$E = H_2O$: The Secret Life of Water

Presented in the International Embryo Physics Course
http://www.embryophysics.org
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By

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$E = H_2O$
The Secret Life of Water

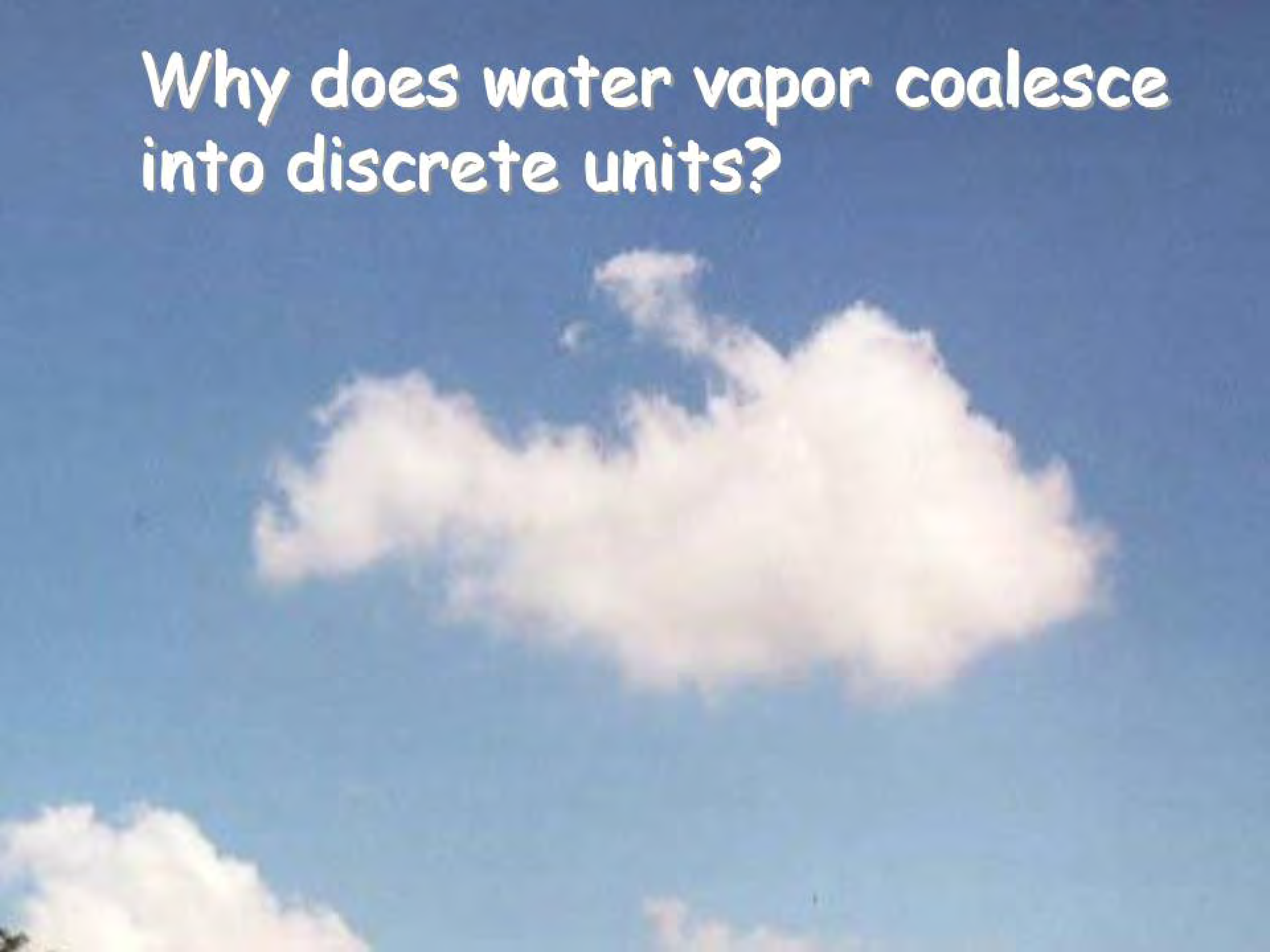
Gerald H. Pollack, PhD
University of Washington
Seattle, Washington


the edge


the rest

to begin....

Things we *ought to know* about water but don't...


Why does water vapor coalesce
into discrete units?

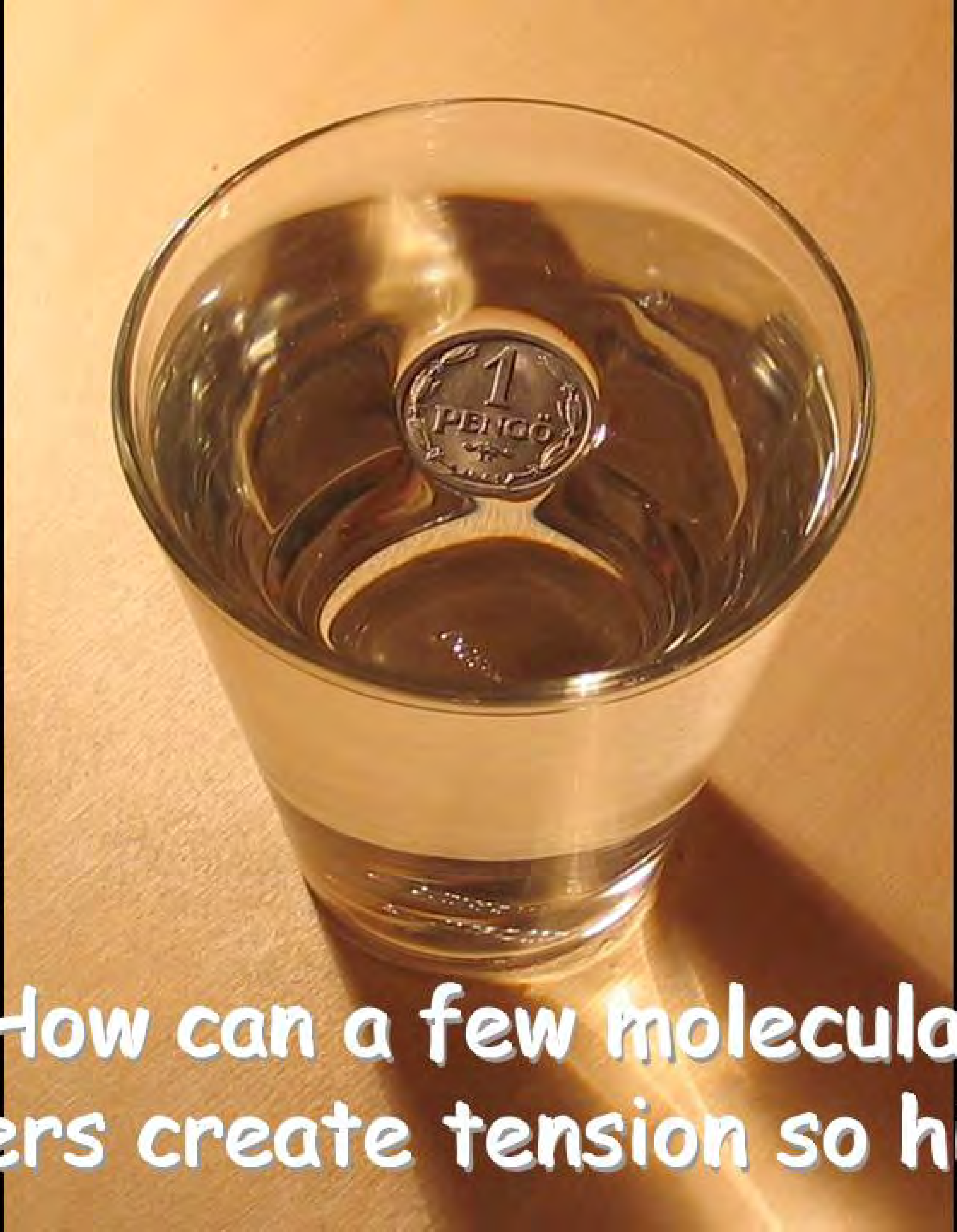

How can water sustain
huge charge separation?


gelatin dessert (95% water)...
Why doesn't the water dribble out?

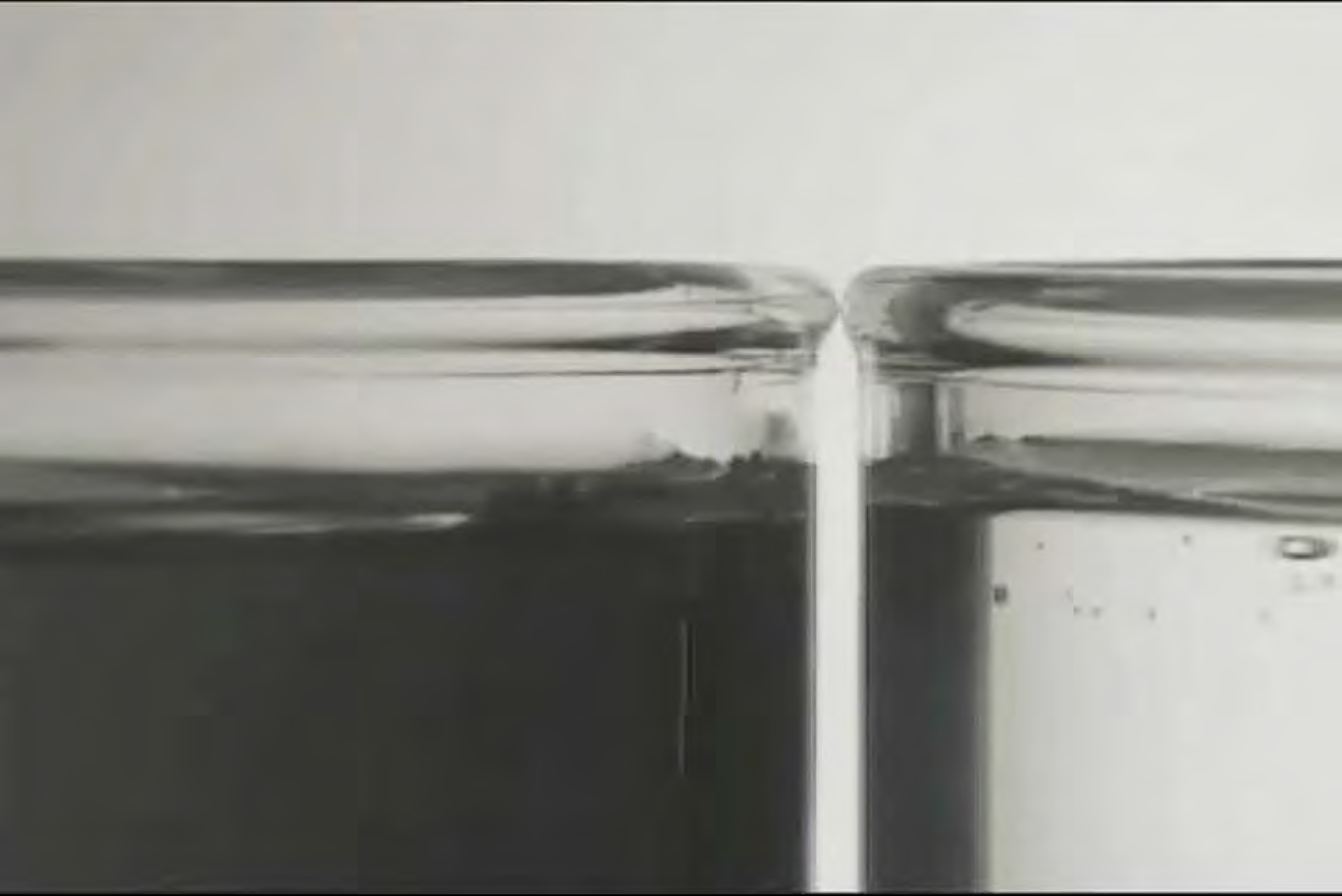
M Nydén, N Lorén, M Rudemo and M Kvarnström, Chalmers, Sweden


another unknown...


1
PENGŐ

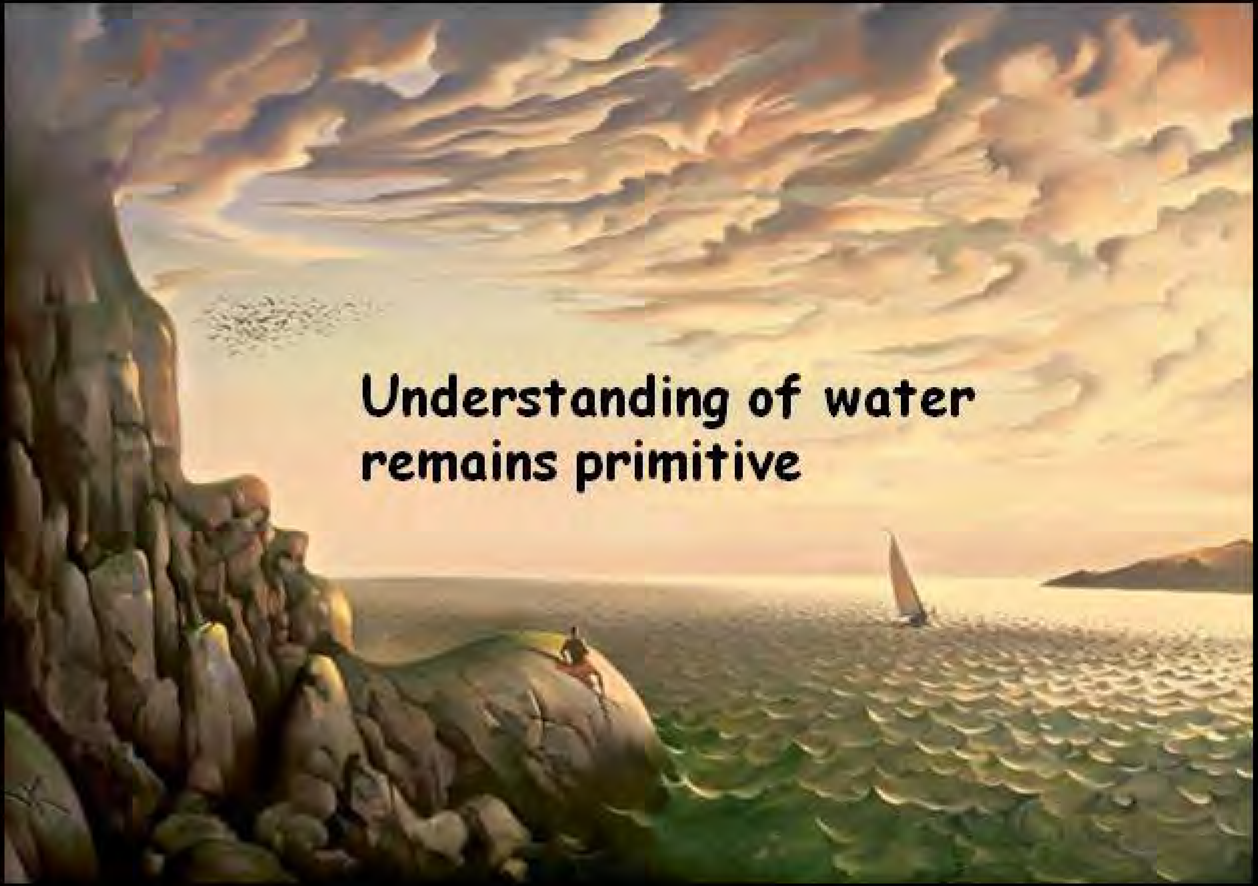


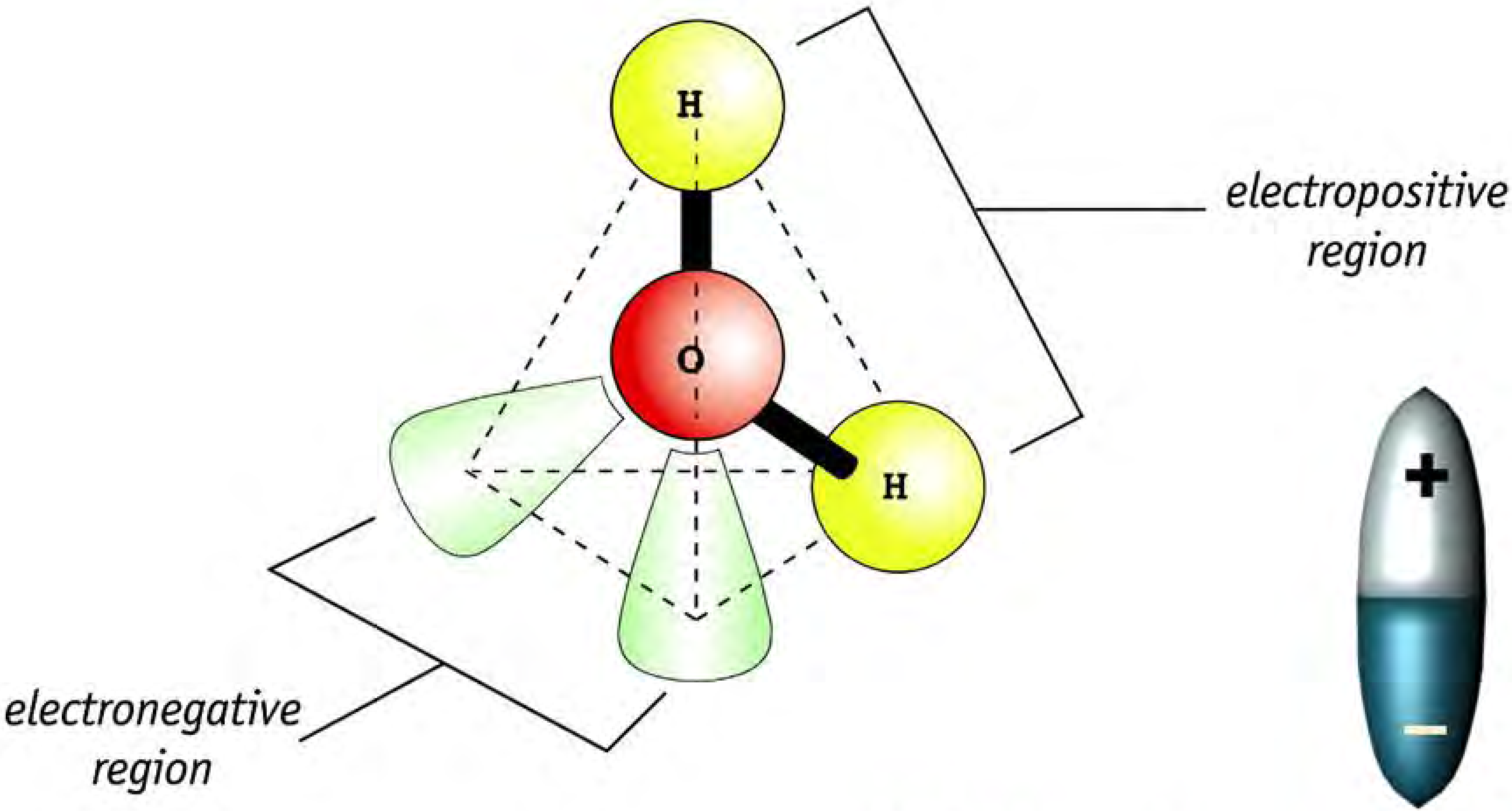
How can a few molecular
layers create tension so high?



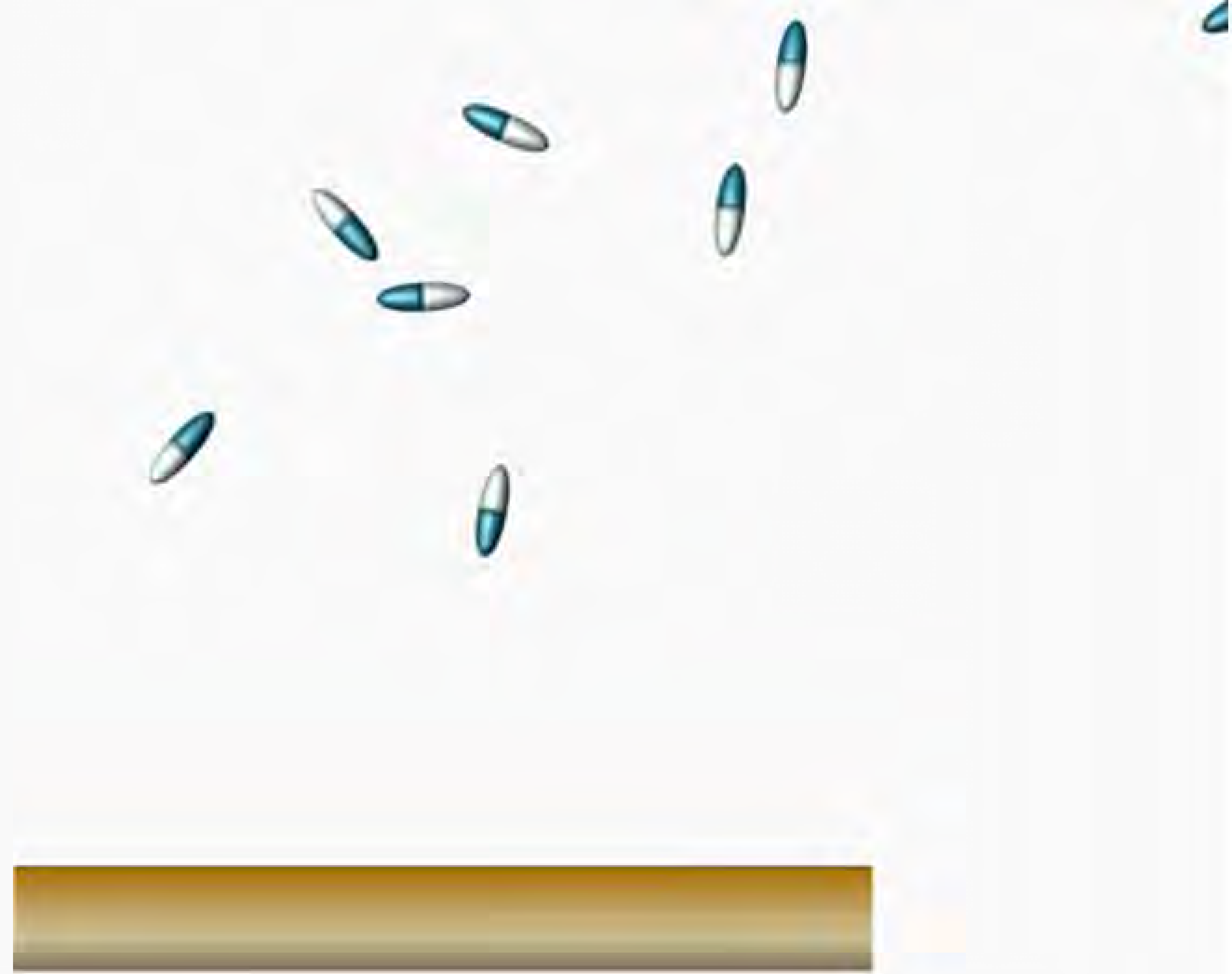
Elmar Fuchs, Wetsus

Many counterintuitive observations
Many unresolved mysteries…

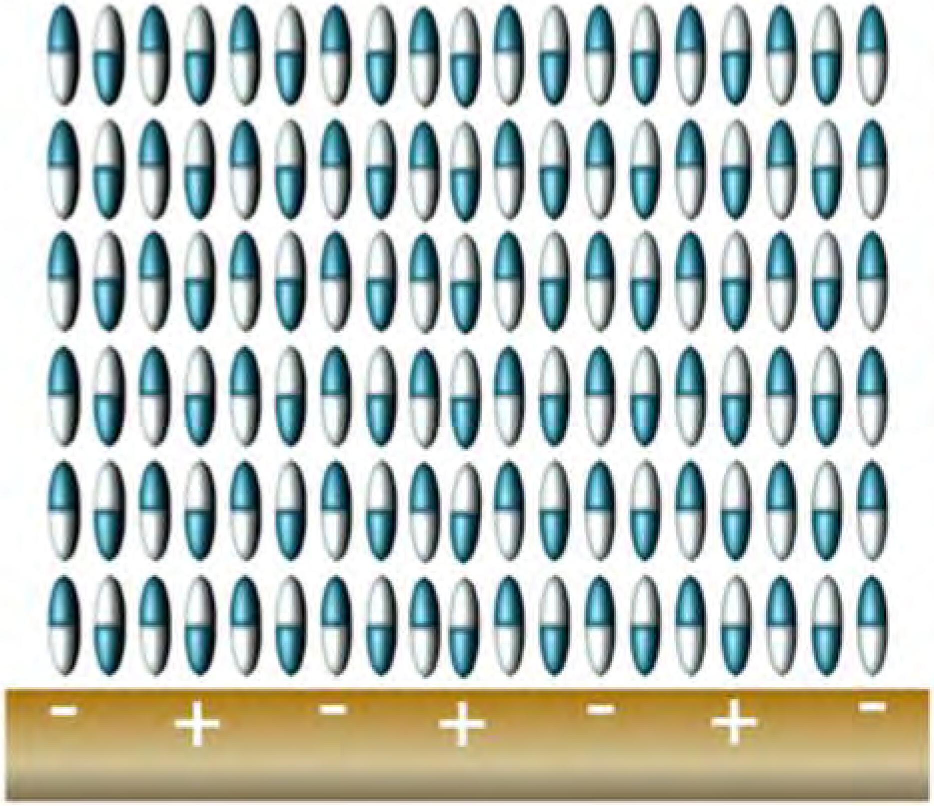




Water is a *dipole*

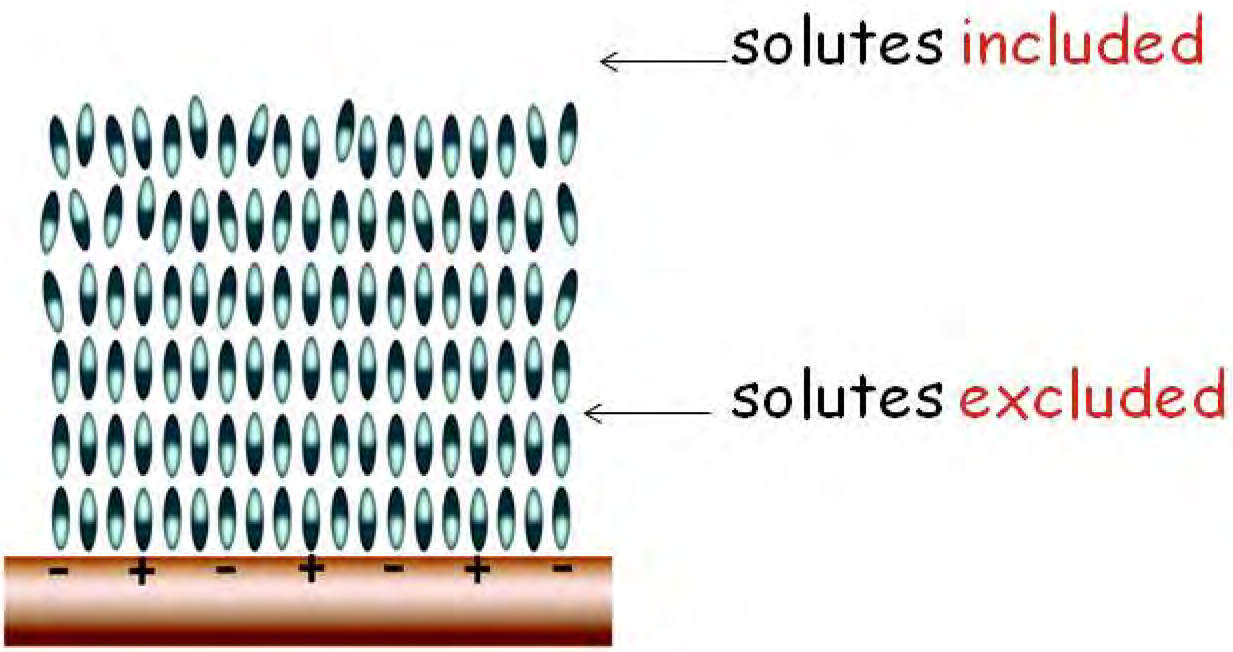


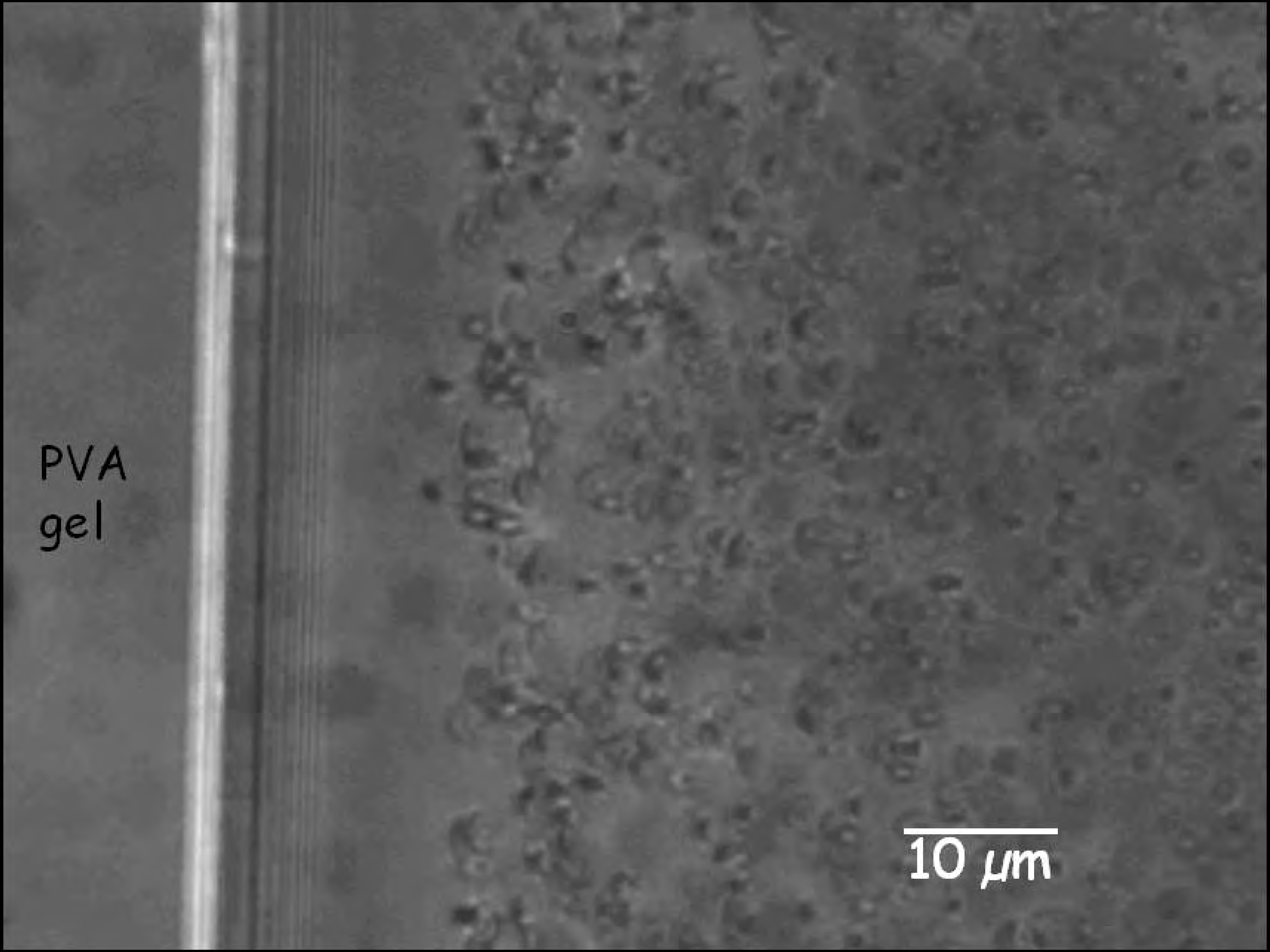
i. klyuzhin

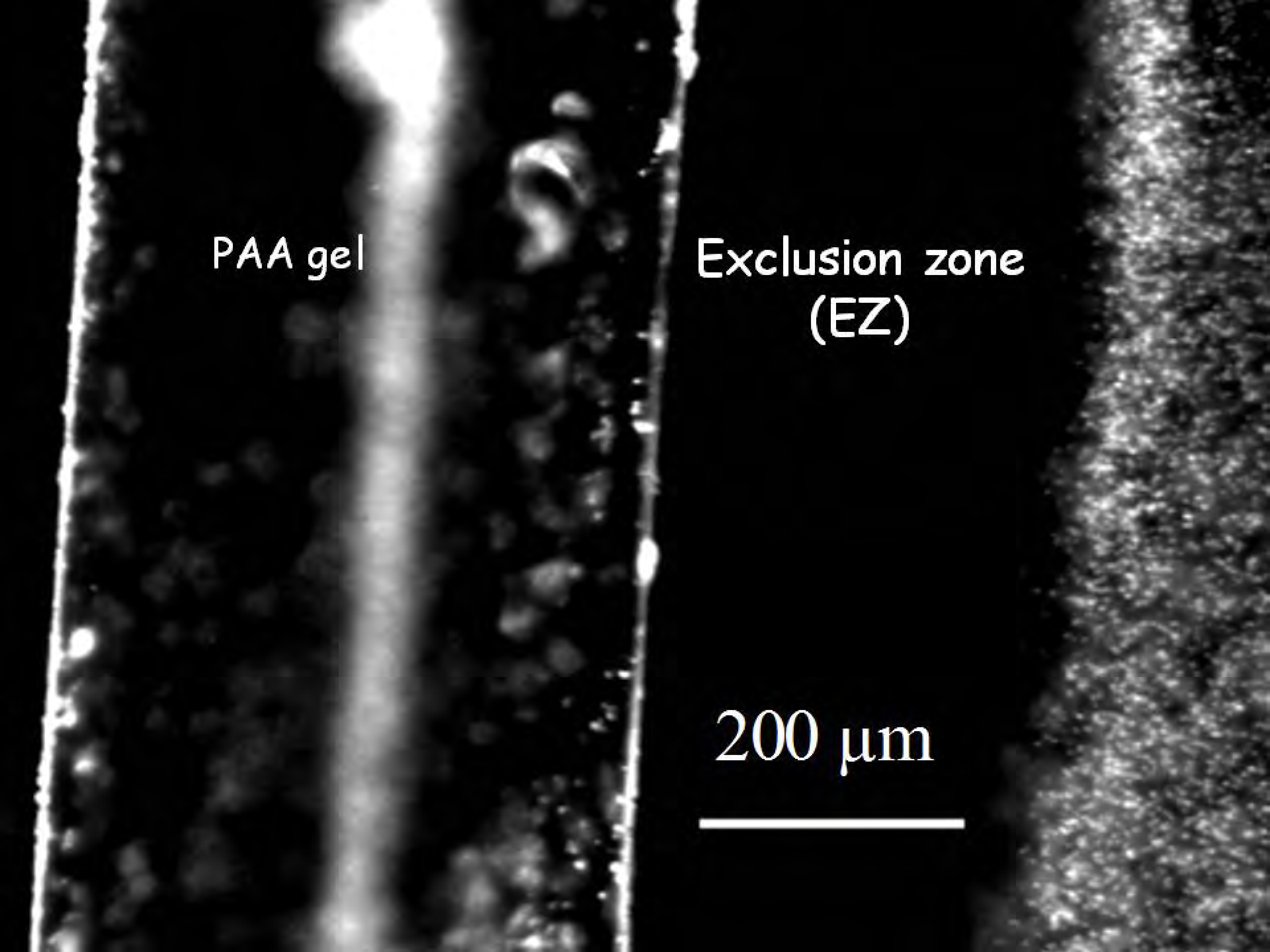


Initial experimental approach:

Test for solute distribution



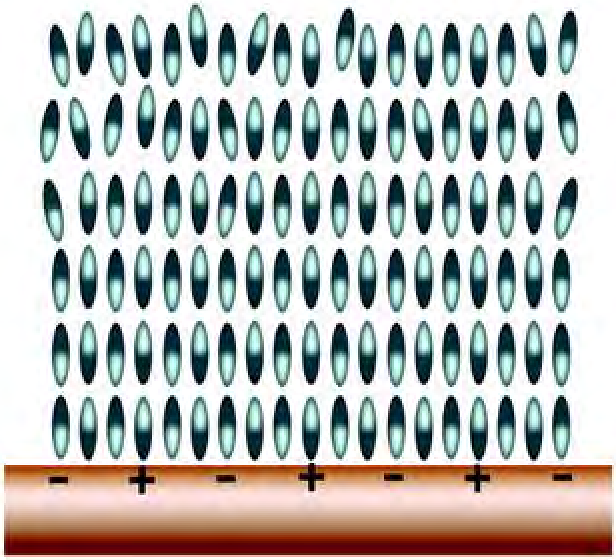

PVA
gel
10 μm


PAA gel
Exclusion zone
(EZ)
200 μm

Basic finding confirmed

- Felix Blyakhman (Ural State Univ)
- Wei-Chun Chin (U. Cal. Merced)
- Toshio Hirai (Shinshu University)
- Mark Banaszak Holl (Univ. of Michigan)
- Tom Lowell (Vermont Photonics)
- Diedrich Schmidt (Tsukuba)
- Gerhard Artmann (Aachen)
- David Maughan (U. Vermont)
- Miklos Kellermayer (Budapest)
- Fettah Kosar (Harvard)

Seems to imply very long range ordering



May provide fresh basis for understanding of water

Getting to the basis...

Questions to Answer

- Is the exclusion phenomenon general?
- Does it really arise from water ordering?
- Can water ordering explain anomalies?
- What energy creates this order?
- Might these findings apply more broadly?

Question #1: Generality

- Surfaces
- Solutes

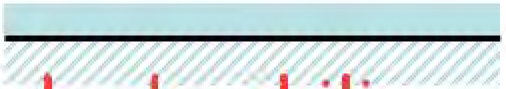
Question #1: Generality

- Surfaces
- Solutes

Question #1: Generality

- Surfaces: hydrophobic vs. hydrophilic
- Solutes

hydrophobic

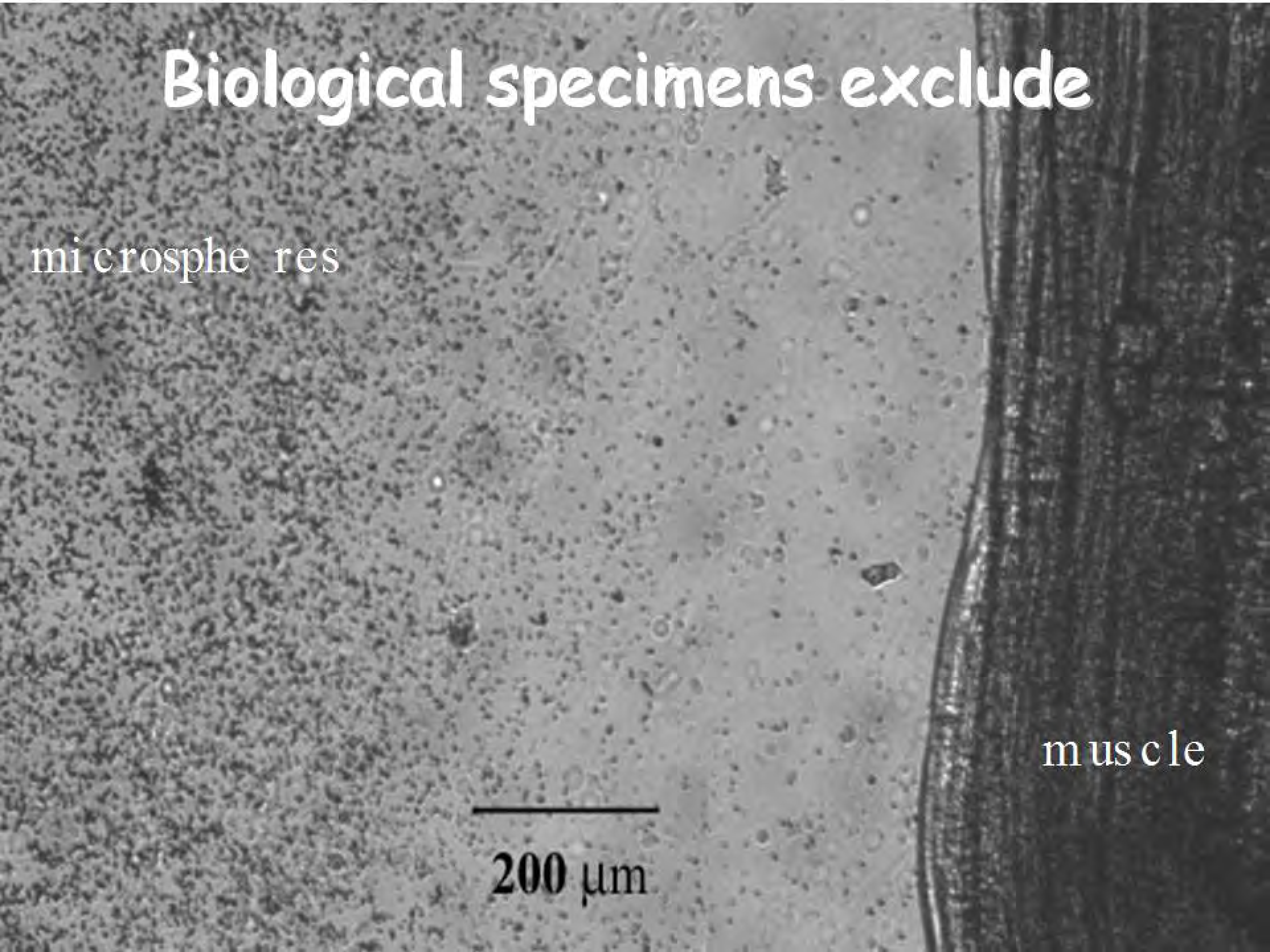


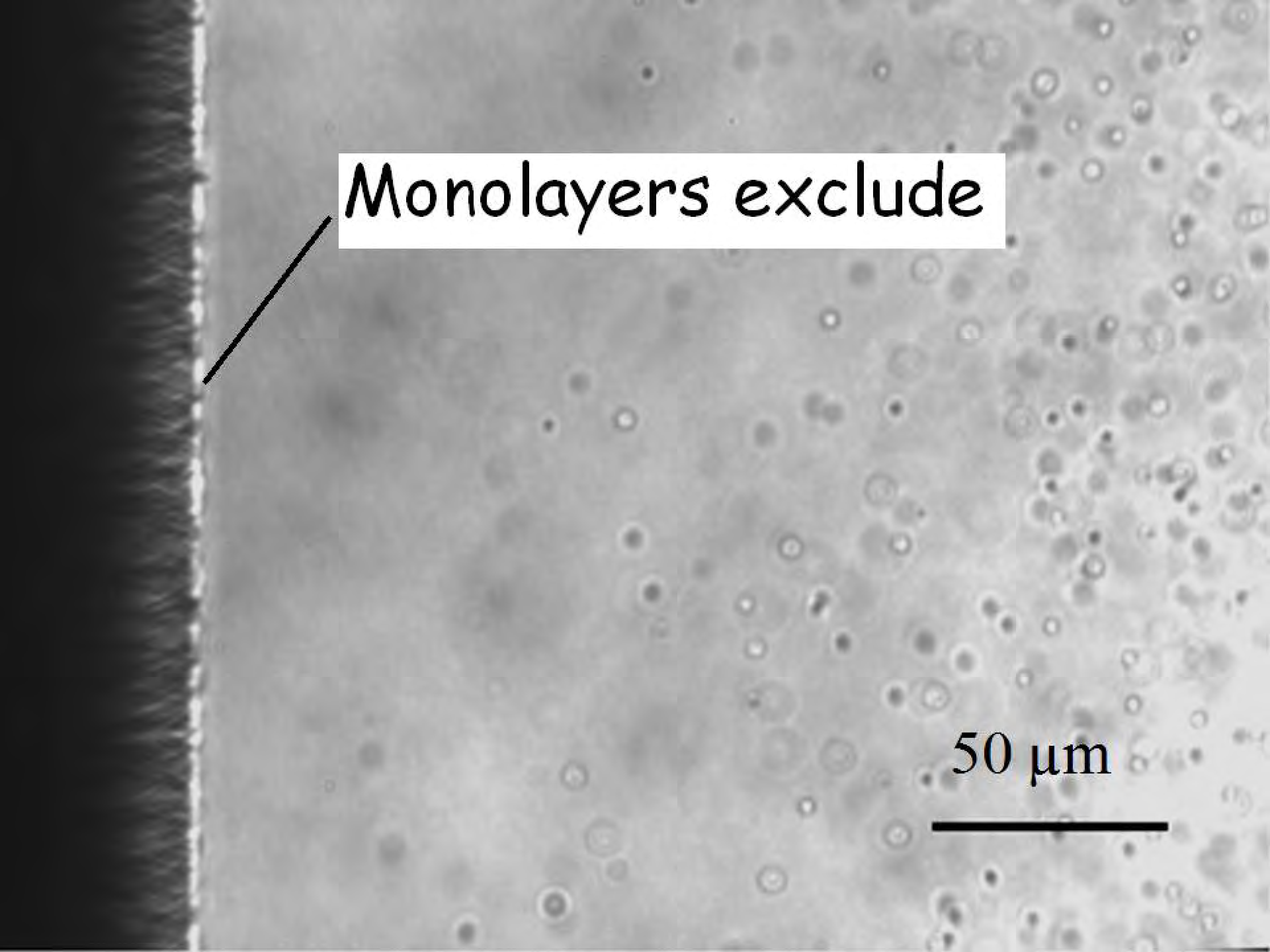
hydrophilic

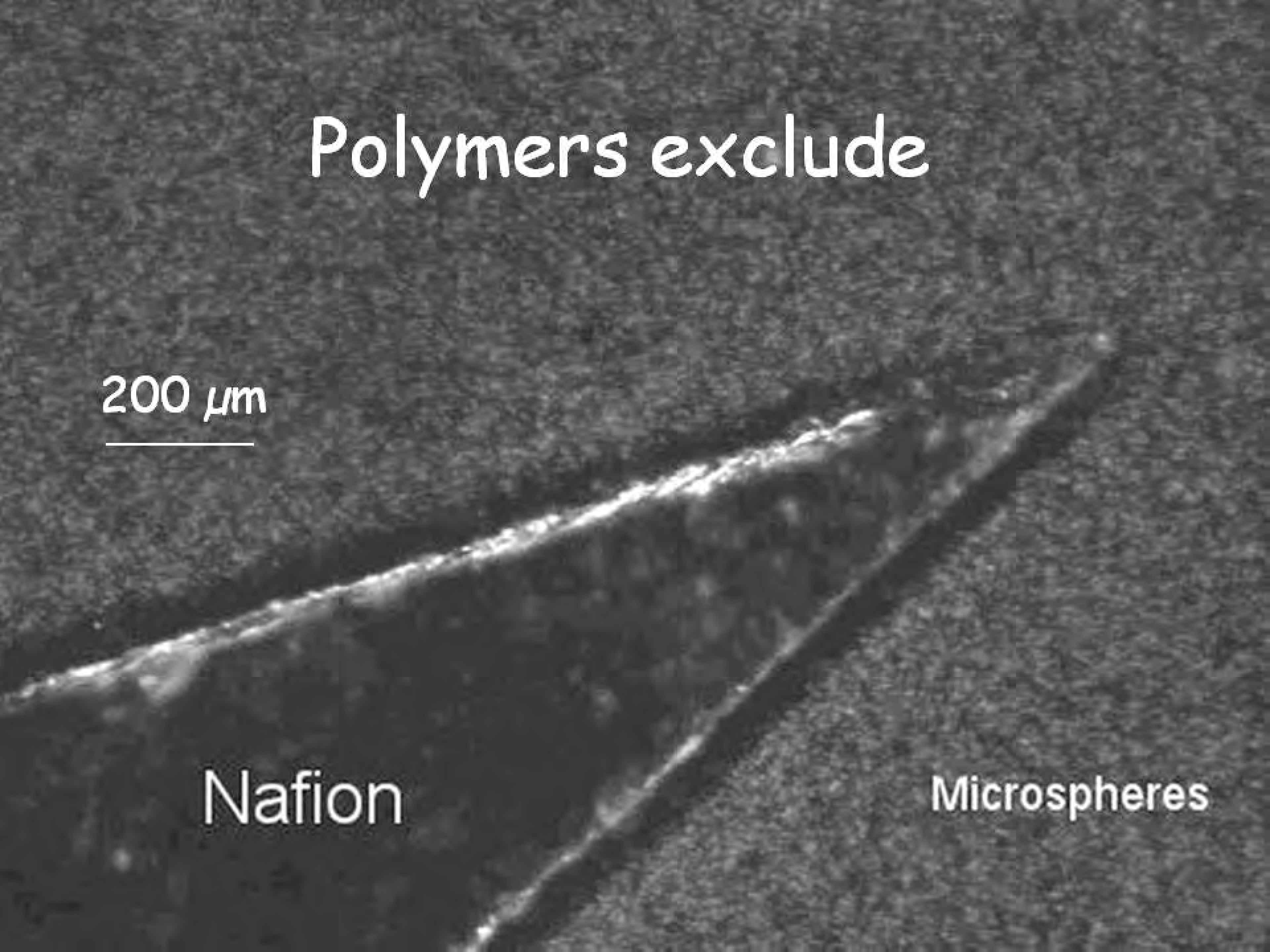
Hydrophilic gel surfaces do exclude

- Polyvinyl alcohol
- Polyacrylic acid
- Polyacrylamide
- PolyHEMA
- Collagen
- Agarose

Biological specimens exclude




Monolayers exclude
50 µm


Polymers exclude
200 μm
Nafion
Microspheres

Generality?

- Surfaces: Numerous hydrophilic surfaces show exclusion
- Solutes

Generality?

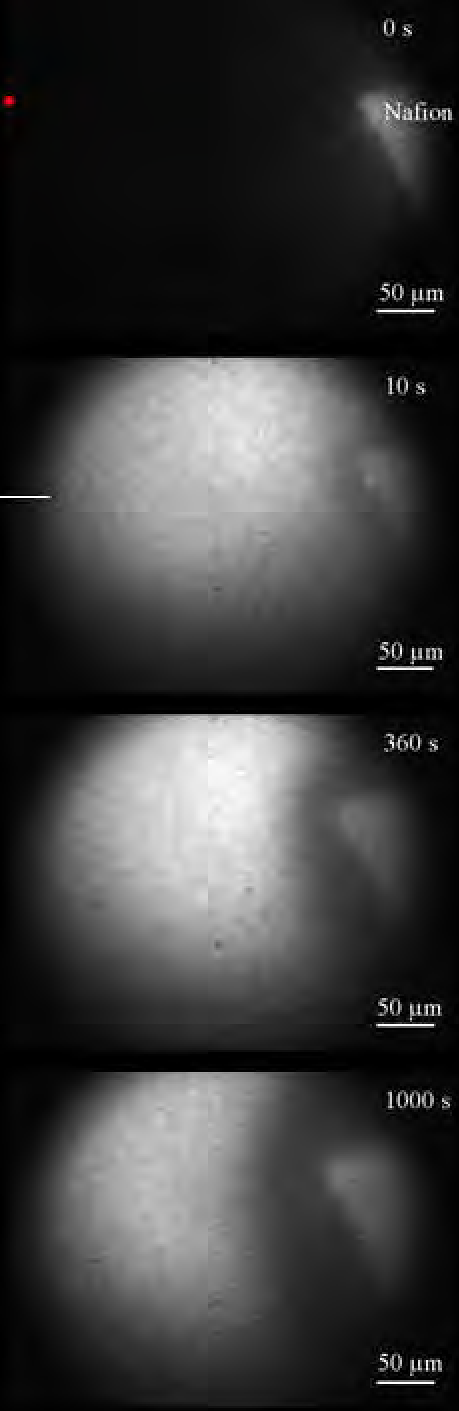
- Surfaces: Numerous hydrophilic surfaces show exclusion
- Solutes

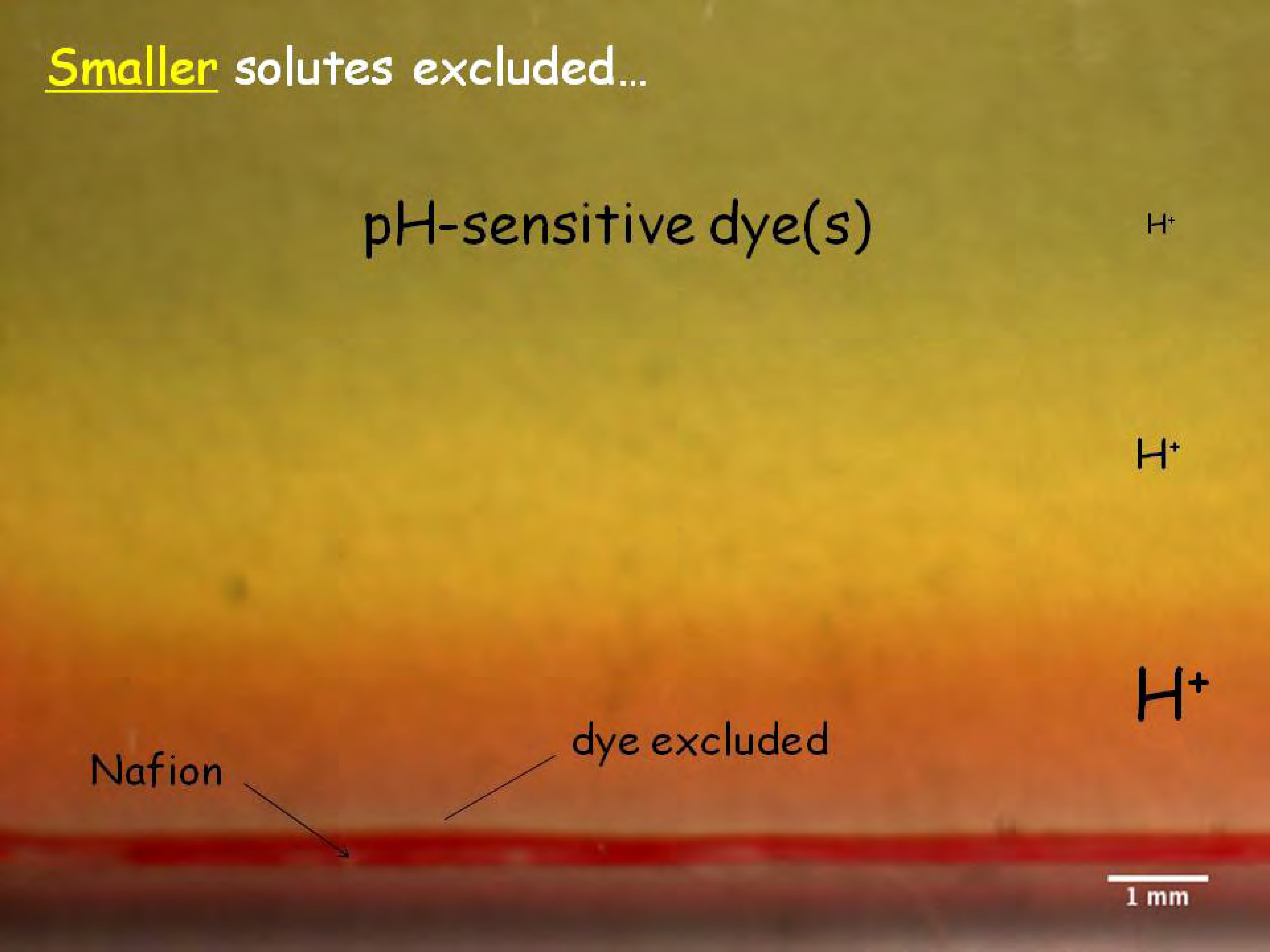
Excluded particles

- Polystyrene microspheres
- Silica microspheres
- Erythrocytes
- Bacteria
- Colloidal gold (4 - 7 nm)
- Quantum dots
- Ash, dirt

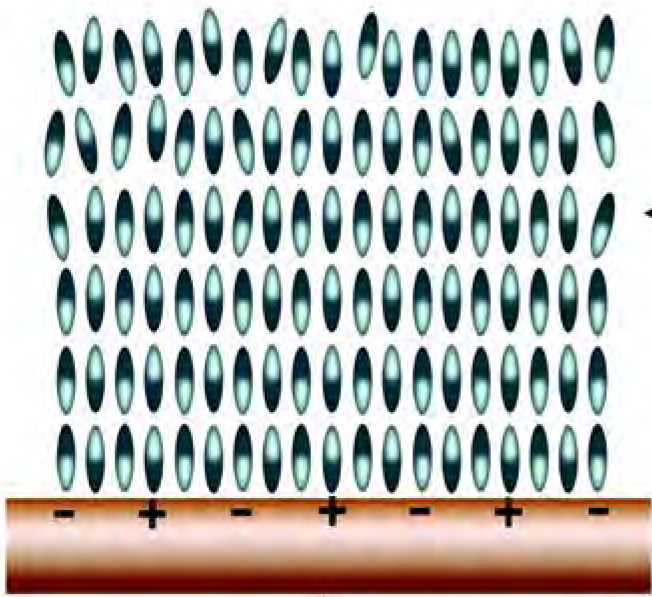
Excluded solutes...

fluorophore-
labeled
albumin




Smaller solutes excluded...
pH-sensitive dye(s)
H+
H+
H+
dye excluded
Nafion
1 mm

Answer to Q1: Generality

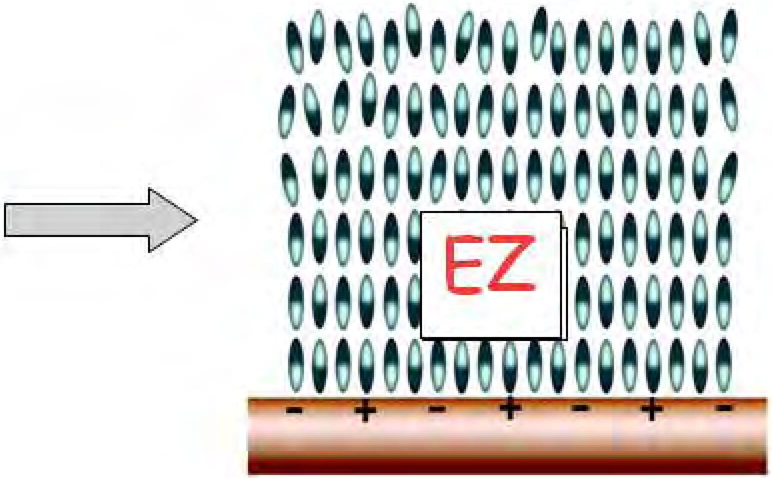


many solutes excluded

many hydrophilic surfaces generate exclusion zones

Question #2

Is this zone physically different from bulk water?



Evidence that EZ is physically different

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
Chai et al., *J Phys Chem,* 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci,* 332: 511-514, 2009.

Evidence that EZ is physically different

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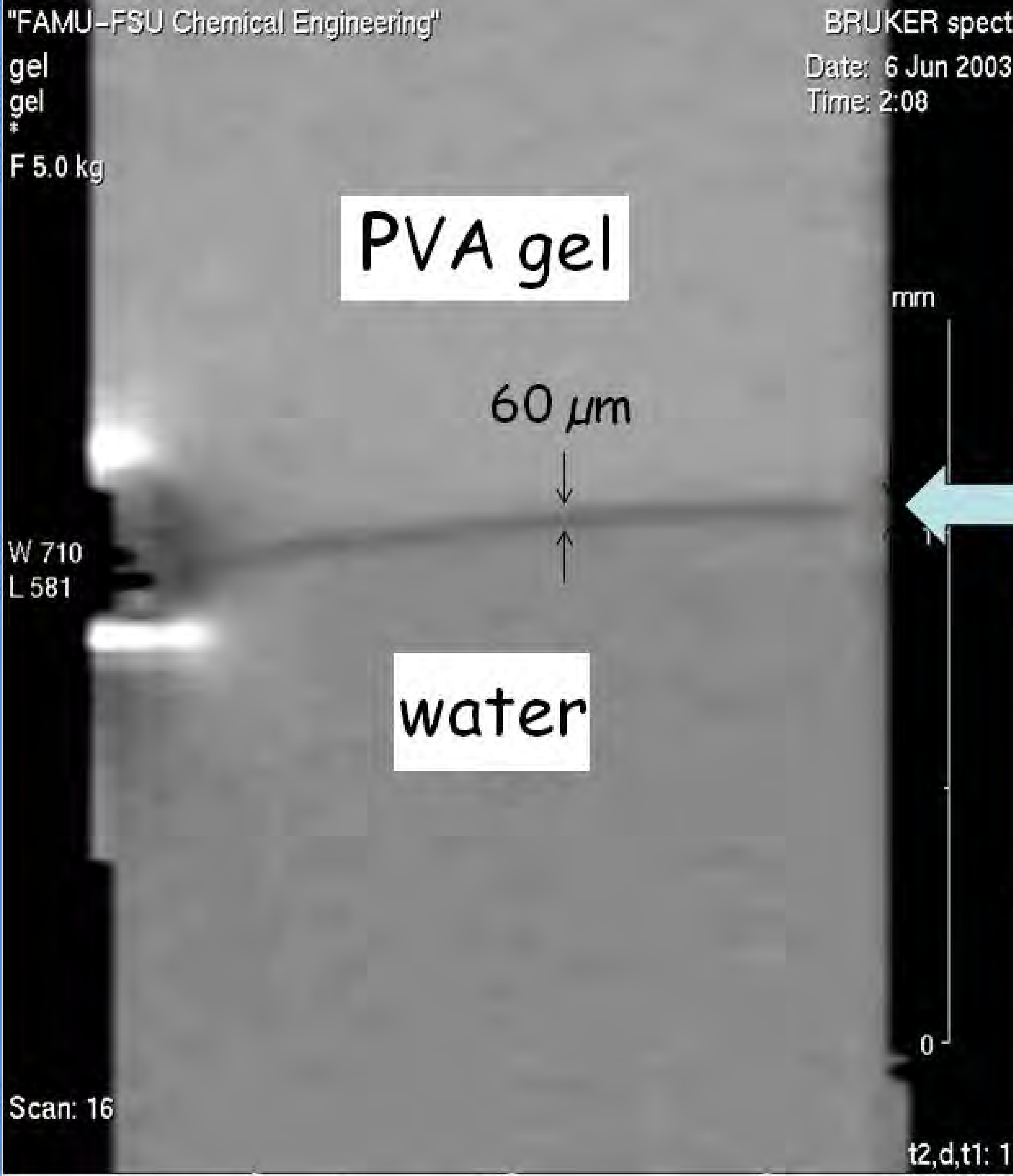
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009.

NMR -- tests molecular freedom



Dark means molecules can't easily rotate

Evidence that EZ is physically different

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009.

NMR -- EZ water molecules constrained

Evidence that EZ is physically different

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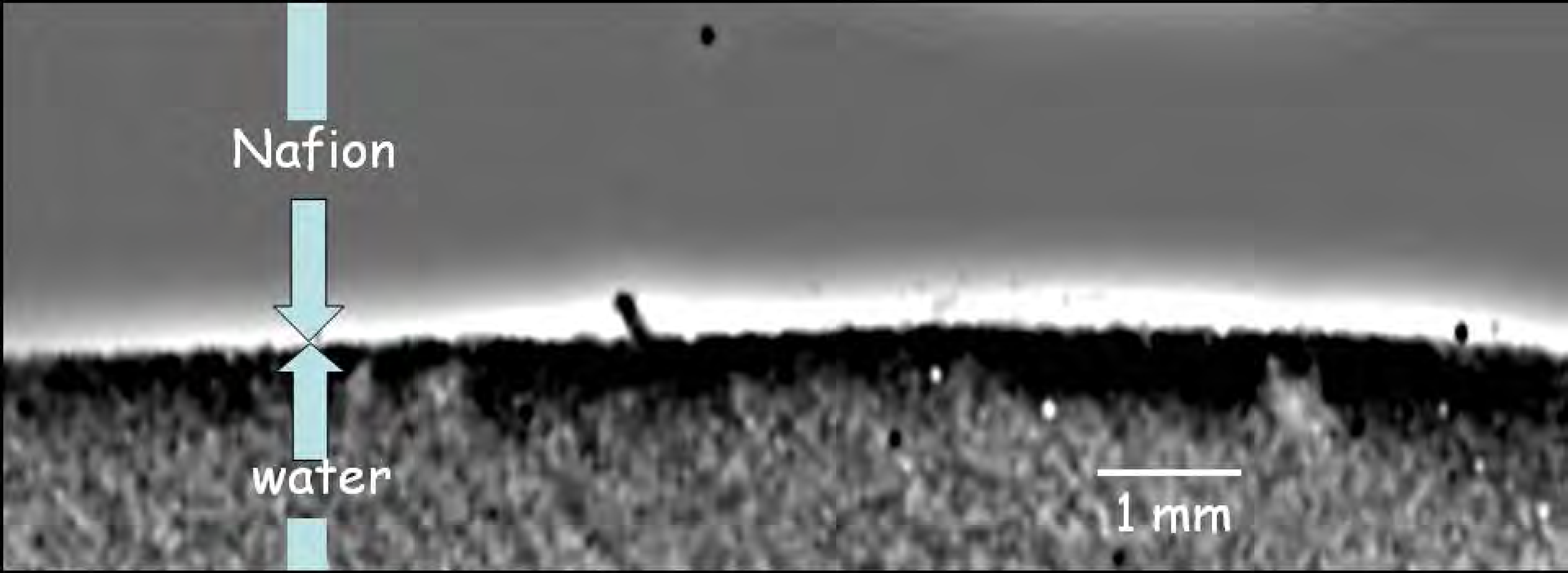
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009.

NMR
Infrared radiation -- temperature x emissivity

Infrared radiation image



E. Khijniak

Evidence that EZ is physically different

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Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009.

NMR

Infrared radiation -- EZ structure more stable

Evidence that EZ is physically different

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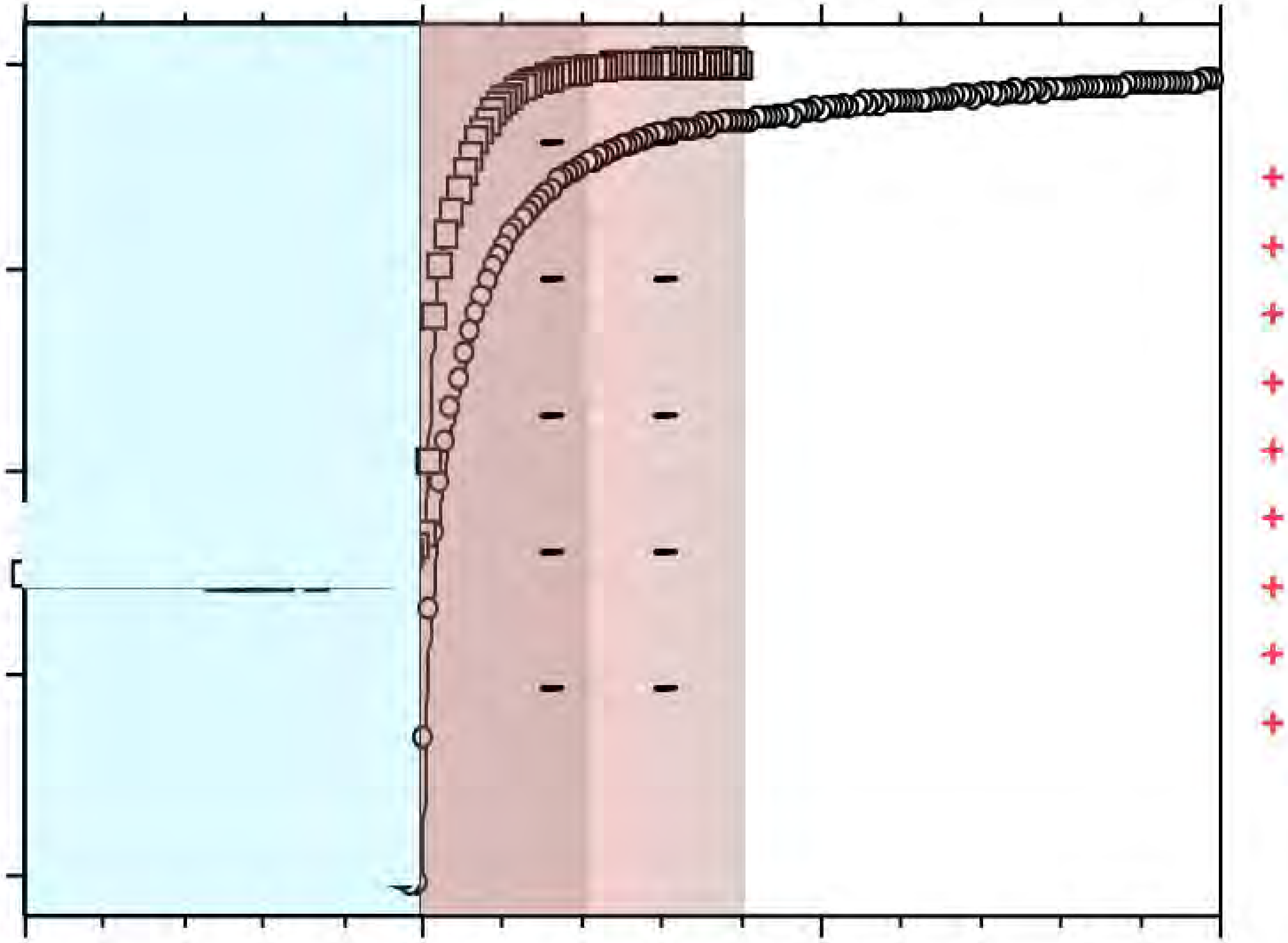
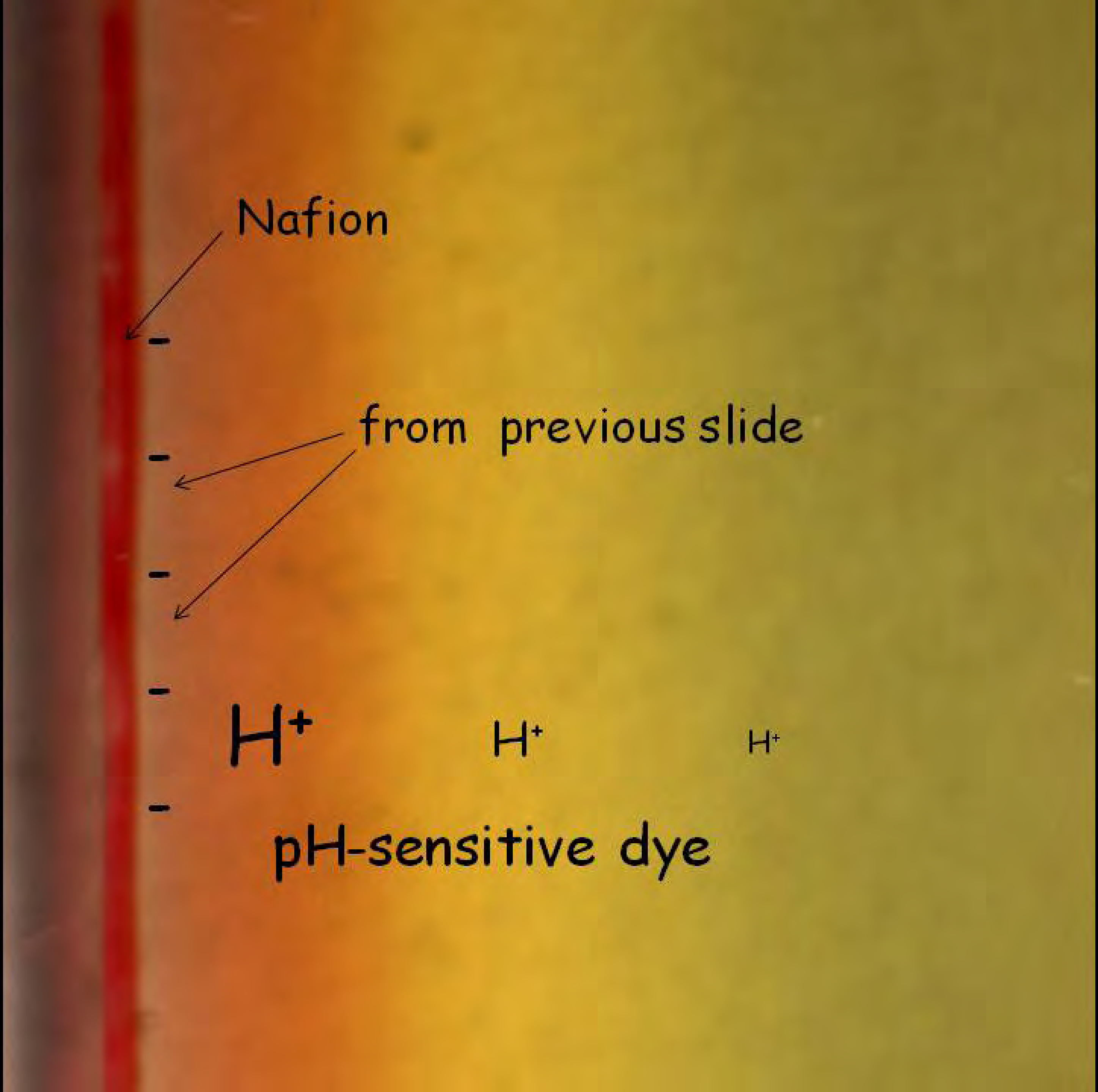
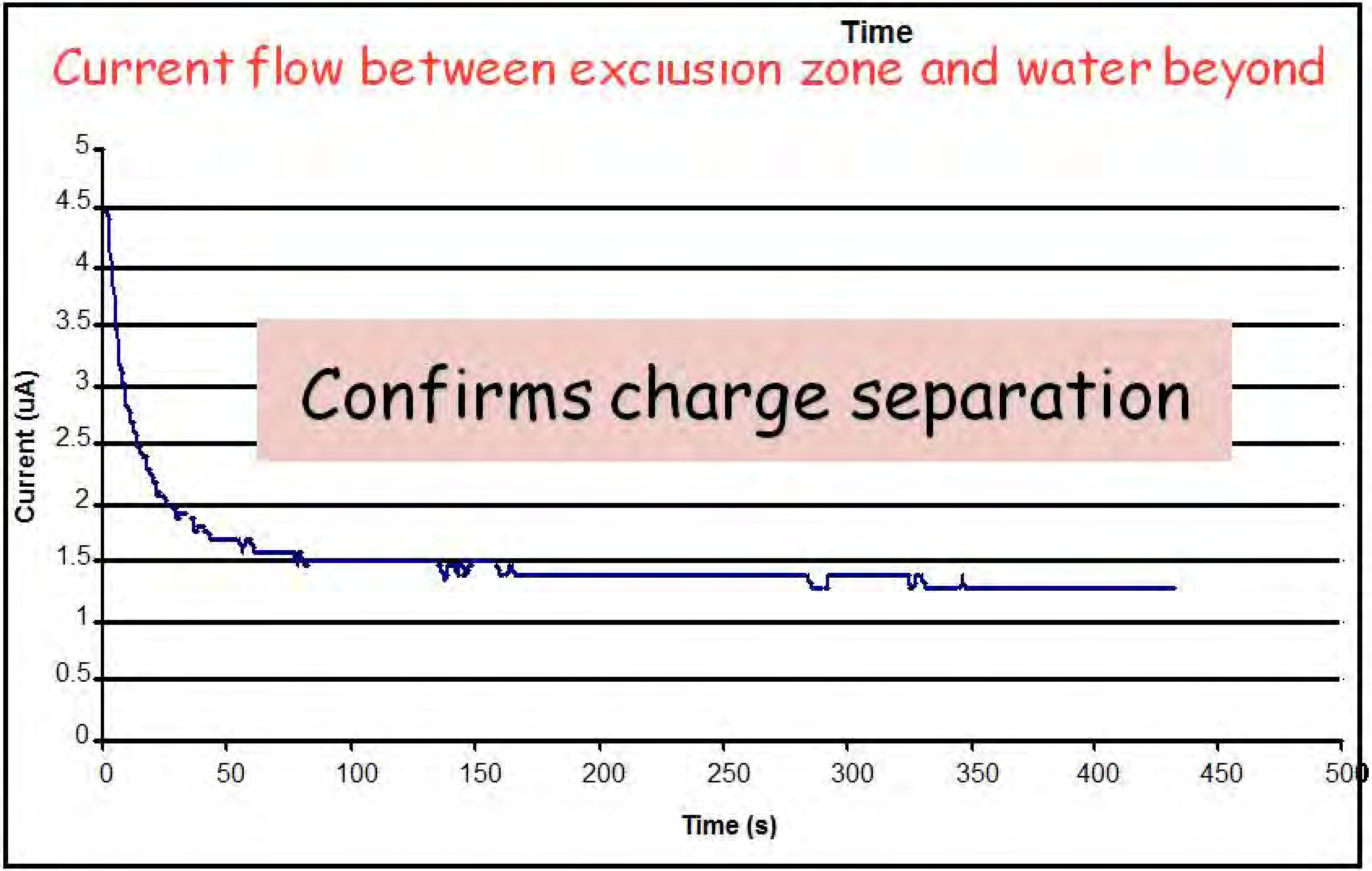
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009.

NMR
Infrared radiation
Electrical potential -- gradients imply charge separation

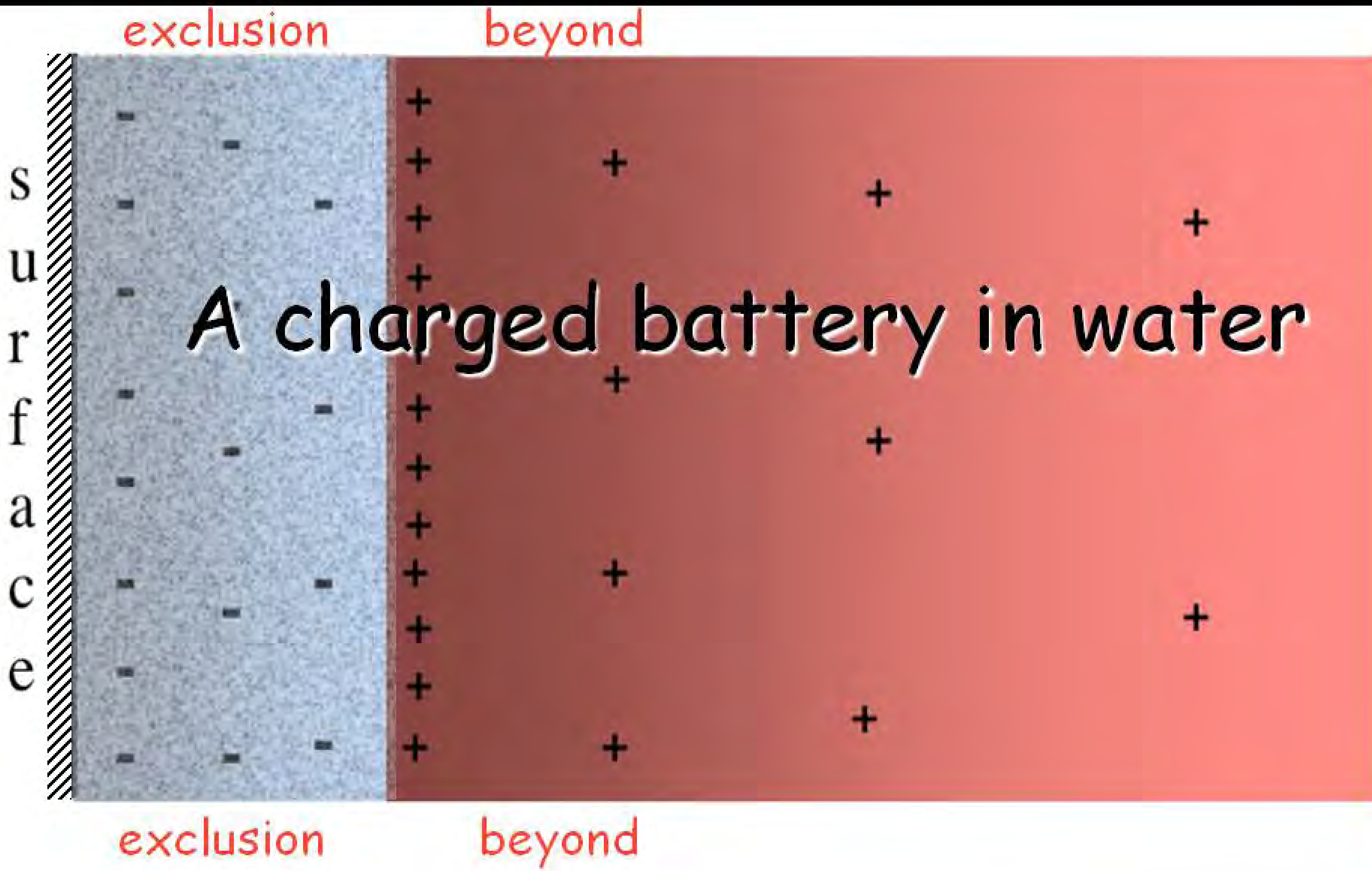



Nafion
-
from previous slide
-
-
-
H+
H+
H+
-
pH-sensitive dye



Time
Current flow between exciusion zone and water beyond
Confirms charge separation
Current (uA)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
350
400
450
500
Time (s)

A charged battery in water



Another charged battery in water…

Evidence that EZ is physically different

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009.

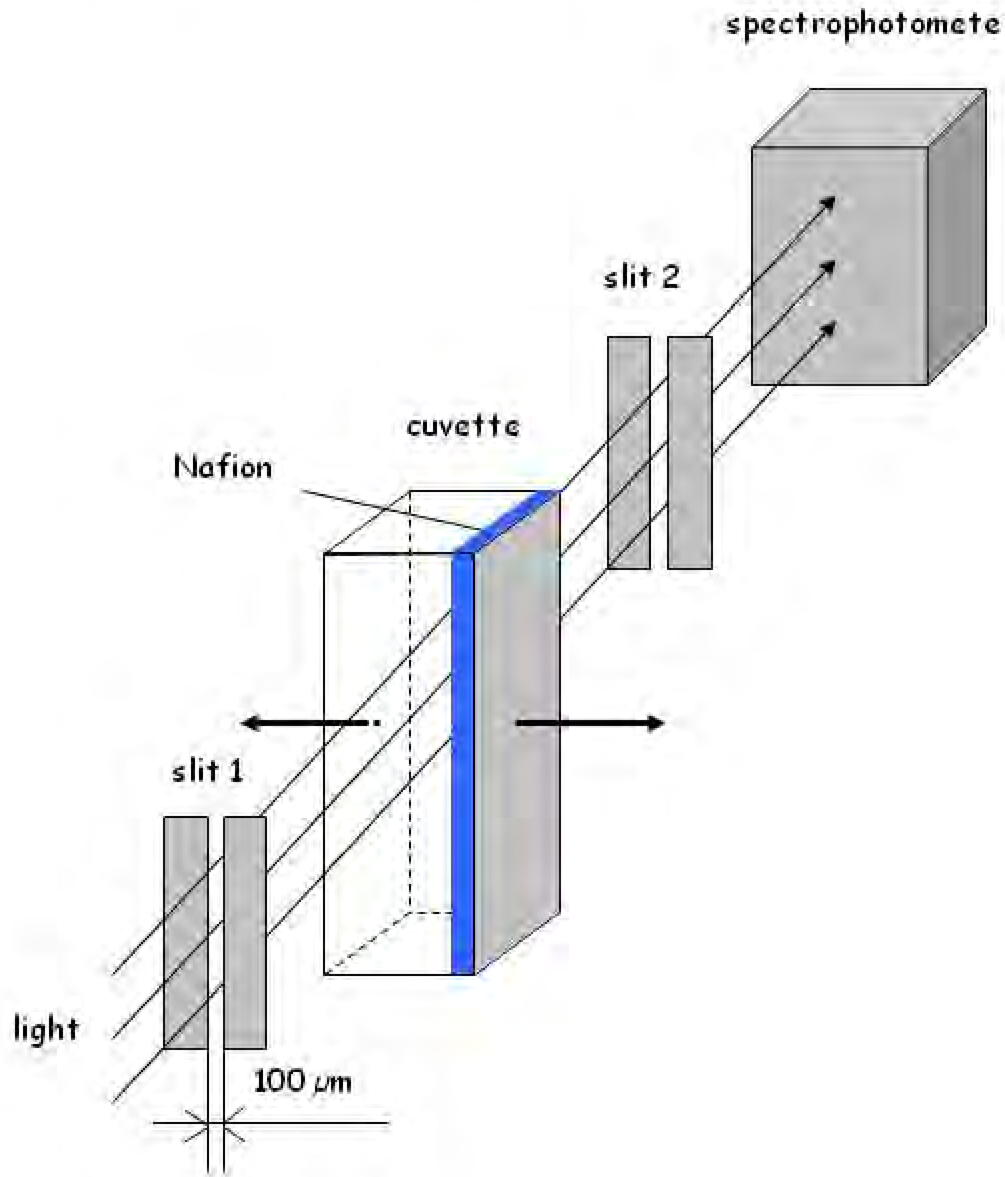
NMR
Infrared radiation
Electrical potential -- EZ has negative charge

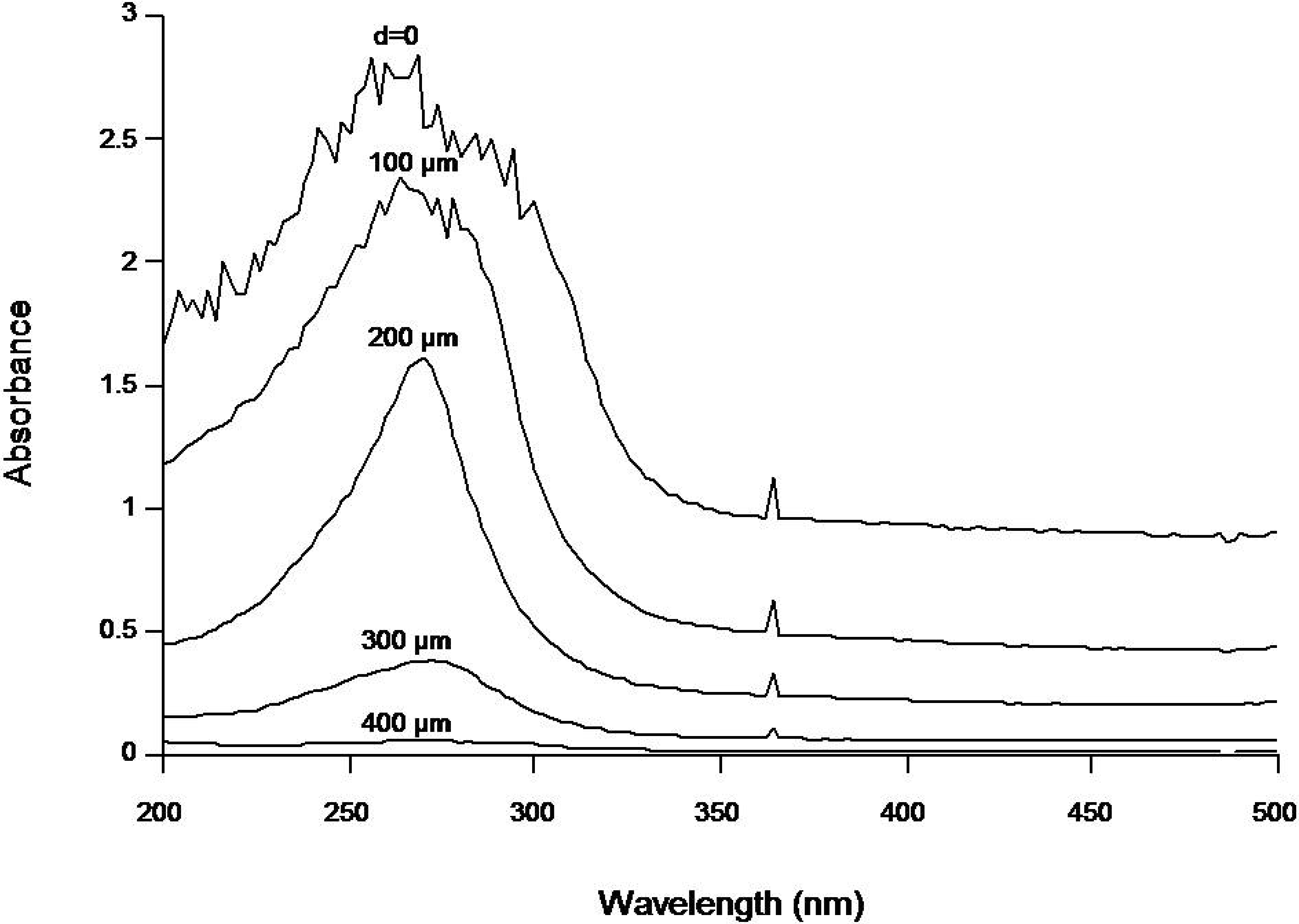
Evidence that EZ is physically different

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009.

NMR
Infrared radiation
Electrical potential
Light-absorption spectrum - distinguishes electron excit. states

UV-VIS absorption spectrum





d=0
100 µm
200 µm
300 µm
400 µm
Absorbance
Wavelength (nm)
0
0.5
1
1.5
2
2.5
3
200
250
300
350
400
450
500

Evidence that EZ is physically different

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009.

NMR
Infrared radiation
Electrical potential
Light-absorption spectrum- EZ absorbs at 270 nm

Evidence that EZ is physically different

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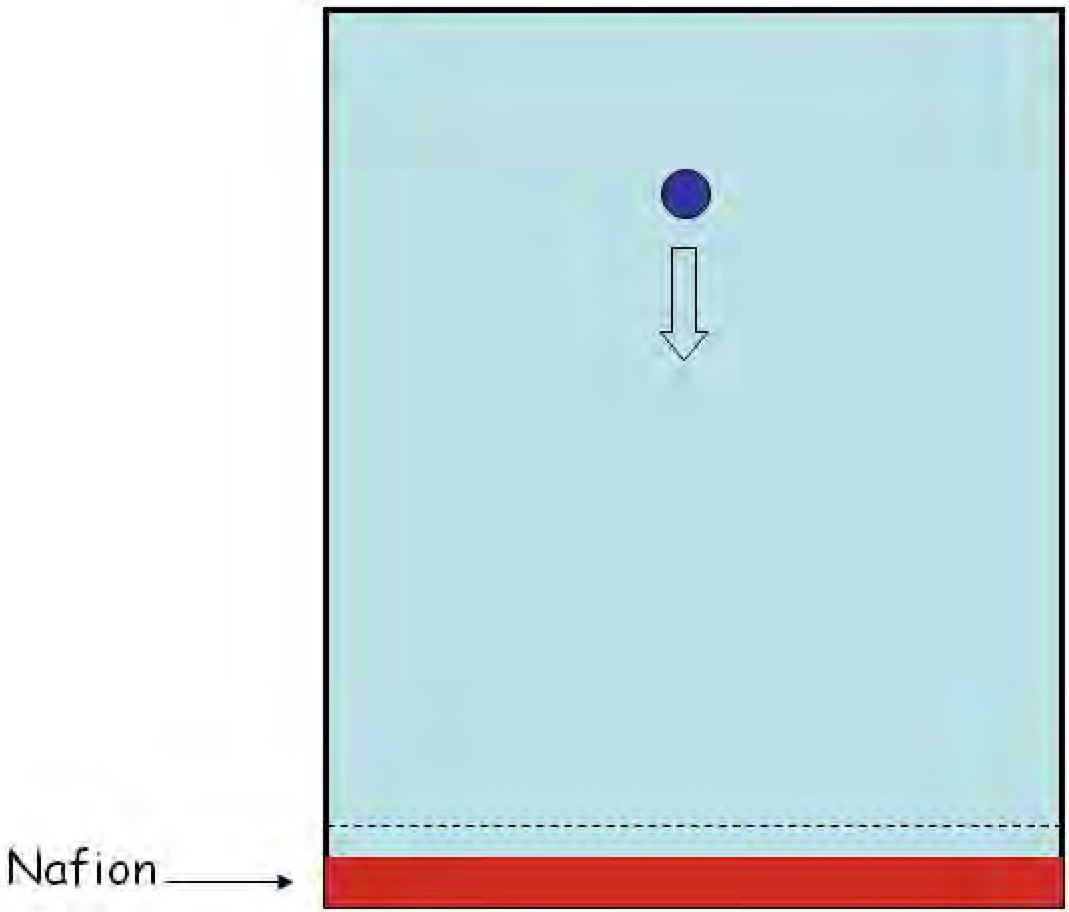
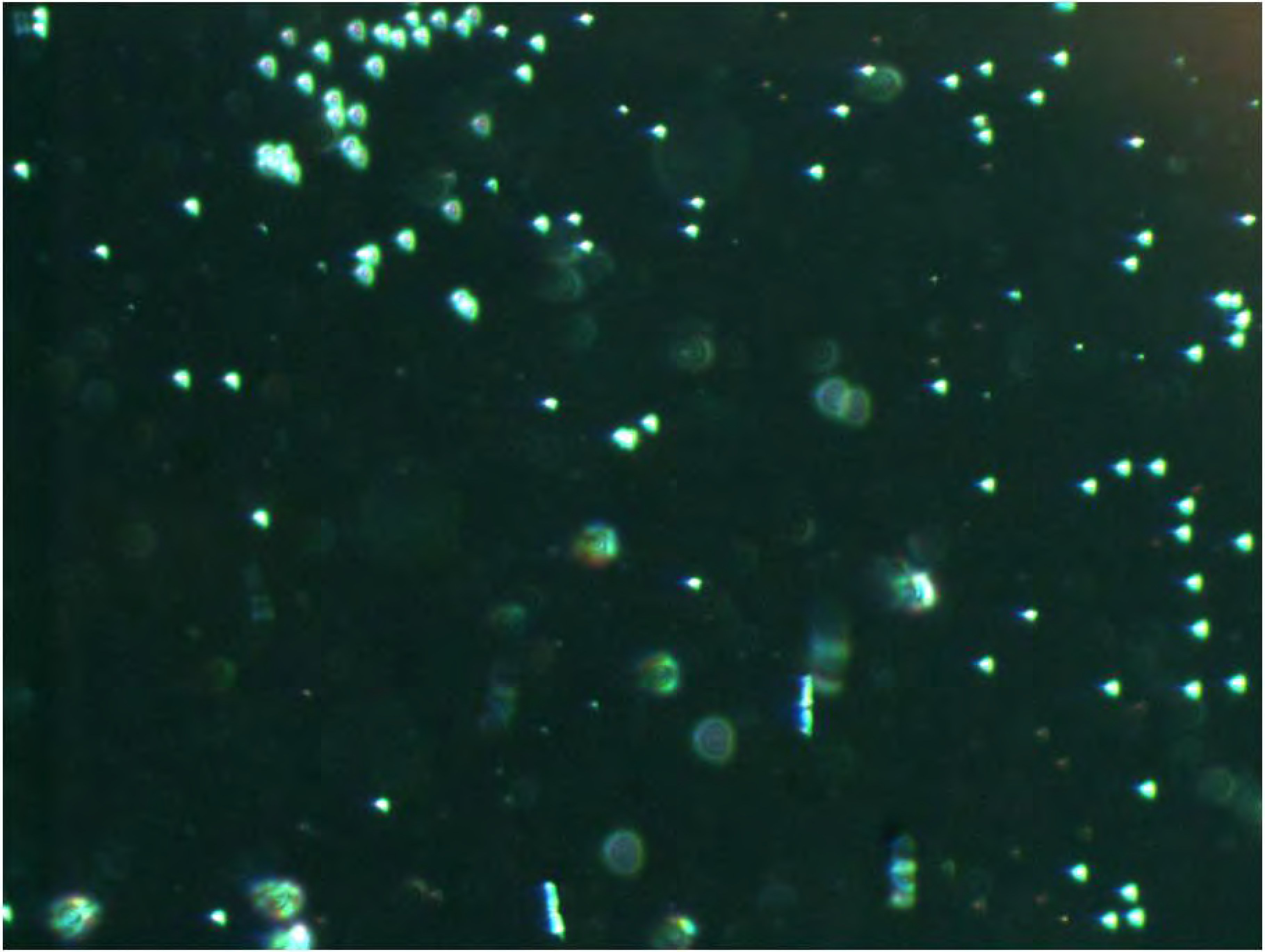
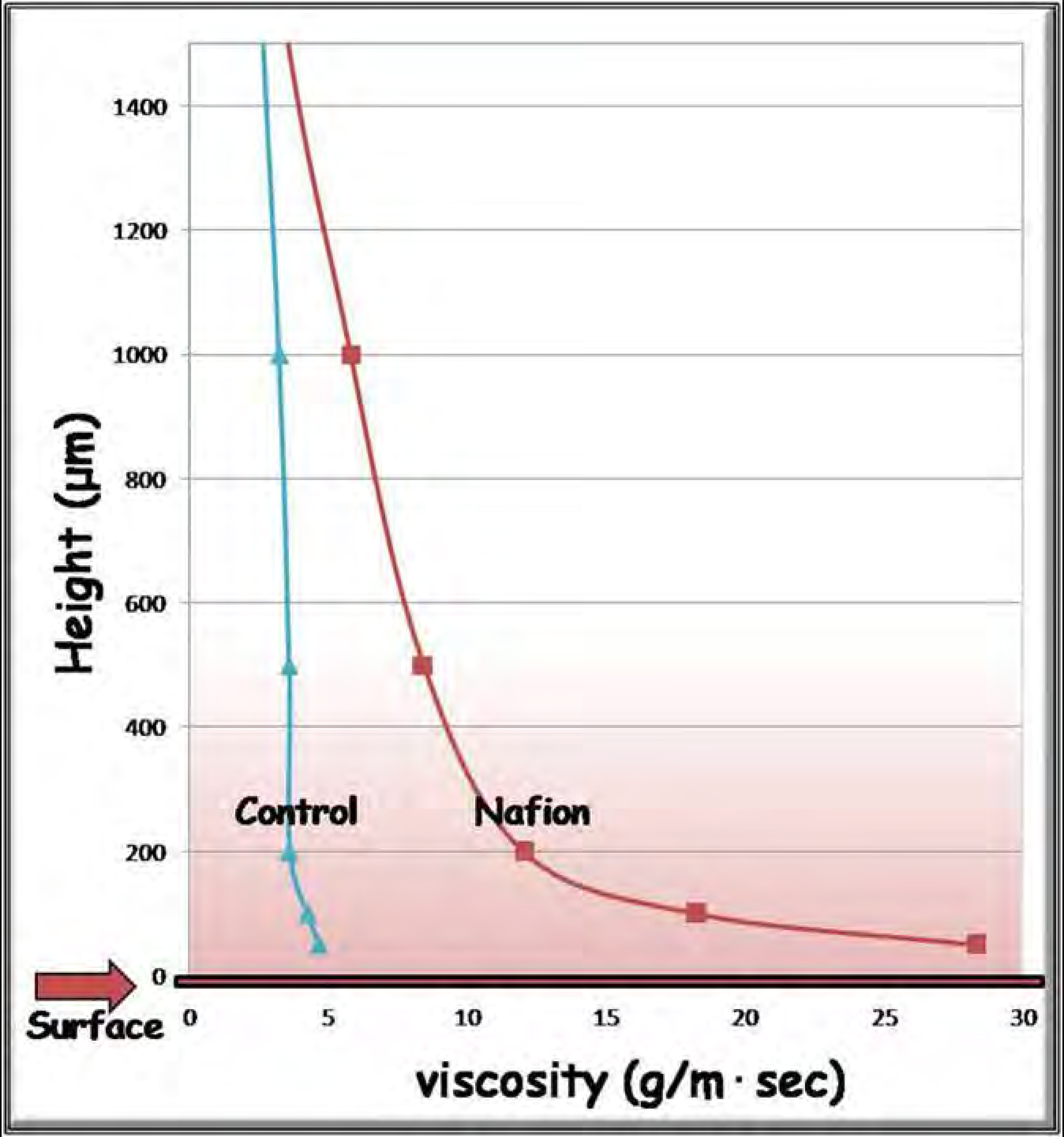
NMR
Infrared radiation
Electrical potential
Light-absorption spectrum
Viscosity (falling ball viscometer) - higher viscosity?

Falling ball viscometry







Height (μm)
1400
1200
1000
800
600
400
200
0
Control
Nafion
Surface
0
5
10
15
20
25
30
viscosity (g/m · sec)

Evidence that EZ is physically different

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009.

NMR
Infrared radiation
Electrical potential
Light-absorption spectrum
Viscosity (falling ball viscometer) - EZ is more viscous

Evidence that EZ is physically different

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
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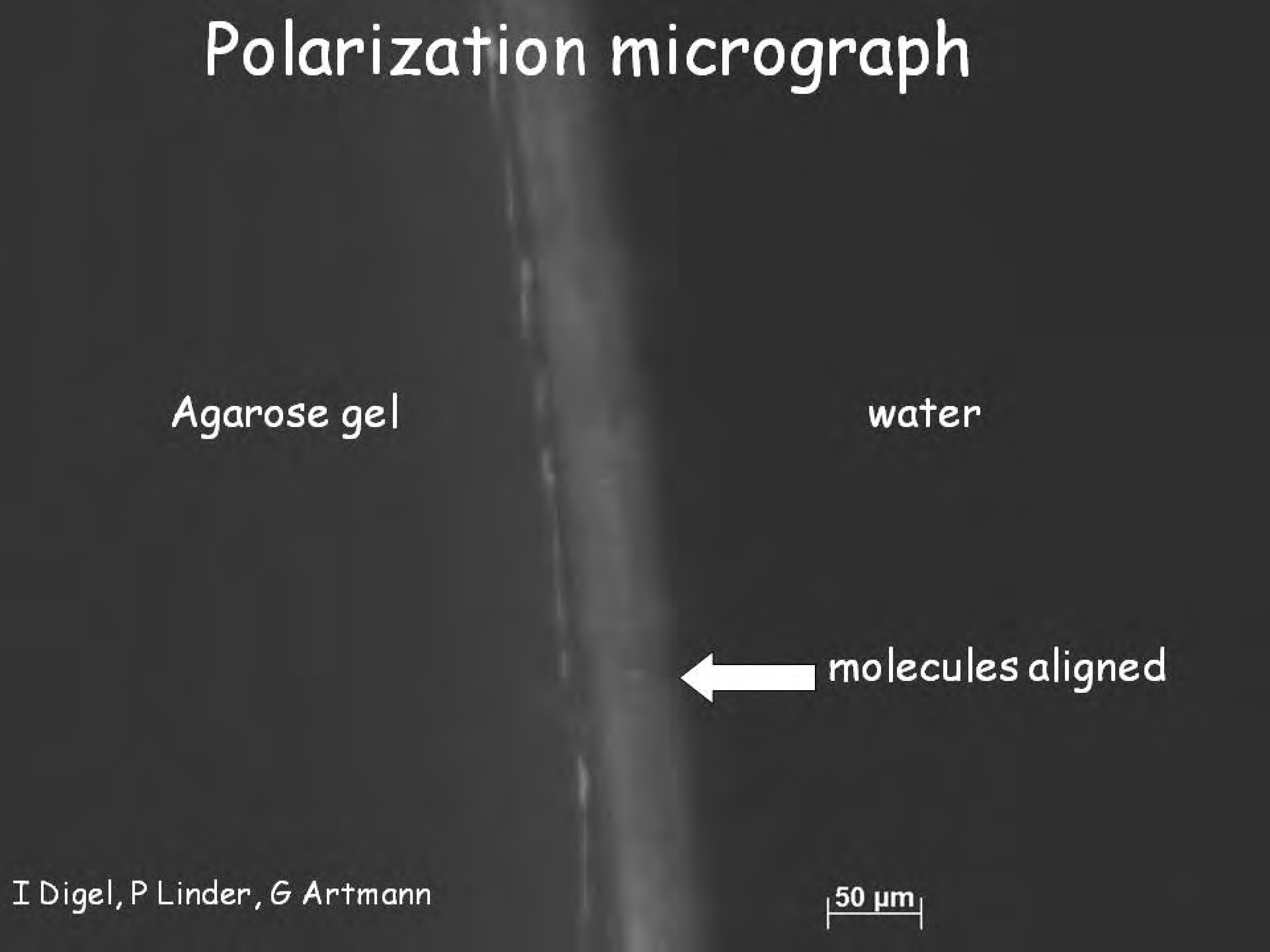
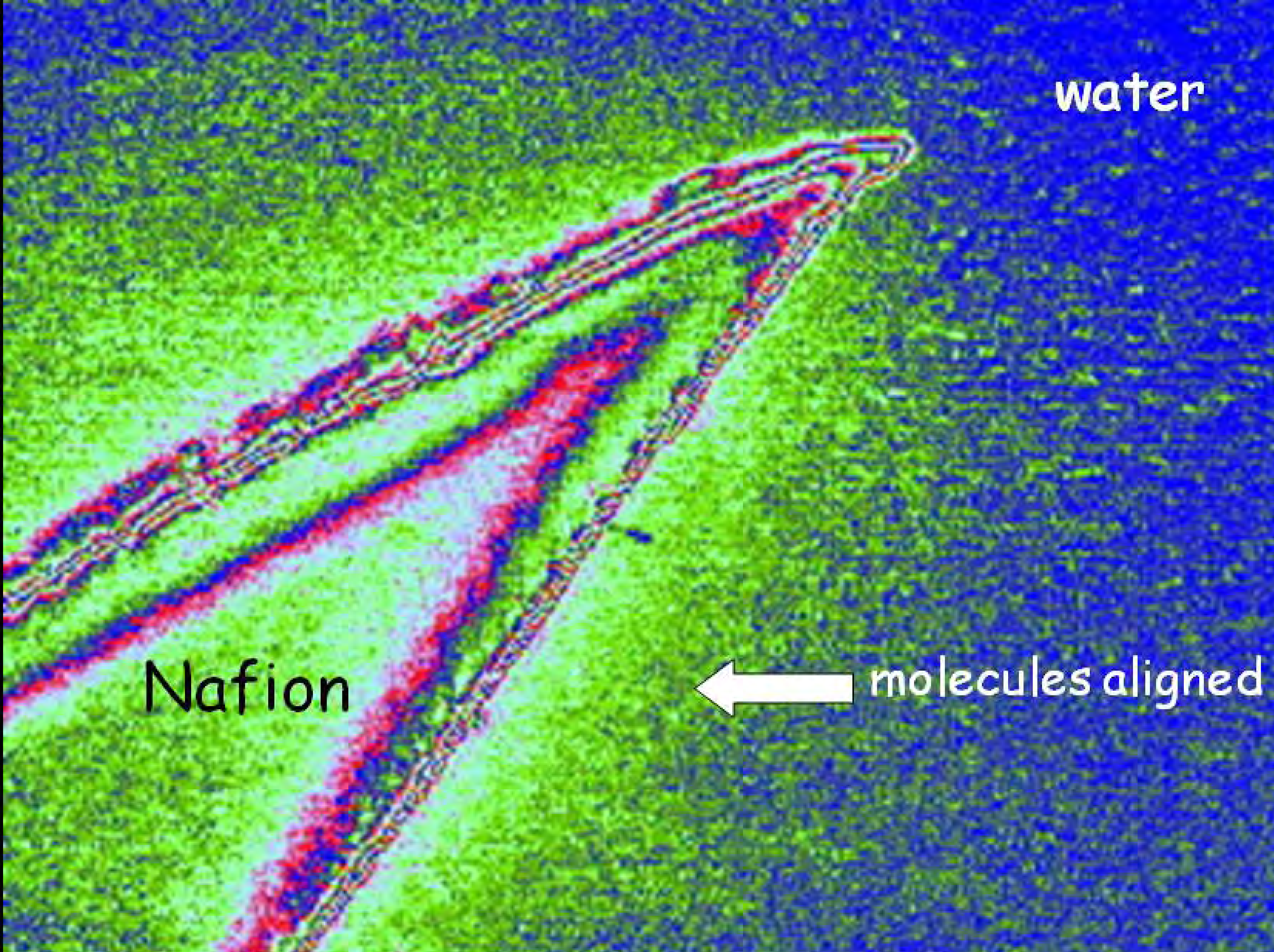
NMR
Infrared radiation
Electrical potential
Light-absorption spectrum
Viscosity (falling ball viscometer)
Polarizing microscopy -- are molecules oriented?

Polarization micrograph



I Digel, P Linder, G Artmann



Collaboration with Werner Kaminsky, UW Dept. Chemistry


200 µ
0.4 / 141
0.9 / 141
1.5 / 137
0.7 / 142
0.3 / 135
0.9 / 135
Nafion
M. Shribak (Woods Hole)
PS 08 0228 1425 43: 21 ms 3 nm ceiling Bkgd: BG 08 0228 1425 07 8-frames

Evidence that EZ is physically different

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
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NMR
Infrared radiation
Electrical potential
Light-absorption spectrum
Viscosity (falling ball viscometer)
Polarizing microscopy -- EZ molecules aligned

Evidence that EZ is physically different

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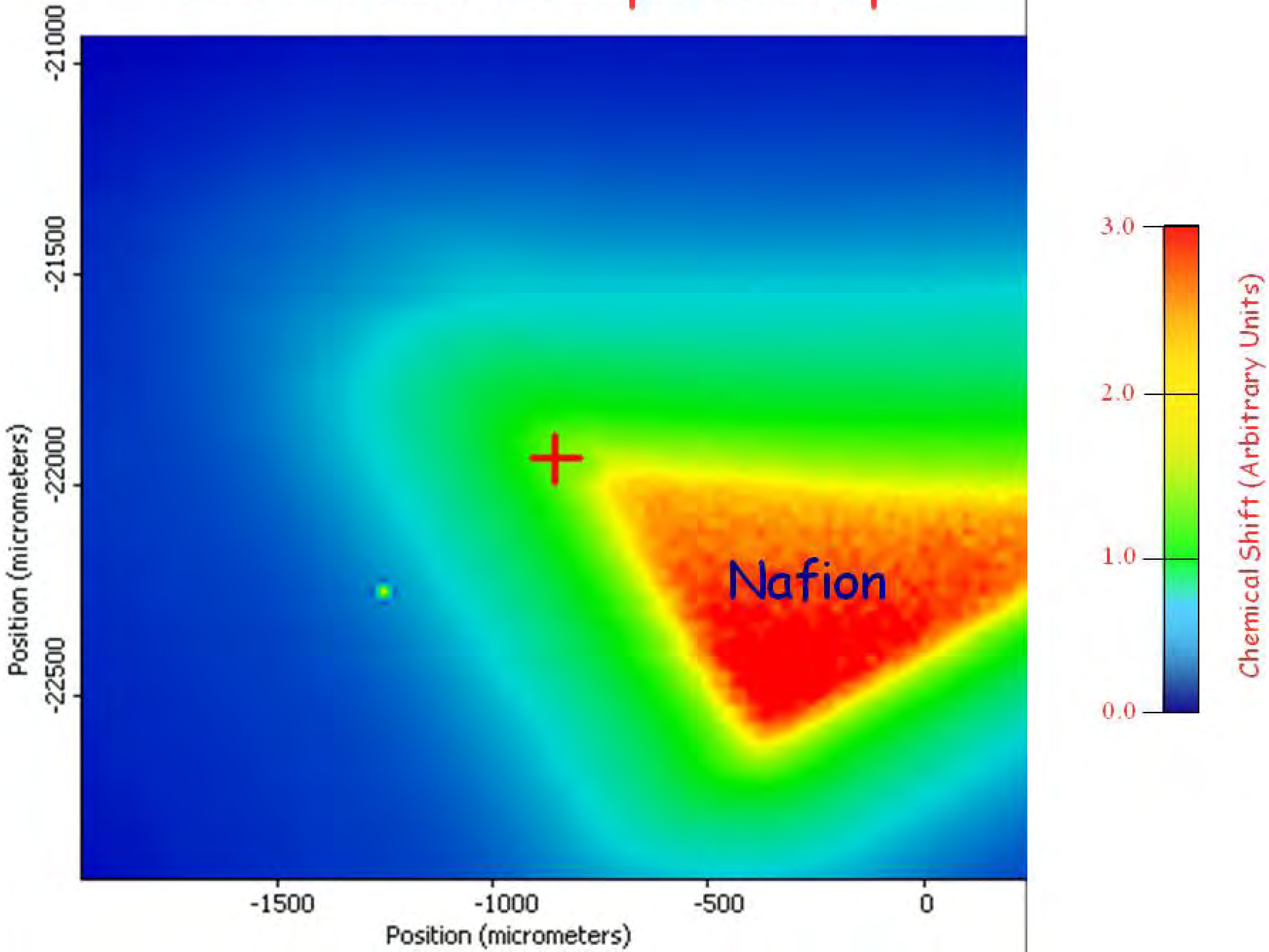
NMR
Infrared radiation
Electrical potential
Light-absorption spectrum
Viscosity (falling ball viscometer)
Polarizing microscopy
Infrared absorption – molecular structure different?

Infrared Absorption Map



Evidence that EZ is physically different

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NMR
Infrared radiation
Electrical potential
Light-absorption spectrum
Viscosity (falling ball viscometer)
Polarizing microscopy
Infrared absorption – molecular structure different

Evidence that exclusion-zone (EZ) water is physically different from bulk water

- EZ water molecules more constrained (NMR)
- EZ molecules more stable (infrared radiation)
- EZ has negative charge (electrical potential)
- EZ absorbs at 270 nm (light-absorption spectrum)
- EZ is more viscous (falling ball viscometry)
- EZ molecules aligned (polarizing microscopy)
- EZ molecular structure different (IR absorption)

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009

Evidence that exclusion-zone (EZ) water is physically different from bulk water

- EZ water molecules more constrained (NMR)
- EZ molecules more stable (infrared radiation)
- EZ has negative charge (potential measurement)
- EZ absorbs at 270 nm (light-absorption spectrum)
- EZ is more viscous (falling ball viscometry)
- EZ molecules aligned (polarizing microscopy)
- EZ molecular structure different (IR absorption)

Zheng et al., *Adv. Colloid and Interface Sci*, 127: 19-27, 2006
Chai et al., *J Phys Chem*, 112: 2242 - 2247, 2008
Zheng et al., *J. Coll. Interface Sci*, 332: 511-514, 2009

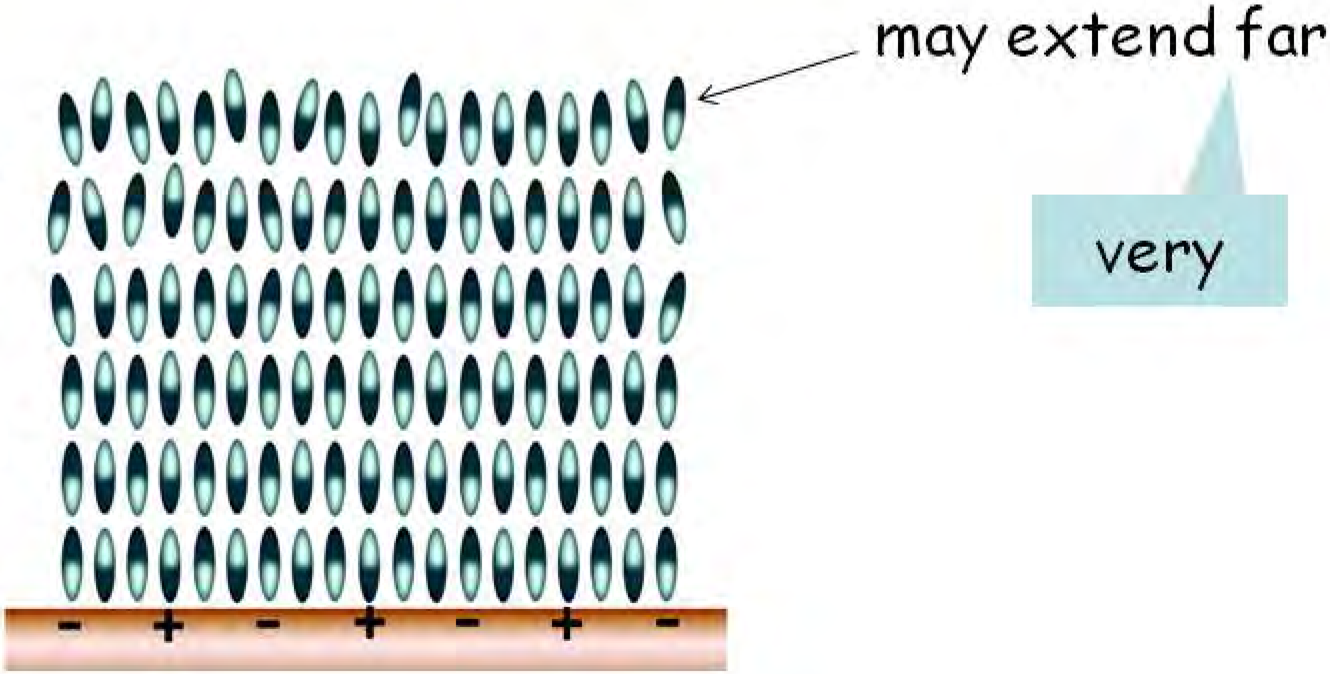
Summary, so far

Liquid crystalline

Negative charge

Excludes solutes

(Non-dipolar?)



Fourth phase of water?

(Sir Wm. Hardy, 1912)

REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 2 APRIL, 1949

The Depth of the Surface Zone of a Liquid*

J. C. HENNIKER
Stanford Research Institute, Stanford, California

TABLE OF CONTENTS

sists of a monolayer of oriented molecules. The recognition of this truth came at the same time as the rejection of the assumption of classical physics that direct intermolecular forces are of long range, of the order of one micron. The long range forces were abandoned in favor of electrical forces directly effective for only a few angstrom units. Subsequently attention has been so focused on the dominant role of the outermost layer of molecules that the inevitable polarizing effect of this oriented layer upon the molecules immediately adjacent to it has been overlooked.

The fact that liquid molecules are already close-packed and that they are therefore readily oriented [illegible] was described. [illegible] paper [illegible] words may be [illegible] influence of a [illegible] small value, not much greater than [illegible] diameter of the molecule itself. Quite another [illegible] range of molecular action is possible in close-packed structures such as fluids and solids, namely, a strain transmitted from [illegible]

"...hundreds of microns in depth"

Answer to Question #2
Is EZ physically distinct from bulk?

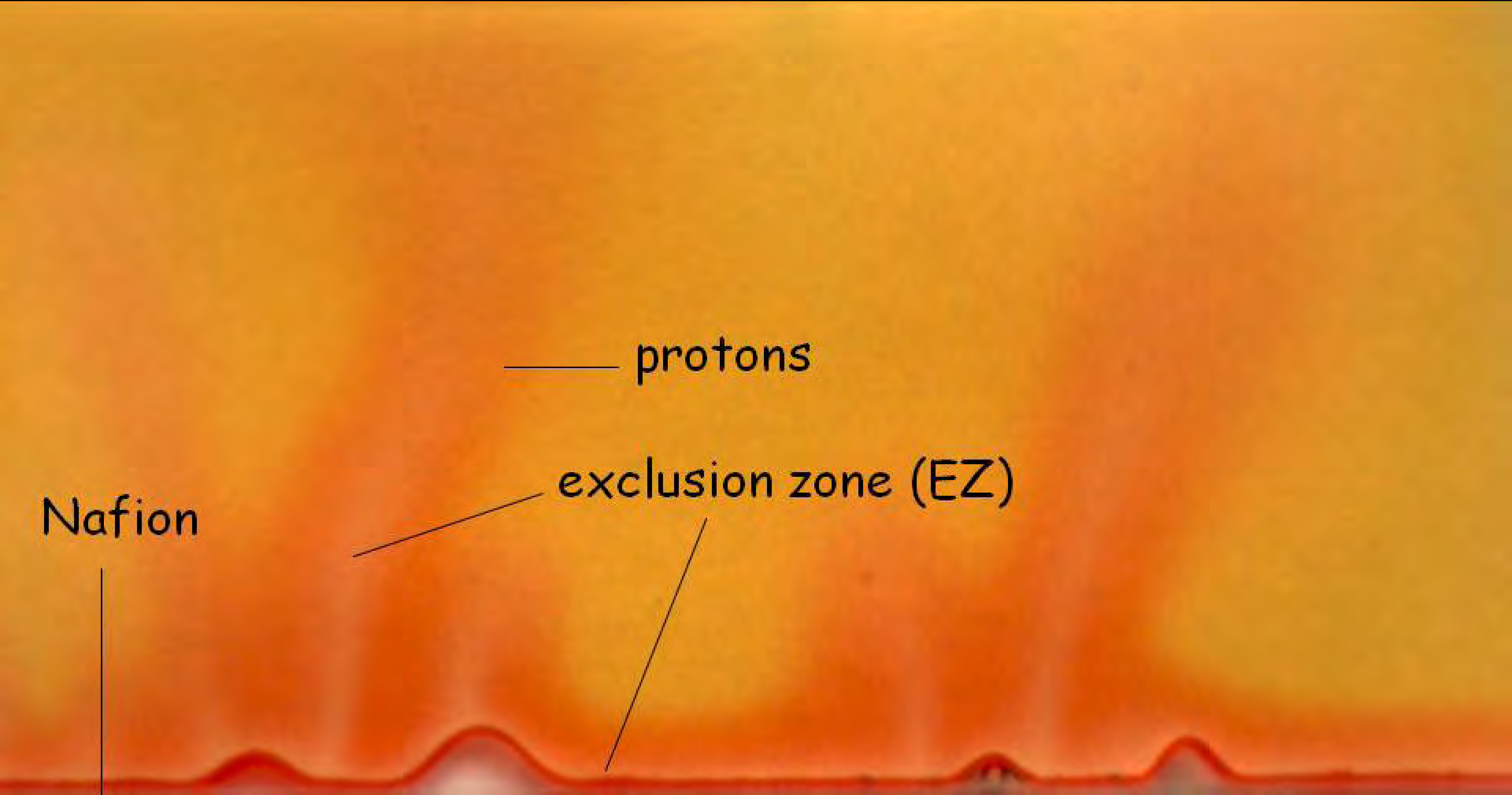
Yes

Liquid crystalline

Question #3: Can crystalline water explain counter-intuitive anomalies?

What behavior do we expect from a crystal?

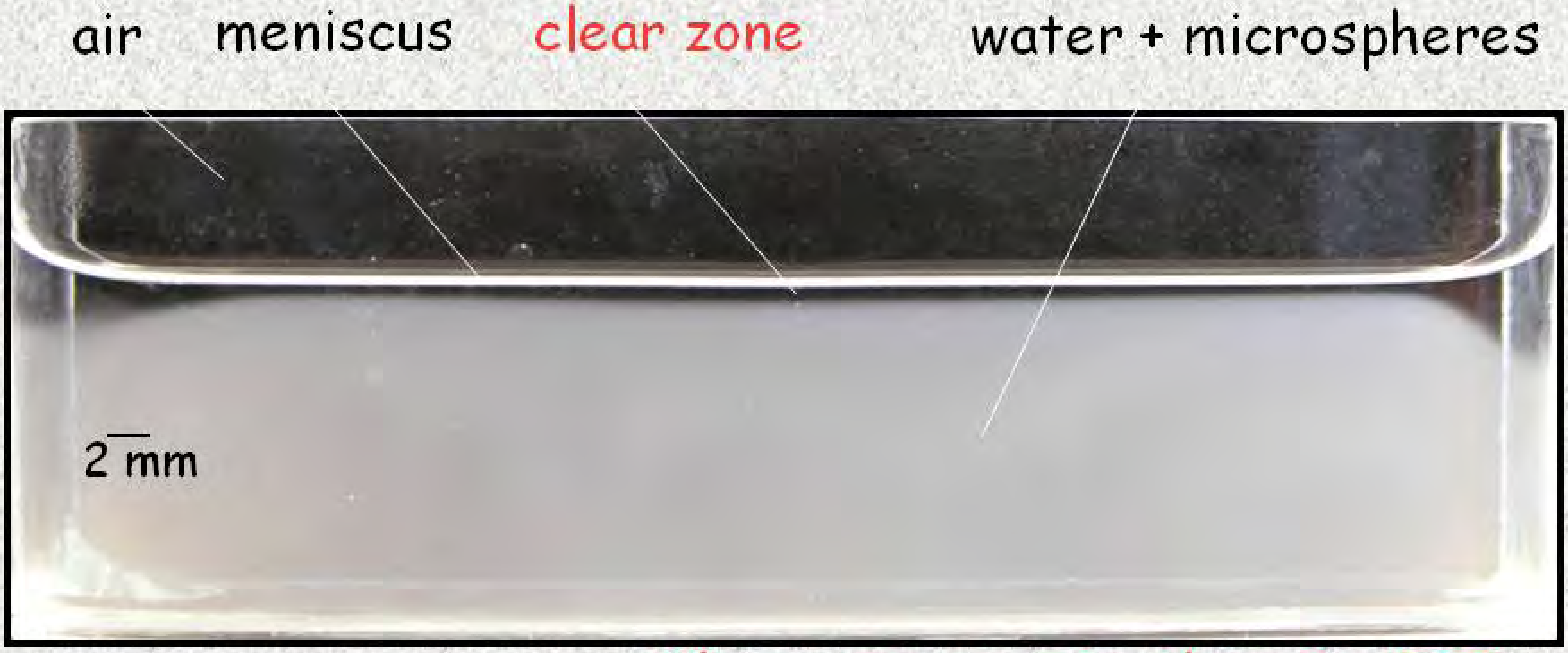
Crystals can grow



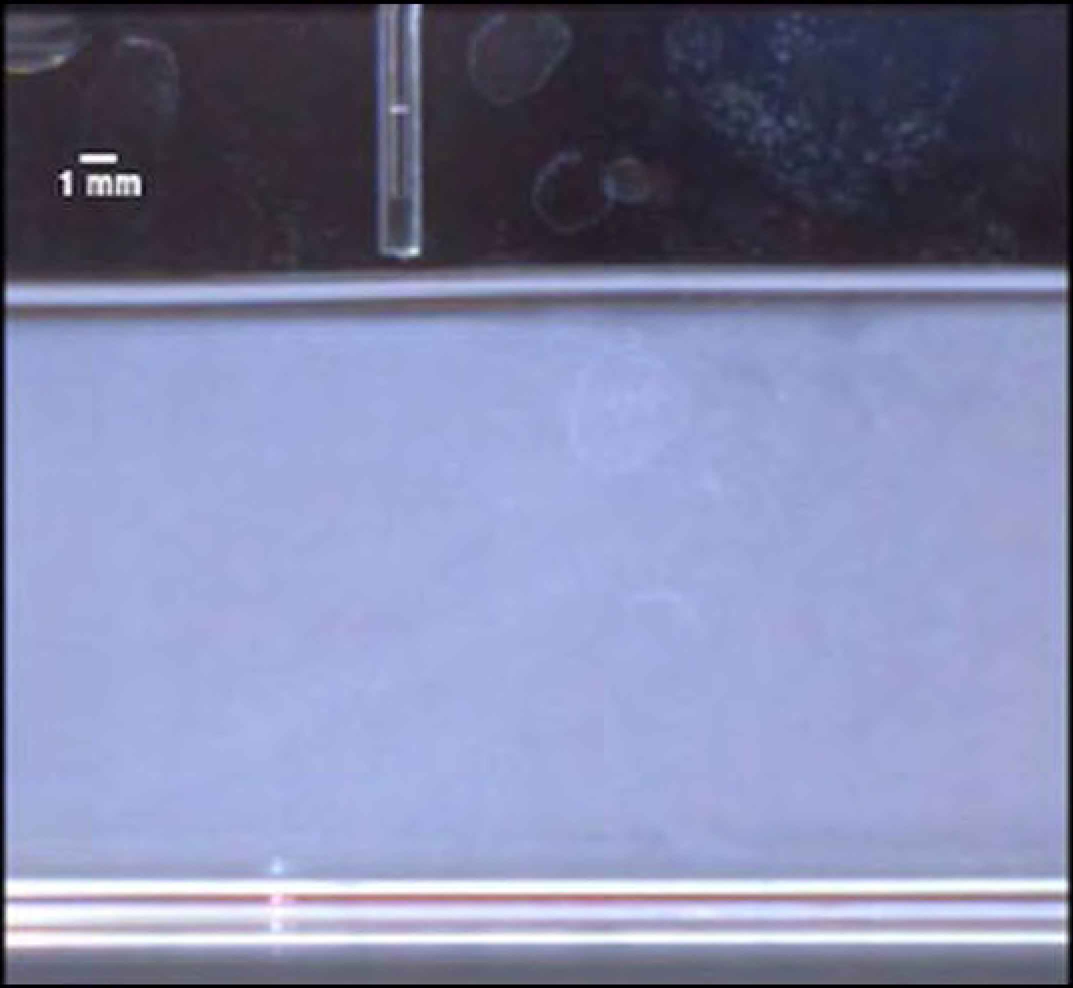
Crystalline elements stick together

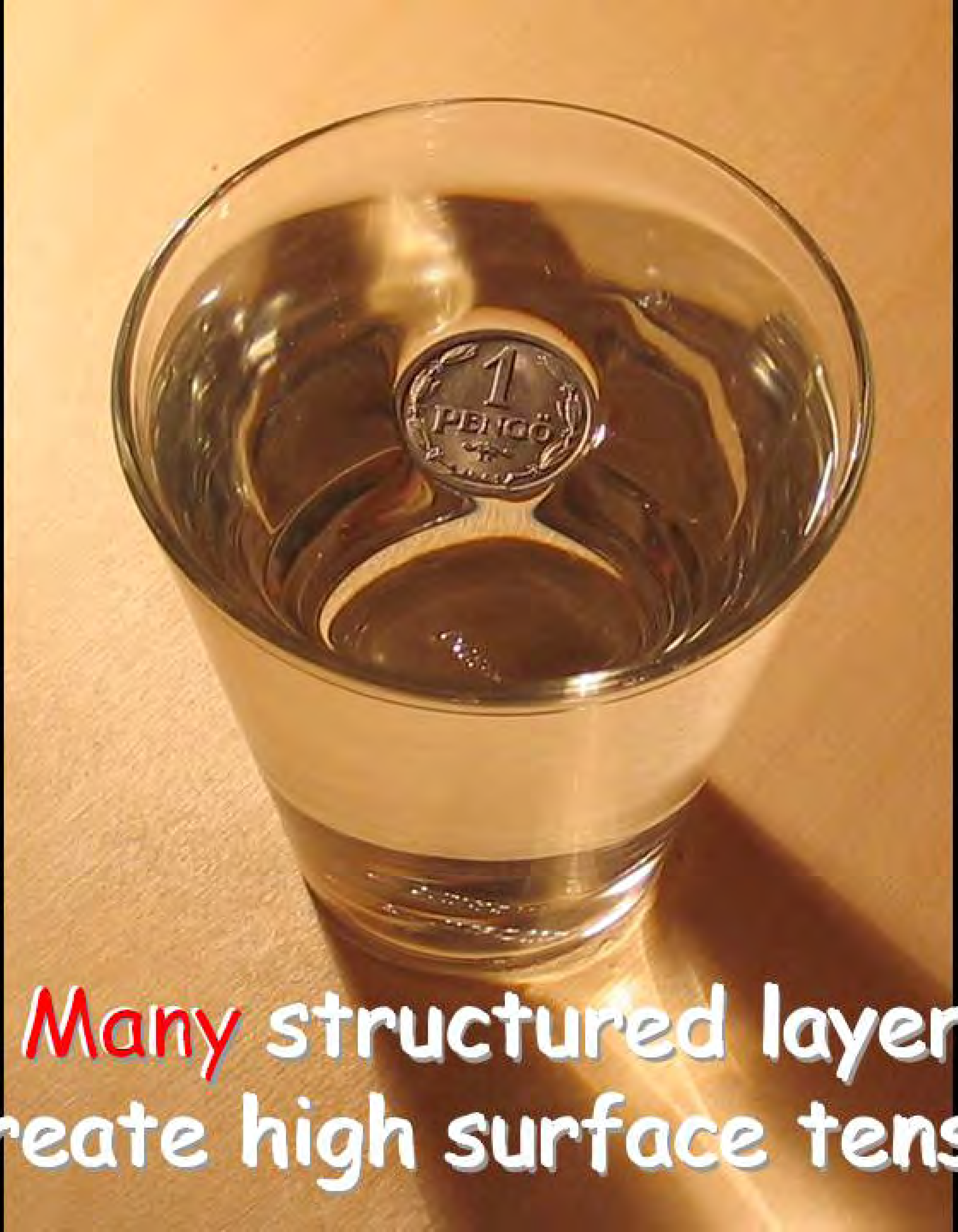

Crevices are filled with liquid crystal
Crystalline water is gel-like
Gel-like water fills your cells

Crystalline water grows at air-water interface

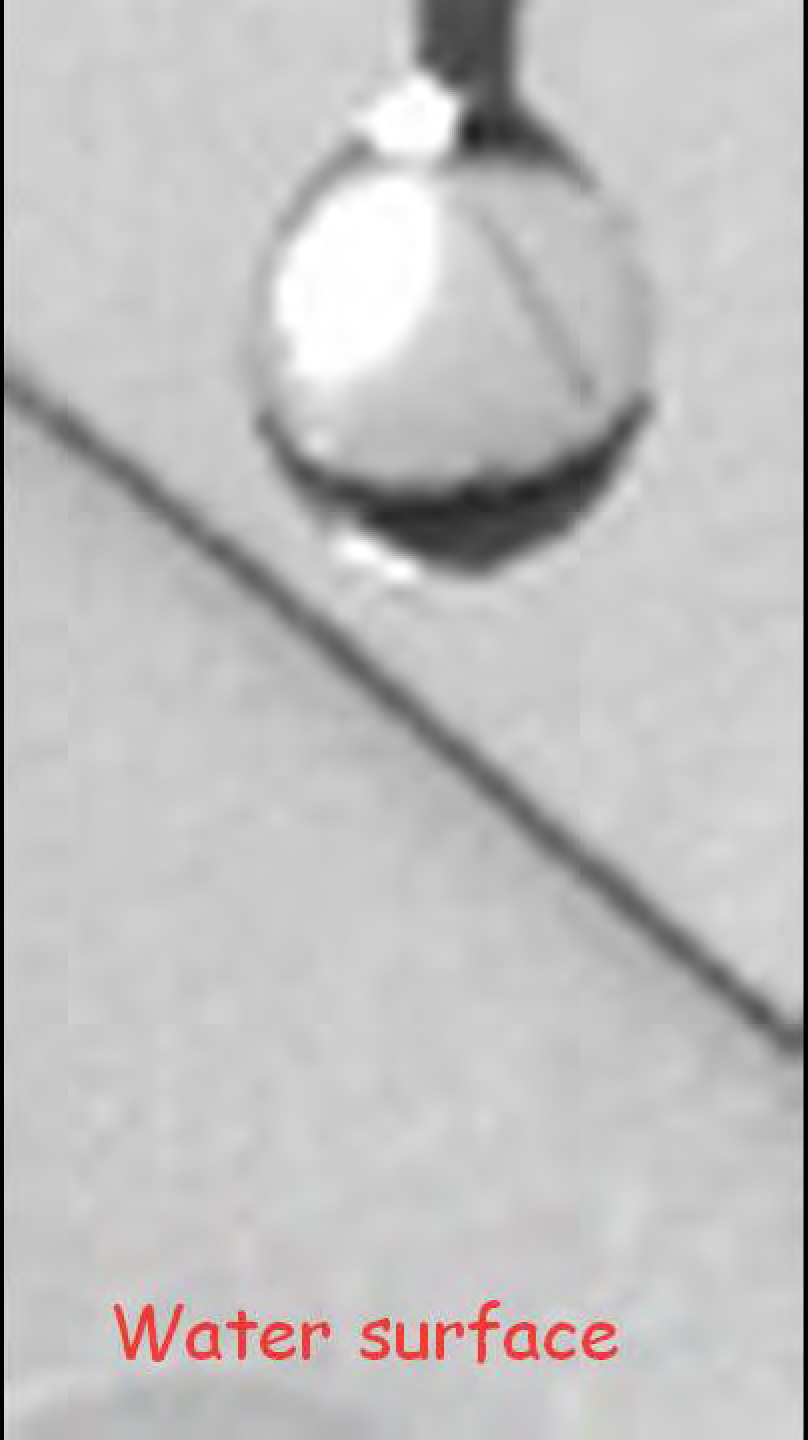


Clear zone similar to EZ
Negative potential
Thick gel-like band

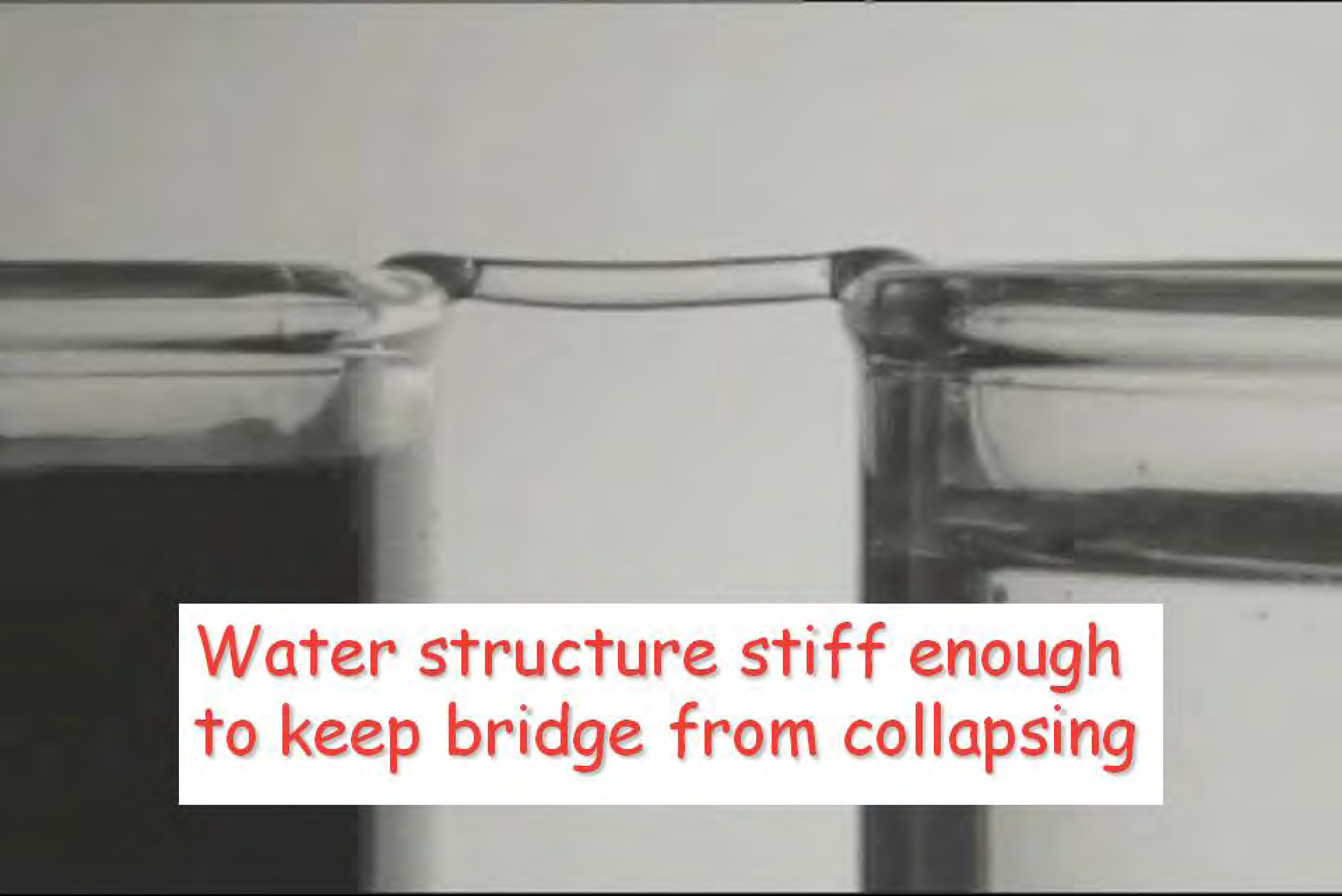

1 mm



Many structured layers create high surface tension


Water surface

Crystals can be pretty stiff



Water structure stiff enough to keep bridge from collapsing

Crystalline zone keeps protons (hydronium ions) out

Answer to Question #3

Yes

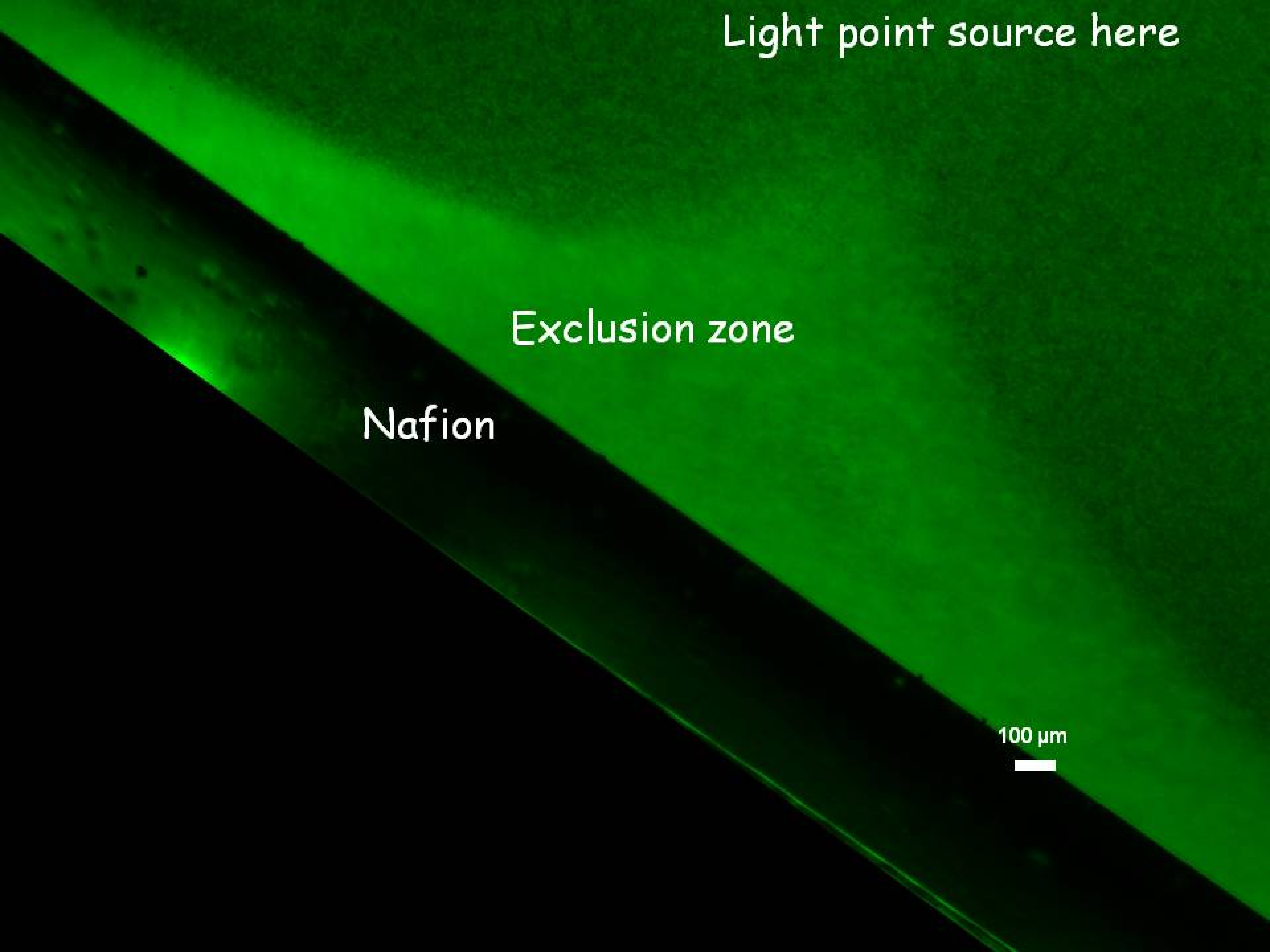
Liquid crystalline water explains many anomalies

It explains why water battery charges remain separated

Question #4

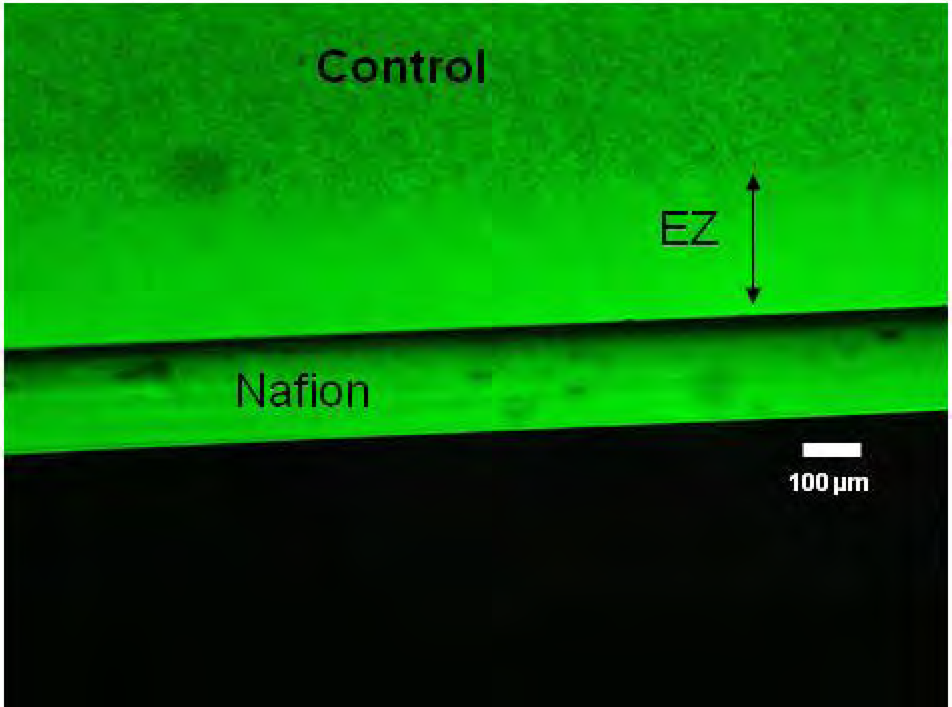
What charges the water battery?

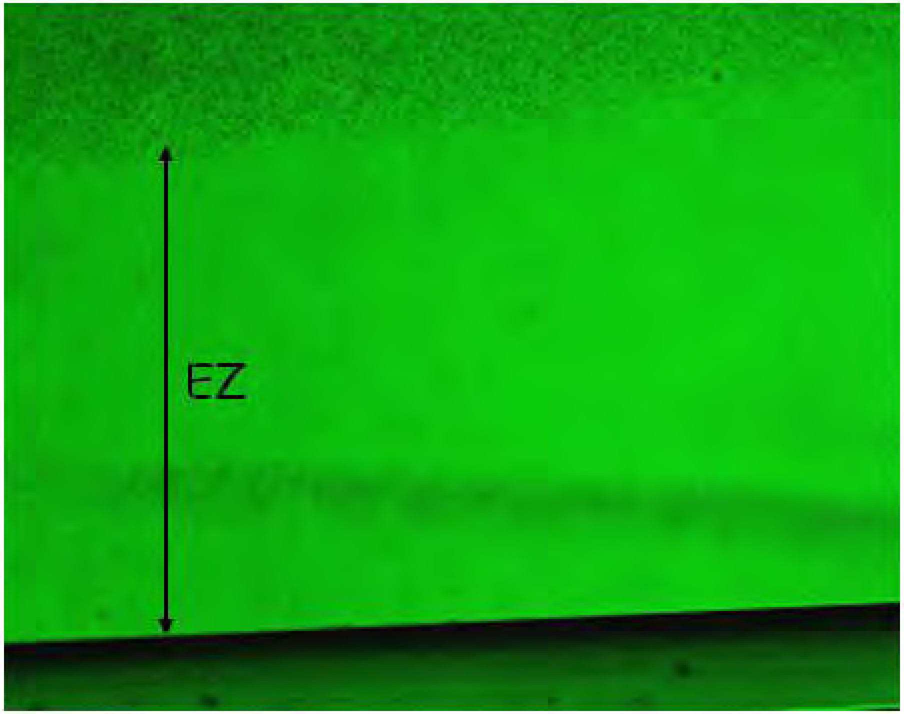
(Incident radiant energy)


Light point source here
Exclusion zone
Nafion
100 µm

Near infrared illumination

With illumination – 5 min

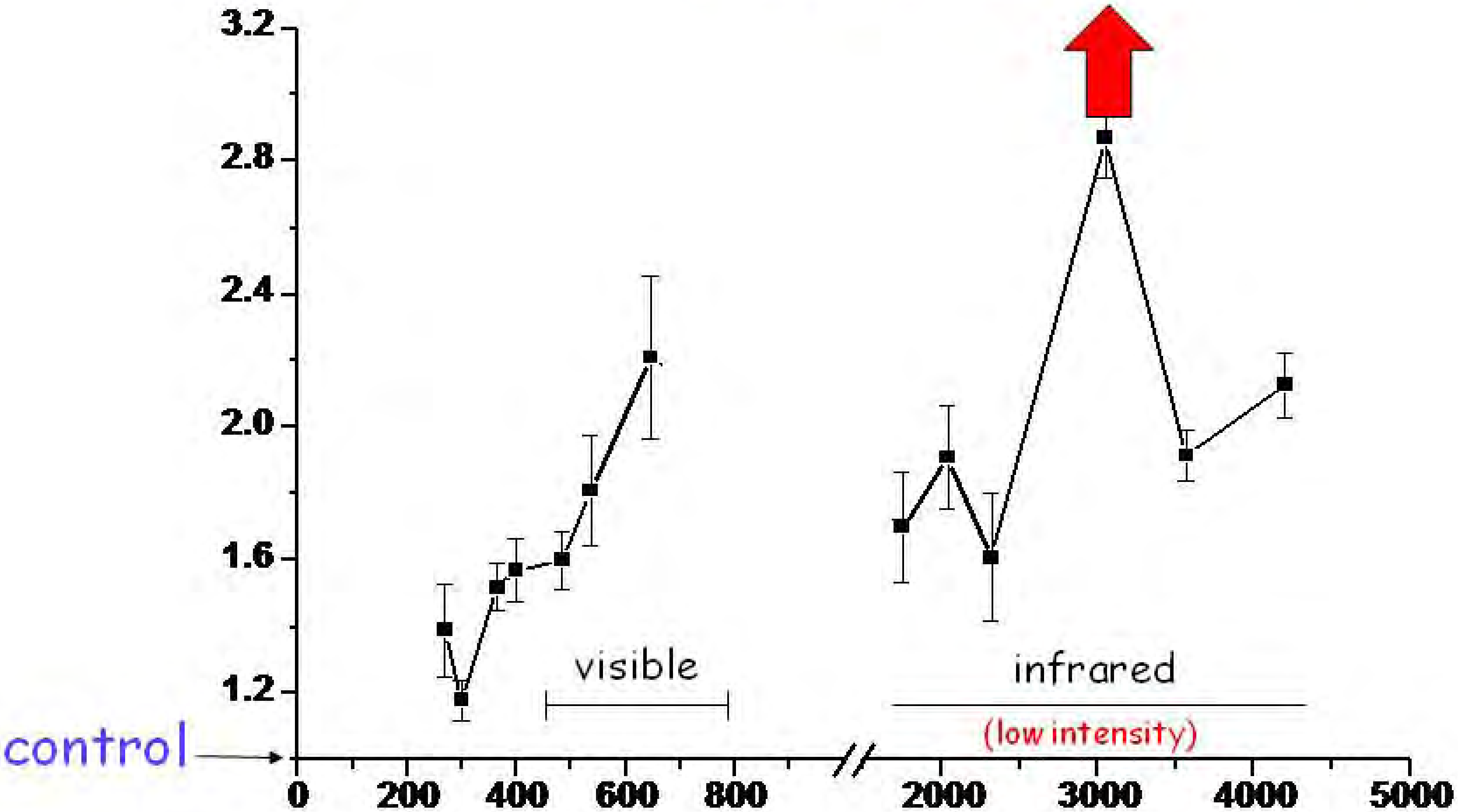


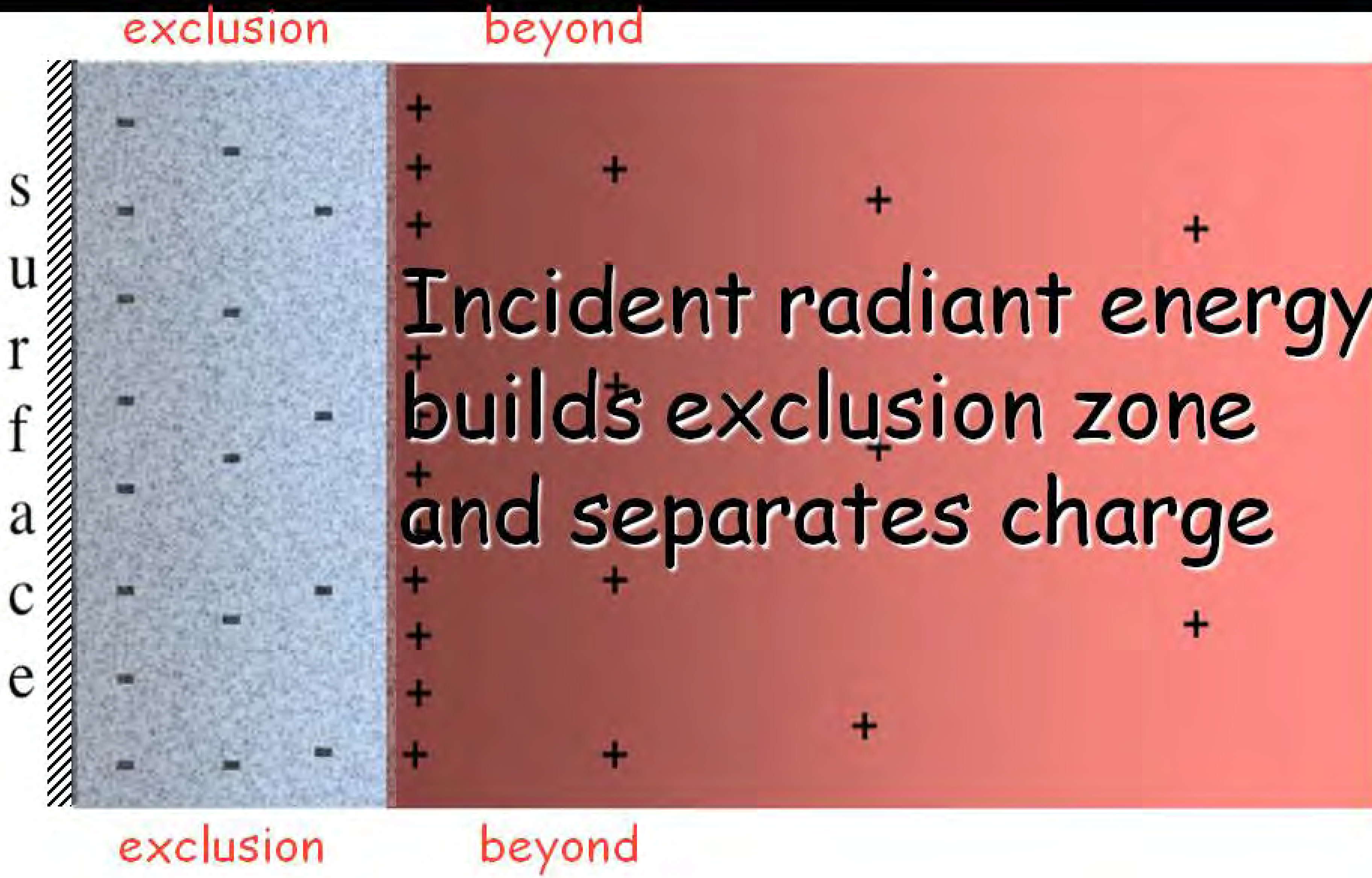


temperature rise < 1°

Effect of Wavelength on EZ Size

(5 min exposure)




exclusion
beyond
surface
Incident radiant energy builds exclusion zone and separates charge
exclusion
beyond

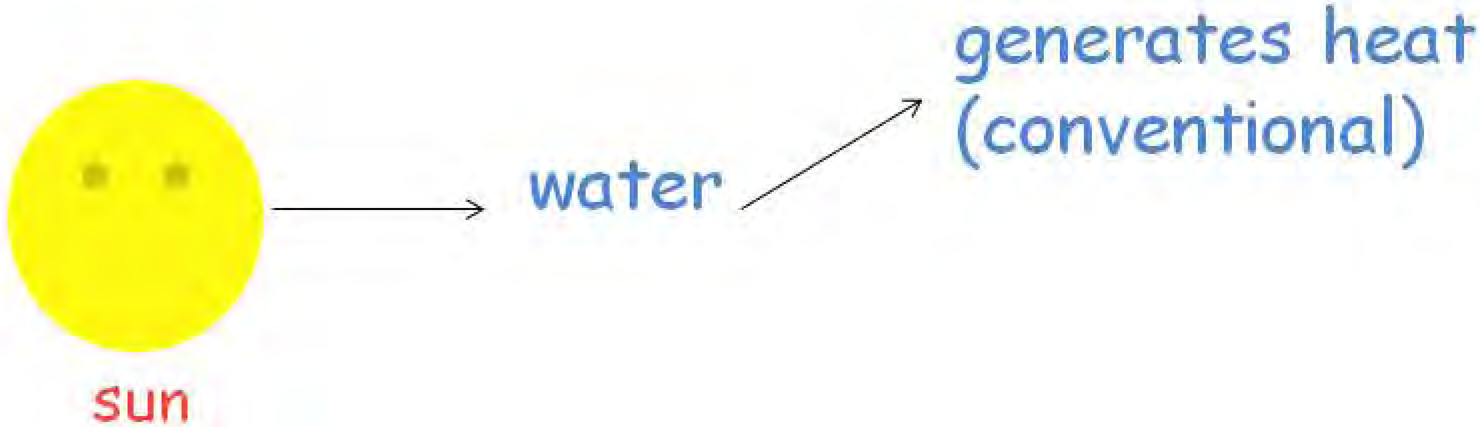
Answer to Question #4
Energy?

EZ buildup powered by photonic energy…

Orders water

Charges the water battery

Possible Energy Flow in Universe



Possible Energy Flow in Universe

sun → water → generates heat (conventional)

water → imparts energy for building order and separating charge

Possible Energy Flow in Universe

sun

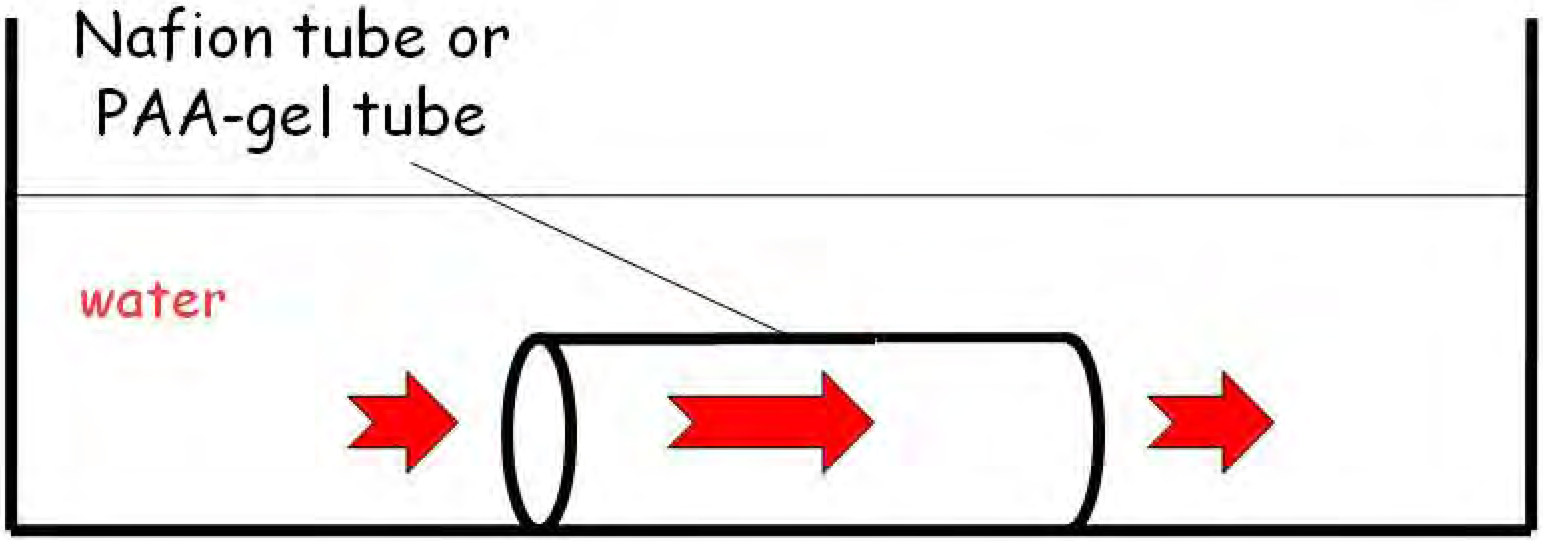
water

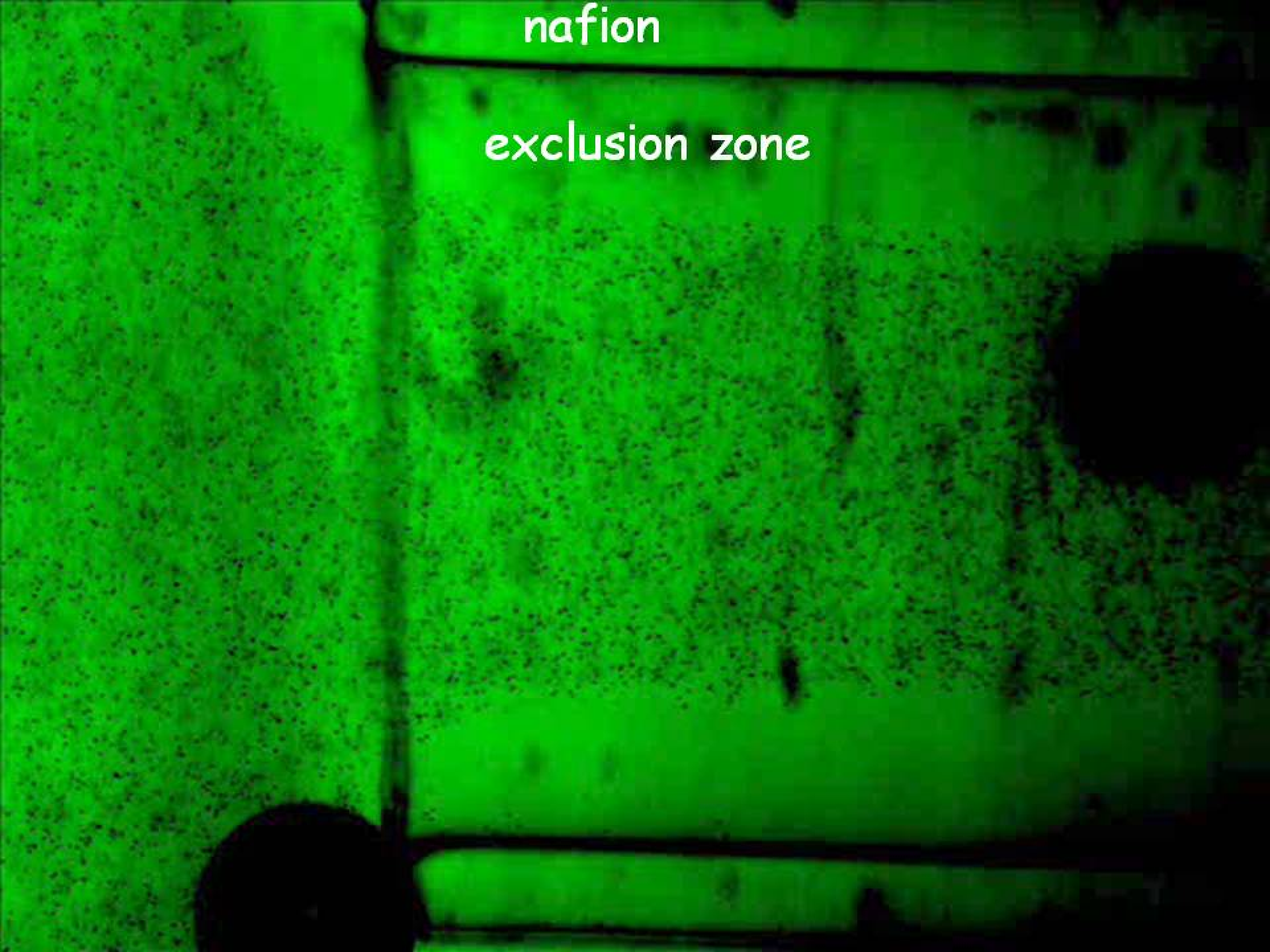
generates heat
(conventional)

imparts energy
for building order
and separating charge

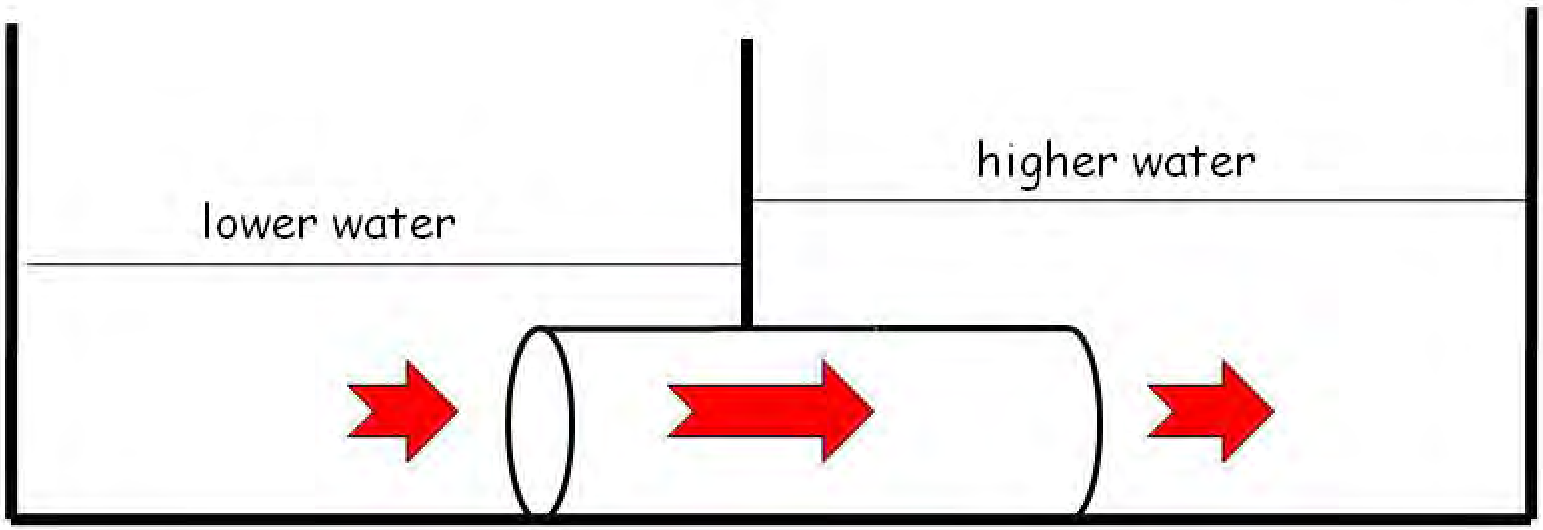
imparts energy to our cells

Incident radiant energy can be harvested...



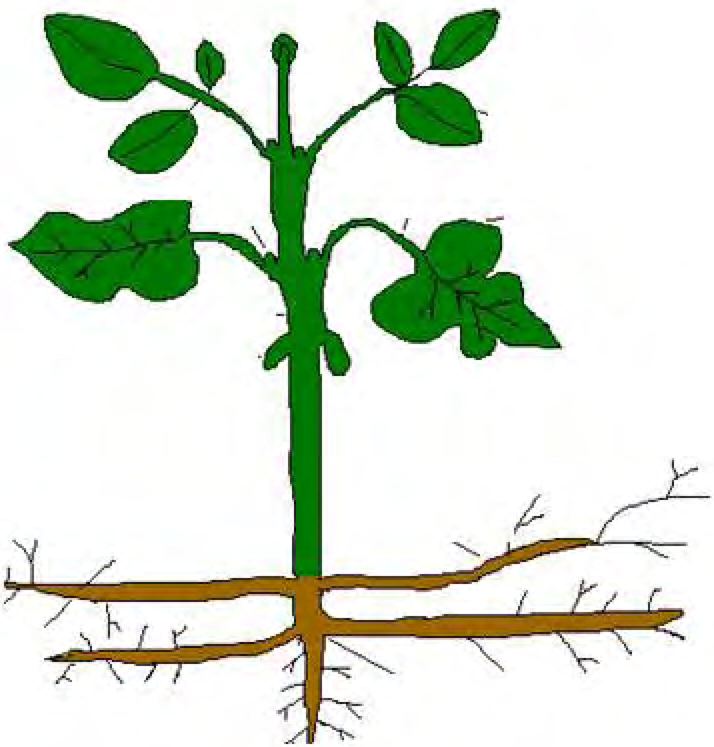

nafion
exclusion zone


Polyacrylic acid gel
EZ



Incident radiant energy harvested to do work

Evidence that incident energy MUST be absorbed



Incident energy might drive Brownian excursions

Light energy in

Motion energy out

Question #5
Why is all of this important?

- Foundational for any/all science involving water and light
  - physics
  - chemistry
  - biology
- Foundational for engineering of genuinely new practical devices

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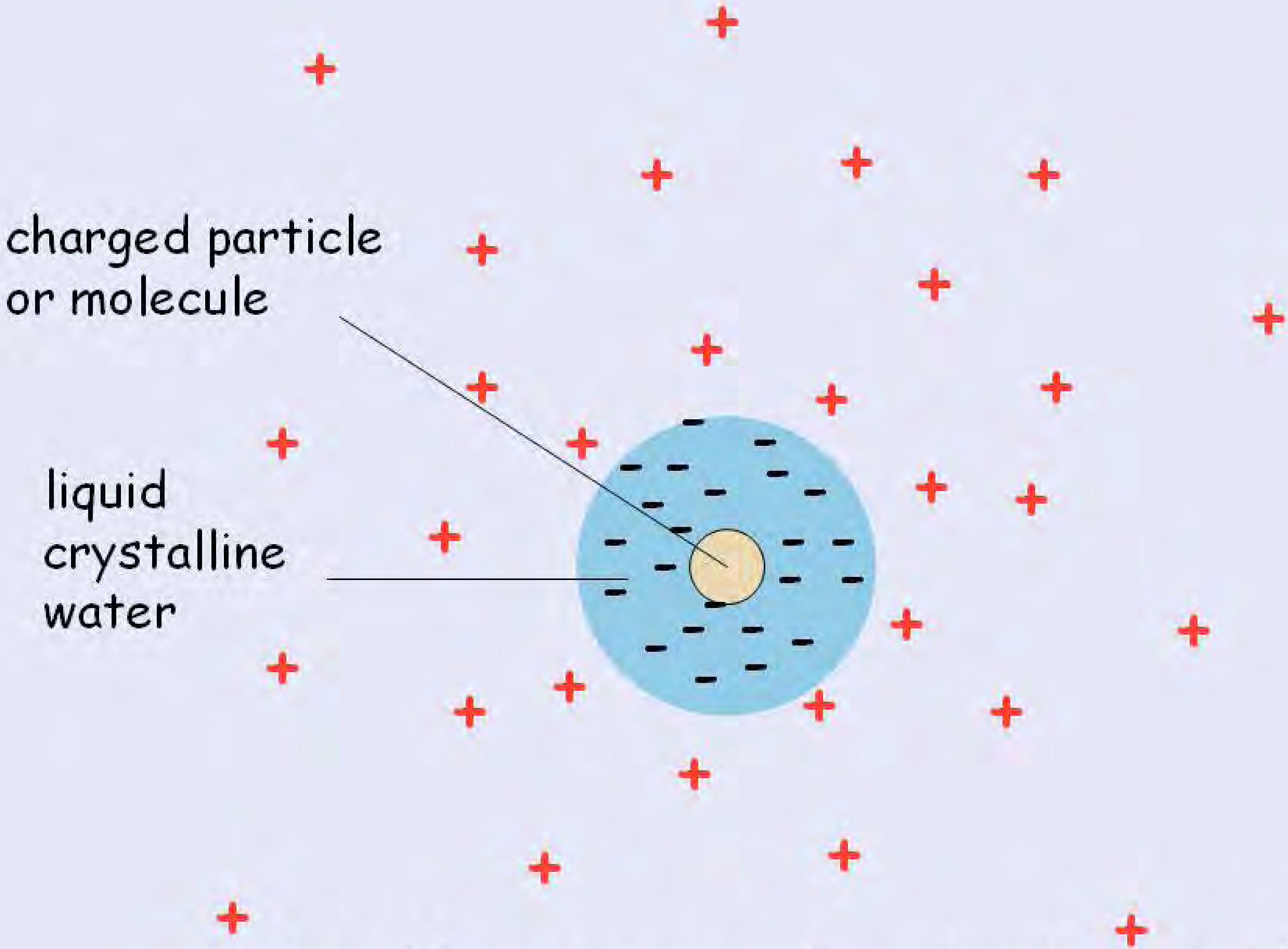
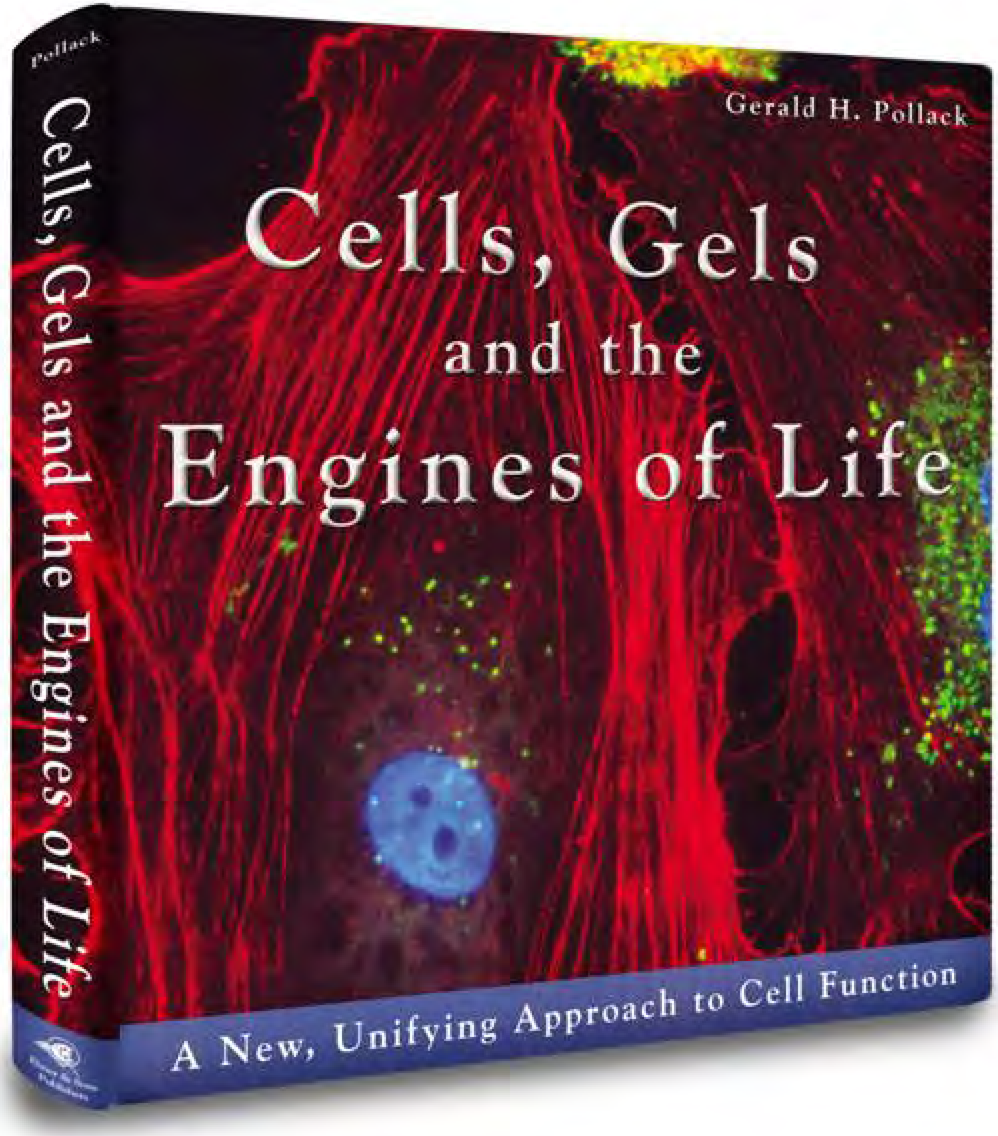
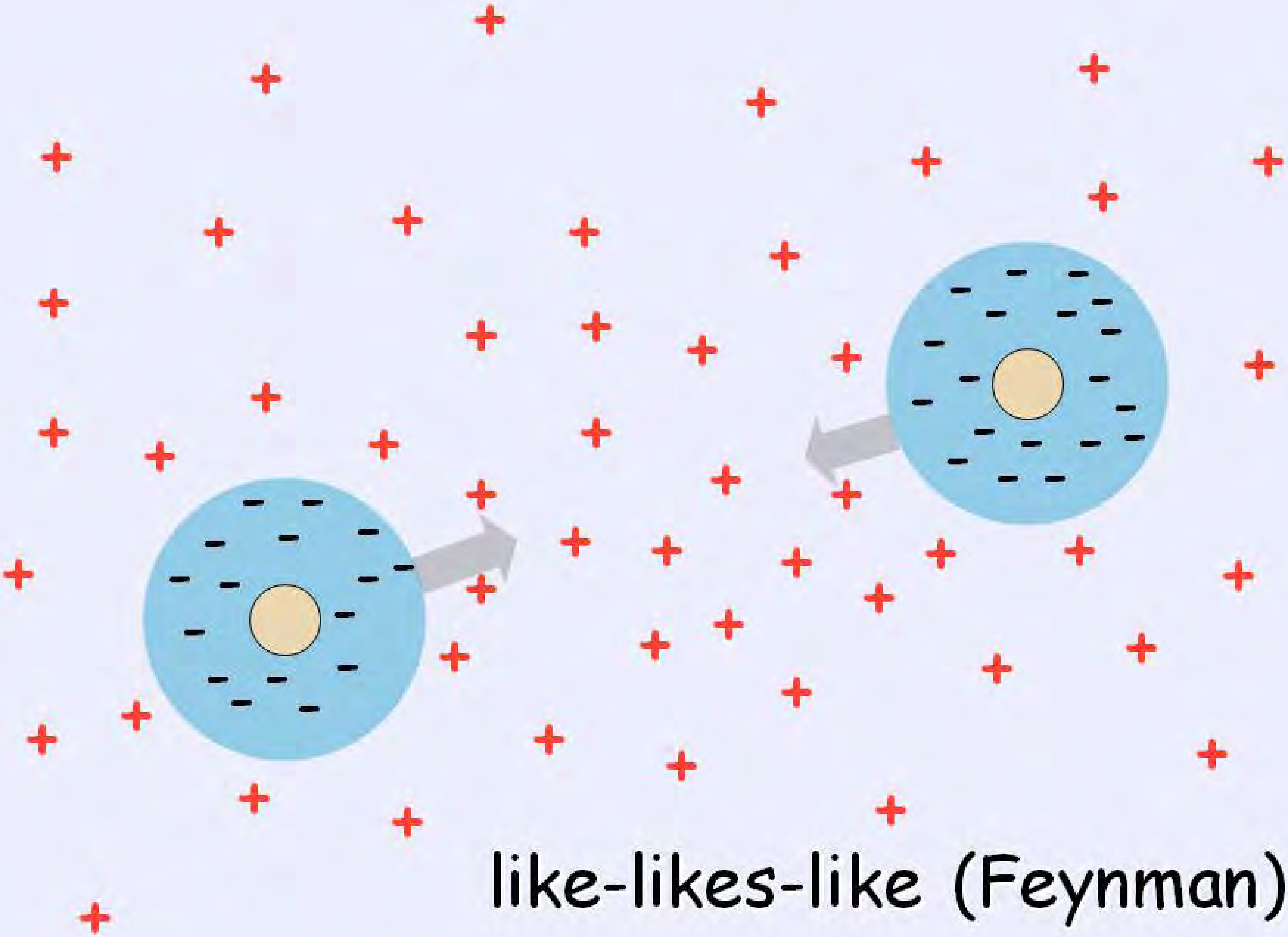
Example:
water,
light,
particles



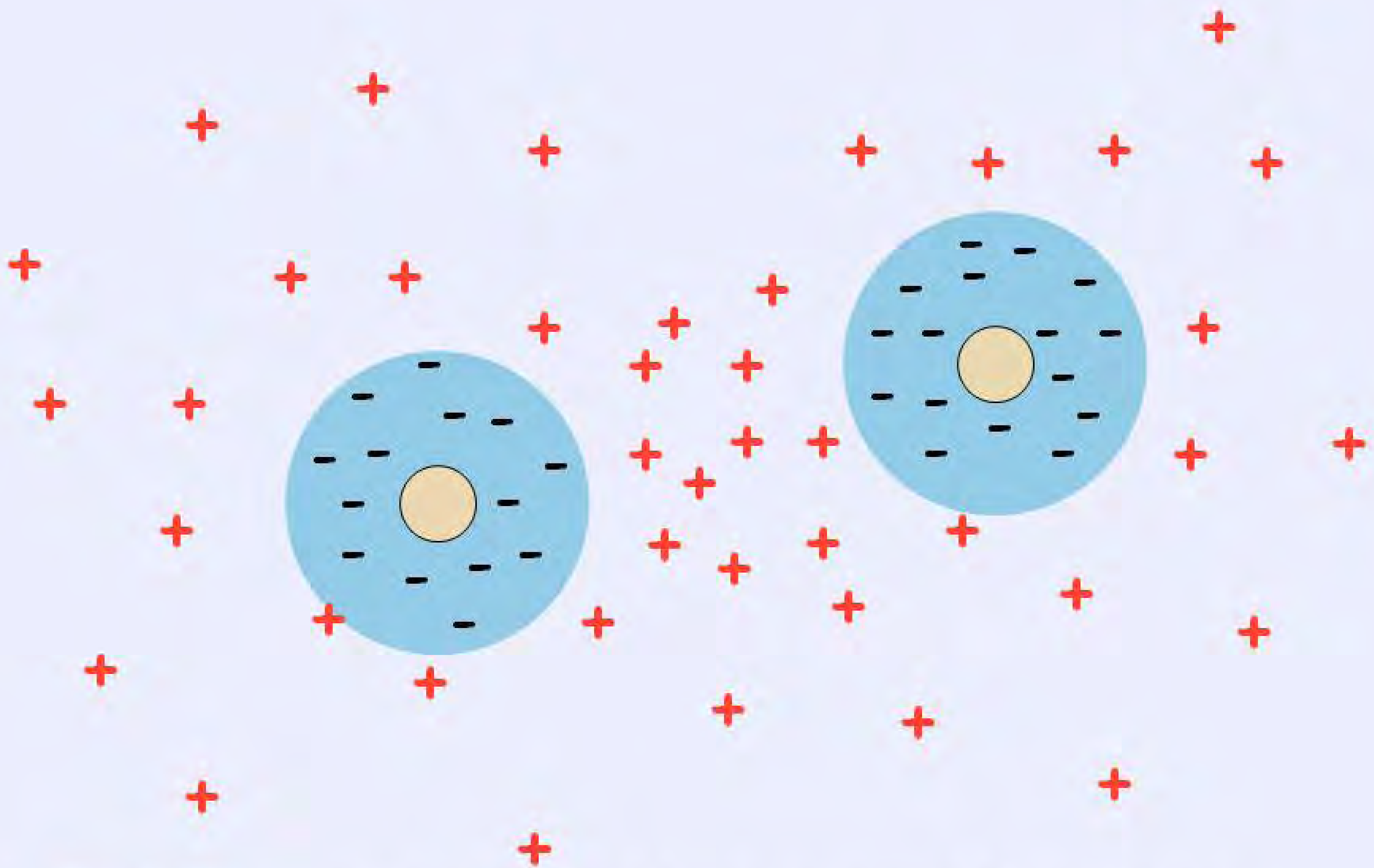
in all aqueous chemical reactions

including chemical reactions in cells...

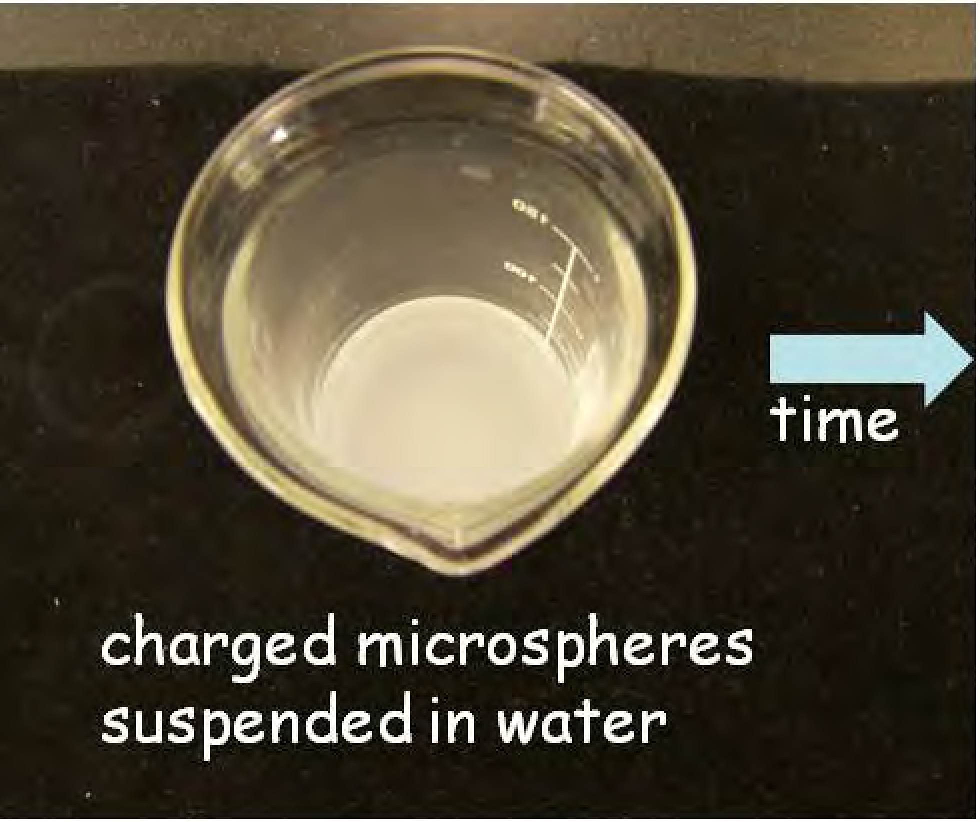




like-likes-like (Feynman)

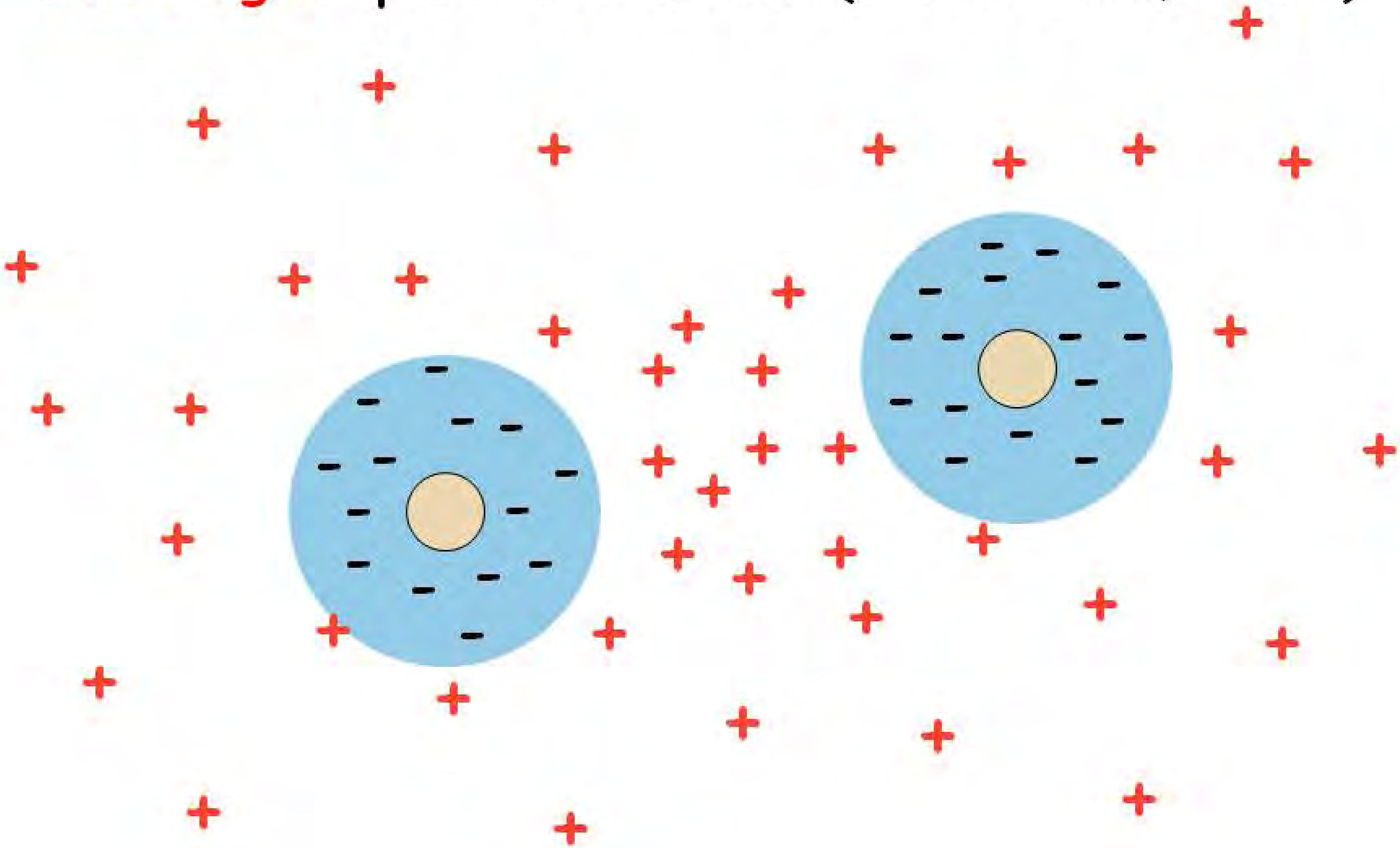


Stability: attractive force = repulsive force



courtesy Norio Ise
Kyoto University

More light: particles closer (Zhao et al., 2008)



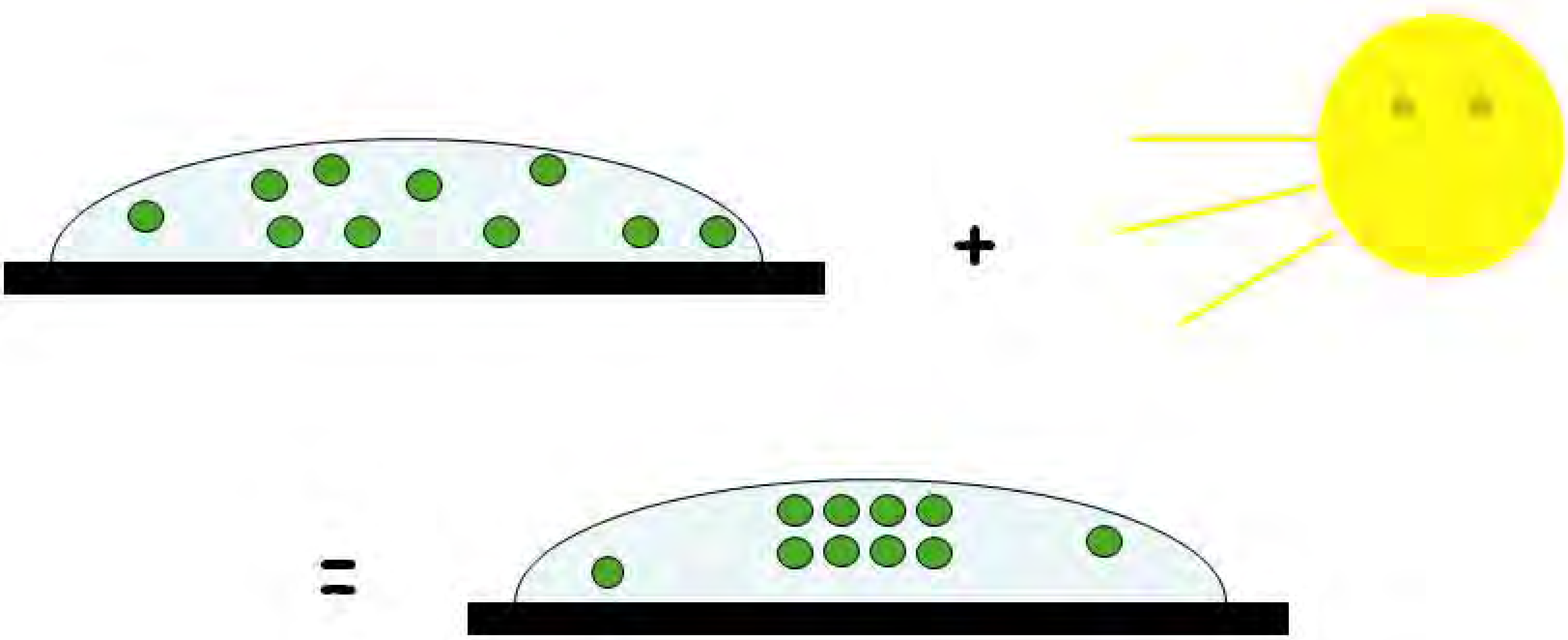

aerosol clusters attract
because like-likes-like
(powered by light)

A special example of like-likes-like…

Origin of Life

Step 1?

dispersed molecules coalesce



Aggregate keeps growing (like cell) self assembly
Has negative charge (like cell)
Has potential energy (like cell)
Has capacity to divide (like cell)

Step 1 in origin of life may be light-induced aggregation

All that's needed:

the sun's energy
molecules
water

Is life being created continually?

Question #5: Why is all of this important?

- Foundational for any/all science involving water and light
  - physics
  - chemistry
  - biology

  unifying
- Foundational for engineering of genuinely new practical devices

Question #5:
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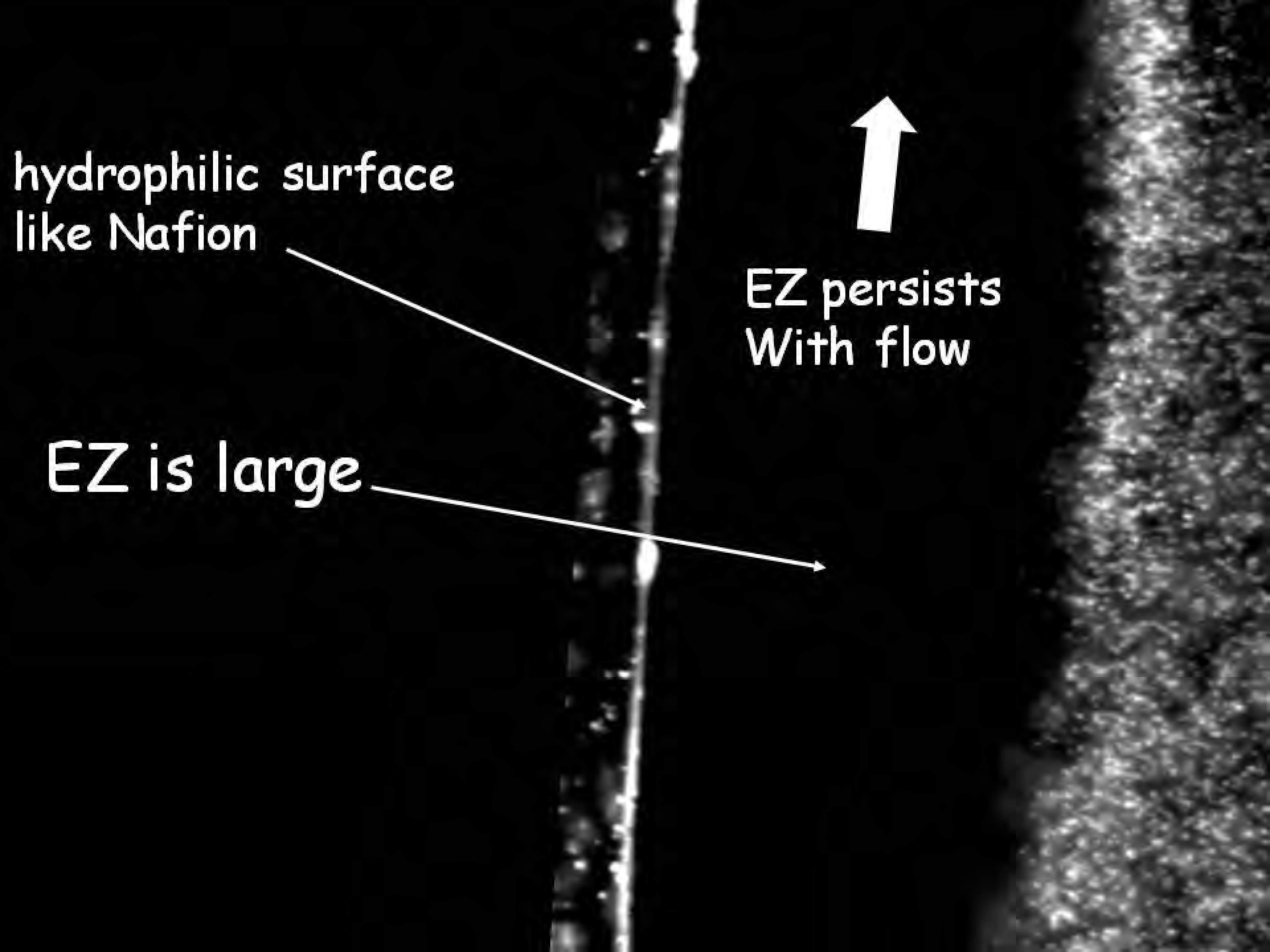
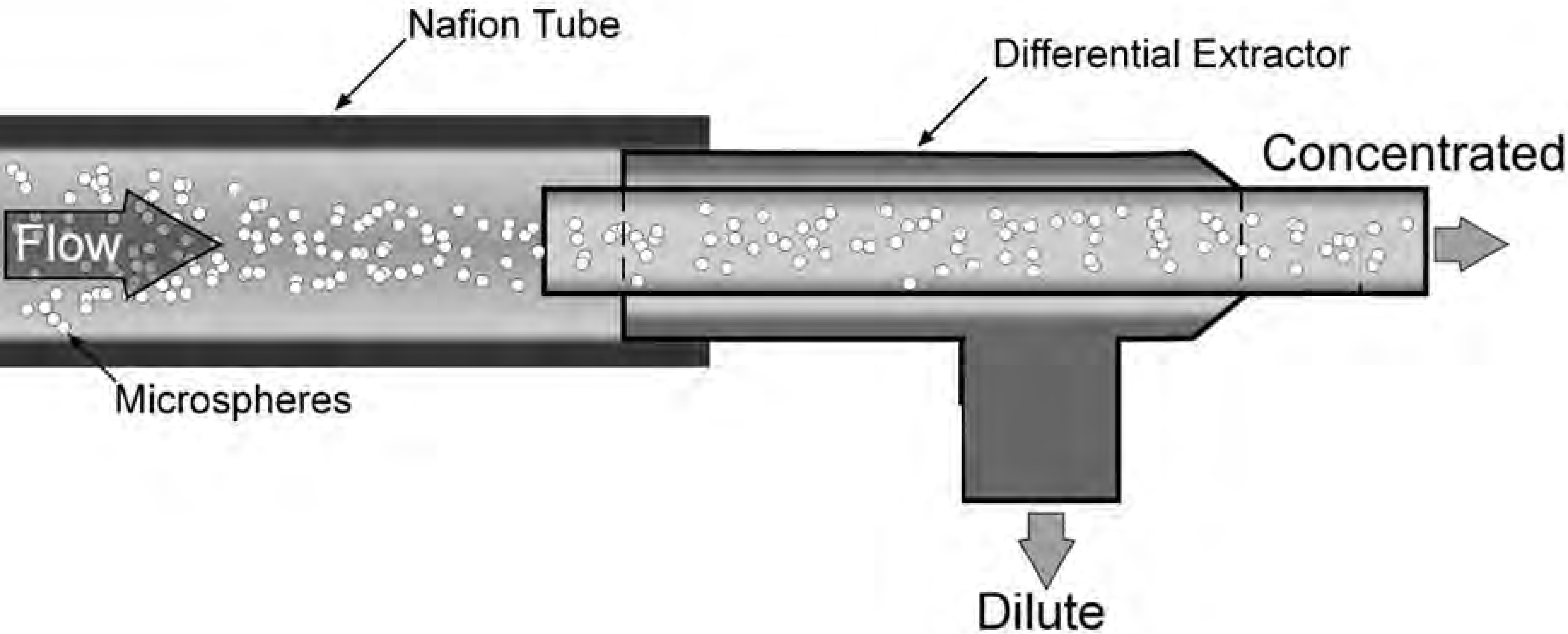
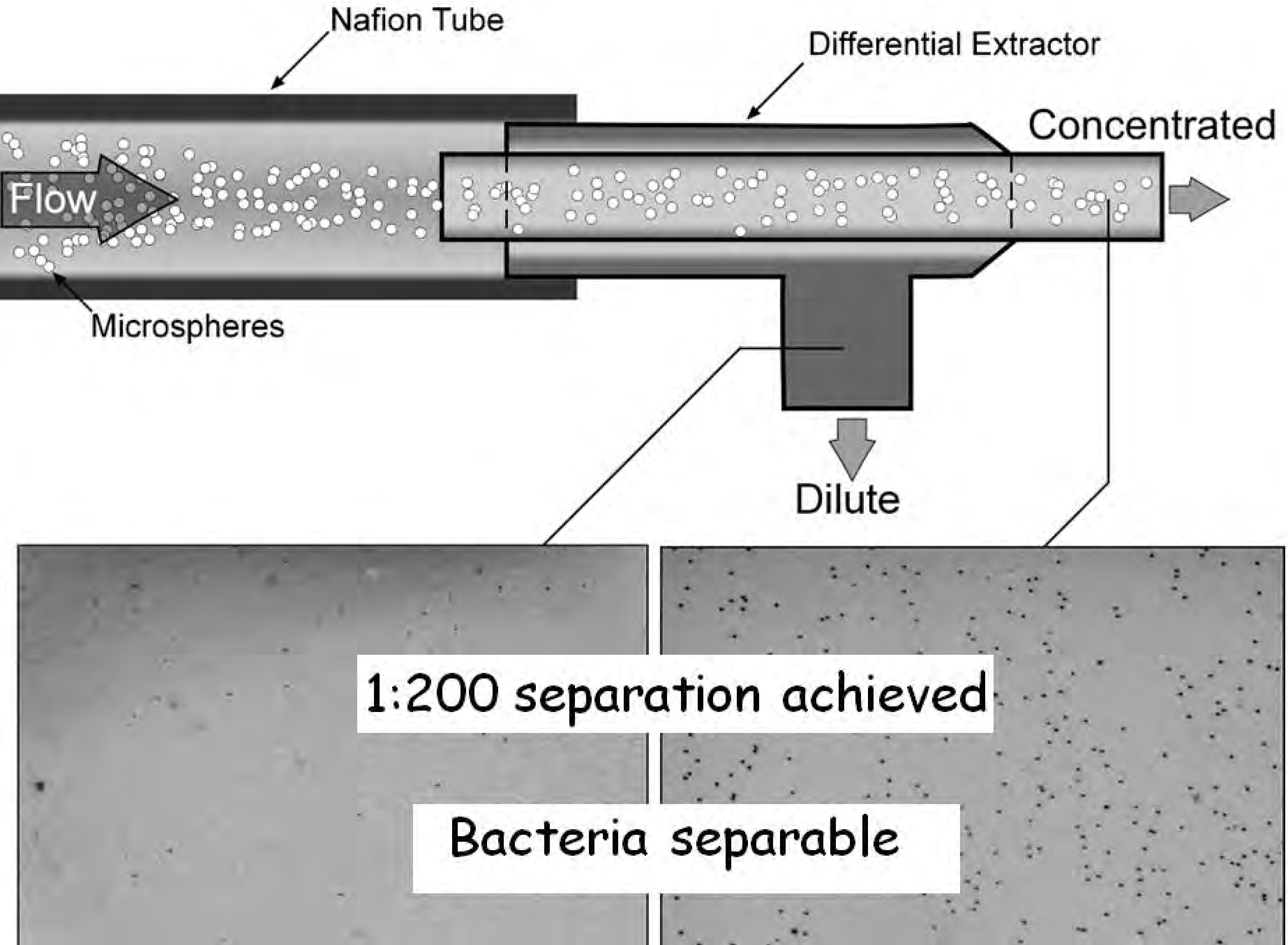
Purifying Contaminated Water


hydrophilic surface
like Nafion
EZ persists
With flow
EZ is large



Nafion Tube
Differential Extractor
Concentrated
Flow
Microspheres
Dilute

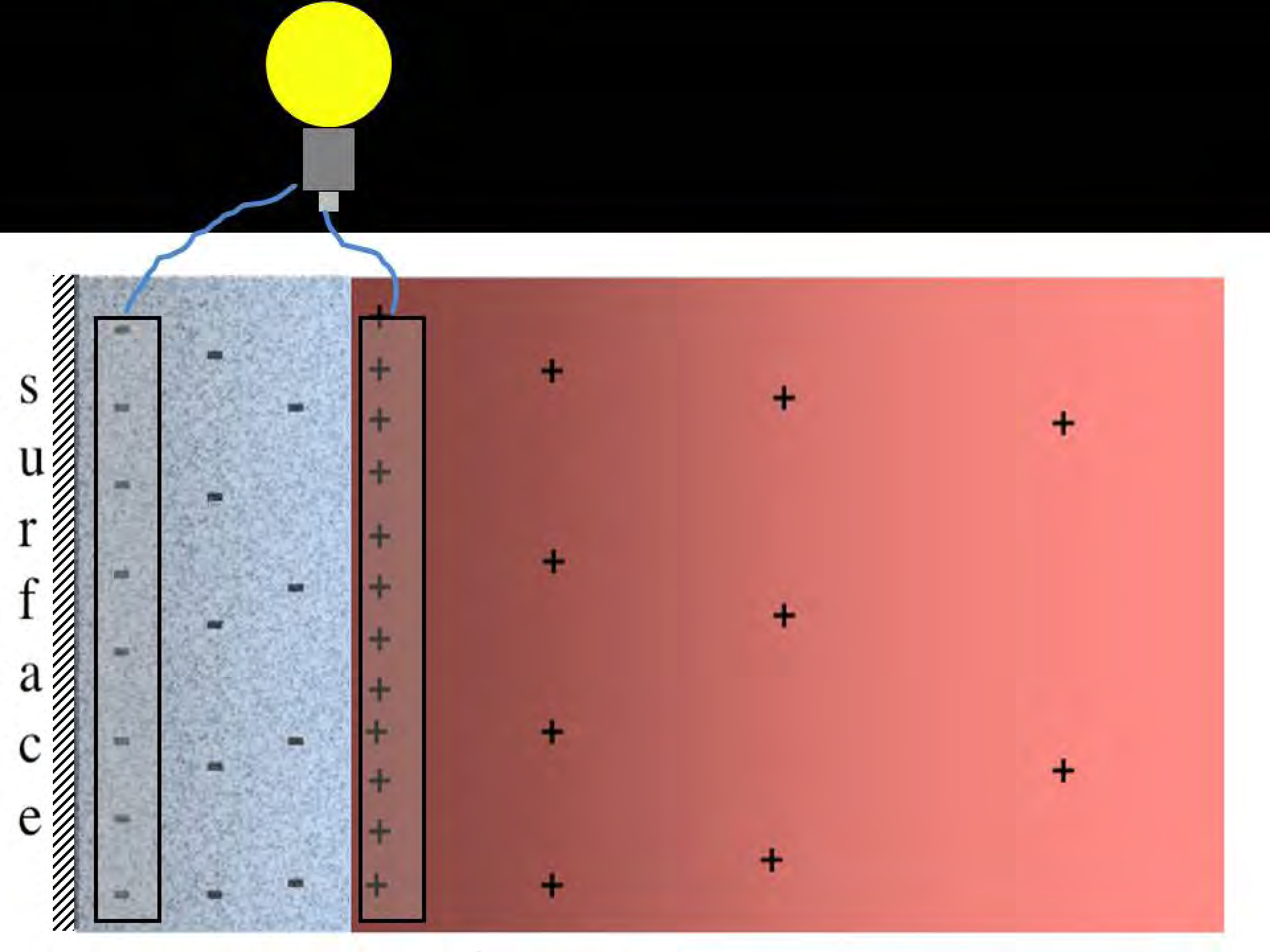

Nafion Tube
Differential Extractor
Concentrated
Flow
Microspheres
Dilute
1:200 separation achieved
Bacteria separable

Scaling up for practicality

Exploring separation of salt

2

Electrical Energy from Light and Water…


surface

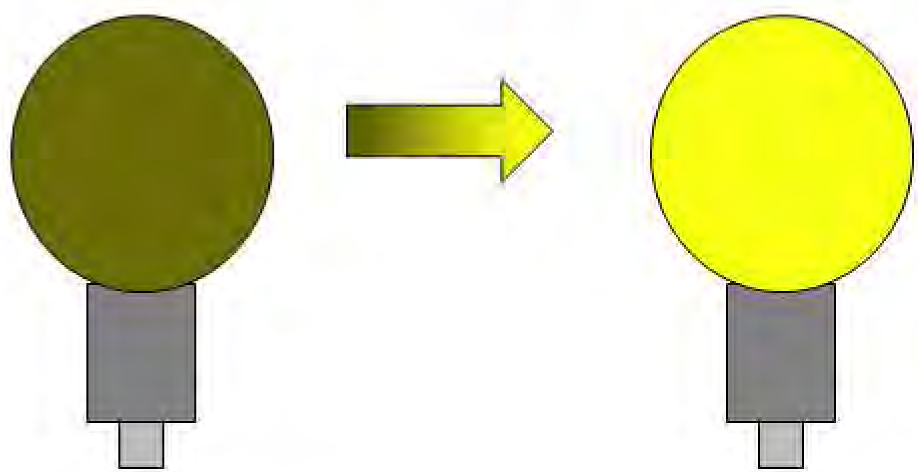
light

↓

charge separation
in water

↓

energy harvest



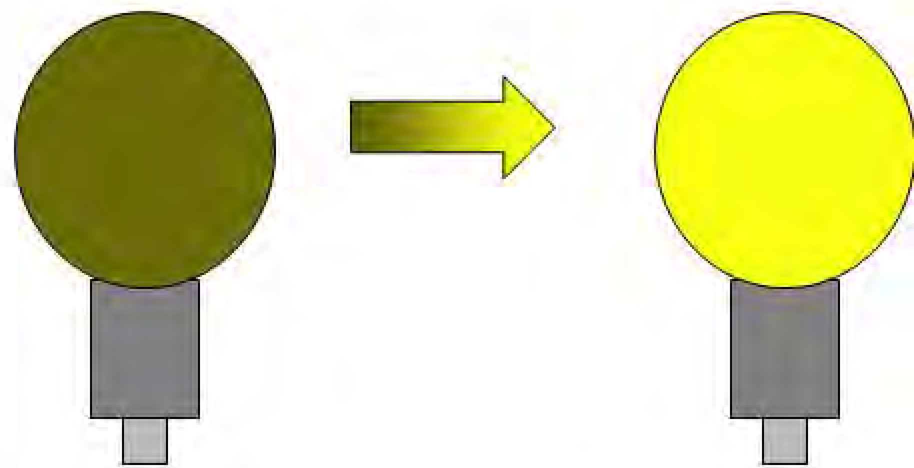
light

↓

charge separation in water

↓

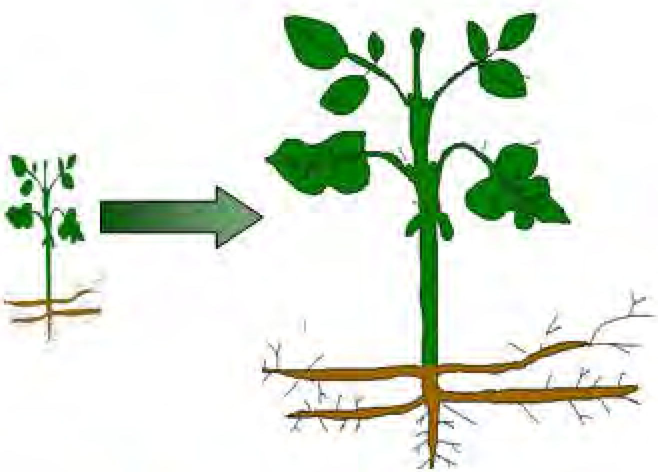
energy



light

charge separation in water

energy

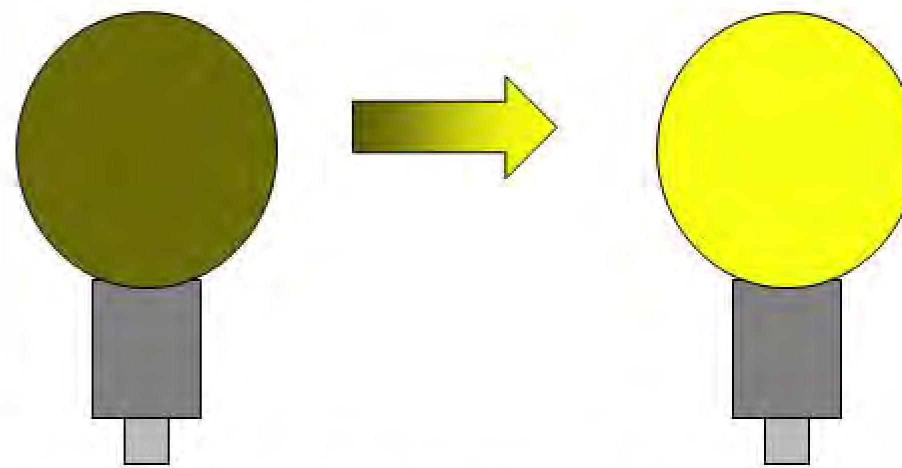


photosynthesis

light

charge separation in water

energy



generic photosynthesis?

Electrical power from generic photosynthesis

Can this replace oil?

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  - biology
- Foundational for engineering of genuinely new practical devices √√

also good to drink…


and inspirational to watch

and fascinating to study


Many thanks!
The interface is interesting