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2269-12

Workshop on New Materials for Renewable Energy

17 - 21 October 2011

Nanotechnology for photovoltaics

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“Modern civilization is the daughter of oil, for this offers to mankind the solar energy in its most concentrated form; that is, in a form in which it has been accumulated in along series of centuries. Modern man uses it with increasing eagerness and thoughtless prodigality for the conquest of the world and [...] oil is to-day the greatest source of energy and wealth. The earth still holds enormous quantities of it, but oil is not inexhaustible.

"The problem of the future begins to interest us ... Is fossil solar energy the only one that may be used in modern life and civilization? That is the question”.

"If our black and nervous civilization, based on oil, shall be followed by a quieter civilization based on the utilization of solar energy, that will not be harmful to progress and to human happiness”.

“Modern civilization is the daughter of coal, for this offers to mankind the solar energy in its most concentrated form; that is, in a form in which it has been accumulated in along series of centuries. Modern man uses it with increasing eagerness and thoughtless prodigality for the conquest of the world and [...] coal is to-day the greatest source of energy and wealth. The earth still holds enormous quantities of it, but coal is not inexhaustible.

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"If our black and nervous civilization, based on coal, shall be followed by a quieter civilization based on the utilization of solar energy, that will not be harmful to progress and to human happiness”.

Giacomo Ciamician, 1906

World Energy Consumption	
Current	15 TW
Projected (2050)	30 TW

Global incident sunlight 125000 TW

“The only big number out there” – Nate Lewis

Nanotechnology for Photovoltaics

Vanni Lughi
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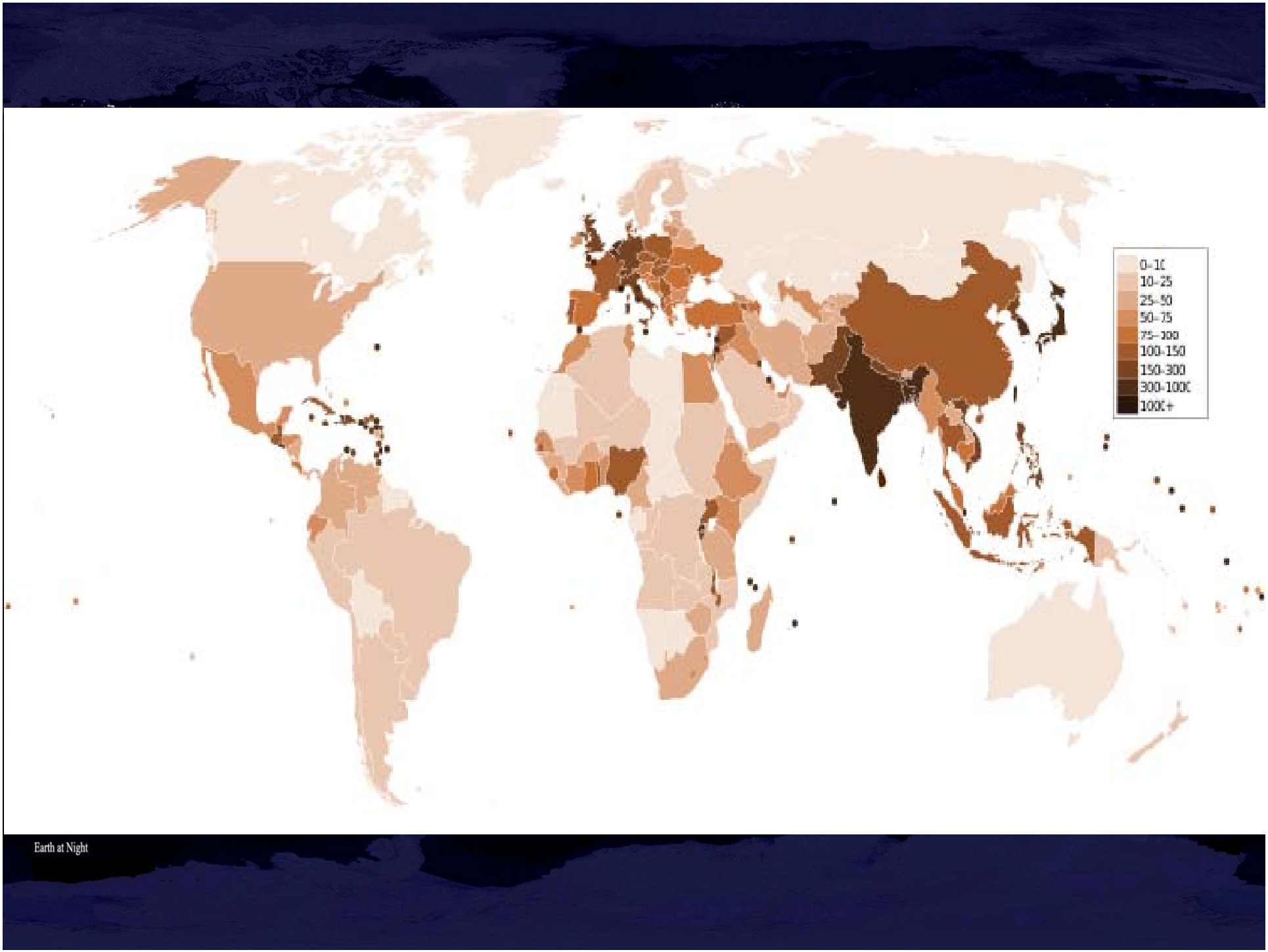
University of Trieste, Italy

Workshop on New Materials for Renewable Energy
ICTP Trieste, October 20th, 2011

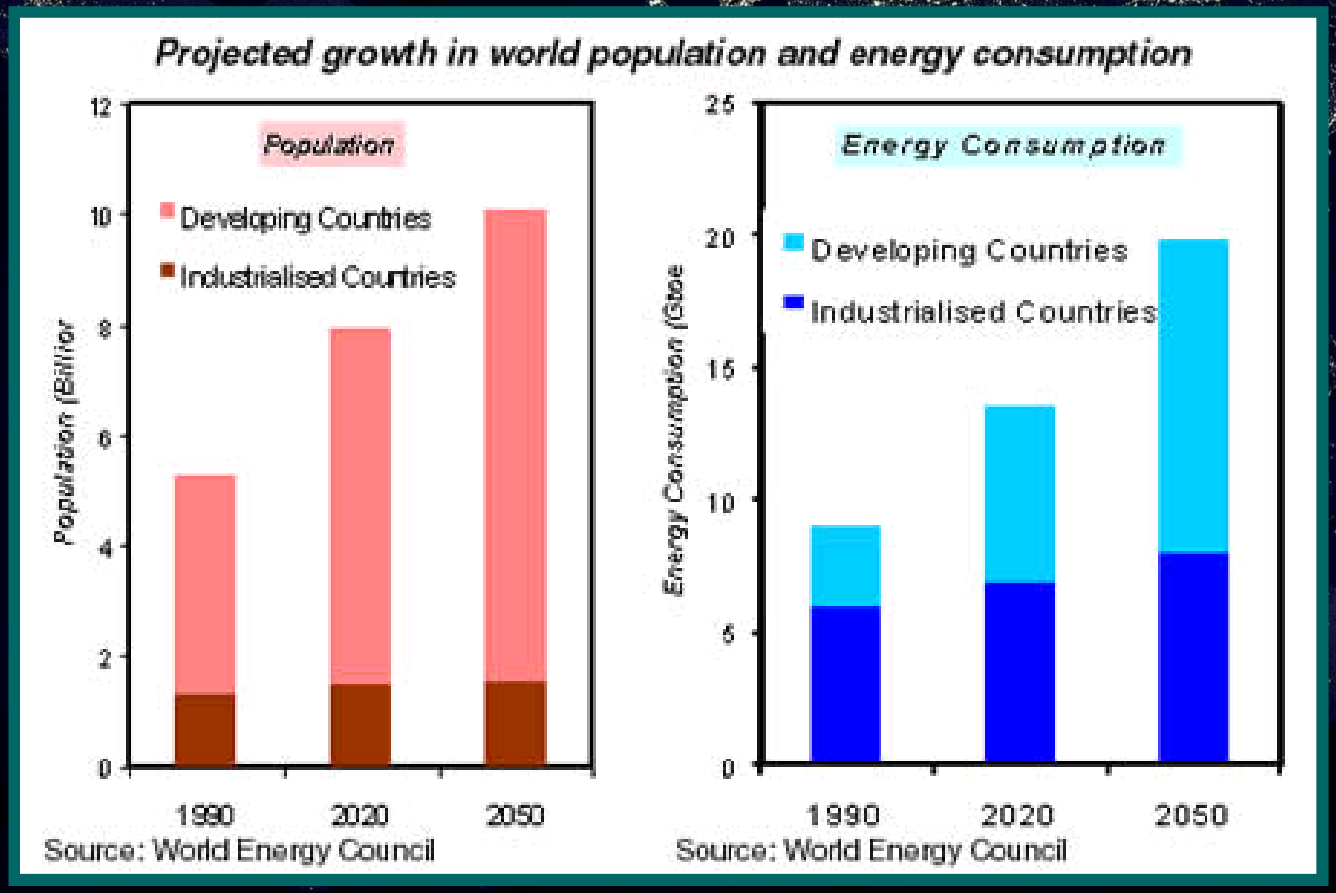
Contents

- Introduction
  - Perspectives on PV
  - State of the art and limitations in current PV
- Nanotechnology and 3rd Generation PV (or 4th ?)
  - Lookout on current approaches
  - Intermediate band nanomaterials
- Concluding Remarks



Earth at Night

Growing Energy Demand in Developing Countries



Earth at Night

Growing Energy Demand in Developing Countries

Different requirements for PV:

- NOT necessarily grid-connected
- NOT necessarily high-efficiency
- Produced locally and cheaply

(NANOTECH ?)

Need for carbon-free energy sources

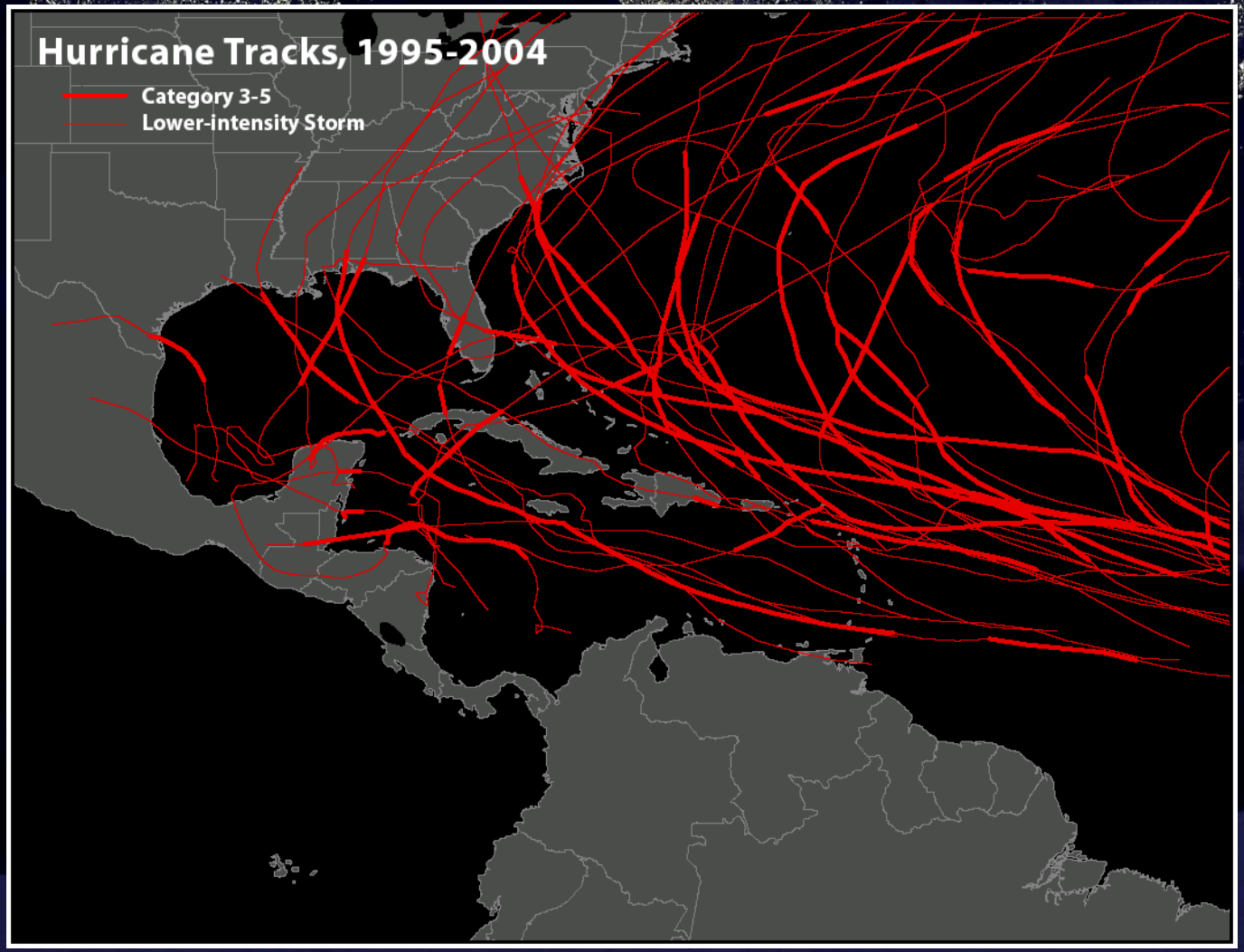
Global temperature seems to be raising

Pasterze Glacier, Austria
Change between 1875 and 2004

http://www.worldviewofglobalwarming.org/pages/glaciers.html

Need for carbon-free energy sources

Atmospheric phenomena



Earth at Night

Need for carbon-free energy sources

Economy

la Repubblica.it

Ultimo aggiornamento **lunedi 08.01.2007 ore 10.45**

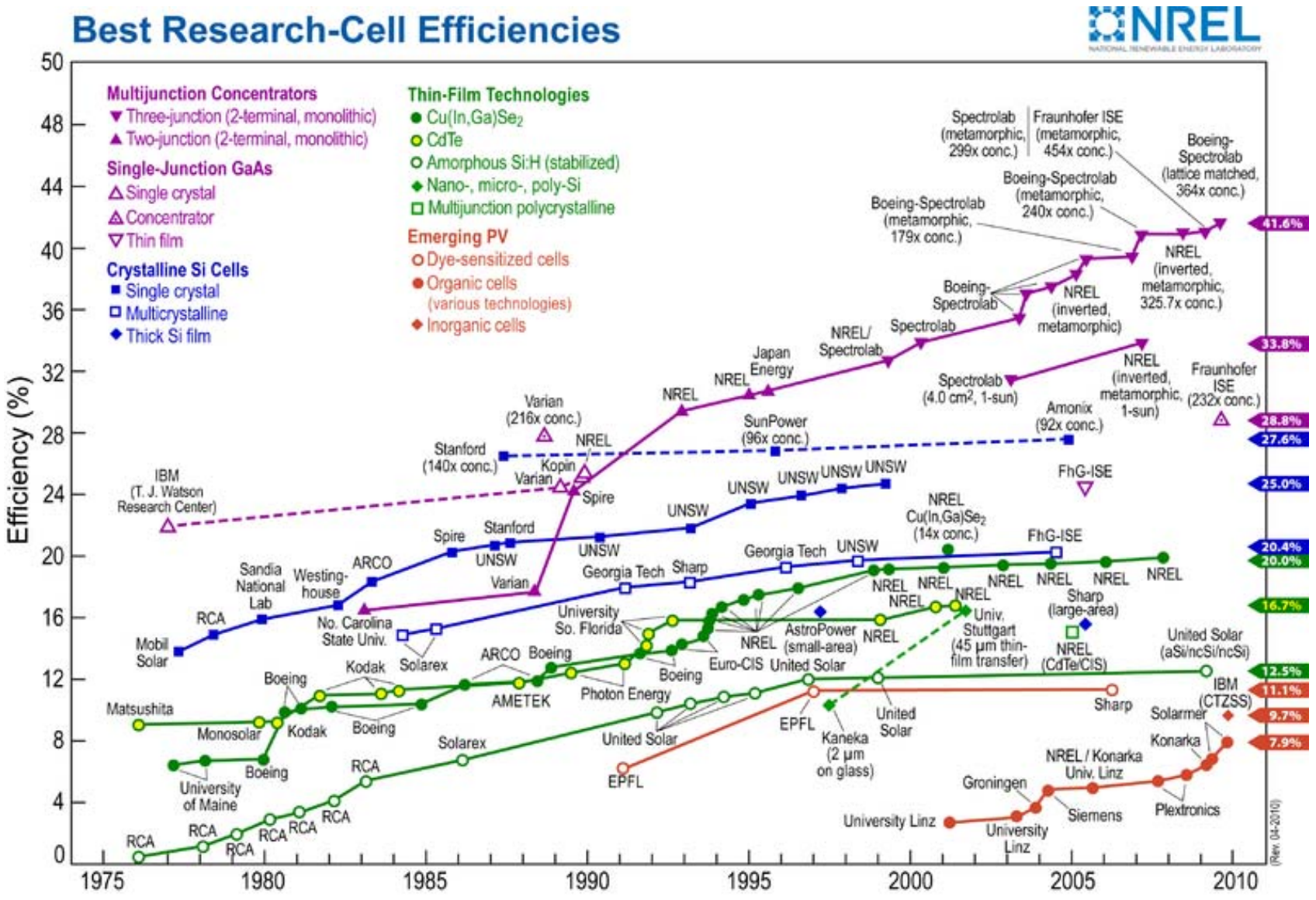
AMBIENTE

Entro gennaio convocati gli esperti che hanno preparato la ricerca per la Ue
Nel conto i danni a turismo e agricoltura e le sanzioni per le violazioni di Kyoto

Clima, minaccia per l'economia l'Italia rischia decine di miliardi

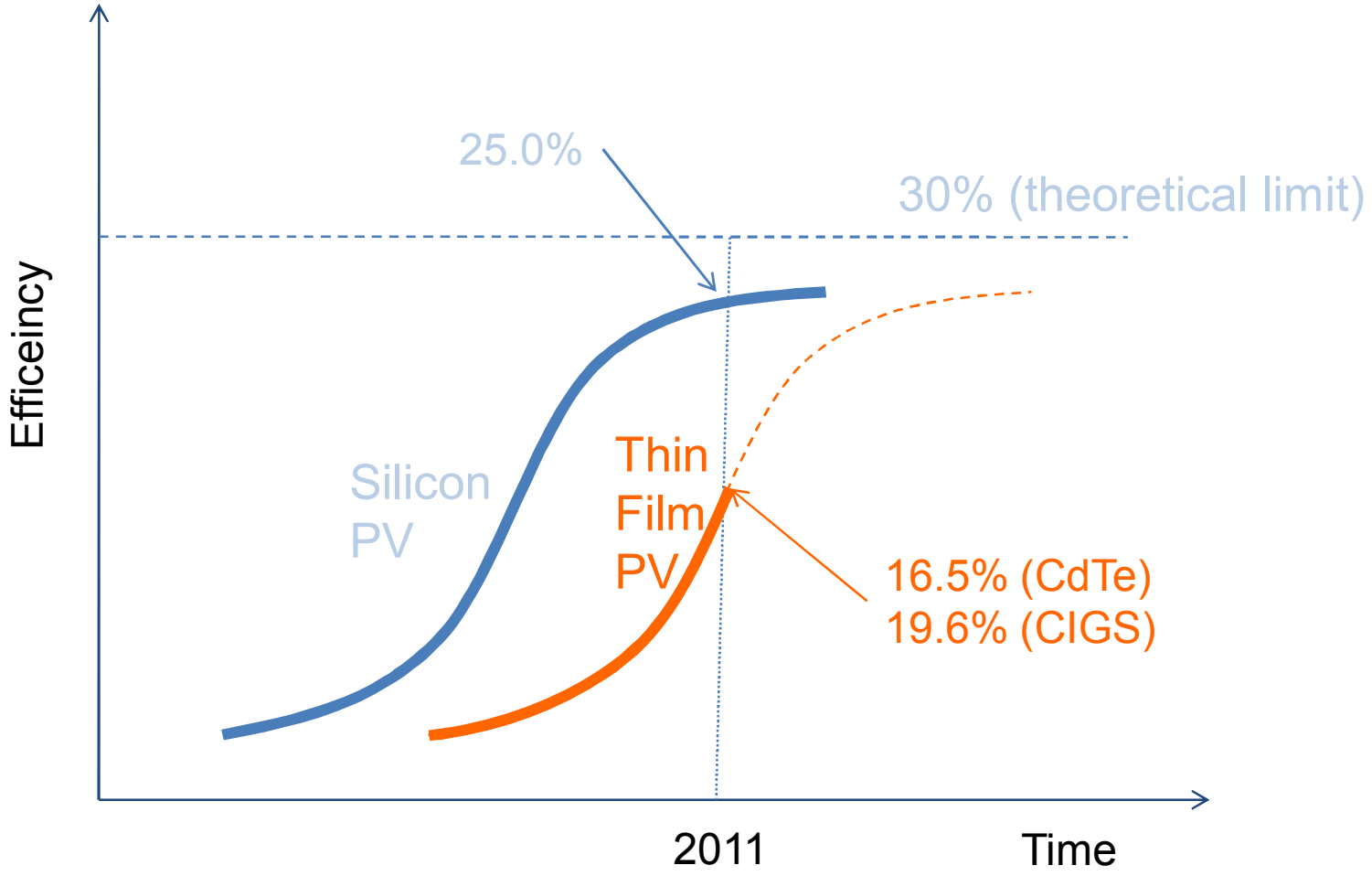
Earth at Night

Technology evolution: Efficiency increase

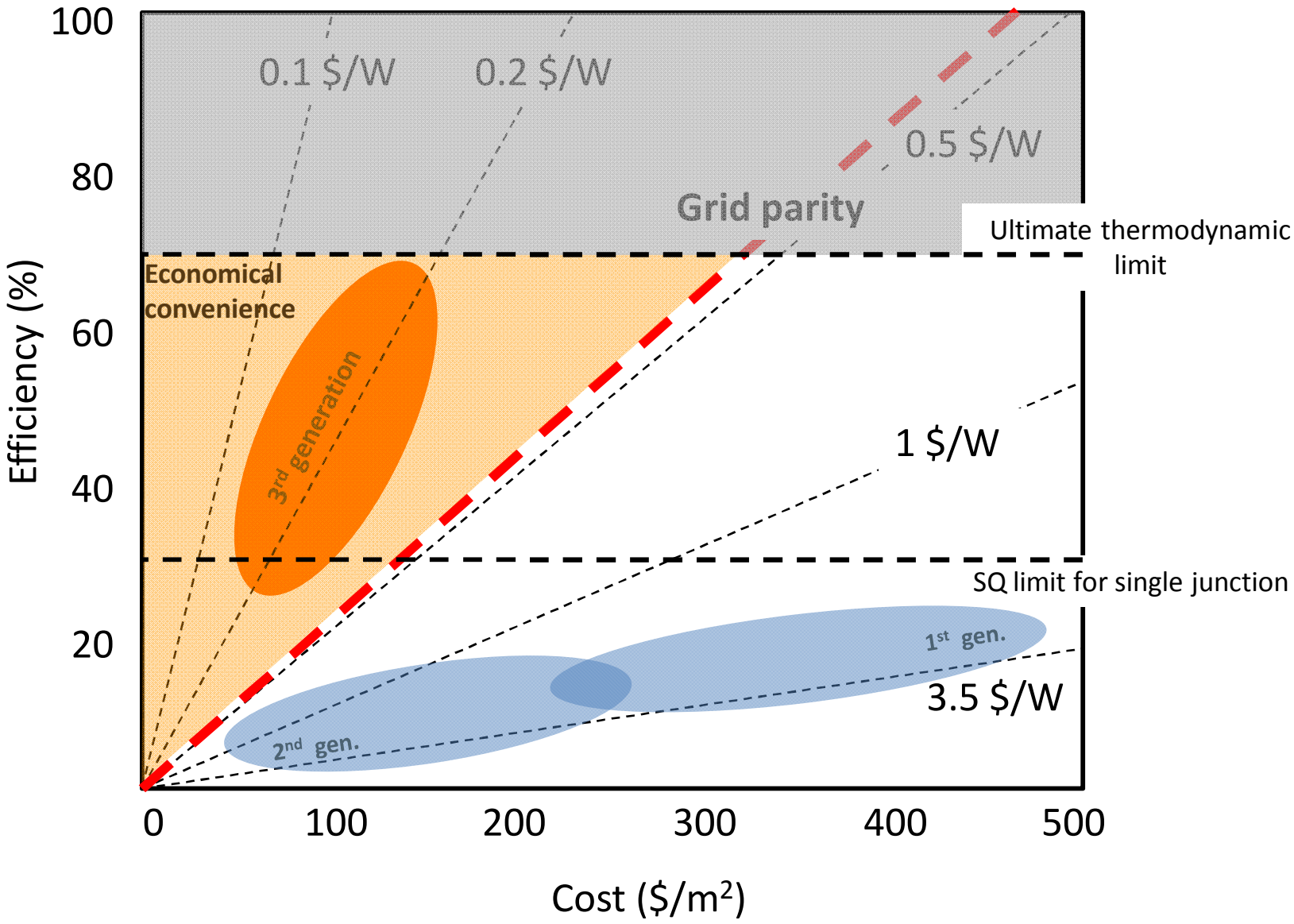


NREL - US Dept.of Energy

Technology evolution: Efficiency increase

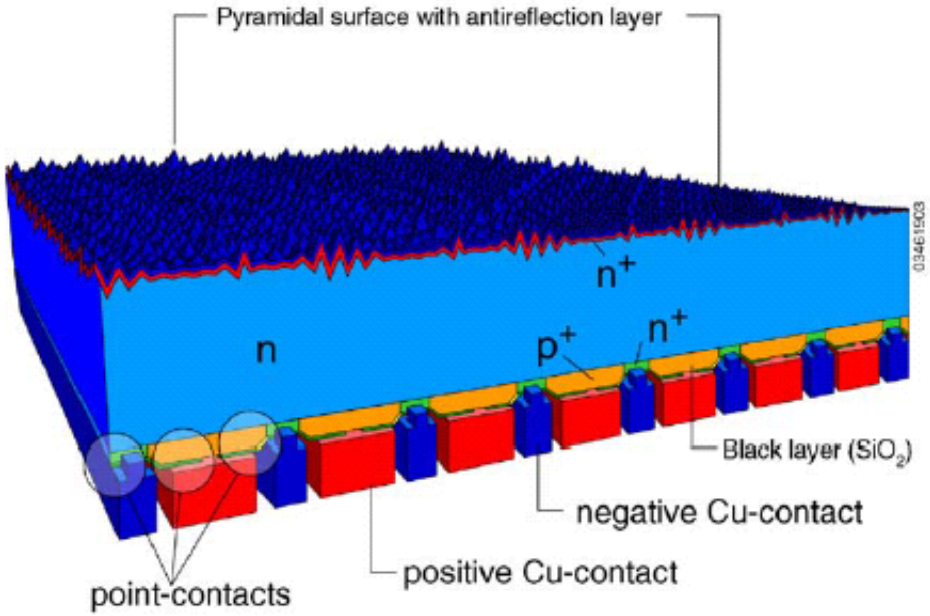


Tecno-Economical Evolution



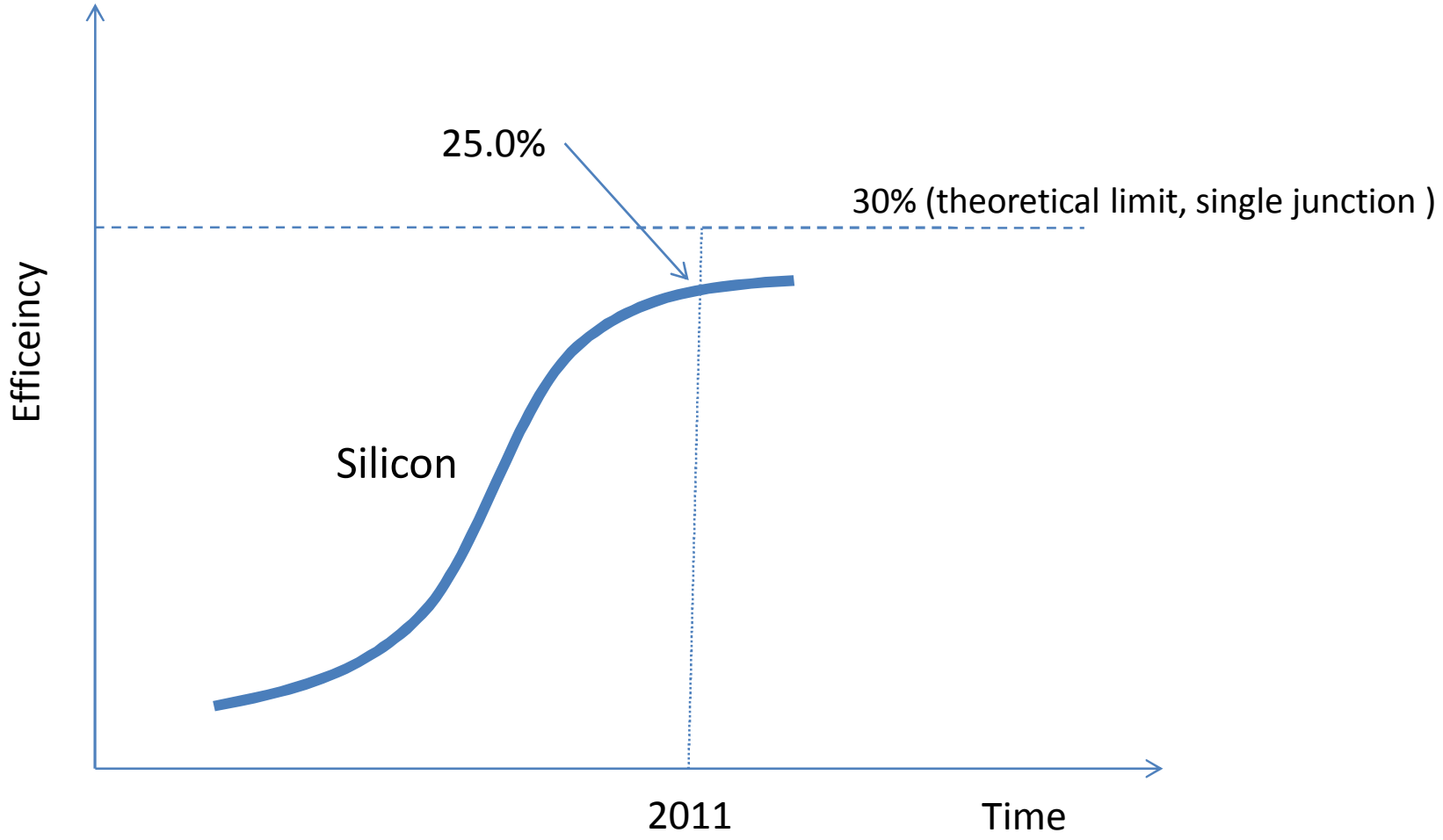
Silicon Technology

Silicon Technology – Record Performance

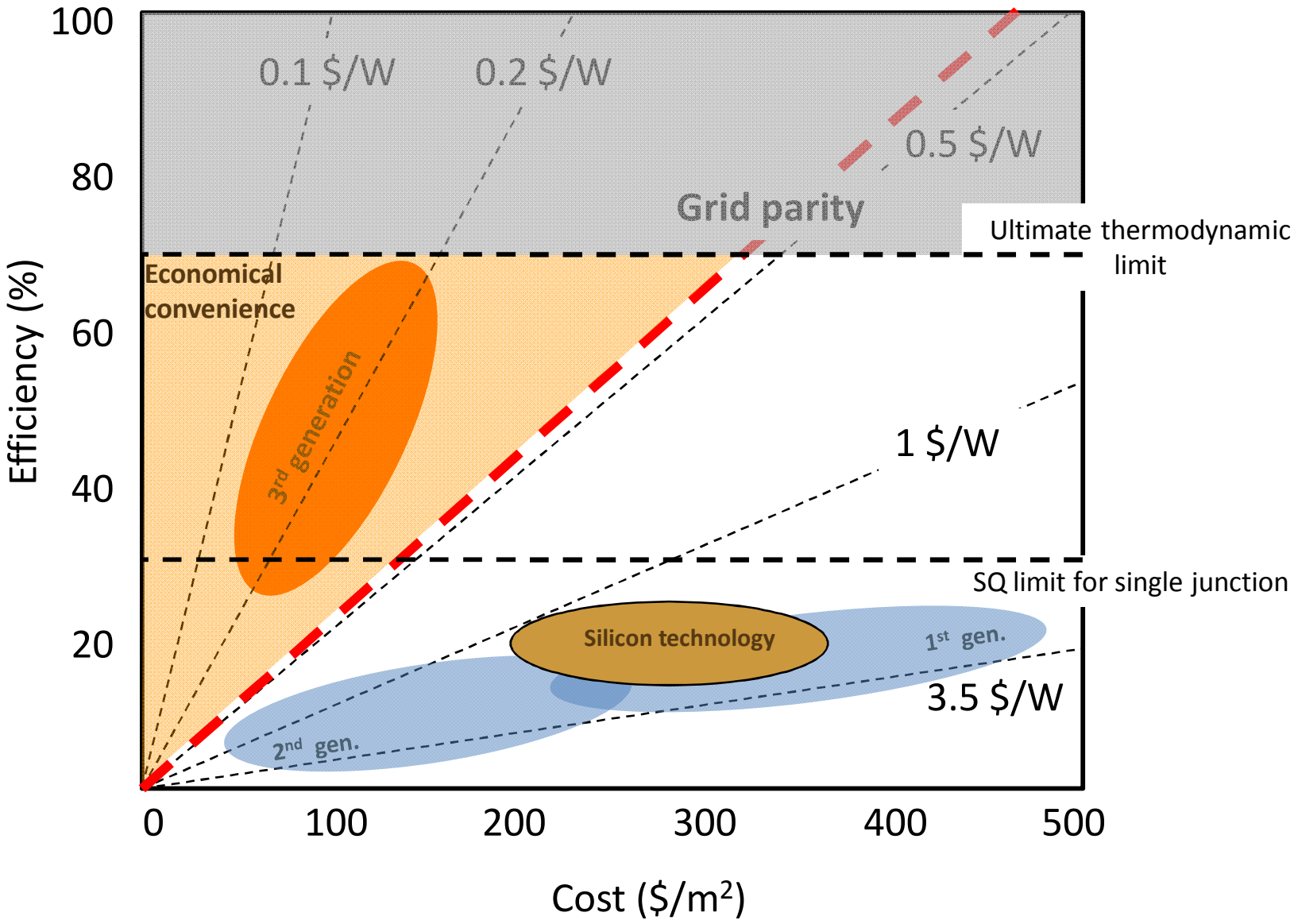


	Single crystal silicon	Polycrystalline
Cell Record	25.0%	20.4%
Module record	22.9%	17.5%
Commercial modules	15-18%	12-15

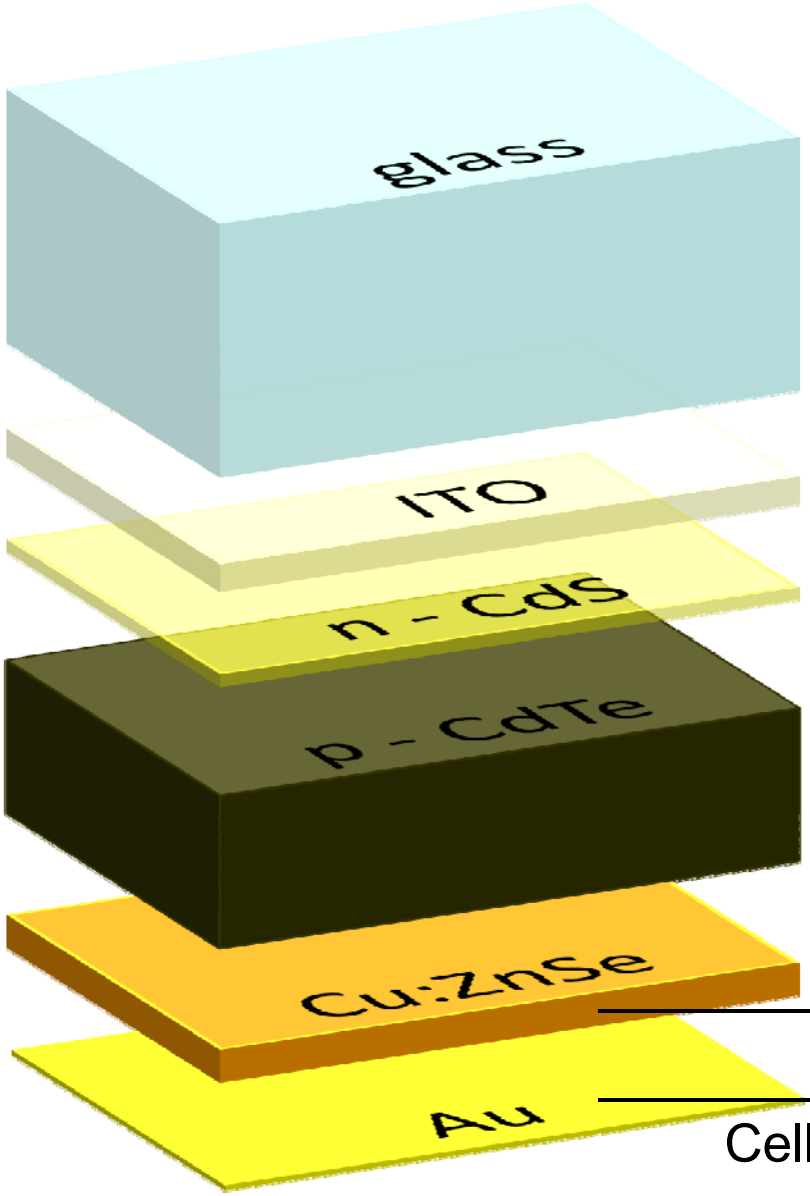
Silicon Technology



Tecno-Economical Evolution

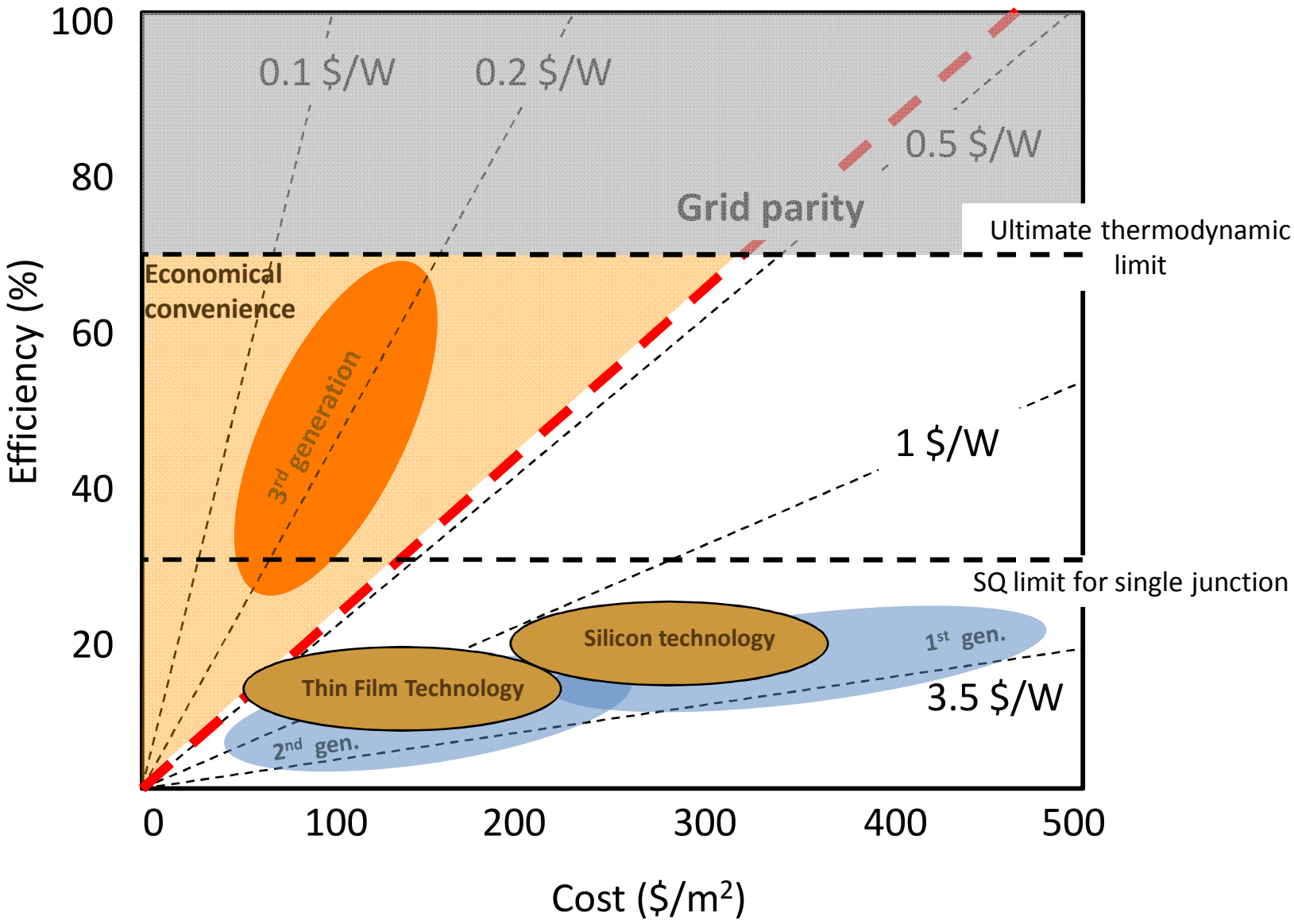


Thin Film Solar Cells

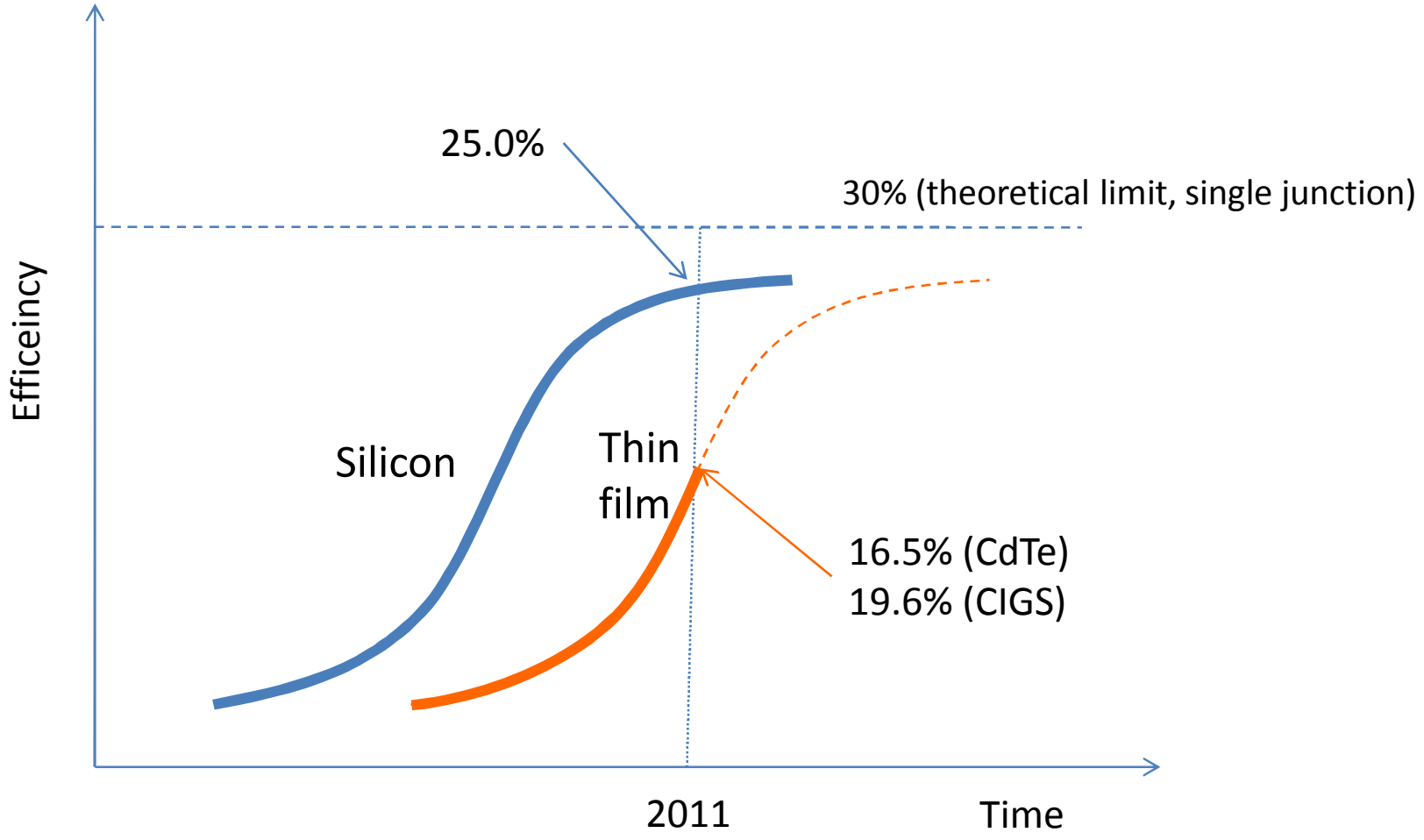


	CdTe	CIGSS	Amorphous Si
Cell Record	16.5%	19.5%	9.5%
Module record	12%	15.7%	--
Commercial modules	9-11%	12.9%	4-7%

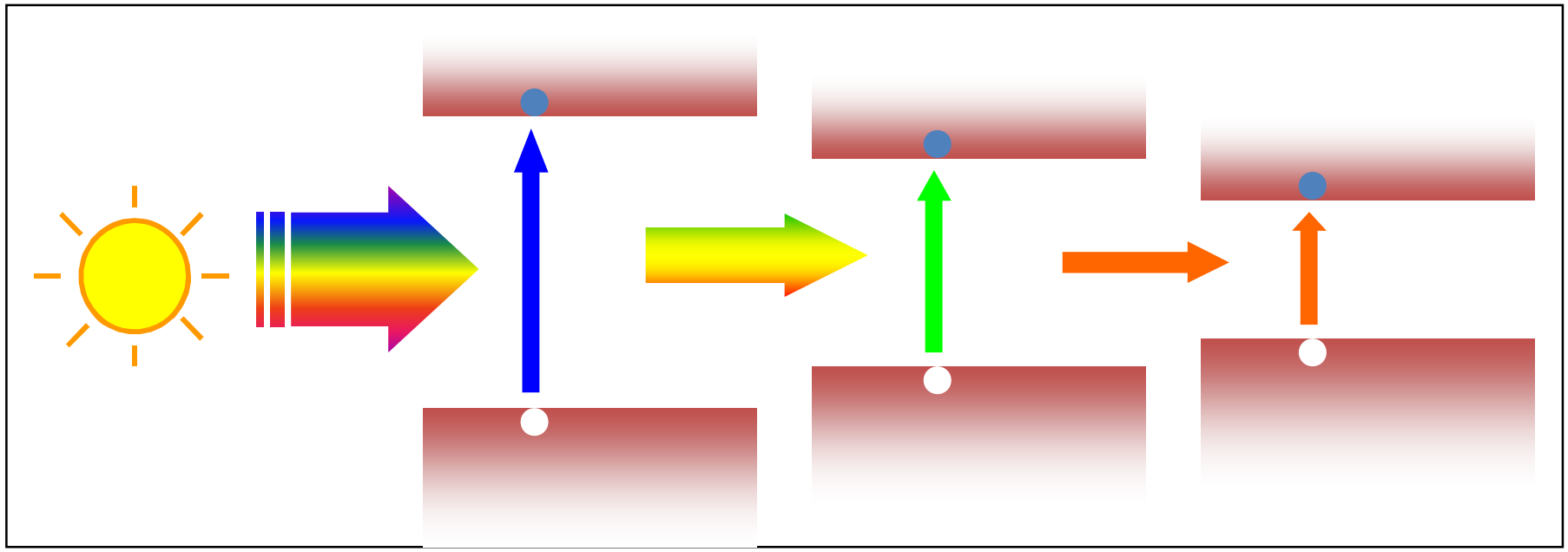
Tecno-Economical Evolution



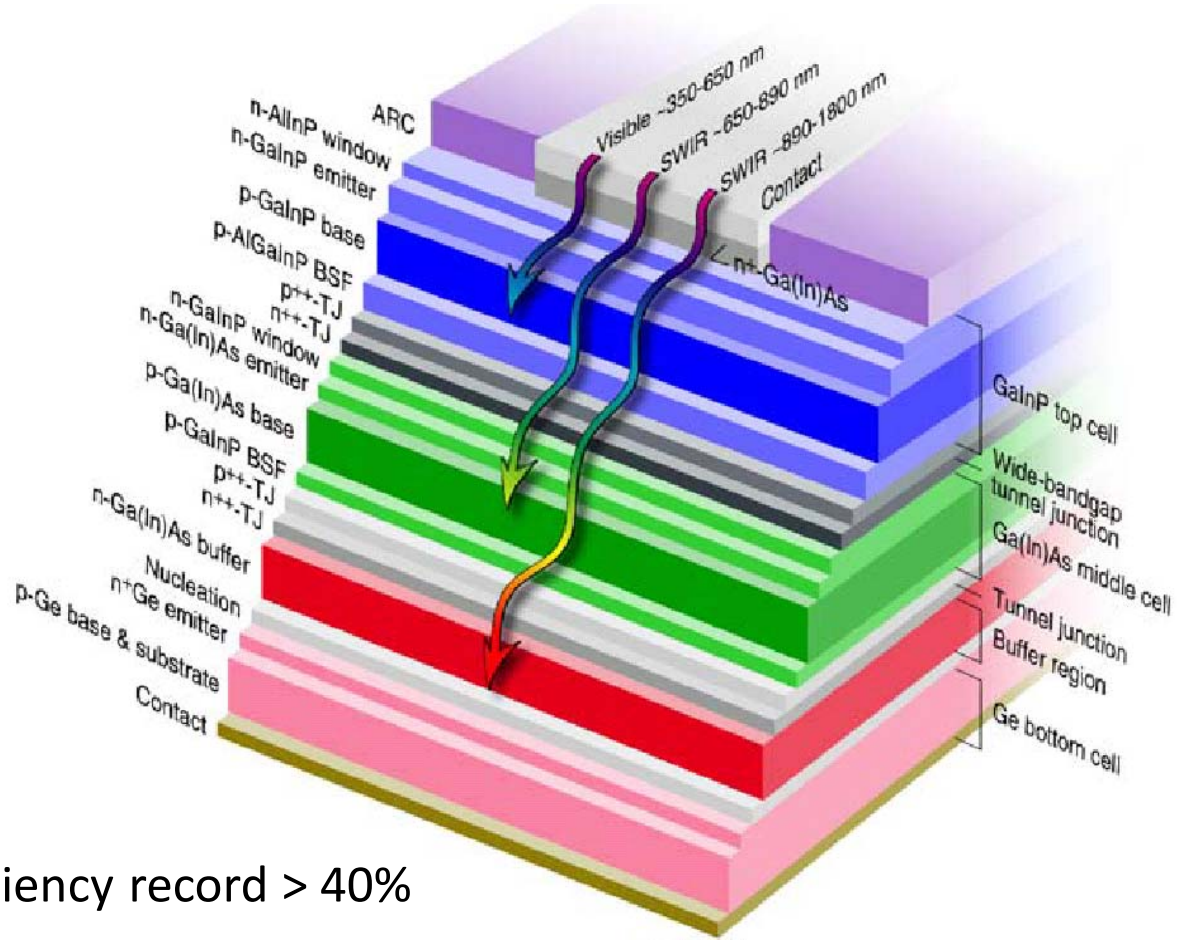
Technology evolution: Efficiency increase



Beyond The Single Junction Limit: Tandem cells

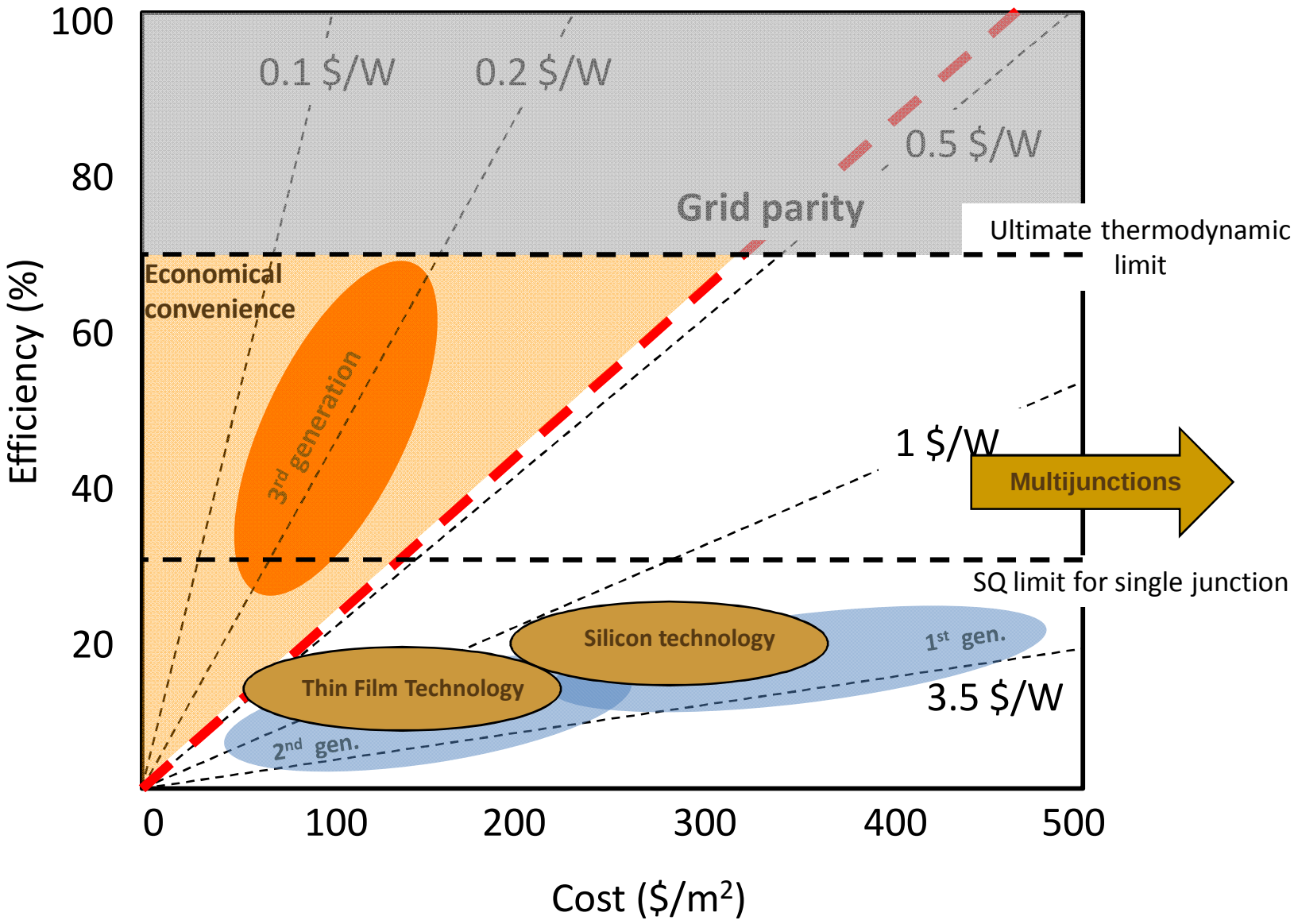


Tandem Cells



- Current efficiency record > 40%
- Multijunction cells – very expensive
- Aerospace applications or terrestrial concentration

Tecno-Economical Evolution



Nanotechnology and 3rd Generation PV (or 4th ?)

Why Nanotechnolgy

- Morphological advantages (surface area)
- Phenomena that govern the optoelectronic properties of materials, charge transfer and transport **occur at the nanoscale**
- Phenomena at the nanoscale are governed by the laws of quantum mechanics

  ⇒ new opportunities for controlling material properties at the macroscale ("untapped physics")

- *Opportunity of combining the advantages of thin film tecnology, and of subtile bandgap engineering*

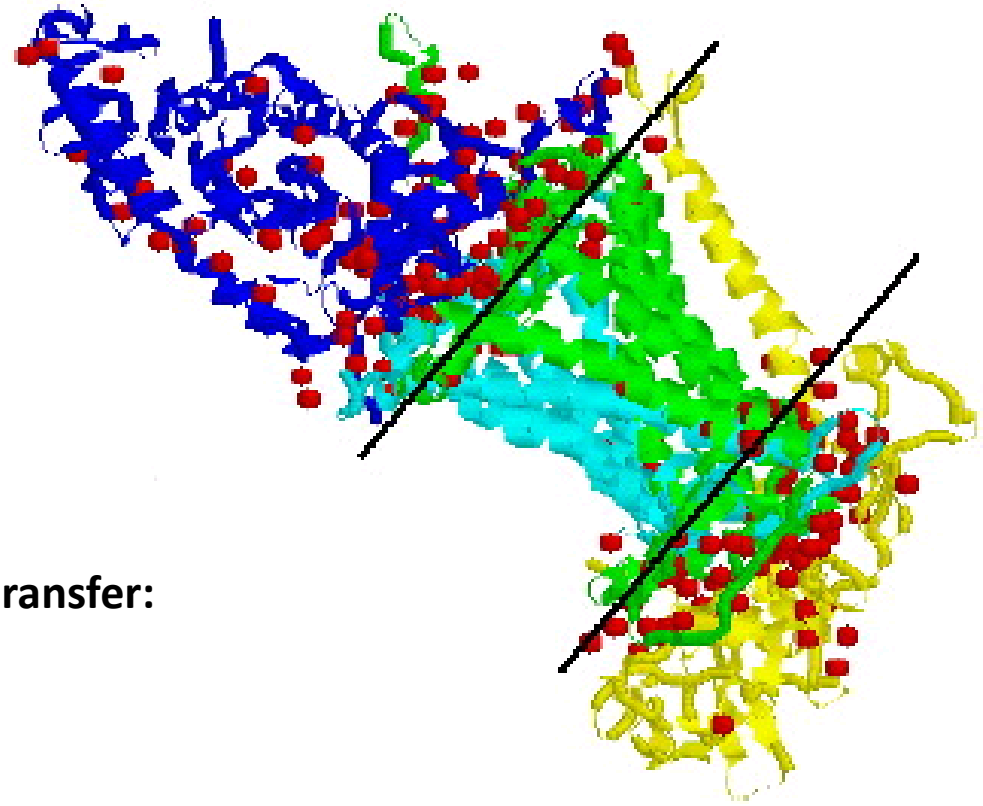
Outlook on Current Nanotech Approaches to PV

Artificial Photosynthesis

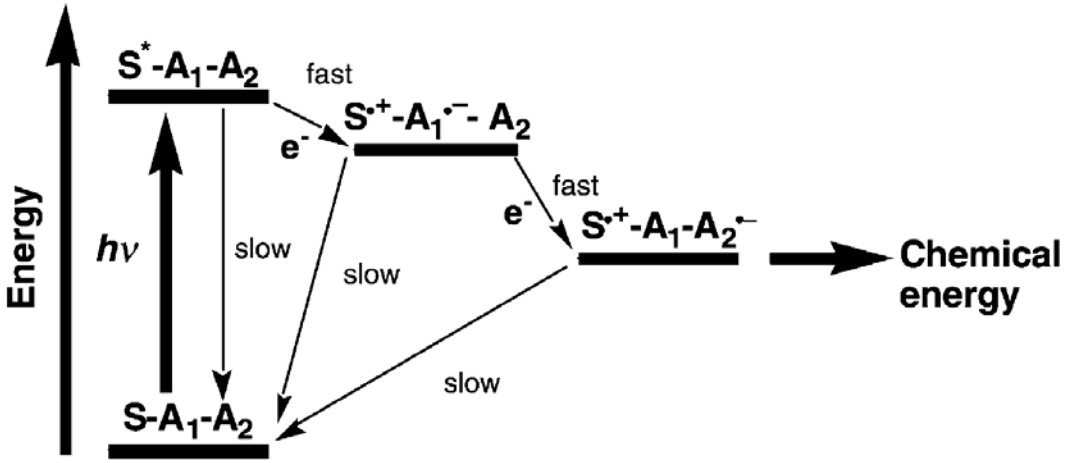
- copying Nature to master charge separation -

Reaction centers in Nature:

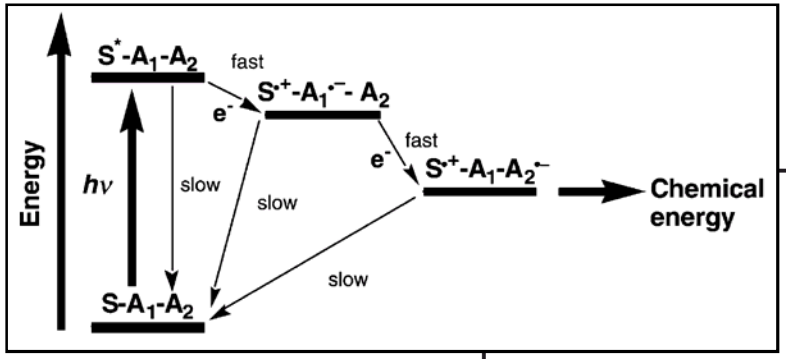
- Multistep **electron** transfer
- Long-lasting charge-separated states (over 10 μs, QE ~100%)

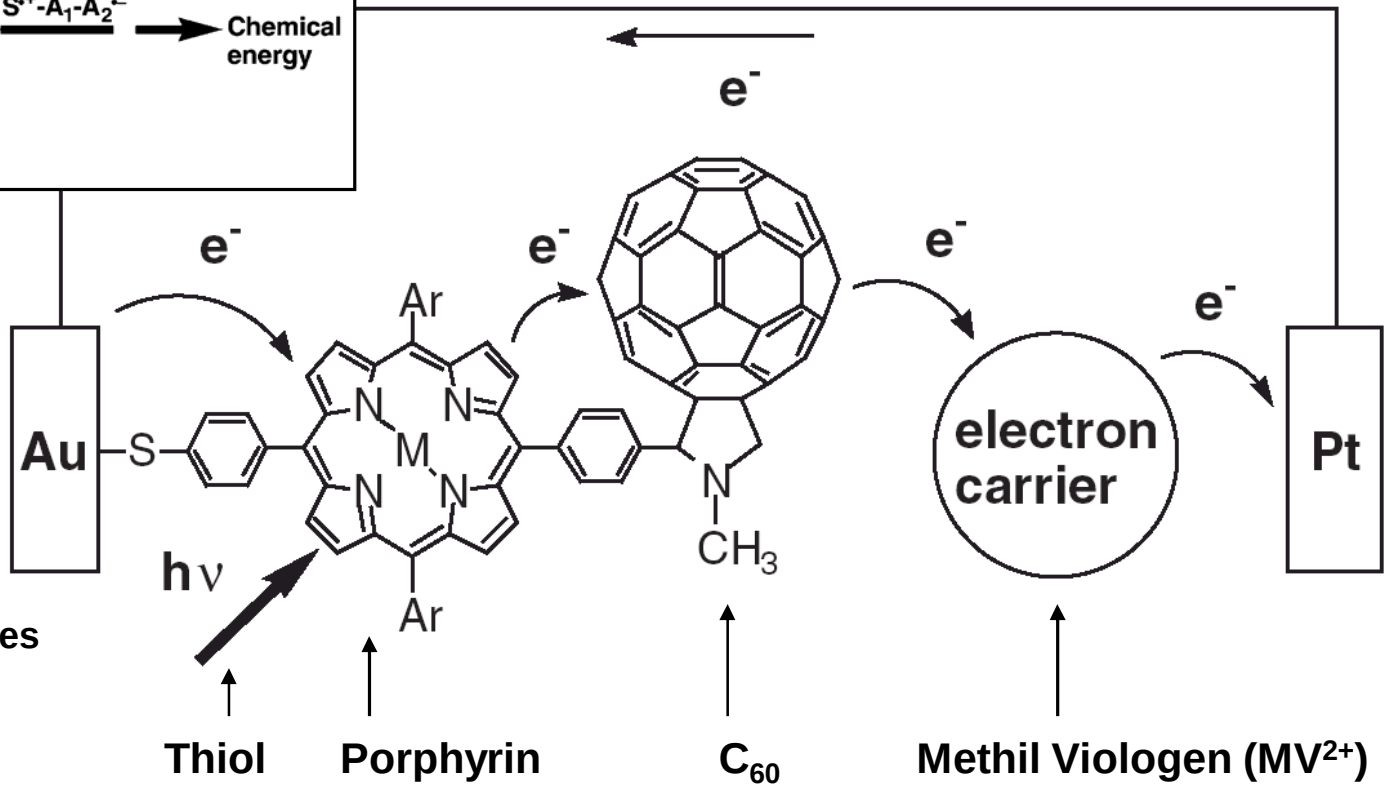


Artificial multistep electron transfer:



Artificial Photosynthesis: Multistep Electron Transfer

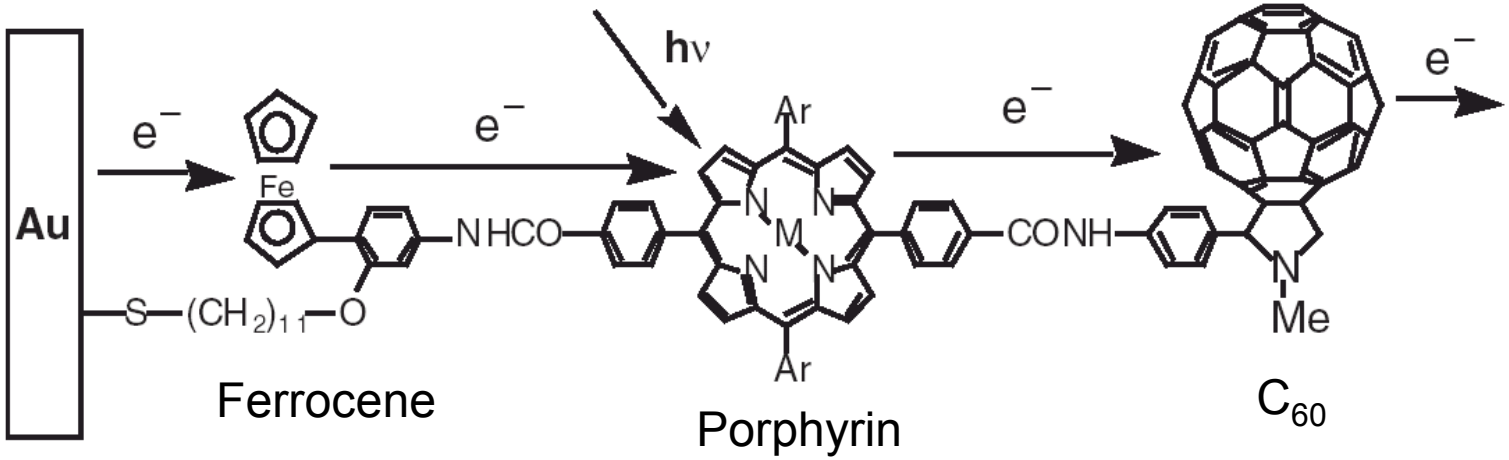


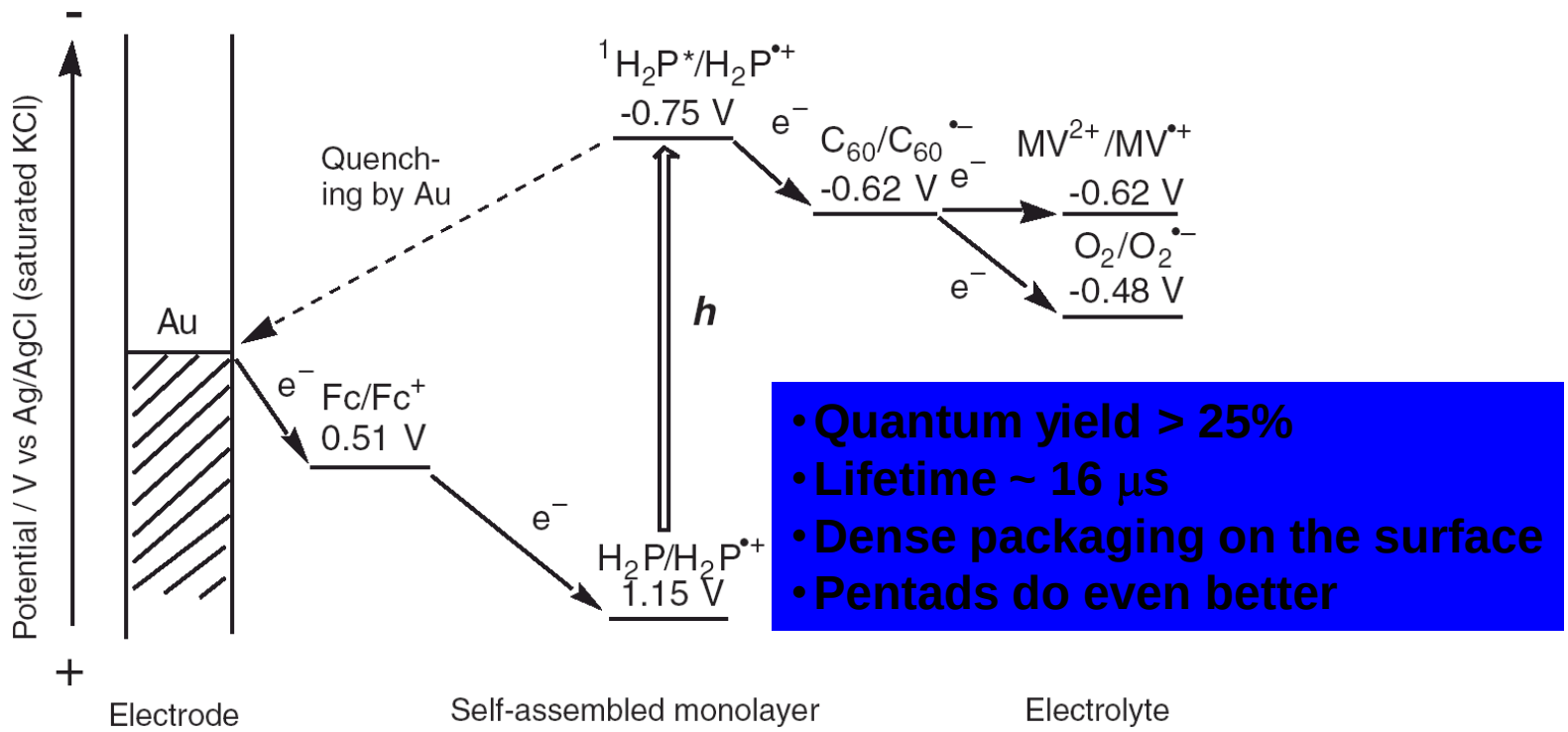


- **Porphyrin-fullerene couples** self-assembled on surfaces
- Donors and acceptors are bonded covalently

- **Quantum yield: 0.5%**
- **Lifetime 0.77 μs**
- **Loose packaging on the surface**

Artificial Photosynthesis: A more efficient scheme

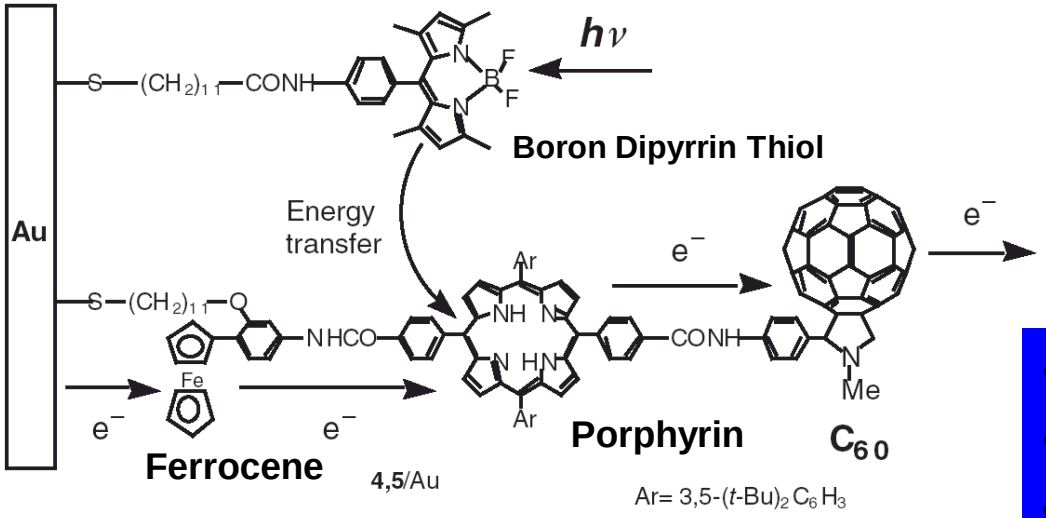




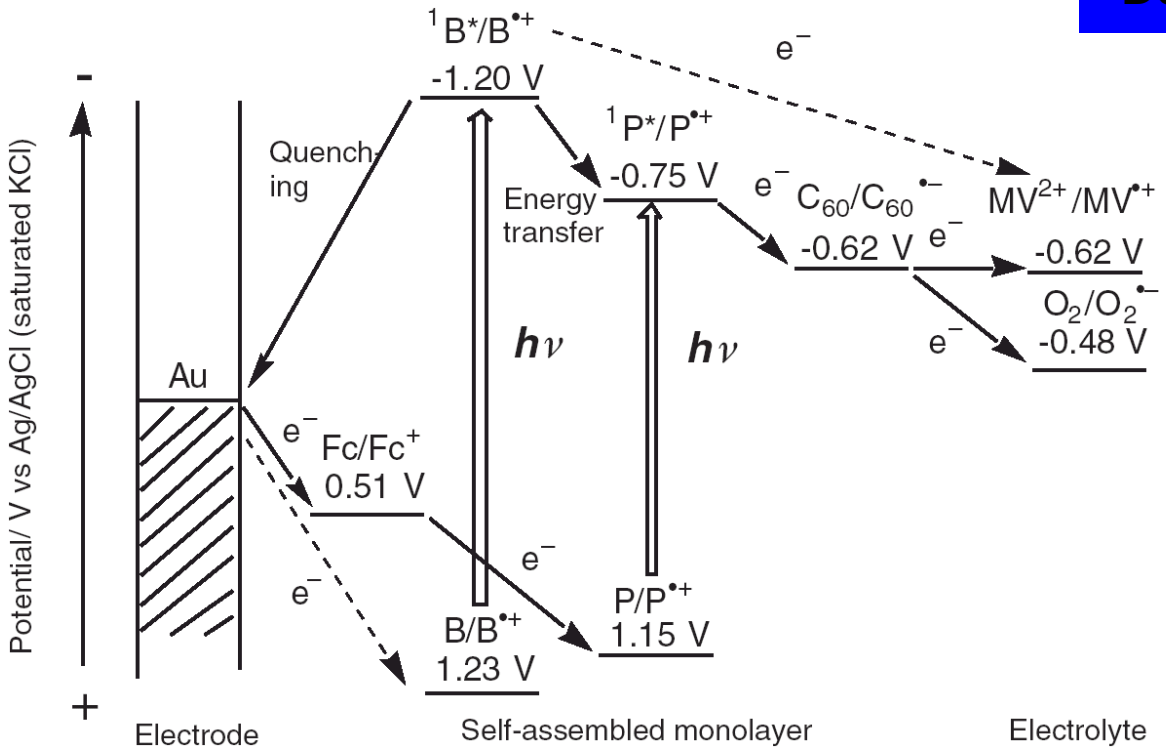
- **Quantum yield > 25%**
- **Lifetime ~ 16 μs**
- **Dense packaging on the surface**
- **Pentads do even better**

H. Imahori et al., Adv. Func. Materials 14, 525 (2004)

Artificial Photosynthesis: Mimicking energy transfer



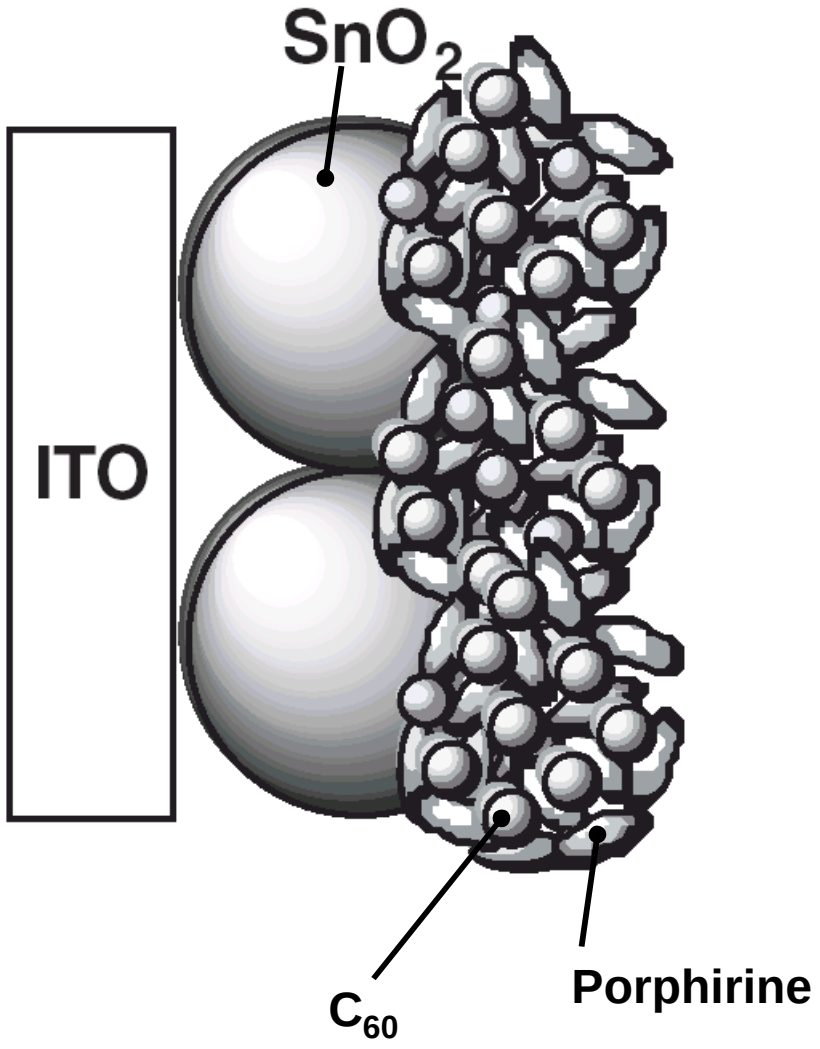
- Quantum yield: up to 50%
- Enhanced spectral absorption
- Dense packaging on the surface



H. Imahori et al., Adv. Func. Materials 14, 525 (2004)

Artificial Photosynthesis:

Multiscale Hierarchical assembly for enhancing absorption



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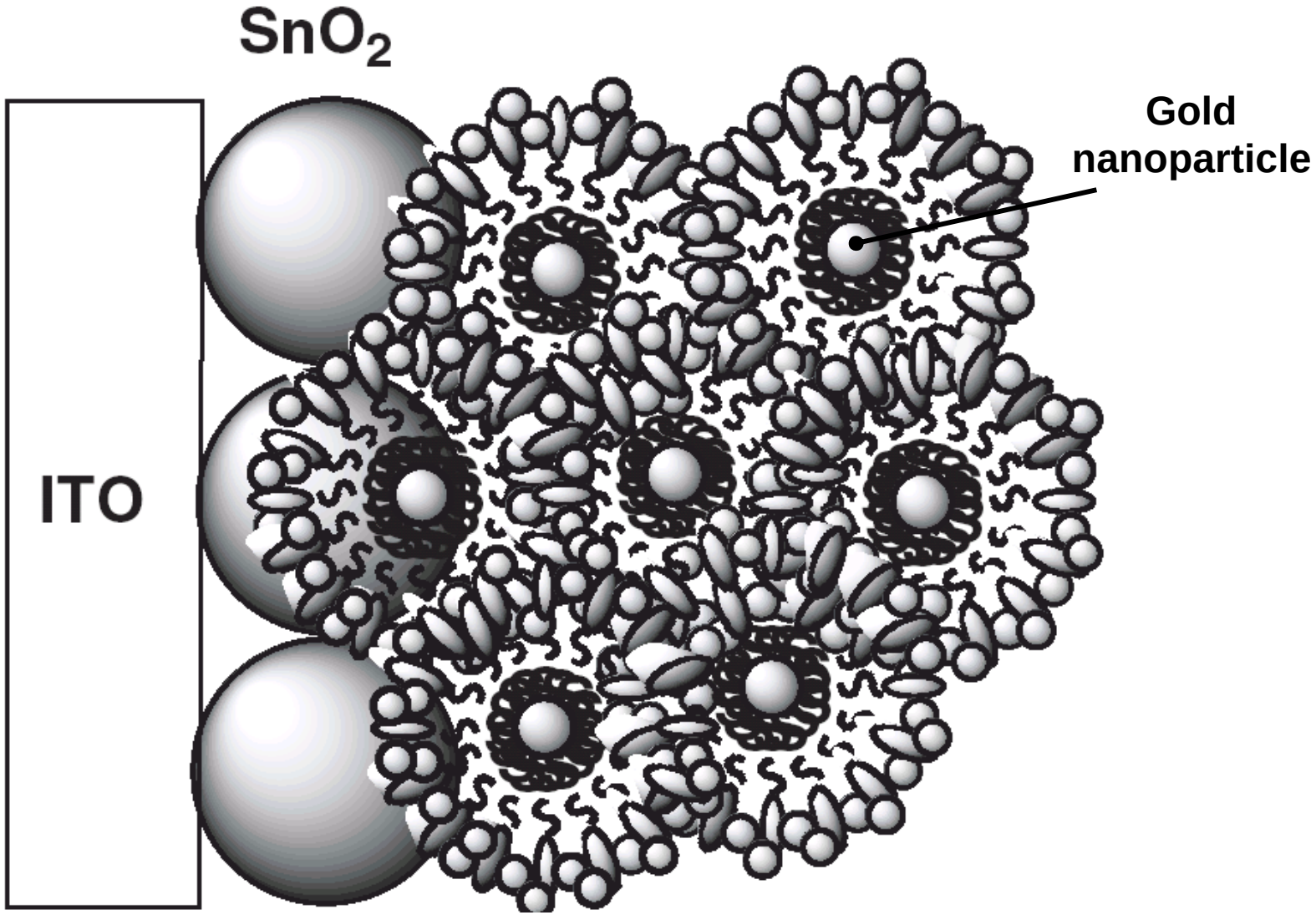
Artificial Photosynthesis:

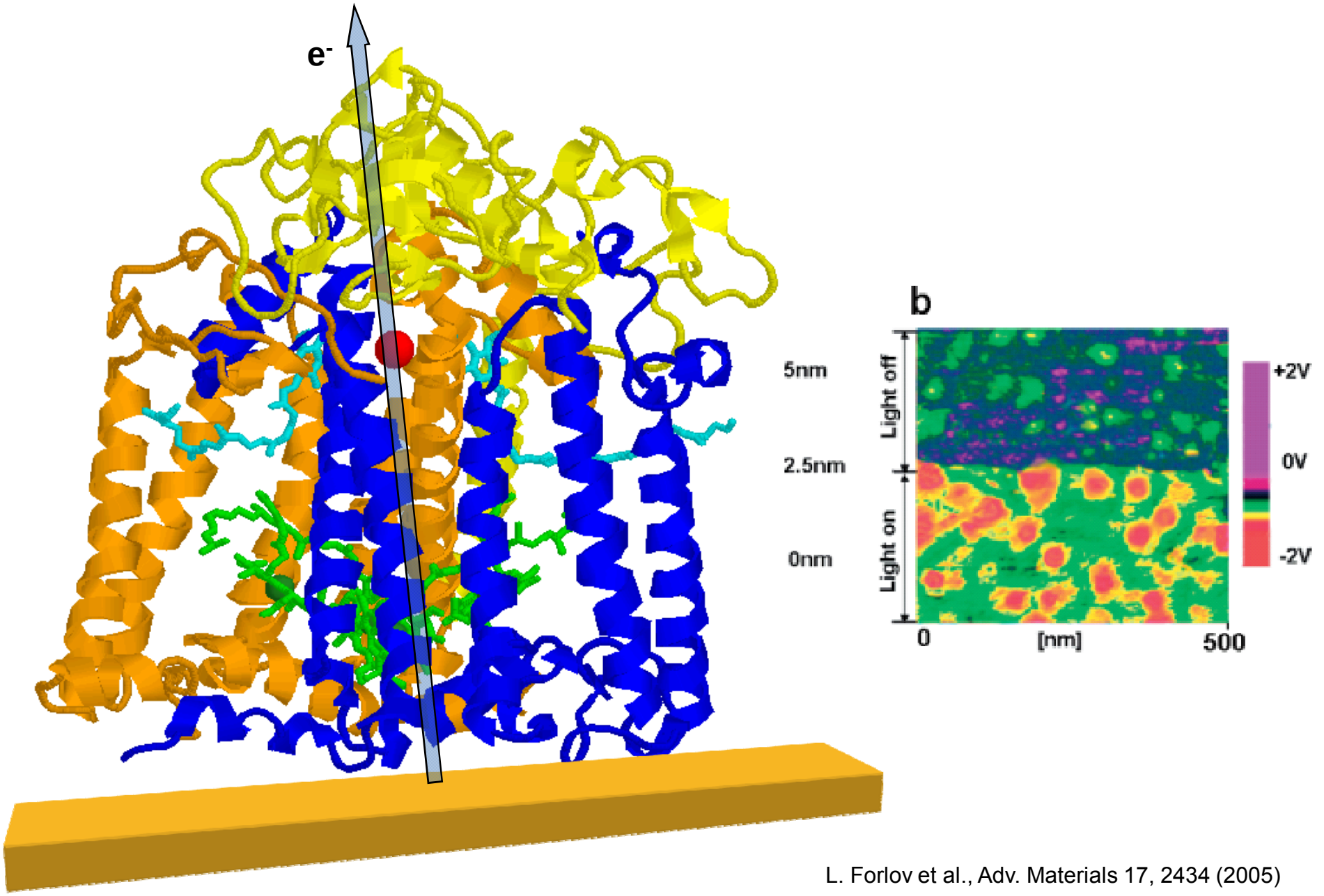
Multiscale Hierarchical assembly for enhancing absorption



H. Imahori et al., Adv. Func. Materials 14, 525 (2004)

“Stealing” from Nature

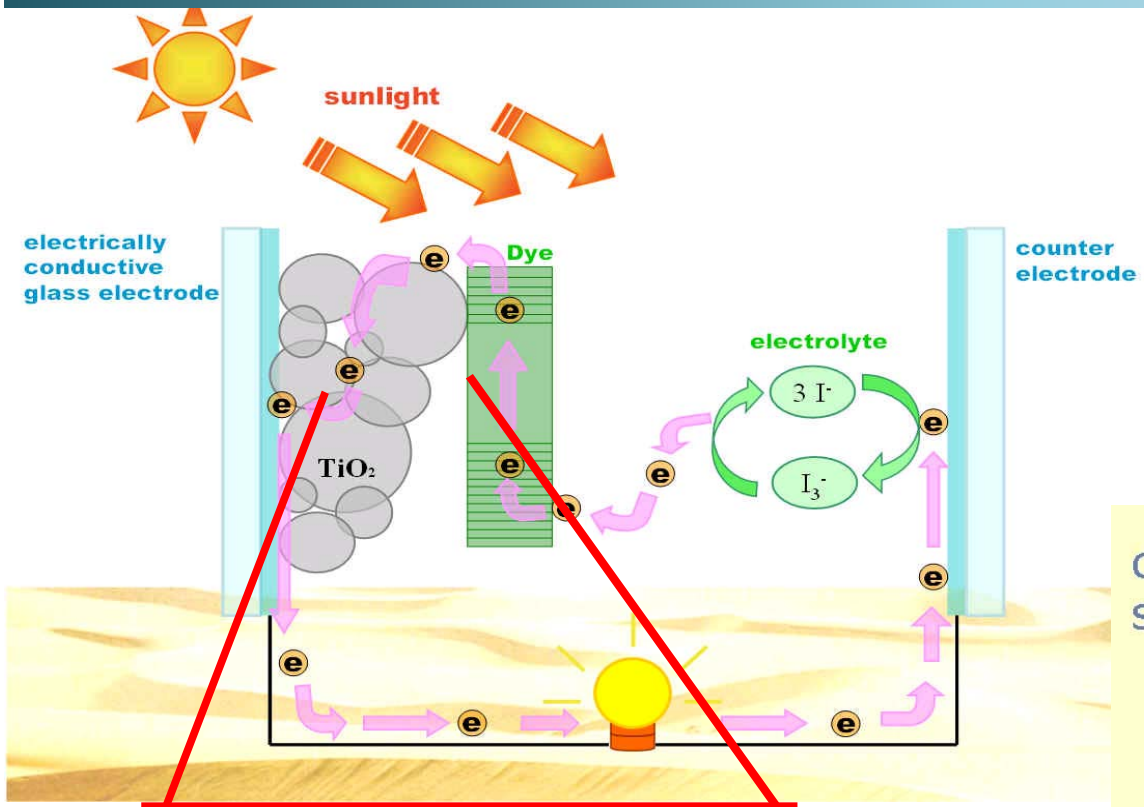
Photoactive reaction centers on metal substrates

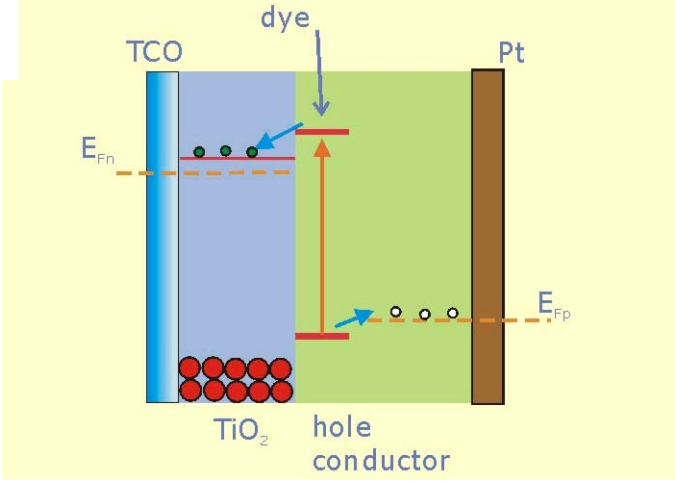


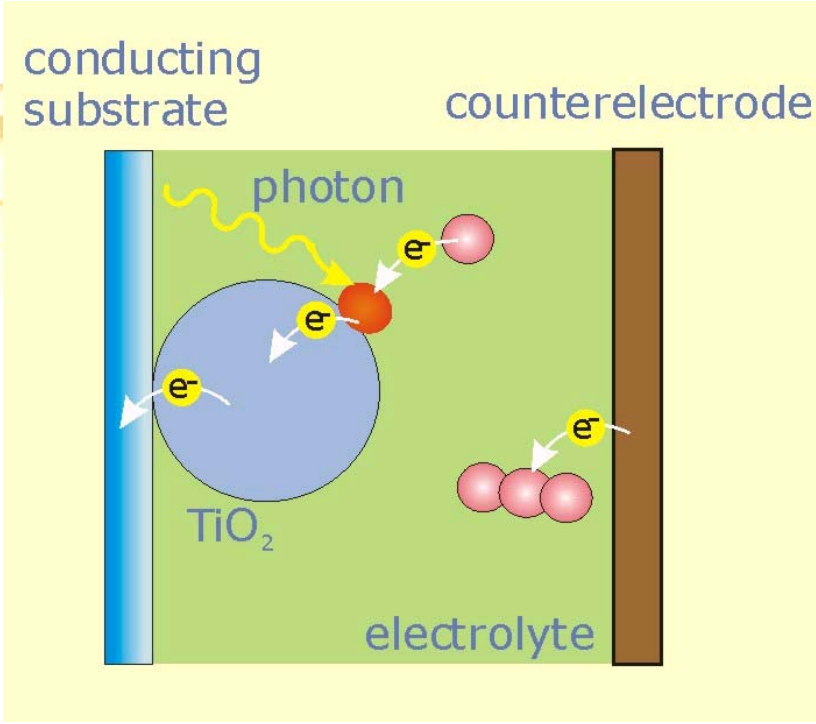
L. Forlov et al., Adv. Materials 17, 2434 (2005)

Dye Sensitized Solar Cells – DSSC

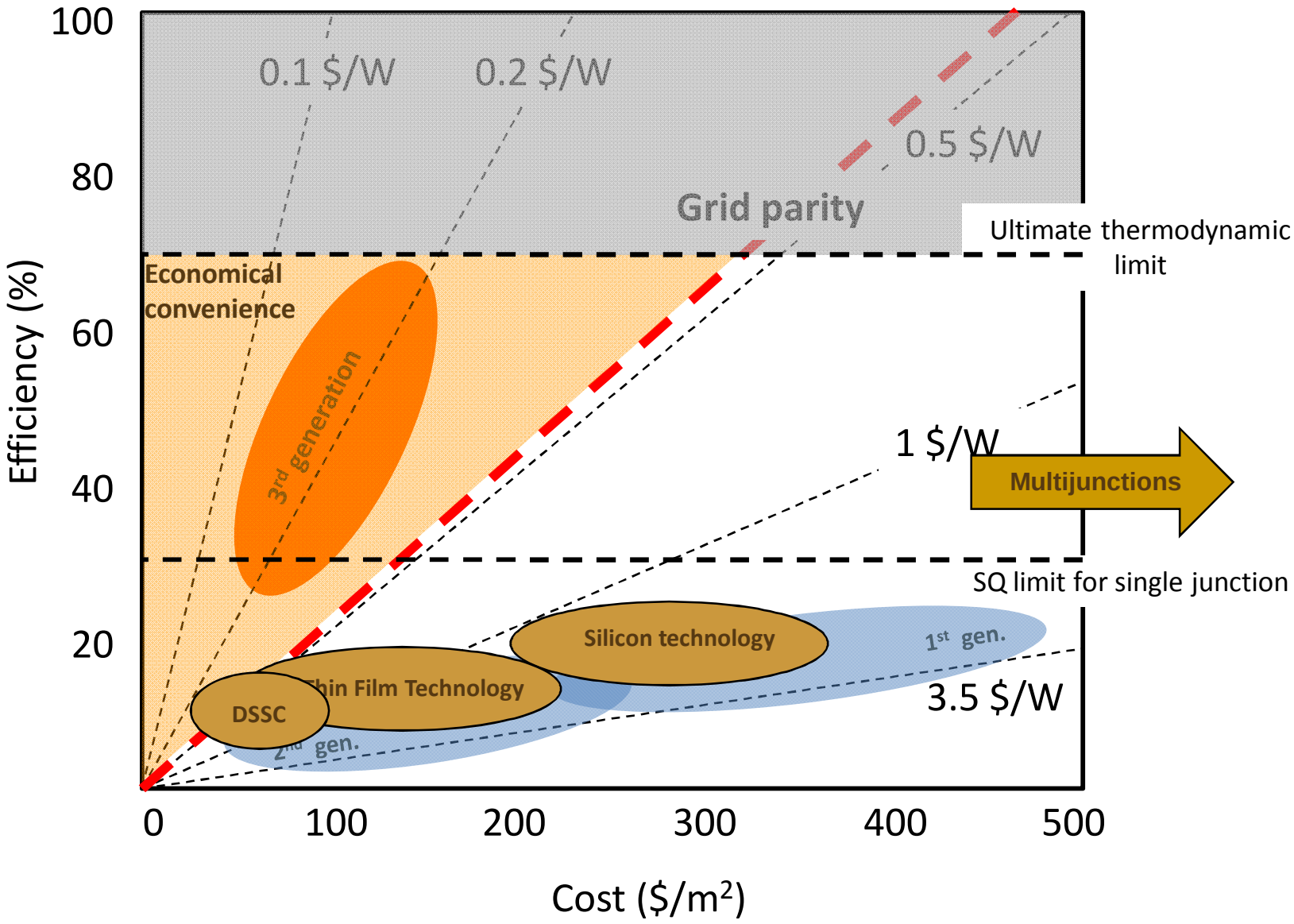
- Exploiting surface area -







Tecno-Economical Evolution

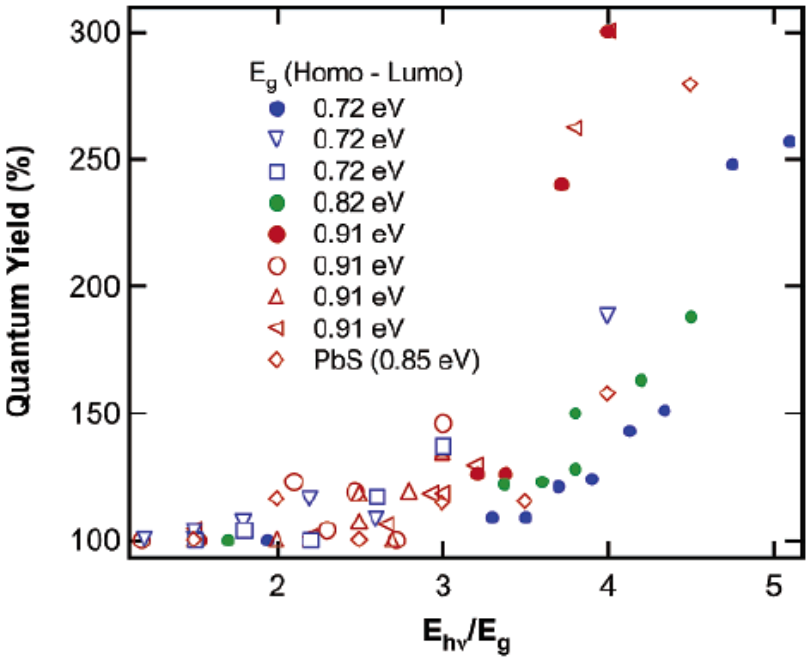


Beyond the single junction limit

- Materials for MEG and HEE: Using High Energy Photons -

- **Multiple exciton generation (MEG)**
  using high energy photons to extract more than one electron per photon

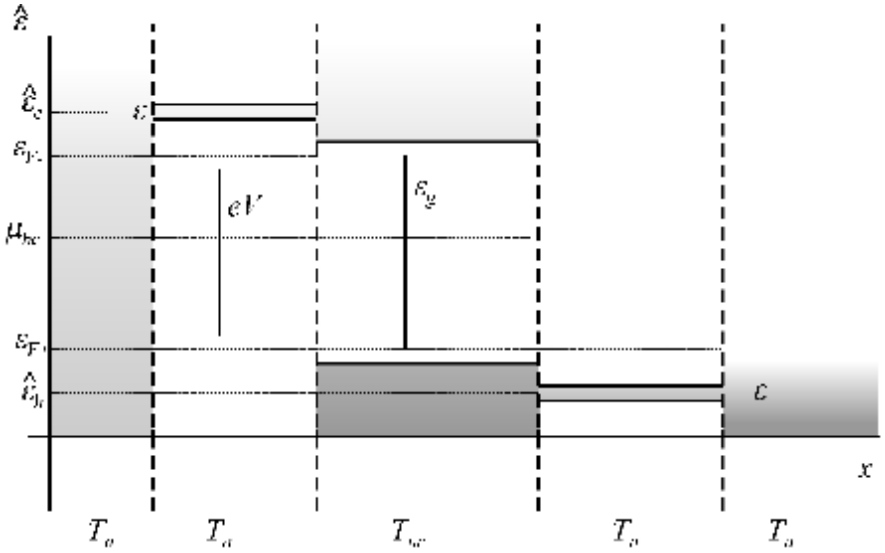
  Limiting efficiency: 45% (86.6% conc.)



A. Nozik's group, NREL

- **Hot electron extraction**
  extracting high energy photogenerated electrons before they thermalize

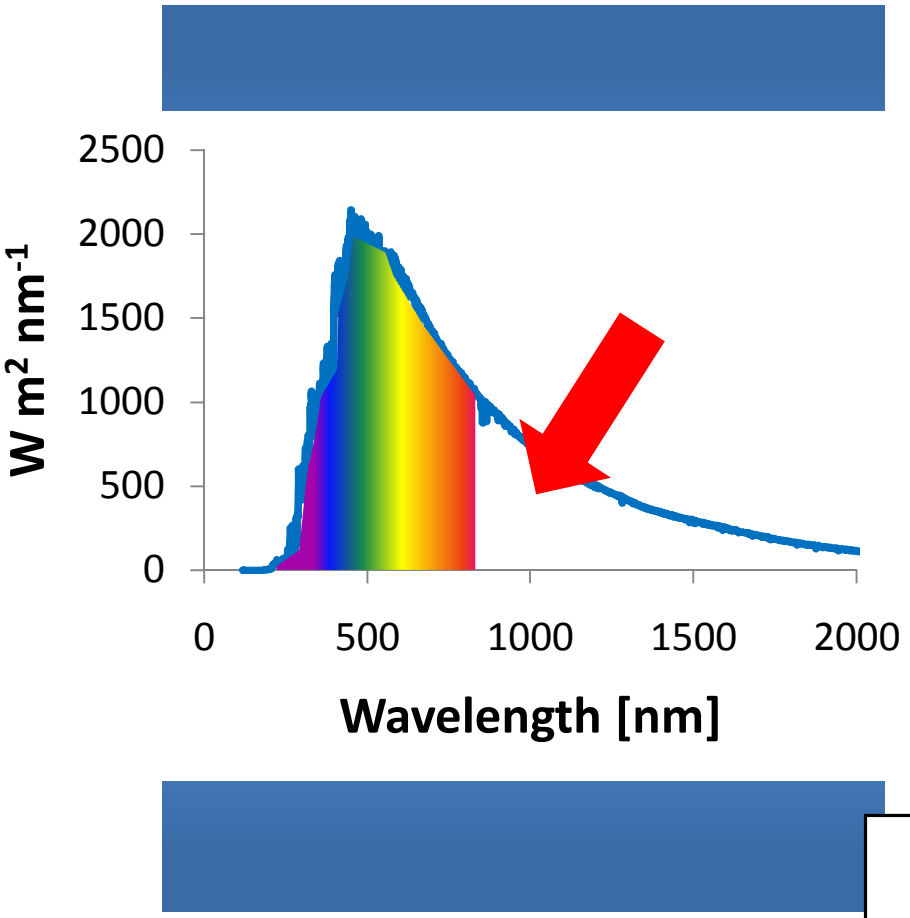
  Limiting efficiency: 66% (86.6% conc.)

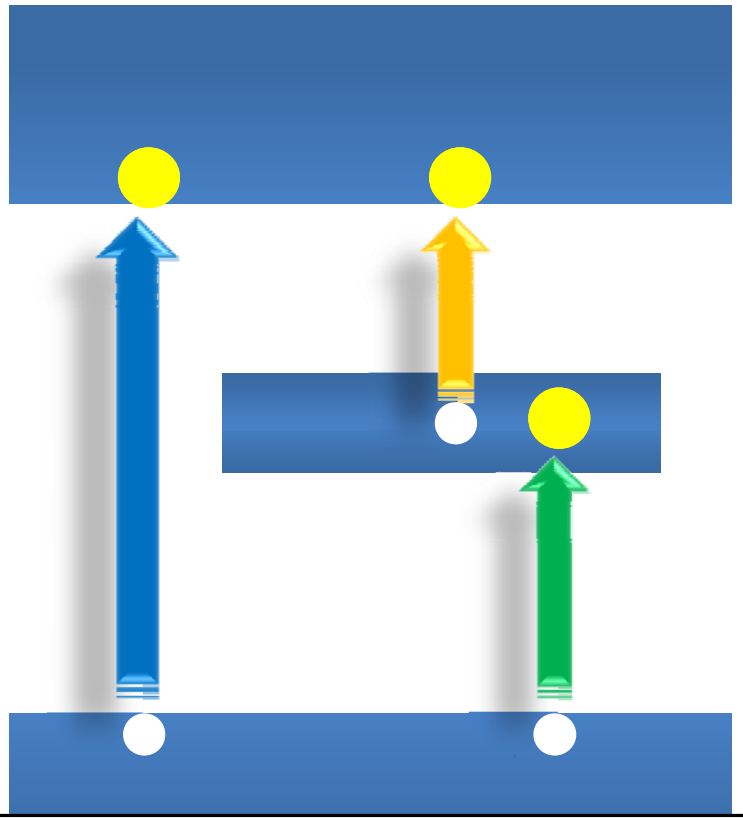


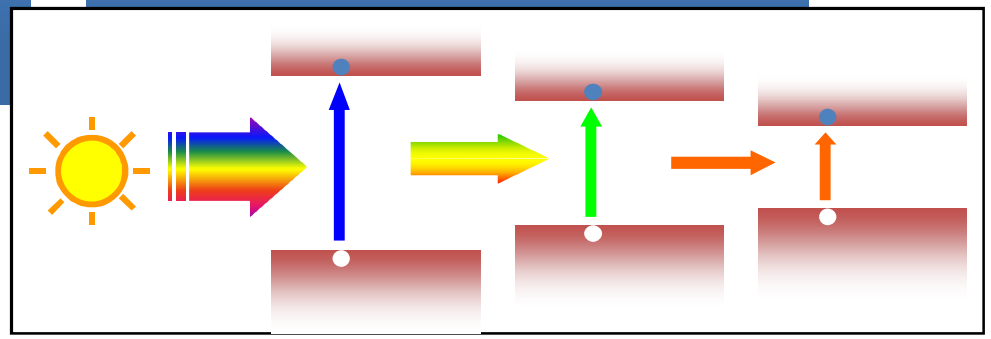
PV Kamat, Nature Chemistry 2 p809 (2010)
A. Pandey, P. Guyot-Sionnest*,J. Phys. Chem. Lett. 1 p45–47 (2010)
JA McGuire et al., ACS Nano 4, p6087 (2010)

Beyond the single junction limit

- Intermediate Band Materials: Using Low Energy Phonons-

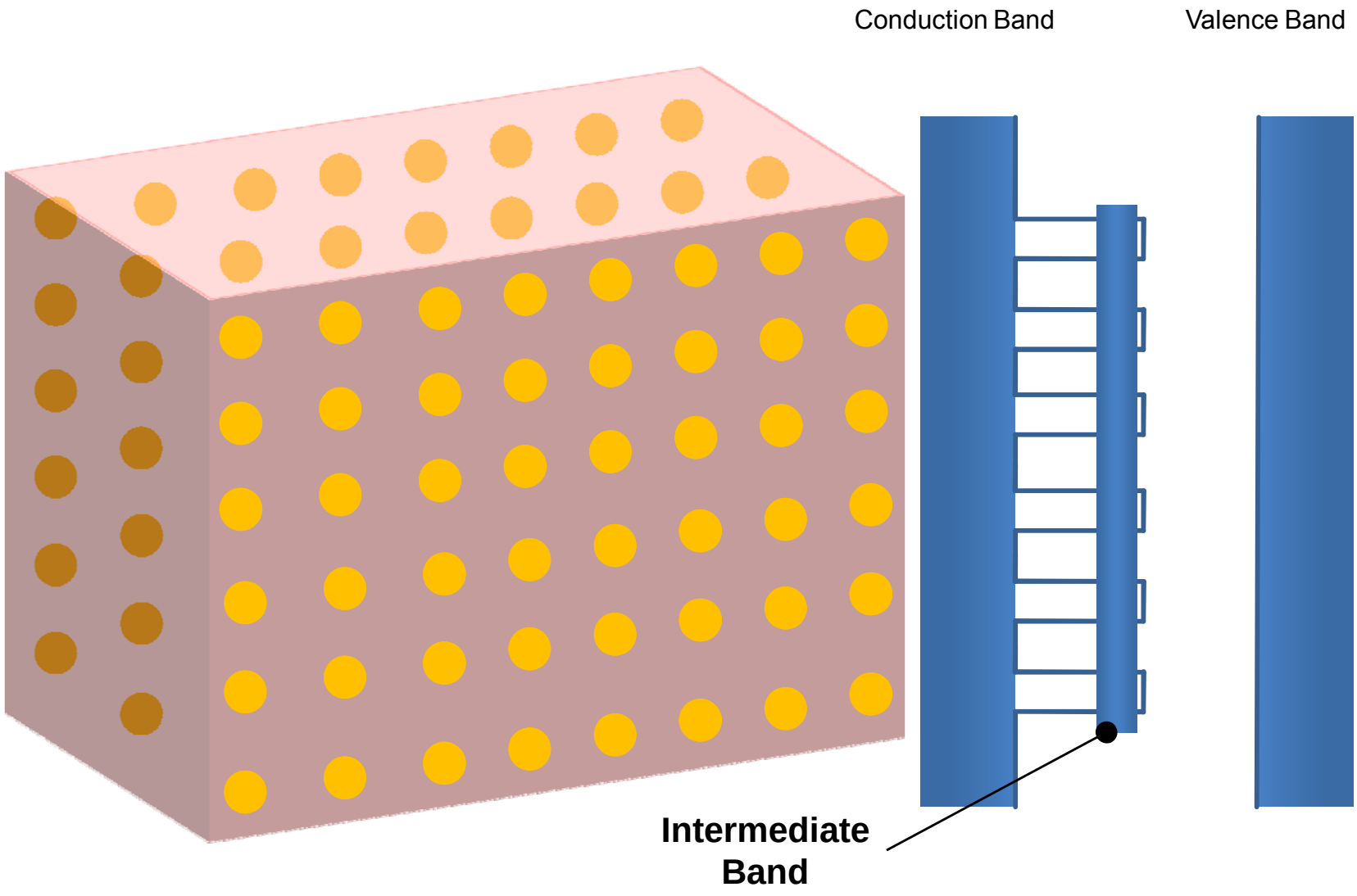




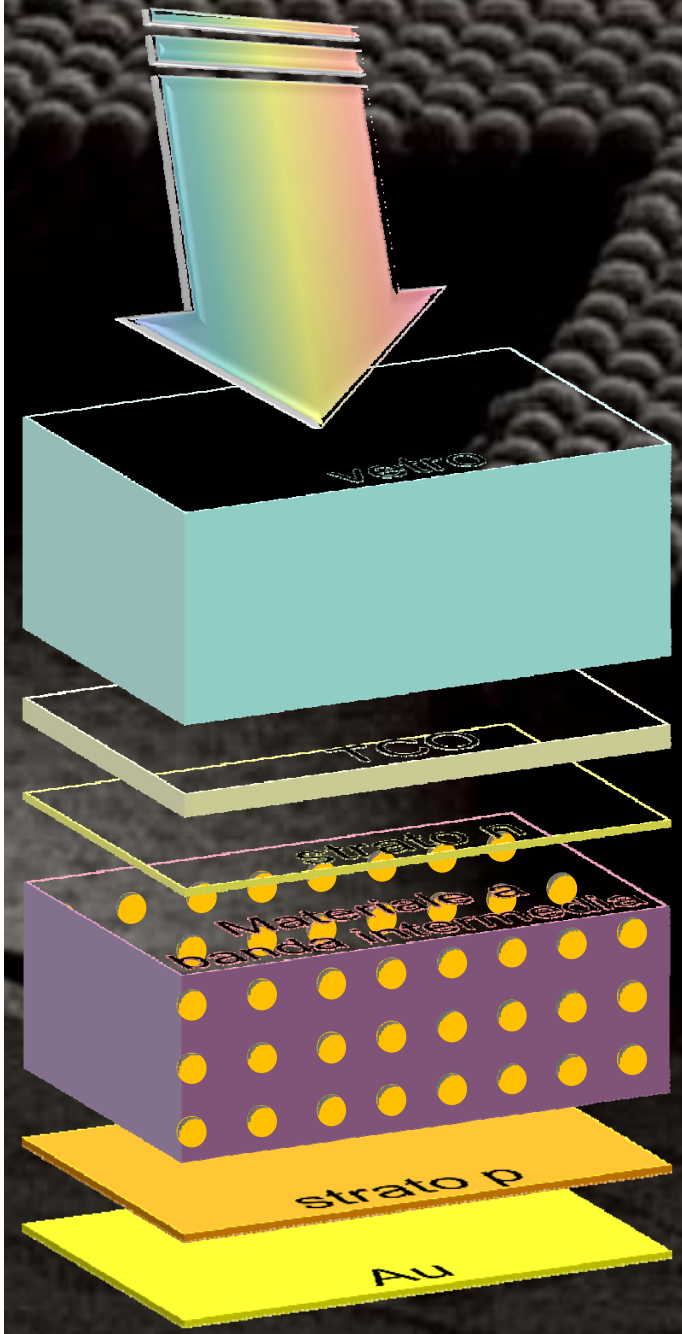


Making an Intermediate Band Material

Quantum dots embedded in a semiconductor



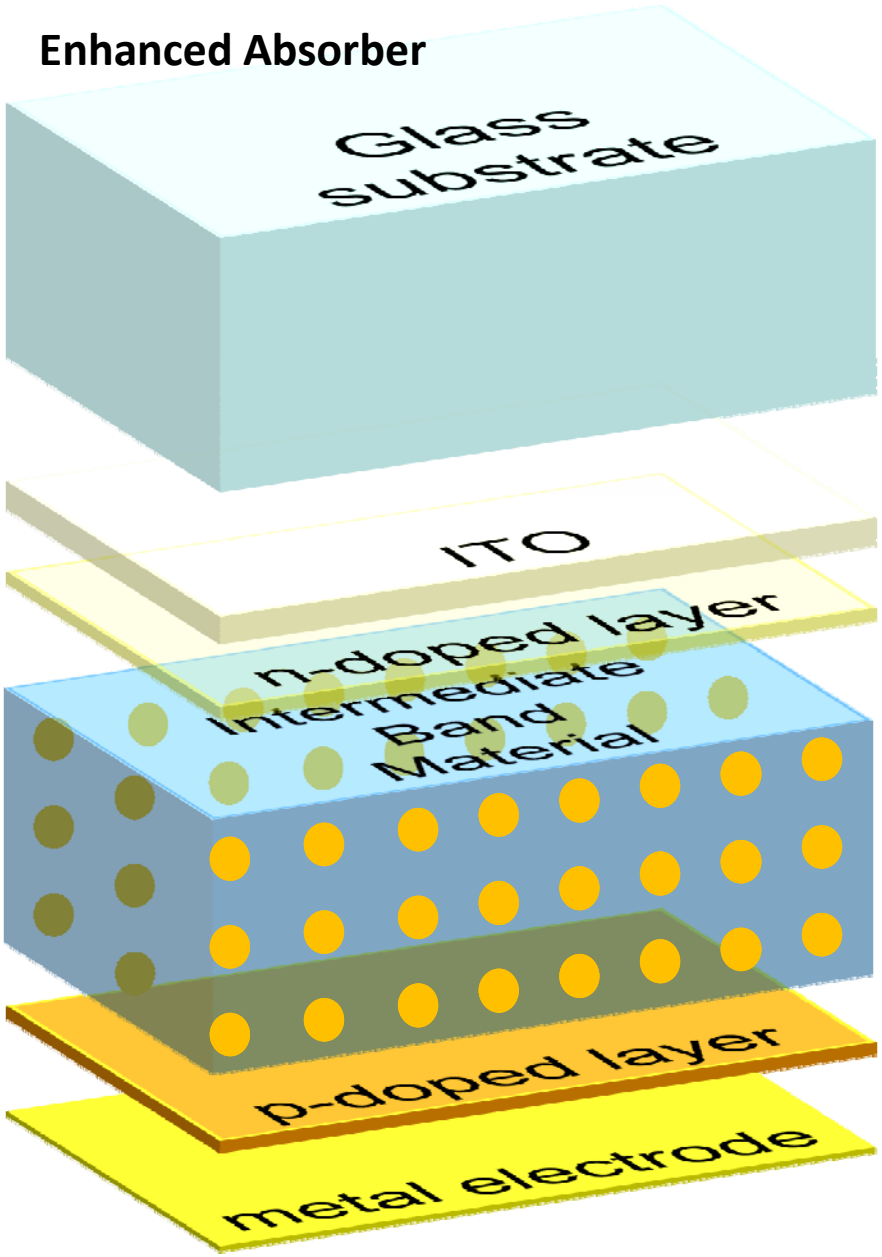
Photovoltaic Devices Based on Intermediate Band Materials



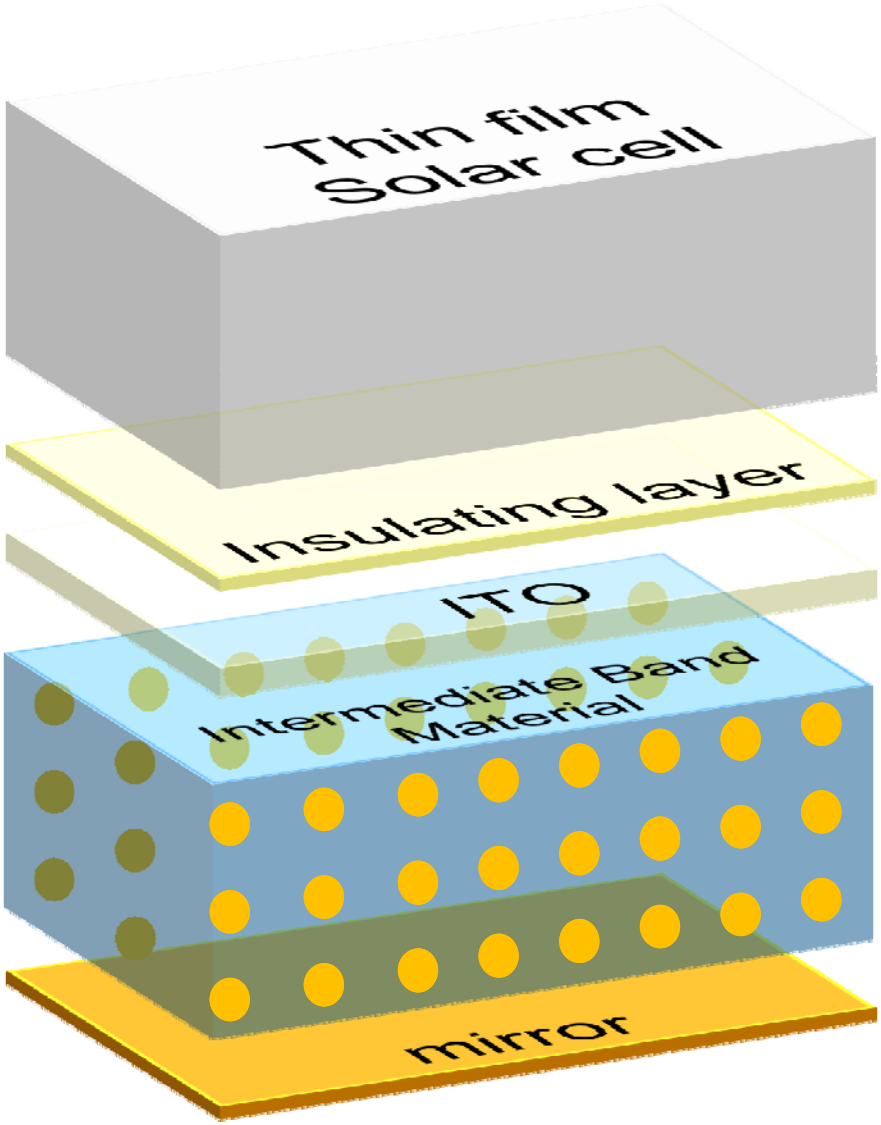
- Max efficiency 47% (63%
- Scalable, low-cost production approaches
- Diversity of substrates – excellent integration (nanoinks and photovoltaic paints)

IB-Based Solar Cell Architectures

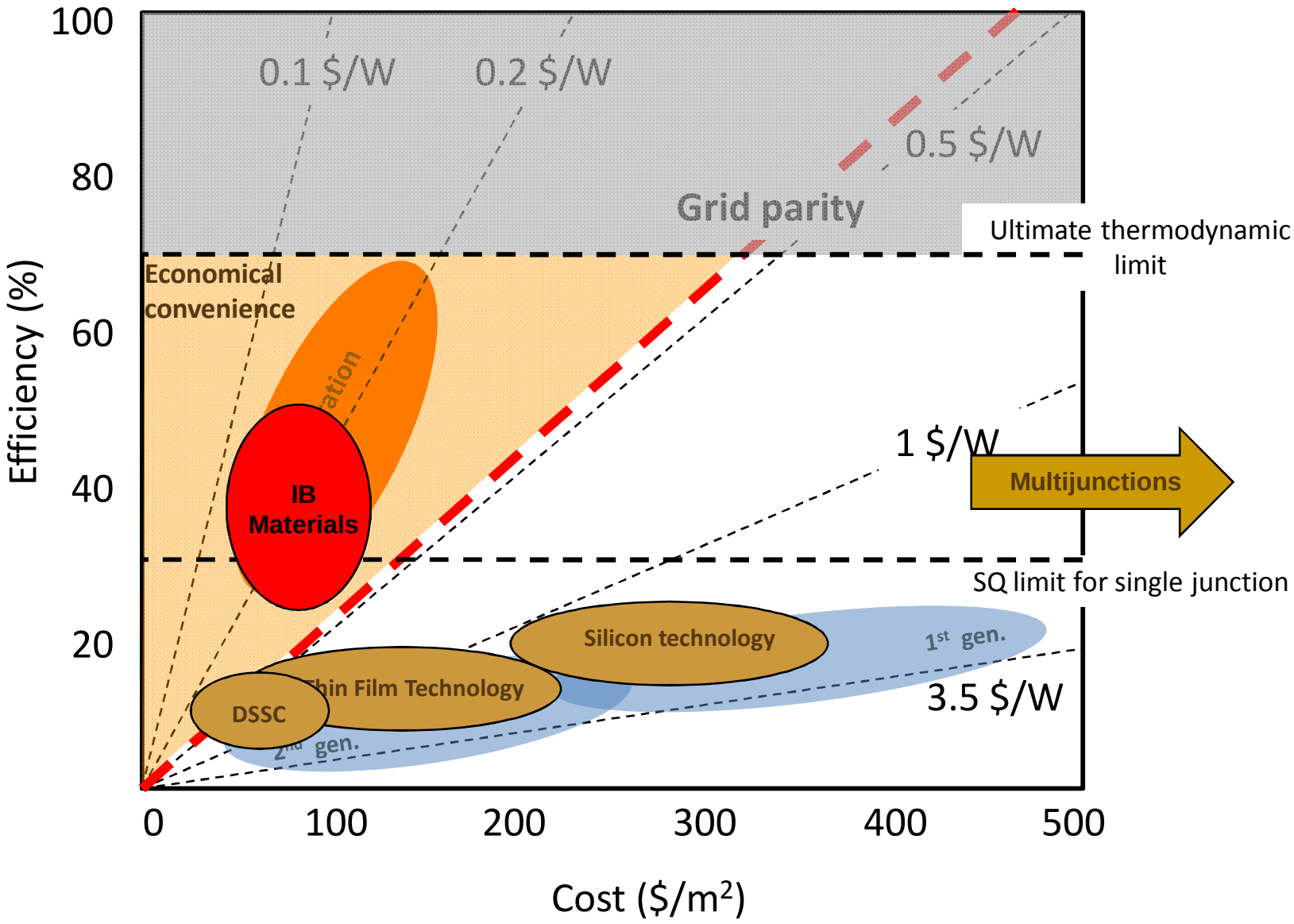
Enhanced Absorber



Upconverter



Tecno-Economical Evolution



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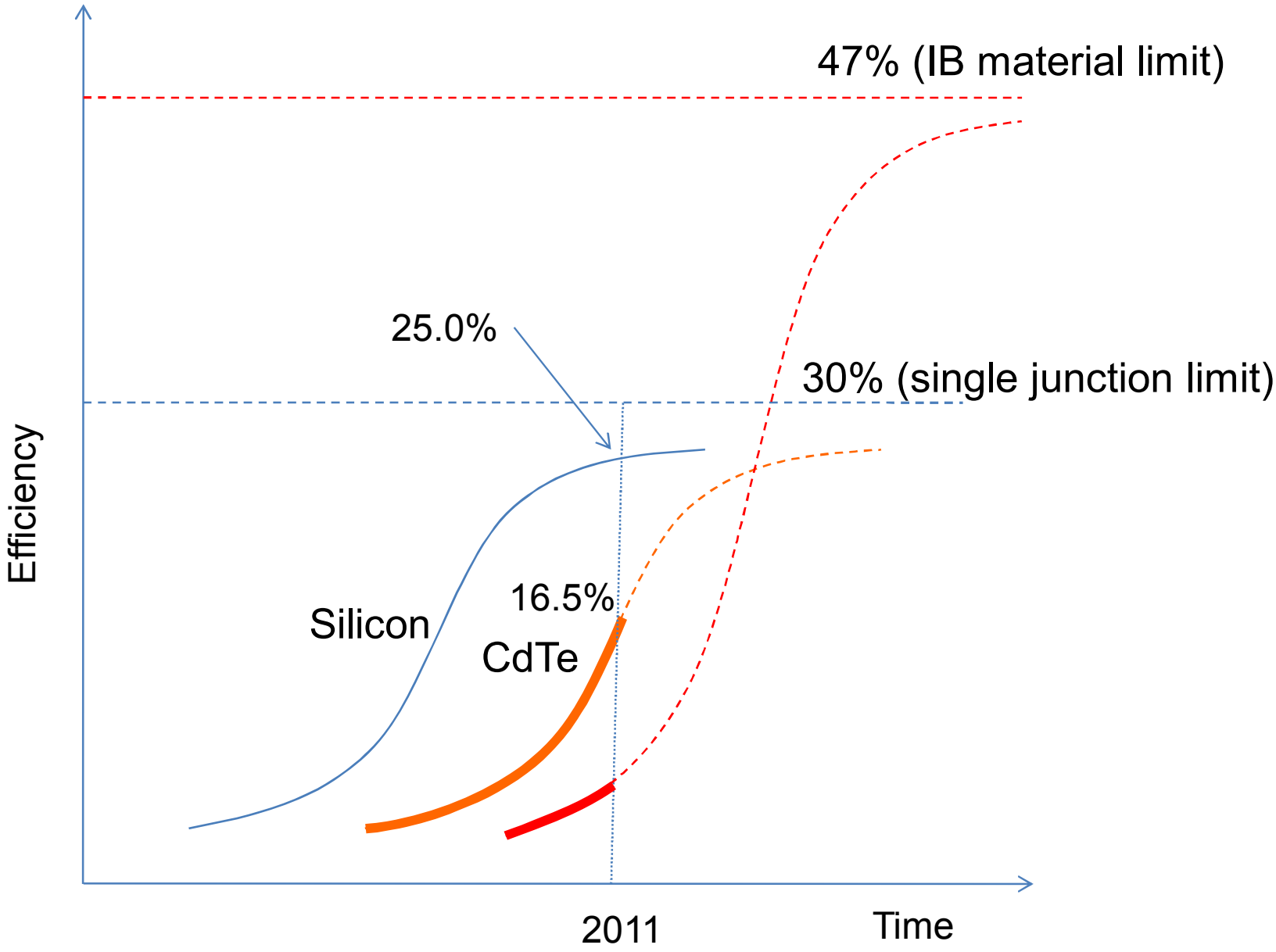
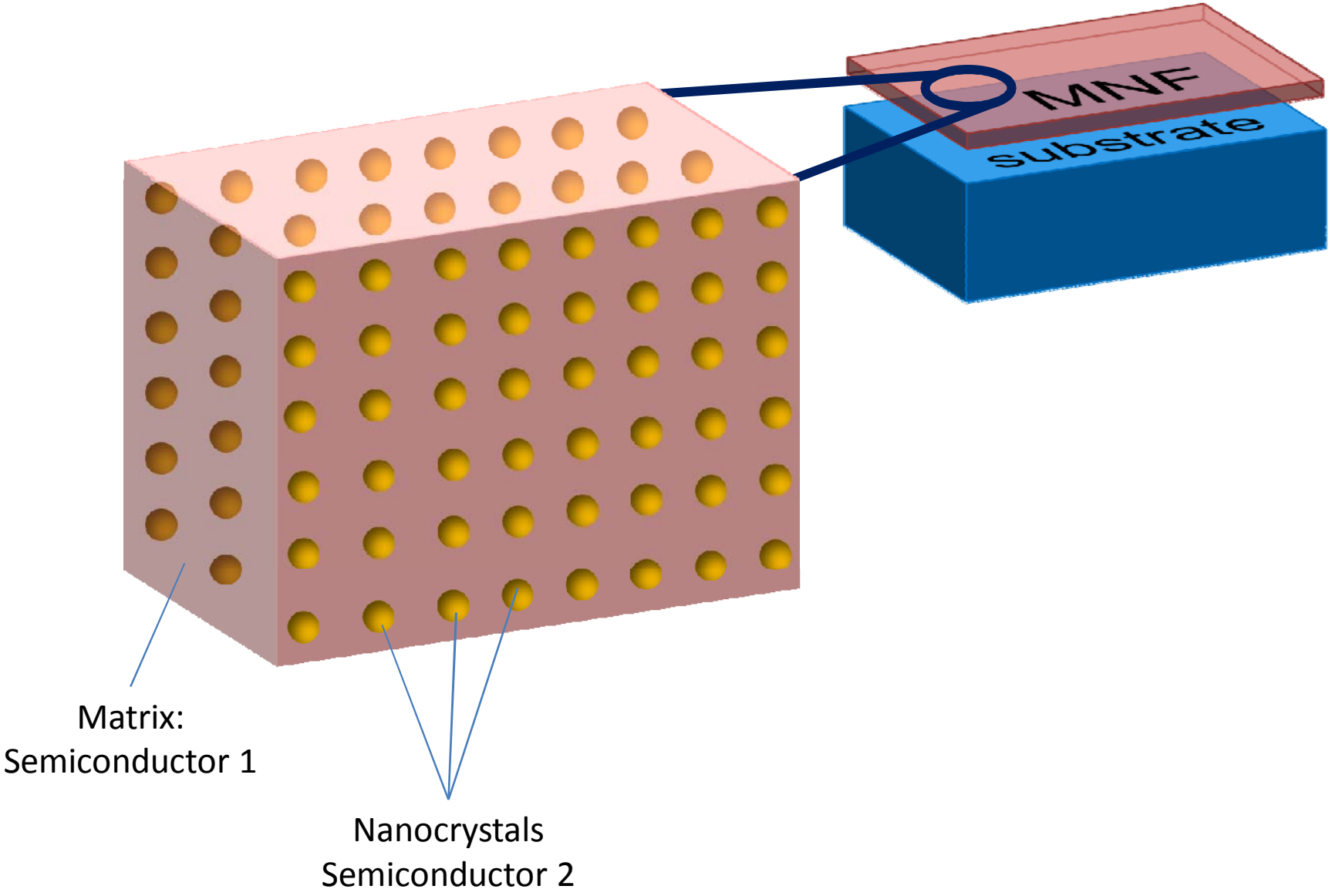


Multiphase Nanostructured Films

- a general approach -

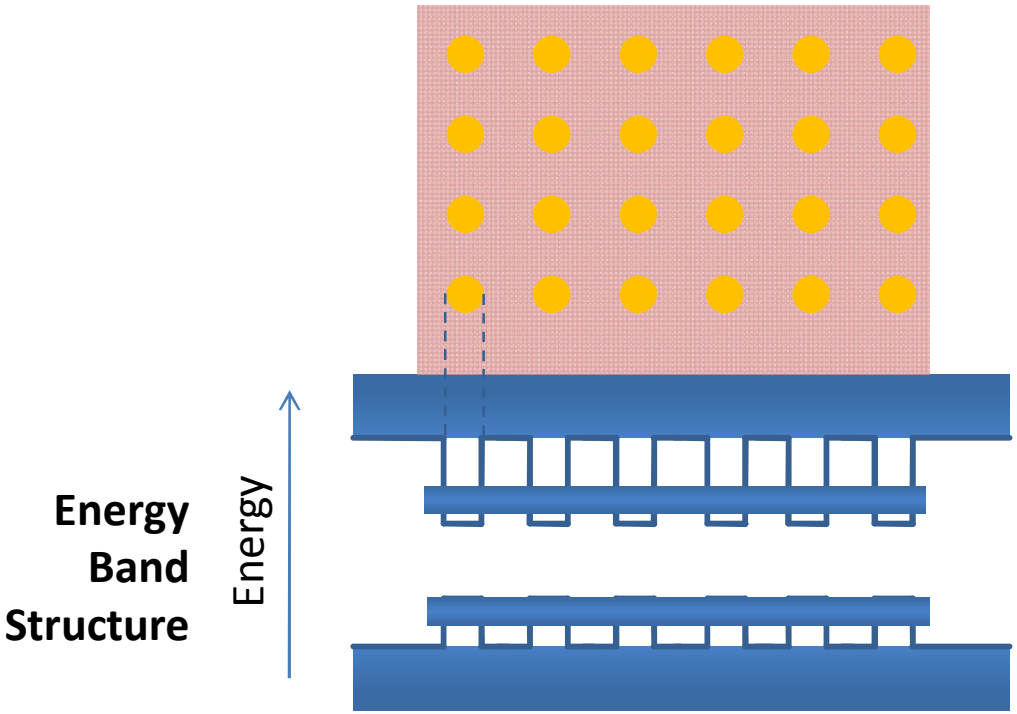


Multiphase Nanostructured Films

- Key Properties -

Emerging properties in nanocrystal arrays:

- Long range transfer of electronic excitations [Kagan, 1996]; Stepped mobility [Roest, 2002]
- Thermally activated transport [Schoonveld, 2000]
- Optical nonlinearity [Takagahara, 1992]

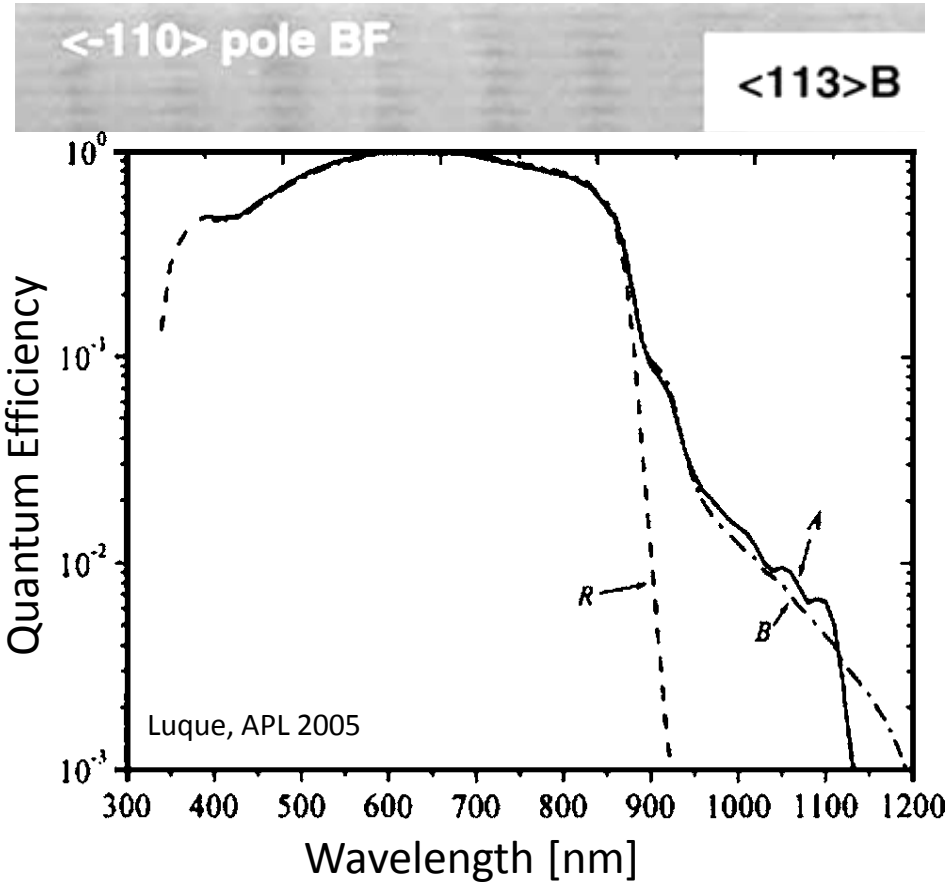


Nanoscale size and spacing

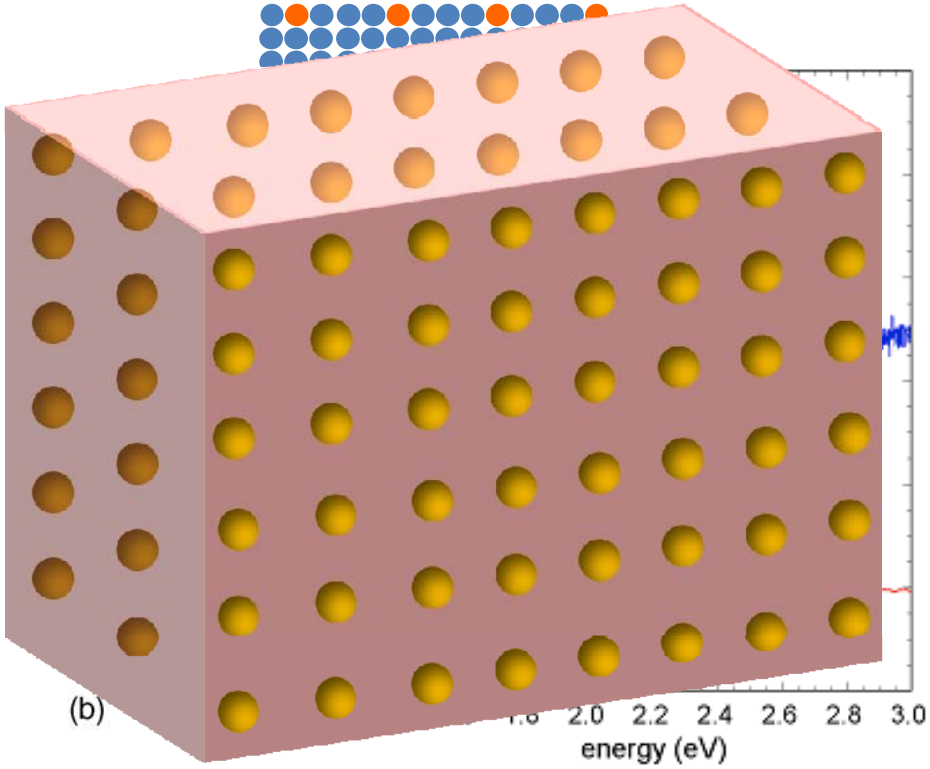
Intermediate Electronic Band

Intermediate Band Materials: State of the Art

Multiphase Nanostructured Films (via MBE)



Multiphase Nanostructured Films by High and Ordered Doping



Concept is demonstrated, however:

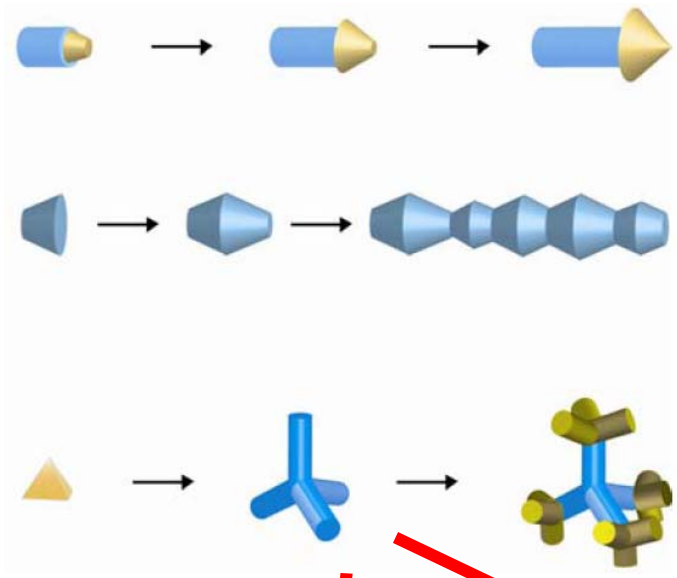
- High cost
- Limited ability of tuning the structure (and therefore the properties)

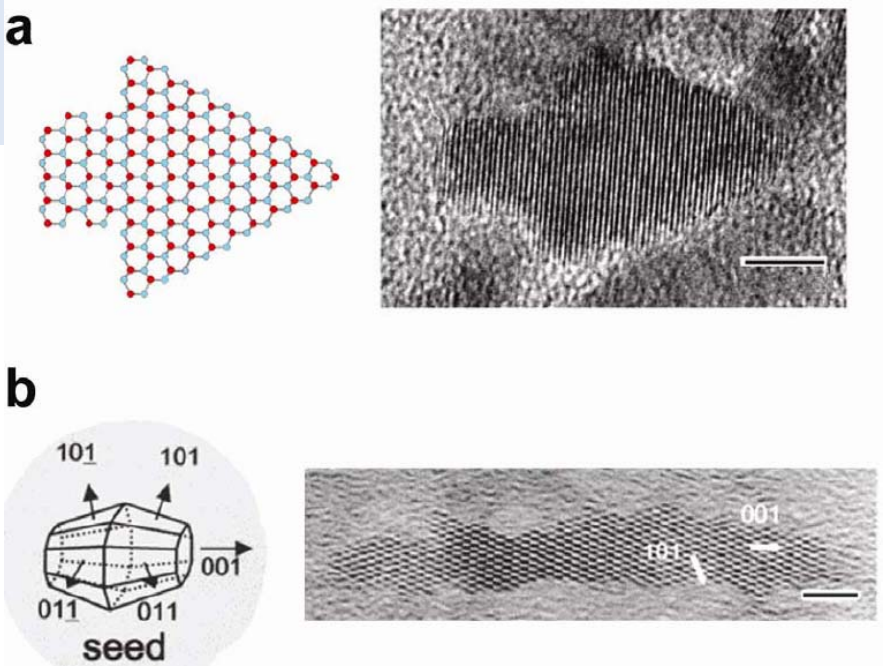
Intermediate Band Materials from Colloidal Solids

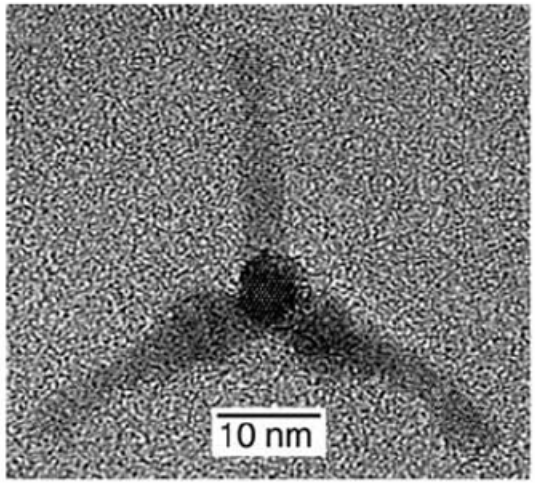
(our contribution)

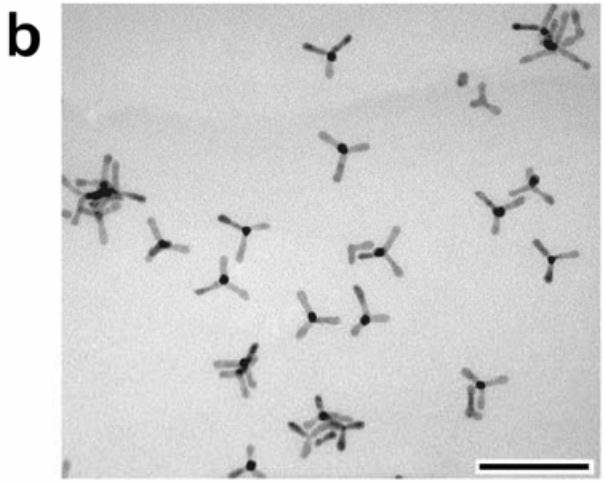
Controlling the Nanocrystal Properties
i.e. Engineering our Building Blocks

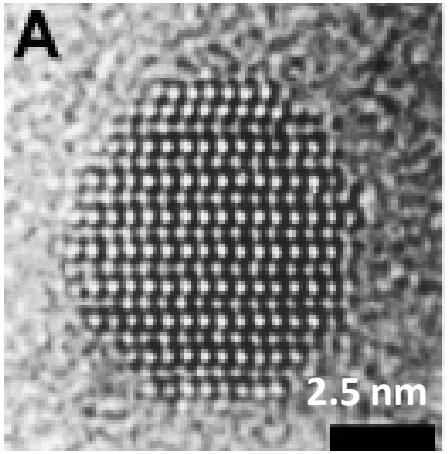
Paul Alivisatos, UC Berkeley





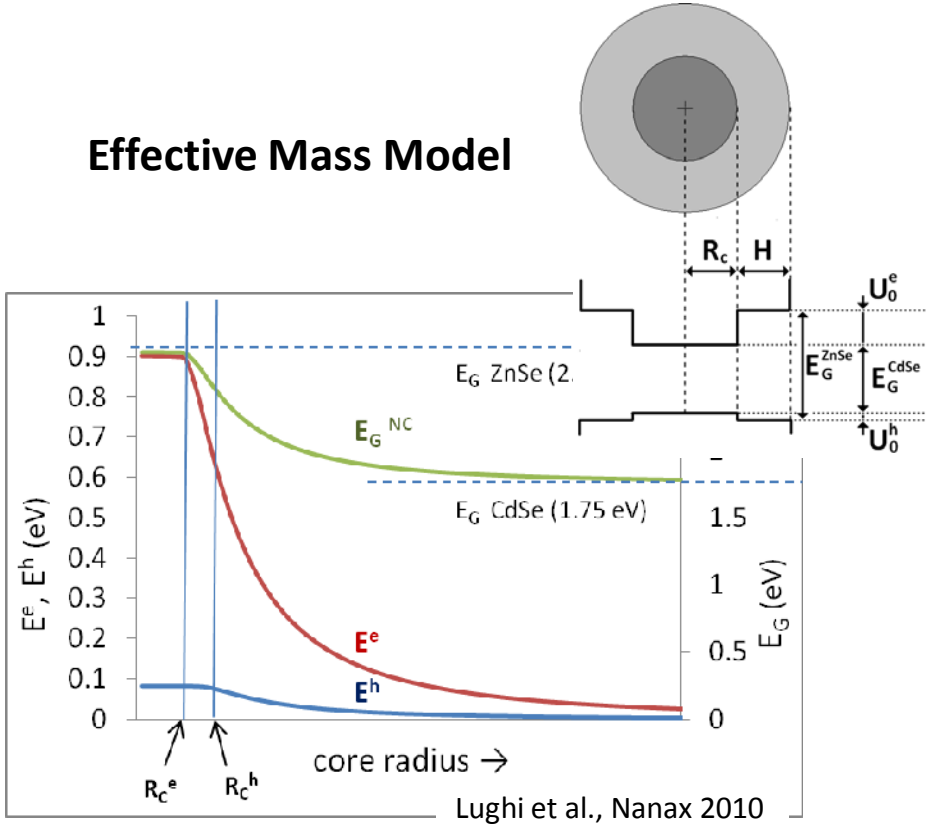






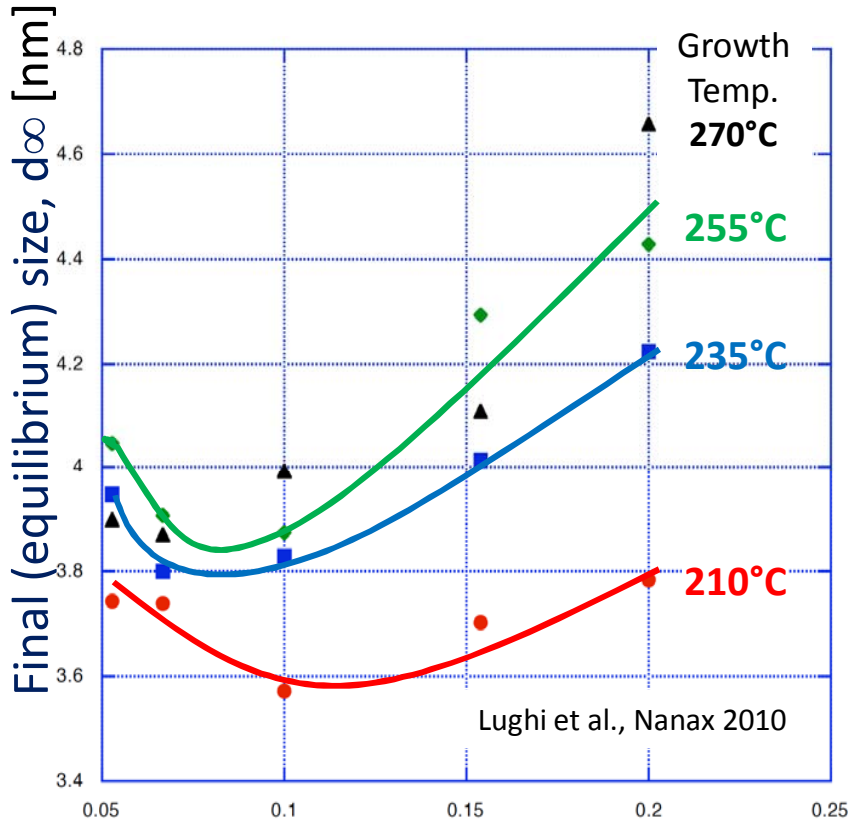
Nanocrystals: Synthesis, Characterization, Modeling

Effective Mass Model

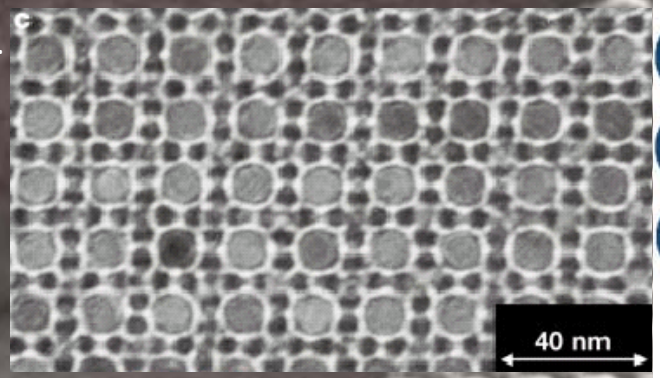


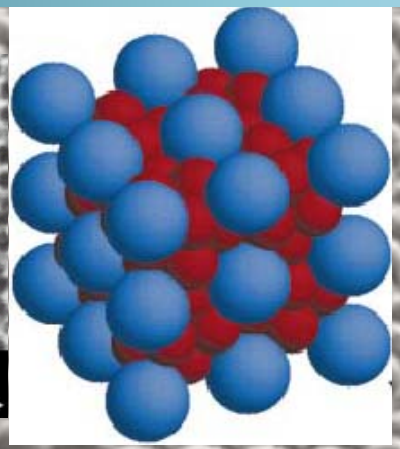
Lughi et al., Nanax 2010

Equilibrium Size Maps for Nanocrystal Synthesis



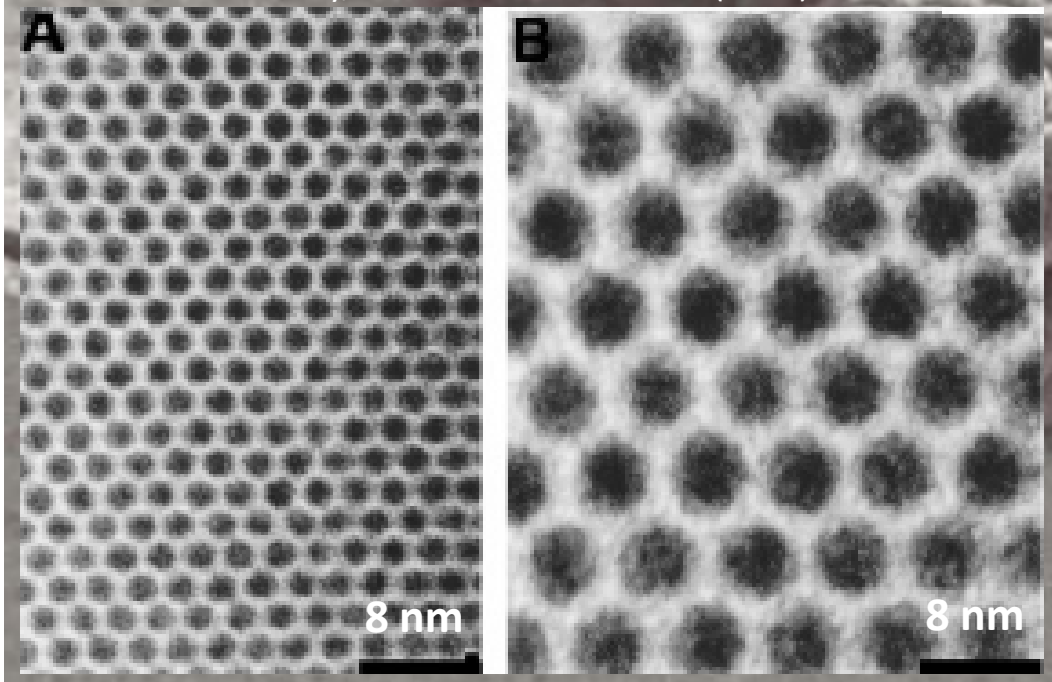
Colloidal solids

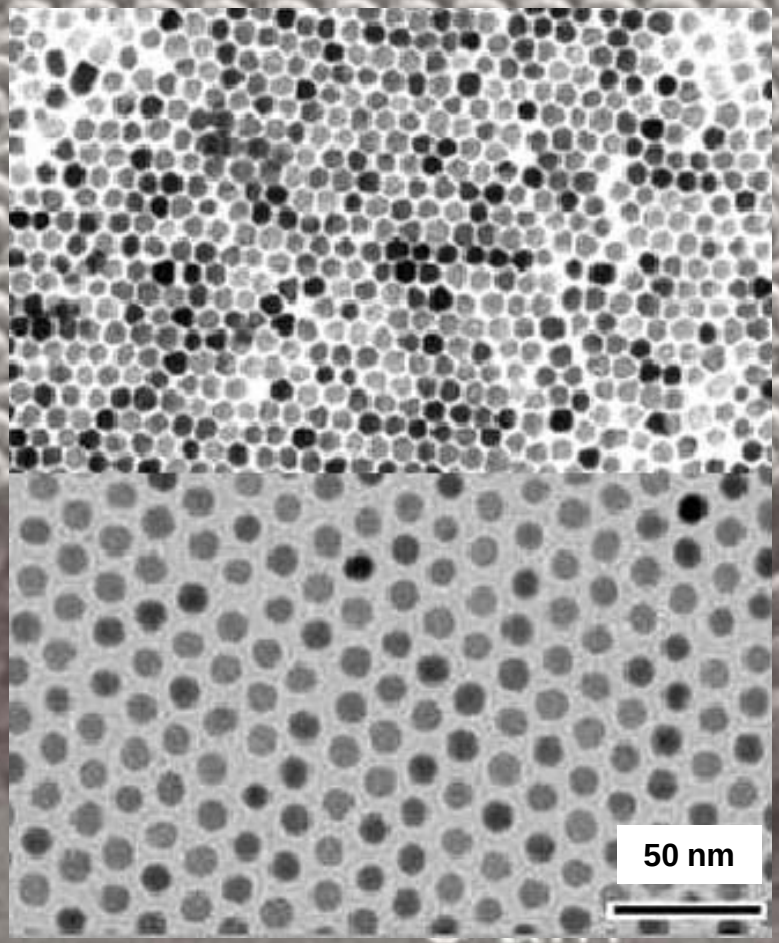




F.X. Redl et al., Nature 423, 968 (2003)

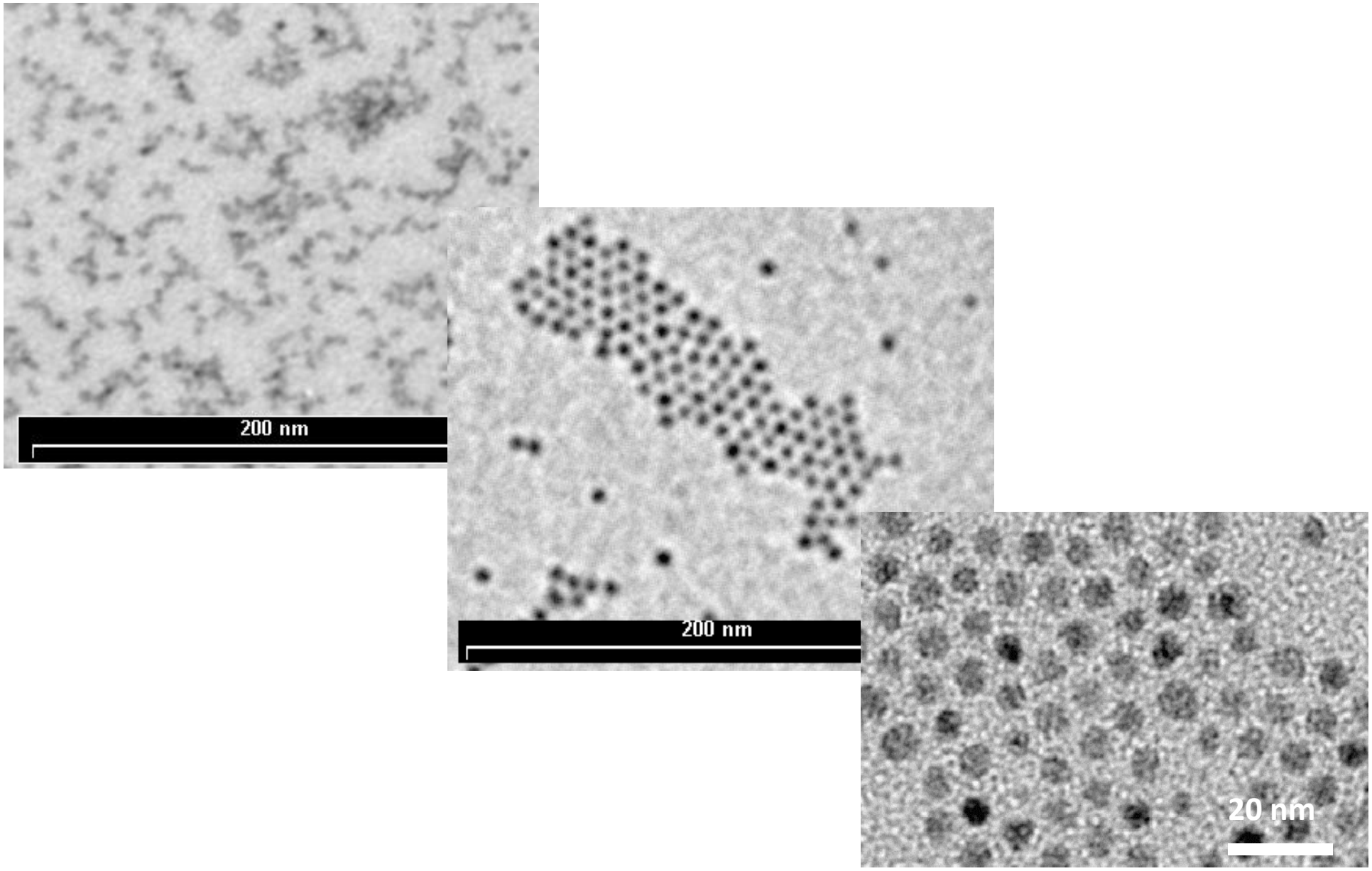
C.B. Murray, Ann. Rev. Mater. Sci 30 (2000)



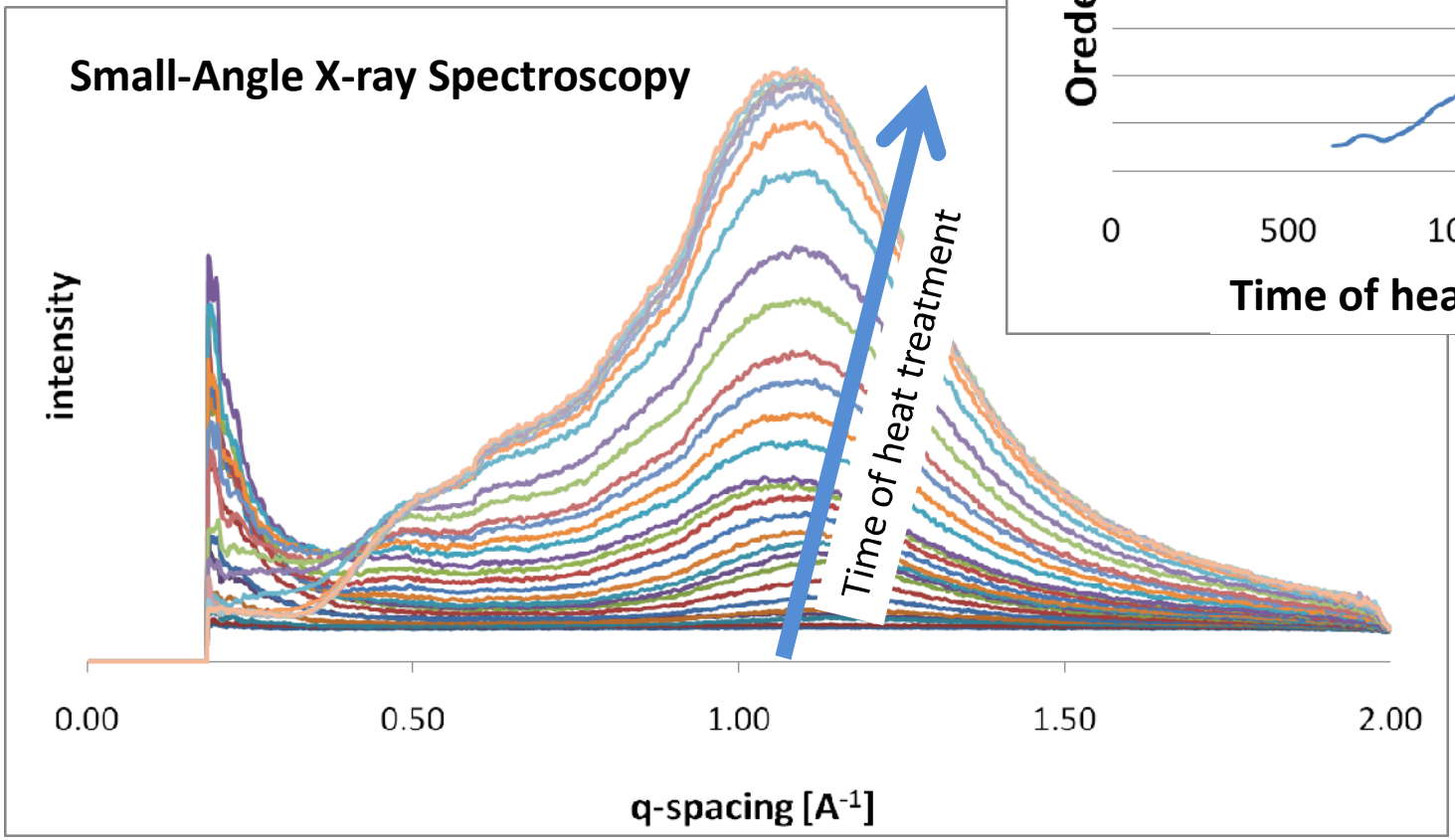


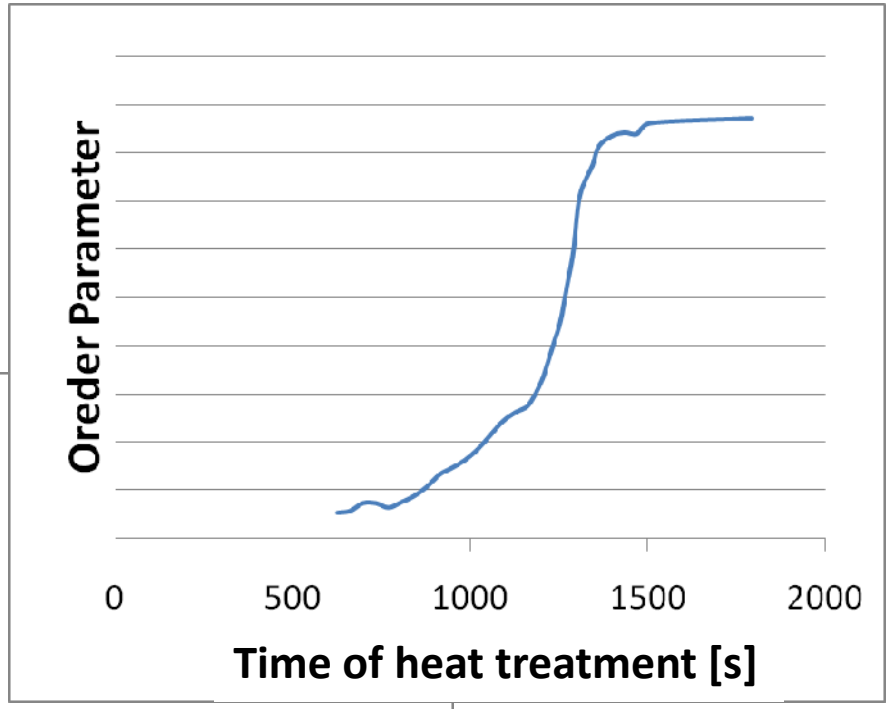
Y. Yin, A.P. Alivisatos, Nature **437**, 664 (2005)

Control of Interparticle Forces

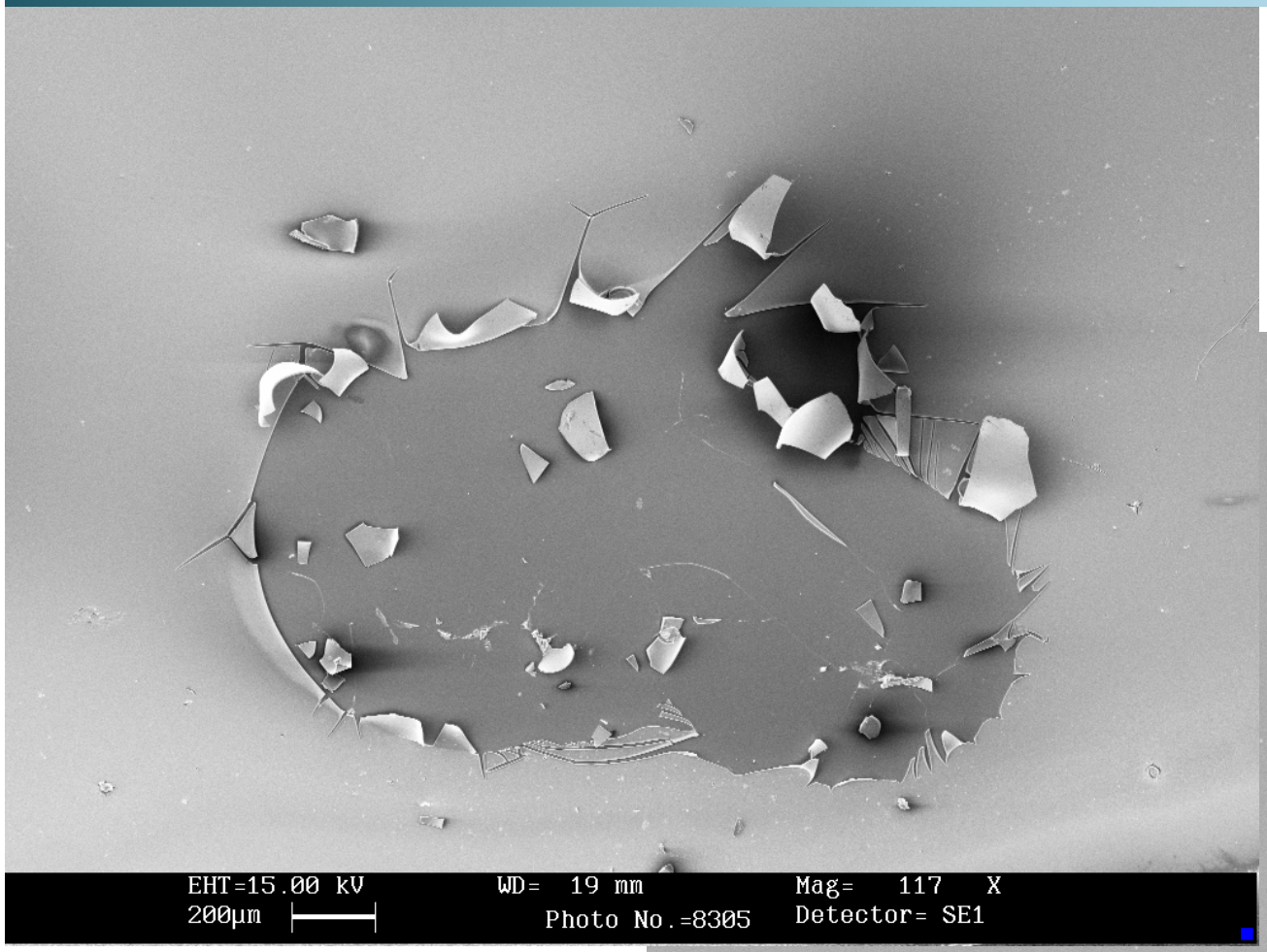


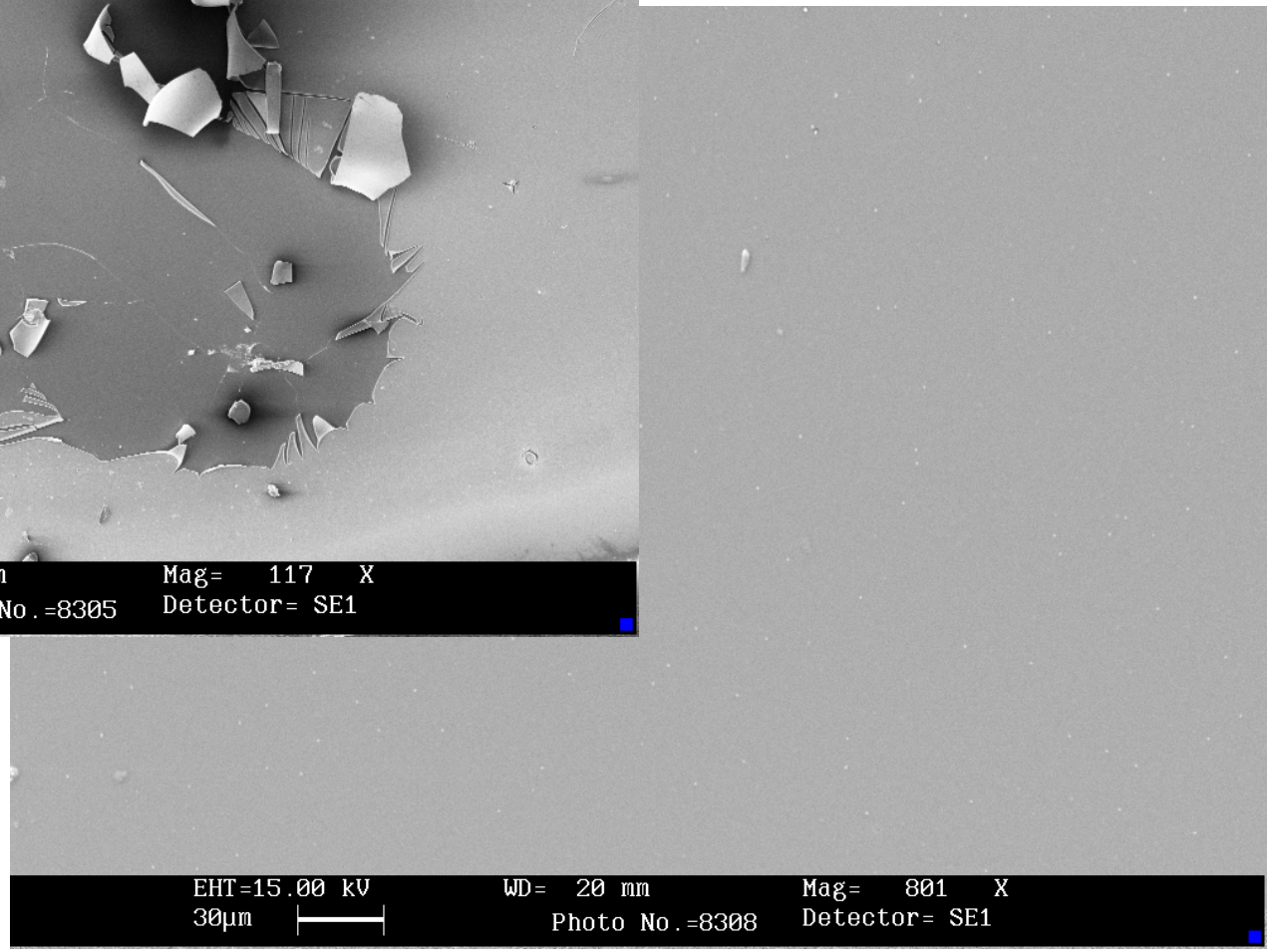
Ordering


Small-Angle X-ray Spectroscopy
intensity
Time of heat treatment
0.00
0.50
1.00
1.50
2.00
q-spacing [A-1]

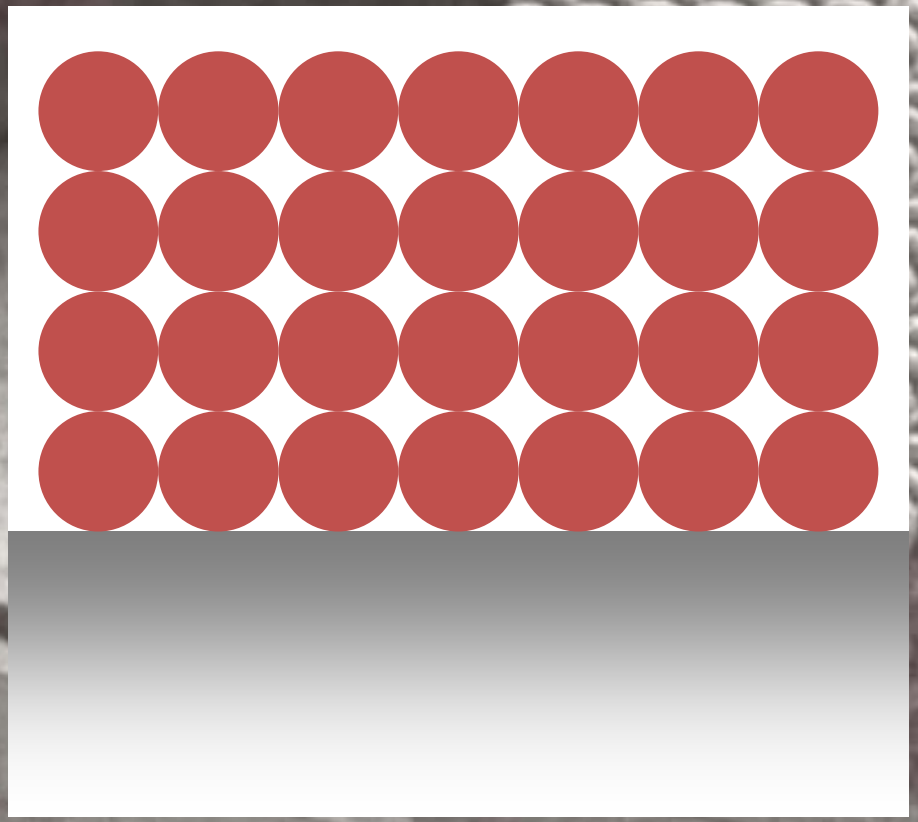

Oreder Parameter
0
500
1000
1500
2000
Time of heat treatment [s]

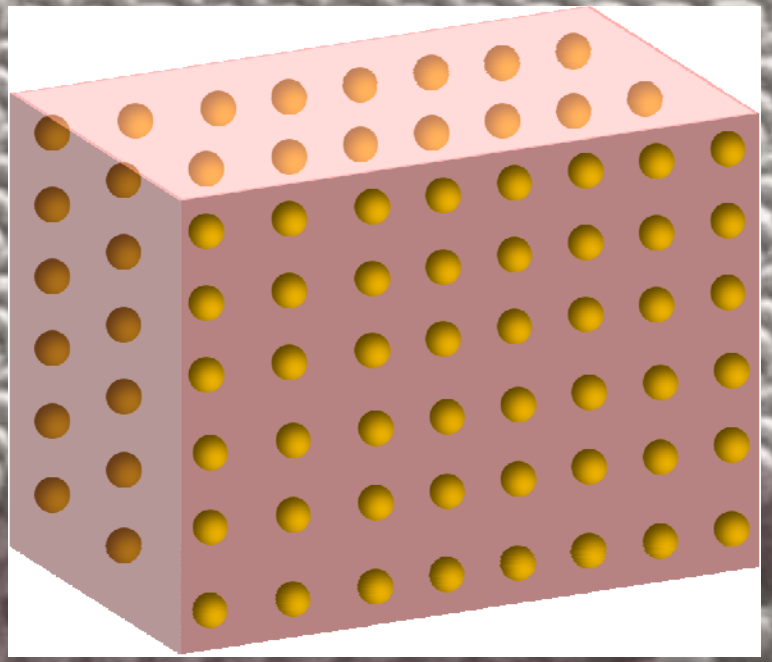
Uniform Thin Films of Close-Packed Nanocrystals





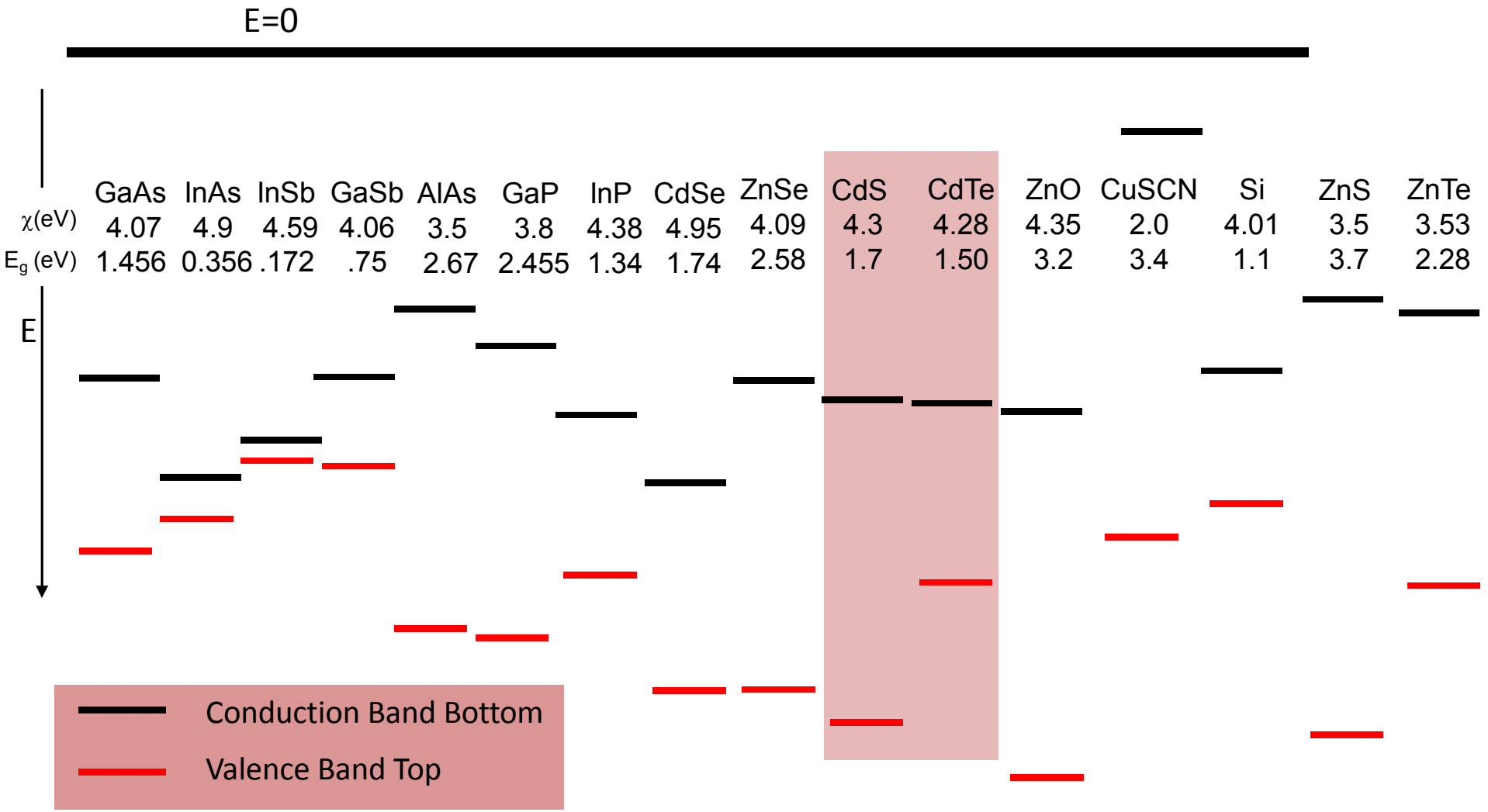
Assemblying Quantum Dots into Colloidal Solid Films





5 µm

Materials System Selection: Energy Level Alignment

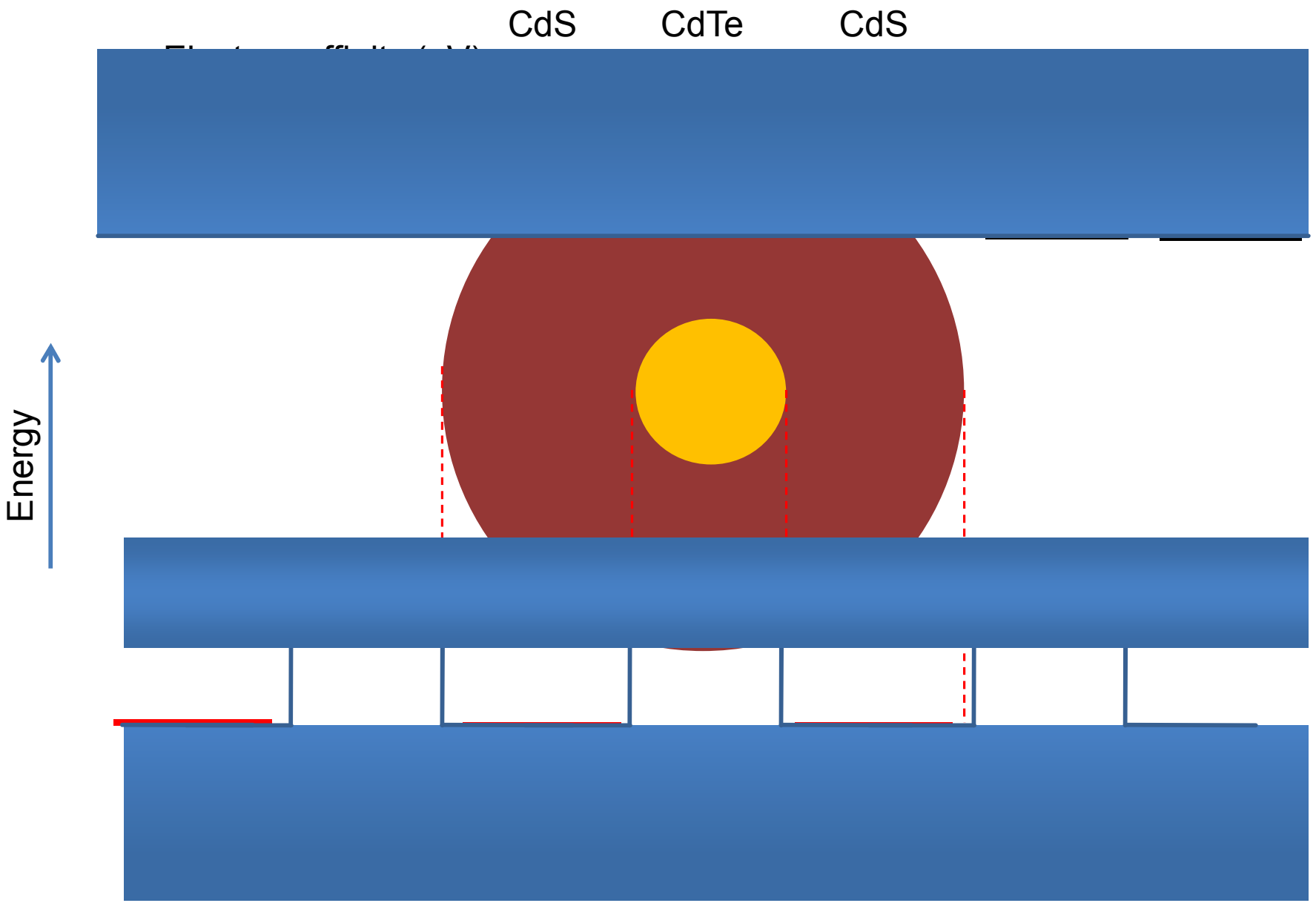


Goldbery Yu.A. *Handbook Series on Semiconductor Parameters*, vol.1, M. Levinshtein, S. Rumyantsev and M. Shur, ed., World Scientific, London, 1996.

RK Swank, *Phys. Rev.* **153**, 844 (1967)

S. Adachi, *Properties of Grup IV, III-V and II-VI Semiconductors,* Wiley 2005

Materials System Selection: Energy Level Alignment



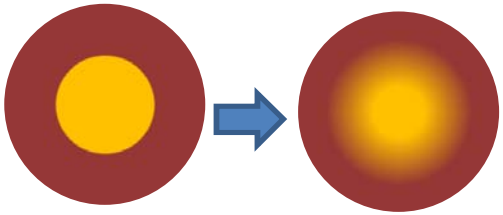
Materials System Selection: Avoiding Interdiffusion

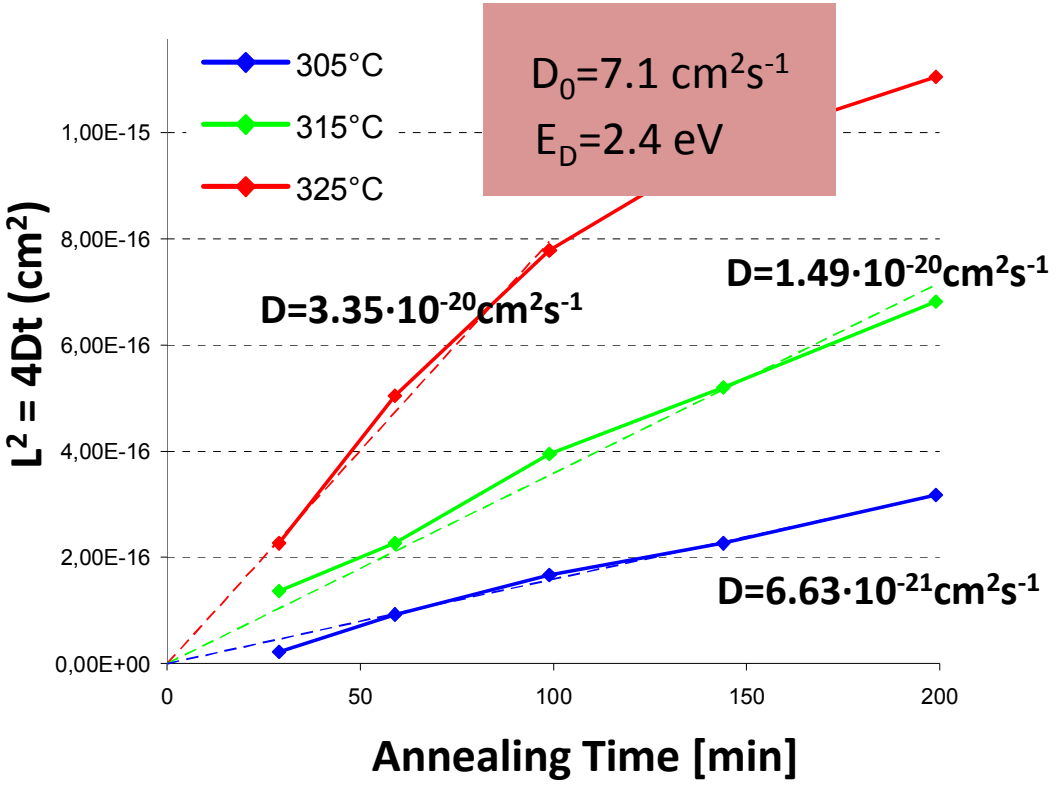
Sintering Kinetics
(as fast as possible)

Interdiffusion in Nanocrystals
(as slow as possible)

Low $T_{melting}$

	$T_{melting}$ [K]
ZnS	2196
ZnSe	1793
ZnTe	1568
CdS	1748
CdSe	1531
CdTe	1365
HgS	1723
HgSe	1072
HgTe	943



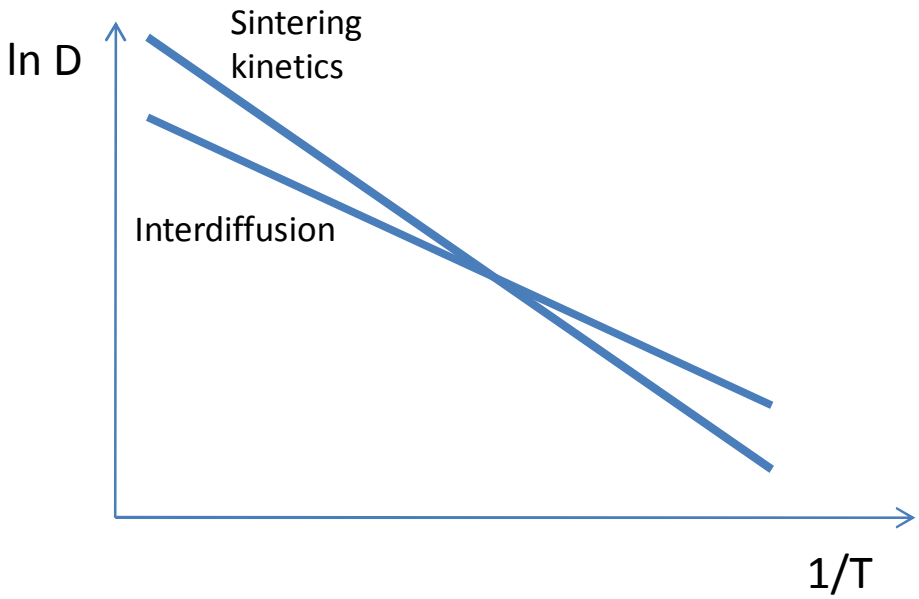


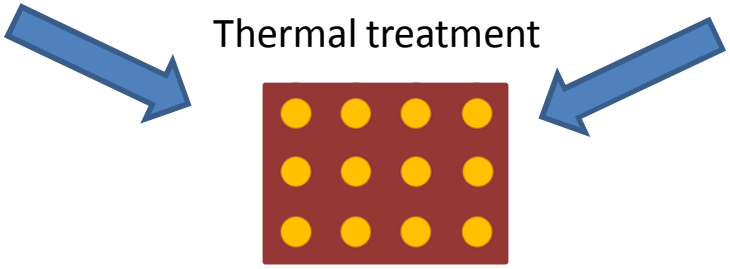
Lughi et al., in prep.

Obtaining a dense nanostructured film: Sintering

At high temperatures, **sintering kinetics** are expected to be **faster than interdiffusion**

Quick heat treatments at high temperature promote sintering rather than interdiffusion (“**Flash Sintering**”)





Materials System Selection: Candidates

CdS/ZnS

CdSe/ZnSe

CdTe/ZnTe

CdTe/CdS

ZnO/InP

ZnO/CdTe

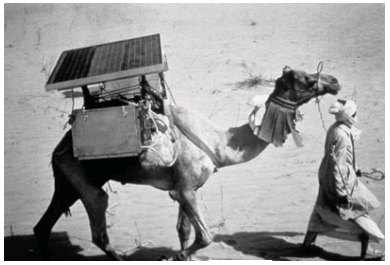
GaAs/InAs

GaAs/InP

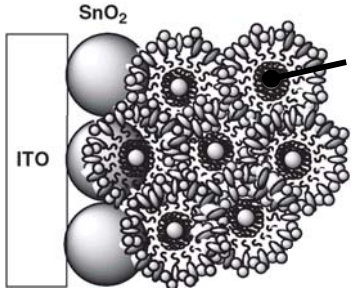
…

Concluding Remarks

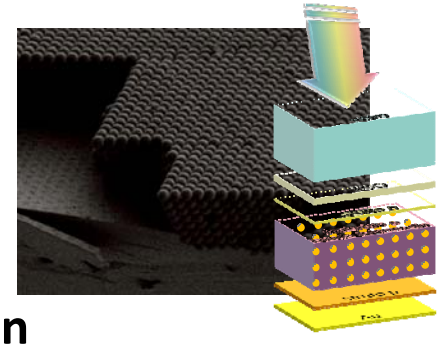
- Need to **monitor the evolution of global energy scenarios** in the near future – **unexpected shift of PV technology implementation** and applications might occur



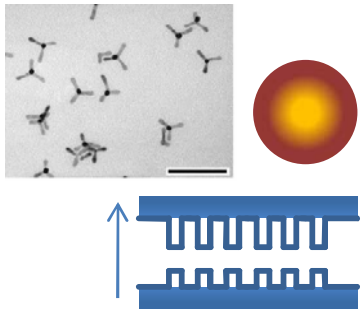
- **Nanotechnology is a natural response to current PV technology needs** – several nanotech-based approaches are being explored



- A promising approach: **Intermediate-band materials based on colloidal films**



- Quantum-dot based colloidal solids **enable unconstrained design of new materials** (the building blocks can be freely engineered)
  - *Potential for low cost materials (bench-top techniques)*
  - *Potential for high-impact applications (e.g. Photovoltaics)*
  - *Ideal platform for studying emerging properties*



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