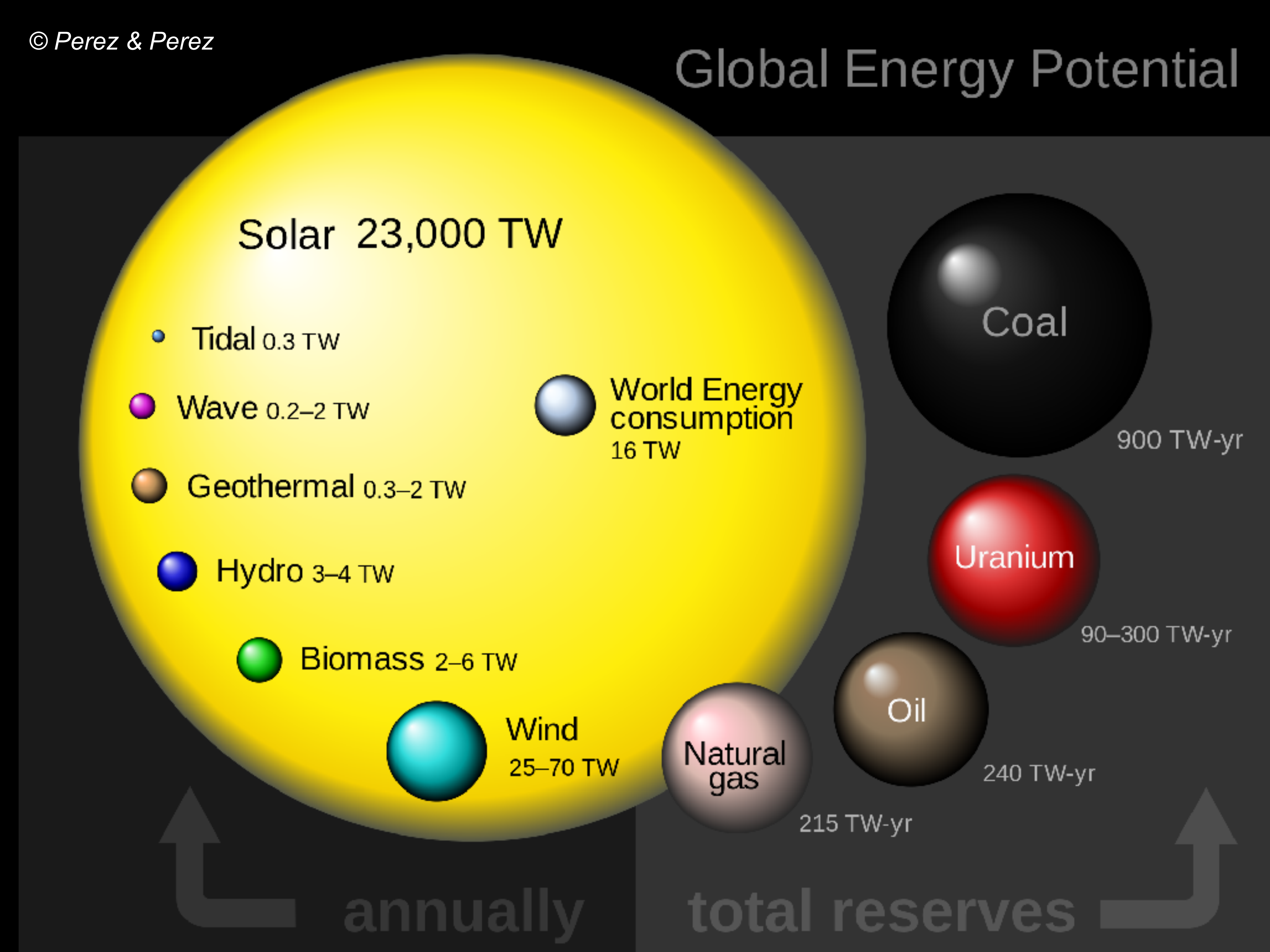
FFFF01+05 vt 2017

Photovoltaics: Basics, technology and current research

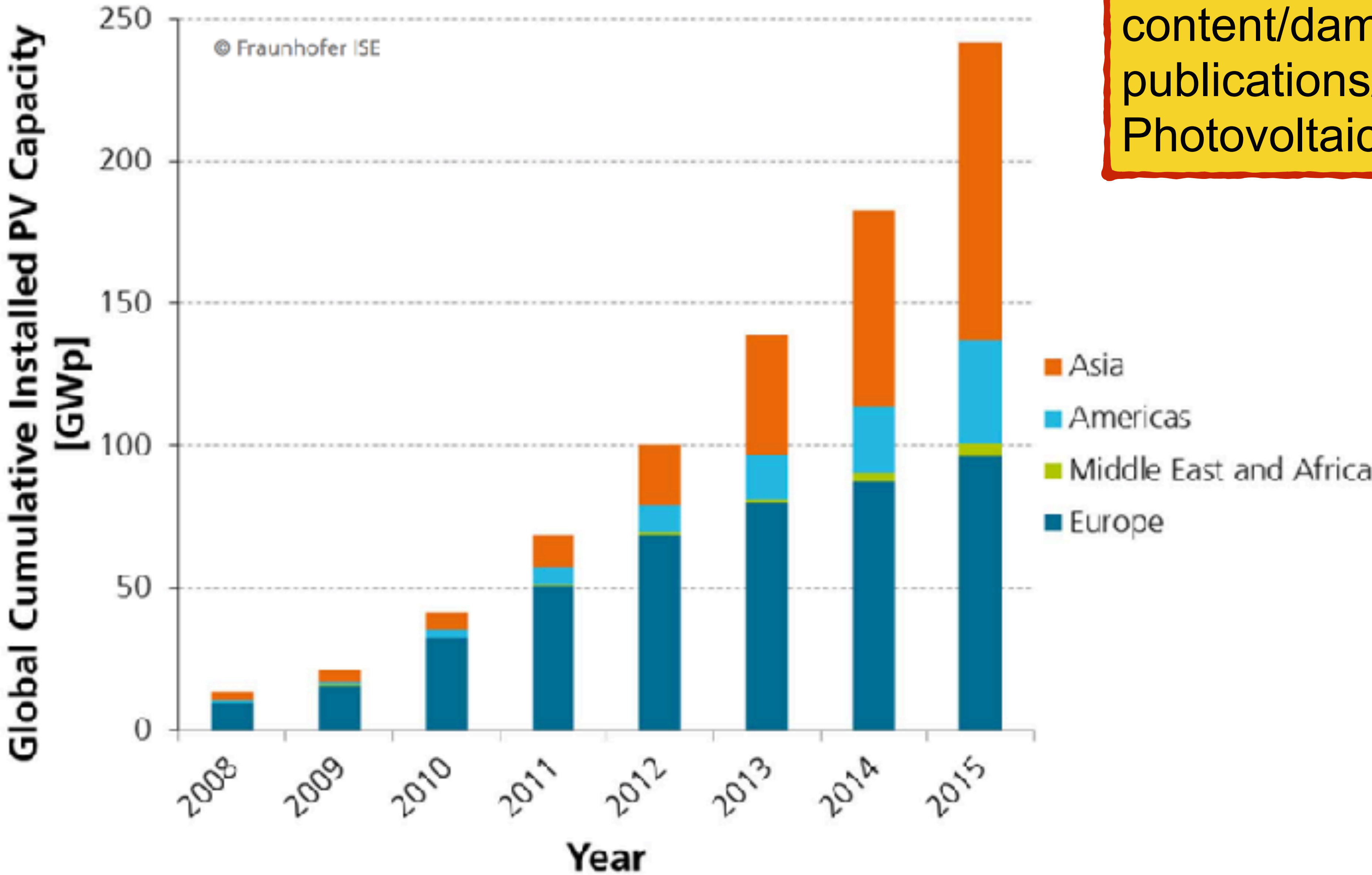
Martin Magnusson
Fasta tillståndets fysik


© Perez & Perez
Global Energy Potential
Solar 23,000 TW
Tidal 0.3 TW
Wave 0.2–2 TW
Geothermal 0.3–2 TW
Hydro 3–4 TW
Biomass 2–6 TW
Wind 25–70 TW
World Energy consumption 16 TW
Coal
900 TW-yr
Uranium
90–300 TW-yr
Oil
240 TW-yr
Natural gas
215 TW-yr
annually
total reserves

Global Cumulative PV Installation until 2015

+ 42% per year 2000 – 2015 !

Current status of PV:
https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf



Data: IHS. Graph: PSE AG 2016

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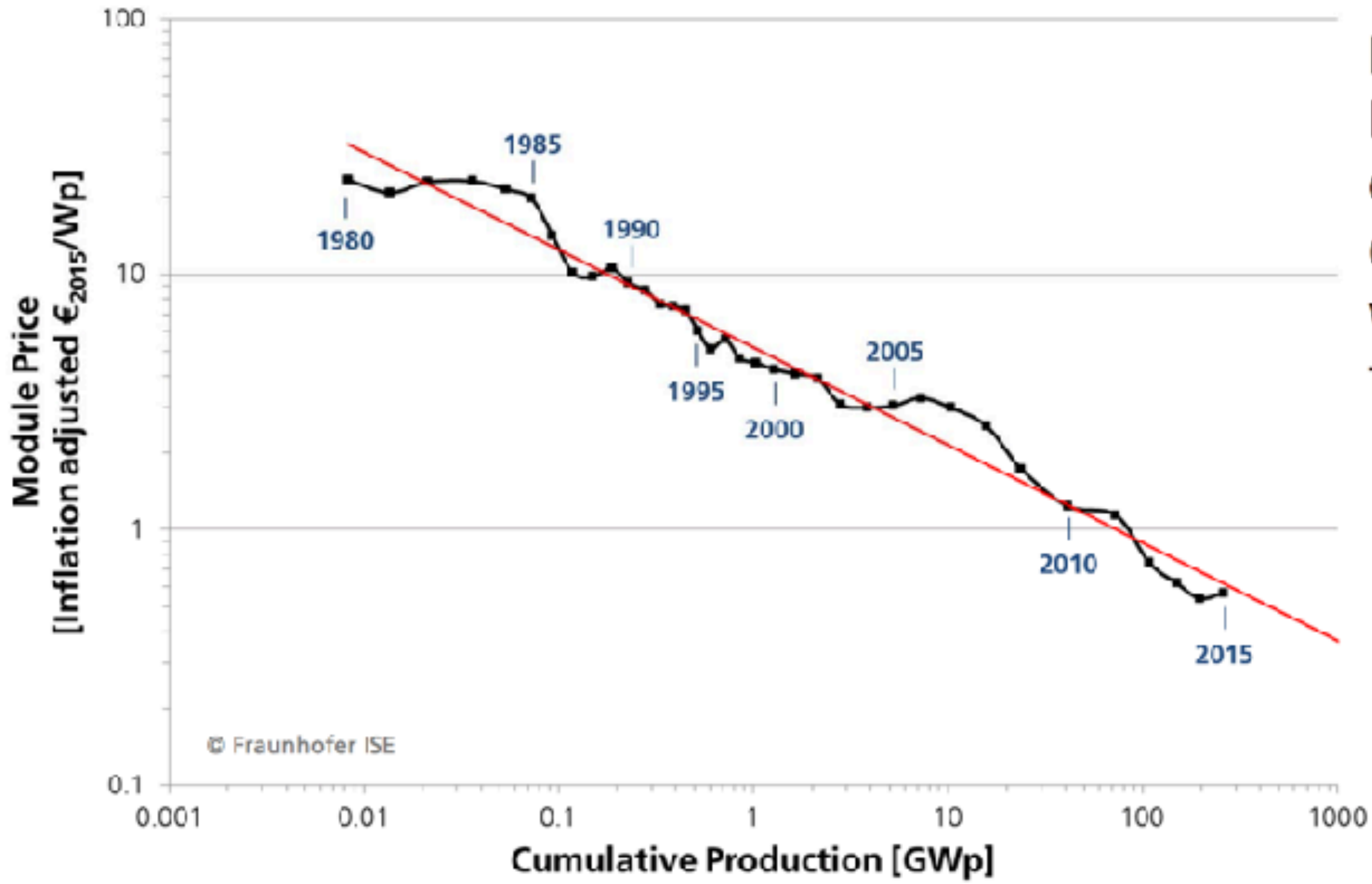
Price Learning Curve

Includes all Commercially Available PV Technologies



Learning Rate:
Each time the cumulative production doubled, the price went down by 23 % for the last 35 years.

Data: from 1980 to 2010 estimation from different sources : Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011 to 2015: IHS. Graph: PSE AG 2016

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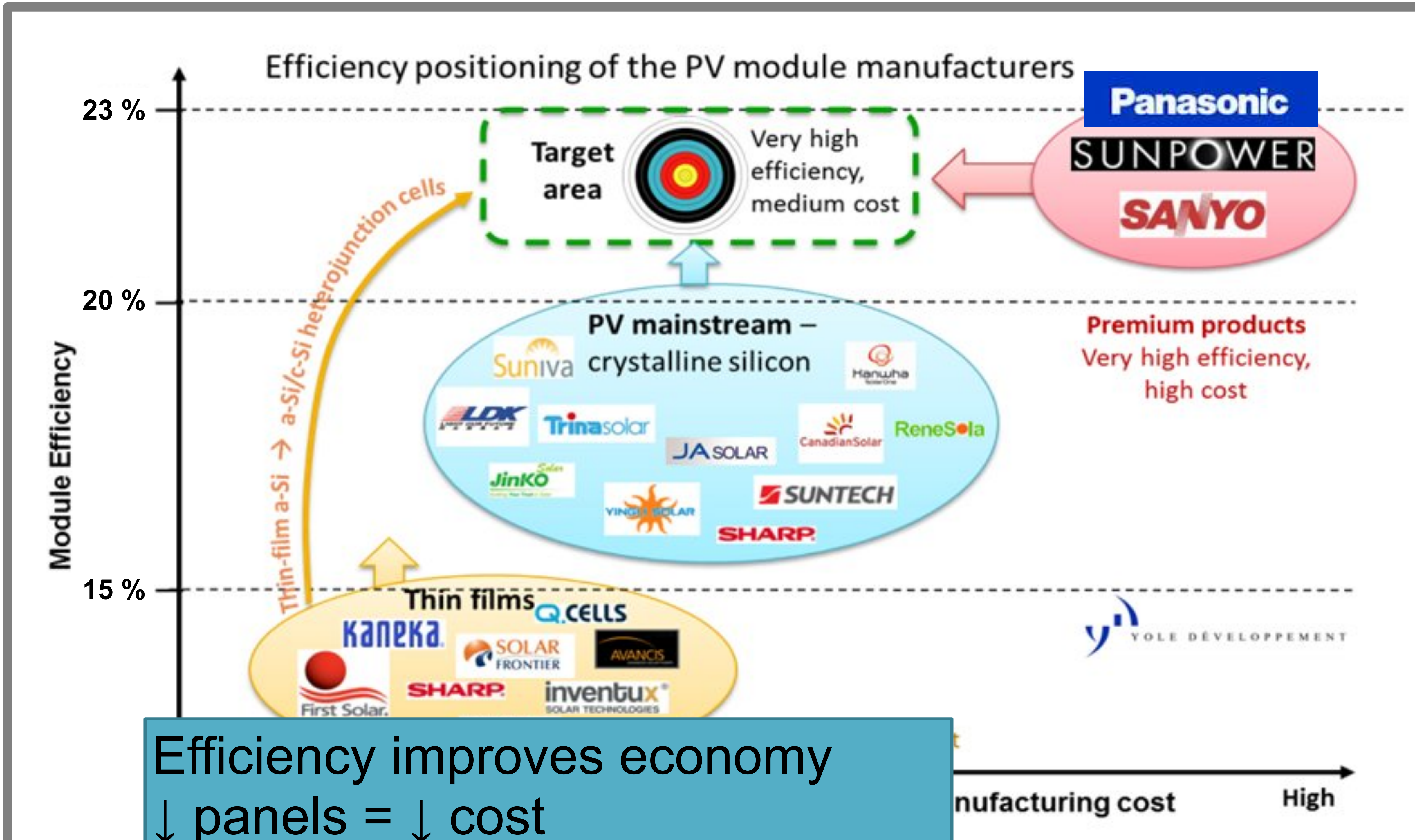
Increased efficiency lowers the cost

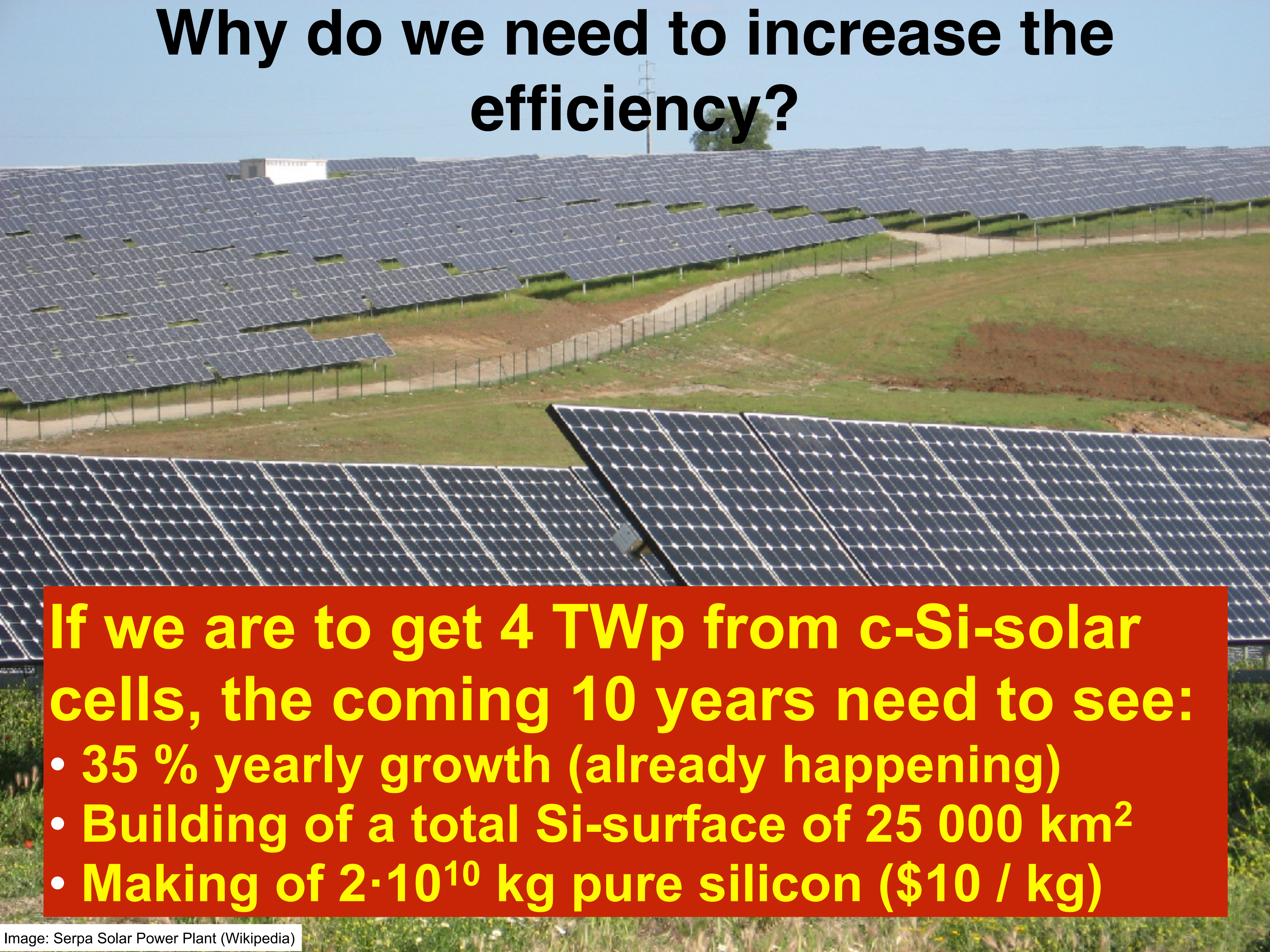


Efficiency improves economy

↓ panels = ↓ cost

↑ power = ↑ price

Why do we need to increase the efficiency?

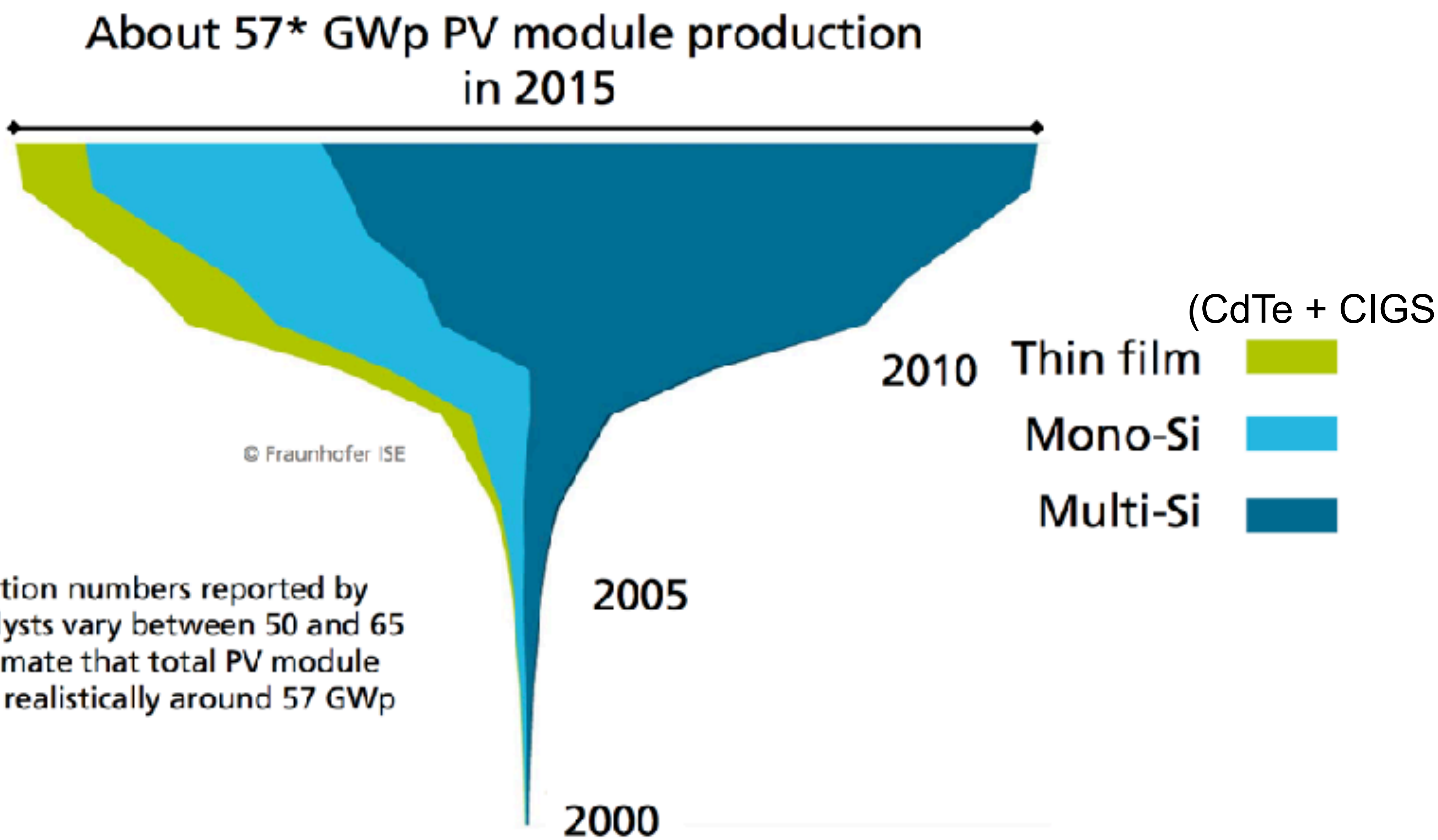


If we are to get 4 TWp from c-Si-solar cells, the coming 10 years need to see:

- **35 % yearly growth (already happening)**
- **Building of a total Si-surface of 25 000 km^2**
- **Making of $2 \cdot 10^{10}$ kg pure silicon (\$10 / kg)**

Image: Serpa Solar Power Plant (Wikipedia)

Annual PV Production by Technology
Worldwide (in GWp)



*2015 production numbers reported by different analysts vary between 50 and 65 GWp. We estimate that total PV module production is realistically around 57 GWp for 2015.

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2016

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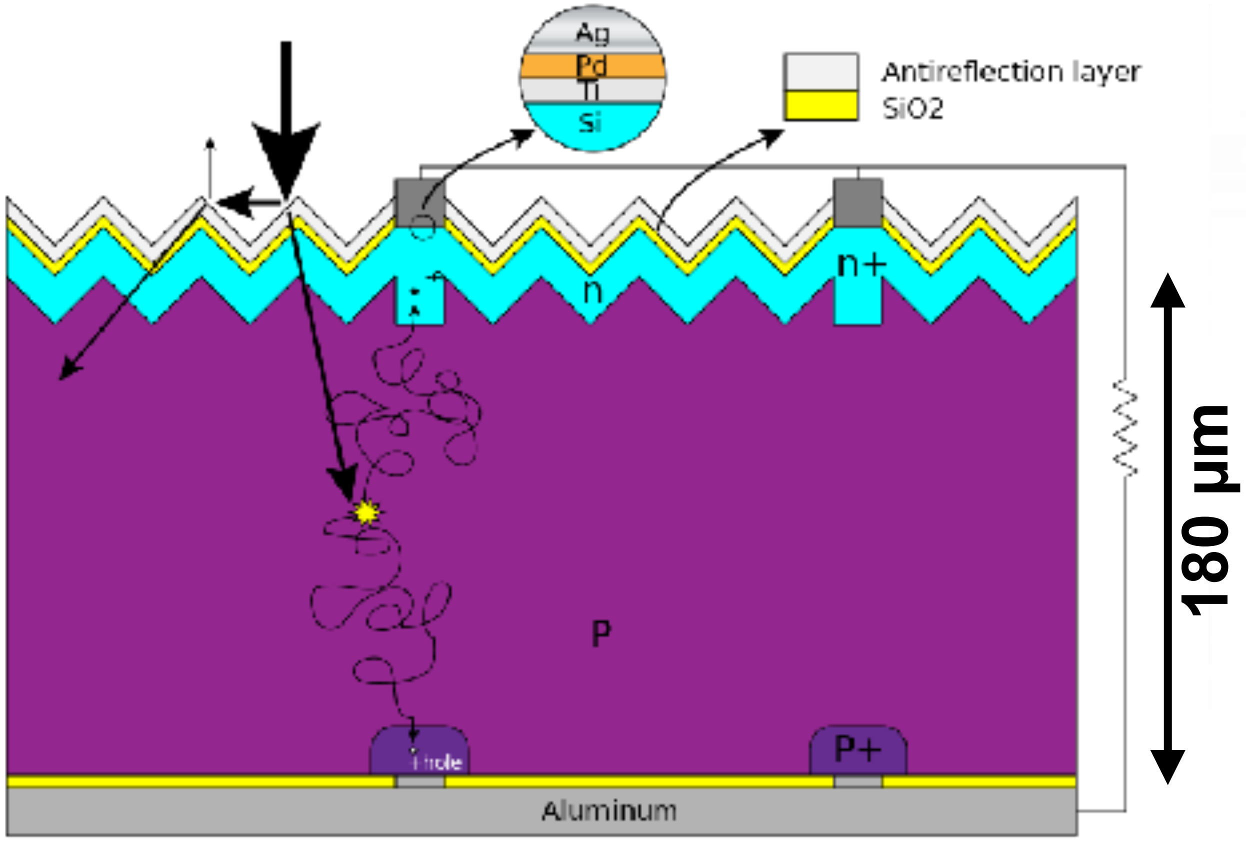
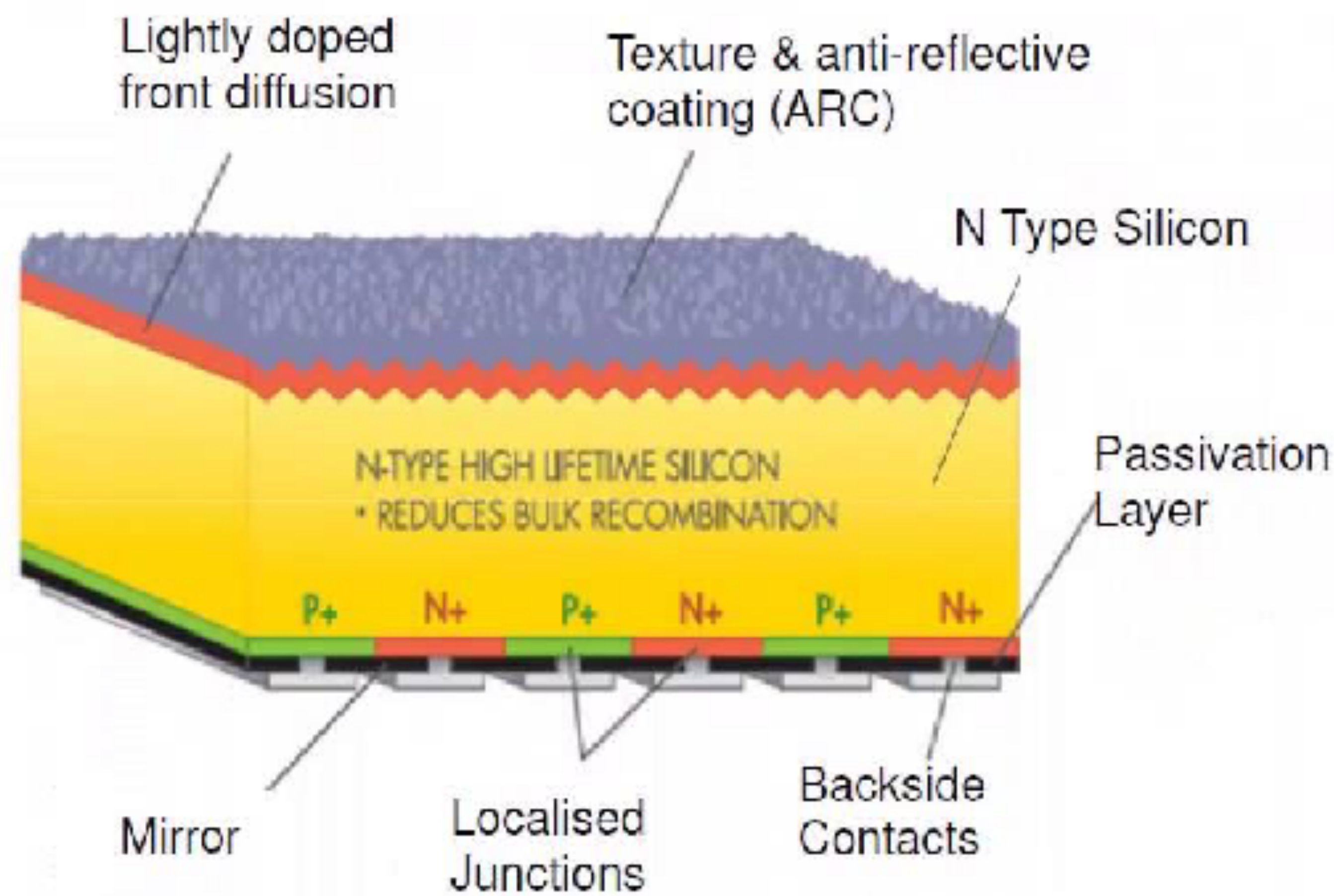
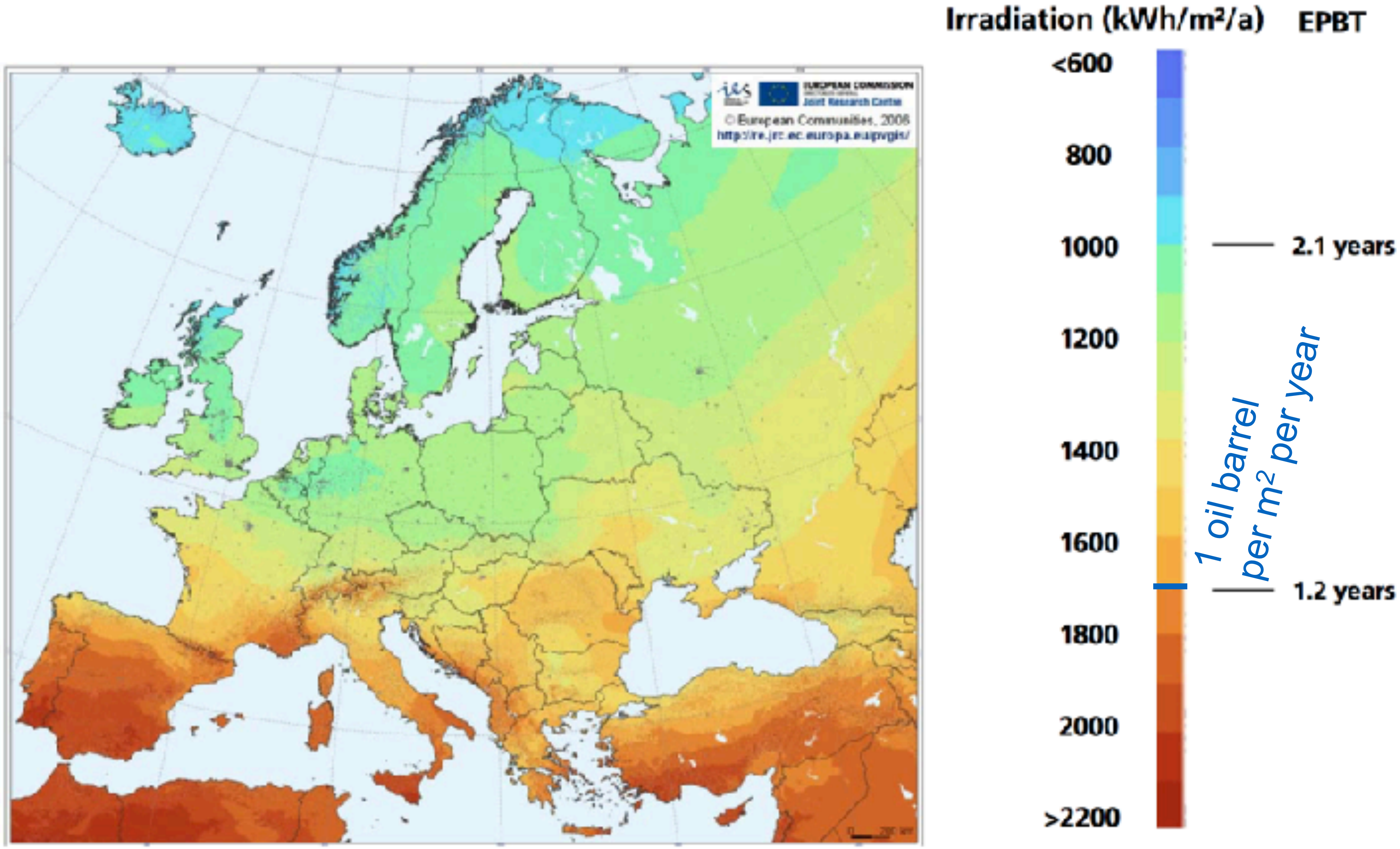
Si solar cells (93% market share)





Technology	Lab efficiency	Module efficiency	Market share (2015)
Polycrystalline	20.8 %	11 – 16 %	68 %
Crystalline	25.0 %	14 – 18 %	~ 17 %
High-end crystalline	25.6 %	up to 22.5 %	~ 8 %

Energy payback time



Data: M.J. de Wild-Scholten 2013. Image: JRC European Commision. Graph: PSE AG 2014 (Modified scale with updated data from PSE AG and FraunhoferISE)

1 – 2 years seems ok for 30+ years of operation

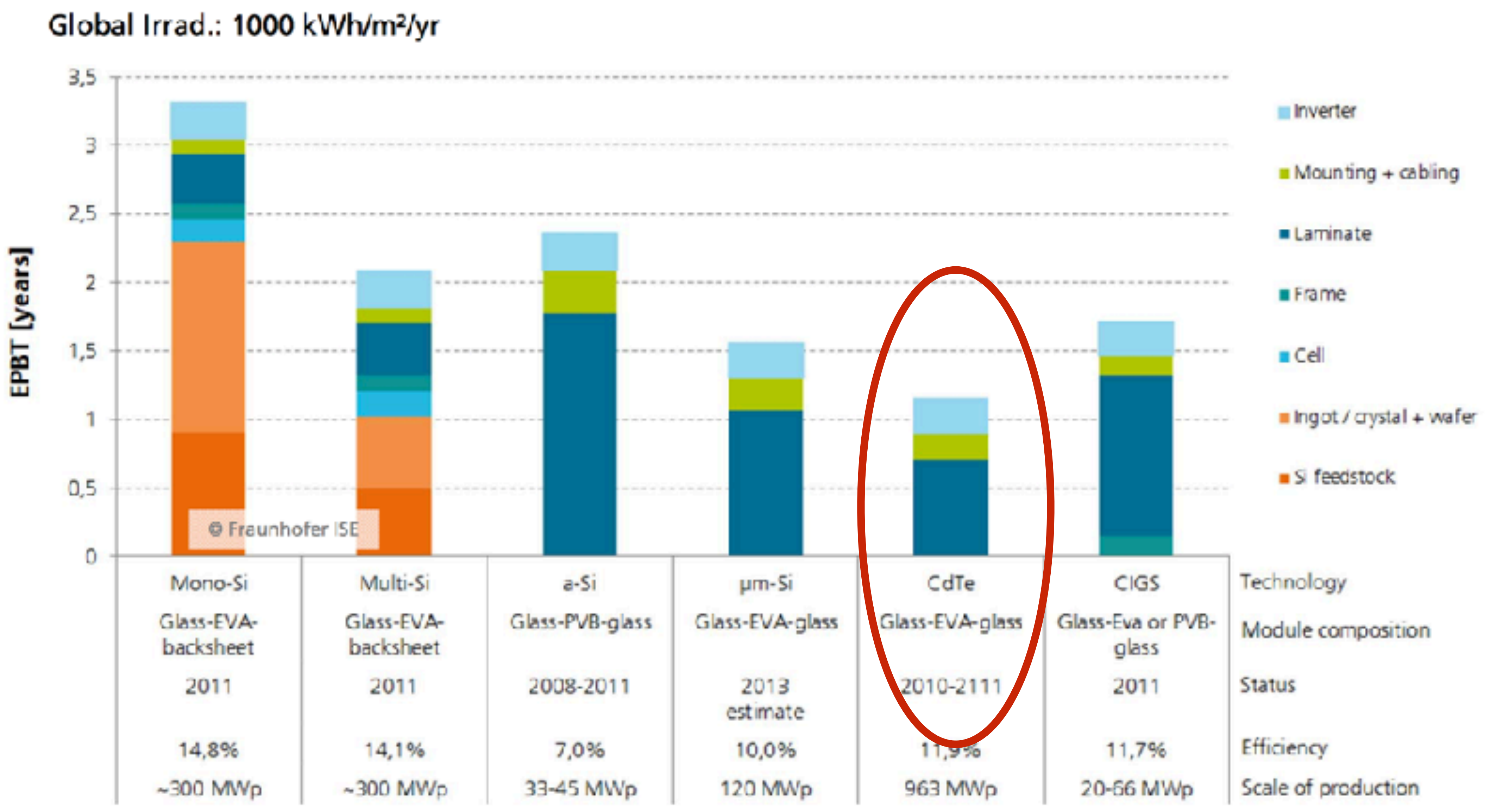
but:

35 % yearly growth:

0,35 · EPBT = ratio of energy used for making new solar cells

CdTe?

Energy Pay-Back Time of Rooftop PV Systems
Different Technologies located in Germany



Data: M.J. de Wild-Scholten 2013. Graph: PSE AG 2014

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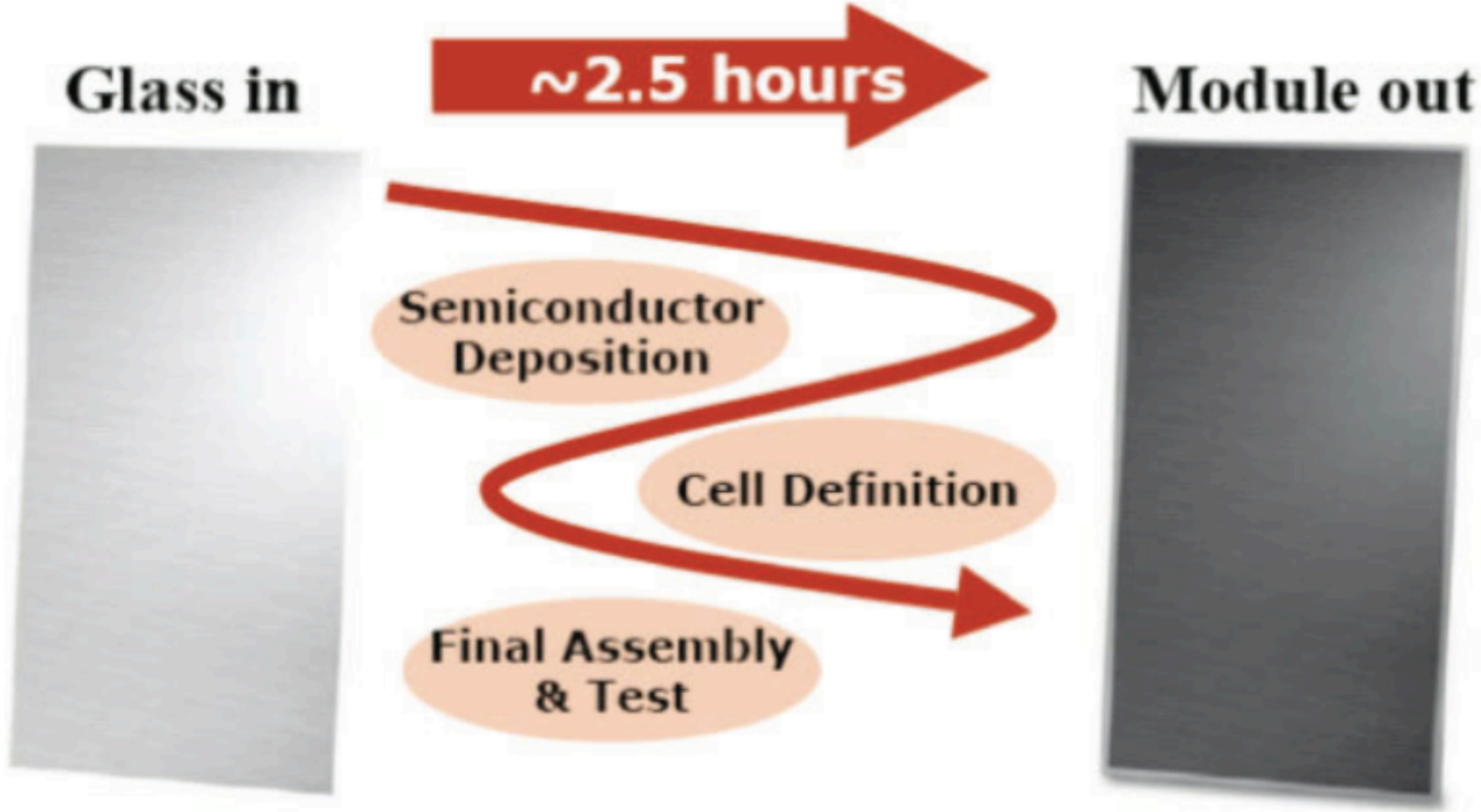
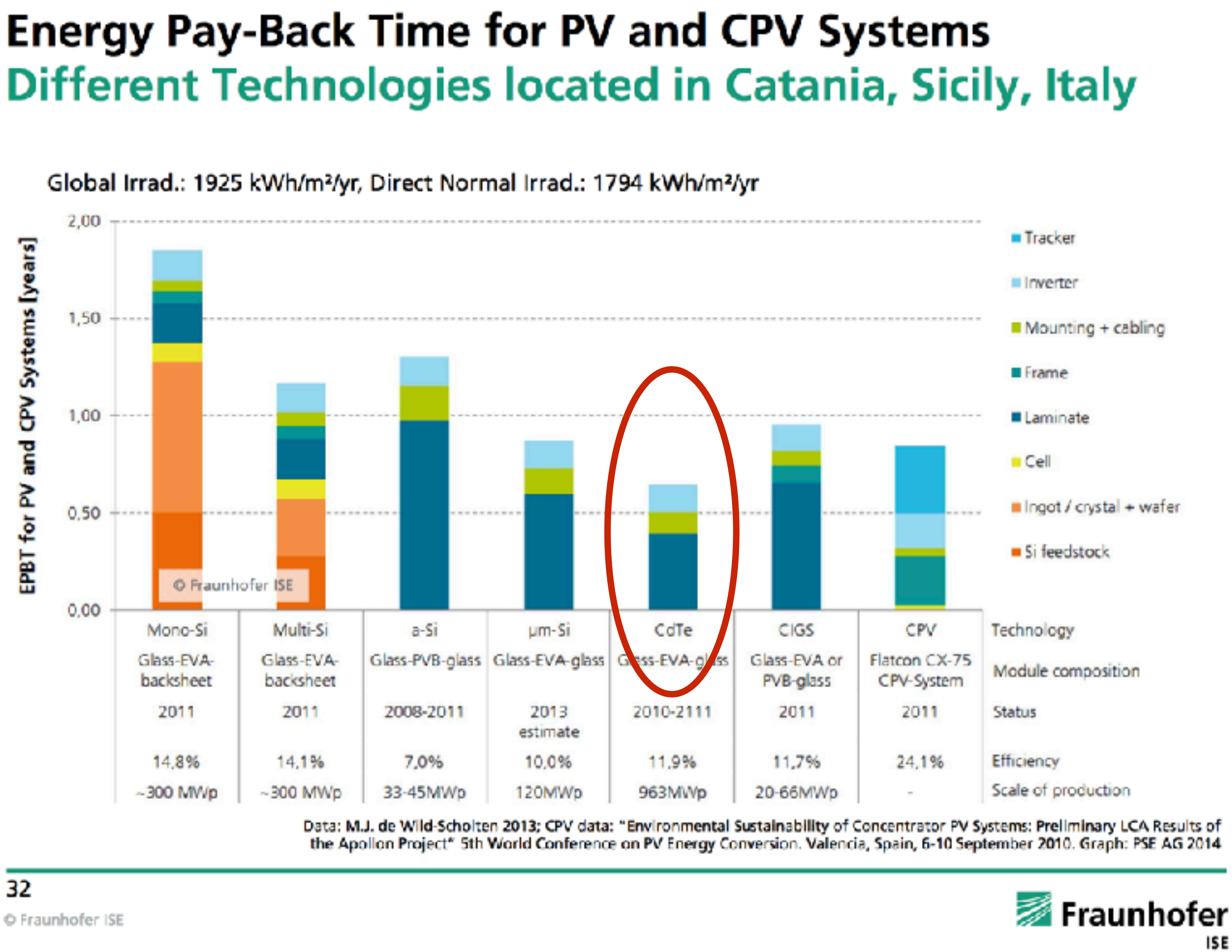
CdTe-thin film solar cells



Source: First Solar

- Cheap, medium efficiency (~ 16 %)
- Limited Te-reserves (1–2 TW)

Advanced PV?


Energy Pay-Back Time for PV and CPV Systems
Different Technologies located in Catania, Sicily, Italy
Global Irrad.: 1925 kWh/m²/yr, Direct Normal Irrad.: 1794 kWh/m²/yr
EPBT for PV and CPV Systems [years]
2,00
1,50
1,00
0,50
0,00
© Fraunhofer ISE
Tracker
Inverter
Mounting + cabling
Frame
Laminate
Cell
Ingot / crystal + wafer
Si feedstock
Technology: Mono-Si, Multi-Si, a-Si, µm-Si, CdTe, CIGS, CPV
Module composition: Glass-EVA-backsheet, Glass-EVA-backsheet, Glass-PVB-glass, Glass-EVA-glass, Glass-EVA-glass, Glass-EVA or PVB-glass, Flatcon CX-75 CPV-System
Status: 2011, 2011, 2008-2011, 2013 estimate, 2010-2111, 2011, 2011
Efficiency: 14,8%, 14,1%, 7,0%, 10,0%, 11,9%, 11,7%, 24,1%
Scale of production: ~300 MWp, ~300 MWp, 33-45MWp, 120MWp, 963MWp, 20-66MWp, -
Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE AG 2014
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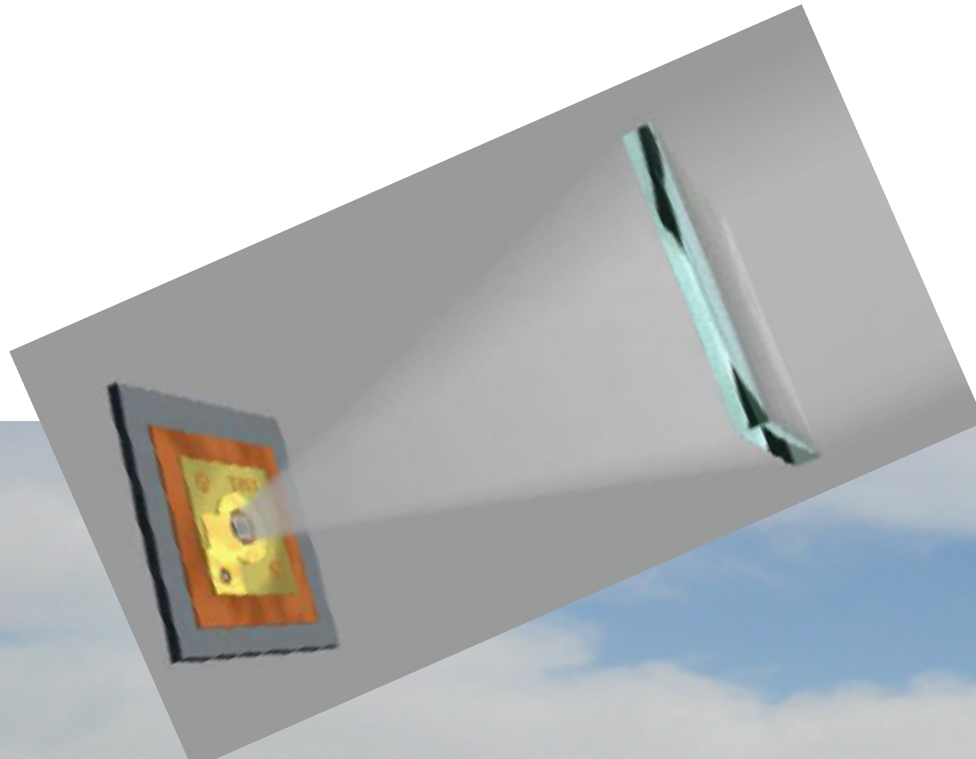
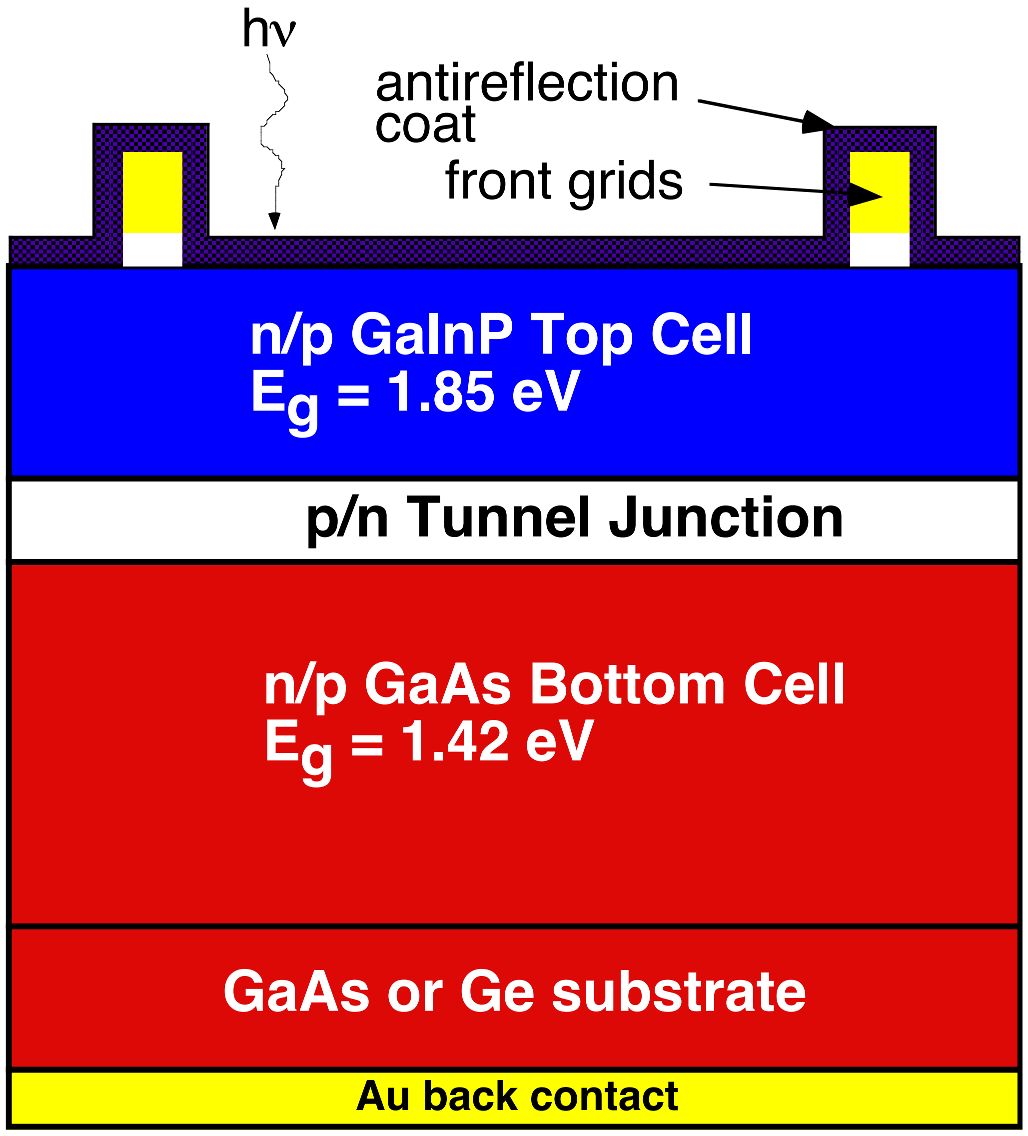
Concentrators

- Sunny climate – direct sunlight
- Require active solar tracking



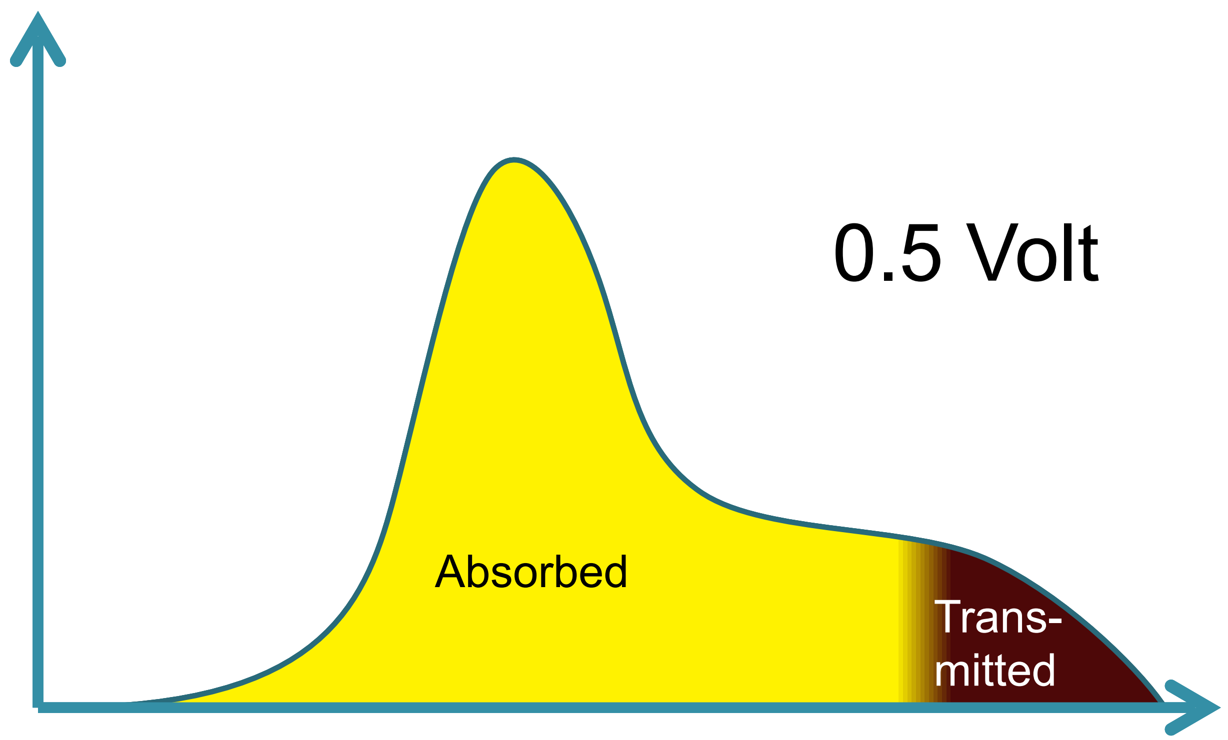
GaInP/GaAs/Ge multi-junction solar cell

- Invented at NREL 1984
- Used in space
  - Mars rovers Spirit and Opportunity
  - 80 % of new satellites
- Highest efficiency on the market today
- Also used in concentrators



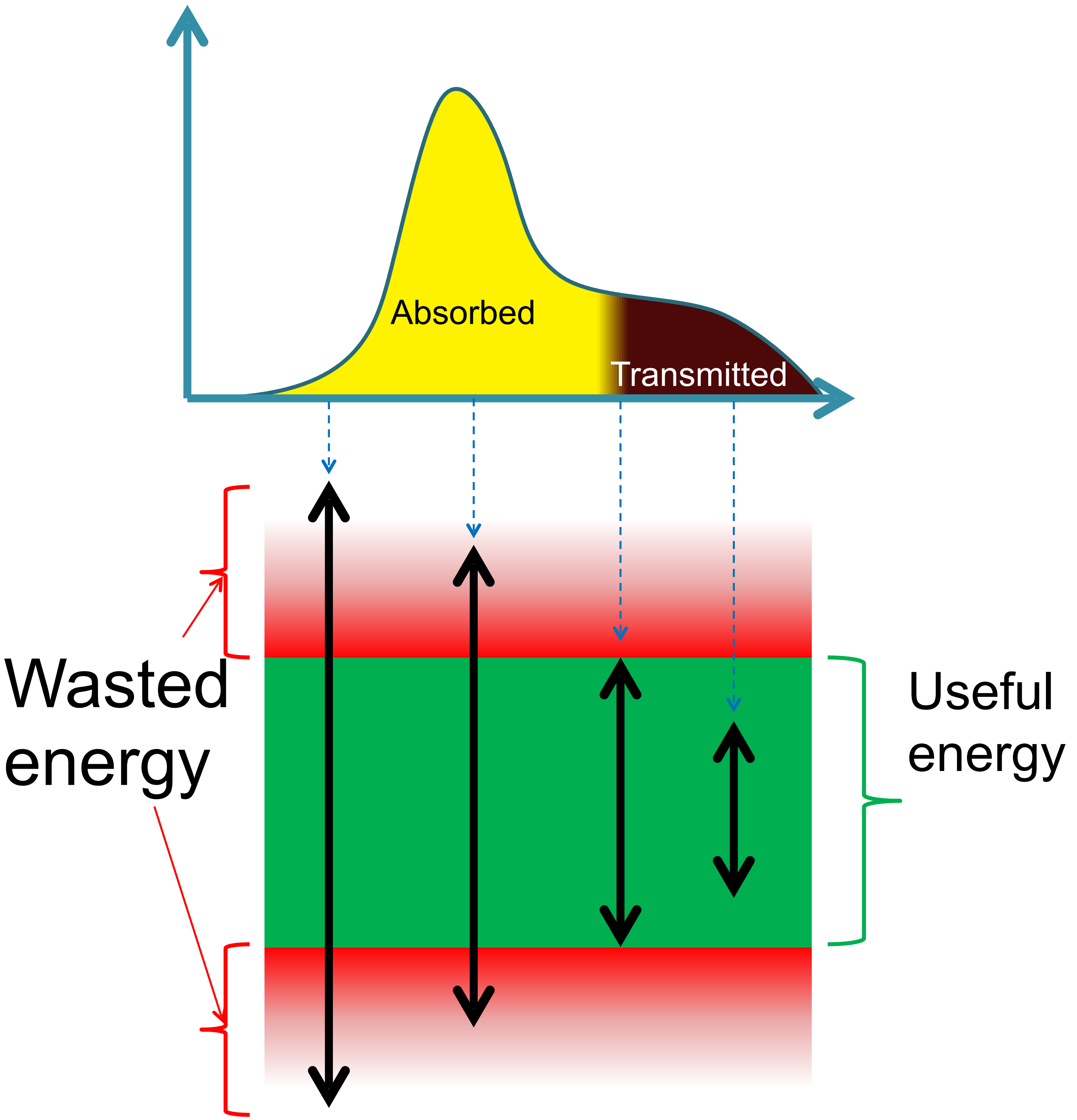
Voltage and absorption

- A single solar cell material produces a fixed voltage
  - If there is enough sunlight
  - The current is proportional to light intensity
- Higher voltage = more transparent
- Lower voltage = more absorption

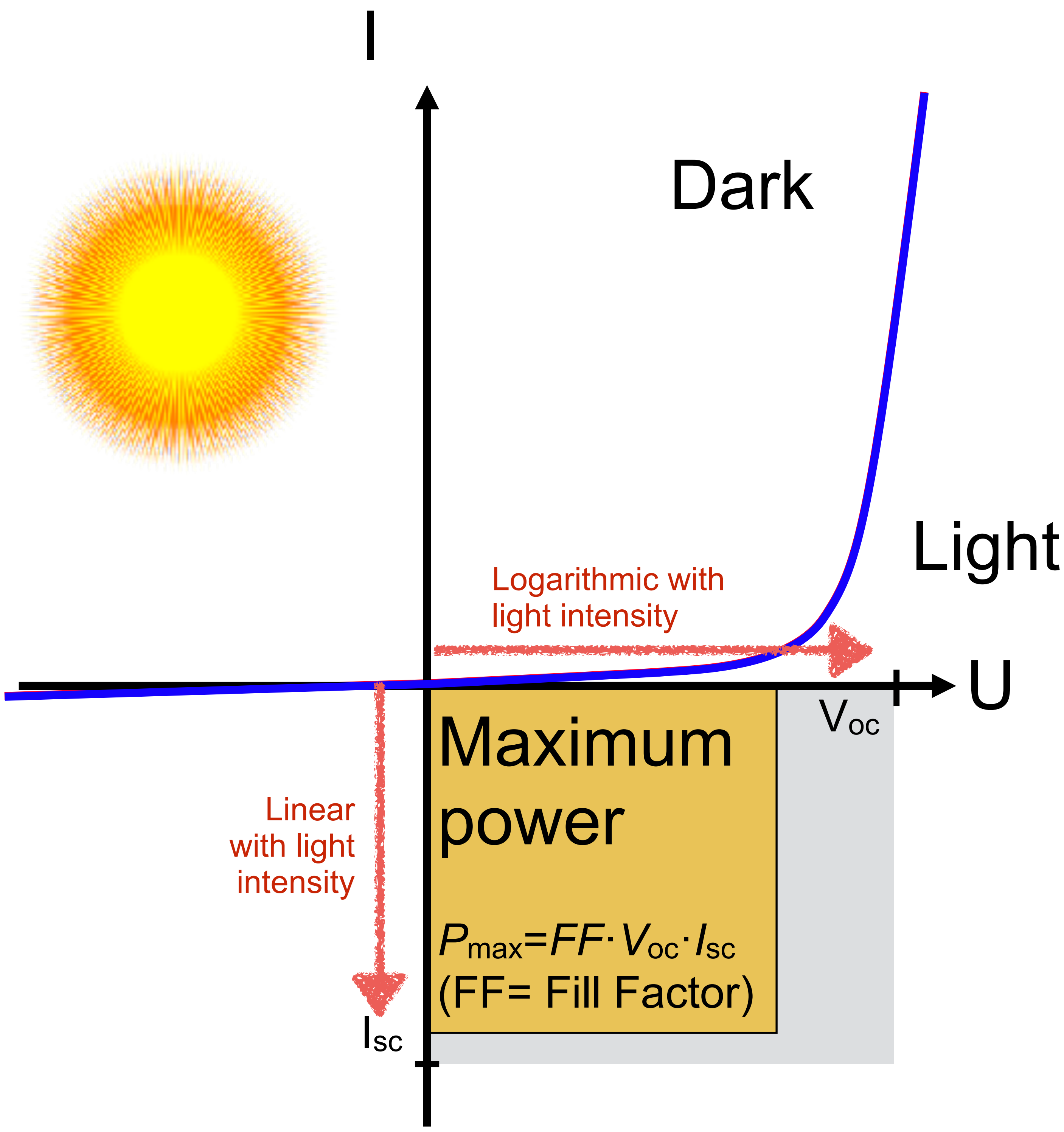


So why not absorb it all?

- Photons have a large range of energies
  - Only one energy fits the material precisely
- Compromise between high absorption (large current) and high voltage
  - $P = U \cdot I$



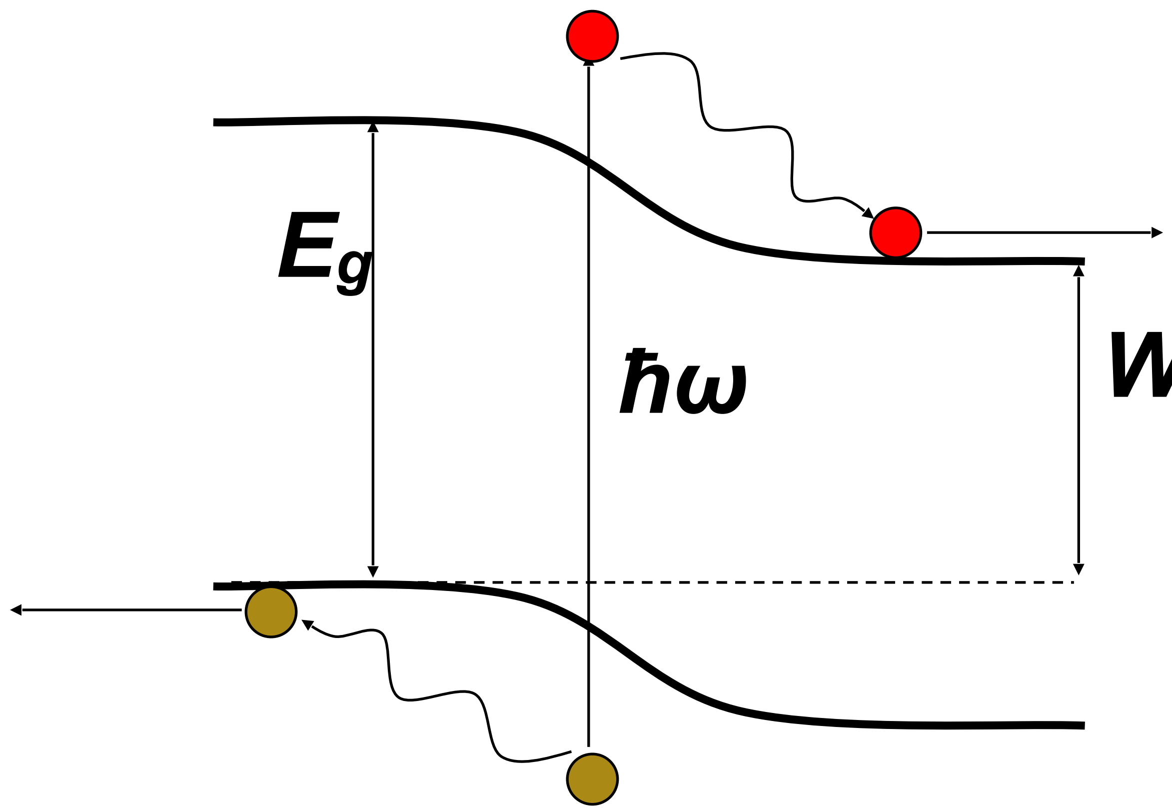
Solar cell principle



- Photogalvanic effect discovered by Becquerel in 1839*
- The modern silicon solar cell was developed by Bell Labs in 1954 to power remote phone exchanges
- The first application of Si PV was in 1958 to power satellites in orbit (Hoffman Electronics)

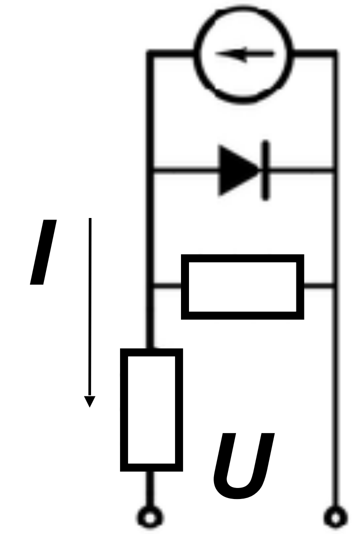
*) E. Becquerel, *"Mémoire sur les effets électriques produits sous l'influence des rayons solaires"*. Comptes Rendus **9**: 561–567 (1839)

Single junction



$W \approx E_g – 0.35$ eV

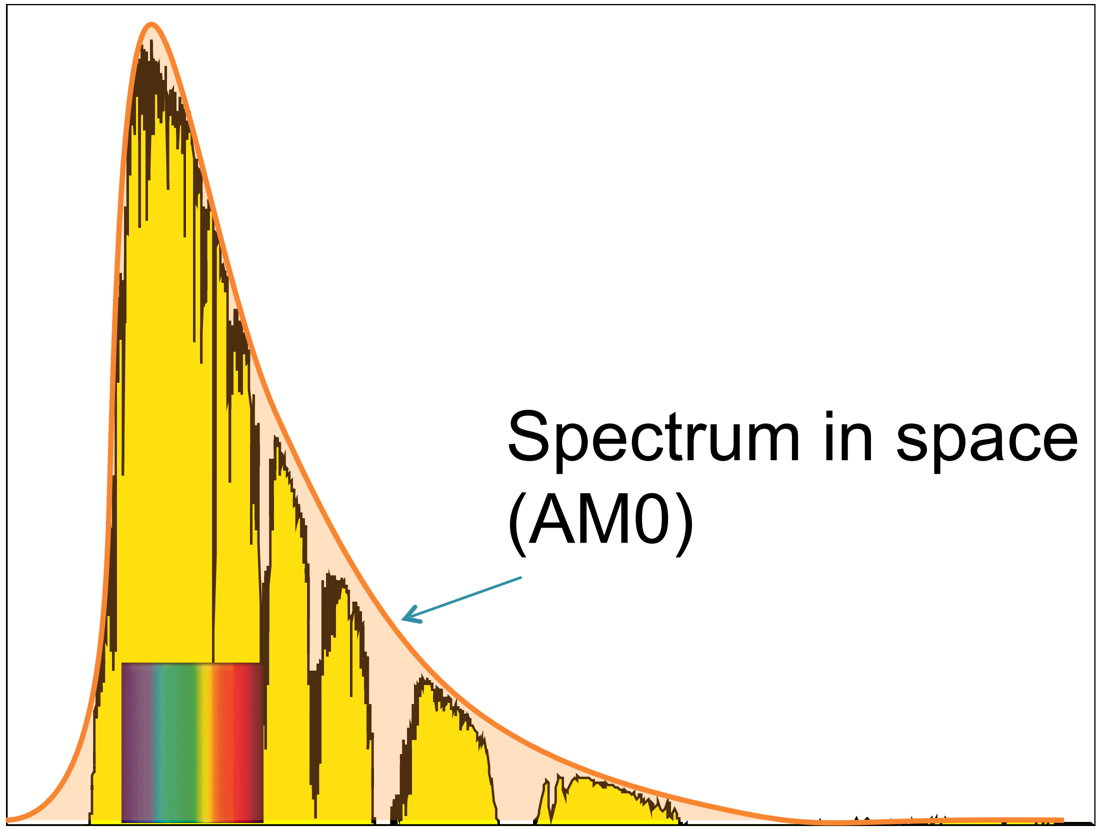
Equivalent circuit



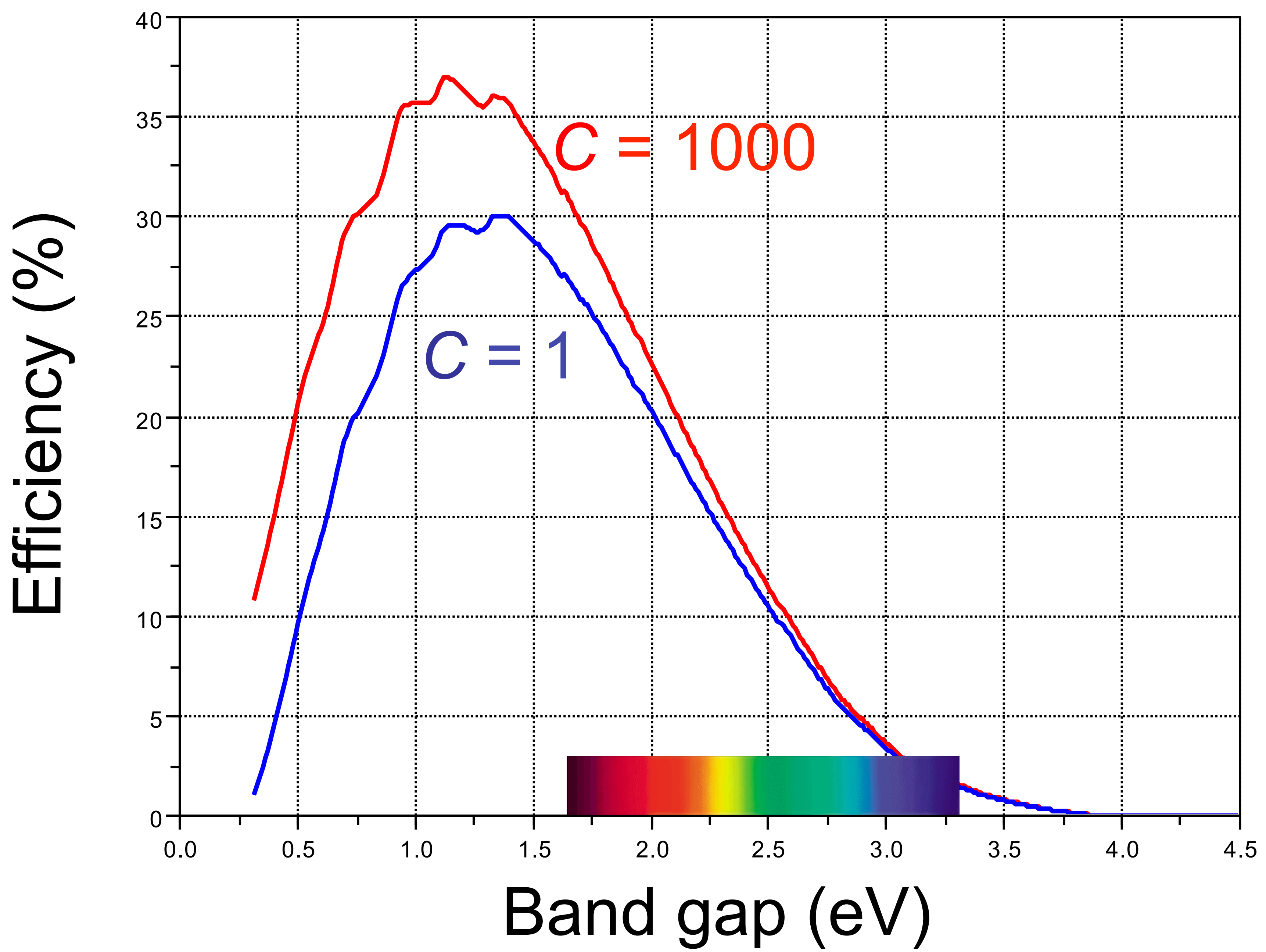
The actual solar spectrum

- AM1.5
  - “Air Mass 1.5”
  - One of several standards for terrestrial solar irradiation
- Actual spectrum varies by time of day, date, location, weather…
  - Important for the function of advanced solar cells

Standard: 1000 W/m²

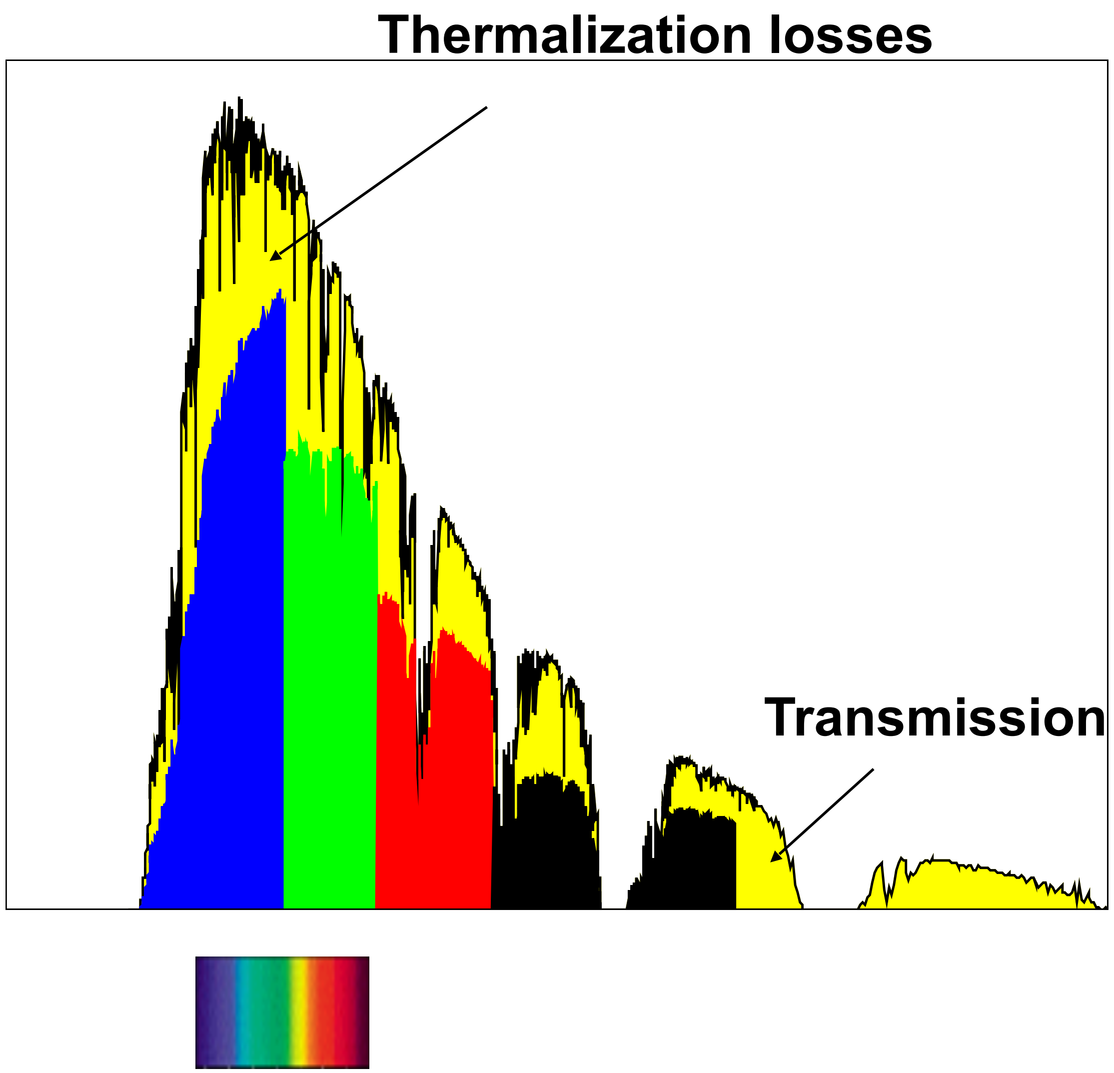


Theoretical ideal for a single material



Single- and multi-junction solar cells

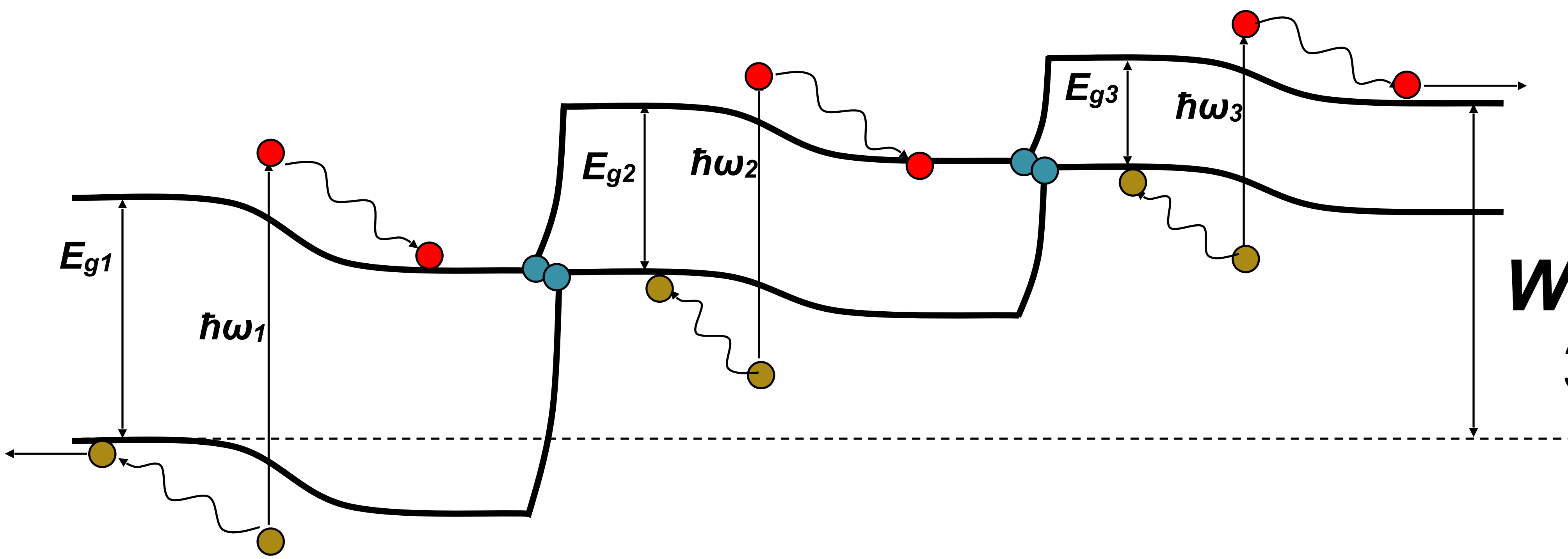
- Theoretical best cases
- Example: silicon *pn*-junction
  – up to 31 % efficiency at 1 sun
- Example: four junctions
  – 49 % efficiency
- Concentration
  – 59 % at 1000 suns
  – Current increases linearly with light intensity
  – Voltage = U(1 sun) + $kT/e \cdot \ln(C)$
    - C = 1000 gives ΔU = 0.18 V
- 36 junctions gives 72 % efficiency



C. H. Henry, "*Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells*", J Appl Phys **51**, 4491 (1980)

Triple junction

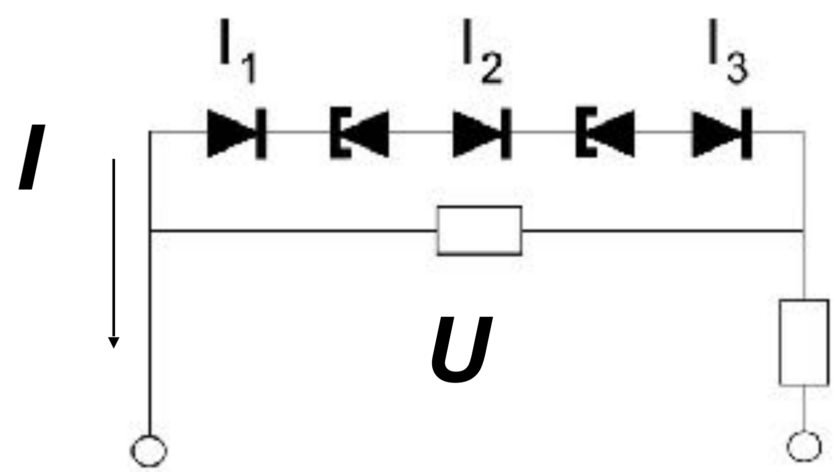
Voltage addition, current reduction



$$W \approx \sum E_g - 3 \cdot 0.35\ \text{eV}$$

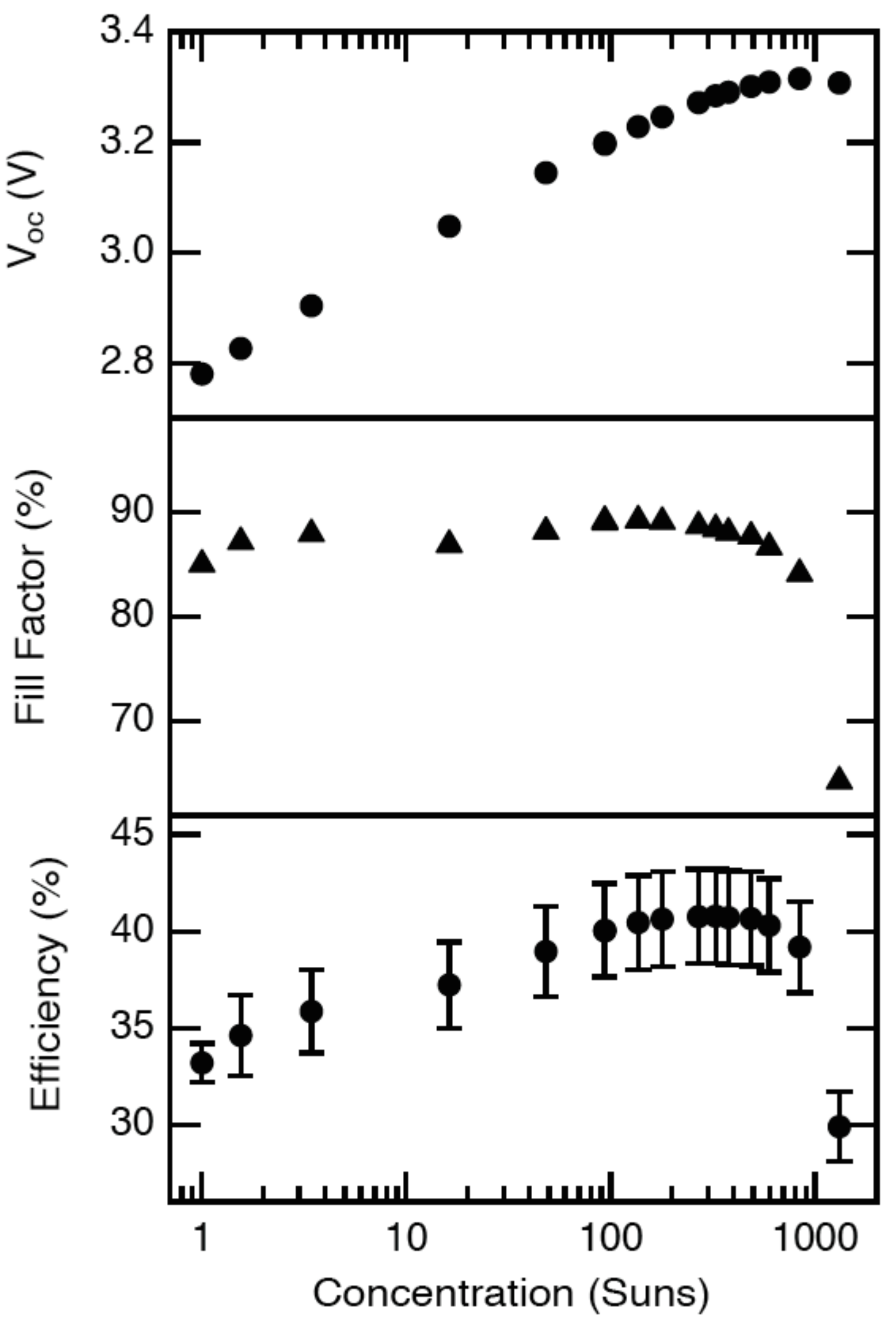
Equivalent circuit

Current matching!

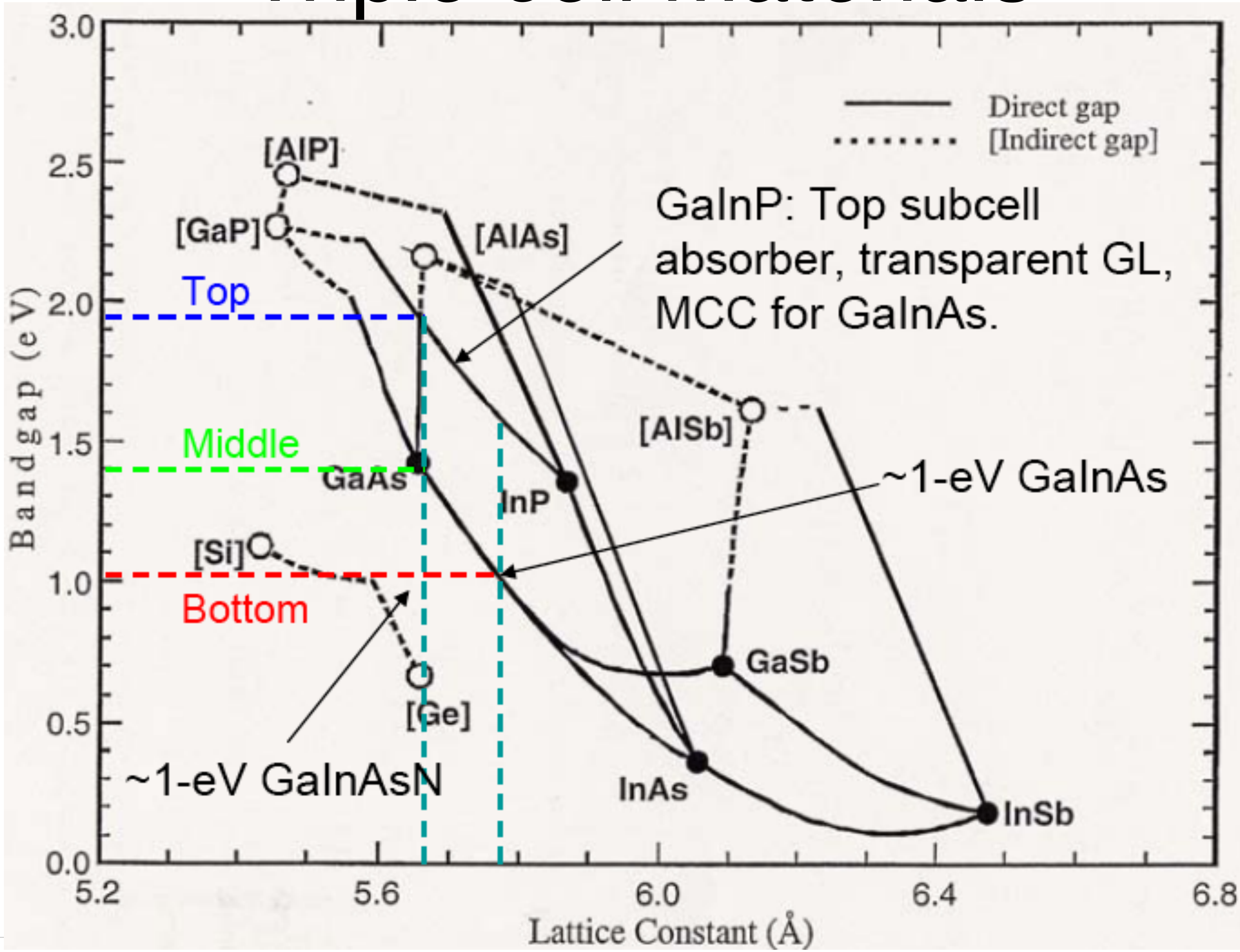


Triple cells under concentrated light

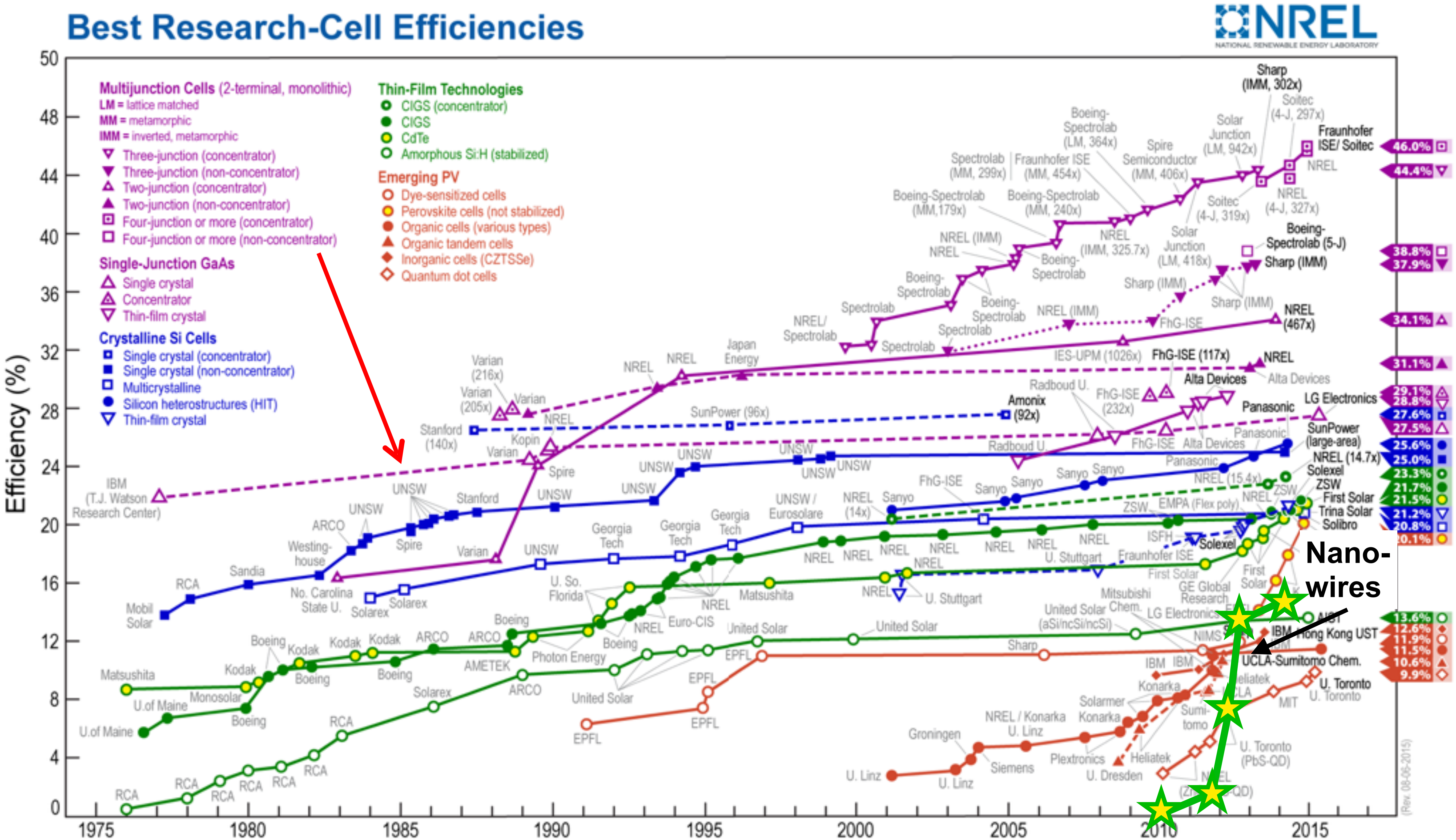
- Efficiency, open circuit voltage and fill factor limited by internal resistance and maximum tunnel current
- Have reached 44 %
- Next step: more materials
  - Dec 2014: Four junctions at 46 %!



Triple cell materials

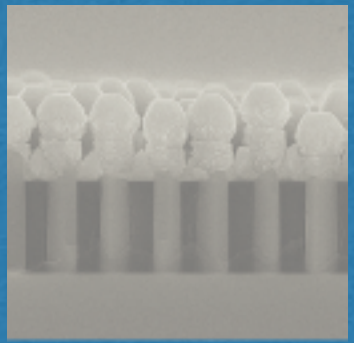


GaAs best single material since 1975

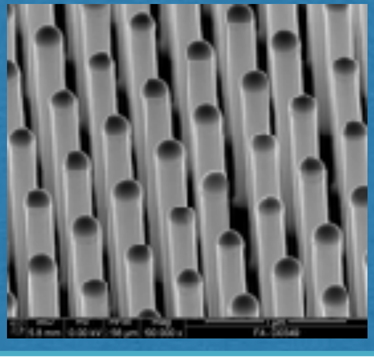


Why is it so hard to increase the efficiency of planar solar cells?

Rare materials can increase efficiency…
But such materials are expensive!



Nanotechnology can be used to reduce the amount of materials and thus make expensive materials cost efficient

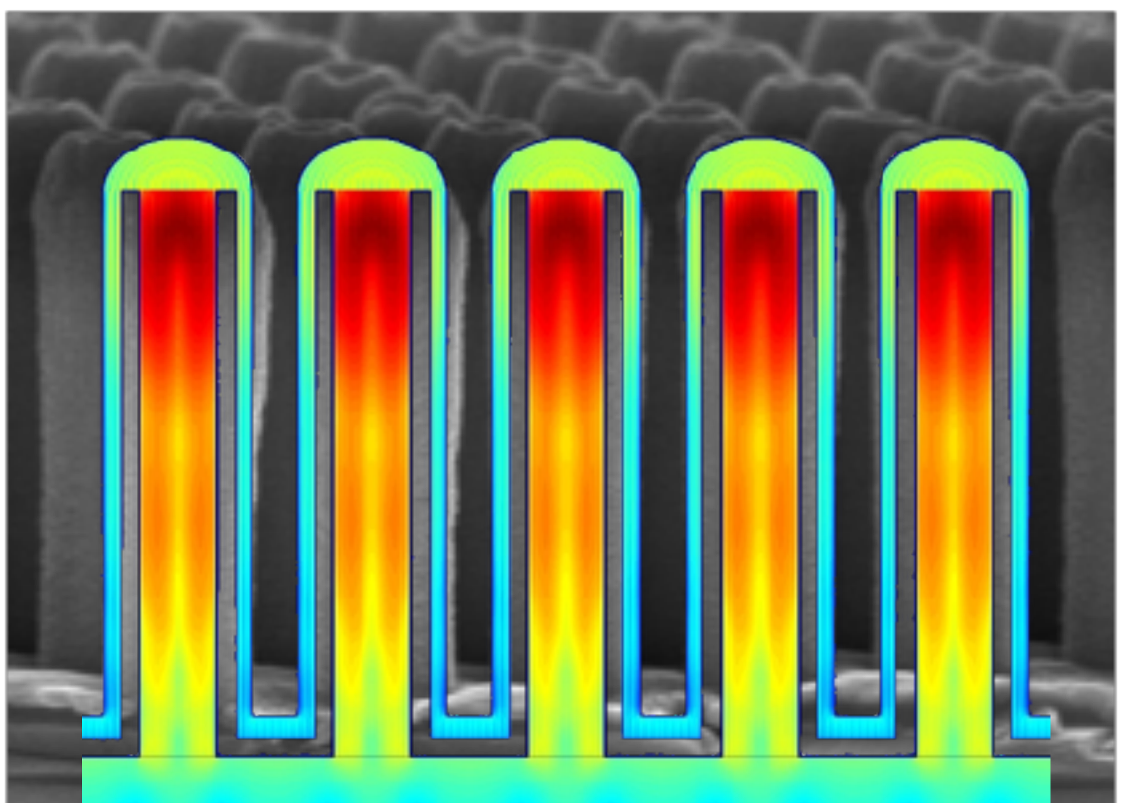


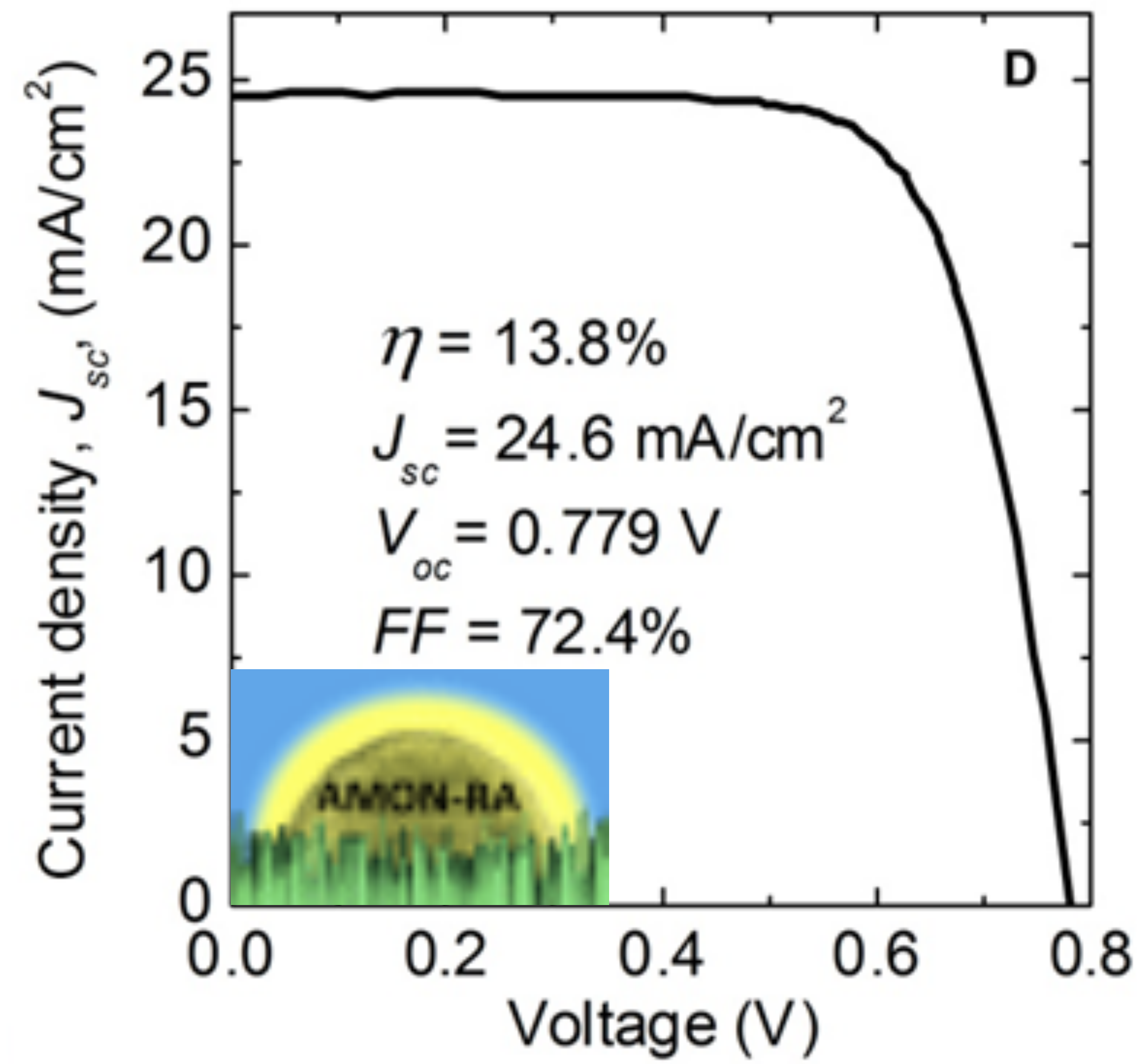
But… the production of nano materials has not been efficient enough

Record nanowire solar cell

Wires capture light efficiently
- 12 % surface coverage
- 83 % of the current from a planar cell

Minimal materials use
- ~ 1 g/m^2
- 1000 × less than a Si cell
- 20 × less than a planar III–V cell





J. Wallentin *et al.*, “InP Nanowire Array Solar Cells Achieving 13.8% Efficiency by Exceeding the Ray Optics Limit”, Science **339**, 1057 (2013)

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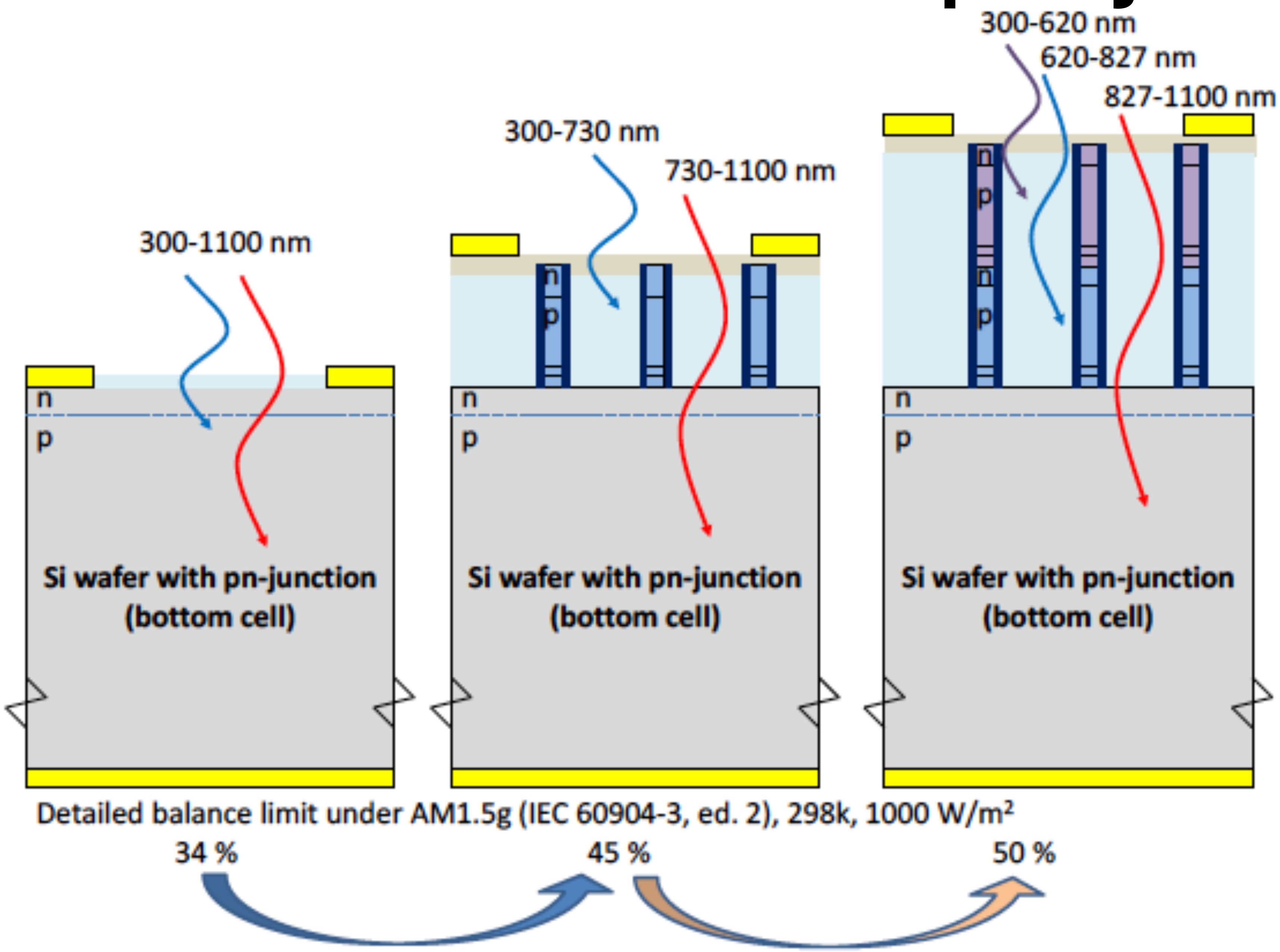
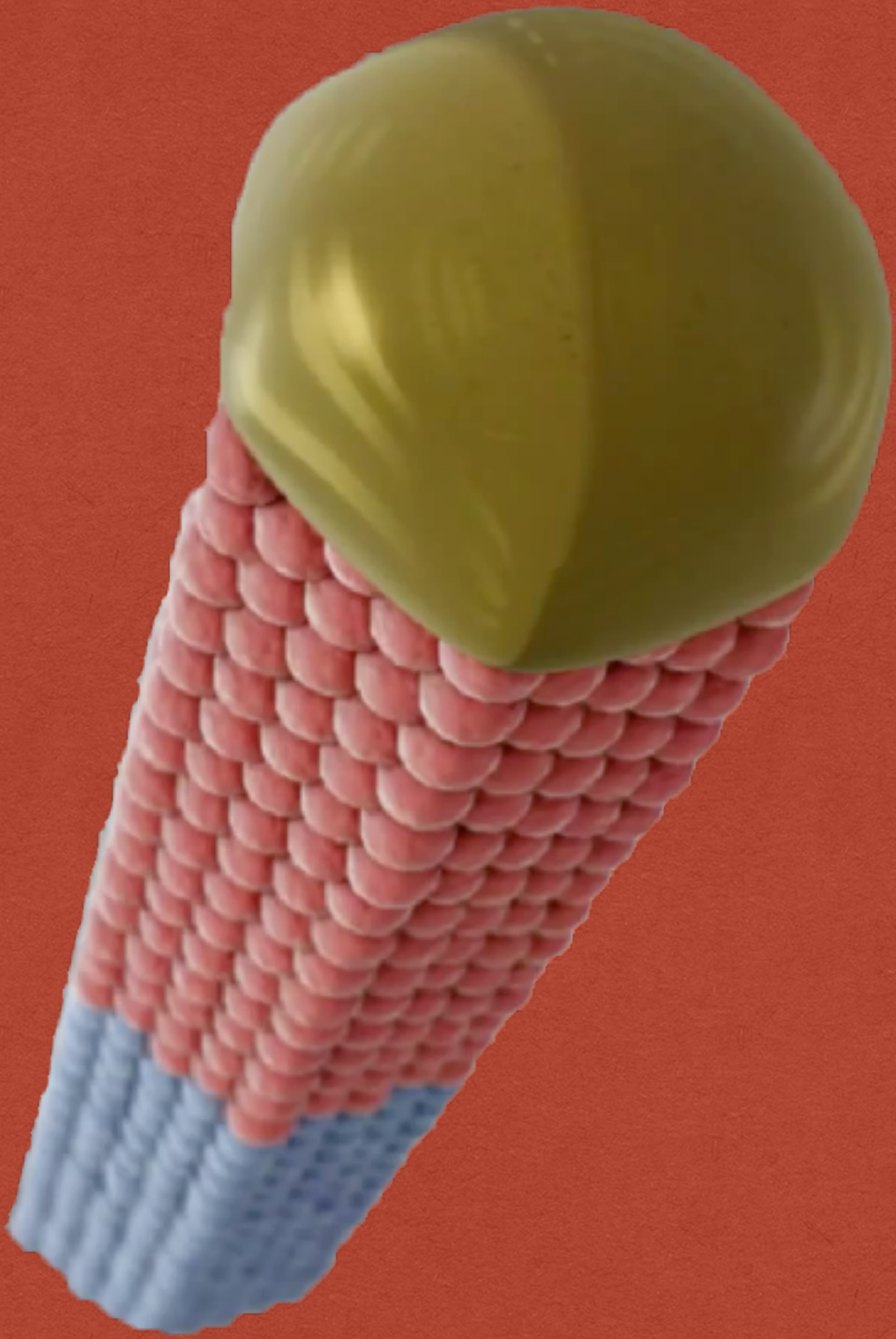
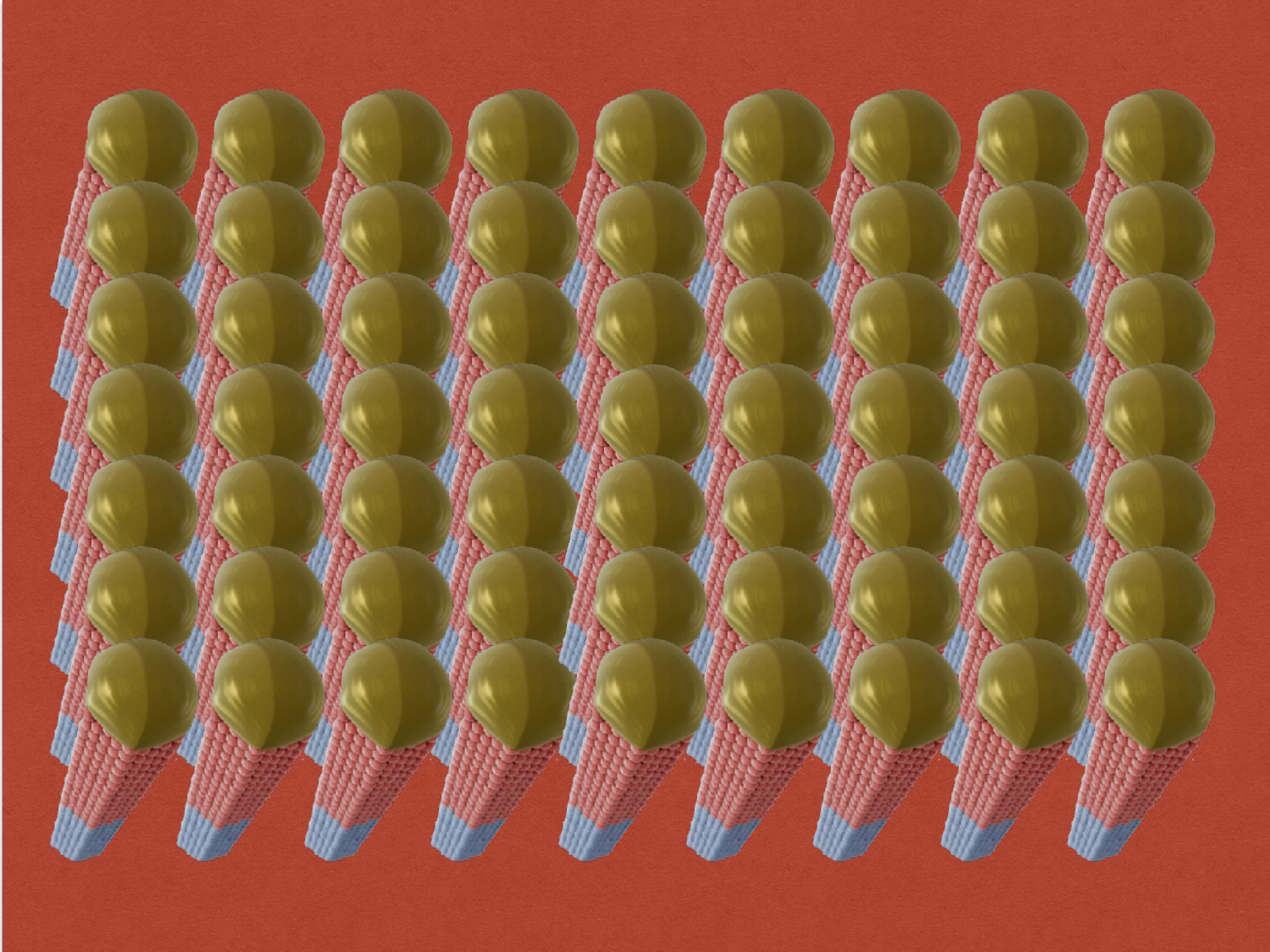
NANO-TANDEM project



Nanowires are great ...





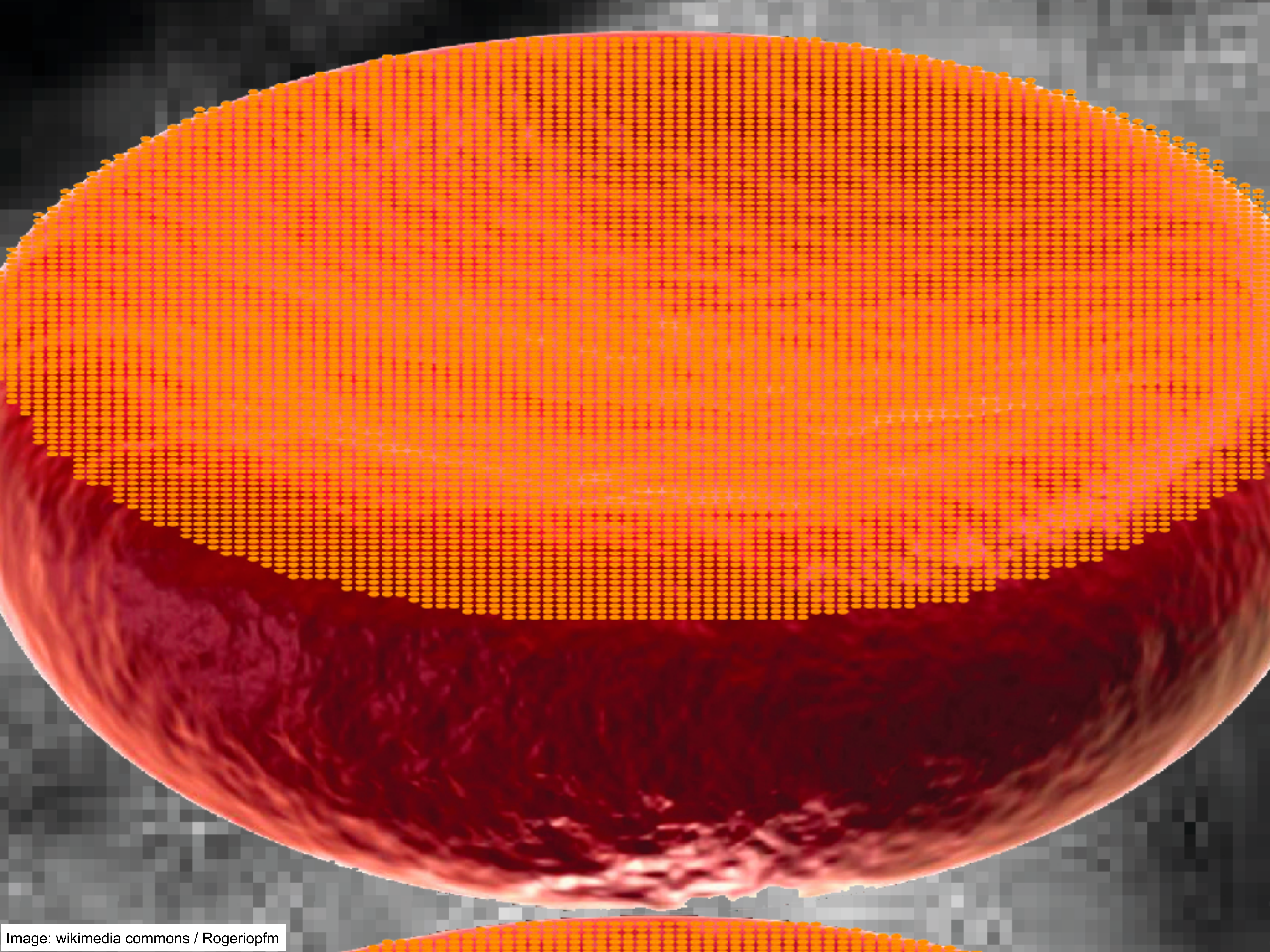


Image: wikimedia commons / Rogeriopfm

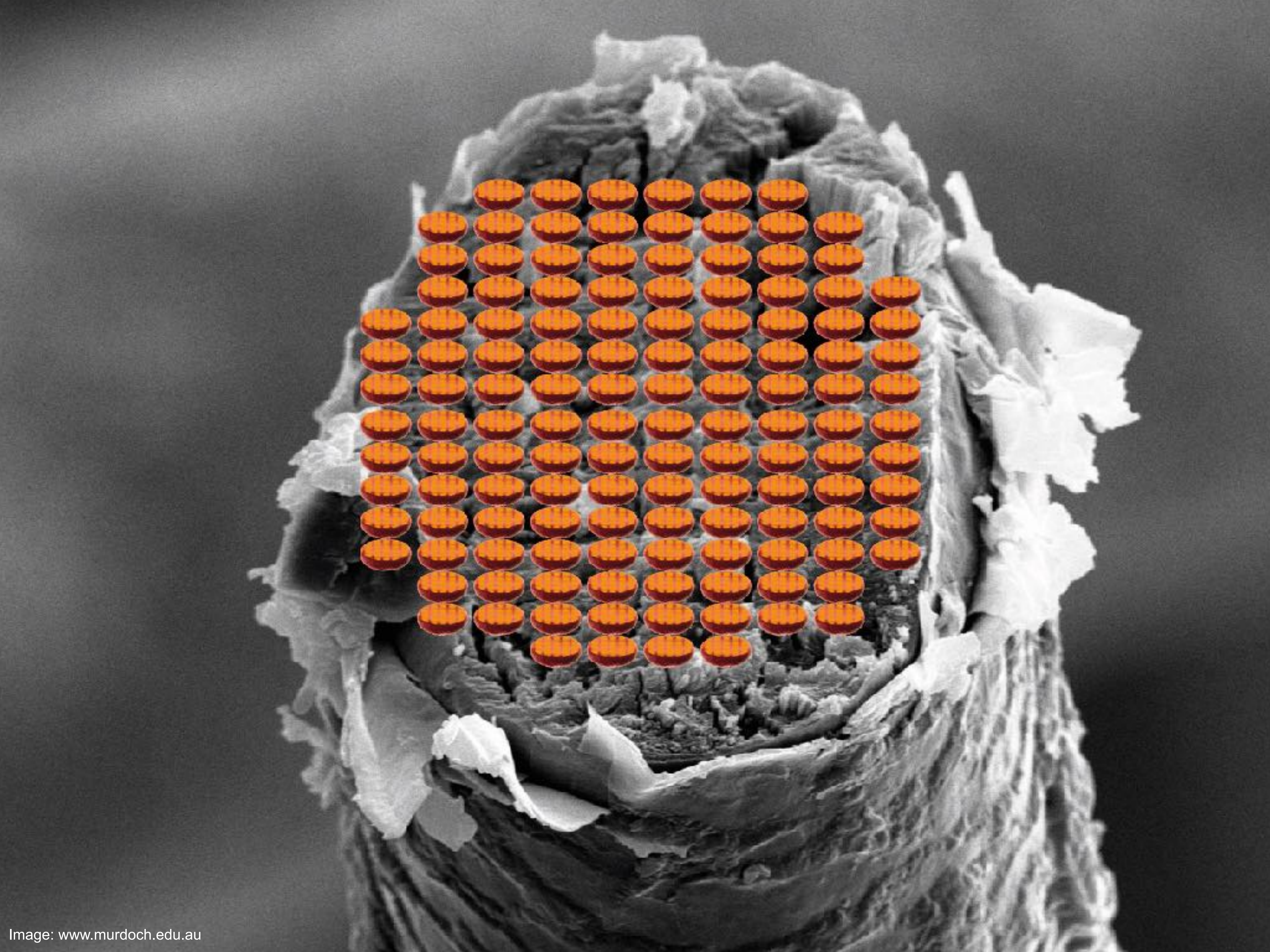


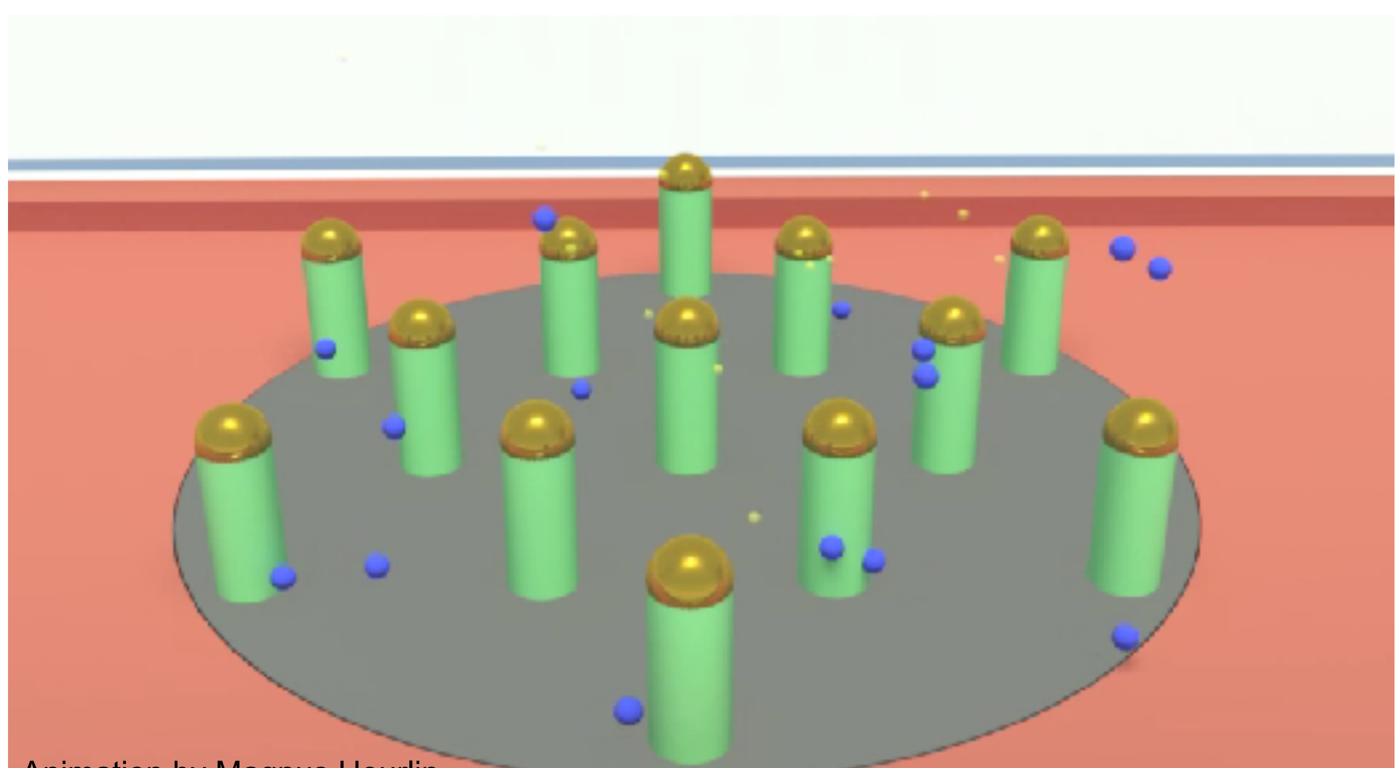
Image: www.murdoch.edu.au

… and we need a **lot** of them!

Image: Serpa Solar Power Plant (Wikipedia)

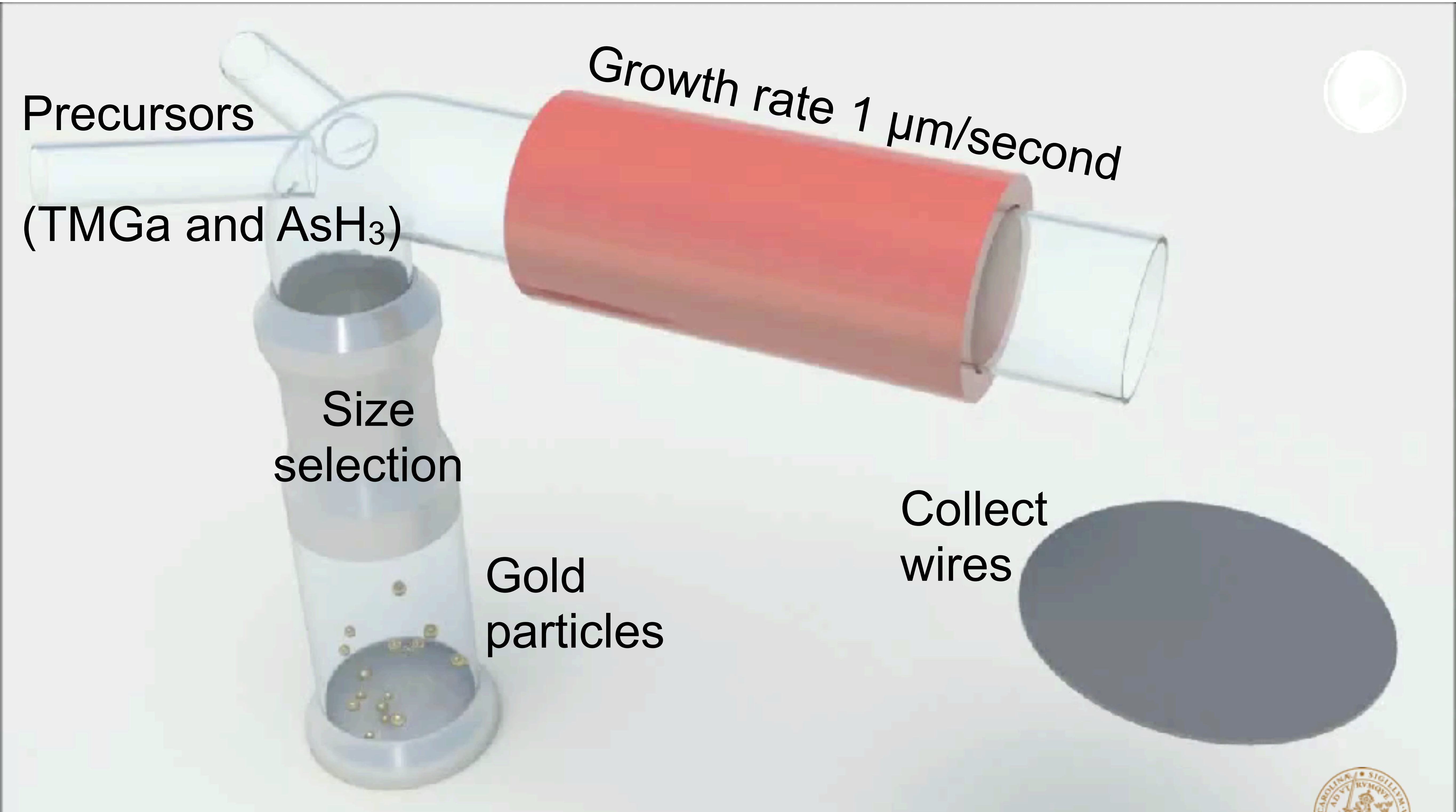
Mass production of nanowires?

- Nanowires are normally grown by MOVPE
- Batch process, cycle time min 30 min (today 2 h)
- Largest machine can handle a few 30 cm wafers
- Wires typically grow 1–10 nm/second
- Currently not an alternative for large surfaces



Animation by Magnus Heurlin

Aerotaxy: nanowire growth



Heurlin *et al.*, ”*Continuous gas-phase synthesis of nanowires with tunable properties*” Nature **492**, 90 (2012)

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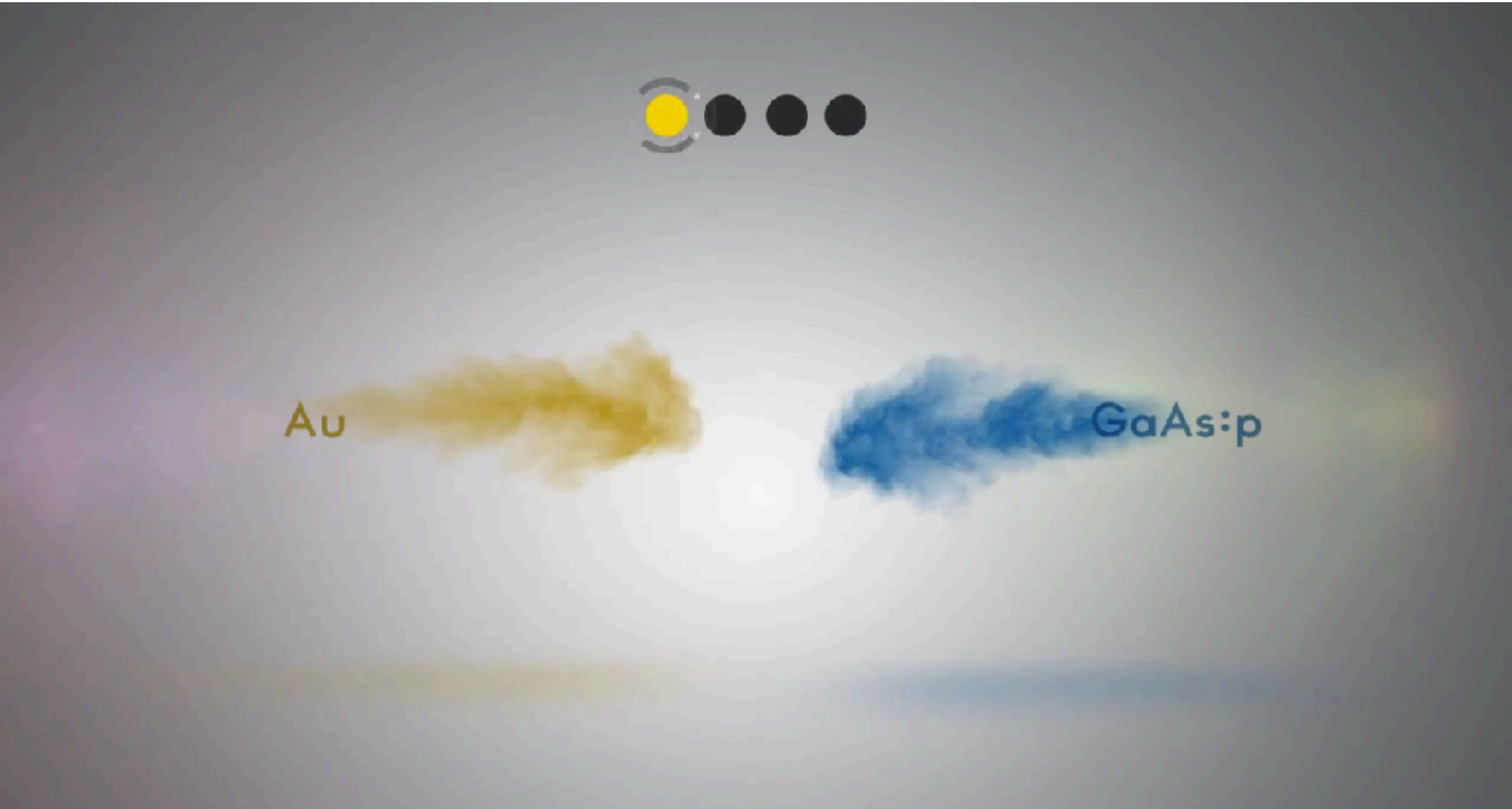
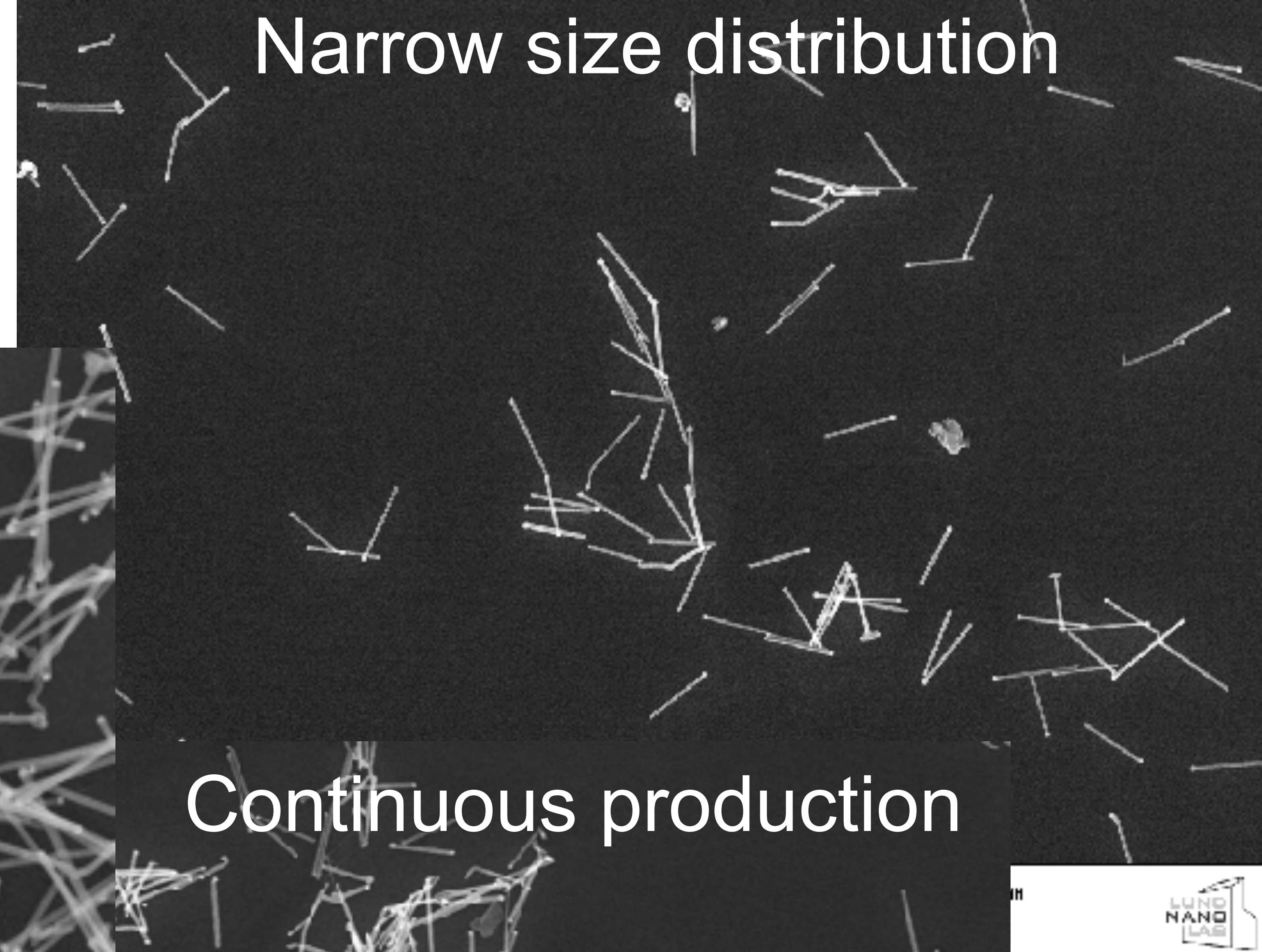
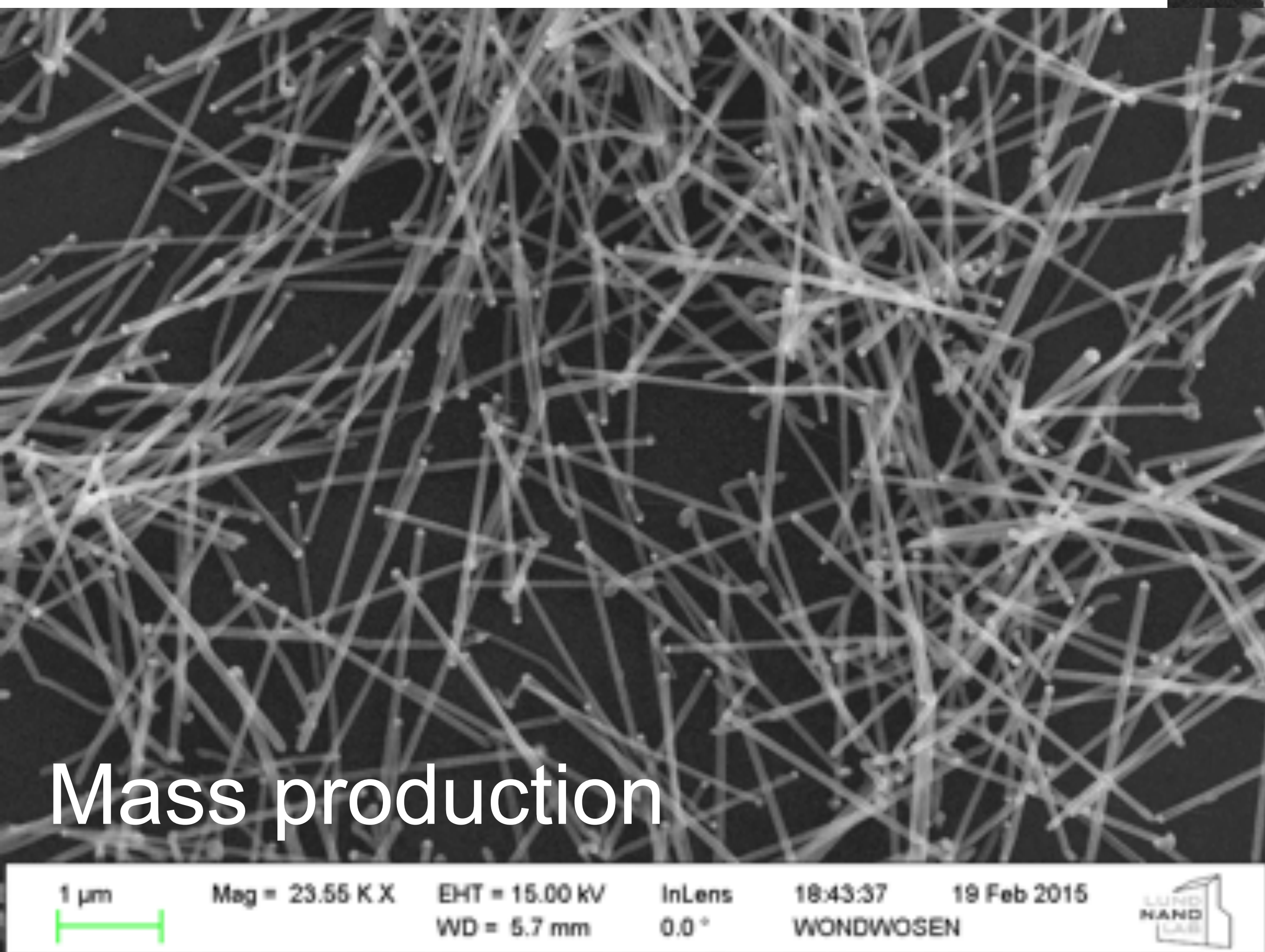
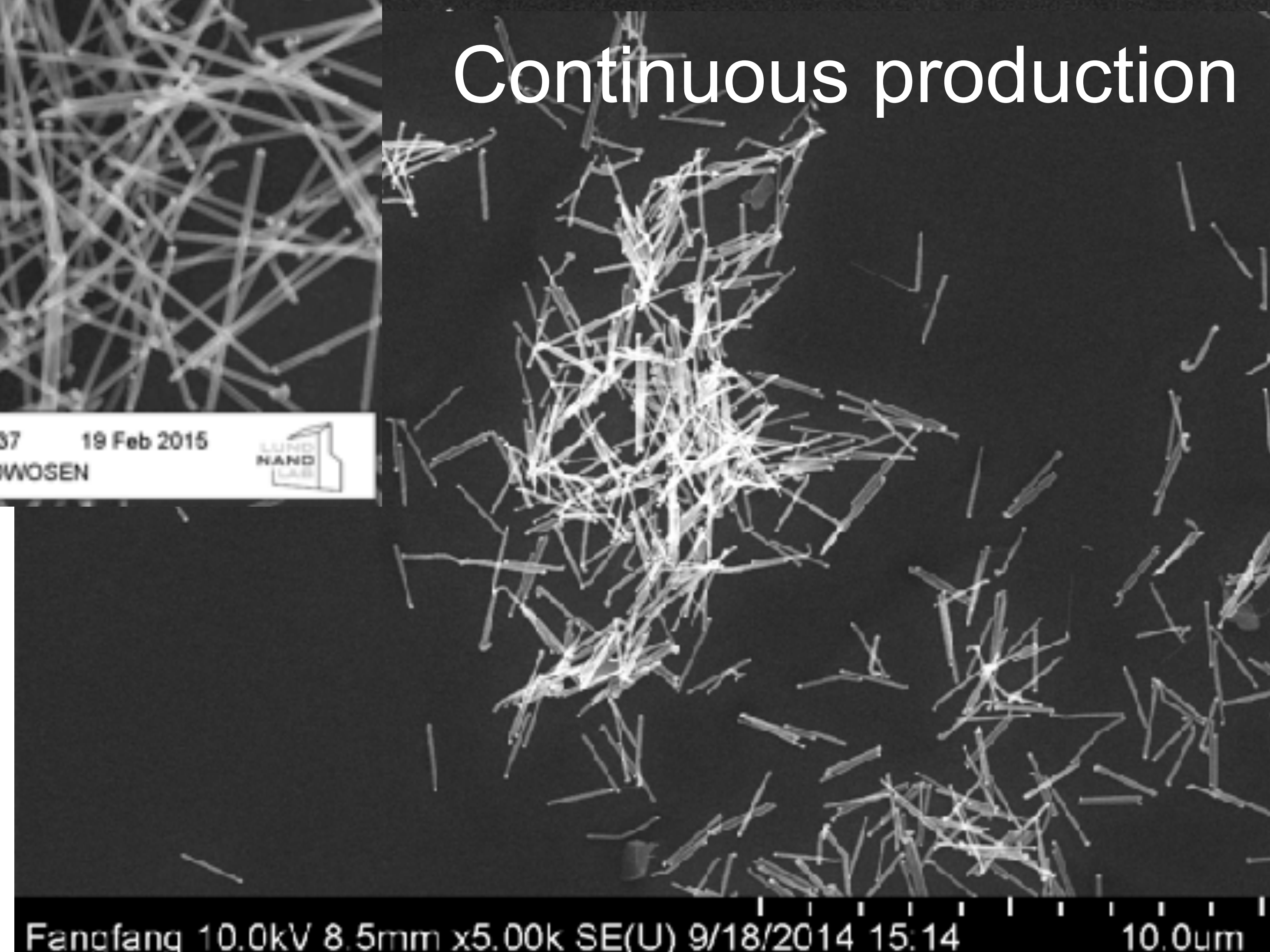


Animation © Sol Voltaics AB

GaAs nanowires



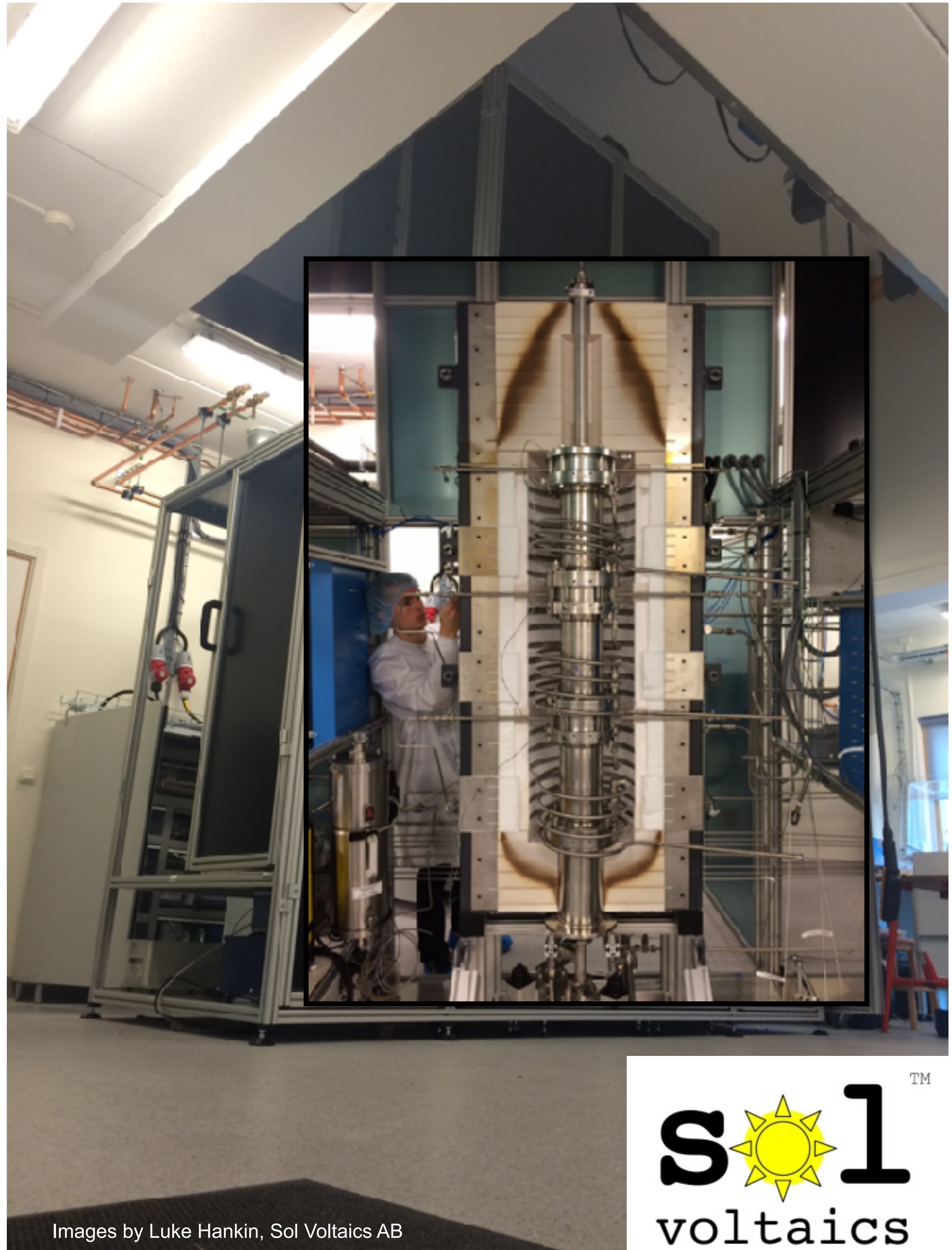




Images: Fangfang Yang / Wondwosen Metaferia
Wires grown in collaboration with Sol Voltaics AB:
Linda Johansson and Greg Alcott

Aerotaxy Gen 4

- Sol Voltaics' lab in Lund
- Pre-pilot production
- Up to six growth stages
- Started late 2014
- Demonstrated upscaled production capability



Images by Luke Hankin, Sol Voltaics AB

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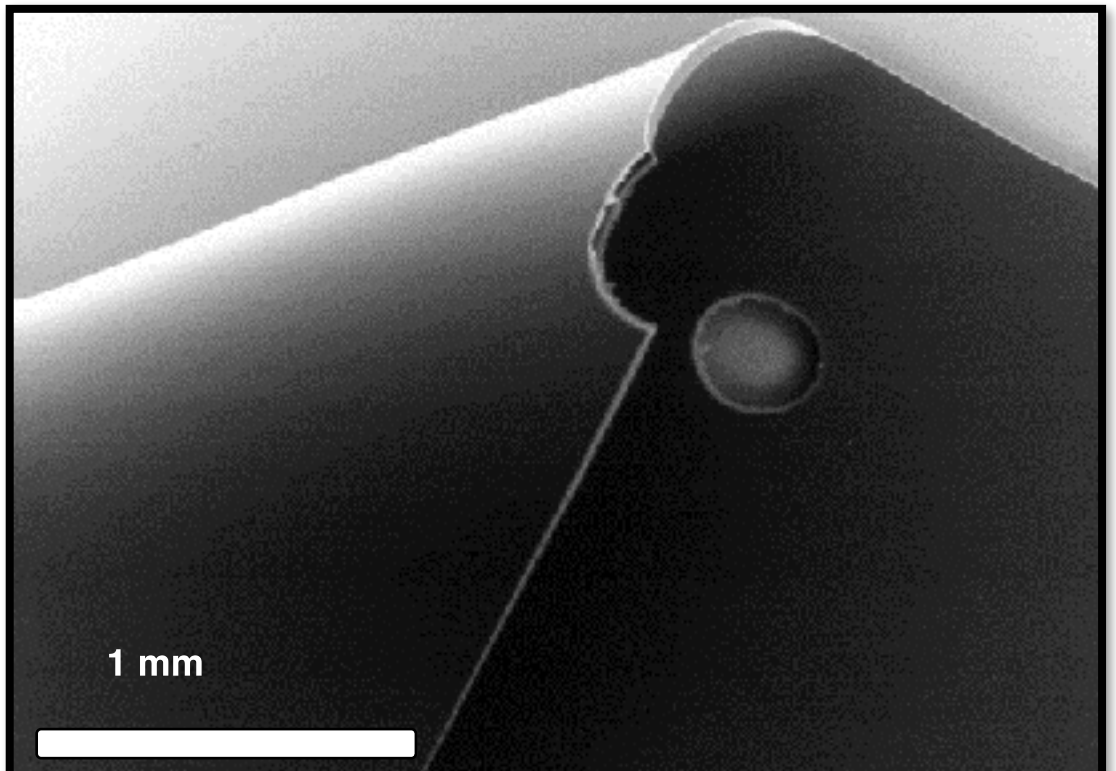
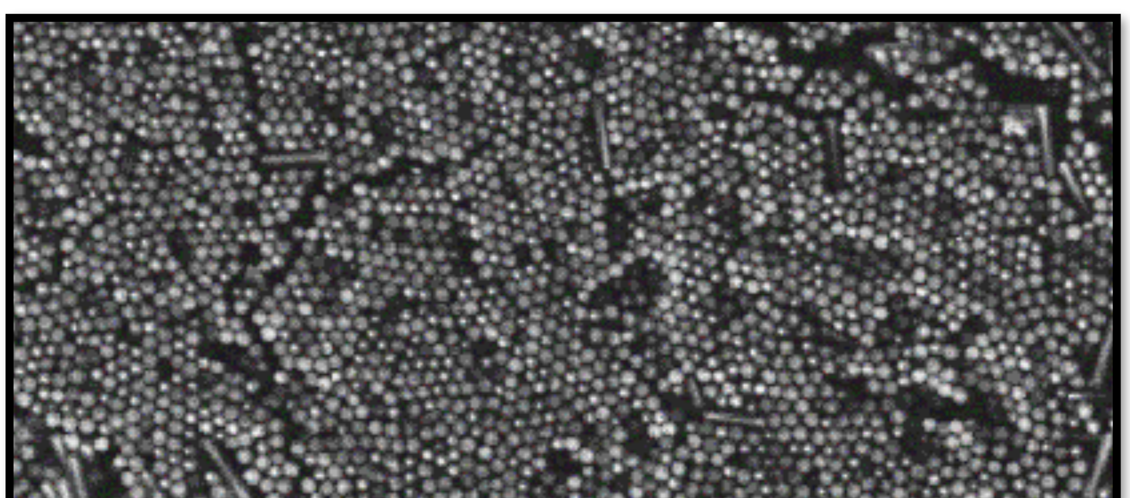
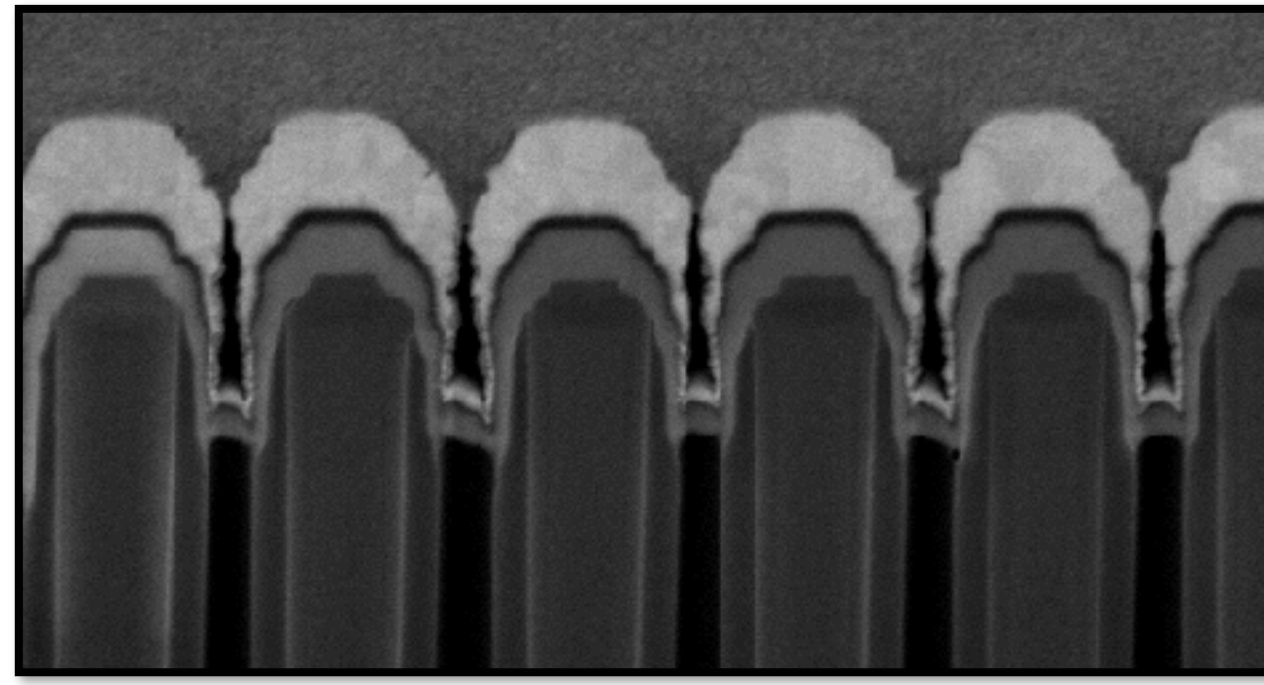
Sol Voltaics technology

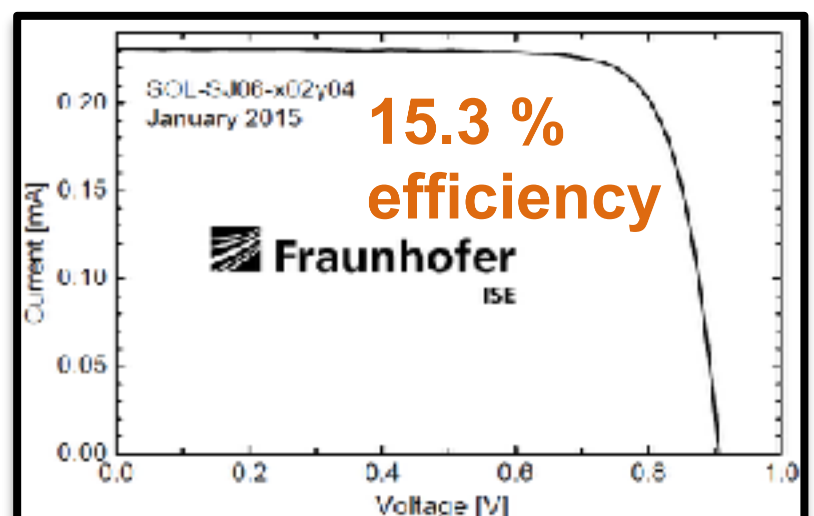
Nanowire film formation





Cell Integration





I Åberg *et al.*,
"A GaAs Nanowire Array Solar Cell With 15.3% Efficiency at 1 Sun" IEEE J Photovolt ***6*** *185 (2016)*

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Thanks for your attention!

Illustration © Sol Voltaics AB

Energimyndigheten

Knut och Alice Wallenbergs Stiftelse

Vetenskapsrådet

European Commission

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Lund University

NANO LUND
A GREAT PLACE TO DO NANOSCIENCE

2017-02-22