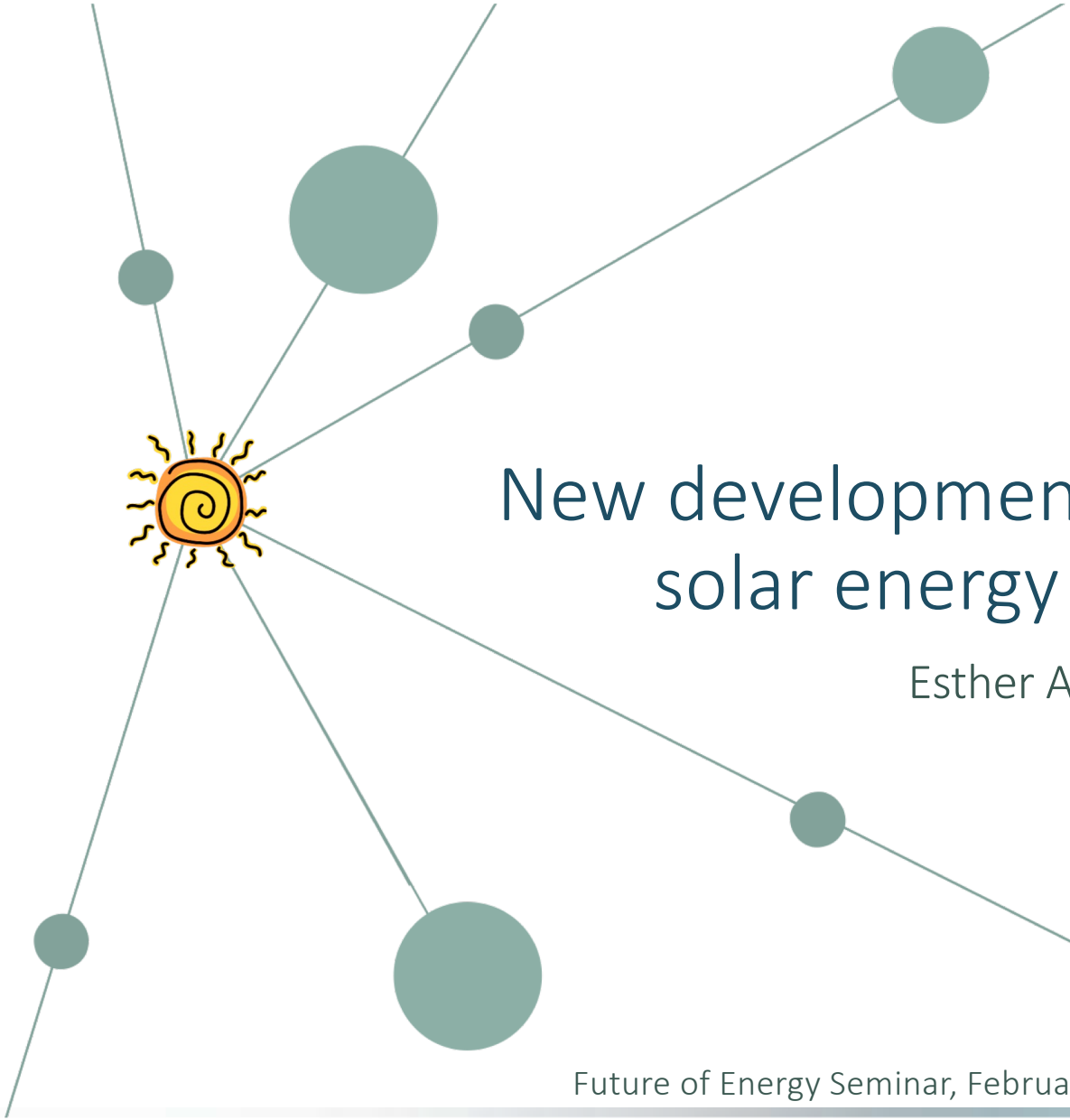


AMOLF physics of functional complex matter

New developments in photonics for solar energy technology

Esther Alarcon Llado

3DPV

Future of Energy Seminar, February 2025

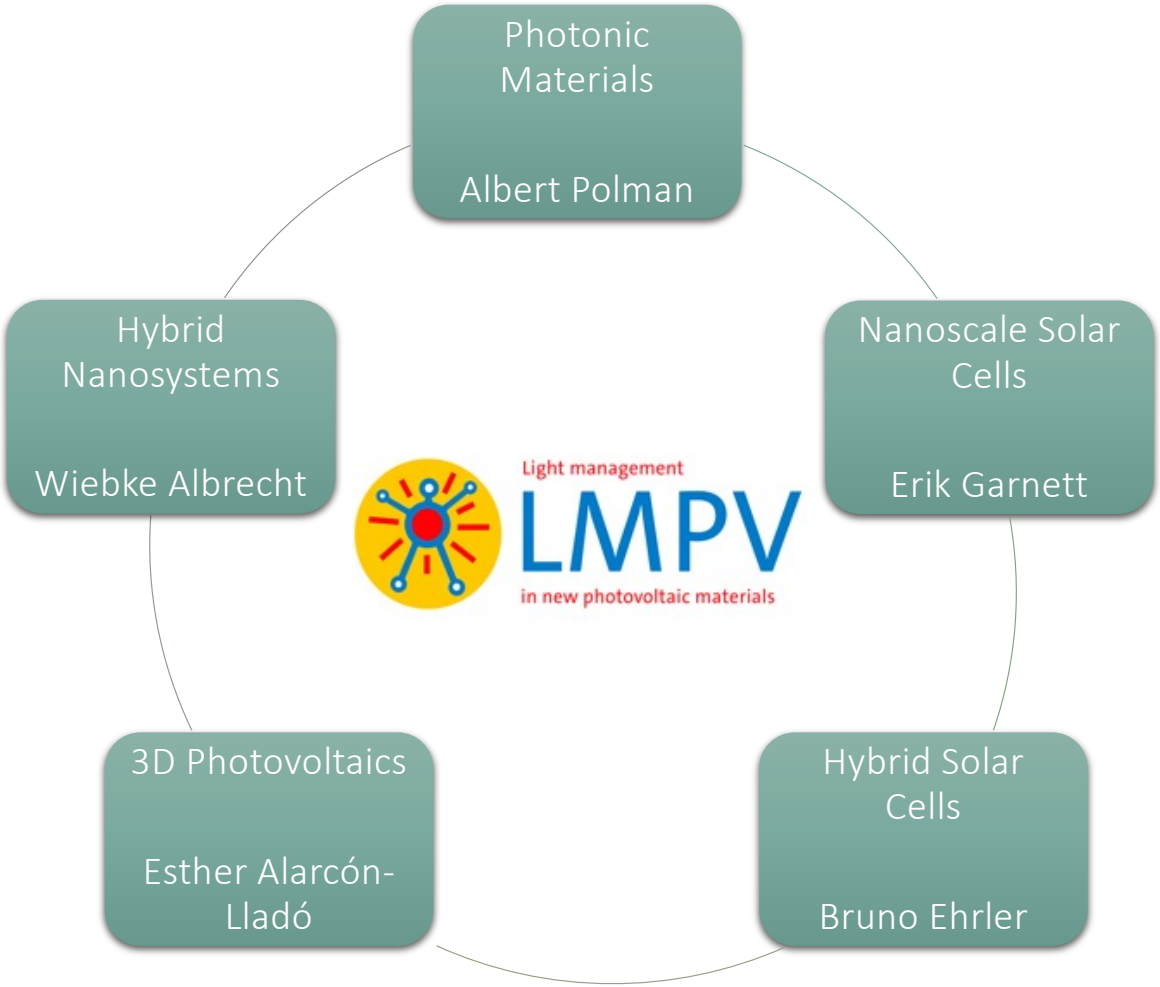
NWO-Institute for physics of functional complex matter

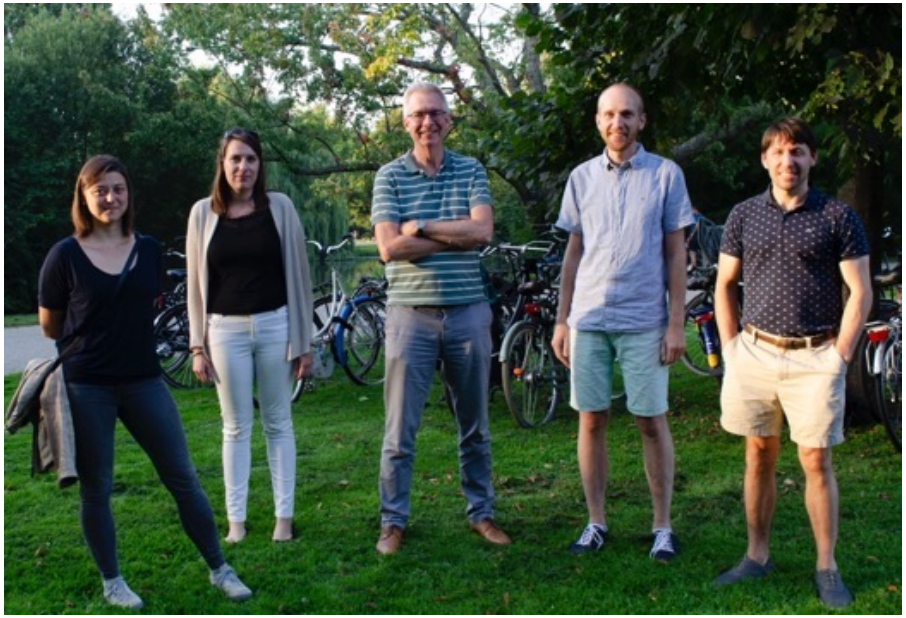
AMOLF physics of functional complex matter



Light Management and New PhotoVoltaic materials (LMPV)

AMOLF physics of functional complex matter





5 groups
30 PhDs + PDs
12 master's students
6 guests
4 Technicians

Work thanks to…



Femius Koenderink
Albert Polman
Erik Garnett
Bruno Ehrler

Jorik van de Groep

Anna Fontcuberta i Morral

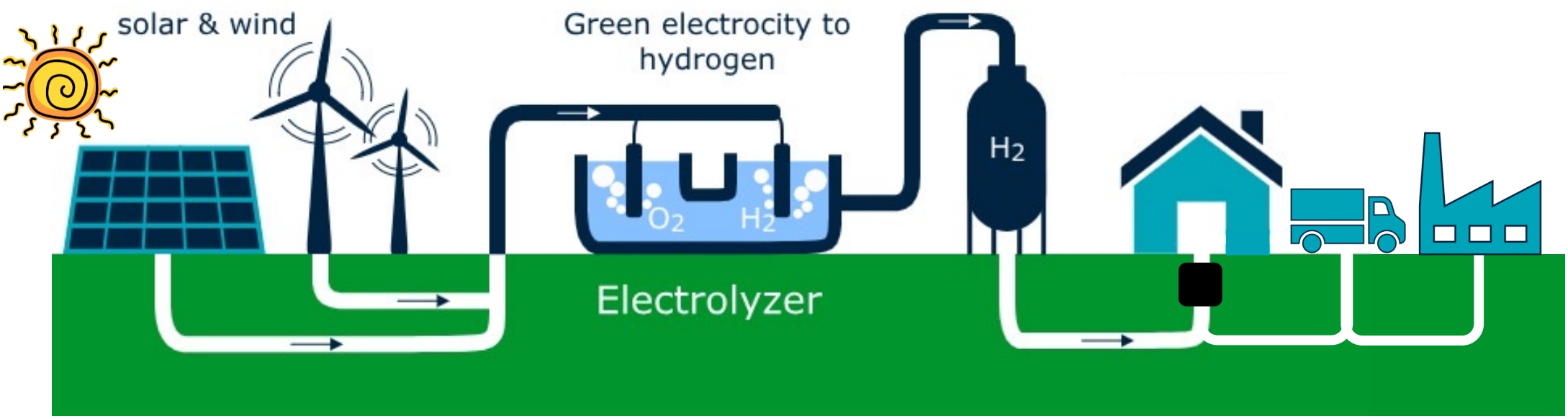
Marian Florescu

Riccardo Sapienza

Juerg Leuthold

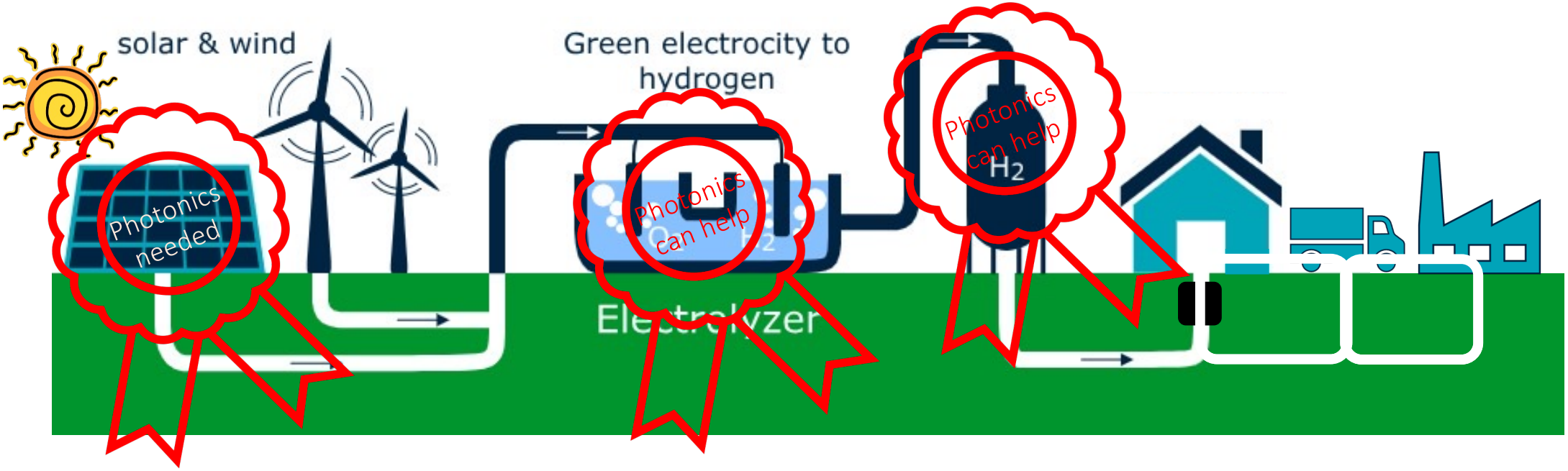
Mark Brongersma

The energy transition



We look for new materials and energy conversion principles for sustainable energy generation.

The energy transition



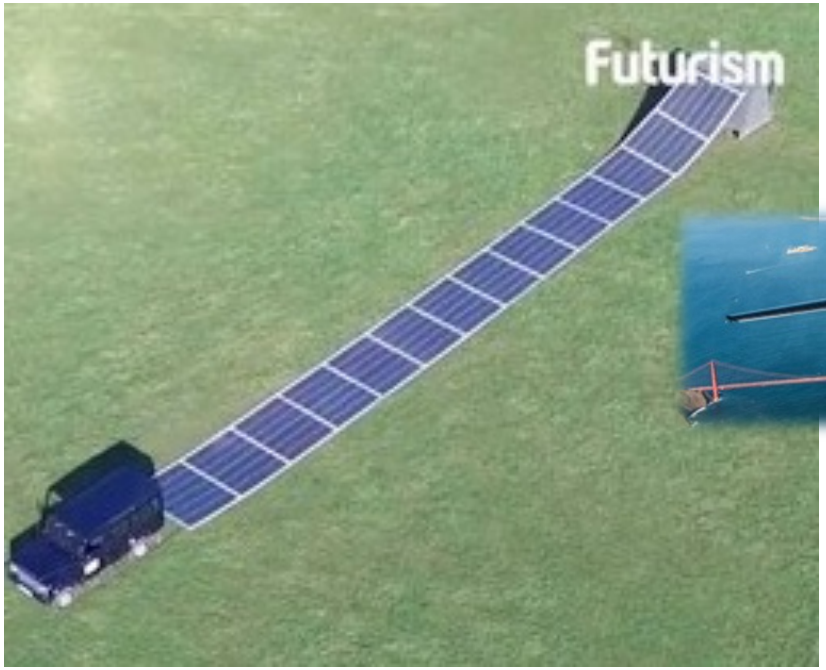
We look for new materials and energy conversion principles for sustainable energy generation.

All surfaces can generate energy…



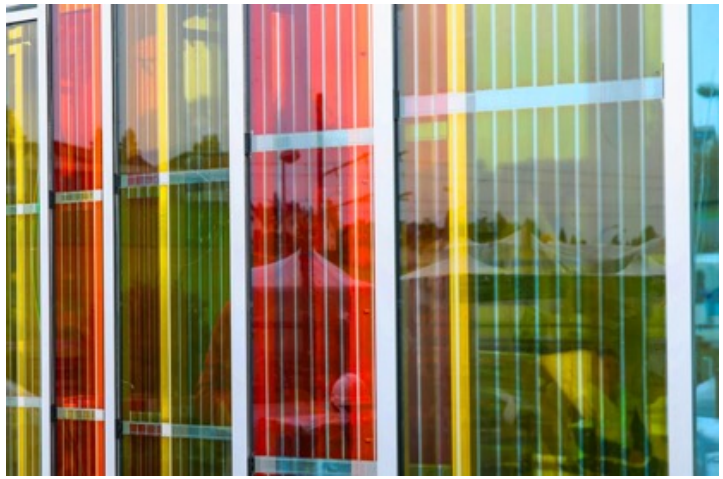
… the solution is design flexibility in PV

Design flexibility in PV









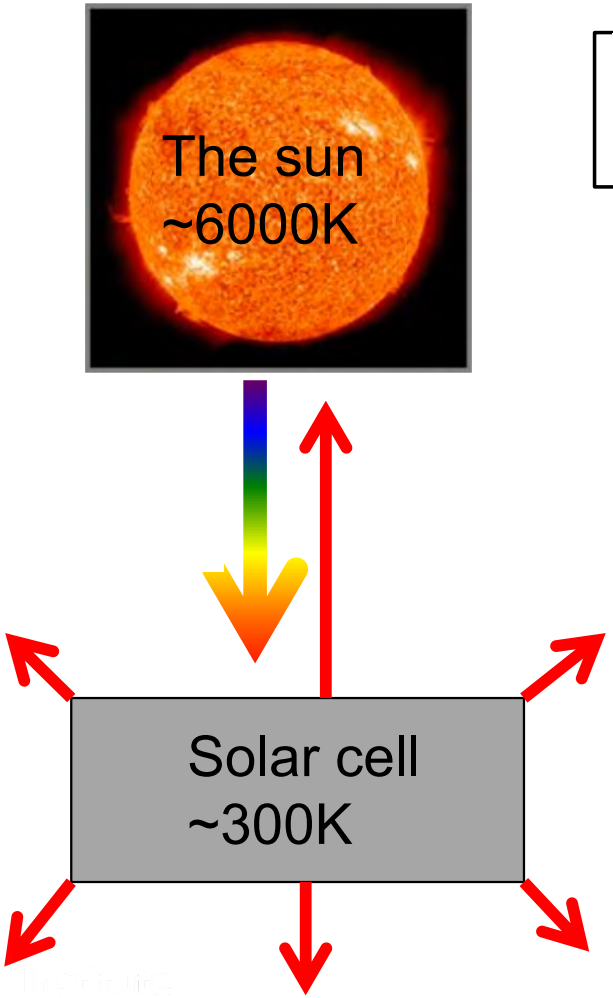
- Shape, weight
- Degree of bending
- Appearance (color, transparency)

Sources: Panasonic, SolarImpulse, EPFL

Photonic engineering with nanostructures

1. Make every atom count
2. Make PV more attractive
3. Tame the solar spectrum

Carnot (thermodynamic) limit

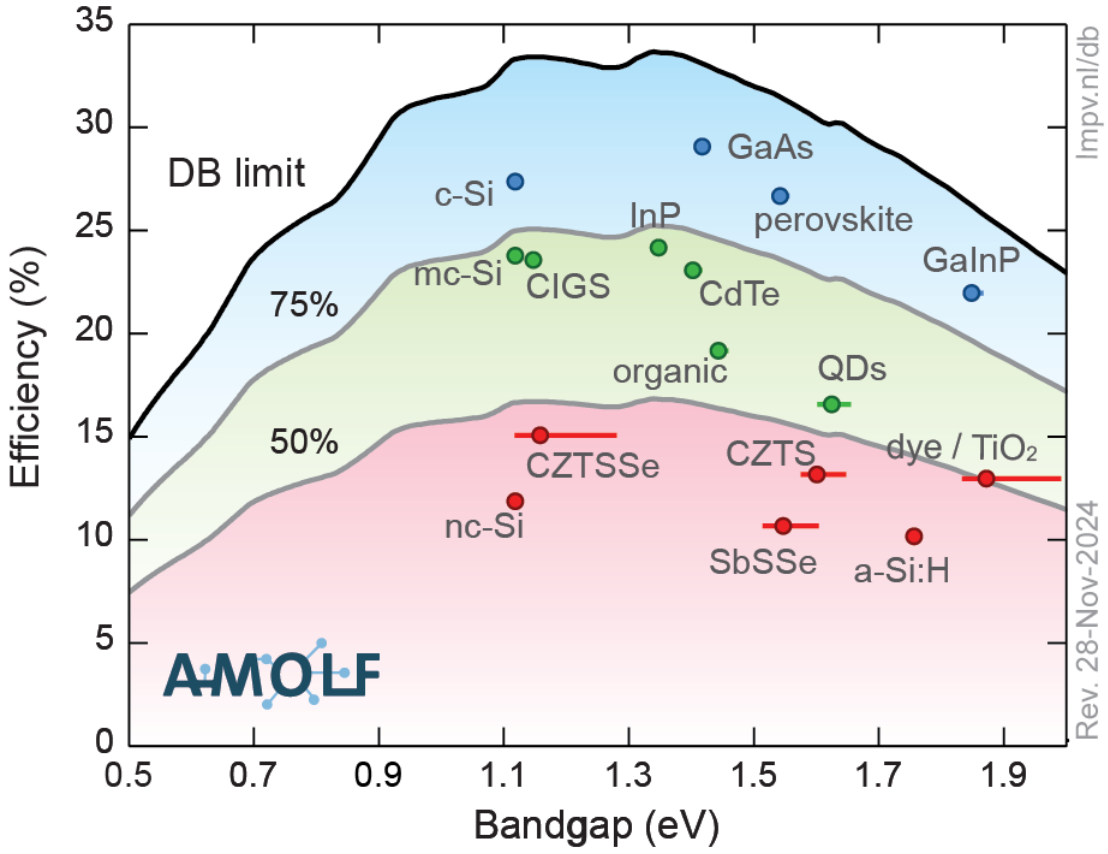


Landsberg limit ~93%

$$\eta = \frac{P_{out}^{max}}{P_{in}}$$

One absorber limit ~ 33%

The maximum efficiency



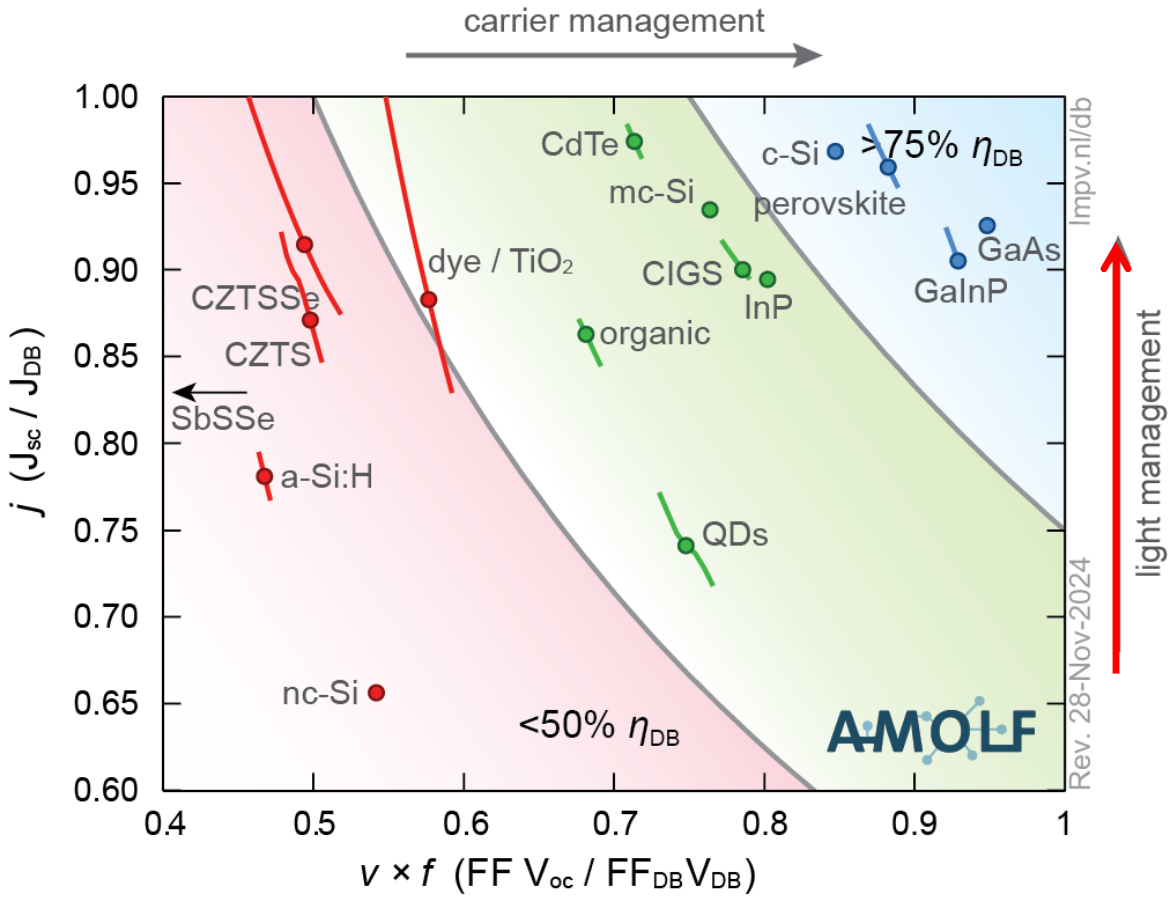
Detailed balance limit

Assumptions:

- No reflectance (R= 0)
- All photons with $E>E_G$ are absorbed
- No electrical losses

www.lmpv.nl

The maximum efficiency



Detailed balance limit

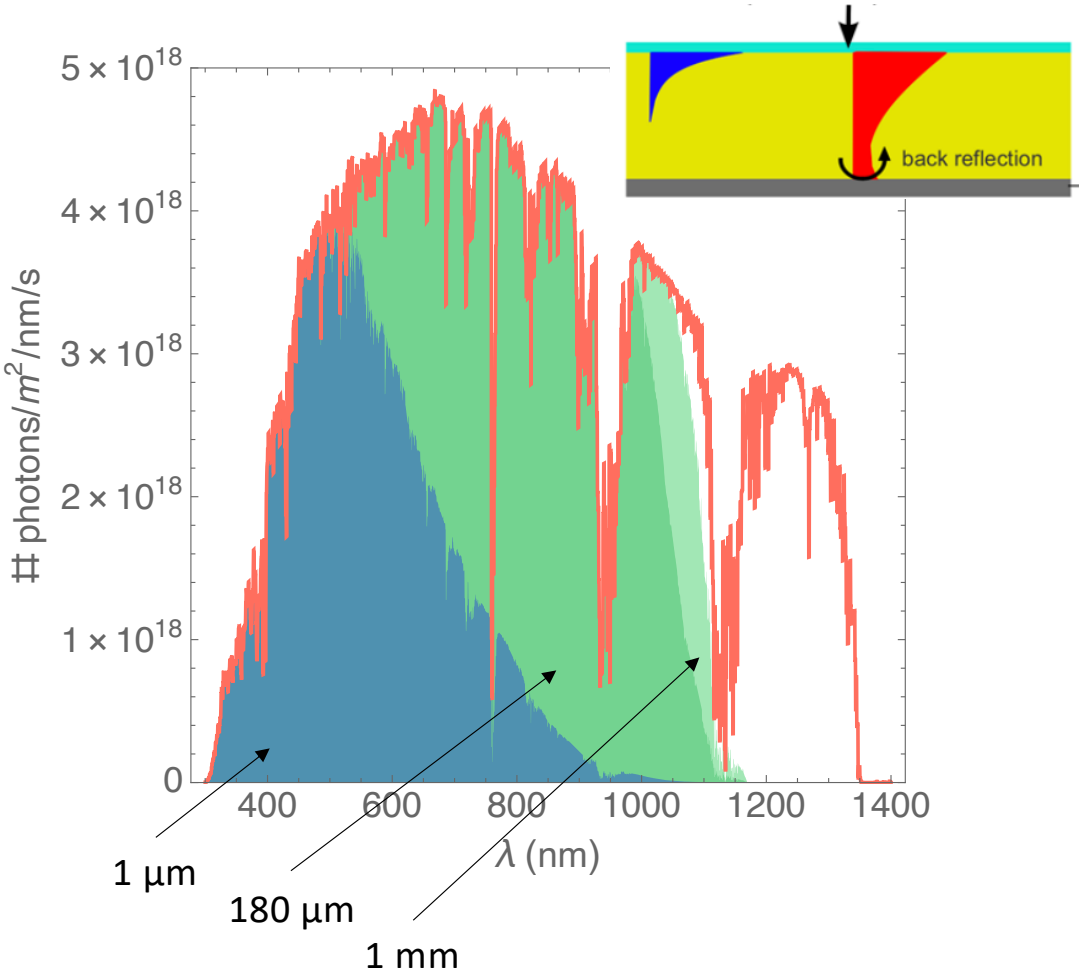
Assumptions:

- No reflectance (R= 0)
- All photons with $E>E_G$ are absorbed
- No electrical losses

$$Power \propto J_{SC}V_{OC}$$

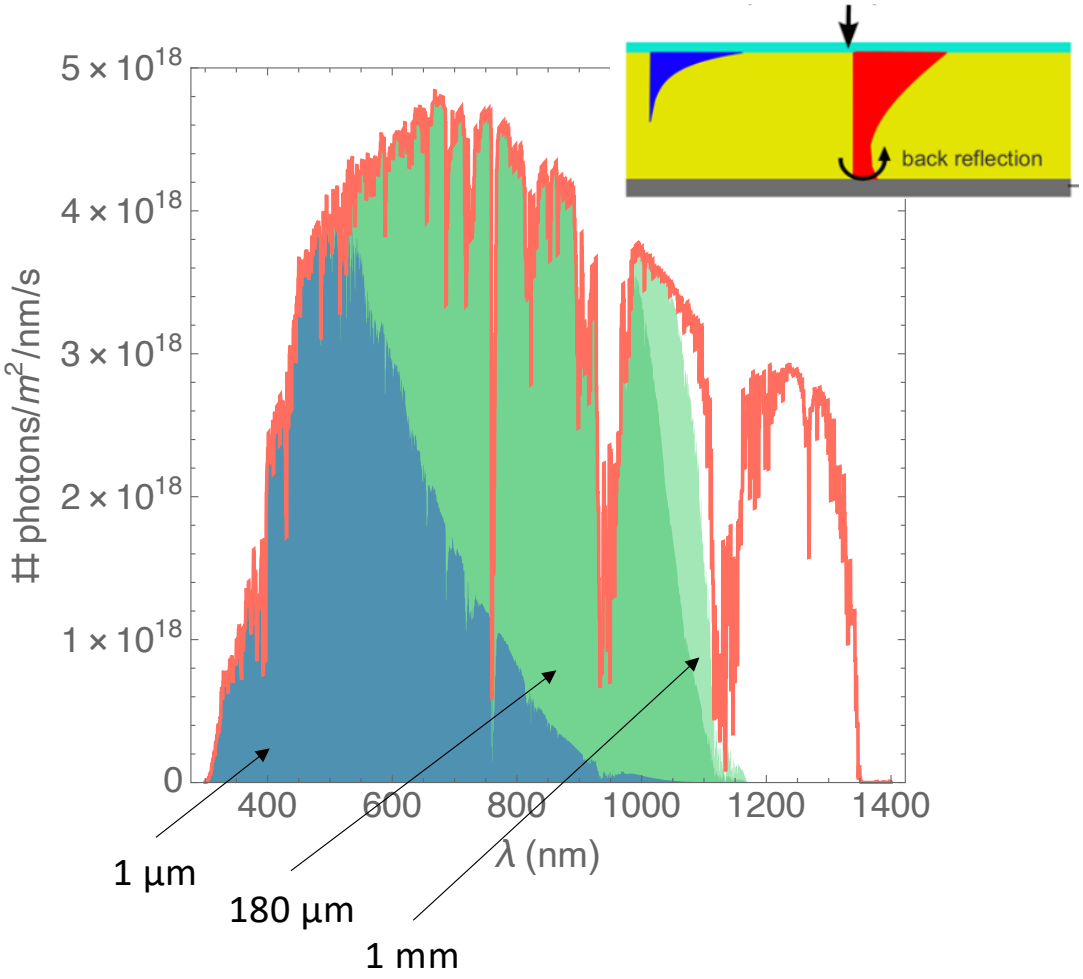
www.lmpv.nl

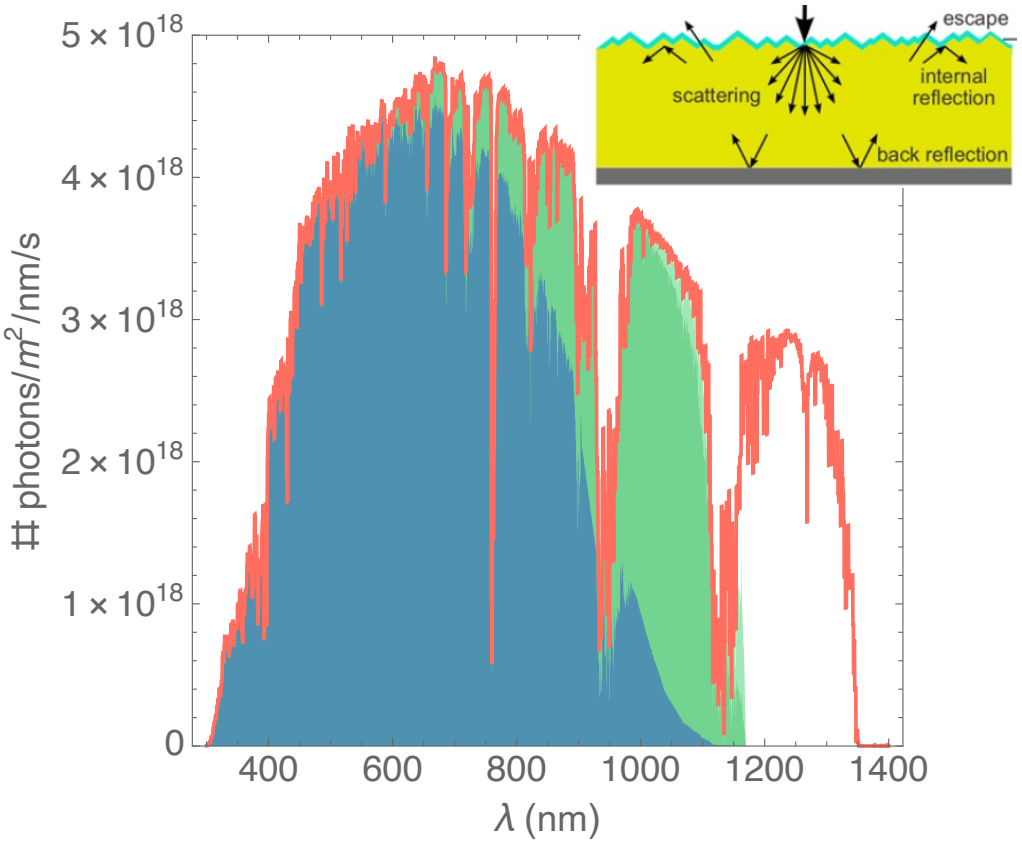
The solar spectrum



$$J_{SC} = e \int_0^{\infty} dE\, N_{ph}(E) IQE(E) Abs\,(E)$$

The solar spectrum



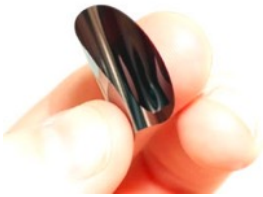


Why even consider ultra-thin Si solar cells?

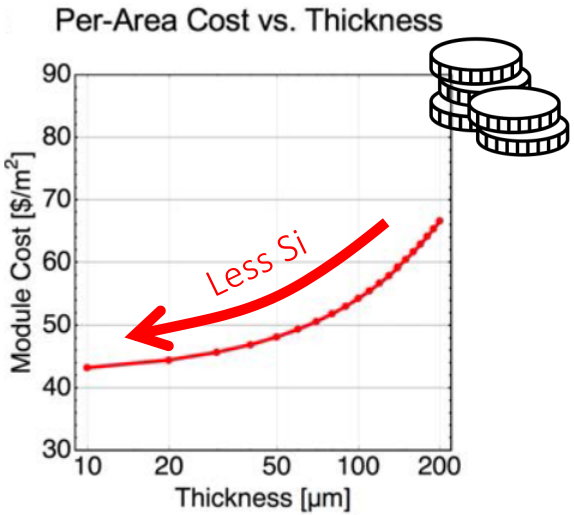


150-200 µm

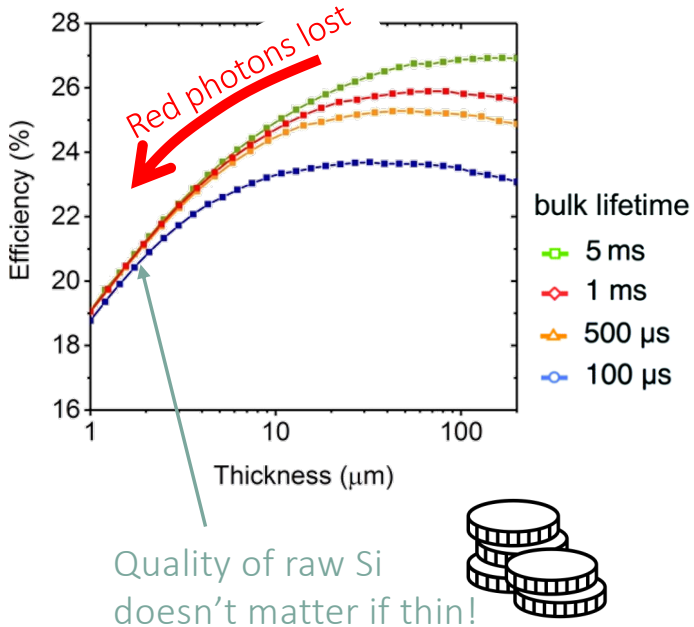




1-30 µm



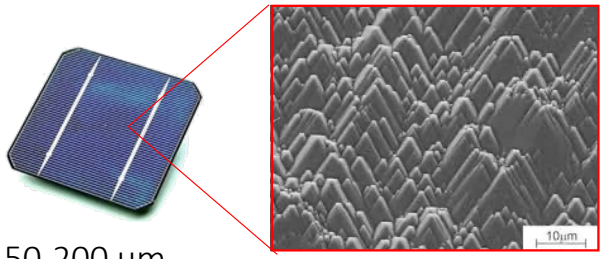
Cost savings from reducing silicon usage (regardless of the module efficiencies)



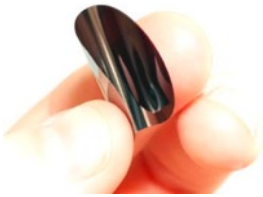
Quality of raw Si doesn't matter if thin!

Liu et al., Ener. Environ. Sci. 13, 12 (2020)

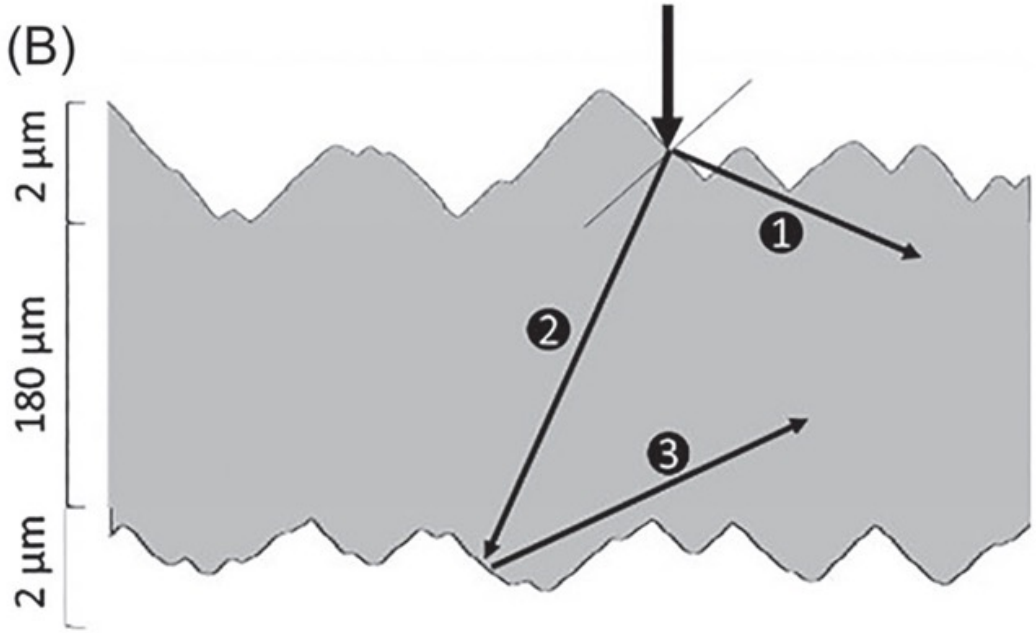
The photonic challenge in ultra-thin Si solar cells



150-200 µm

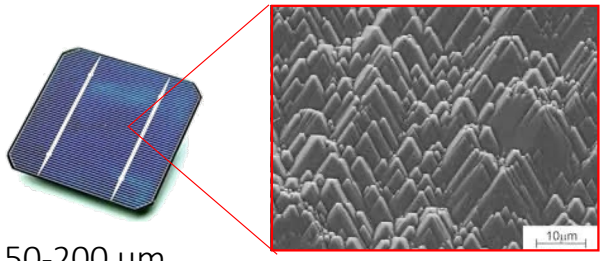


1-30 µm

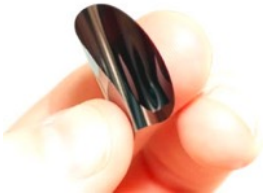


R. Saive, ProgPhotovoltResAppl.2021;1–13

The photonic challenge in ultra-thin Si solar cells

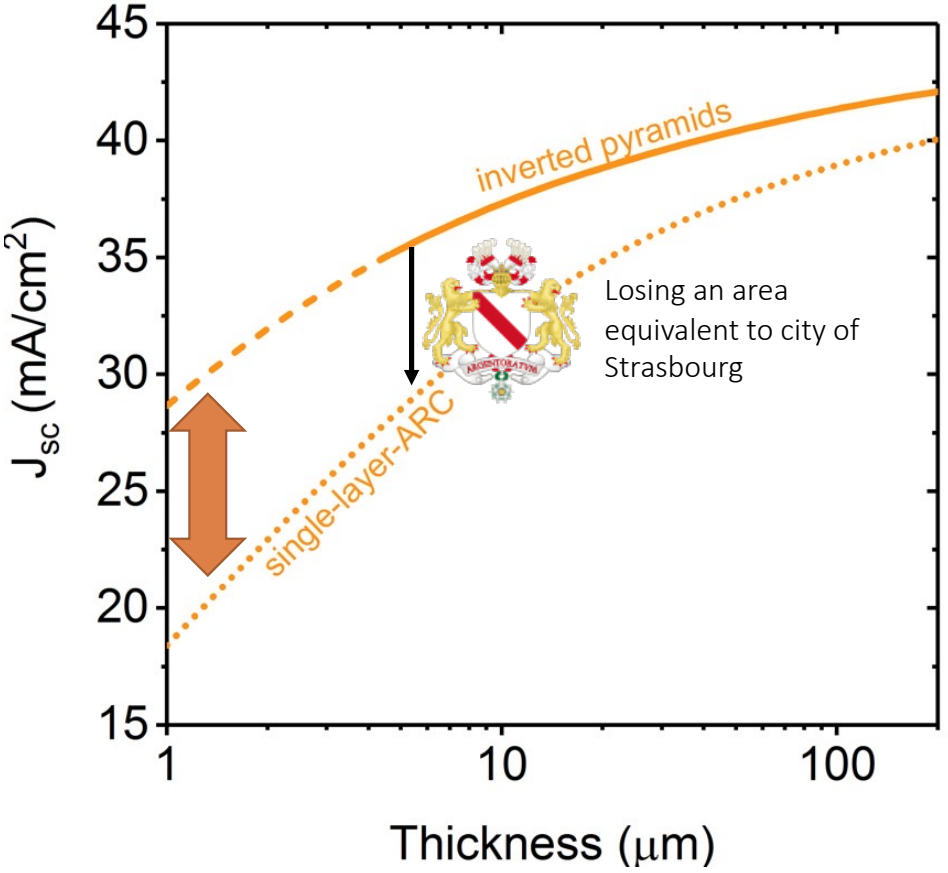


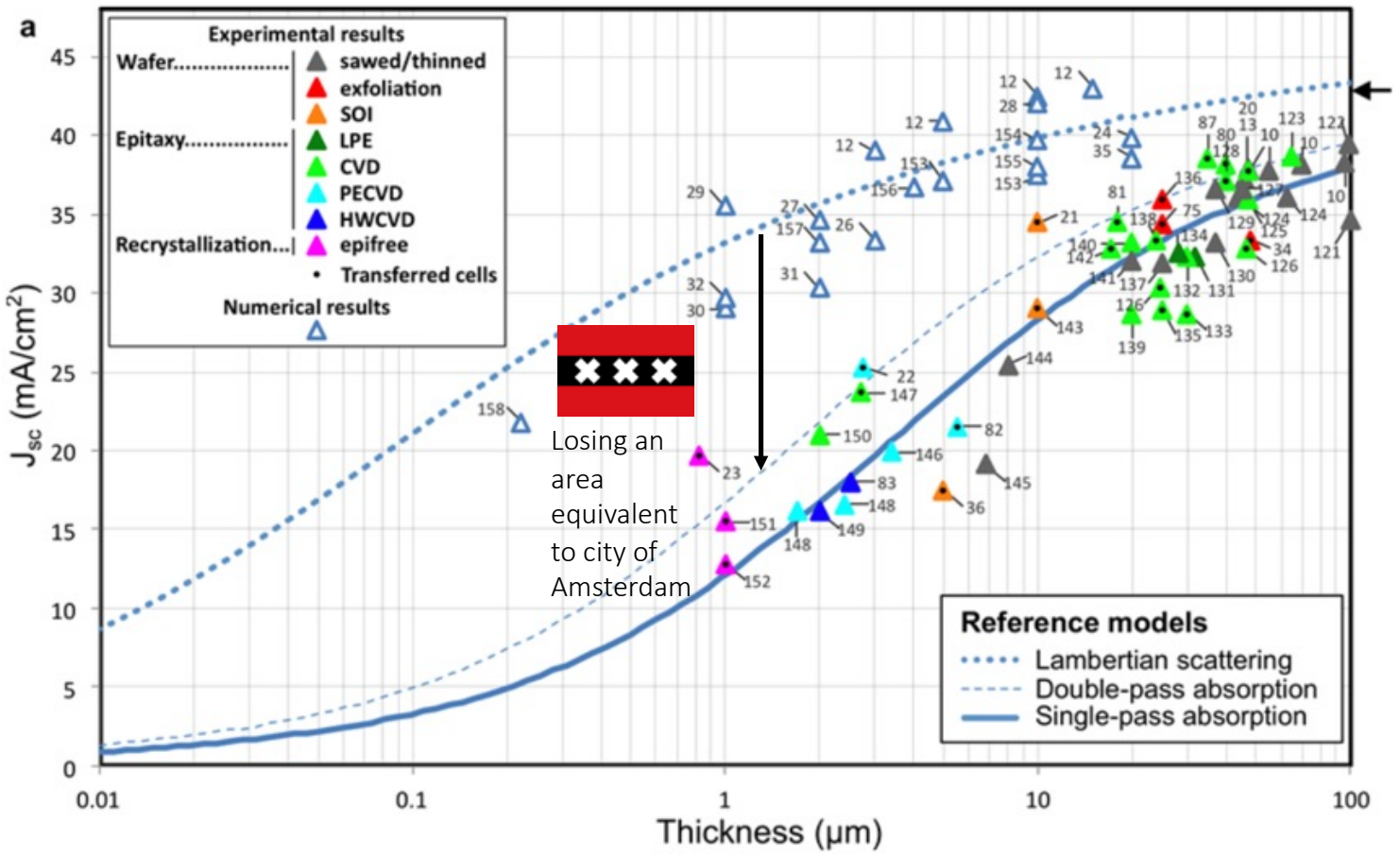
150-200 µm



1-30 µm

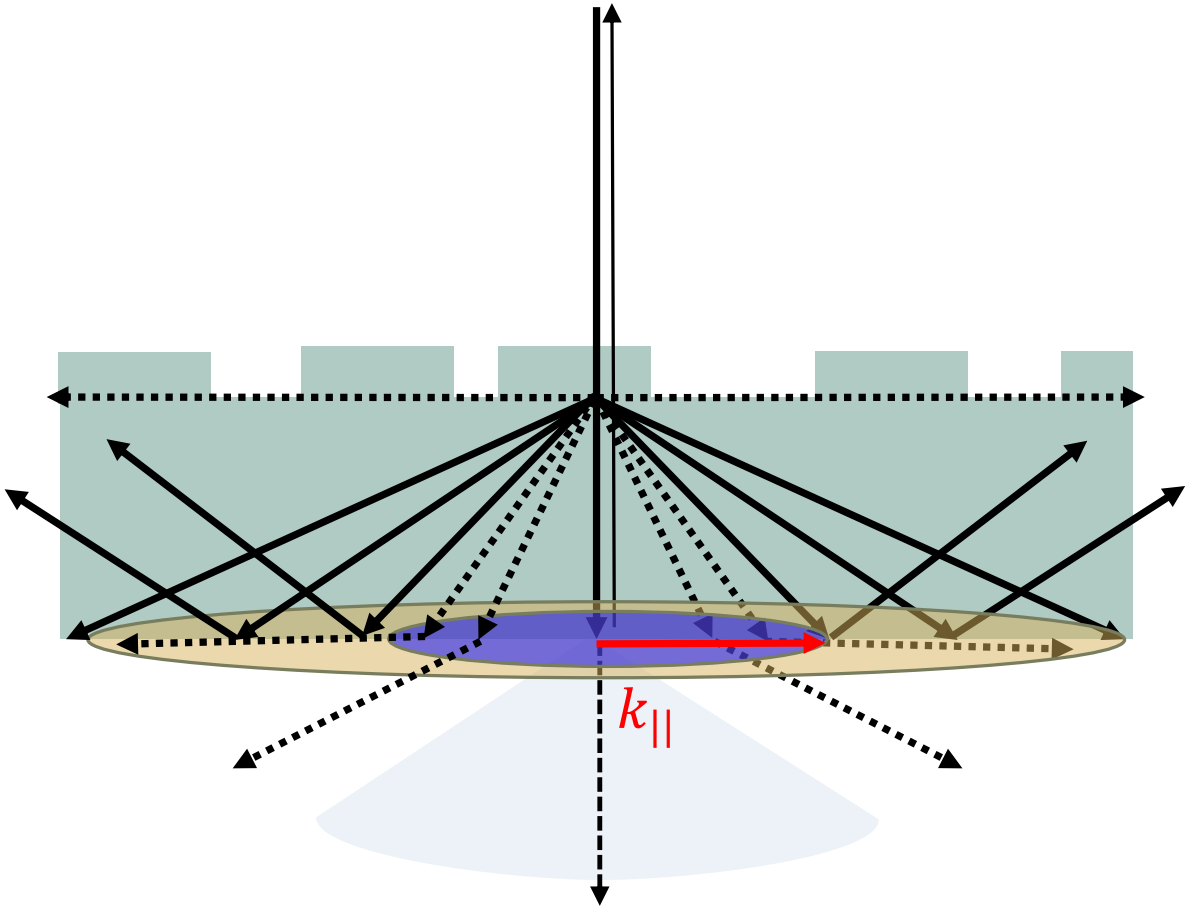
Nano-photonic light trapping





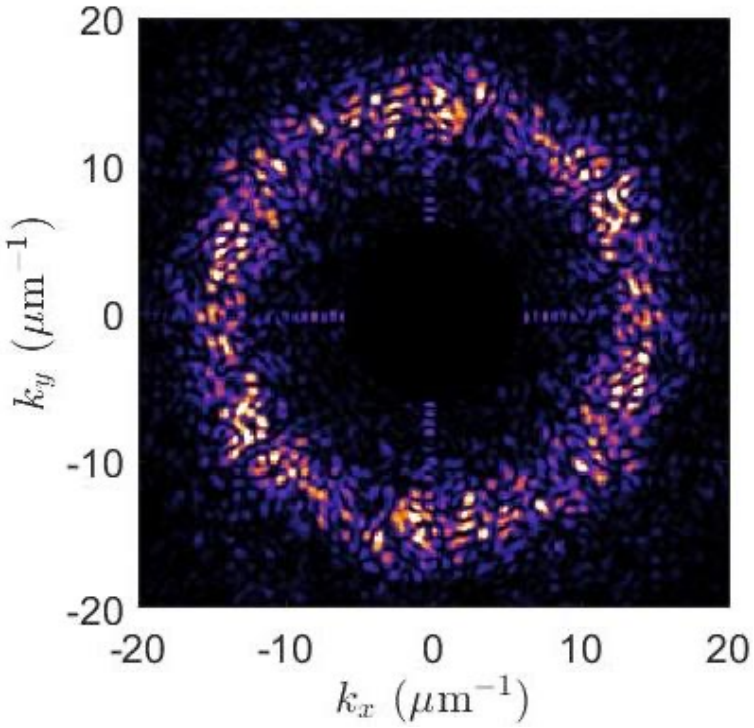
Massiot, Cattoni, Collin, Nat. Energy (2020)

Diffraction and coupling to waveguide modes



Scape cone

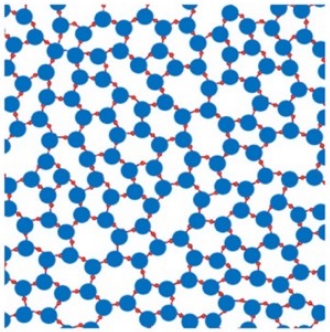
Ideal power distribution



Hyperuniform state of matter

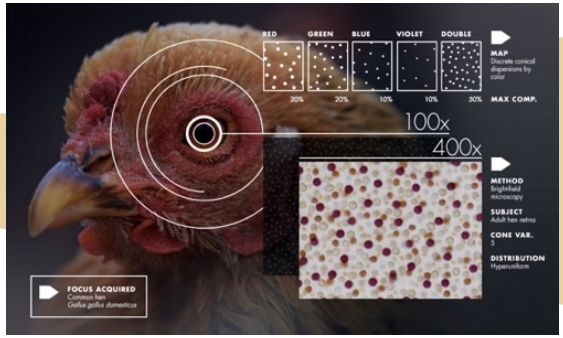
AMOLF physics of functional complex matter

Structure of amorphous solids



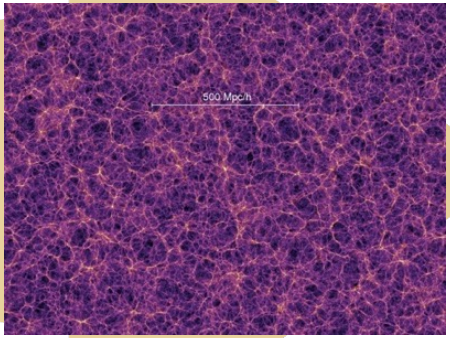
Science Advances (2020)
PRL 119, 136002 (2017)

Distribution of avian photo-receptors



Physical Review E, 89, 022721 (2014)

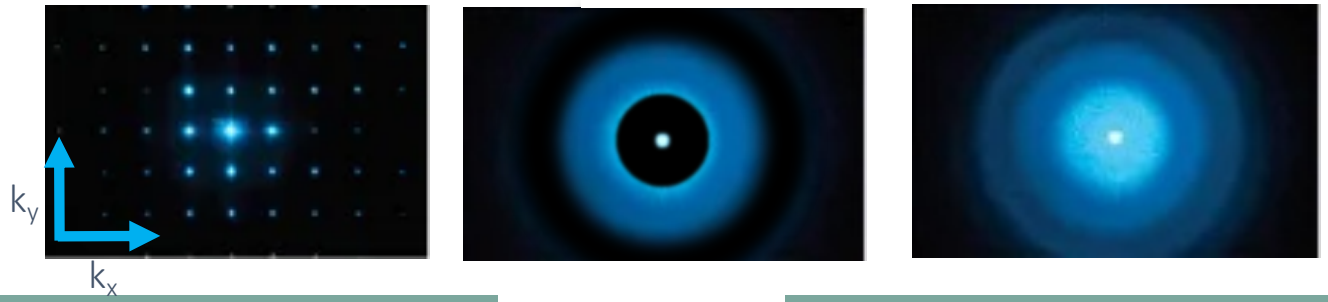
Large-scale structure of the universe



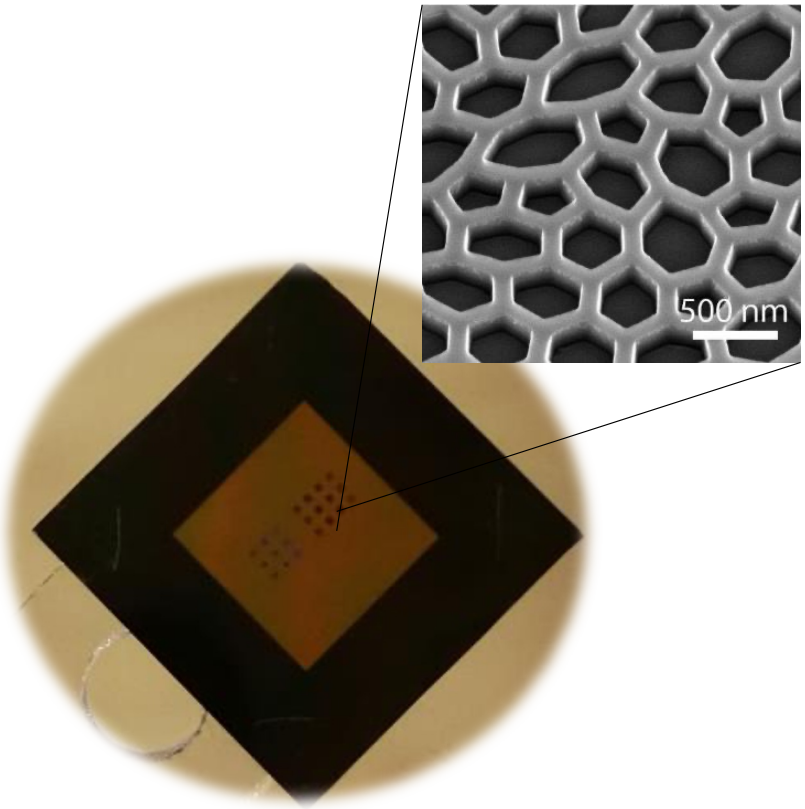
Nature 435, 629 (2005)

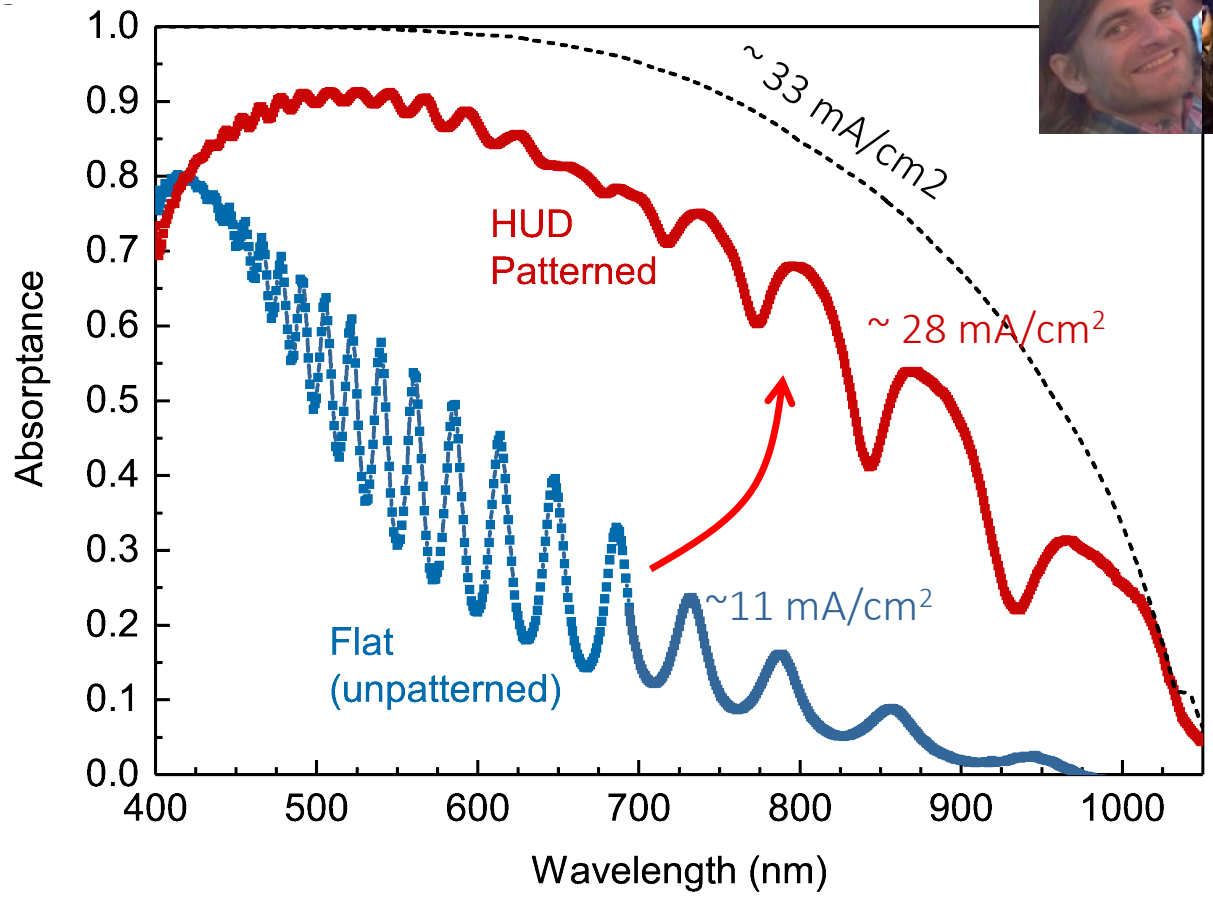
Nature's hidden order

periodic ⟷ HUD ⟷ random



Absorption enhancement



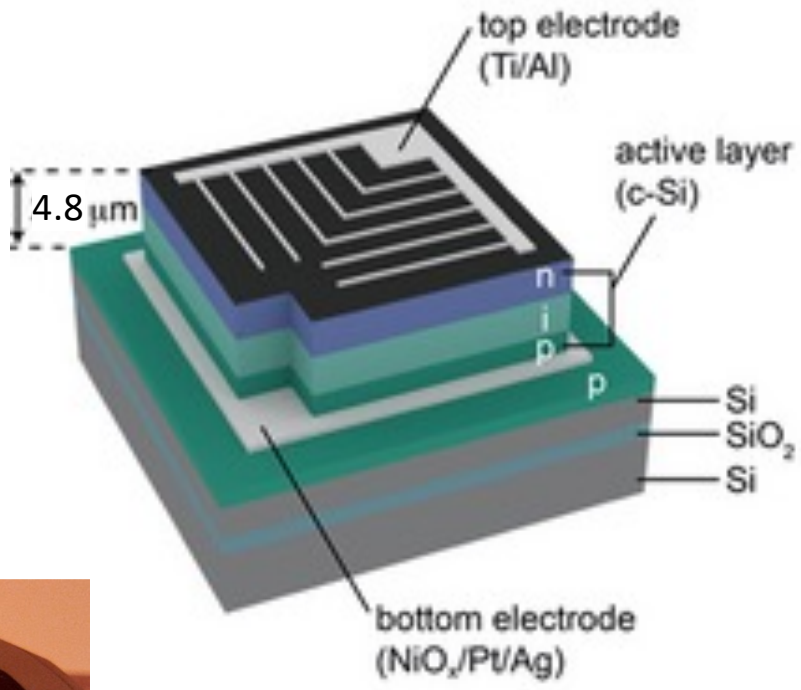




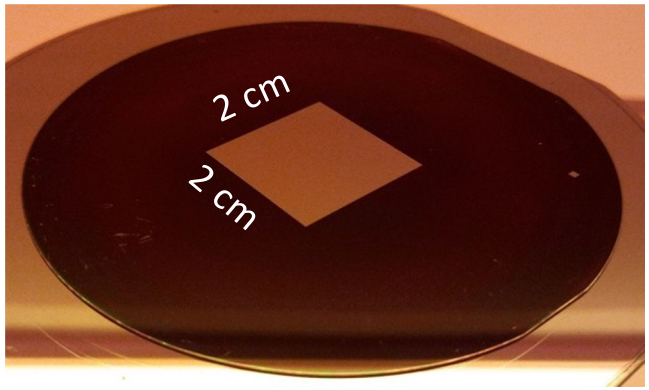
Tavakoli et al., ACS Photonics 2022

Preliminary data on 4.8 µm-thick Si cell

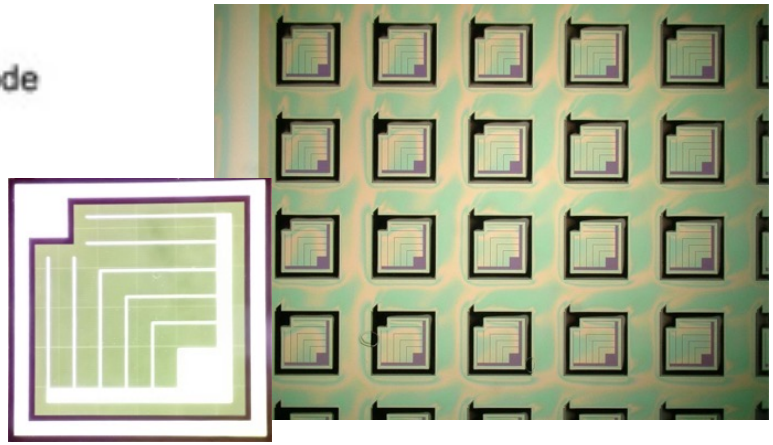




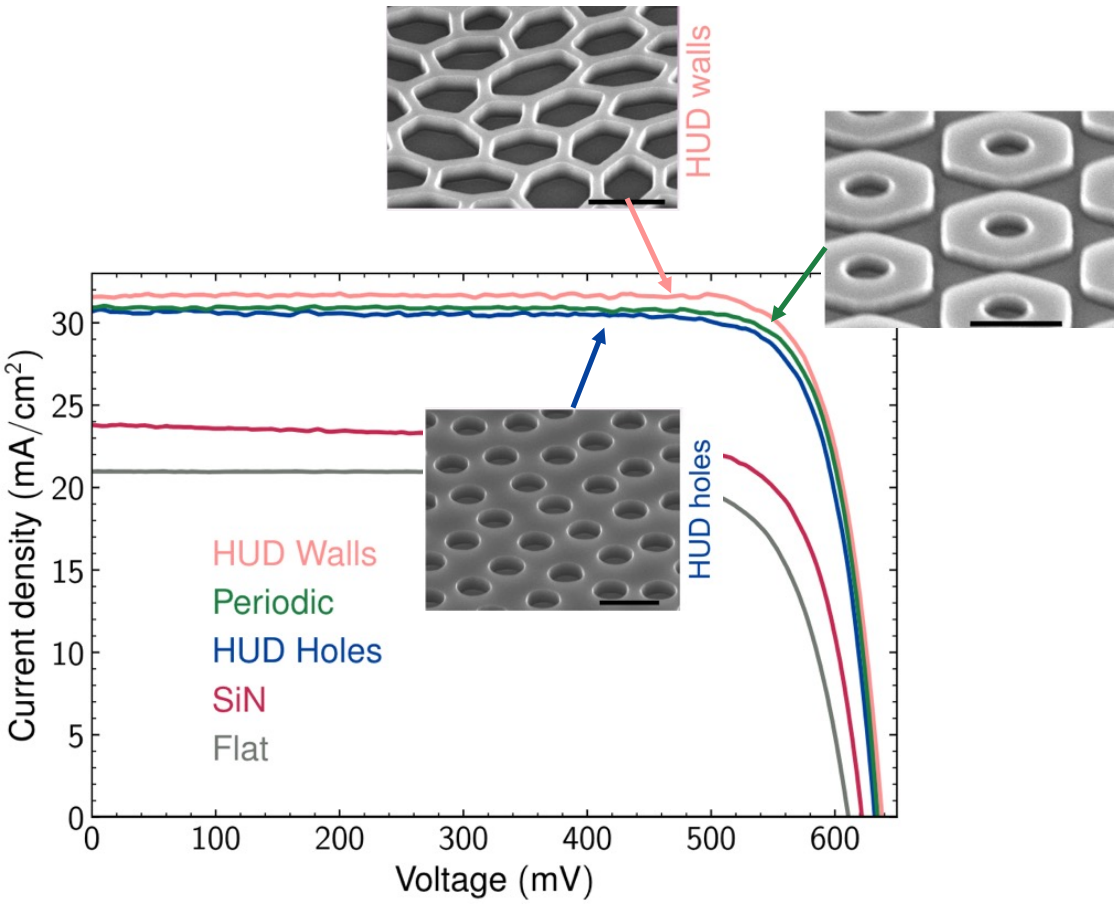
cm-scale patterning
(2 x 2 cm^2 fields)

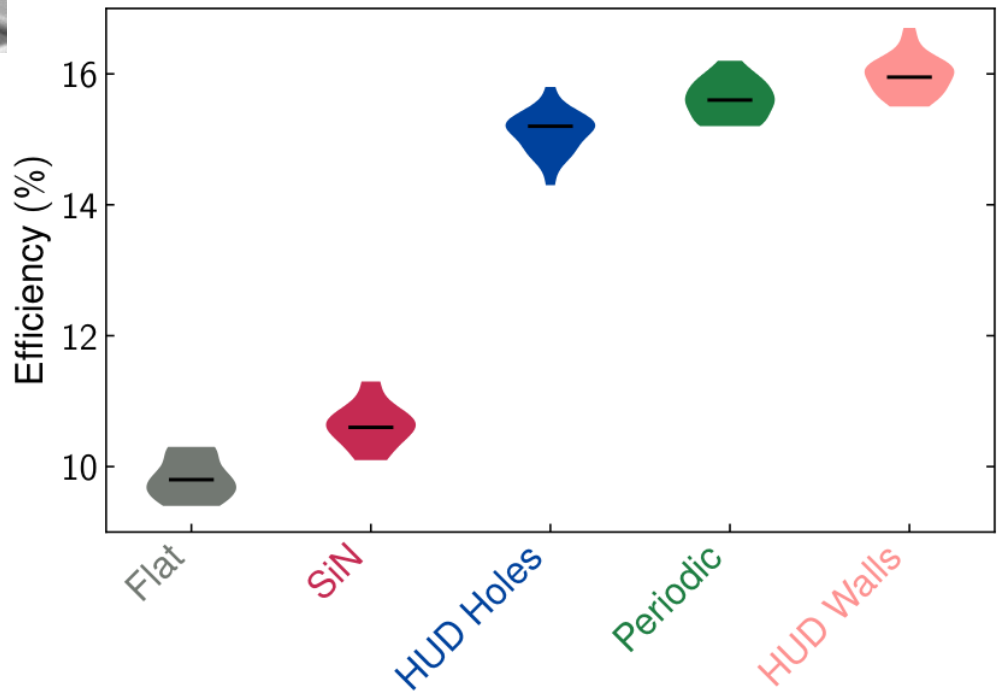


1.6 x 1.6 mm^2 solar cell demo

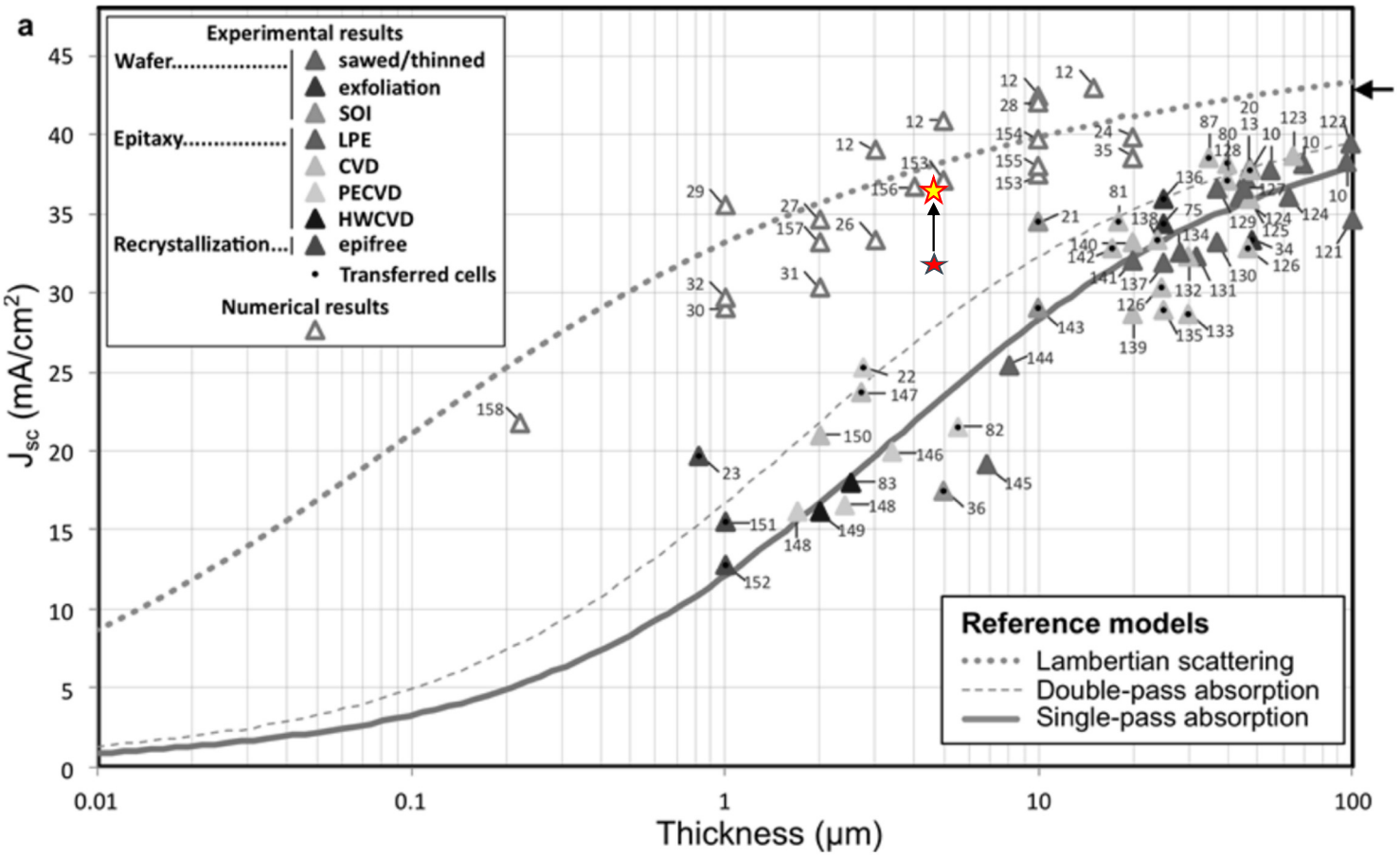


Preliminary data on 4.8 µm-thick Si cell





Putting things in perspective

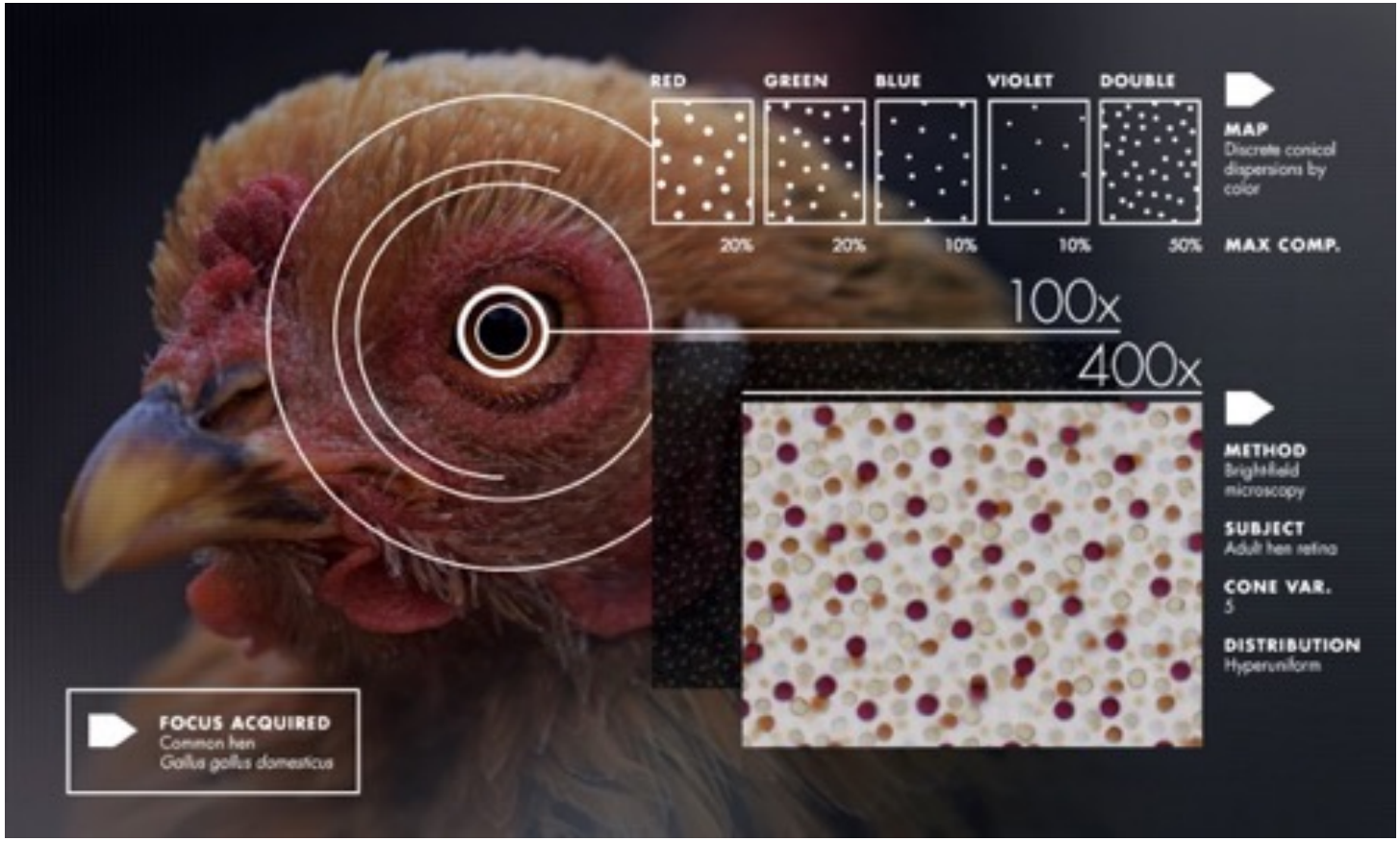


Can we improve diffracted power & distribution?

Massiot, Cattoni, Collin, Nat. Energy (2020)

Maximising diffracted power

Combining (multi-)color building blocks



Can we improve diffracted power & distribution?

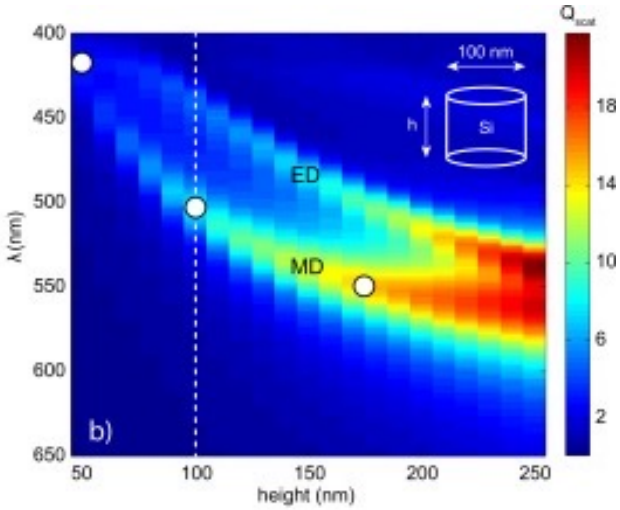
Physical Review E, 89, 022721 (2014)

Maximising diffracted power

Combining (multi-)color building blocks

Resonant



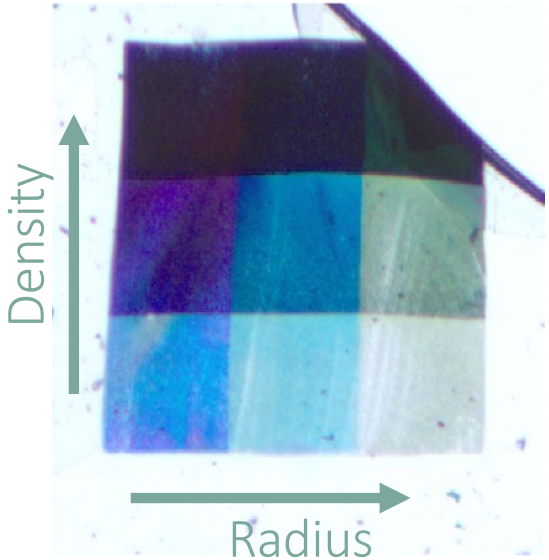


Van der Groep, Polman, Opt. Expr. (2013)

Resonant-like

Real footprint

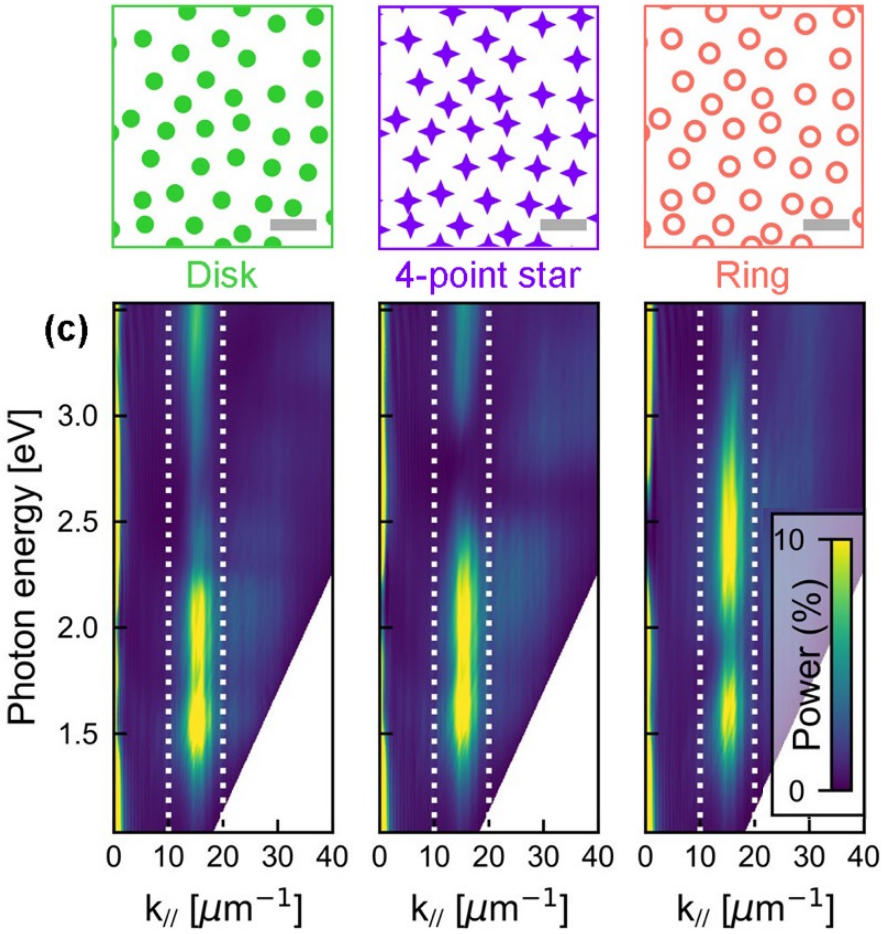
absorption footprint



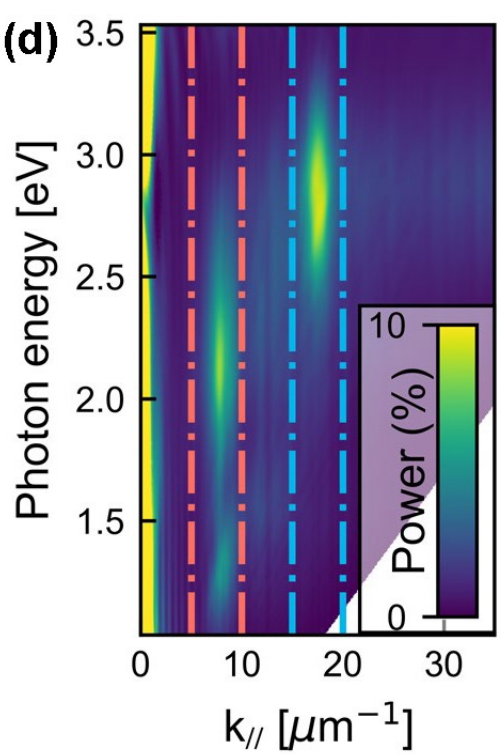
Nanotechnology 25, 014015 (2014)

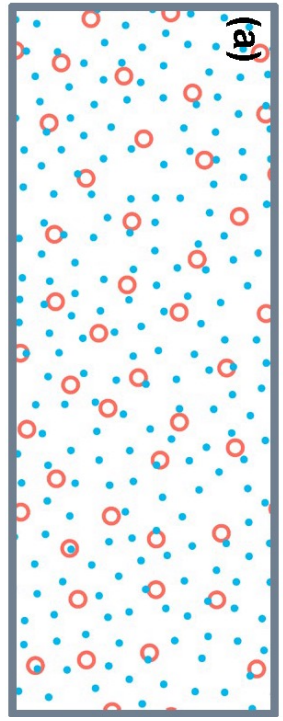
Color and angle selectivity

Color-selective building blocks

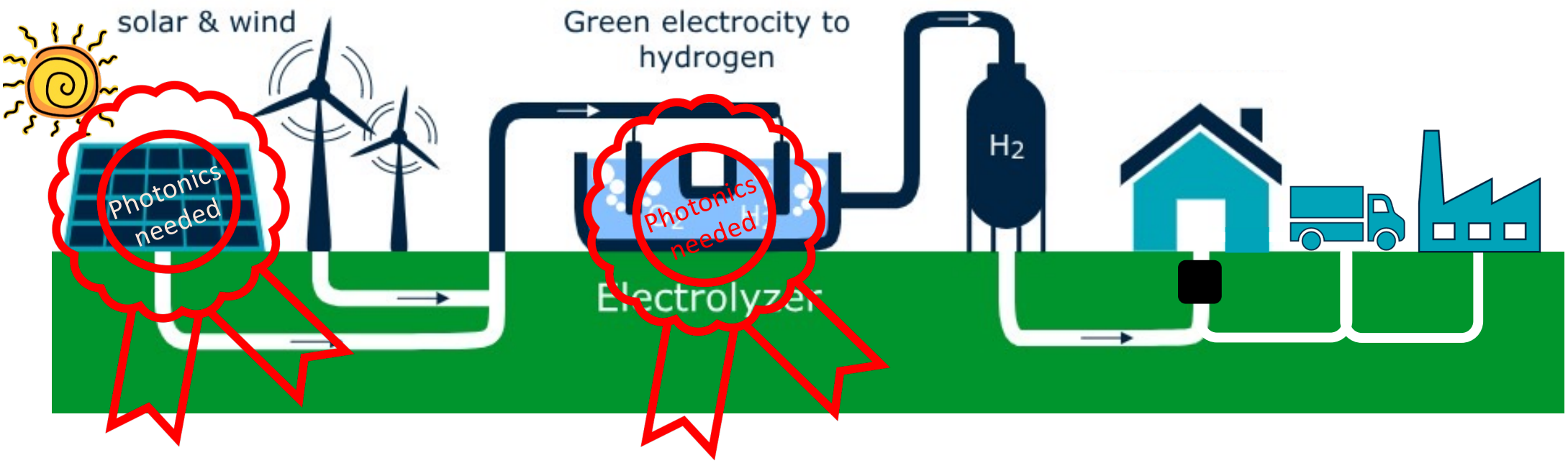


Combining angle-selective arrangements



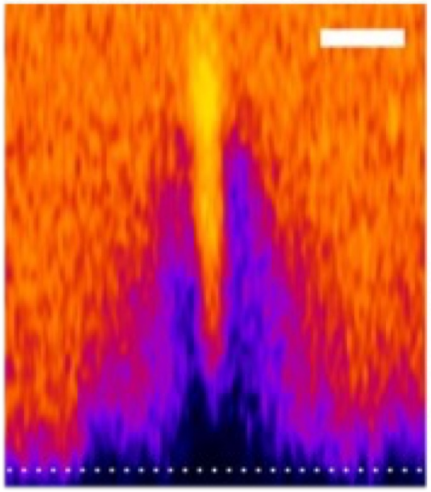


The energy transition



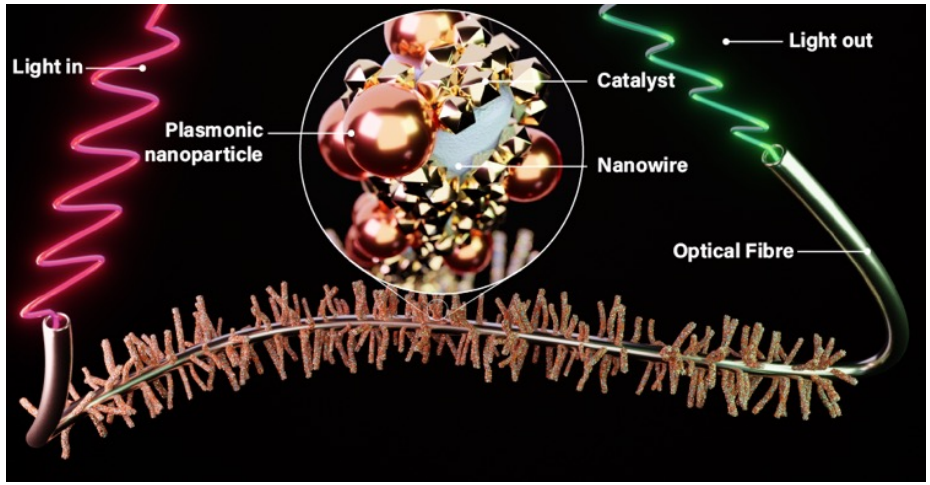
Manipulating Light for Chemistry

AMOLF physics of functional complex matter



Nanoscale light management

- Extreme (non)-resonant light trapping
- Nanoscale waveguiding
- Color selectivity
- Non-resonant surface light enhancement



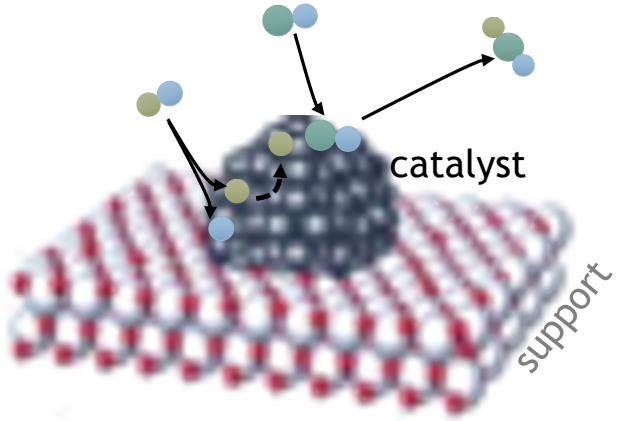
New (photo)(electro)chemical reactor designs

- Bringing light/energy where and when needed

Light-driven thermo catalysis

AMOLF physics of functional complex matter

Catalysis



Pollution control

Chemical production

selective oxidation

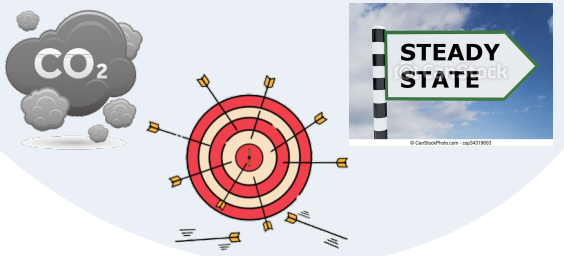
Fuel production

Heat management is crucial

Selectivity
Minimal waste
Efficiency
Safety

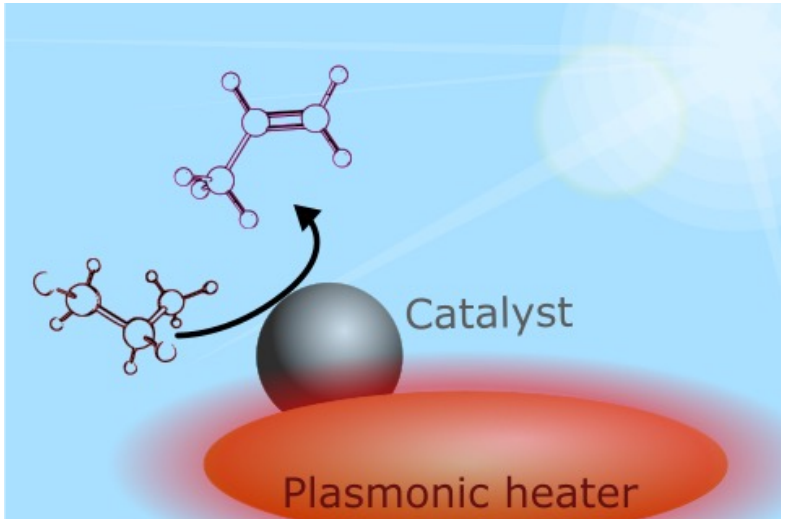


Wisman et al., Science 364, 6442 (2019)



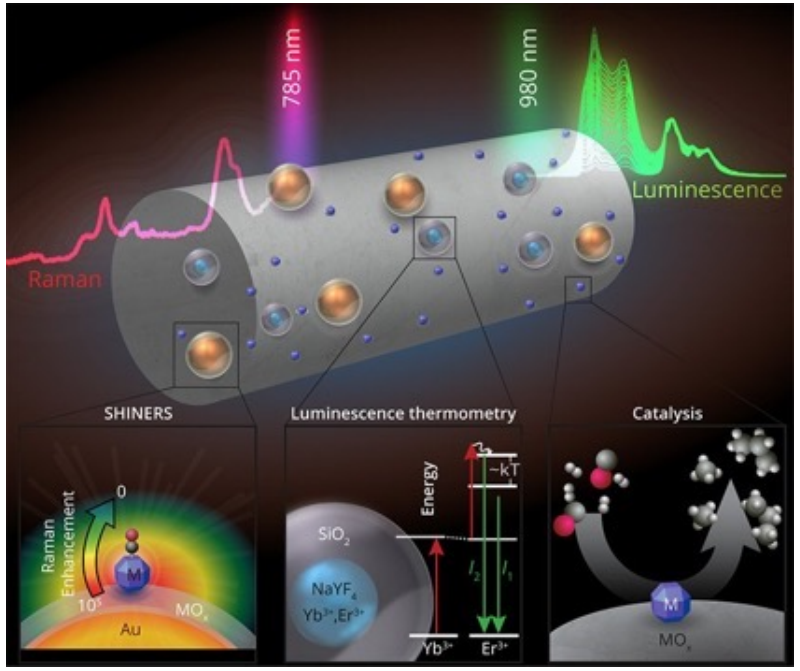
There is a *brighter* solution…

- Hot spot generation
- Dynamic (cw→ps) heating
- Catalyst regeneration



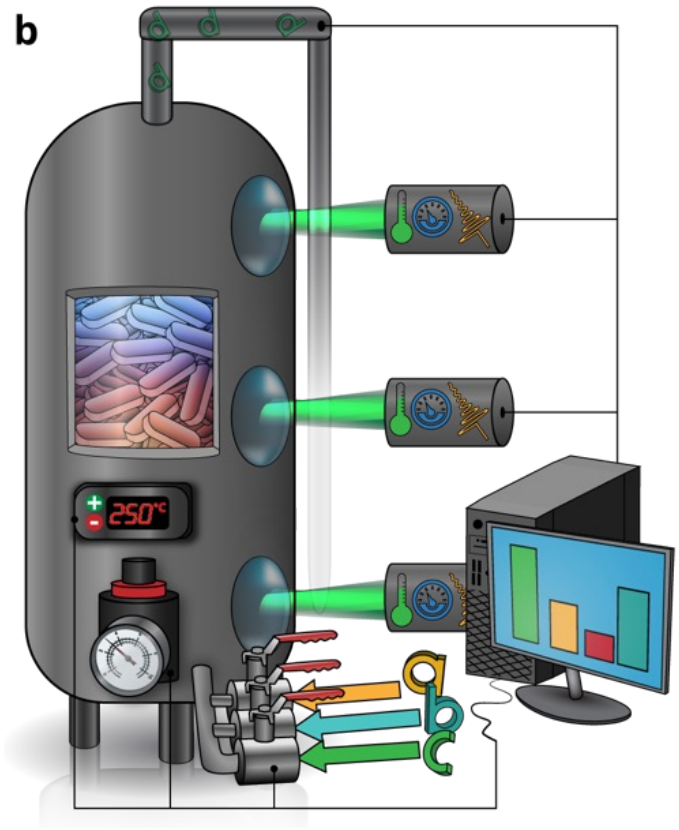
Entirely new way to make chemical processes more active, selective and energy efficient

- Thermometry
- Reaction rate/product metrology
- Operando probing



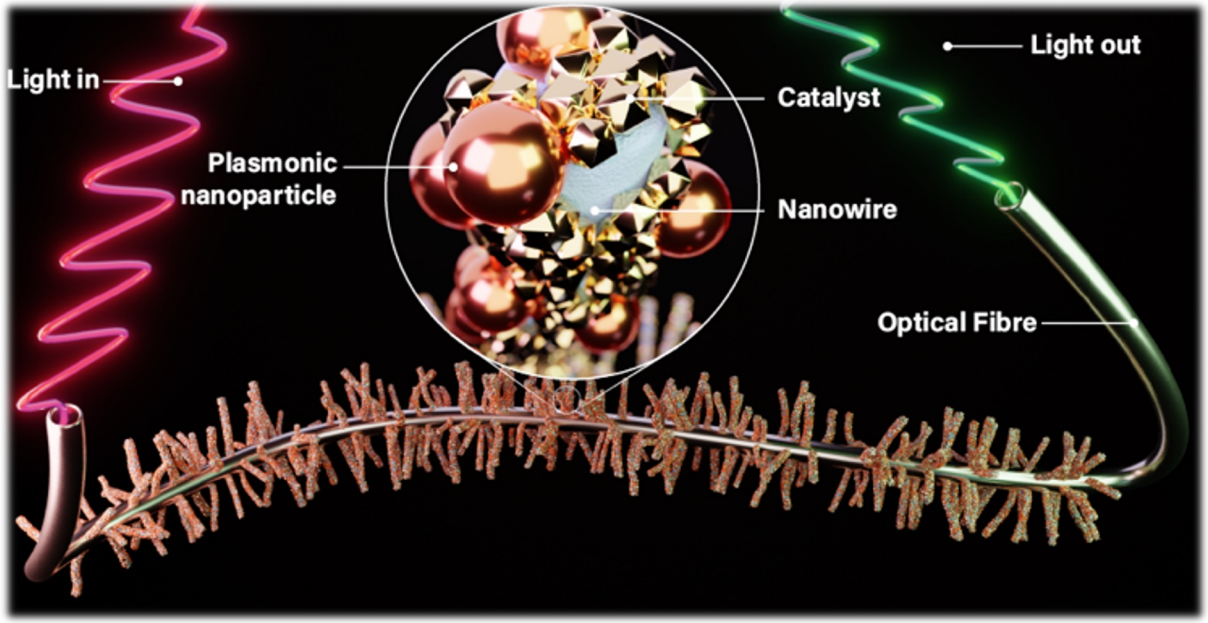
Monitor spectroscopic fingerprints of the reactive species involved in the chemical pathways as they proceed in space and time

A key challenge…



Nat. Catal. 2019, ACS Nano 2020

Bringing light to the reactor



- Multiplexing and controlled outcoupling
- 2D or 3D?
- …

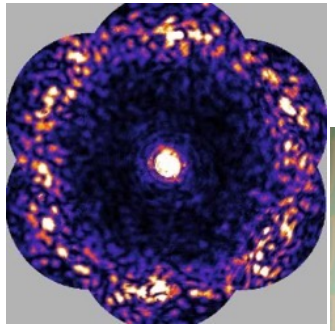
Summary

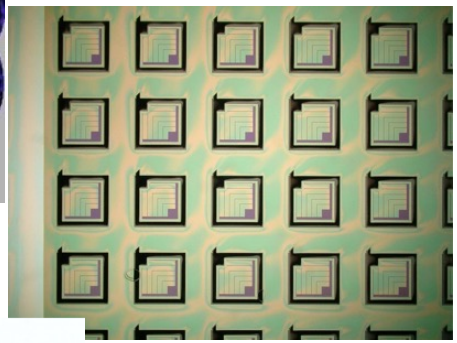
PV can extremely benefit from HUD

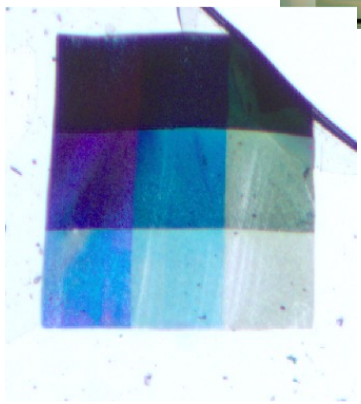
- enhance light paths
- maximize specific power generation
- create new looks and flexibility to inorganic PV

Challenges

- Fabrication implementation
- Industrial involvement







Thanks!