AMOLF physics of functional complex matter

university of groningen

Large-Area Solar Power Enabled by Perovskites

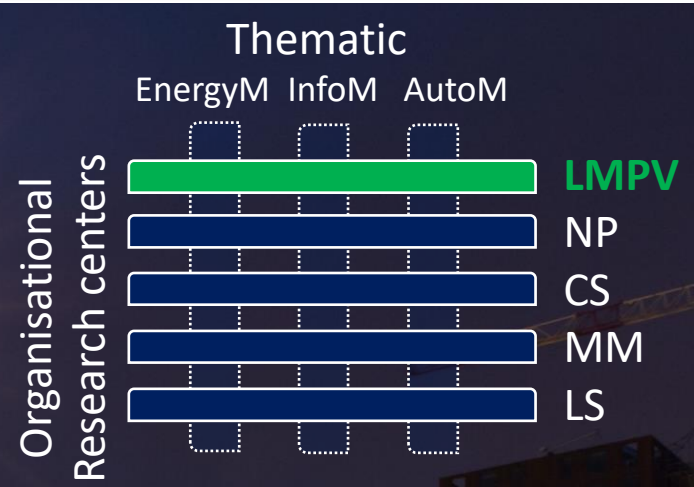
Bruno Ehrler

Where we are

NWO-Institute for physics of functional complex matter

LMPV one of five Research centers





Picture credit: Mark Knight

Acknowledgements

Dr. Lucie McGovern
Dr. Loreta Muscarella
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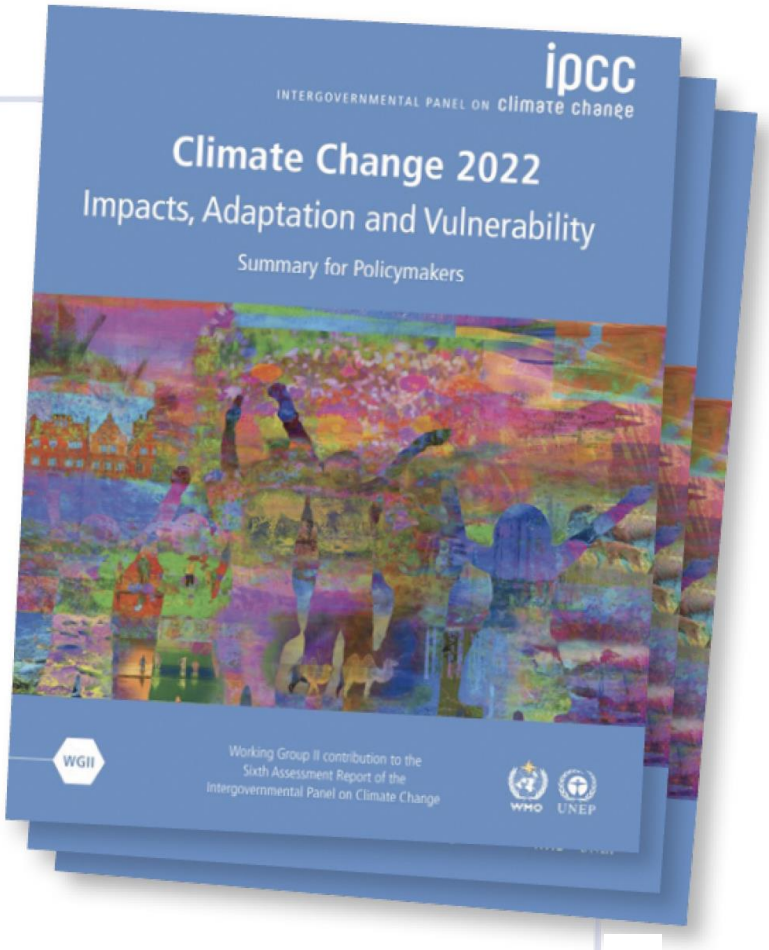



RWE
288
KRUPP
SIEMENS



Climate change: we must act now!

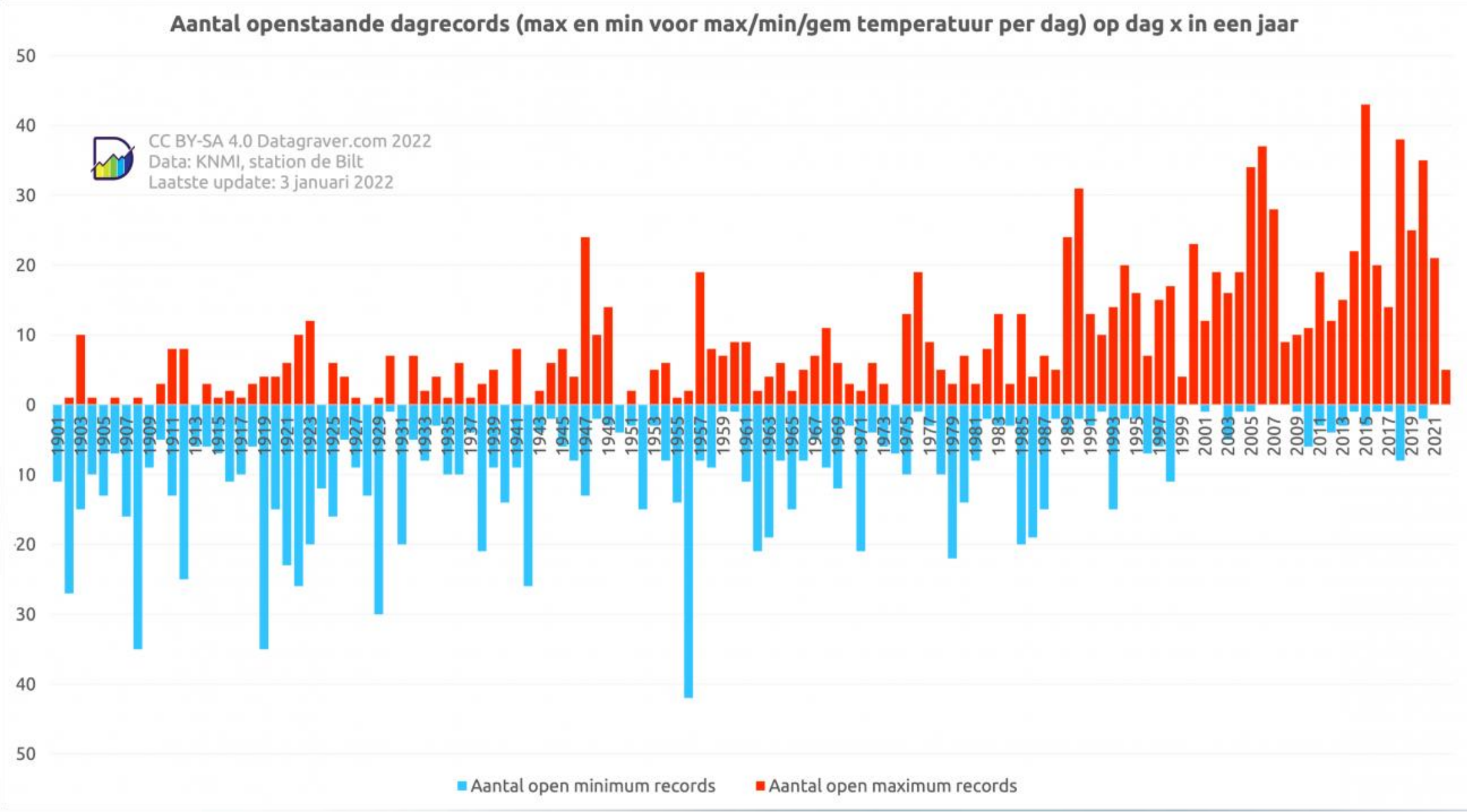
"**The scientific evidence is unequivocal:** climate change is a threat to human wellbeing and the health of the planet. Any further delay in cencerted global action will miss the brief, rapidly closing window to secure a live-able future. This report offers solutions to the world."

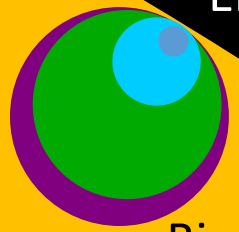


Rapport Climate change 2022, IPCC (2022)

- Sea level rise
- Severe weather events
- Threats to crop yield, freshwater supplies, wildlife, biodiversity
- Human health, poverty, displacement

Climate change happening now





Electricity use

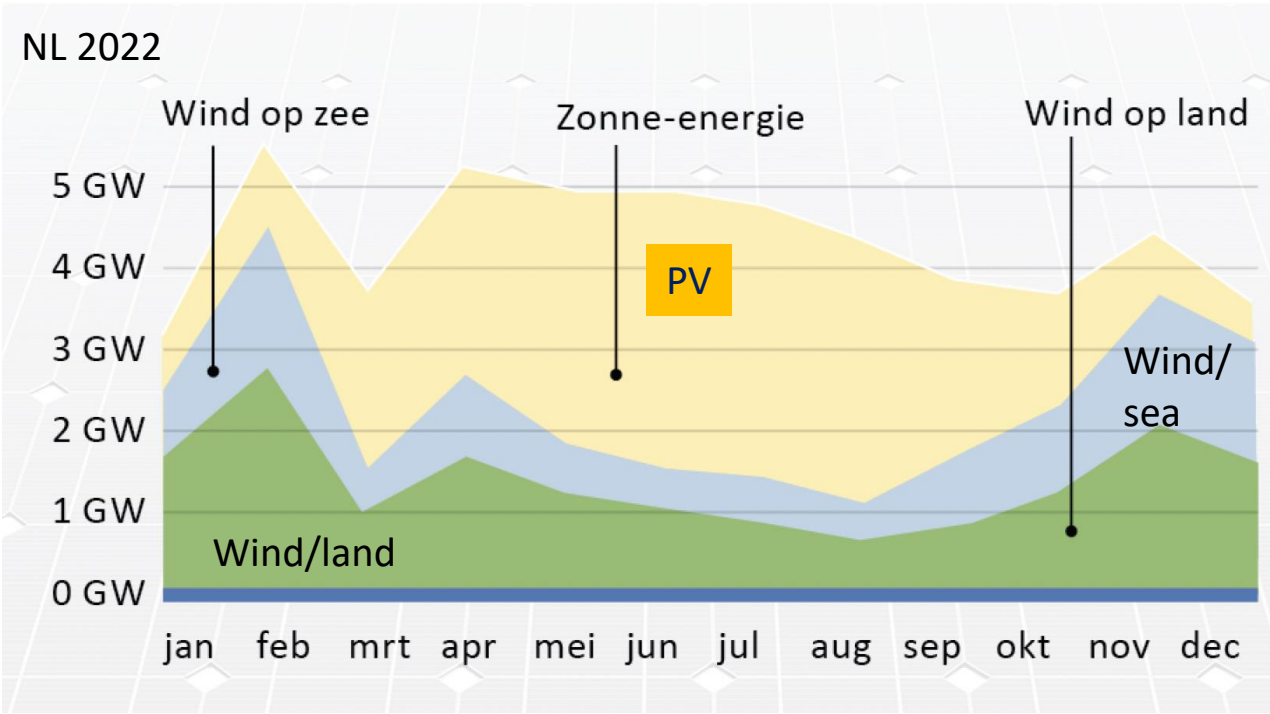
Total energy use

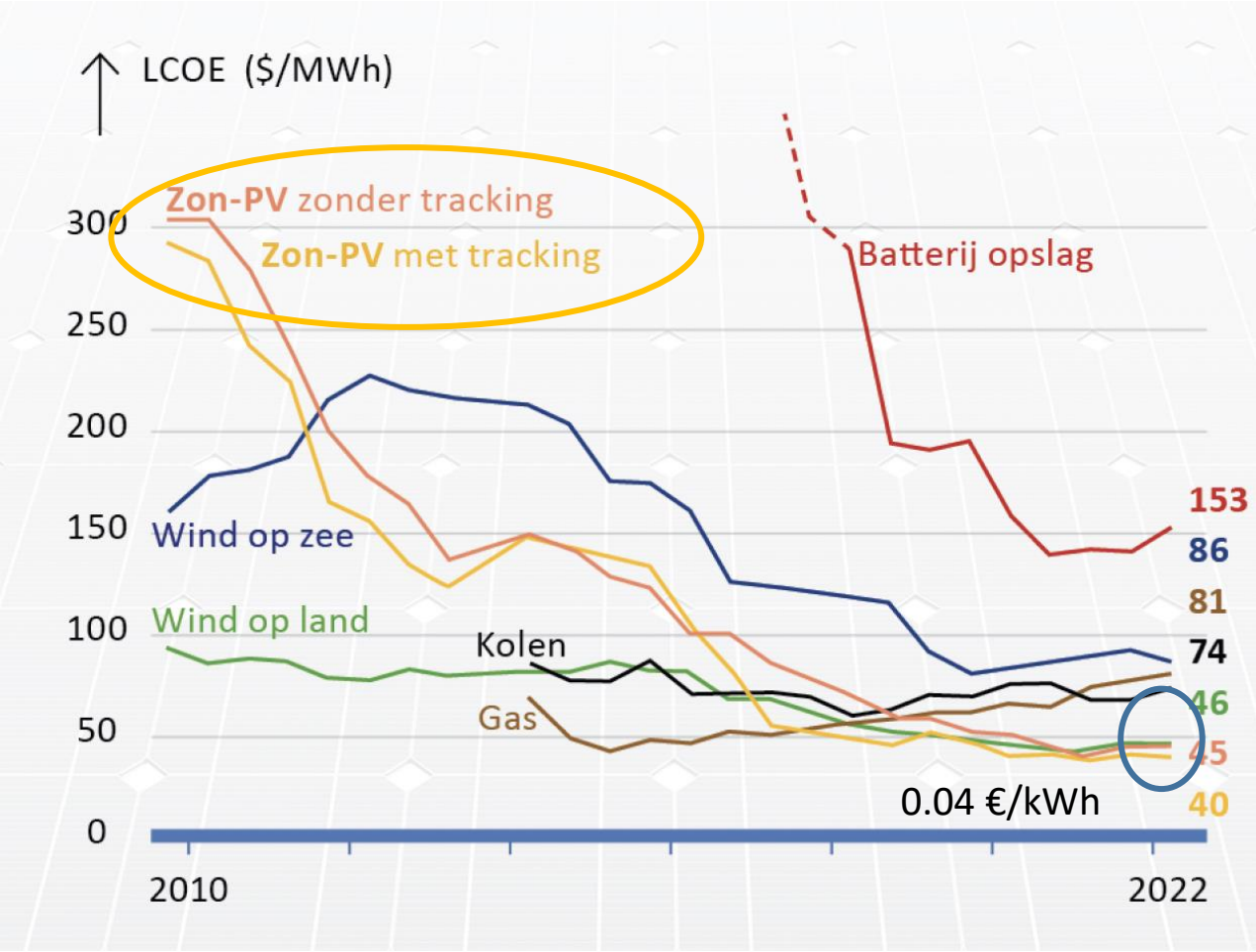
Wind energy

Sun

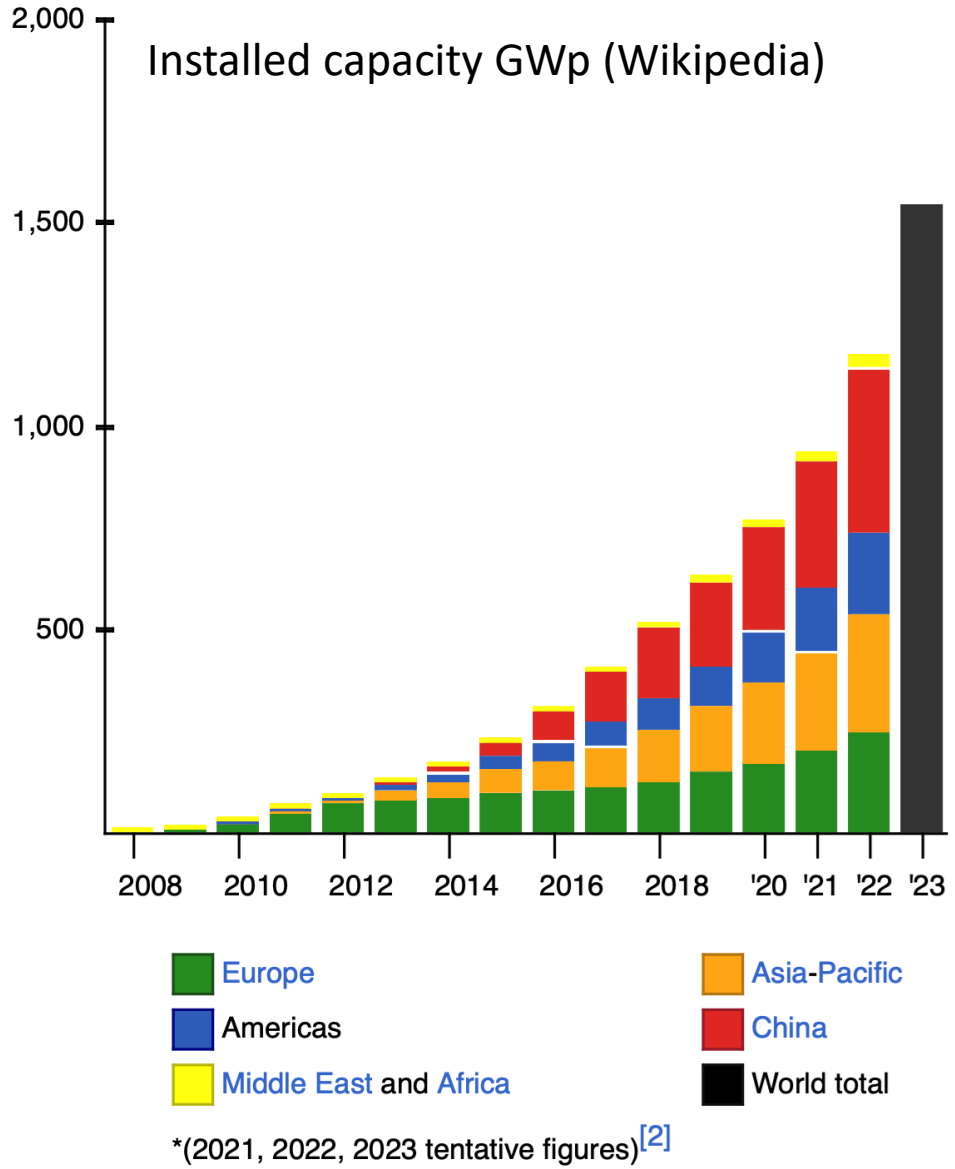
Biomass

Solar photovoltaics will play a major role





Solar photovoltaics will play a major role



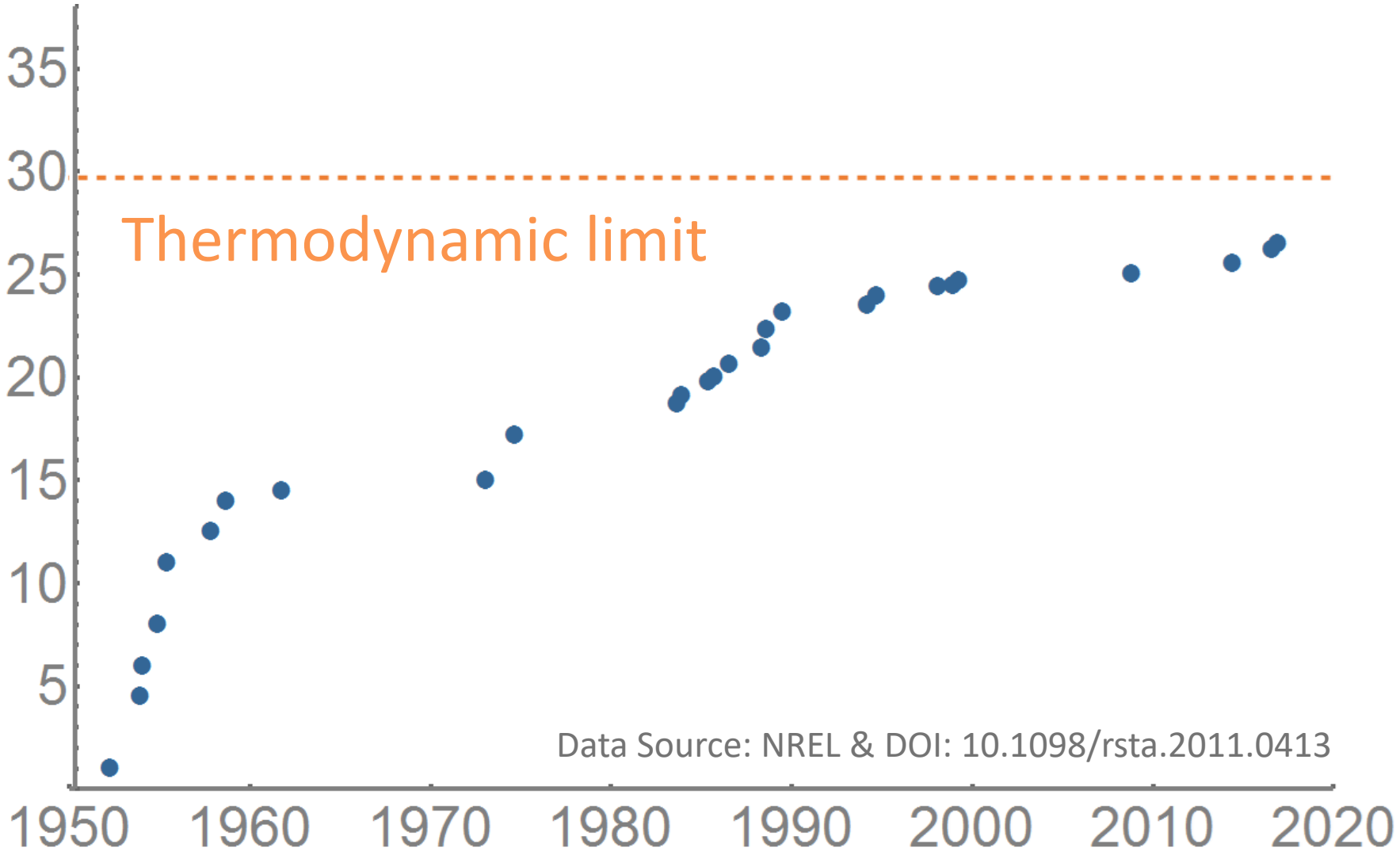
Need to go to 60,000 GWp

- How long is the price going to drop?
- Assume module price = 0; still other costs
- Efficiency will matter more and more
- No replacement for Si in the next 10-15 years, but maybe additions

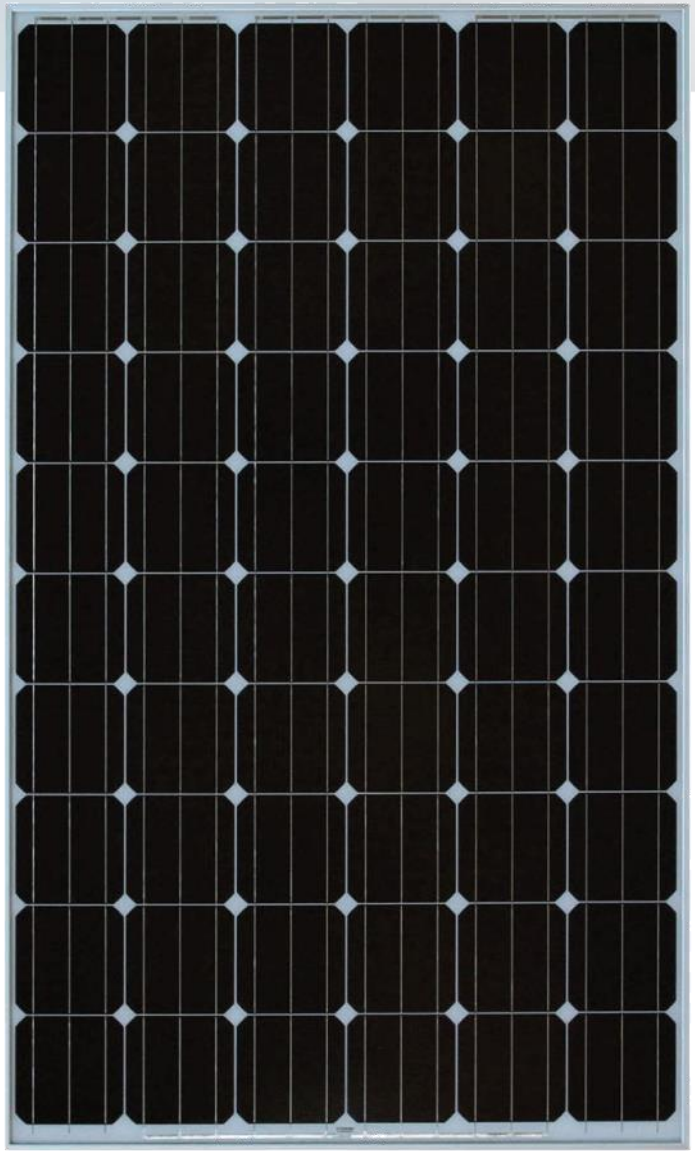
Part 1: Why improve silicon solar cells?
Part 2: What is a perovskite
and what is it good for?
Part 3: SolarNL

Part 1
Why improve silicon solar cells?

Si Solar Cell Efficiency Close to Limit

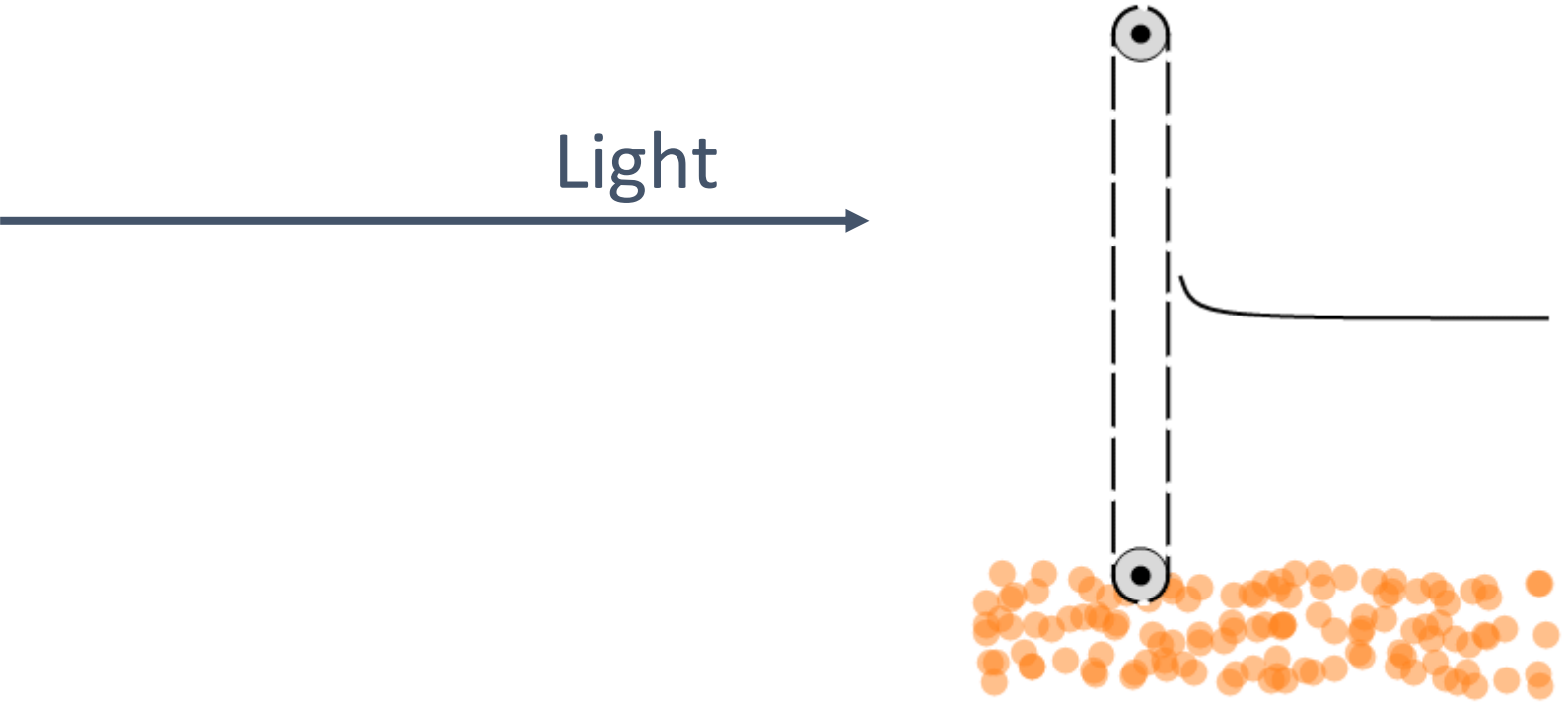


Light



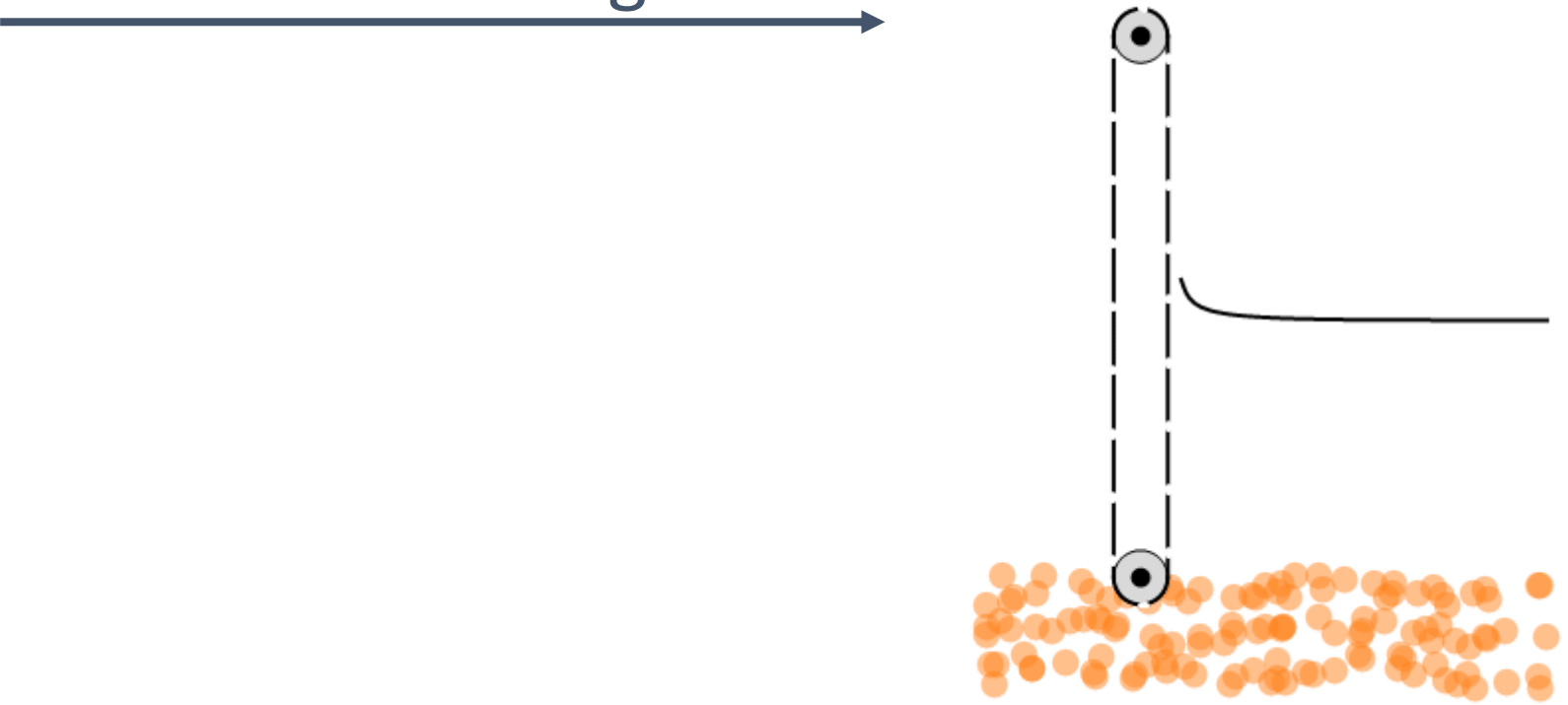
Electrons

Light

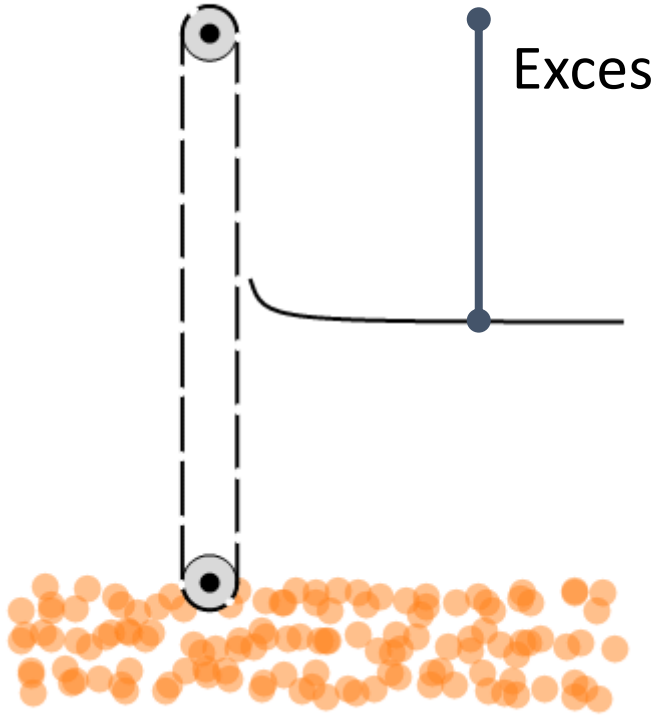




Light

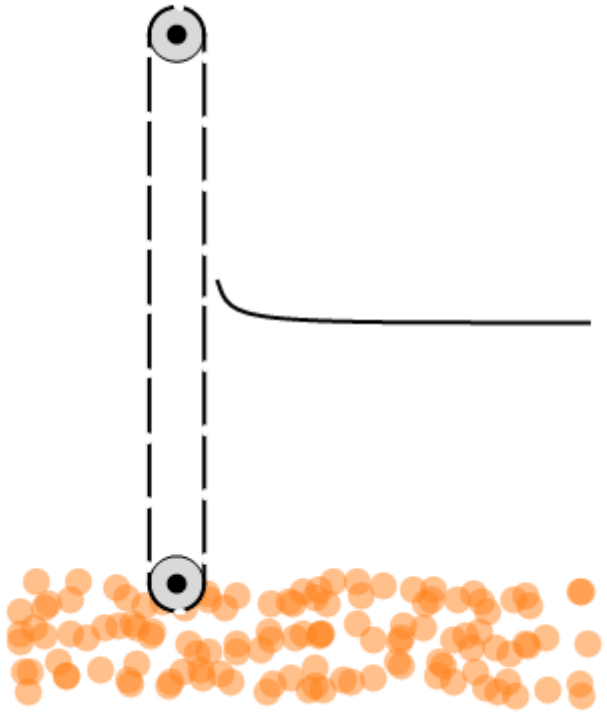


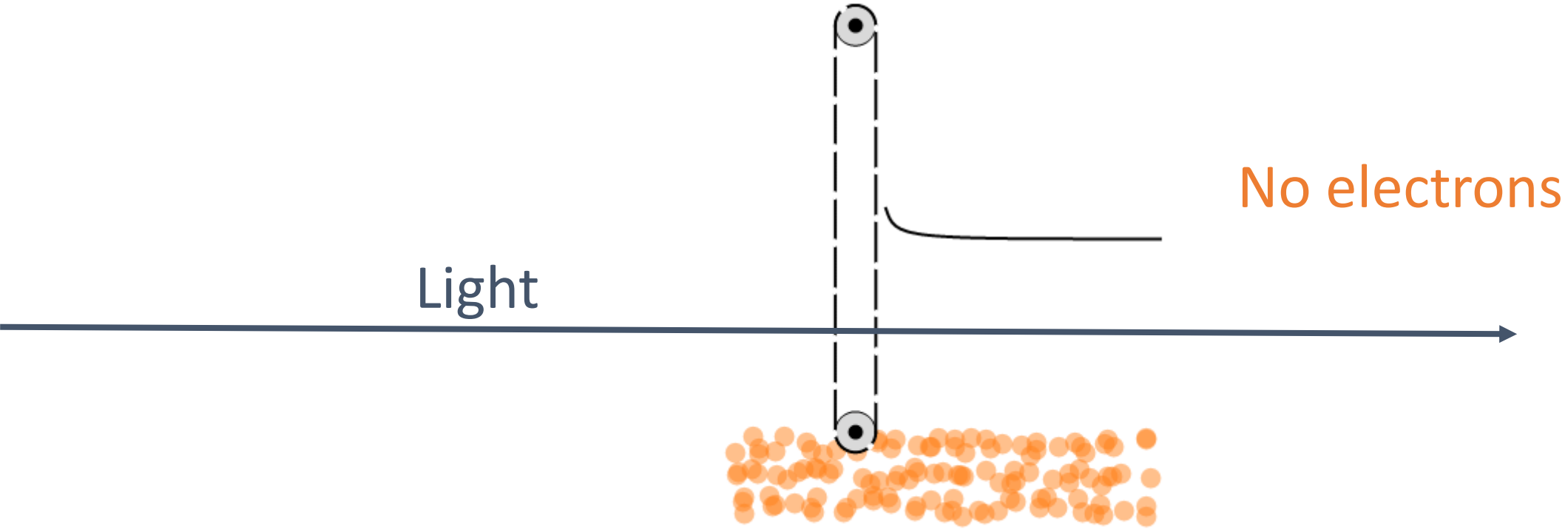
Light



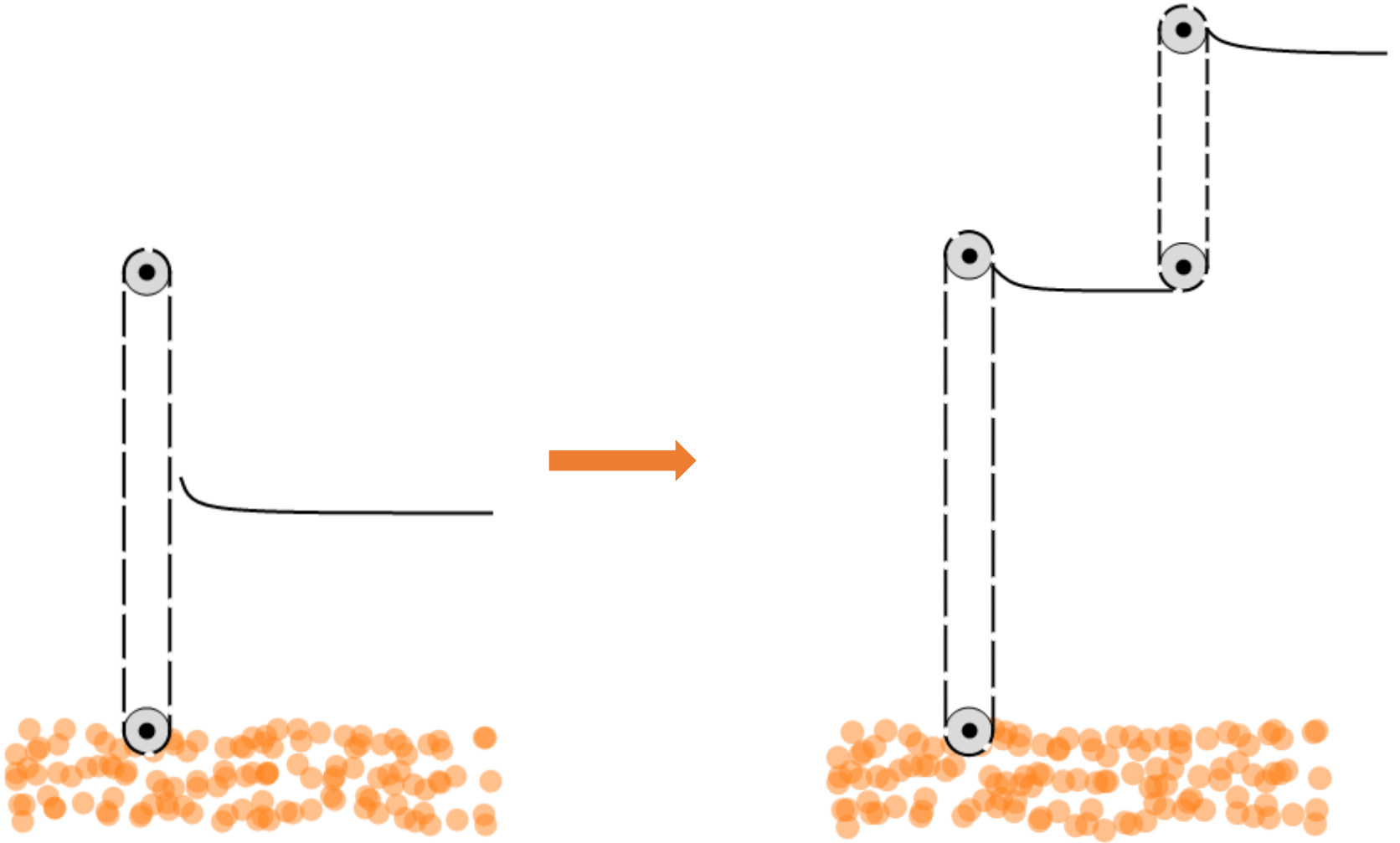
Electrons

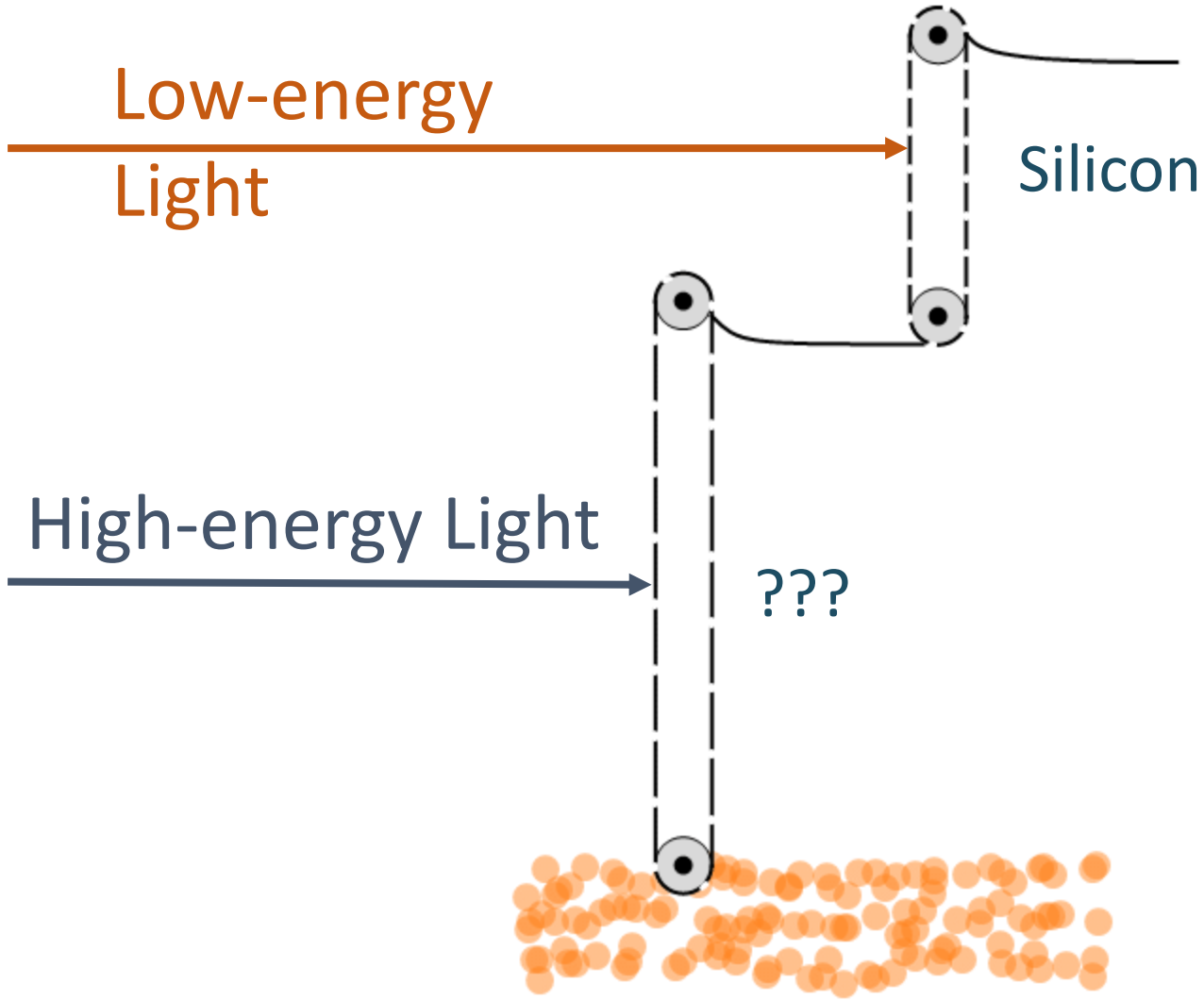
Light



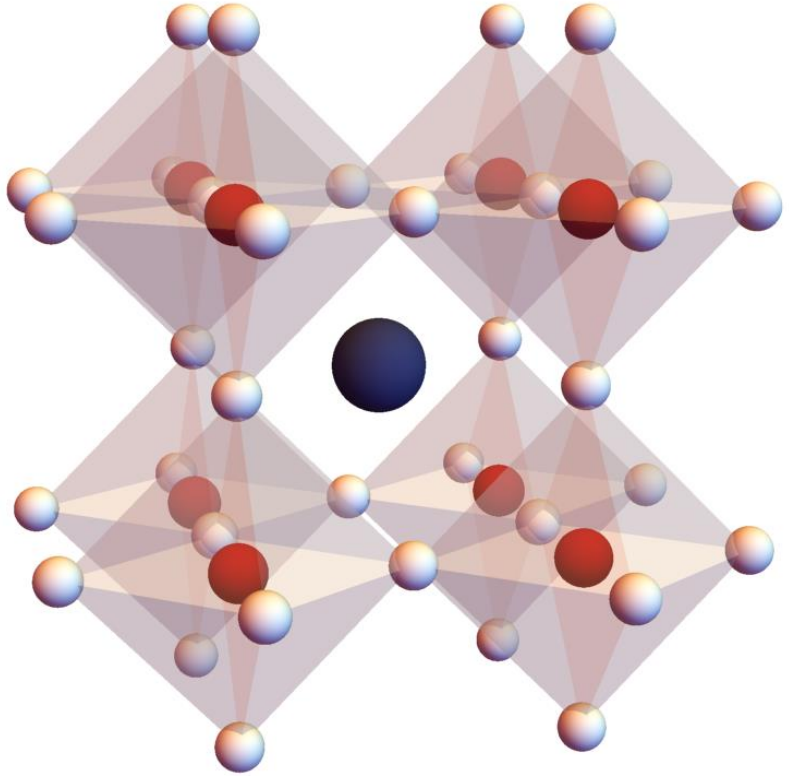

No electrons
Light



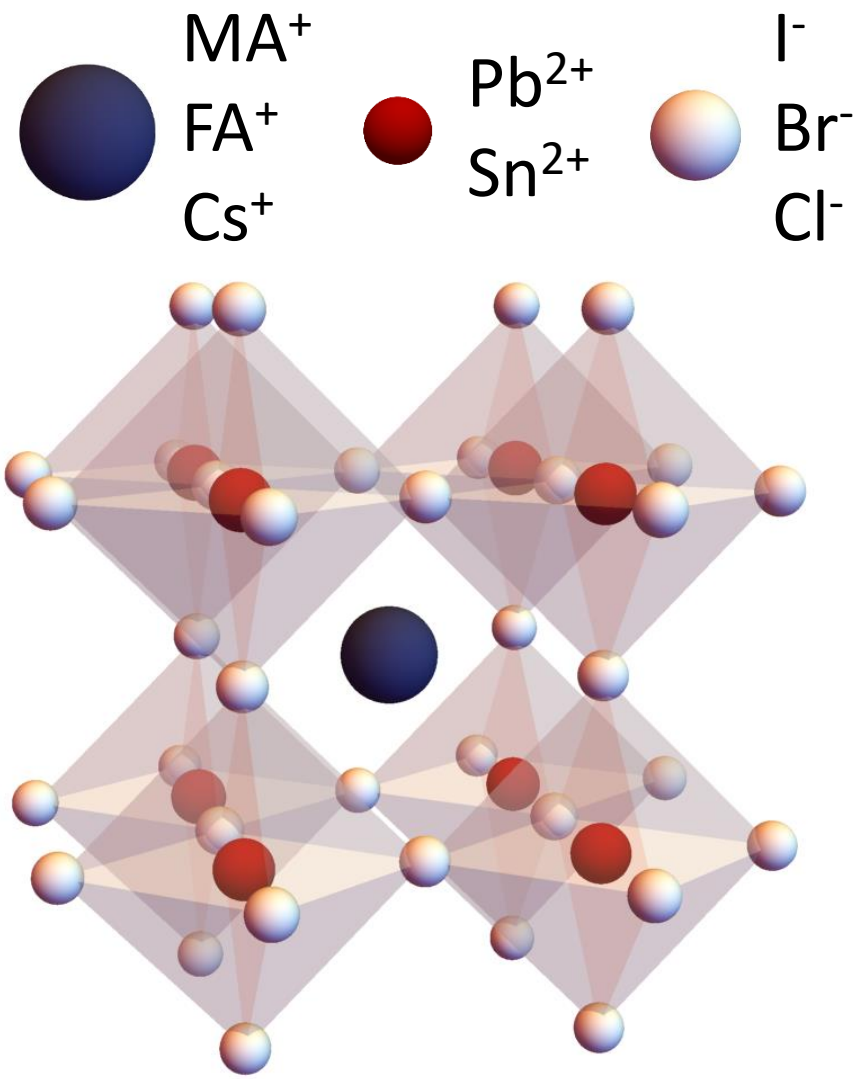


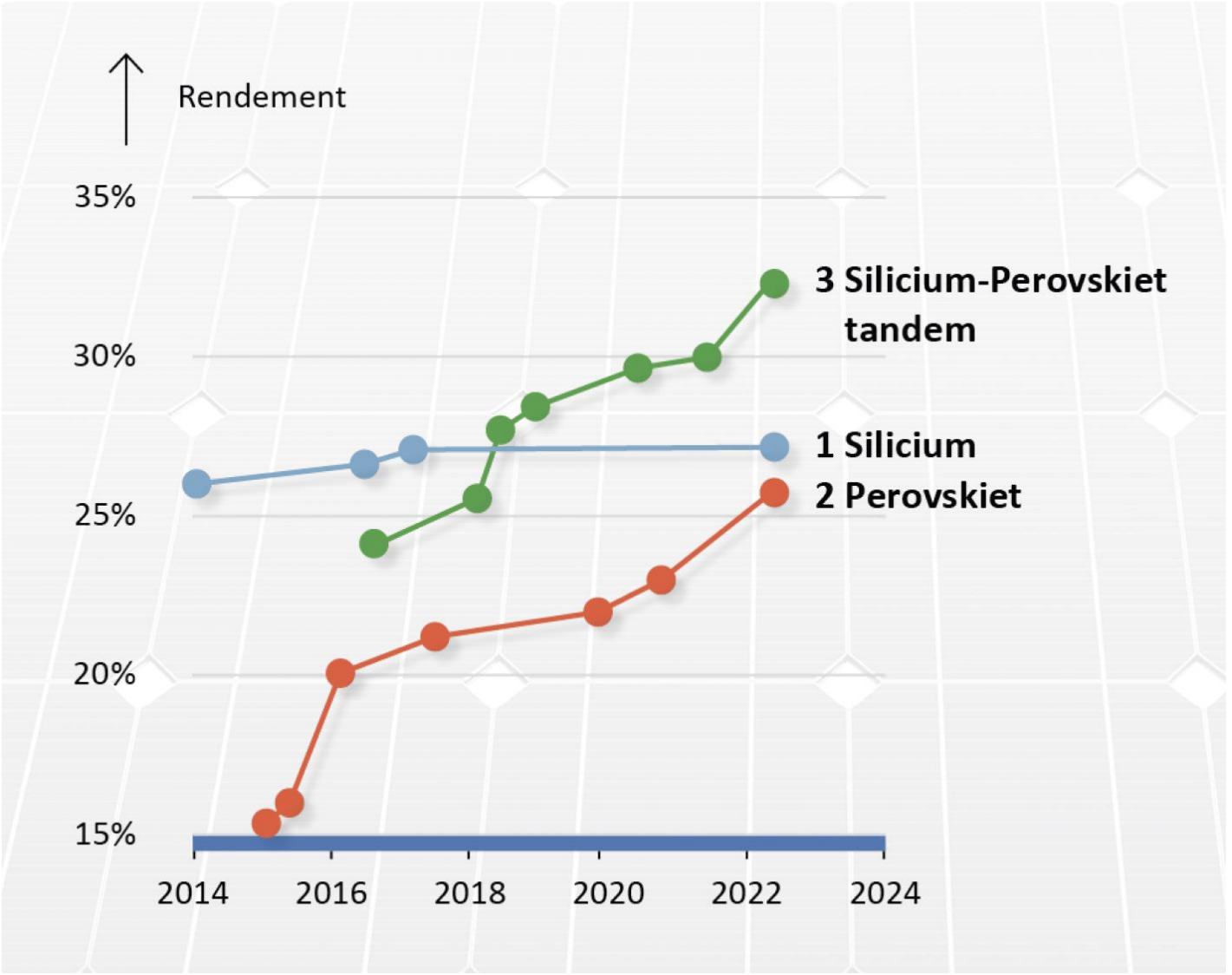

Low-energy
Light
Silicon
High-energy Light
???

Part 2
What is a perovskite and what is it good for?

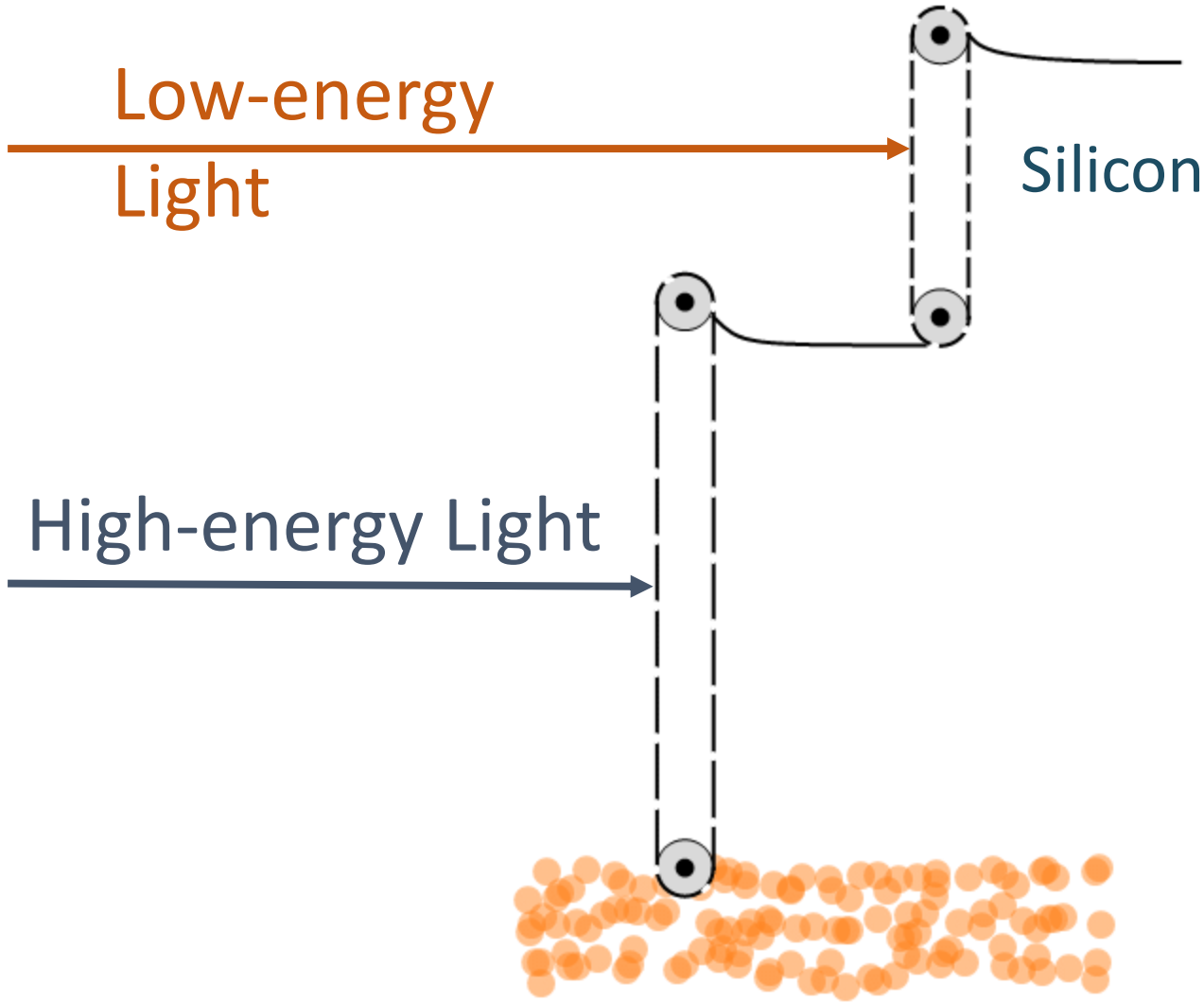


The rise of perovskites



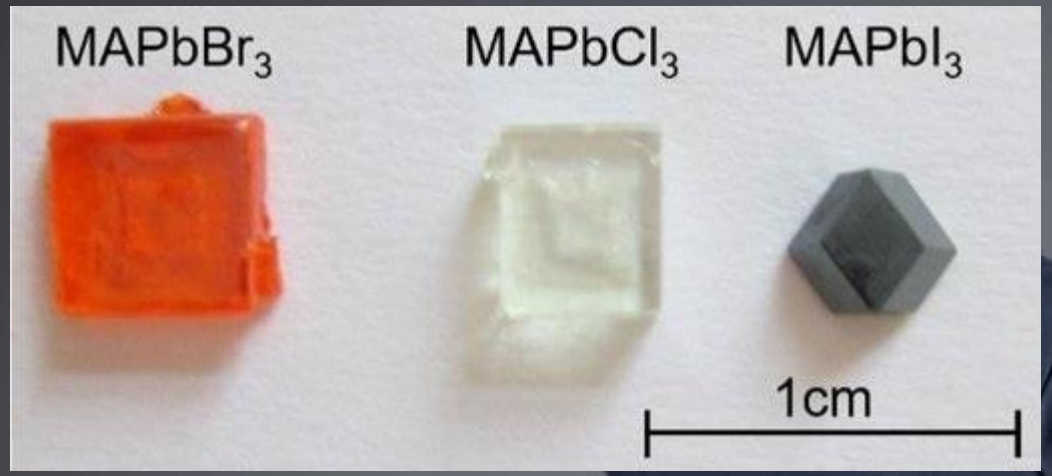


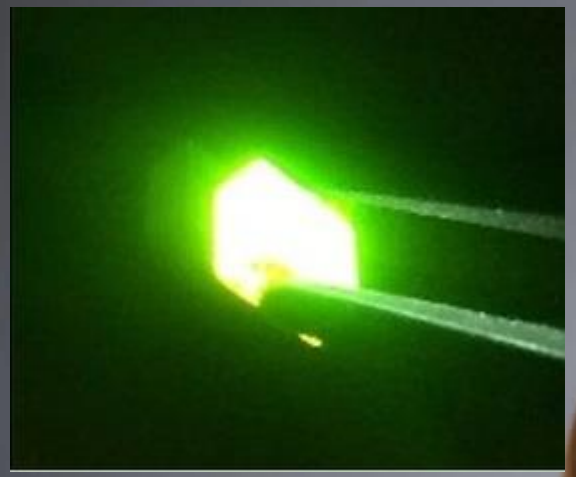
NREL efficiency chart



- Theoretical efficiency 45%
- With optimized perovskite top cell > 32% possible

Perovskiets are Salts

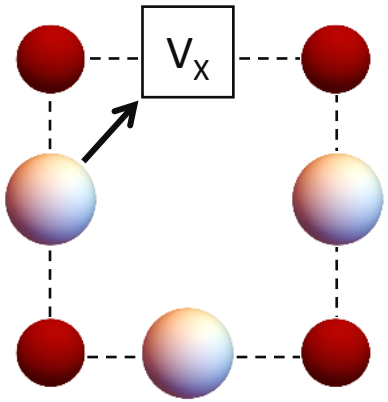


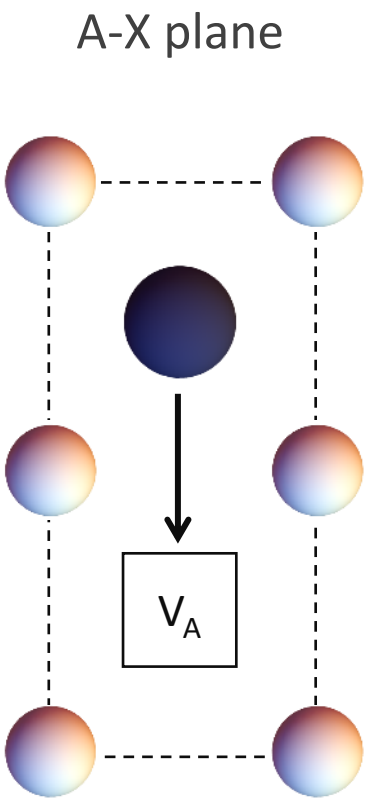


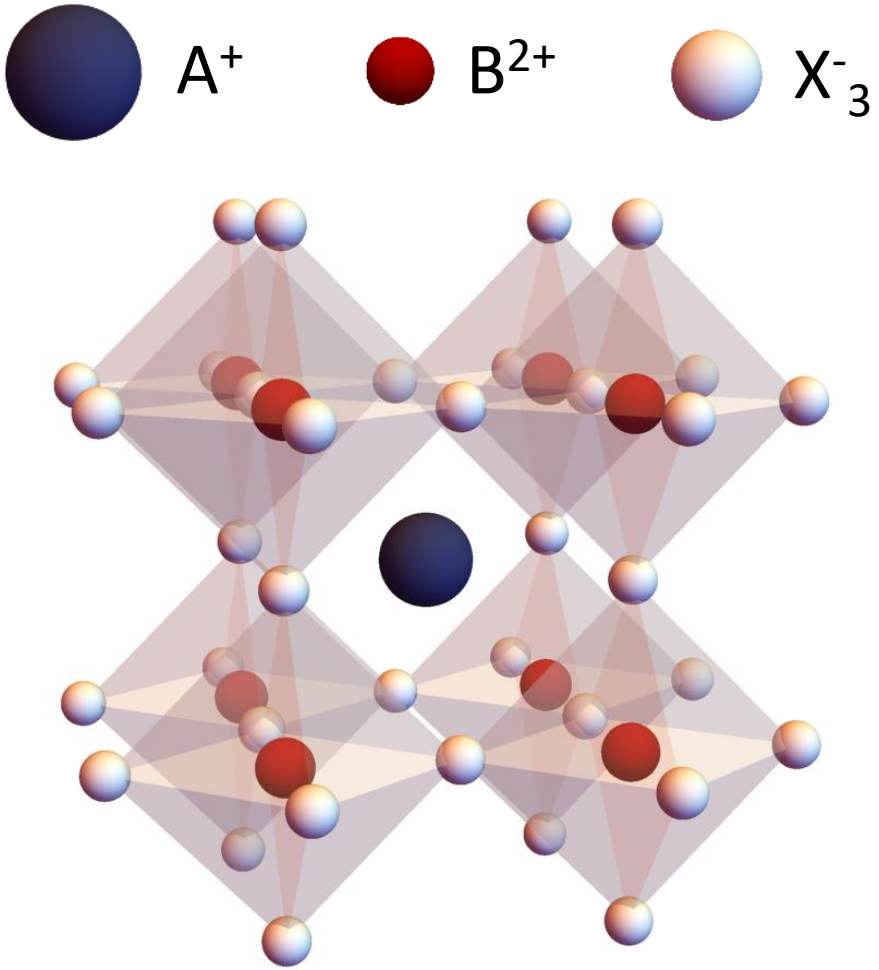
Thomas Riedl group Uni Wuppertal

2 Issues:
Stability
Toxicity

Perovskites are salt crystals

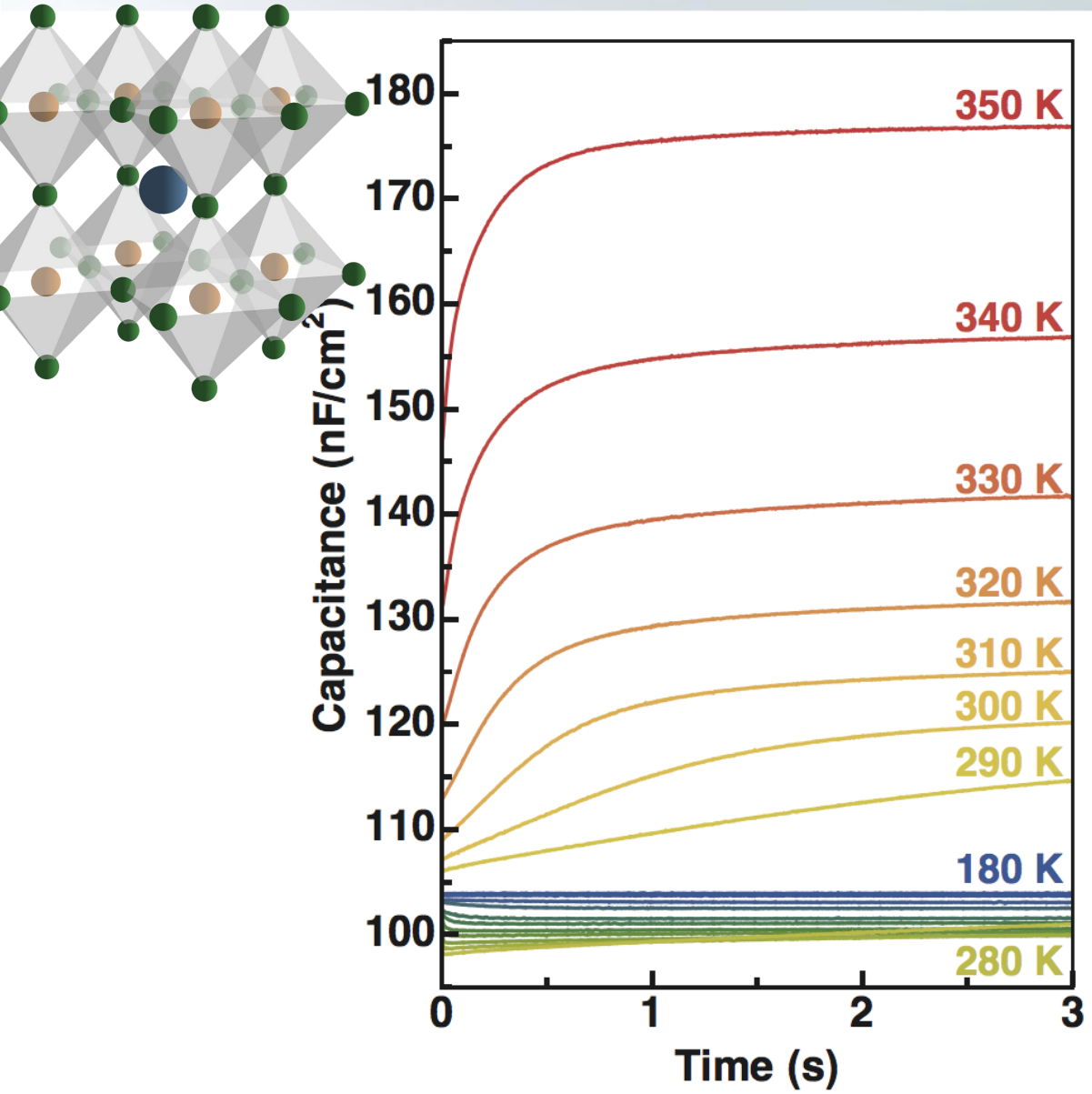






Measuring ion migration

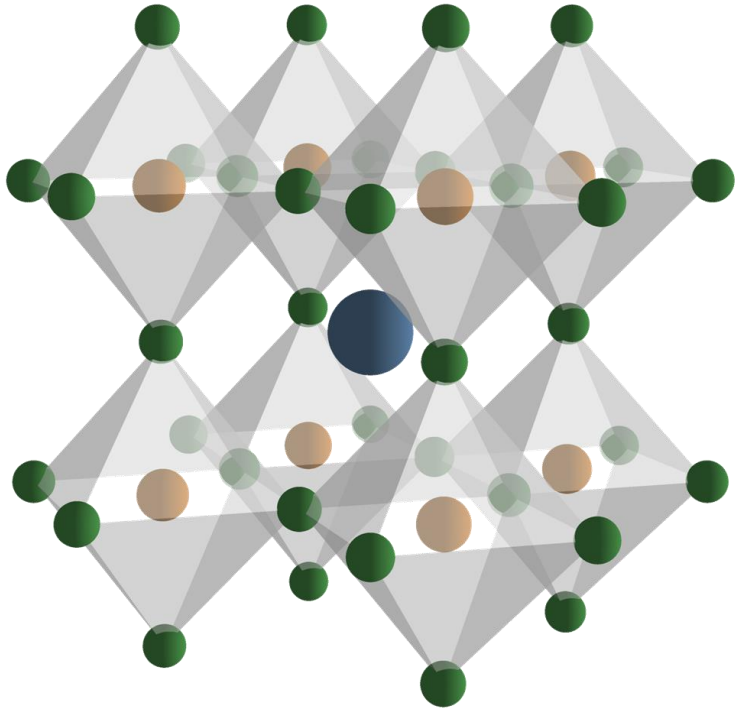
Capacitance shows ion migration in $MAPbI_3$



Moritz Futscher *et al.* Materials Horizons **6**, 1497-1503 (2019)

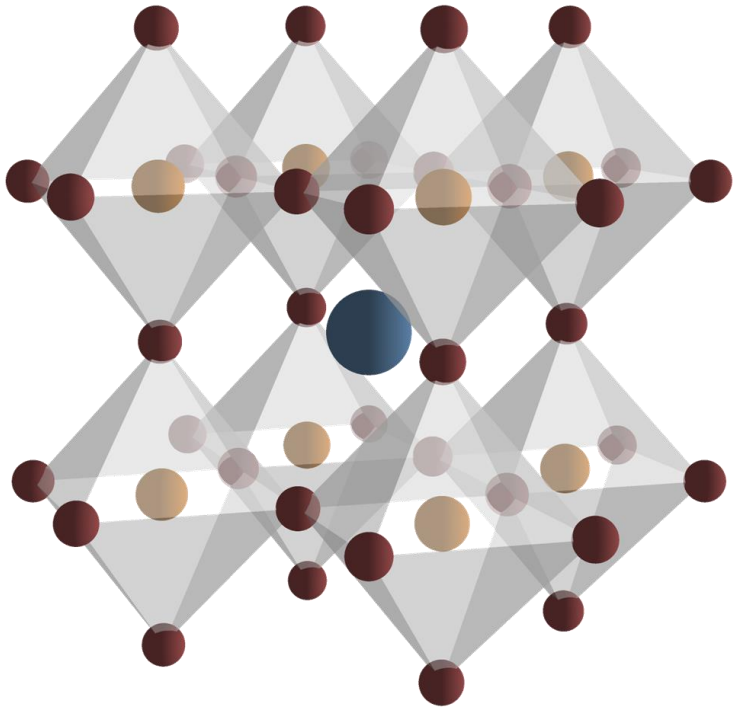
How to suppress ion migration?

How does ion migration relate to stability?



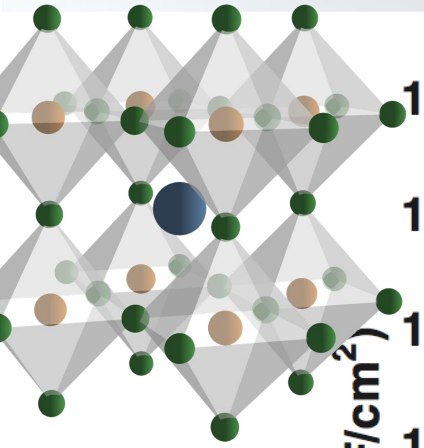
$MAPbI_3$

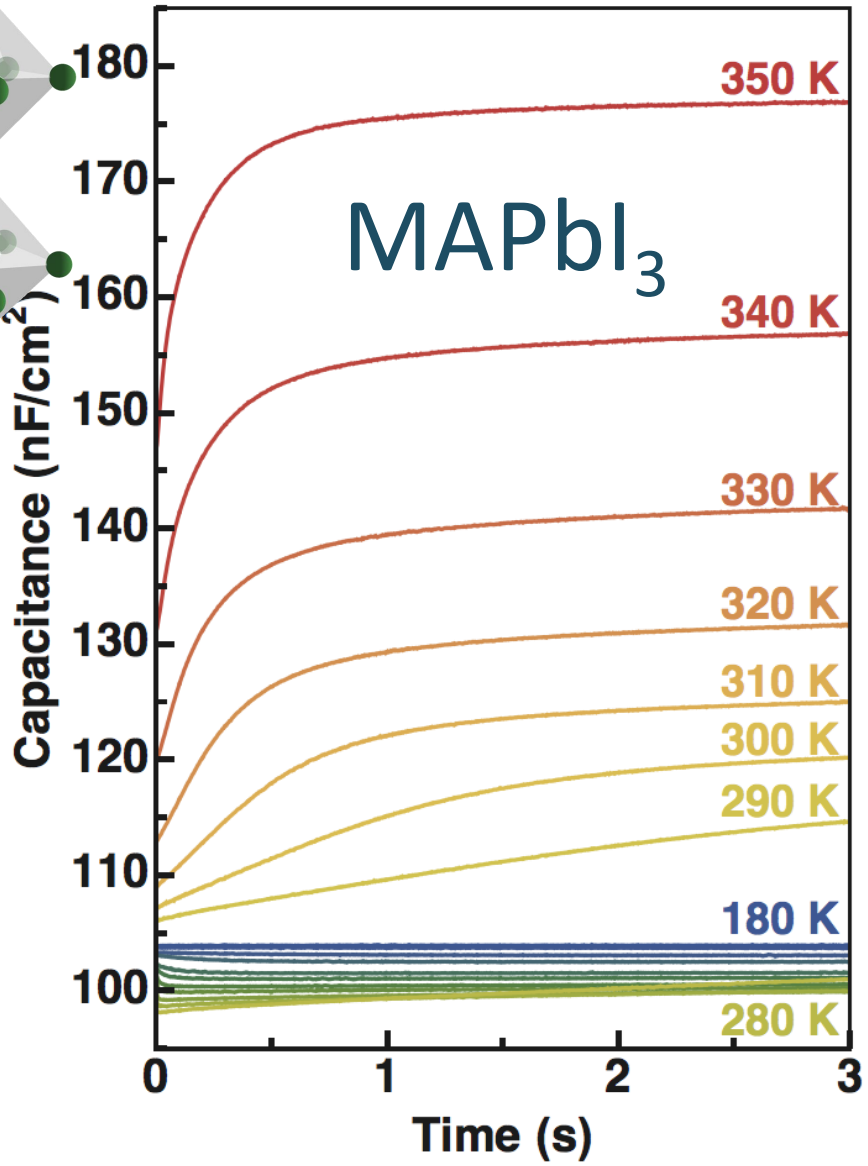
vs.

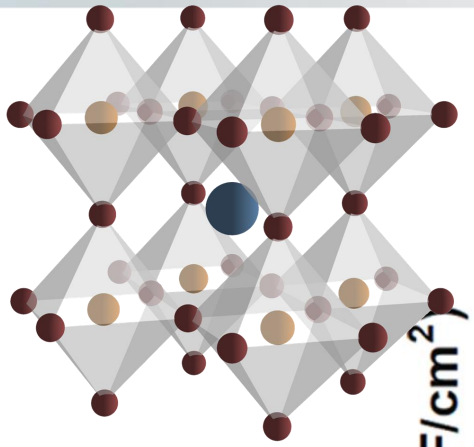


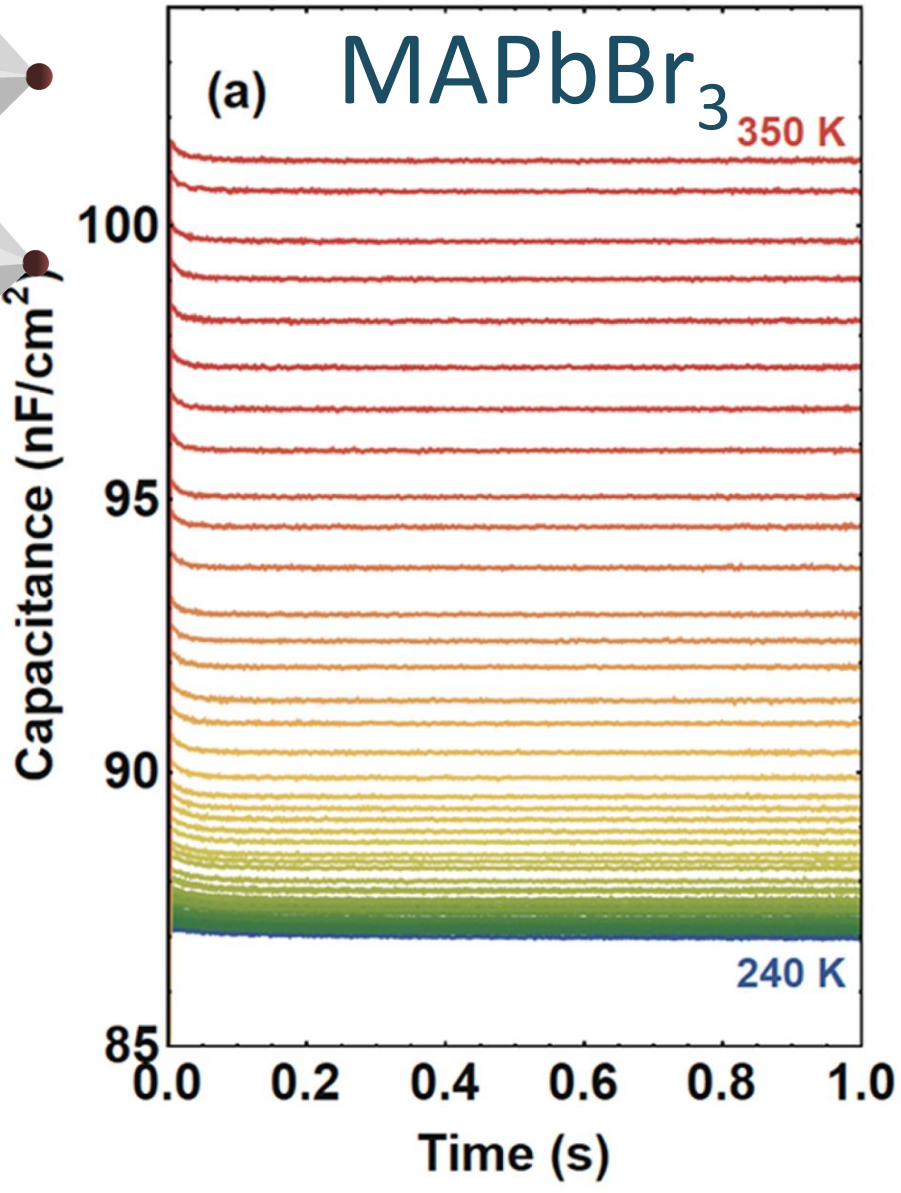
$MAPbBr_3$

Capacitance response of $MAPb(I/Br)_3$



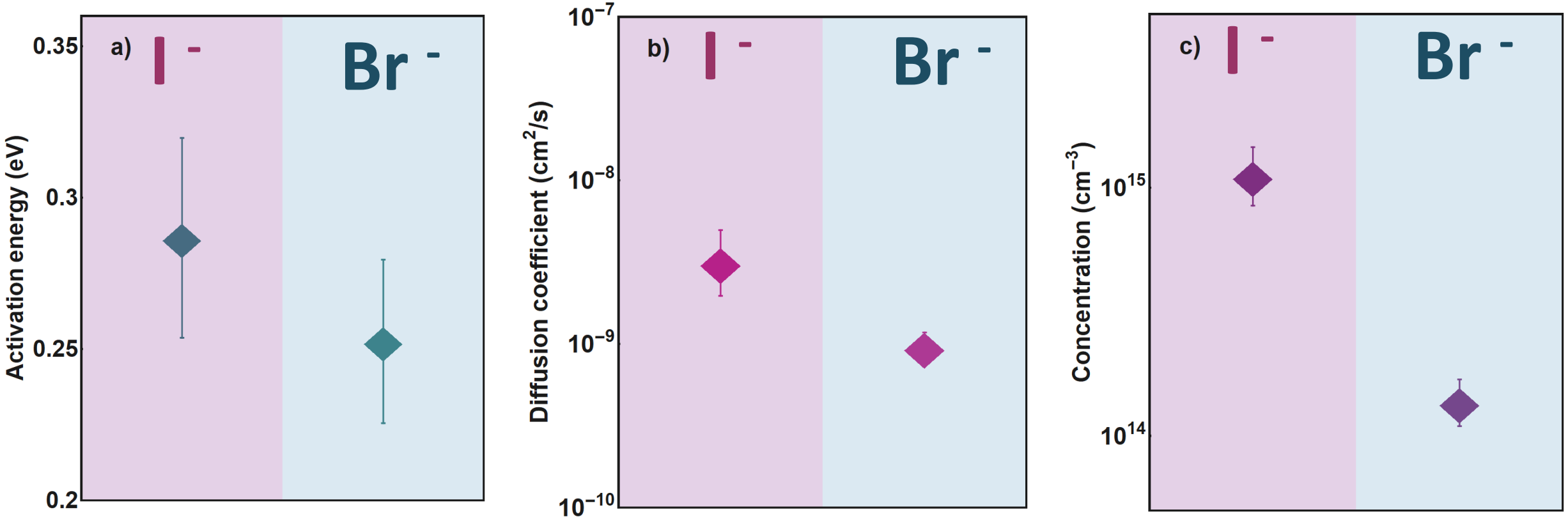






Moritz Futscher *et al.* Materials Horizons **6**, 1497-1503 (2019)

Lucie McGovern et al. J. Phys. Chem. Lett. 2020


a)
I -
Br -
Activation energy (eV)
0.35
0.3
0.25
0.2
b)
I -
Br -
Diffusion coefficient (cm²/s)
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
c)
I -
Br -
Concentration (cm⁻³)
10¹⁵
10¹⁴

Suppression of ion migration

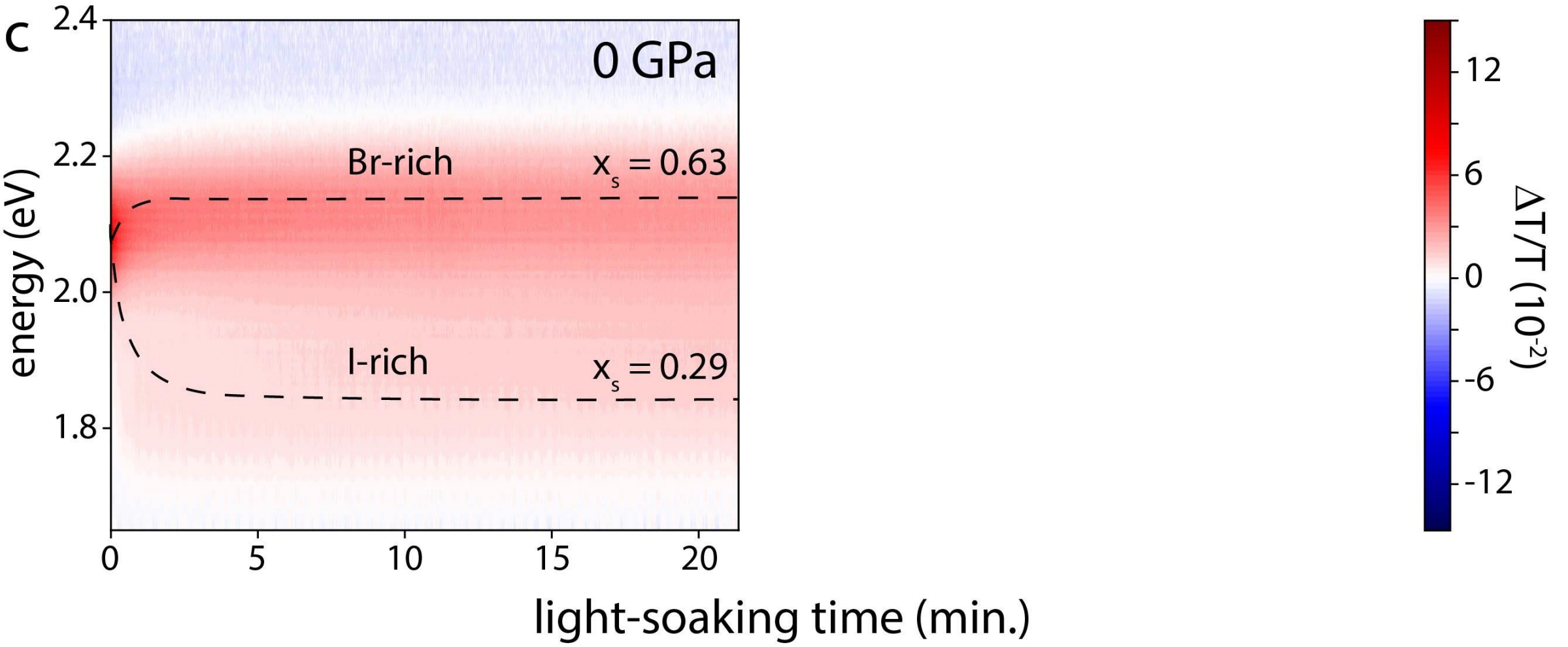
- So ion motion is slower
- Slowing the ions down:
  - Now lifetime minutes – hours (10^0 – 10^2 minutes)
  - Needed lifetime 20 years (10^7 minutes)

$$D = D_0(N_{ion}) \times e^{\frac{-E_A}{kT}}$$

- So decrease density by 5 orders of magnitude, or increase activation energy by factor 10
- Is there another way?

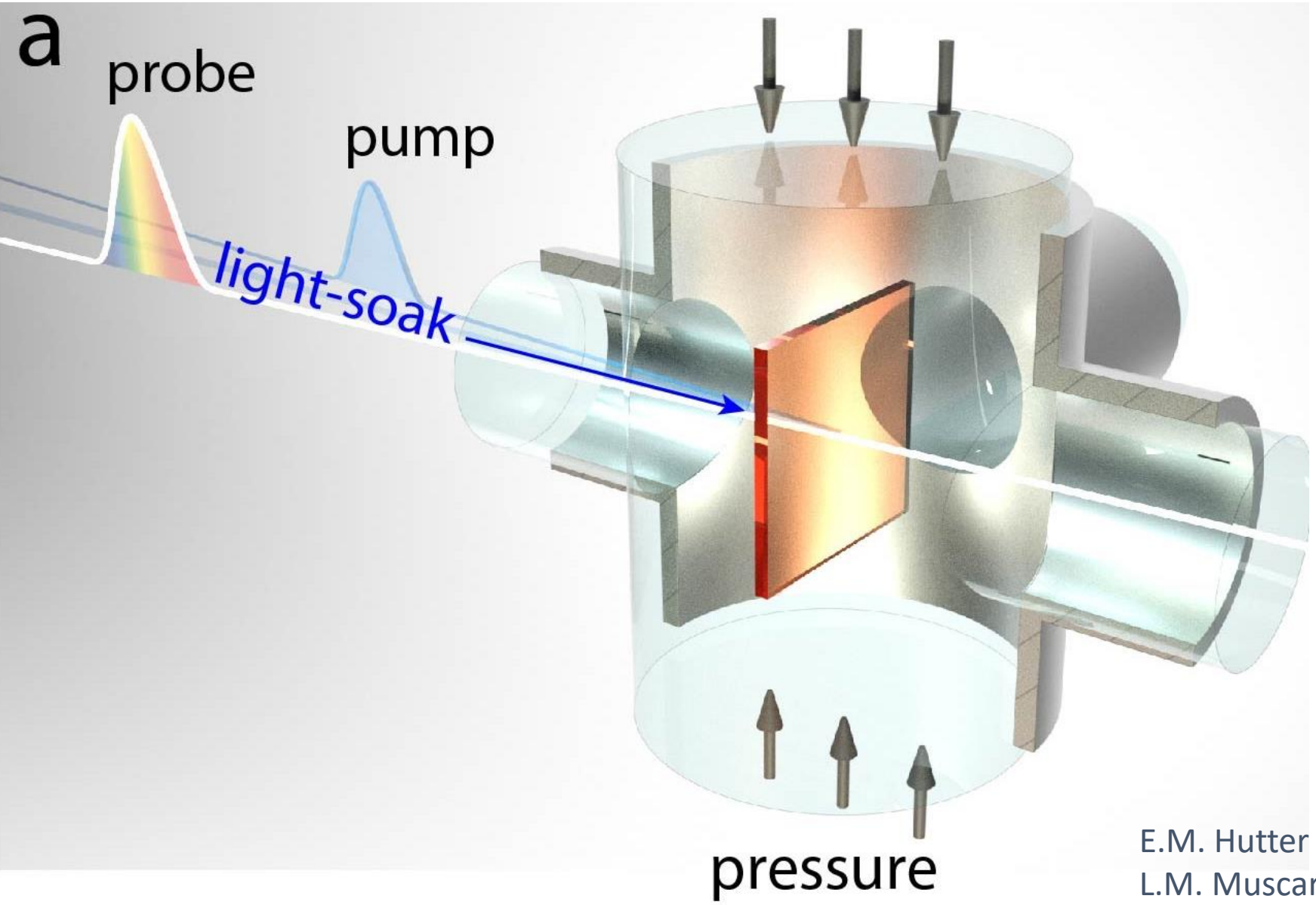
Use strain to suppress ion migration

Phase segregation



E.M. Hutter et al., Cell Reports Physical Science 2020
L.M. Muscarella et al., ACS Energy Letters 2020

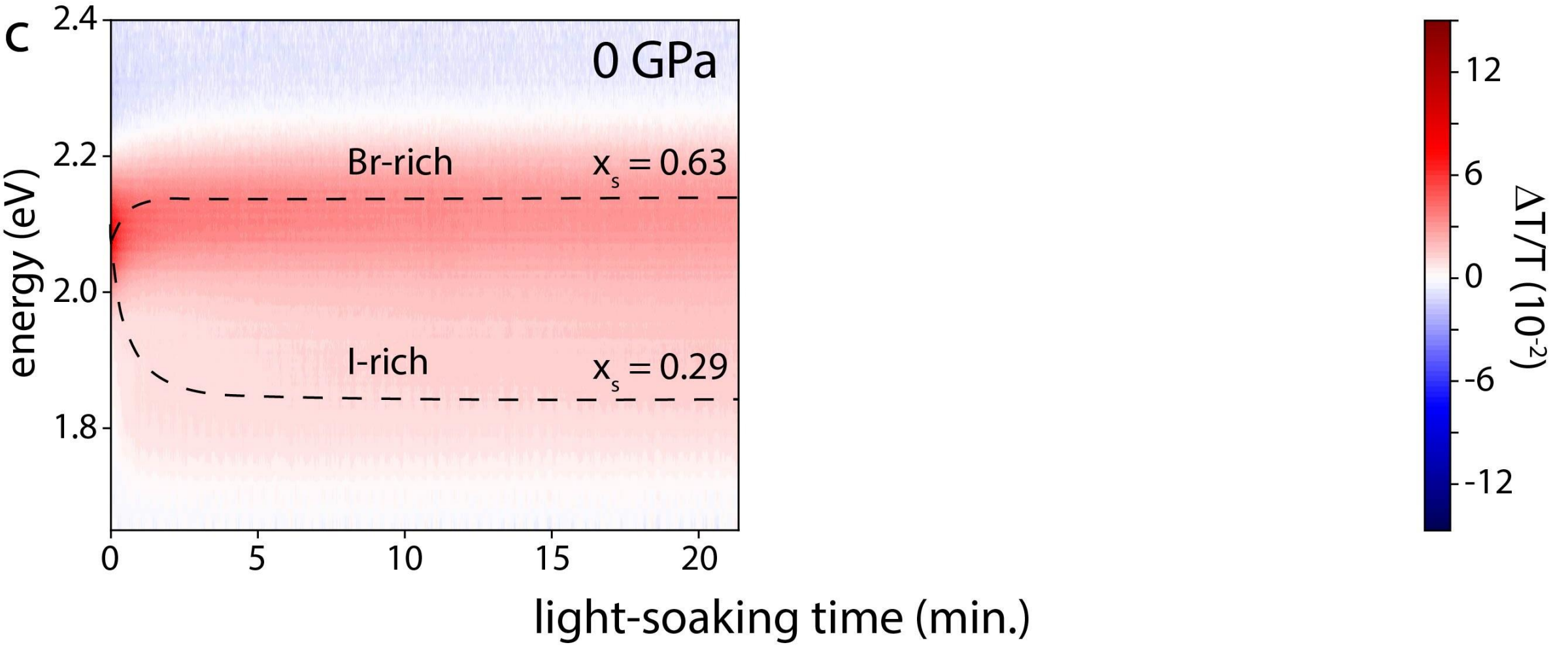
Phase segregation



- Test both phases at the same time

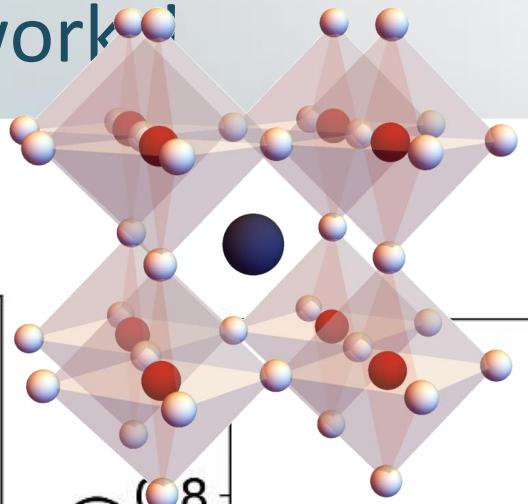
E.M. Hutter et al., Cell Reports Physical Science 2020
L.M. Muscarella et al., ACS Energy Letters 2020

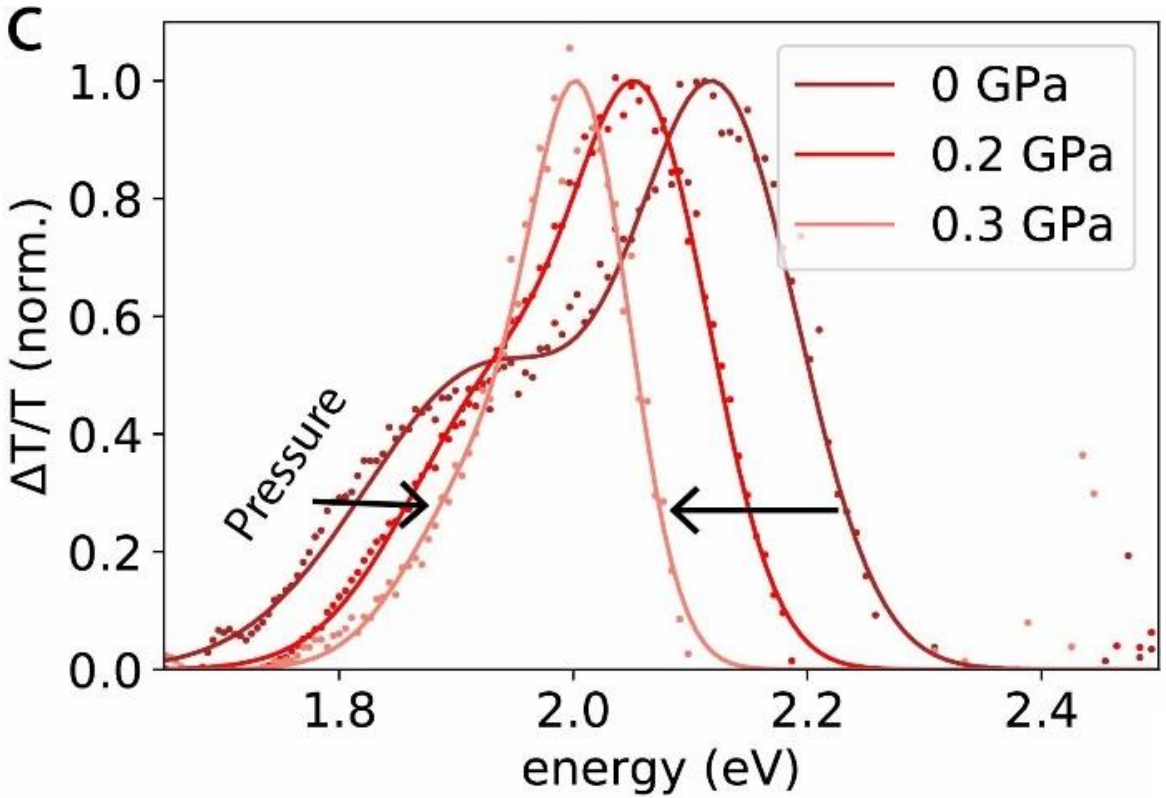
Phase segregation

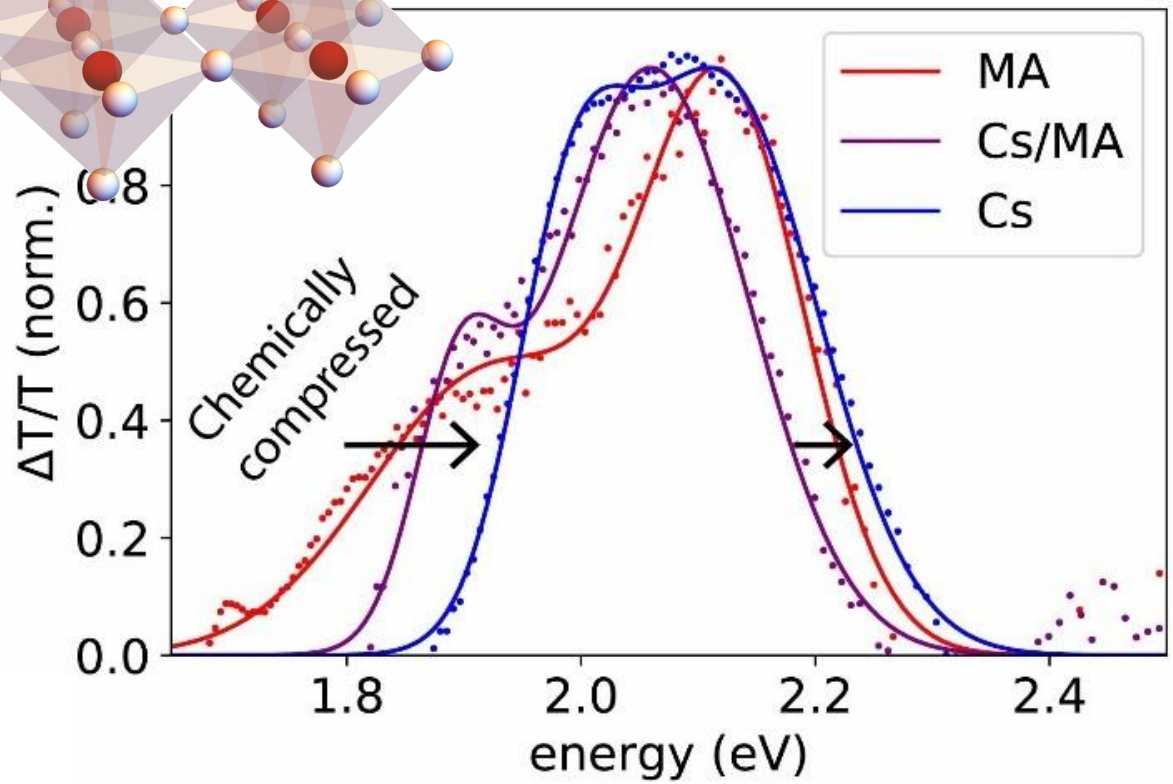


E.M. Hutter et al., Cell Reports Physical Science 2020
L.M. Muscarella et al., ACS Energy Letters 2020

Also chemical compression work



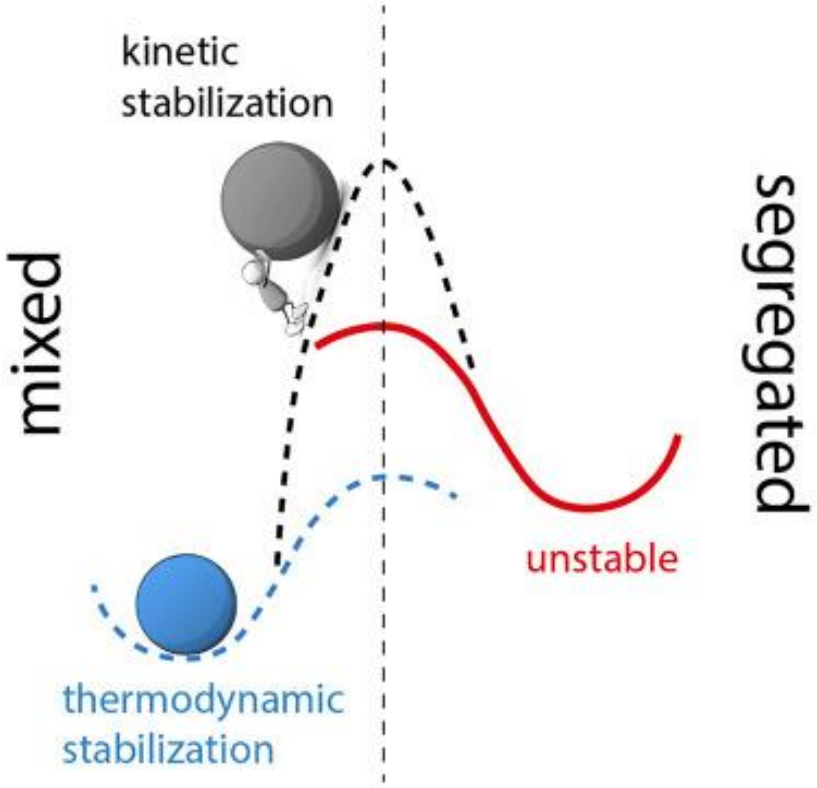




E.M. Hutter et al., Cell Reports Physical Science 2020
L.M. Muscarella et al., ACS Energy Letters 2020

Stability → Suppression ion migration

- Additives can slow down ion migration
- For applications (> 20 years) kinetic stabilization alone difficult
- Best: Thermodynamic stabilization. Can be achieved by choosing the unit cell size



B. Ehrler, E.M. Hutter, Matter 2020

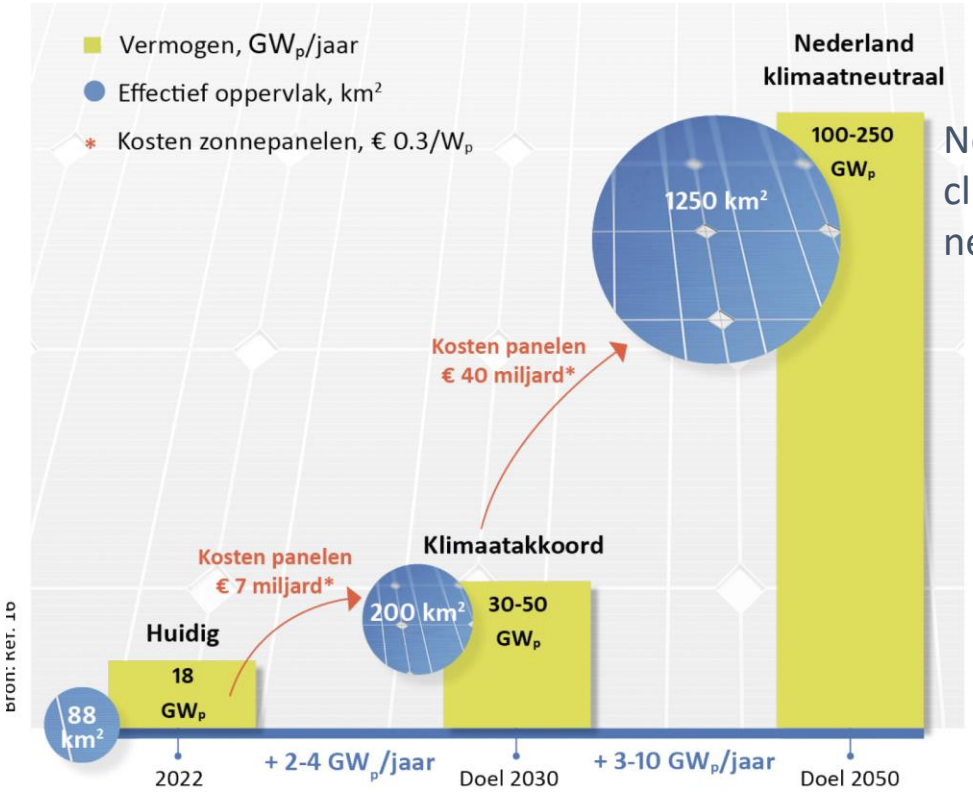
Part 3
SolarNL



We must install PV at a very large scale

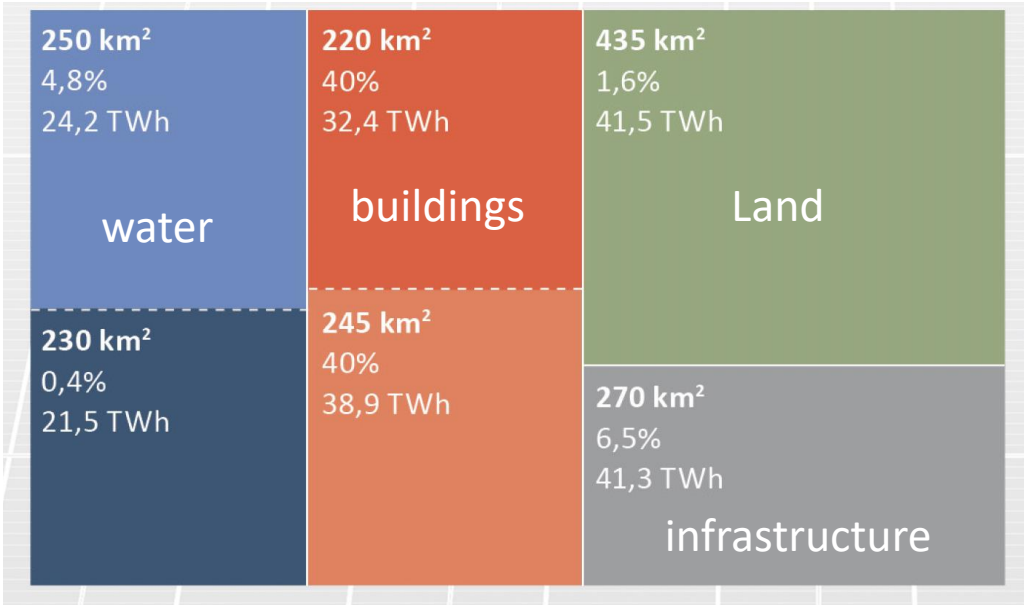
250 GW_p=1.250 km^2 → 3% of the NL land area

(20% efficiency)



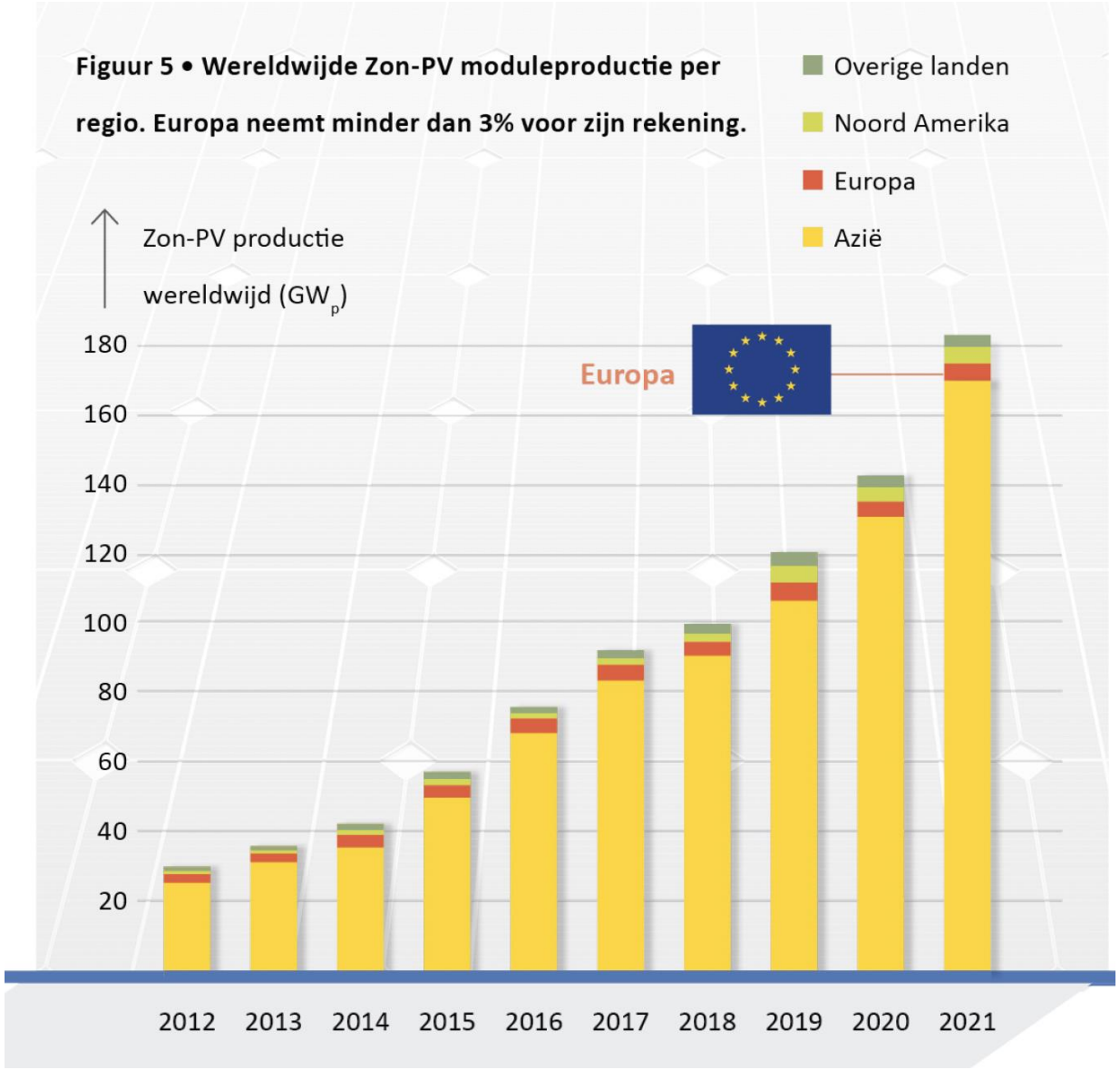
Netherlands climate neutral

We have enough space for 1.250 km^2 of PV



From: Ruimtelijk Potentieel zonnestroom in Nederland
Generation.Energy, TKI Urban Energy (2021)

But we are missing an opportunity in Europe





We have REPowerEU on the table. The renewables are cheap, they are home-grown, they make us independent. We will deploy renewables this year that are an equivalent to round about 8 billion cubic metres. So the renewables are really our energy insurance for the future.

Ursula von der Leyen, 7/09/2022
President of the European Commission

Plan for the Netherlands

AMOLF physics of functional complex matter

SolarNL.eu







AMOLF physics of functional complex matter

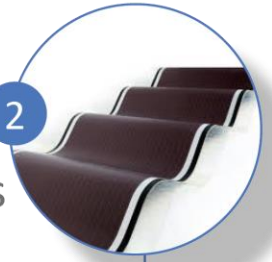
Programmalijn 1 Zonnecellen



MCPV



Programmalijn 2 Zonnefolies



HyET Solar



Programmalijn 3 Integratie



· Solarge · Exasun · Energyra

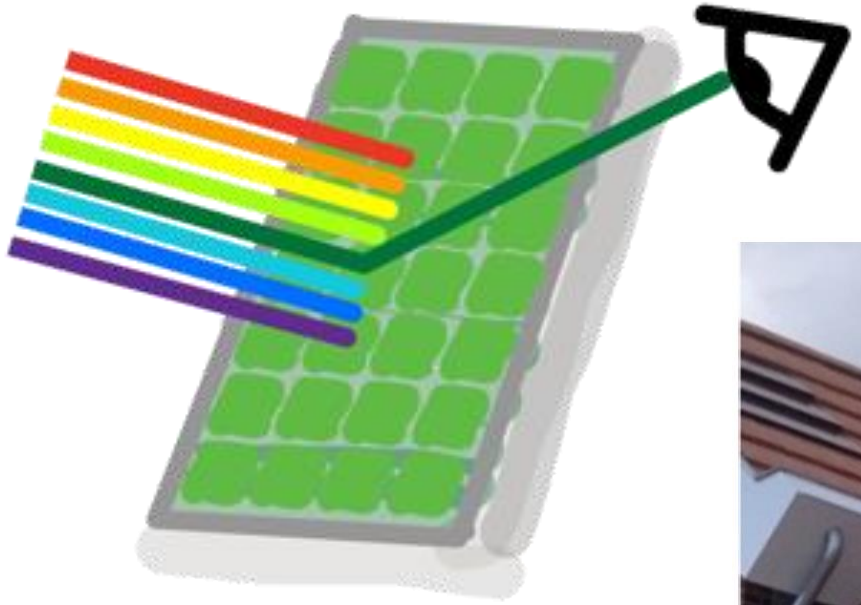
· Taylor · IM Efficiency

· Lightyear Layer



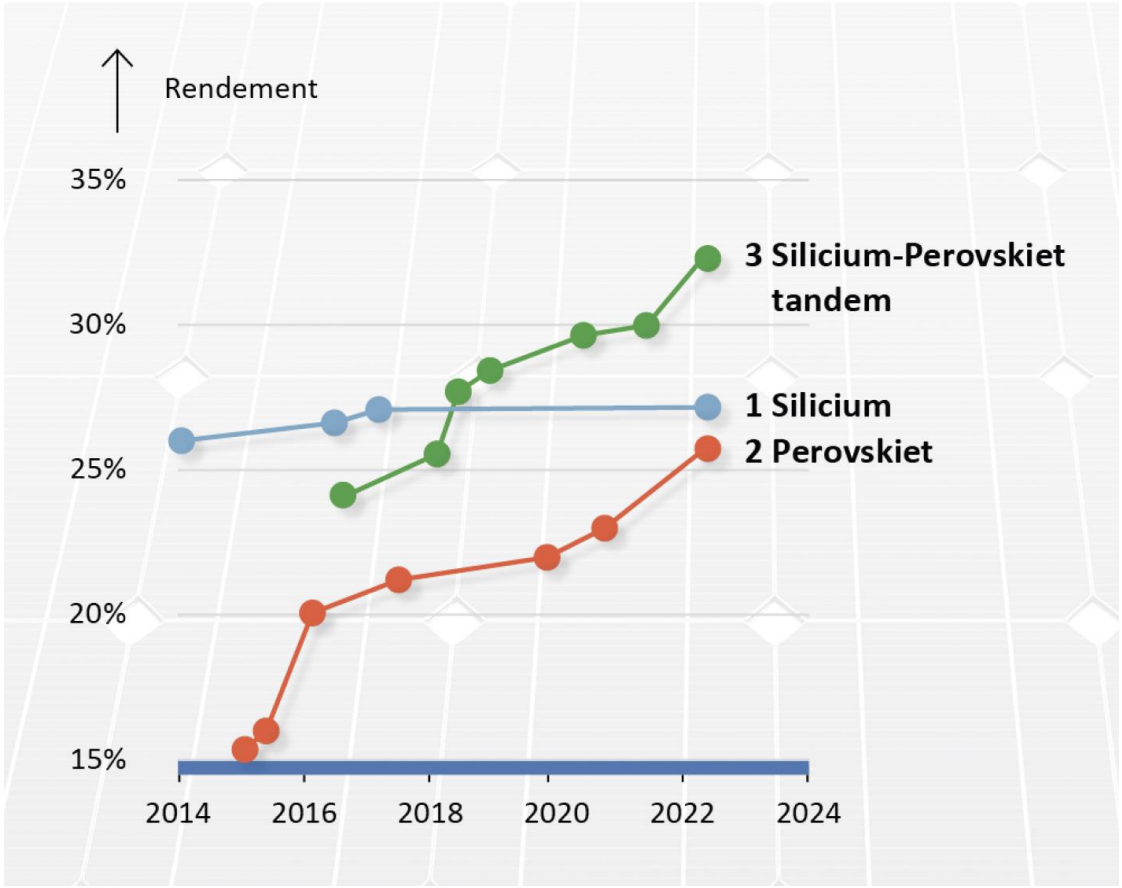
TNO – SolarLab

Research plays a large role





Efficiency saves space





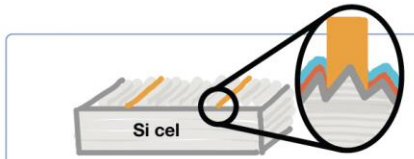
1% efficiency = 1 Delft

SolarLab basic science program

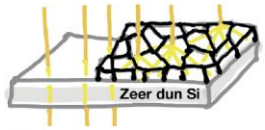
with AMOLF, RUG, TUD, TUE, UT, UU, UvA

AMOLF physics of functional complex matter





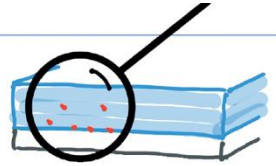
Optimized contacts of HJT cells with Cu and ALD



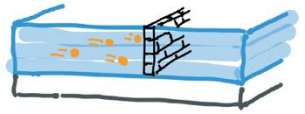
Nanostructures to enable very thin Si



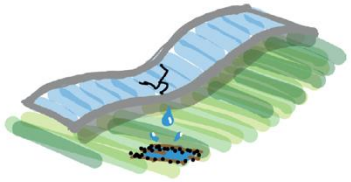
ML and human interaction to optimize factories



Finding and removing defects in perovskites



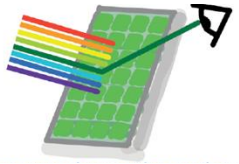
Stopping ion migration to make perovskites stable



Reducing lead in perovskite materials to improve environmental performance



Solar modules from bio-plastics



Light management for coloured solar modules



Selective reflectors for tandem solar cells steer light to sub-cells

Ecosystem creation



Plan for the Netherlands

AMOLF physics of functional complex matter

SolarNL.eu

Local production
Lower CO2 footprint
Integrated solutions
Ecosystem generation







Where could we go?

Bryer scenario, Energy Watch Group 2019

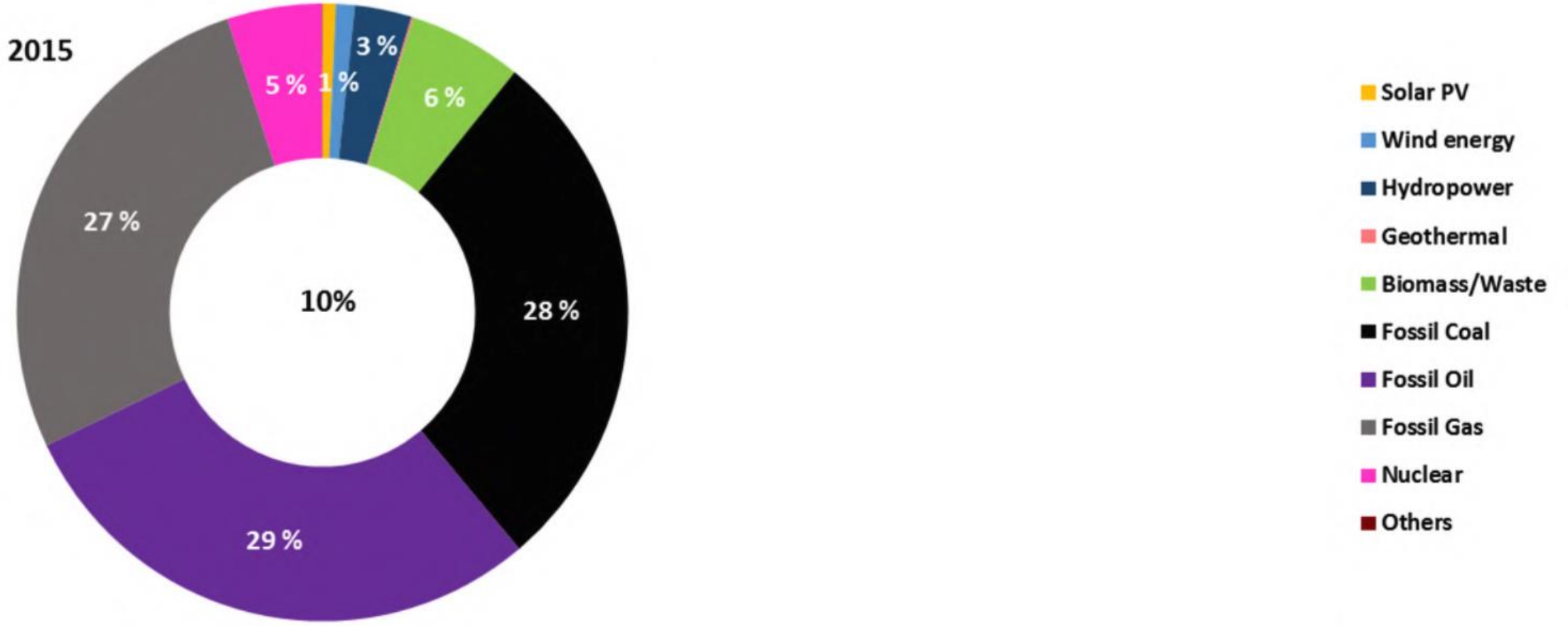


Figure KF-2: Shares of primary energy supply in 2015 and 2050.

Even Shell predicts ~1/3 solar PV



Summary

- Perovskite tandem cells have the potential for high efficiency
- Stability: main problem ion migration
  - Additives can suppress ion migration by different mechanisms
  - Kinetic vs. thermodynamic stabilization
  - Any halide mixture can be thermodynamically stabilized given a suitable unit cell size
- Is toxicity an issue?

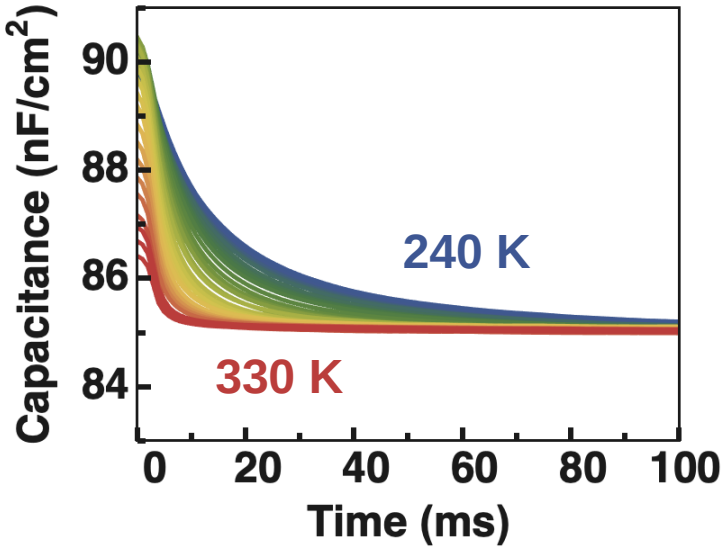


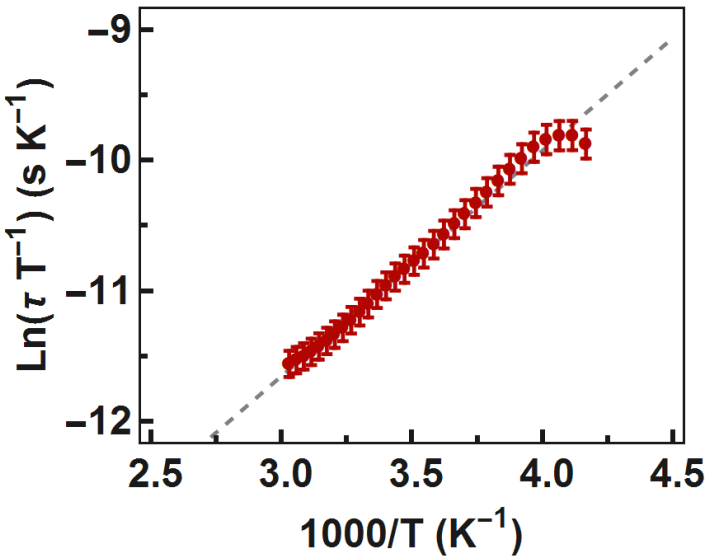
Transient ion drift

Drift of mobile ions towards the contact interfaces:

Device geometry:
ITO/NiO_X/Perovskite/C_{60}/BCP/Al

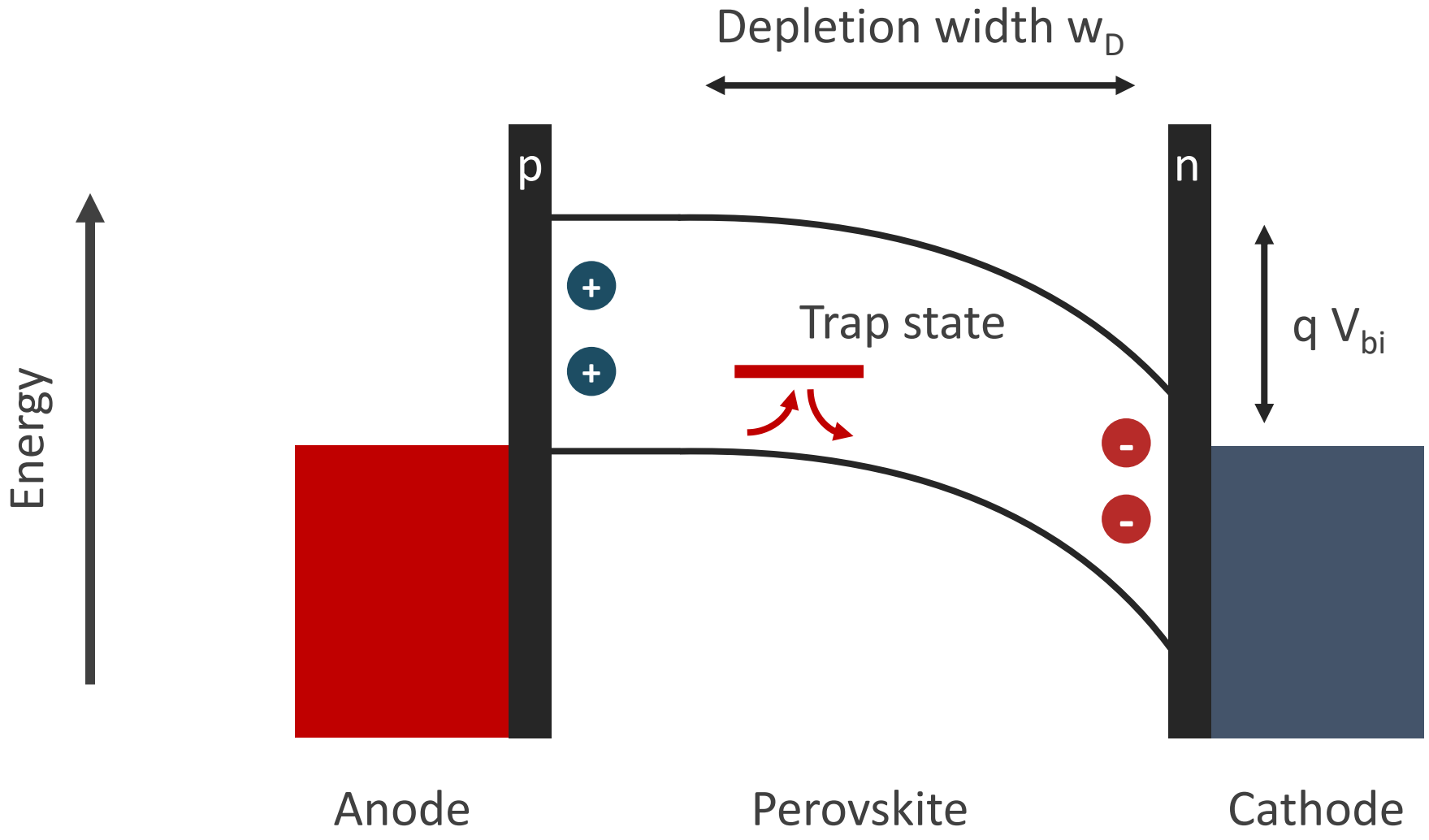
$$C(t) = C(\infty) \pm \mathrm{C}(\infty)\frac{N_{Ion}}{2N}\exp\left(-\frac{t}{\tau}\right) \qquad \frac{T}{\tau} = \frac{q^2 N D_0}{\varepsilon\varepsilon_0 k_B}\exp\left(-\frac{E_A}{k_B T}\right)$$



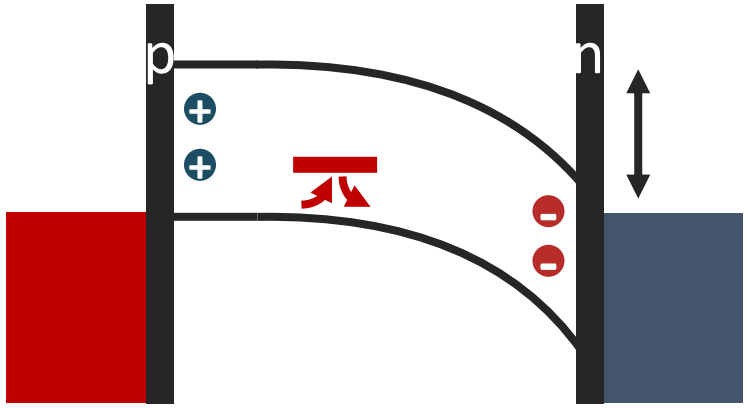


→ N_{ion} = 9 10^{16} cm^{-3}
E_A = 0.14 ± 0.01 eV
D = (3.1 ± 0.4) 10^{-11} cm^2/s

The effect of trap states



The effect of trap states



	Electronic defect states	Mobile ions
Decay time	De-trapping: $\tau_{detrap} = \frac{1}{\sigma \nu_{th} N_T} \exp\left(\frac{E_T}{k_B T}\right) \approx 10^{-10} - 10^{0}\text{s}$	Drift: $\tau_{drift} = \frac{w_D^2 k_B T}{D q V_{bi}} \approx 10^{-3} - 10^{0}\text{s}$

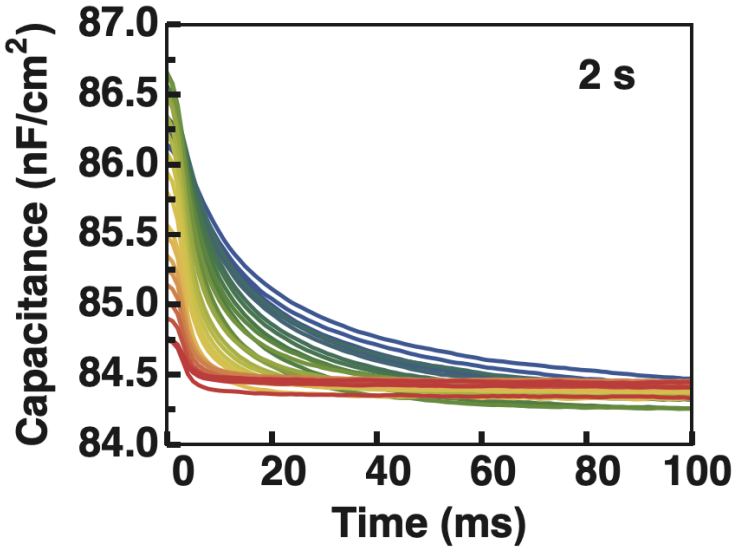
Moritz H. Futscher *et al.* The Journal of Chemical Physics 152, 044202 (2020)

Electronic defect states versus mobile ions

Measuring the time-dependent capacitance allows for distinguishing between ionic and electronic effects.

Device geometry:
ITO/NiO_X/Perovskite/C_{60}/BCP/Al

Mobile ions



Electronic defect states versus mobile ions

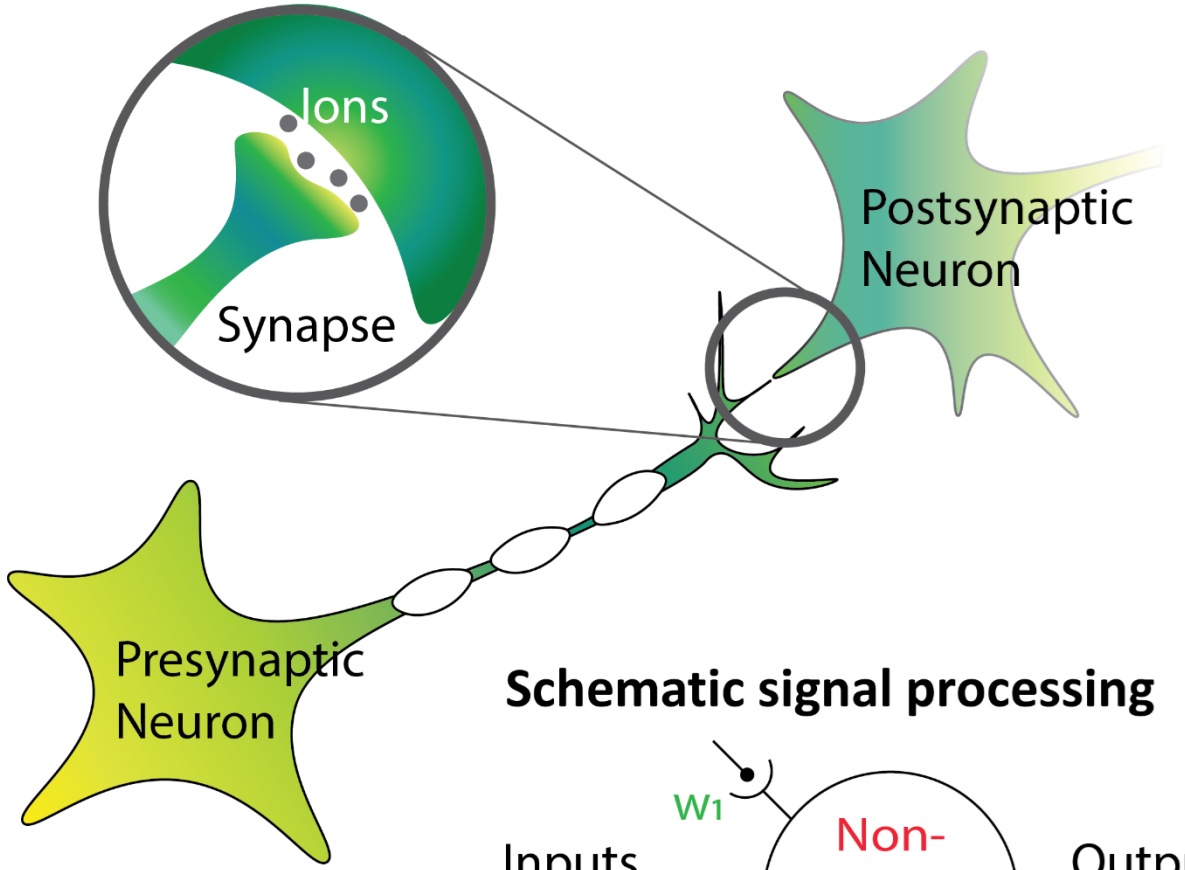
Measuring the time-dependent capacitance allows for distinguishing between ionic and electronic effects.

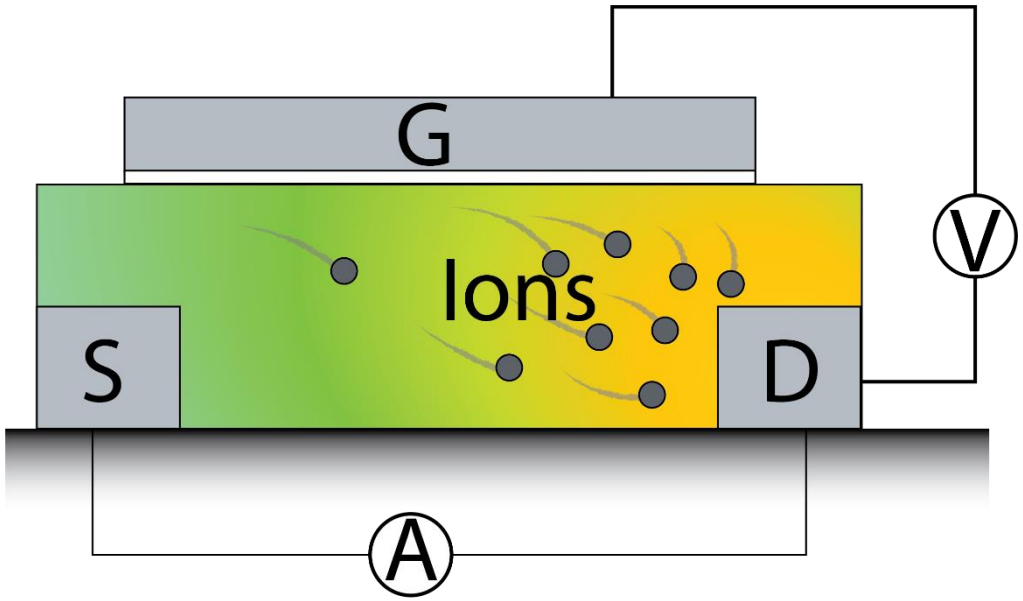
Device geometry:
ITO/NiO_X/Perovskite/C_{60}/BCP/Al

	Activation energy (eV)	Concentration (cm^{-3})
Doping density	-	7×10^{17}
Mobile ions	0.14 ± 0.01	5×10^{16}
Traps	0.08 ± 0.01	3×10^{15}

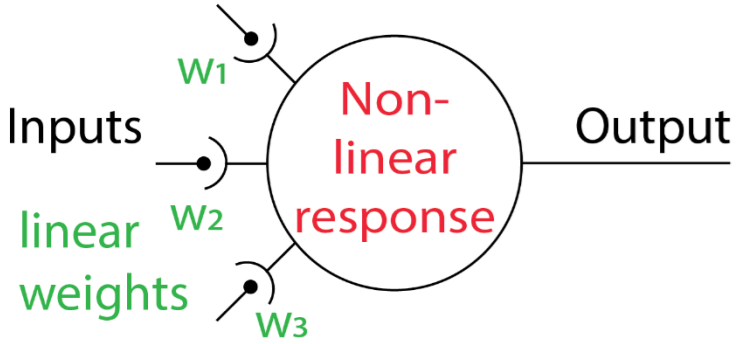
Side comment

Biological Synaptic Switching





Schematic signal processing



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