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Thermophotovoltaic devices for solar and thermal energy conversion

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Outline

➢ **Introduction**
Thermophotovoltaics (TPV)

Solar thermophotovoltaic devices
Concept: using an intermediate solar absorber – thermal emitter
Key challenges – Ongoing research and sample results

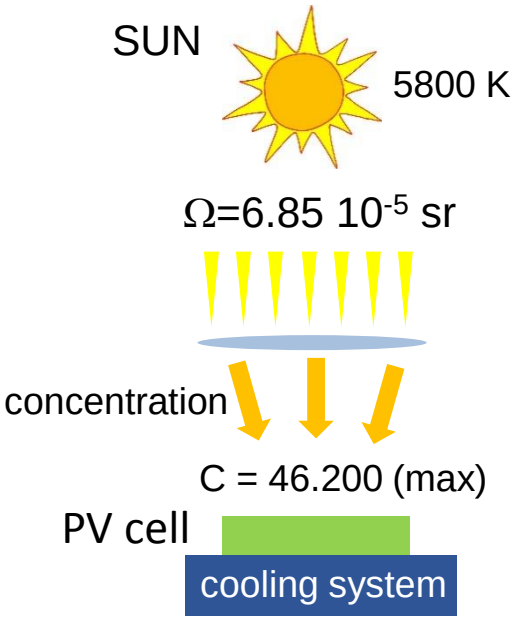
Thermionic-thermophotovoltaic devices
Concept: high-temperature energy storage and hybrid conversion
Key challenges – Ongoing research and sample results

Near-field thermophotovoltaic devices
Concept: electrical power enhancement using evanescent waves
Key challenges – Ongoing research and sample results

Conclusions

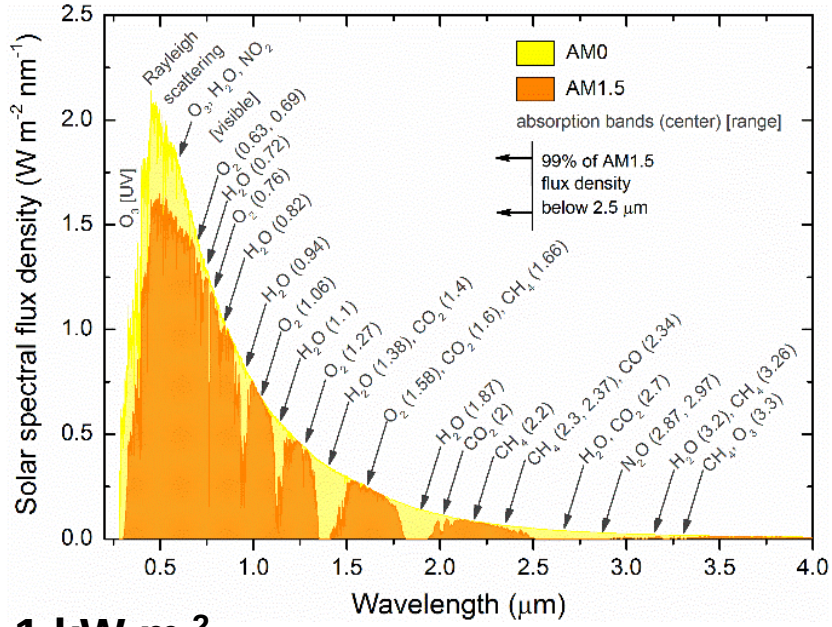
Solar/Thermo-photovoltaics

Solar photovoltaics



Irradiation spectrum

[0.3-2.5] microns
not tunable



q_{Sun}(AM1.5)=**1 kW m^{-2}**

PV cell materials

Si, CIGS, CdTe, AsGa,…, perovskites bandgap E_g ~ [1-1.5] eV

Best (research) conversion efficiencies NREL chart, 2018

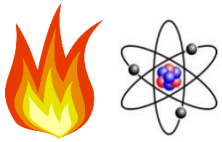
21 – 34 % (SJ) > 45% (MJ)

Max: 33% (no conc.), 41% (max conc.)

Solar/Thermo-photovoltaics

Thermophotovoltaics

WASTE HEAT



1000-2000 K

emitter

$\Omega \sim \pi$ sr

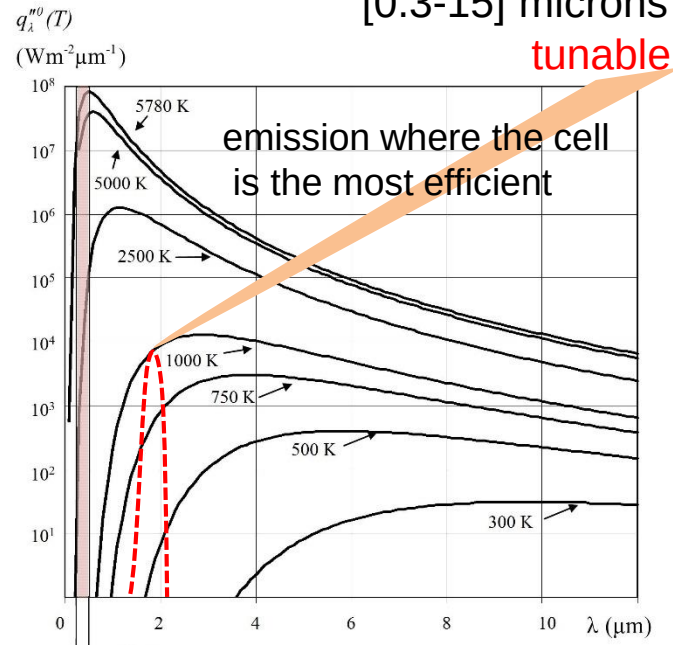
PV cell

cooling system

Irradiation spectrum

[0.3-15] microns

tunable



$q_{bb}(T_e$=1000-2000 K)=**57-907 kW m^{-2}**

PV cell materials

mostly compounds from the III-V group (In, As, Ga, Sb,…) bandgap E_g ~ [0.17-0.8] eV

Best (research) conversion efficiencies Dupré et al., Springer, 2017

20 – 25 % **[limited data!]**

Max: Carnot efficiency (T_e=2000 K & T_c=300K: **85%**)

Thermophotovoltaics

Journal articles over the years

Web of Science

(topic or title contains "thermophotovoltaic*")

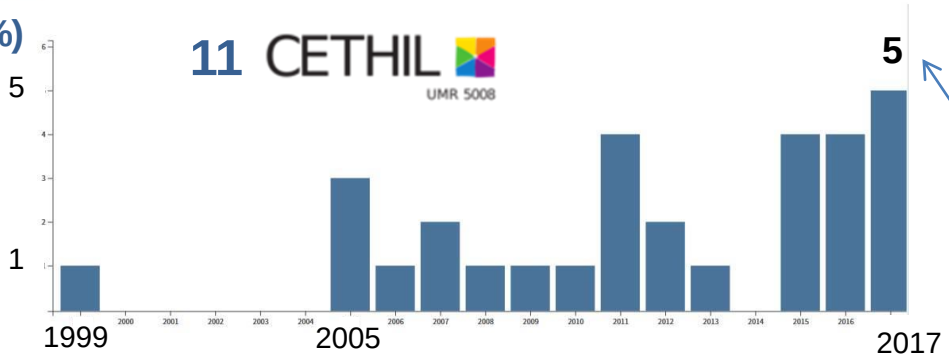
Total Publications

811

("**Niche**")

30 (at least one co-author with a French affiliation)

(=3.7%)



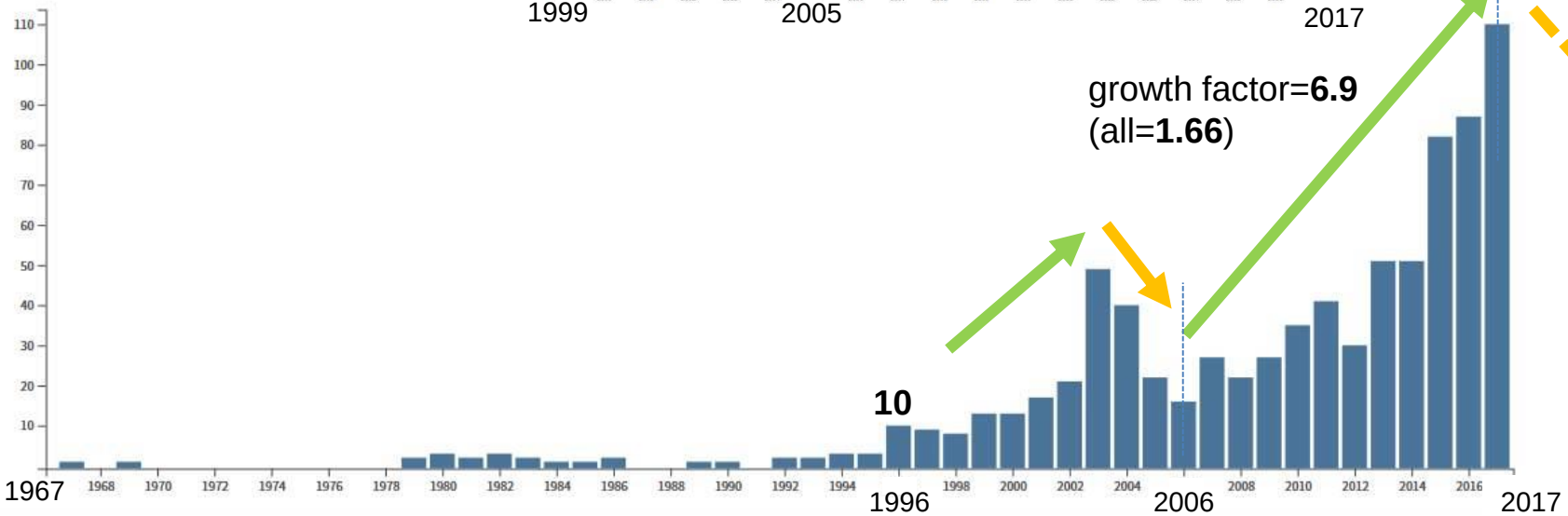
5

(= 4.5%)

110

?

growth factor=**6.9**
(all=**1.66**)

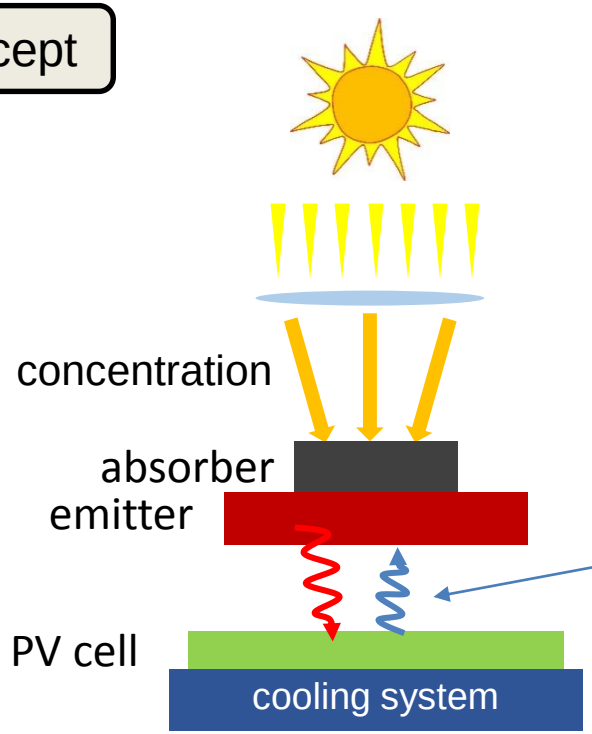


10

"Ups" and "downs". Clear "up" since 2006

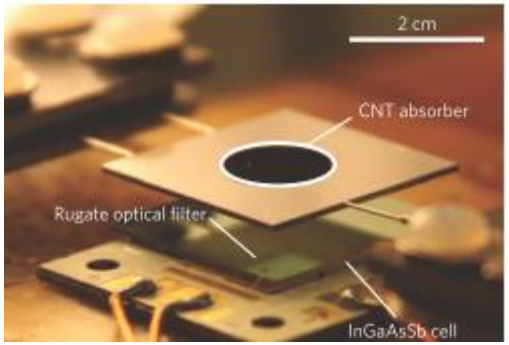
Solar thermophotovoltaics

Concept



Advantage: spectral tuning of radiation emitted toward the cell to maximize efficiency

Practical implementation in the lab



MIT STPV device

Max. theoretical efficiency

Complex device, C=46.200, T_e=2500 K & T_c=300K: **85.4%**

Harder & Würfel, SST, 2003

Planar device, C=4.4, T_e=1060 K & T_c=300K: **45.3%**

Datas & Algora, PIP, 2013

Best (research) efficiency

6.8%

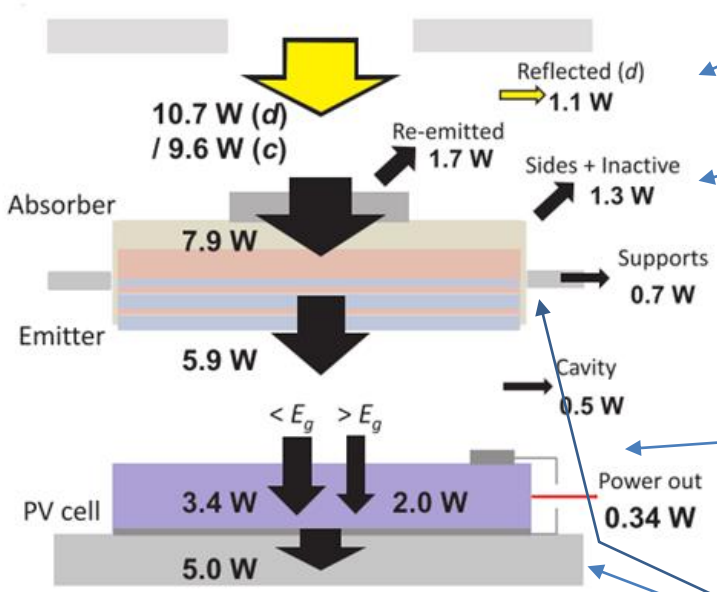
Biermann et al., Nature Energy, 2016

Promising but many challenges to overcome

Solar thermophotovoltaics

Key challenges

Losses



Lenert et al., Nature Energy, 2014

Research & **technological** needs

- photonics
- high-temperature material science
- thermal radiation transfer
- low-bandgap semiconductor material science
- electrical engineering
- thermal insulation / cooling

Many challenges: multi- and interdisciplinary solutions

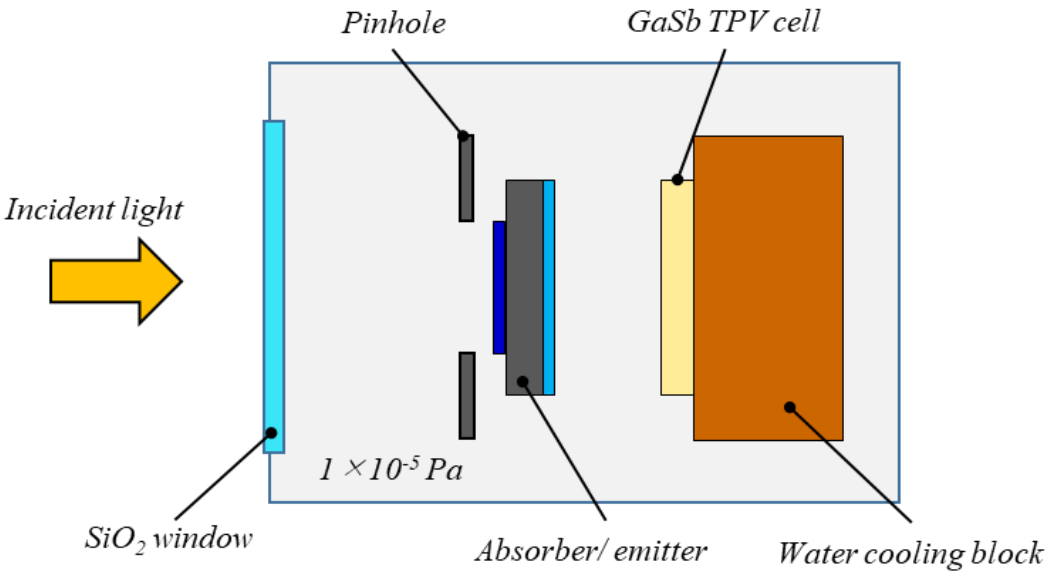
Solar thermophotovoltaics

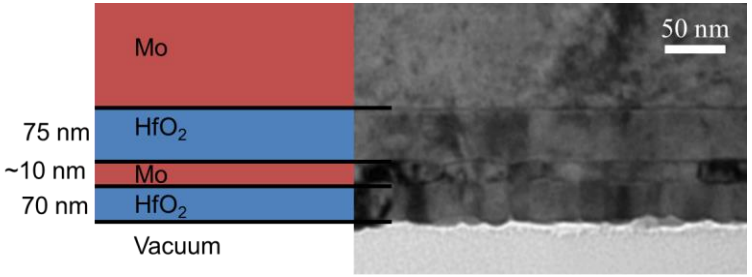
Sample results

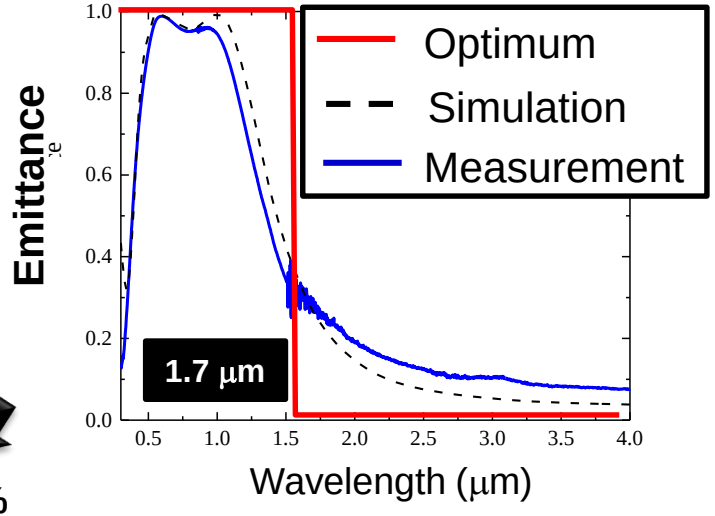
Univ. Tohoku STPV device

Absorber-emitter design

Collaboration: Univ. Tohoku - CETHIL







Shimizu et al., J. Photon. Energy, 2015

Kohiyama, et al., Applied Phys. Express, 2016

Efficiency = 5.1%

Blandre et al., Optics Express, 2018

Material science and thermal radiation design

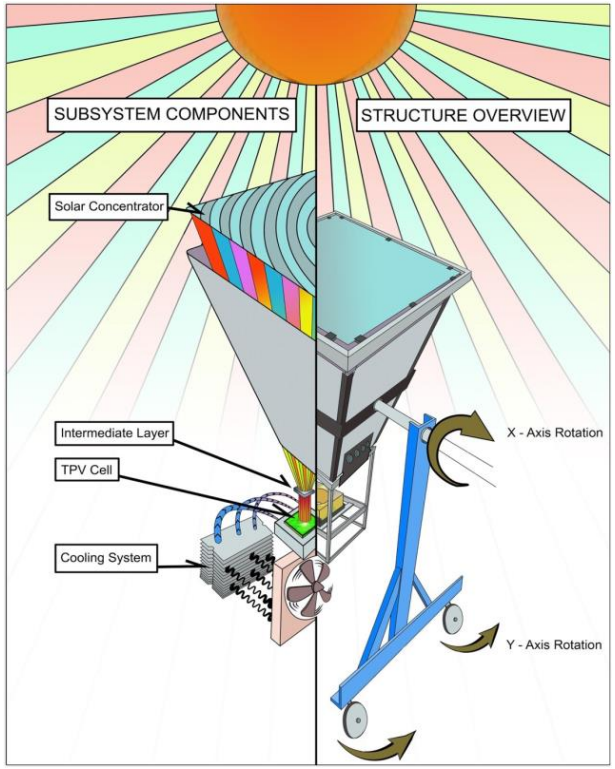
Solar thermophotovoltaics

Sample results

B.S. senior design project at the University of Utah

5 students x 8 h x 32 weeks

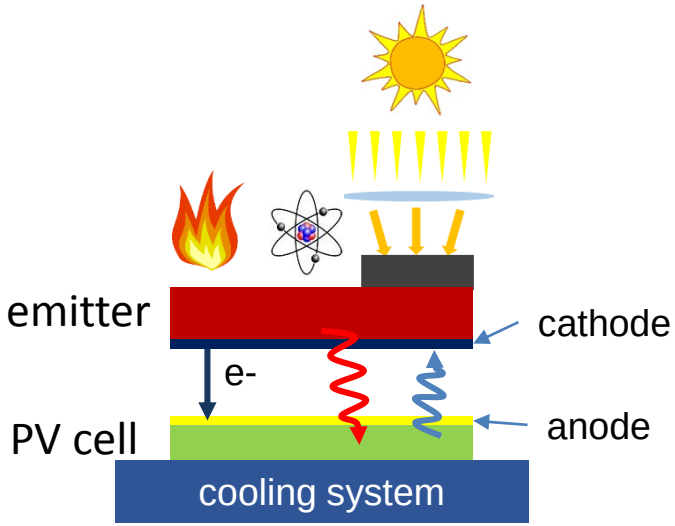
Collaboration: Univ. Utah - CETHIL



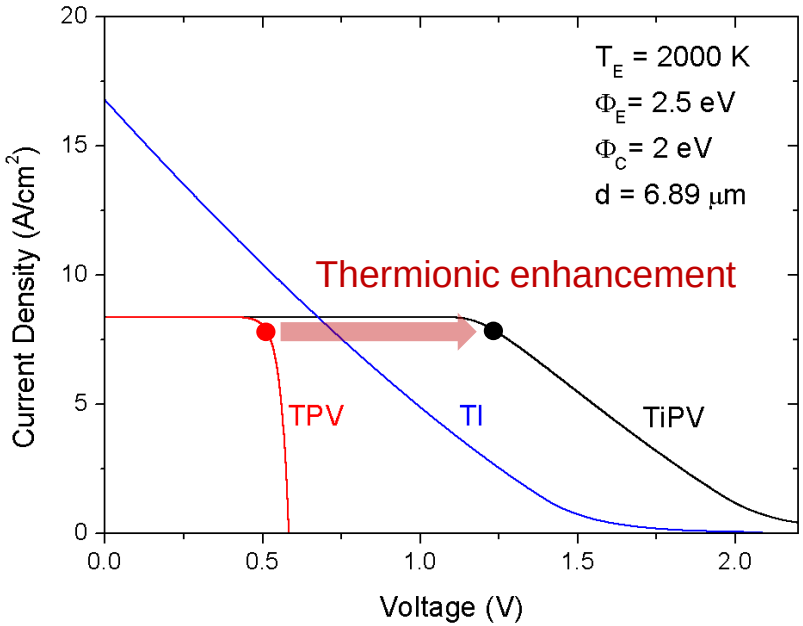
Nice educational design project requiring multidisciplinary skills

Thermionic-thermophotovoltaic devices

Concept



Datas, Applied Phys. Letters, 2016



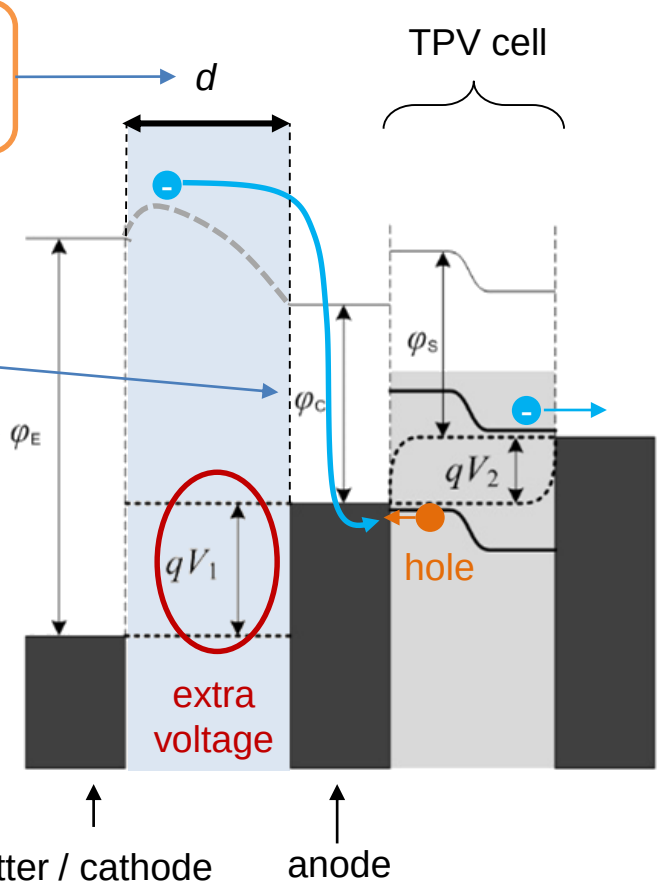
Enhanced output voltage and grid-less front contact

Thermionic-thermophotovoltaic devices

Key challenges

small distance & vacuum

low workfunction



Datas, Applied Phys. Letters, 2016

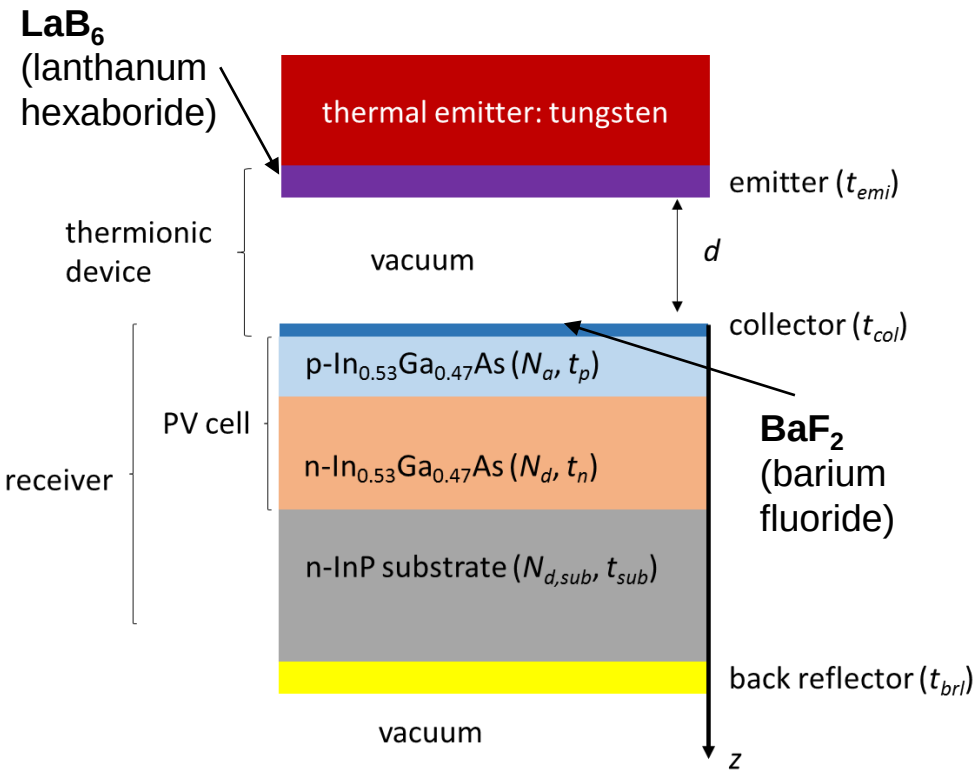
Challenges: low workfunction coatings, small-gaps to reduce the space-charge

Thermionic-thermophotovoltaic devices

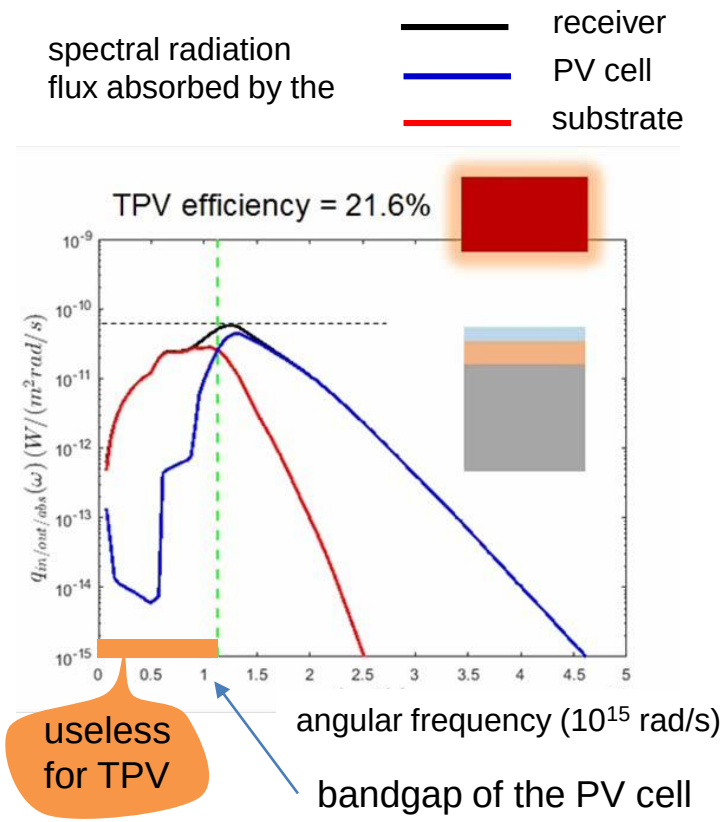
Ongoing research

Sample results

Collaboration: IES Madrid - CETHIL



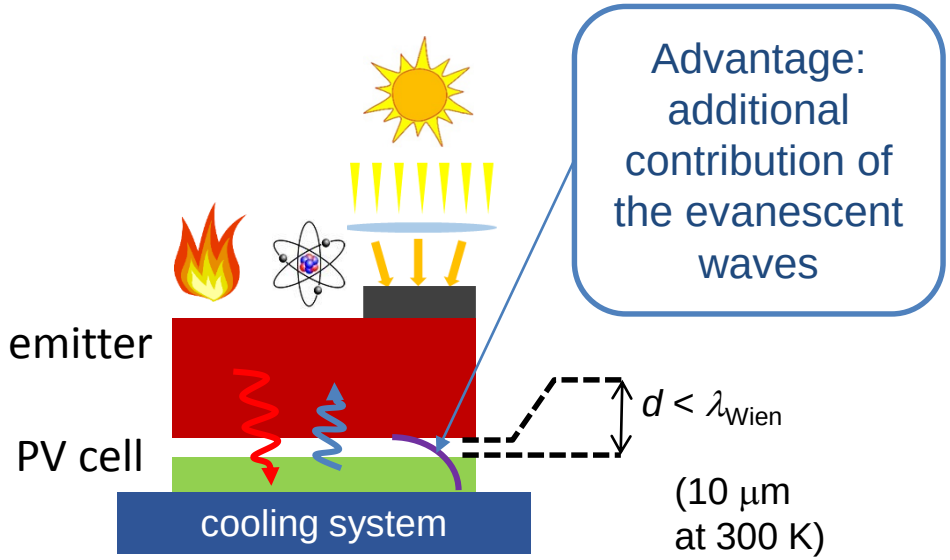
Radiation – electrical simulations



Materials to be found to optimize both thermionic and thermophotovoltaic conversions

Near-field thermophotovoltaic devices

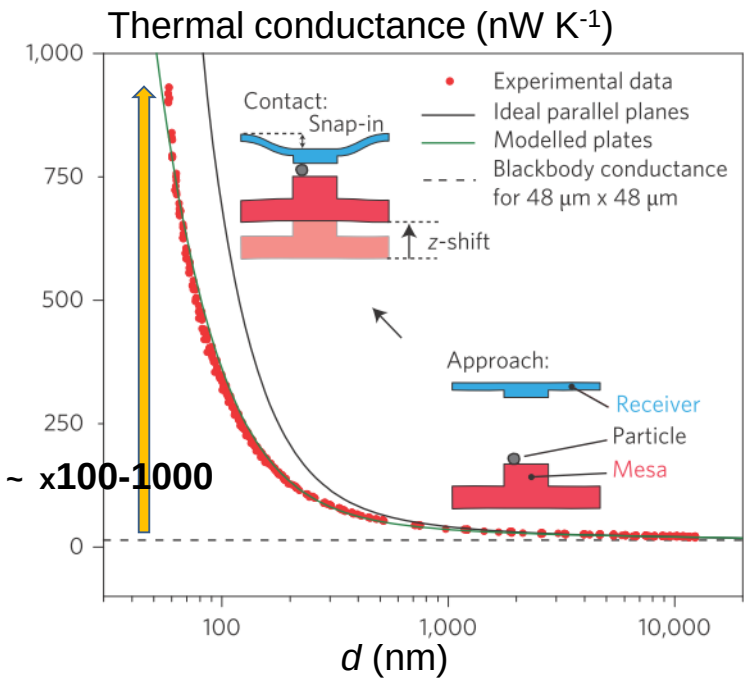
Concept



Pan et al., IEEE TED, 2000

Whale & Cravhalo, IEEE TEC, 2002

Near-field radiation effects experimentally observed multiple times



Song et al., Nature Nanotechnology, 2016

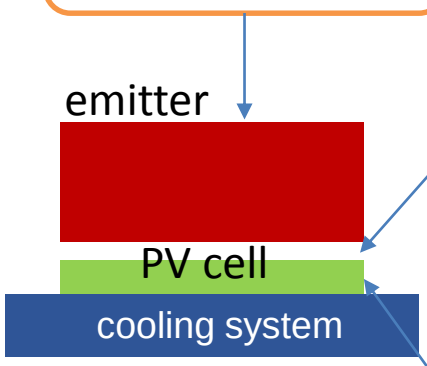
See also Bernardi et al., Nature Communications, 2016

Theoretically predicted huge near-field enhancements of electrical power

Near-field thermophotovoltaic devices

Key challenges

large emitter temperature



building a sub-micron gap

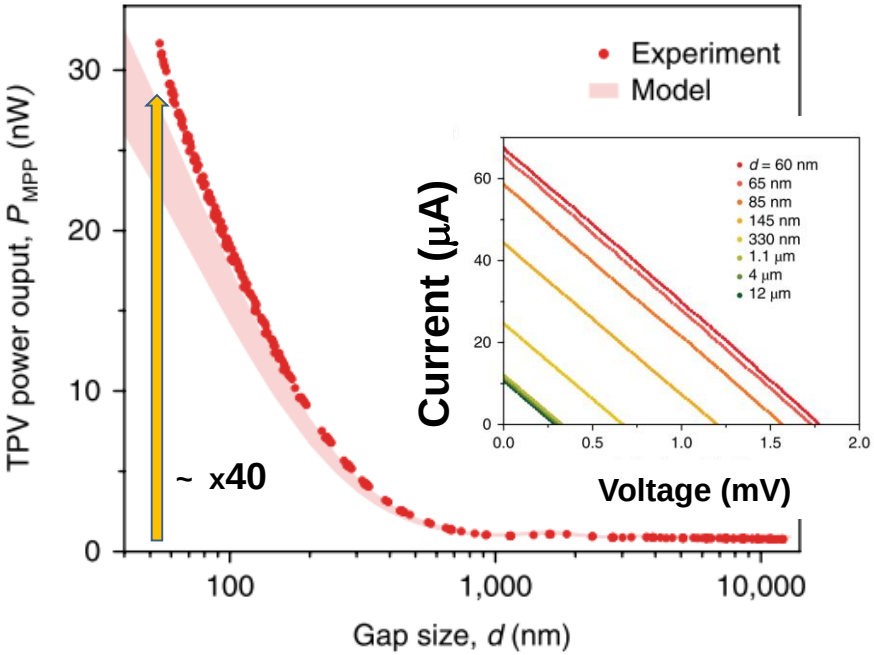
efficient low band-gap PV cell in near-field illumination conditions

Experiments

First (inconclusive attempt) DiMatteo et al., PRL, **2001**

Very recent breakthrough

Fiorino et al., Nature Nanotechnology, **2018**



Huge challenges, recent breakthrough, lot of room for improvement

Near-field thermophotovoltaic devices

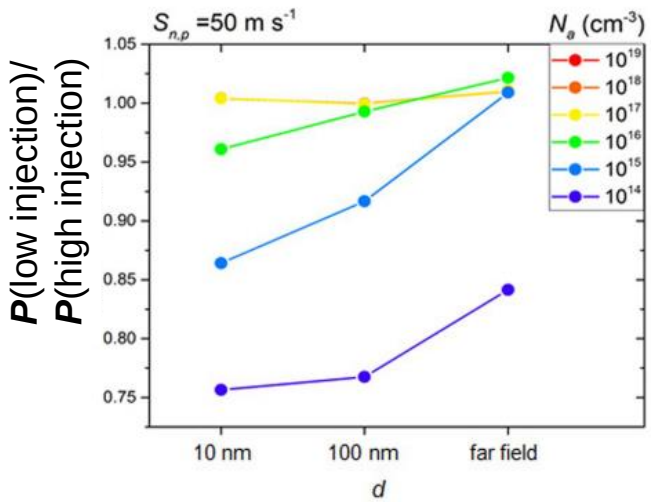
Sample results | Radiative-electrical design

CETHIL

Collaboration: Univ. Utah - CETHIL

High-injection effects?

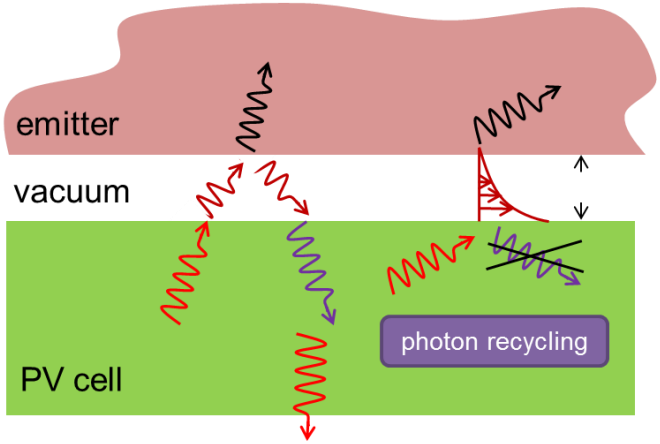
p-on-n GaSb cell



Optimum doping of the p-doped layer (N_a) is function of emitter-cell distance (d) and cell top surface passivation

Blandre et al., Sci. Reports, 2017

External luminescence in NF-TPV devices



Radiative recombination/total recombination (performances of the PV cell) **increases in the near-field**

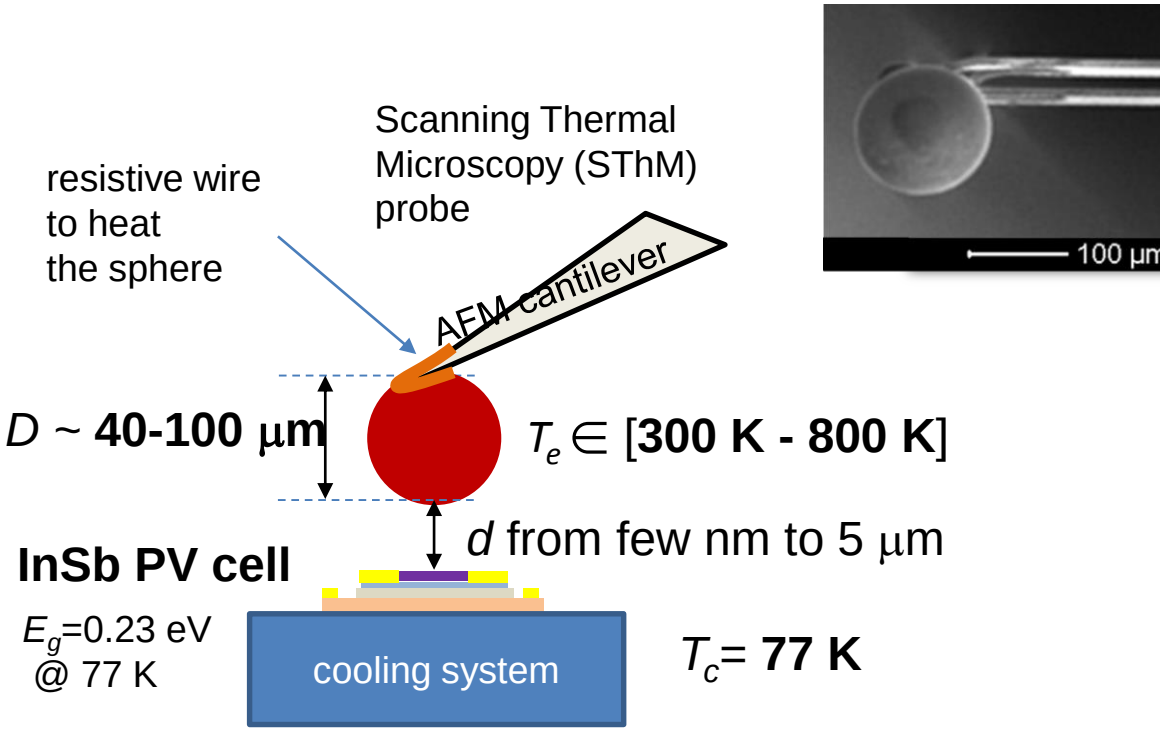
DeSutter et al., PR Applied, 2017

Specific design of the PV cell according to near-field radiation conditions

Near-field thermophotovoltaic devices

Ongoing research

Collaboration: CETHIL – IES Montpellier

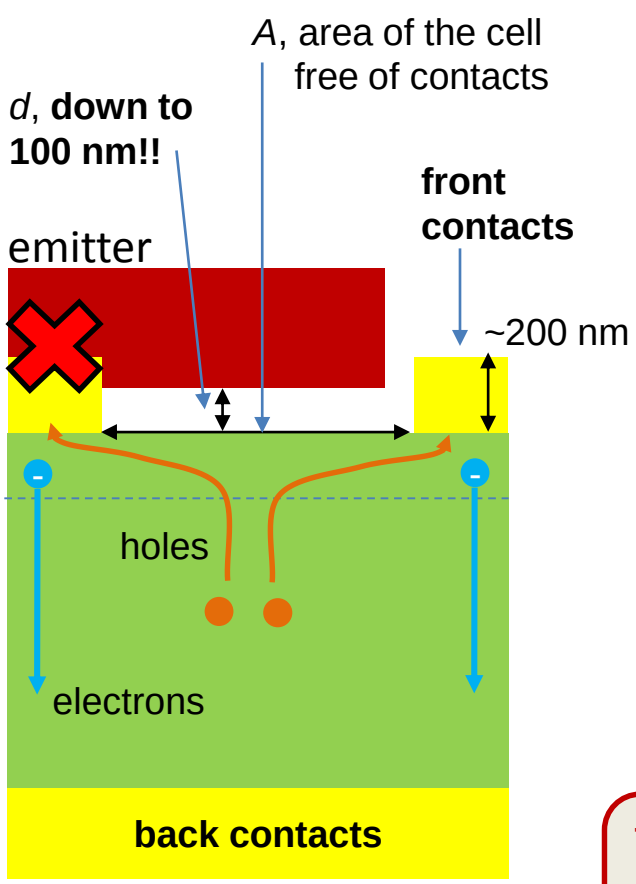


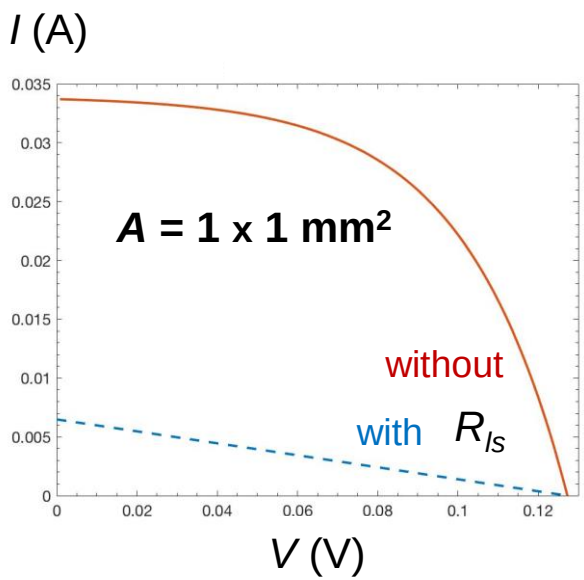
Micro-scale lab experiment with a spherical emitter and a very low bandgap cell at around 77 K

Lucchesi et al., **Poster JNES**, 2018

Near-field thermophotovoltaic devices

Ongoing research

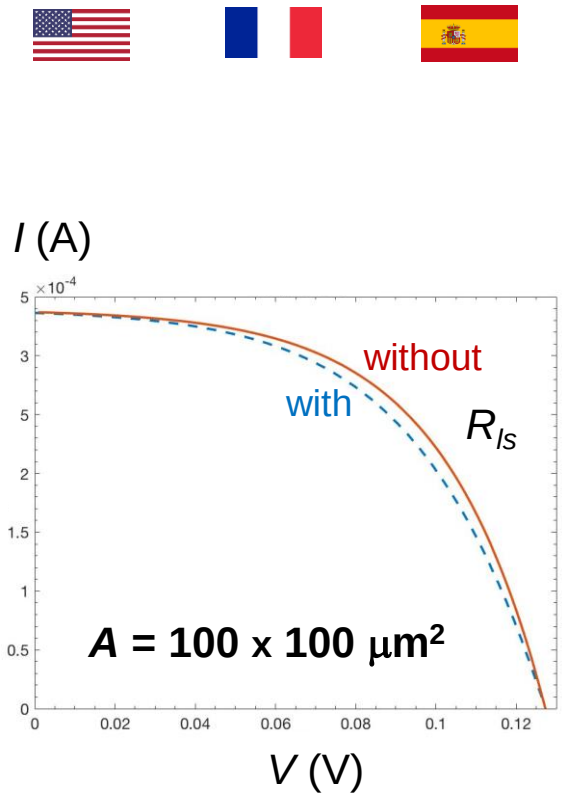




p-on-n InAs cell

d = **100 nm**

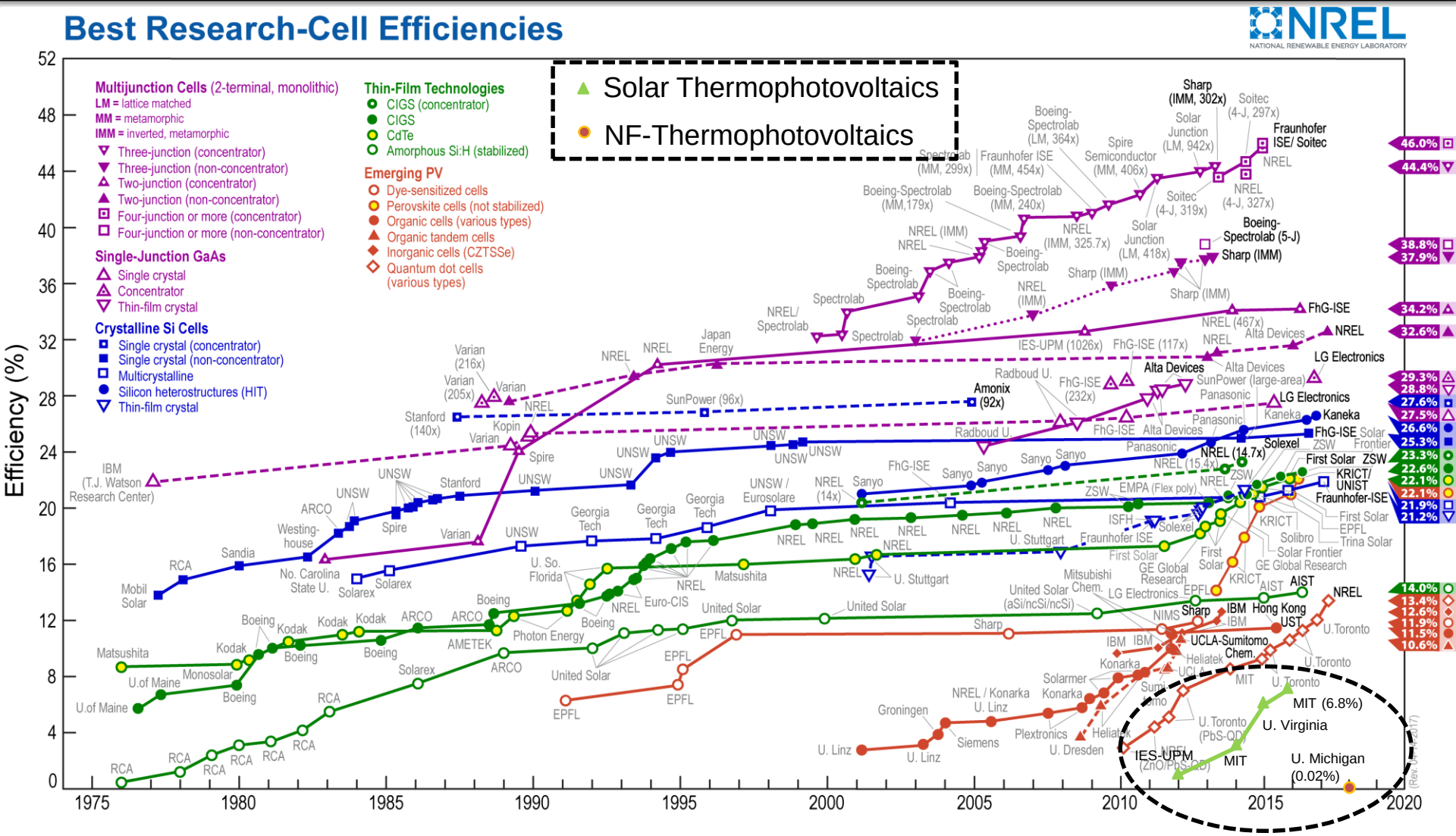
Collaboration:
Univ. Utah - CETHIL - IES Madrid



Technological issues with front contacts because of high currents and lateral series resistance (R_{ls})

Milovich et al., in preparation, 2018

A chart for TPV devices?



Best research TPV device power outputs?

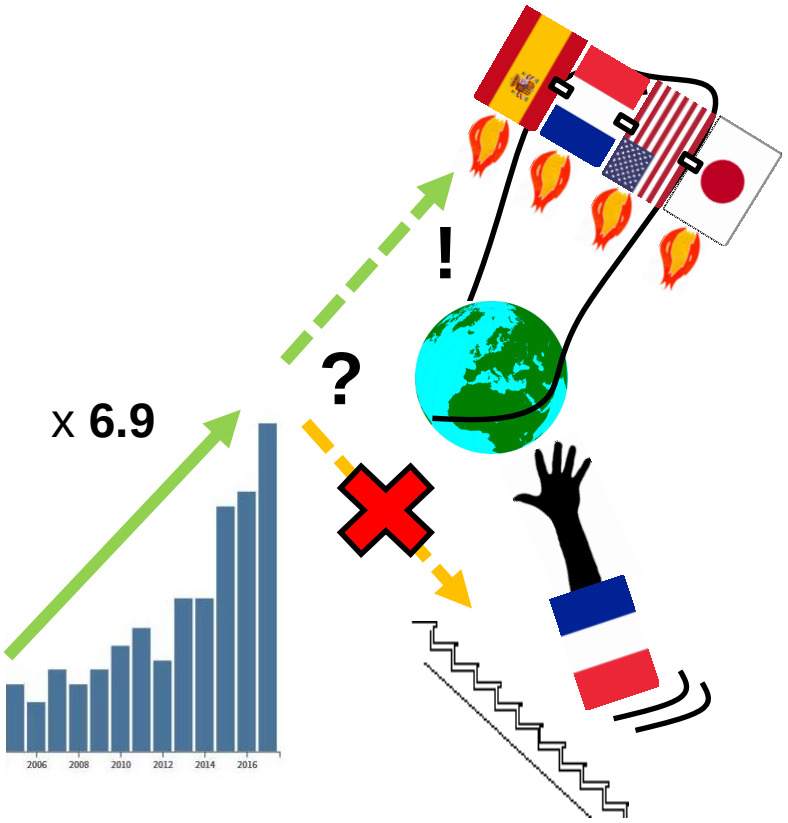
Conclusions

Key challenges require expertise in

- thermal radiation / photonics
- semiconductor material science
- low-bandgap PV cell design, fabrication & characterization
- thermal insulation
- nanoscale device fabrication (NF-TPV)

Multi- & interdisciplinary research is required with international collaborations

"A picture speaks a thousand words"



Further readings and acknowledgments

Further details on our recent results

STPV
TIPV
NF-TPV

Blandre et al., Optics Express, 2018
Datas, APL, 2016
DeSutter, Vaillon, Francoeur, Phys. Rev. Applied, 2017
Blandre, Chapuis, Vaillon, Sci. Reports, 2017

Lucchesi et al., poster, JNES 2018

Acknowledgements

DEMO-NFR-TPV
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AMADEUS
(IES Madrid)

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(Univ. Utah)

Merci pour votre attention