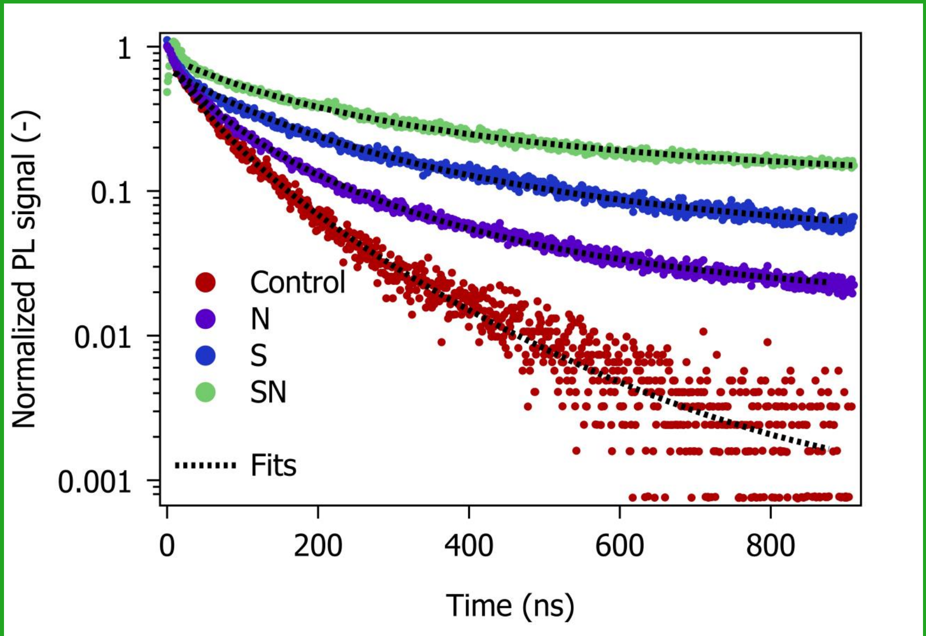
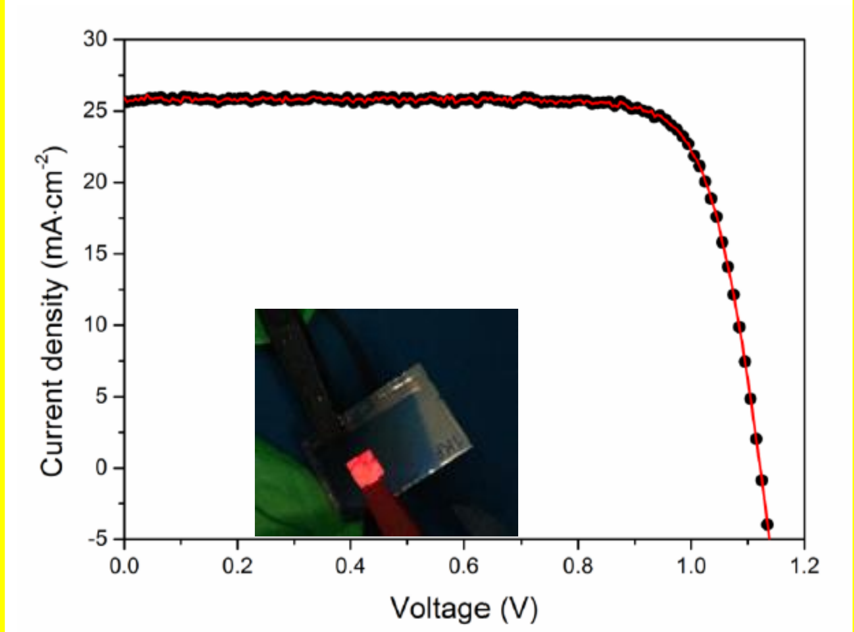
Molecular Photovoltaics and Perovskite Solar Cells

21st Sede Boker Symposium, Negev Israel 2018

The impact of molecular modulators on perovskite charge carrier recombination dynamics





$-dn/dt = k_1 \times n + k_2 n^2$

$dn_{ph}/dt = k_2 n^2$

PCE = 23.25 %

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

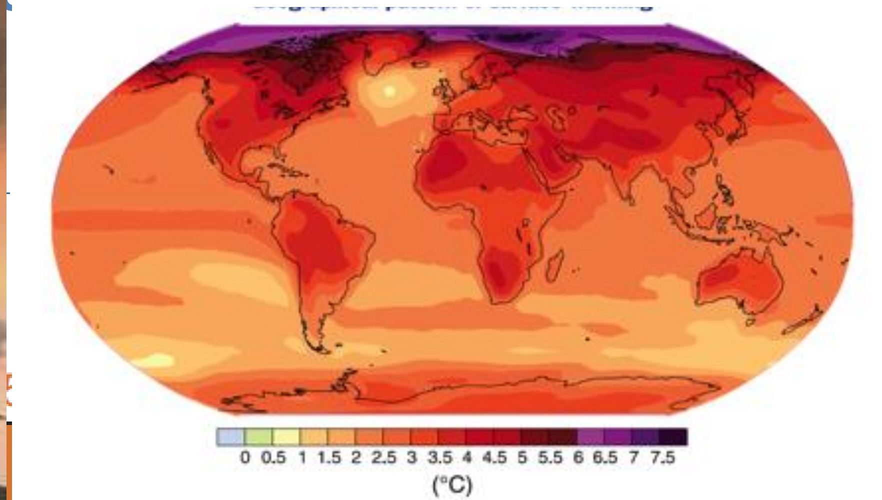
NANYANG TECHNOLOGICAL UNIVERSITY

MAX-PLANCK-GESELLSCHAFT

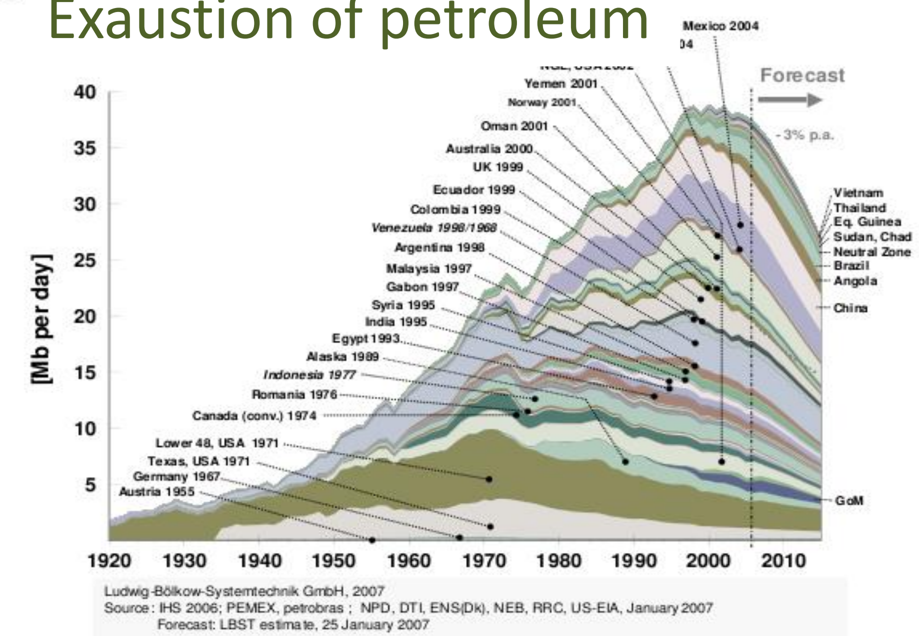
Michael Graetzel
Global Energy Prize Laureate 2017
michael.graetzel@epfl.ch

The problem

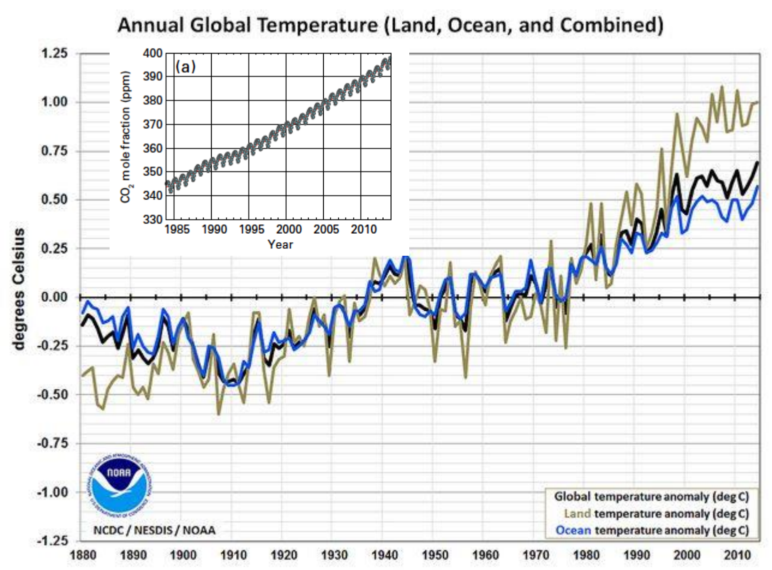
Global warming



Exaustion of petroleum



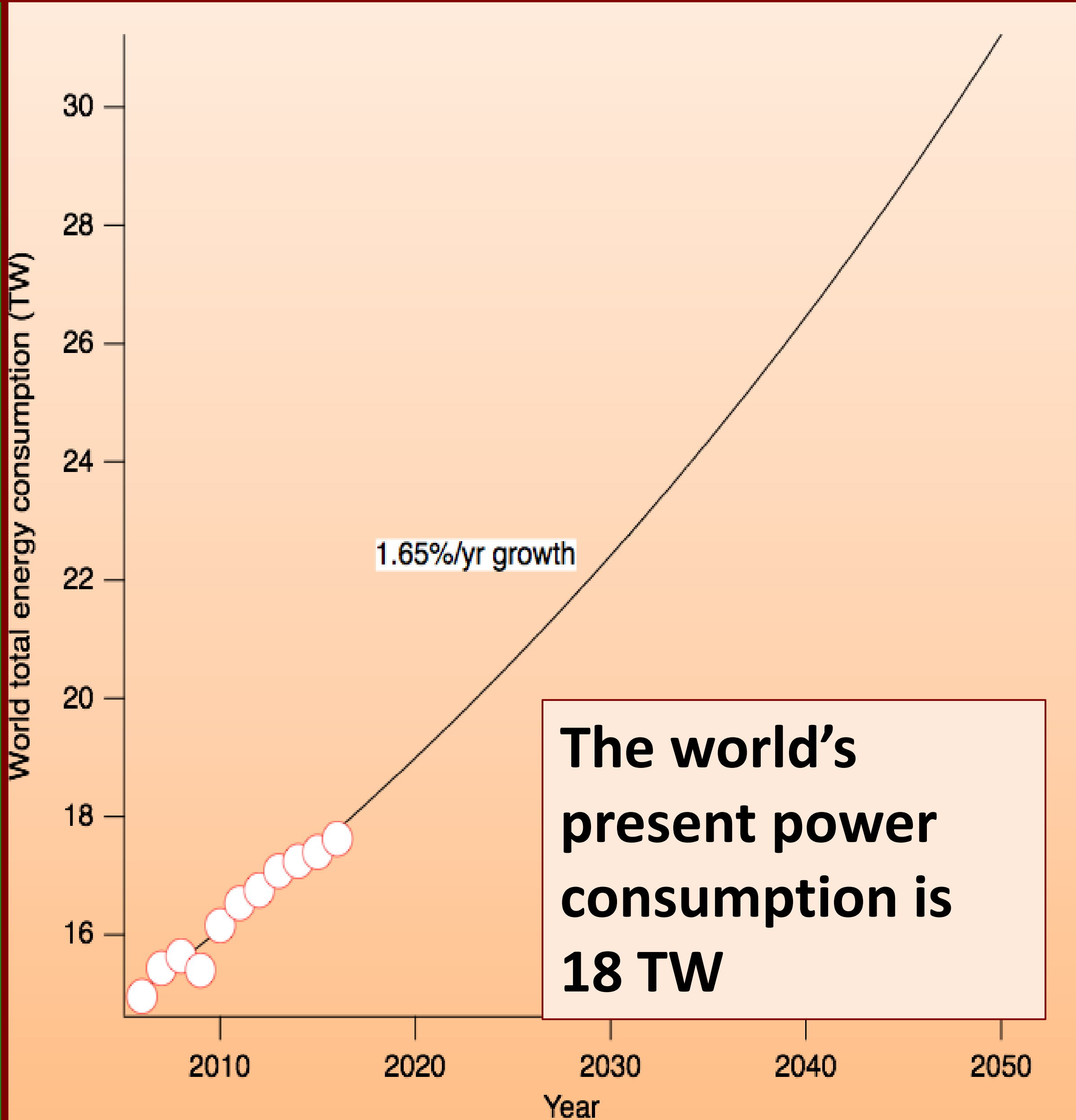
Oil causes global warming and environmental disasters



20 April 2010: the BP platform "Deepwater Horizon" explodes in the Golf of Mexico killing 11 people and causing an unprecedented ecological disaster by spilling at least 1 billion liters of oil in the ocean.

US National US National Oceanic and Atmospheric Administration (NOAA): CO_2 level passed the critical level of 400 ppm ! in Oct. 2015 !

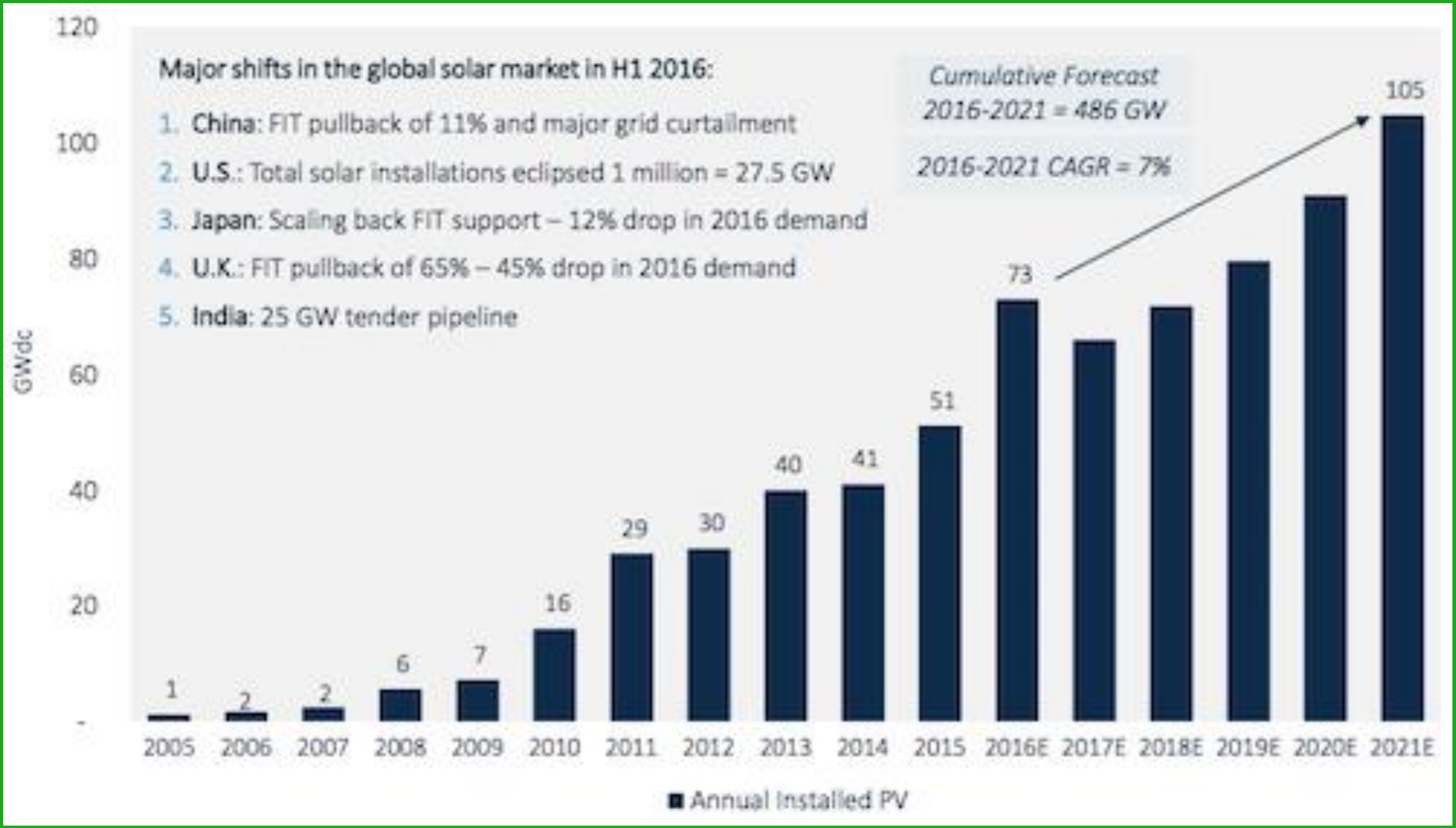
The Terrawatt Challenge



- Another 15 TW needed by 2050
- Only 16% of energy consumption is in electricity generation
- What will be used to 'fuel' this growth?

Courtesy: Jao van de. Lagrmaat
NREL, USA

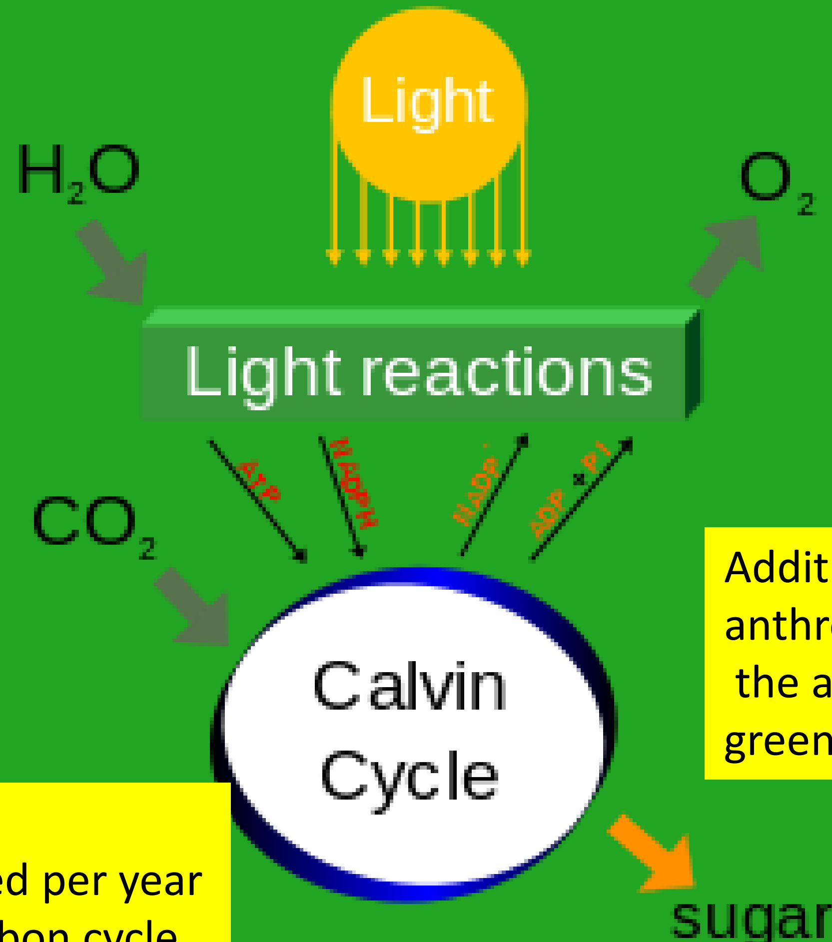
The annual installation of photovoltaics has been growing strongly, but it still contributes only 0.3 % to the world's total energy needs.



Future growth of Si-PV to the TW scale may be compromised by high capex and declining marginal value

Photosynthesis shows the way

Converts ca 90 terrawatt of the 178’000 terrawatt solar power that strikes the Earth to chemical energy stored in fossile fuels



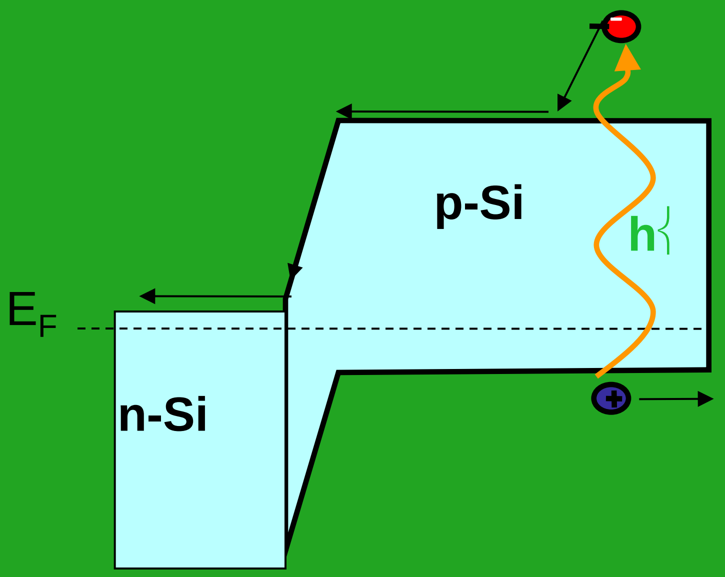
Additional 40 billion tons/year of anthropogenic CO_2 rejected in the atmosphere resulting in green house warming

750 billion tons of CO_2 assimilated and recycled per year through the natural carbon cycle

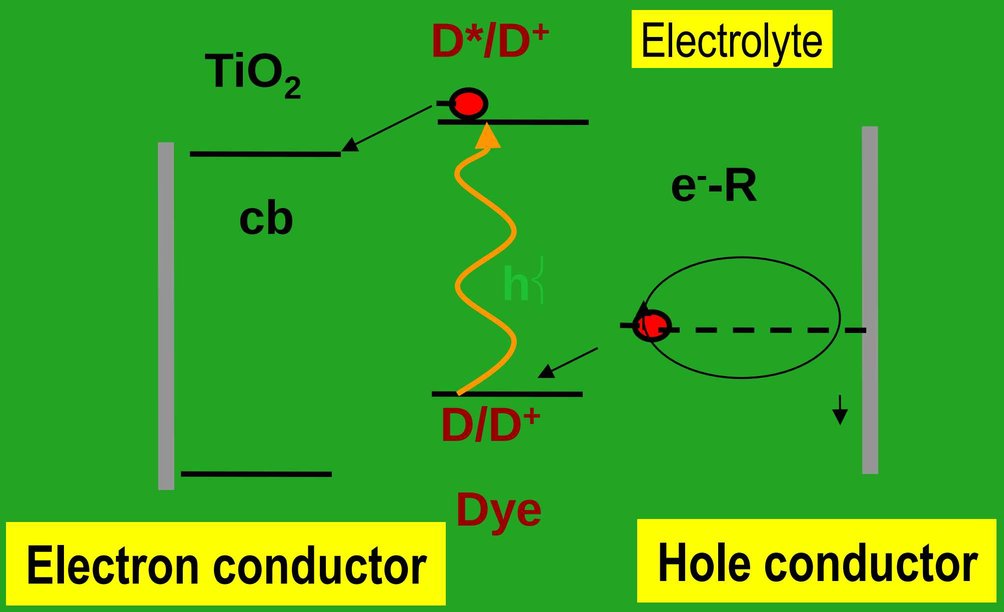
$CO_2 + 2\ H_2O + 8\ \text{photons} \rightarrow [CH_2O] + O_2 \quad \Delta G^* = 477\ \text{KJ/mole}$

Photo-induced charge generation in dye sensitized sola cells is different from conventional photovoltaic devices

p-n junction photovoltaic cells



dye sensitized solar cells DSC

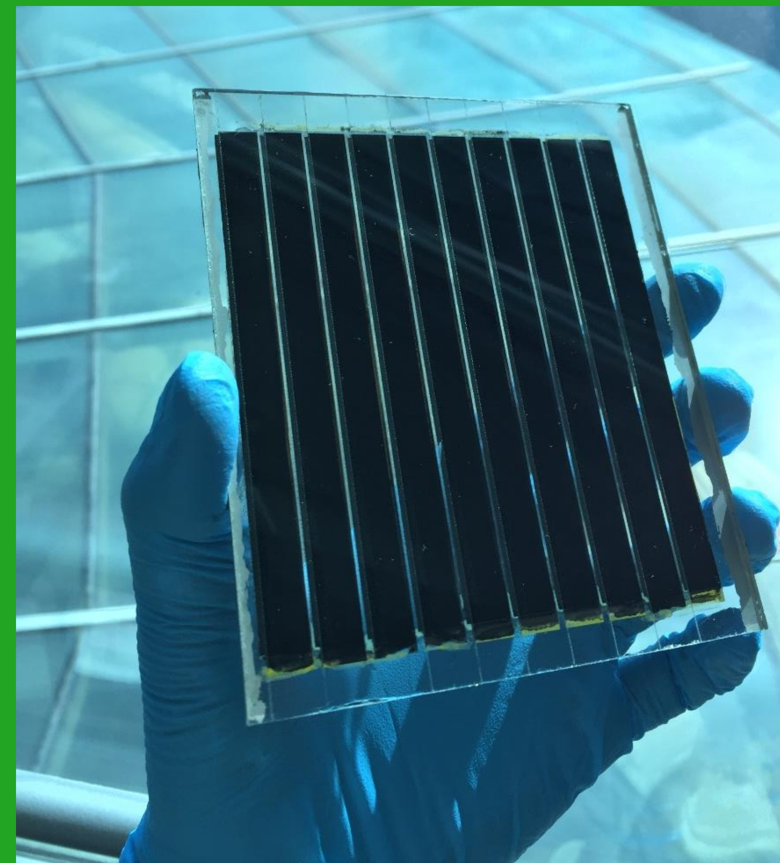


Charge separation by electric field at the p-n junction minority carrier lifetime is a key issue in photoelectric ¨convrsion

Charge separation by kinetic competition as in photosynthesis. No minority charge carrier involved in photoelectric energy conversion

Perovskite Solar Cells (PSCs) emerged from Dye Sensitized Solar Cells

Dye sensitized solar cell (DSC) → Perovskite solar cell (PSC)



Dye sensitized solar cell
courtesy Sony corporation

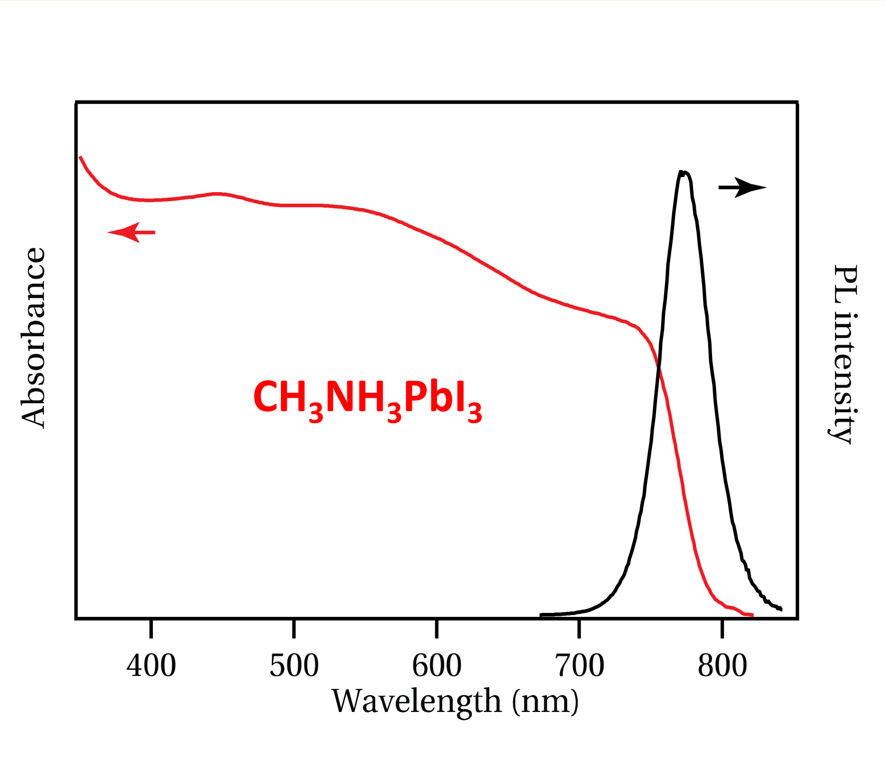
Pervovskite solar cell
courtesy Subodh Mhalkalsar NTU

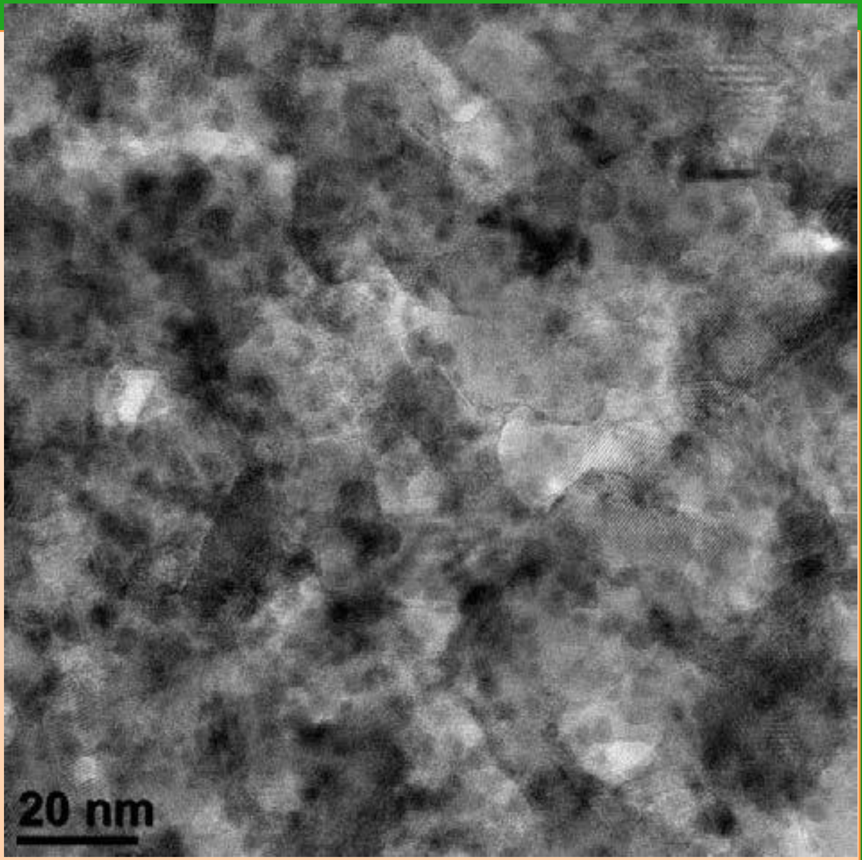
Outline

- The stunning rise of pervoskite solar cells
- Recent research advances to increase their efficiency and stability
    - Multi-cation formulations, the power of solid state NMR analysis.
    - The amazing impact of molecular modulators
    - Boosting the PSC stability.

Applications for solar fuel generation

Perovskite solar cells (PSCs) emerged from dye sensitized solar cells

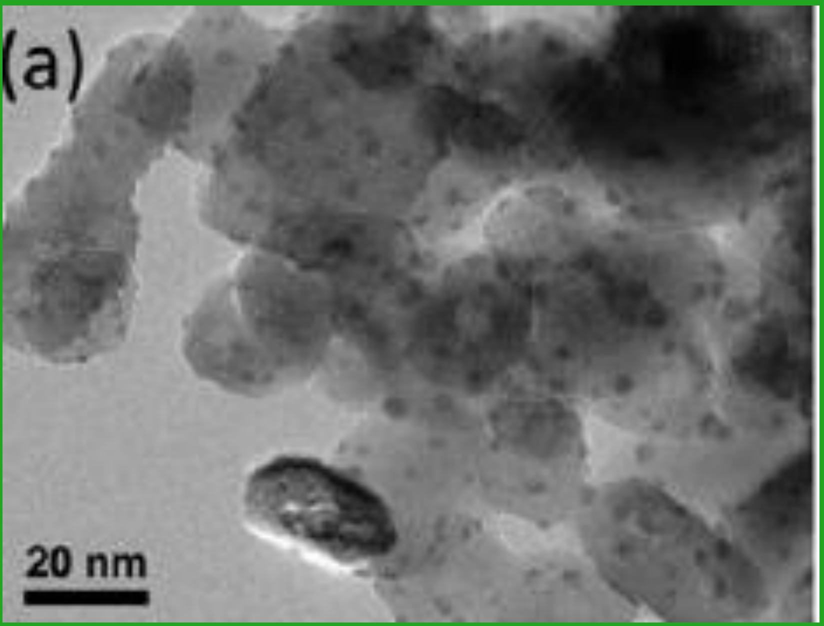




- Perovskite pigment replaces the molecular sensiizer in a dye sensitized solar cells (T.Miyasaka, et al. JACS 2009, 131, 6050–6051, N.G Park et al *Nanoscale 2011,* **3**, 4088-4093)
- unstable in liquid electrolyte based DSSC
- stable and more efficient in solid state hole conductor based DSSC

6.5% efficient perovskite quantum-dot-sensitized solar cell†

Jeong-Hyeok Im, Chang-Ryul Lee, Jin-Wook Lee, Sang-Won Park and Nam-Gyu Park*



Mesoscopic TiO_2 film impregnated with MAPbI3 perovskite quantum dots

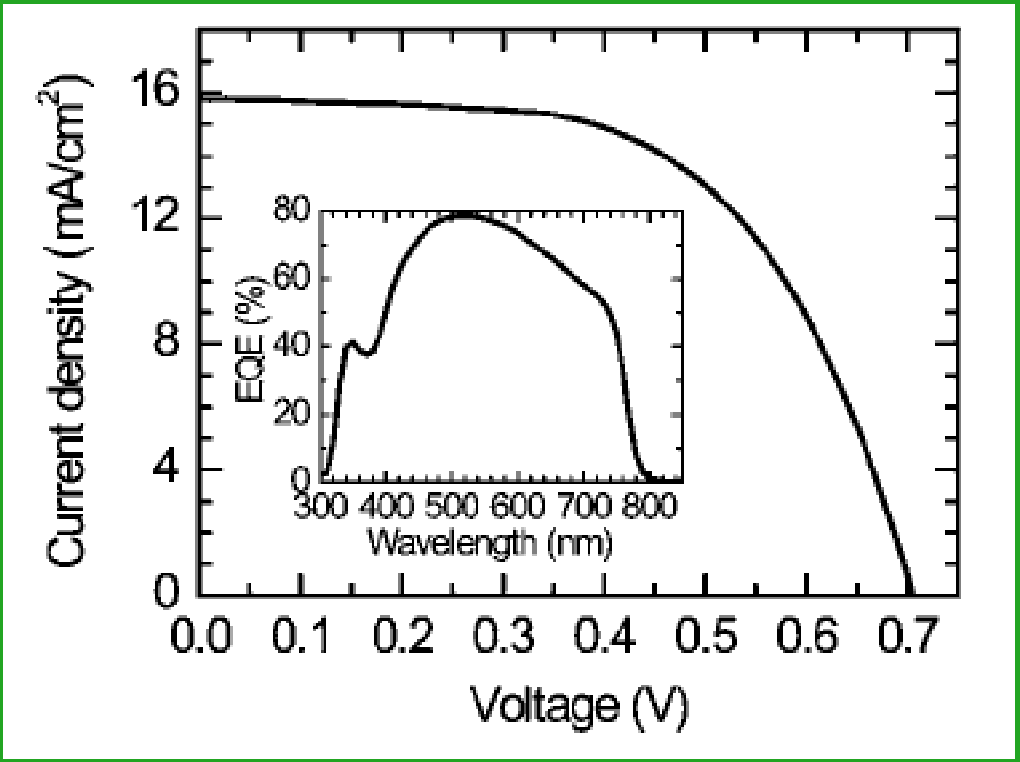


Fig. 5 Photocurrent–voltage curve and EQE for the perovskite $(CH_3NH_3)PbI_3$ QD-sensitized TiO_2 film whose surface was modified with $Pb(NO_3)_2$. Thickness of TiO_2 film was 3.6 μm and the redox electrolyte used was composed of 0.9 M LiI, 0.45 M I_2, 0.5 M *tert*-butylpyridine and 0.05 M urea in ethyl acetate.

Nanoscale, 2011, **3**, 4088

SCIENTIFIC REPORTS

OPEN

Lead Iodide Perovskite Sensitized All-Solid-State Submicron Thin Film Mesoscopic Solar Cell with Efficiency Exceeding 9%

SUBJECT AREAS:
NANOPHOTONICS
OPTICAL MATERIALS AND DEVICES
INORGANIC CHEMISTRY
APPLIED PHYSICS

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5 July 2012

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6 August 2012

Published
21 August 2012

Hui-Seon Kim[1], Chang-Ryul Lee[1], Jeong-Hyeok Im[1], Ki-Beom Lee[1], Thomas Moehl[2], Arianna Marchioro[2], Soo-Jin Moon[2], Robin Humphry-Baker[2], Jun-Ho Yum[2], Jacques E. Moser[2], Michael Grätzel[2] & Nam-Gyu Park[1]

[1]School of Chemical Engineering and Department of Energy Science, Sungkyunkwan University, Suwon 440-746, Korea, [2]Laboratory for Photonics and Interfaces, Institute of Chemical Sciences and Engineering, School of Basic Sciences, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland.

Correspondence and requests for materials should be addressed to M.G. (michael.graetzel@epfl.ch) or N.-G.P. (npark@skku.

We report on solid-state mesoscopic heterojunction solar cells empl
ammonium lead iodide $(CH_3NH_3)PbI_3$ as light harvesters. The perov
methylammonium iodide with PbI_2 and deposited onto a submicron
pores were infiltrated with the hole-conductor *spiro*-MeOTAD. Illum
generated large photocurrents (J_{SC}) exceeding 17 mA/cm², an open
and a fill factor (FF) of 0.62 yielding a power conversion efficiency (
date for such cells. Femto second laser studies combined with photo
showed charge separation to proceed via hole injection from the exc
spiro-MeOTAD followed by electron transfer to the mesoscopic TiO_2
dramatically improved the device stability compared to $(CH_3NH_3)P$

Sciencexpress

Efficient Hybrid Solar Cells Based on Meso-Superstructured Organometal Halide Perovskites

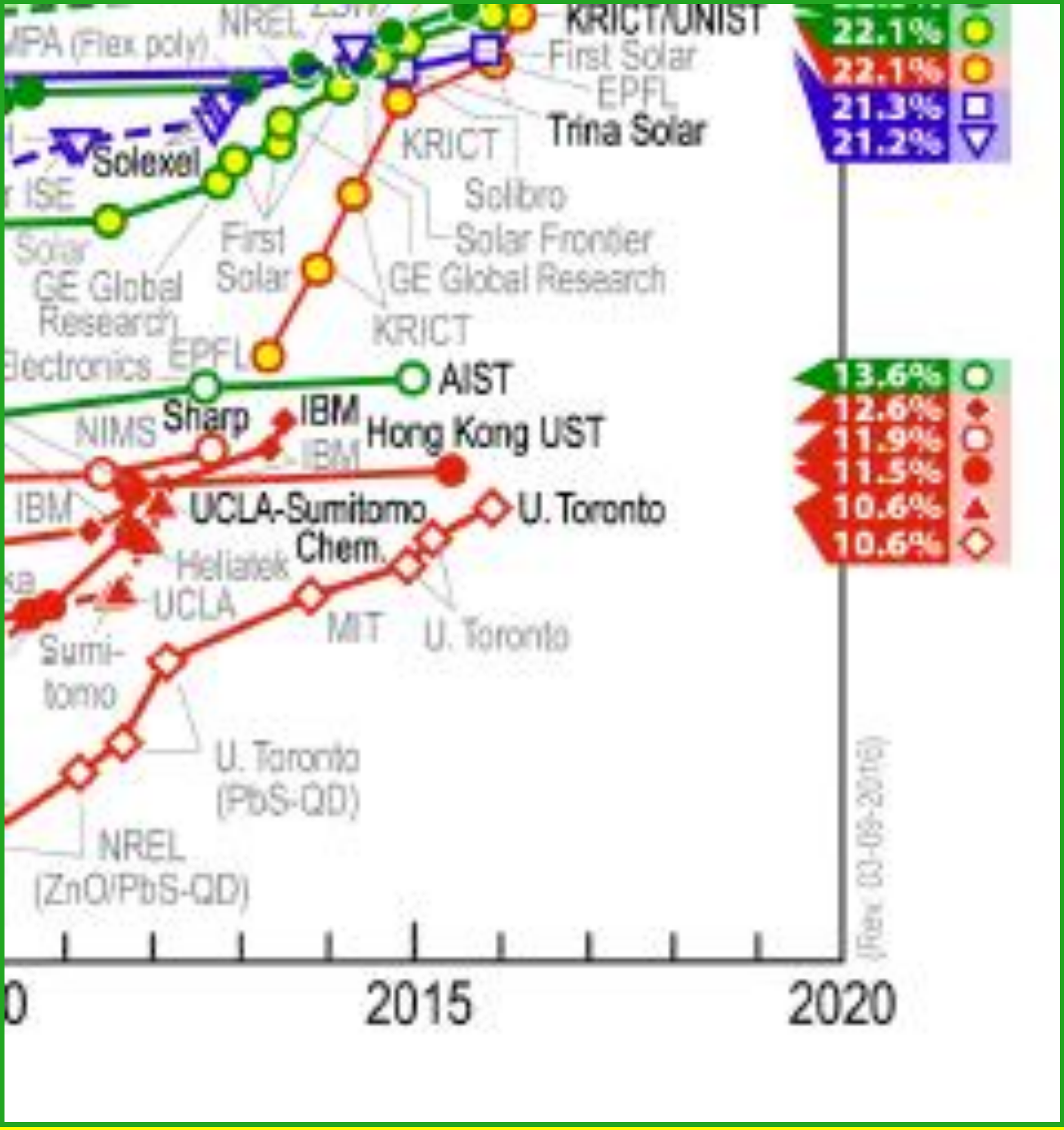
Michael M. Lee,[1] Joël Teuscher,[1] Tsutomu Miyasaka,[2] Takurou N. Murakami,[2,3] Henry J. Snaith[1]*

[1]Clarendon Laboratory, Department of Physics, University of Oxford, Oxford OX1 3PU, UK. [2]Graduate School of Engineering, Toin University of Yokohama, 1614 Kurogane, Aoba, Yokohama 225-8503, Japan. [3]Research Center for Photovoltaic Technologies, National Institute of Advanced Industrial Science and Technology, Central 5, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8565, Japan.

*To whom correspondence should be addressed. E-mail: h.snaith1@physics.ox.ac.uk

The energy cost associated with separating tightly-bound excitons, photo-generated electron-hole pairs, and extracting free charges from highly disordered low mobility networks represent fundamental losses for many low-cost photovoltaic technologies. We report a low-cost, solution-processable solar cell based on a highly crystalline perovskite absorber with intense visible-to-near-infrared absorptivity that has a power conversion efficiency of 10.9% in a single junction device under simulated full sunlight. This "meso-superstructured solar cell" (MSSC) exhibits exceptionally few fundamental energy losses illustrated by generating open-circuit photovoltages of over 1.1 volts, despite the relatively narrow absorber band gap of 1.55 electron volts. The functionality arises from the use of mesoporous alumina as an inert scaffold which structures the absorber and forces electrons to reside in and be transported through the perovskite.

Power conversion efficiency (PCE) of PSCs reached 22.1 % surpassing PCE of polycrystalline silicon cells



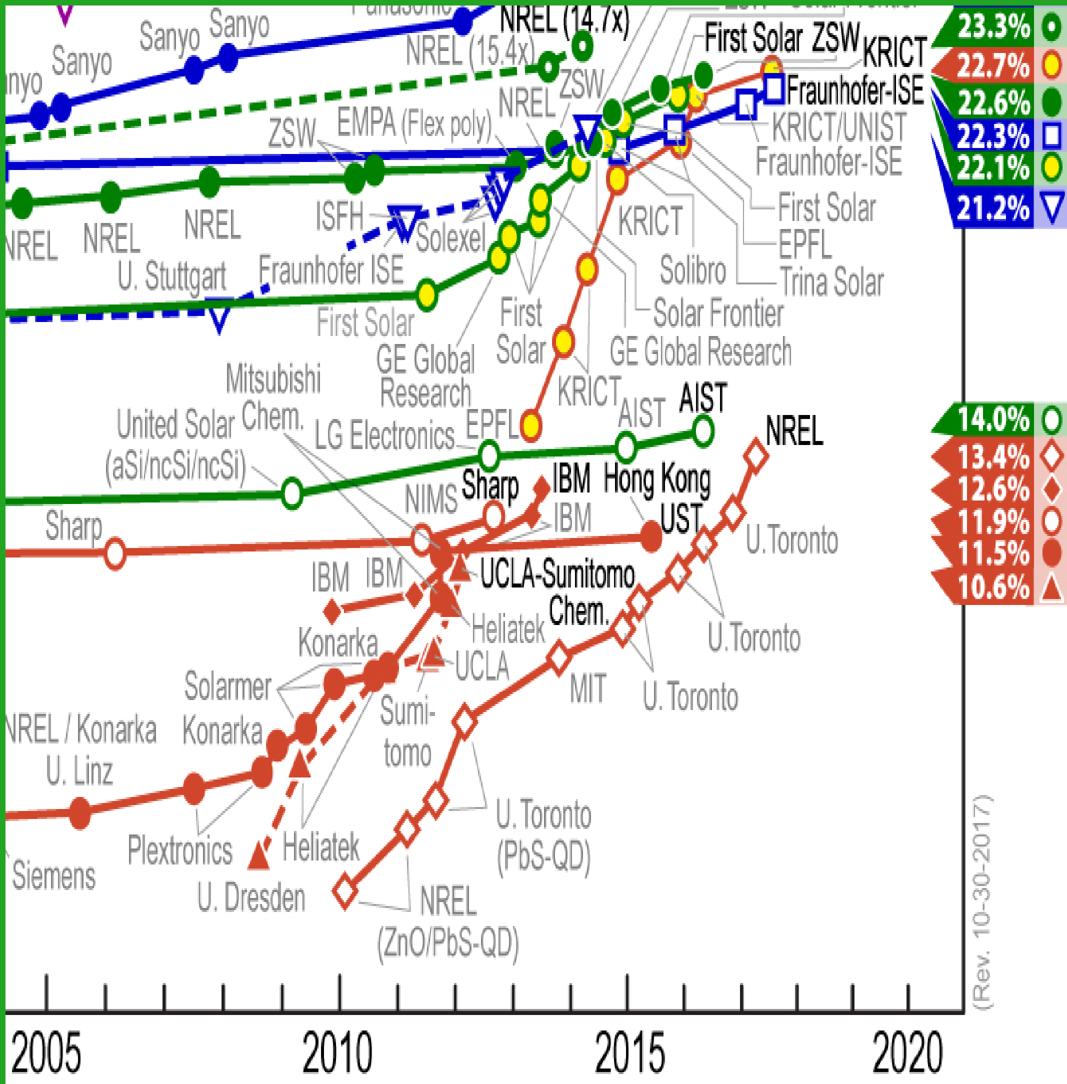
NREL chart showing certified efficiencies of best laboratory cells

Dr. Dongqin Bi, LPI,EPFL

Prof. Anders Hagfeldt.
Director LSPM. EPFL

Best Research-Cell Efficiencies

FÉDÉRALE DE LAUSANNE



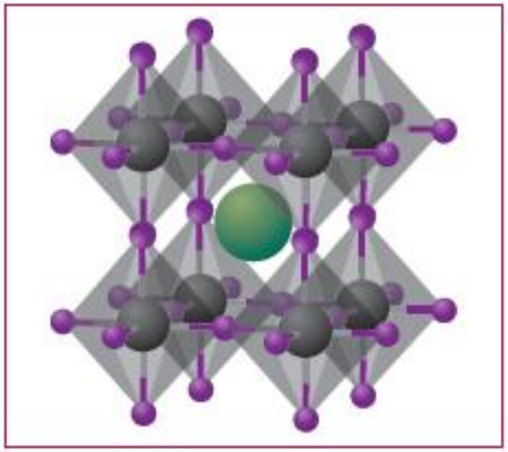
Prof. Anders Hagfeldt.
Director LSPM. EPFL

Dr. Dongqin Bi, LPI,EPFL

commentary

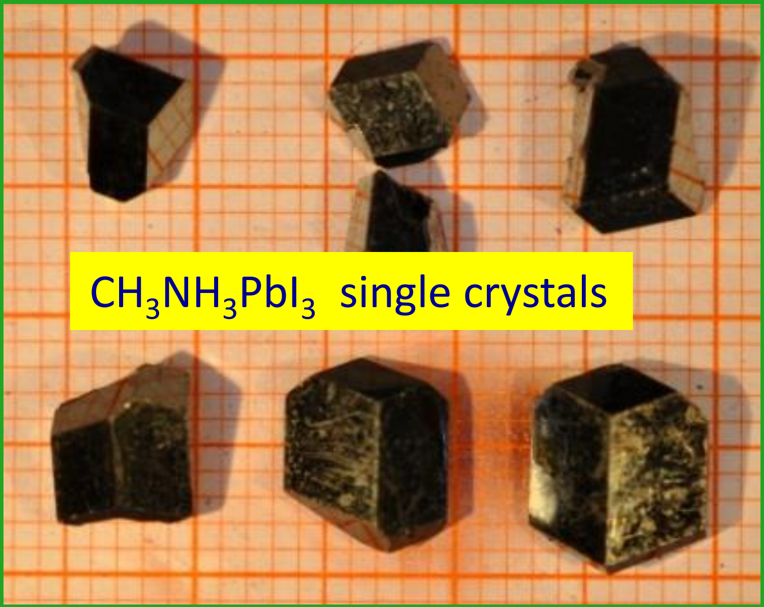
NATURE MATERIALS | VOL 13 | 2014 I 838

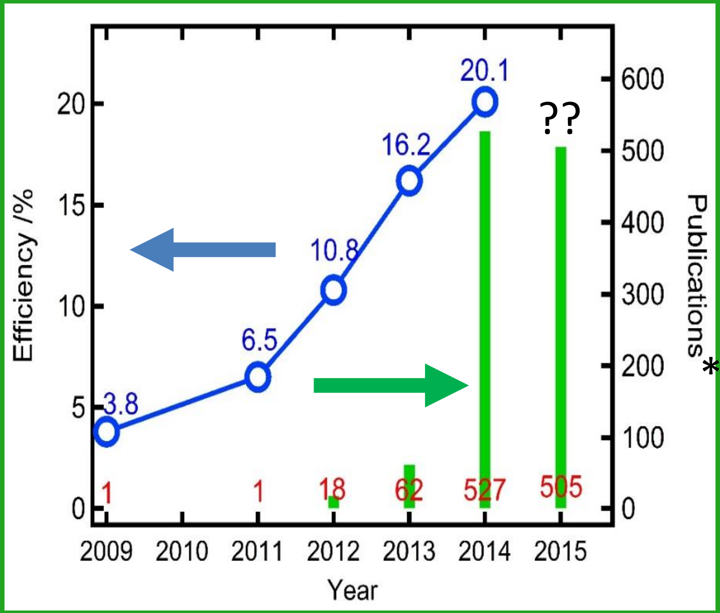
The light and shade of perovskite solar cells



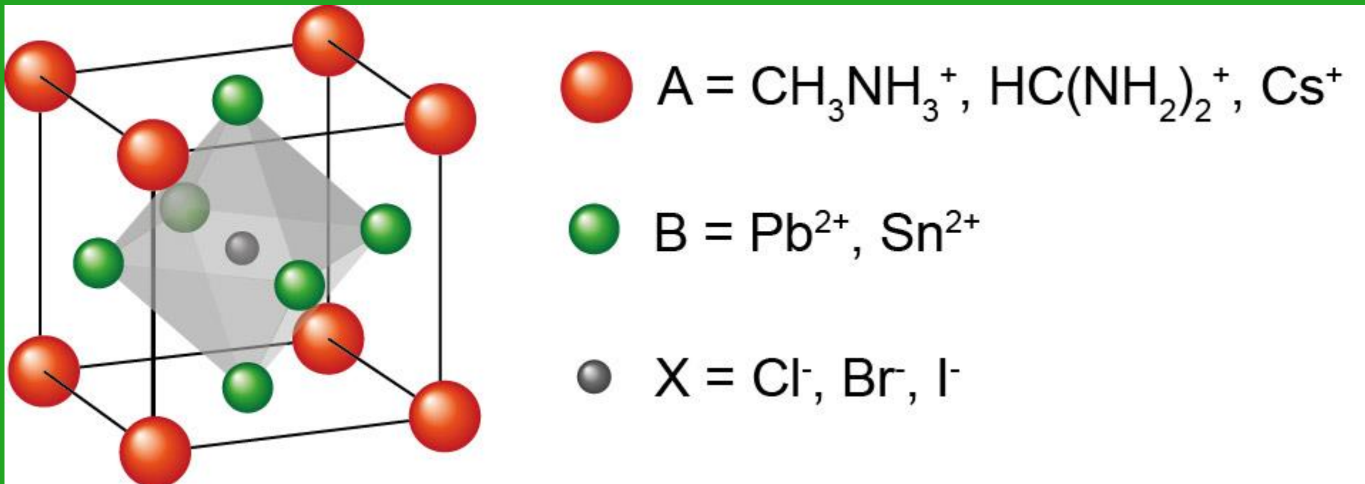
Michael Grätzel

The rise of metal halide perovskites as light harvesters has stunned the photovoltaic community. As the efficiency race continues, questions on the control of the performance of perovskite solar cells and on its characterization are being addressed.





Metal halide perovskites are powerful solar light harvesters



General formular
ABX_3

$CH_3NH_3PbX_3$, ein Pb(II)-System mit kubischer Perowskitstruktur

$CH_3NH_3PbX_3$, a Pb(II)-System with Cubic Perovskite Structure

Dieter Weber

Institut für Anorganische Chemie der Universität Stuttgart

Z. Naturforsch. **33 b, 1443–1445** (1978); eingegangen am 21. August 1978

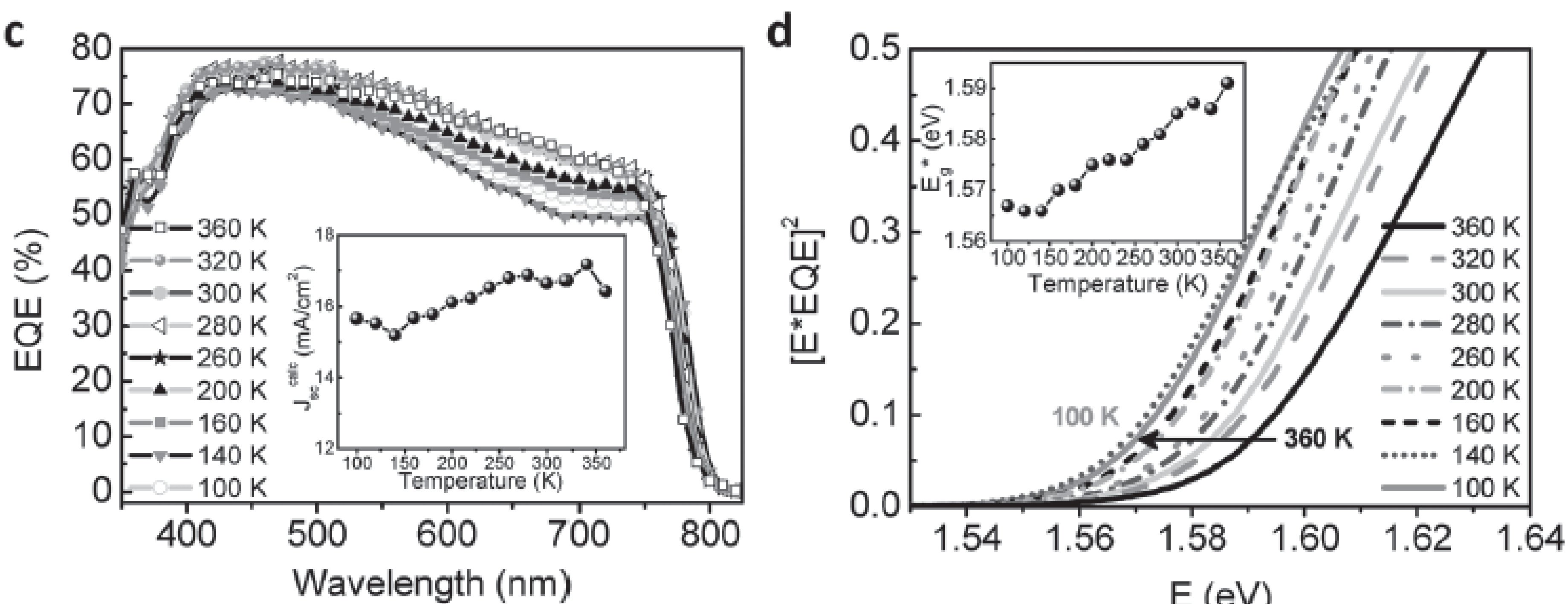
- Strong light absorption in the visible
- Tunable band gap
- Small exciton dissociation energy (<30 meV)
- Low defect concentration
- High open circuit voltage close to band gap energy

Materials Views
www.MaterialsViews.com

ADVANCED MATERIALS
www.advmat.de

Identifying Fundamental Limitations in Halide Perovskite Solar Cells

Wei Lin Leong, Zi-En Ooi, Dharani Sabba, Chenyi Yi, Shaik M. Zakeeruddin, Michael Graetzel, Jeffrey M. Gordon, Eugene A. Katz, and Nripan Mathews*



Outline

- The stunning rise of pervoskite solar cells
- Recent research advances to increase their efficiency and stability
  - **Multi-cation formulations, the power of solid state NMR analysis**
  - The amazing impact of molecular modulators
  - Boosting the PSC stability

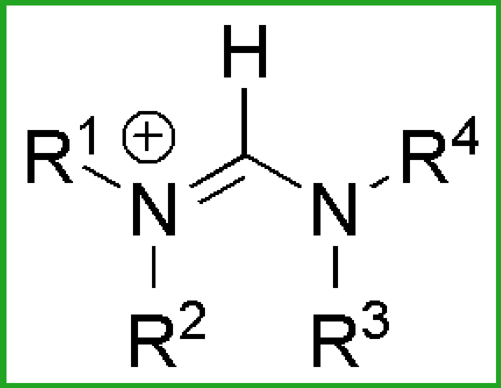
Applications for solar fuel generation

Today’s most efficient pervoskite solar cells employ mixtures of A cations and iodide /bromide as anion

General composition $FA_{1-x}MA_xPb(I_{1-x}Br_x)$

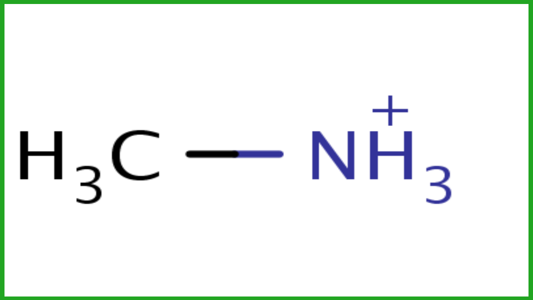
FA =

formamidinium



$R^1 – R^4$ = H

X = 0.15 gives optimal results



MA = methylammonium

N. Pellet *et al.*, Mixed-Organic-Cation Perovskite Photovoltaics for Enhanced Solar -Light Harvesting. *Angew. Chem. Int. Ed.* **53**, 3151-3157 (2014).

N. J. Jeon *et al.*, Compositional engineering of perovskite materials for high-performance solar cells. *Nat.* **517**, 476-480 (2015).

Angew.Chem: Int. Ed. 2014

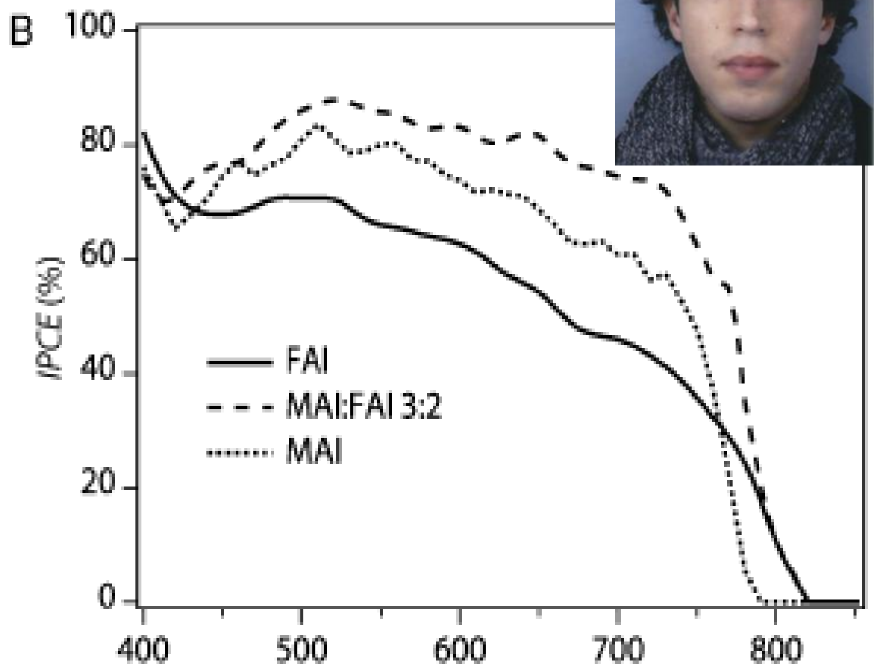
Perovskite Solar Cells

DOI: 10.1002/anie.201309361

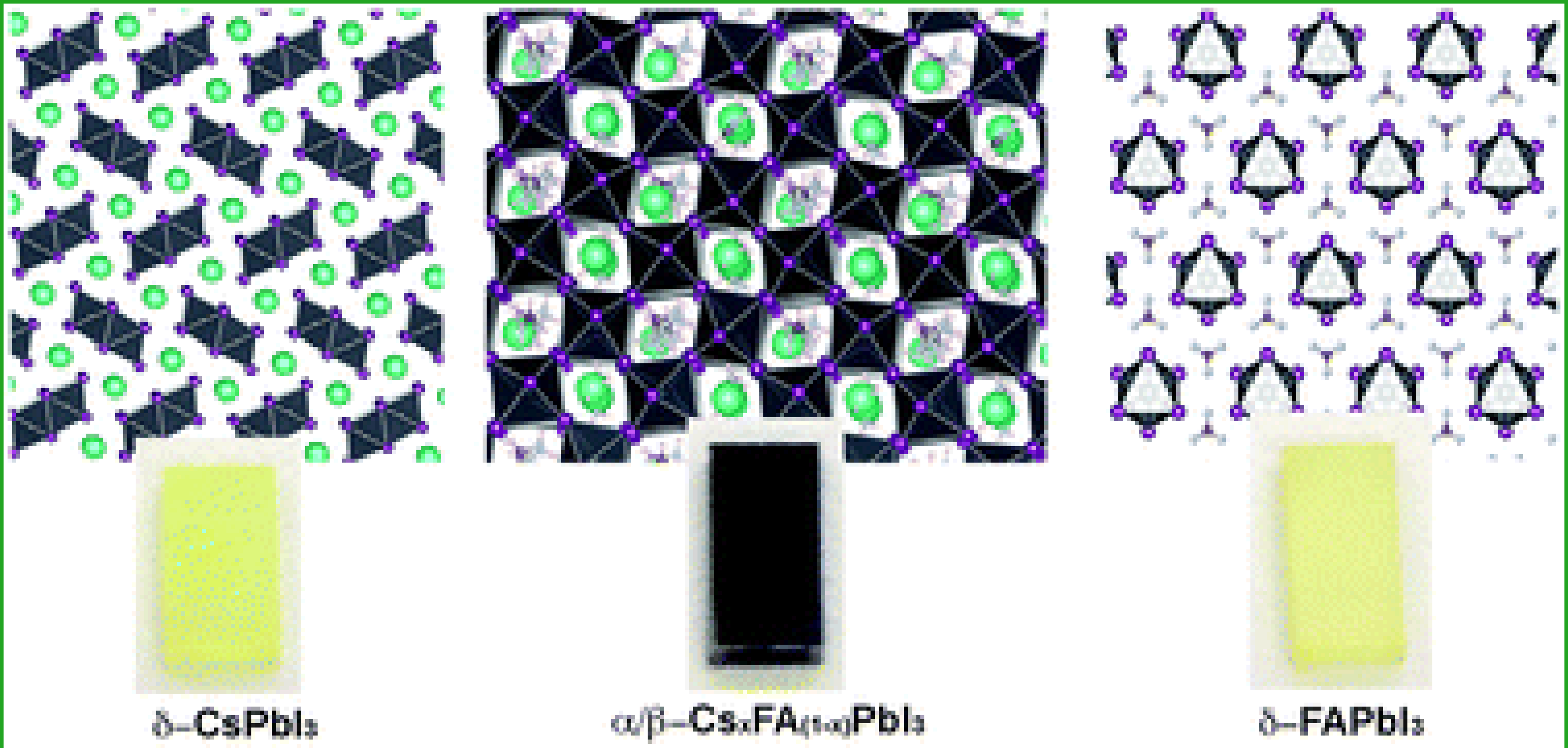
Mixed-Organic-Cation Perovskite Photovoltaics for Enhanced Solar-Light Harvesting**

*Norman Pellet, Peng Gao, Giuliano Gregori, Tae-Youl Yang, Mohammad K. Nazeeruddin, Joachim Maier, and Michael Grätzel**

Abstract: *Hybrid organic–inorganic lead halide perovskite $APbX_3$ pigments, such as methylammonium lead iodide, have recently emerged as excellent light harvesters in solid-state mesoscopic solar cells. An important target for the further improvement of the performance of perovskite-based photovoltaics is to extend their optical-absorption onset further into the red to enhance solar-light harvesting. Herein, we show that this goal can be reached by using a mixture of formamidinium ($HN{=}CHNH_3^+$, FA) and methylammonium ($CH_3NH_3^+$, MA) cations in the A position of the $APbI_3$ perovskite structure. This combination leads to an enhanced short-circuit current and thus superior devices to those based on only $CH_3NH_3^+$. This concept has not been applied previously in perovskite-based solar cells. It shows great potential as a versatile tool to tune the structural, electrical, and optoelectronic properties of the light-harvesting materials.*



Stabilisation of mixed Cs^{+} /formamidinium A-cation perovskites



The stable fprms pf $CsPbI_3$ and $FaPbI_3$ are non –perovskite delta phases at room temperature
Amazingly, upon mixing a stable peroxide structure forms spontaneously

J.-W. Lee, D.-H. Kim, H.-S. Kim, S.-W. Seo, S.M. Cho and N.-G. Park,
Formamidinium + Cesium Hybridization for Photo+ Moisture Stable Perovskite Solar Cell
Adv. Energy Mater., 2015, 5,1501310.

Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

COMMUNICATION

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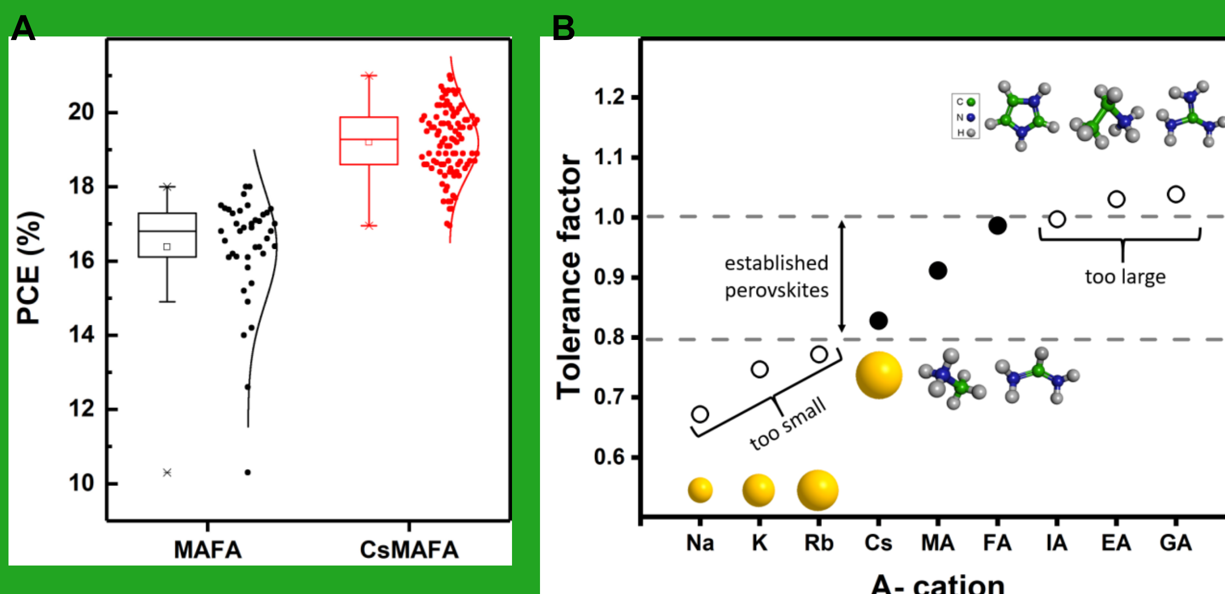
Cite this: DOI: 10.1039/c5ee03874j

Received 24th December 2015, Accepted 14th March 2016

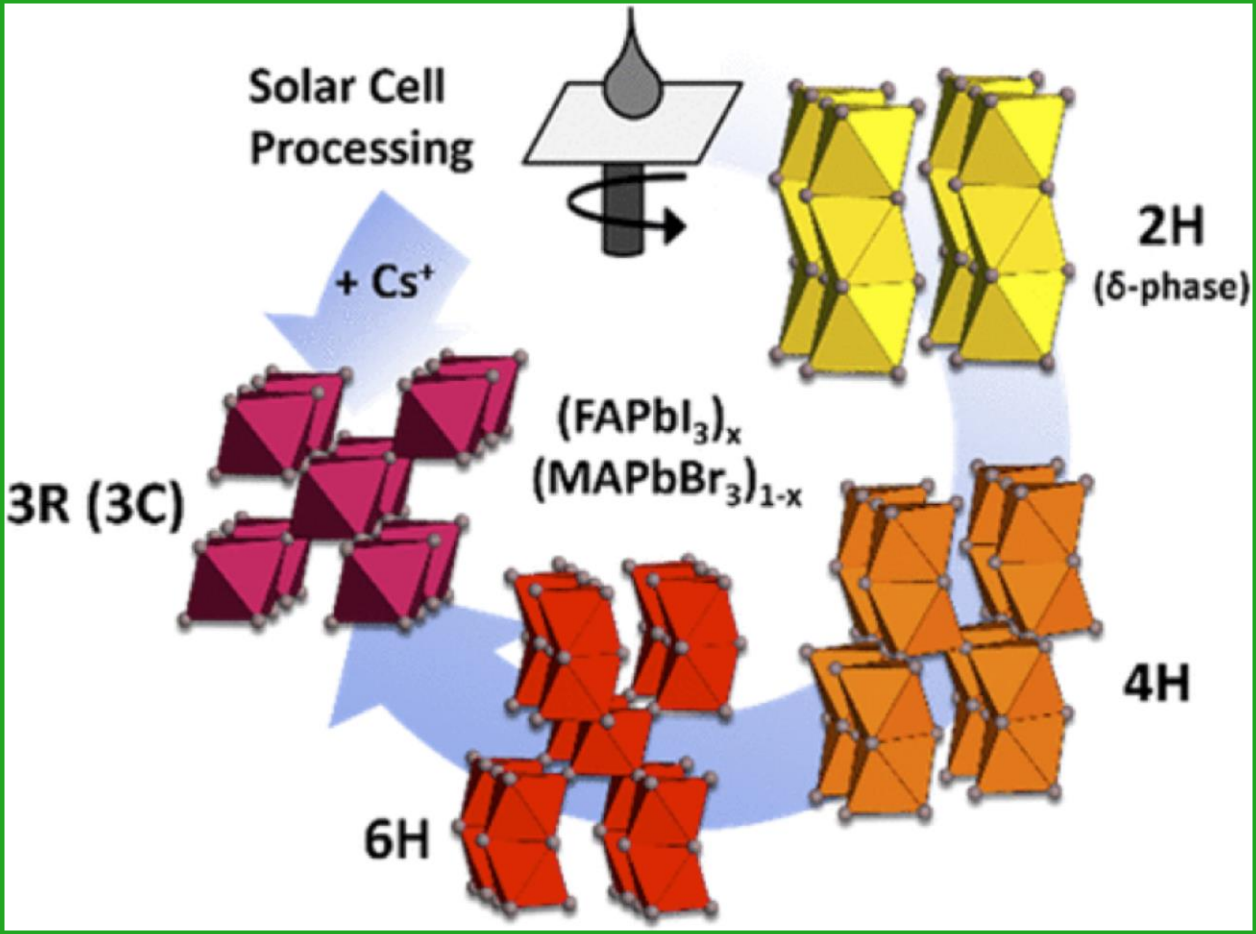
DOI: 10.1039/c5ee03874j

Cesium-containing triple cation perovskite solar cells: improved stability, reproducibility and high efficiency†

Michael Saliba,‡*[ab] Taisuke Matsui,‡[c] Ji-Youn Seo,[a] Konrad Domanski,[a] Juan-Pablo Correa-Baena,[d] Mohammad Khaja Nazeeruddin,[b] Shaik M. Zakeeruddin,[a] Wolfgang Tress,[a] Antonio Abate,[a] Anders Hagfeldt[d] and Michael Grätzel[a]



The many faces of mixed ion perovskites: unraveling and understanding the crystallization process

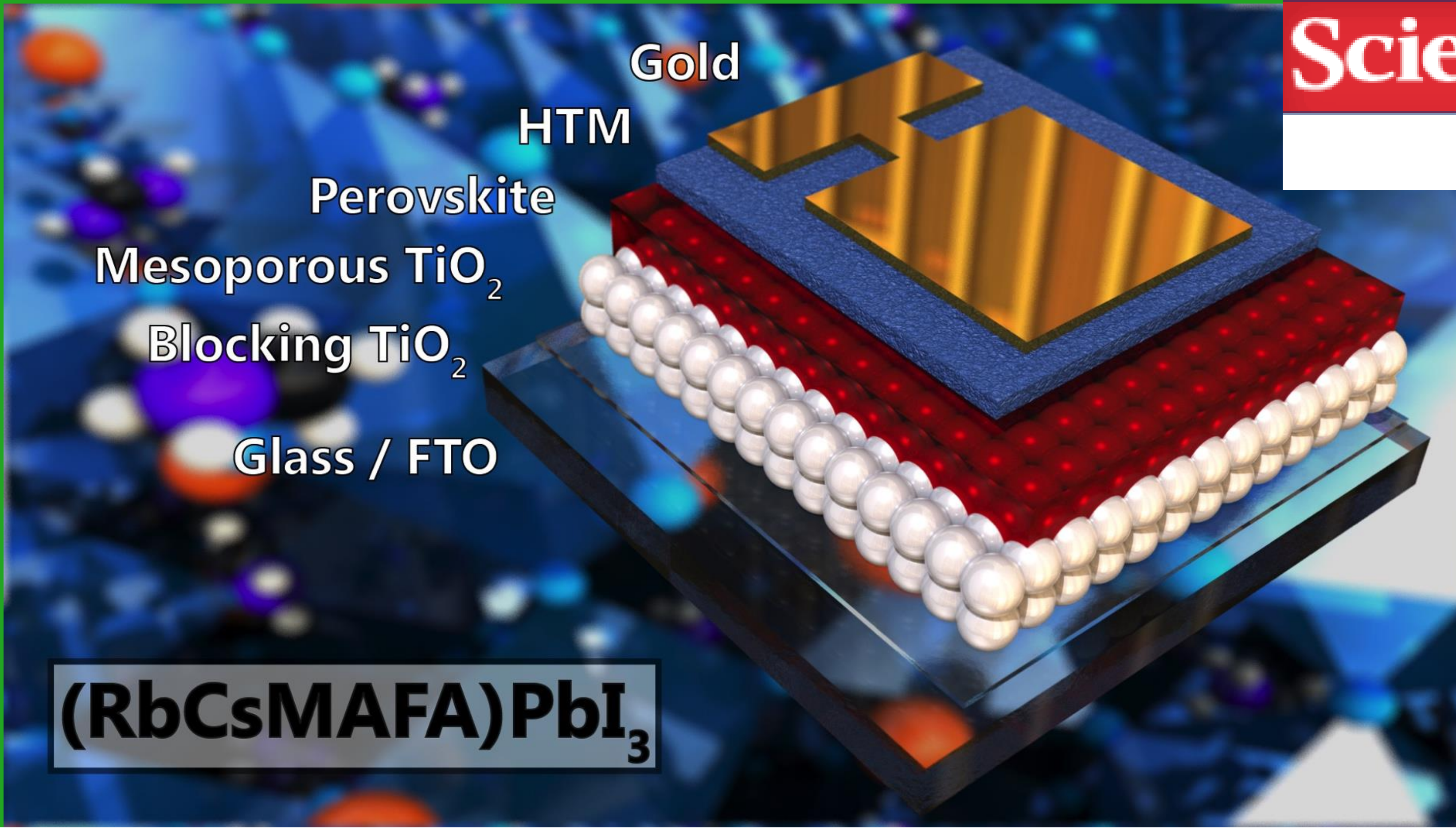


Paul Gratia
EPFL graduate student

P. Gratia et.al
ACS Energy Lett., 2017, 2 (12), pp 2686–2693

The role of Cs ions is to short-cut the formation of pervoskite crystals avoiding the intermediate formation of 2H, 4 H and 6 H hexagonal phases which are detrimental to PSC performance.

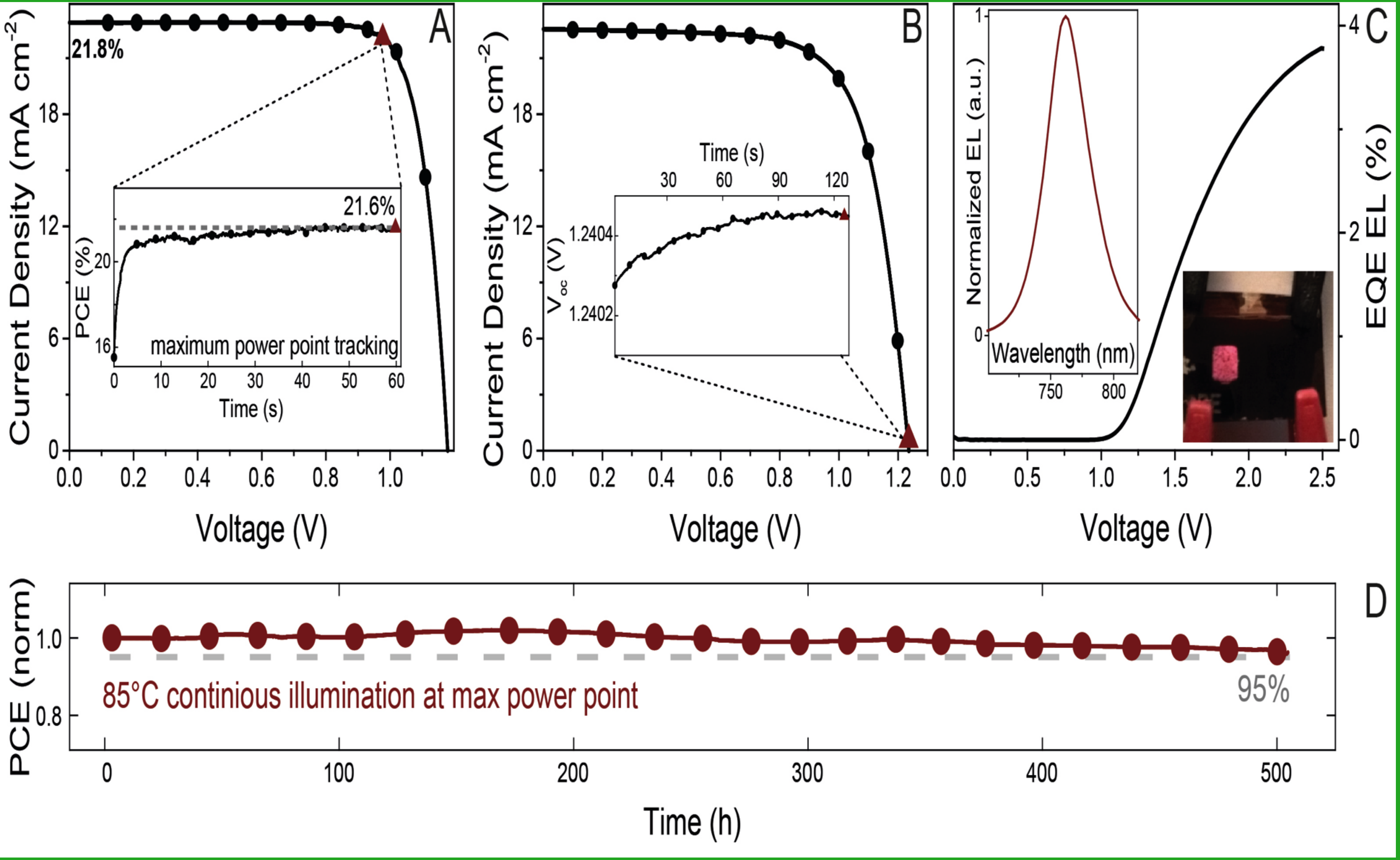
Top- performing perovskite formulation uses A cation cascade with Rb



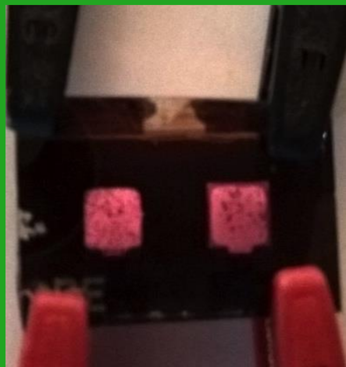
Incorporation of rubidium cations into perovskite solar cells improves photovoltaic performance

Michael Saliba,[1*†] Taisuke Matsui,[1,2*] Konrad Domanski,[1*] Ji-Youn Seo,[1] Amita Ummadisingu,[1] Shaik M. Zakeeruddin,[1] Juan-Pablo Correa-Baena,[3] Wolfgang R. Tress,[1] Antonio Abate,[1] Anders Hagfeldt,[3] Michael Grätzel[1†] 10.1126/science.aah5557 (2016).

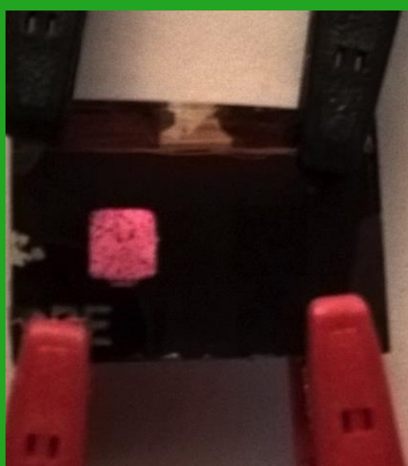
Quadruple A cation perovskite sets new records for solar power conversion efficiency, open-circuit voltage and electroluminescence quantum yield along with extraordinary high temperature stability.



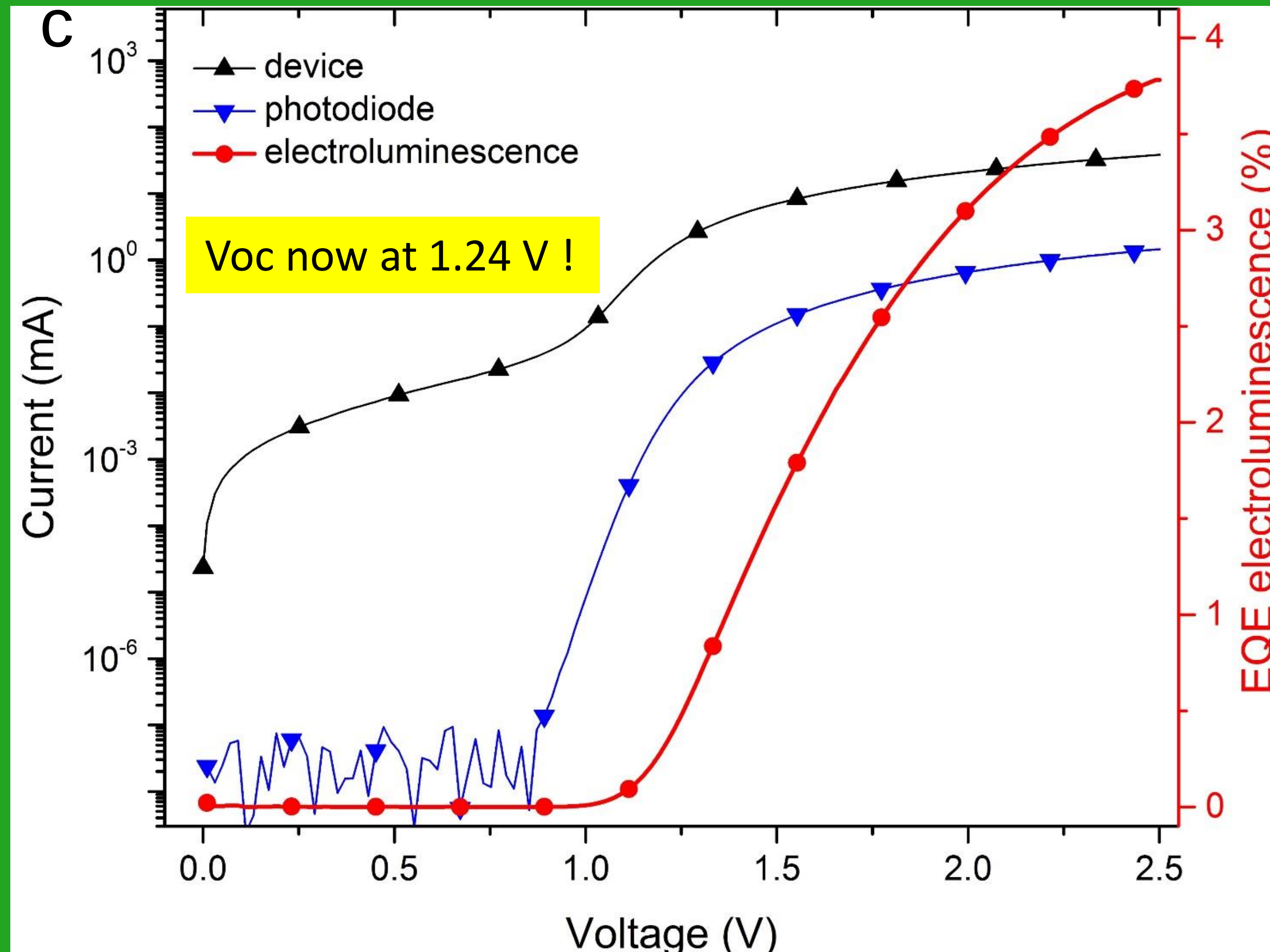
A good solar cell that is a good LED



LED



solar cell or photodetector



Science, 354, 206-209 (2016)

Wolfgang Tress,
Konrad Domanski
Michael Saliba
Taisuke MAtsui

Electro-luminescence offers a powerful tool to probe the level of radiation- less recombinaton in perovskite solar cells

Ross, R. T. *J. Chem. Phys.* **46,** 4590 (1967).

$$V_{oc} = V_{oc\text{-}ideal} + (kT/q)\ln\phi_{ext}$$

$$V_{oc\text{-}ideal} \simeq E_g - 0.23\ \text{V}$$

E_g = band gap energy expressed in electron volt
ϕ_{ext} = external quantum yield of electroluminescnce at an applied forward bias voltage where J = Jsc

$$V_{oc} = \frac{k_B T}{e}\ln\left(\text{EQE}_{EL}\frac{J_{ph}}{J_{em,0}} + 1\right)$$

$$J_{ph} = e\int \text{EQE}_{PV}(E)\,\Phi_{AM1.5g}(E)\,dE$$

$$J_{em,0} = e\int \text{EQE}_{PV}(E)\,\Phi_{BB}(E)\,dE$$

The maximum open circuit photovoltage of a $CH_3NH_3PbI_3$ based photovoltaic under standard AM 1.5 illumination is 1.55 – 0.23 = 1.32 V

Magic angle spinning (MAS) solid-state NMR a powerful tool to probe the lattice structure, composition and dynamics of metal halide perovskites

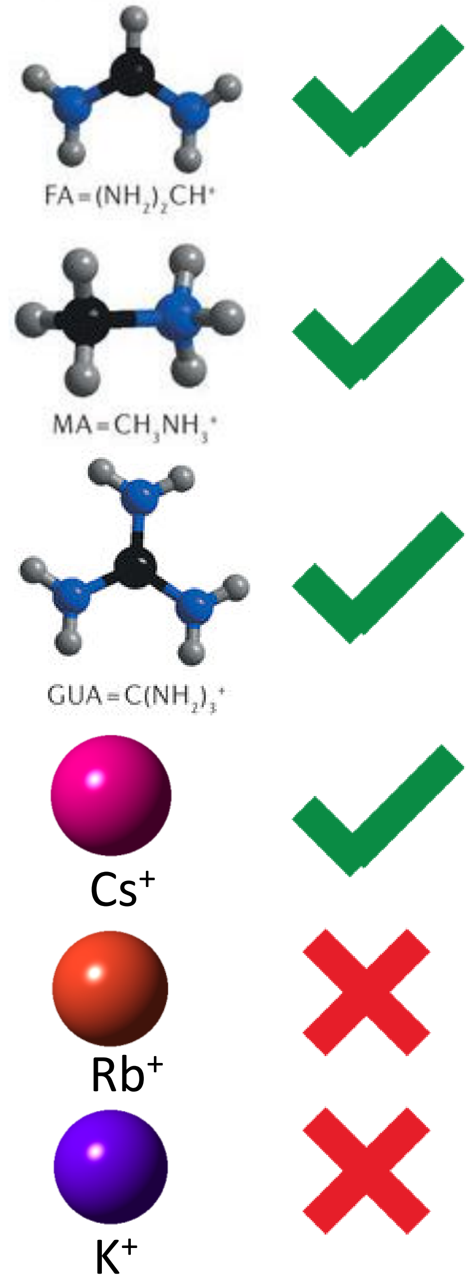
Structure

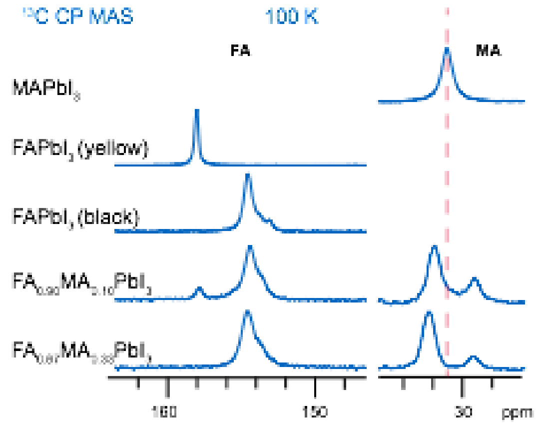
D.J. Kubicki, D. Prochowicz, A. Hofstetter, S.M. Zakeeruddin, M. Grätzel, L.Emsley
"Phase Segregation in Cs-, Rb- and K-Doped Mixed-Cation (MA)x(FA)1-xPbI3 Hybrid Perovskites from Solid-State NMR"
J.Am.Chem.Spc, 139, 14173-14180 (2017)

Dynamics

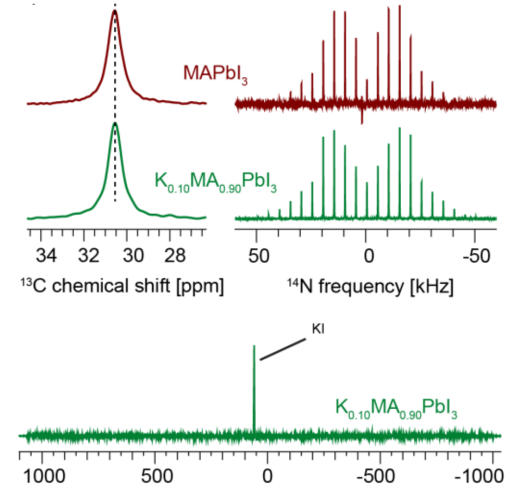
D.J. Kubicki, D. Prochowicz, A. Hofstetter, P. Pechy, S.M. Zakeeruddin, M. Grätzel,L. Emsley
"Cation Dynamics in Mixed-Cation (MA)x(FA)1-xPbI3 Hybrid Perovskites from Solid-State NMR"
J. Am. Chem. Soc., 139, 10055-10061 (2017)

Structure: NMR yields local and nucleus-specific information

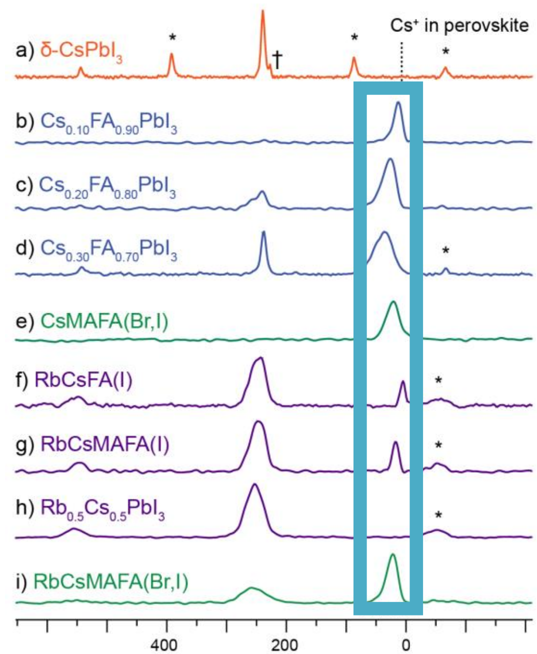




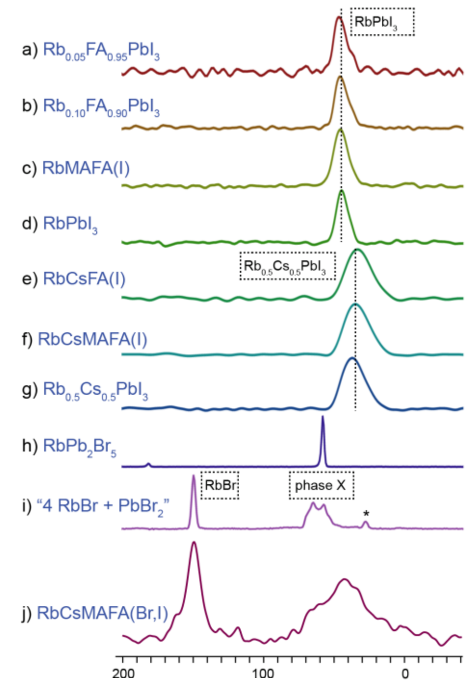
^{13}C chemical shift [ppm]



^{39}K shift [ppm]

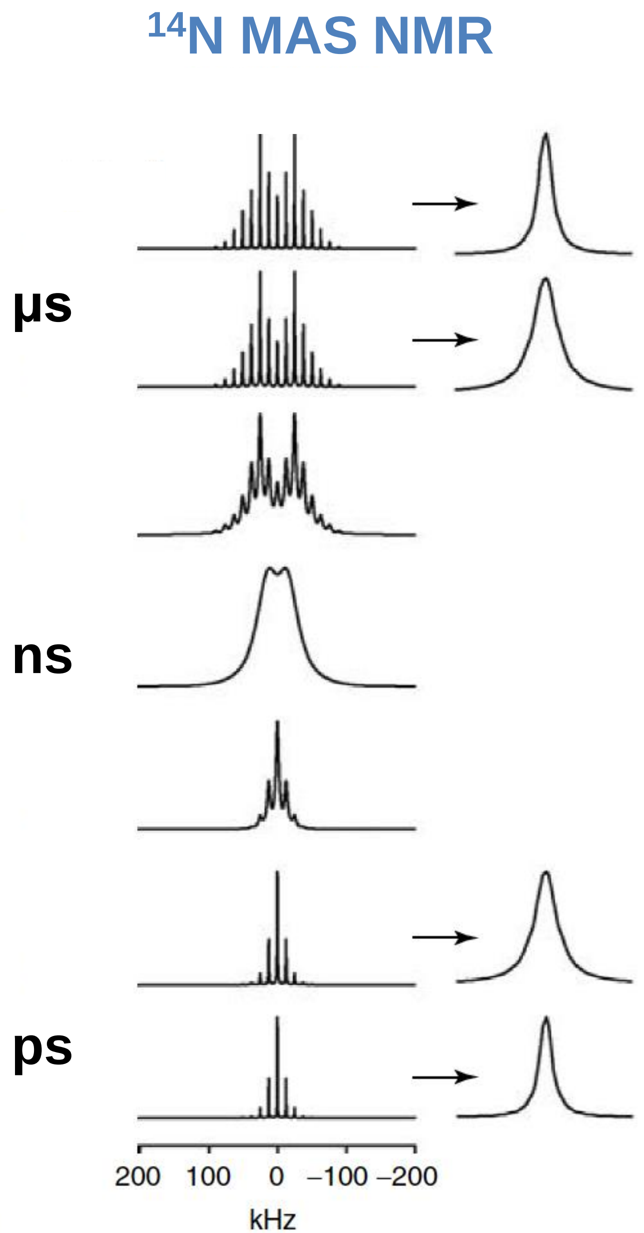


^{133}Cs shift [ppm]



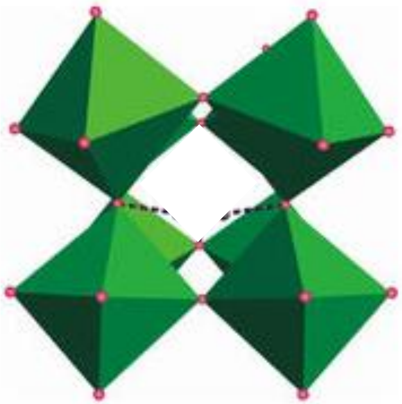
^{87}Rb shift [ppm]

Dynamics: ps — ns — µs — ms — s timescale motions

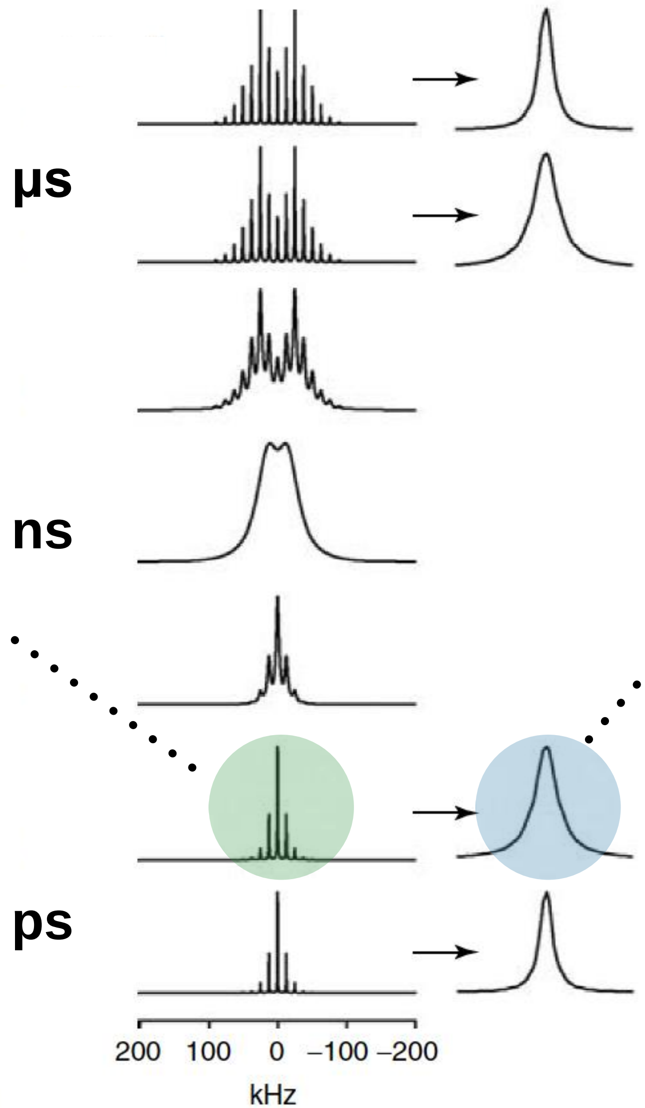


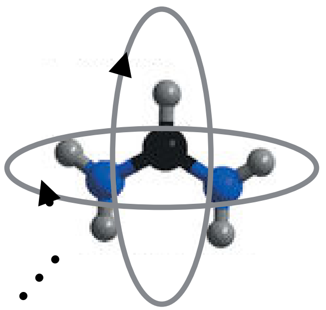
Dynamics: ps — ns — μs — ms — s timescale motions

^{14}N MAS NMR



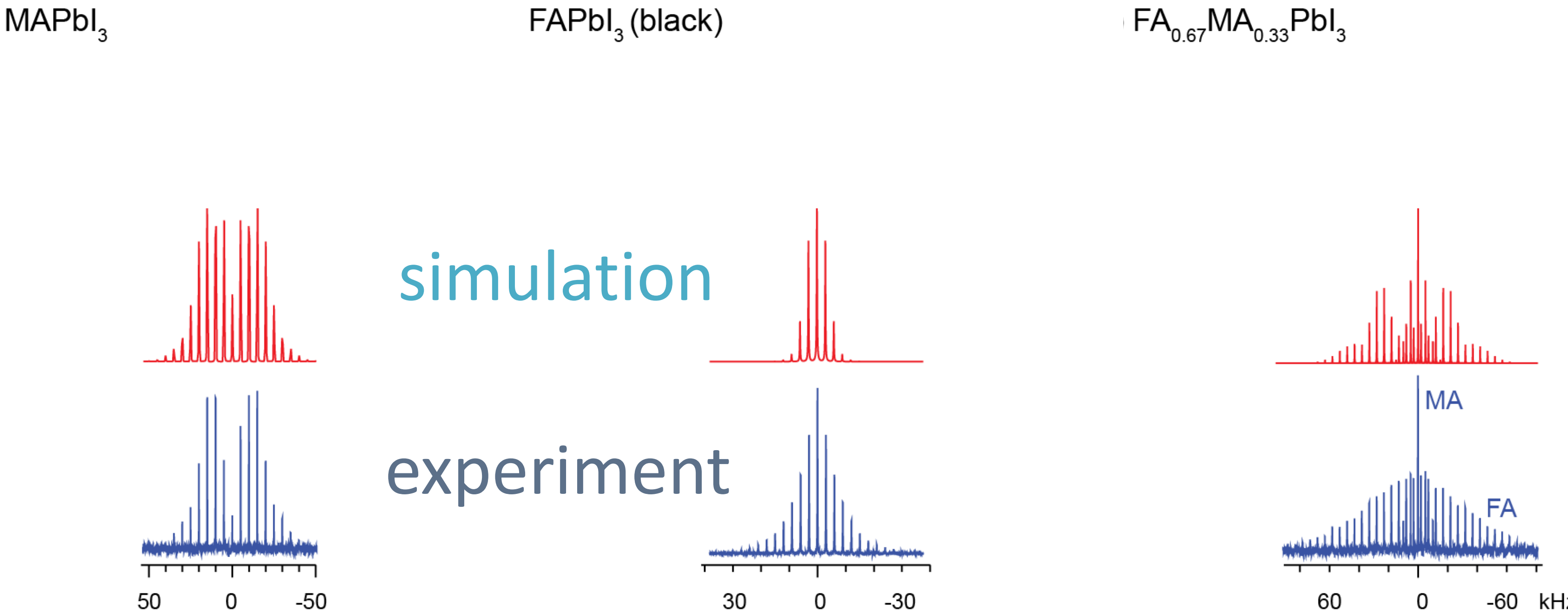
envelope:
cage symmetry





line widths:
reorientation dynami

FA reorients faster than MA



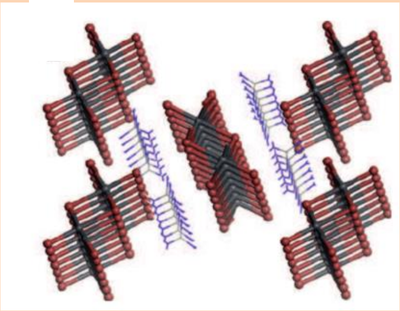
τ = (**108 ± 18**) ps

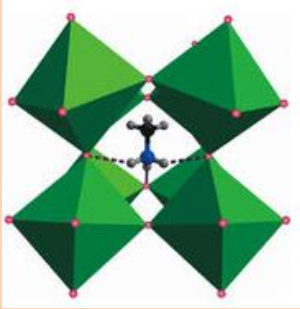
τ = (**8.7 ± 0.5**) ps

τ^{MA} = (**133 ± 46**) ps

τ^{FA} = (**12 ± 5**) ps

Kubicki *et al*., JACS **2017**, *139*, 10055

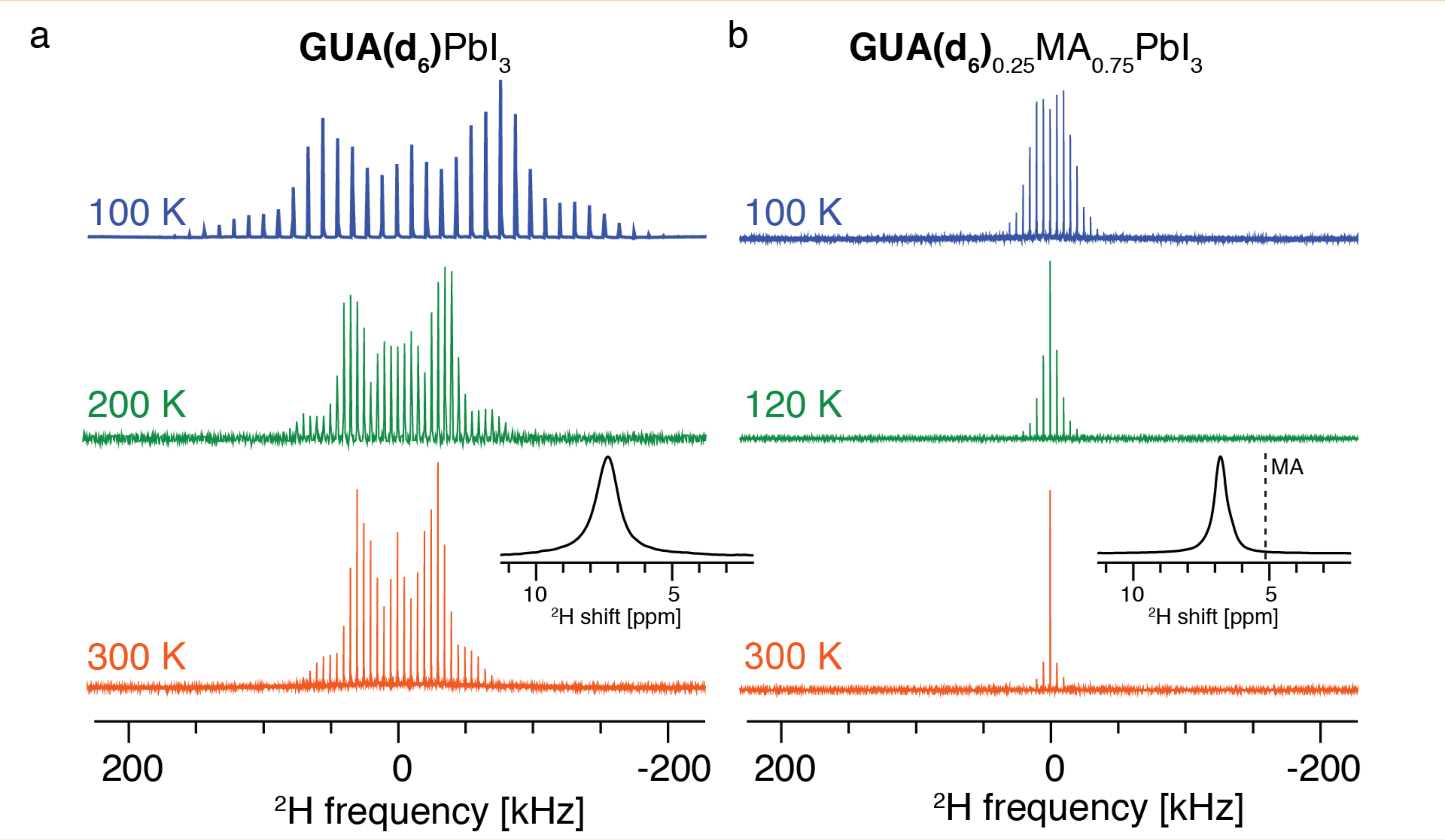


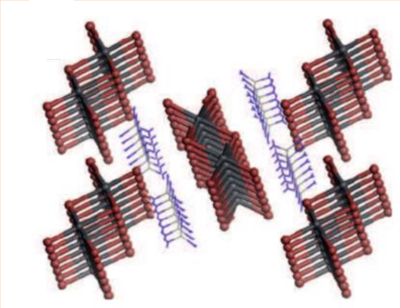


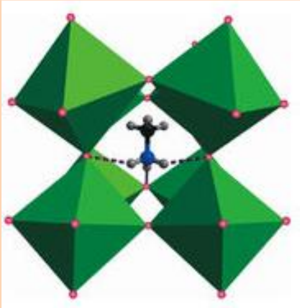
Angew Chem Int Ed Engl. **2016**, 55, 14972

1D

3D



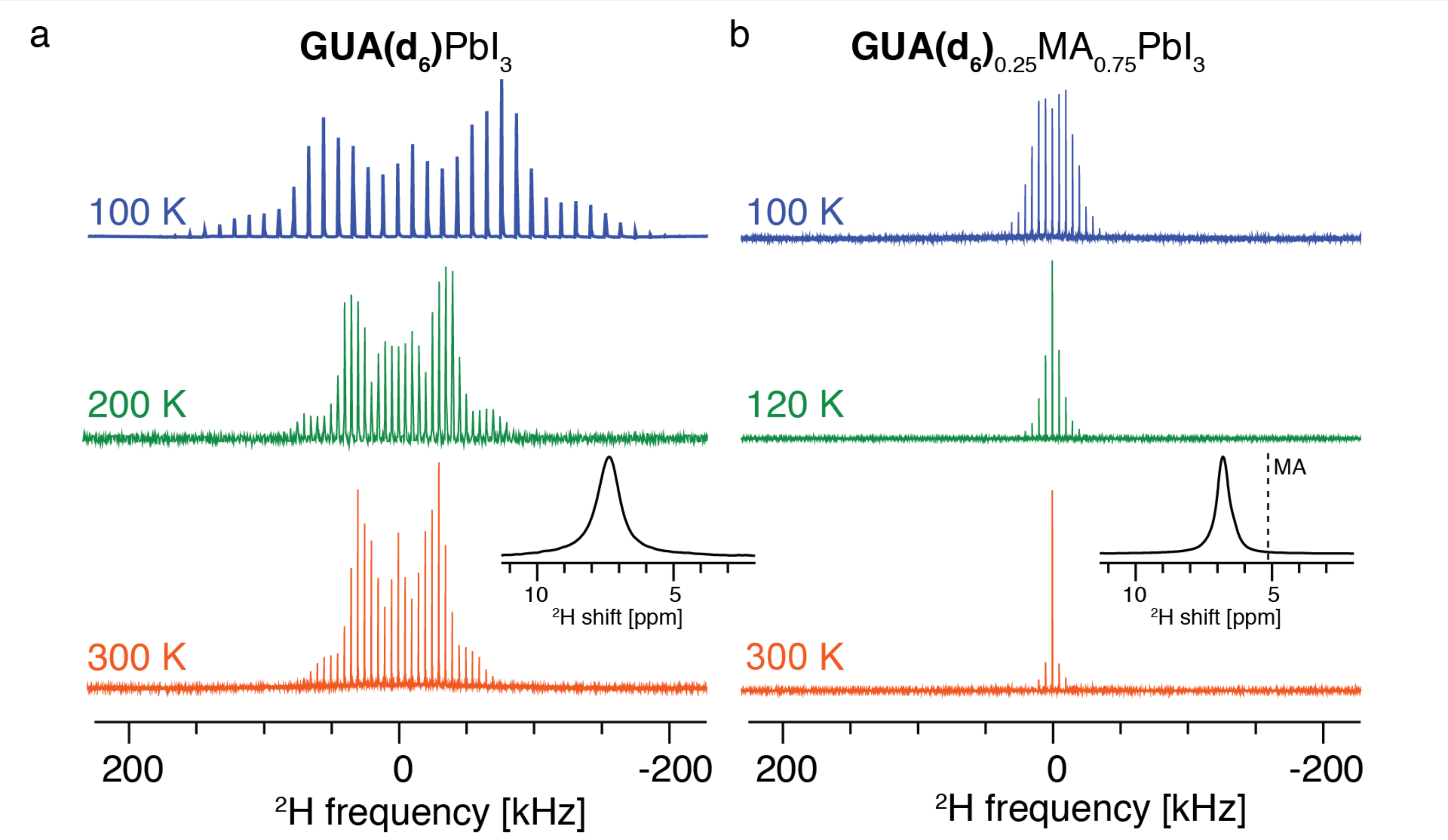




Angew Chem Int Ed Engl. **2016**, 55, 14972

1D

3D



Outline

- The stunning rise of pervoskite solar cells
- Recent research advances to increase their efficiency and stability
  - Multi-cation formulations, the power of solid state NMR analysis
  - **The advent of molecular modulators**
  - Boosting the PSC stability

Applications for solar fuel generation

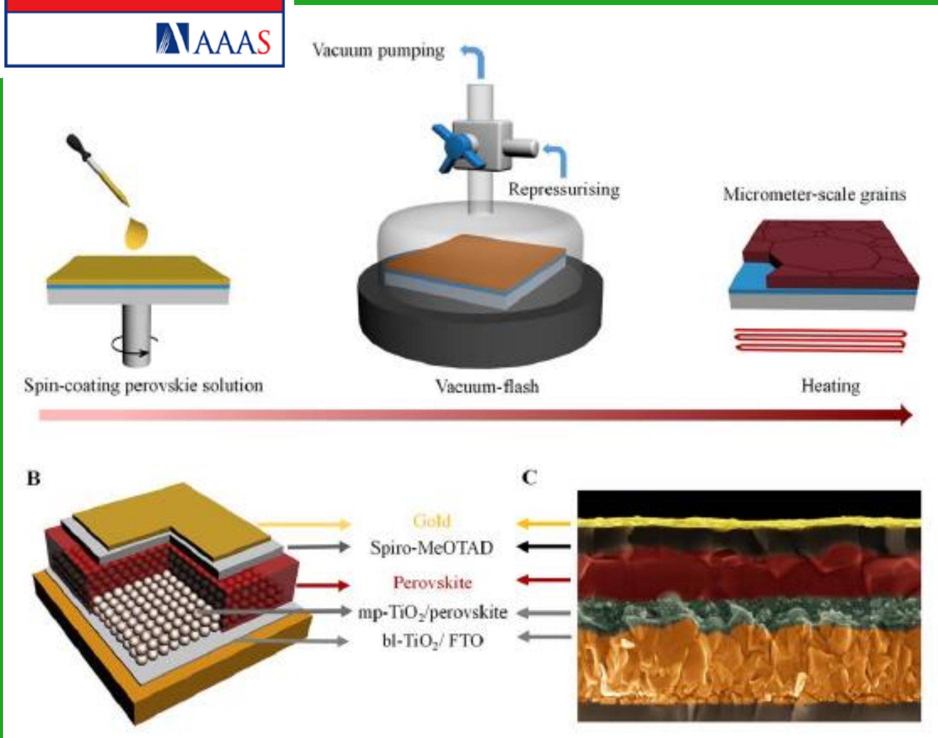
A vacuum flash–assisted solution process for high-efficiency large-area perovskite solar cells

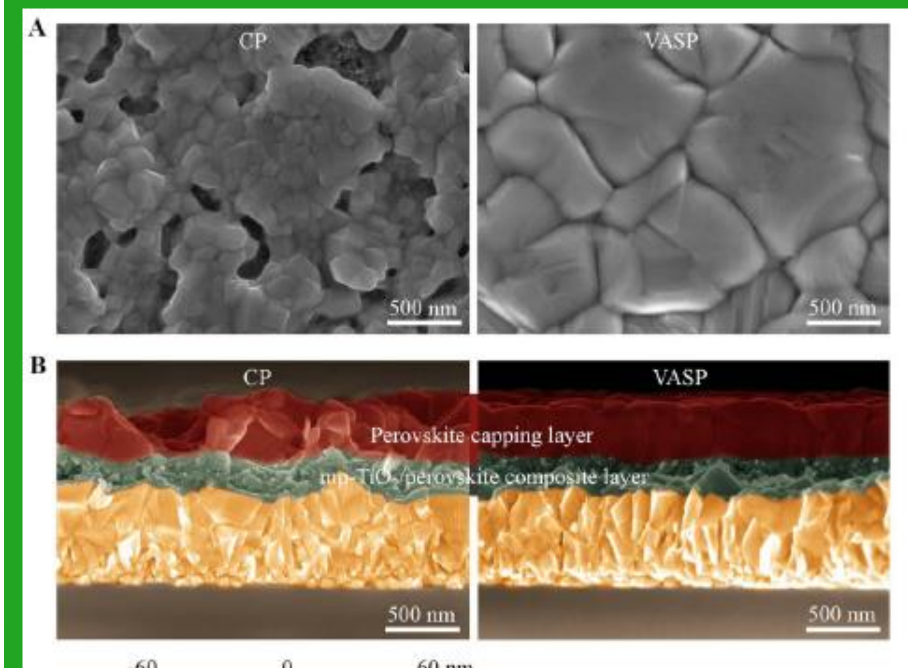
Xiong Li,[1]* Dongqin Bi,[2]* Chenyi Yi,[1]* Jean-David Décoppet,[1] Jingshan Luo,[1] Shaik Mohammed Zakeeruddin,[1] Anders Hagfeldt,[2] Michael Grätzel[1]†

Dr. Xiong Li

Science AAAS

Li *et al. Science,*10.1126/science aaf8060 (2016)





Vacuum flash treatment produces smooth and shiny perovskite films of high quality yieliding a PCE of 19.6% fpr 1cm^2 device size

Molecular Engineering of Scalable Perovskite Solar Cells with over 20% Efficiency and High Operational Stability

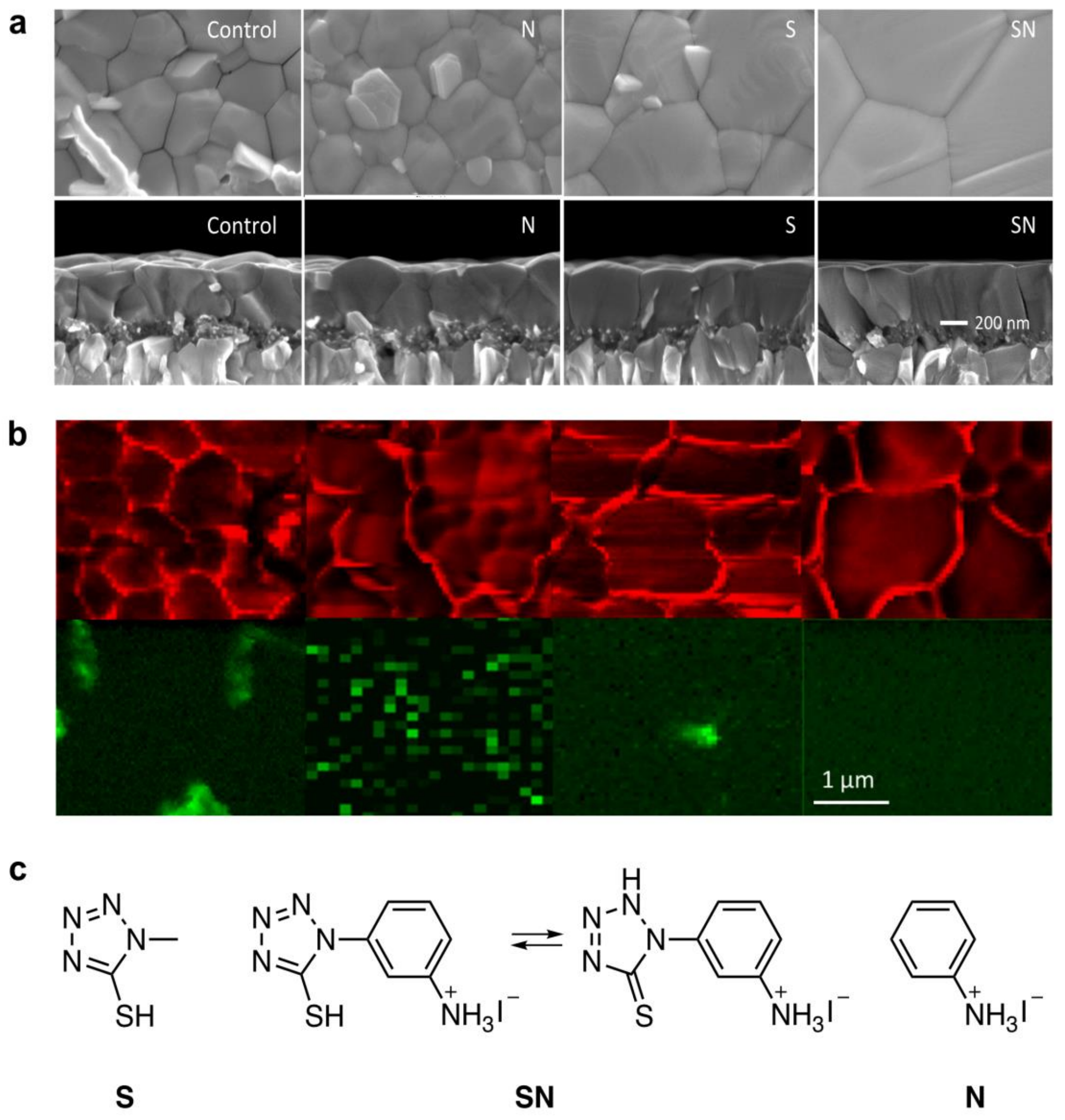
Perovskite composition

$FA_{0.9}Cs_{0.1}PbI_3$

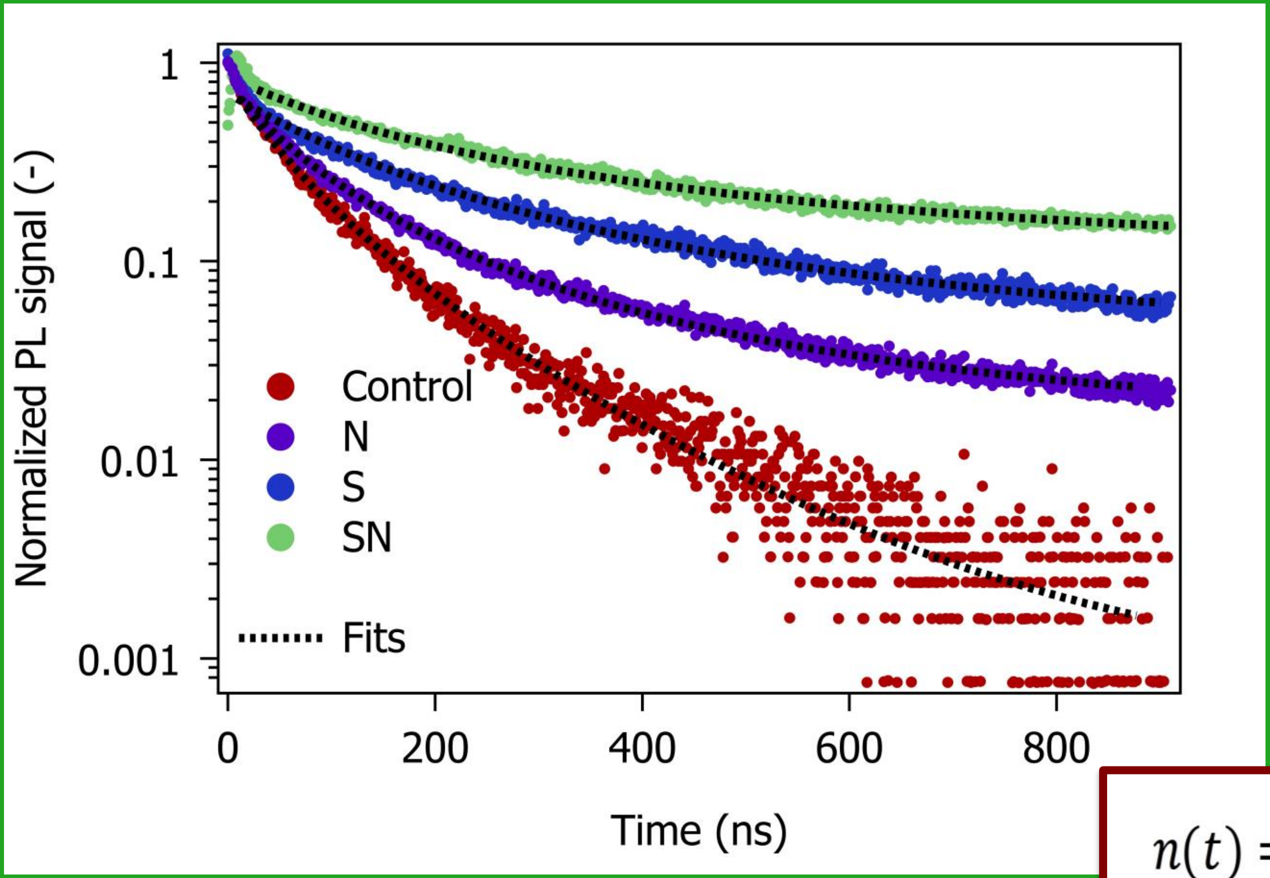
Dr. Xiong Li

Dr. Dongqin Bi,

D. Bi, X. Li, J. Milic et.al, submitted



Time resolved photoluminescnce decay reveals effective suppression of radiationless carrierrecombination by molecular modulators



	τ_1 (ns)
Control	380
N	1690
S	2020
SN	2770

$$I_{PL} \approx dn_{ph}/dt = k_2\, n^2$$

$$-dn/dt = k_1 \times n + k_2\, n^2$$

$$n(t) = \frac{k_1}{k_2} \cdot \frac{1}{e^{k_1 t} \cdot \left(1 + \frac{k_1}{n^0 k_2}\right) - 1}$$

$$I_{PL}(t) \sim \frac{dn_{h\nu}}{dt} = k_2 n^2 = \frac{k_1^2}{k_2} \cdot \frac{1}{\left[e^{k_1 t} \cdot \left(1 + \frac{k_1}{n^0 k_2}\right) - 1\right]^2}$$

Carrier recombination dynamics in a semiconductor device

$\circledR_r \bullet n \bullet p$

radiative electron-hole

$\beta_{nr} \bullet n \bullet p$

non-rad. direct electron-hole

$k_{tr}\ n$

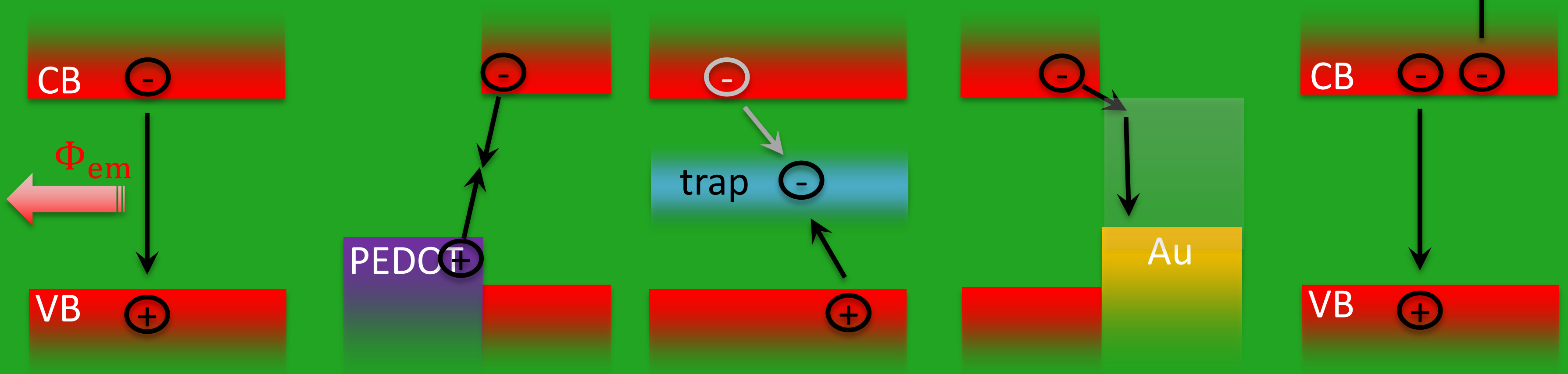
via bulk **defects** (SRH type)

$v_{srec}\ n$

at **surfaces** (wrong electrode)

$An^2\ p$

Auger recombination



→ enters thermodynamic limit

→ replace HTM, add passivation layer

→ pure, defect-free/tolerant material

→ passivation, reduction of contact area

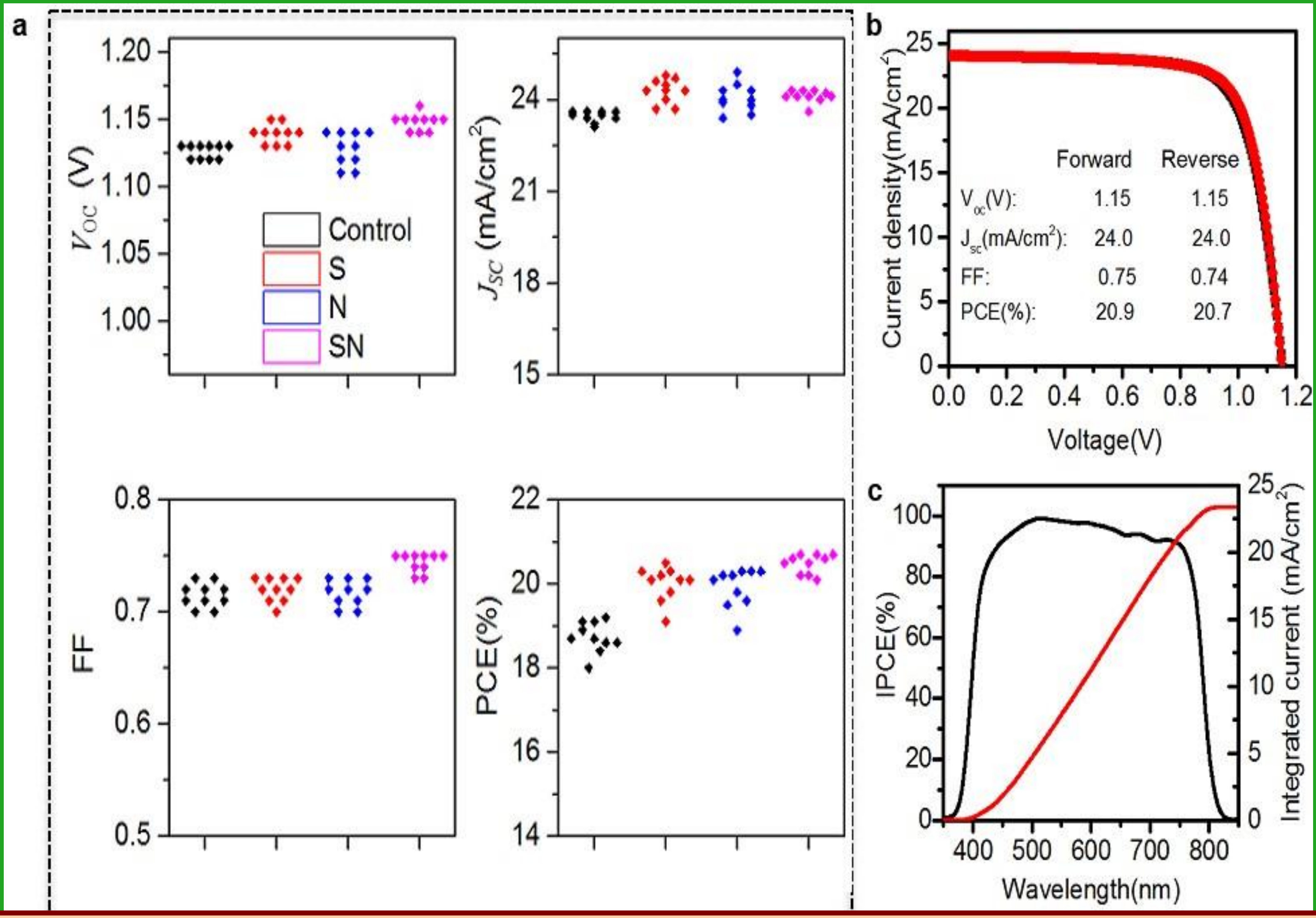
→ material property (avoid indirect semiconductor)

unavoidable in absorber

Should be avoided

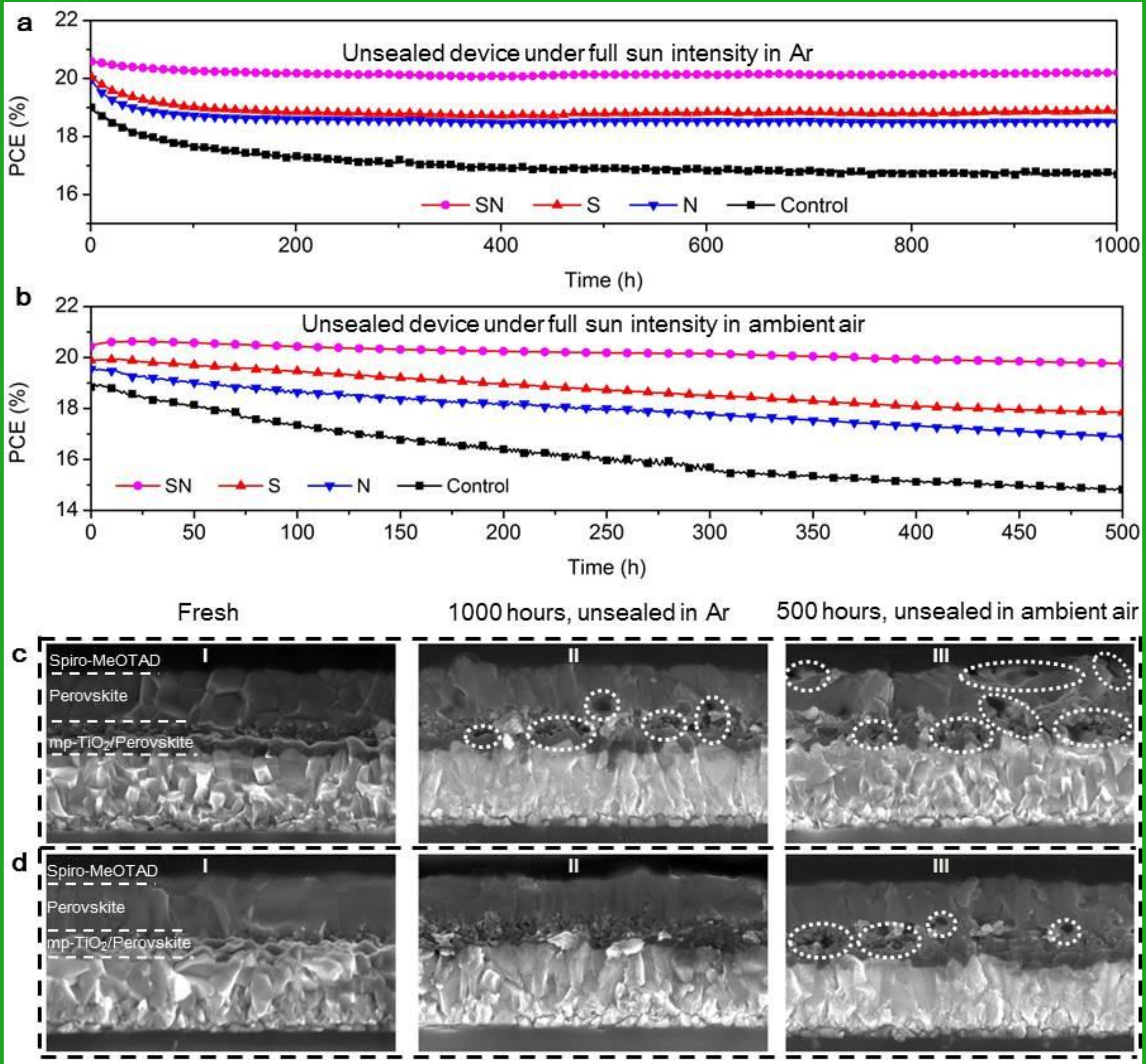
Wolfgang Tress

The positve impact of our new bifunctional modulator on PV performance

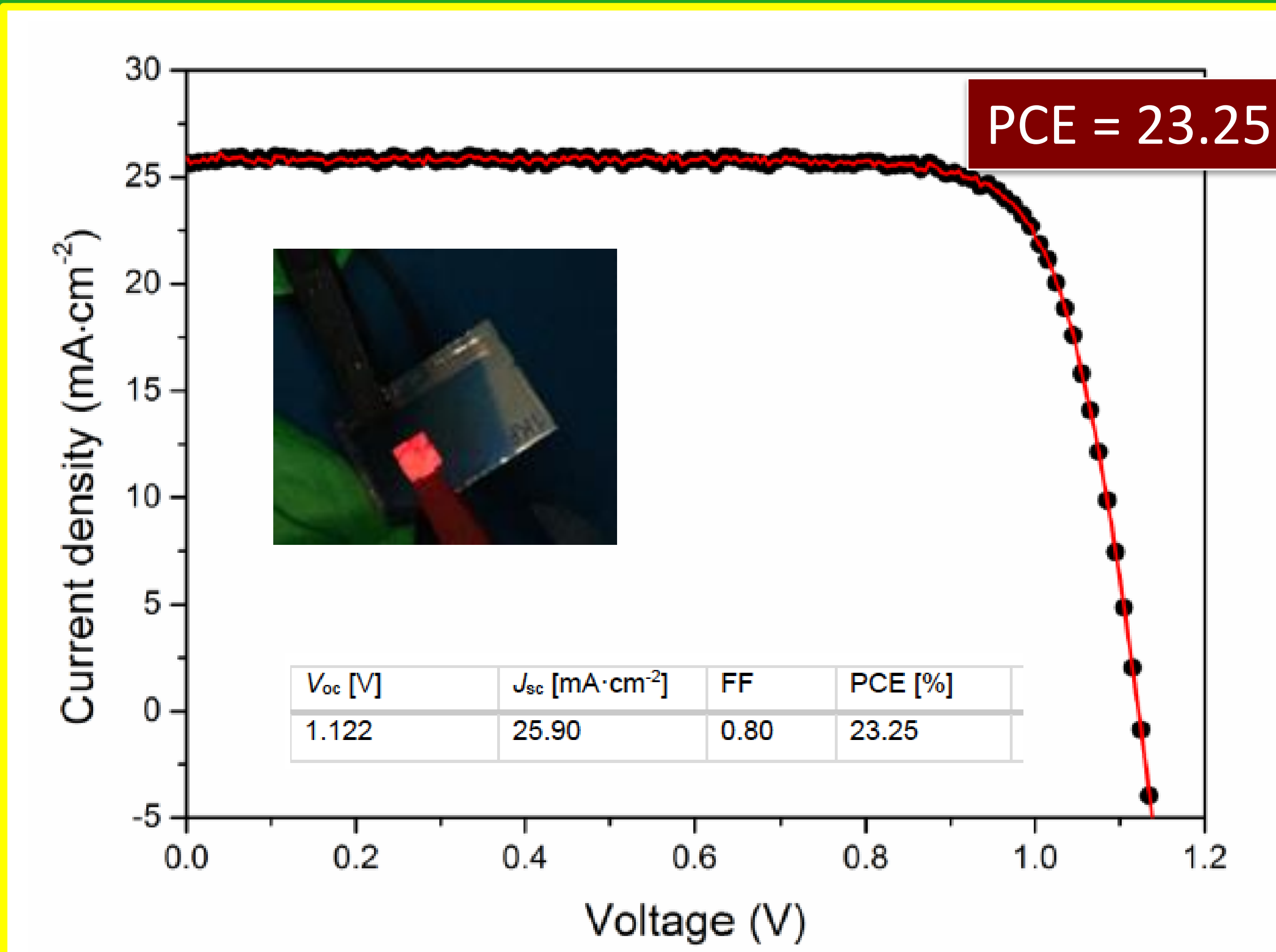


a) .PV metrics of perovskite solar cells with different additives. **b**, *J-V* curves of the champion cell under standard AM 1.5 solar radiation. **c**, IPCE spectrum (black curve) and projected photocurrent (red curve).

The impact of the molecular mpdulators on operationlal stability of PSCs



Our present power conversion efficiency record is (PCE) is 23.25 %



V_{oc} [V]	J_{sc} [mA·cm^{-2}]	FF	PCE [%]
1.122	25.90	0.80	23.25

Dr. Yuhang Liu

Lichen Zhao

Outline

- The stunning rise of pervoskite solar cells
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  - Multi-cation formulations, the power of solid state NMR analysis
  - The amazing impact of molecular modulators
  - **Boosting the PSC stability**

Applications for solar fuel generation

The quest for operational stability of perovskite solar cells

K. Domanski et.al. Nature Energy 2018, https://doi.org/10.1038/s41560-017-0060-5

nature energy

ARTICLES

https://doi.org/10.1038/s41560-017-0060-5

Systematic investigation of the impact of operation conditions on the degradation behaviour of perovskite solar cells

Konrad Domanski[1*], Essa A. Alharbi[1], Anders Hagfeldt[2], Michael Grätzel[1] and Wolfgang Tress[1,2*]

Perovskite solar cells have achieved power-conversion efficiency values approaching those of established photovoltaic technologies, making the reliable assessment of their operational stability the next essential step towards commercialization. Although studies increasingly often involve a form of stability characterization, they are conducted in non-standardized ways, which yields data that are effectively incomparable. Furthermore, stability assessment of a novel material system with its own peculiarities might require an adjustment of common standards. Here, we investigate the effects of different environmental factors and electrical load on the ageing behaviour of perovskite solar cells. On this basis, we comment on our perceived relevance of the different ways these are currently aged. We also demonstrate how the results of the experiments can be distorted and how to avoid the common pitfalls. We hope this work will initiate discussion on how to age perovskite solar cells and facilitate the development of consensus stability measurement protocols.

One year long stable operation under full sunlight corresponding to 11 years outdoors achieved with carbon based PSCs featruing a 2D/3D perovskie architecture

ARTICLE

Received 19 Aug 2016 | Accepted 20 Apr 2017 | Published 1 Jun 2017

DOI: 10.1038/ncomms15684

OPEN

One-Year stable perovskite solar cells by 2D/3D interface engineering

G. Grancini[1], C. Roldán-Carmona[1], I. Zimmermann[1], E. Mosconi[2,3], X. Lee[4], D. Martineau[5], S. Narbey[5], F. Oswald[5], F. De Angelis[2,3], M. Graetzel[4] & Mohammad Khaja Nazeeruddin[1]

Amino-valeric acid AVA

Despite the impressive photovoltaic performances with power conversion efficiency beyond 22%, perovskite solar cells are poorly stable under operation, failing by far the market requirements. Various technological approaches have been proposed to overcome the instability problem, which, while delivering appreciable incremental improvements, are still far from a market-proof solution. Here we show one-year stable perovskite devices by engineering an ultra-stable 2D/3D $(HOOC(CH_2)_4NH_3)_2PbI_4/CH_3NH_3PbI_3$ perovskite junction. The 2D/3D forms an exceptional gradually-organized multi-dimensional interface that yields up to 12.9% efficiency in a carbon-based architecture, and 14.6% in standard mesoporous solar cells. To demonstrate the up-scale potential of our technology, we fabricate $10 \times 10\ cm^2$ solar modules by a fully printable industrial-scale process, delivering 11.2% efficiency stable for >10,000 h with zero loss in performances measured under controlled standard conditions. This innovative stable and low-cost architecture will enable the timely commercialization of perovskite solar cells.

Science

REPORTS

Cite as: N. Arora *et al.*, *Science* 10.1126/science.aam5655 (2017).

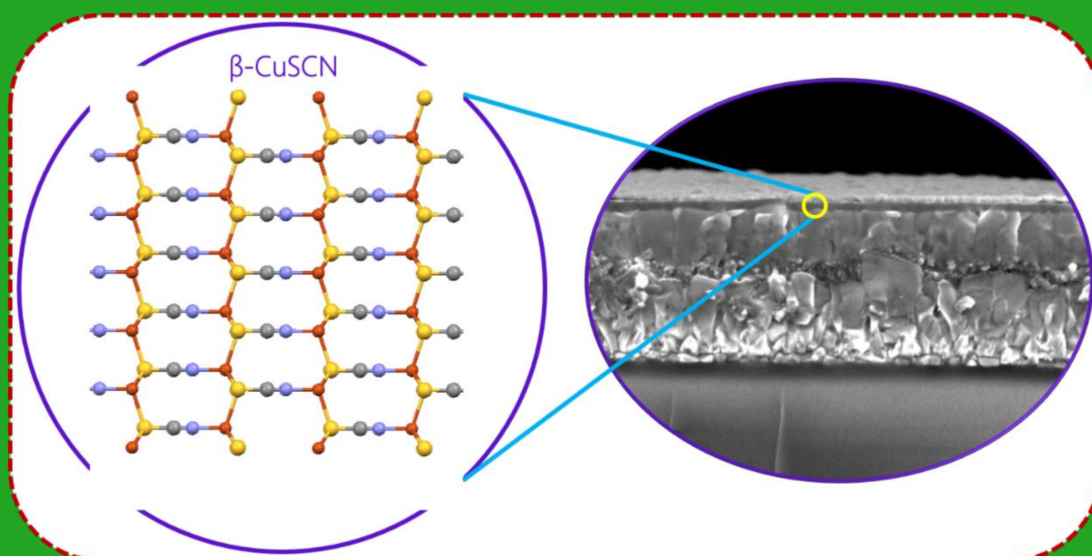
Perovskite solar cells with CuSCN hole extraction layers yield stabilized efficiencies greater than 20%

Neha Arora,[1]* M. Ibrahim Dar,[1]*† Alexander Hinderhofer,[2] Norman Pellet,[1] Frank Schreiber,[2] Shaik Mohammed Zakeeruddin,[1] Michael Grätzel[1]†

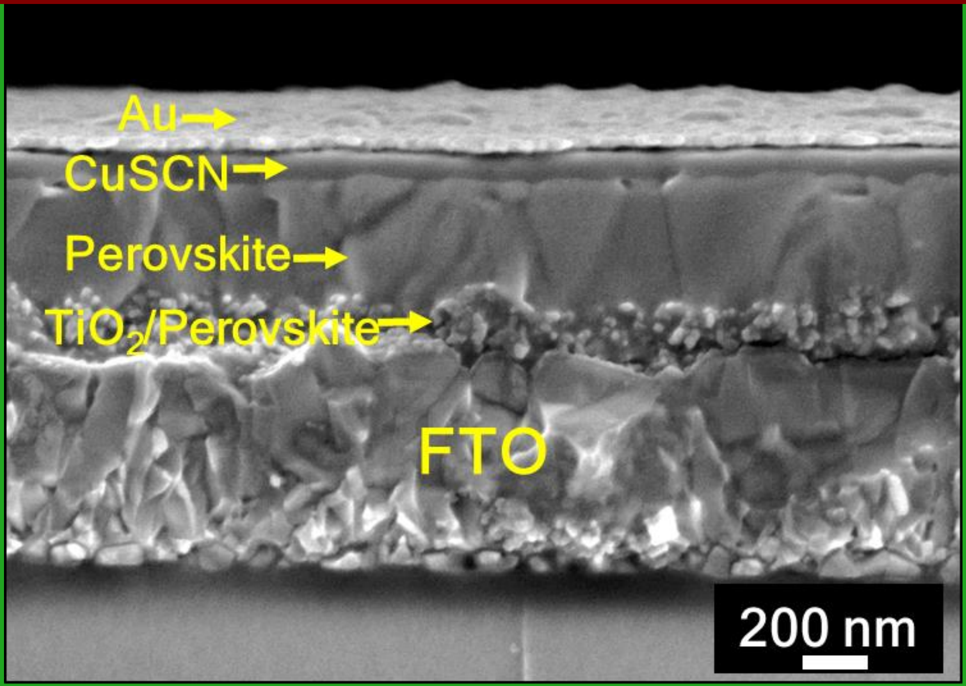
[1]Laboratory of Photonics and Interfaces, Department of Chemistry and Chemical Engineering, Ecole Polytechnique Federale de Lausanne, Lausanne CH-1015, Switzerland. [2]Institut für Angewandte Physik, Universität Tübingen, 72076 Tübingen, Germany.

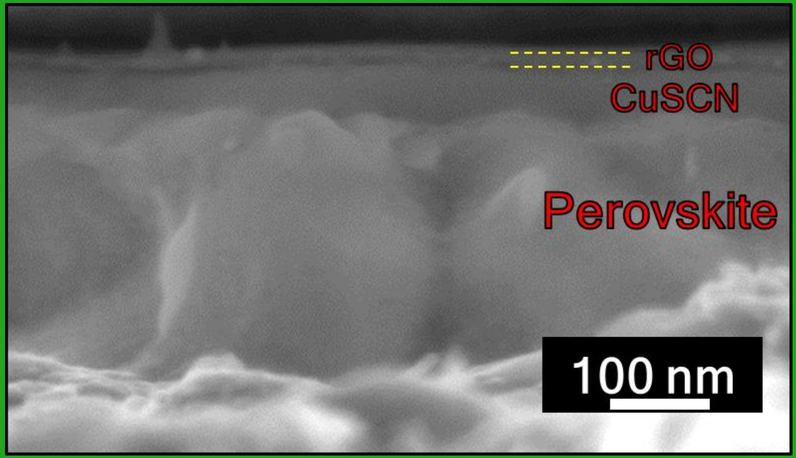
*These authors contributed equally to this work.

†Corresponding author. Email: ibrahim.dar@epfl.ch (M.I.D.); michael.graetzel@epfl.ch (M.G.)

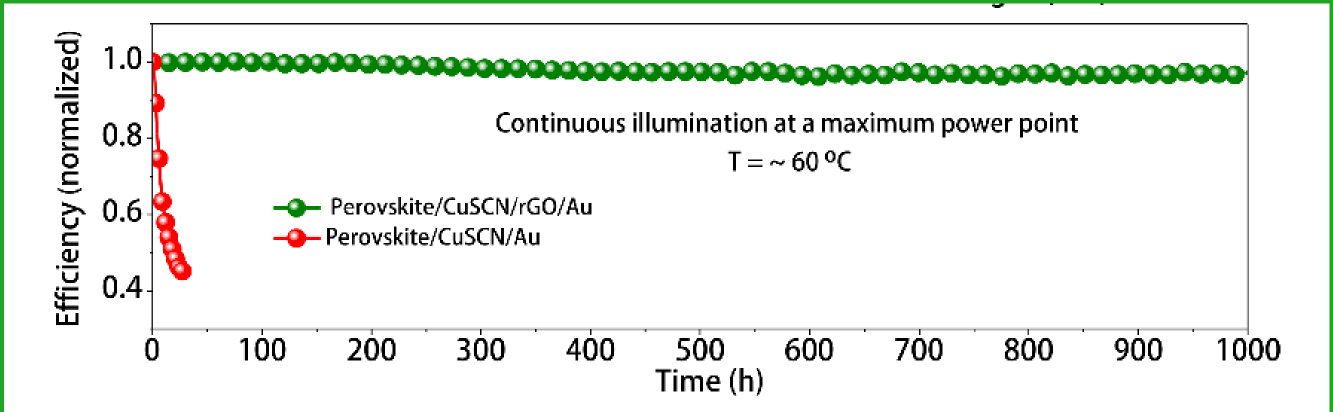


Operational stability of un-encapsulated CuSCN based device and un-encapsulated CuSCN based device containing a thin layer of rGO (as a spacer layer between CuSCN and gold layers), examined at a maximum-power-point under continuous full-sun illumination at 60 °C in nitrogen atmosphere.





Morphological characterization of CuSCN/rGO/Au sample



Adv. Sci. 2016, 1600269

www.MaterialsViews.com

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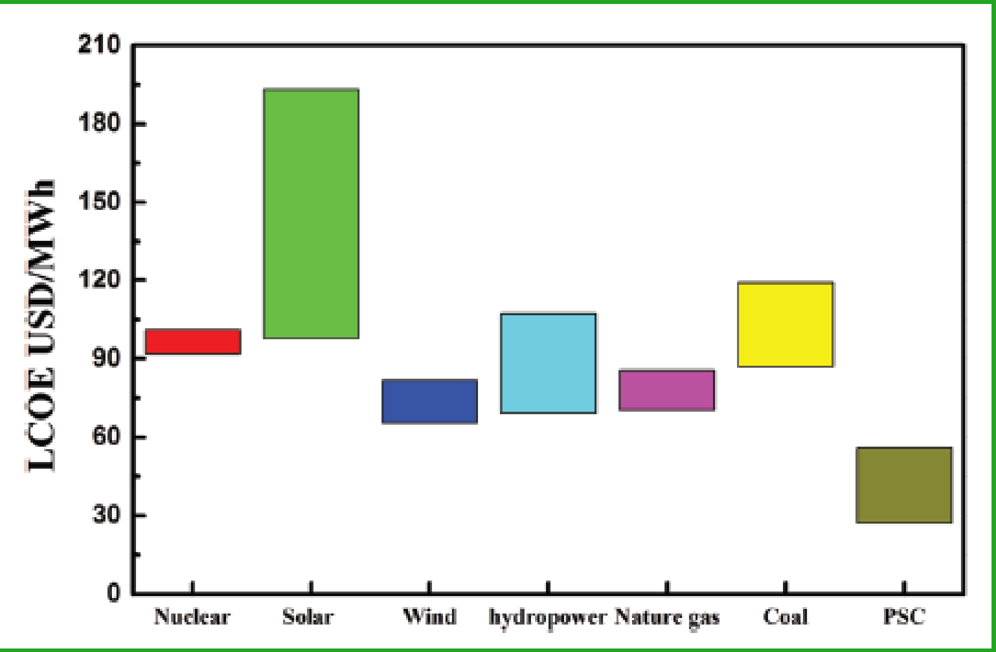
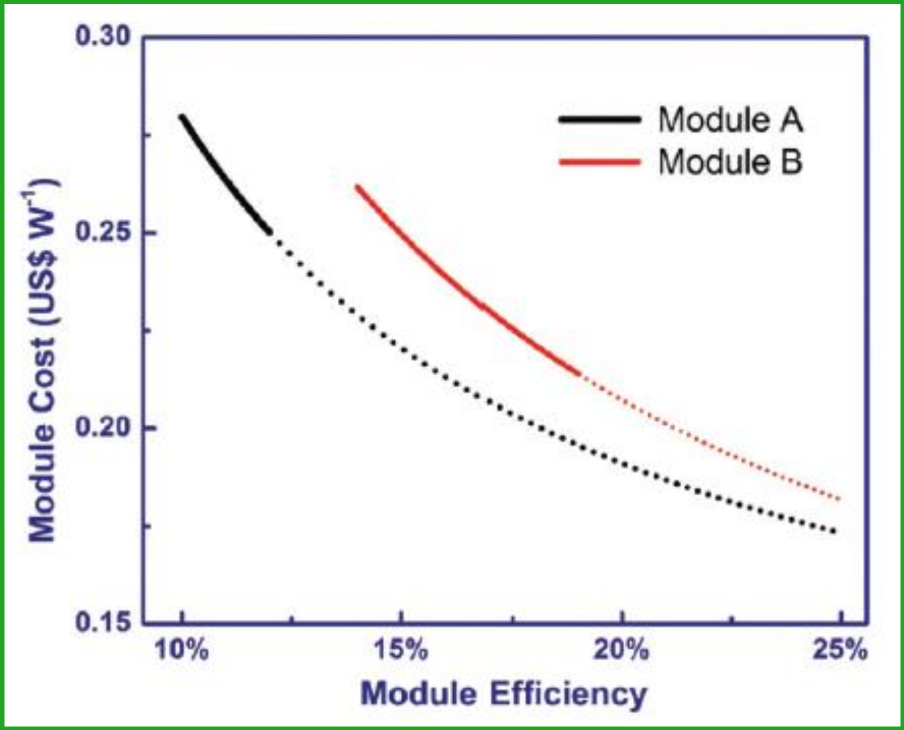
www.advancedscience.com

Cost-Performance Analysis of Perovskite Solar Modules

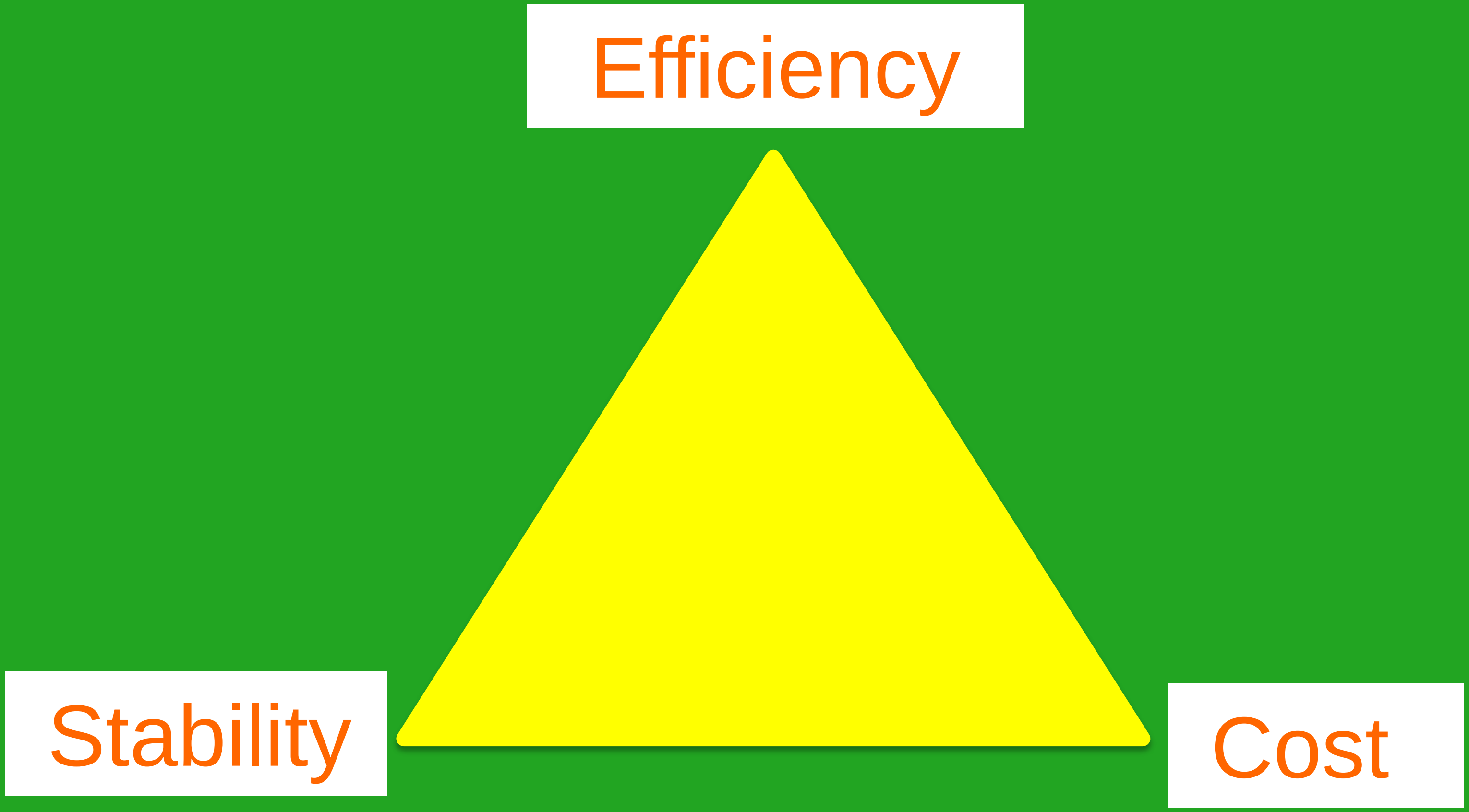
*Molang Cai, Yongzhen Wu, Han Chen, Xudong Yang, Yinghuai Qiang, and Liyuan Han**





Pepvskite solar cells (PSC) offer lowest cost of all energy producing technologies

The “Golden Triangle” of photovoltaics



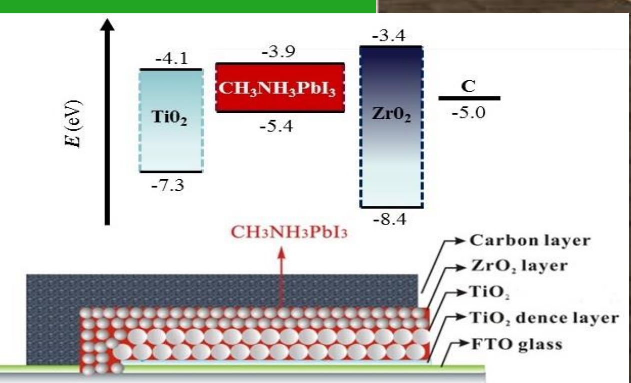
Science
2014
AAAS

Anyi Mei,[1*] Xiong Li,[1*] Linfeng Liu,[1] Zhiliang Ku,[1] Tongfa Liu,[1] Yaoguang Rong,[1] Mi Xu,[1] Min Hu,[1] Jiangzhao Chen,[1] Ying Yang,[1] Michael Grätzel,[2] Hongwei Han[1]†

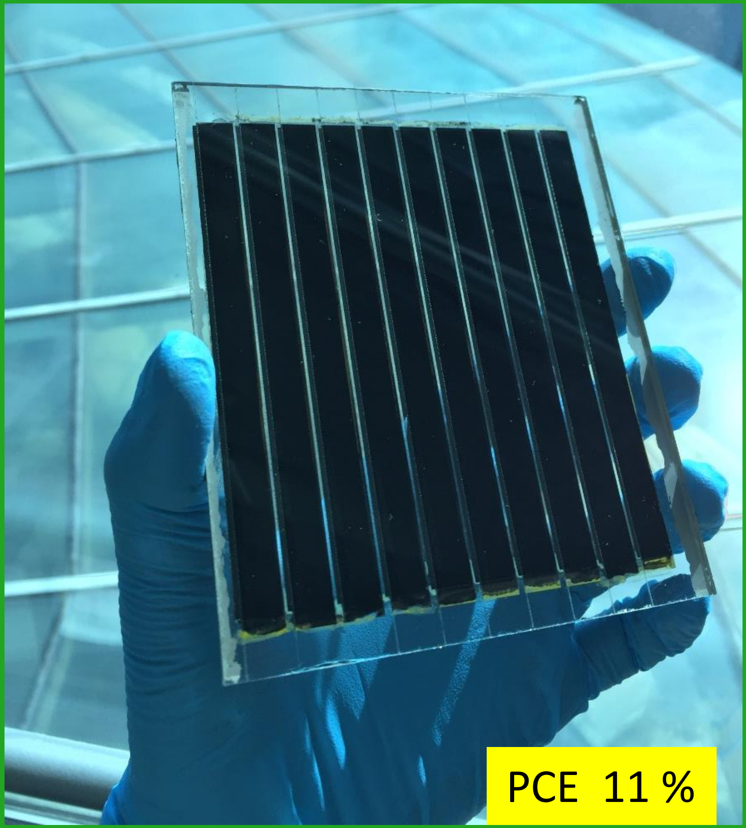
A hole-conductor–free, fully printable mesoscopic perovskite solar cell with high stability

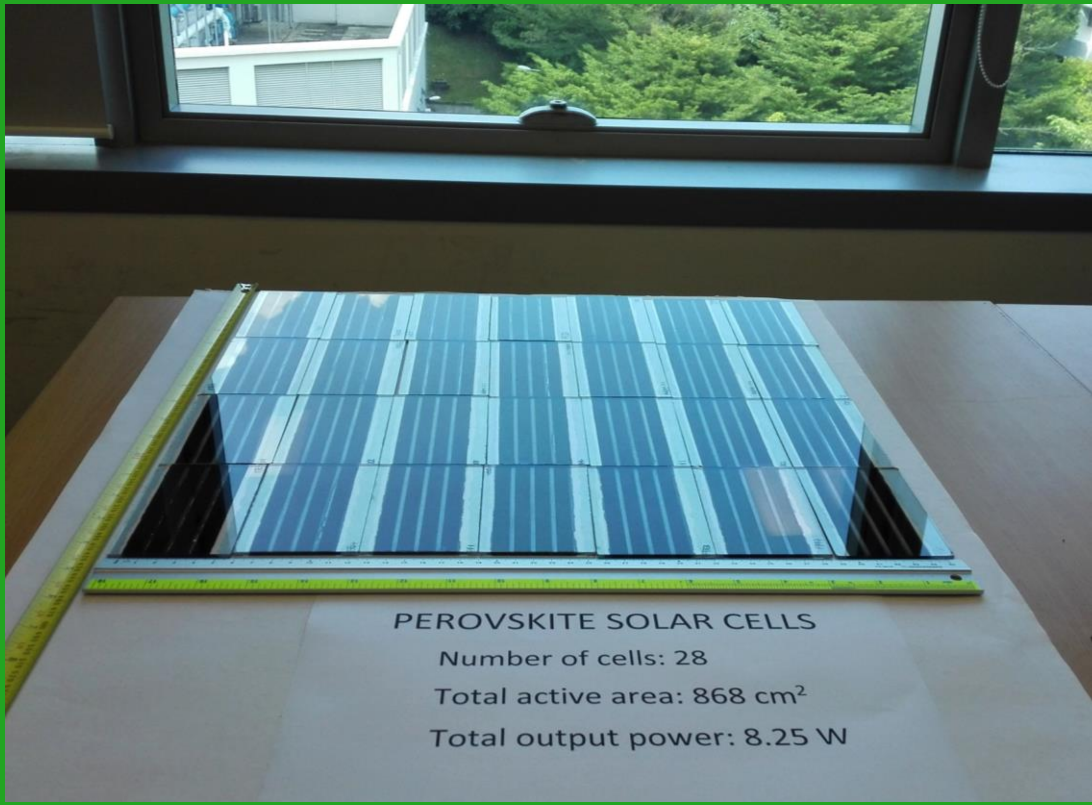
MGC
太阳能电池研究中心
格兰泽尔介观太阳能电池研究中心
Michael Grätzel Center for Mesoscopic Solar Cells

June 2016



Pervoskite solar cell modules produced at NTU Singapore





Courtesy Prof. Subodh Mhaikalsar, Nripan Matthew NTU Singapore

Dyesol Perovskite solar cell protoype

Outline

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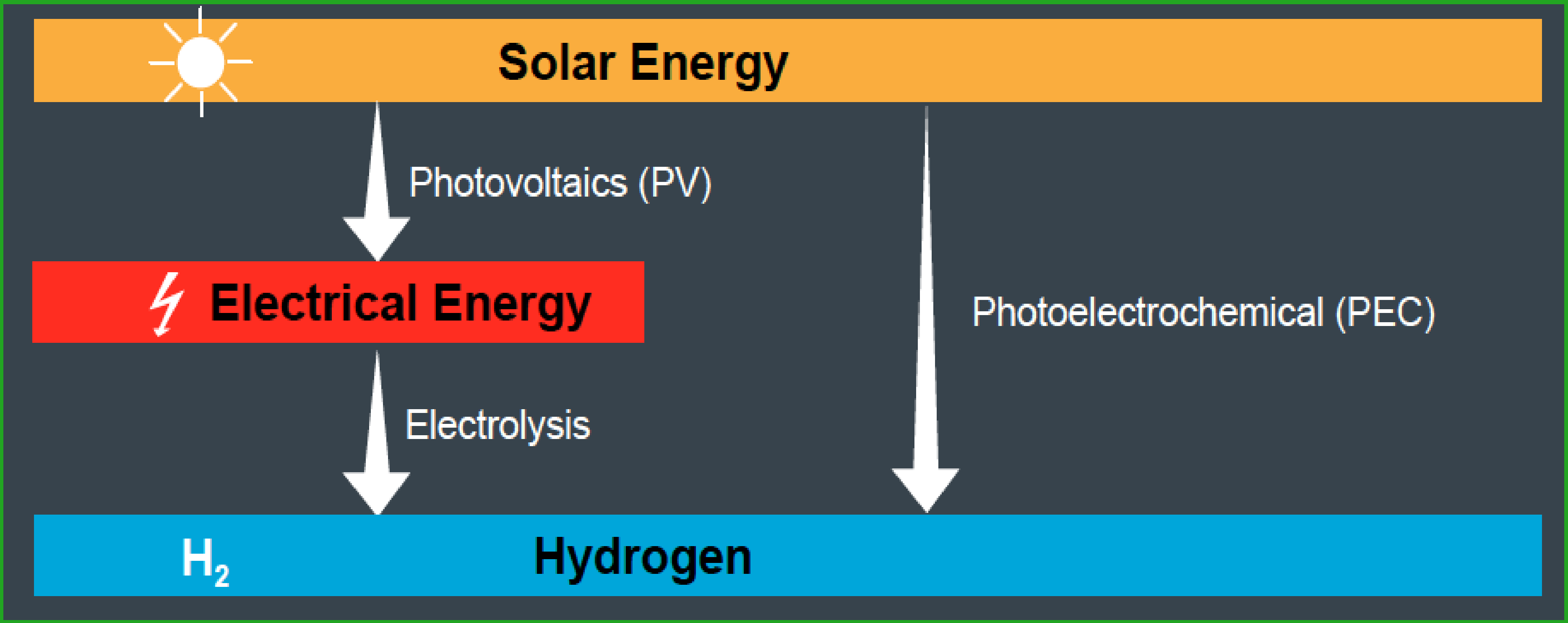
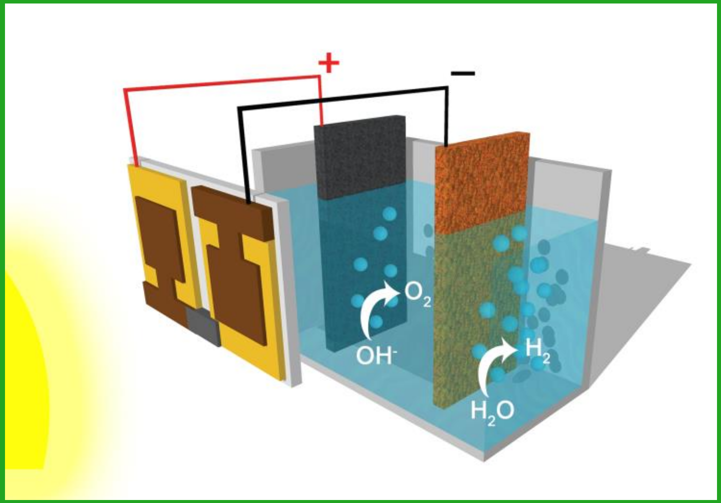
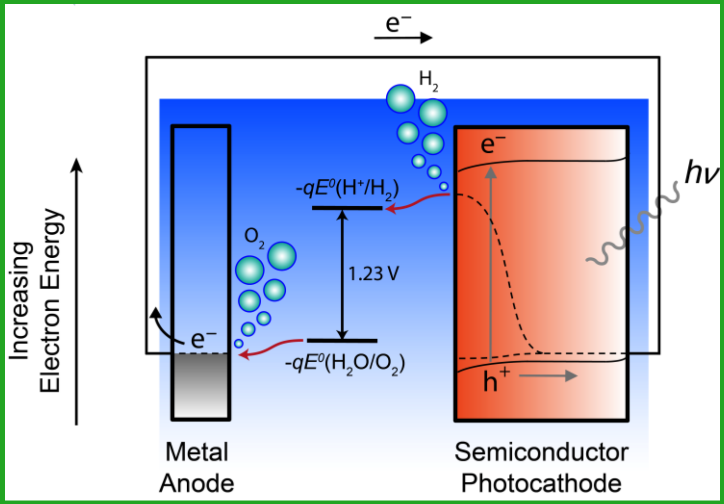
  - The amazing impact of molecular modulators
  - Boosting the PSC stability
  - **solar fuel generation**
  - Applications

Solar fuel research in LPI







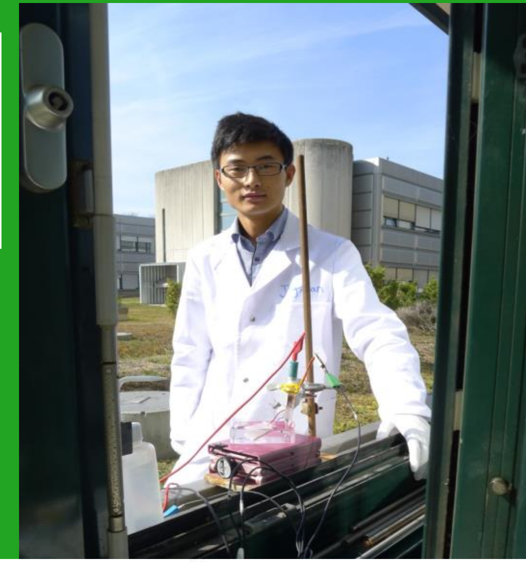
WATER SPLITTING

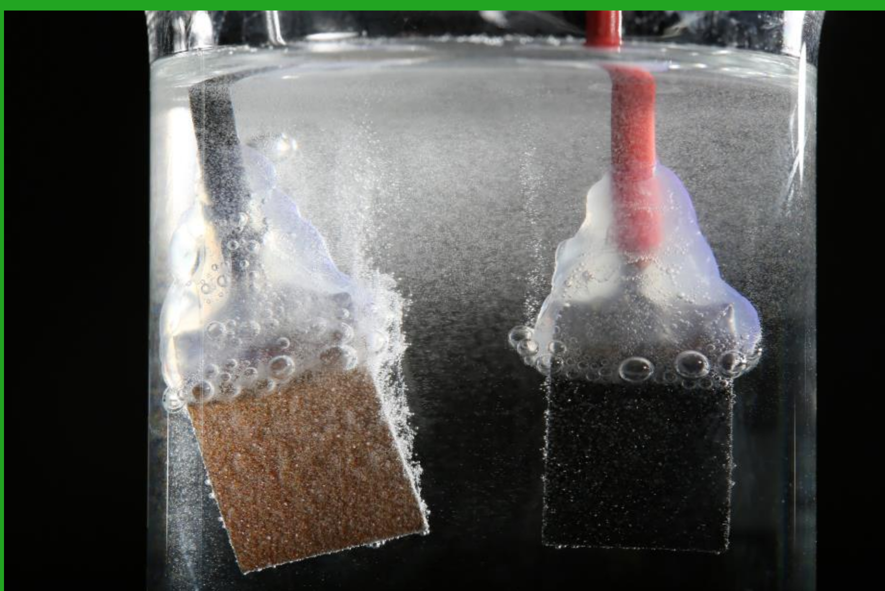
Water photolysis at 12.3% efficiency via perovskite photovoltaics and Earth-abundant catalysts

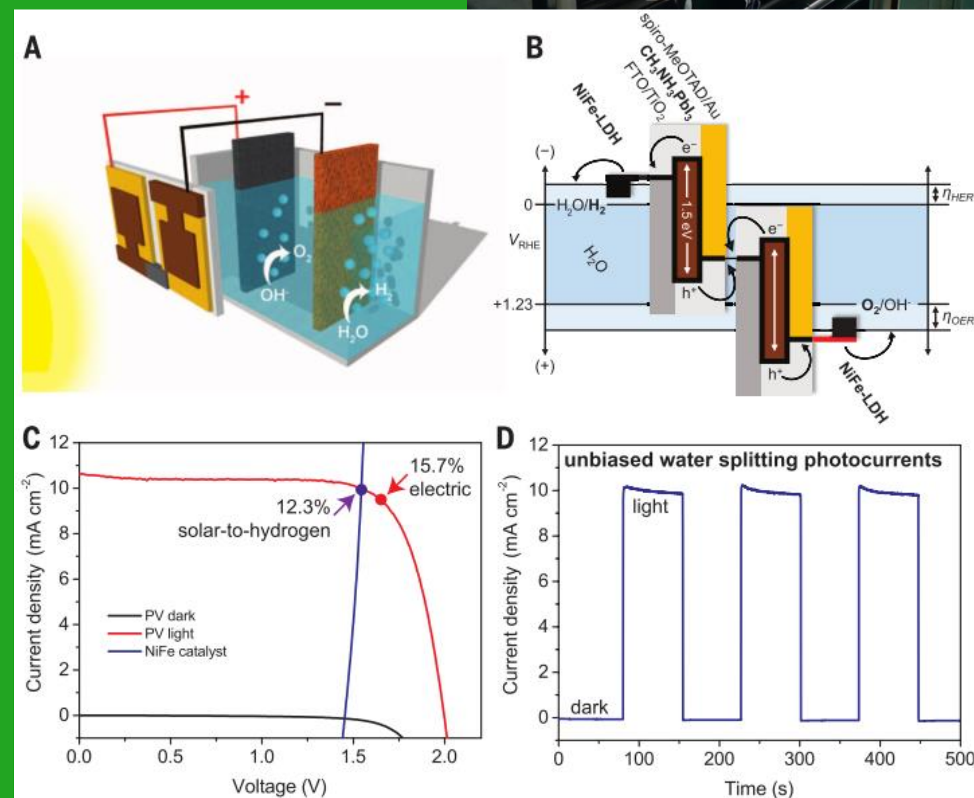
Jingshan Luo,[1,2] Jeong-Hyeok Im,[1,3] Matthew T. Mayer,[1] Marcel Schreier,[1] Mohammad Khaja Nazeeruddin,[1] Nam-Gyu Park,[3] S. David Tilley,[1] Hong Jin Fan,[2] Michael Grätzel[1]*

Science AAAS

JIngshan Luo



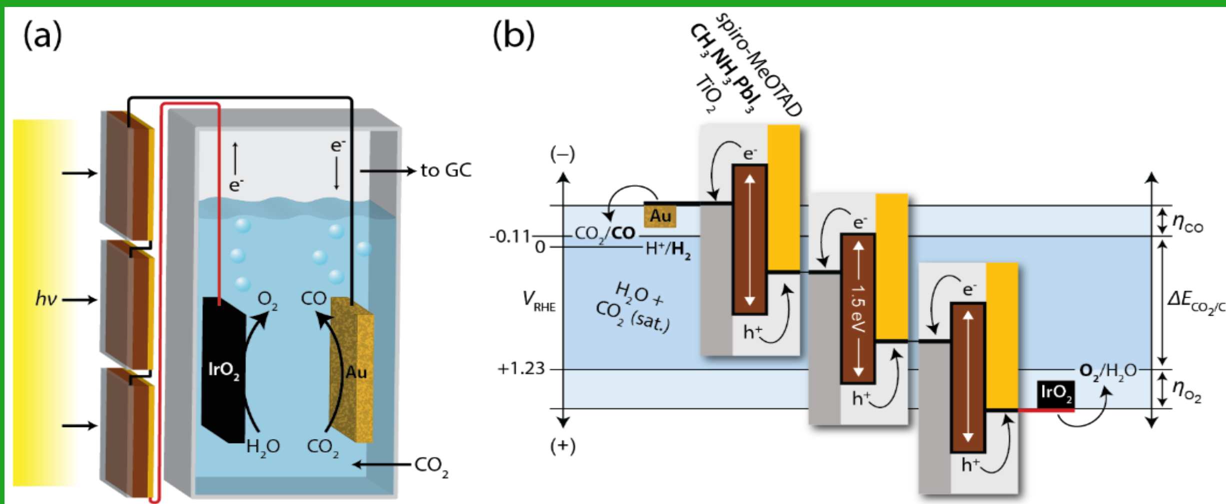




Luo, J... Grätzel, M. et al. *Science* **2014**, *345*, 1593.

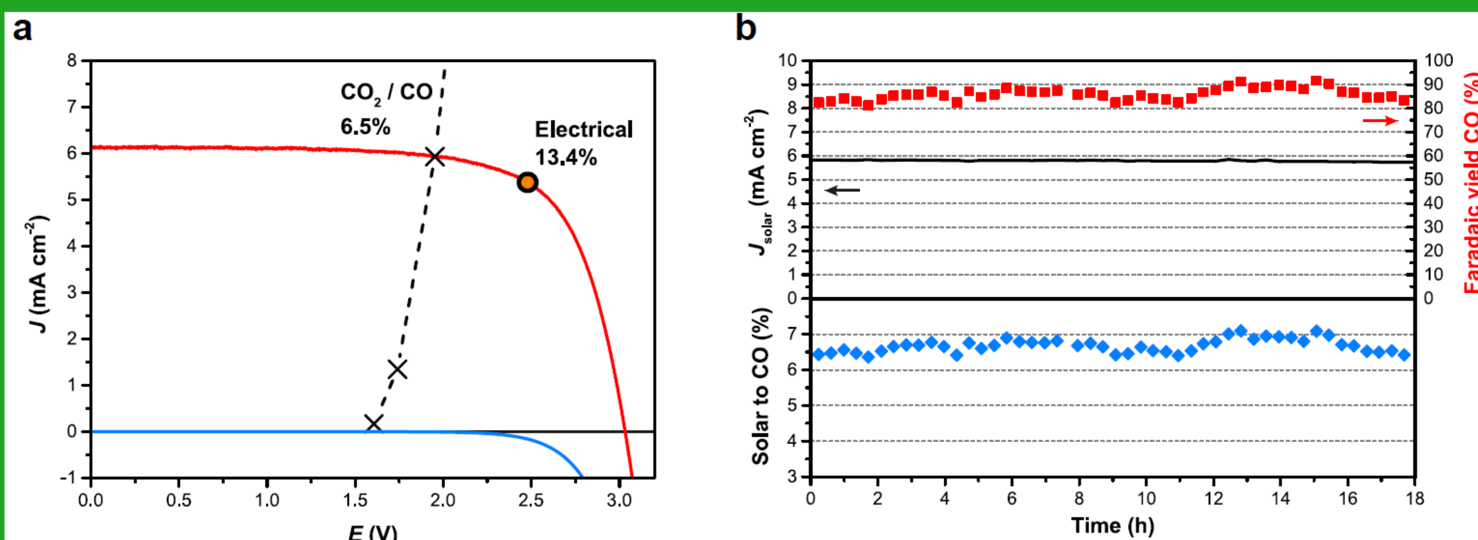
Triple junction mesoscopic pervoskite cells achieve the reduction of CO_2 to CO with 6.5 % solar to CO (STCO) conversion efficiency using water as electron source

$$CO_2 \rightarrow CO + \frac{1}{2} O_2 \;,\; \Delta G^* = +1.34 \text{ eV}$$



Marcel Schreier

6.5 % Solar to CO



M. Schreier et al. Nature Communications 6, 7326 (2015)

Breakthrough Energy Ventures to invest > 1 billion in energy research

Beating Nature at Its Own Game

Bill Gates on Linked in March 14 , 2017

We need thousands of scientists following all paths that might lead us to a clean energy future. That's why a group of investors and I recently launched Breakthrough Energy Ventures, a fund that will invest more than $1 billion in scientific discoveries that have the potential to deliver cheap and reliable clean energy to the world.

Hyundai NEXO fuel cell car

Outline

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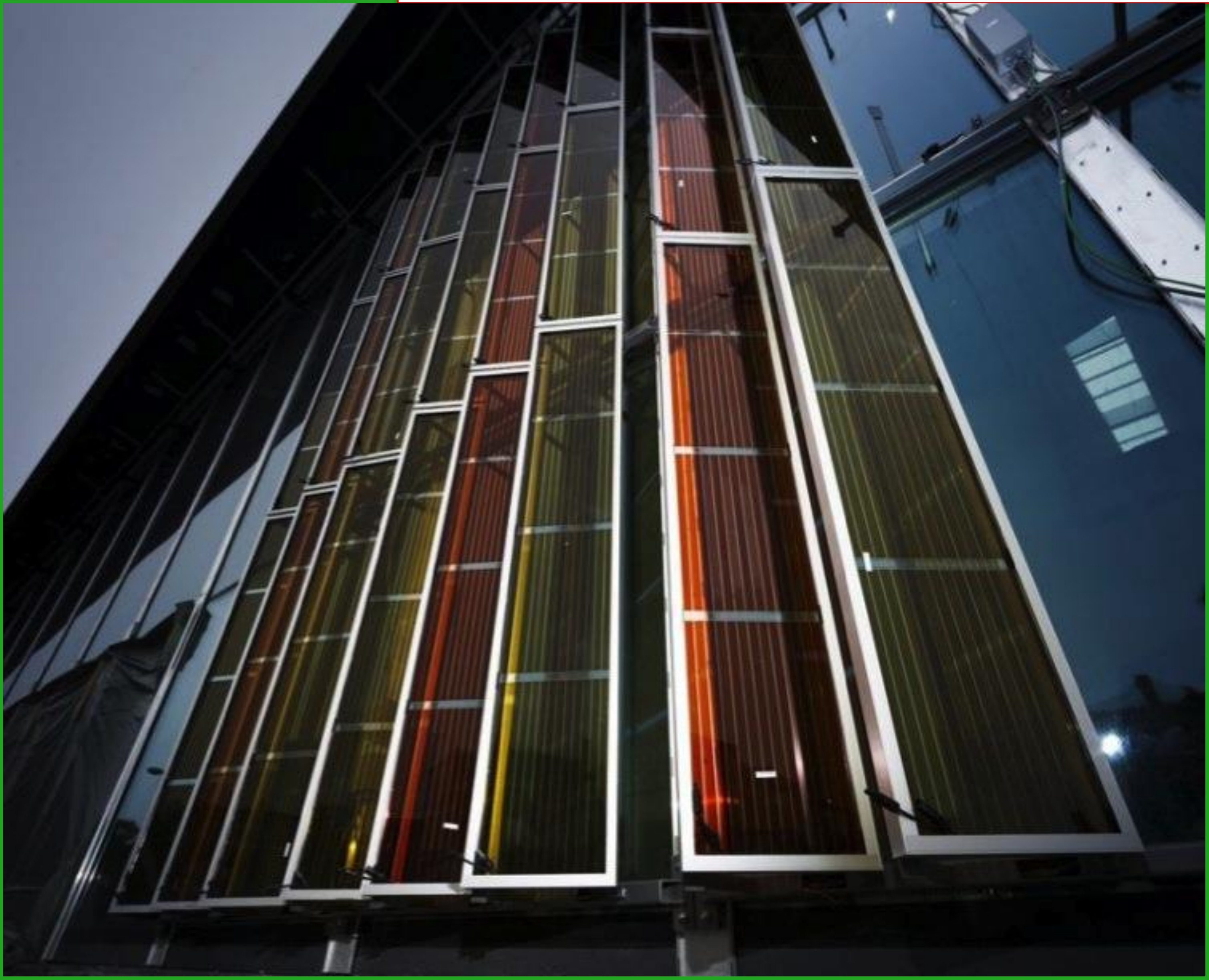
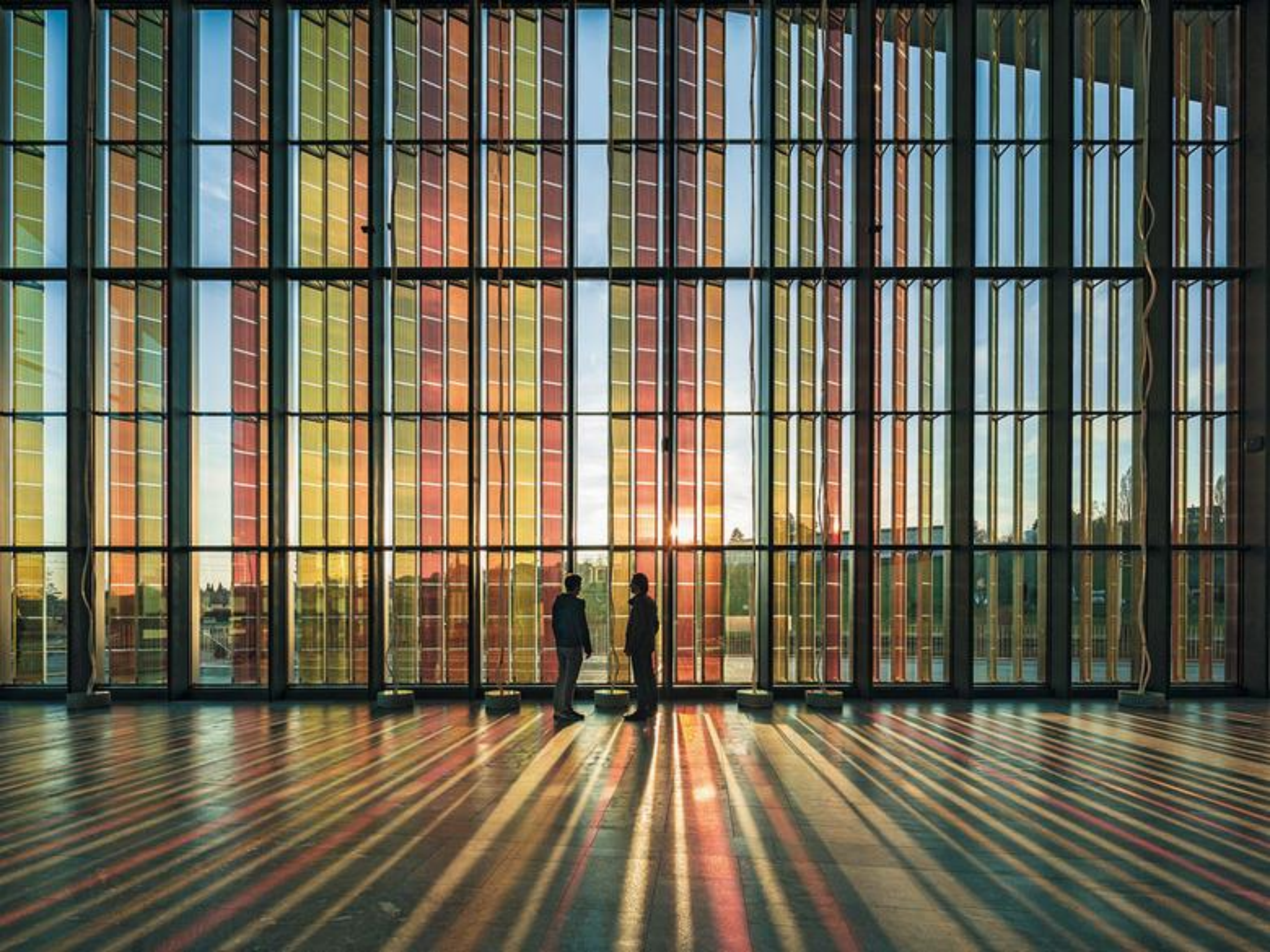
  - The amazing impact of molecular modulators
  - Boosting the PSC stability
  - solar fuel generation
  - **Applications**

TODAY

Swiss Tech Convention Center





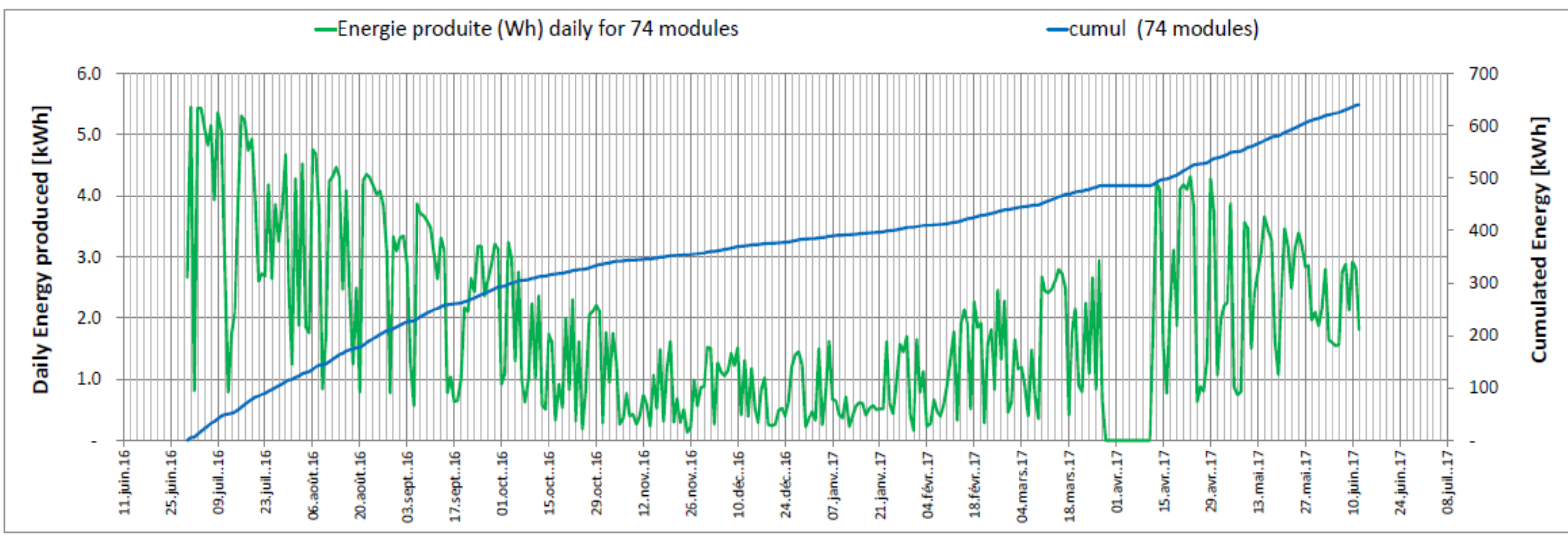
Electric car charging station powered by H.Glass panels

The first Energy Noise Barrier made with H.Glasss panels. Energy yield: 1’012.5 kWh / year

Tracking energy output of H.Glass modules as sound barriers at the Bern-Zurich motorway

Swisscom Bern

- Commissioned in May, 2016
- PV Fence
- 74 Mod 32 cells, green color,
- Follow on projects: Yes



Green H..Glass panels in Lausanne Ouchy

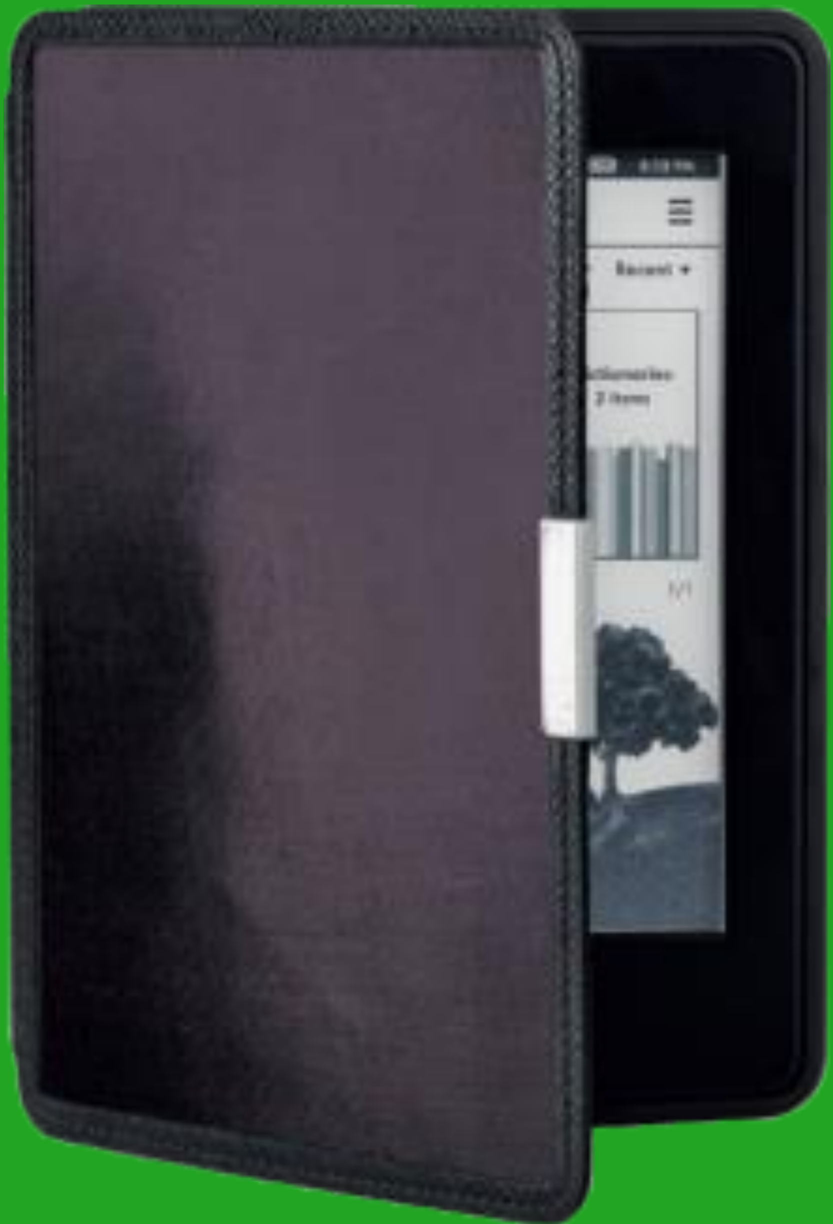
DSC energy glass modules entering now the private market

Fam. Reinhard Basel

- Commissioned in June, 2016
- PV Railing
- 16 Mod 54 cells, green color, 9.6 m^2
- Follow on projects: Yes

Graz Science Tower featuring 1000 m2 DSC panels produced by HGlass (formerly G2E) inaugurated on Sept.21 2017

DSC powered E-reader from EXEGER with eternal battery life

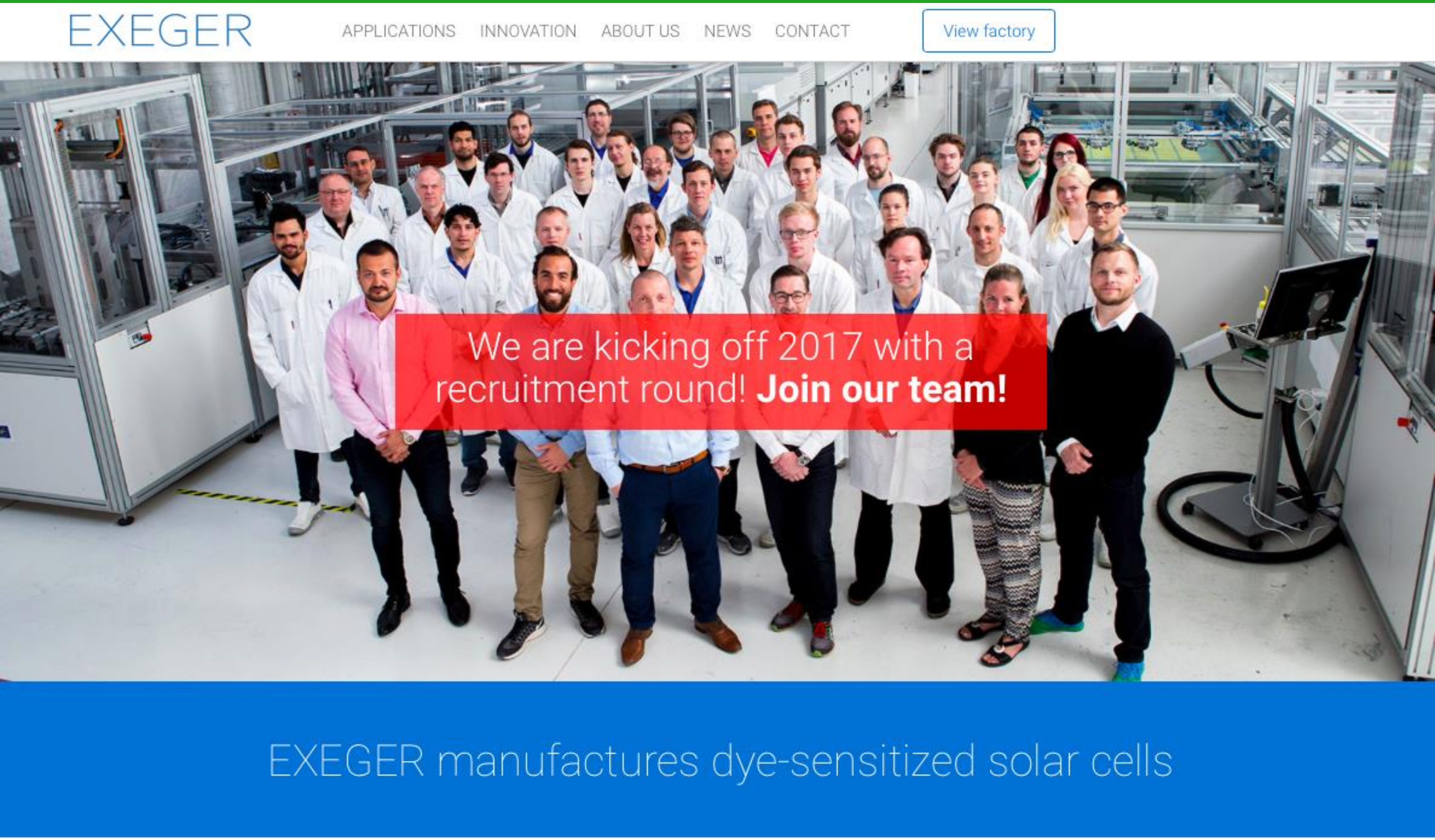


http://www.exeger.com/

E-reader with eternal life.

EXEGER has developed the prototype pictured here through seamless integration of the world's best indoor solar cell. The product has eternal life in standard indoor illumination alone.

Job creation in Sweden through production of dye-sensitized solar cells



http://www.exeger.com/

Focus-induced photoresponse (FIP)
A revolutionaty new application of Dye sensitized technology

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3d -distance
measurement
And imaging

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Lungenschmied
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"Focus-induced
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a
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PM

Technologies. The solution to your sensing challenge: XperYenZ™ sensor systems. Paving the way for sensing applications that have never been possible before.

World premier presentation
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room 16a at 2:10 p.m

Market share of PV panels by Technology Group 2014-2030

Table 7 Market share of PV panels by technology groups (2014-2030)

Technology		2014	2020	2030
Silicon-based (c-Si)	Monocrystalline	92%	73.3%	44.8%
	Poly- or multicrystalline			
	Ribbon			
	a-Si (amorph/micromorph)			
Thin-film based	Copper indium gallium (di)selenide (CIGS)	2%	5.2%	6.4%
	Cadmium telluride (CdTe)	5%	5.2%	4.7%
Other	Concentrating solar PV (CPV)	1%	1.2%	0.6%
	Organic PV/dye-sensitised cells (OPV)		5.8%	8.7%
	Crystalline silicon (advanced c-Si)		8.7%	25.6%
	CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V		0.6%	9.3%

Based on Fraunhofer Institute for Solar Energy Systems (ISE) (2014), Lux Research (2013) and author research

IRENA: End-of-Life Management of Solar Photovoltaic Panels, 2016

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