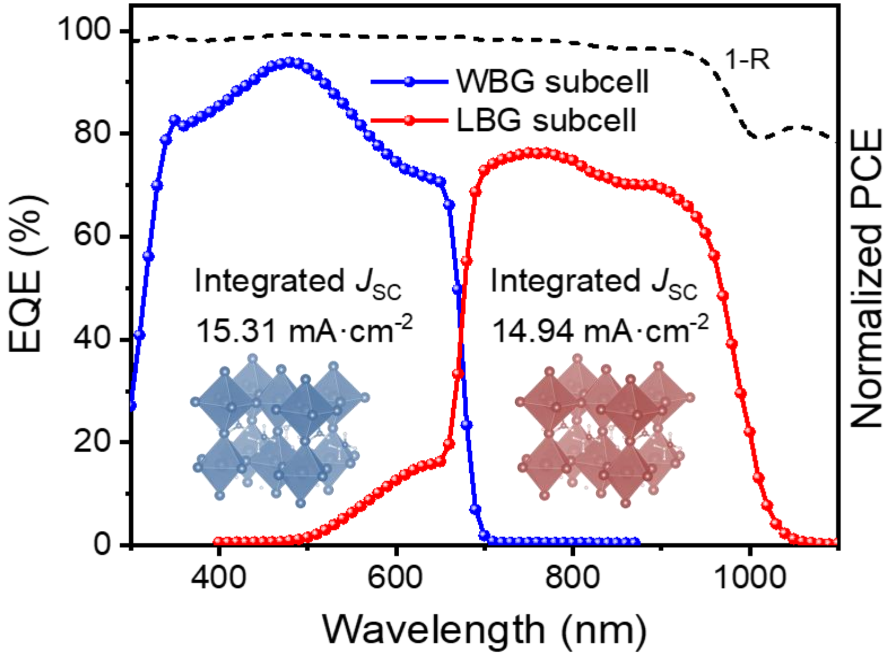


Article | Published: 29 March 2023

All-perovskite tandem 1 cm^2 cells with improved interface quality

Rui He, Wanhai Wang, Zongjin Yi, Felix Lang, Cong Chen, Jincheng Luo, Jingwei Zhu, Jarla Thiesbrummel, Sahil Shah, Kun Wei, Yi Luo, Changlei Wang, Huagui Lai, Hao Huang, Jie Zhou, Bingsuo Zou, Xinxing Yin, Shengqiang Ren, Xia Hao, Lili Wu, Jingquan Zhang, Jinbao Zhang, Martin Stolterfoht, Fan Fu, ... Dewei Zhao
+ Show authors



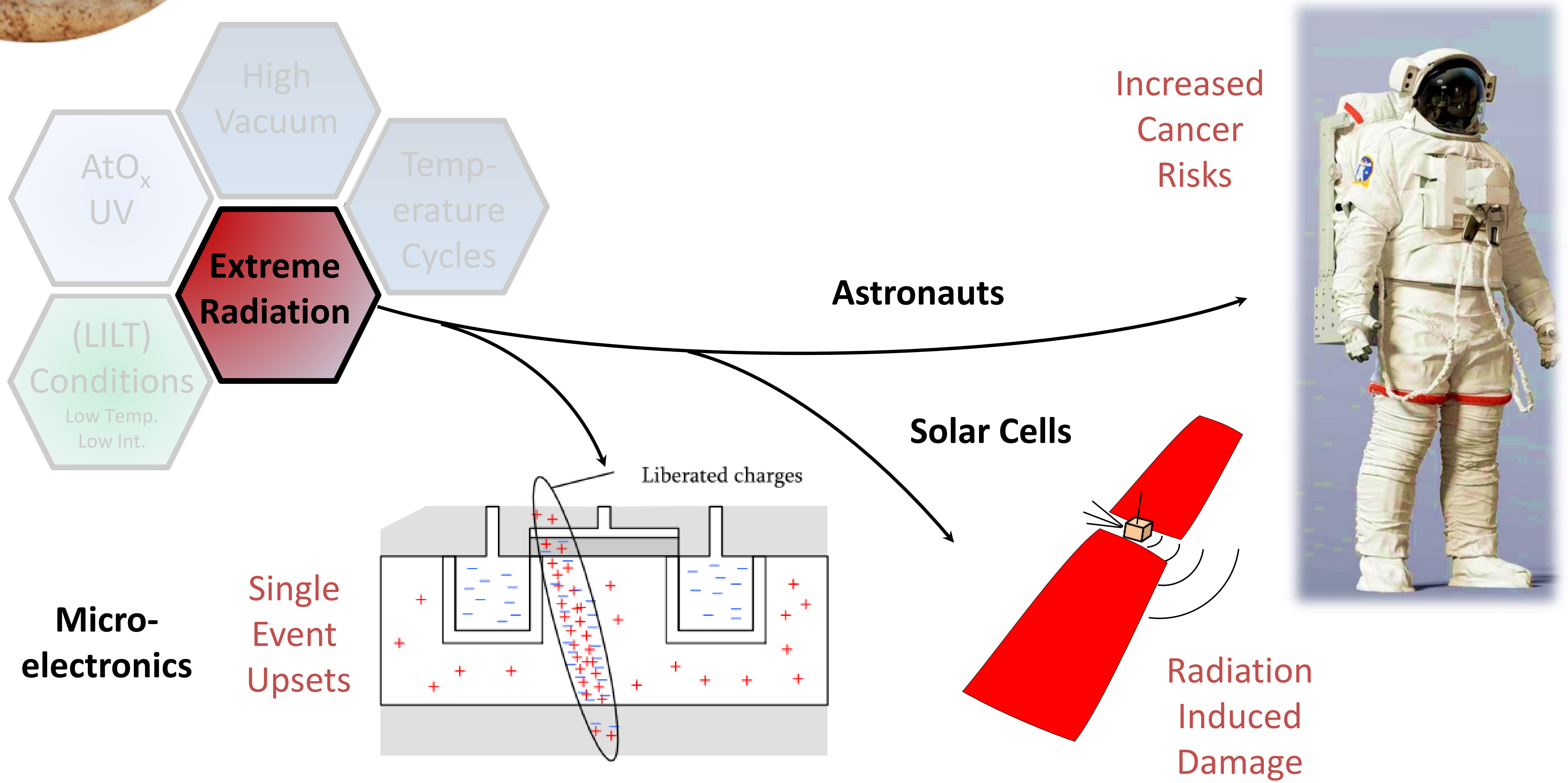


nature

R. He, W. Wang, Z. Yi, F. Lang et al.

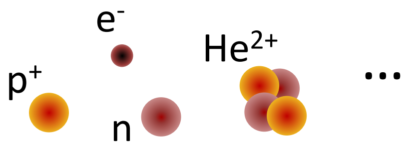
Space Solar Cells on ISS: 215kWatt Power

The Harsh Radiation Environment in Space

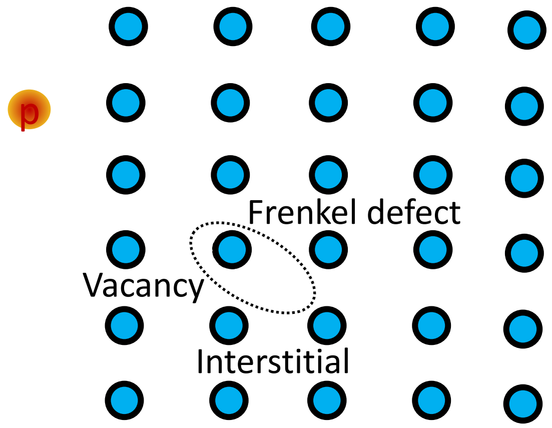


(1) Todd, B.; Uznanski, S. Radiation Risks & Mitigation in Electronic Systems. *CAS - Cern Accel. Sch. Power Convert.* **2015**, *003* (May 2014), 1–19. https://doi.org/10.5170/CERN-2015-003.245.

Radiation Damage → Electronic Defects



Nuclear Scattering Displacement Damage



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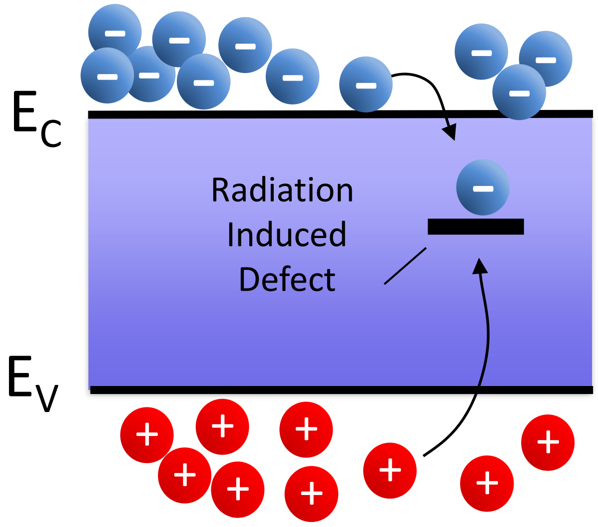

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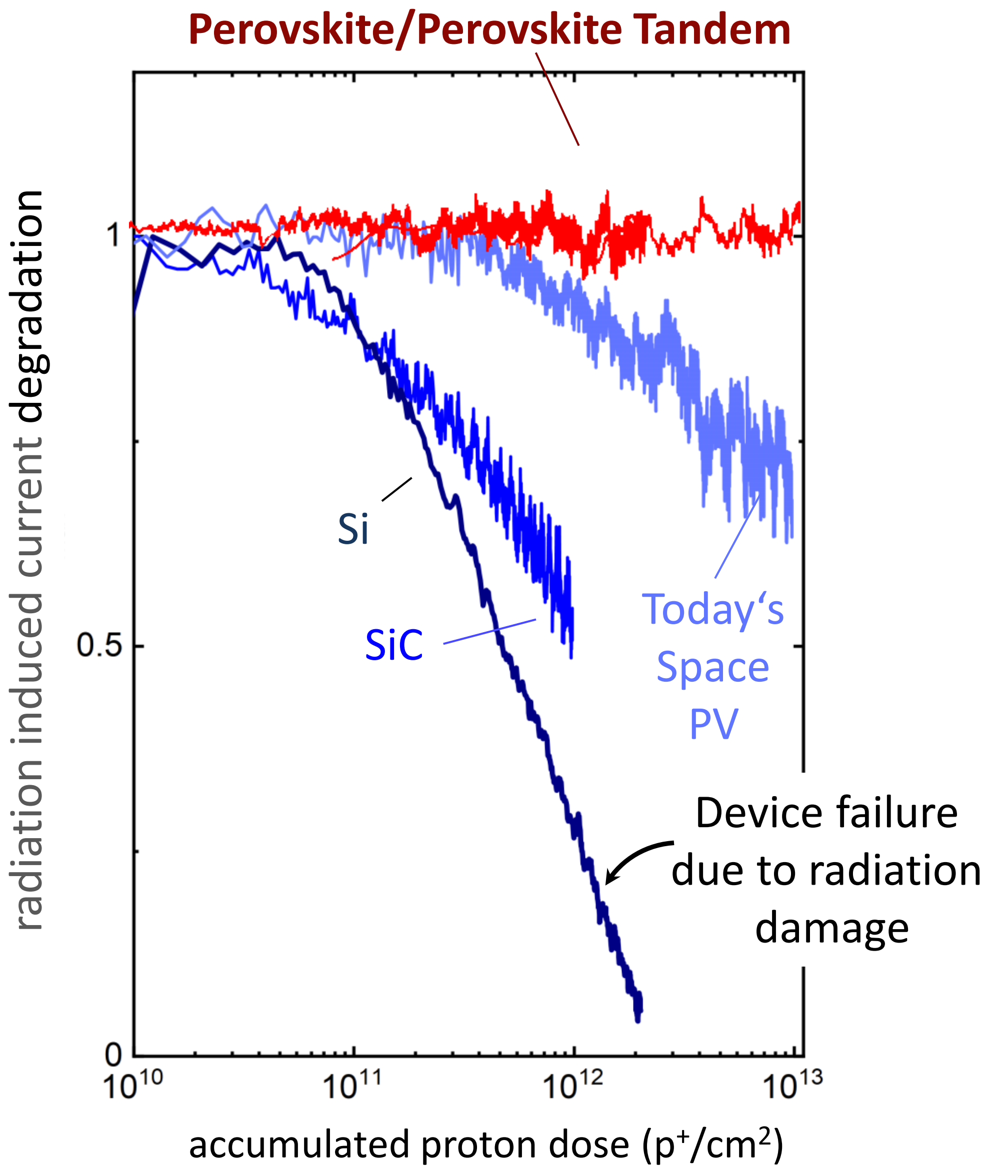
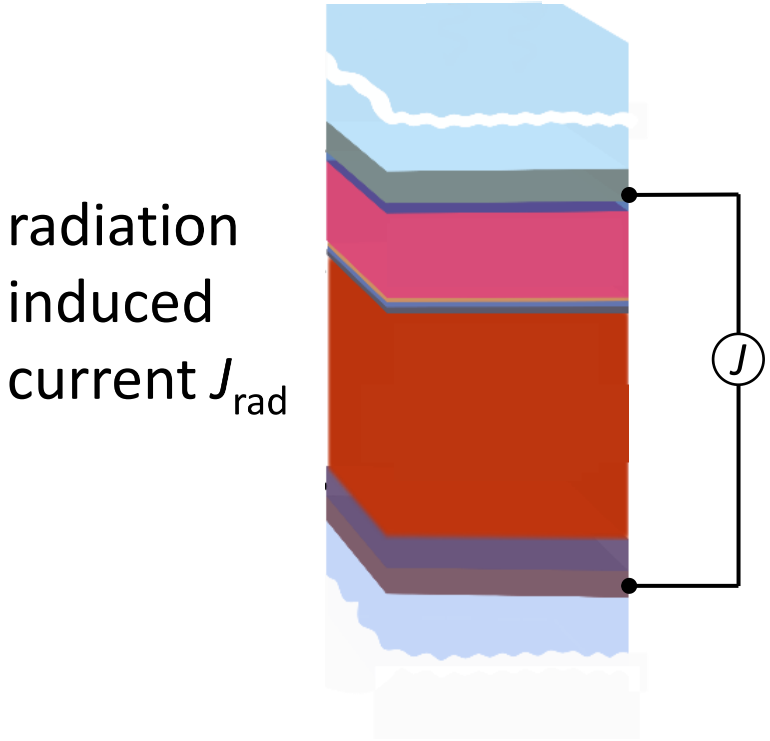
"A leak for electrons"

In-situ Measurements under Proton Irradiation

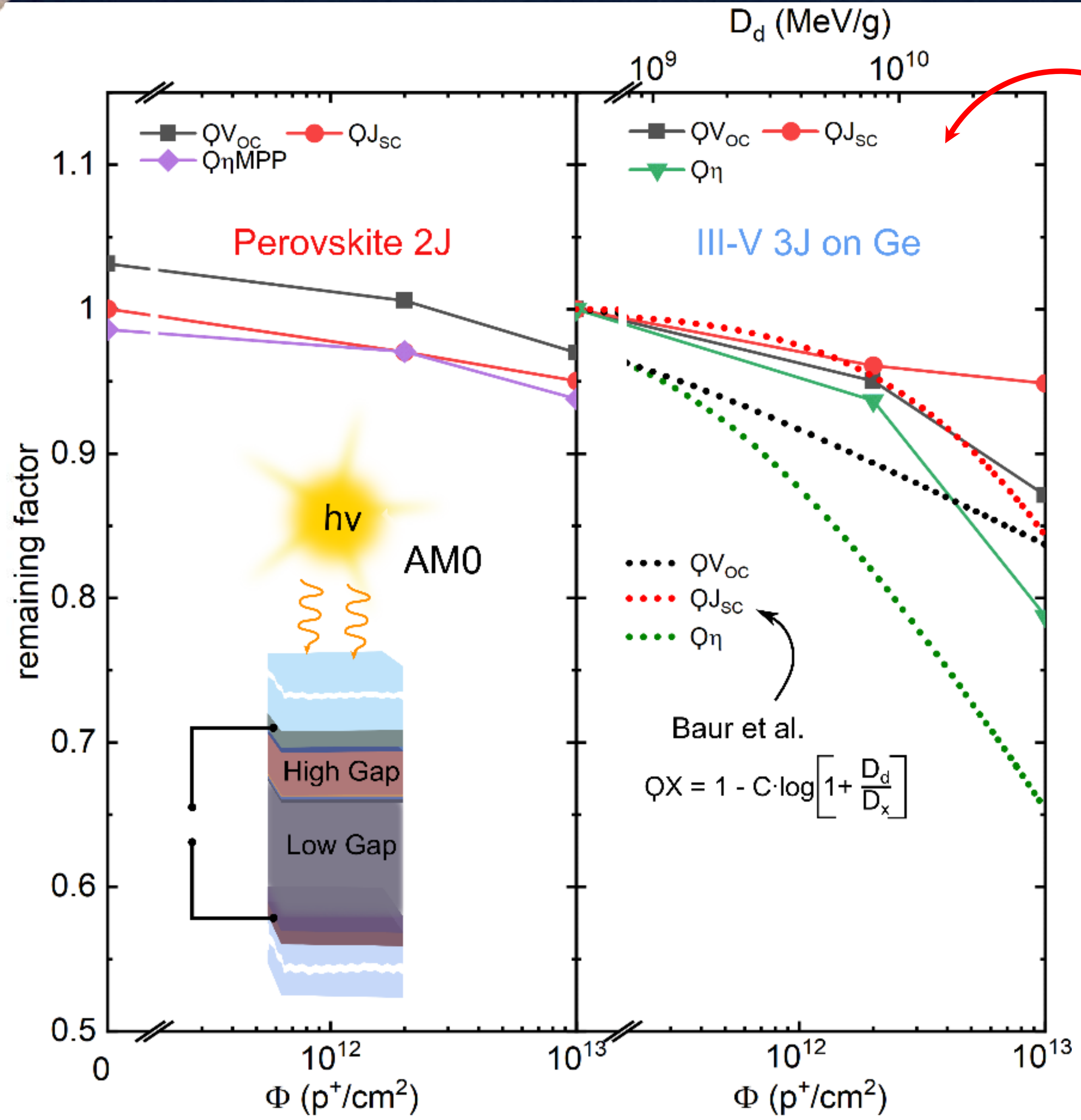




Dr. Giles Eperon

Perovskite/Perovskite Tandem extraordinarily stable !

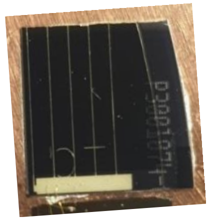
Damage under AM0 illumination



~100 years in LEO
~10 years in GEO
~1 year around Jupiter

Dr. Giles Eperon

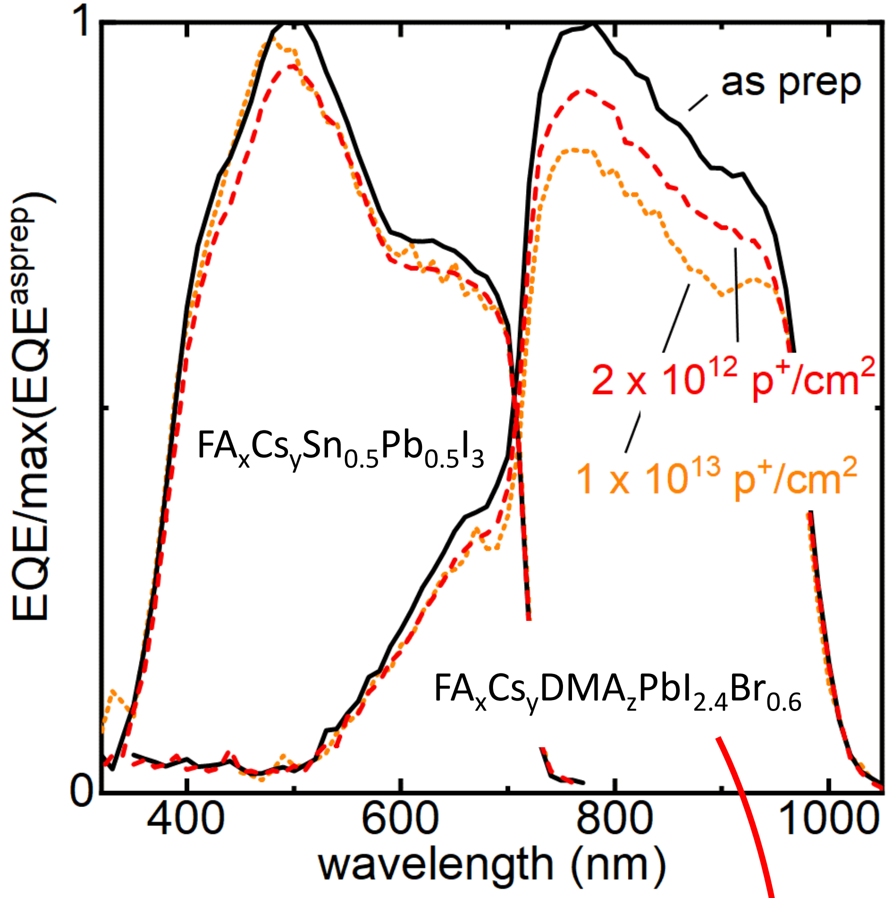
Commercial III-V triple junction space solar cell



	Φ (p^+/cm^2)
	1×10^{13}
Perovskite 2J	**0.94**
III-V 3J on Ge this exp.	**0.78**
III-V 3J on Ge Baur et al.	**0.65**

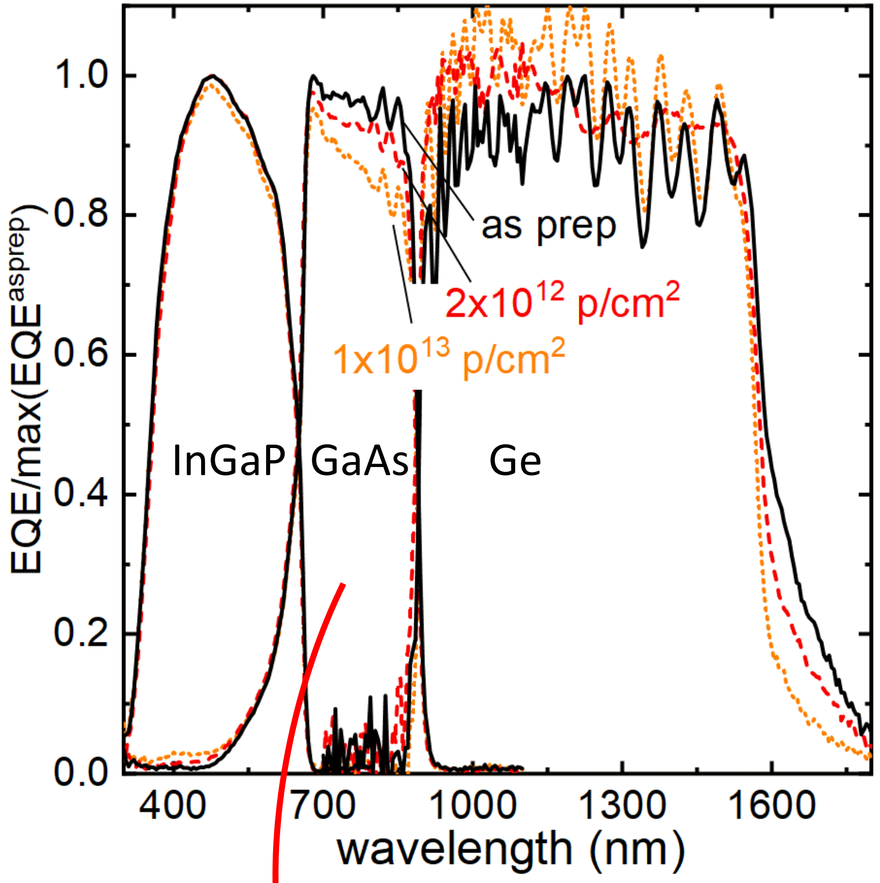
Degradation in Spectral Response

Perovskite 2J



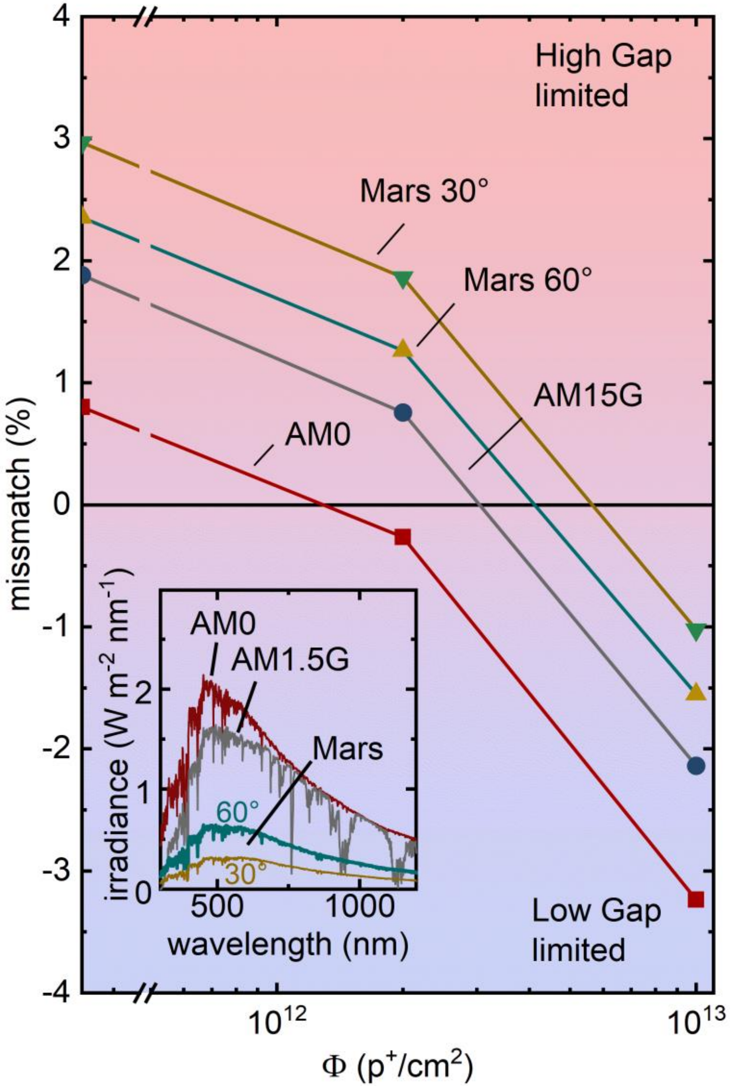
Radiation damage in the low gap bottom subcell

III-V 3J on Ge

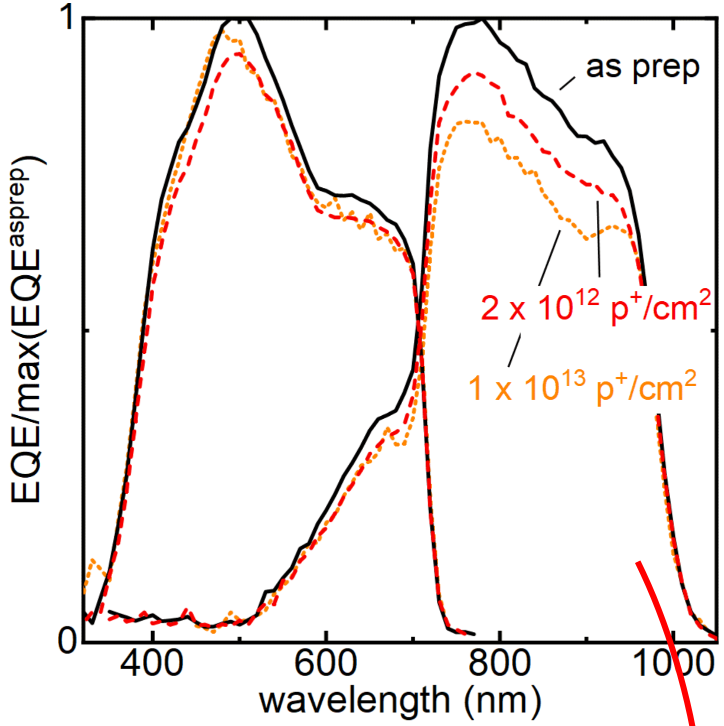


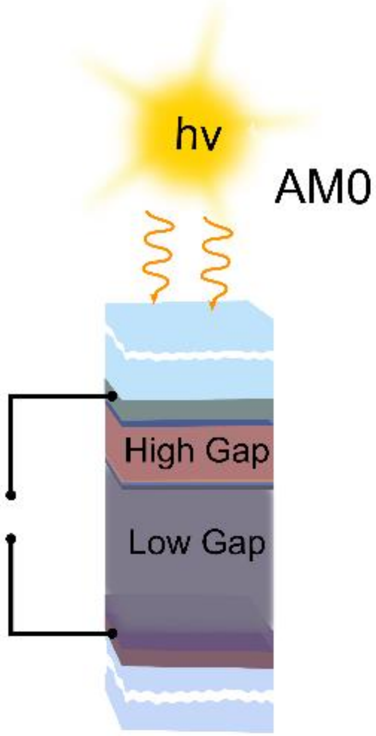
Radiation Damage in the GaAs middle subcell

Fun Fact: Radiation Hardness & Sun Spectrum



Perovskite 2J

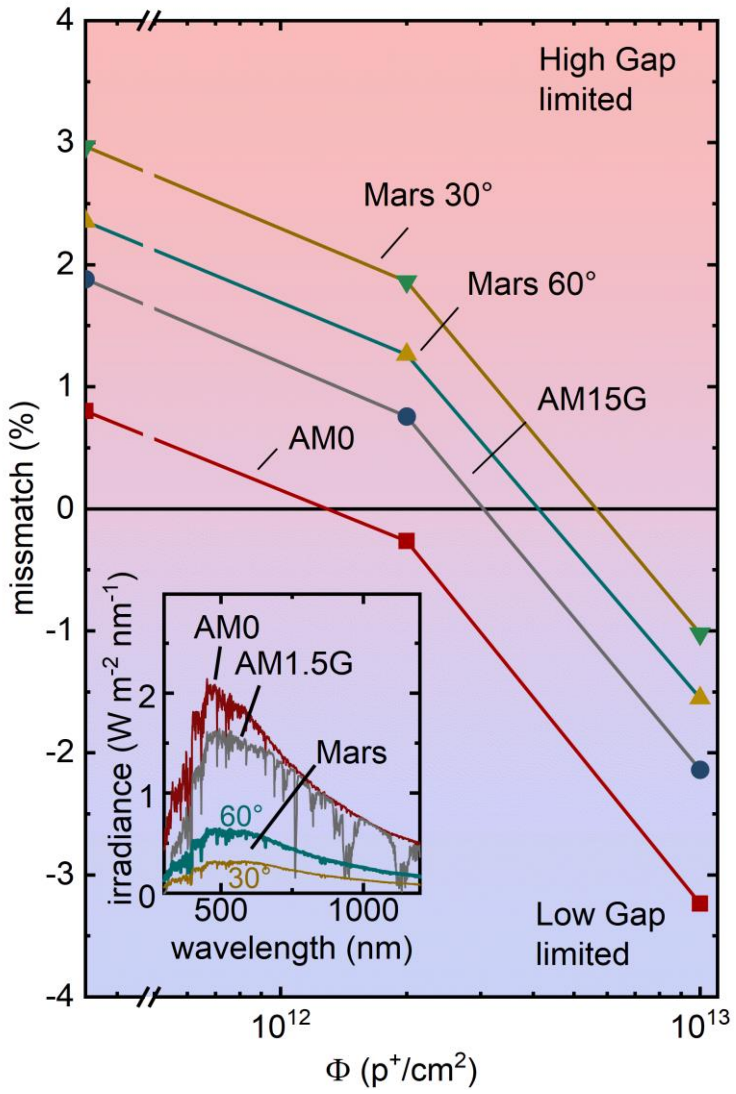




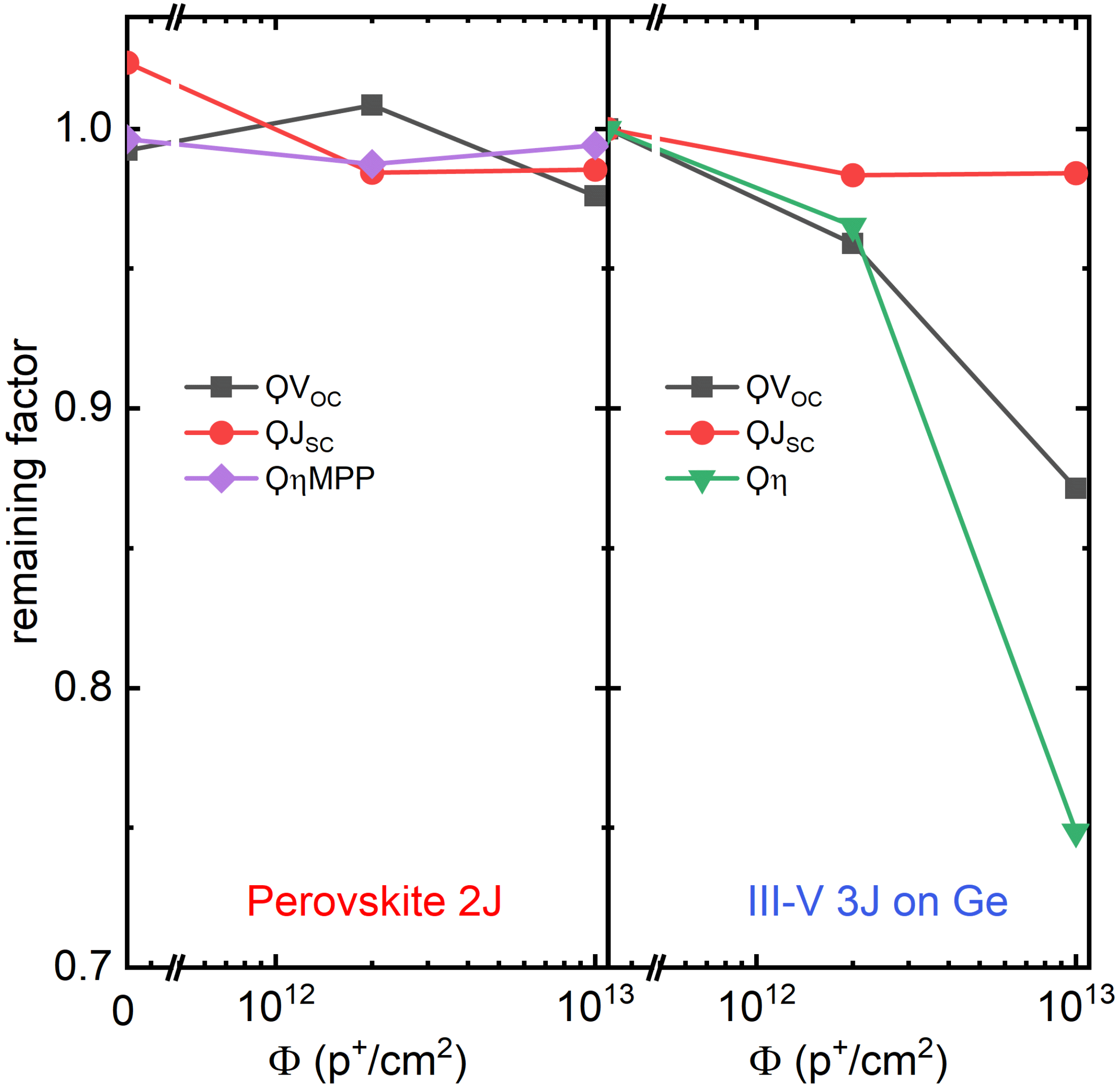
Radiation damage in the low gap bottom subcell

Will this subcell damage limit the Tandem ?

Fun Fact: Radiation Hardness & Sun Spectrum



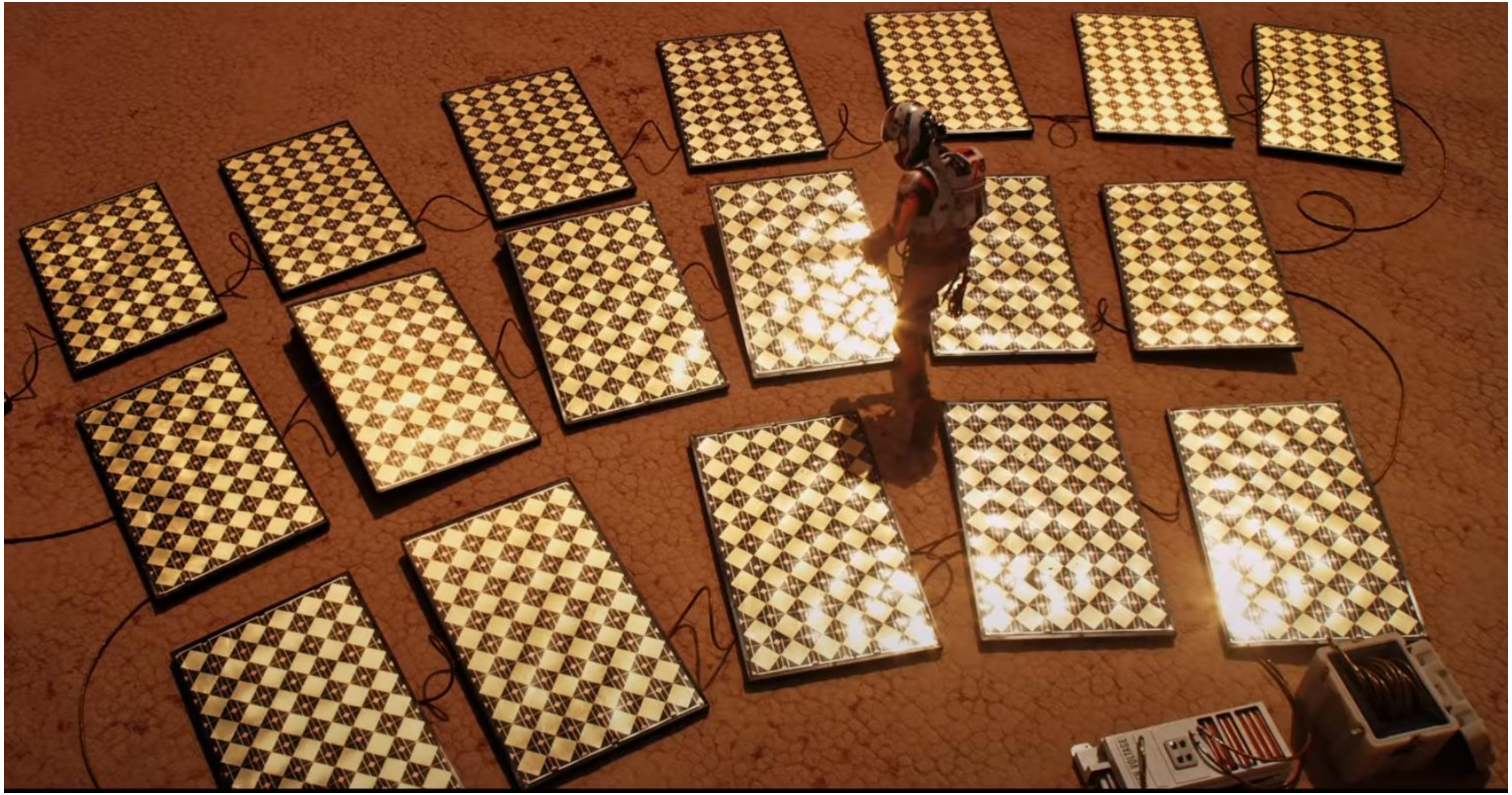
Under AM1.5G or Mars Spectrum



Perovskite/Perovskite Tandem PV for Mars

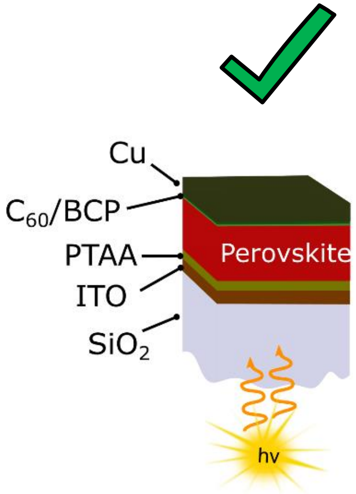
Picture from the Movie „The Martian “

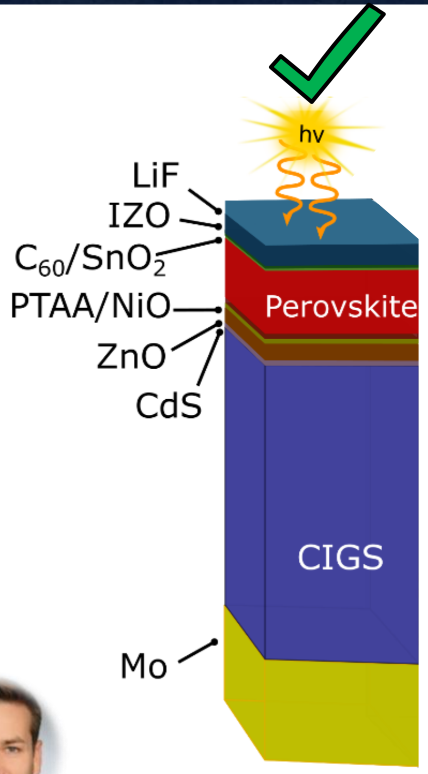
Perovskite/Perovskite Tandem PV for Mars

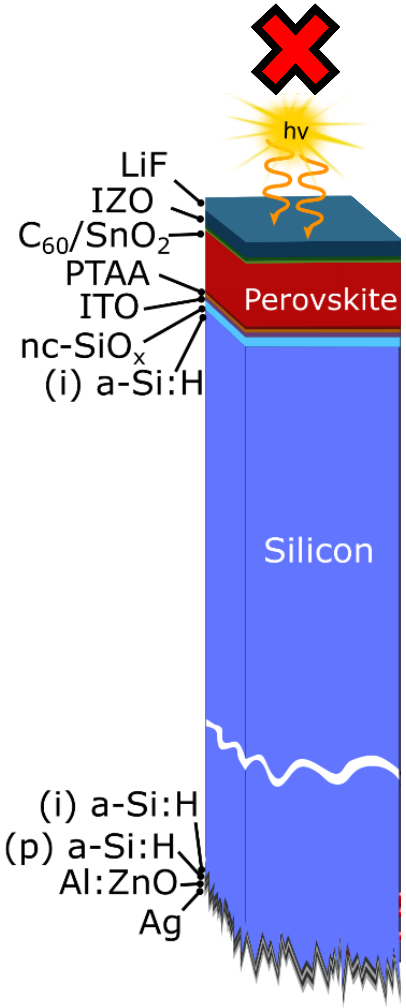


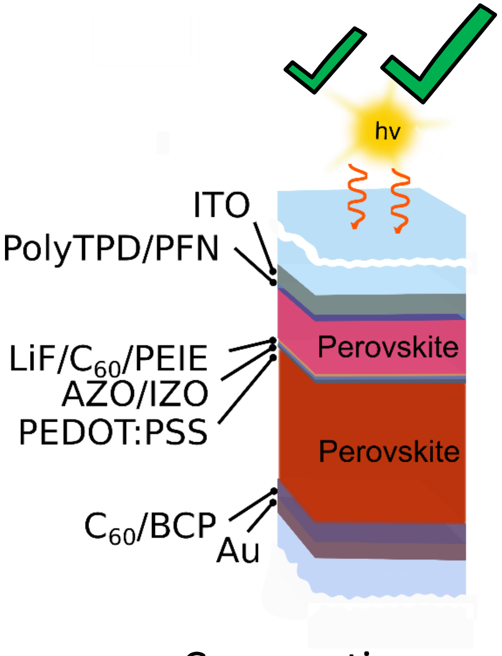
Picture from the Movie „The Martian “

Radiation Hardness Overview









Cooperation with

Prof. Steve Albrecht

HZB Helmholtz Zentrum Berlin

HySPRINT Helmholtz Innovation Lab

Joule

Alexander von Humboldt Stiftung / Foundation

STRANKS LAB

UNIVERSITY OF CAMBRIDGE

Cooperation with

Dr. Giles Eperon

NREL NATIONAL RENEWABLE ENERGY LABORATORY

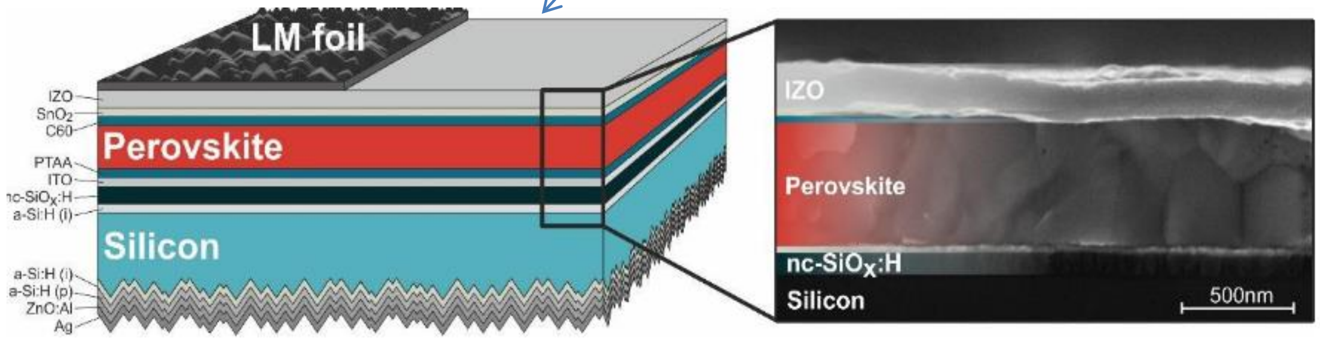
SwiftSolar

Lang F. et al. (2021) **Adv. En. Mat**,
Lang F. et al. (2020) **Joule**, 4, 1054–1069
Lang F. et al. (2019) **Energy & Environmental Science** 12 (5), 1634
Lang F. et al. (2018) ***Adv. Mater***. 30, 1702905 (2018).
Lang F. et al. (2016) **Advanced Materials** , 28 (39), 8726

In-Situ Example: Perovskite/SHJ Tandem

Dr. Marco Jost
Prof. Steve Albrecht

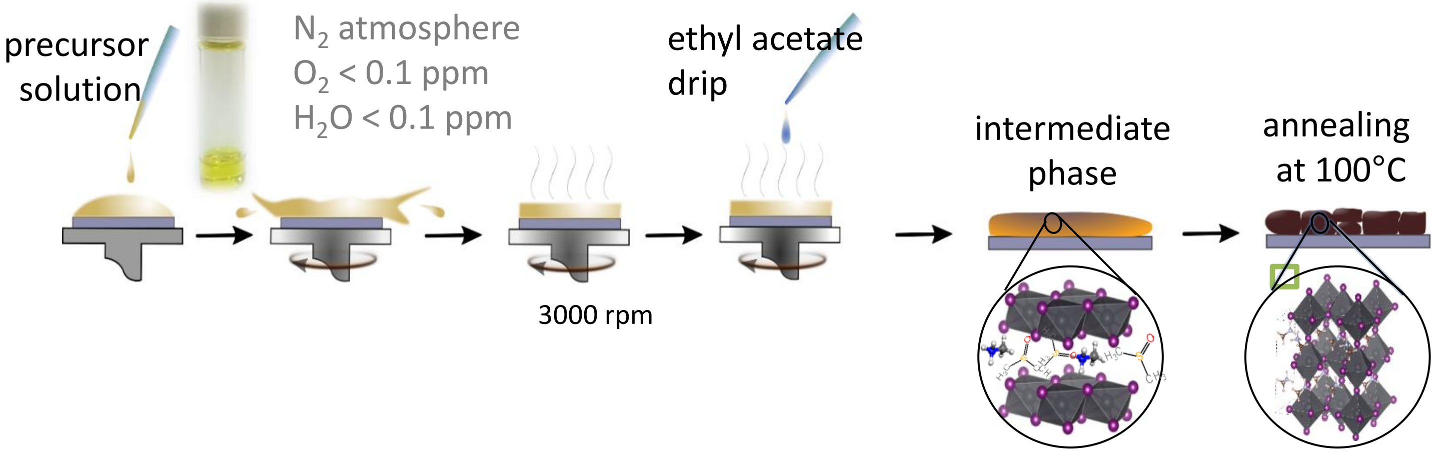
25.5%   23.4%

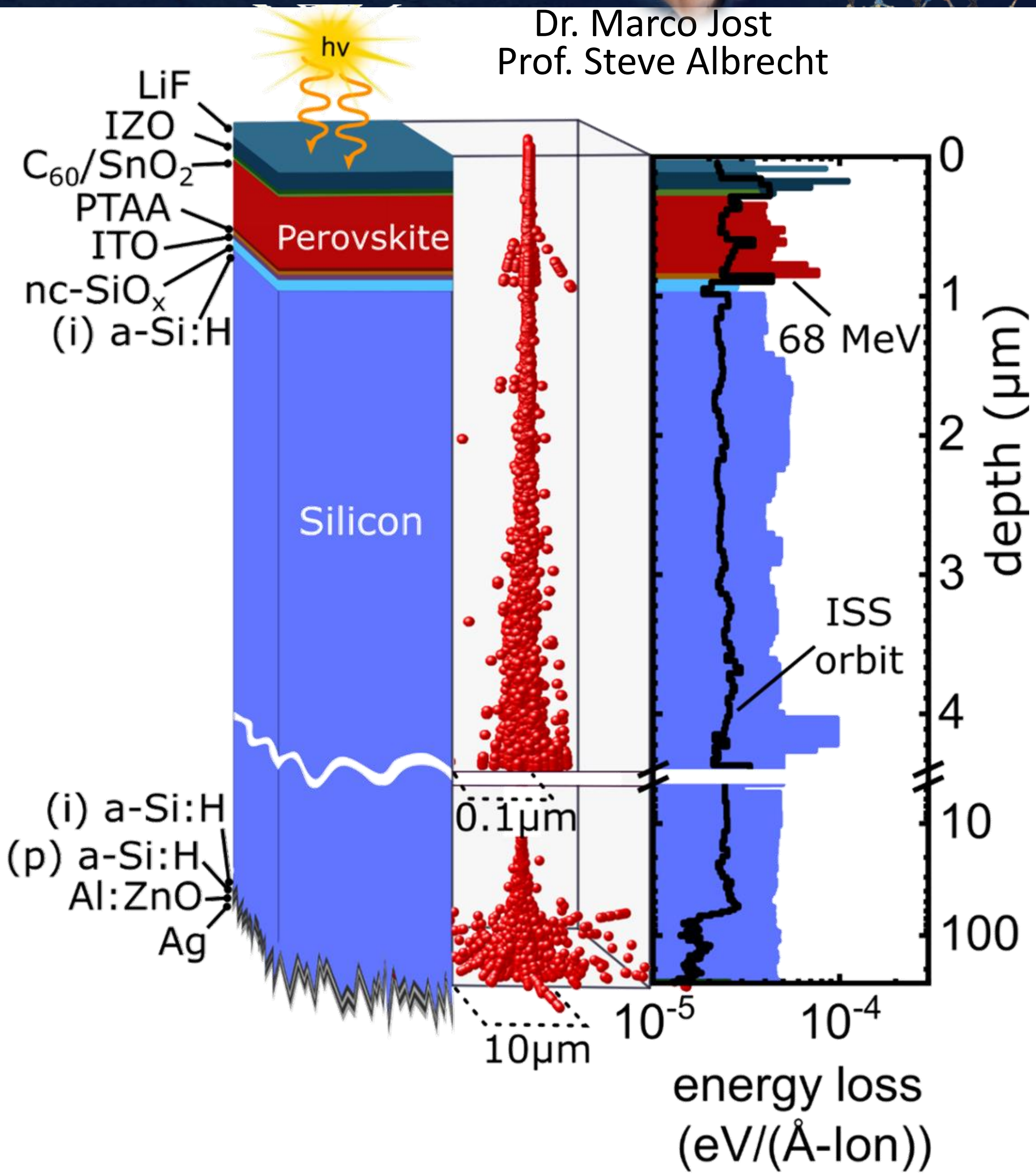


Jošt, M., (2019). *Energy & Environmental Science*.

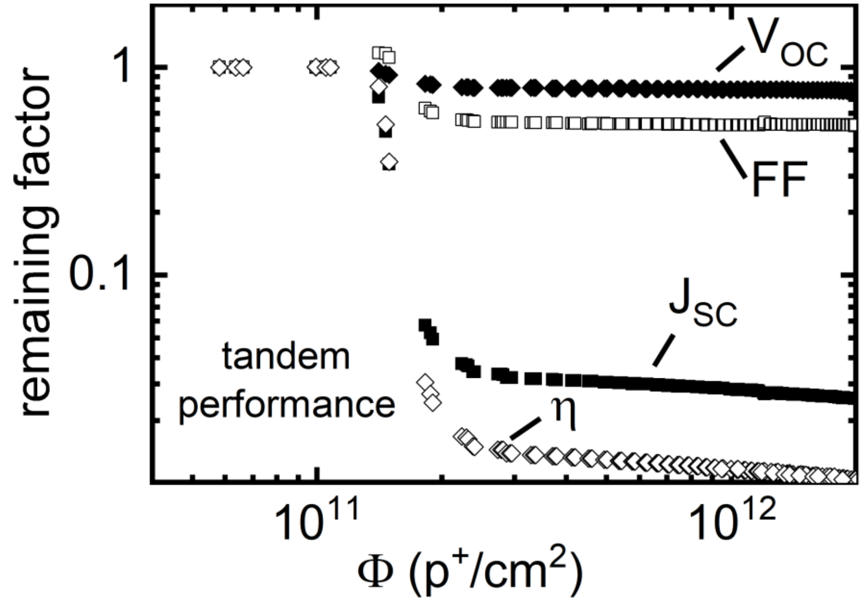
Triple Cation Perovskite

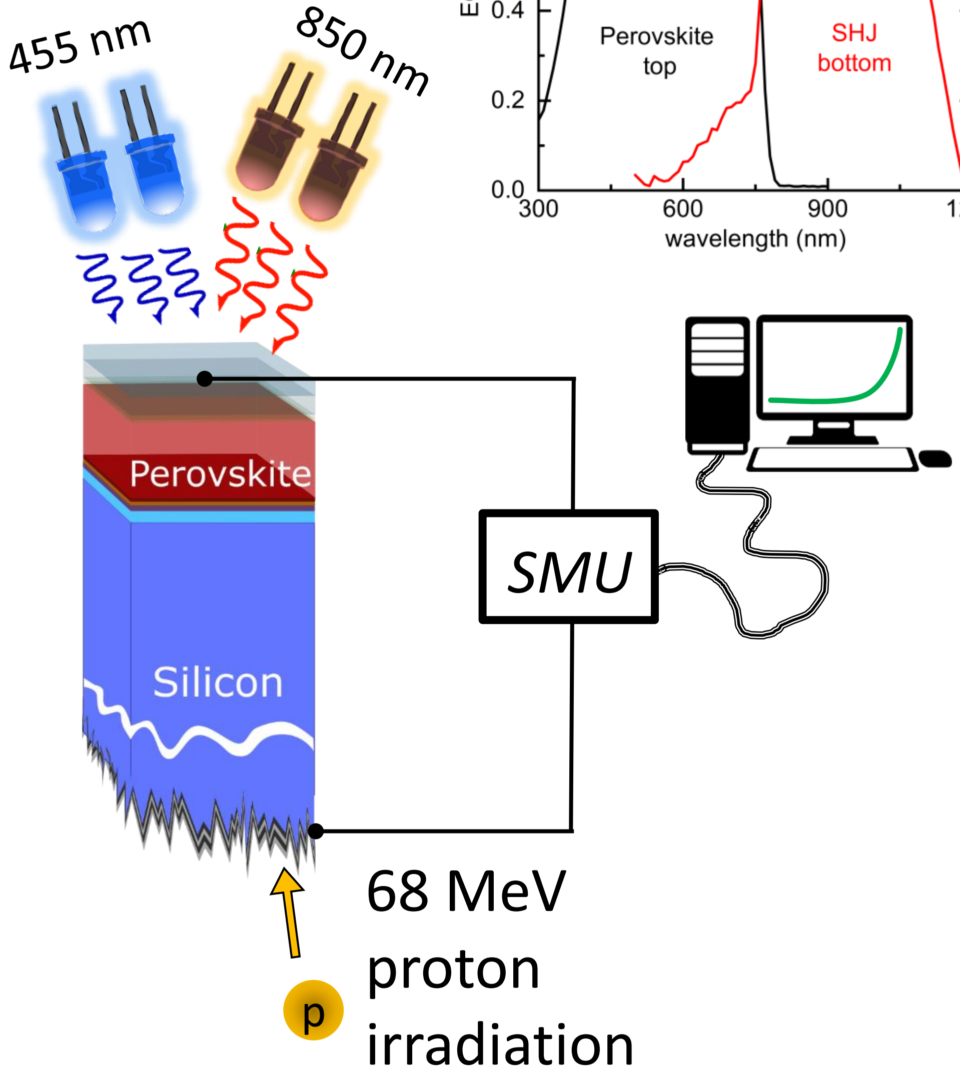
$[Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}]Pb(I_{0.83}Br_{0.17})_3$

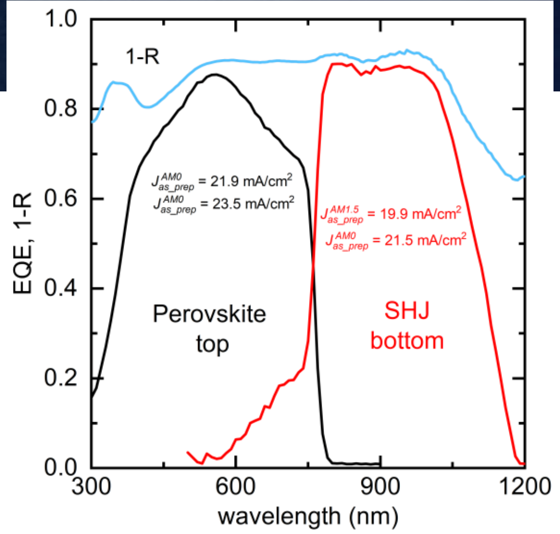




In-Situ Example: Perovskite/SHJ Tandem

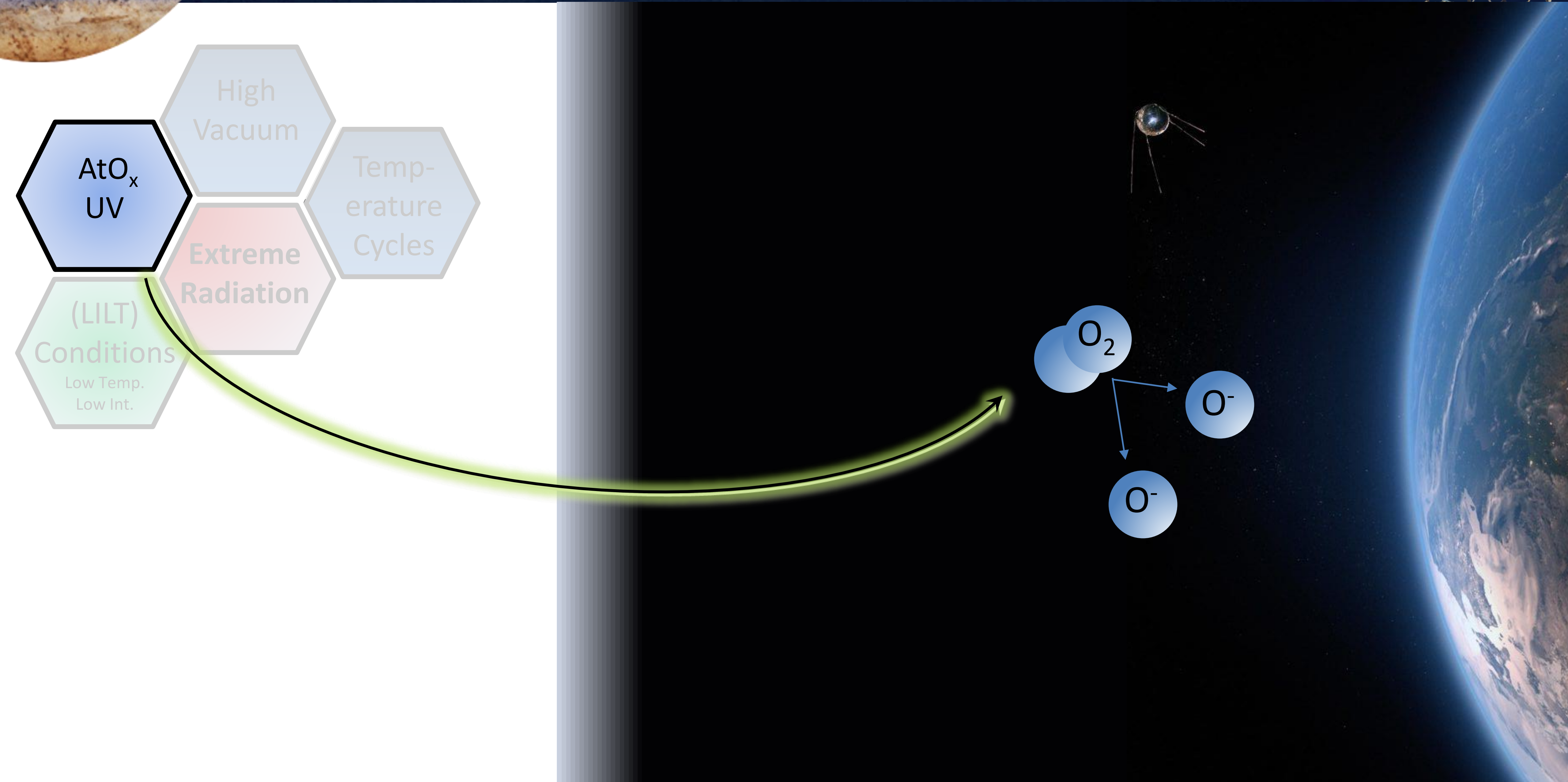




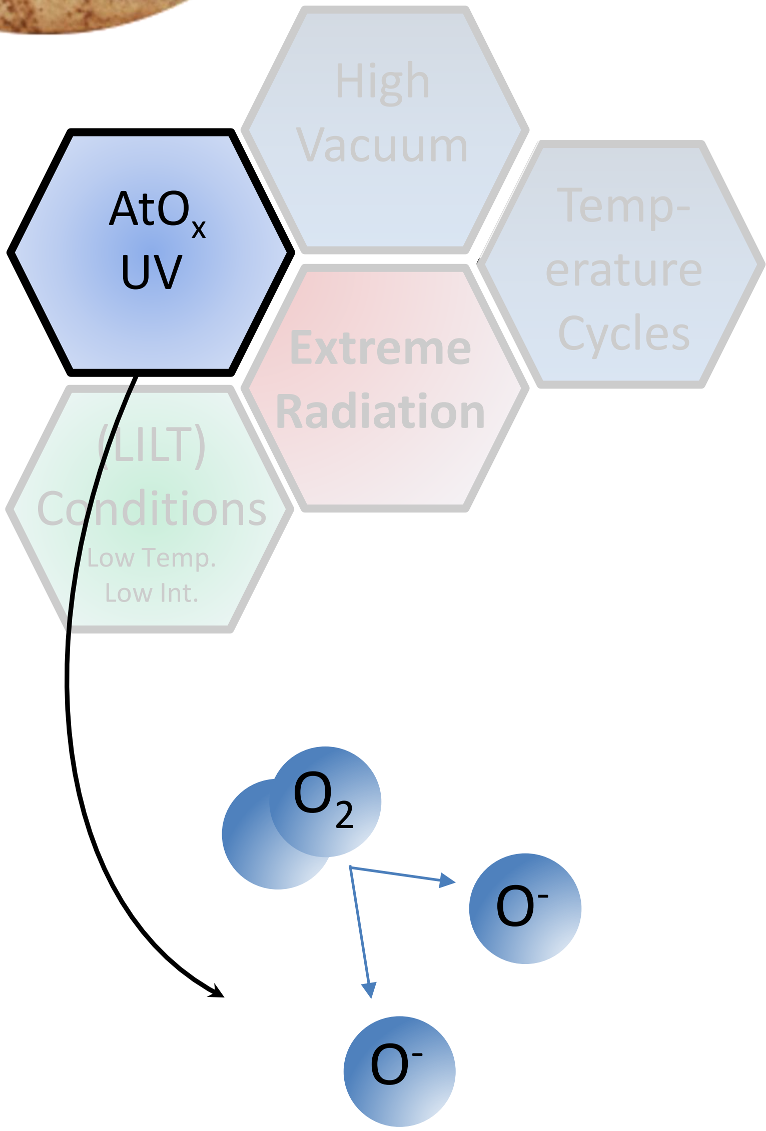


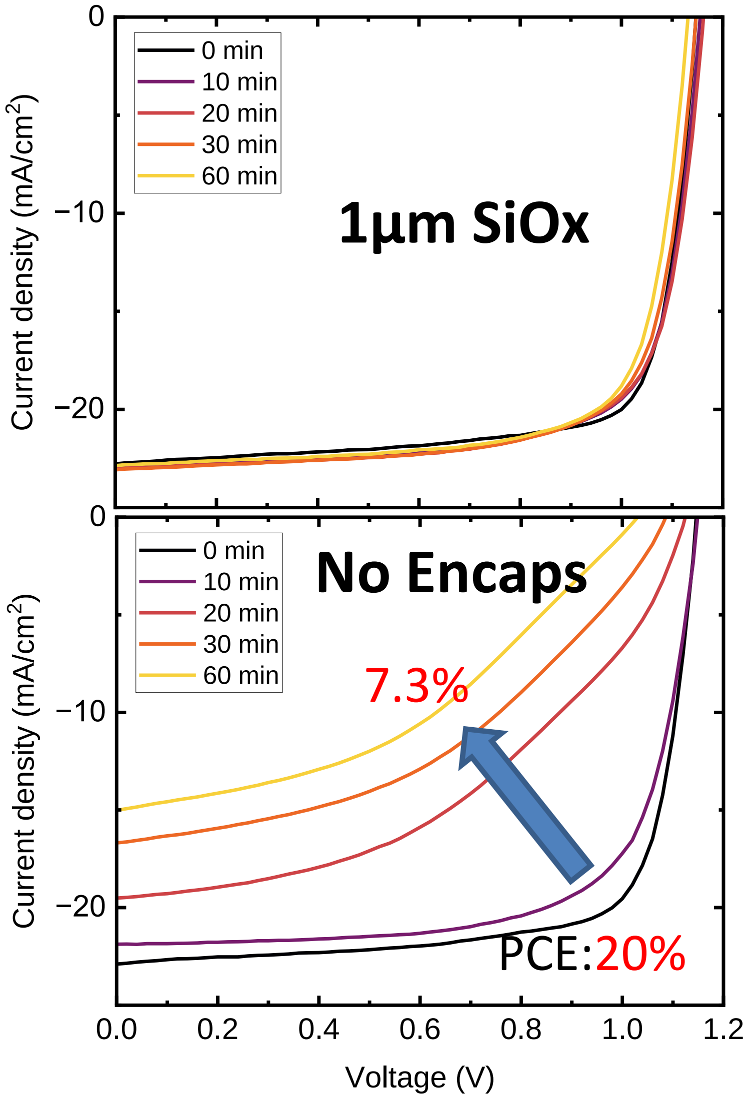
Lang, F., et al. Joule, 4(5), 1054–1069, 2020

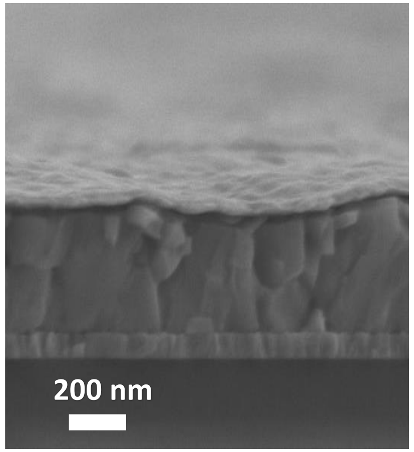
Atomic Oxygen AtOx



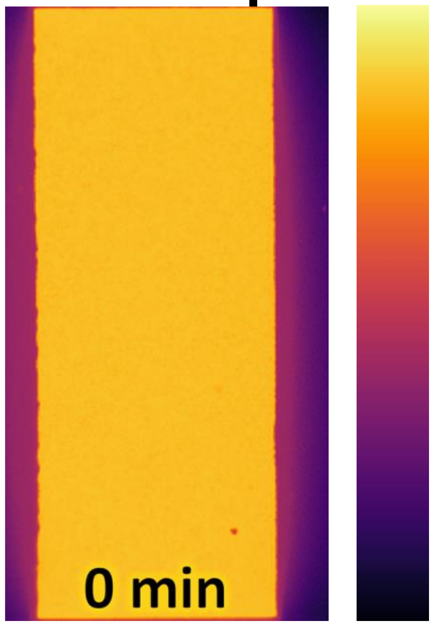
Ph.D. student
Biruk Alebachew





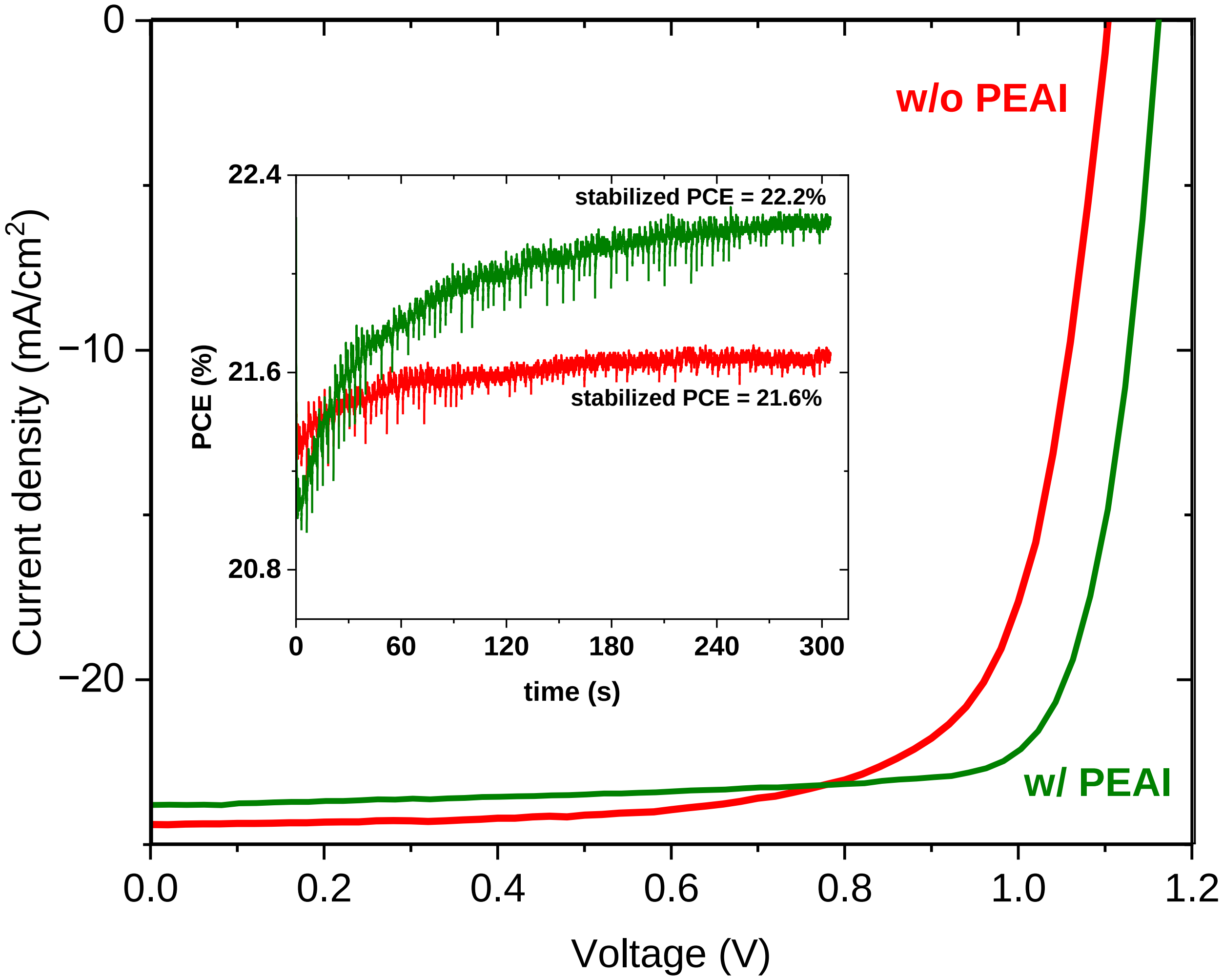


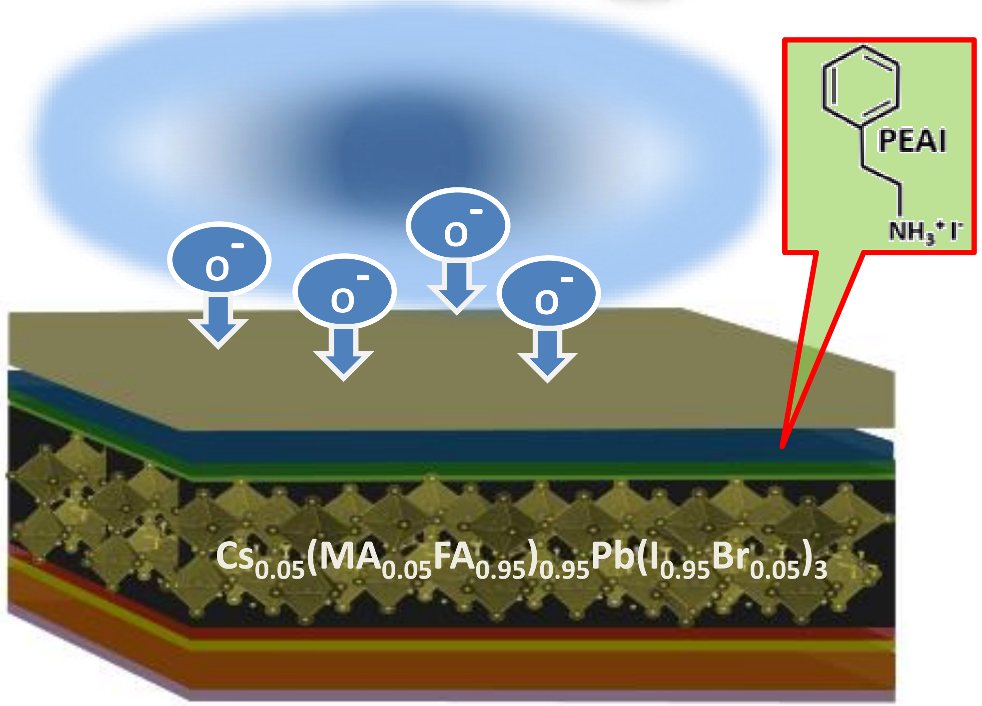
No Encaps



2D/3D Perovskite Single Junctions

Ph.D. student
Biruk Alebachew





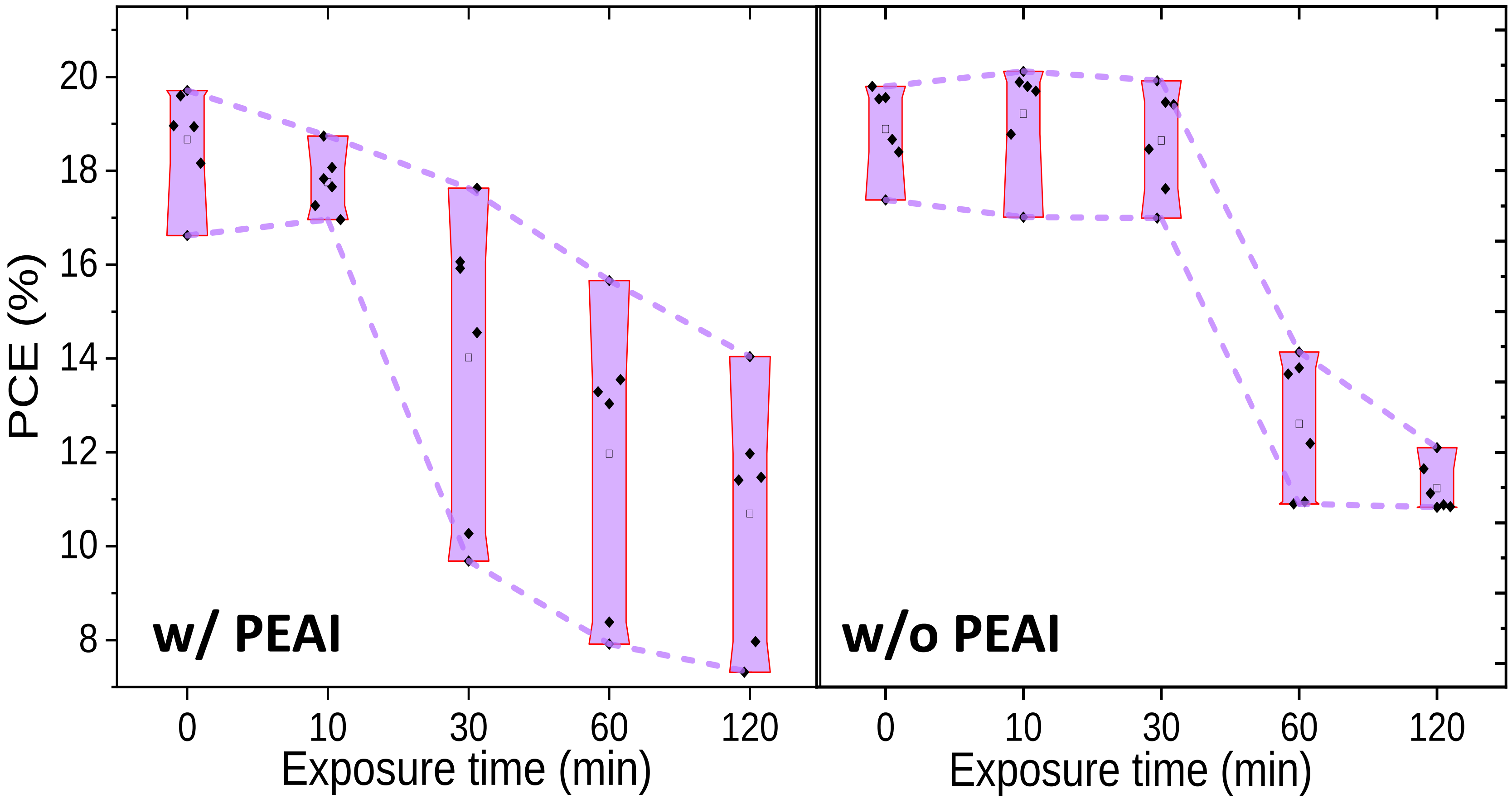
Will they be stable under AtOx ?

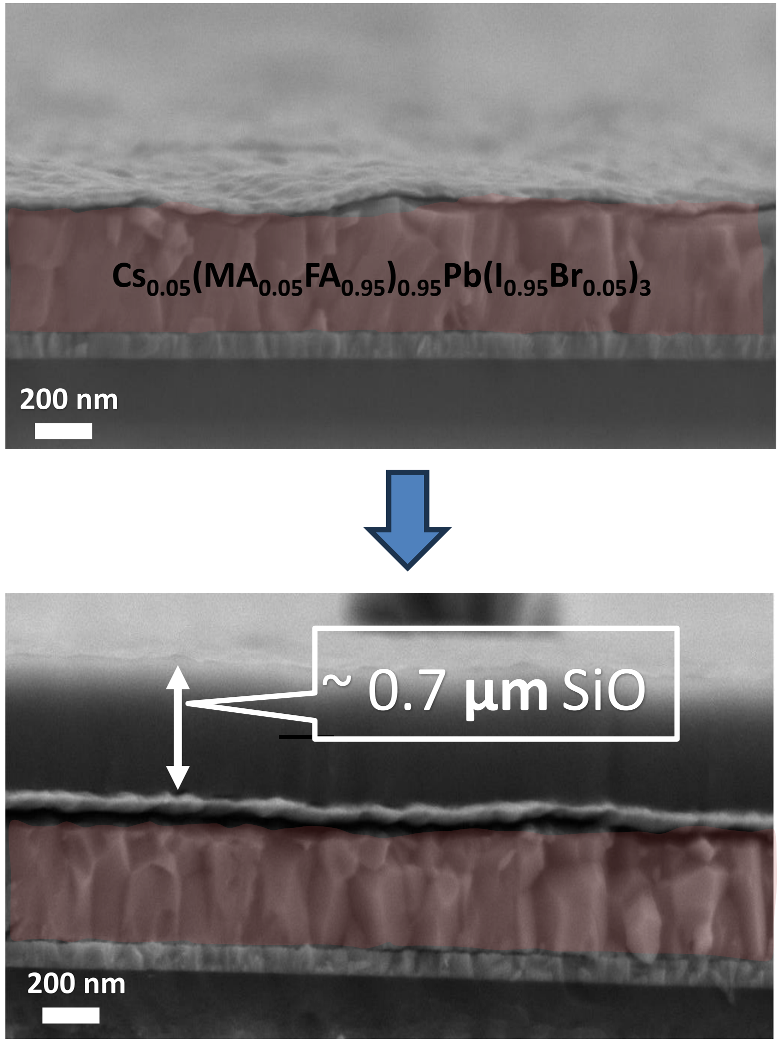
PEAI-interlayer improves the PCE and known to improve moisture stability as well

Seid, et al. Small, 2024

Ph.D. student
Biruk Alebachew

2D/3D Perovskite SC's degrade faster and more severe

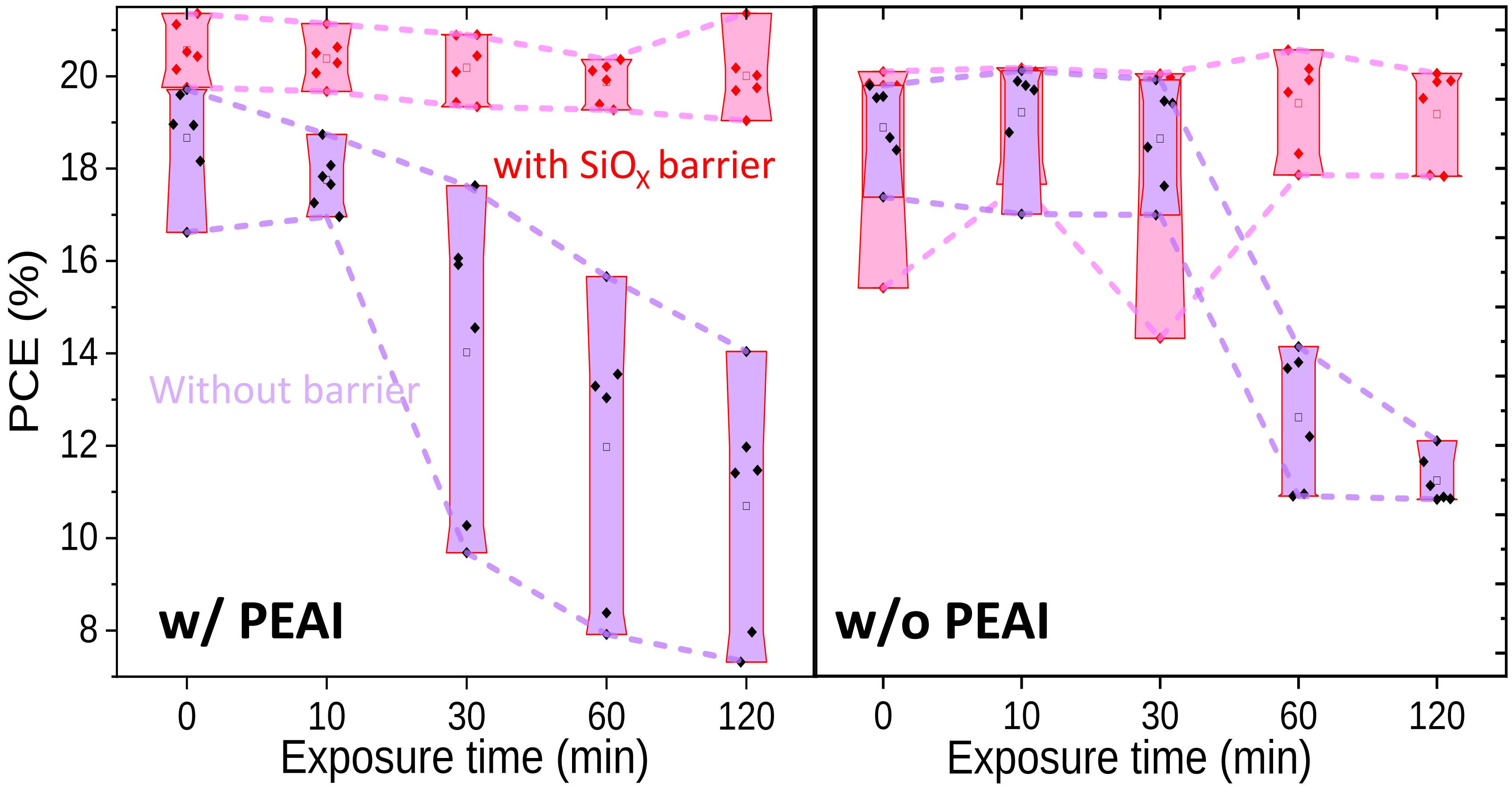


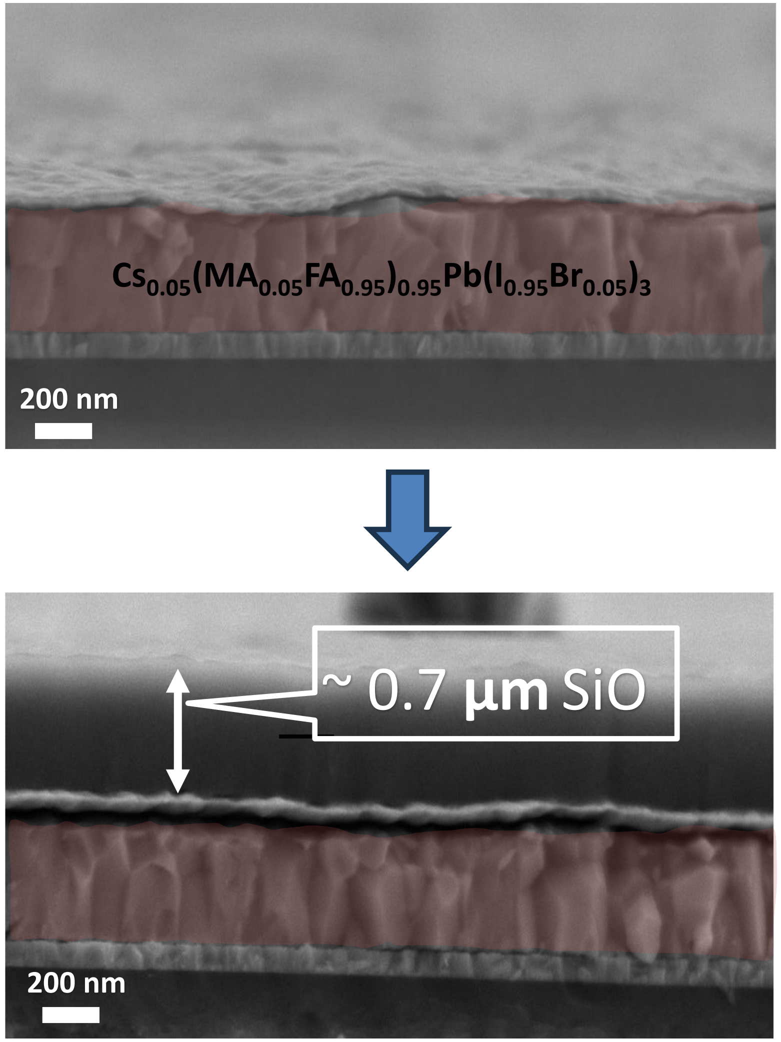


Seid, et al. Small, 2024

AtOx Degradation + SiOx Barrier

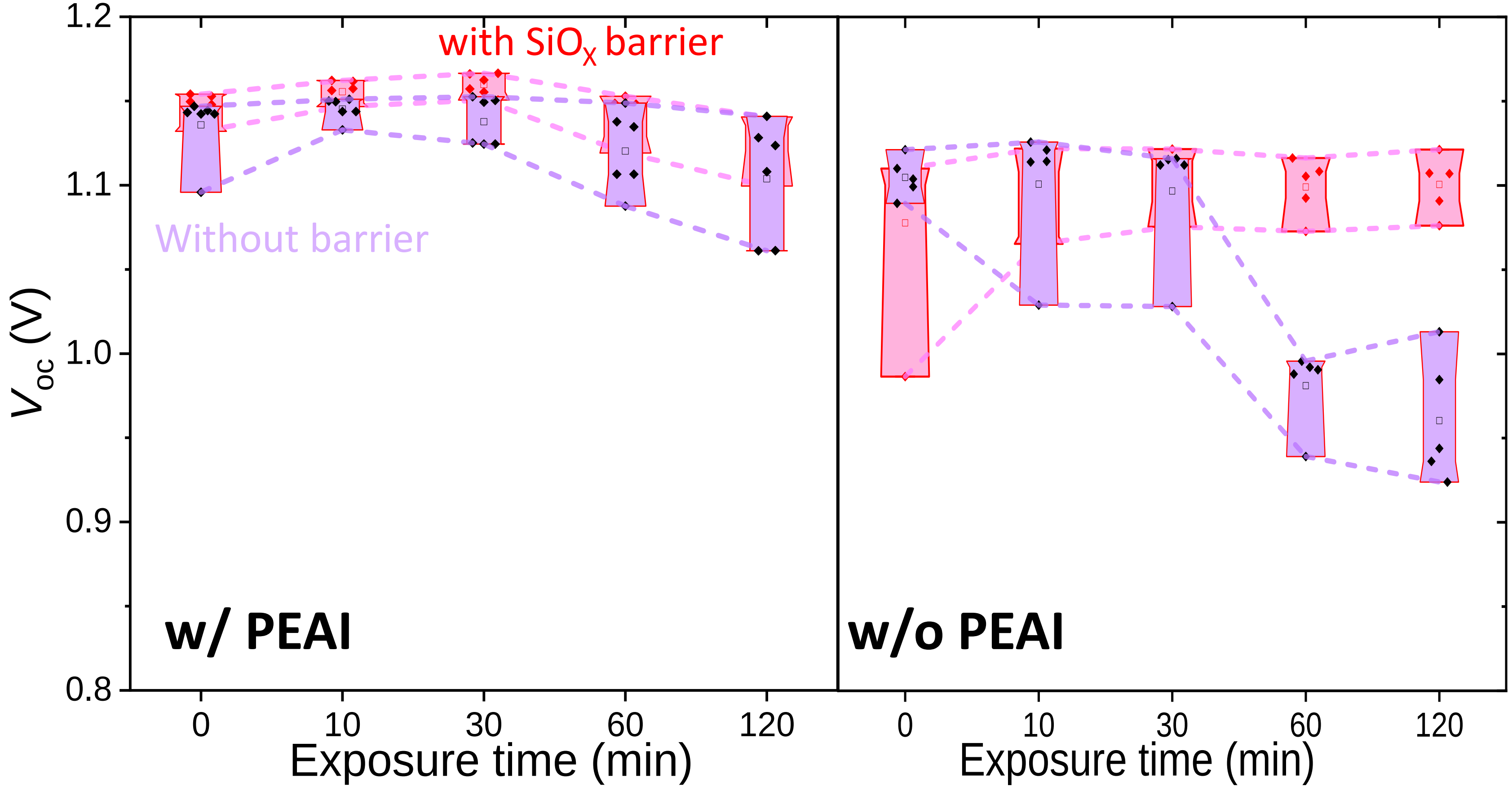
Ph.D. student
Biruk Alebachew

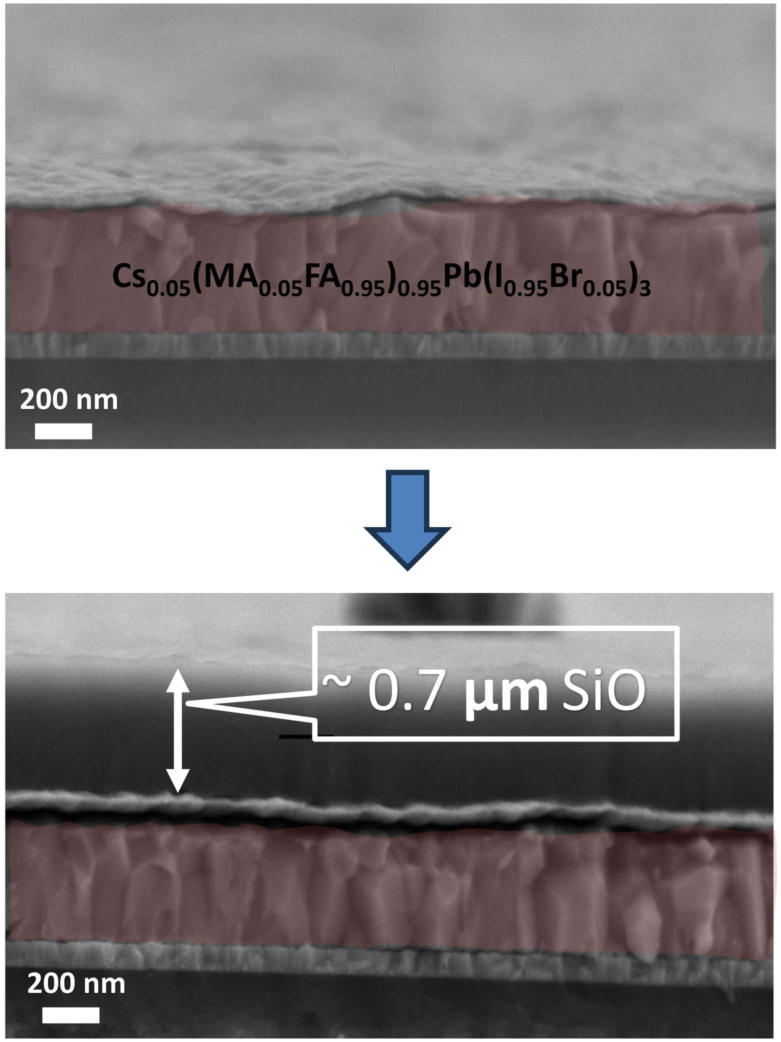




Seid, et al. Small, 2024

AtOx Degradation + SiOx Barrier





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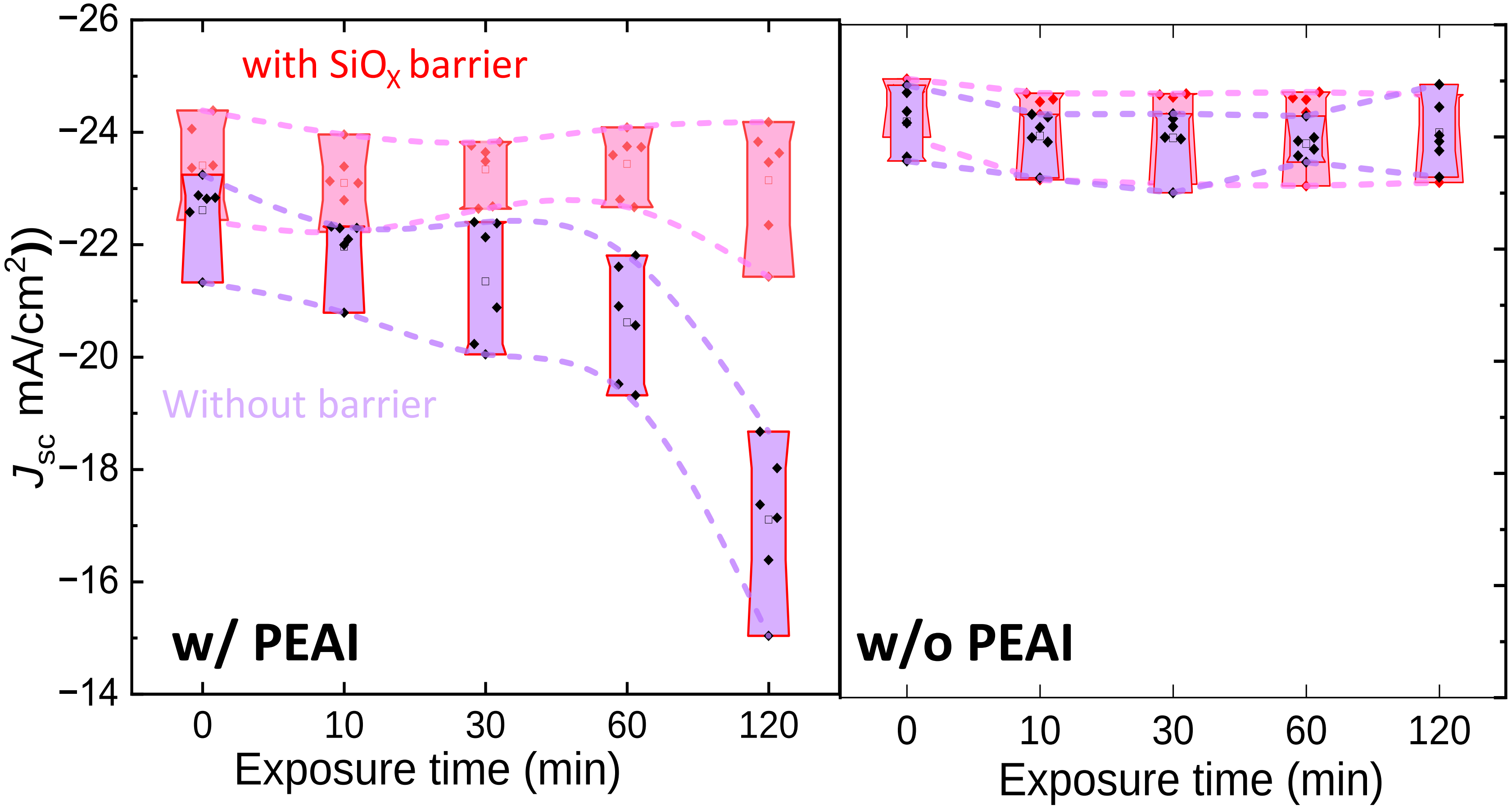
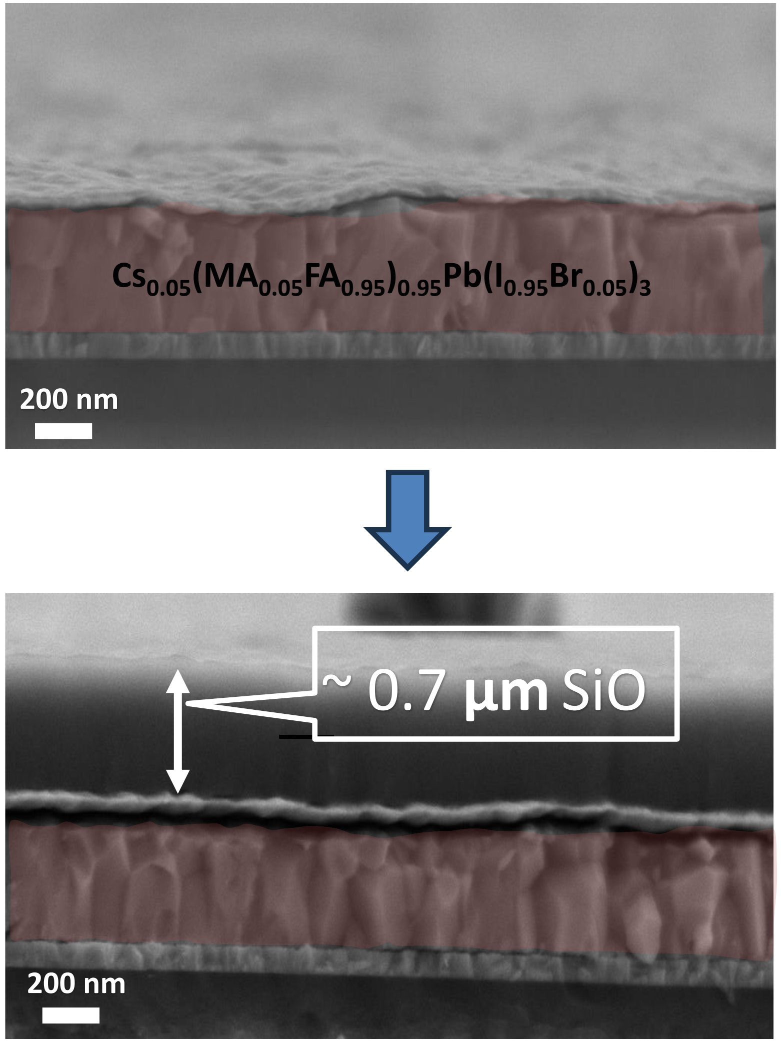
AtOx Degradation + SiOx Barrier

Ph.D. student
Biruk Alebachew





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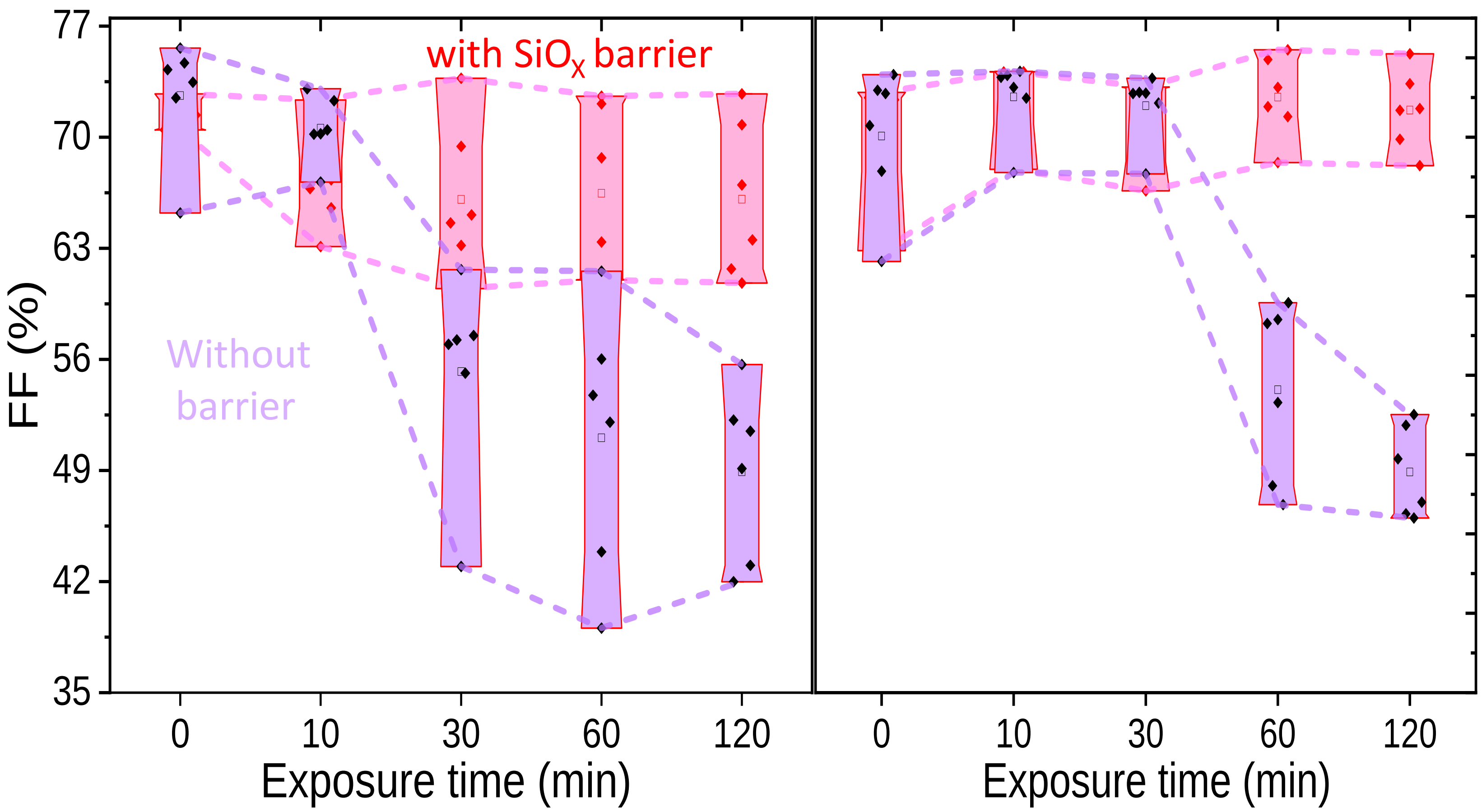
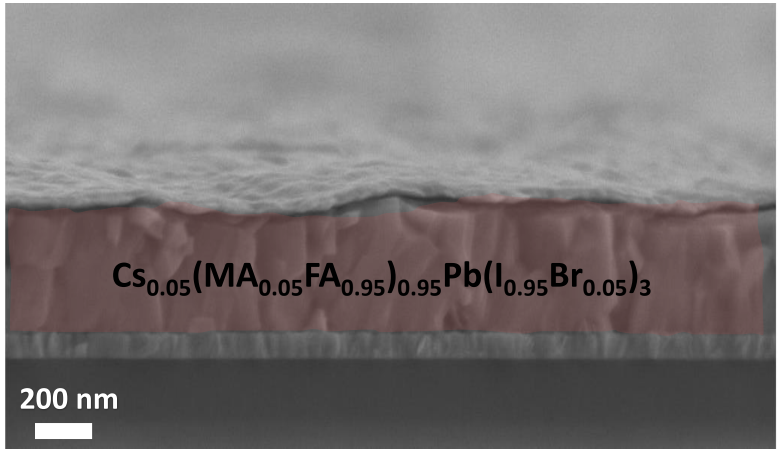
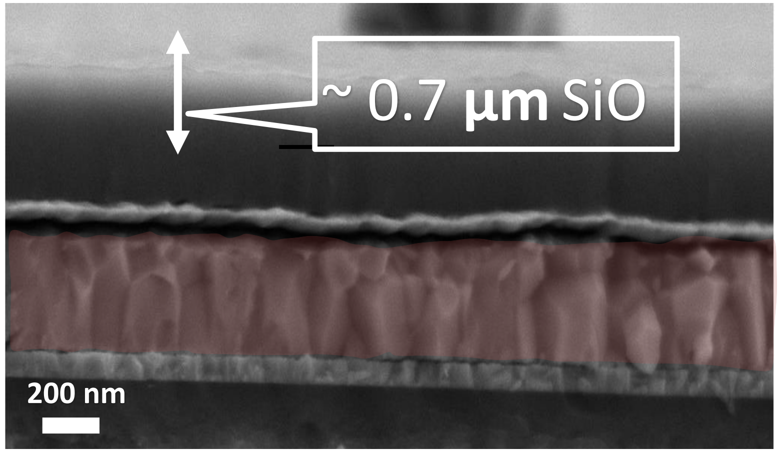
AtOx Degradation + SiOx Barrier

Ph.D. student
Biruk Alebachew







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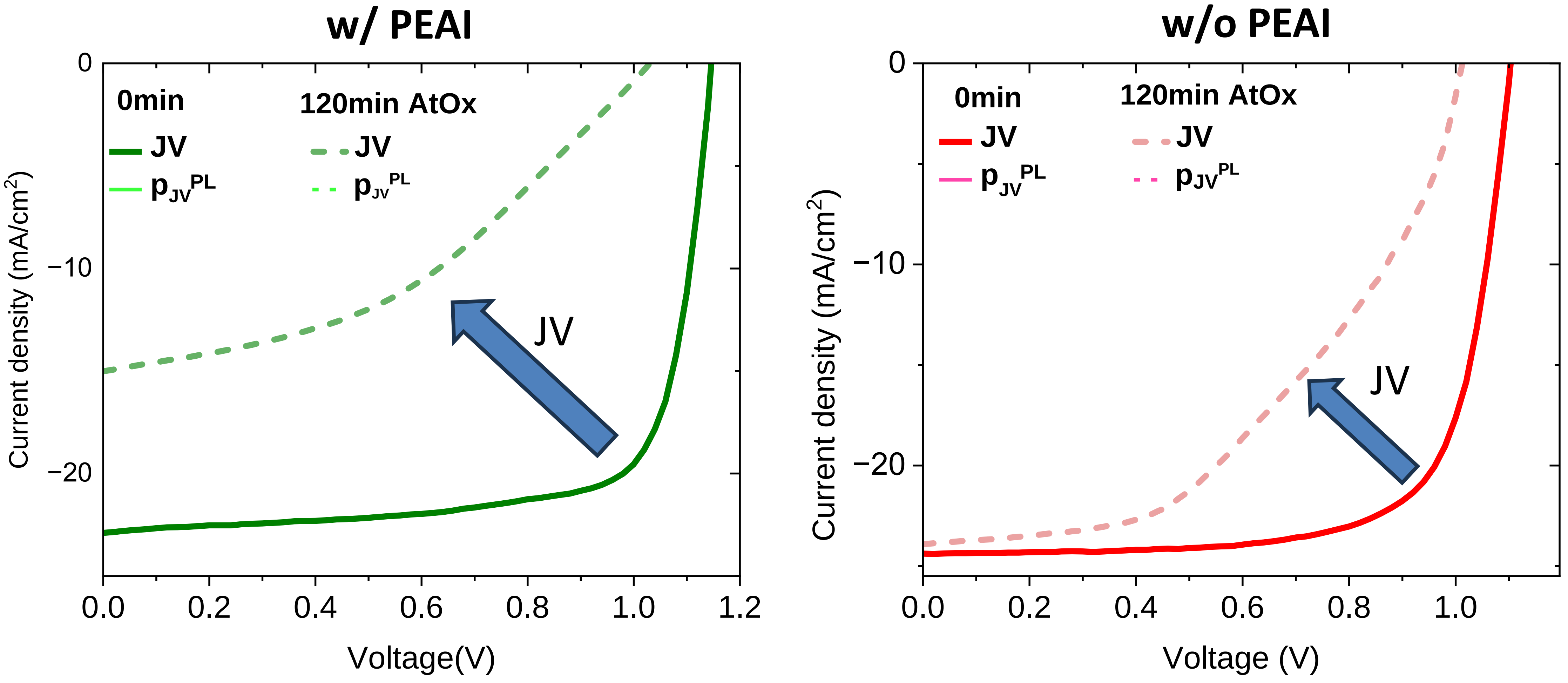
JV characteristics

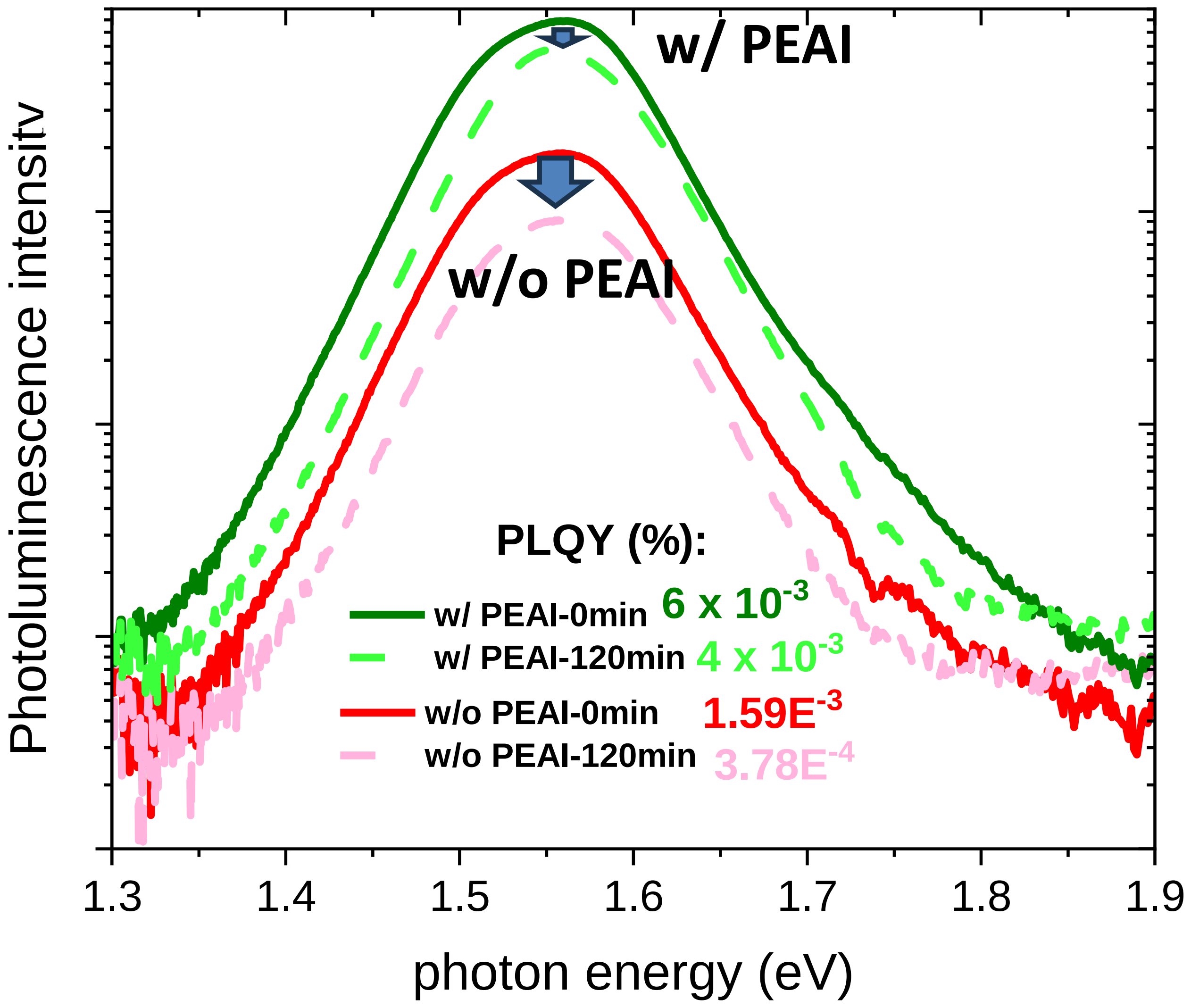


Seid, et al. Small, 2024

Quasi-Fermi Level Splitting (QFLS) from PL

Photoluminescence

$$\boldsymbol{QFLS_{PL}} = k_B T \cdot \ln\left[I \cdot \boldsymbol{PLQY} \cdot \frac{J_{gen}}{J_0} \right]$$



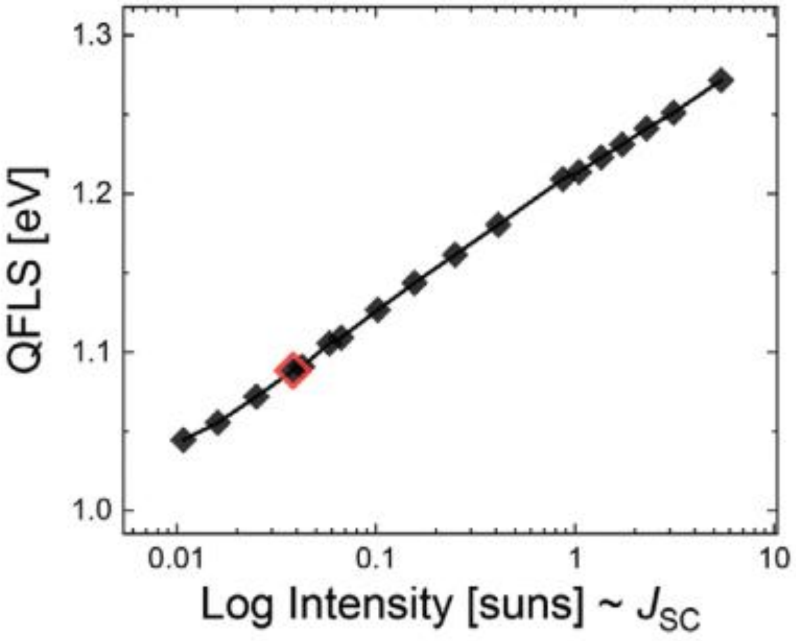
Lang, F.;, M. *ACS Energy Lett.* **2021**, 3982–3991.

Seid, et al. Small, 2024

Constructing pseudo-light JV curves

How To Quantify the Efficiency Potential of Neat Perovskite Films: Perovskite Semiconductors with an Implied Efficiency Exceeding 28%

Dr. M. Stolterfoht



Linear x - Axis

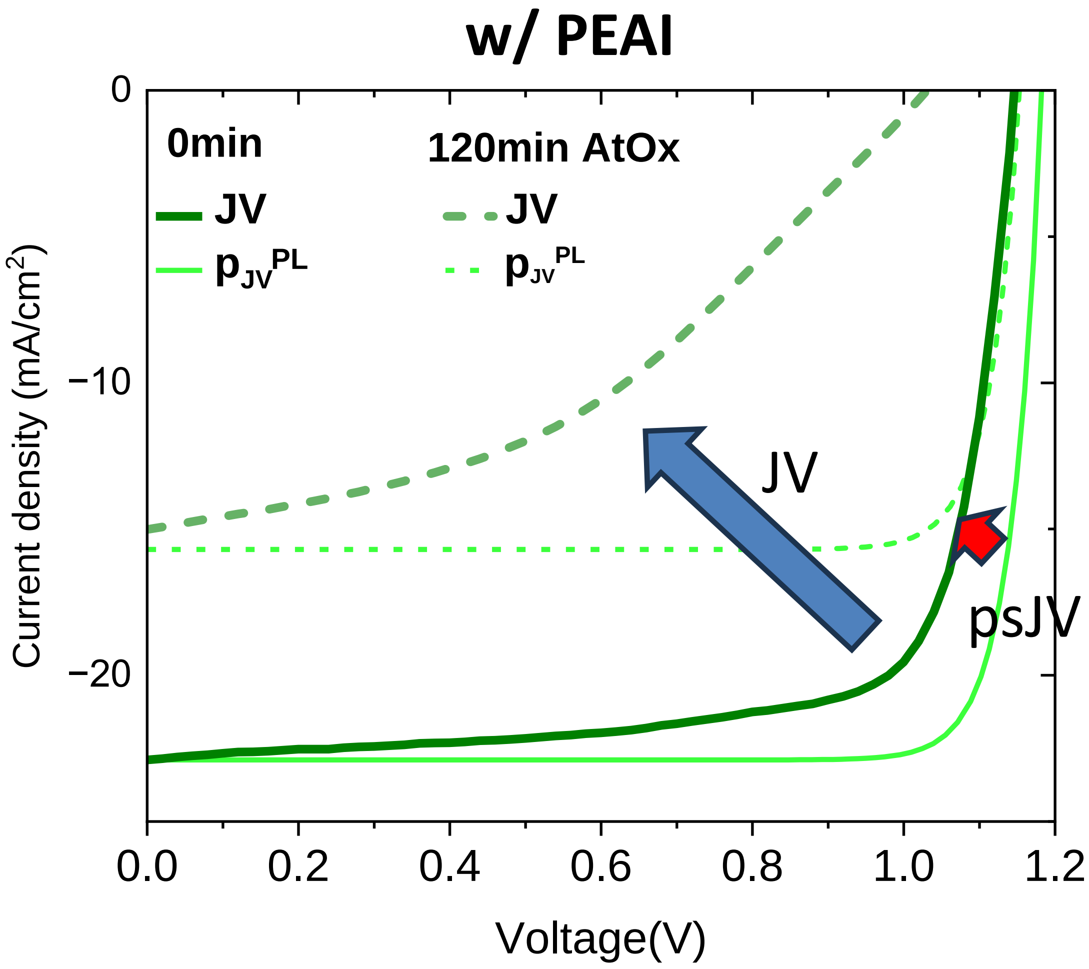
Flip x – and y - Axis

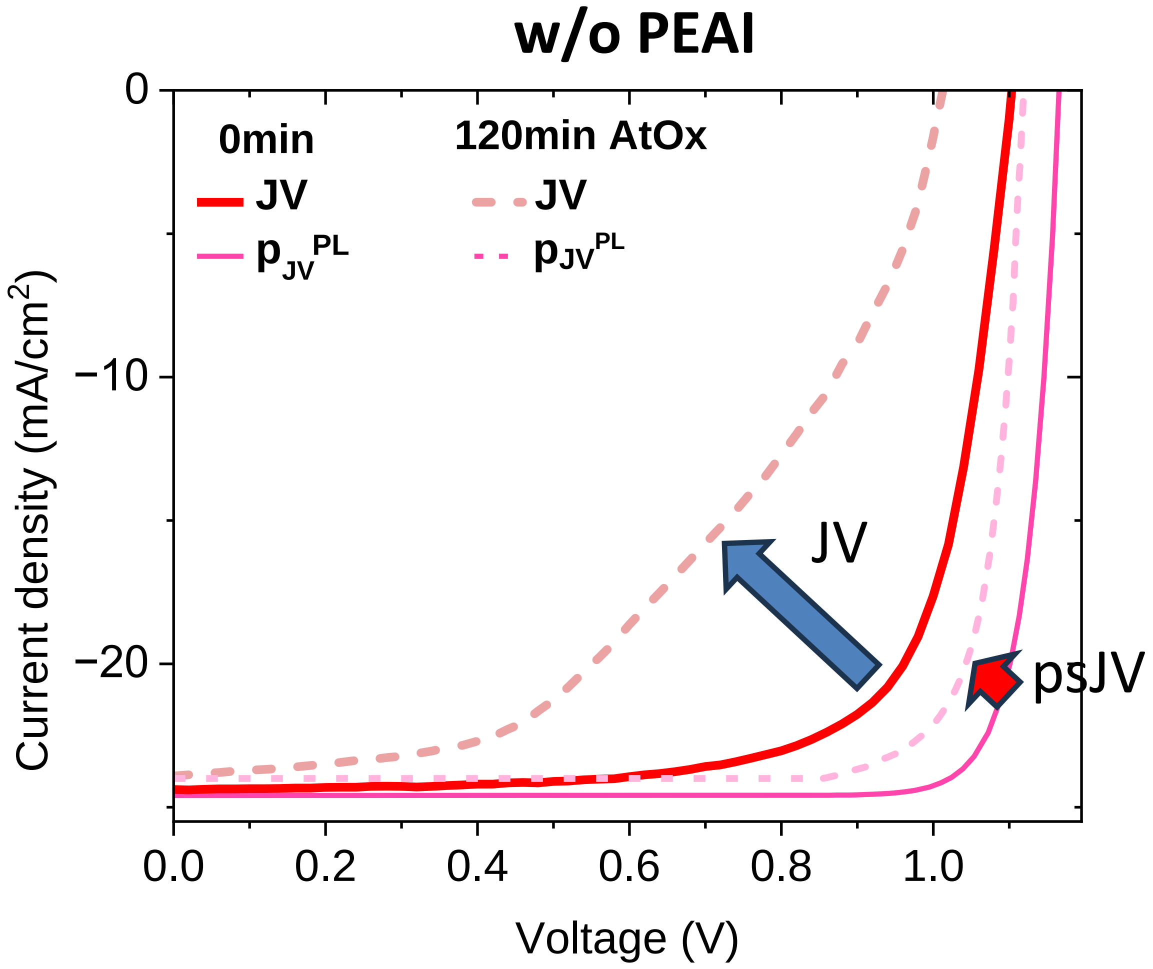
Substract J_{Gen}

Pseudo-light-JV

Stolterfoht, M. et al. Adv. Mater. 2020, 32 (17), 2000080.

pseudo-light JV vs JV characteristics





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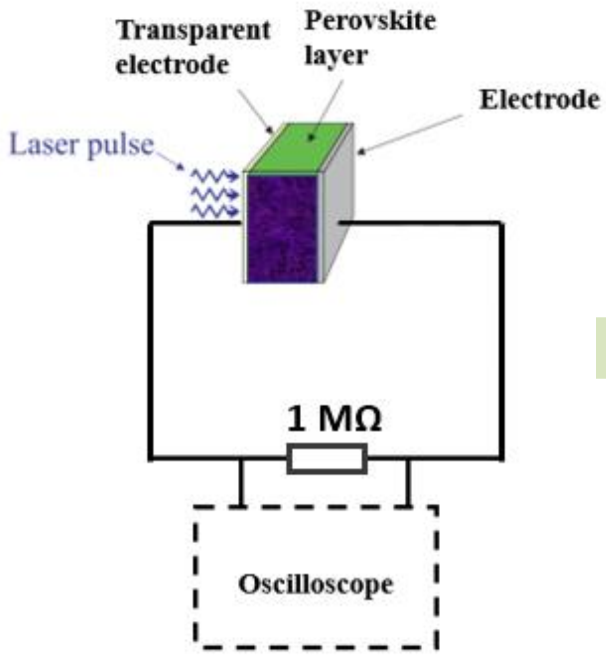
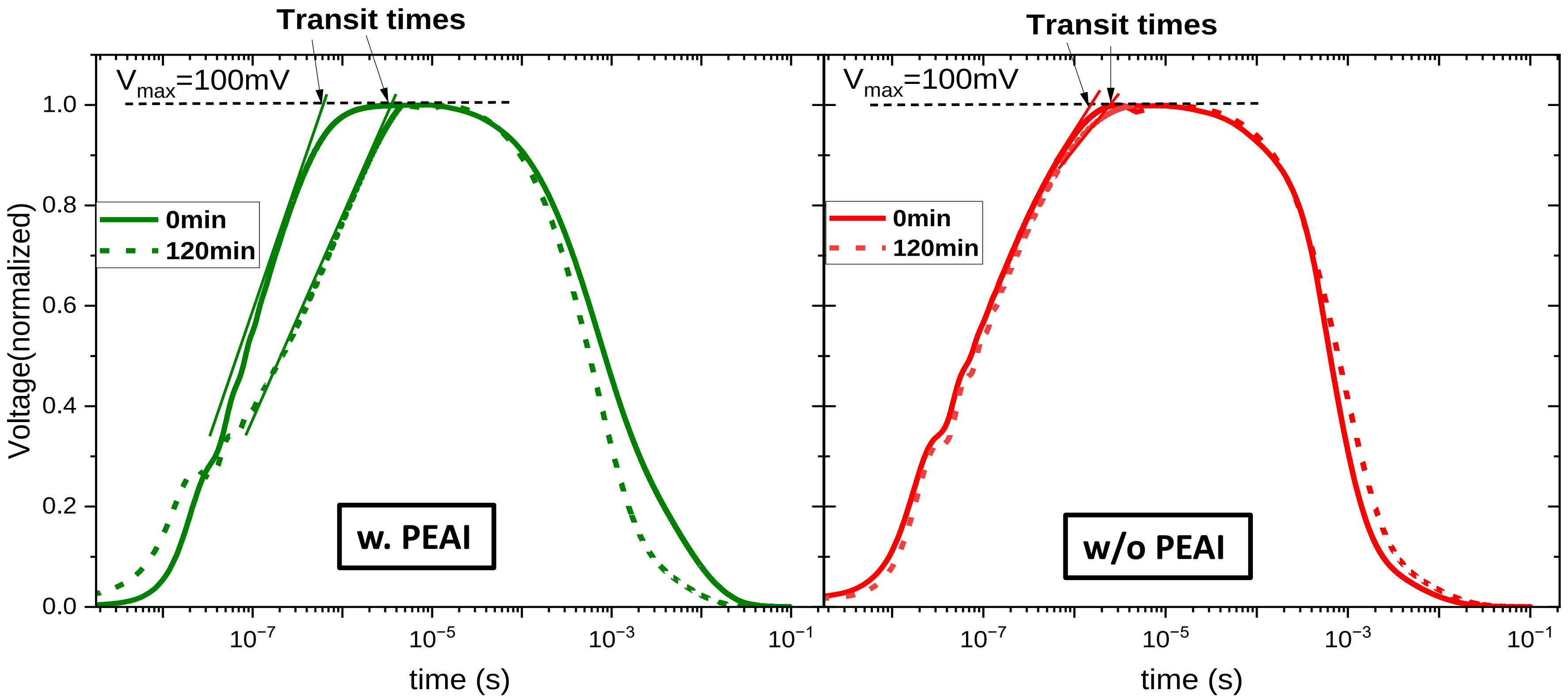
Resistance-dependent Photovoltage (RPV) measurements

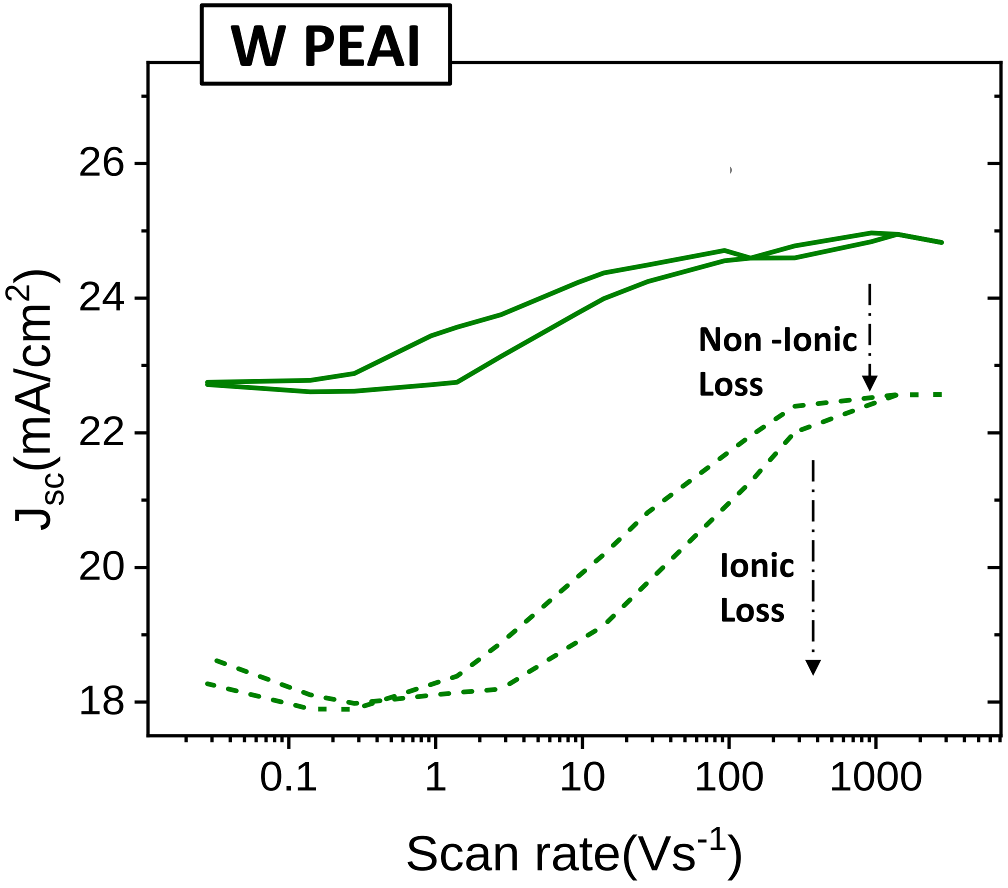


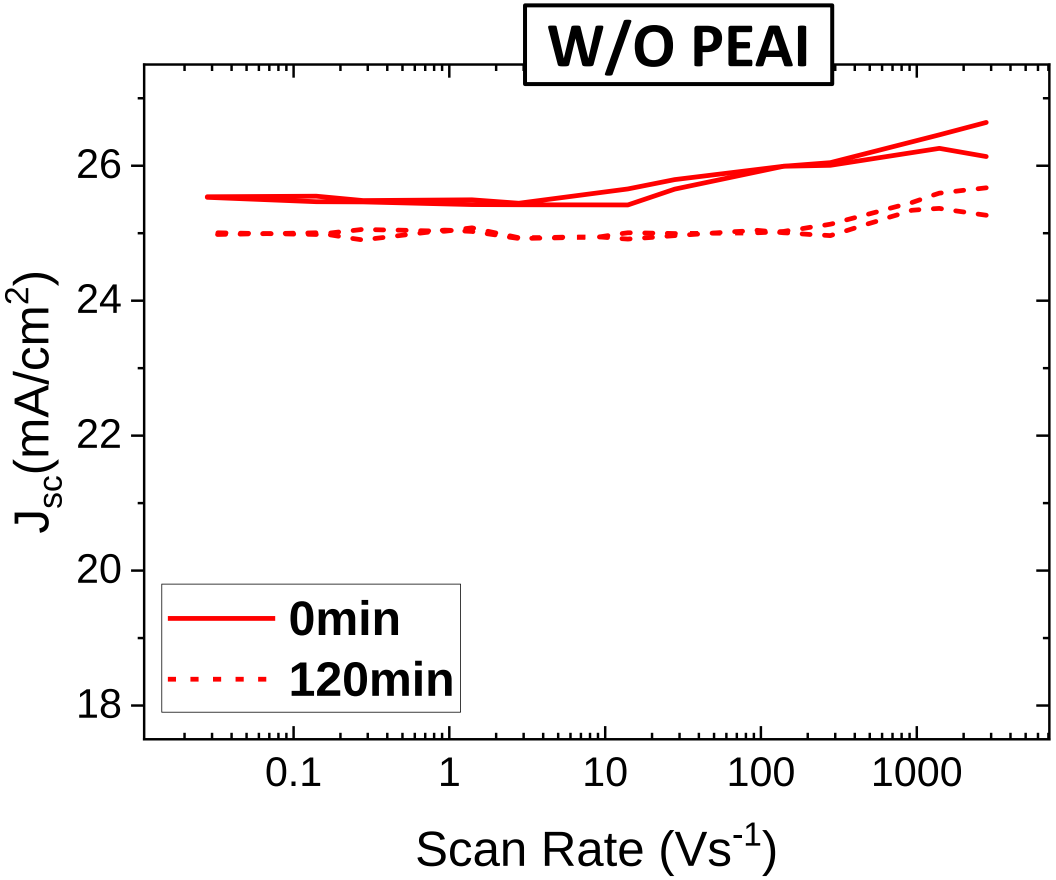


- PEAI-passivated devices: – Low Mobility Interlayer formed

Seid, et al. Small, 2024

Further: Enhanced Ionic Losses

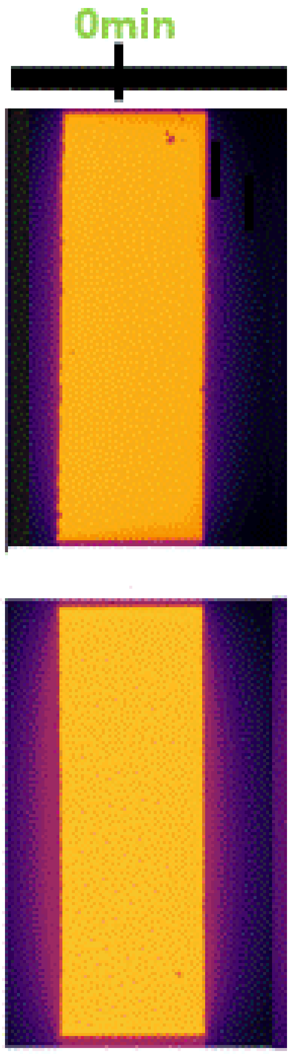




Electroluminescence Imaging

Control

2D Passivated



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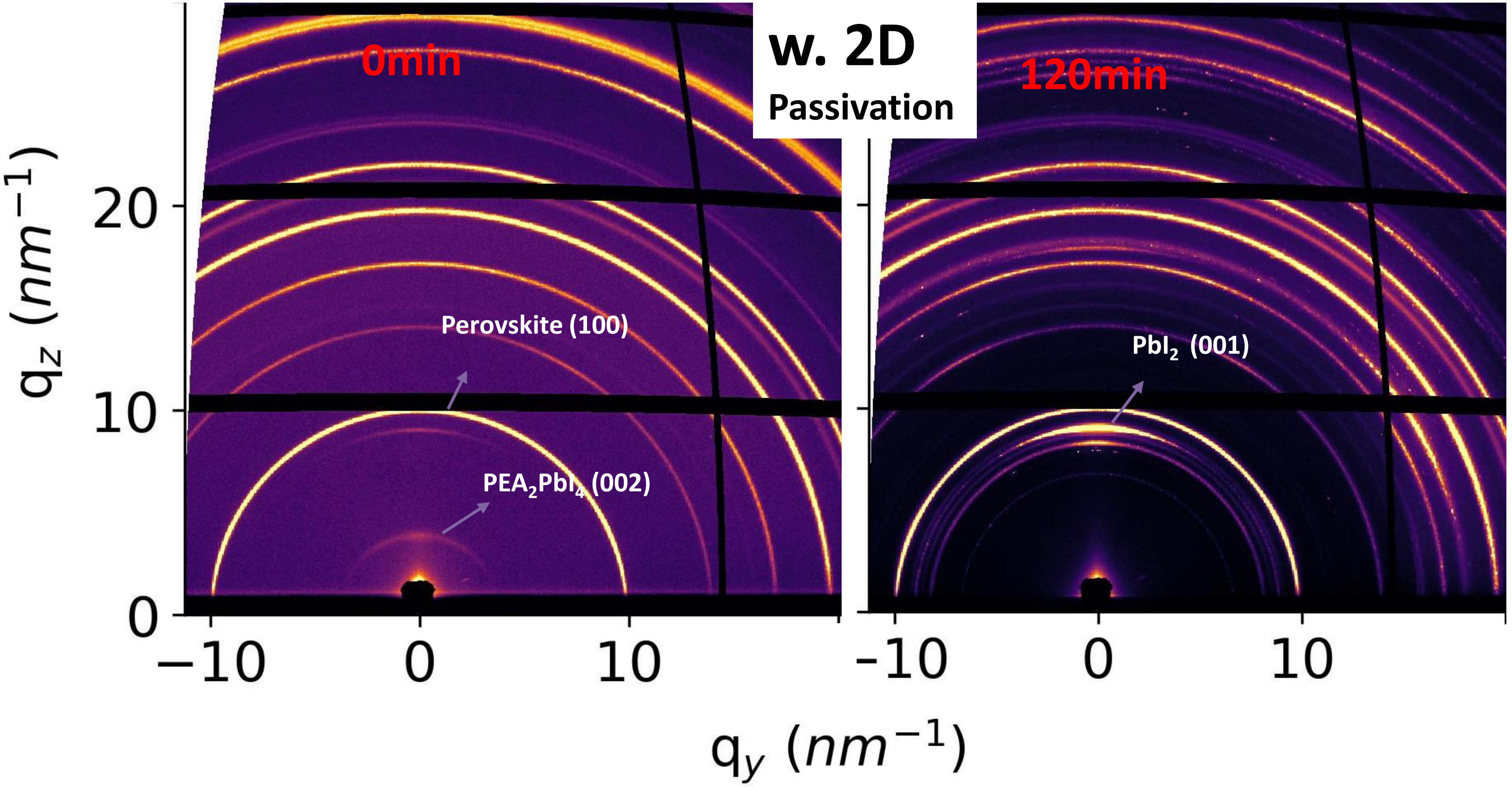
GIWAX



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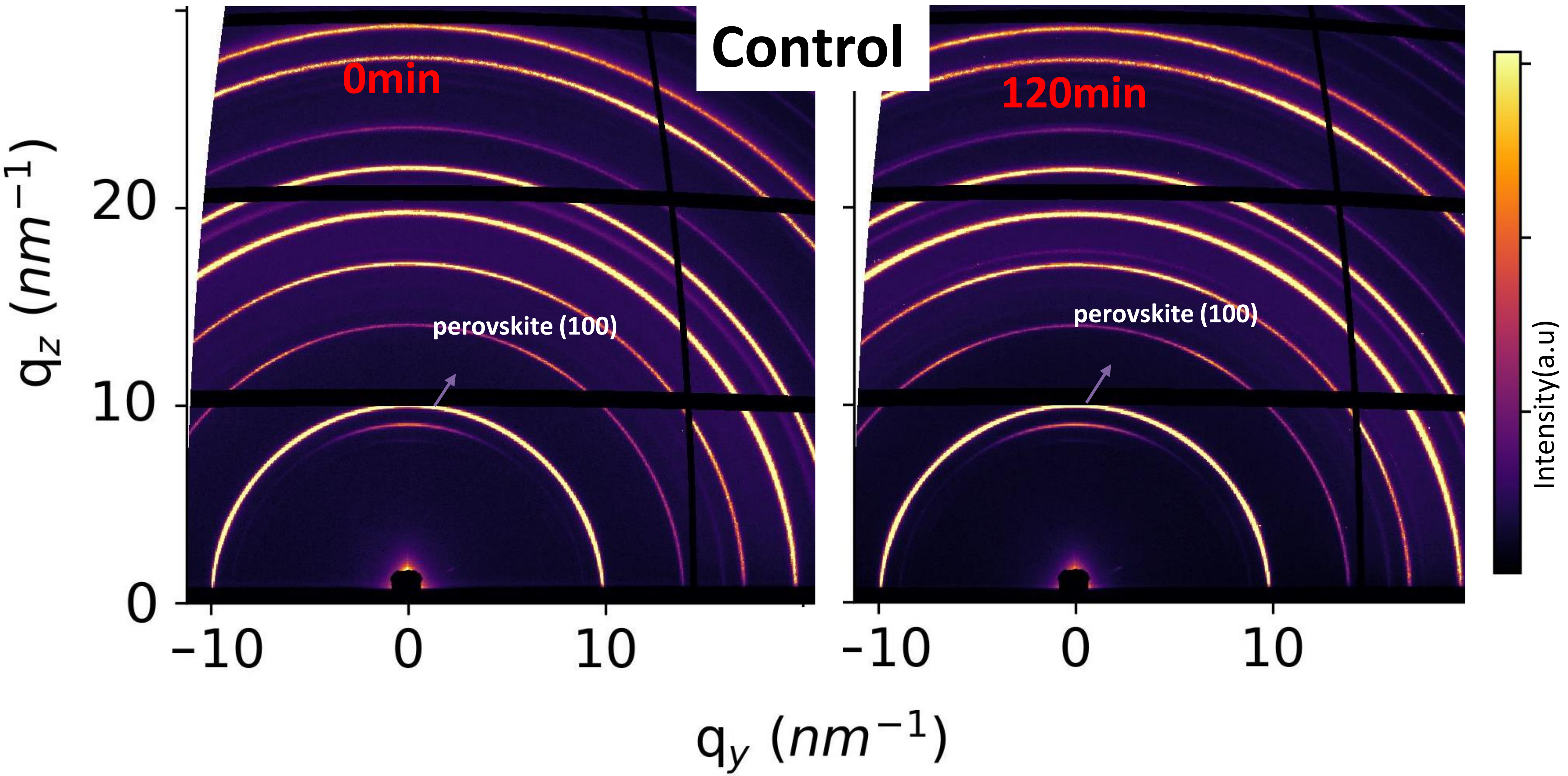
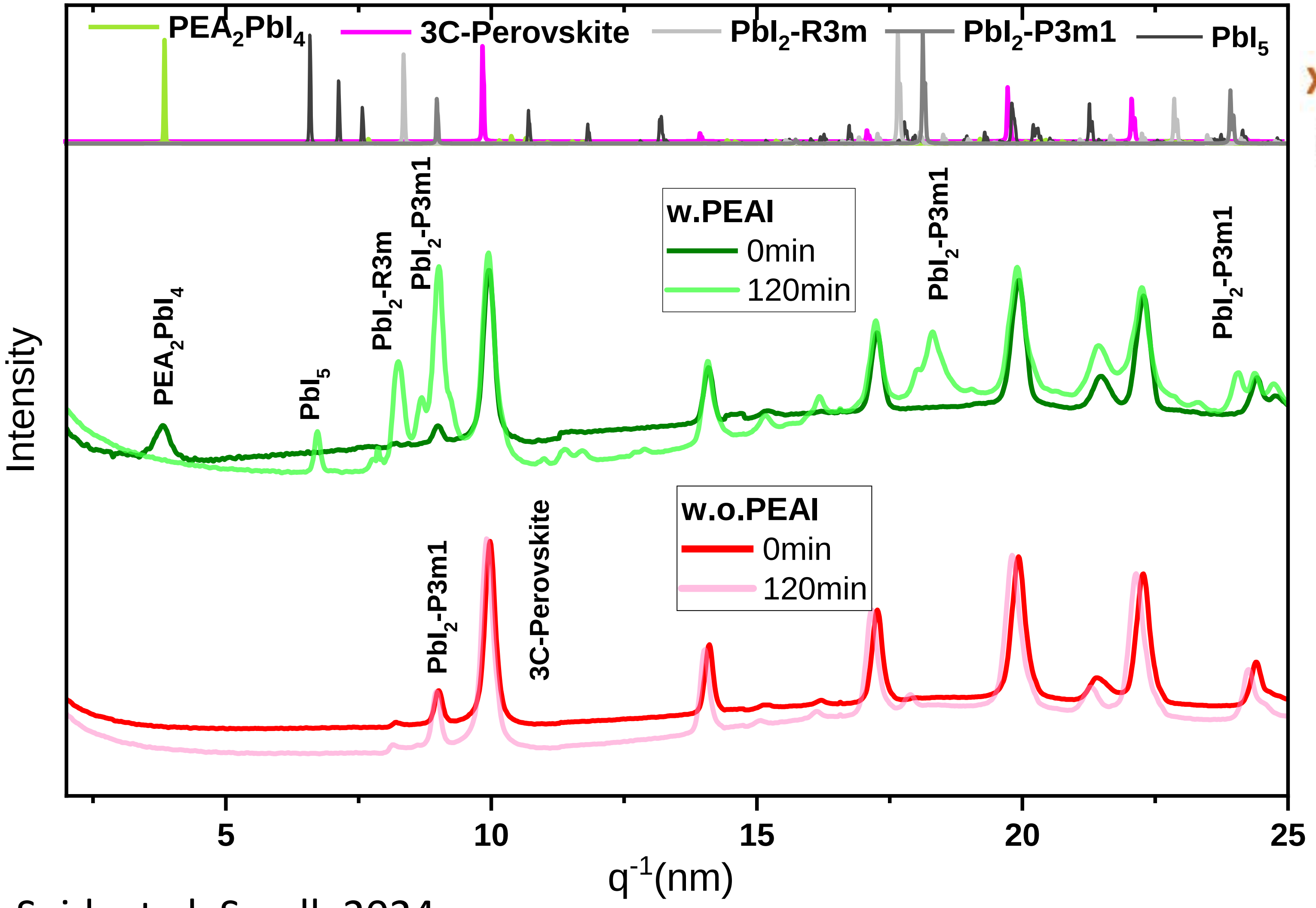
GIWAX

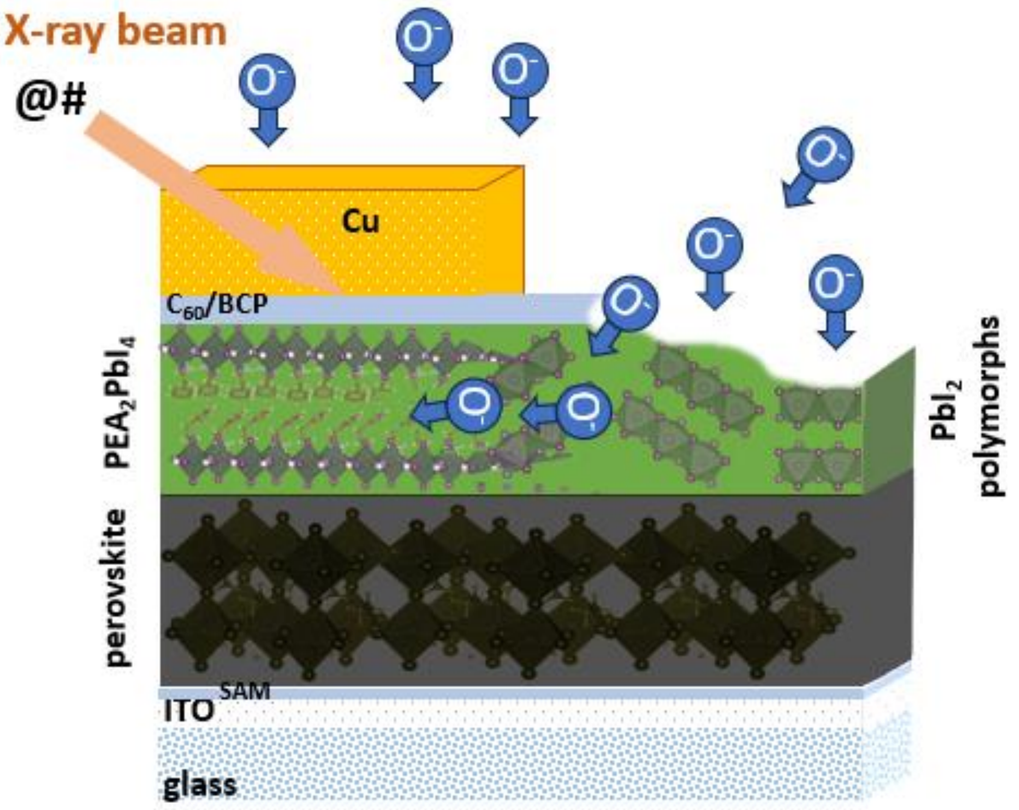


Seid, et al. Small, 2024

Lateral AtOx Ingress and Degradation

@#, θ=0.5°

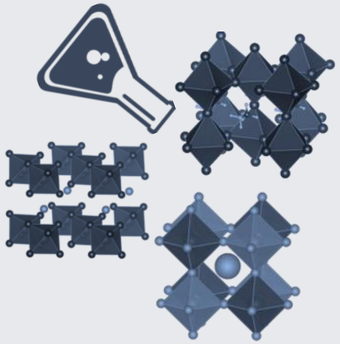




Seid, et al. Small, 2024

The ROSI Group in a Nutshell

Radiation Tolerant Soft Semiconductors

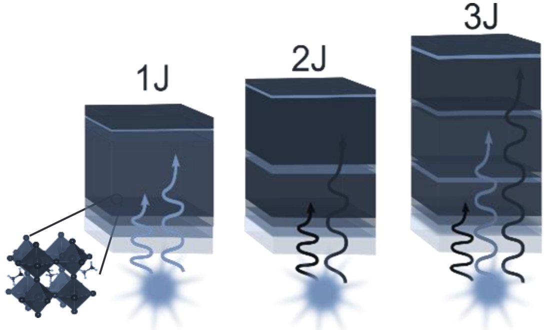


- Library of Radiation Tolerant Soft Semiconductors
- Resilient Contact Systems
- Deeper Understanding of their Stability

Universität Potsdam

HZB Helmholtz Zentrum Berlin

Next Generation Space Photovoltaics



- Resilient Space Solar Cells
- Successful In-Orbit Demonstration

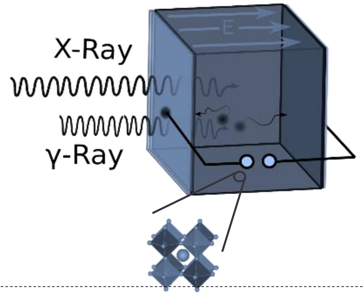
HySPRINT Helmholtz Innovation Lab

TU berlin

University of Cambridge

SwiftSolar

Reliable Radiation Detectors

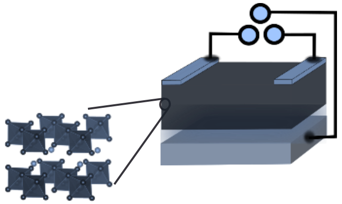


- Reliable Radiation Detectors with High Sensitivity
- New Medical Diagnostics that work with Lower Doses

HZB Helmholtz Zentrum Berlin

University of Cambridge

Radiation Tolerant Electronics



- Radiation Tolerant Field Effect Transistors

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SwiftSolar

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