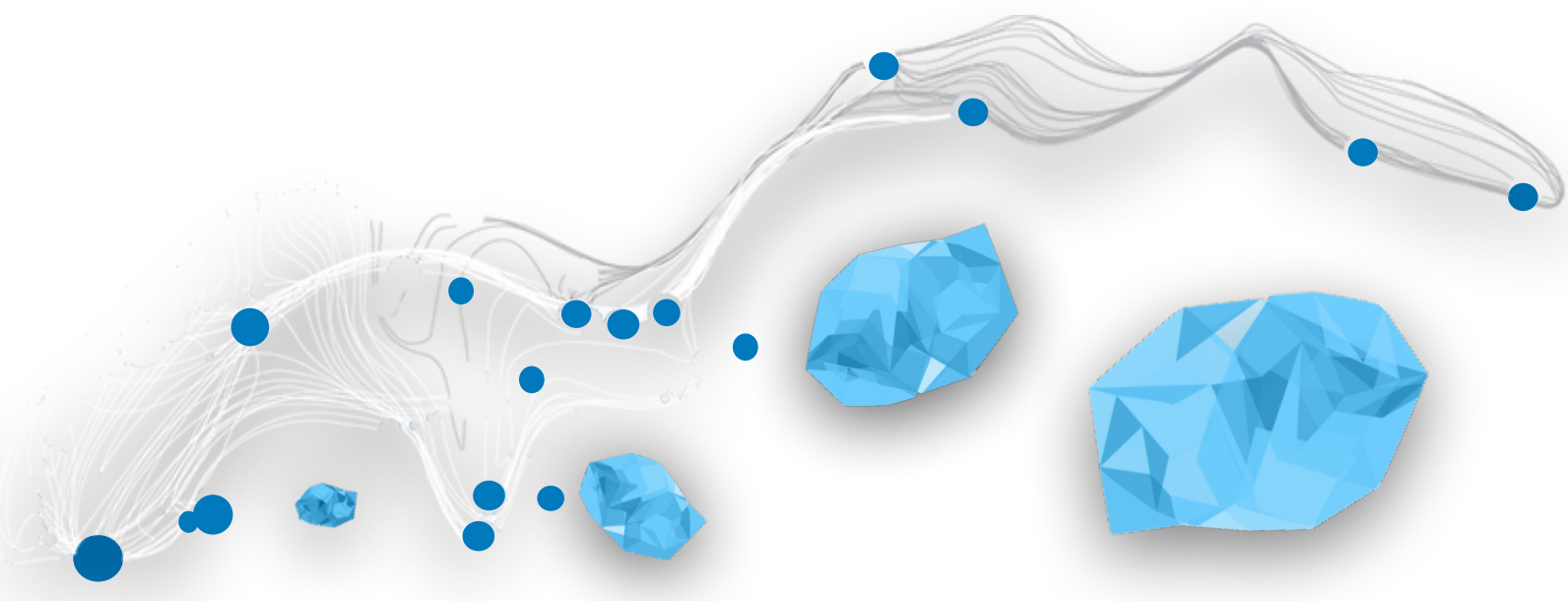




# Bubbles and Hydrogen

February 7<sup>th</sup> 2019

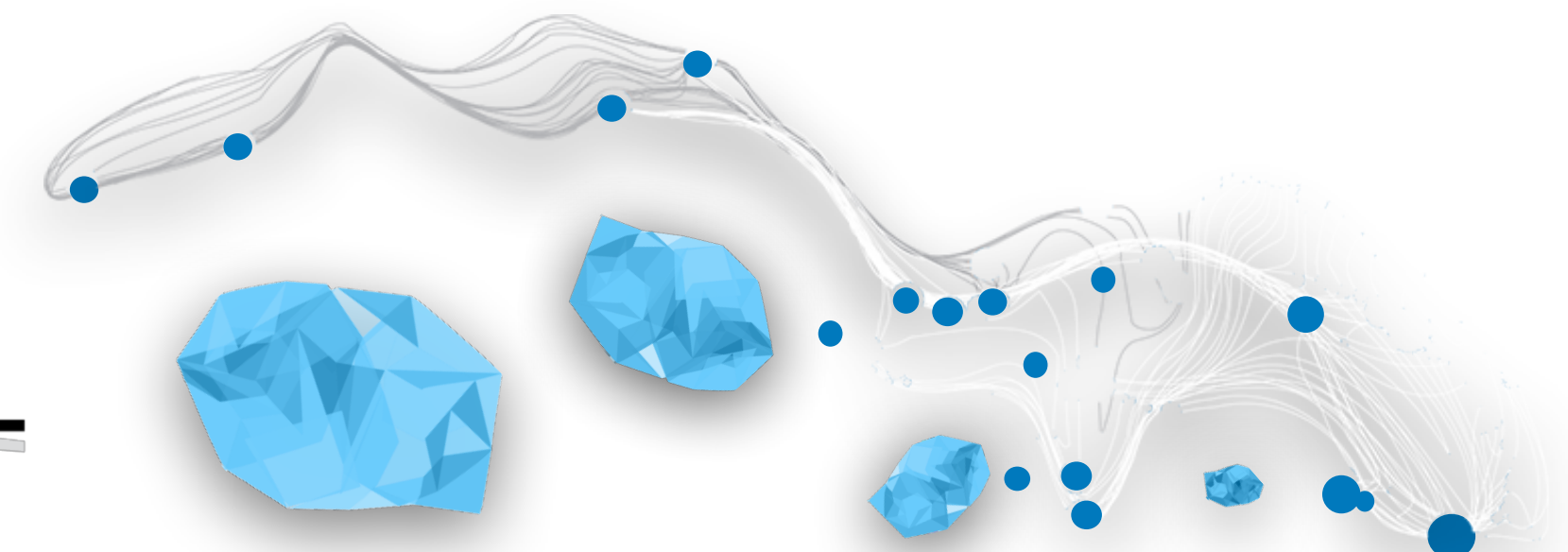
David Fernández Rivas



UNIVERSITY  
OF TWENTE.

1

**BμBCLEAN**





An aerial photograph of the University of Twente campus, showing various buildings, green spaces, and a river. Three white circles with black outlines are overlaid on the image, containing the text 'UT Intro', 'My Intro', and 'Cavitation' from left to right.

UT Intro

My Intro

Cavitation

**UNIVERSITY  
OF TWENTE.**



# Mesoscale Chemical Systems Group

1 Postdoc  
1 PhD  
3 MSc  
4 BSc



Academic staff

Assistant

David Fernandez Rivas  
Tenured, May 2017

Associate

Niels Tas



Full

Han Gardeniers



2 Cleanroom technicians

ca. 18 PhD students - 3 Postdocs

UNIVERSITY OF TWENTE

of Fluid Mechanics

Supplementary materials Metrics

2017, pp. 529-548

Streaming flow by oscillating bubbles: quantitative diagnostics via particle tracking velocimetry

Inez <sup>(a1)</sup>, Massimiliano Rossi <sup>(a2)</sup>, David Fernandez Rivas <sup>(a3)</sup>, Christian J. Kahler <sup>(a4)</sup> ...

10.1017/jfm.2017.229 Published online: 10 May 2017

NEW ARTICLE ON JFM

Our newest article is entitled "Streaming flow by oscillating bubbles: quantitative diagnostics via particle tracking velocimetry". It is the result of a collaboration with two o...

SUN 21 MAY 2017

Read more

MCS GETS MORE "REPRODUCIBLE SONOCHEMISTRY" INSIDE THE BAG!

Researchers from MCS have articulated an international collaboration (Portugal, Finland and India). The results were presented in a Keynote lecture given at the last European ...

MON 27 MAR 2017

Read more

WED 15 FEB 2017

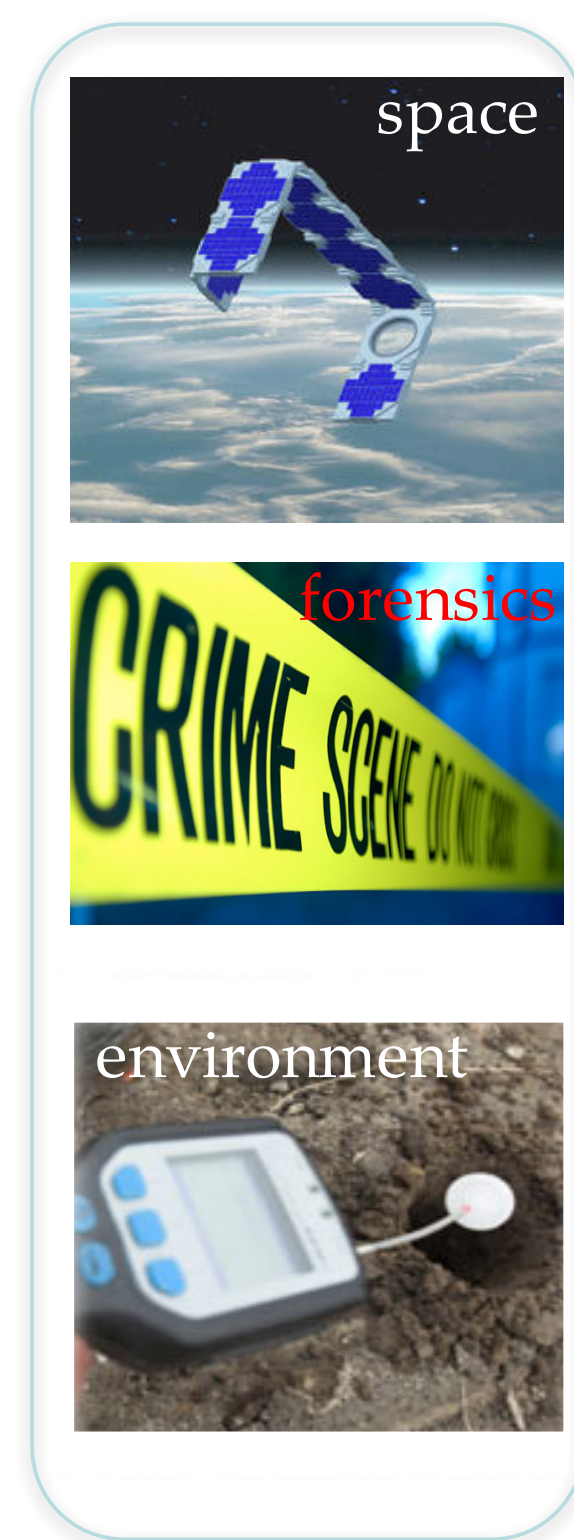
PLASMA-LIQUID INTERACTIONS PAPER SELECTED IN EXCLUSIVE HIGHLIGHTS 2016



# Mesoscale Chemical Systems Group



- Miniaturization in analytical chemistry
- Mobile and "point-of-care" applications (medical care, forensics, environment, space, industrial process, safety)
- Life Sciences (tissue, cells, body fluids)
- Benefits:
  - compactness of equipment (incl. reduced power and chemical supplies)
  - limited sample size
  - improved analytical performance related to advantages of down-scaling



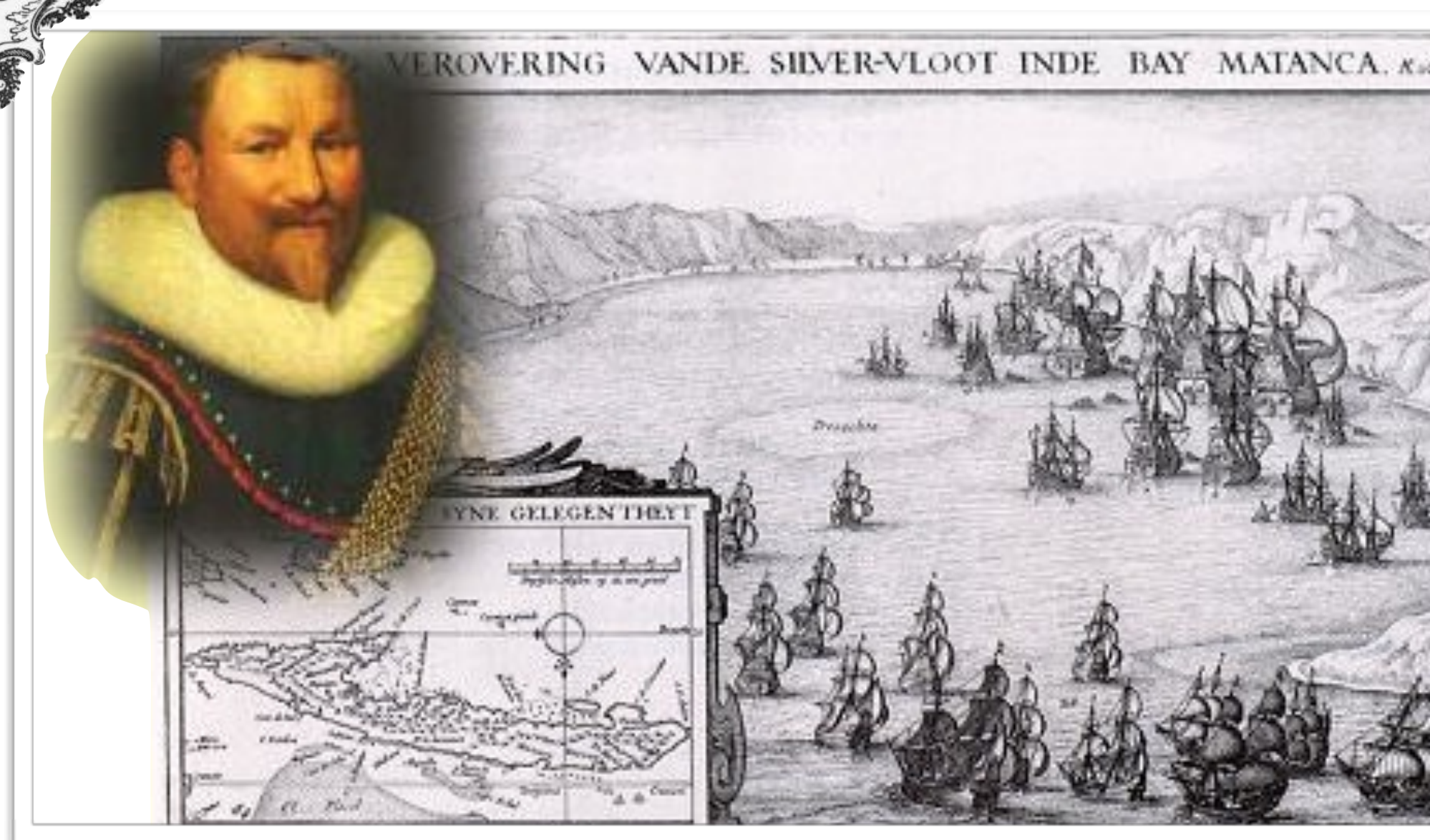


# From Cuba to NL History tracing back to 1628

## Havana Matanzas

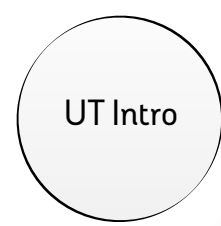


## Geotroyeerde Westindische Compagnie,



Opportunities Given by "restrictions".





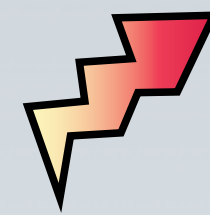
# Vision

## Exploiting Bubbles for Chemistry and Medicine

Leading an excellent scientific team  
to address 21<sup>st</sup> Century Challenges.



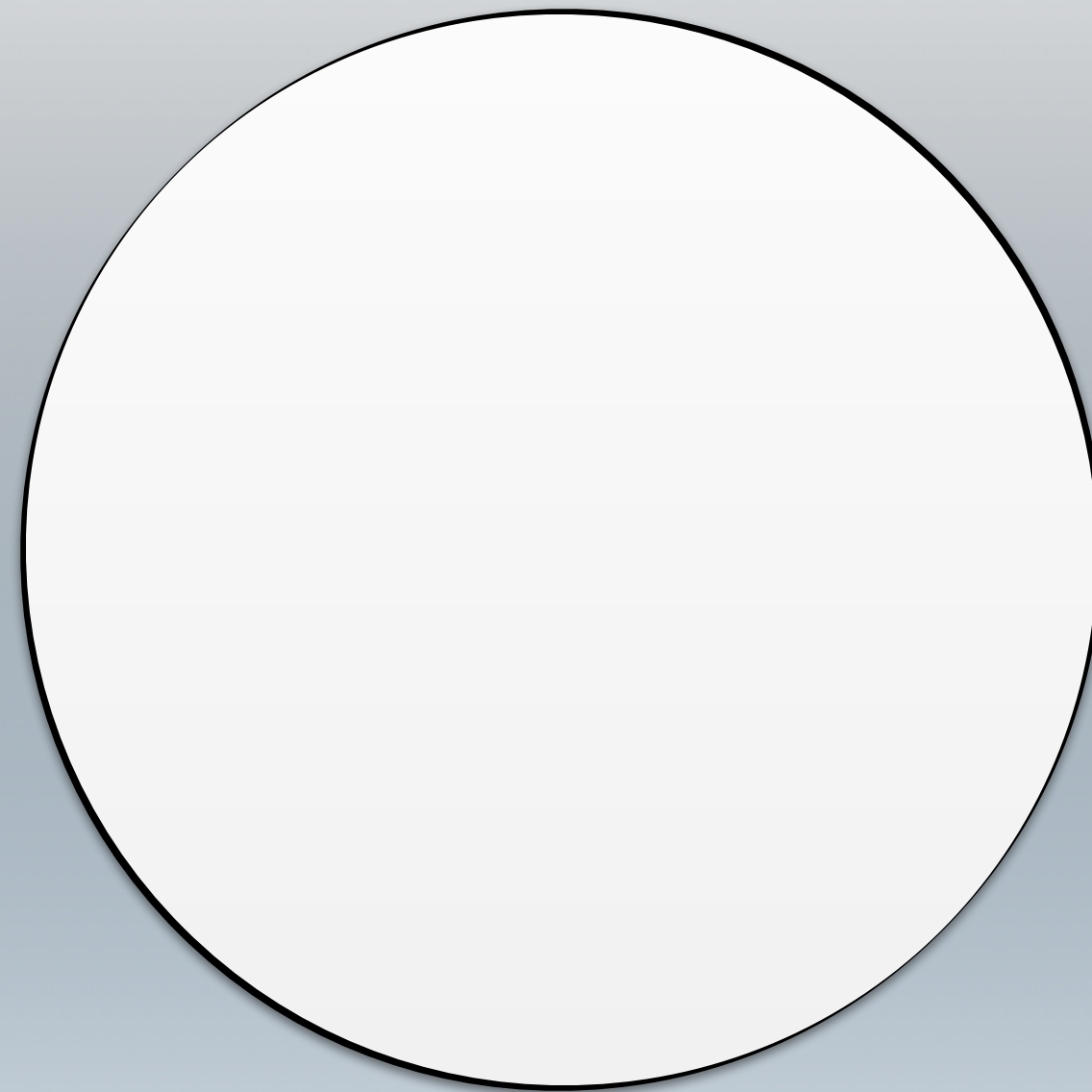
Generating employment and  
public-private-partnerships.



Health Water Energy



# Cavity = Bubble





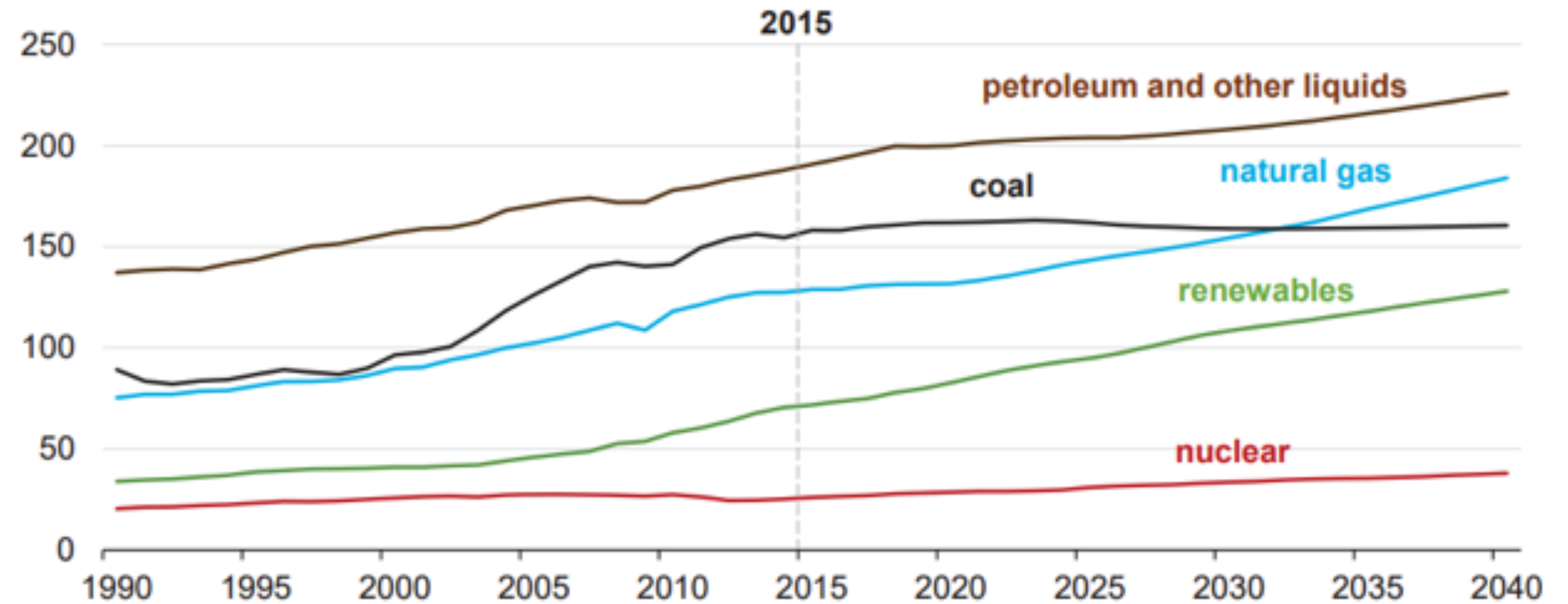
# How much are we consuming?

Solar and wind rising from 0.4% of energy consumption in 2009 to an estimated 1.9% in 2019

Non-hydro renewables estimated growth rate of 12.7%.

Renewing Renewables,  
The Economist Intelligence Unit  
February, 2019

**World energy consumption by energy source**  
quadrillion Btu

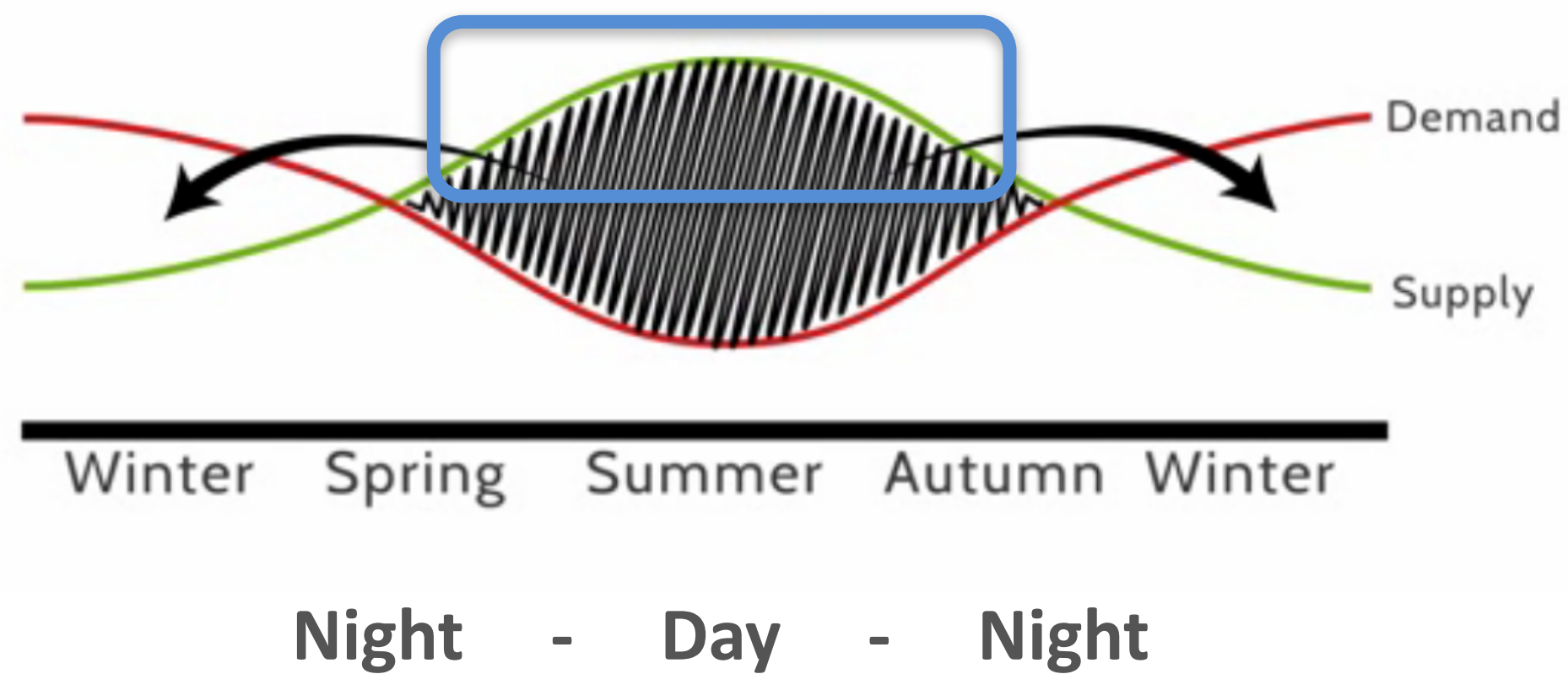




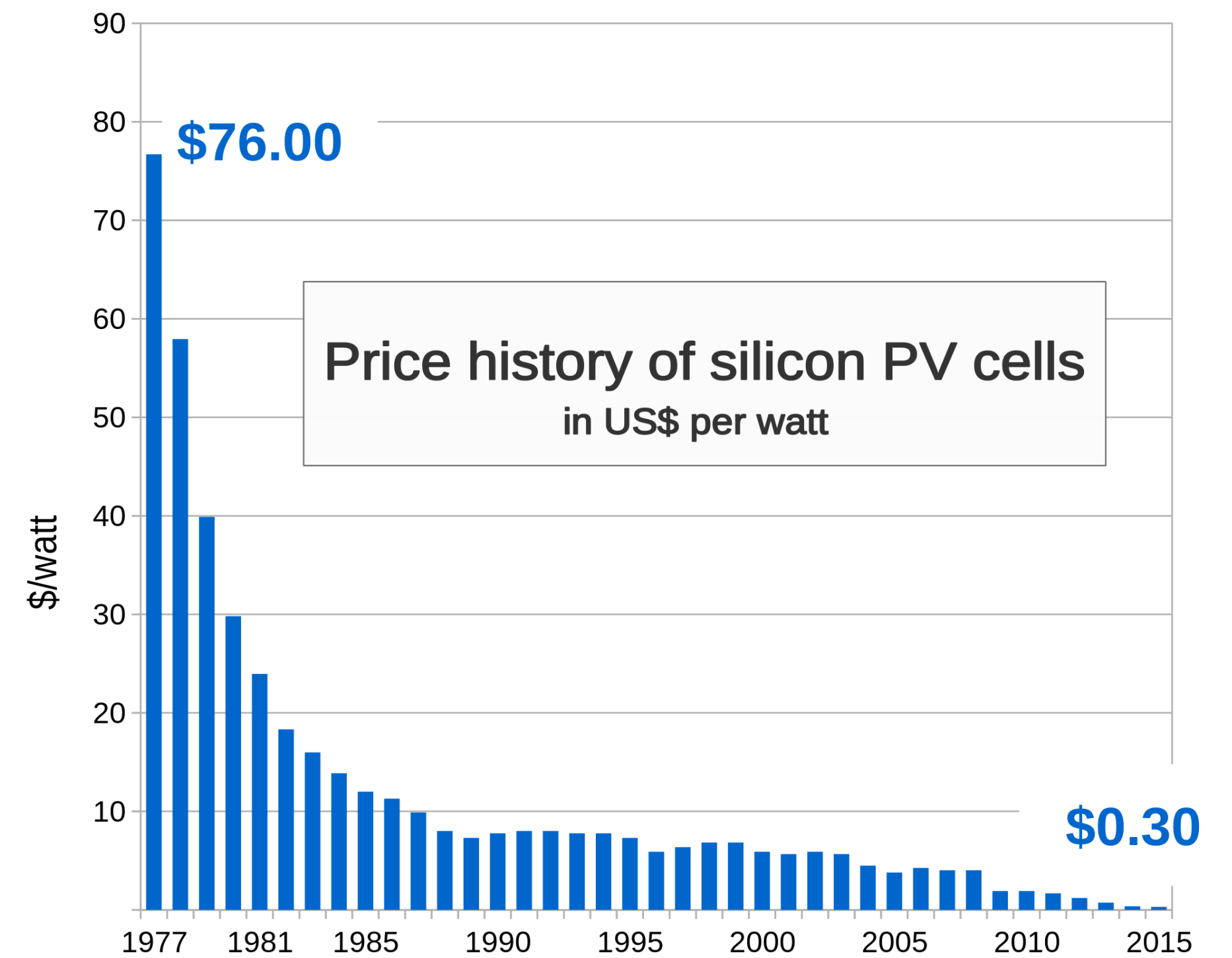
# Storage of renewable energy

## Intermittency is a problem ...

What to do with this surplus?



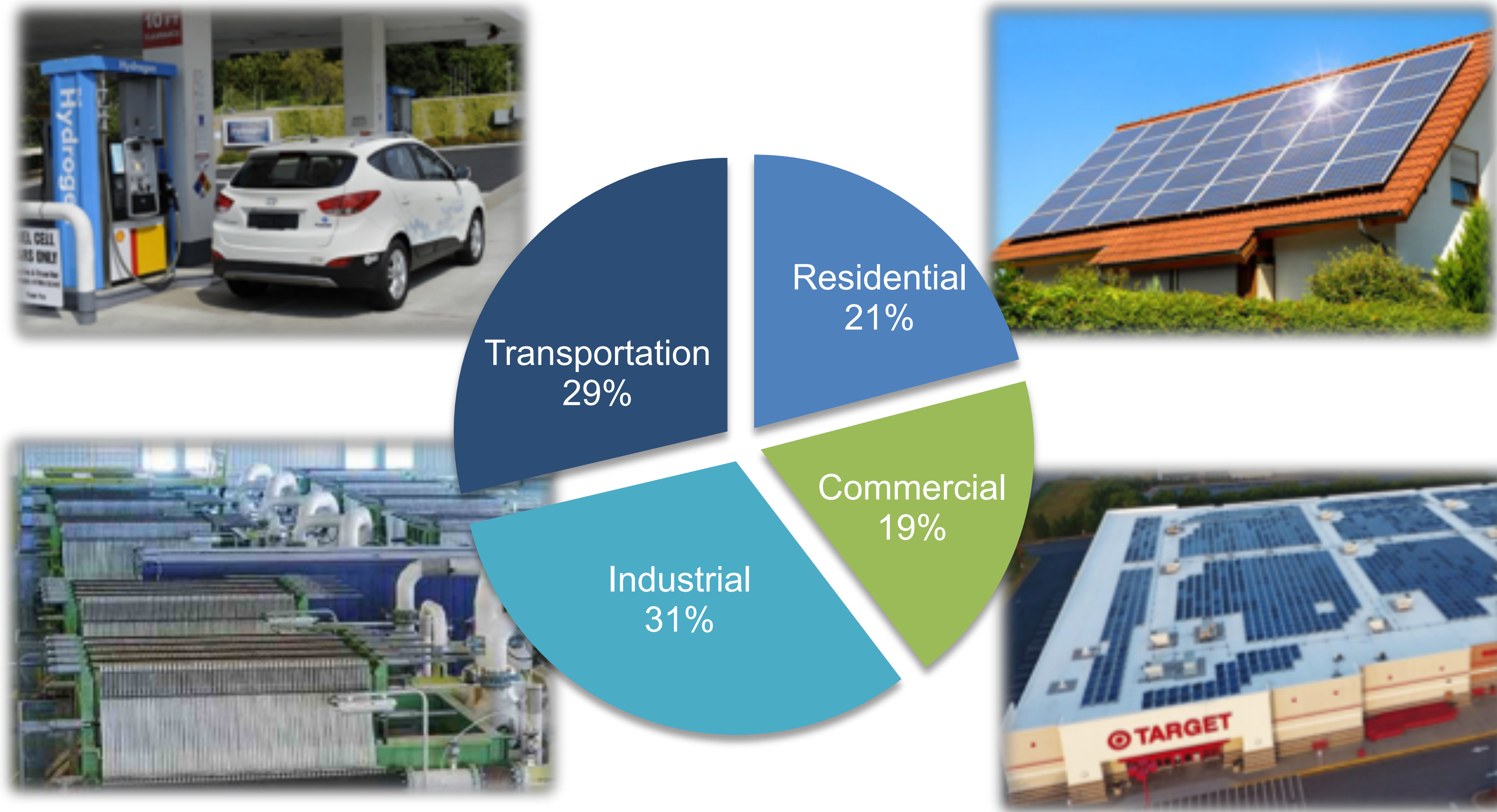
## Solar is almost inexpensive



Source: Bloomberg New Energy Finance & pv.energytrend.com



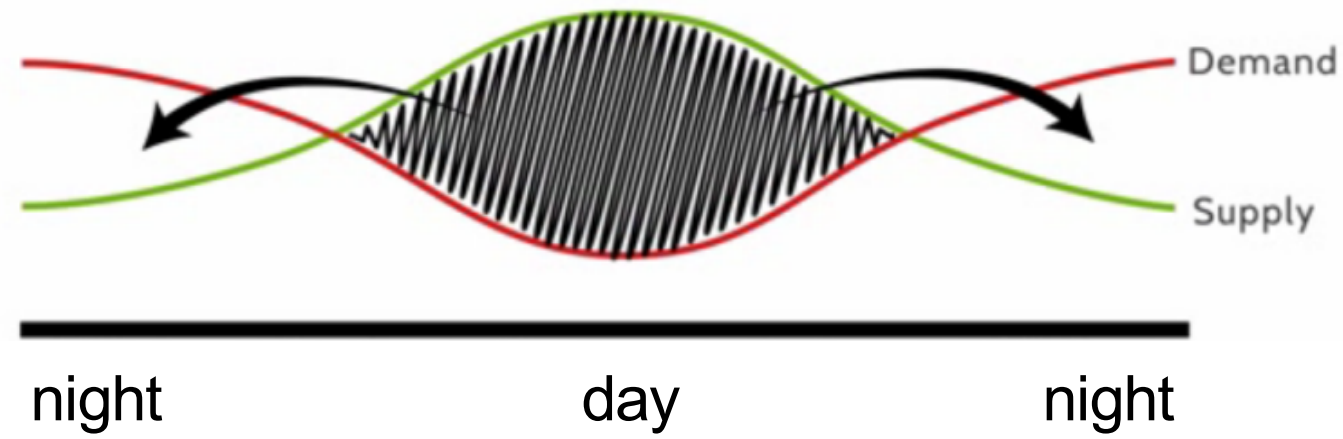
# Solar Intermittency Troubled Sectors



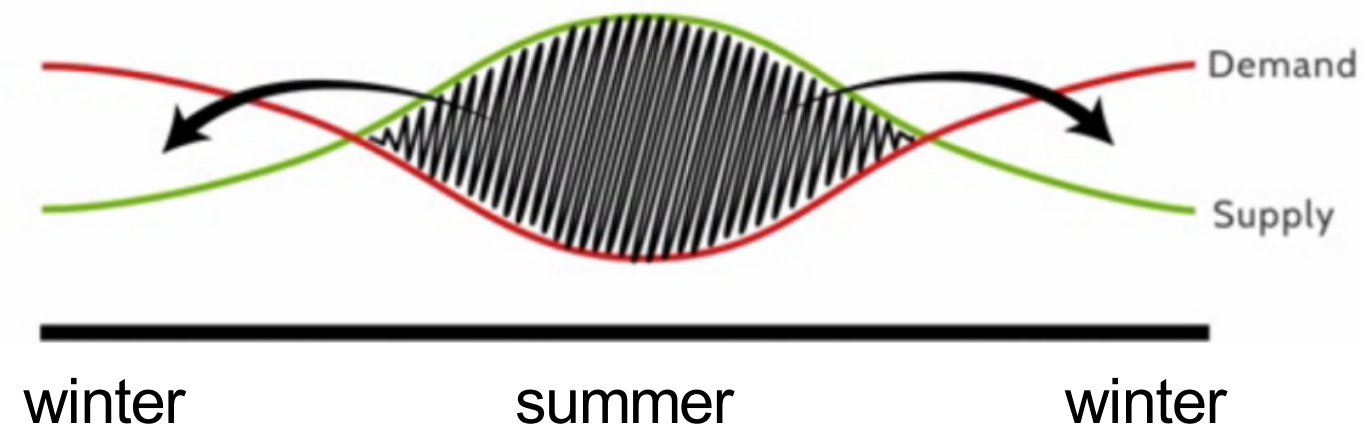


# Clean transport (?)

## Daily Storage



## Seasonal Storage





# What H<sub>2</sub> can provide

- Fuels are transportable
- They have large energy density
- It is “easy” to store them

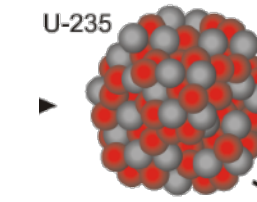


99% of storage (127 GW total = 2.5%)



Energy of 5 Kg of H<sub>2</sub> =  
125,000 Kg of Water tallest Swiss Dam

Thermal Energy  
(Calorific Content) kWh/Kg



22.5x10<sup>6</sup> Ur-235 (Fission)



13.0

Gasoline (Fossil)



8.3

Ethanol (Green)



39.4

Hydrogen

5.55

Mars Bar





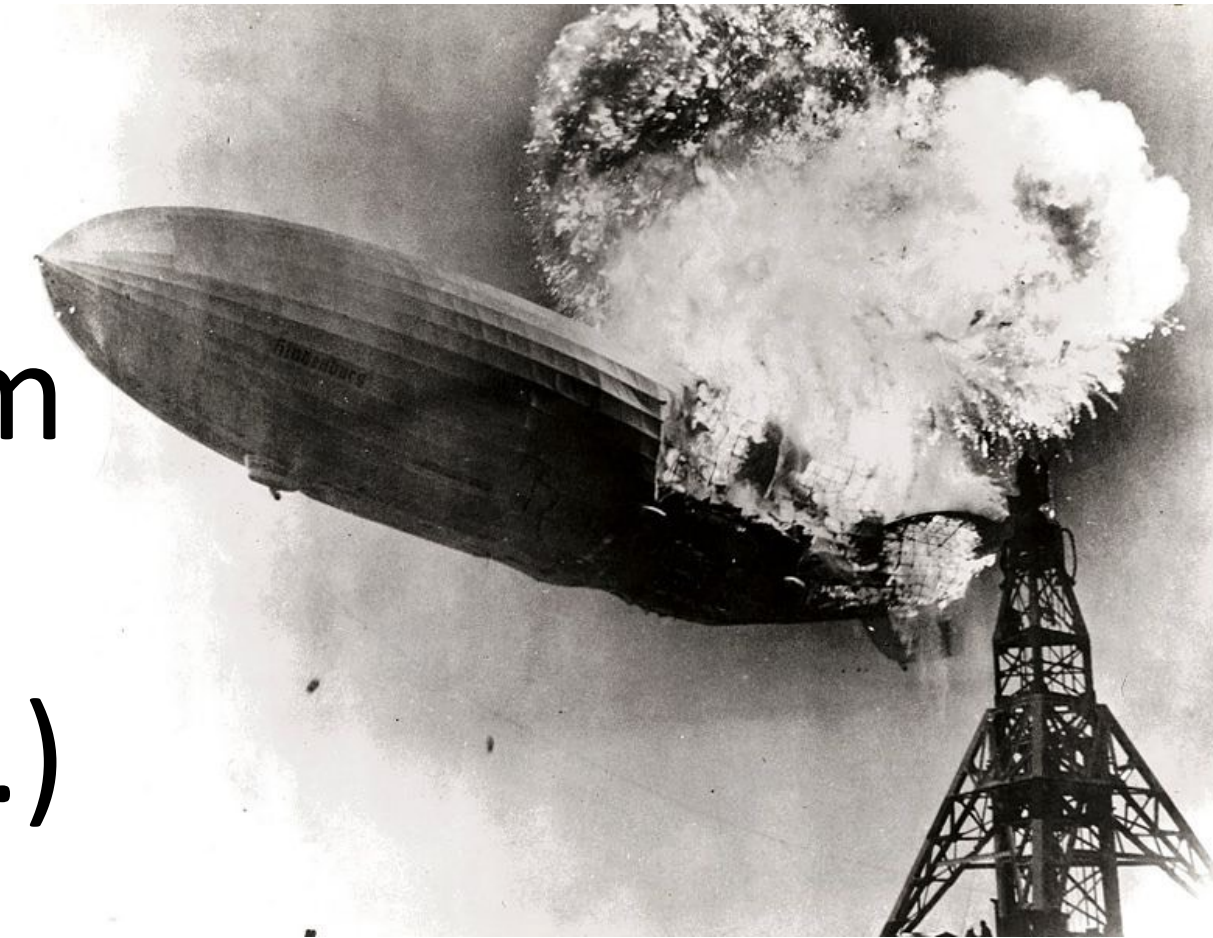
# Focusing on Hydrogen

Fuels are “easy” to store ...



depending on its form

(gas, liquid, metal hydride,...)

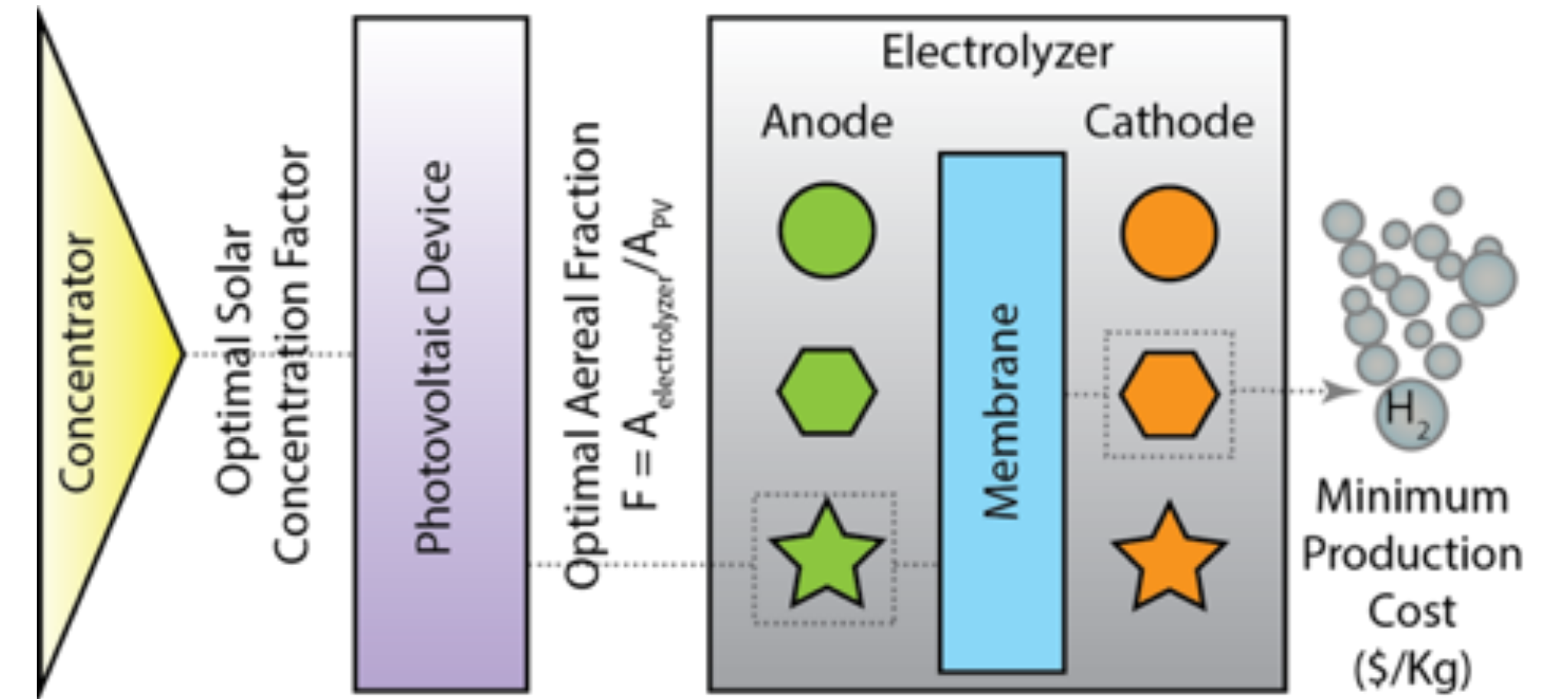
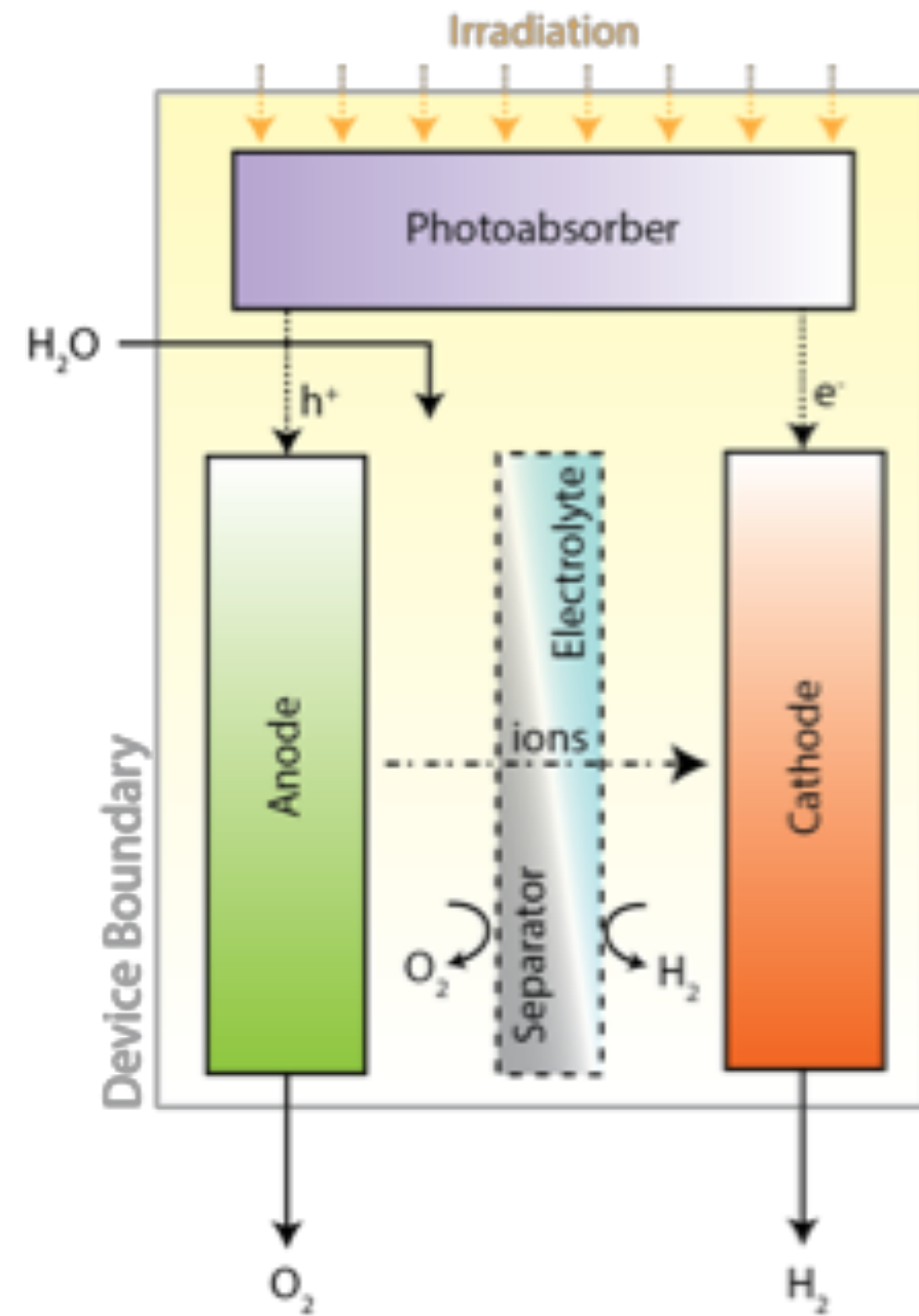


Scalable solar-fuel generators challenges:

1. Developing cost-effective components and processes
2. Component integration  
(light-capture, catalysis, mass transport)

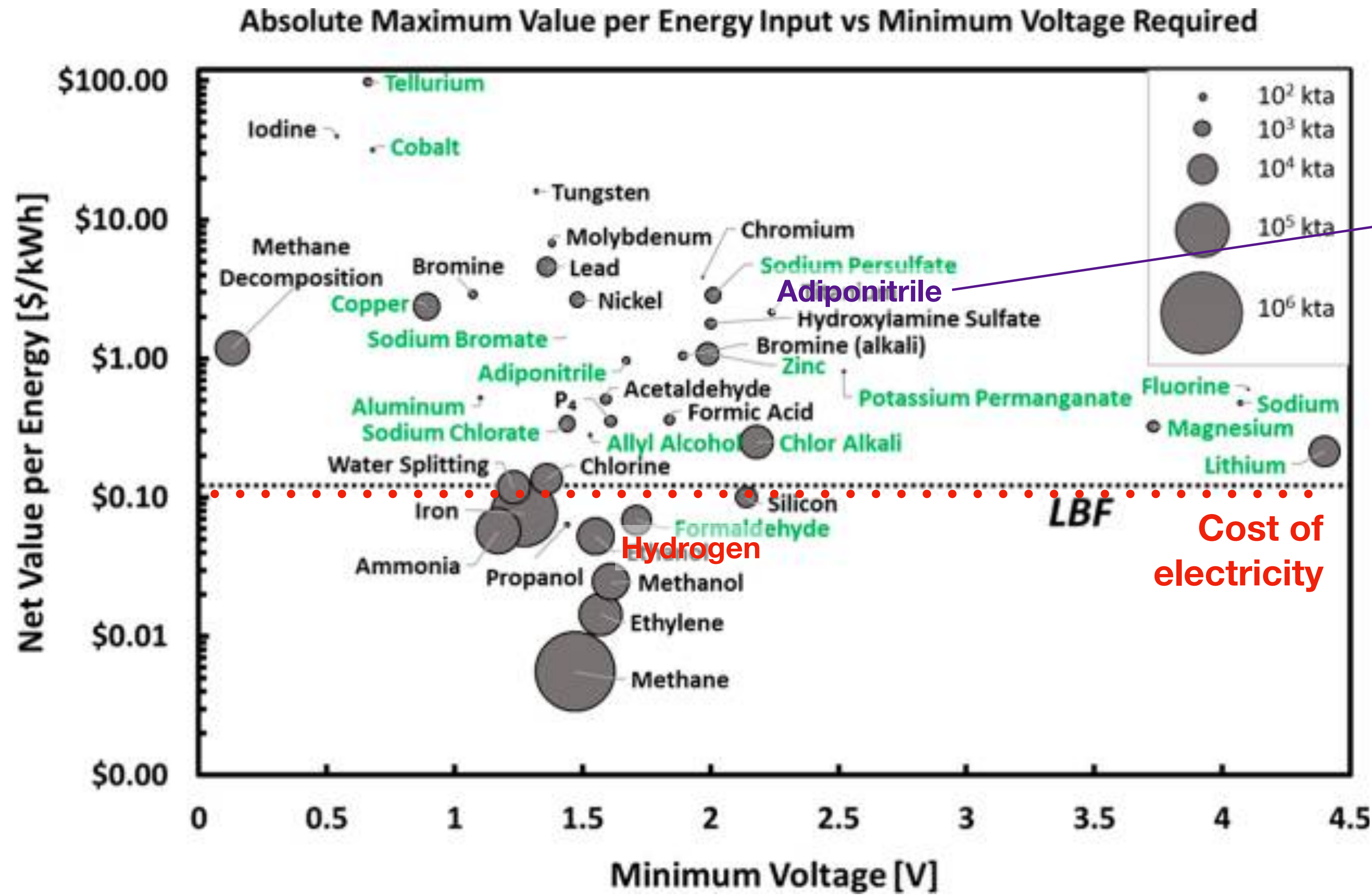


# Design elements

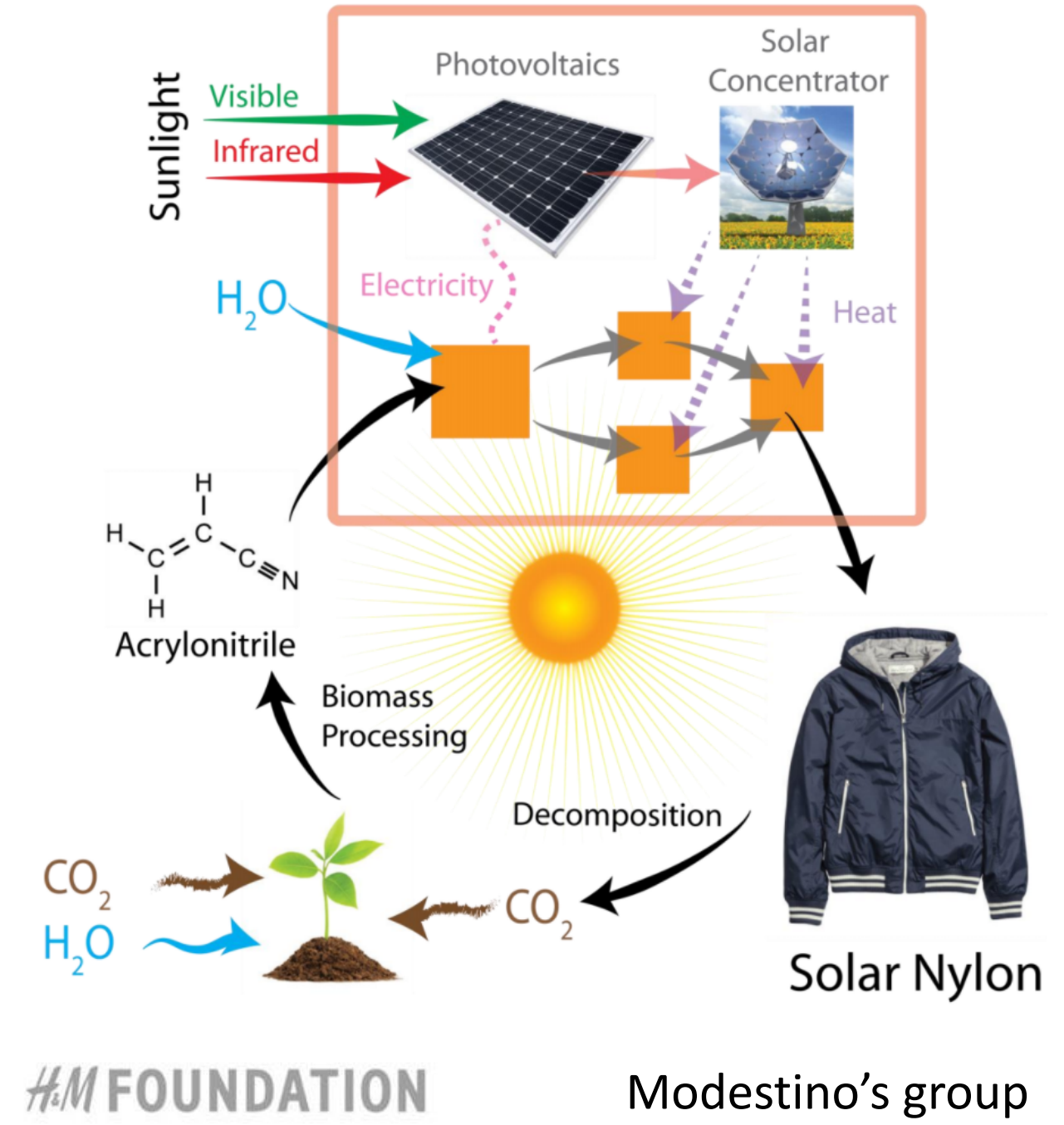




# Commercially relevant processes



NYU  
New Frontiers for Solar-Chemical Process





# What do we call Solar Hydrogen?

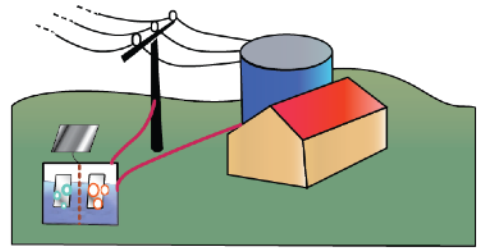
H<sub>2</sub> produced via water electrolysis using sunlight as clean renewable energy source



... and others



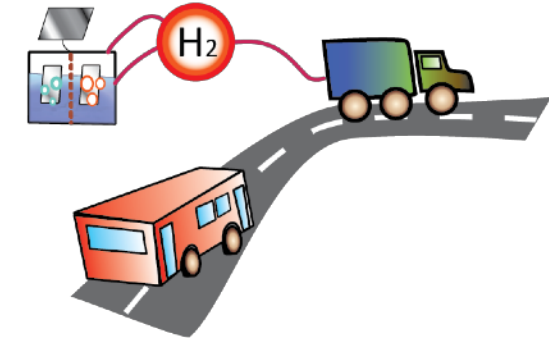
i) Grid-level energy storage



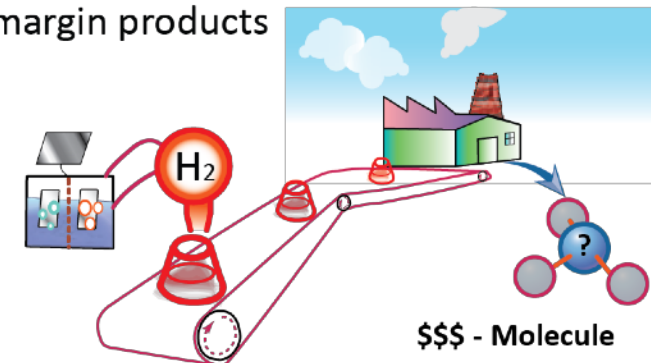
ii) Local energy system



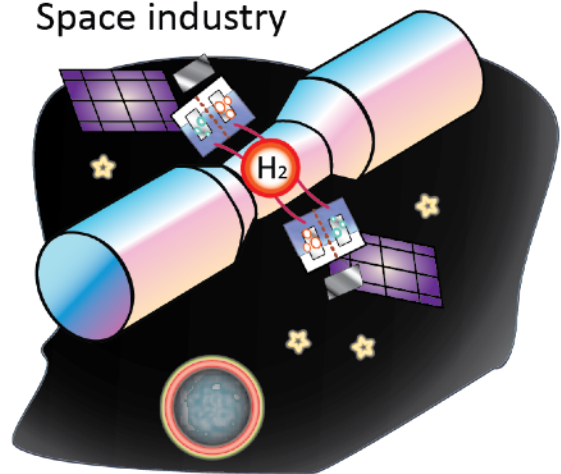
iii) Transportation



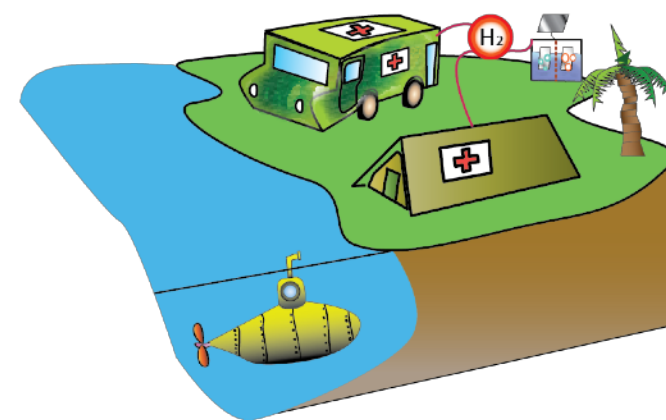
iv) High-margin products



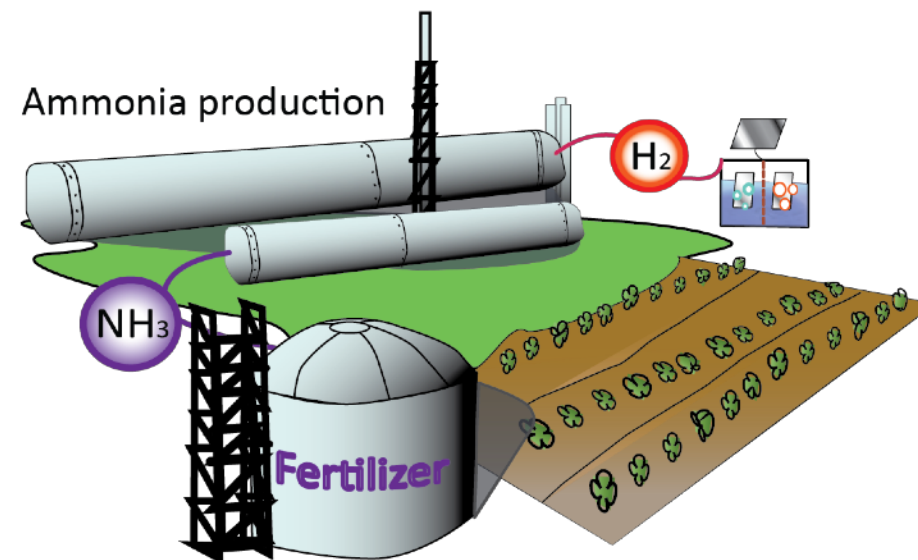
v) Space industry



vi) Military industry



vii) Ammonia production



## Energy & Environmental Science



PERSPECTIVE

[View Article Online](#)  
[View Journal](#)



Cite this: DOI: 10.1039/c7ee03639f

### Pathways to electrochemical solar-hydrogen technologies

Shane Ardo,<sup>id</sup>\*<sup>a</sup> David Fernandez Rivas,<sup>id</sup>\*<sup>b</sup> Miguel A. Modestino,<sup>\*c</sup> Verena Schulze Greiving,<sup>\*d</sup> Fatwa F. Abdi,<sup>id</sup><sup>e</sup> Esther Alarcon Llado,<sup>f</sup> Vincent Artero,<sup>id</sup><sup>g</sup> Katherine Ayers,<sup>id</sup><sup>h</sup> Corsin Battaglia,<sup>i</sup> Jan-Philipp Becker,<sup>id</sup><sup>j</sup> Dmytro Bederak,<sup>id</sup><sup>k</sup> Alan Berger,<sup>l</sup> Francesco Buda,<sup>id</sup><sup>m</sup> Enrico Chinello,<sup>n</sup> Bernard Dam,<sup>o</sup> Valerio Di Palma,<sup>p</sup> Tomas Edvinsson,<sup>id</sup><sup>q</sup> Katsushi Fujii,<sup>id</sup><sup>r</sup> Han Gardeniers,<sup>id</sup><sup>b</sup> Hans Geerlings,<sup>o</sup> S. Mohammad H. Hashemi,<sup>s</sup> Sophia Haussener,<sup>id</sup><sup>t</sup> Frances Houle,<sup>id</sup><sup>u</sup> Jurriaan Huskens,<sup>id</sup><sup>v</sup> Brian D. James,<sup>w</sup> Kornelia Konrad,<sup>d</sup> Akihiko Kudo,<sup>x</sup> Pramod Patil Kunturu,<sup>y</sup> Detlef Lohse,<sup>id</sup><sup>y</sup> Bastian Mei,<sup>id</sup><sup>z</sup> Eric L. Miller,<sup>aa</sup> Gary F. Moore,<sup>id</sup><sup>ab</sup> Jiri Muller,<sup>ac</sup> Katherine L. Orchard,<sup>ad</sup> Timothy E. Rosser,<sup>ad</sup> Fadl H. Saadi,<sup>id</sup><sup>ae</sup> Jan-Willem Schüttauf,<sup>af</sup> Brian Seger,<sup>ag</sup> Stafford W. Sheehan,<sup>id</sup><sup>ah</sup> Wilson A. Smith,<sup>id</sup><sup>o</sup> Joshua Spurgeon,<sup>id</sup><sup>ai</sup> Maureen H. Tang,<sup>id</sup><sup>aj</sup> Roel van de Krol,<sup>id</sup><sup>e</sup> Peter C. K. Vesborg,<sup>id</sup><sup>ag</sup> and Pieter Westerik<sup>id</sup><sup>b</sup>



ISSN 1754-5706



PERSPECTIVE  
Shane Ardo, David Fernandez Rivas, Miguel A. Modestino, Verena Schulze Greiving et al.  
Pathways to electrochemical solar-hydrogen technologies

Lorentz center

## Pathways to Solar Hydrogen Technologies

Workshop: 13 - 17 June 2016, Leiden, the Netherlands

Scientific Organizers

- Shane Ardo, UC Irvine
- David Fernandez Rivas, U Twente
- Miguel Modestino, EPFL Lausanne
- Verena Stimberg, U Twente

Scientific Advisors

- Katherine Ayers, Proton OnSite
- Frances Houle, LBNL/JCAP
- Jurriaan Huskens, U Twente
- Roel van de Krol, Helmholtz-Zentrum Berlin
- Eric McFarland, UC Santa Barbara
- Eric Miller, US Dept of Energy
- Patricia Osseweijer, TU Delft

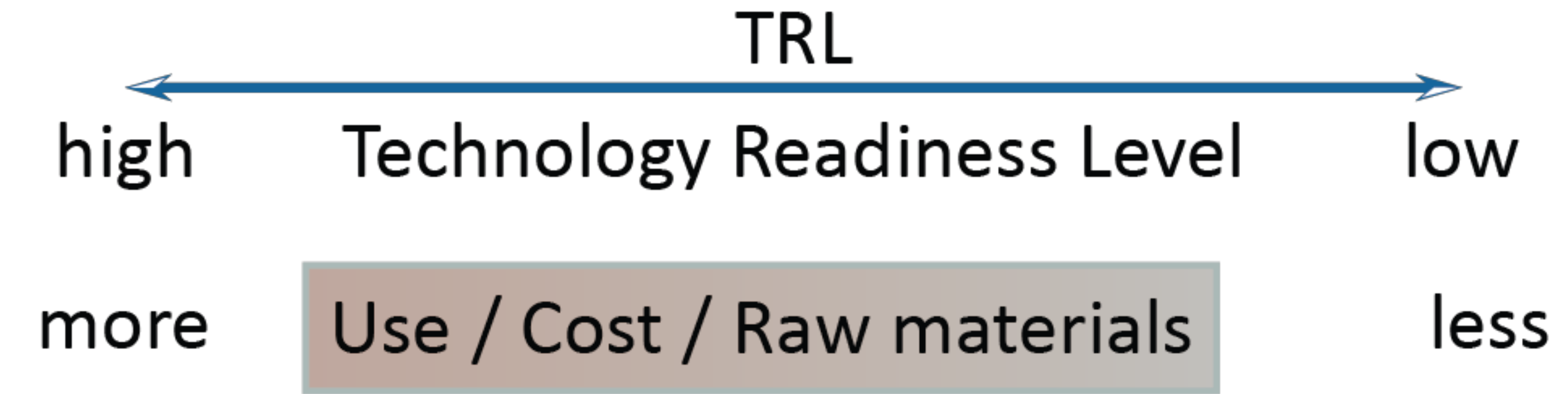
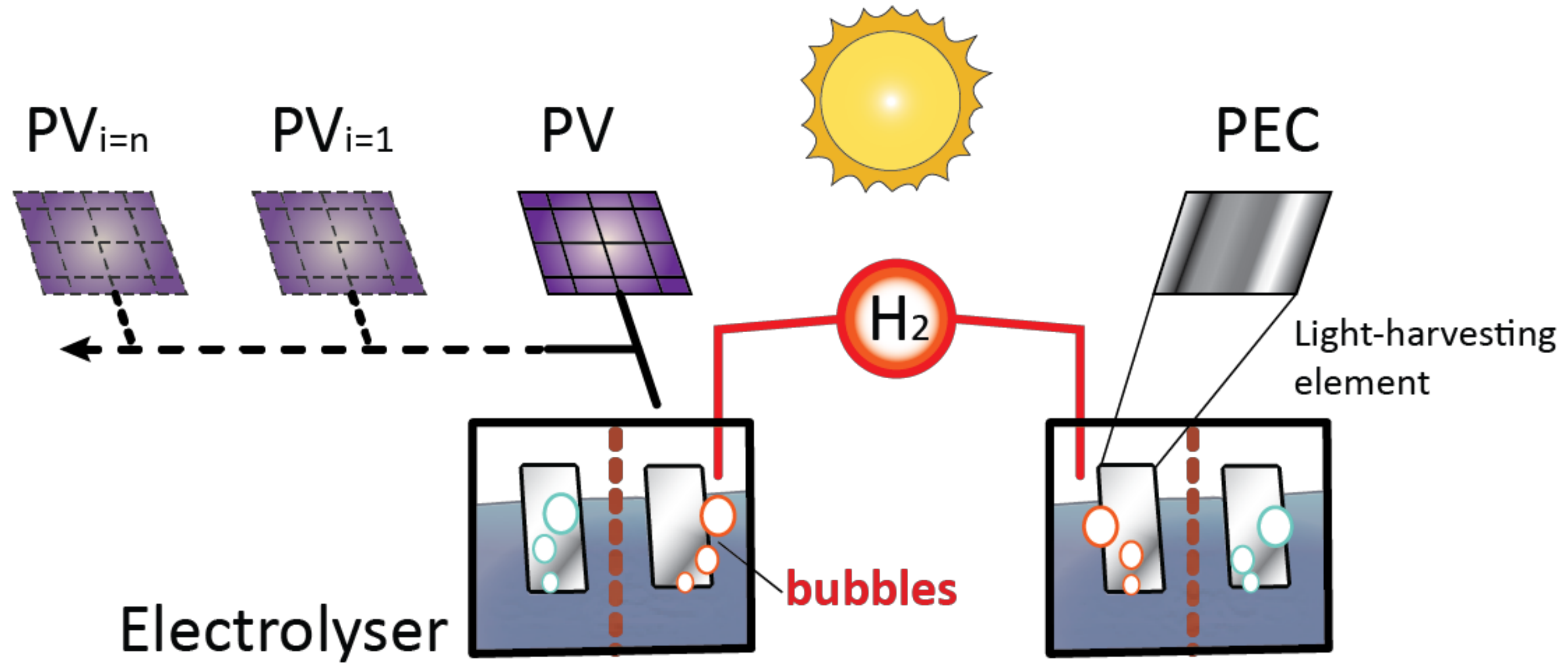


The Lorentz Center is an international center for scientific workshops. Its aim is to organize workshops for researchers in an atmosphere that fosters collaborative work, discussions and interactions. For registration see: [www.lorentzcenter.nl](http://www.lorentzcenter.nl)

Image: artistic rendition of a technology to produce and store hydrogen based on solar energy. Poster design: SuperNova Studios, NL.

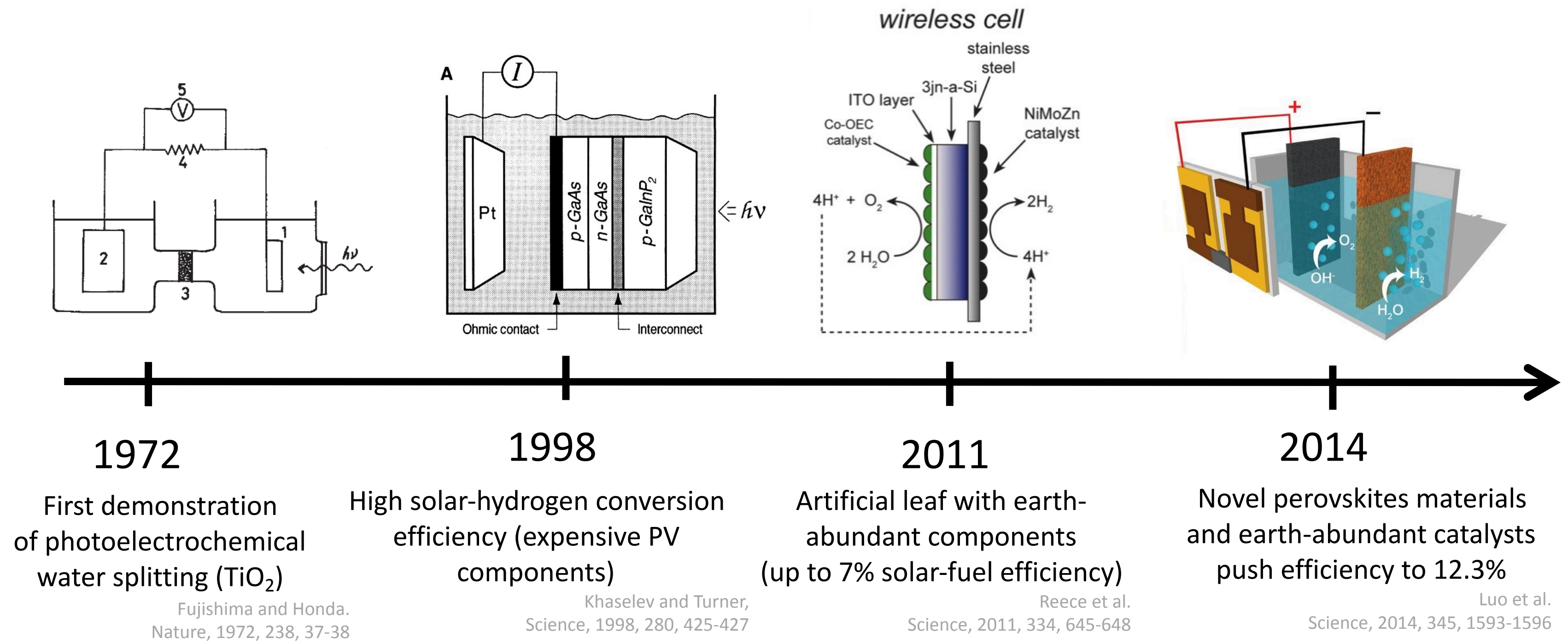
2018 HOT Article!







# 45 years of Solar-H<sub>2</sub> Research

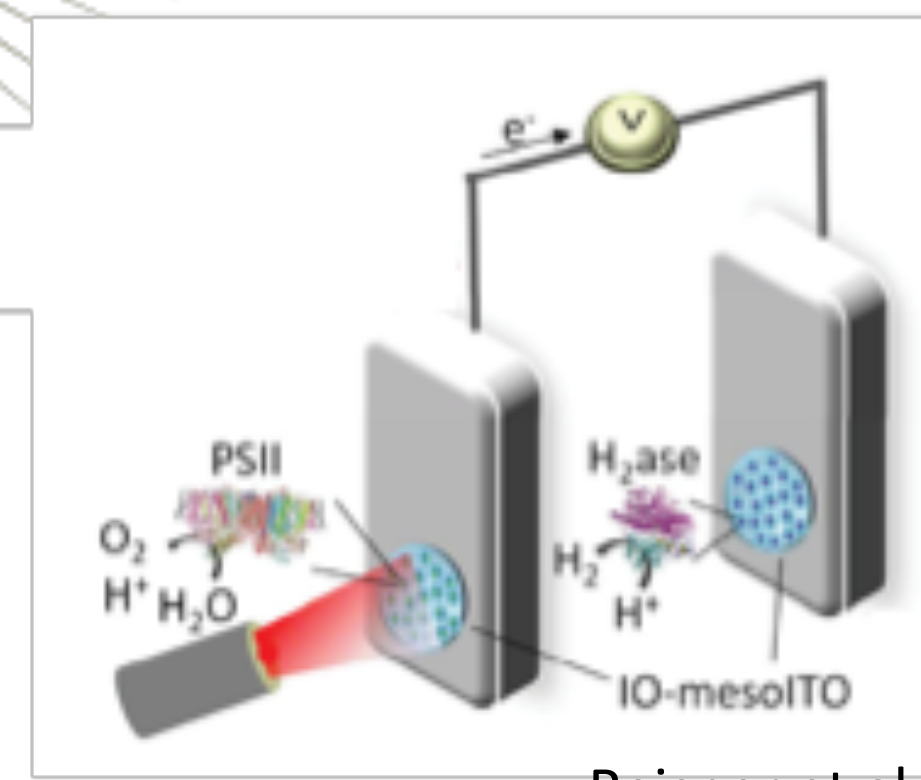
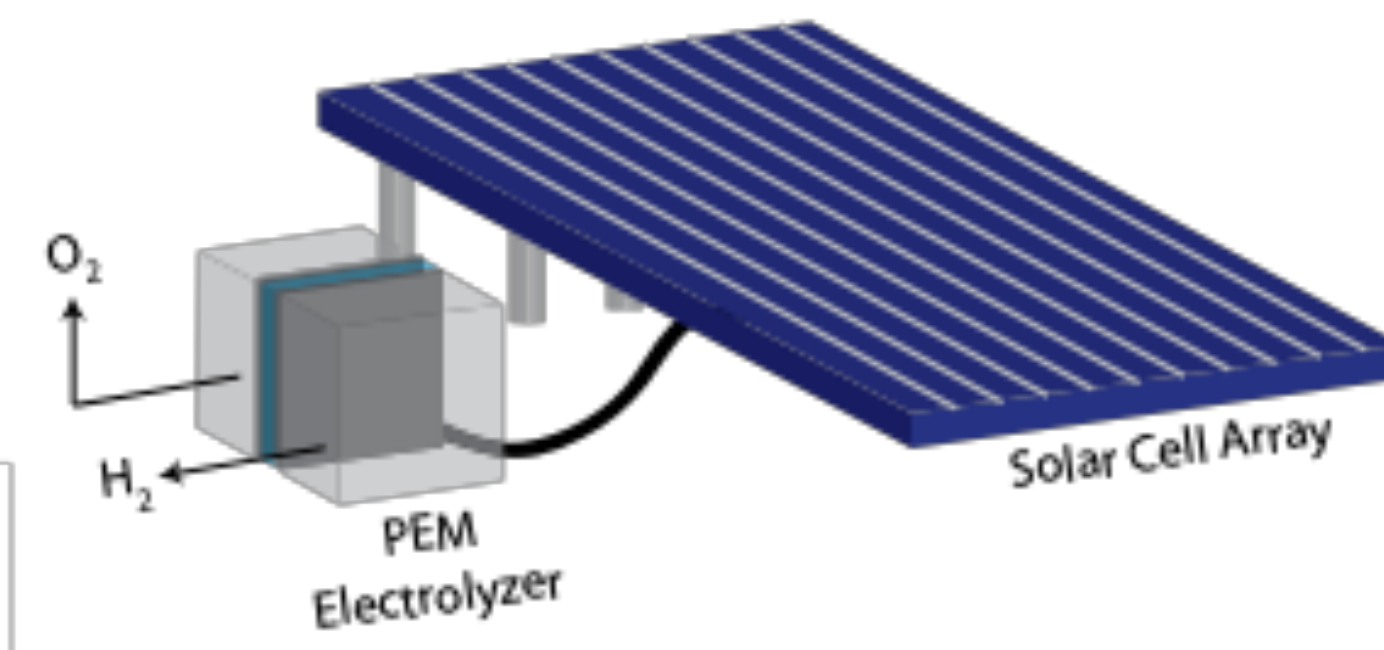
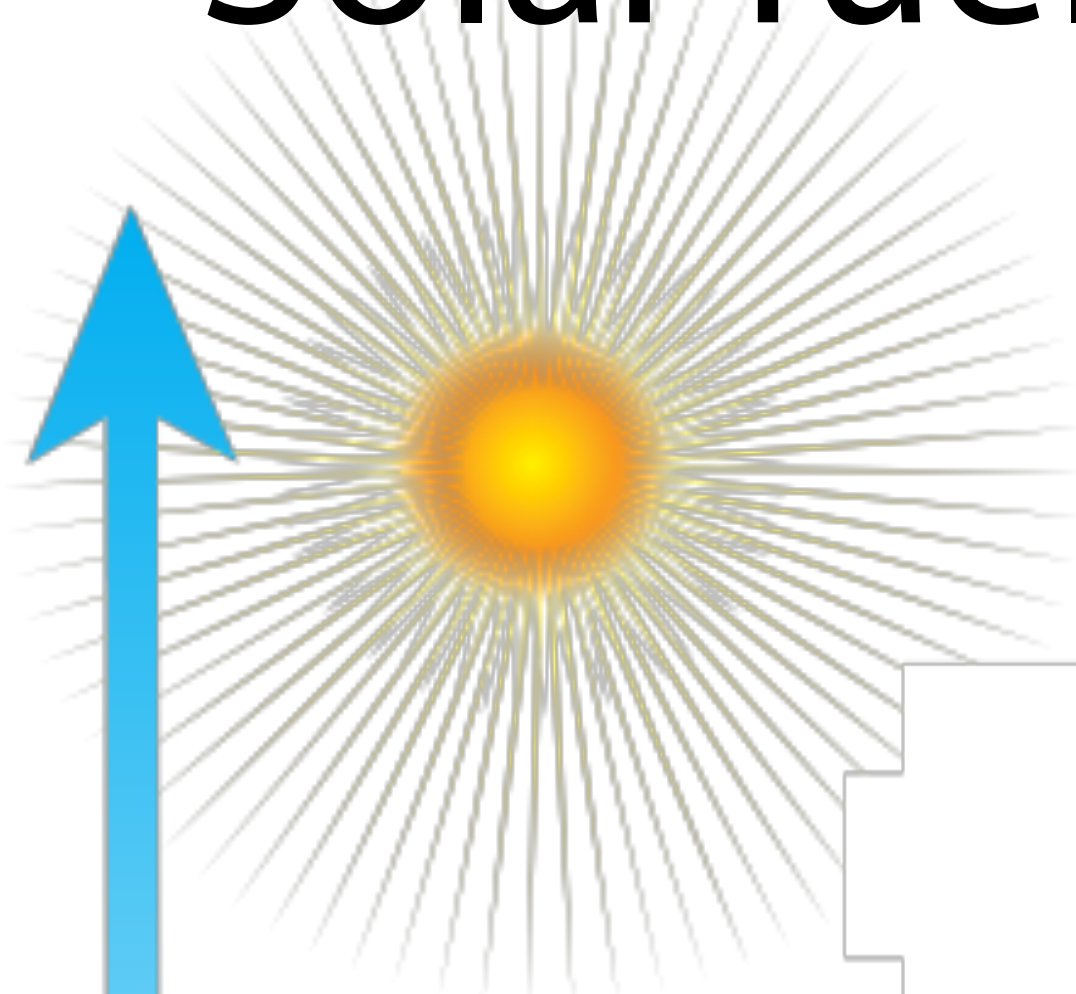




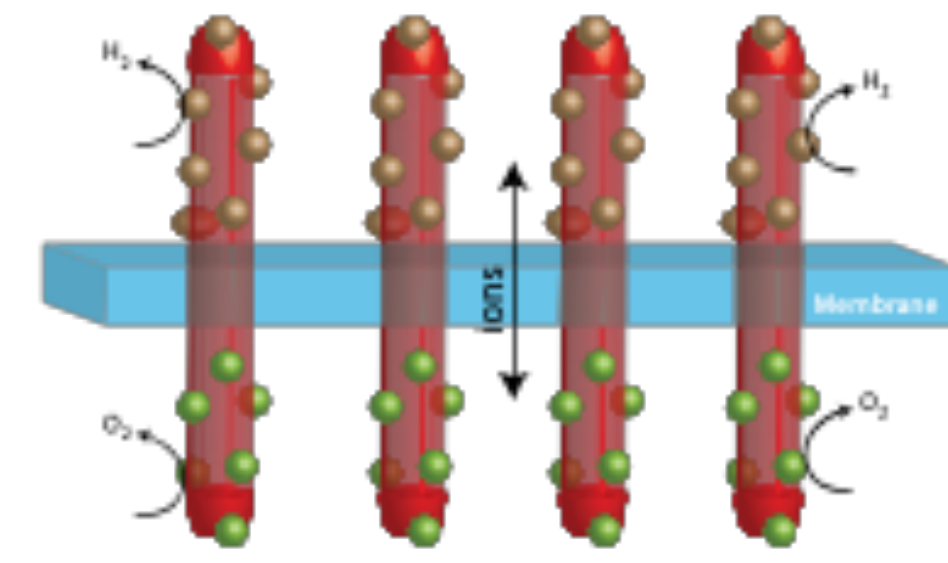
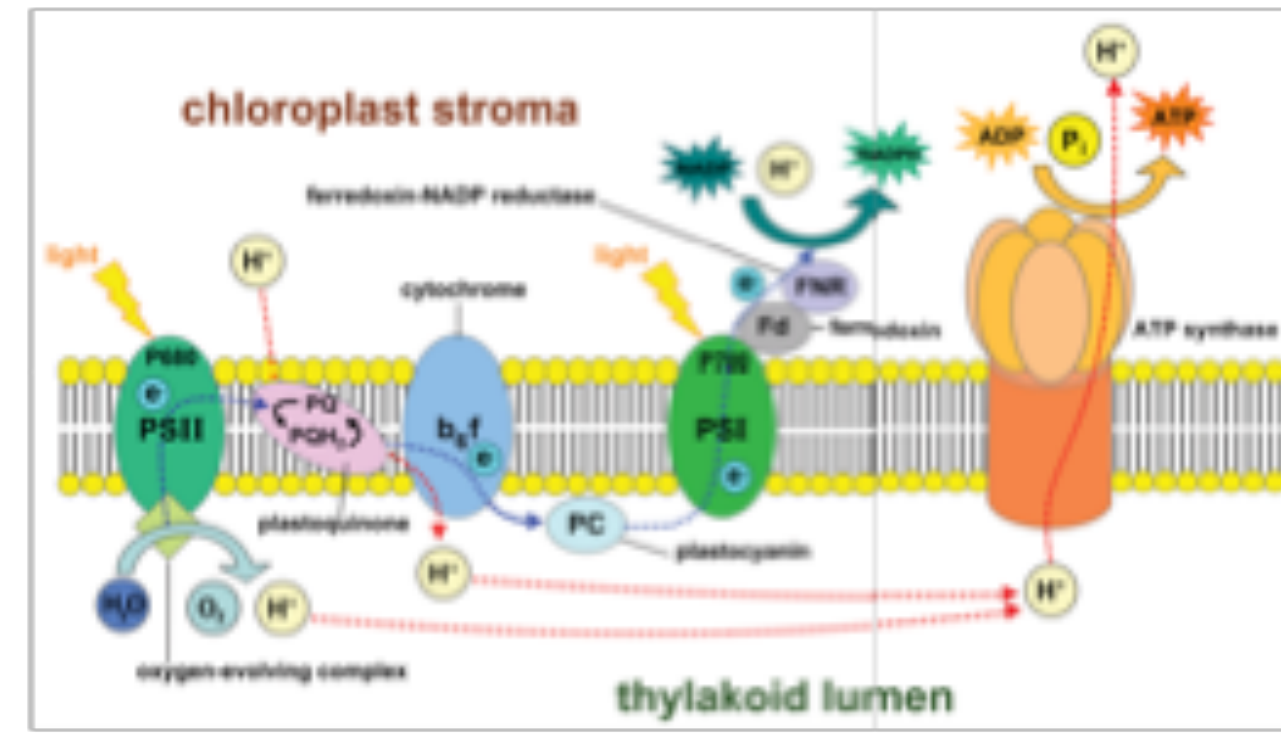
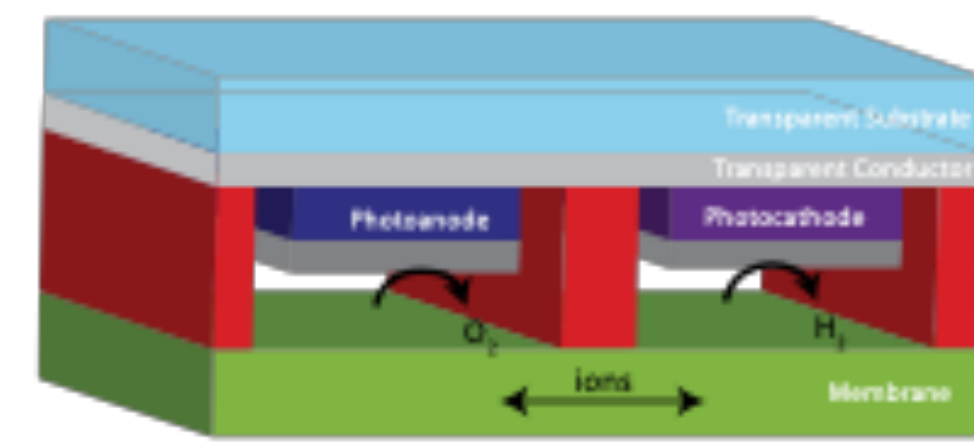
# Solar fuels device taxonomy

Decoupled

Integrated



Reisner et al. JACS 2015

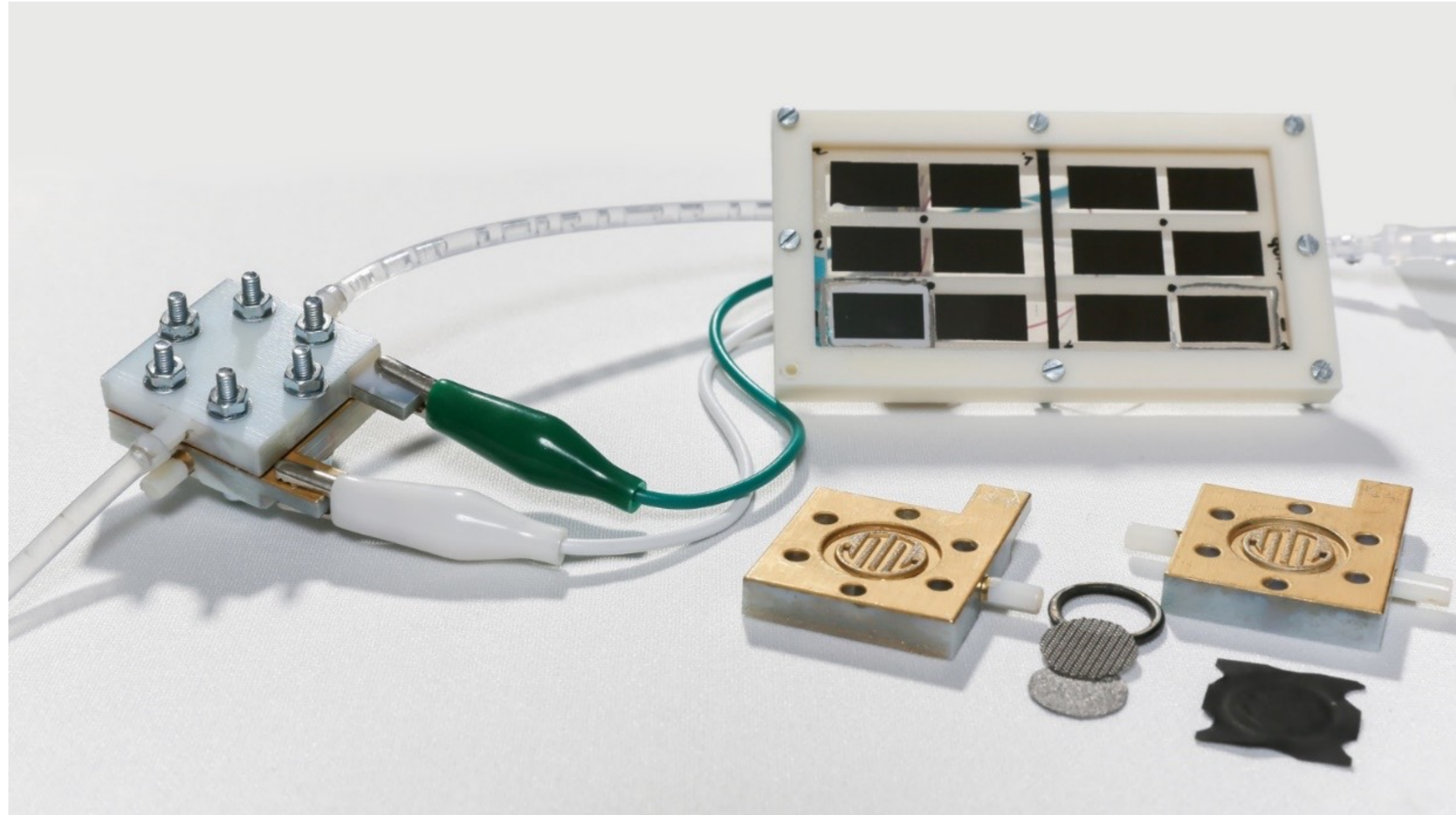


Biological

Artificial



# SHINE's PV/Electrolysis approach





# Coming soon (somewhere) near you



Challenge: decarbonization of the global economy.

Solution: expand renewable energy sources and integrate them in developed industry, energy, and mobility infrastructures.

“Green” hydrogen from renewable energy using PEM electrolysis.

SILYZER integrates fluctuating energy sources such as sun and wind.

<https://www.siemens.com/global/en/home/products/energy/renewable-energy/hydrogen-solutions.html>



# Coming soon (somewhere) near you

## Large Scale H<sub>2</sub> Plants

Large scale renewable energy storage, grid management or industrial applications that demand fast response times or compressor-less operation should consider our Proton PEM hydrogen plant for their hydrogen production needs.

Nel Hydrogen is the acknowledged specialist in large scale electrolyser plants. The M Series modular skid based platform enables flexible plant configuration and installation for medium to large scale H<sub>2</sub> plants based on water electrolyser technology.

- Tailored to any demand
- Turnkey solutions
- Large capacity at minimum footprint
- Hydrogen produced at pressure
- Scaled to any capacity
- Proton PEM technology



<https://nelhydrogen.com/assets/uploads/2016/05/Nel-Electrolysers-Brochure-2018-PD-0600-0125-Web.pdf>

<https://www.siemens.com/innovation/de/home/pictures-of-the-future/energie-und-effizienz/smart-grids-und-energiespeicher-elektrolyse-wasserstoff-im-energiepark-mainz.html>



# Coming soon (somewhere) near you

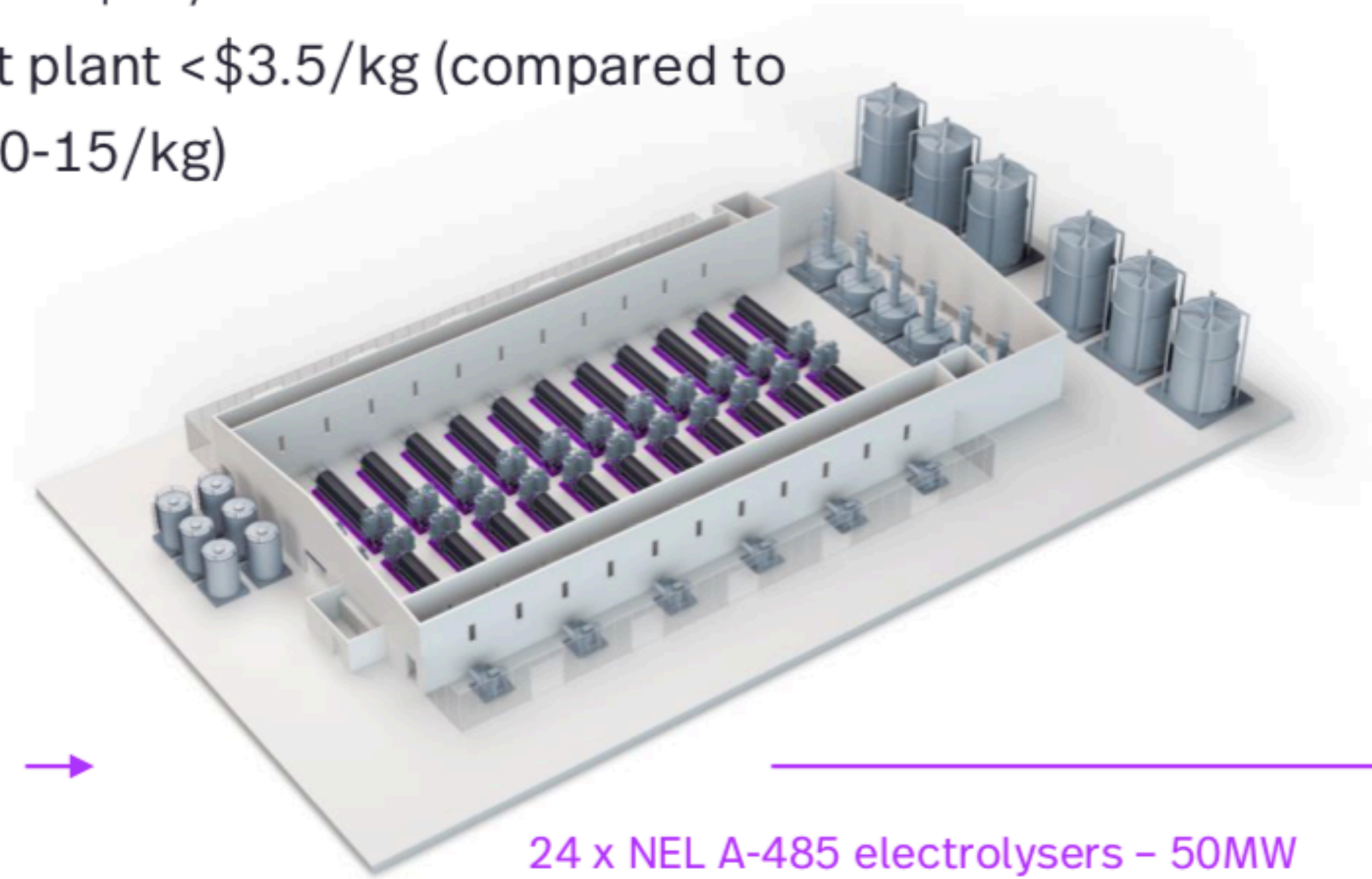
## Hydrogen can be produced at a very competitive price from renewable

Project examples

Renewable power at <\$50/MWh enables production of H2 at plant <\$3.5/kg (compared to a pump price of \$10-15/kg)



<\$50/MWh



24 x NEL A-485 electrolyzers - 50MW

<\$3.5/kg



>55,000 cars/year



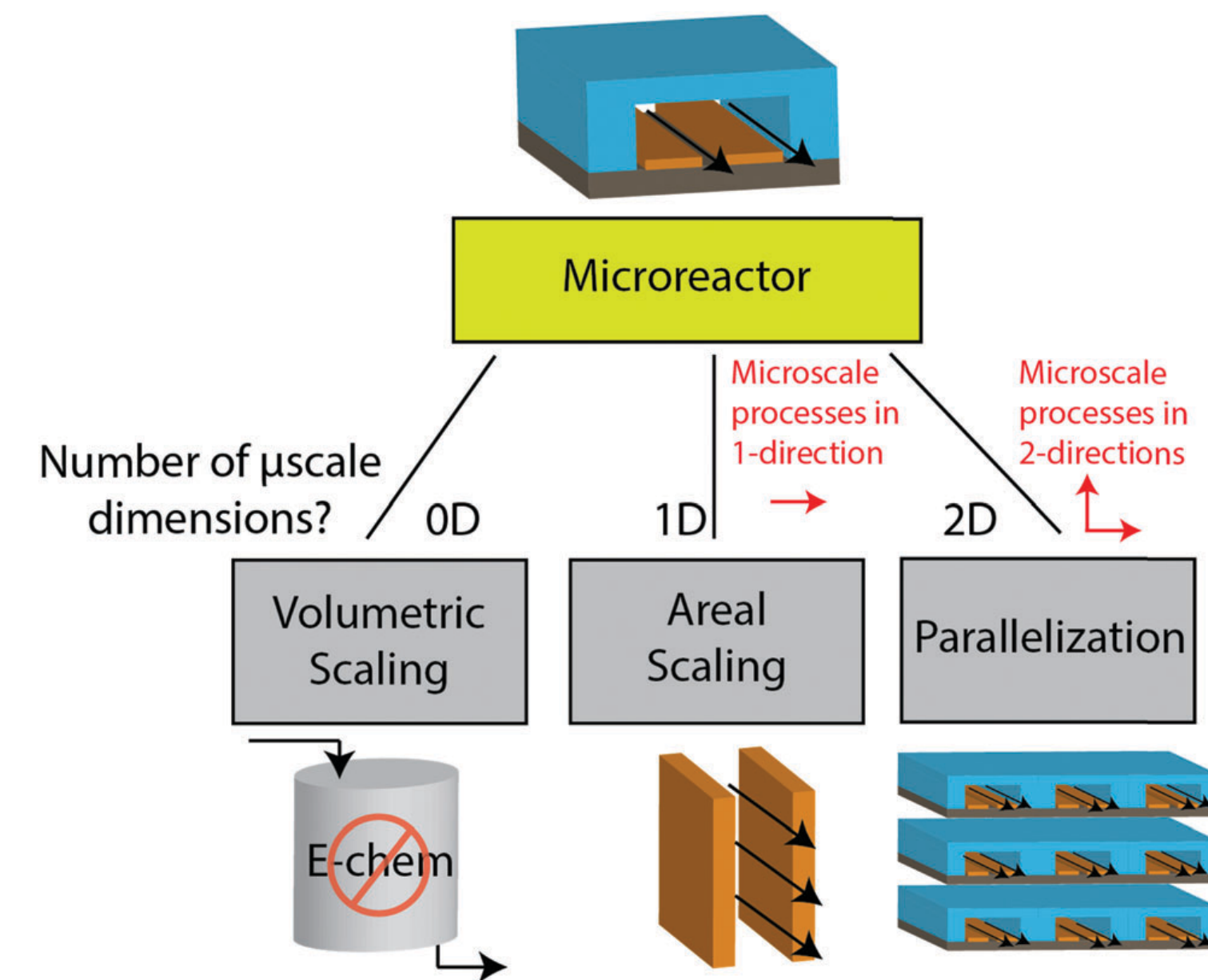
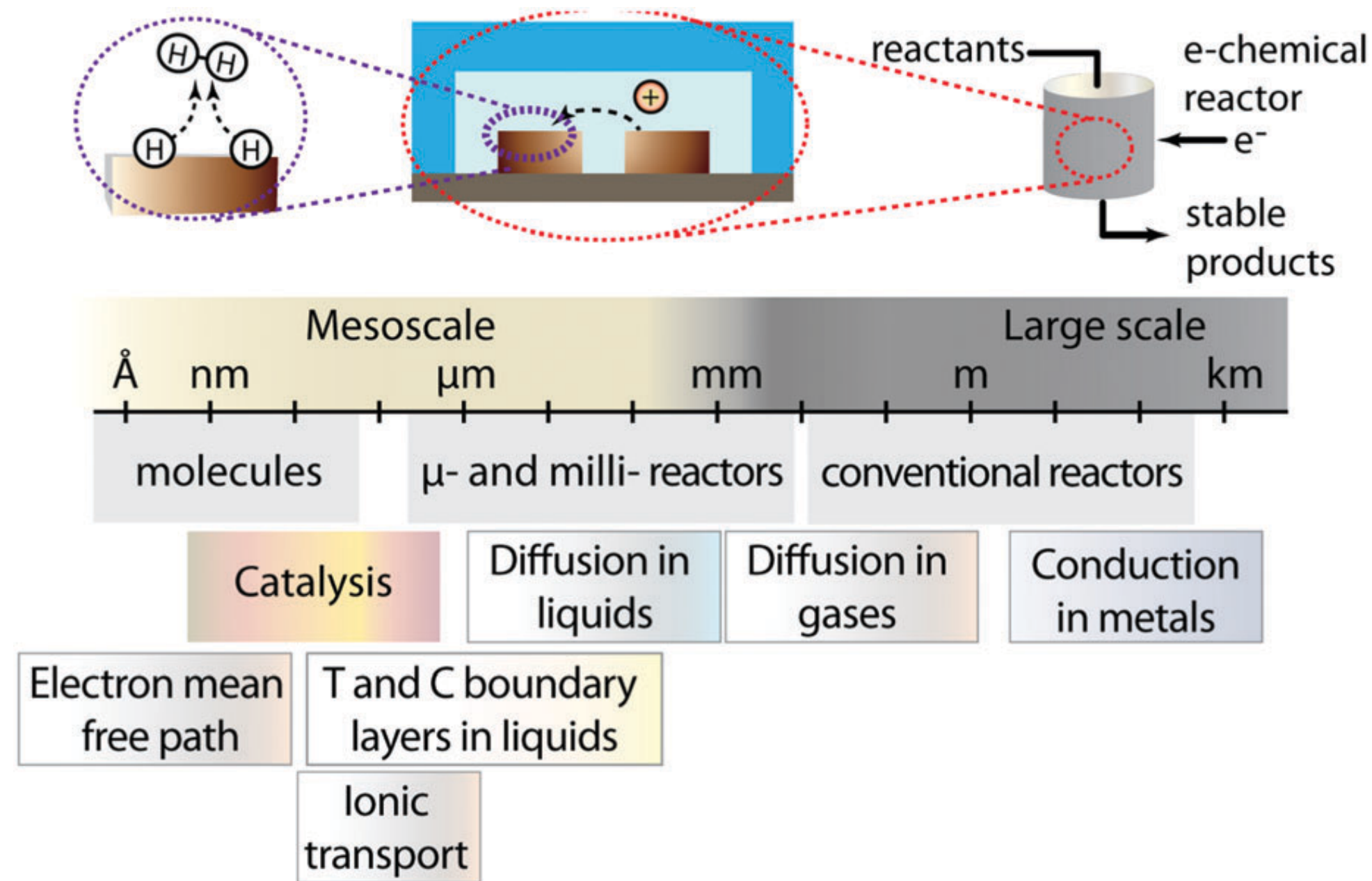
>1,000 buses/year



>500 trucks/year

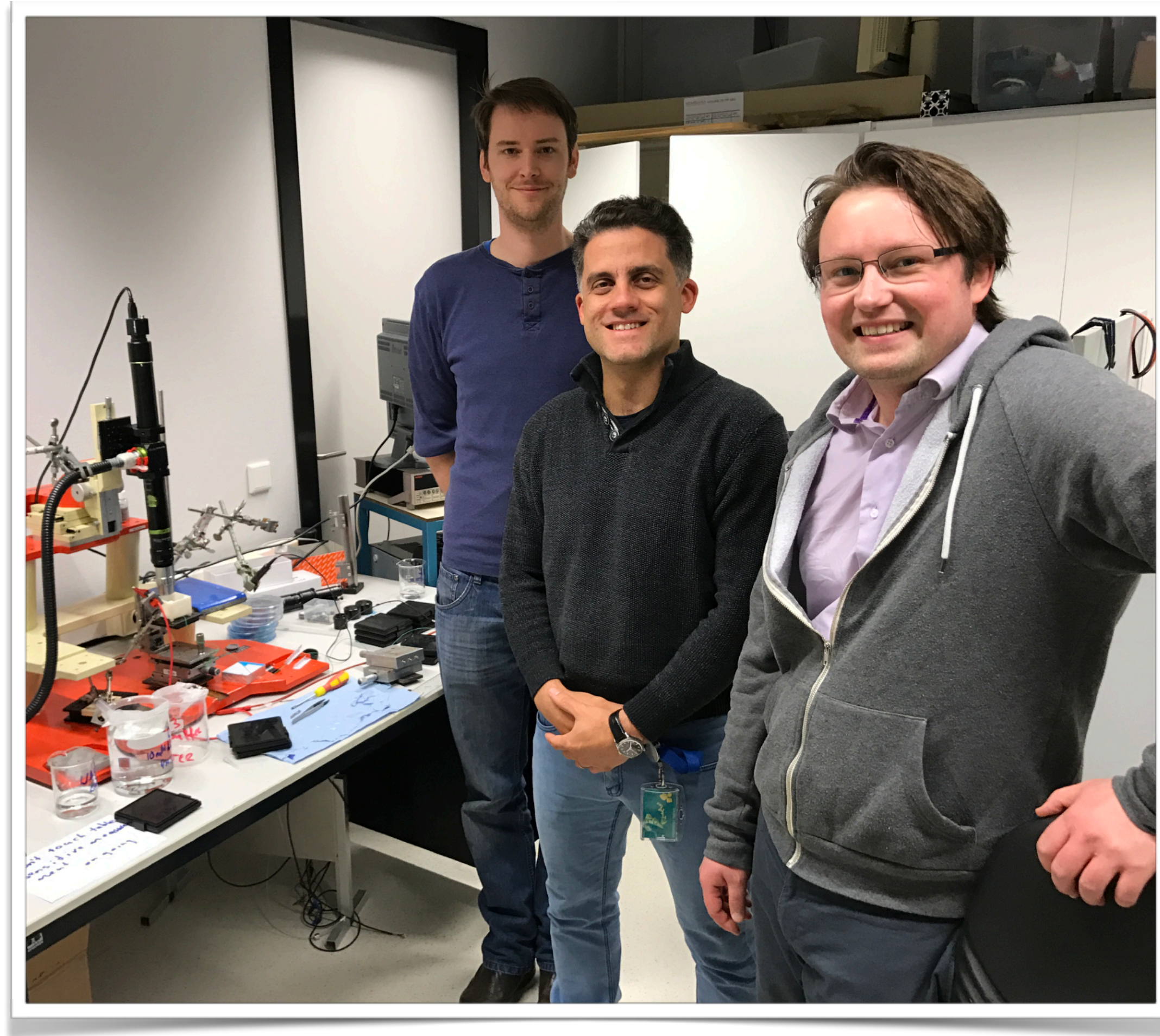



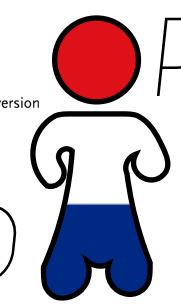


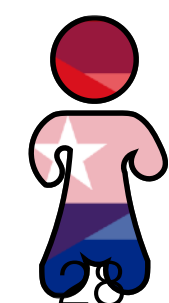


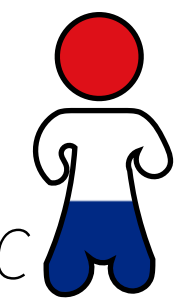


# TEAM



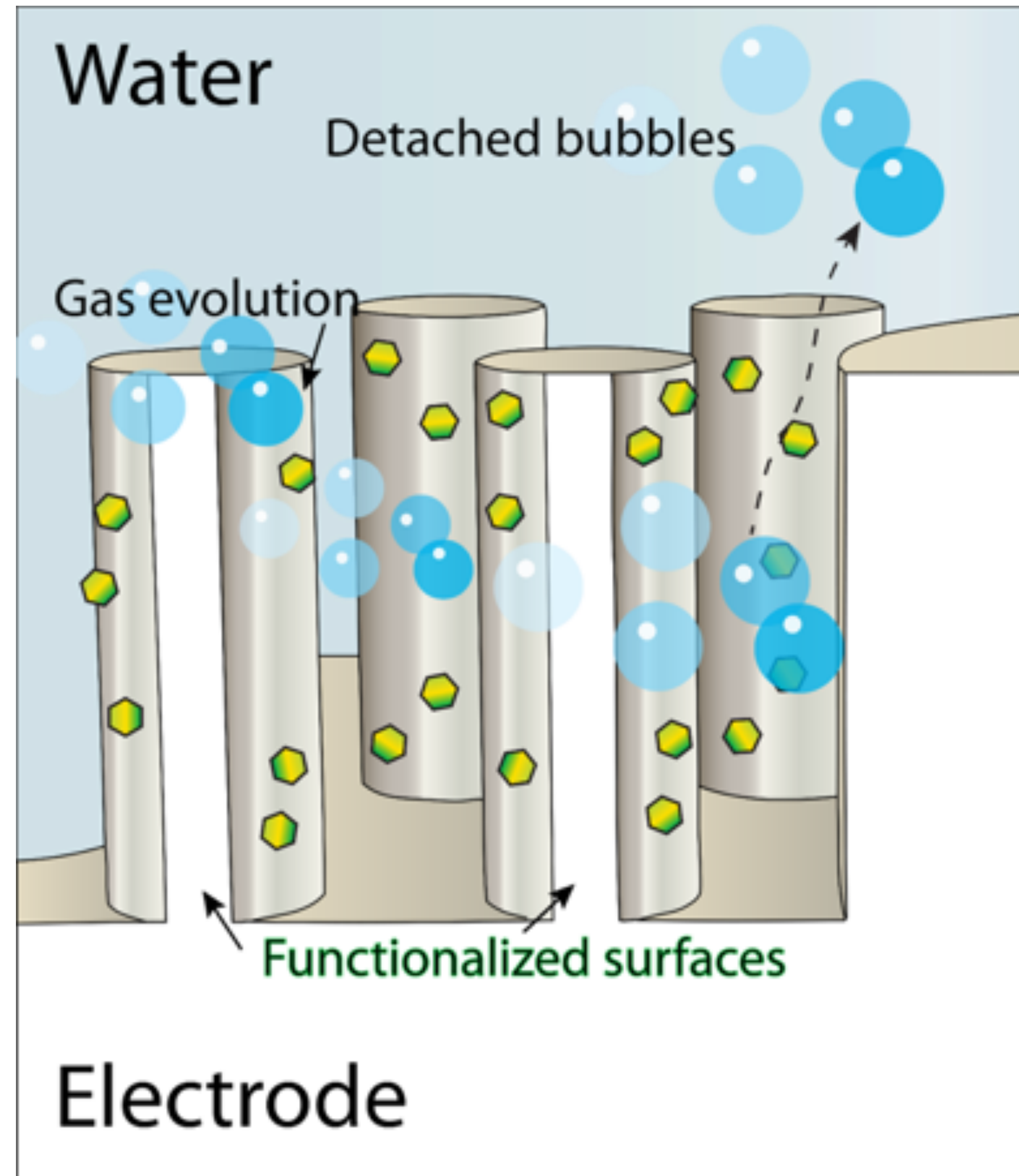
 MCEC  
Netherlands Center for  
Multiscale Catalytic Energy Conversion  
Peter  
PhD 



Sebastiaan  
MSc 

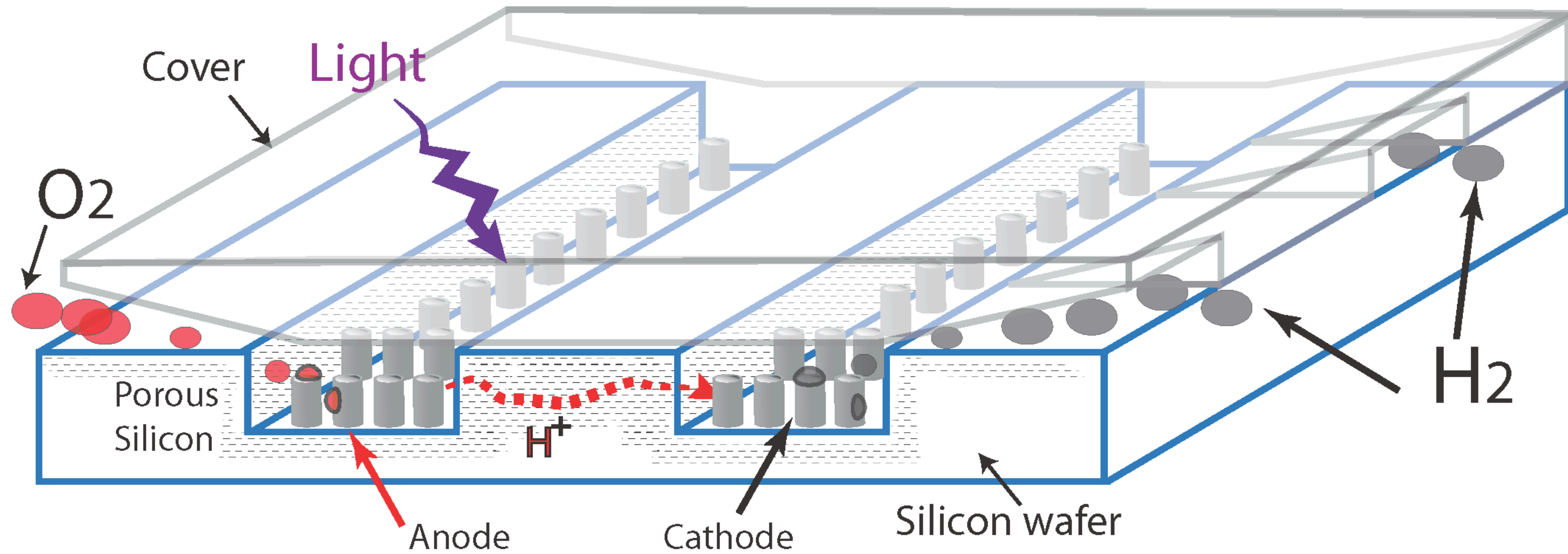


# Ideal world



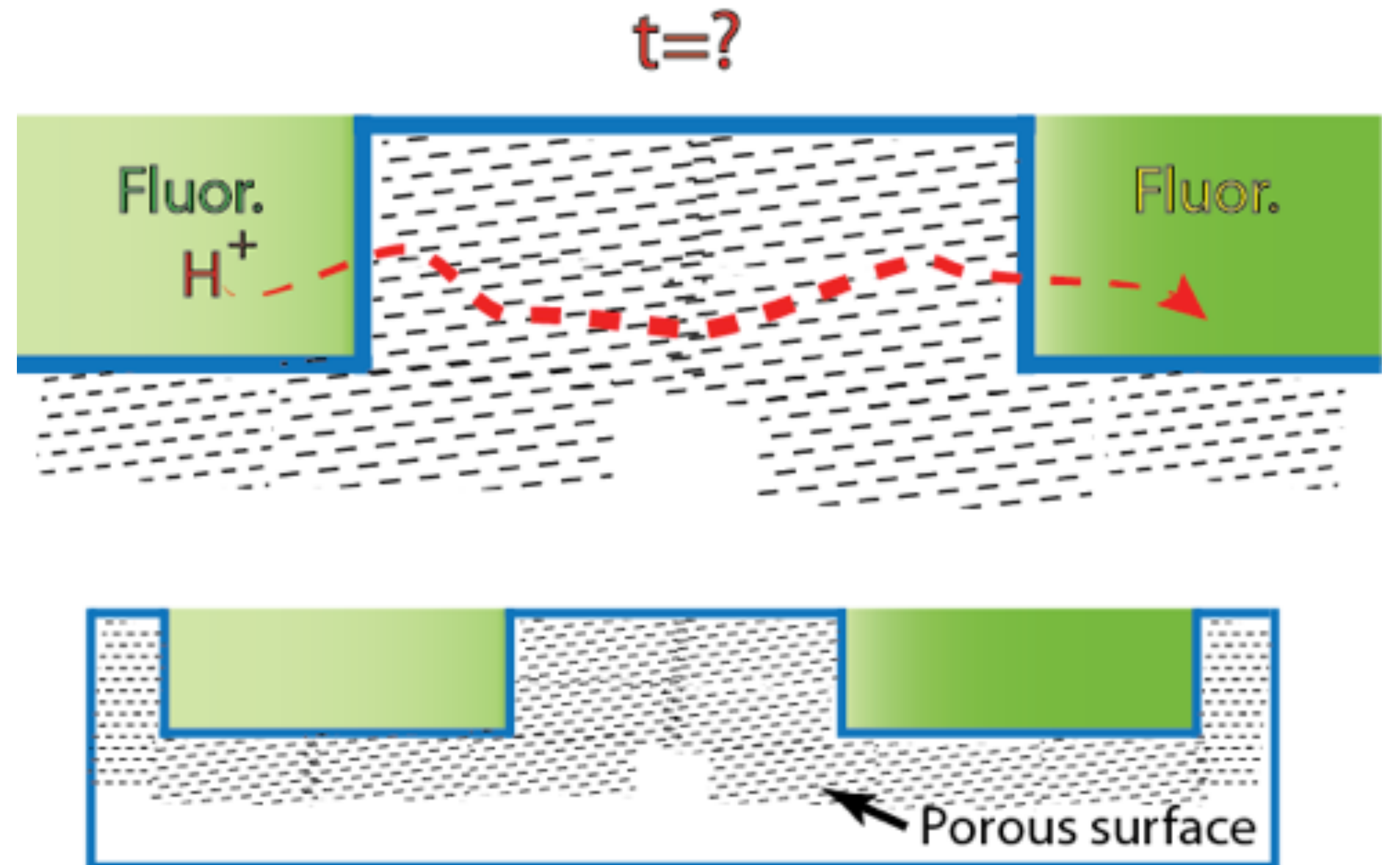
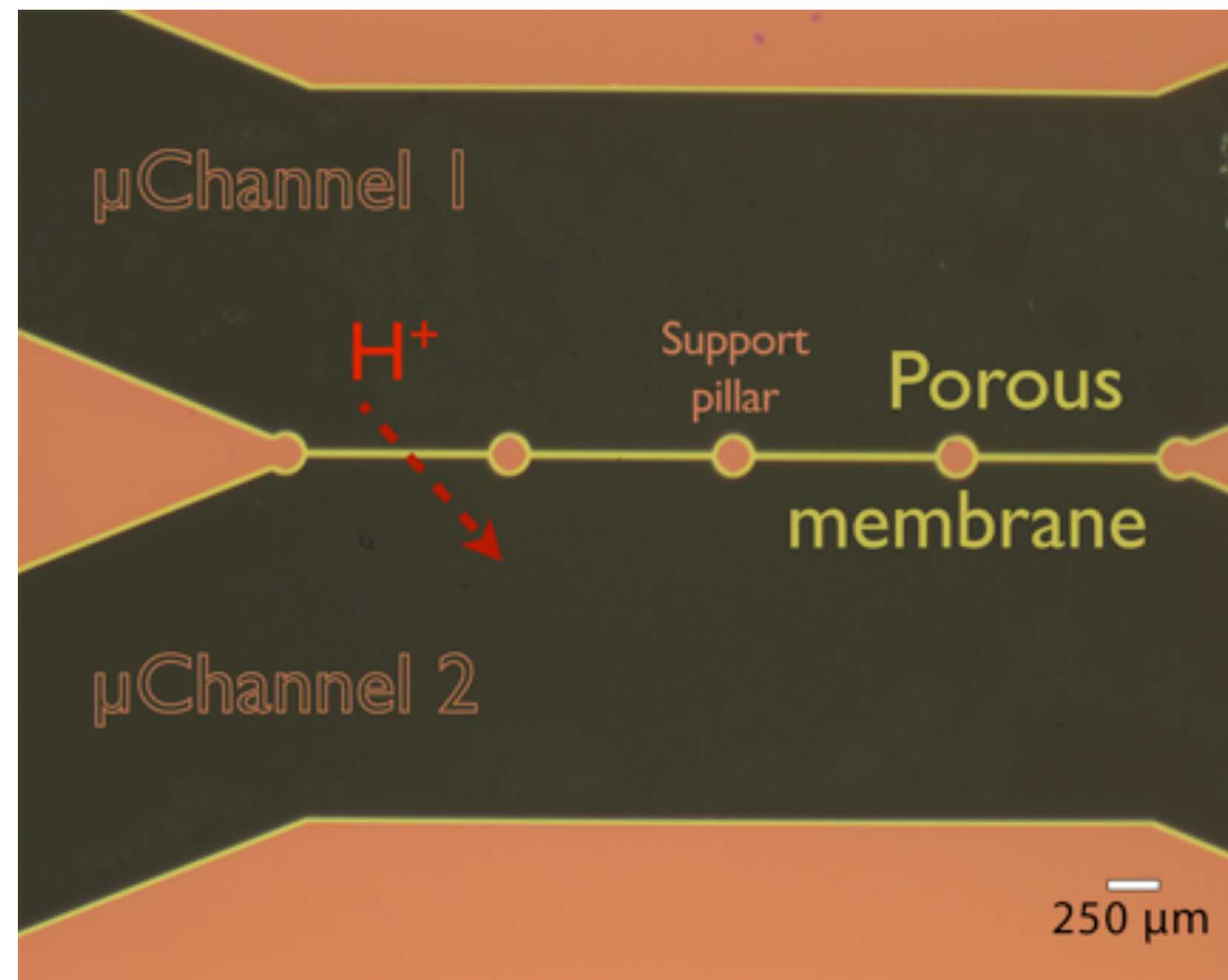


# Transport Device



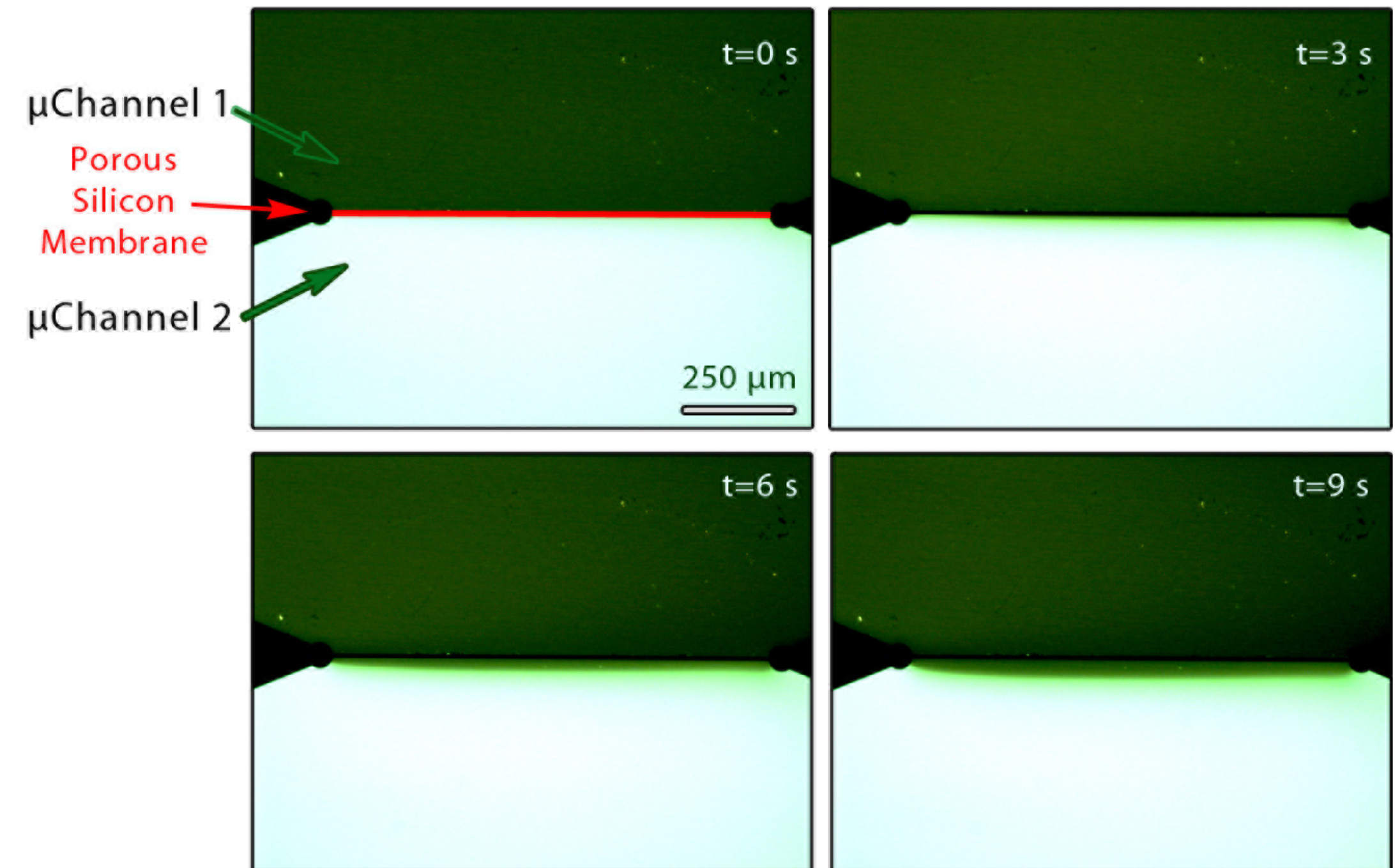
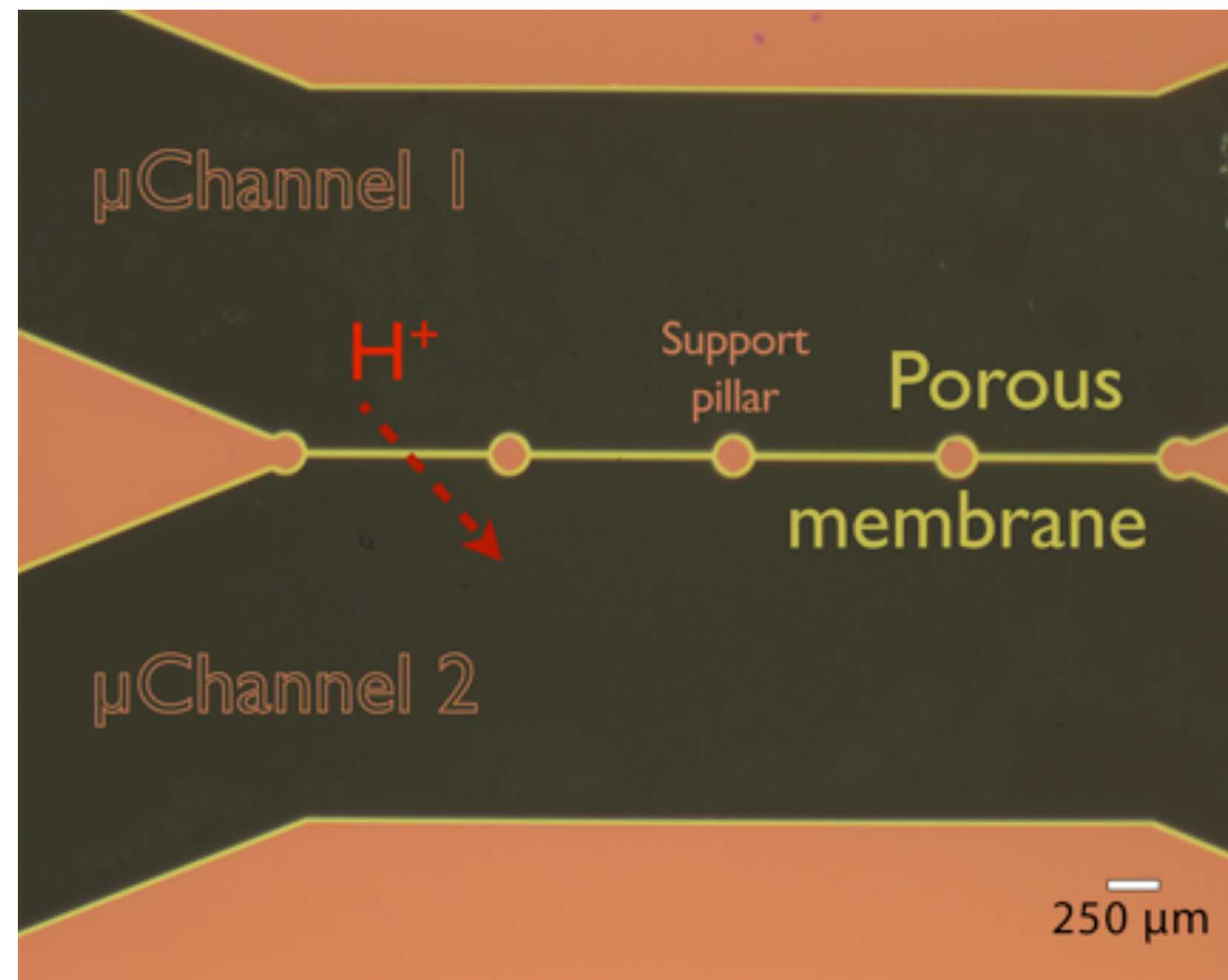


# Proton Management *Transport in Porous Silicon*



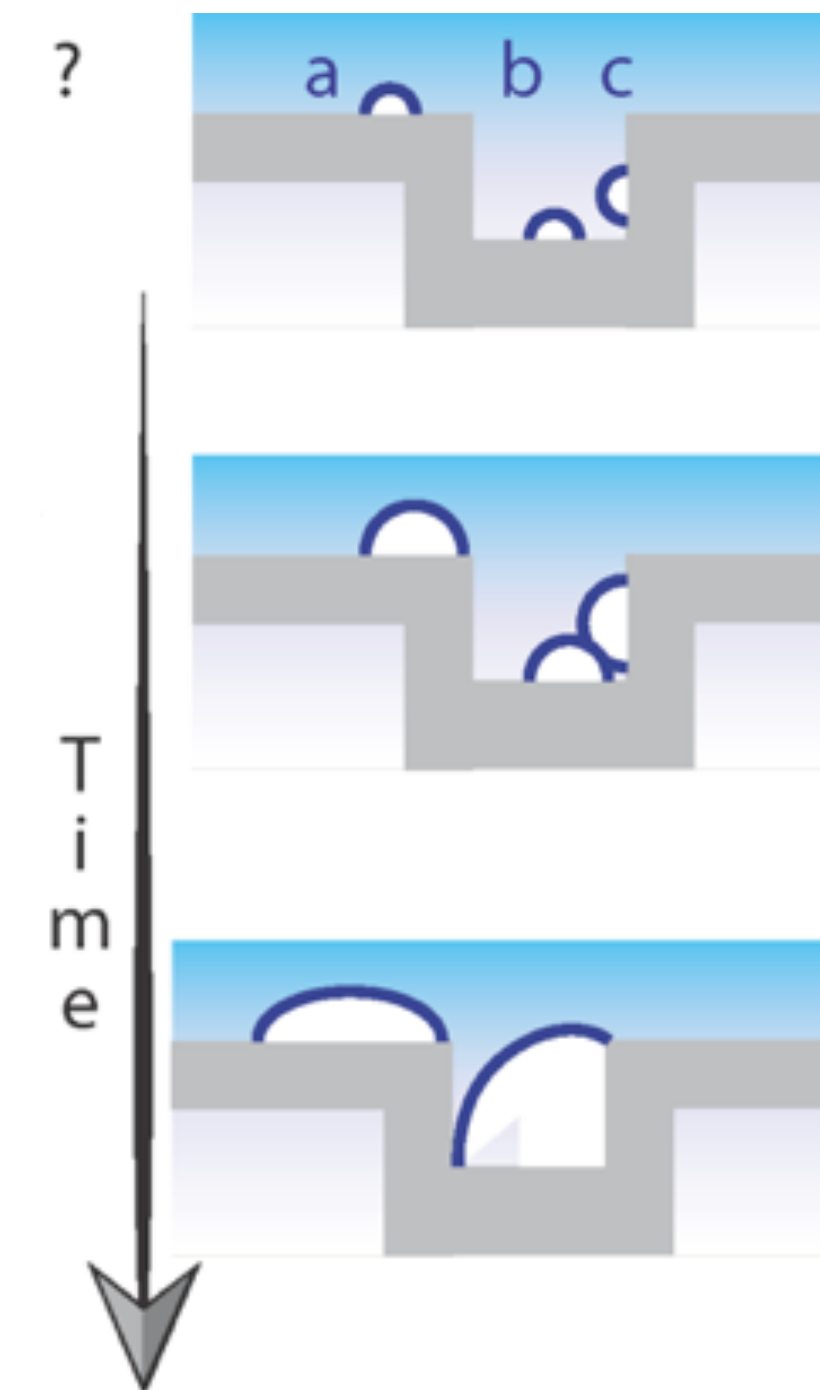
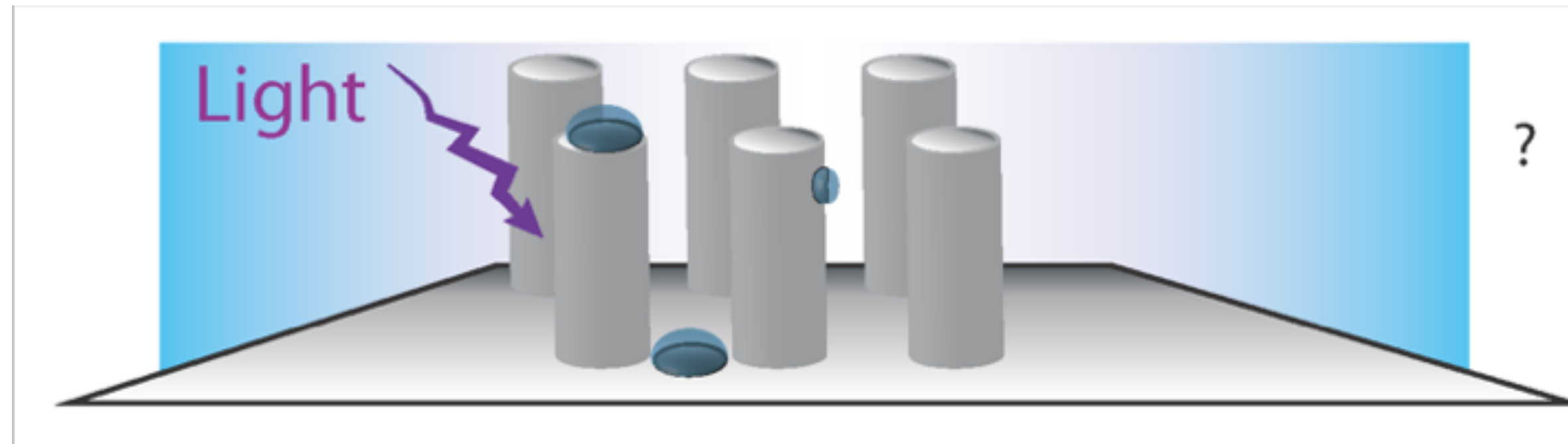
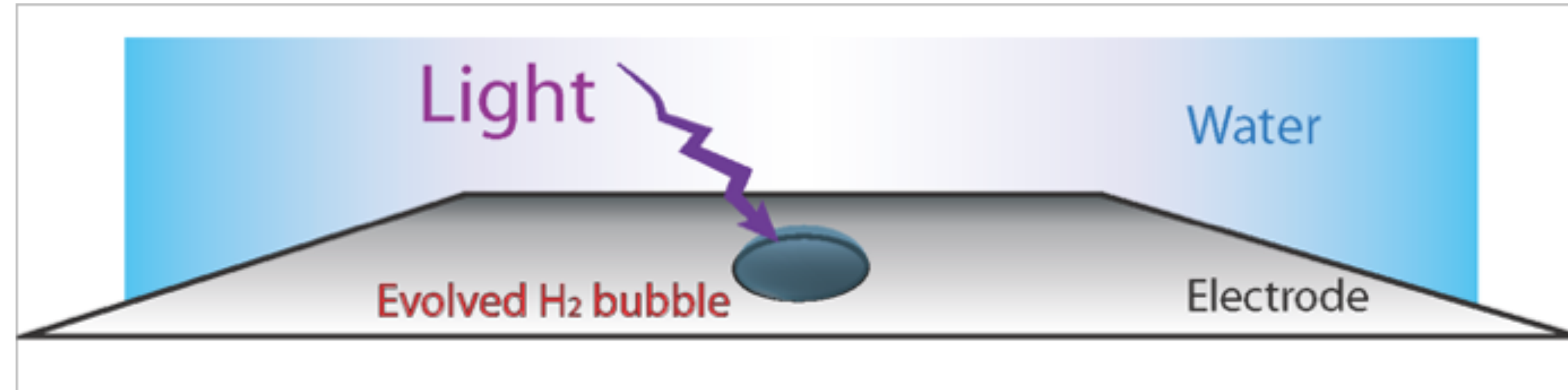


# Proton Management *Transport in Porous Silicon*





# Our experience





# Our approach

## Nucleation

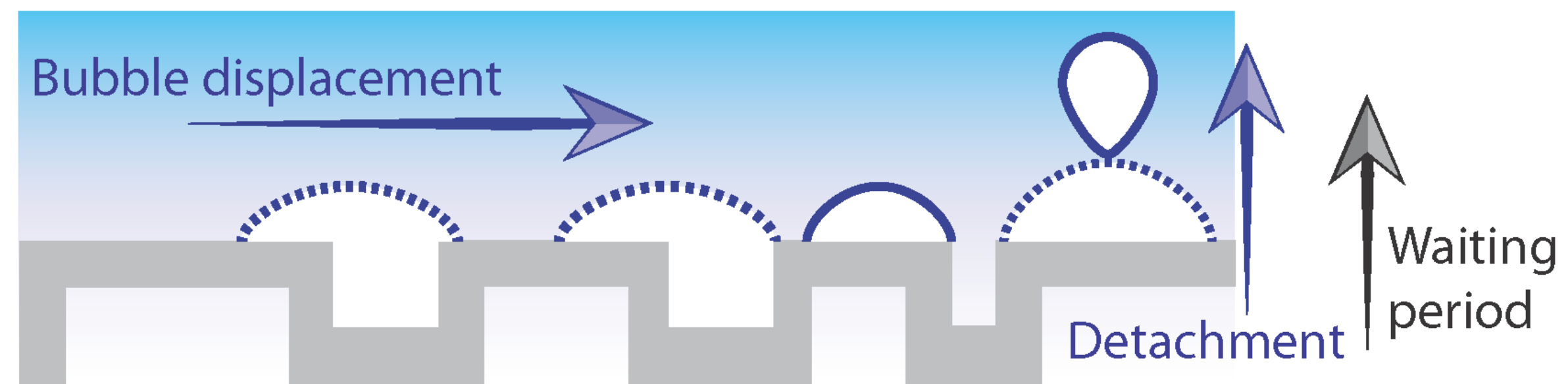
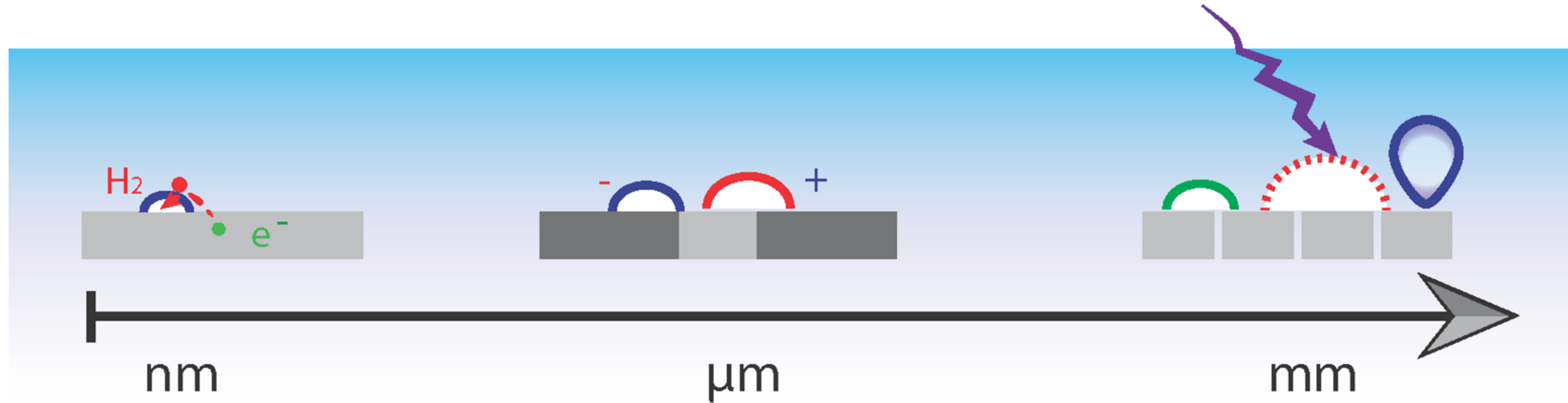
Multi-Phase reaction  
Nanotopology, Surfactants  
PZC, catalysts...

## Growth-coalescence

Surface properties  
Boundary layers  
Bubble charge

## Advection

Bubble detachment  
Local mass transfer  
Light interaction



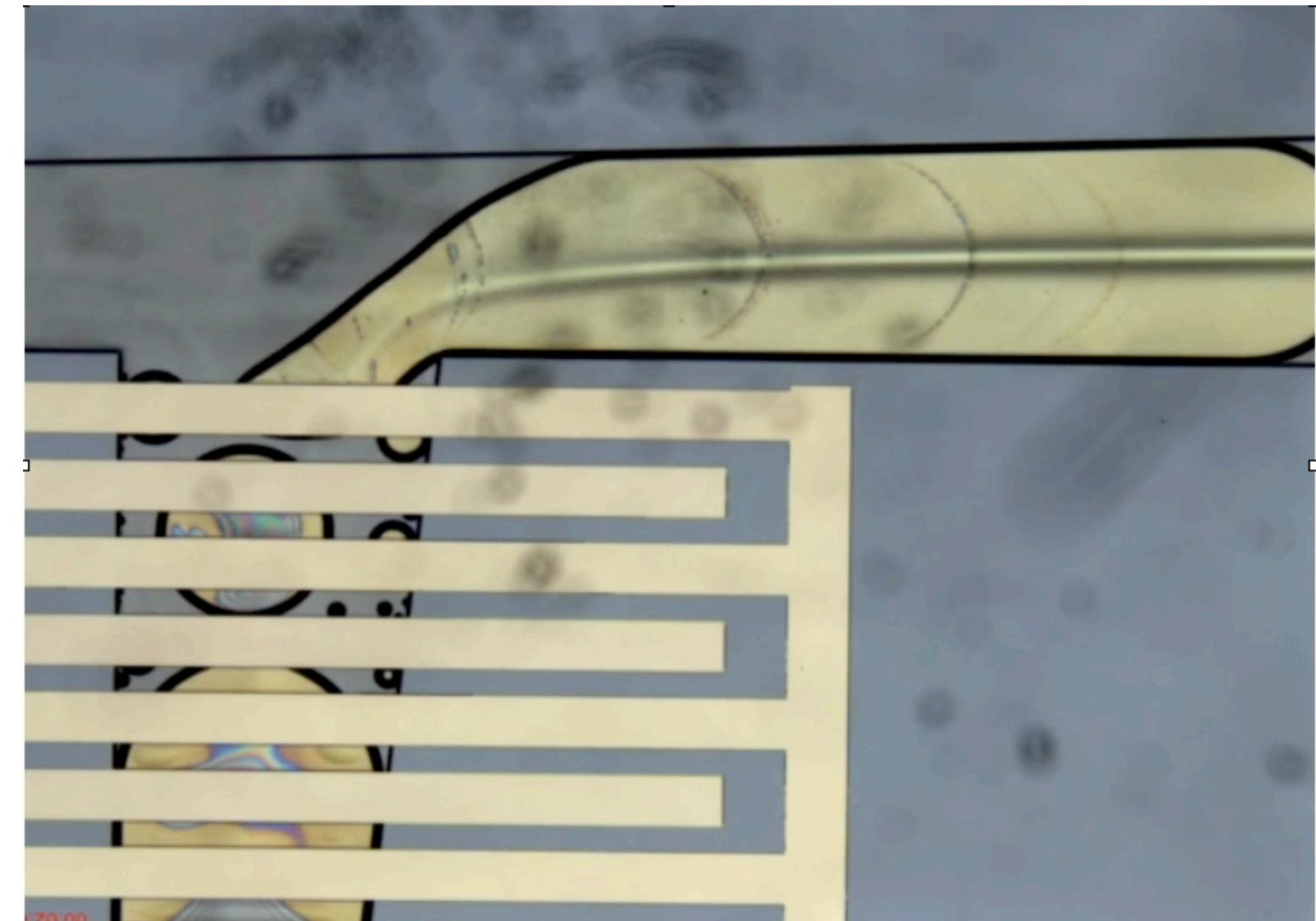
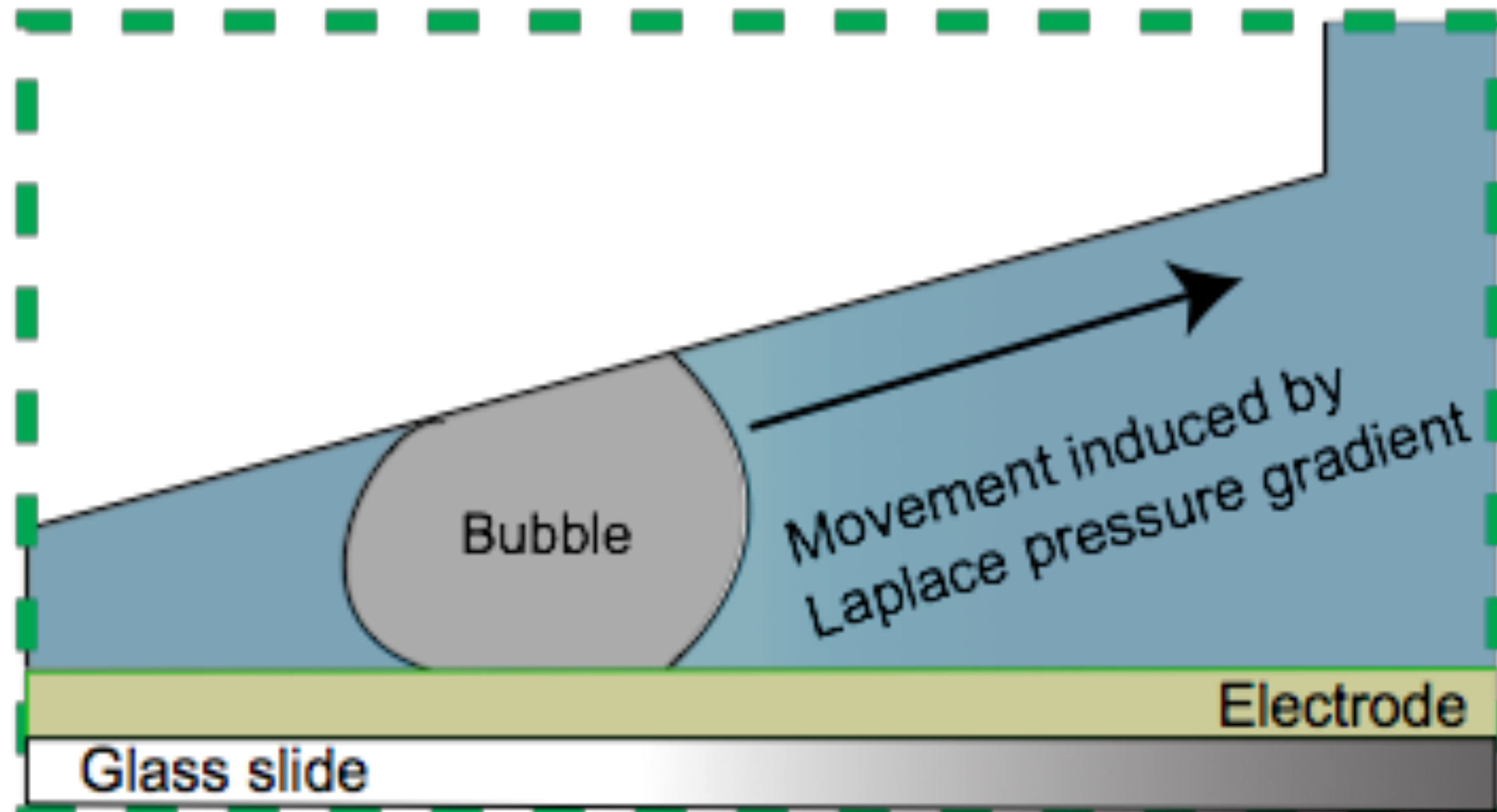
"Roughness" gradient



# Our approach

## Gas transport– Passive self-pumping

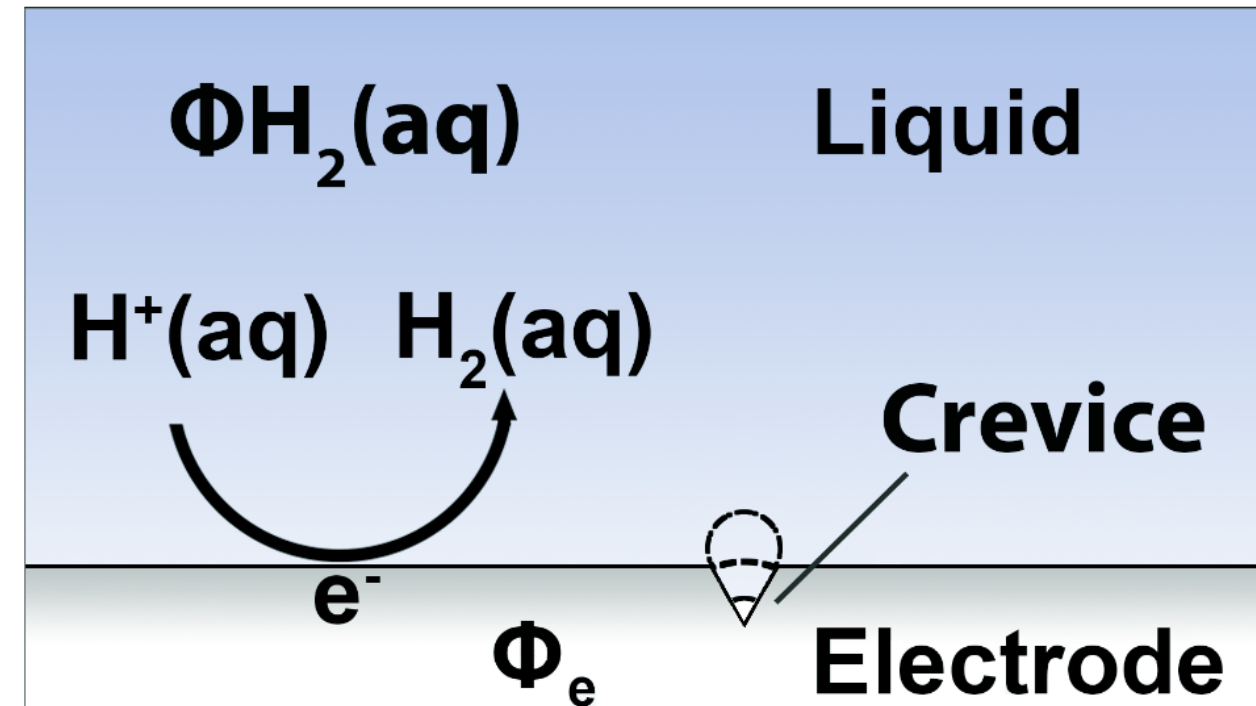
### Side View



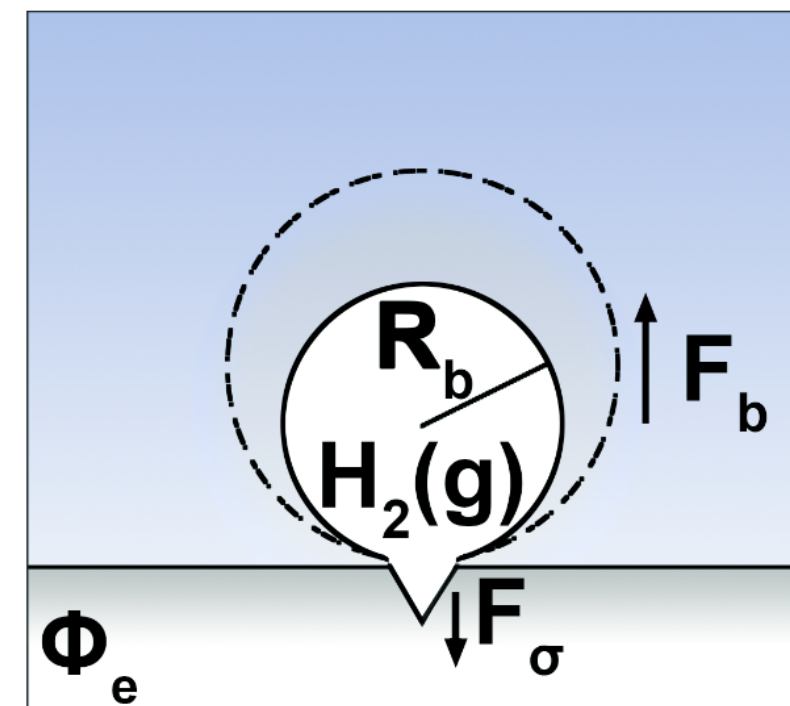


# Bubble Evolution

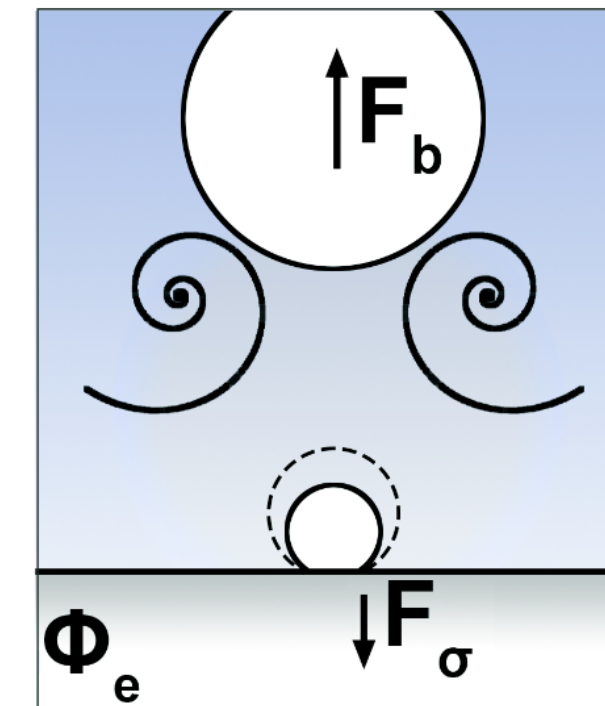
**A) Nucleation**



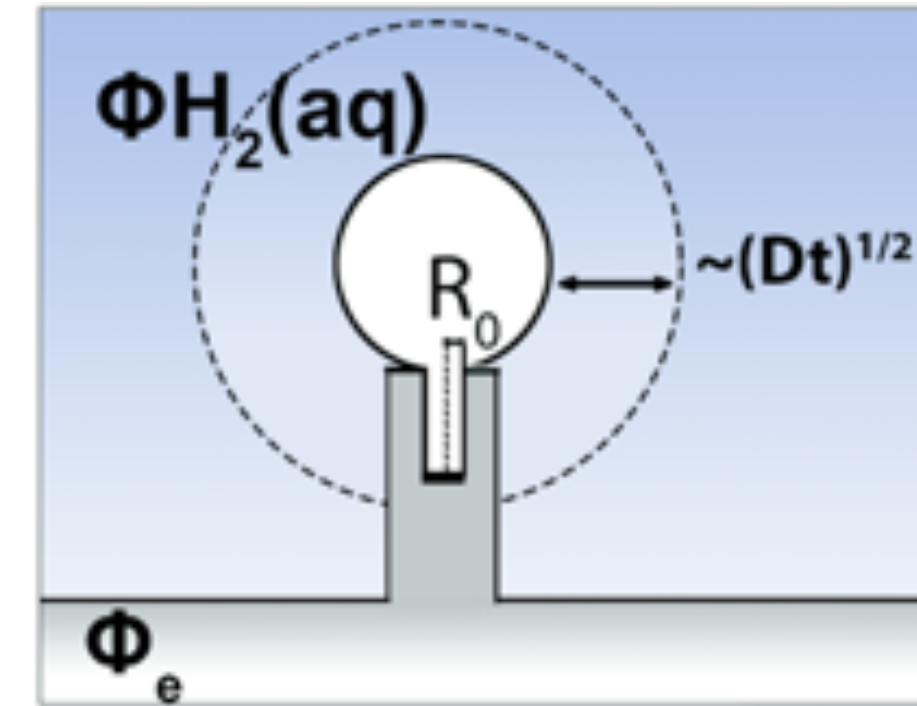
**B) Growth**



**C) Detachment**



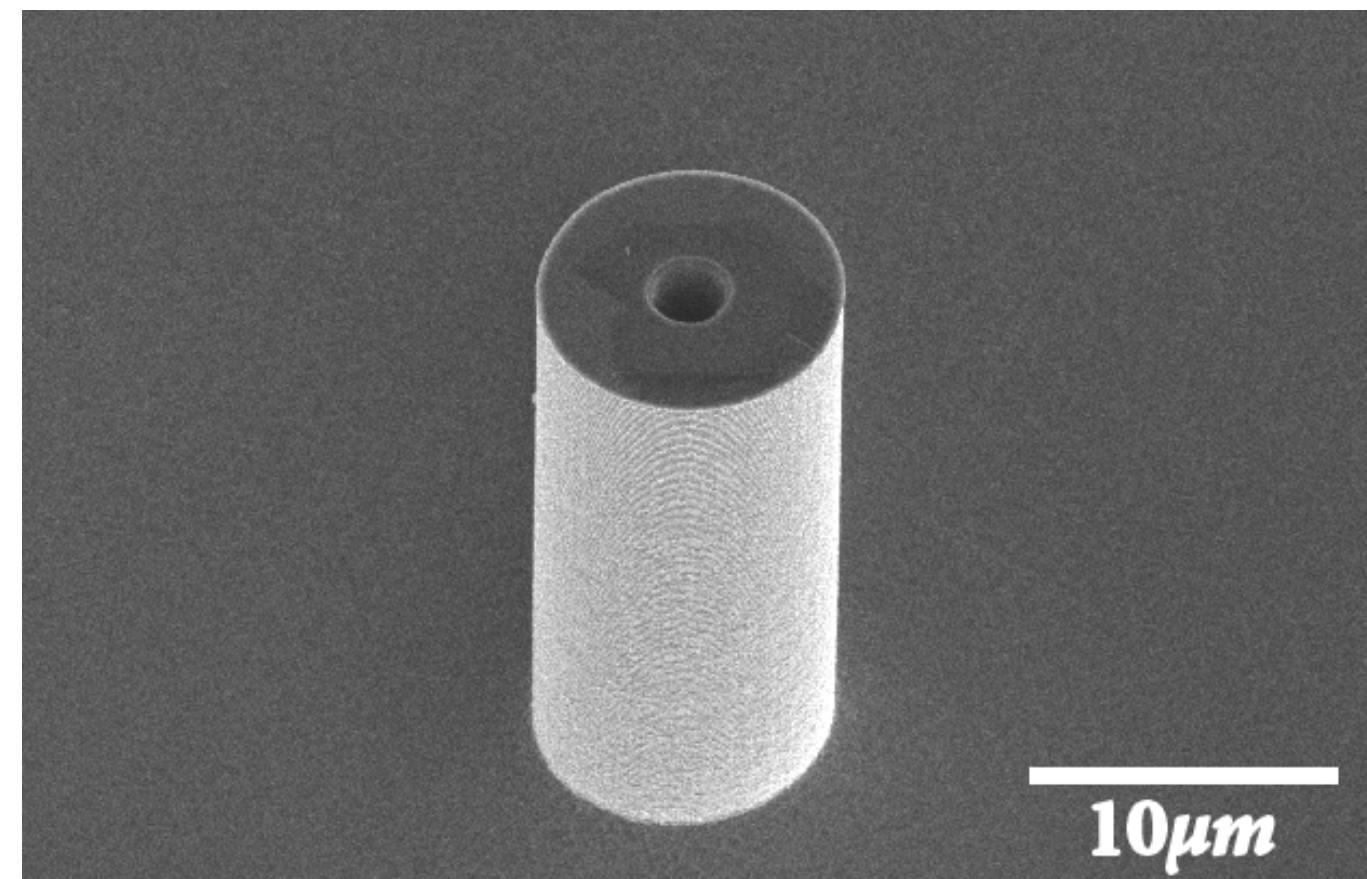
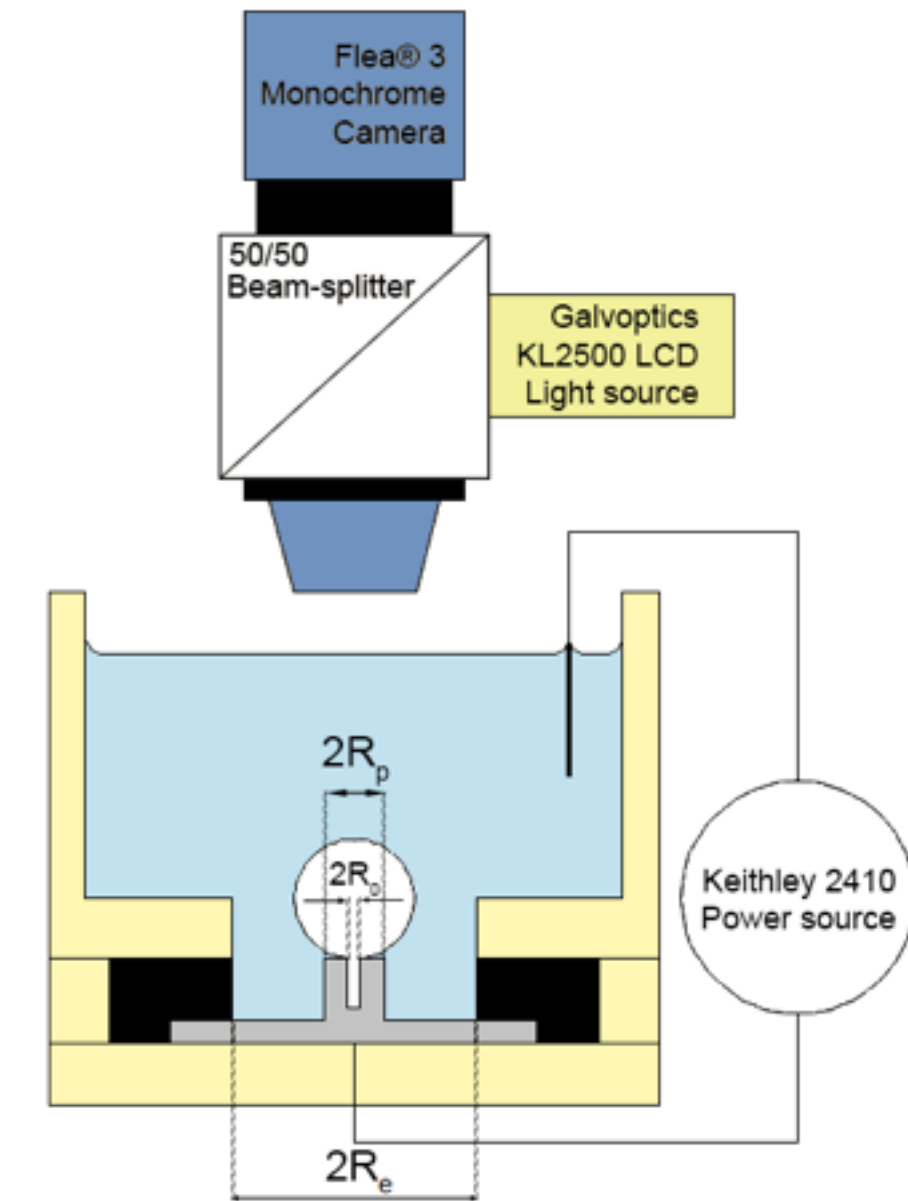
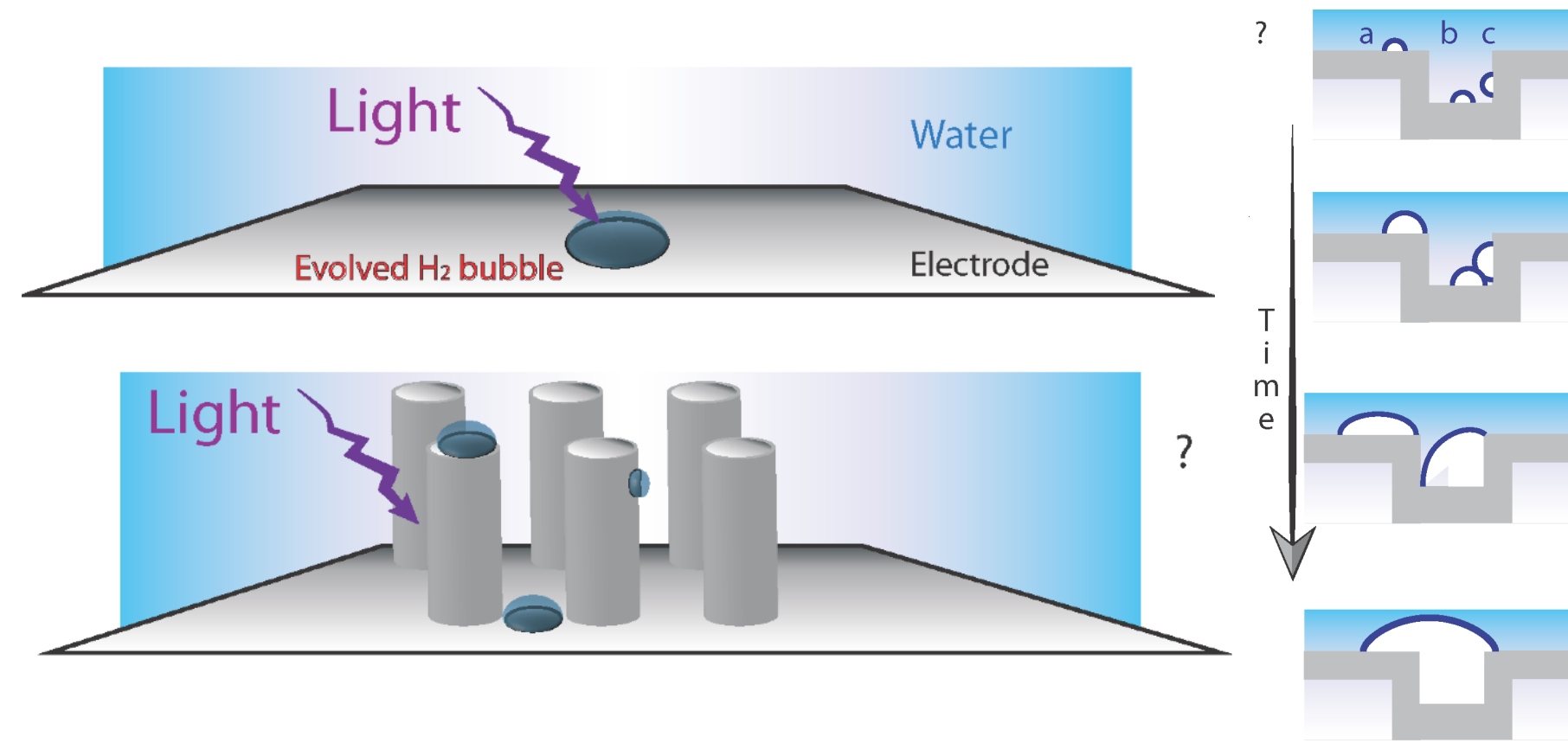
**Artificial nucleation**



van der Linde, P., et al. (2018). Gas bubble evolution on microstructured silicon substrates. Energy & environmental science, 11(12), 3452-3462.

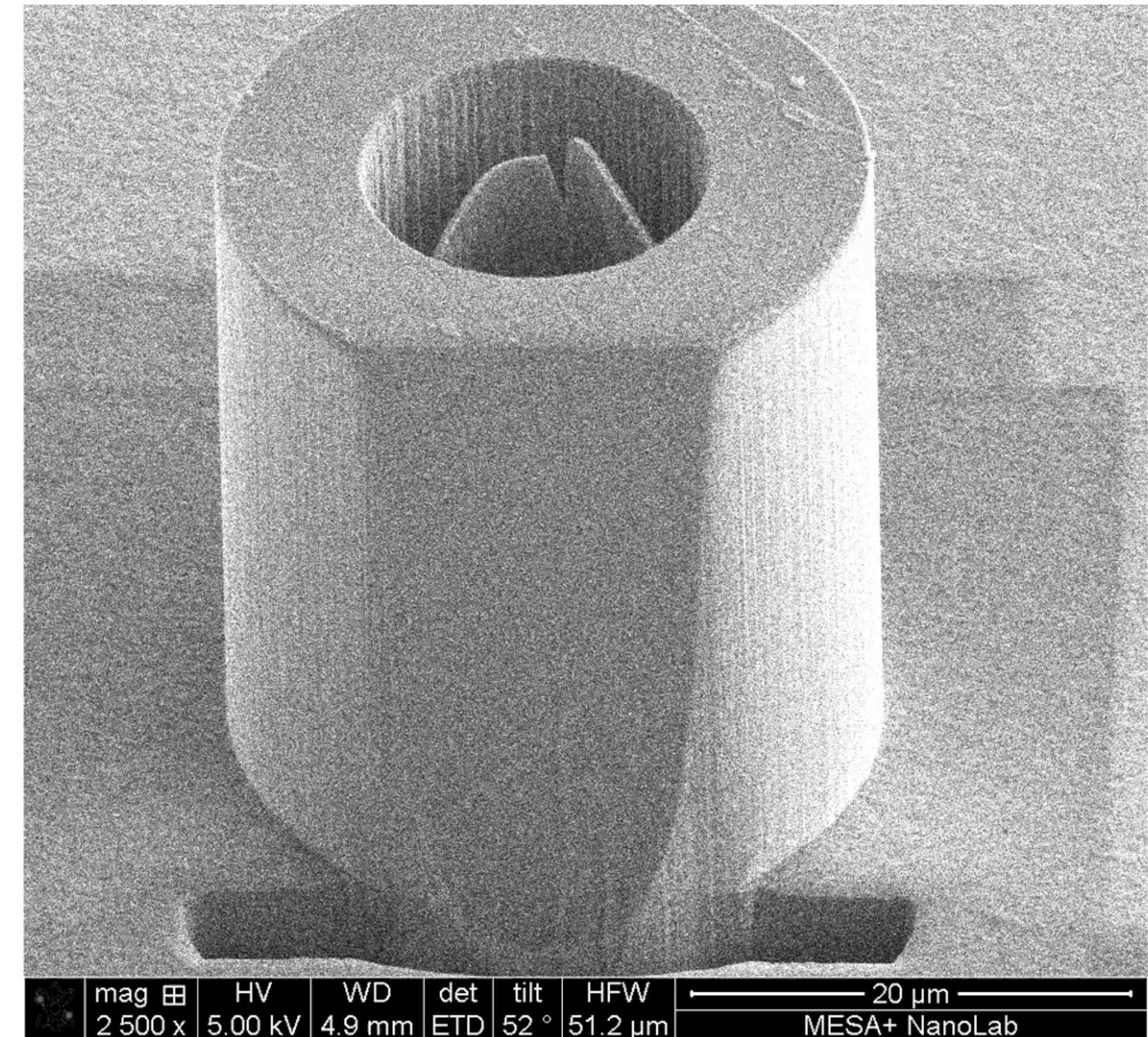
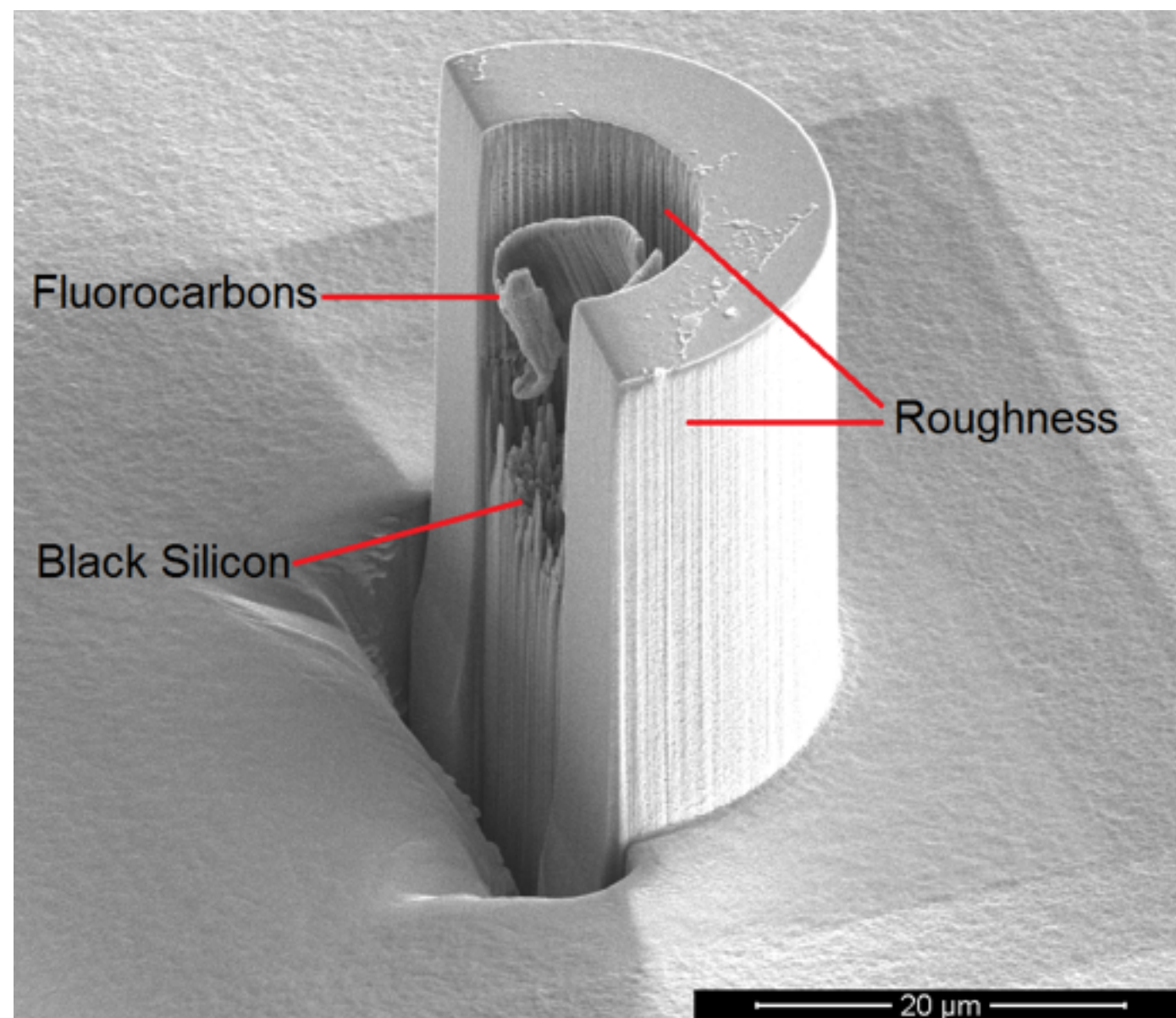
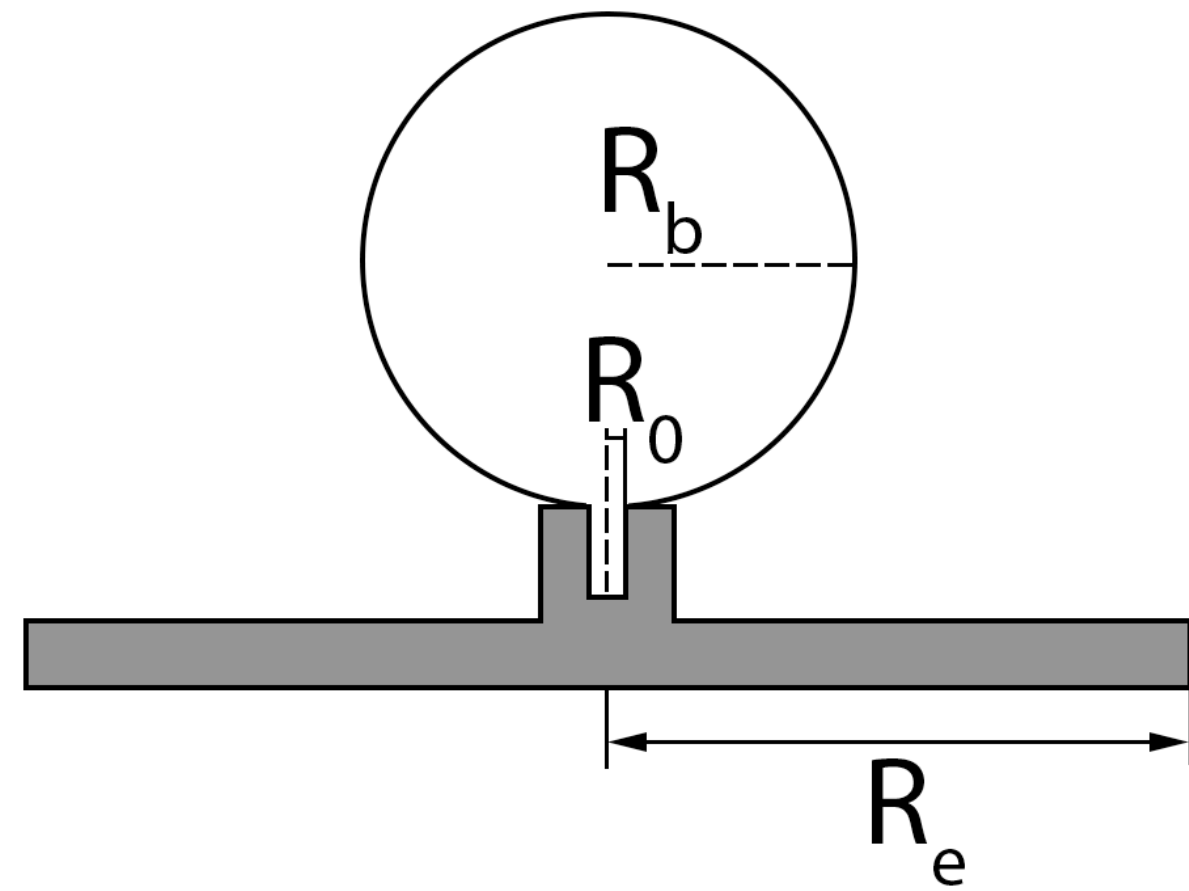


# Bubble Evolution



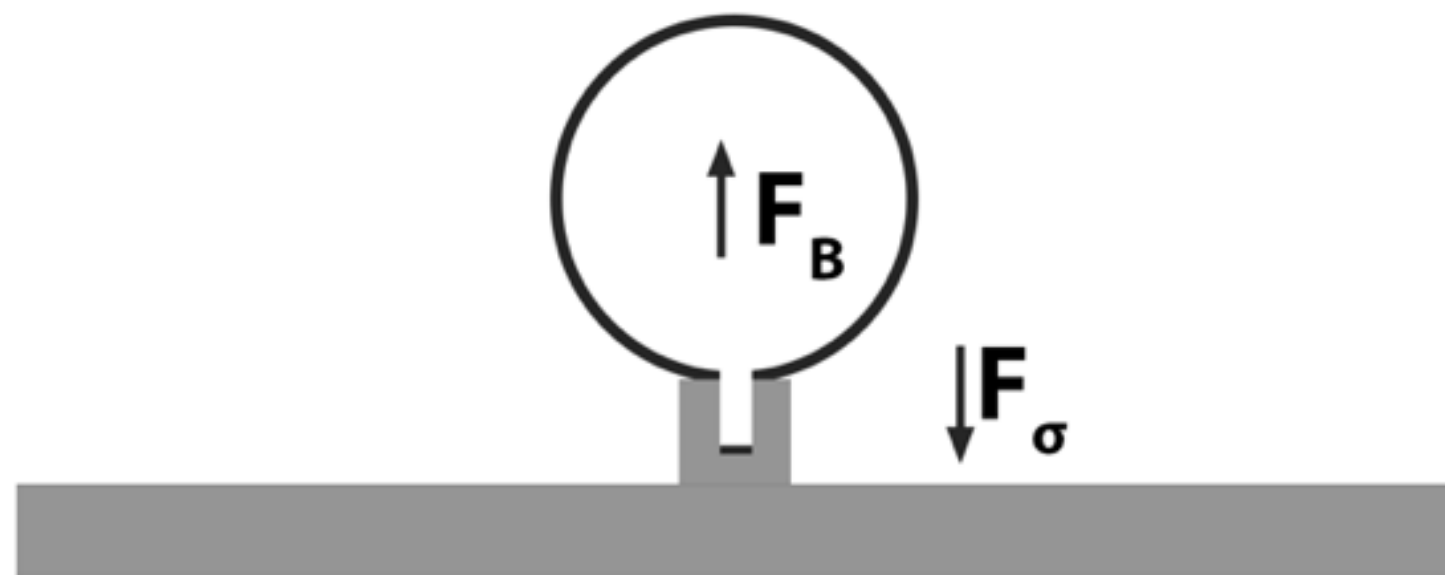
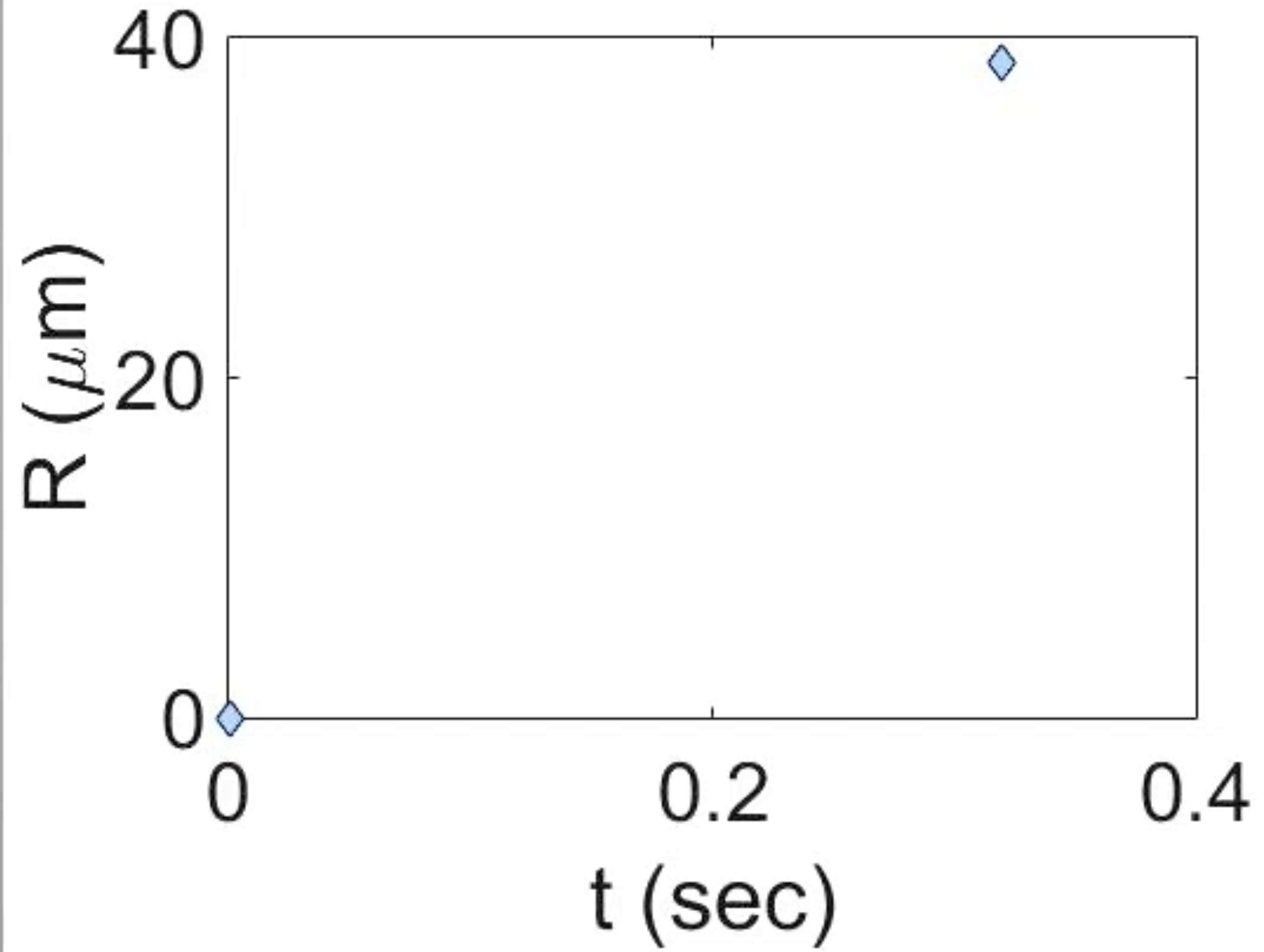
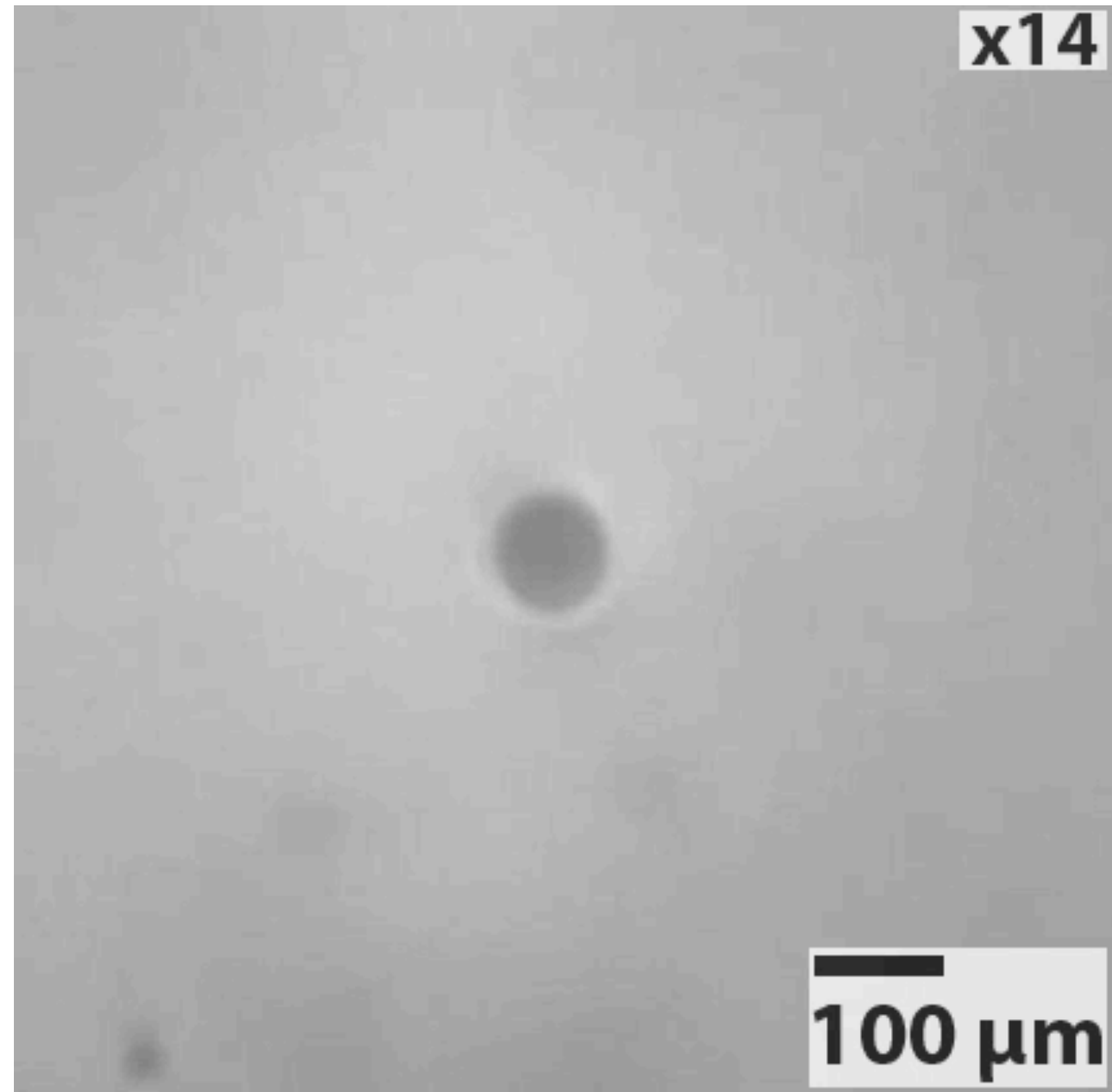


# Trapping bubbles



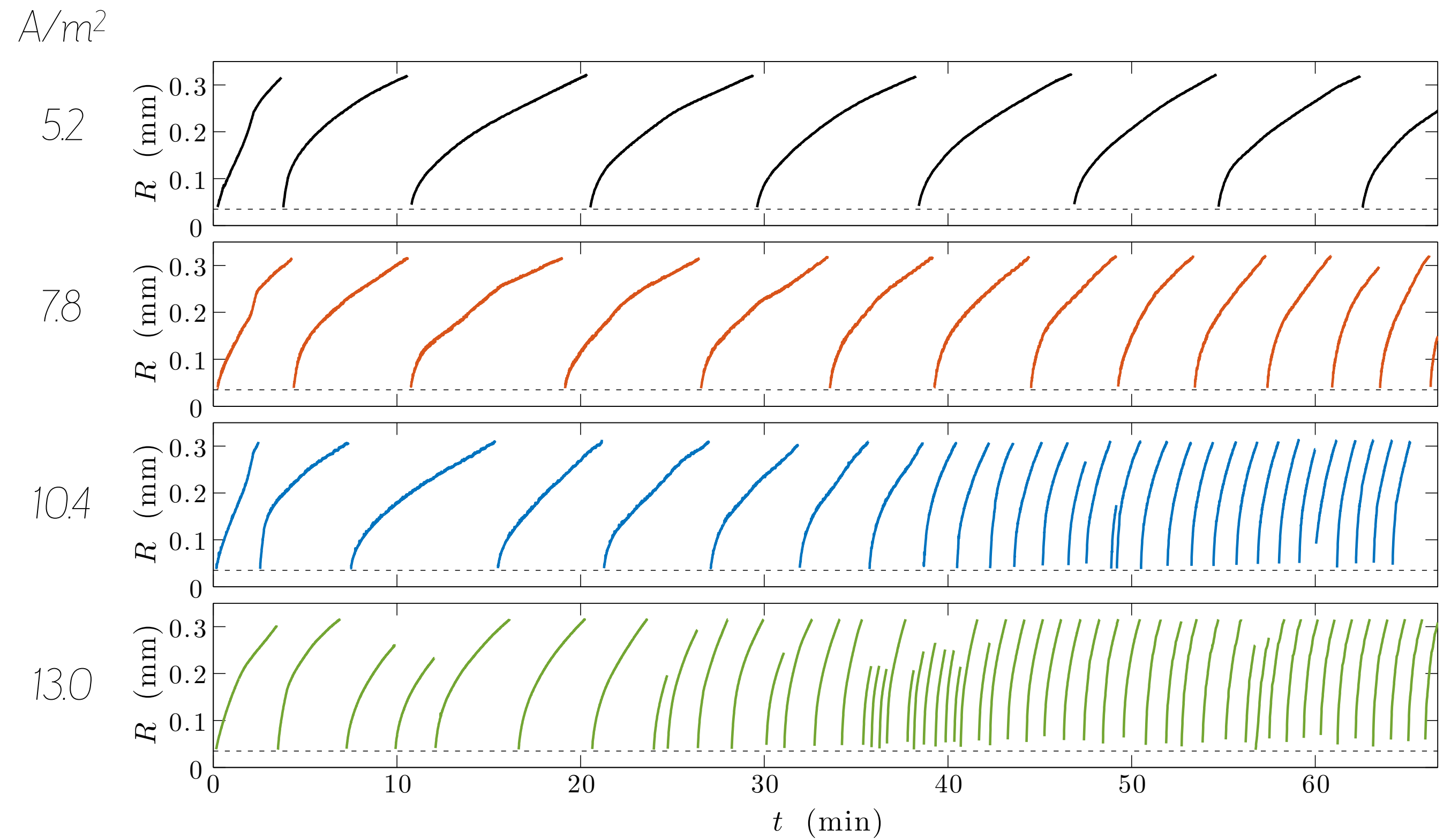
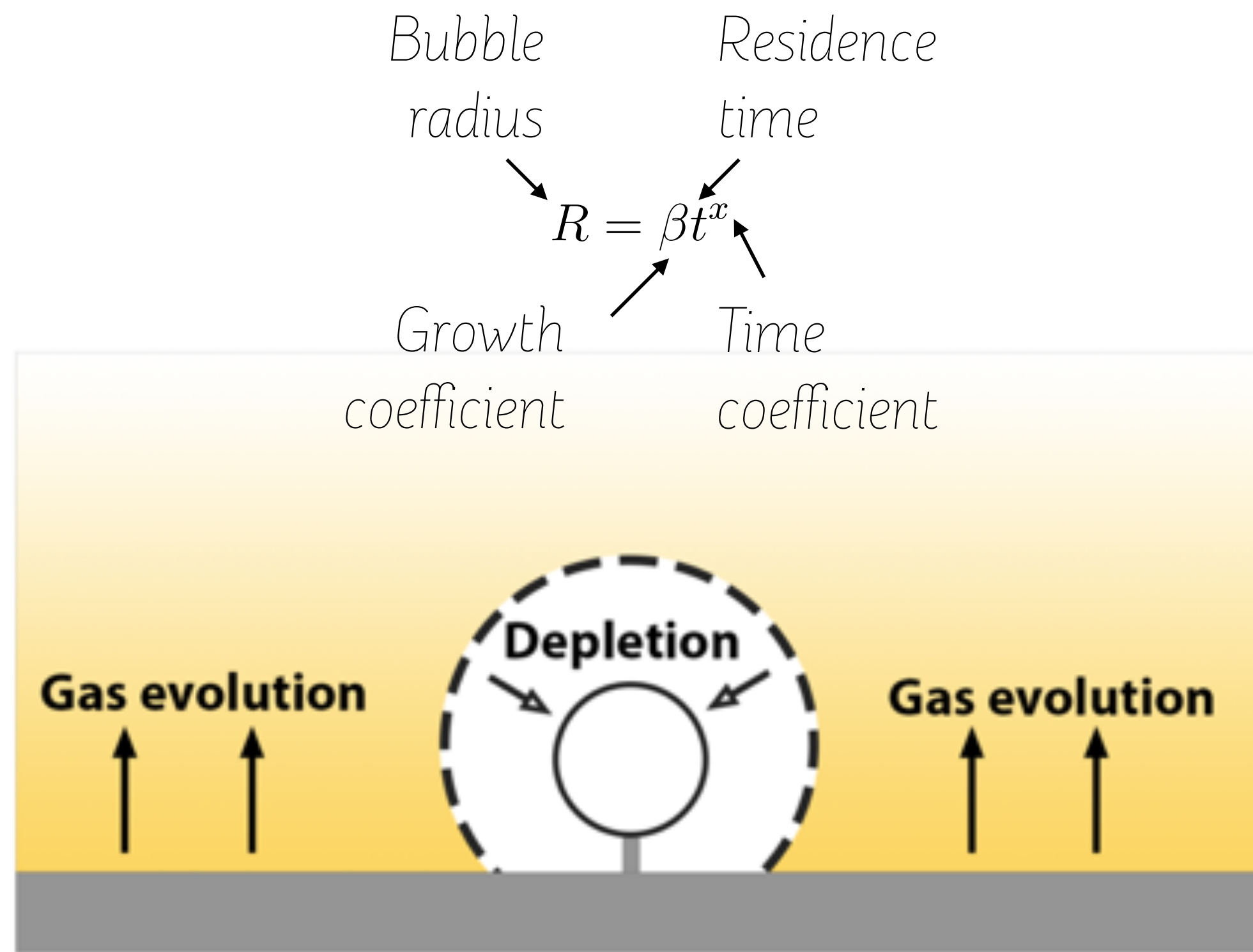


# Contemplating bubbles



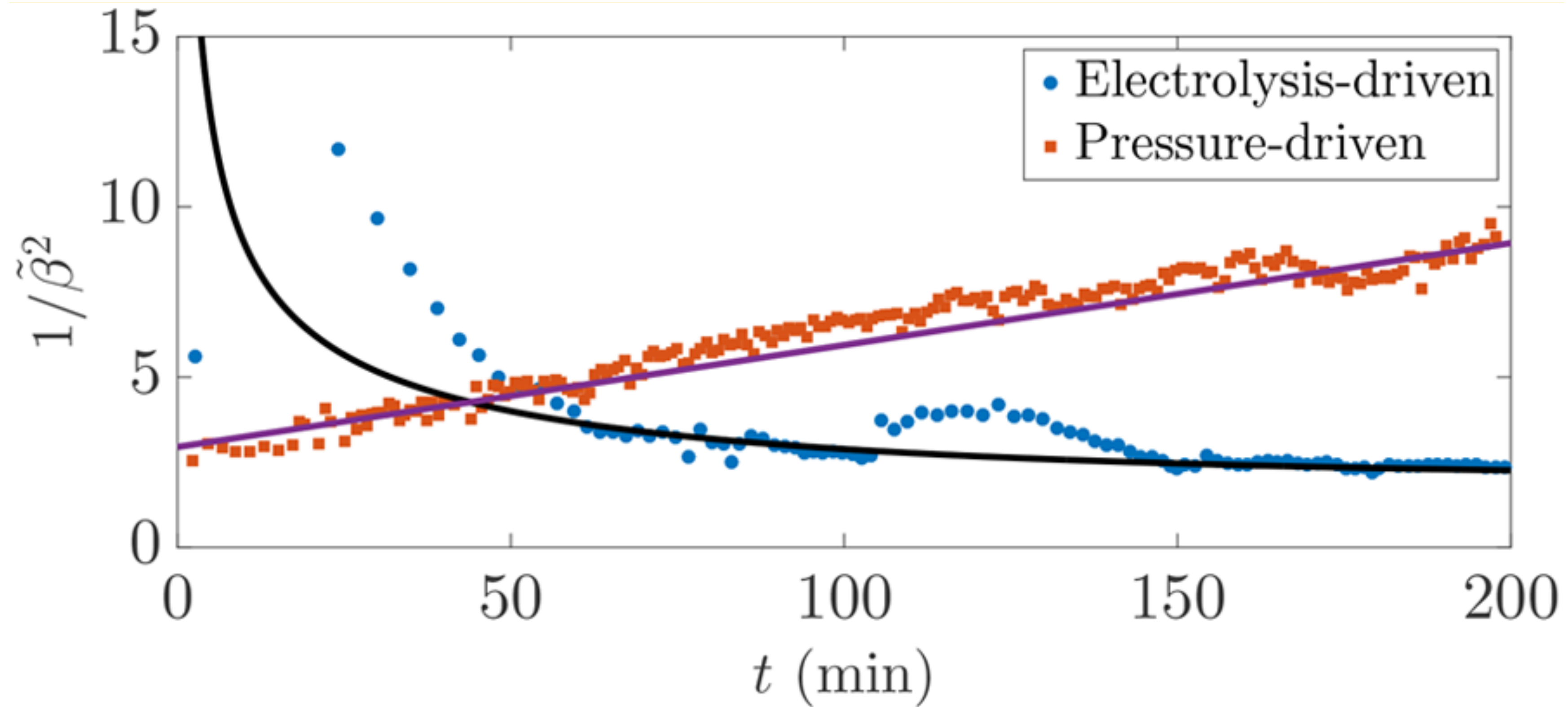


# Radii of bubbles





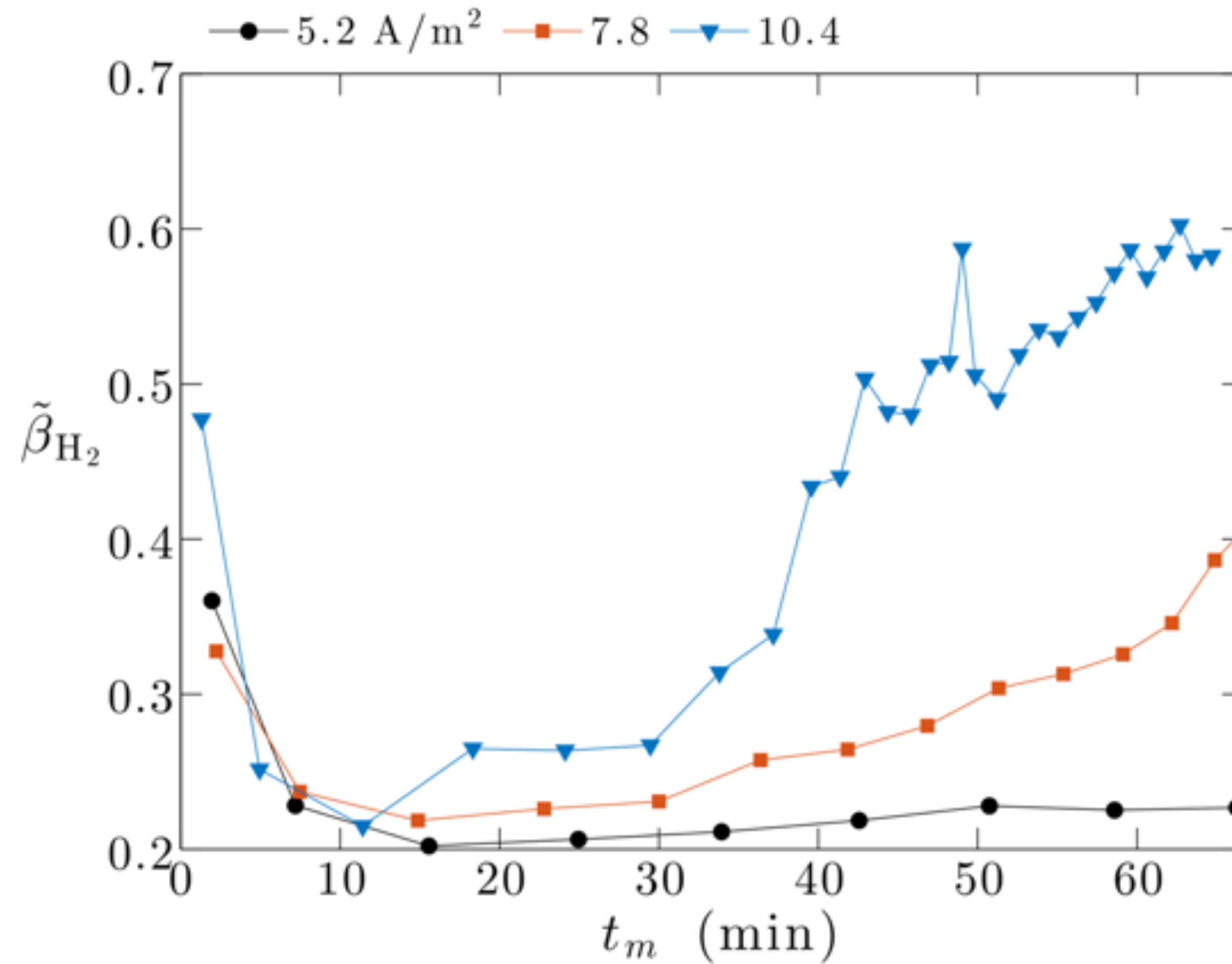
# Comparing bubbles



van der Linde, et al. "Electrolysis-Driven and Pressure-Controlled Diffusive Growth of Successive Bubbles on Microstructured Surfaces." *Langmuir* 33.45 (2017): 12873-12886.



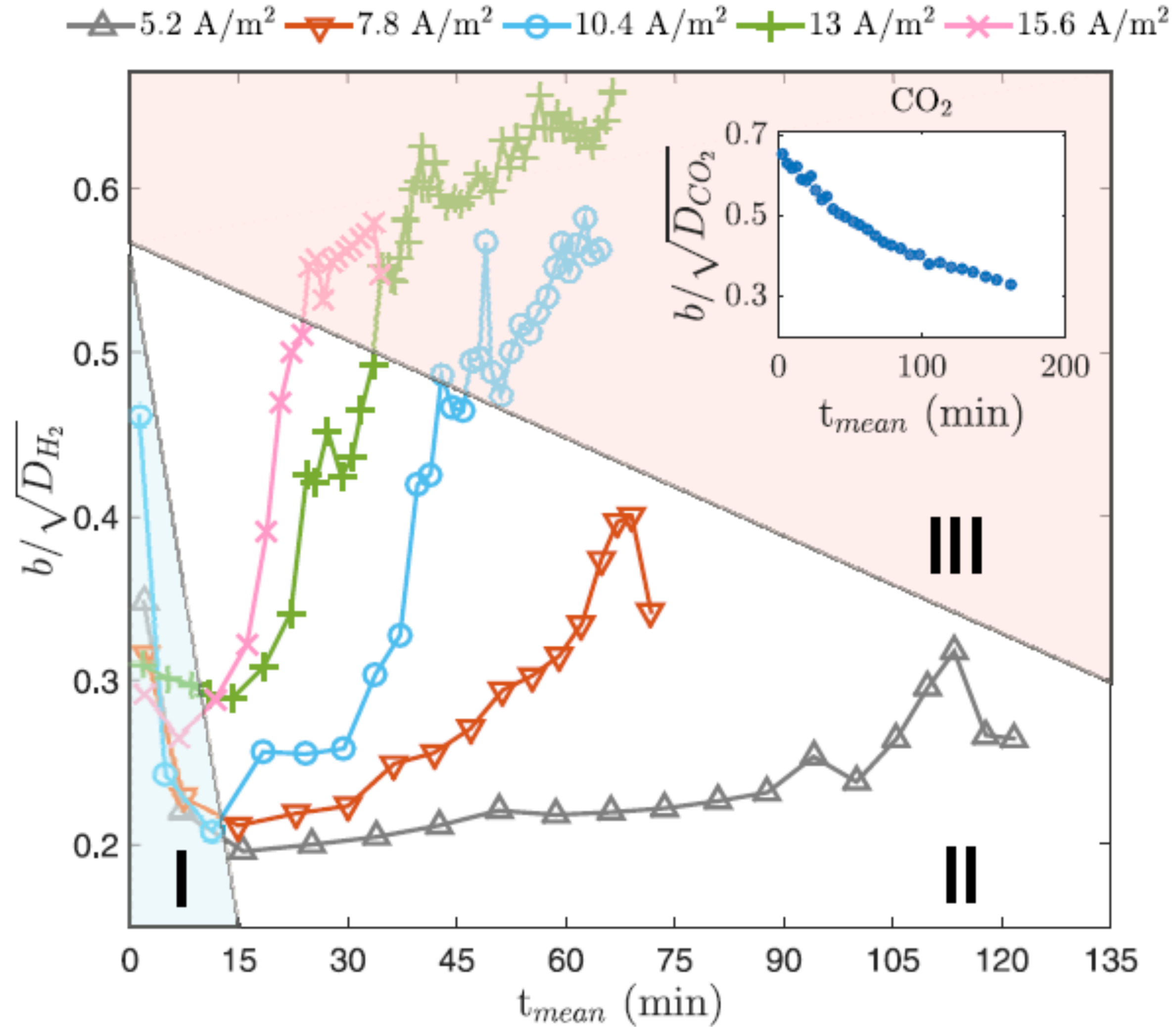
# Growing bubbles



van der Linde, et al. "Electrolysis-Driven and Pressure-Controlled Diffusive Growth of Successive Bubbles on Microstructured Surfaces." *Langmuir* 33.45 (2017): 12873-12886.



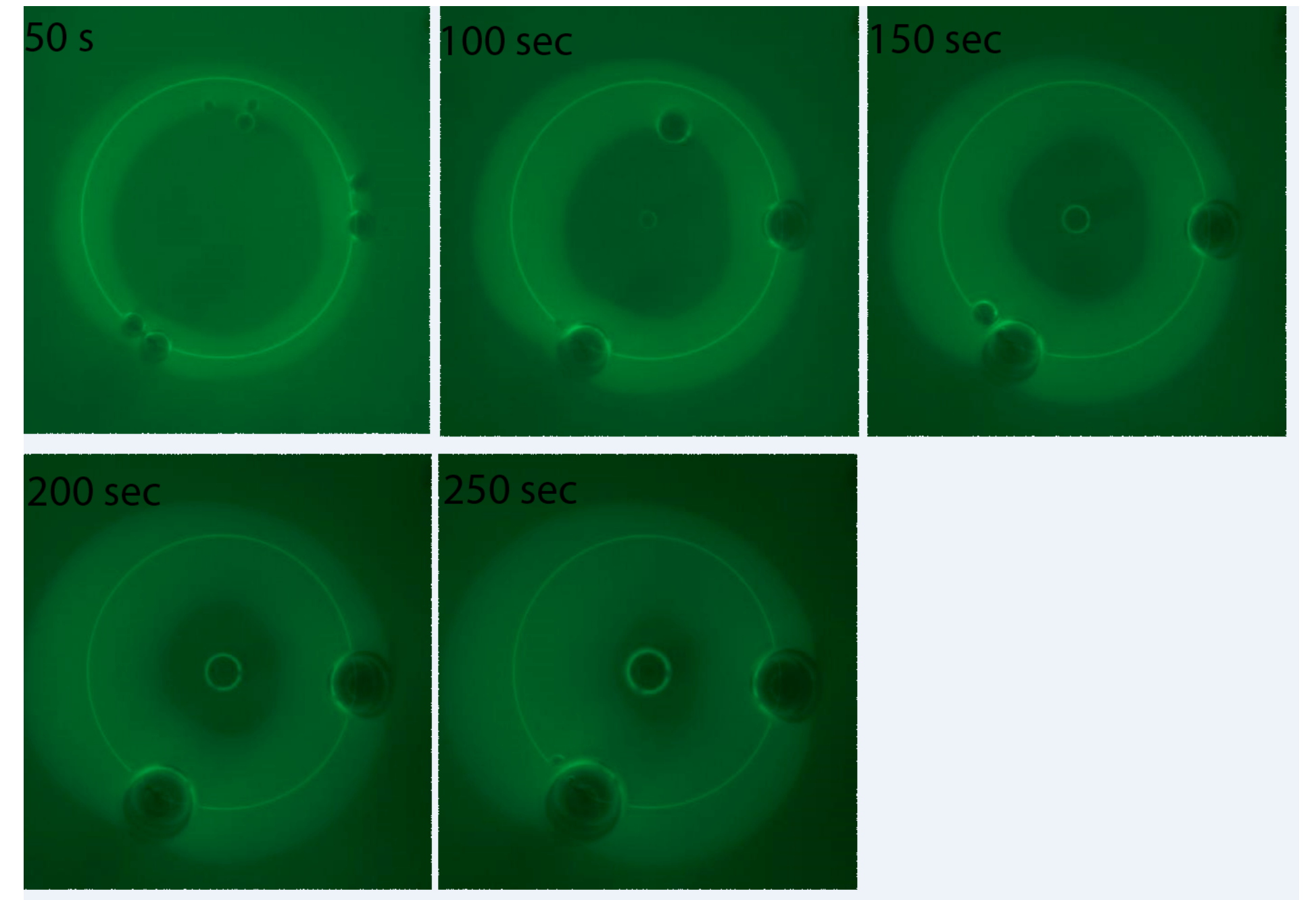
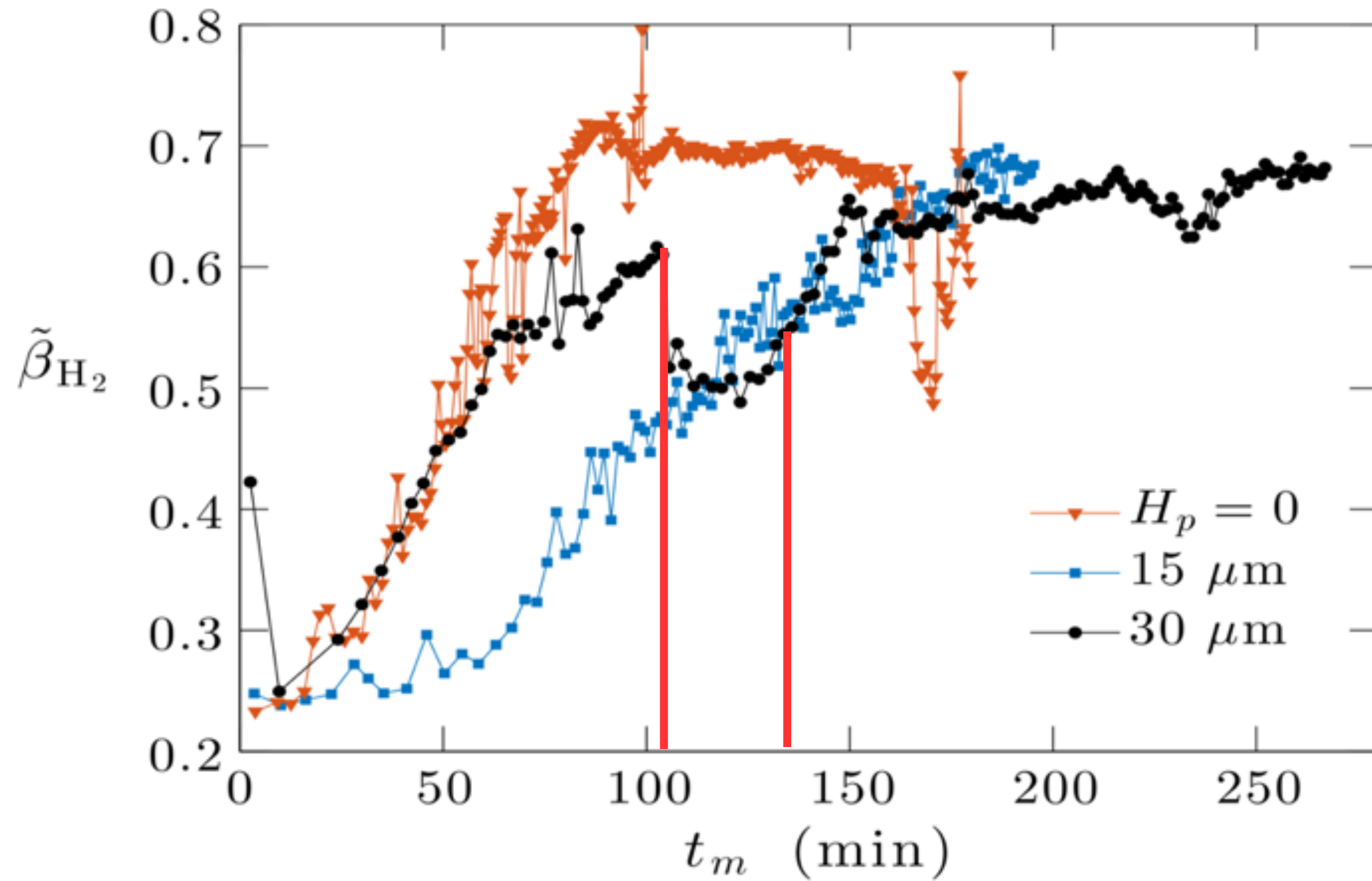
# Growing bubbles



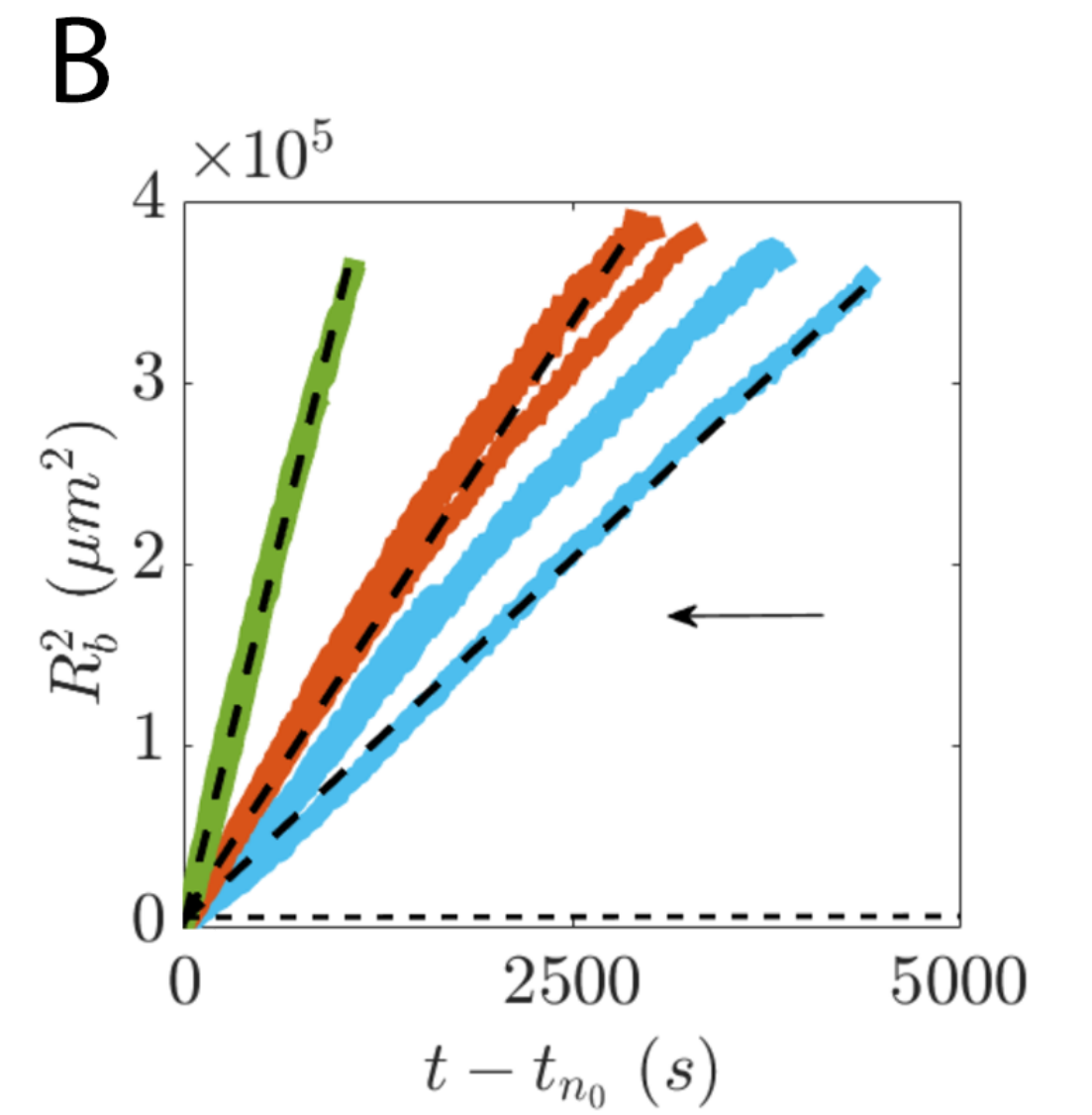
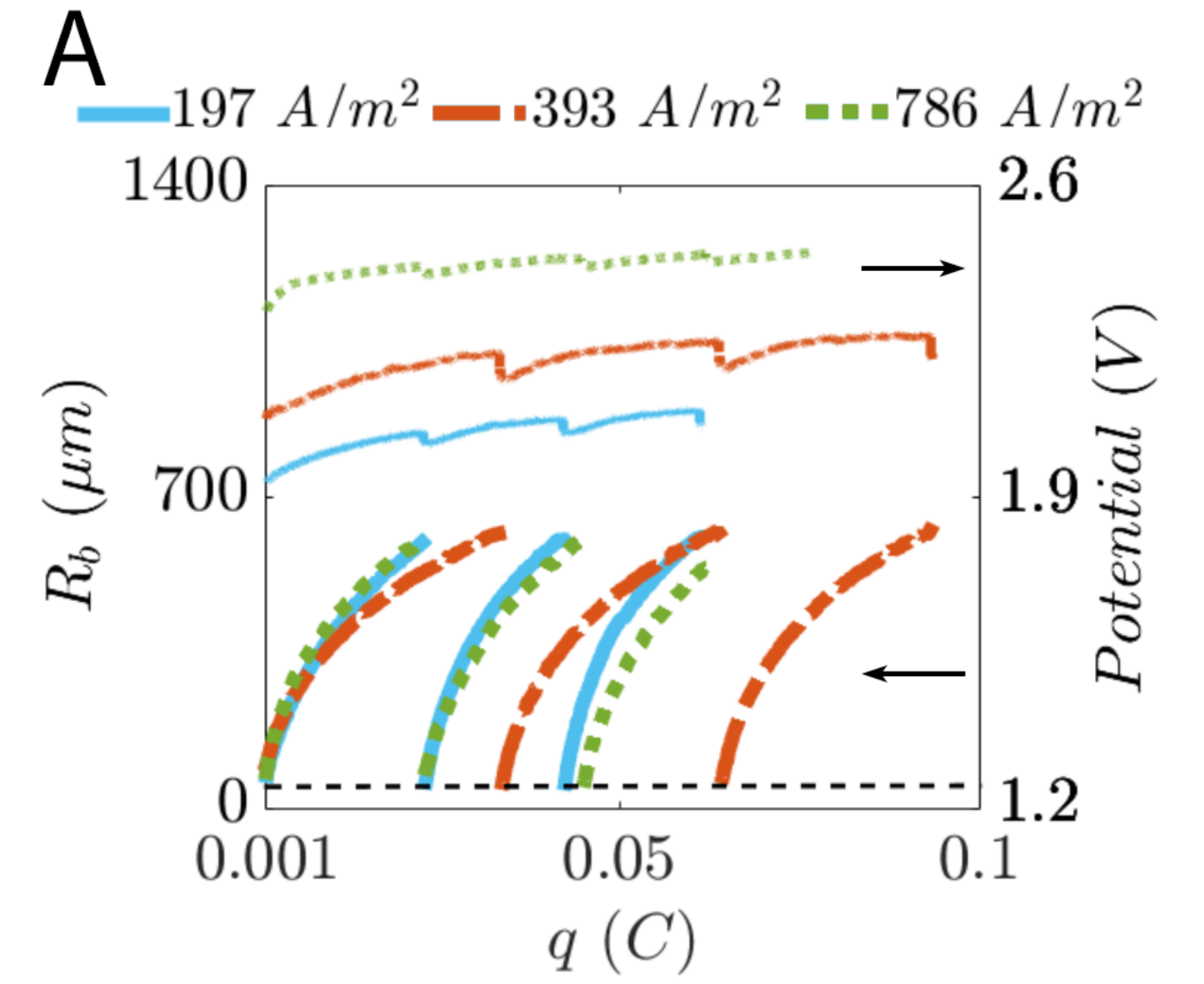
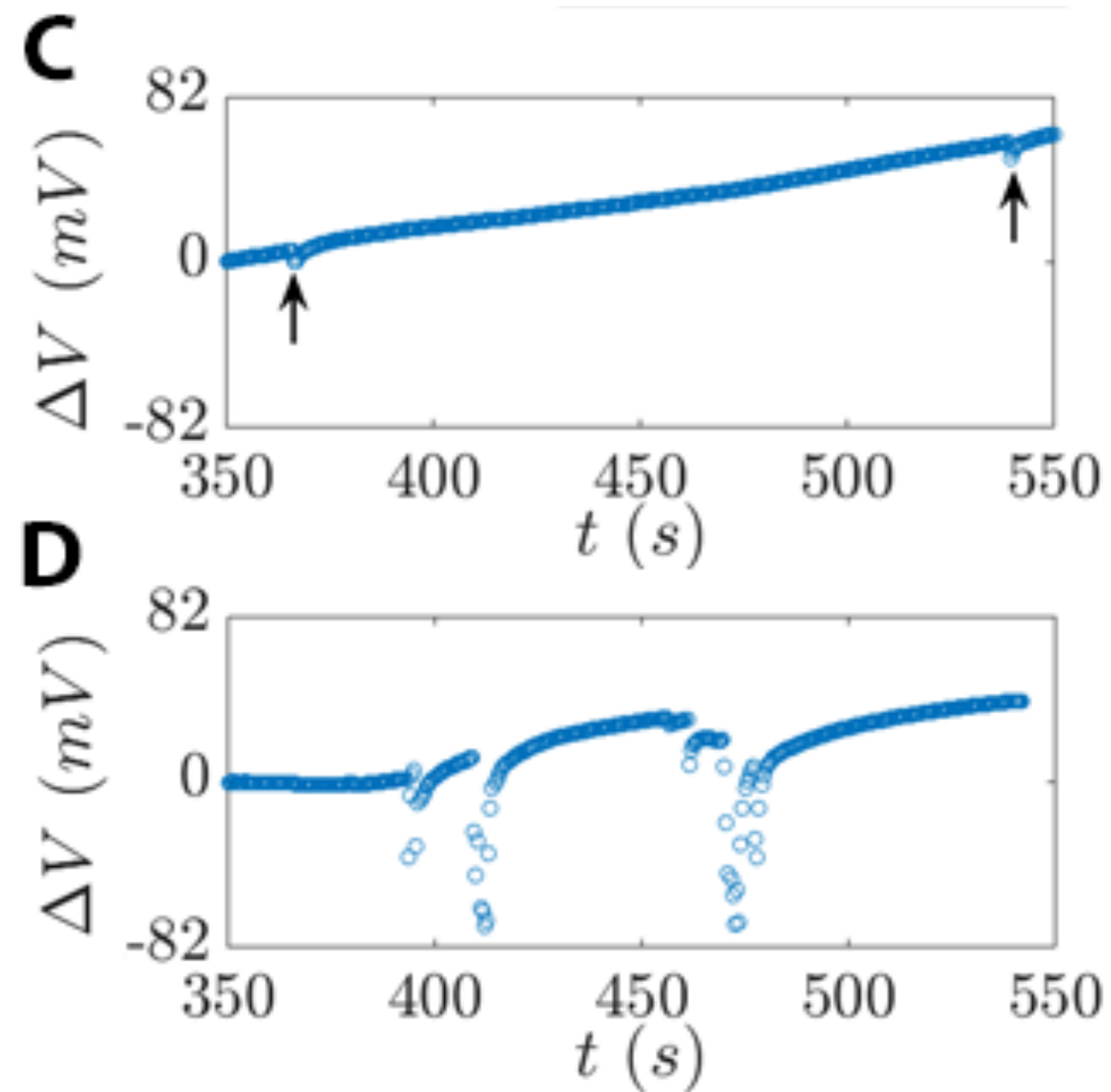
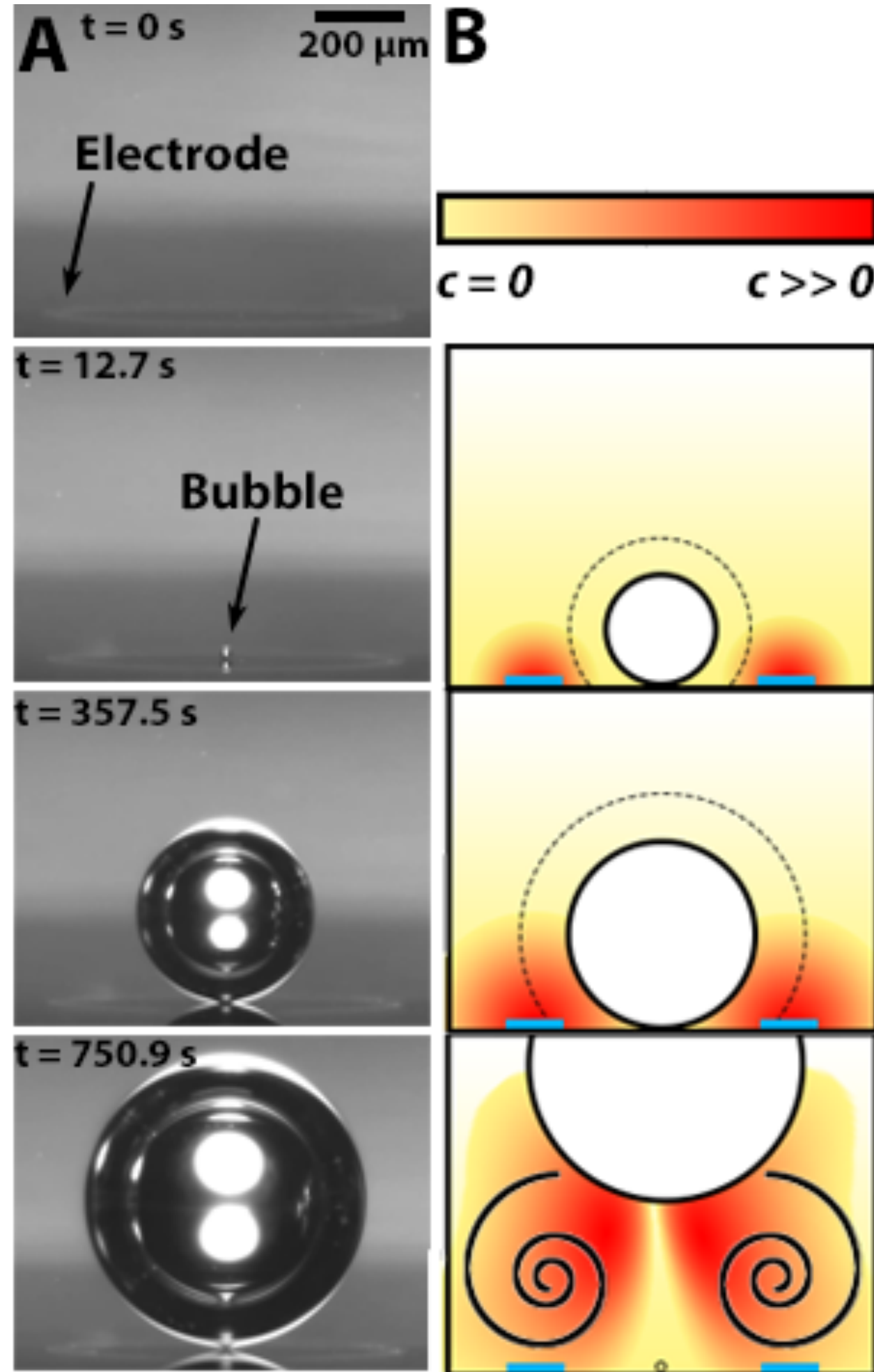
van der Linde, et al. "Electrolysis-Driven and Pressure-Controlled Diffusive Growth of Successive Bubbles on Microstructured Surfaces." Langmuir 33.45 (2017): 12873-12886.



# Parasite bubble detection

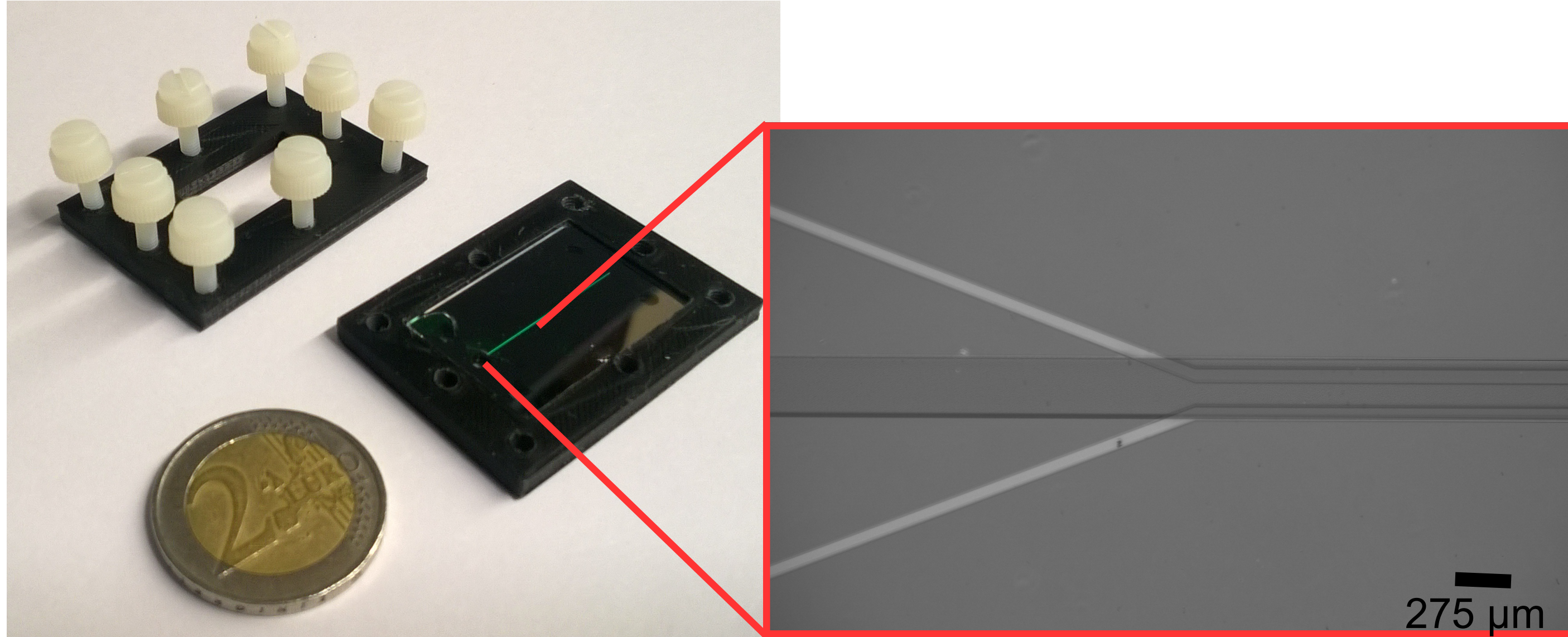




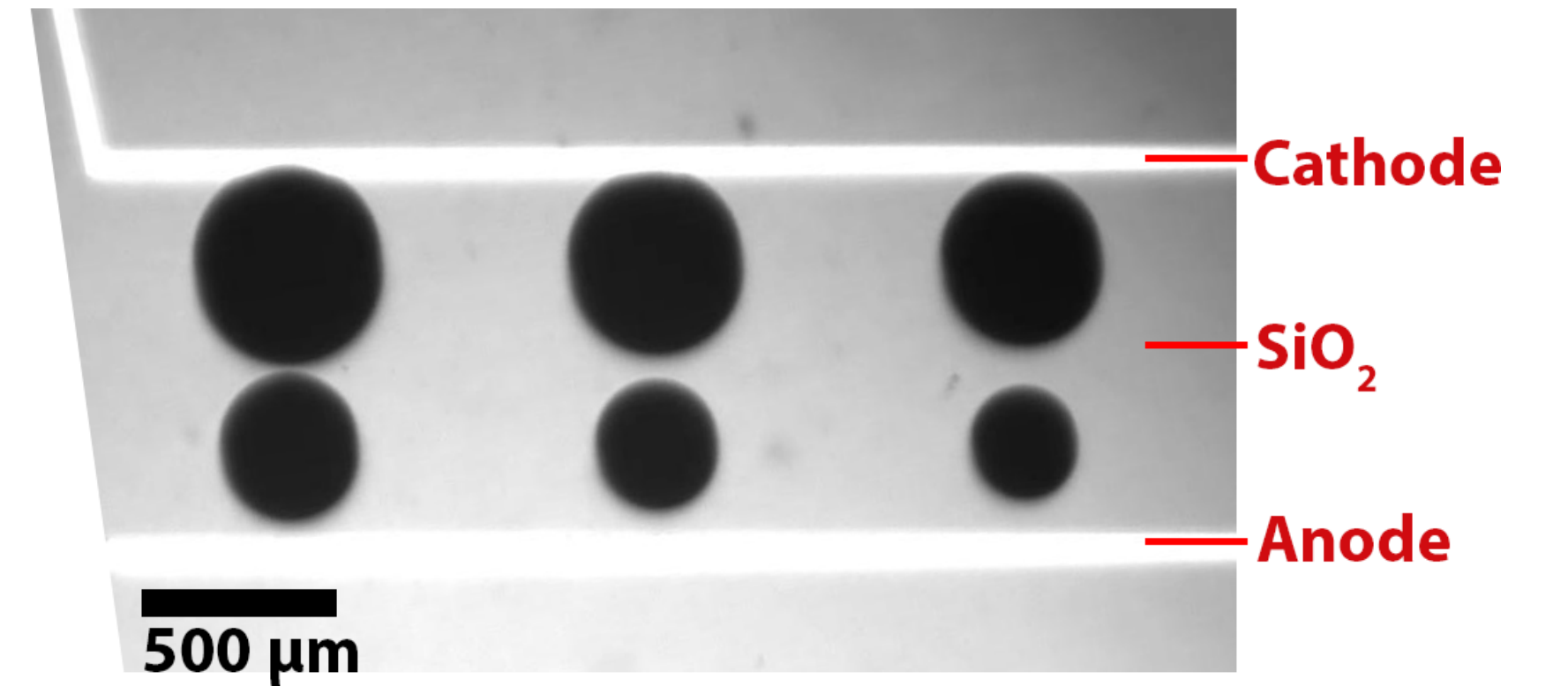


in preparation





Top view



*Work in progress ...*



Looking for ...

*Funds, collaboration, good questions!!*  
**... and motivated students!!**



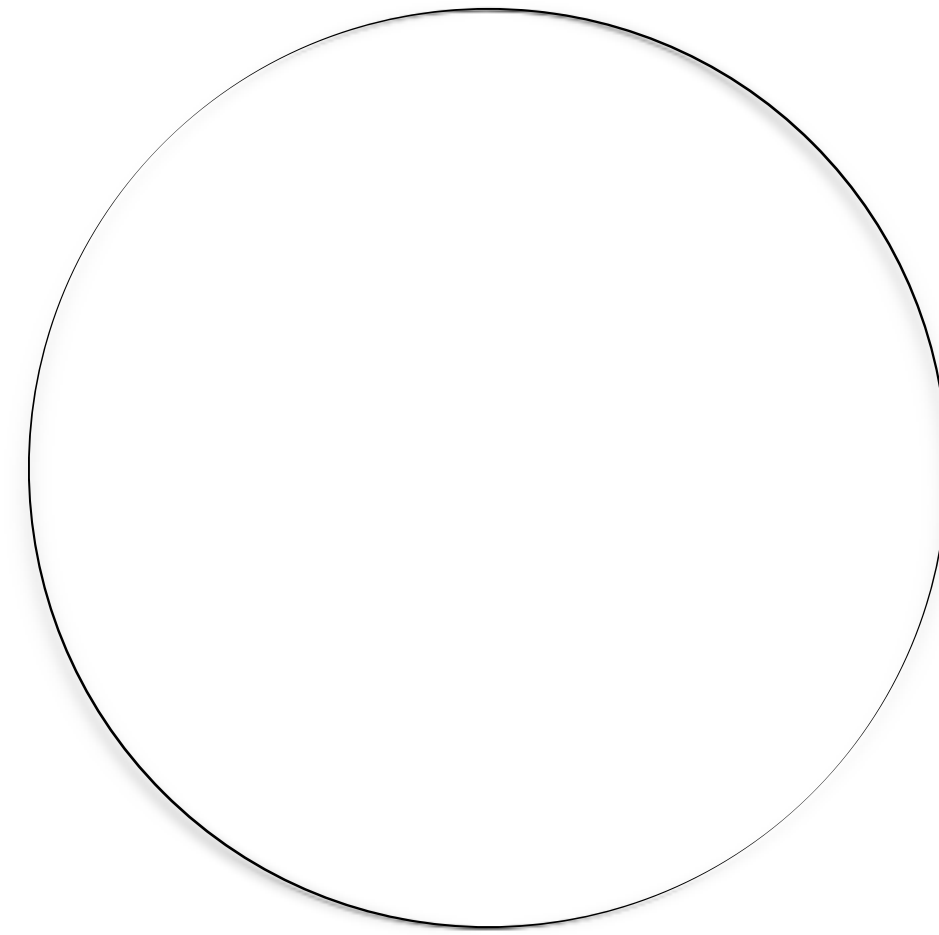
On a given day of the year, the Dogon people of Mali can fish in the sacred water of Lake Antogo. The lake is emptied in minutes. BBC, Human Planet: Deserts - Life in the Furnace





# Thank you for your time

*Team September 2018*



*InkBeams®*

*... huge list of collaborators*

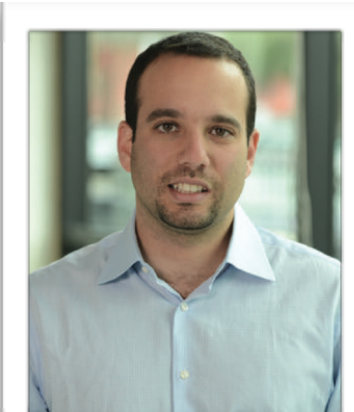


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*more on  
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H. Gardeniers D. vd Meer

D. Lohse



M. Modestino

