UNIVERSITY OF CAMBRIDGE

Alexander von Humboldt Stiftung/Foundation

HZB Helmholtz Zentrum Berlin

HySPRINT Helmholtz Innovation Lab

PVcomB

Stabilität von Perowskit-basierten Einzel- und Tandem-Solarzellen unter Protonenbestrahlung

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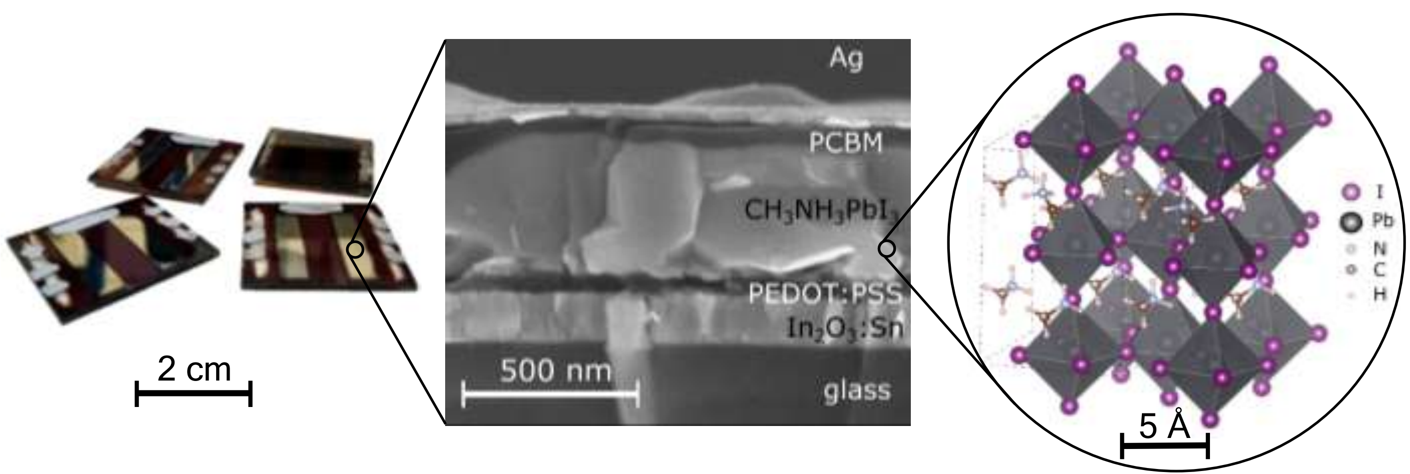
Jürgen Bundesmann, Andrea Denker **HZB**

Tobias Bertram, Anna Belen Morales-Vilches, Bernd Stannowski, Christian A. Kaufmann **PVComB**



Outline

1. Eigenschaften Organisch-Inorganischer Perowskite
2. Motivation: Warum sollten wir Perowskit-Solarzellen im Weltraum verwenden ?
3. Radiation Hardness of perovskite single junction solar cells
4. Perovskite/Silicon Tandem Solar Cells
5. Perovskite/CIGS Tandem Solar Cells
6. Zusammenfassung

InGAP/GaAs/Ge ist doch perfekt

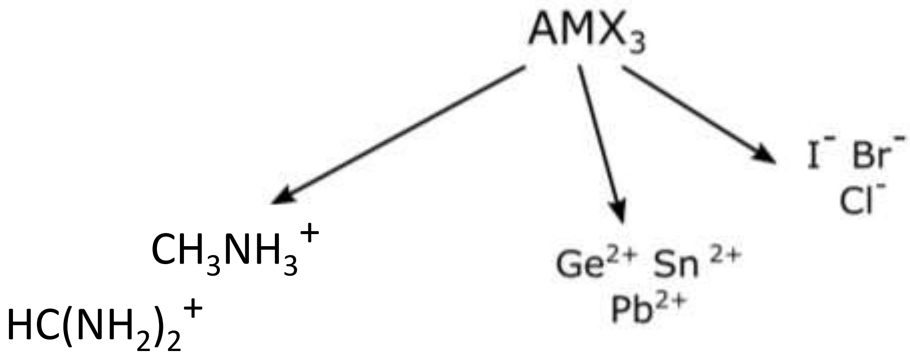
In-situ measurements during proton irradiation

More In-situ measurements during proton irradiation

η > 29%*, to be commercialized soon

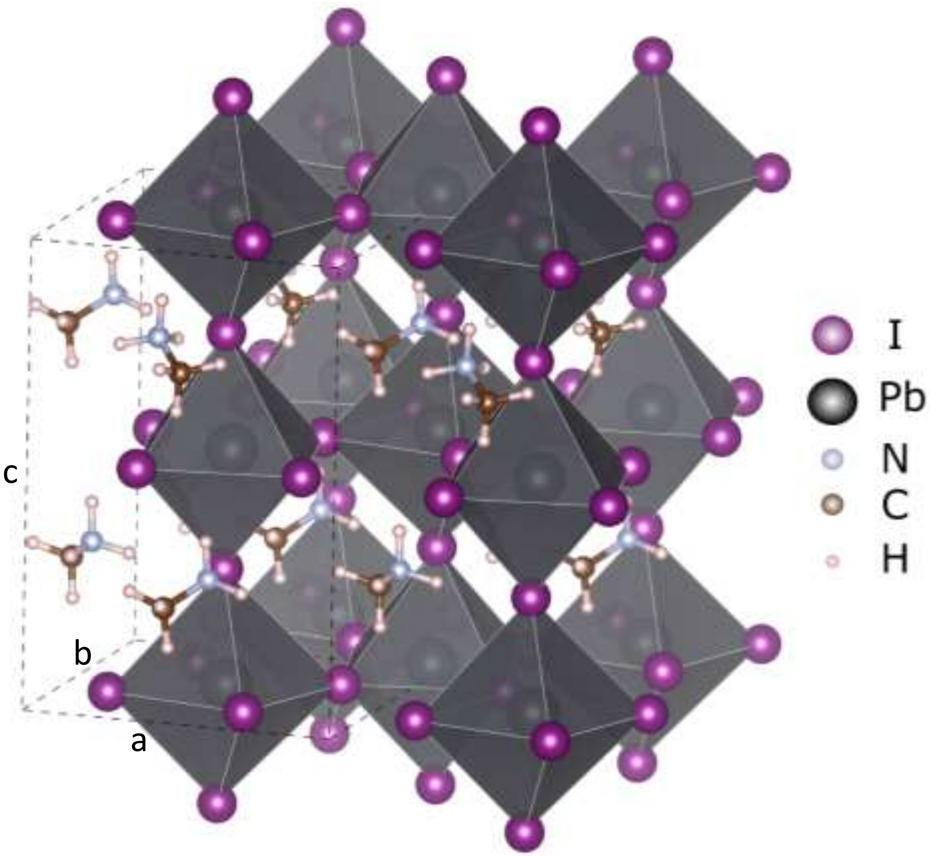
can be flexible and lightweight!

Organic-Inorganic Halide Perovskites



$CH_3NH_3PbI_3$, a solution processable, crystalline semiconductor with a high charge carrier mobility:

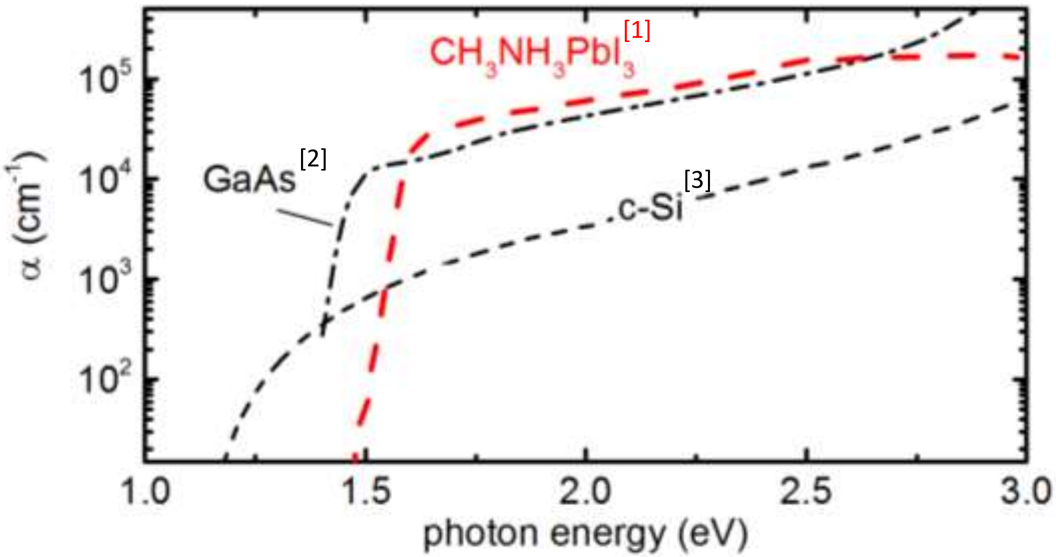
	μ [cm^2/Vs]
c-Si	≈ 10^3 [2]
solution processable organic semiconductors	$10^{-5} – 10^0$ [3]
$CH_3NH_3PbI_3$	≈ 10^2 [4]

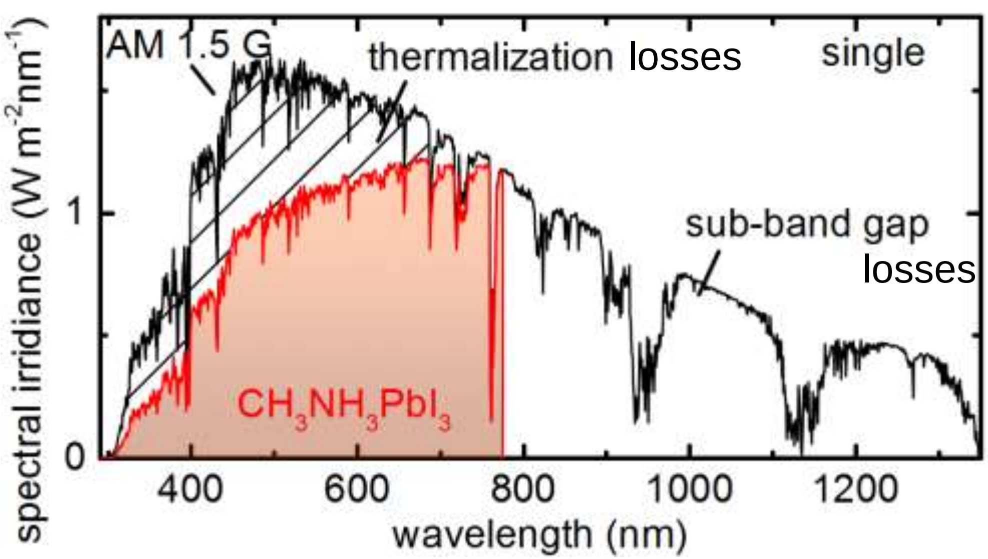


tetragonal crystal structure of $CH_3NH_3PbI_3$,
a = b = 8.81 Å, c = 12.71 Å [1]

[1] M. T. Weller, *et al.*, *Chem. Commun.* **51,** 4180–4183, (2015).
[2] S. M. Sze, J. C. Irvin, *Solid. State. Electron.* ***11***, 599, (1968).
[3] H. Hoppe, *et al., J. Mater. Res.* ***19***, 1924, (2004).
[4] Q. Dong, *et al., Science* ***347***, 967, (2015).

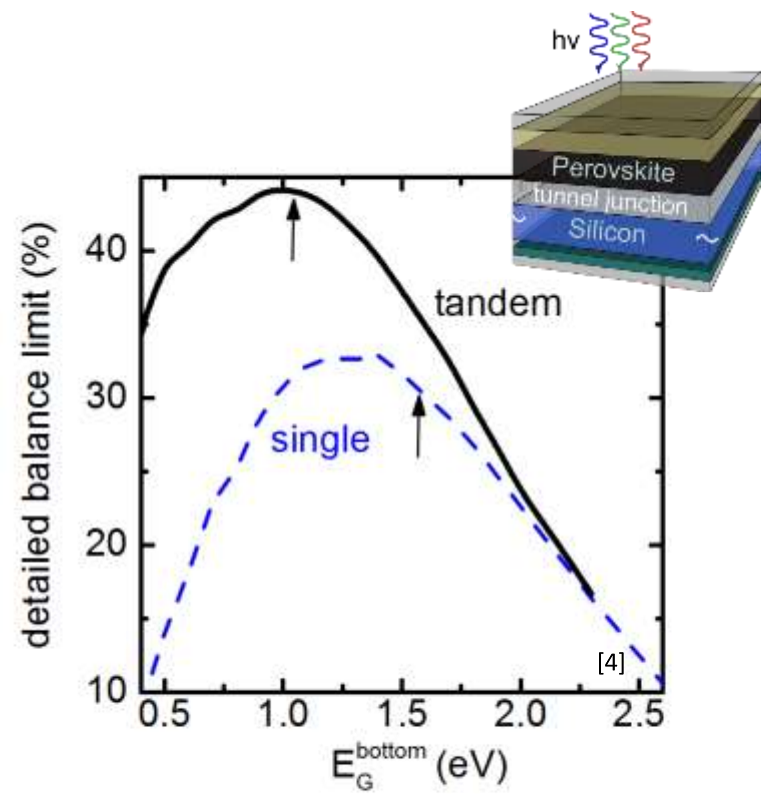
Optical Properties of $CH_3NH_3PbI_3$





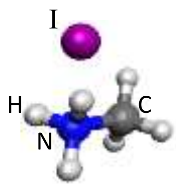
$CH_3NH_3PbI_3$

- direct semiconductor
- E_G = 1.6 eV
- $\alpha \approx 10^5$ cm^{-1} above 1.7 eV



[1] S. De Wolf *et al., J. Phys. Chem. Lett.* ***5***, 1035, (2014).
[2] C. Schinke, *et al., AIP Adv.* ***5***, 67168, (2015).
[3] D. E. Aspnes, A. A. Studna, *Phys. Rev. B.* ***27***, 985 (1983).
[4] W. Shockley, H. J. Queisser, *J. Appl. Phys.* **32,** 510 (1961).

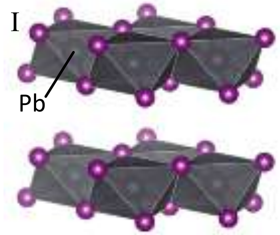
Solution Processing of $CH_3NH_3PbI_3$ Thin-Films



CH_3NH_3I

1 : 1

+



PbI_2

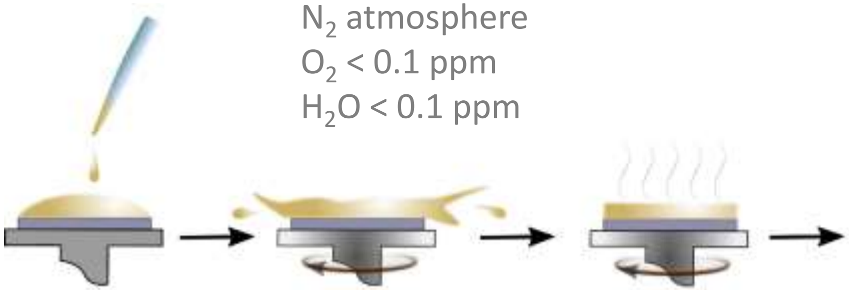
solvent

12h, 60°C

precursor solution

CE&N online

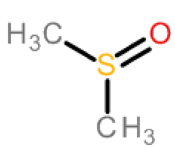
precursor solution



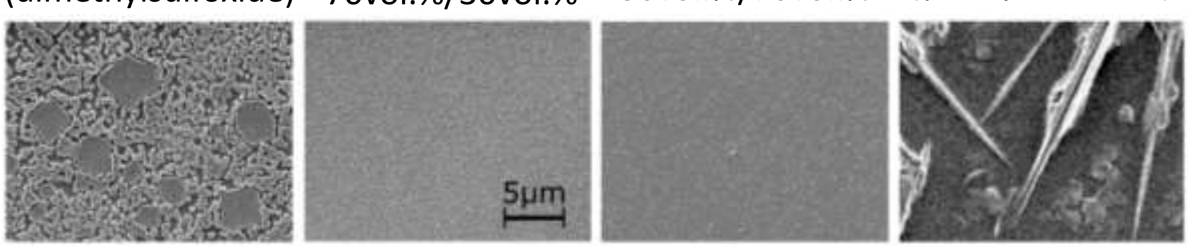
N_2 atmosphere

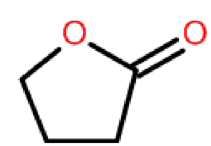
$O_2 < 0.1$ ppm

$H_2O < 0.1$ ppm



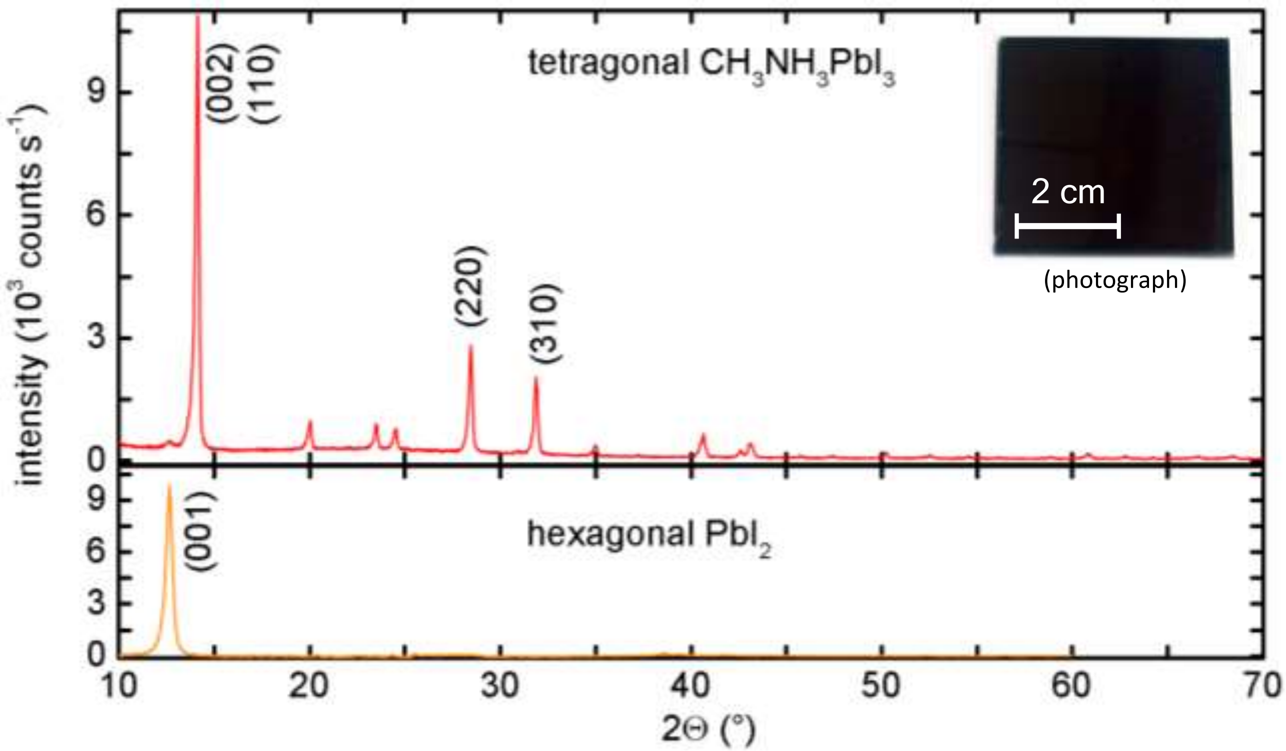
DMSO (dimethylsulfoxide)	DMSO/GBL 70vol.%/30vol.%	DMSO/GBL 30vol.%/70vol.%	GBL (γ-butyrolactone)

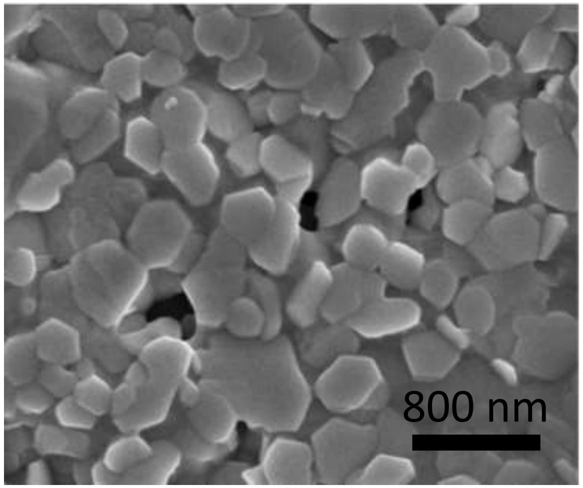




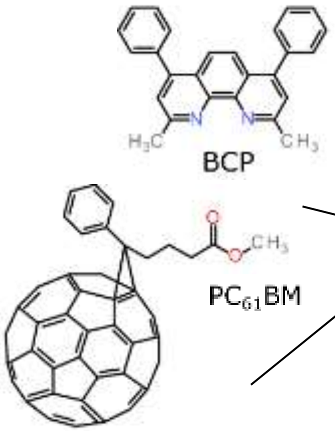
[1] N. J. Jeon, *et al. Nat. Mater.* **13,** 897–903, (2014).

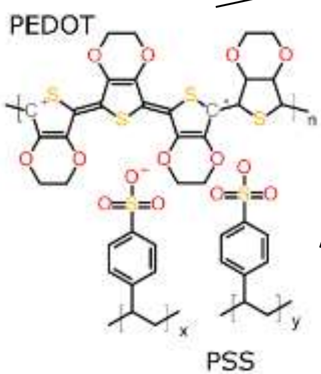
Polycrystalline $CH_3NH_3PbI_3$ Thin-Films

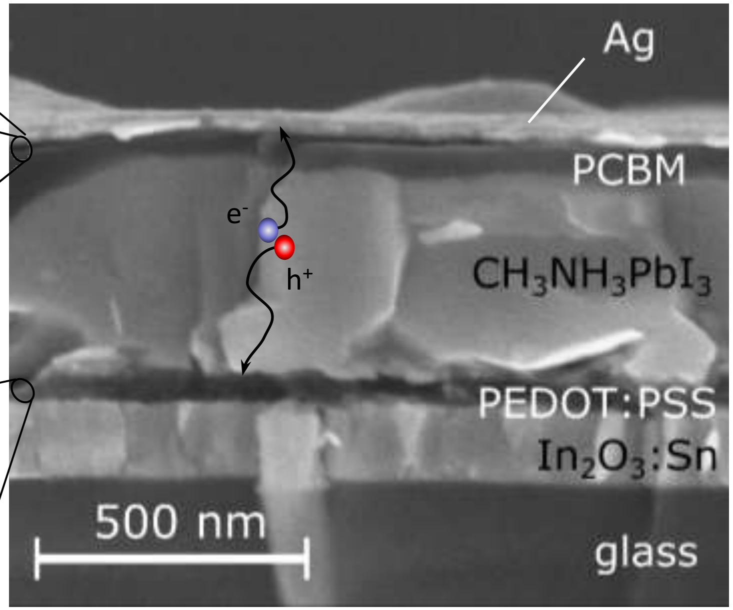


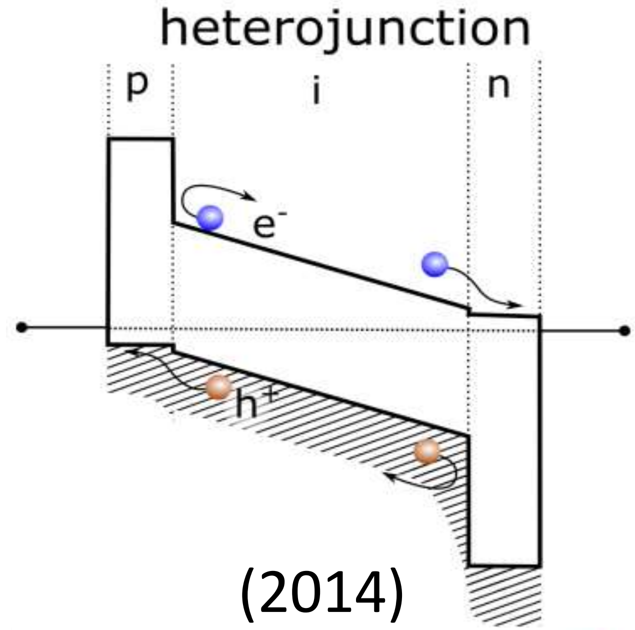


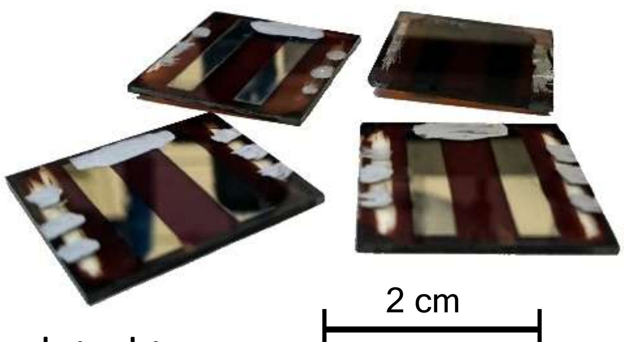
Perovskite Solar Cells



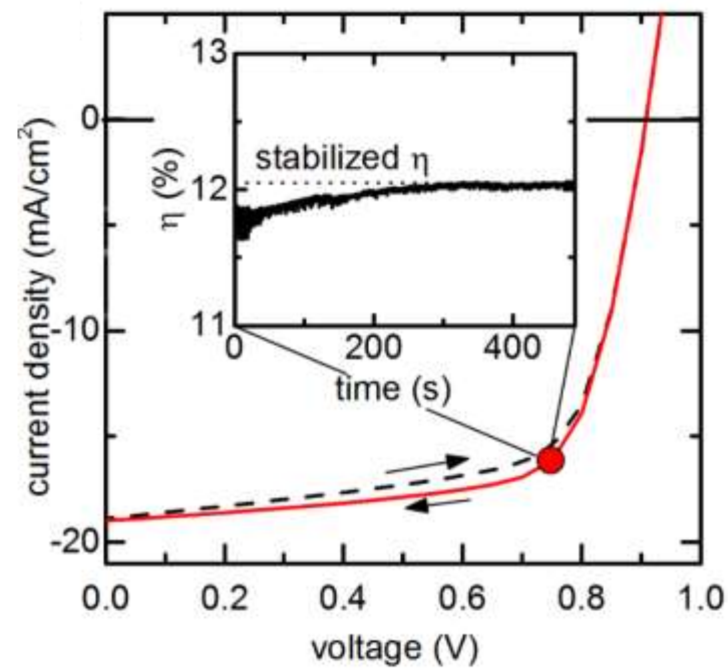




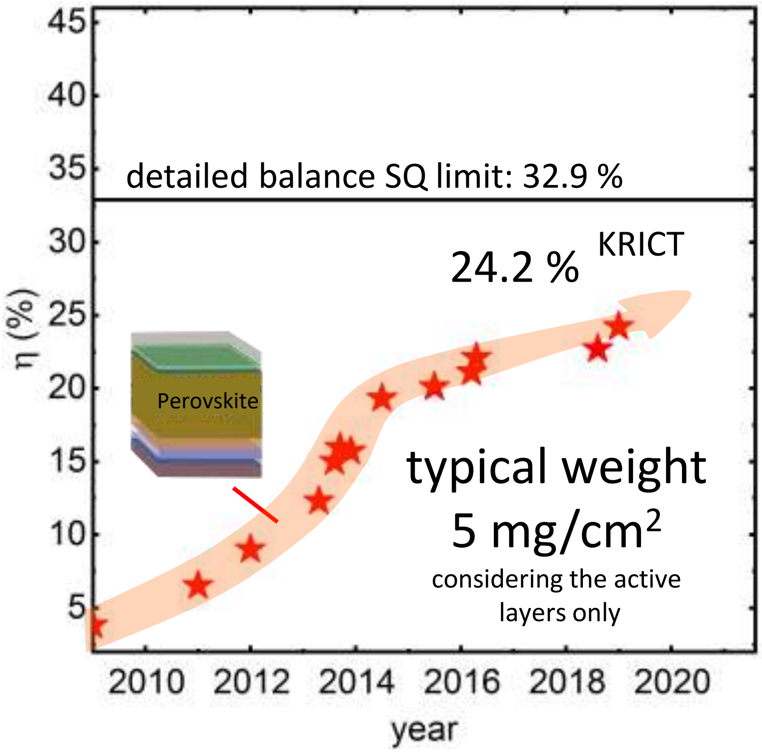


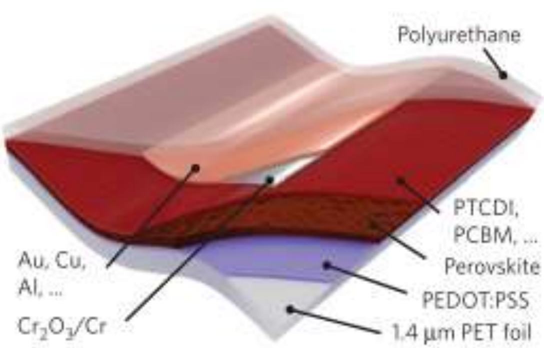


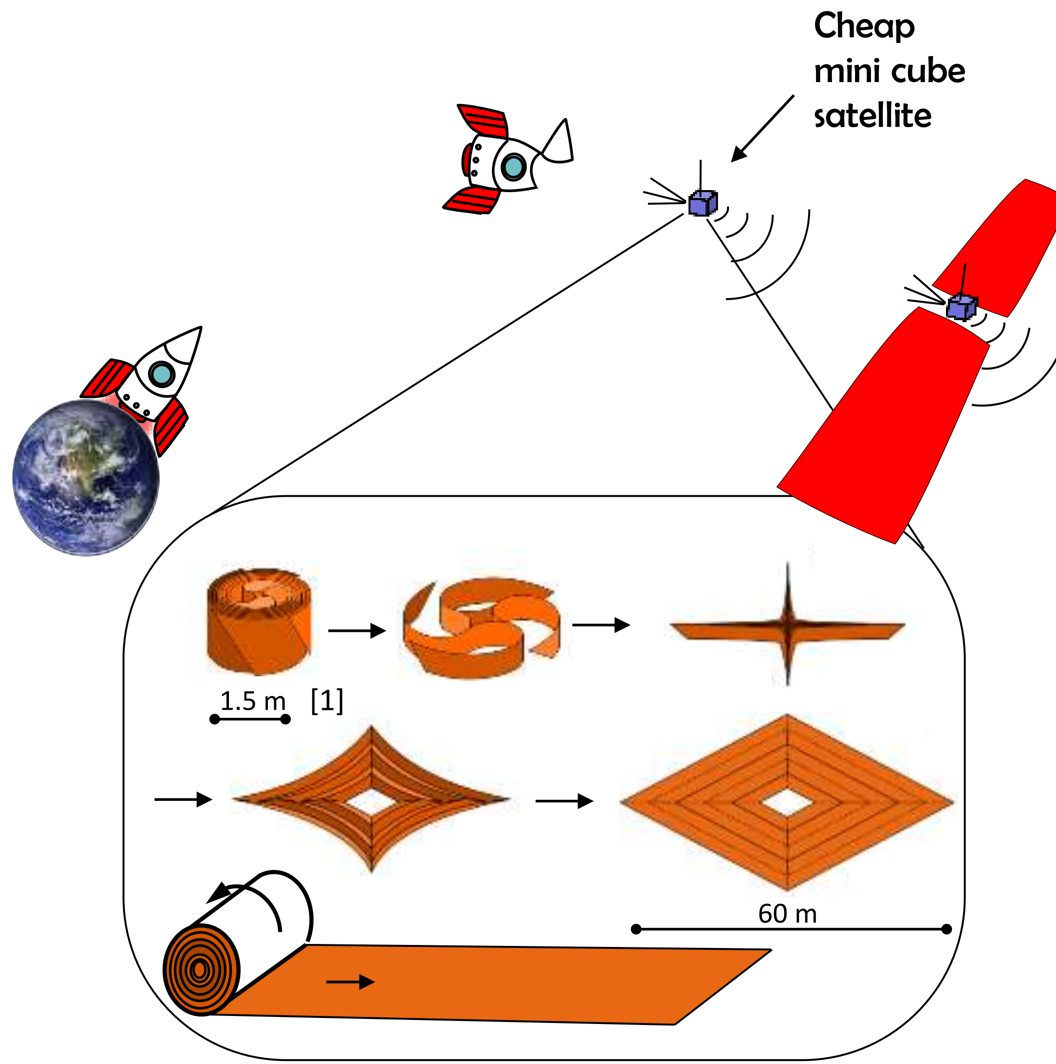
(Usually encapsulated to avoid influence of O_2 & H_2O)



Motivation: Ultralight Solar Cell Arrays for Space



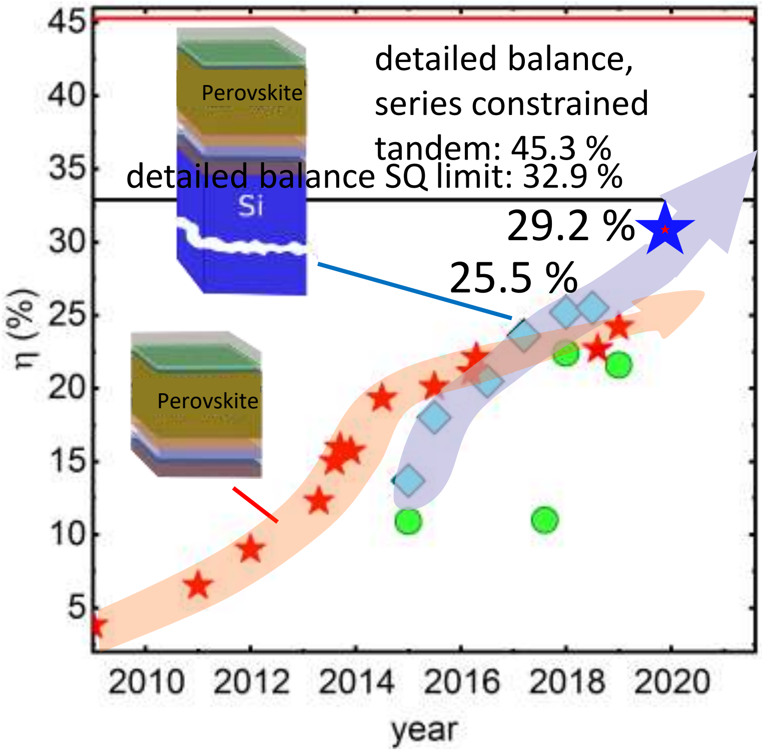




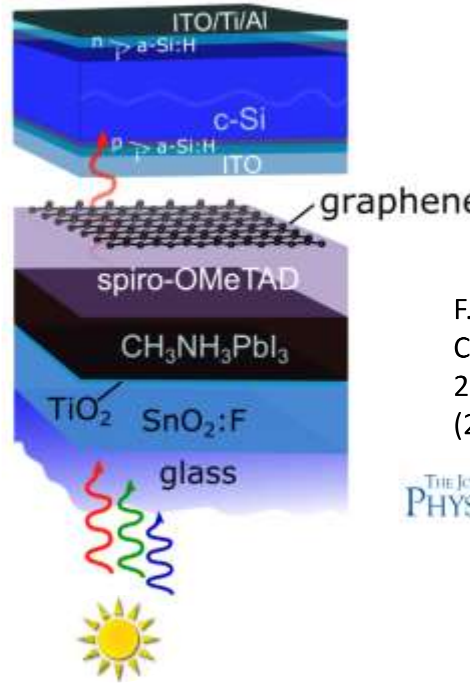
[2] Kaltenbrunner, M. *et al. Nat. Mater.* **14**, 1032–1039 (2015).

[1] M. Arya, et al, 2016 AIAA Spacecr. Struct. Conf. pp. 141–152.

Motivation: Ultralight Solar Cell Arrays for Space



S. Albrecht



2014

A = 1.03 cm^2

η = 13.2%

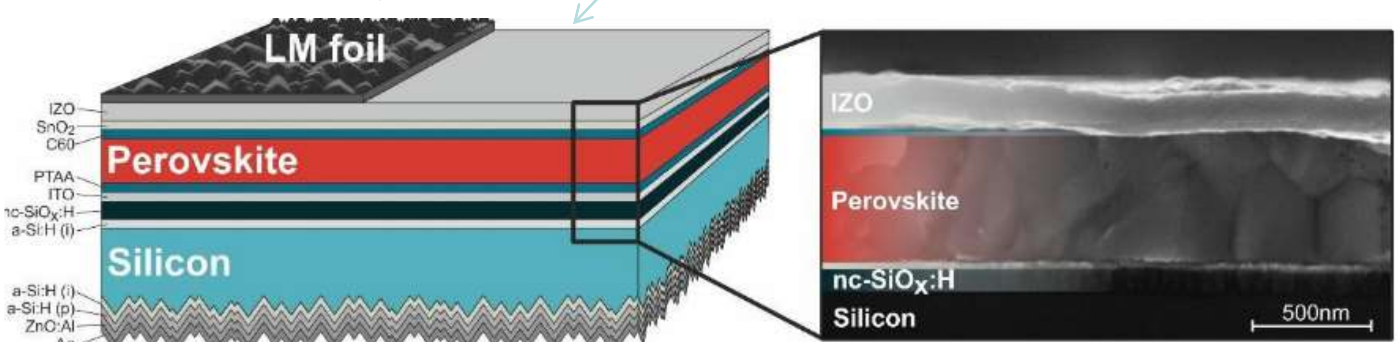
F. Lang, *et al.*, Phys. Chem. Lett. **6**, 14, 2745–2750, (2015).

THE JOURNAL OF PHYSICAL CHEMISTRY Letters

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

25.5%

23.4%



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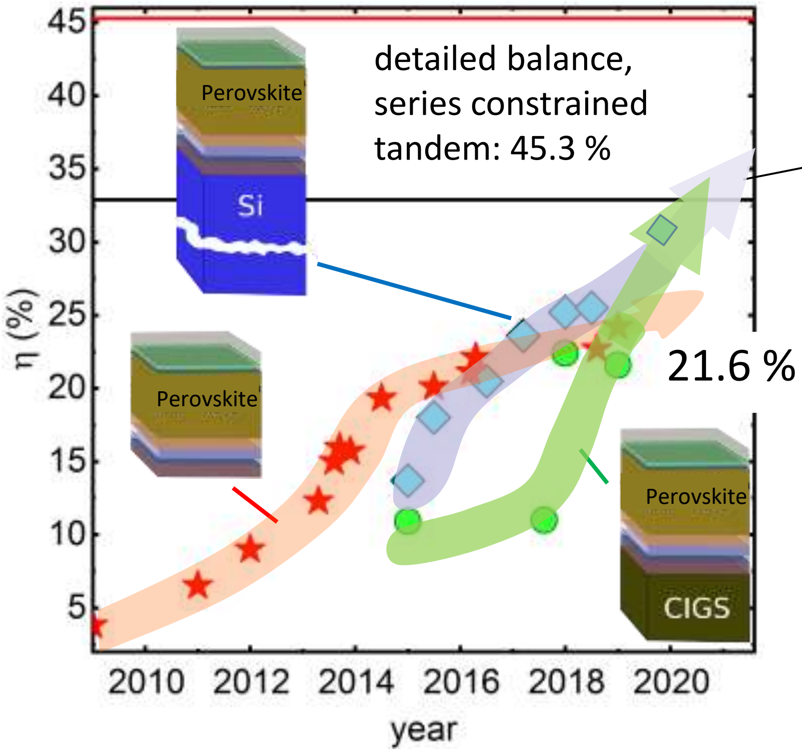
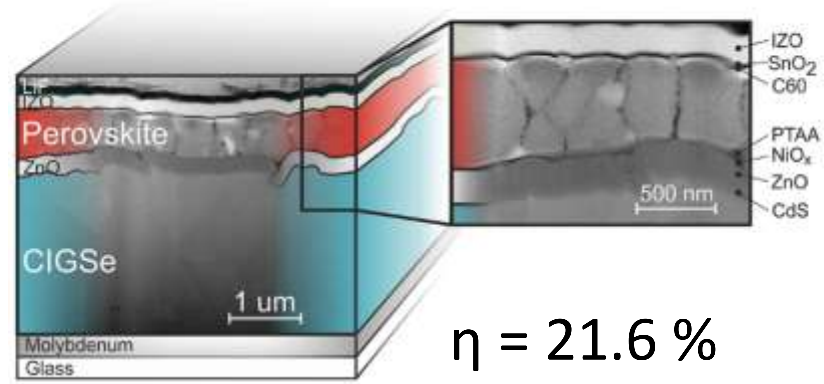
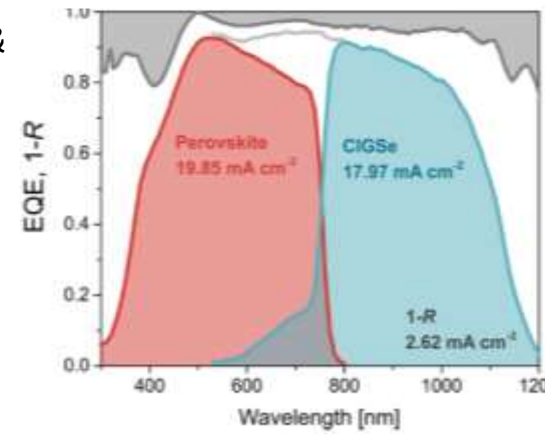




Jošt, M., (2019). *Energy & Environmental Science*.

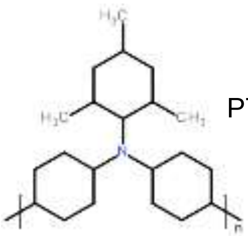
η = 21.6 %

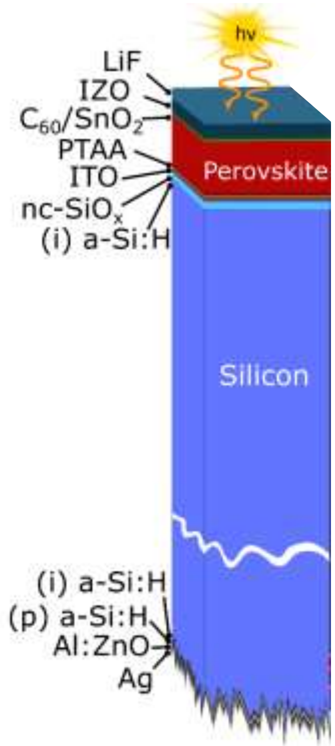


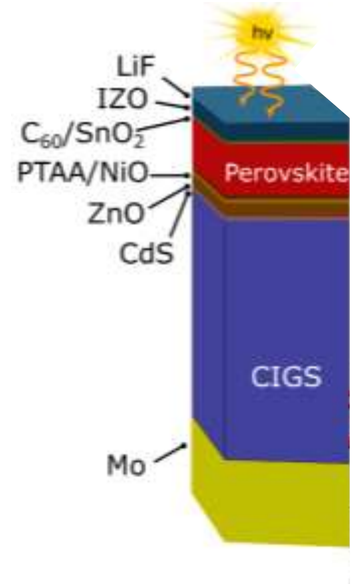
Perovskite/CIGS based multijunction solar cells:

- Highly efficient
- Flexible
- Several µm thin
- Lightweight
- Stowable
- Deployable

Perovskite based Single and Tandem Photovoltaics





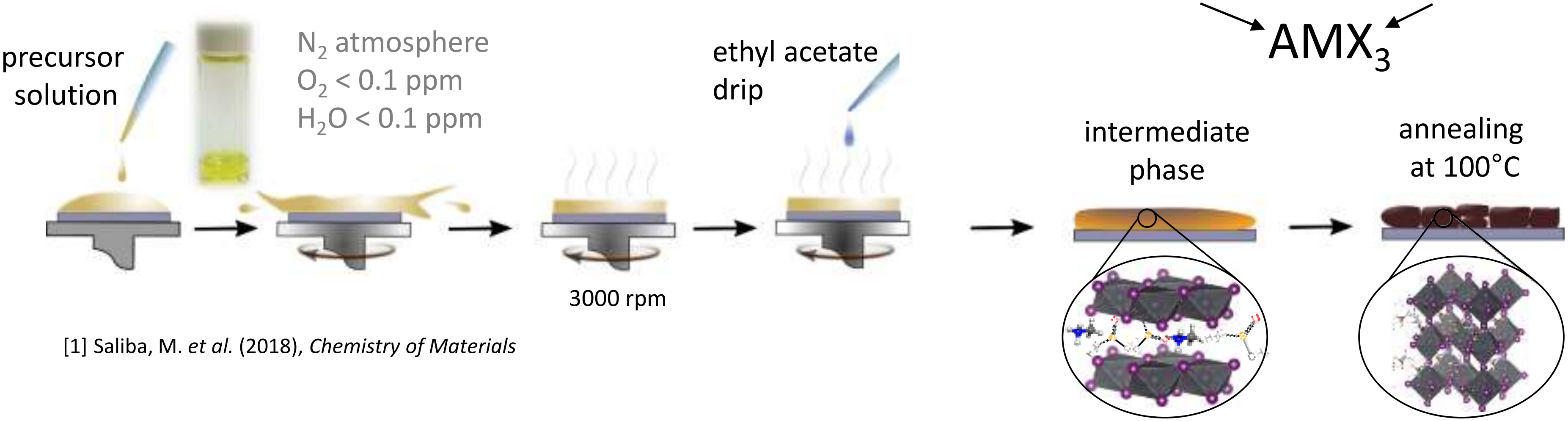


Dr. Marco Jost
Prof. Steve Albrecht
HySPRINT
Helmholtz Innovation Lab

Triple Cation Perovskite

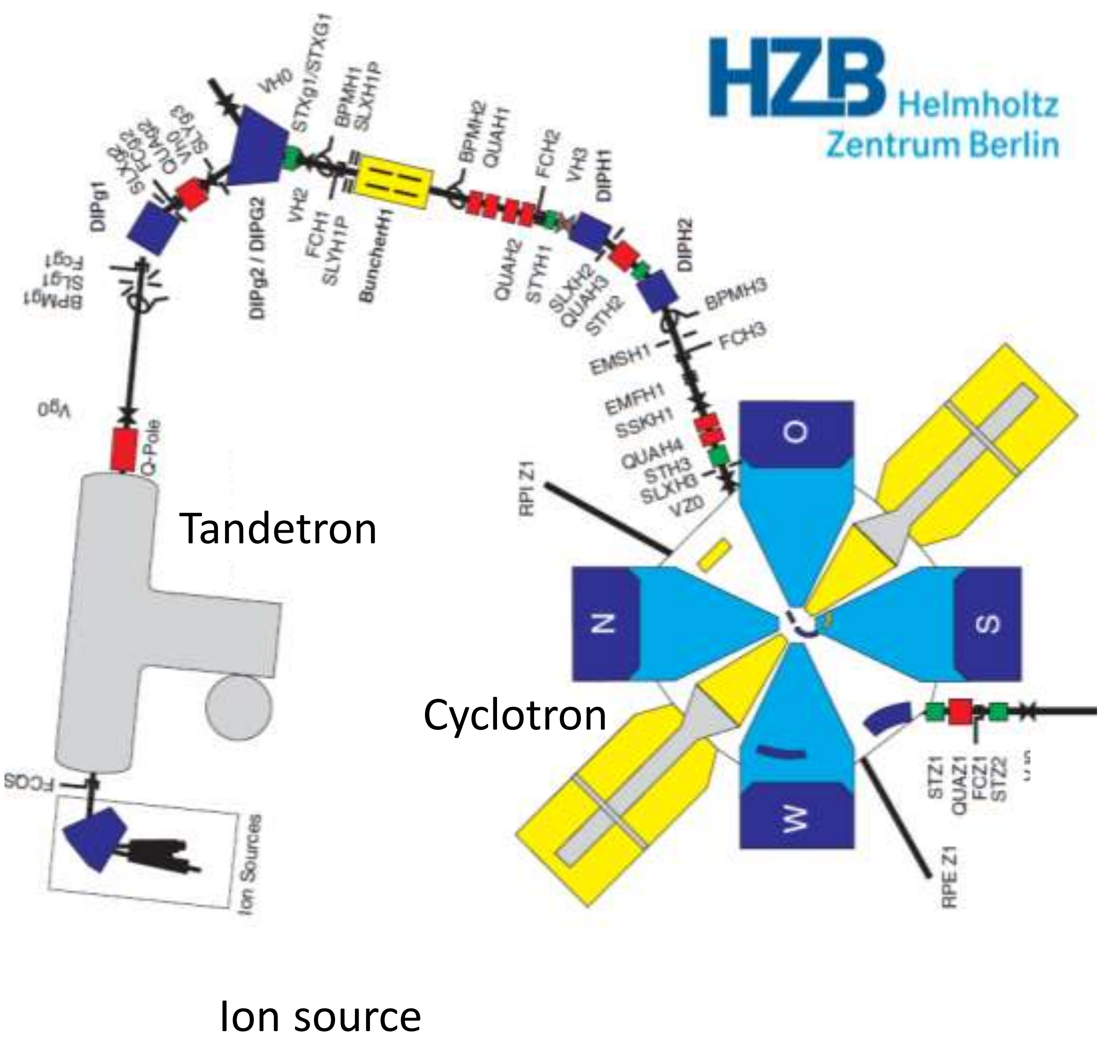
$$[Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}]Pb(I_{0.83}Br_{0.17})_3$$

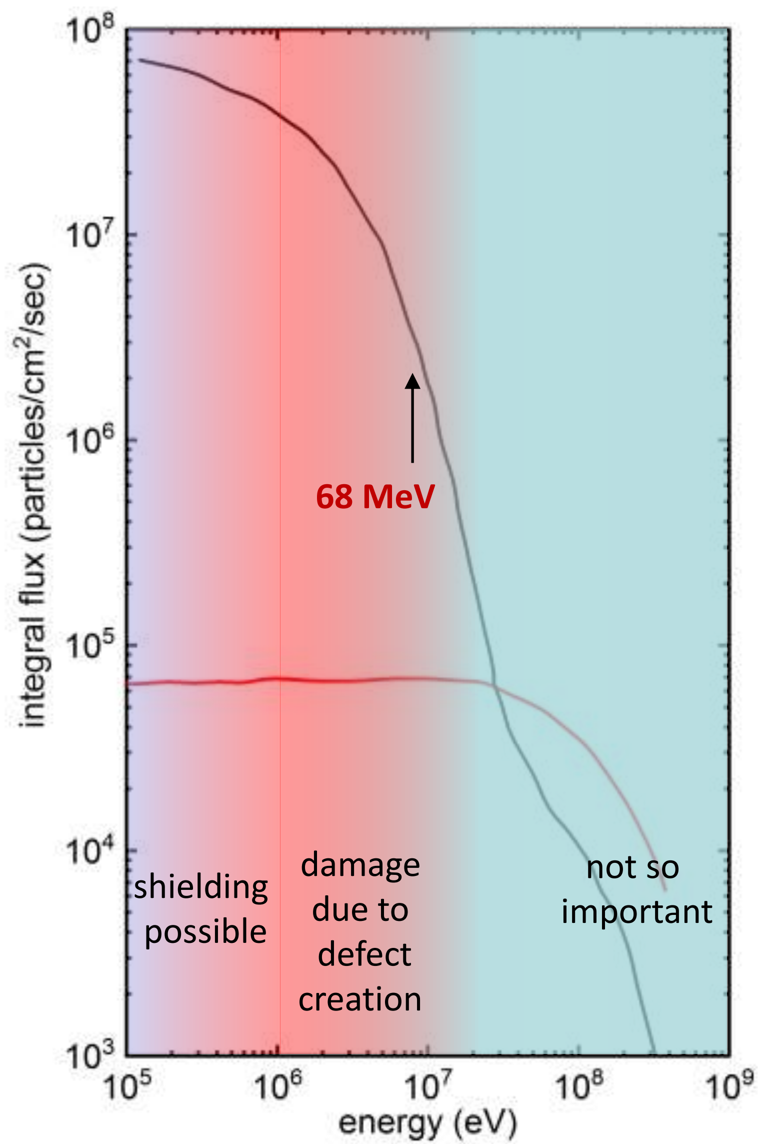
$$AMX_3$$



[1] Saliba, M. *et al.* (2018), *Chemistry of Materials*

Proton Irradiation





[1] J. Röhrich et al., Rev. Sci. Instrum. **83**, 02B903 (2012).

[2] Walters et al. (2006). *IEEE 4th World Conf. on Photovoltaic Energy* (Vol. 2, pp. 1899–1902).

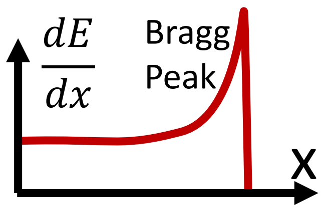
Proton Irradiation

Stopping power

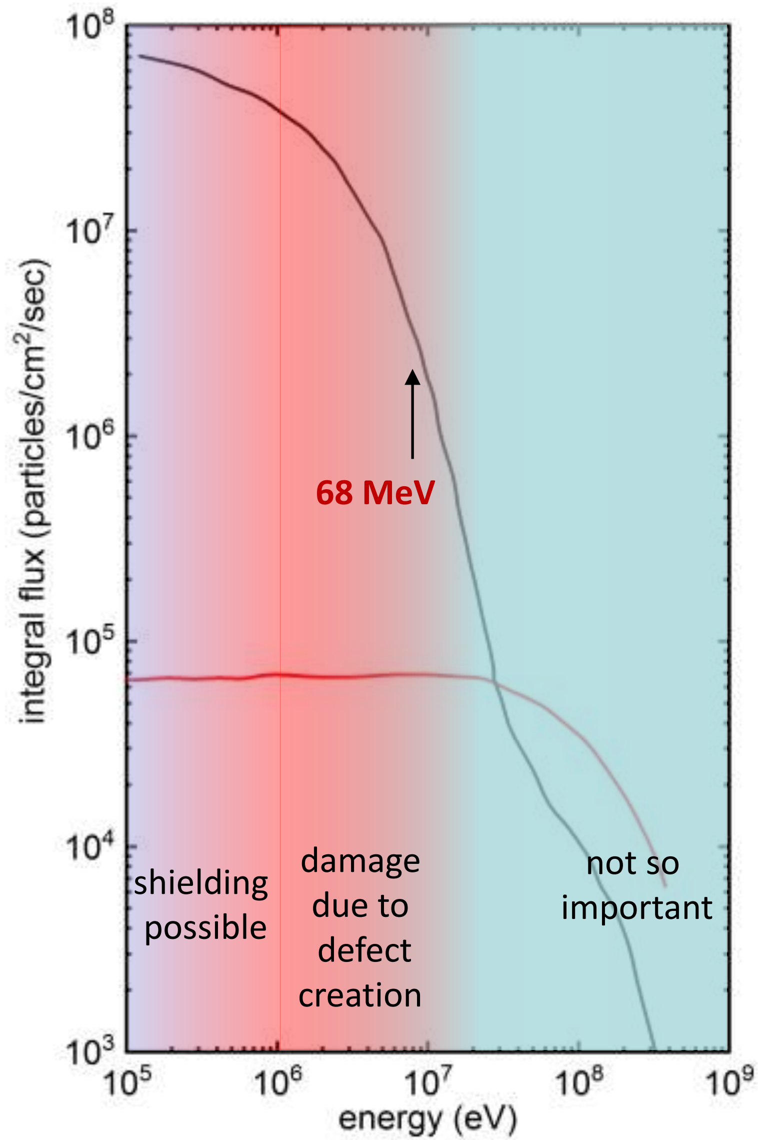
$$\frac{dE}{dx} \sim \frac{1}{E^2}$$

Depth in target

Energy of the proton



68 MeV to replicate the uniform damage of a true space environment considering polyenergetic & omnidirectional proton irradiation



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InGAP/GaAs/Ge ist doch perfekt

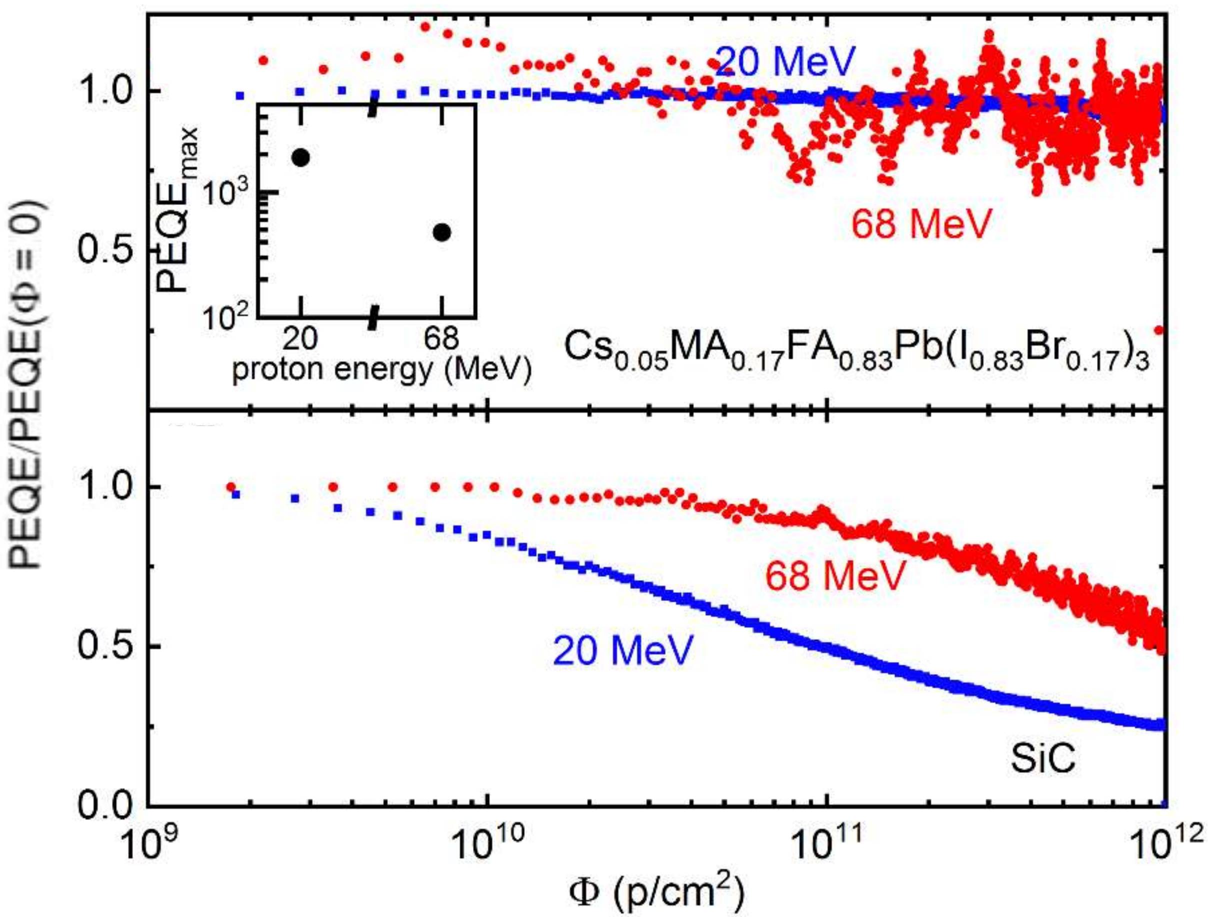
In-situ measurements during proton irradiation

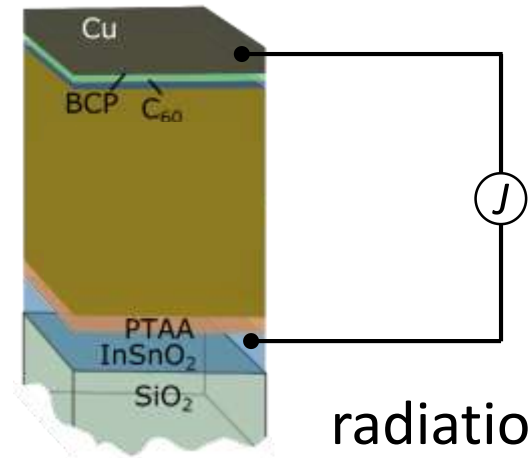
More In-situ measurements during proton irradiation

η > 29%*, to be commercialized soon

Can be flexible and lightweight!

In-situ measurements of the degradation of J_{rad}



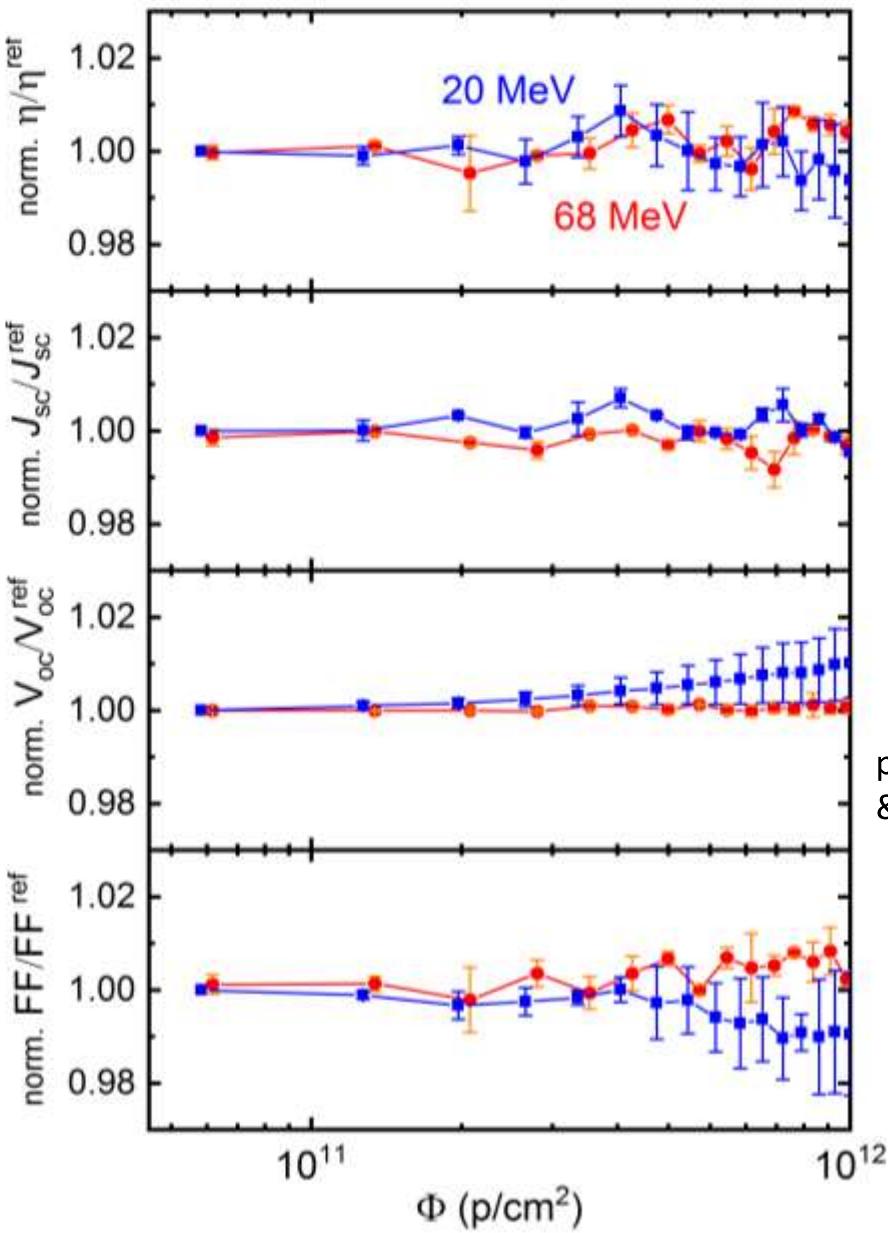


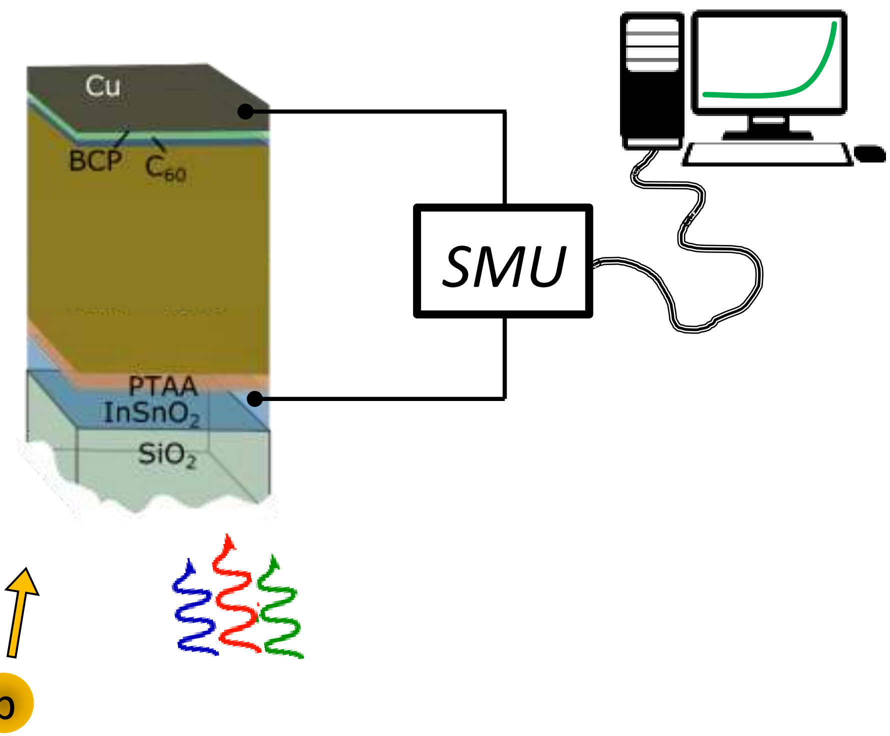
radiation induced current J_{rad}

$$PEQE = \frac{J_{rad}}{\phi}$$

proton beam flux

In-situ Characterization of PV Performance





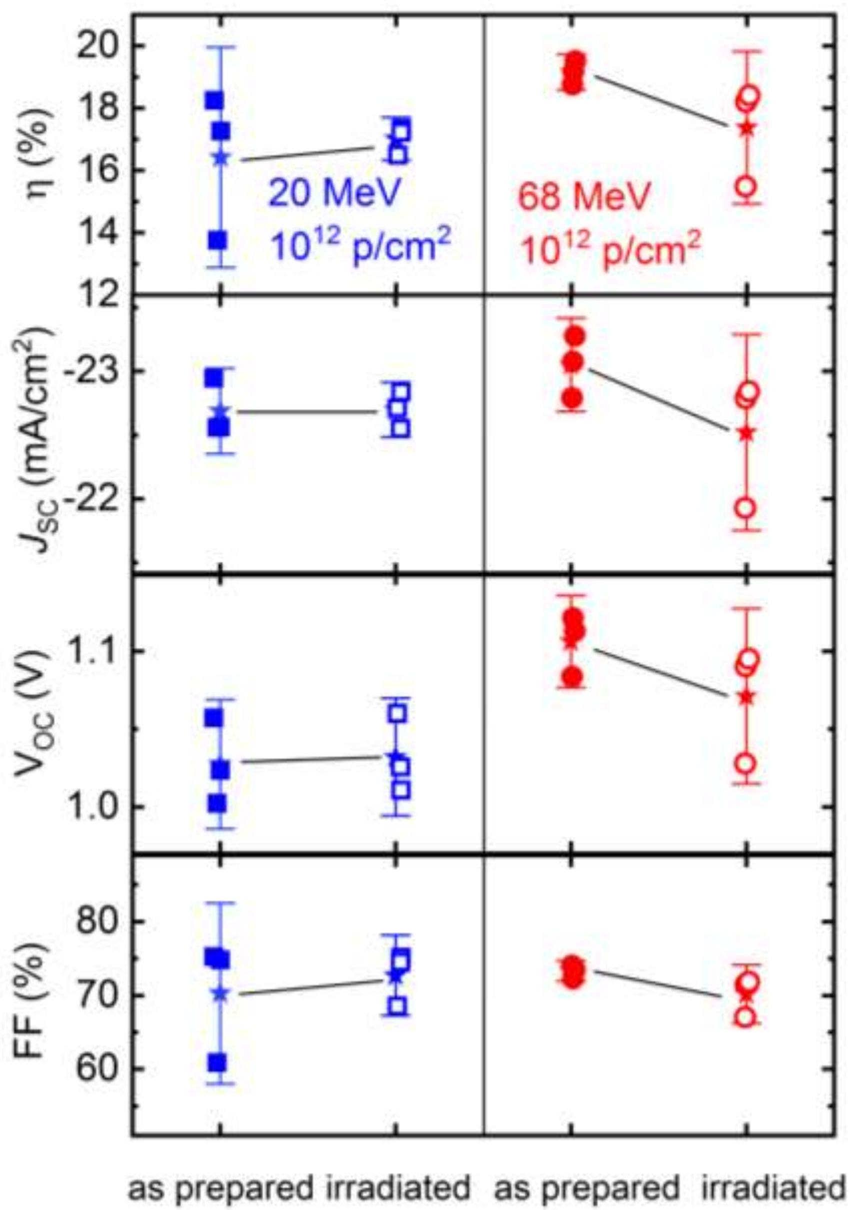
proton irradiation
& light illumination

In-elastic scattering

Instable isotopes

Be^{7}, Na^{22}, Na^{24}, K^{42}, K^{43}, Rb^{100}, Rb^{101}, In^{111}, J^{123}, Te^{123}, Pb^{201}

A < 10^3 Bq → Characterization @ AM1.5

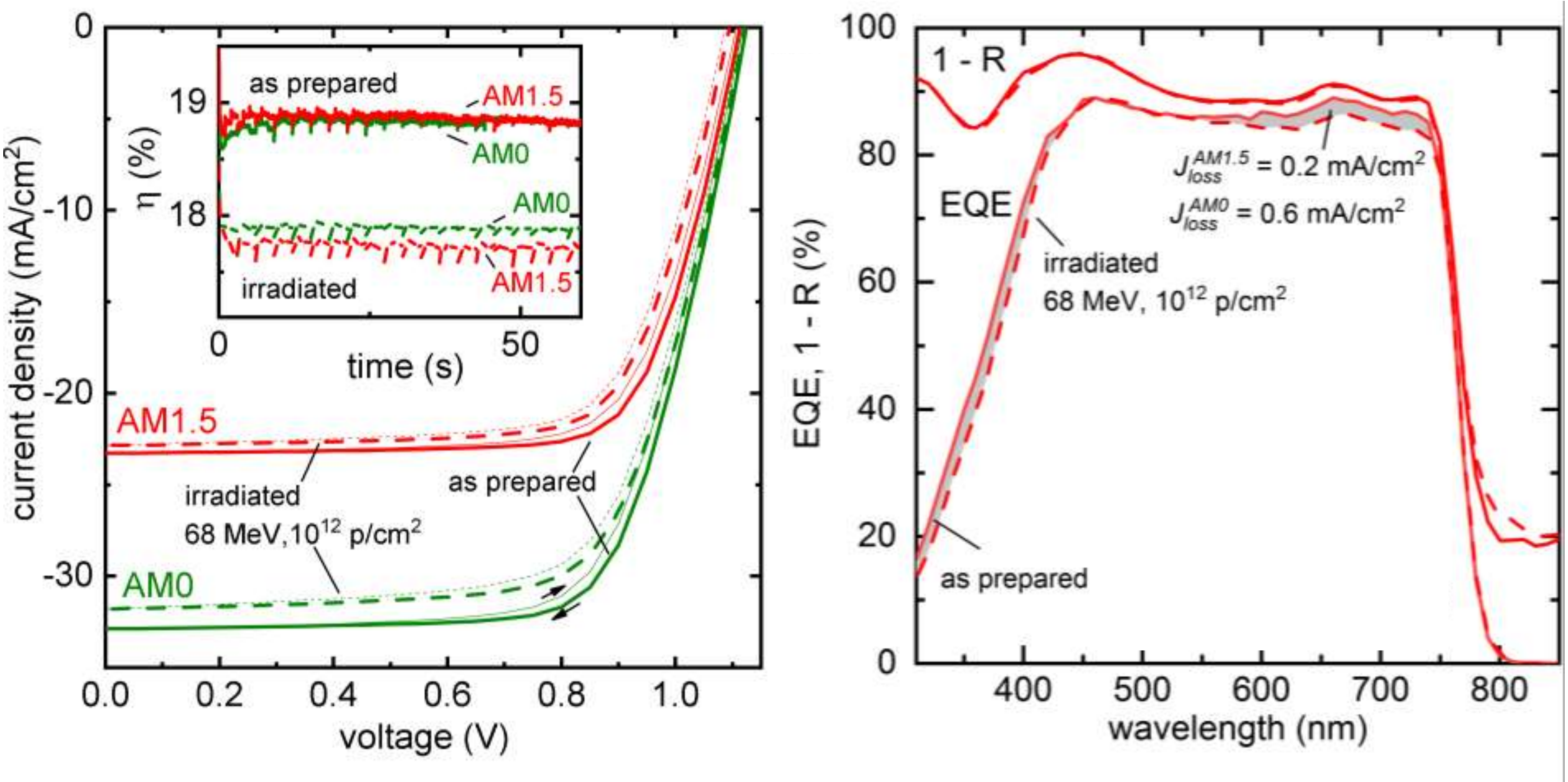


20 MeV:		68 MeV:	
• **η**	→	• **η**	↘
• J_{sc}	→	• J_{sc}	↘
• V_{OC}	→	• V_{OC}	↘
• *FF*	→	• *FF*	↘

- Degradation @
  68 MeV >> 20 MeV

- SRIM simulations
  # vacancies & interstitials
  68 MeV << 20 MeV

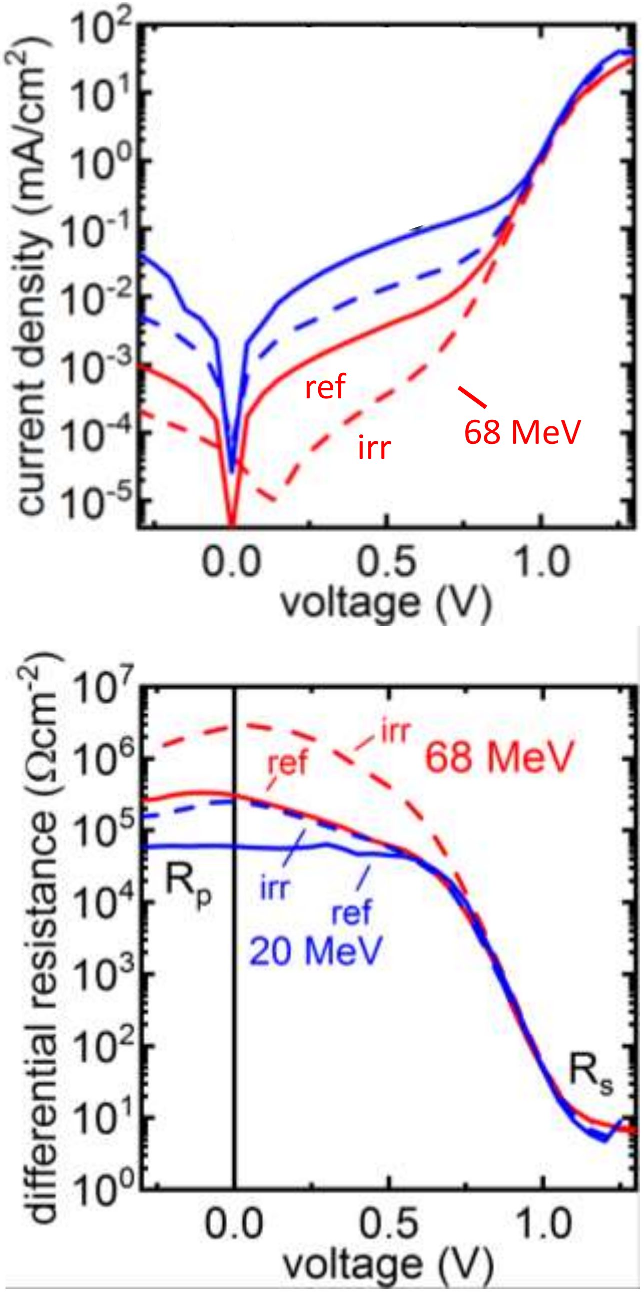
After 3 weeks, A < 10^4 Bq



- AM0 = 135 mW/cm^2
  - $\eta_{MPP}^{as\ prep}$ = 18.8 %
  - $\eta_{MPP}^{irr.}$ = 17.8 %

Lang, F., et al.,
Energy Environ. Sci.
2019, 12, 1634.

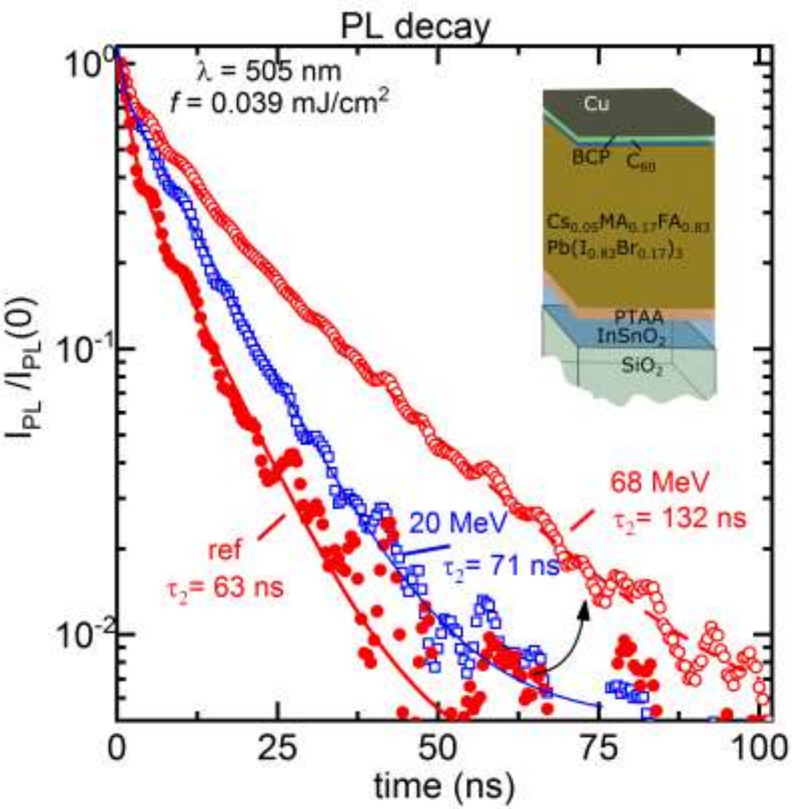
Dark *J*-V characteristics

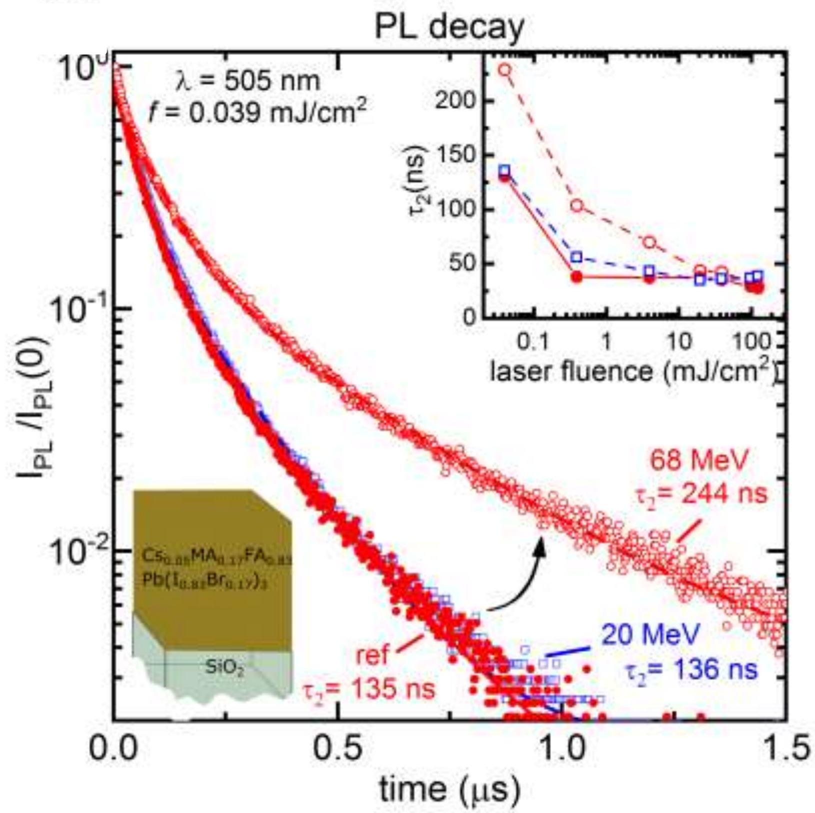


Increase in rectification ???

→ reduced recombination after irradiation ?

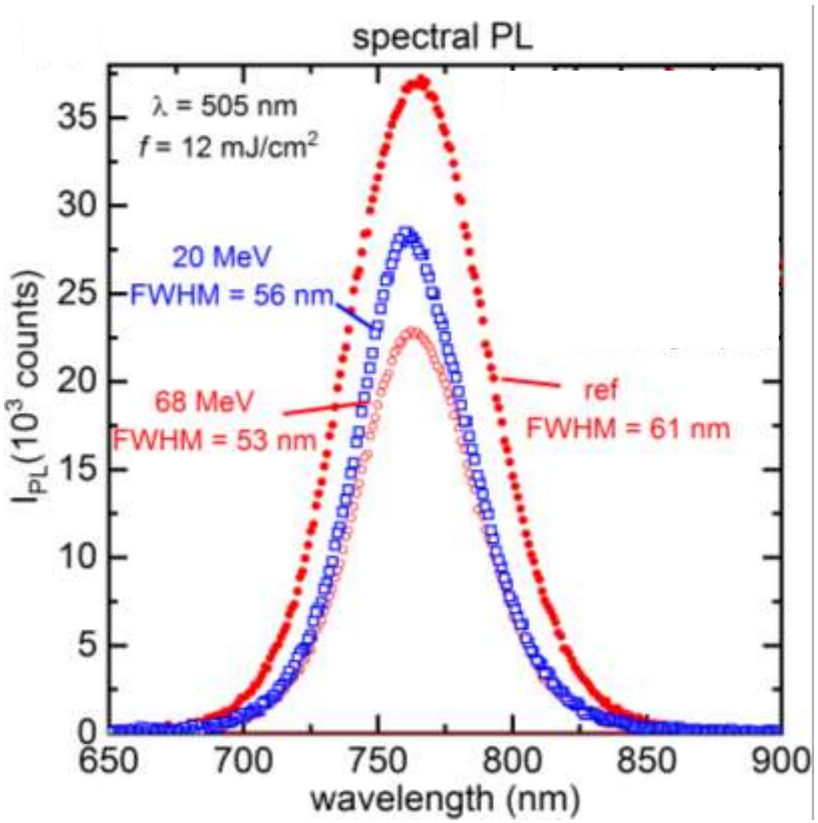
Photoluminescence Decay





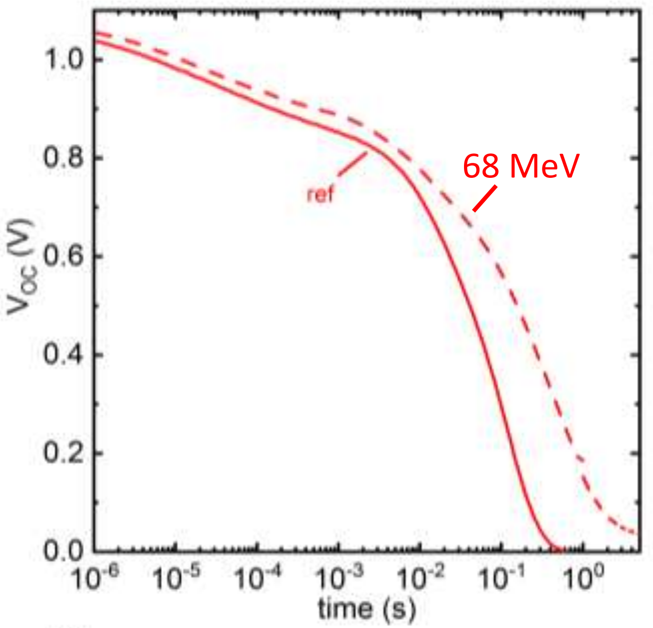
→ Suggests reduced recombination after irradiation with 68 MeV

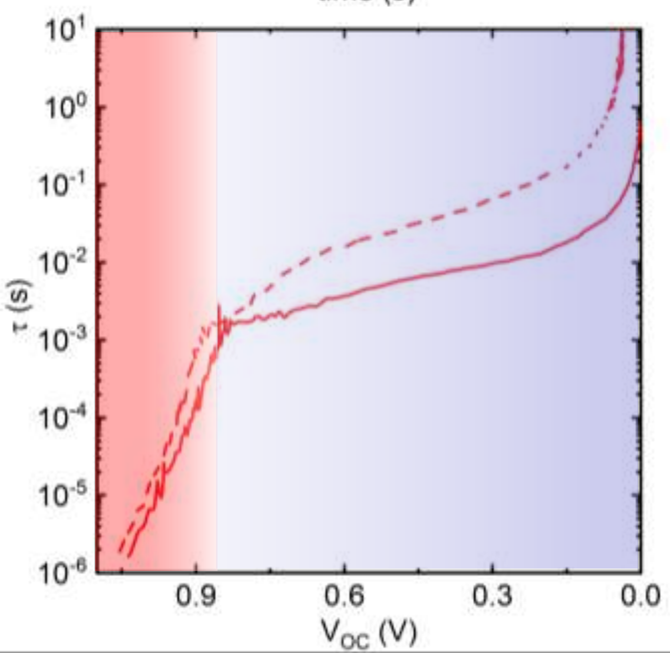
Spectral Photoluminescence

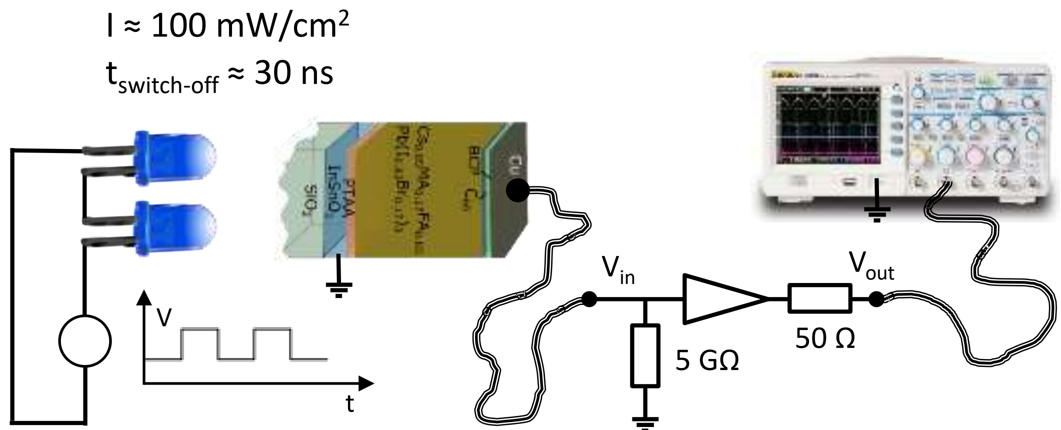


→ Suggests <u>increased</u> recombination after irradiation with 68 MeV

V_{OC} decay







$$-\frac{dn}{dt} = -\frac{n}{\tau_{rec}} \qquad n \approx e^{\left(\frac{qV_{OC}}{kT}\right)}$$

$$\tau_{rec} = -\frac{kT}{q}\left(\frac{dV_{OC}}{dt}\right)^{-1}$$

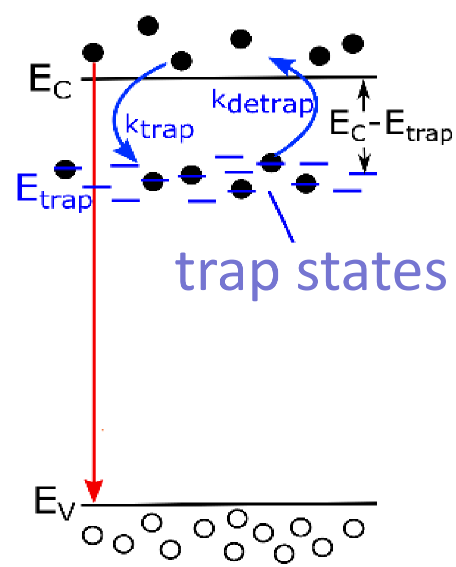
→ Suggests reduced Shockley-Read Hall recombination after irradiation

Apparent lifetime due to trapping and detrapping ??

PHYSICAL REVIEW VOLUME 97, NUMBER 2 JANUARY 15, 1955

Trapping of Minority Carriers in Silicon. I. *P*-Type Silicon

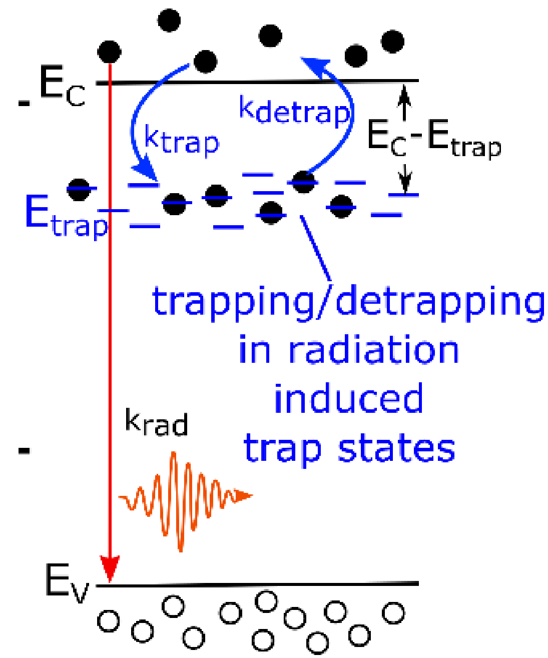
J. A. HORNBECK AND J. R. HAYNES
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 11, 1954)



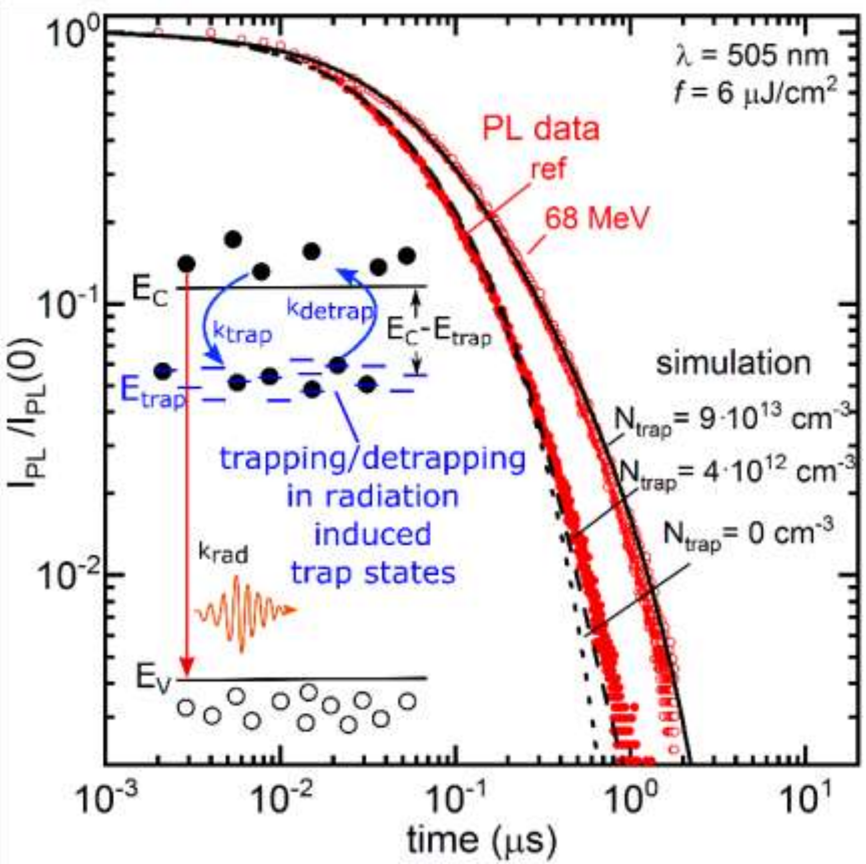
$$\frac{\mathrm{d}n_e^i}{\mathrm{dt}} = -\underbrace{\gamma_{Auger} \cdot {n_e^i}^2 \cdot n_h^i}_{Auger} - \underbrace{\mathrm{k}_{rad} \cdot n_e^i \cdot n_h^i}_{radiative} - \underbrace{k_{trap} \cdot n_e^i \cdot N_{trap} \cdot \left(1 - \frac{n_{trap}^i}{N_{trap}}\right)}_{trapping} + \underbrace{k_{detrap} \cdot n_{trap}^i \cdot N_{trap}}_{detrapping}$$

$$\frac{\mathrm{d}n_{h\mathrm{h}}^i}{\mathrm{dt}} = -\underbrace{\gamma_{Auger} \cdot n_e^i \cdot {n_h^i}^2}_{Auger} - \underbrace{\mathrm{k}_{rad} \cdot n_e^i \cdot n_h^i}_{radiative}$$

$$\frac{\mathrm{d}n_{trap}^i}{\mathrm{dt}} = \underbrace{k_{trap} \cdot n_e^i \cdot N_{trap} \cdot \left(1 - \frac{n_{trap}^i}{N_{trap}}\right)}_{trapping} - \underbrace{k_{detrap} \cdot n_{trap}^i \cdot N_{trap}}_{detrapping}$$



Trapping & Detrapping ?



$k_{trap} \sim 2.9 \cdot 10^{-8}\ cm^3/s$

$k_{detrap} \sim 8.5 \cdot 10^{-9}\ cm^3/s$

Hornbeck & Heynes model

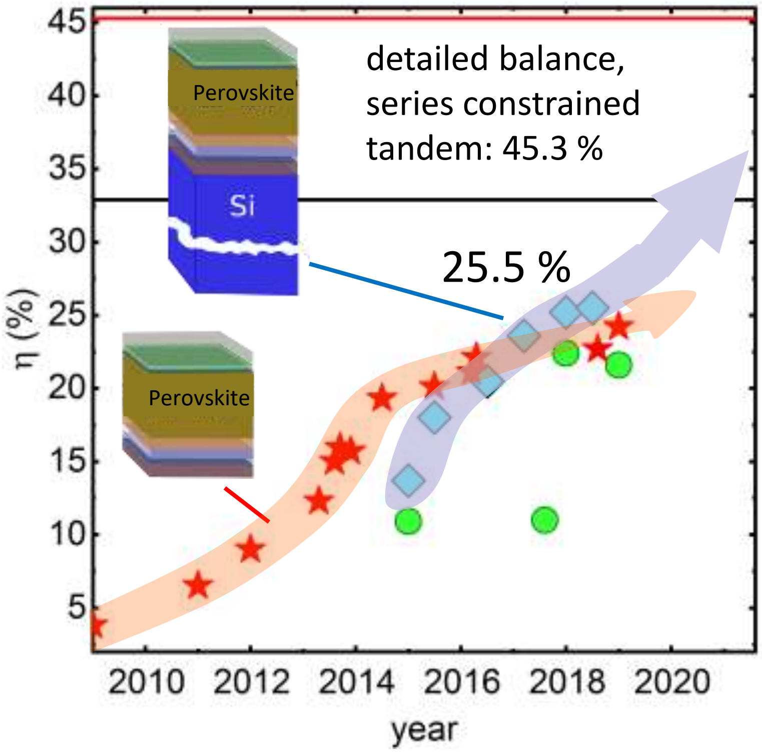
$$E_C - E_{trap} = k_B T \cdot \ln\left(\frac{N_C}{N_t} \cdot \frac{k_{trap}}{k_{detrap}}\right)$$

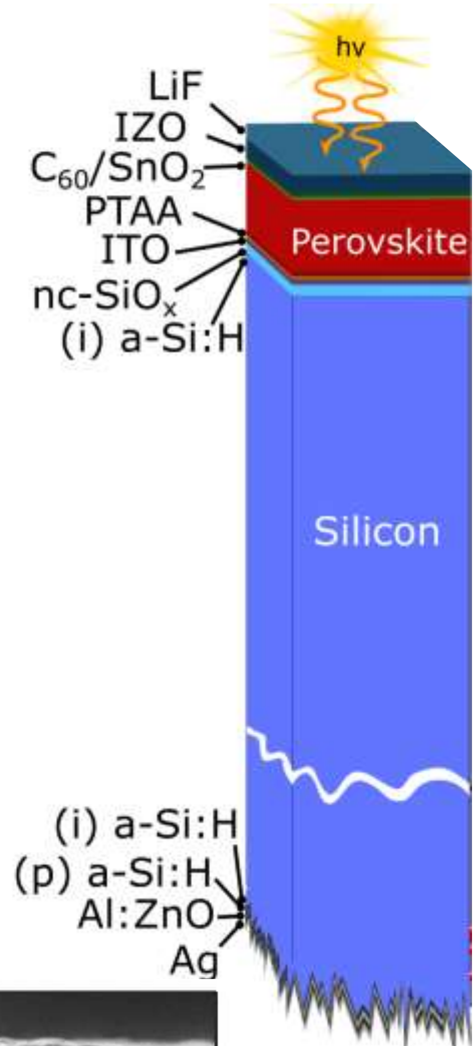
$E_c\text{-}E_{trap} = 0.31\ eV$

Minority carrier trapping & detrapping can explain the observations

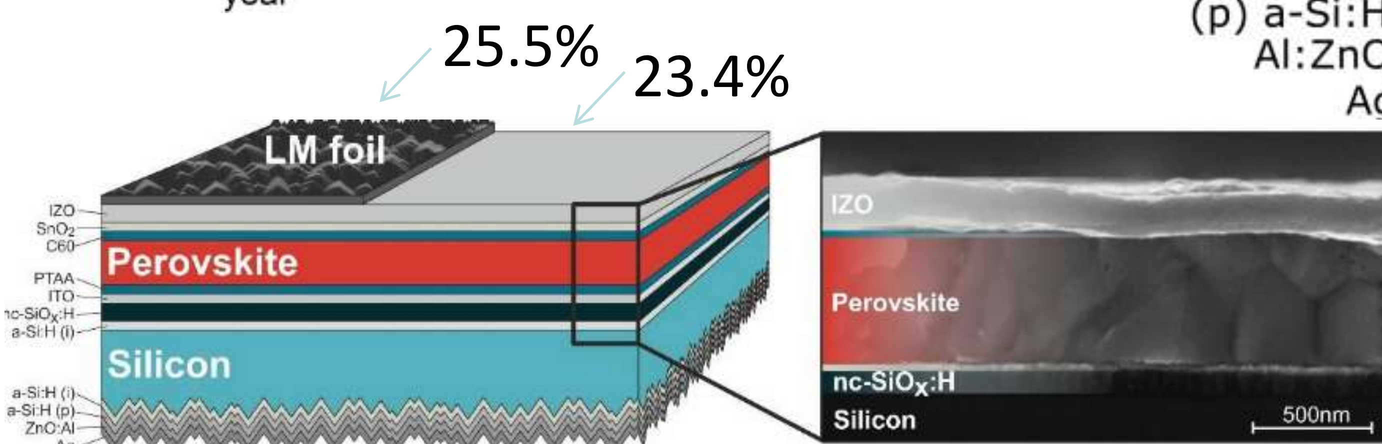
→ Is it true ?

Motivation: Ultralight Solar Cell Arrays for Space





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



Unpublished Data
please email
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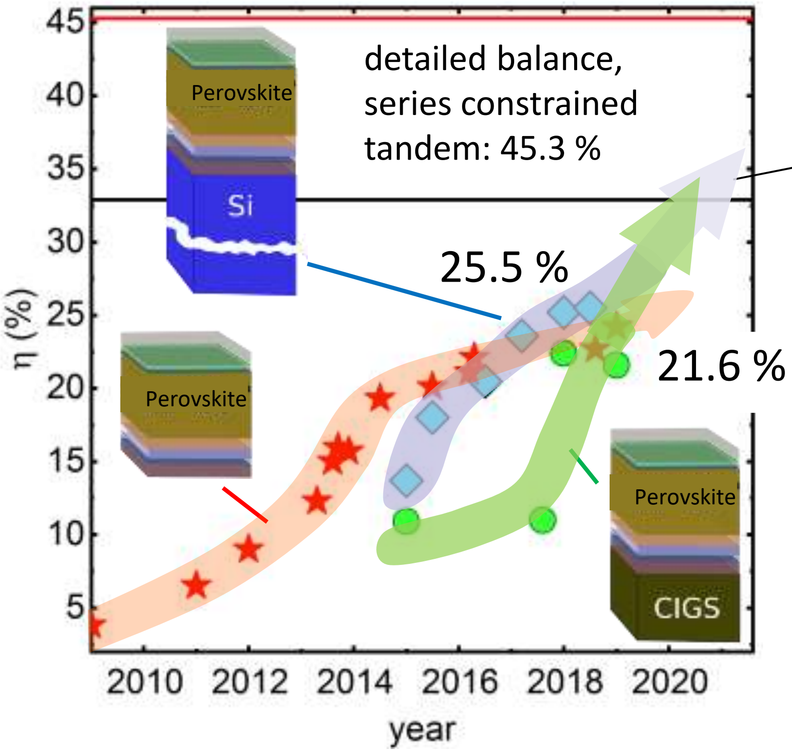
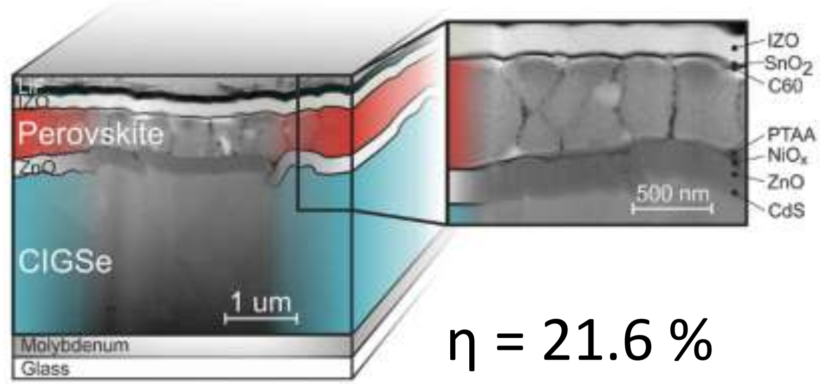
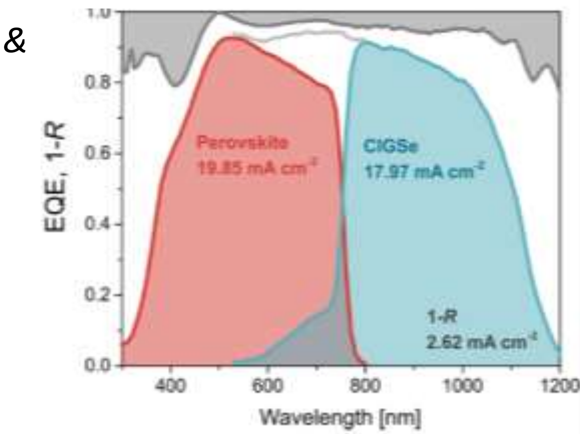
Motivation: Ultralight Solar Cell Arrays for Space





η = 21.6 %

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



Perovskite/CIGS based multijunction solar cells:

- Highly efficient
- Flexible
- Several µm thin
- Lightweight
- Stowable
- Deployable

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