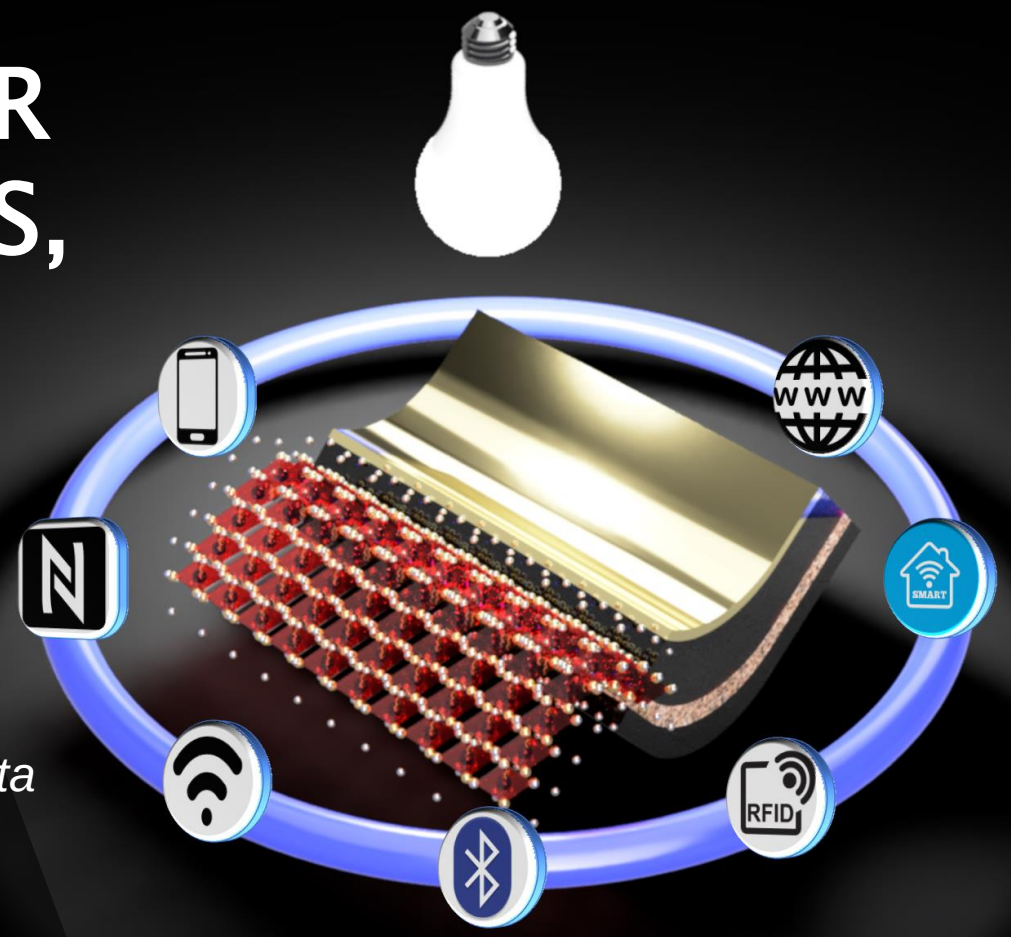
PHOTOVOLTAICS FOR INDOOR LIGHT HARVESTING: PROGRESS, CHALLENGES AND PERSPECTIVES



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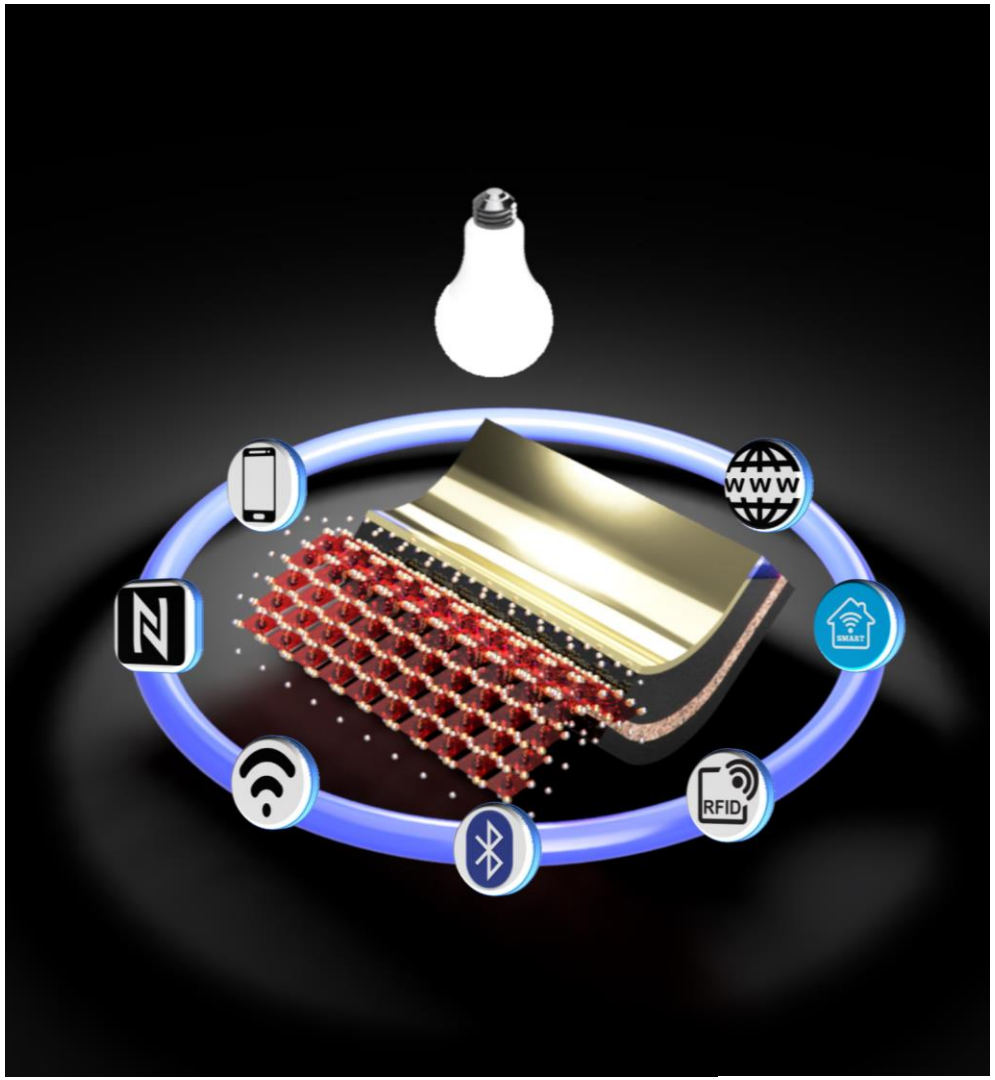
CHOSE POLO SOLARE ORGANICO REGIONE LAZIO
Università di Roma Tor Vergata
Nano Innovation 2020 Conference & Exhibition
Rome, 15-18 September

Outline

- Indoor light harvesting
- Markets and applications of indoor PV
- Photovoltaic technologies
- Test conditions: indoor vs outdoor
- Strategies for high indoor efficiencies
- Indoor perovskite solar cells
- Challenges and perspectives



Photovoltaics for indoor light harvesting

OUTDOORS

- Solar farms (**MWs**)
- Building-integrated

INDOORS

Harvesting of artificial light inside buildings

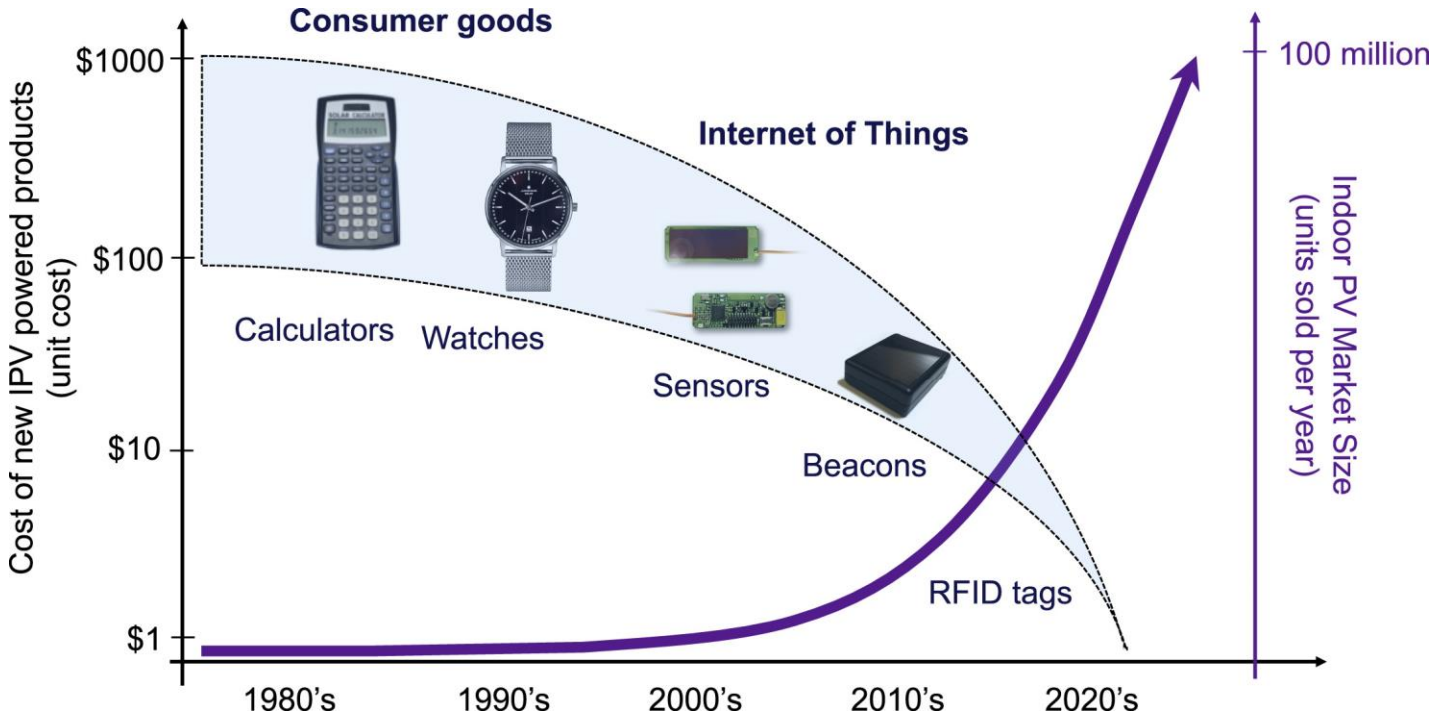
- Product-integrated (**µW-mW**)

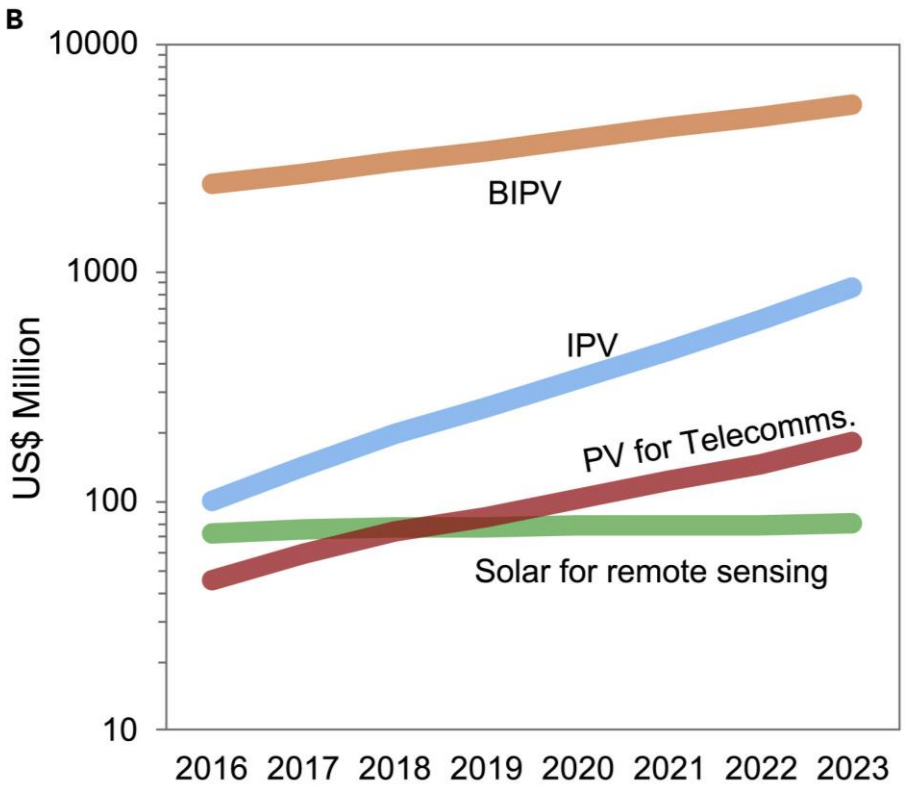
✓ Improvement in buildings' **sustainability**

✓ Reduction of **battery** usage

✓ **Portability**

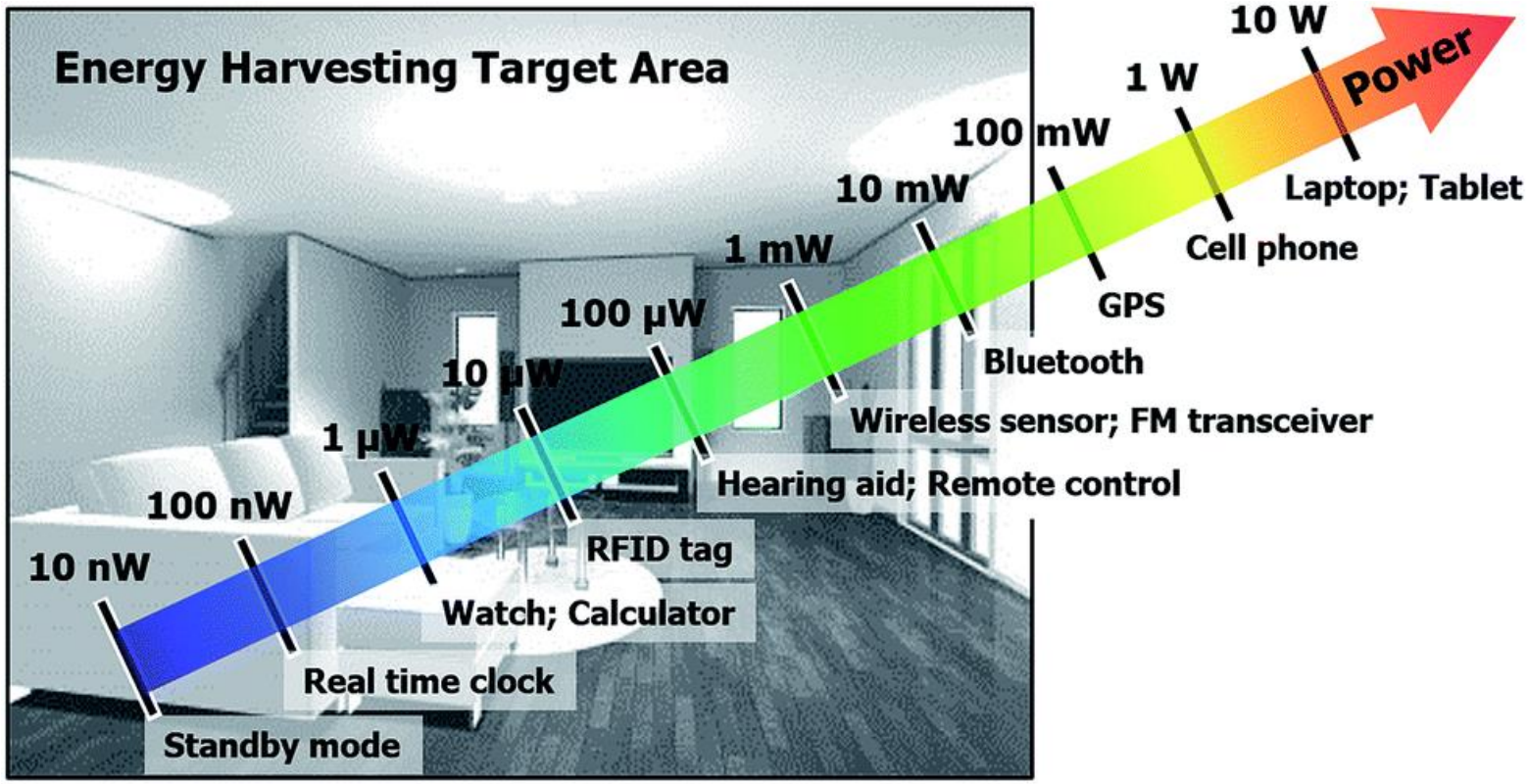
Applications and markets





- Market rise associated with **lowering of consumers products' cost**
- **Fastest growth** among alternative small volume PV markets

Applications of indoor PV



- **Consumer** electronics
- Healthcare and **biomedical** devices
- Building-integrated and indoor appliances
- **Communication** technologies
- WSN and RFID
- Sensors for the **Internet of Things**

Arai, R. et al. J. Mater. Chem. A. (2019) 35, 7, 20187-20192

Photovoltaic technologies

First Generation
Crystalline silicon solar cells

Second Generation
Thin film solar cells

Third Generation
DSSC, OPV, perovskite, multi-junctions

Crystalline Silicon cells

Mono-crystalline cells

Efficiency: 18%~25.6%

Multi-crystalline cells

Efficiency: 17%~20.8%

Thin film solar cells

CdTe cells

Efficiency: 18.3%~22.1%

Amorphous silicon cells

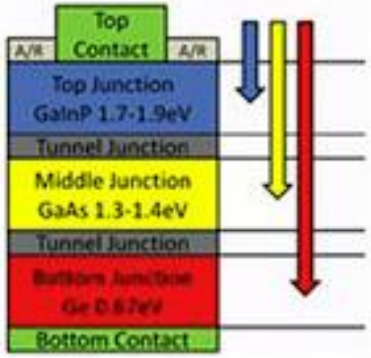
Efficiency: 13.4%

CIGS cells

Efficiency: 20.4%~22.6%

Multi-junction cells

Multijunction solar cells

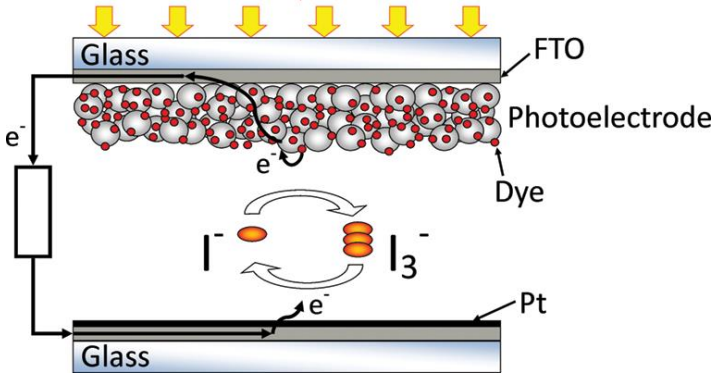


Efficiency: ~45%

N. Amin et al. (2017) Encycl. Sus. Tech., 10.1016/B978-0-12-409548-9.10092-2

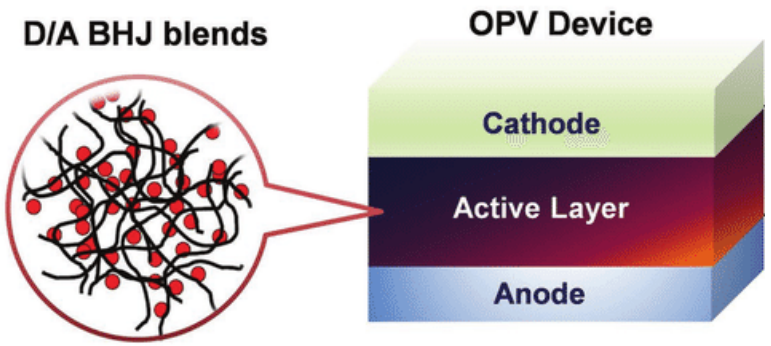
Photovoltaic technologies – 3rd generation

DYE-SENSITISED SOLAR CELLS (DSSC)



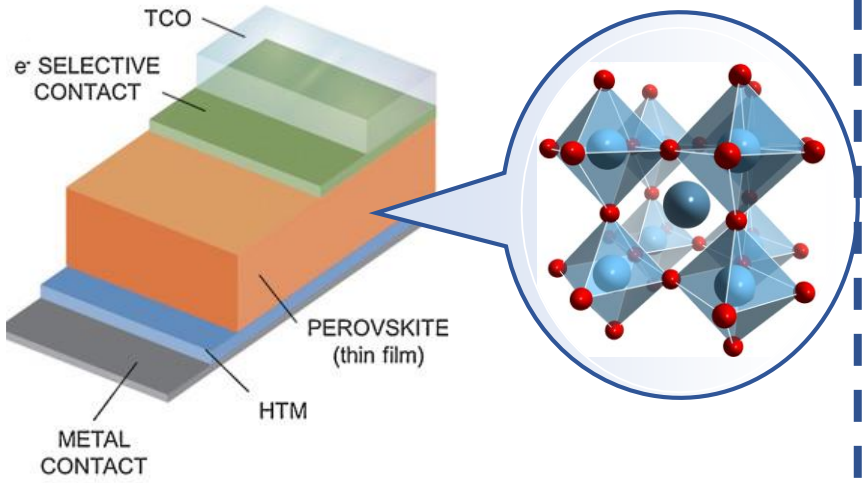
- Photosensitive **organic dye**
- Efficiency: 12.3%

ORGANIC PHOTOVOLTAICS (OPV)



- Donor/acceptor system of **polymers and small molecules**
- Efficiency: 17.4%

PEROVSKITE SOLAR CELLS (PSC)



- Hybrid organic inorganic **perovskite crystalline** absorber
- Efficiency: 25.2%

Photovoltaic technologies – 3rd generation

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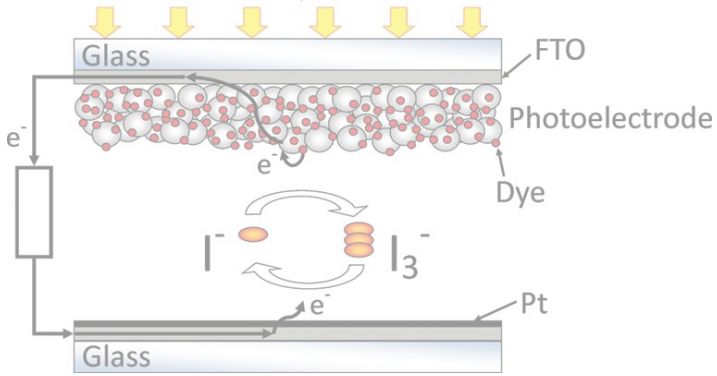

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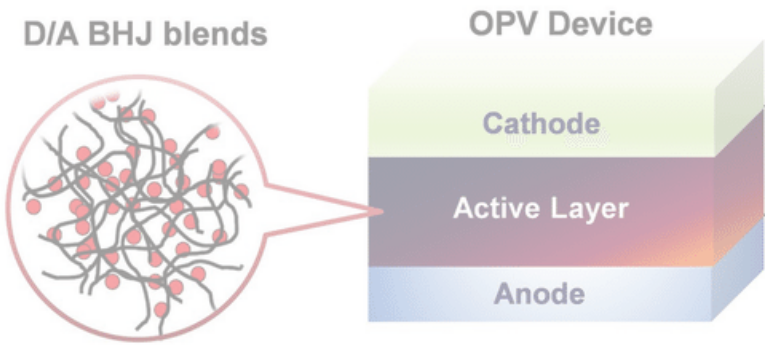

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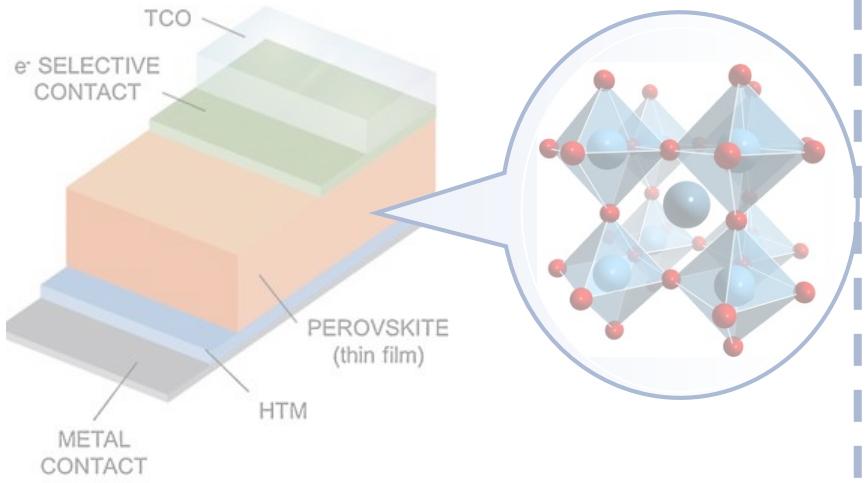
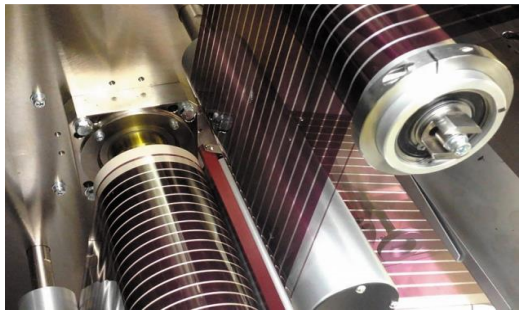
PEROVSKITE SOLAR CELLS (PSC)



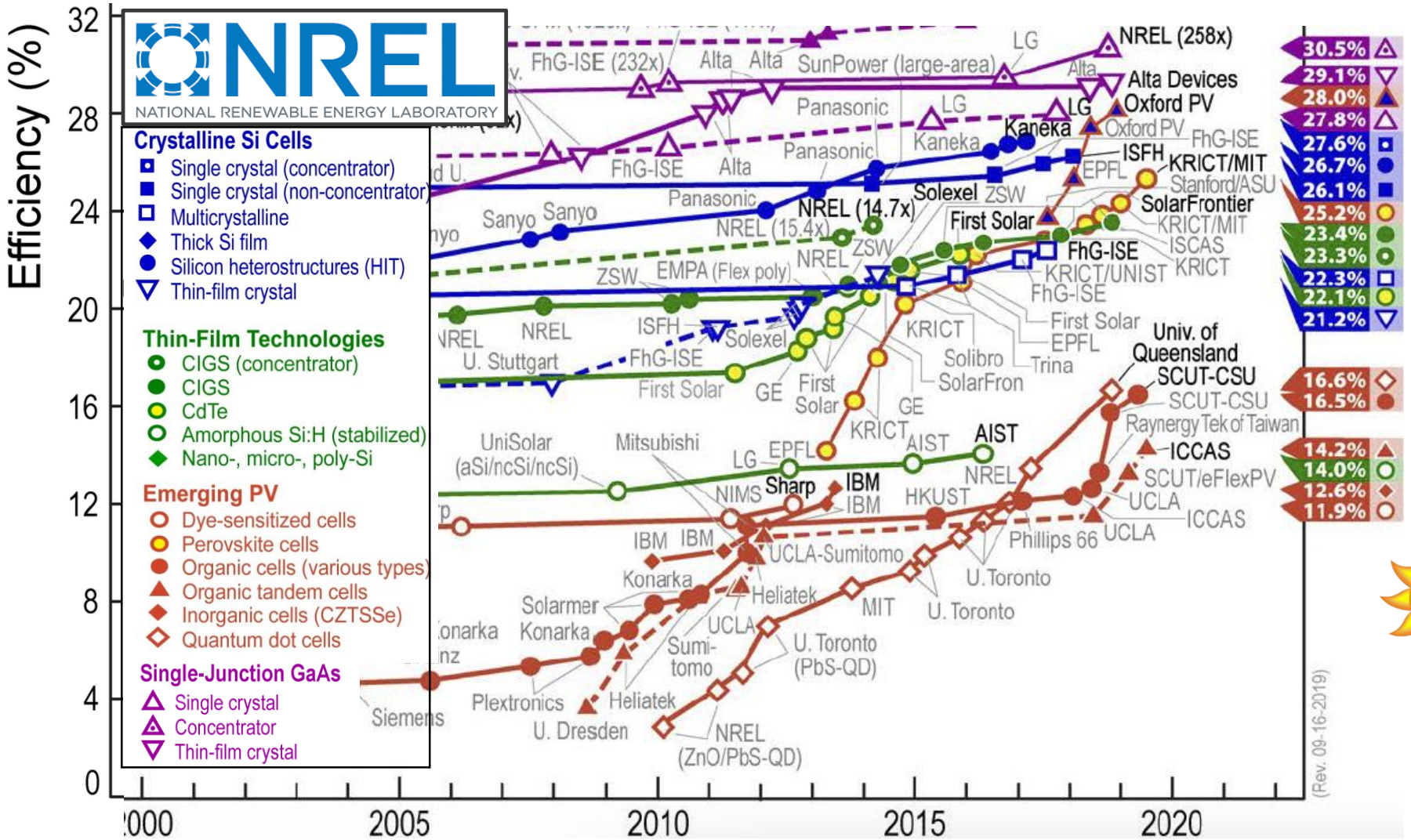
- Hybrid organic inorganic **perovskite crystals**
- Efficiency: 25.2%



- Low-cost
- Printability
- Flexibility
- Colour-tunable, semi-transparent

Sutton R. (2016) Adv. En. Mat., 6, 8, 1502458

PV performance evolution @STC



PEROVSKITE SOLAR CELLS*

3.8% (2009) →
25.2% (2019)

*performance at 1 sun (1000 W/m^2)

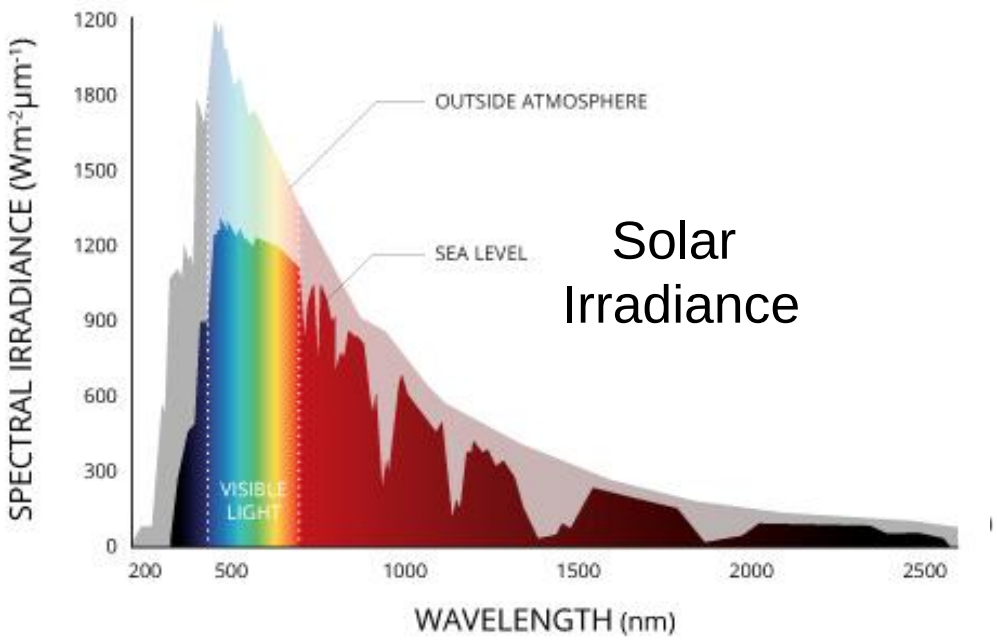
…what happens in indoor conditions?

Outdoor vs Indoor

STANDARD TEST CONDITIONS

~100 klx

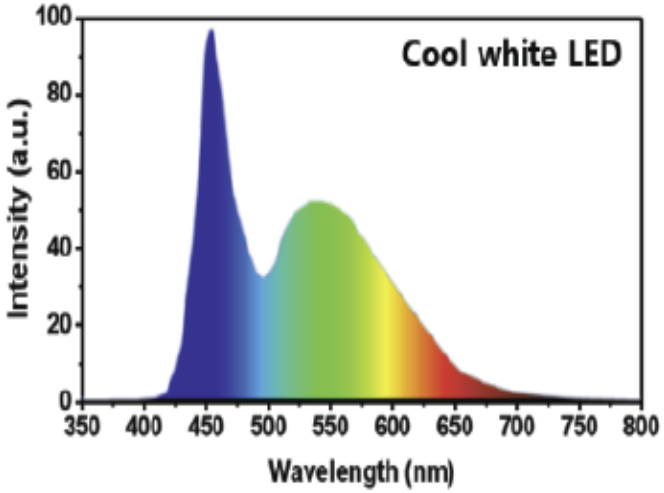
Temperature	25 °C
Irradiance	1000 W/m^2
Air mass	1.5

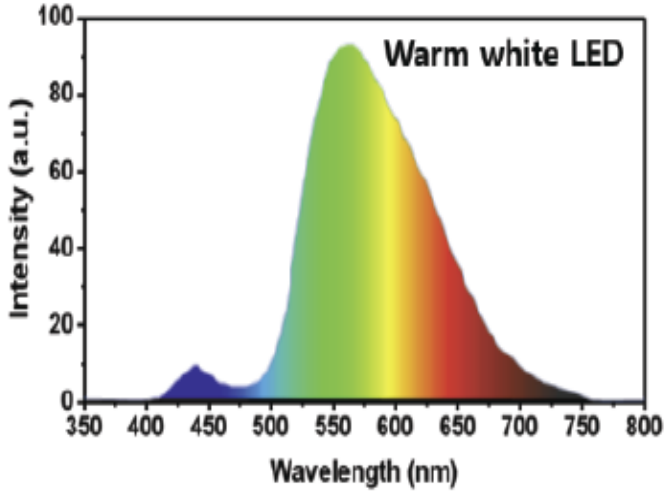


Solar Irradiance

INDOOR ILLUMINATION

Low light 50 lx | Living room 200 lx | Office 500 lx | Supermarket 1000 lx

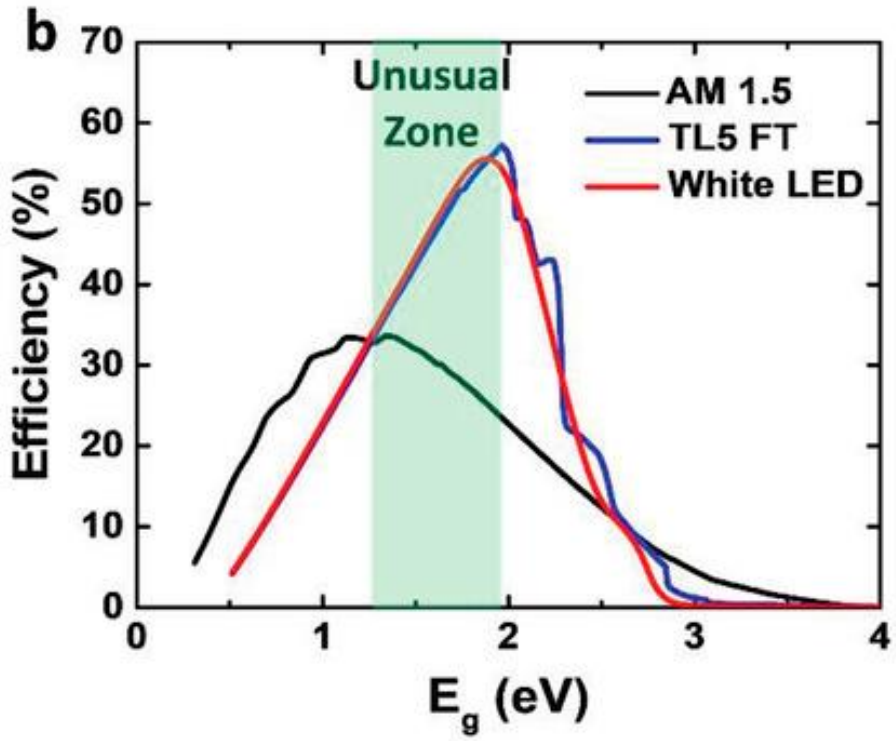




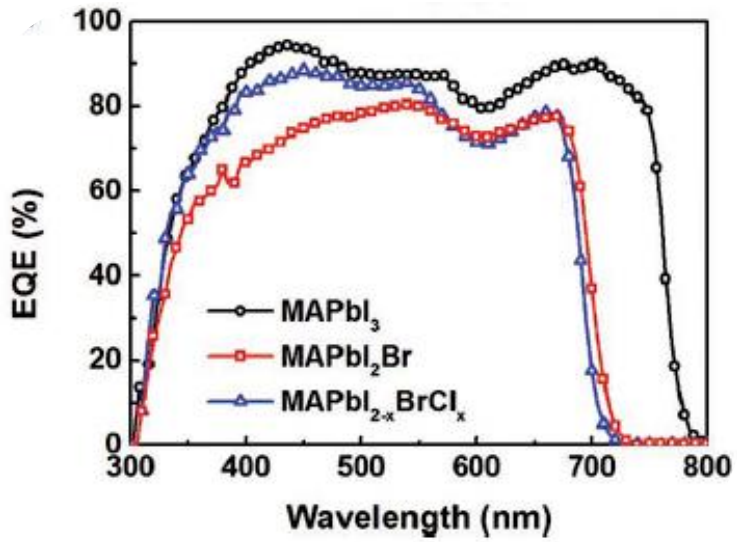
Different optimization of indoor PV compared to outdoor cells!

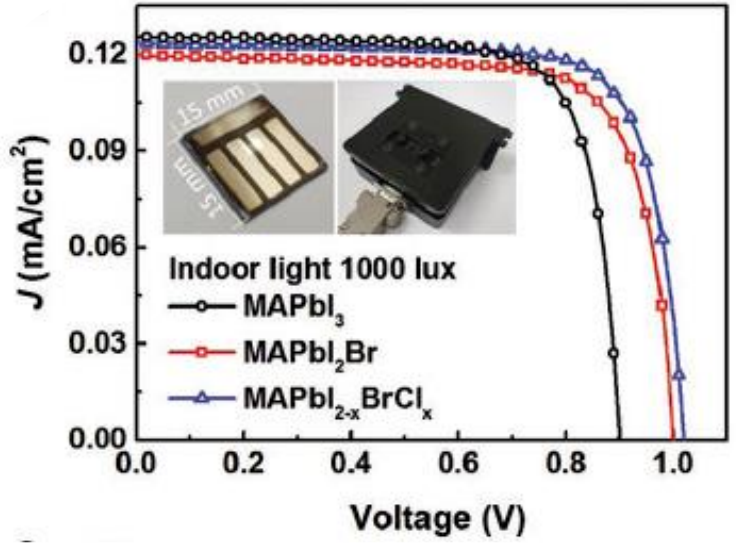
Strategies for highly efficient indoor PV

❖ *Bandgap engineering*



- Eg opt. @AM1.5G = **1.1 eV**
- Eg opt. @Indoor = **1.9 eV**





Compositional tuning of perovskite:

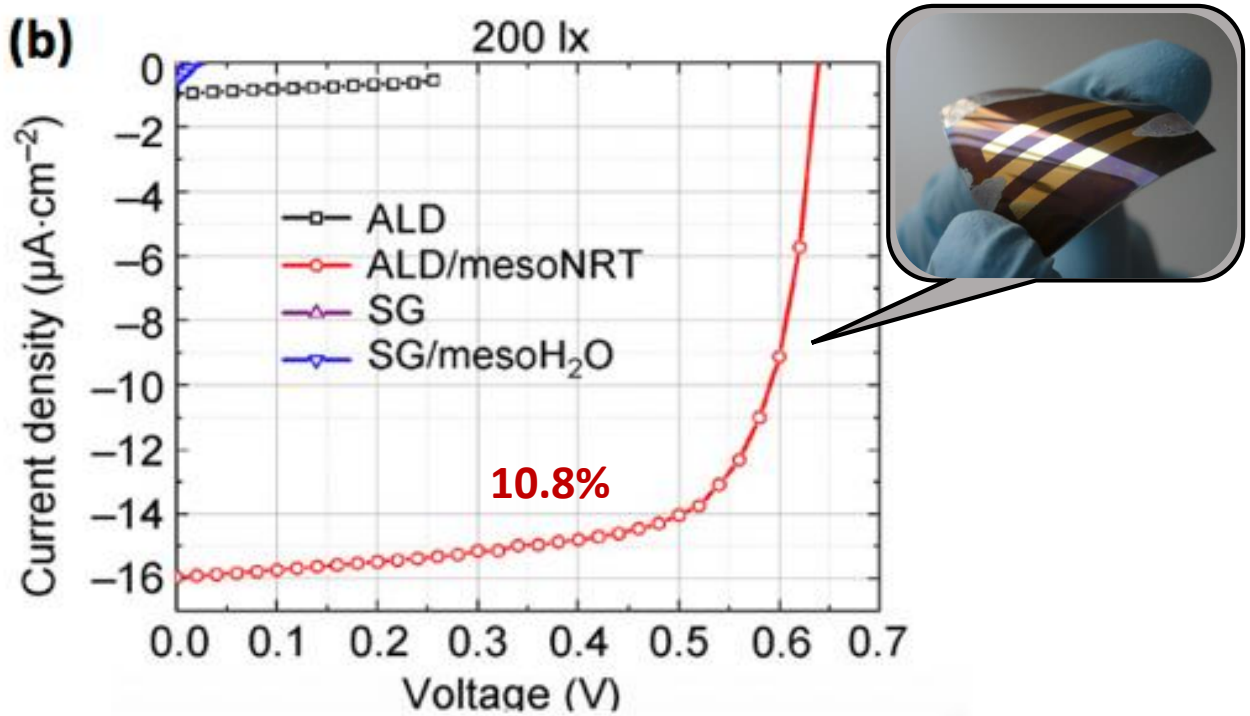
- Eg increase 1.6 eV -> 1.8 eV
- PCE increase **30% -> 36%**

Wu M. et al. (2019) Adv. En. Mat. 9, 37, 1901863
Cheng R. et al. (2019) Adv. En. Mat. 99, 38, 1901980

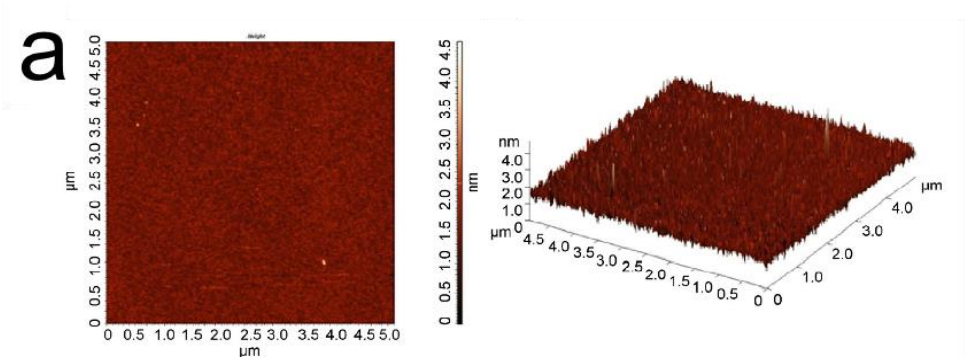
Strategies for highly efficient indoor PV

❖ *Suppression of charge recombination*

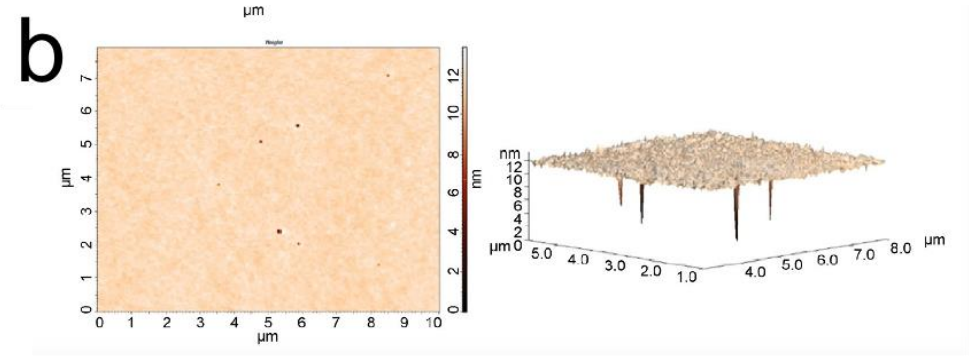
- Minimization of dark currents by insertion of compact, **defect-free transport layers**



TiO_2 electron transporting layer (ETL)



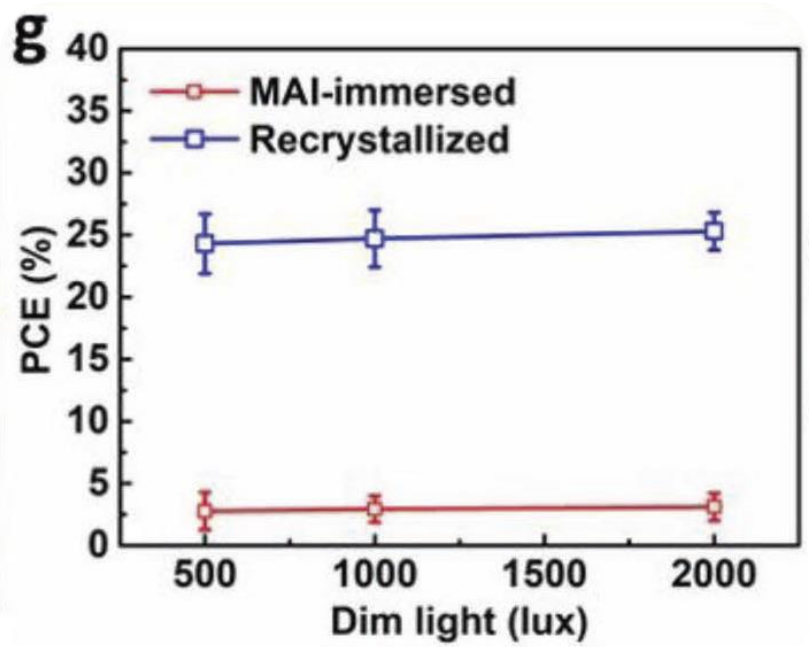
Vapour-deposited (ALD) film: **PCE > 10%**

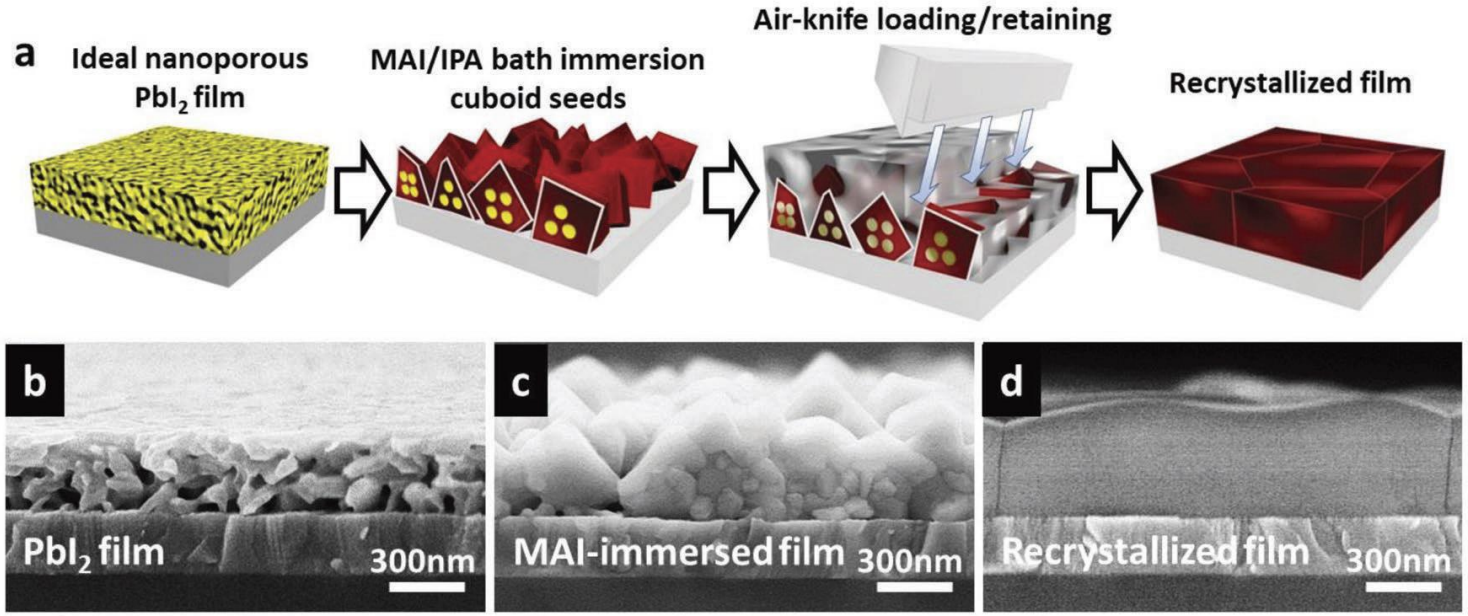


Solution-processed (SG) film: PCE < 1%

Strategies for highly efficient indoor PV

❖ *Suppression of charge recombination*



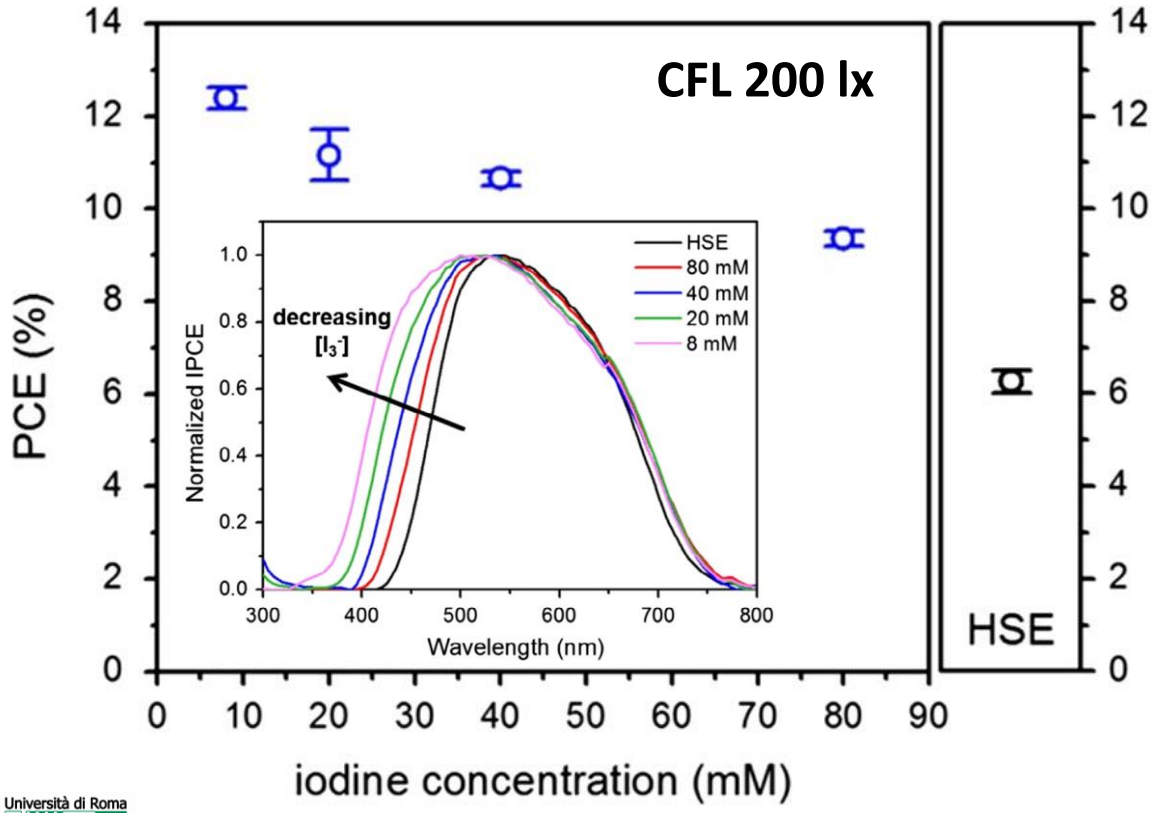


- Minimization of trap-mediated recombination by **morphological control** of the active layer

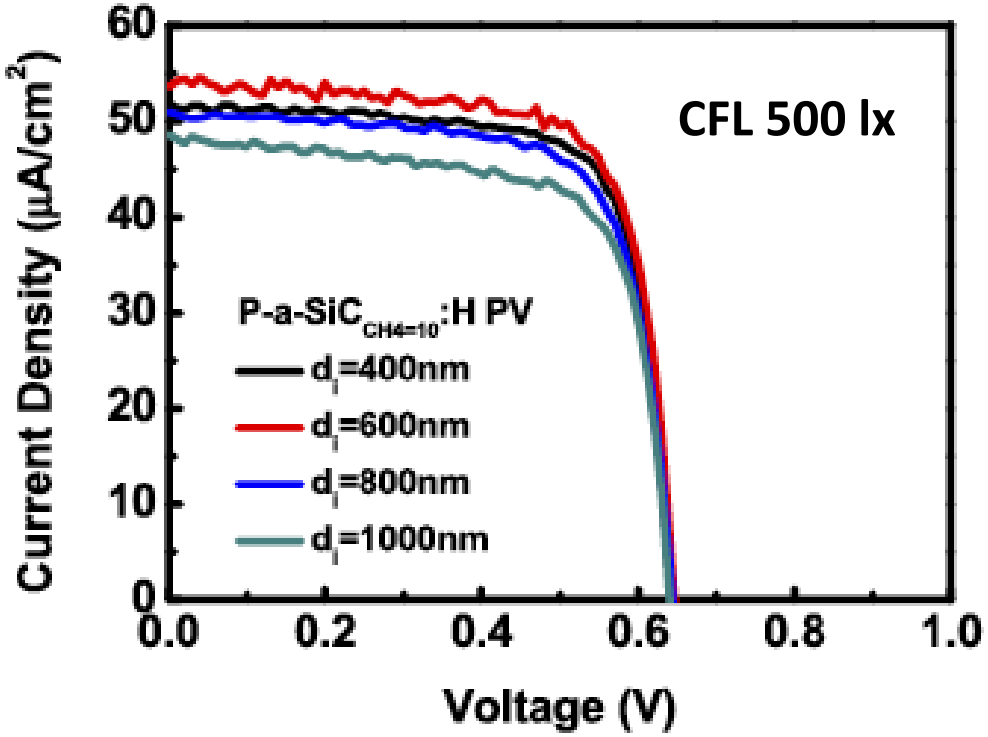
Strategies for highly efficient indoor PV

❖ *Light absorption and charge transport*

- Dilution of electrolyte increases **transparency** (light absorption) of DSSC



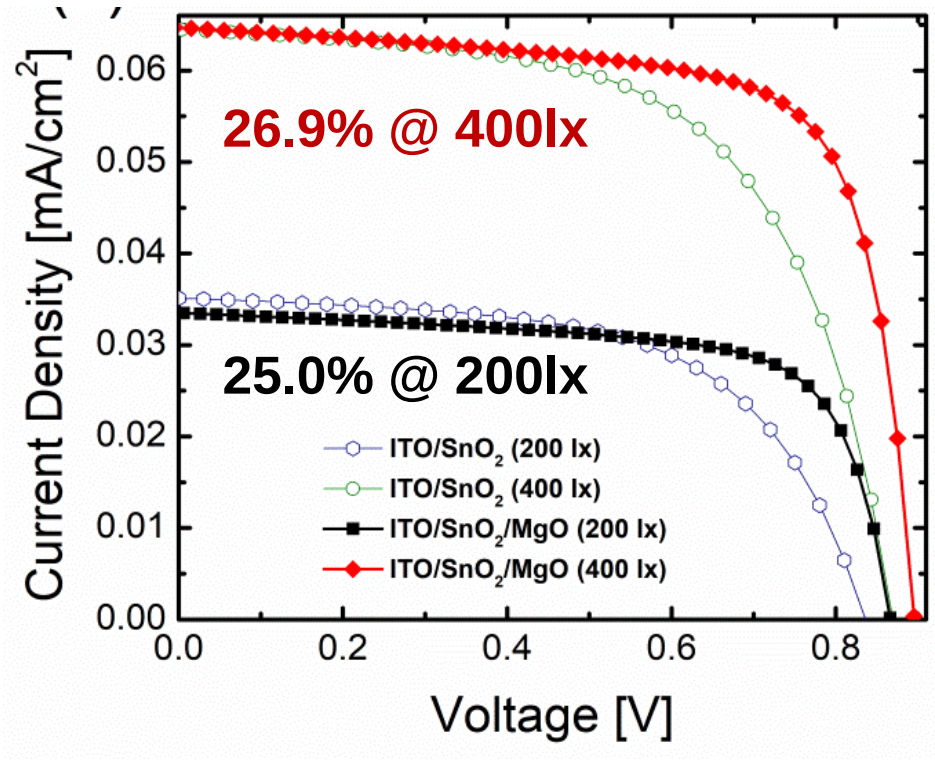
- Increase in **active layer thickness** improves photogeneration in amorphous Si

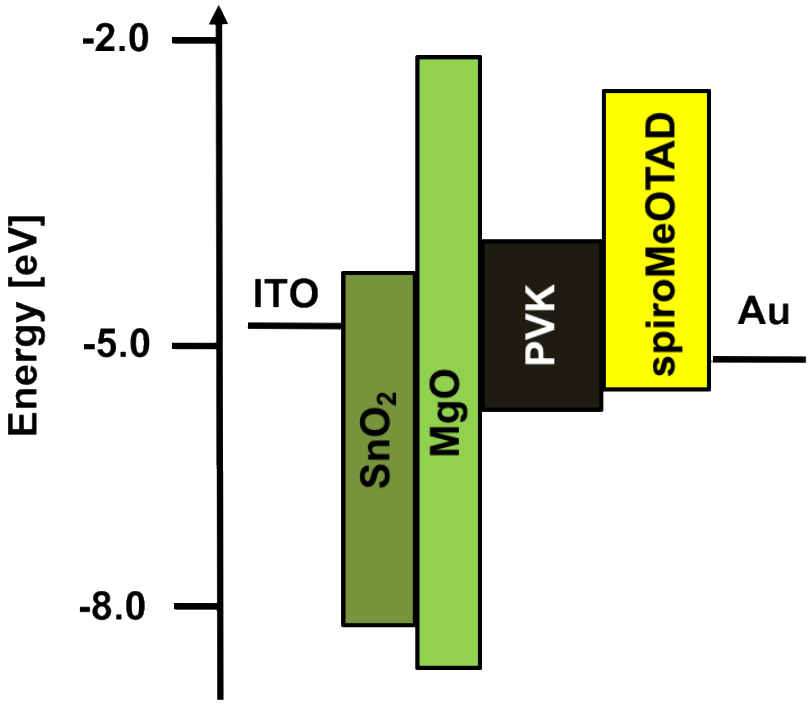


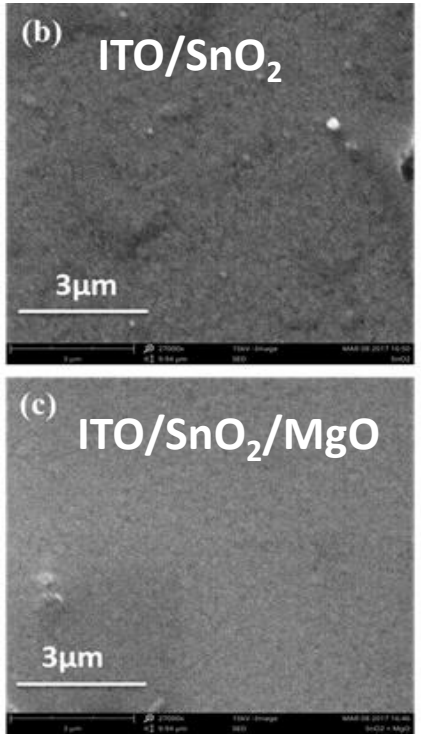
F. De Rossi et al. (2015) Applied Energy 156, 413–422
M. Kao et al. (2017) Sci. Rep. 7, 12706

Indoor perovskite solar cells

Composite SnO_2/MgO ETL for rigid PSCs



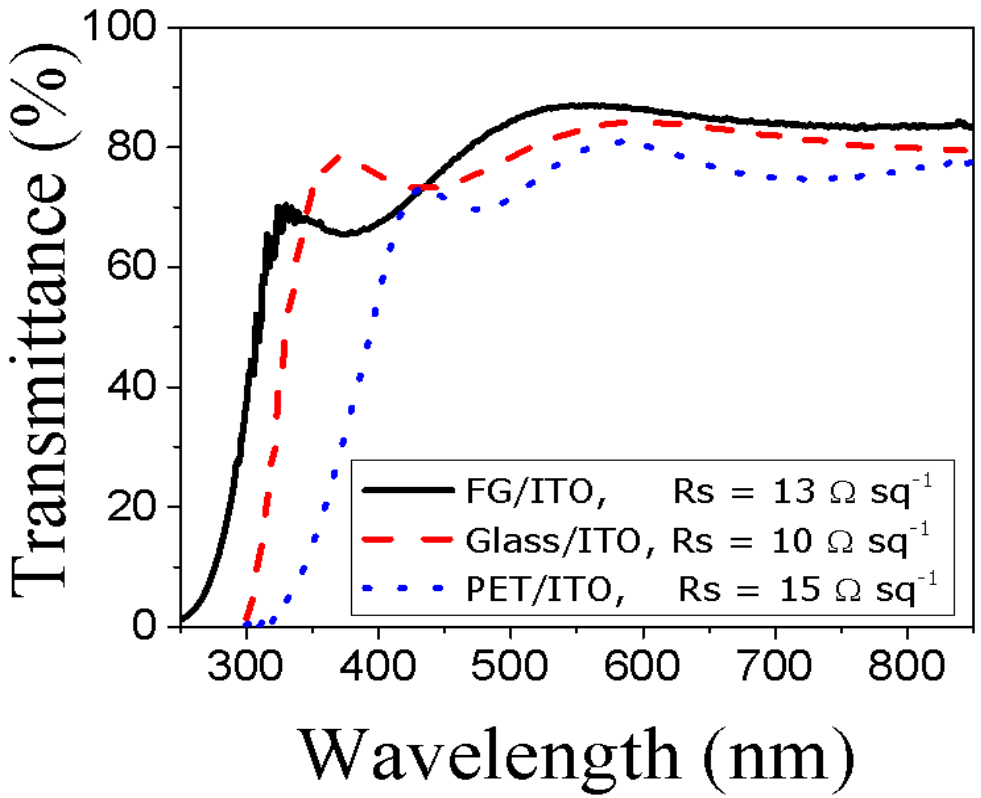


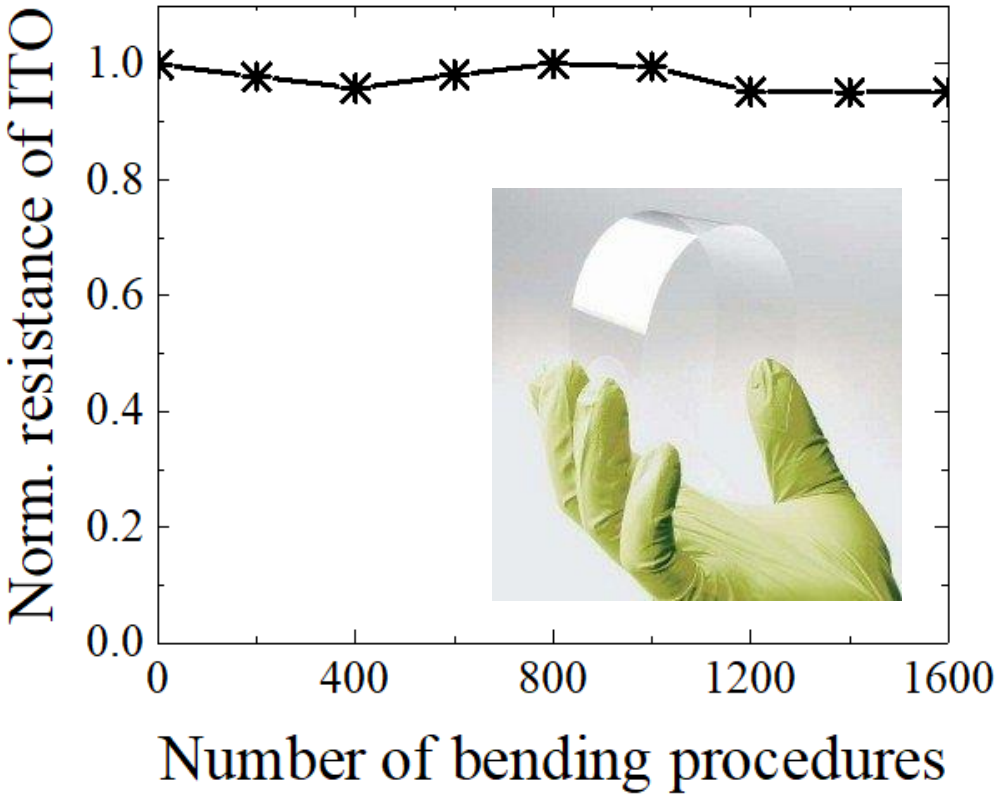


- MgO interlayer **blocks recombination** (insulating thin layer)
- **Reduces ETL roughness** and defects at interface

Indoor perovskite solar cells

Flexible PSCs on R2R-coated ultrathin glass



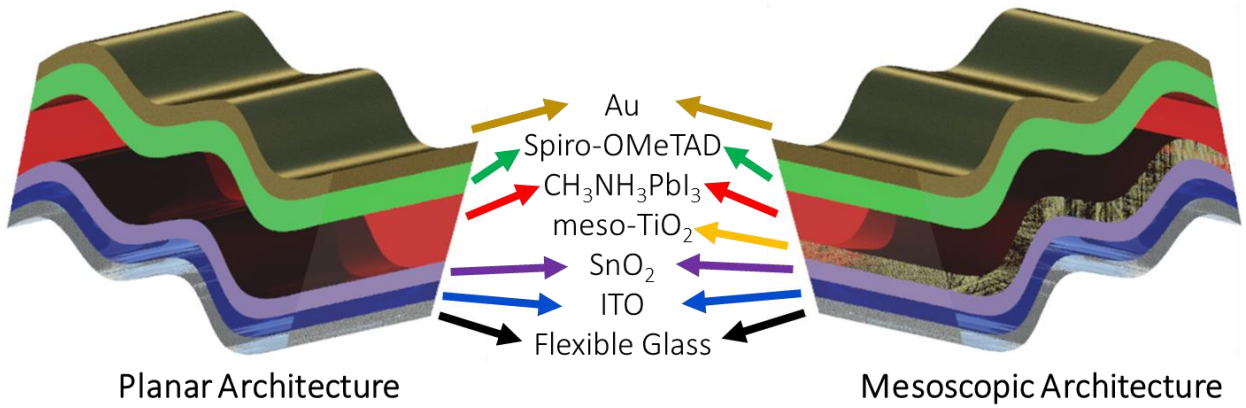


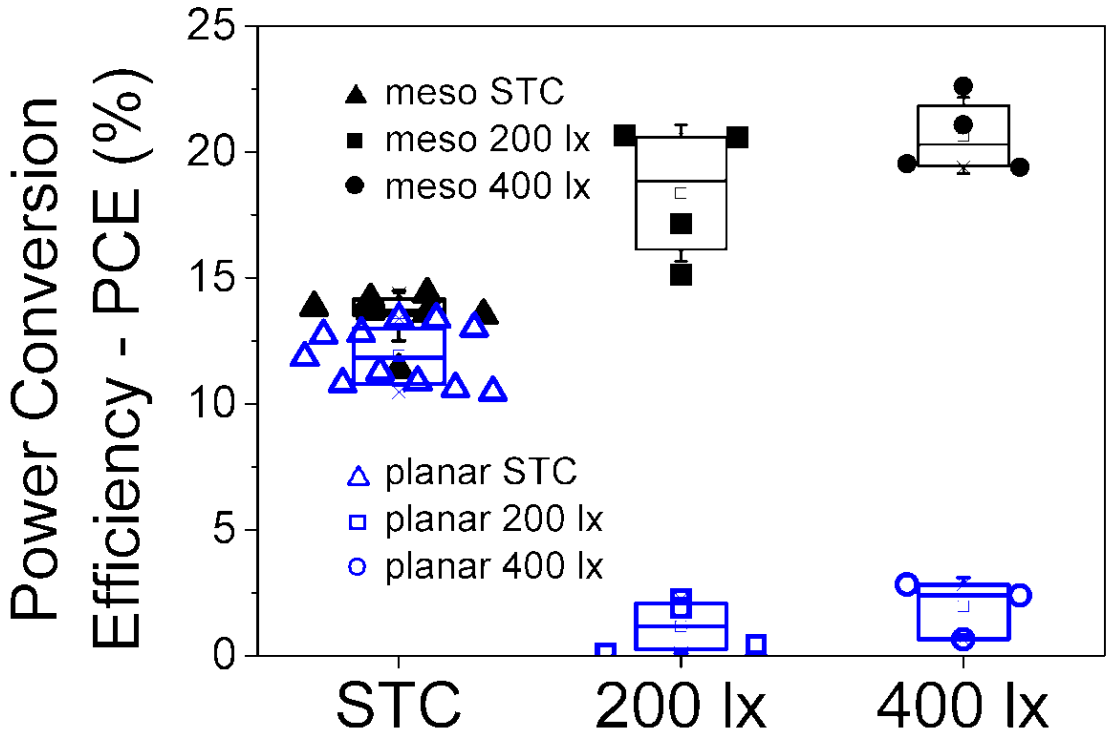
- Optimal optical, electrical, surface properties and bendability of **flexible glass**

Indoor perovskite solar cells

Fraunhofer FEP

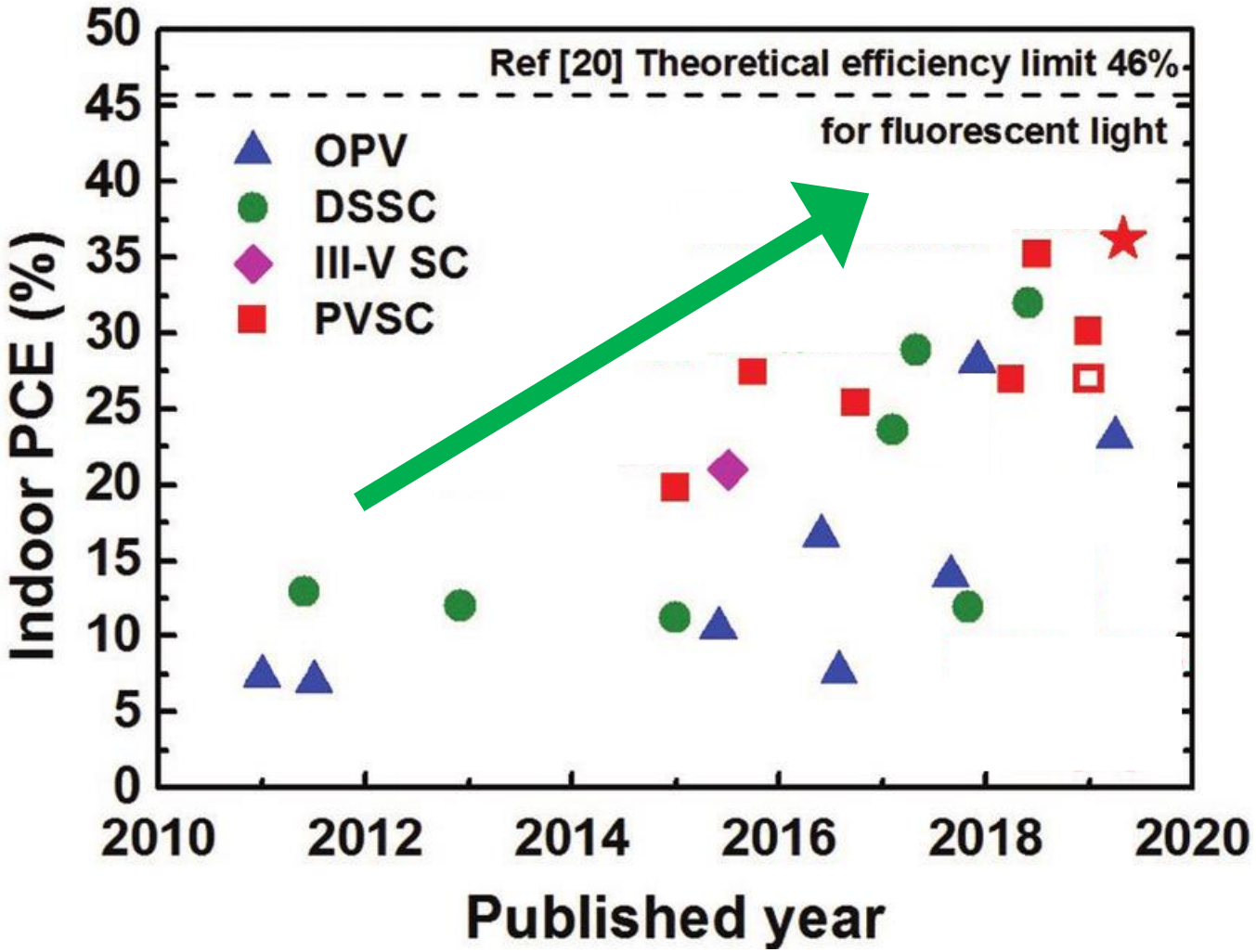
Flexible PSCs on R2R-coated ultrathin glass



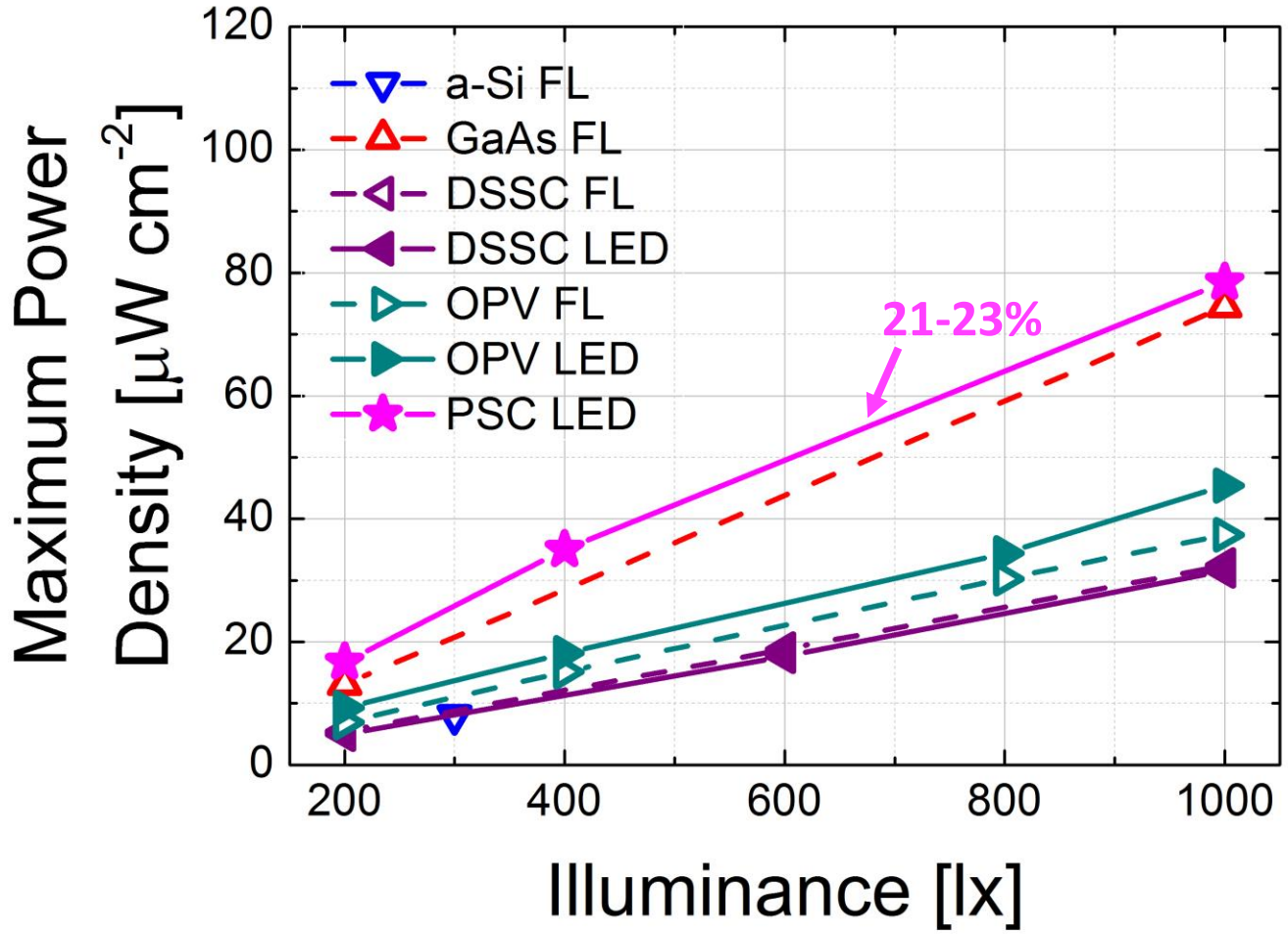


- Enhancement of electron lifetime and charge extraction with **mesoporous scaffold**
- Suppression of **leakage currents**

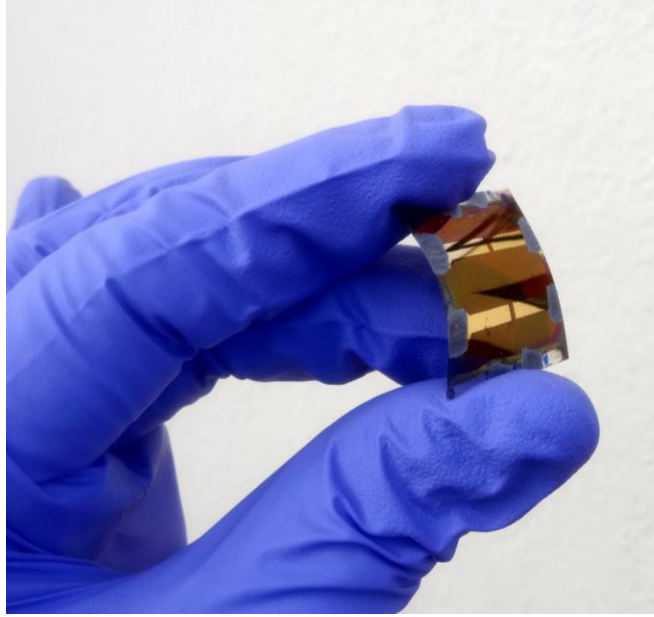
Progress of indoor PV



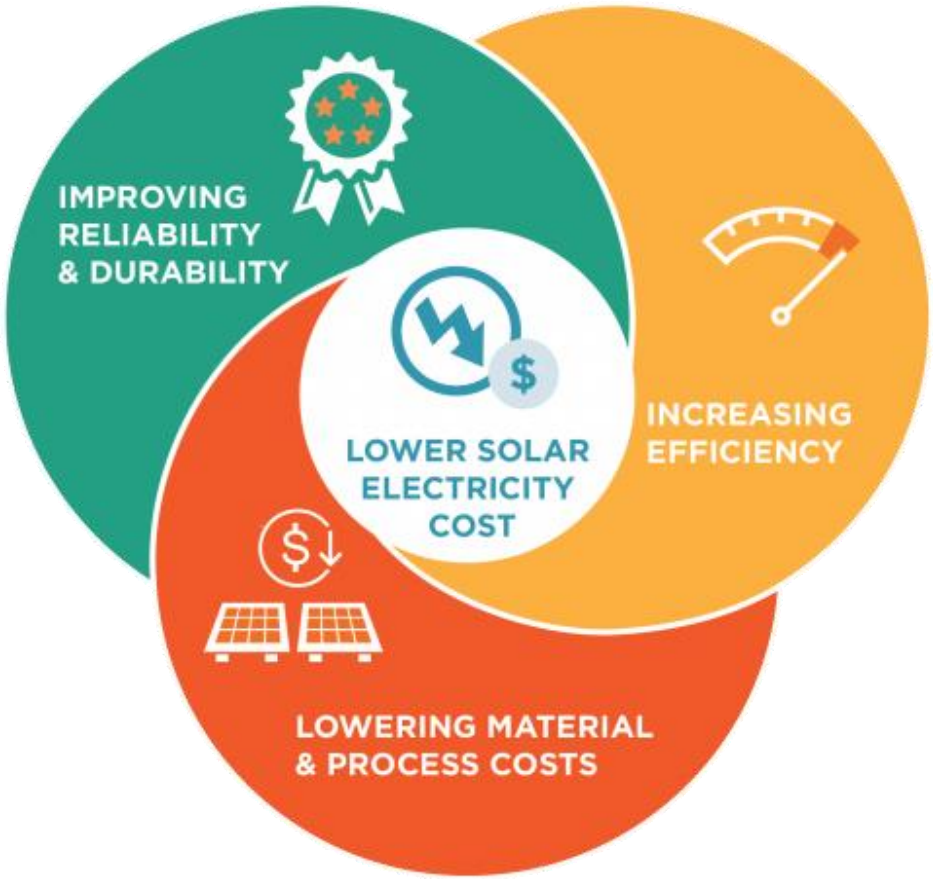
Progress of indoor PV - flexible

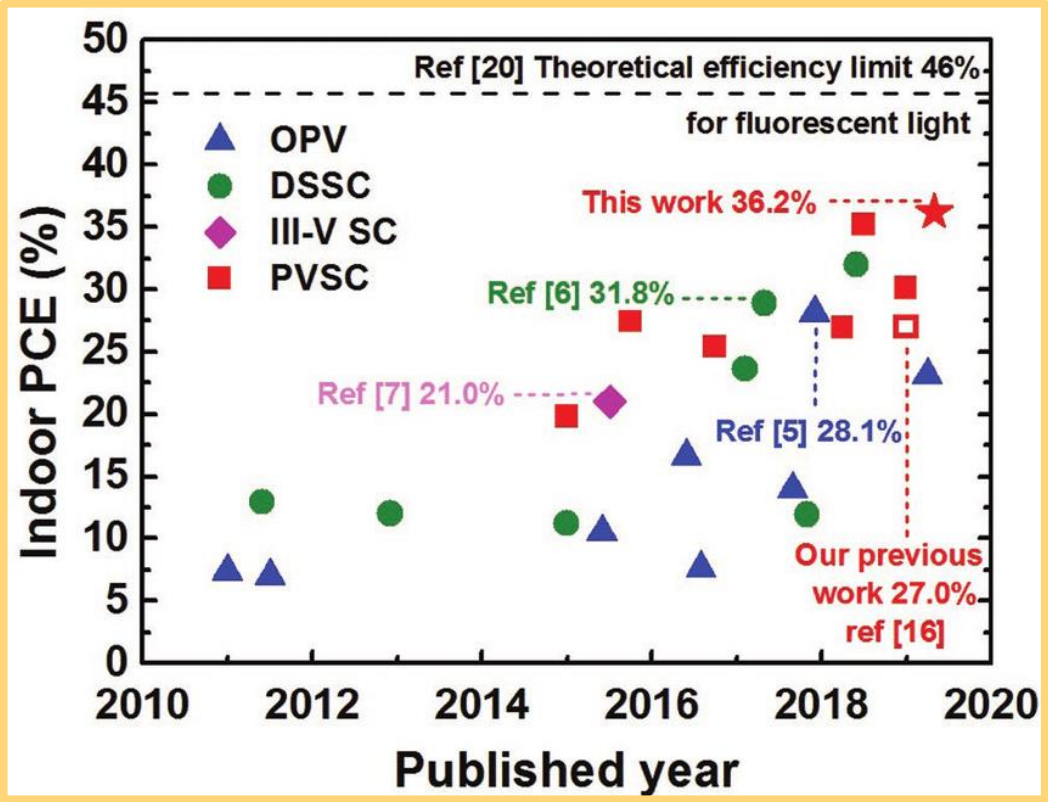


Perovskite solar cells on R2R-coated flexible glass



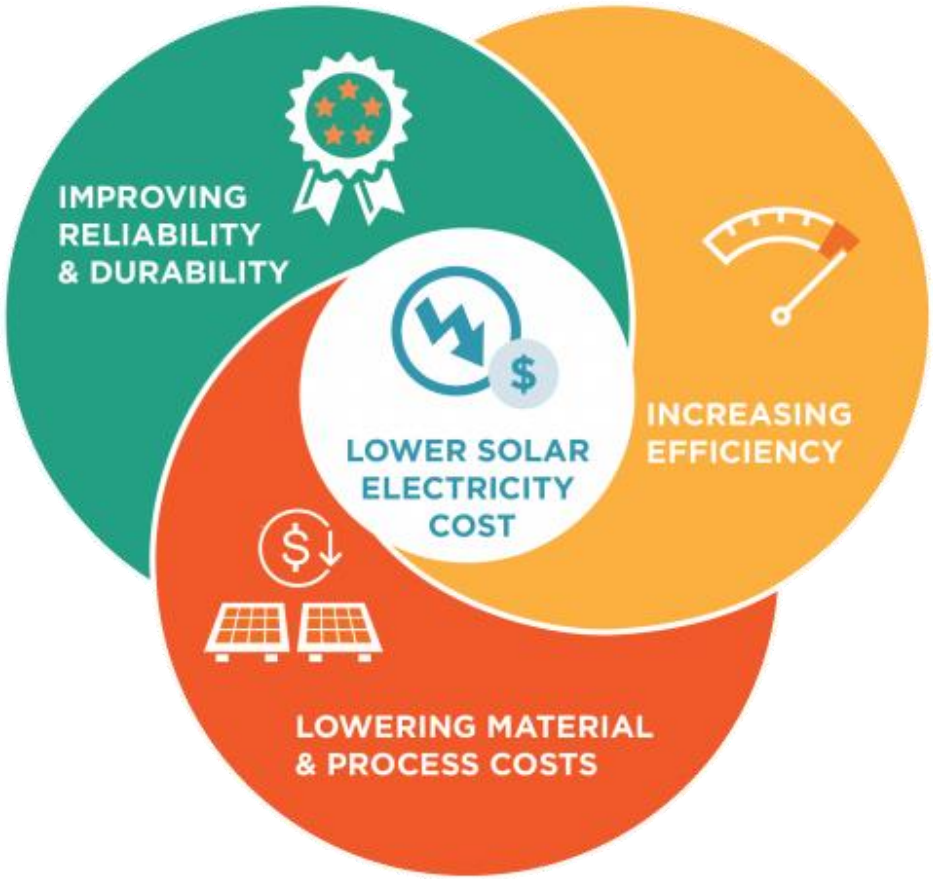
Challenges & perspectives

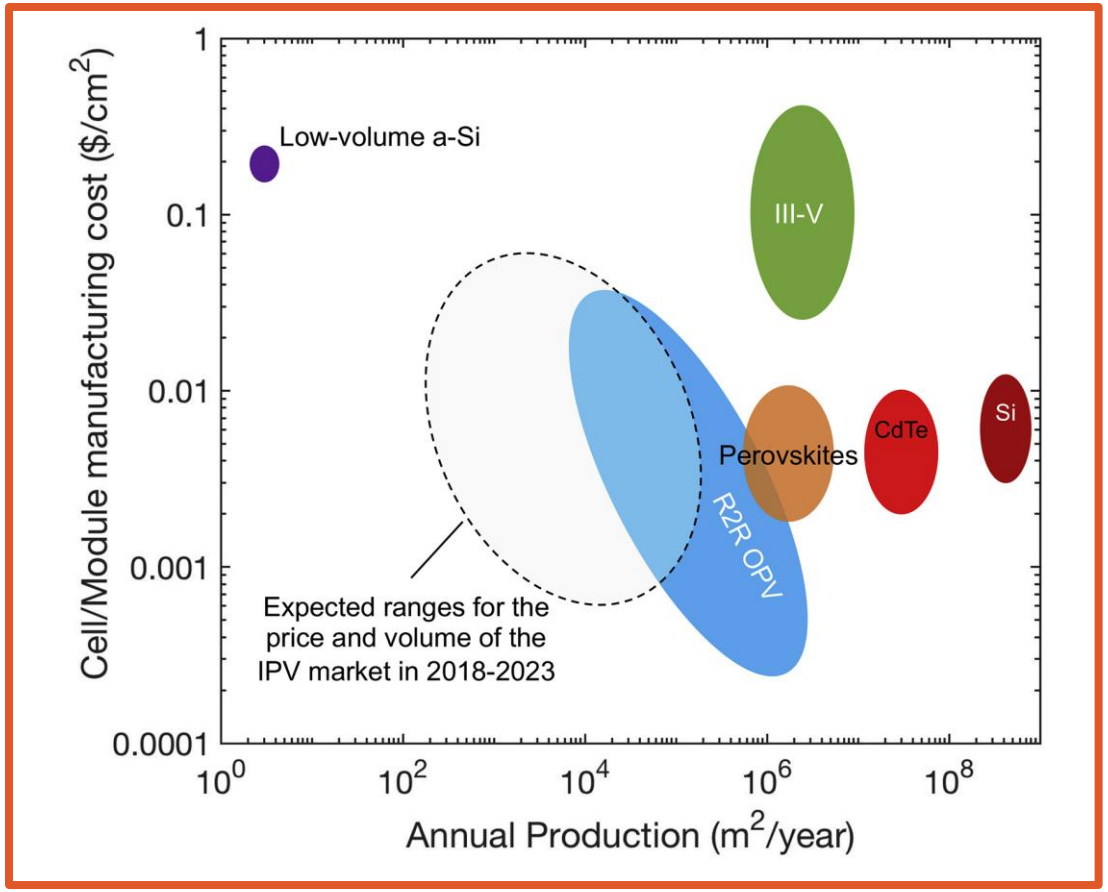




- Big margin of efficiency improvement for indoor PV (theoretical max. **50-60%,** depending on type of lamp)

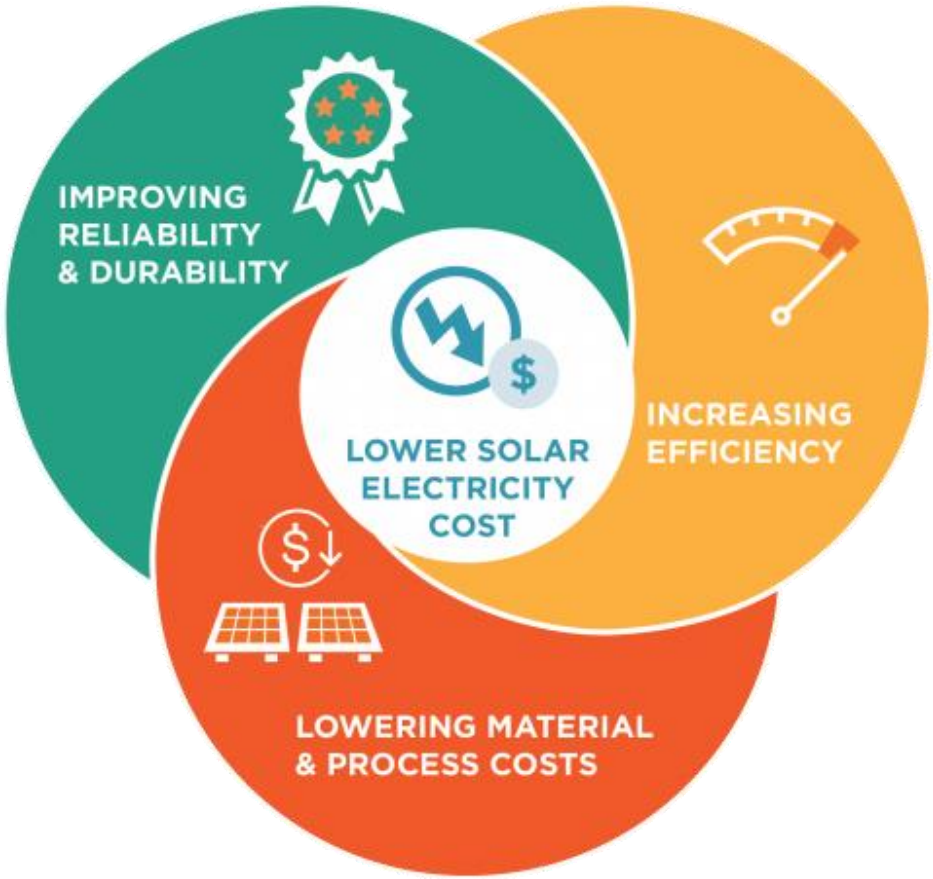
Challenges & perspectives

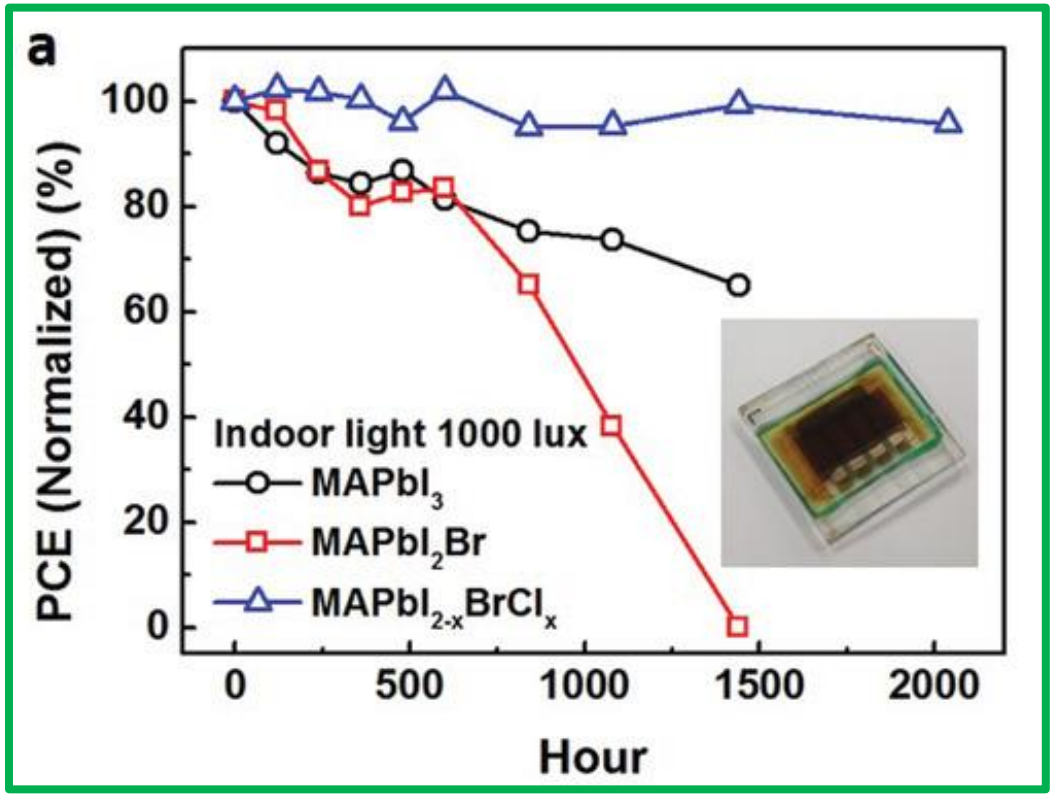




- Low-cost **printing techniques**
- Replacement of expensive and rare materials
- Predicted **increasing production volumes**

Challenges & perspectives



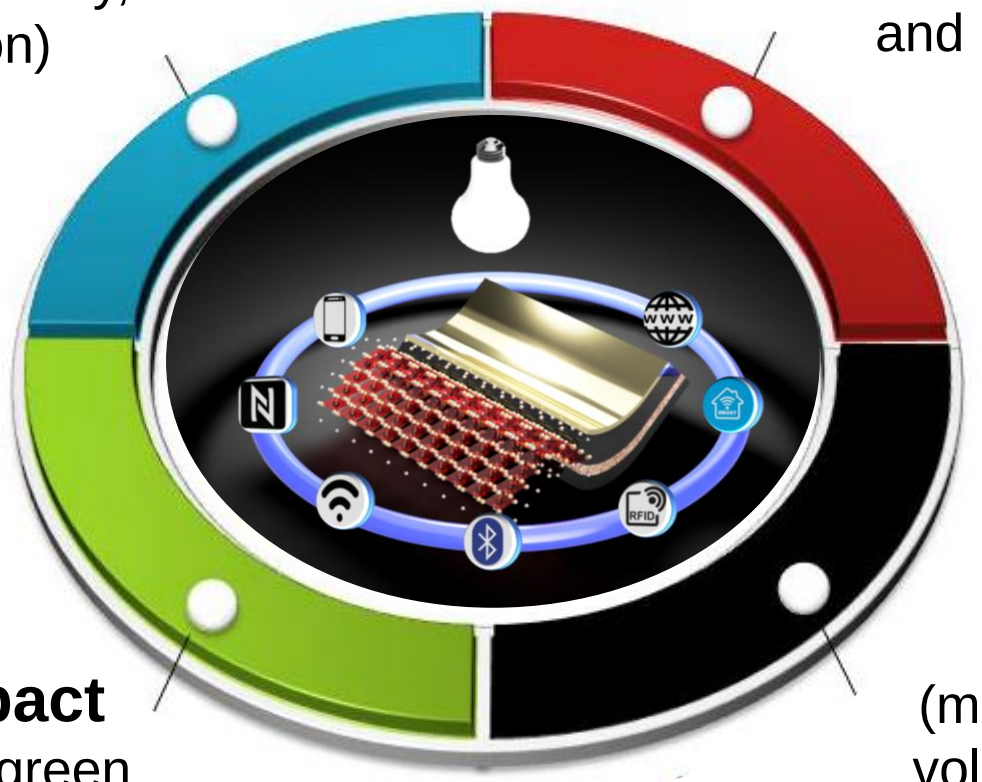


- **Milder operating conditions** indoor vs outdoor
- Efficient **encapsulation** methods
- Compositional engineering and material optimisation for stable indoor PV

Conclusions – how to choose the best indoor PV?

Functionality
(transparency, colour, flexibility, weight, easy integration)

Efficiency
(STC, indoor low lighting e.g. CFL and LED lamps, 200-1000 lx)



Stability and environmental impact
(toxic elements content, green solvents, lifetime in indoors)

Cost and commercialization
(market readiness, production volumes, cost of raw materials and processes)

Acknowledgments

Prof. Thomas M. Brown
Dr. Sergio Castro-Hermosa
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Prof. Franco Cacialli
Dr. Andrea Zampetti

Prof. Maria Adriana Creatore
Dr. Valerio Zardetto

Dr. John Fahlteich
Dr. Matthias Fahland
Michiel Top

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Thanks for your attention!