Unorthodox and Exciting Applications of Solar Energy Research

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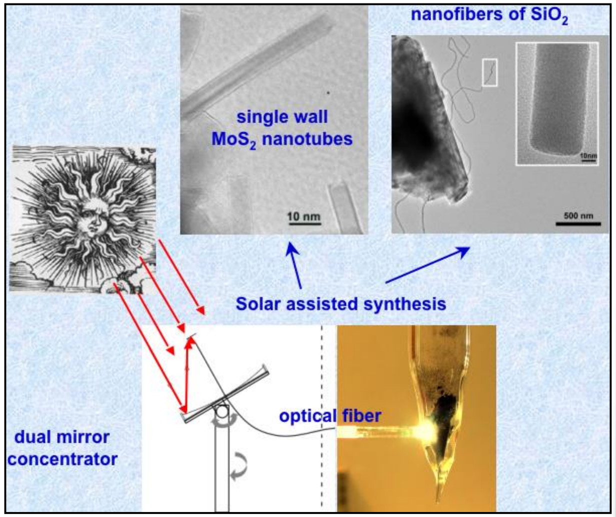
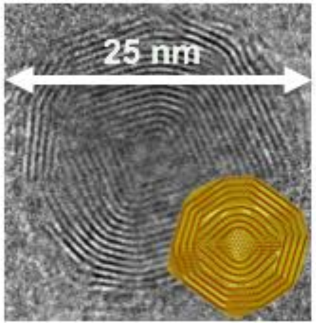
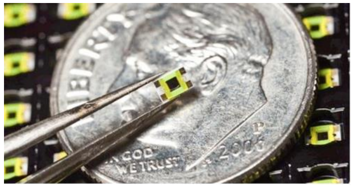
1) Solar-driven synthesis of novel nano-materials

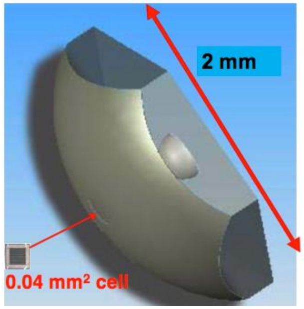


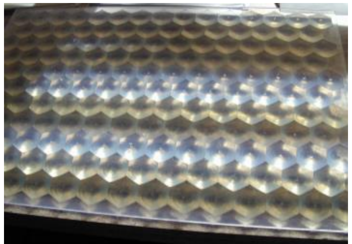


2) Ultra-high algal bioproductivity

3) Solar electricity for *private commercial* space missions







Solar Paradigms: Mature, affordable, large-scale (GW)

1) Solar thermal for *electricity* production.

Concentrate sunlight → generate steam → drive turbines.

Yearly-average conversion efficiency ≈ 16%

Admits gas backup heating *and* thermal storage

(temperatures of 350-550°C) → dispatchability

Avoided capacity for utilities– not just energy savings

2) Photovoltaics: Direct conversion to electricity

Mainly Silicon technology.

Inexpensive, ~20% efficient *modules*.

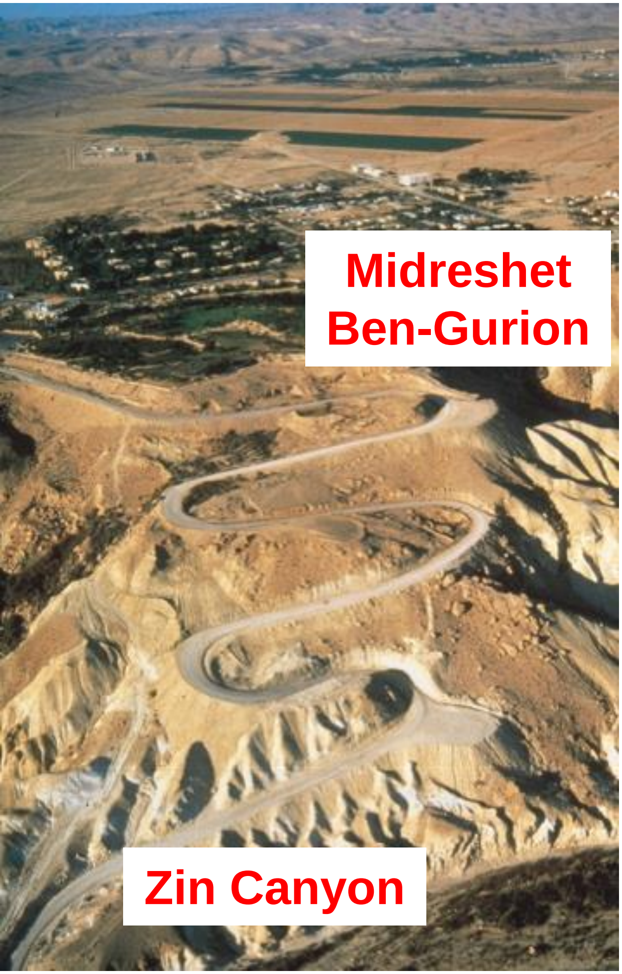
Stable, robust, modular, growing rapidly.

But electrical storage technologies are (still) inadequate.

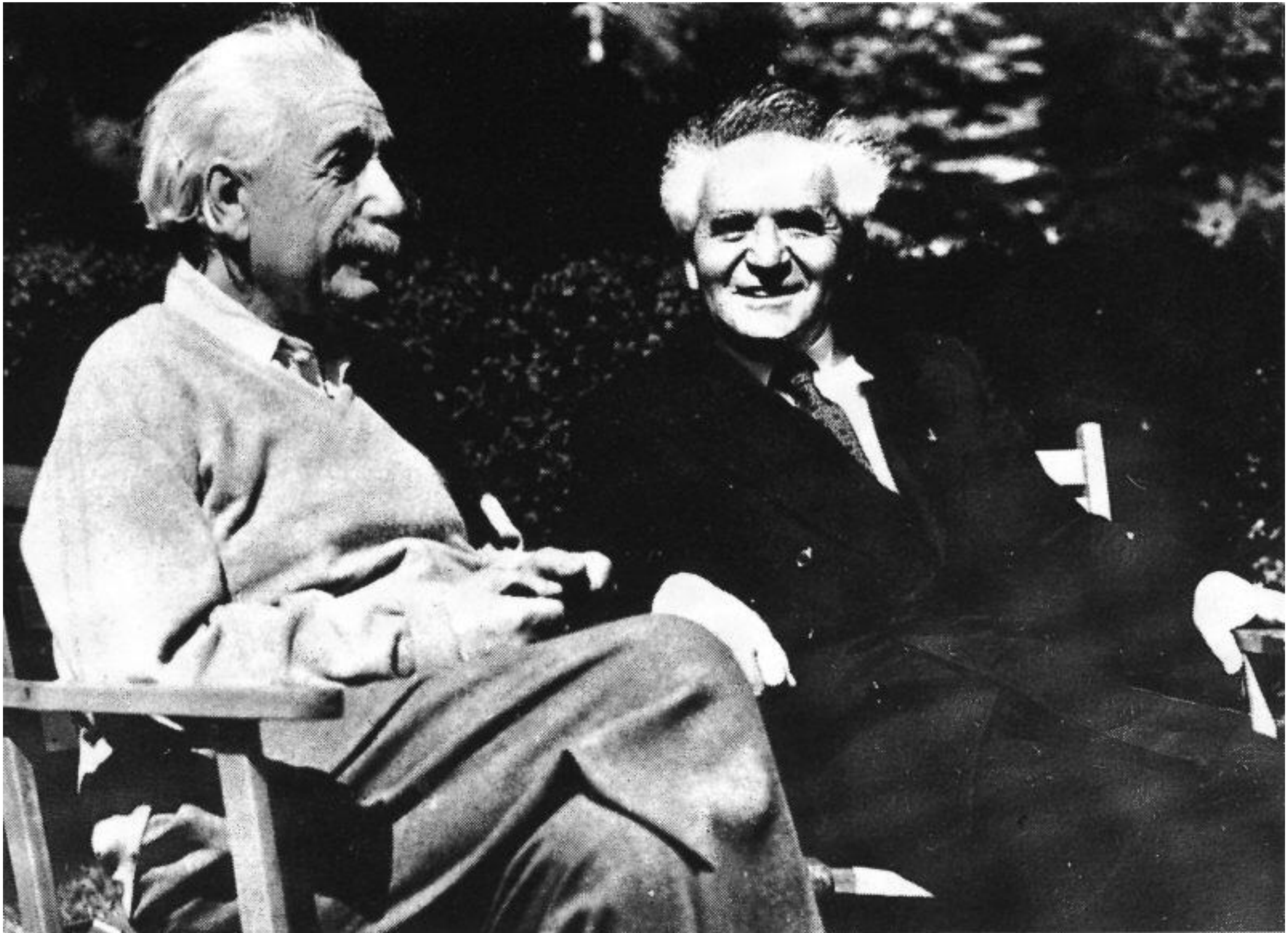
Today we’ll be exploring novel, unorthodox uses of solar energy:

Aspiring to futuristic applications rather than just implementing mature technologies.

Blaustein Institutes for Desert Research: An interdisciplinary Faculty in desert science, exploring fundamental and applied scientific issues (founded 1977)



David Ben-Gurion, Israel's founding premier, deeply appreciated the importance of excellence in academia



Maps drawn to same scale.

1) A new and distinct solar paradigm:

Synthesizing singular nanomaterials at the service of human technology, via concentrated solar (instead of using solar to supply heat, electricity or fuels)

Examples: MoS_2, Cs_2O, SiO_2, SiC, WS_2, WSe_2, $MoSe_2$

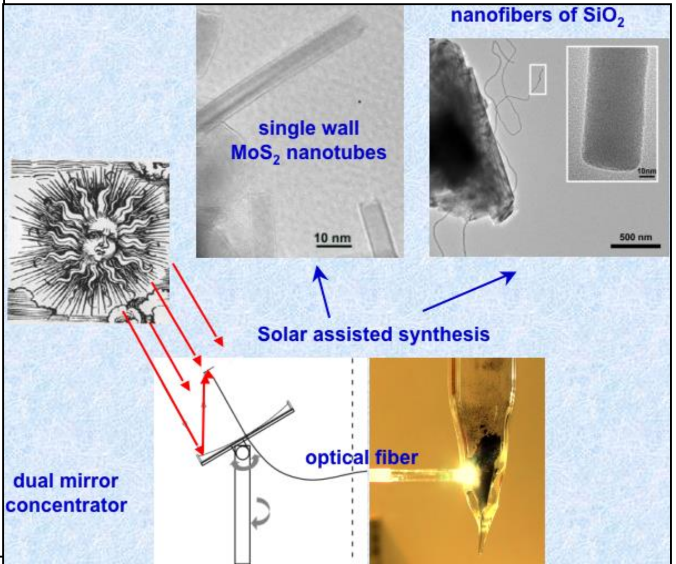
Practical motivation: Remarkable lubricating, optical, thermal, catalytic, electronic or adhesive properties

In collaboration with Reshef Tenne's group at the Weizmann Institute (Rehovot, Israel)

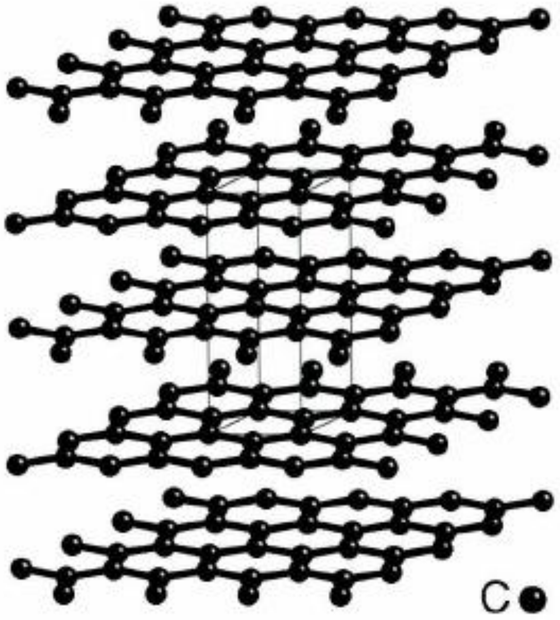
Our BGU group: Daniel Feuermann, Eugene A. Katz, JG

Advantages relative to the key alternatives of pulsed laser ablation and chemical vapor deposition:

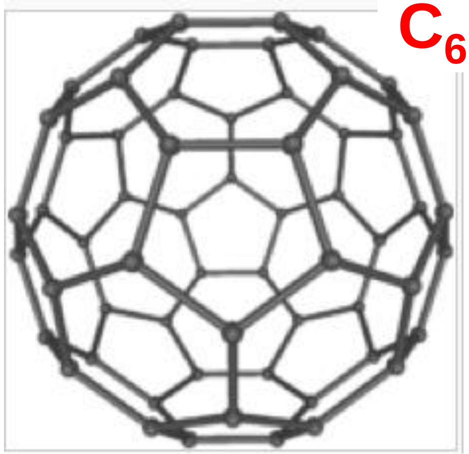
1. **Safer (no toxic reagents)**
2. **Far faster (minutes rather than hours)**
3. **Scalable – hence the potential of commercialization**



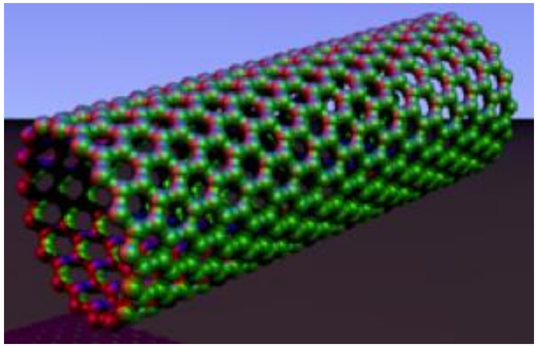
First fullerenes (closed-cage nano-structures) and nanotubes: Carbon



C: Graphite



C_{60}



Sobering realities:

a) Carbon nanotubes were found to be carcinogenic to humans

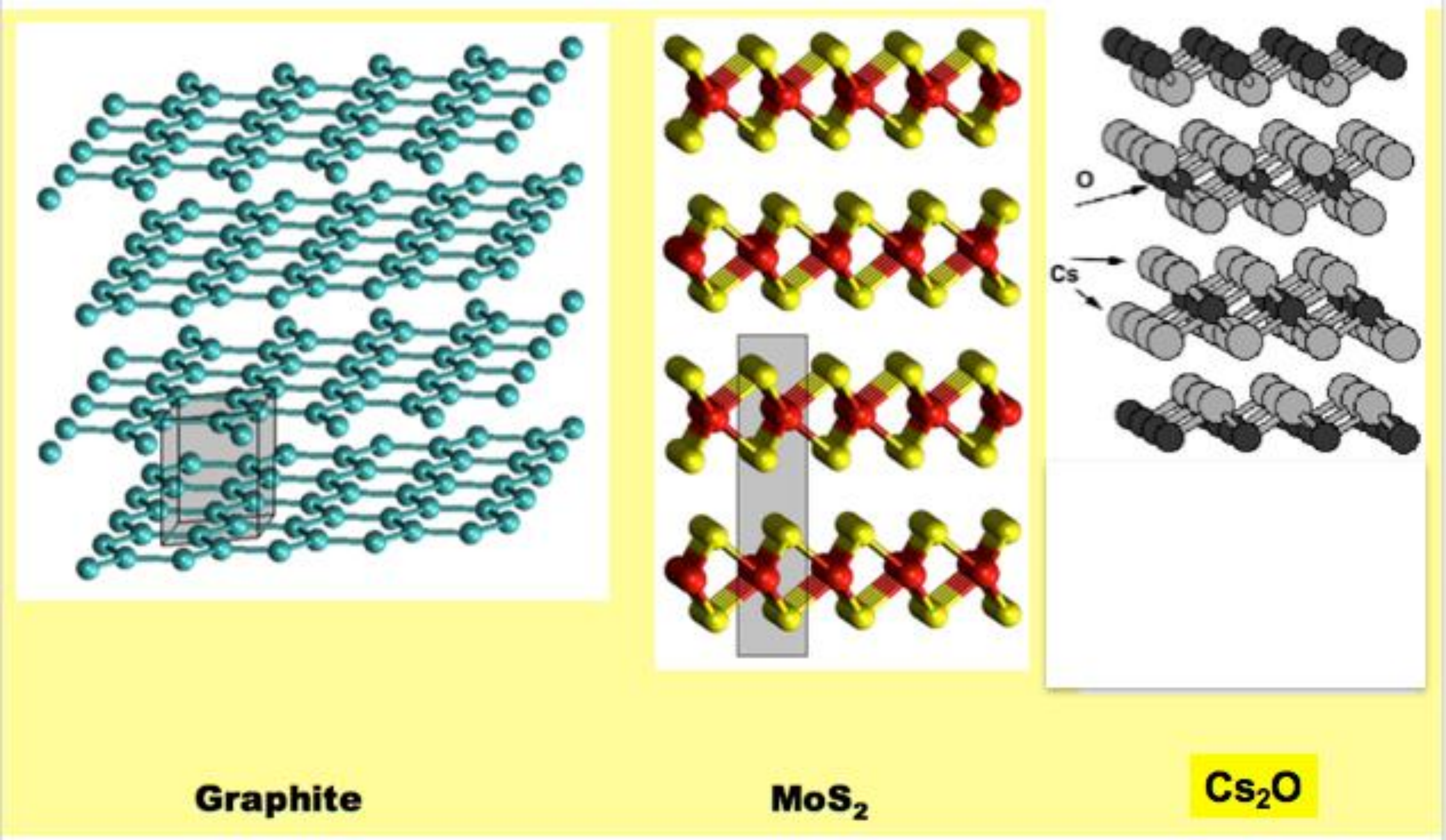
b) No rational synthesis found for C_{60} - only by arc-discharge chambers → exorbitant costs, problematic scalability

R. Tenne (1992): Fullerene-like and nanotube structures should *not* be restricted to Carbon: they should be realizable from *layered* compounds, e.g., MoS_2 , $MoSe_2$, WS_2, WSe_2, GaS, ... (and none of their nano-structures, so far, appear to pose occupational health hazards).

Examples of layered materials:

Strong in-plane covalent bonds ↔

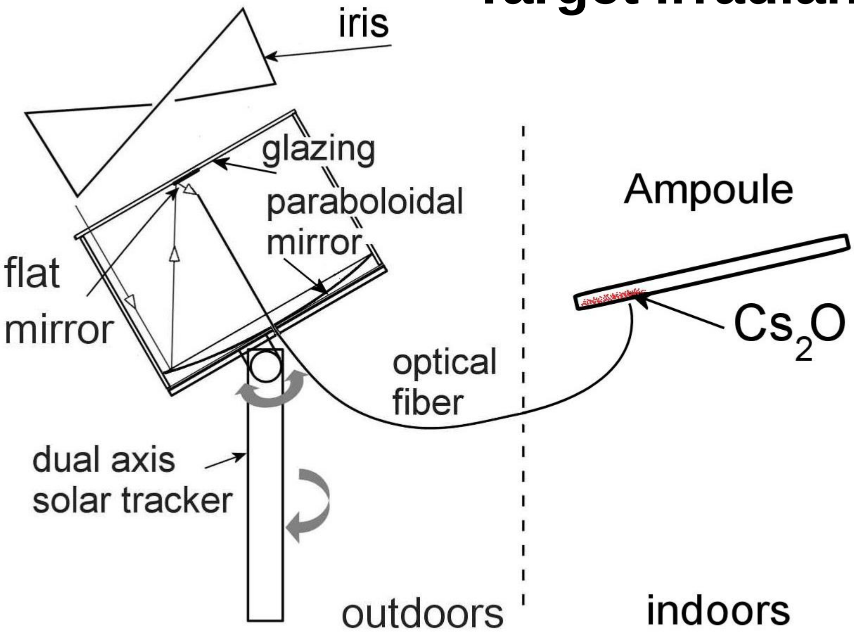
but weak inter-layer van der Waals bonds ↕

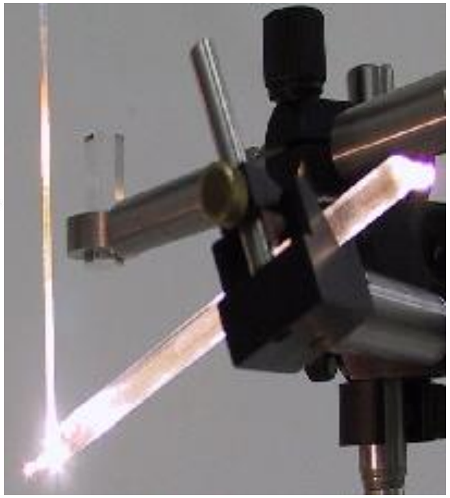


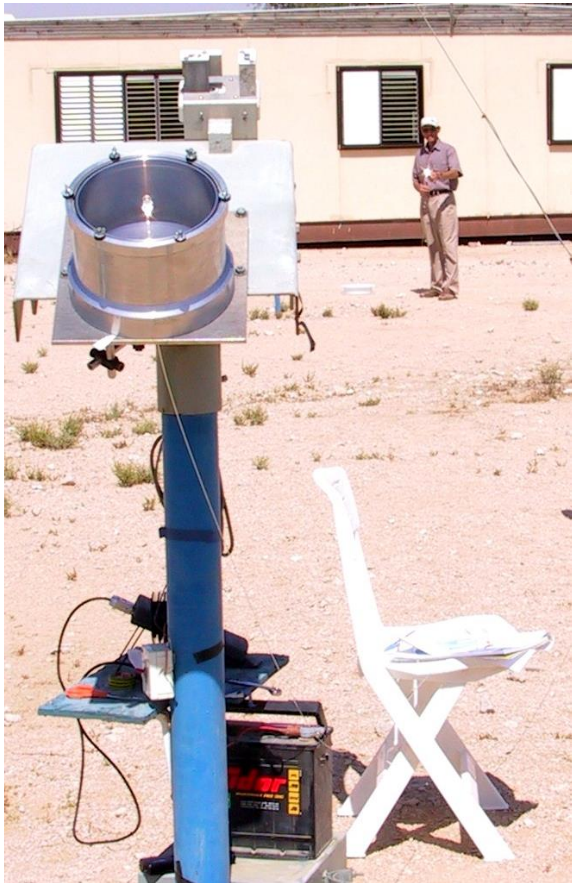
Chronological promenade through our solar concentrators

Generation 1: Solar fiber-optic mini-dish

Target irradiance ≈ 4,000 suns







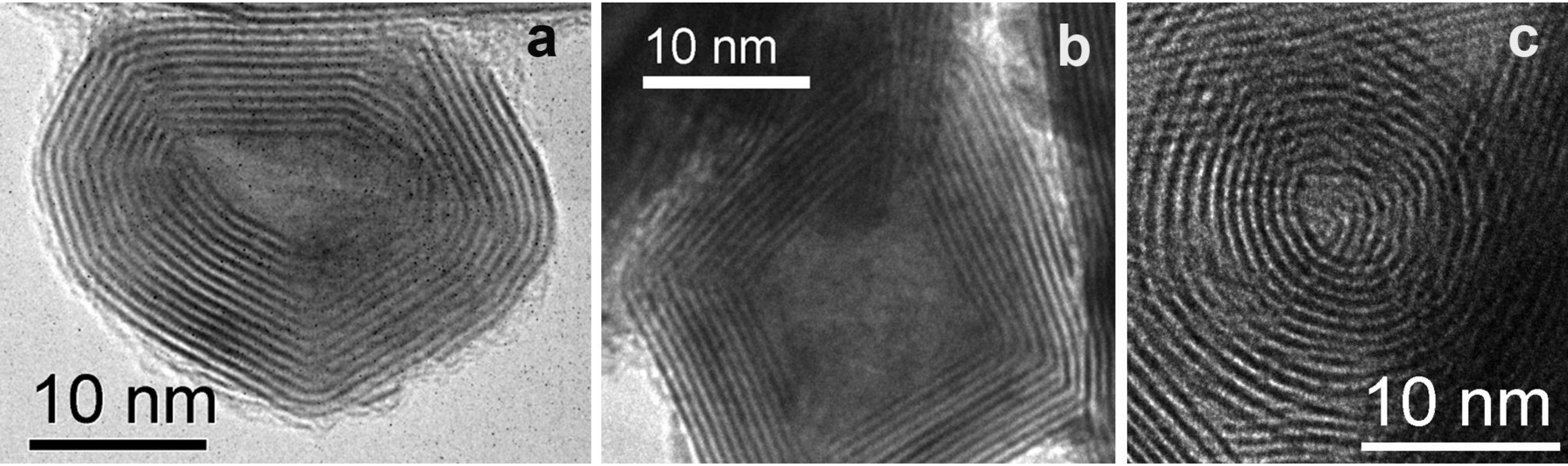
$D_{aperture}$ = 200 mm

Optical fiber core diameter = 1.0 mm

1st effort: Cs_2O - used to tailor photo-detector and photo-emitter coatings, but violently reactive upon exposure to air → expensive photonic-device preparation

Fullerene-like nano-structures (*if* producible) should mitigate that reactivity.

Sample Transmission Electron Microscope (TEM) images for Cs_2O



Inexpensive, photo-thermal process for synthesizing fullerene-like Cs_2O with concentrated sunlight: confirmed with materials characterization tools:

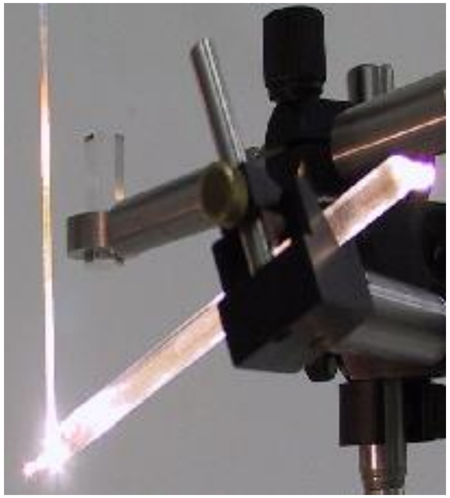
TEM, High-Resolution TEM, Energy Dispersive x-ray Spectroscopy (EDS), Electron Energy Loss Spectroscopy (EELS)

and stable upon exposure to air

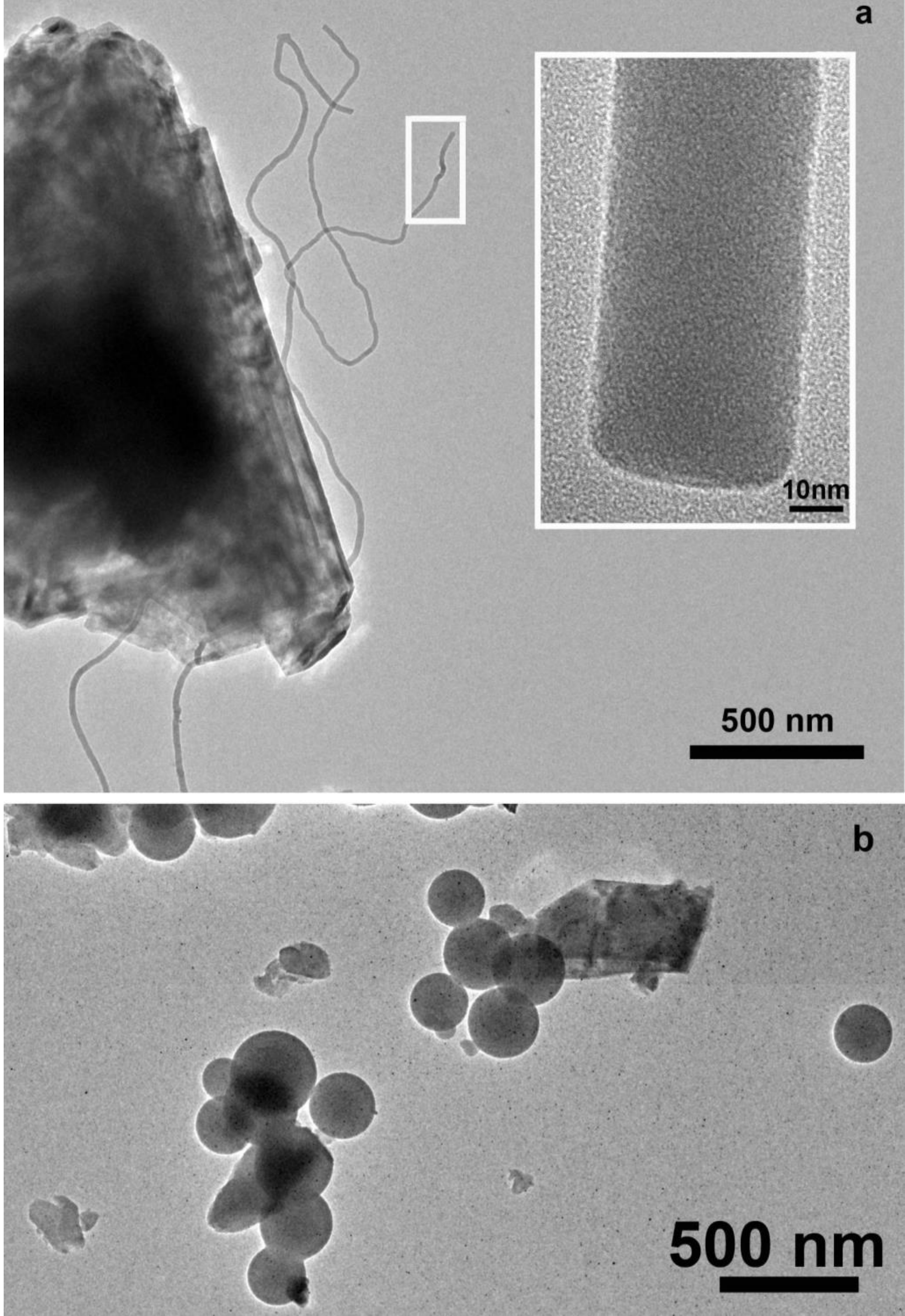
WIS + BGU teams, *Advanced Materials* 18, 2993-2996

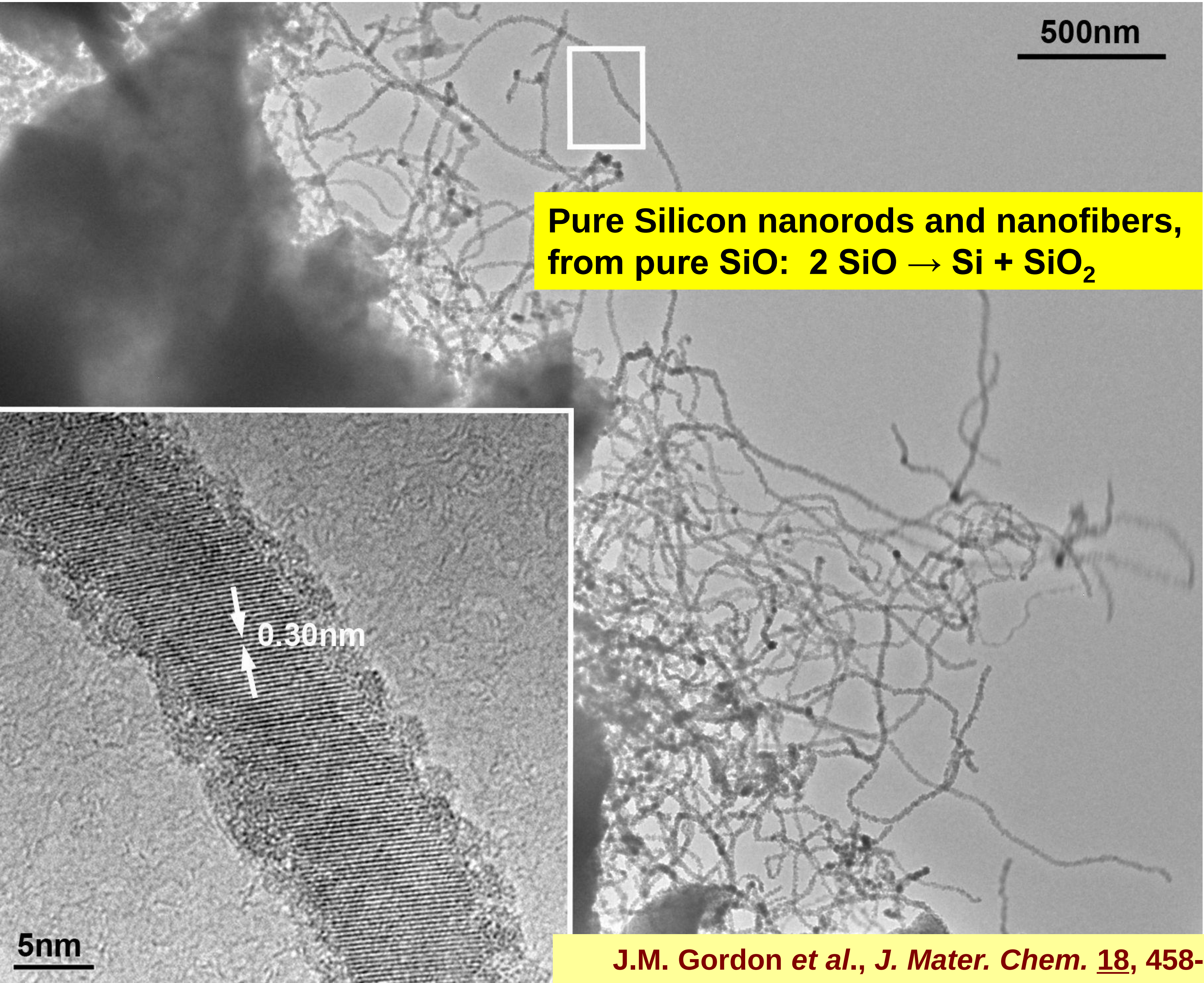
SiO_2 nanofibers and nanospheres (for the nano-photonics industry)

First production of SiO_2 nanostructures *directly* from (pure) quartz



Apparent key to success: creating a naturally ultra-hot, continuous, extensive annealing region conducive to the requisite molecular rearrangements



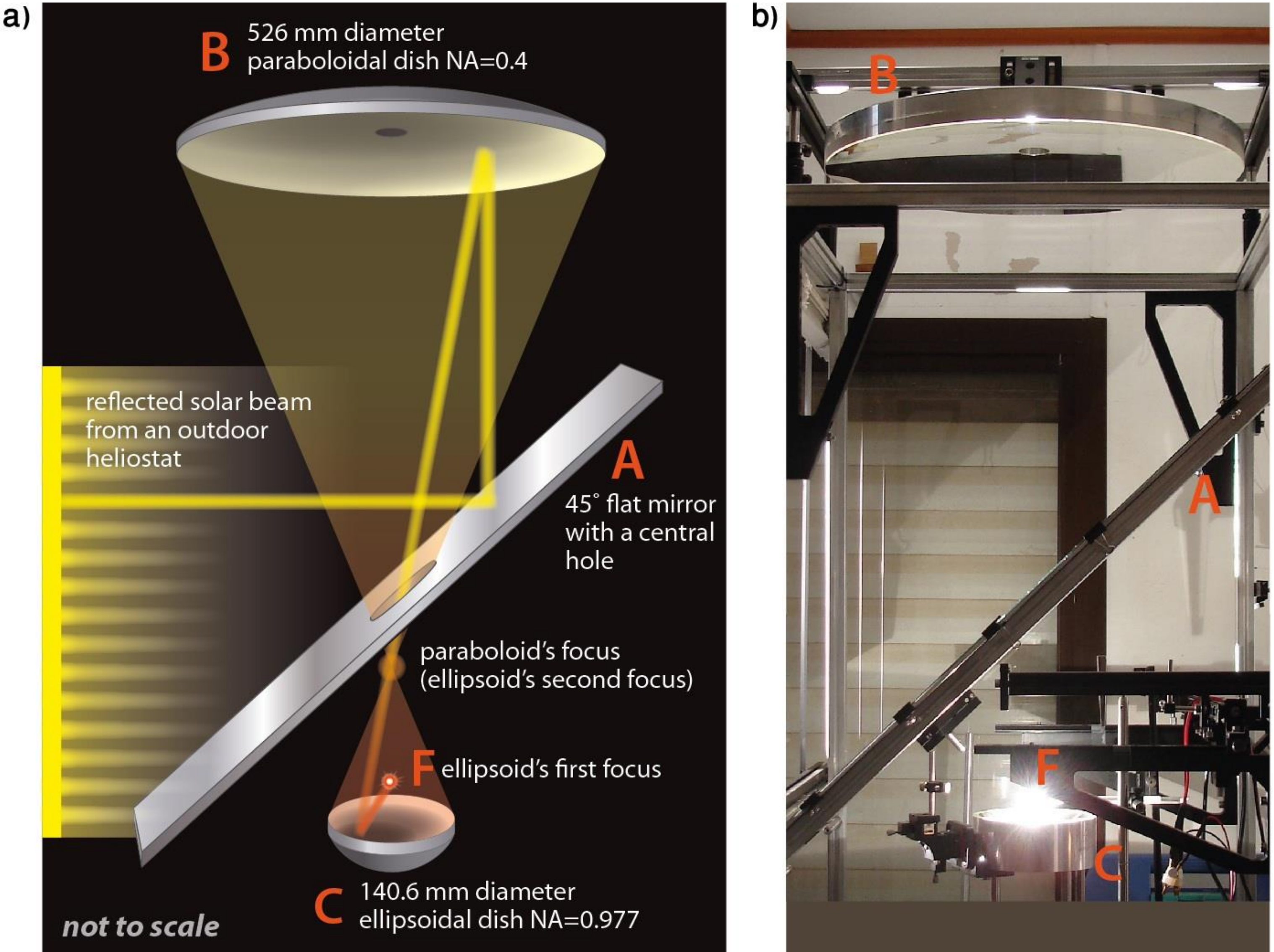


Pure Silicon nanorods and nanofibers, from pure SiO: 2 SiO → Si + SiO_2

J.M. Gordon *et al*., *J. Mater. Chem.* 18, 458-462

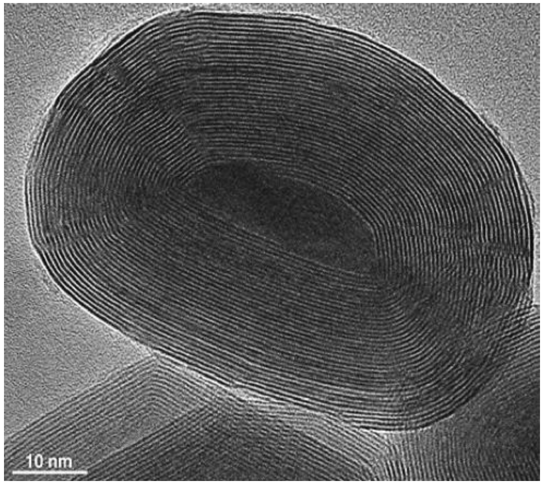
Generation 2: solar furnace that can attain ~15,000 suns

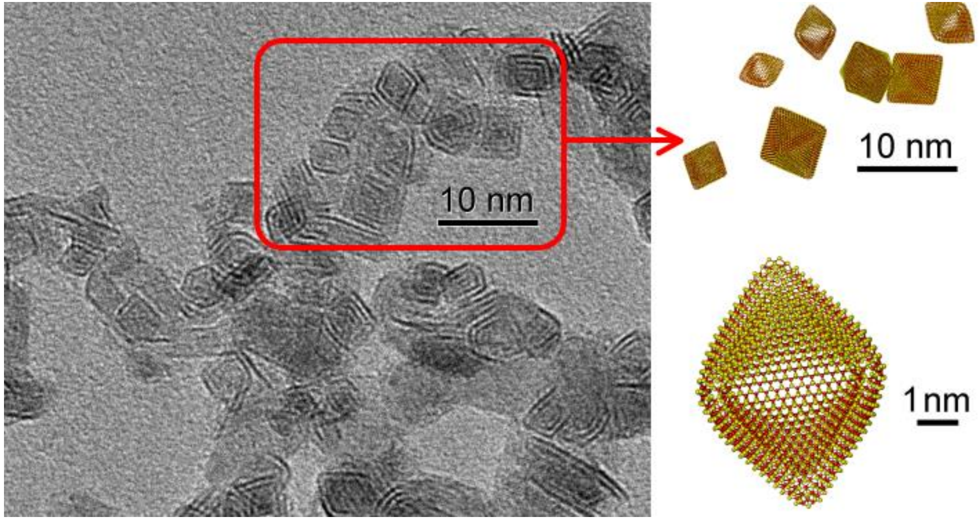
Higher temperatures permit access to more metastable (and hence more remarkable) nanostructures



Nature's true inorganic fullerenes: MoS_2 nano-octahedra, the basic smallness limit

Previously found: far larger, hollow, multi-wall, quasi-spherical MoS_2

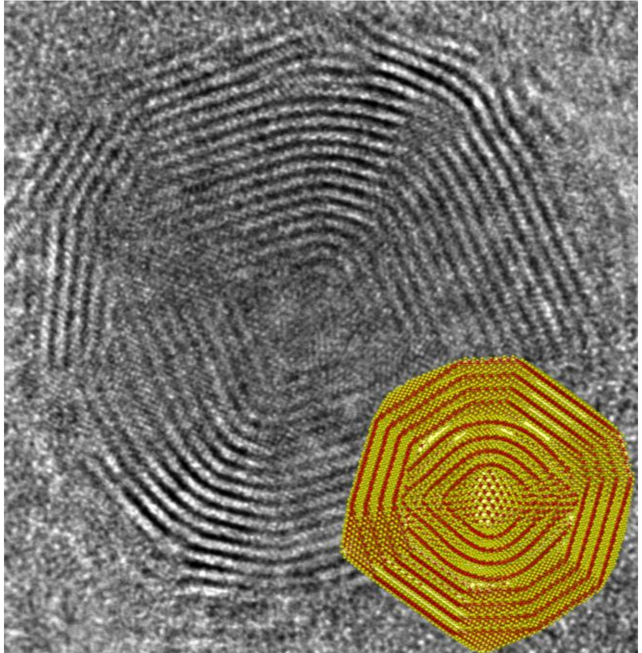




Practicality: super-lubricant and super-catalyst (but yields were sparse)

WIS+BGU teams

Angew. Chem. Int. Ed. 50, 1810-1814



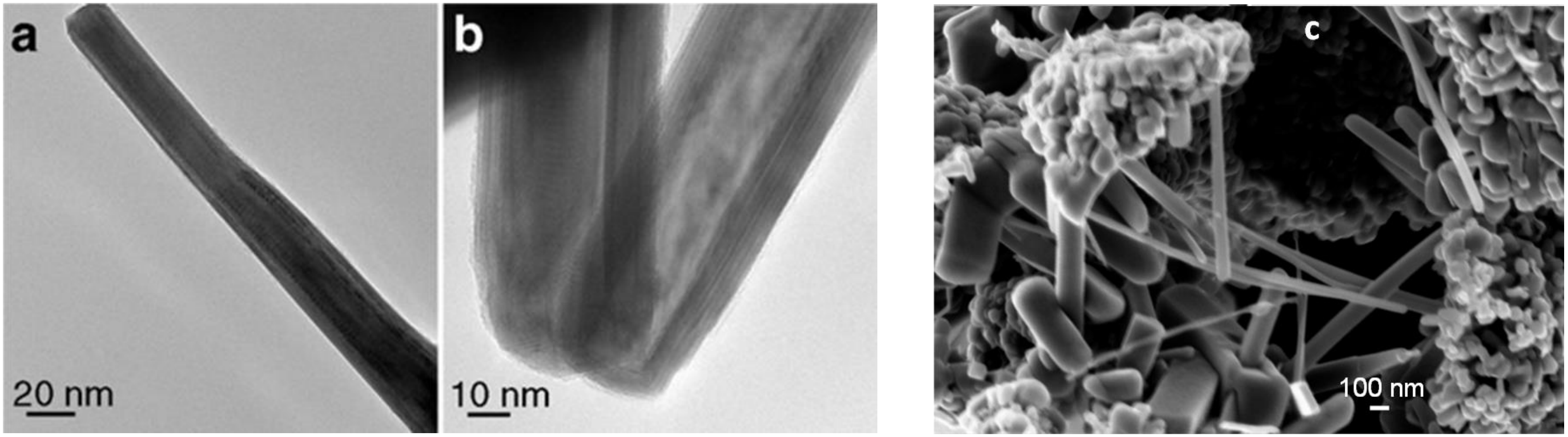
Can *hybrid* nano-structures (nano-octahedral core and quasi-spherical shells) exist?

Motivation: simultaneous presence of *both* metallic (nano-octahedra) *and* semi-conducting (quasi-spherical structure) properties in a *single* nano-particle.

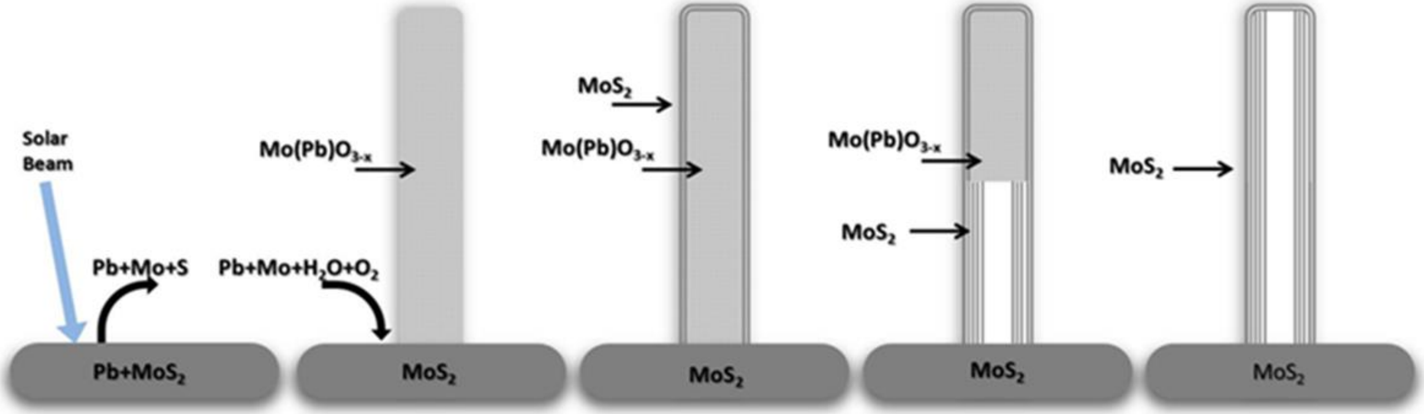
The question had never been asked, and no experimental results had ever shown this, until ...

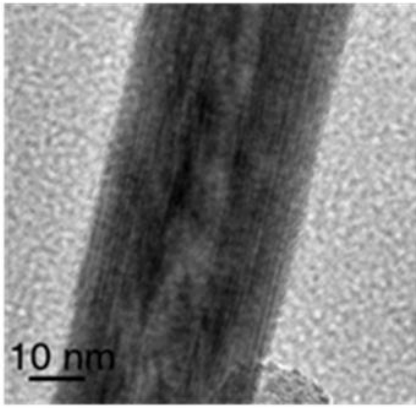
Massive increases in nanotube yields via Pb catalysis: MoS_2, $MoSe_2$, WS_2, WSe_2

[*J. Am. Chem. Soc.* 134, 16379-16386]



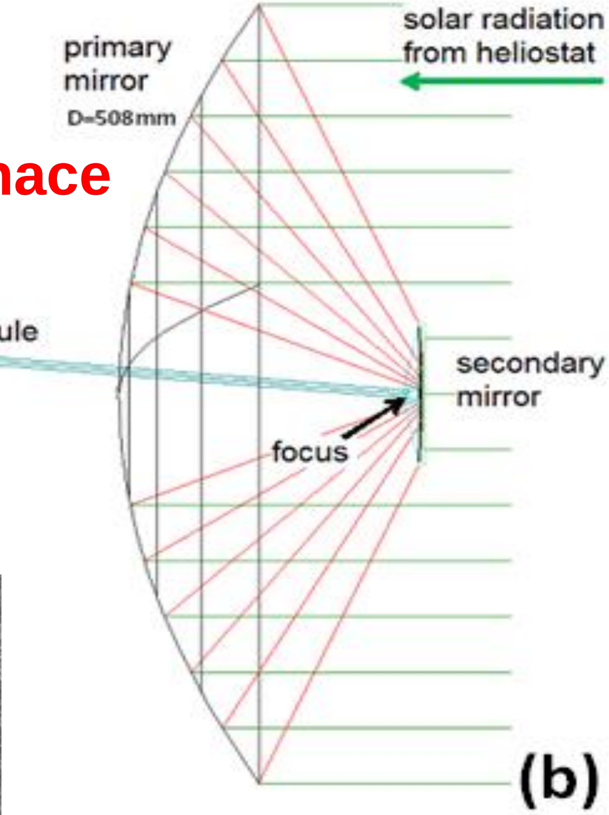
Deciphering reaction pathways via irradiation of variable duration (“snapshots”)

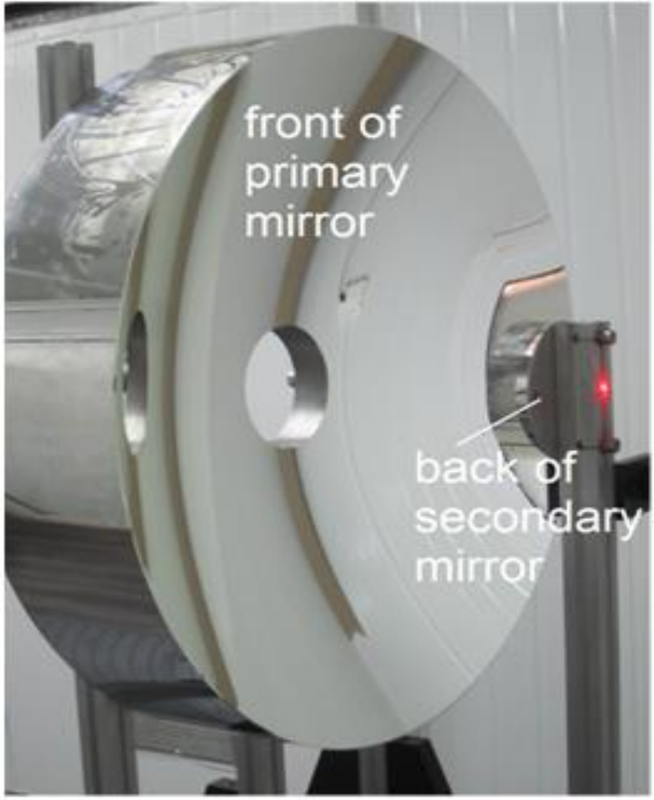




30,000-sun solar furnace

$D_{aperture}$ = 508 mm





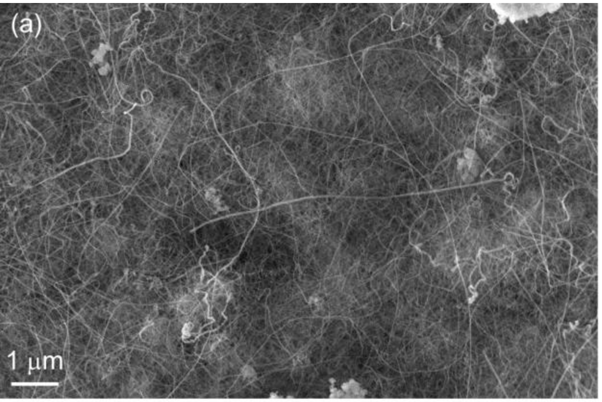
Highest measured solar concentration (in air/vacuum) to date

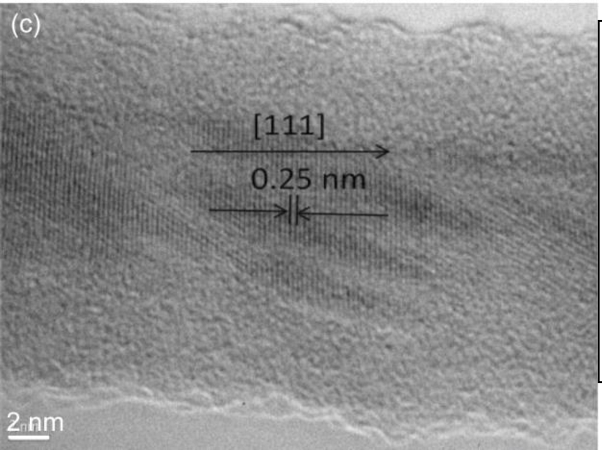
Rapid, high-yield, safe synthesis of SiC nanowires

***Nanotechnology* <u>24</u>, 335603**

<u>In progress</u>: Graphene in *high yield.*

Boron nitride (BN) fullerenes (nano-onions)





Ultra-high bioproductivity from algae

(Collaboration: Yair Zarmi of our department, Reliance Industries Ltd., Mumbai, India)

Aim: Dramatic increases in algal bioproductivity.

New predictive capability now *confirmed experimentally.*

Strategy: Find the optimal synchronization of (1) biological, and (2) photonic time scales.

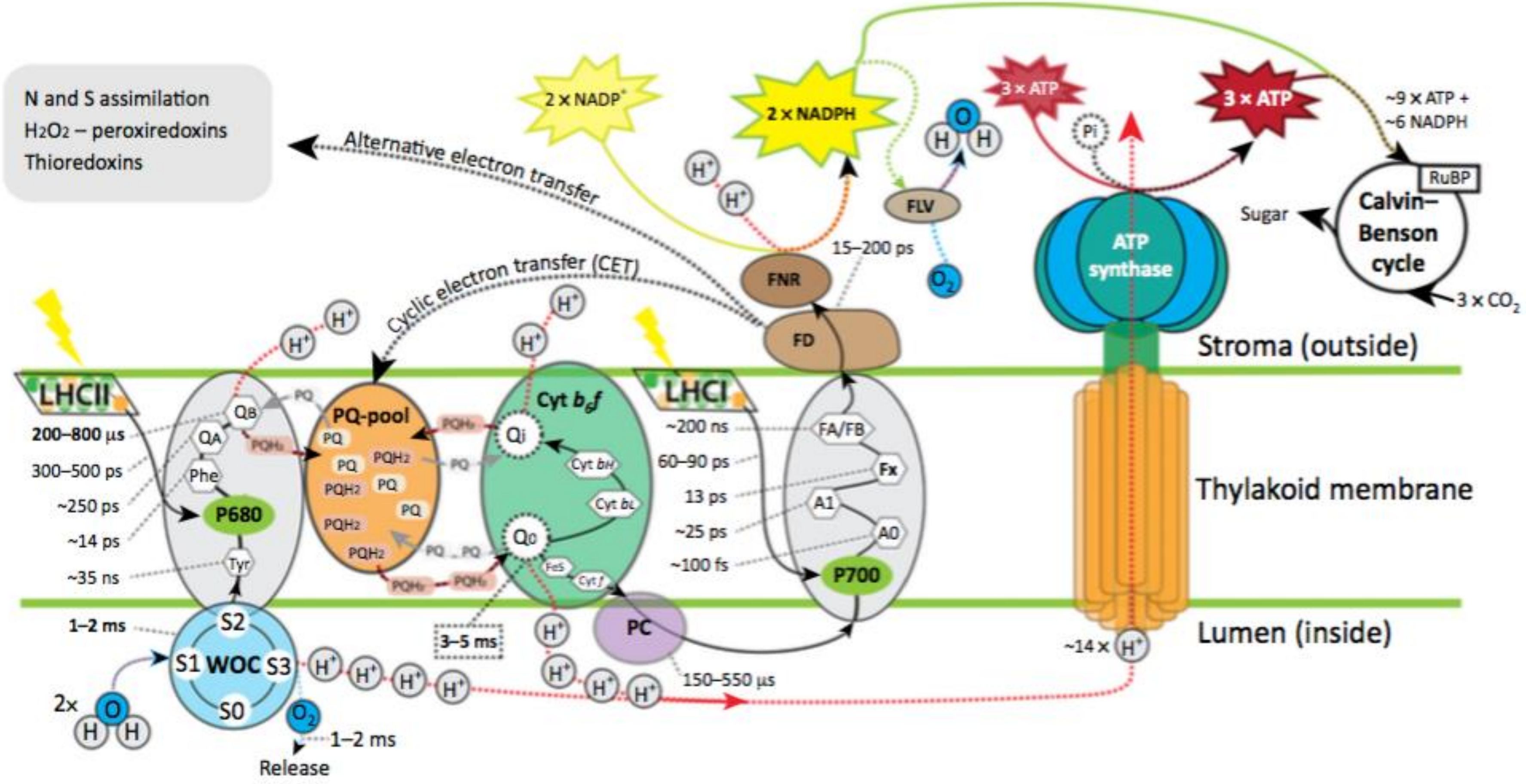
Do algae have a built-in potential for far higher bioproductivity than found in nature?

Key degree of freedom: light-dark cycles – prior studies were plagued by misguided choices

pulsed LEDs

Basic picture (flow diagram) of algal photosynthesis

Bottom line: $6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2$



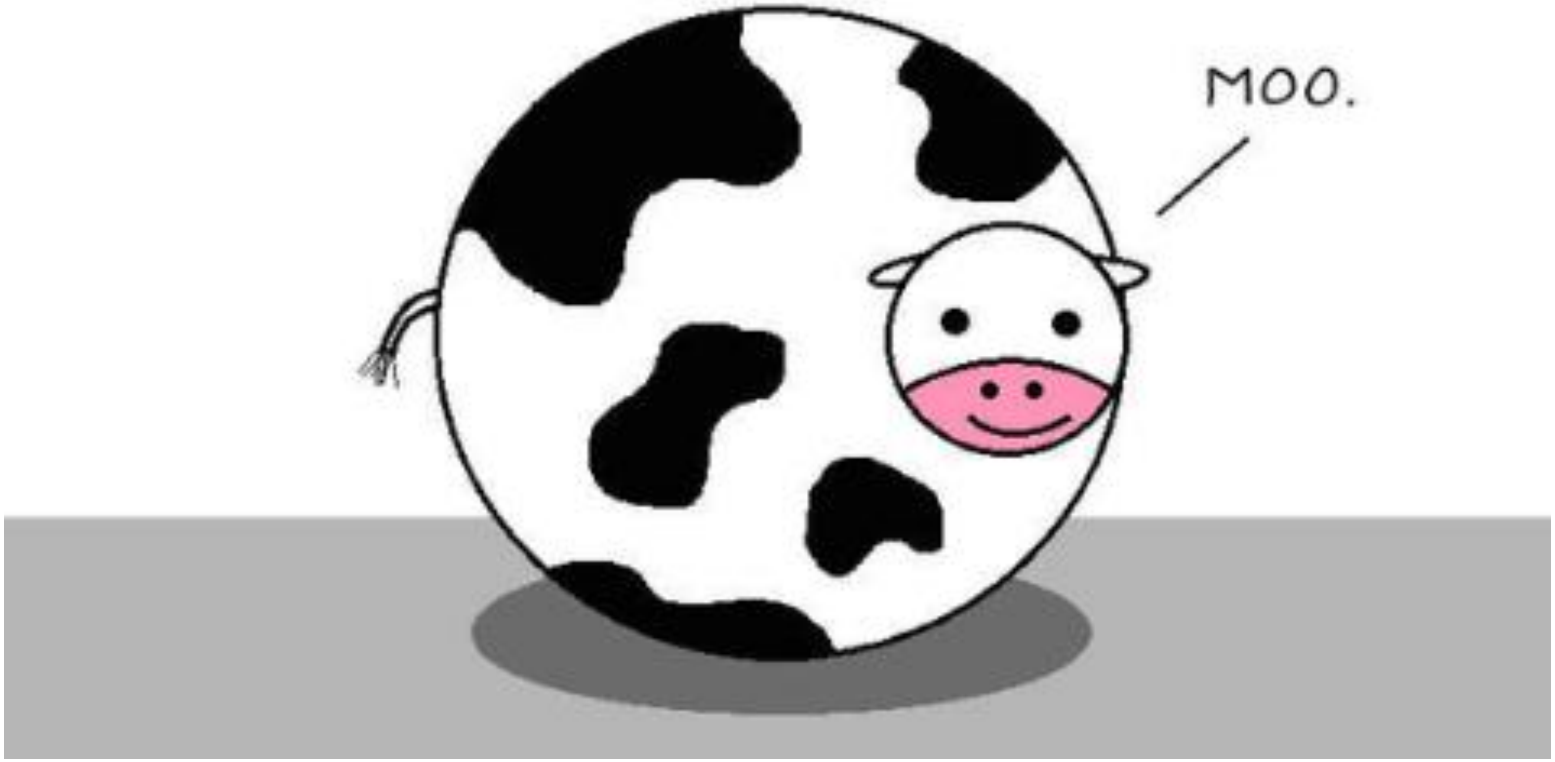
What are the key rate-limiting processes for bioproductivity?

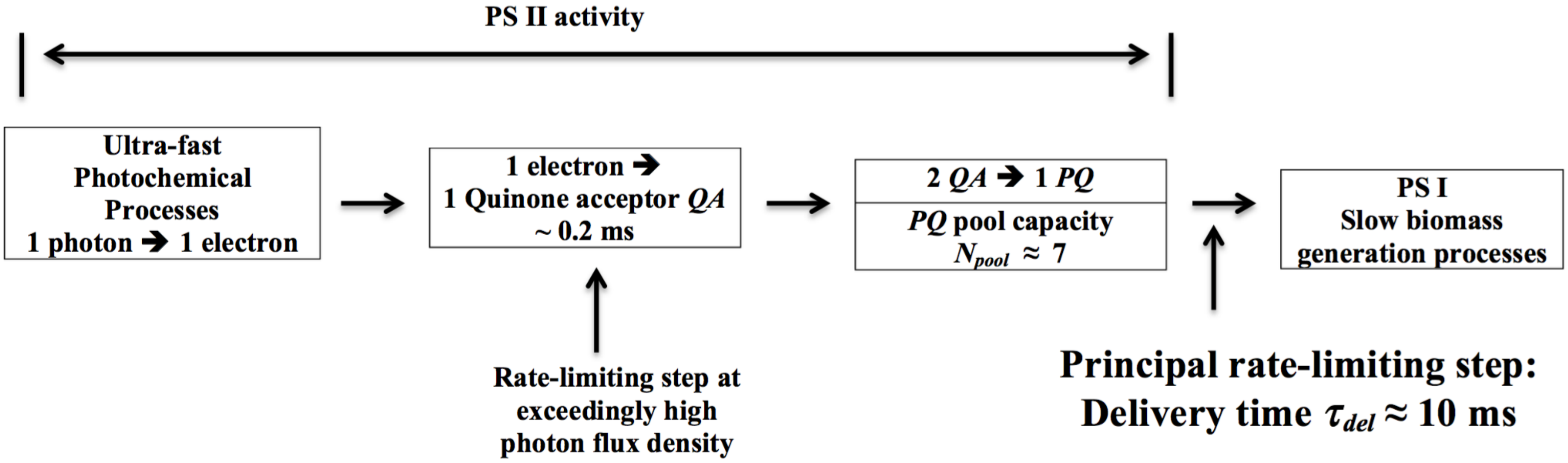
How simple a biophysical picture can suffice?

A physicist’s approach:

minimum complexity and maximum physical insight

Assume a spherical cow of uniform density.





PS II activity

Ultra-fast Photochemical Processes
1 photon → 1 electron

1 electron →
1 Quinone acceptor *QA*
~ 0.2 ms

Rate-limiting step at exceedingly high photon flux density

2 *QA* → 1 *PQ*

***PQ* pool capacity**
$N_{pool} \approx 7$

PS I
Slow biomass generation processes

Principal rate-limiting step:
Delivery time $\tau_{del} \approx 10$ ms

1 photon → 1 electron (very short time scale)

2 photons are needed to produce 1 PQ

→ pivotal role of photon arrival statistics

If the PQ pool is full and photons keep generating PQs, then “clogging” occurs (a waste of photonic input).

Motivates synchronizing pulsed light input to surmount the bottleneck.

Let’s make a coarse prediction based on simple photon arithmetic:

Rate of photon input = (intensity I) × (antenna cross-section *A*)

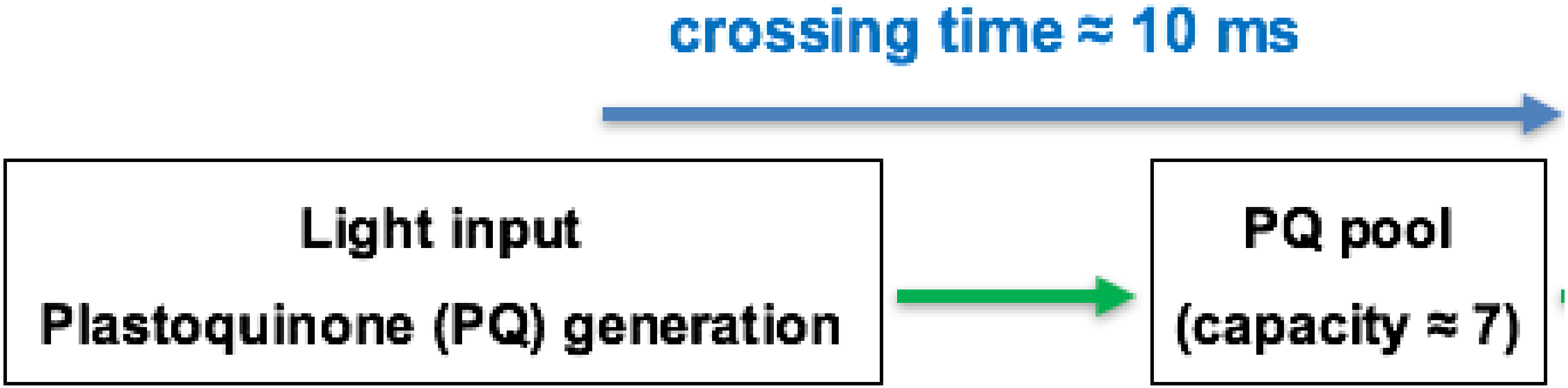
e.g., $A \approx 1\ \text{nm}^2$ and $I = 1{,}000\ \mu\text{mol/(s-m}^2)$ → 600 photons/s

For perspective: peak solar input ≈ 2,000 $\mu\text{mol/(s-m}^2)$

(referring to Photosynthetically Active Radiation, PAR, only)

2 photons are needed to generate 1 PQ → 1 PQ generated every 3.3 ms

For continuous irradiation: With a “crossing time” of ~10 ms, only 1 PQ can be harvested every 10 ms.



crossing time ≈ 10 ms

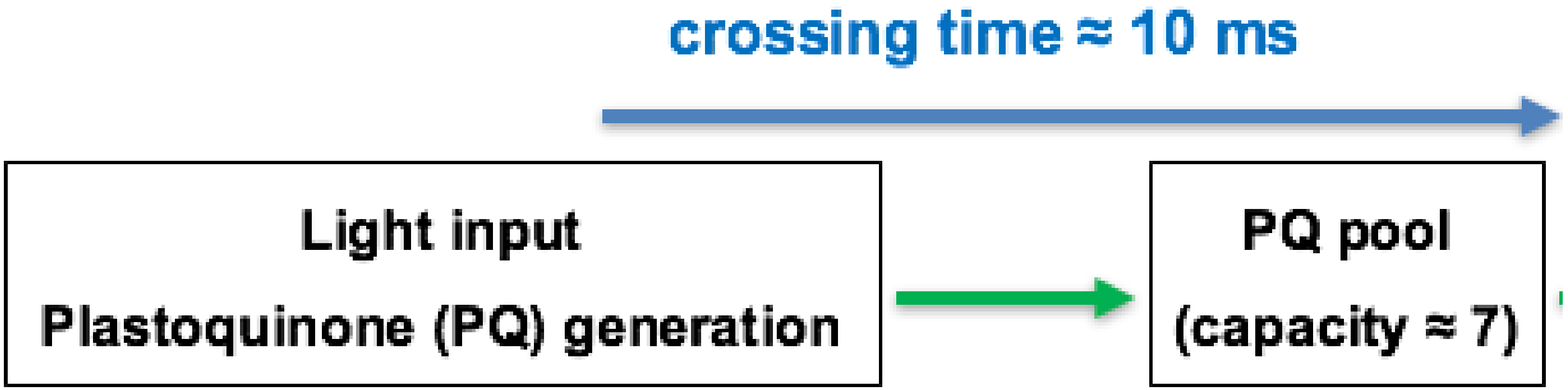
Light input

Plastoquinone (PQ) generation

PQ pool

(capacity ≈ 7)

But there are 3 PQs generated every 10 ms → potential improvement of ~3X if we apply judicious light pulsing (at this particular light intensity).



crossing time ≈ 10 ms

Light input

Plastoquinone (PQ) generation

PQ pool

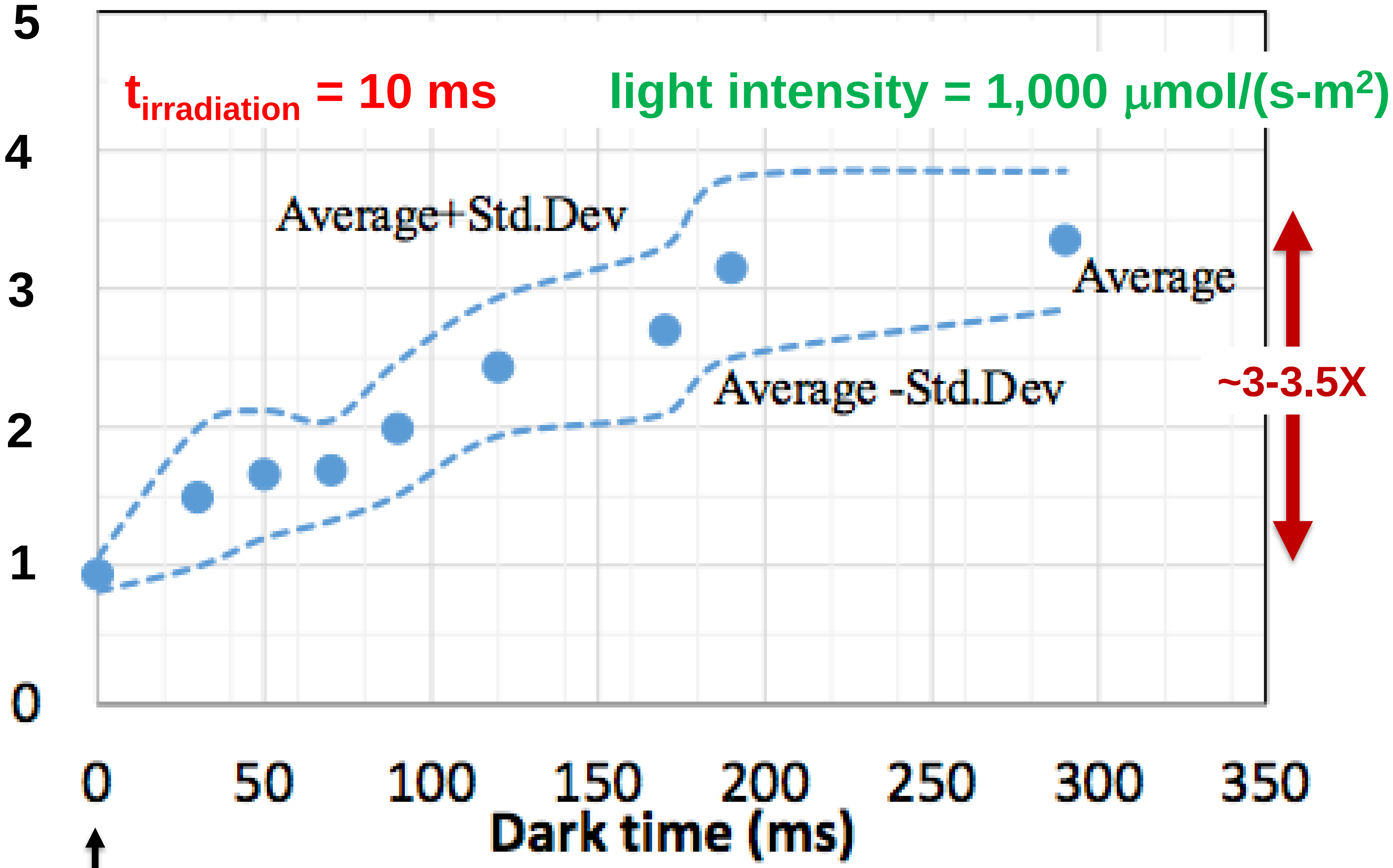
(capacity ≈ 7)

Let's try: a 10 ms pulse at I = 1,000 μmol/(s-m^2), which generates 3 PQs (PQ pool capacity ≈ 7), after which we provide a longer dark time to harvest them → ~3X in photon efficiency

Now, let's do the experiments (at Reliance Industries Ltd, India)

Specific growth rate *per photon*

normalized to continuous irradiation

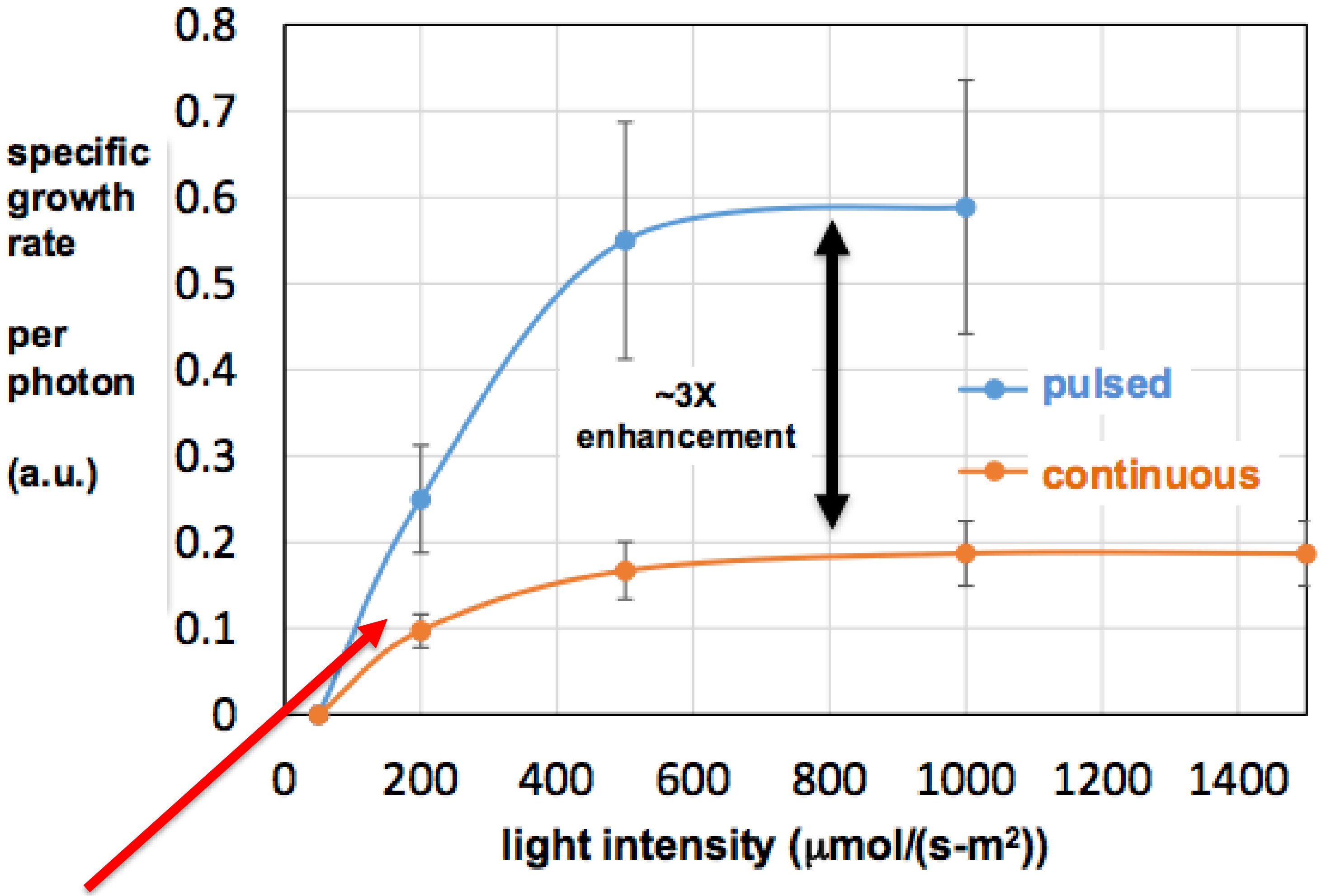


$t_{irradiation}$ = 10 ms

light intensity = 1,000 μmol/(s-m^2)

~3-3.5X

dark time = 0
means continuous irradiation



and basic photon statistics predict how this enhancement *lessens* with light intensity (consistent with the data)

Specific growth rate (per photon) as a function of light intensity (white LEDs):

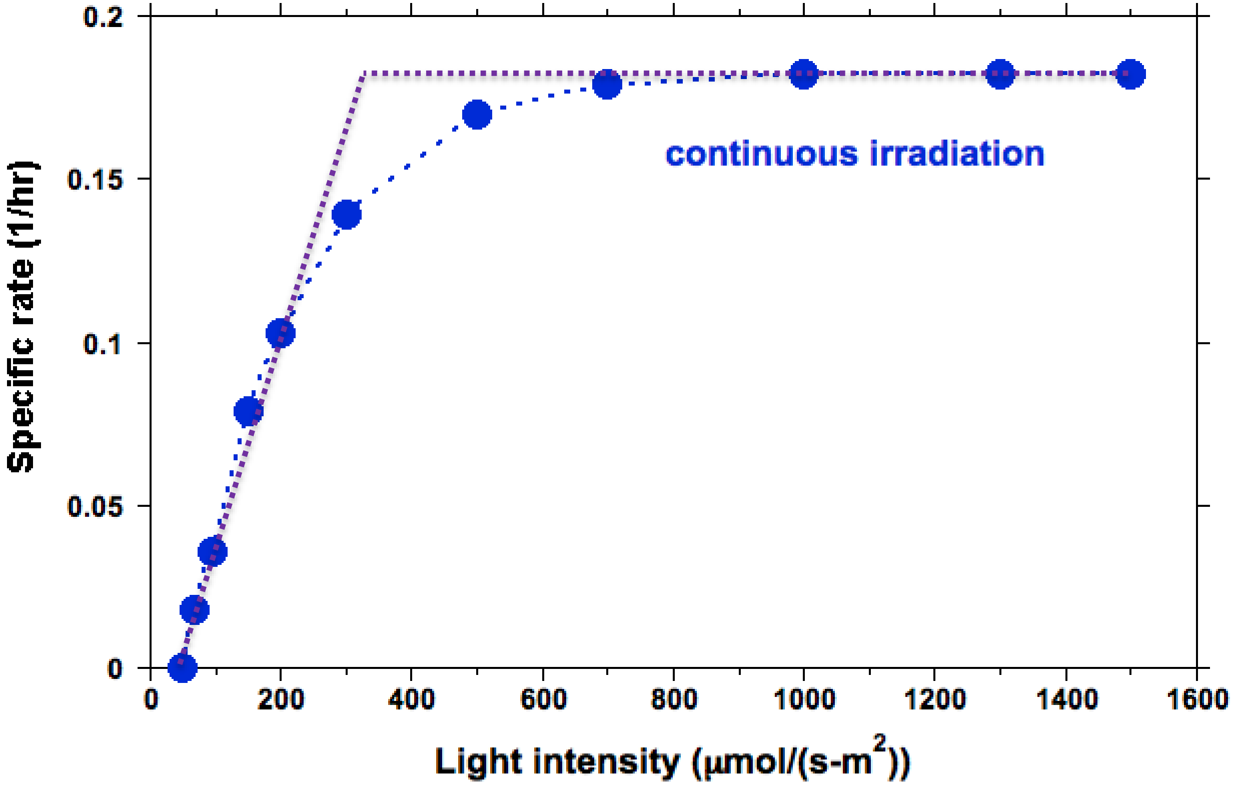
(a) continuous irradiation, (b) 300 ms cycle with $t_{irradiation}$ = 10 ms, t_{dark} = 290 ms

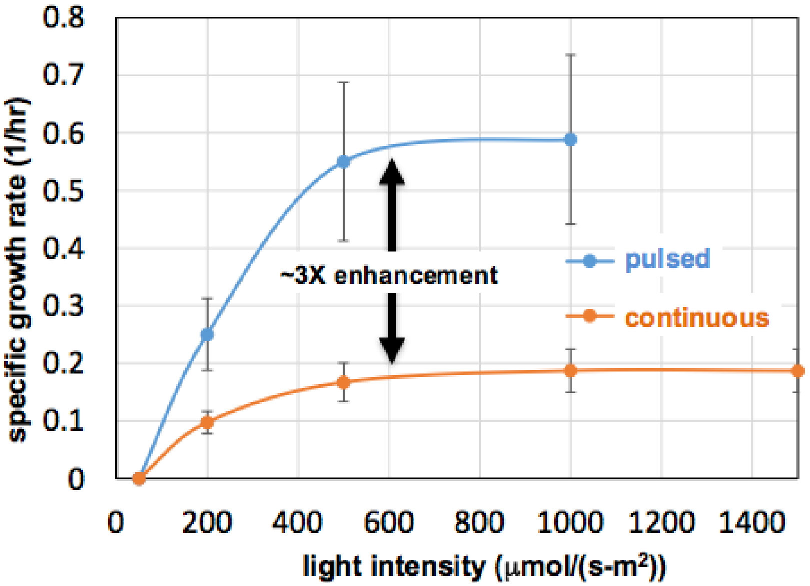
Basic prediction: For <u>continuous</u> irradiation, at what intensity should bioproductivity “saturate”?

Do the arithmetic based on “clogging” of the PQ channel

→ ~330 μmol/(s-m²).

And then do the experiment:





The ~3X enhancement is in ***photon efficiency***.

But the longer dark time means *time-averaged* bioproductivity is low.

How do we translate this advance into a 3X enhancement in bioproductivity?

Two pathways: (1) Outdoor solar reactors – via innovative opto-mechanics

(2) Indoor pulsed-LED systems - decoupling solar and photon delivery, *and* we can *tailor* spectrum, intensity and pulsing protocols (a proposal that is rational provided the electricity comes from renewables, e.g., solar, wind, hydroelectric)

- **Challenges and realizations reserved for our future reunions.**

Exciting prospect/prediction: Higher light intensity and/or longer pulse time *could* yield photon-efficiency enhancements exceeding 10X.

- **Latest update: experimental evidence of the 10X improvement!**

Payoffs:

- Hundreds of percent higher bioproductivity.
- With LEDs: Indoors, avoid contamination, 24 hr/day, control: spectrum (more efficient with red LEDs), intensity, pulse times and temperature.
- Much smaller footprint for vertical reactors.
- Scalable
- Direct adaptability to products more lucrative than biofuels, e.g., antibody generation / pharmaceuticals.

Explosive growth of *private, commercial* space missions.

Dramatically alters specs for on-board solar electricity generation

Creates the need for novel concentrators and solar cells. Why?

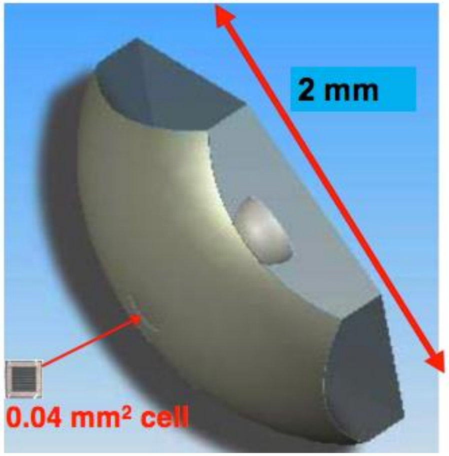
Military and government space programs: Cost is no object.

Private space vehicles: Cost is paramount (subject to reliability).

PV cells on past satellites were ultra-efficient but ultra-expensive

Concentrating (by ~100 X) vastly diminishes the photovoltaic (PV) contribution to system cost: replacing 99% of exorbitant PVs by inexpensive optics.

Our program: In collaboration with Penn State U. and the U.S. Air Force



A few examples of the private commercial companies involved:

Market for on-board solar electricity production:

~10 MW today.

At ~US$100/W (in space) → one *billion* US$

(and projected to increase rapidly with time).

SpaceX

Boeing

Blue Origin

Rocket Lab

Orbital Sciences

Sierra Nevada Corp.

Virgin Galactic

XCOR Aerospace

Made in Space

Ad Astra Rocket

Planetary Resources

ARCA Space

OneSpace

PLD Space

Nanoracks ...

Launch costs are falling rapidly

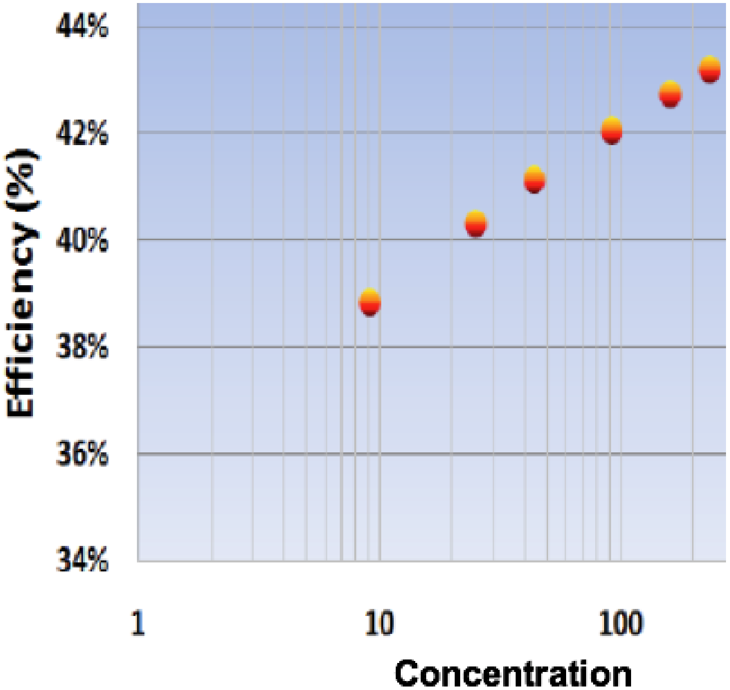
→ solar power is a sizable fraction of satellite cost

→ $/W becomes pivotal

→ affordable max. specific power (W/kg) is crucial: room for improvement relative to today's best solutions >4X (via innovative optics)

3-pronged strategy beyond the basic virtue of concentration:

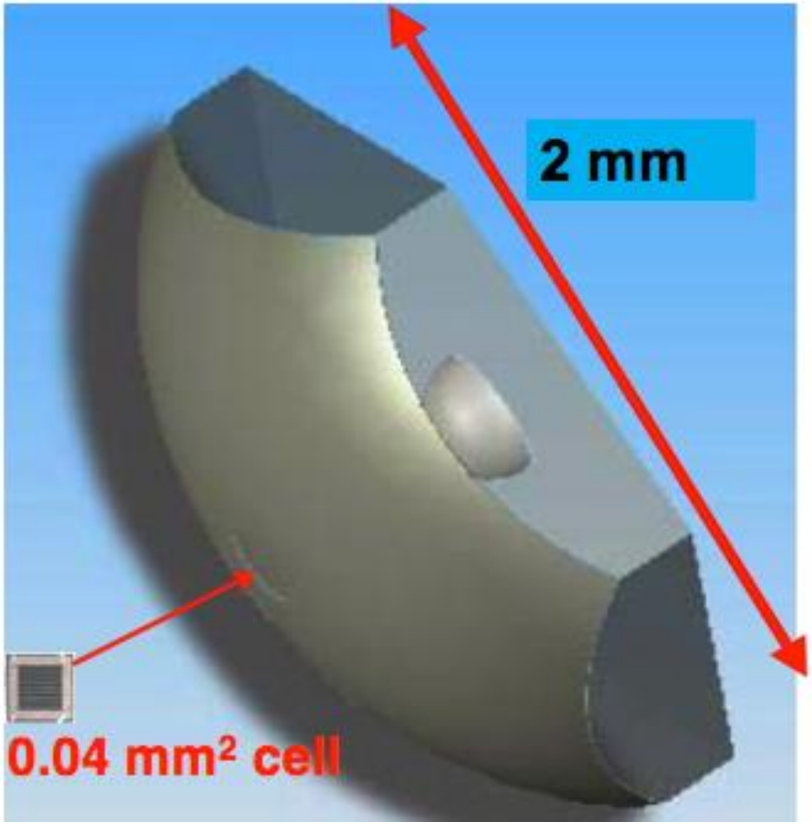
(a) Benefit from the PV efficiency boost at high concentration

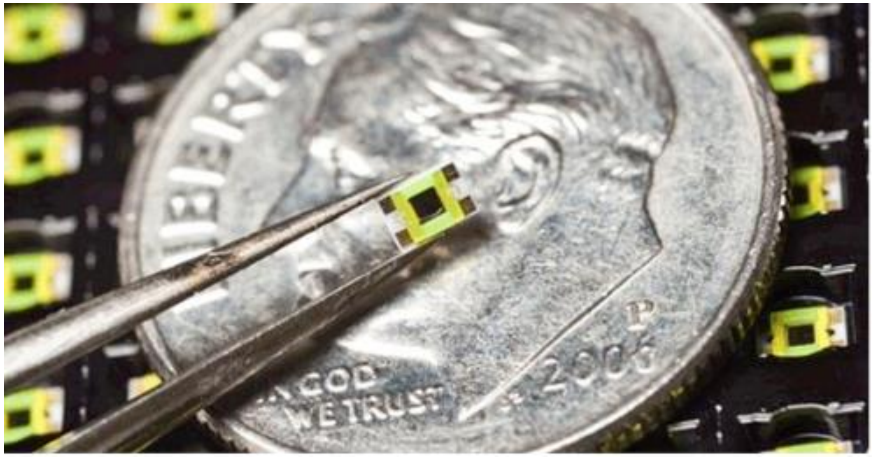


(measured)

3-pronged strategy beyond the basic virtue of concentration:

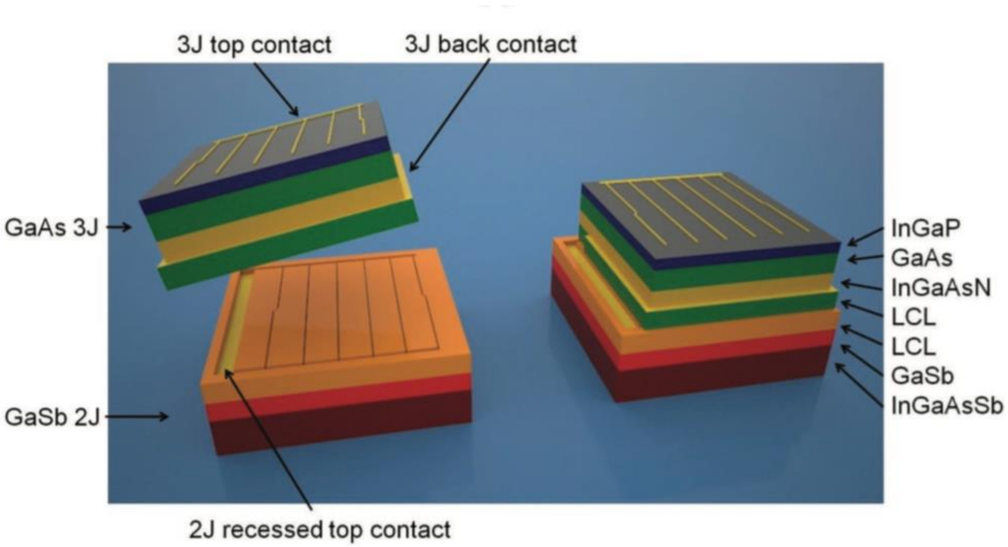
(b) Reduce PV cells to sub-mm dimensions (system volume $\propto L^3$), and hence shrink the concentrator to mm dimensions.

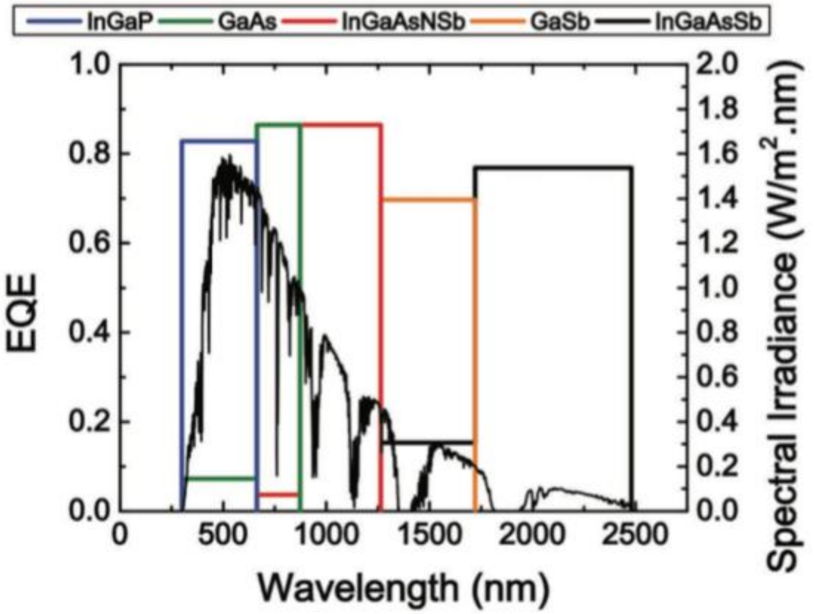




3-pronged strategy beyond the basic virtue of concentration:

(c) Advanced multi-junction PV cells exploit the full solar spectrum





5-junction cells now in fabrication

Near-term aim: 50% efficiency under concentration

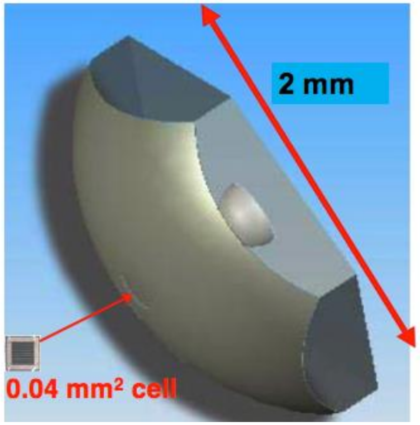
Full experimental characterization scheduled in our BGU solar lab

→ results will guide the next generations of suitable PV cells

Concentration requires accurate tracking: always aimed at the sun.

Laws of optics → basic relation between max. concentration *C* and optical tolerance angle θ (max. permitted misalignment): $\theta \propto 1/\sqrt{C}$

Quantify: $\theta = \pm 5^\circ$ is achievable and realistic for private satellites (USAF tests) → feasible concentration $C \le 100$



These are new, demanding constraints

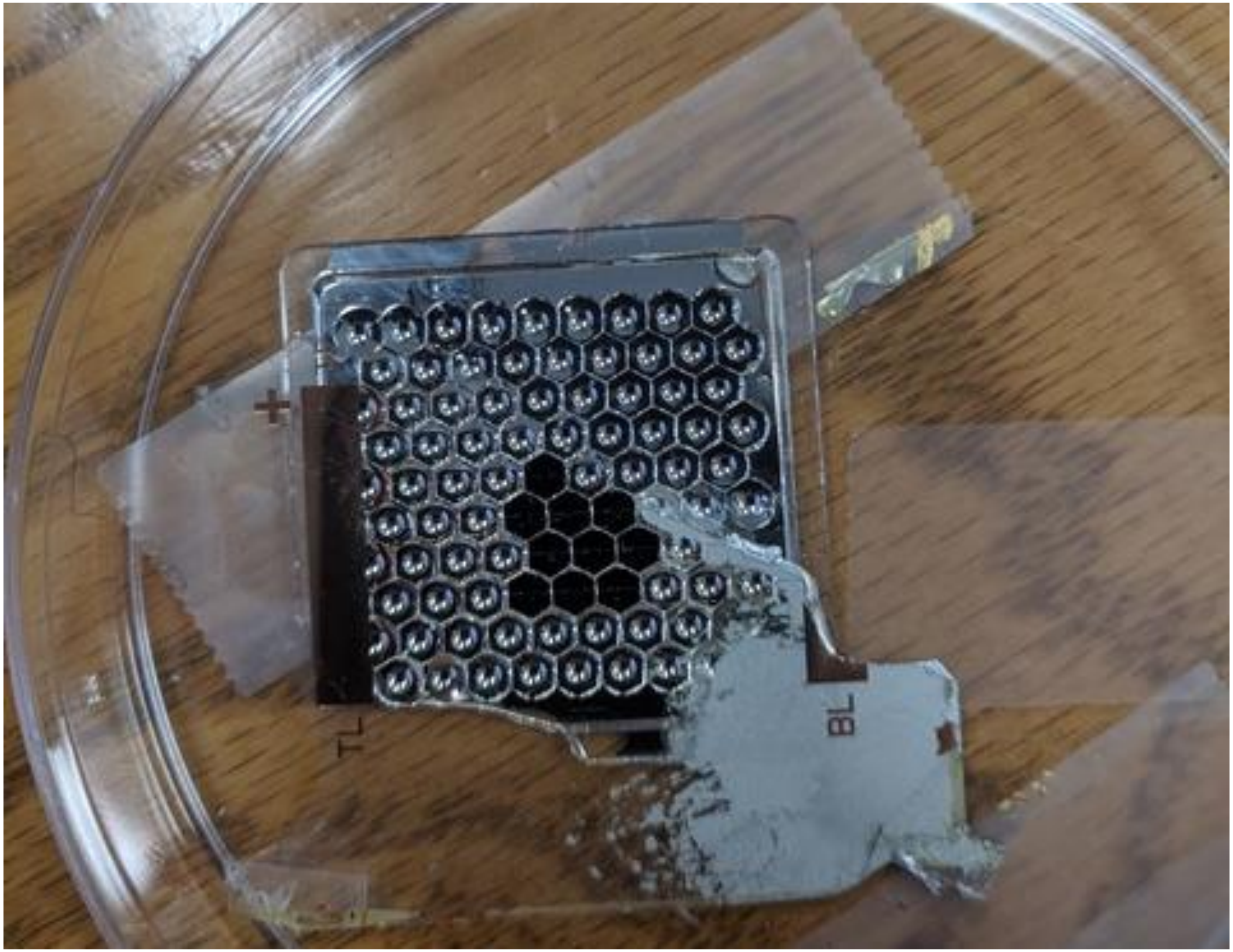
very low mass – ultra-high efficiency – high tolerance

for designing suitable optics.

Our 1st prototype: Simple optic for 0.65 × 0.65 mm^2 cells.

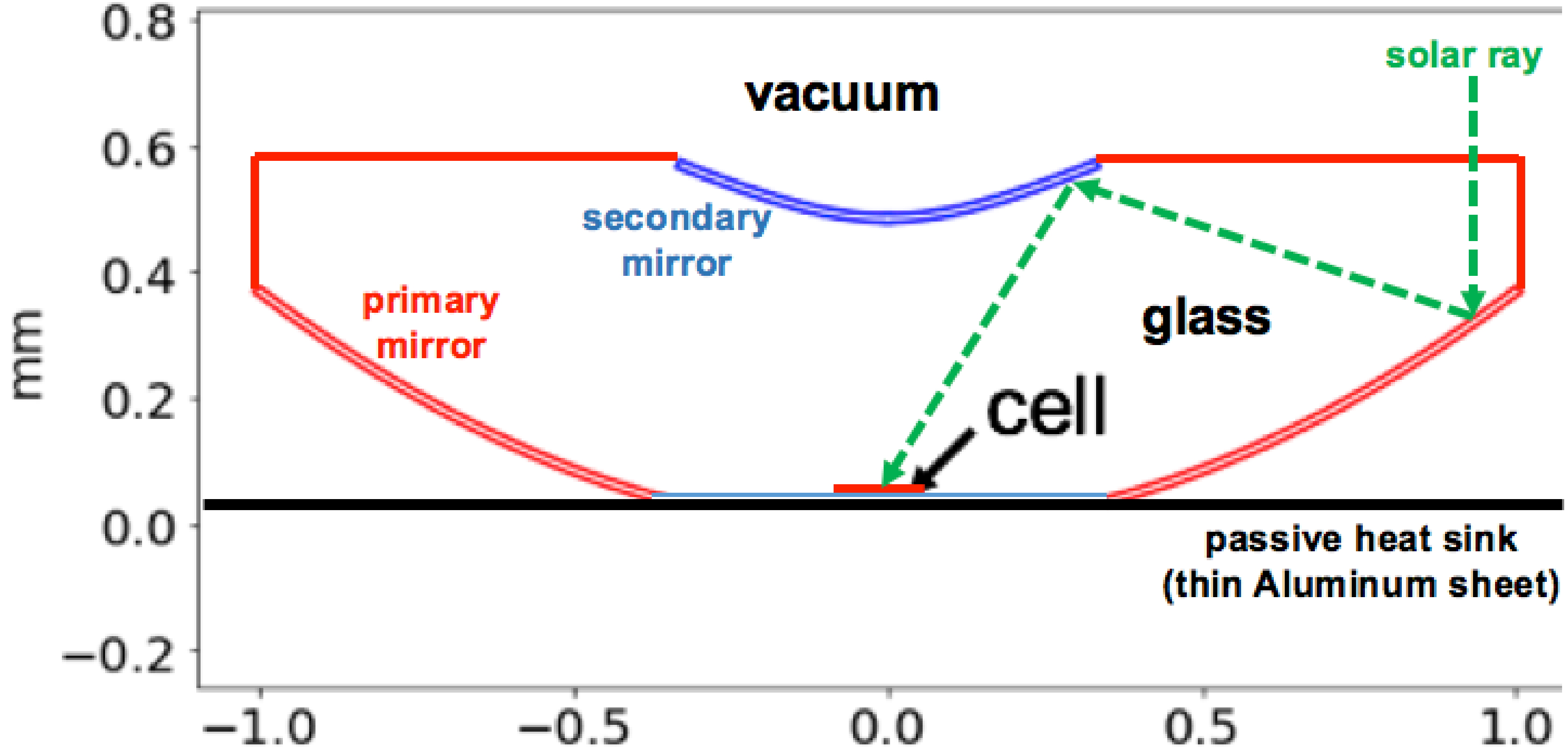
Each hexagon’s diagonal = 5 mm.

The 10 black hexagons have the solar cell installed.



Challenges in highly-constrained optical design

Example of an ultra-compact glass-filled, dual-mirror concentrator

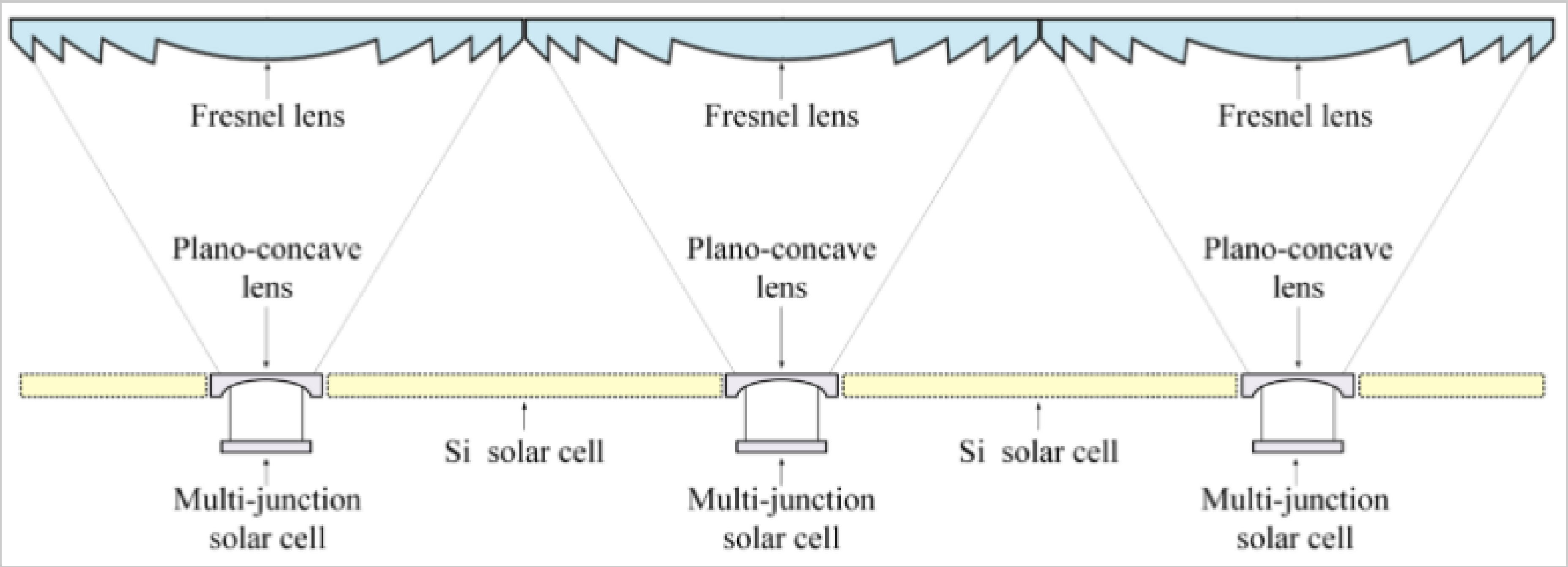


Why glass-filled? (1) attainable optical tolerance ∝ refractive index (1.5 for glass)

(2) ease of fabrication and internal alignment by glass molding

Second generation: accommodate a “fail-safe” option

Ability to provide *some* power (affordably) even if solar aiming fails



Highly challenging: optics that are *both* compact *and* high-performance for the fail-safe option.

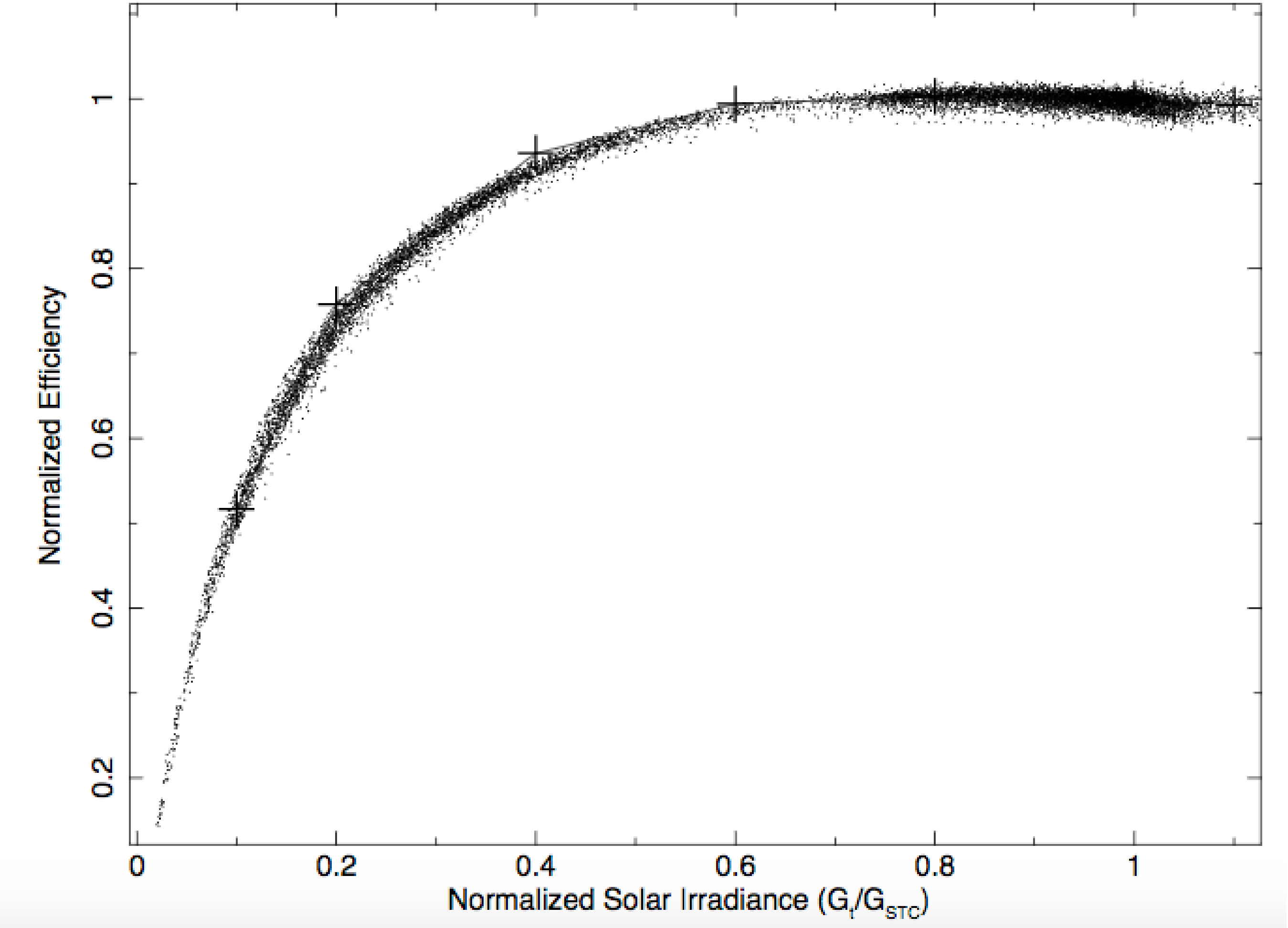
Key value for distant missions (e.g., Jupiter, Saturn):

Concentration compensates for poor cell performance at low irradiance

Earth: 1 A.U. Jupiter: 5.2 A.U. Saturn: 9.5 A.U.

Irradiance ∝ 1/(distance)^2 Jupiter: 0.037 (1/27) Saturn: 0.011 (1/90)

Concentration of ~100 “restores” efficiency losses inherent to low irradiance.



Australian Space Agency – established 1 July 2018

Launch center: RAAF Woomera Range Complex (latitude = 31°S)

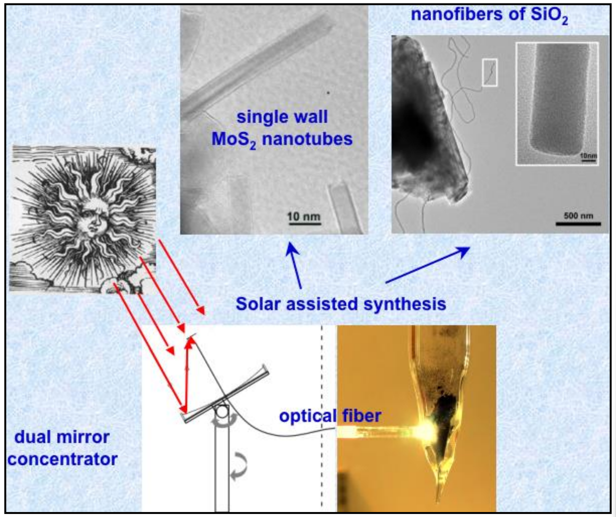
Australian
Space Agency

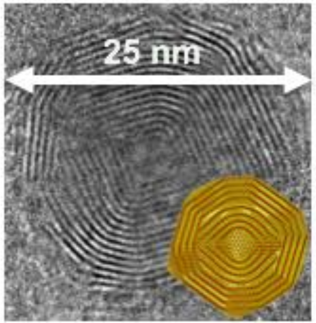
“ ... engaging with companies nationwide ... already signed Strategic Statements of Intent and Cooperation with 3 industry partners, all with investments in South Australia, including Airbus, Sitael and Nova Systems. Fleet Space Technologies and Myriota, both South-Australian start-ups, have launched satellites and a payload that can help farmers and other industries.”

Unorthodox and Exciting Applications of Solar Energy Research

Jeffrey Gordon, Professor Emeritus http://www.bgu.ac.il/~jeff/
Department of Solar Energy & Environmental Physics
Jacob Blaustein Institutes for Desert Research
Ben-Gurion University of the Negev, Sede Boqer Campus, Israel

1) Solar-driven synthesis of novel nano-materials





2) Ultra-high algal bioproductivity

3) Solar electricity for *private commercial* space missions