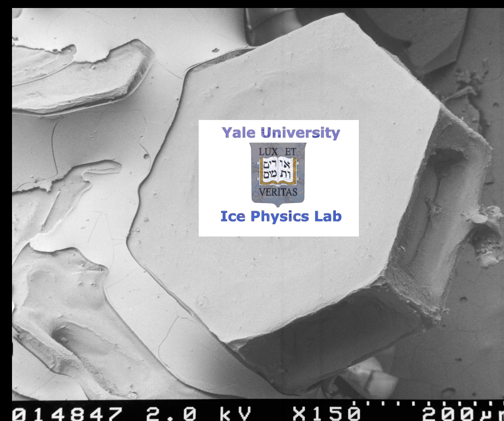
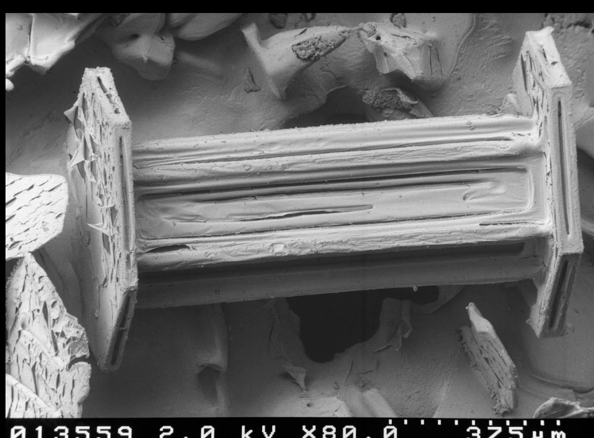
the Quantum Electrodynamics of snowflakes, ice skating, exobiology & other such matters



Y. Furukawa



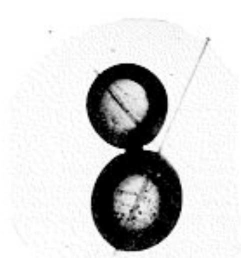
J.S. Wettlaufer

Yale University

& Nordita

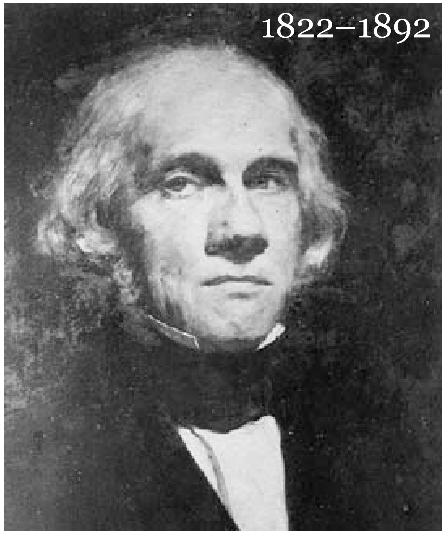
September 8, 1842: Michael Faraday (1791-1867) initiates scientific investigation into what we now know as surface melting.

(a)



(b)

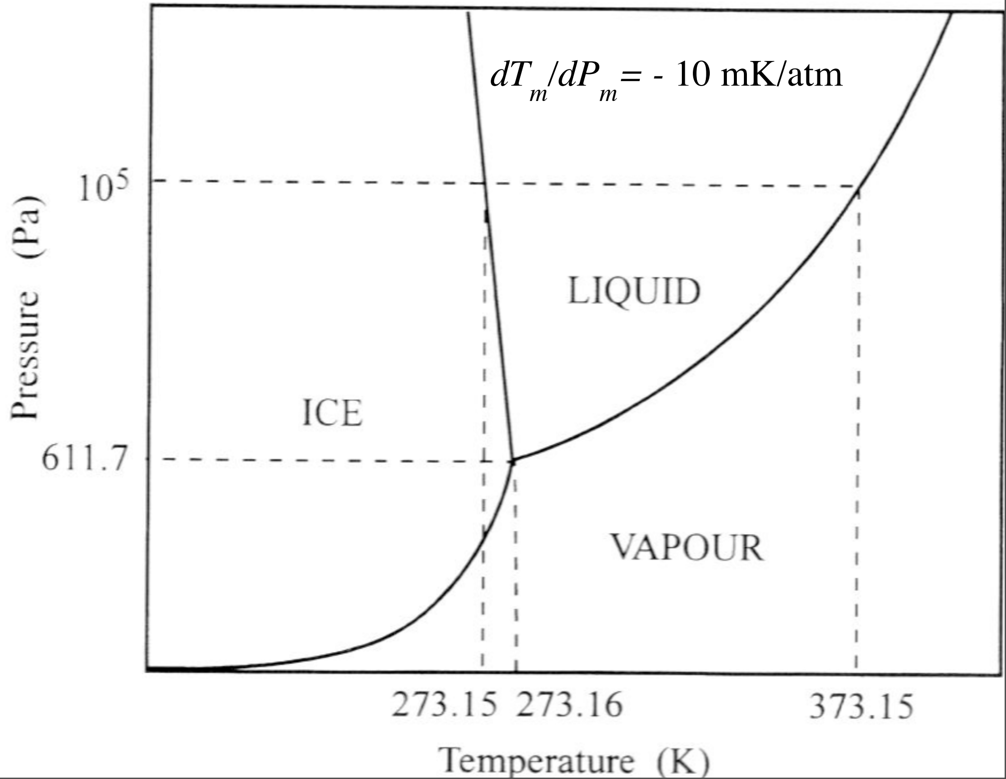
- *"When wet snow is squeezed together, it freezes into a lump (with water between) and does not fall asunder as so much wetted sand or other kind of matter would do."*
- *"All this seems to indicate that water at 32°F will not continue as water, if it be between two surfaces of ice touching or very near to each other."*
- *"The ice probably acts as a nucleus, but it appears that the effect of <u>one surface of ice on water is not equal to the joint effect of two</u>."*

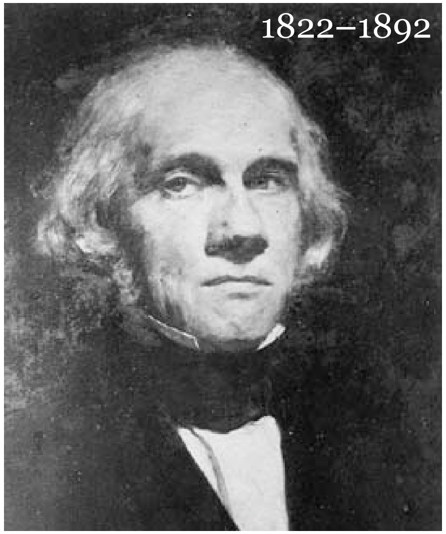


James Thomson predicted (1849) and showed that ice melts under pressure.

William Thomson (later Lord Kelvin) communicated his brother's interpretation of Faraday's experiments to the Royal Society on 25 April, 1861

"I think the experiments are in perfect accordance with my own theory, and tend to its confirmation."





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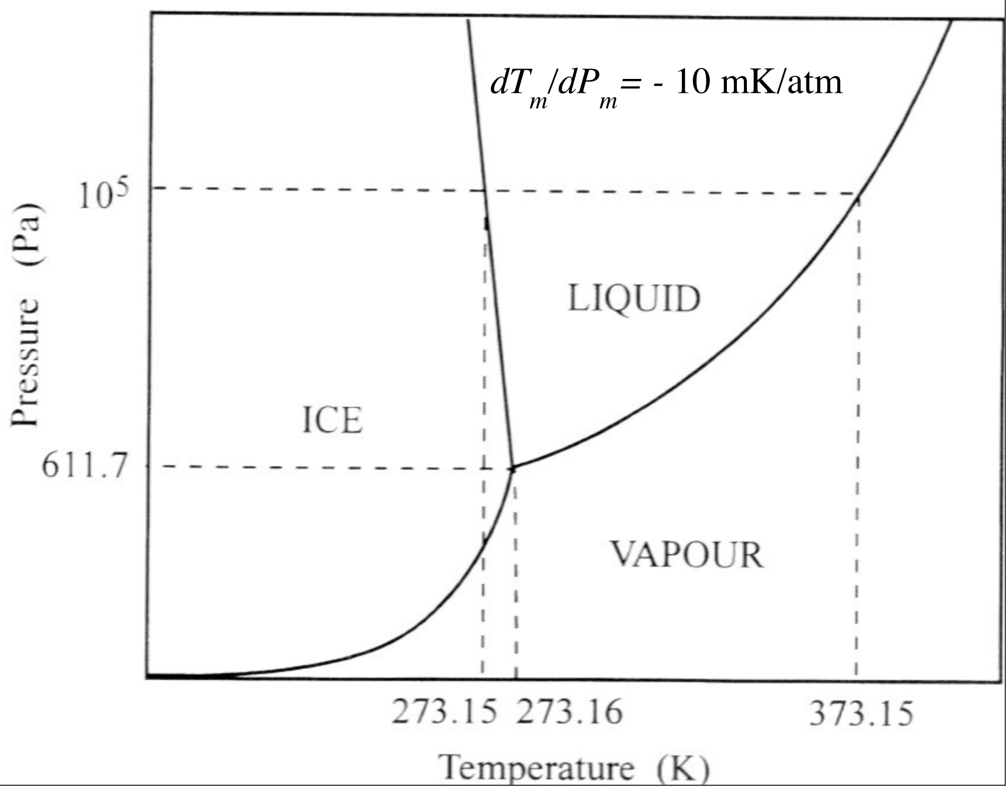


In 1900 Kelvin proclaimed:

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

& "X rays are a hoax."

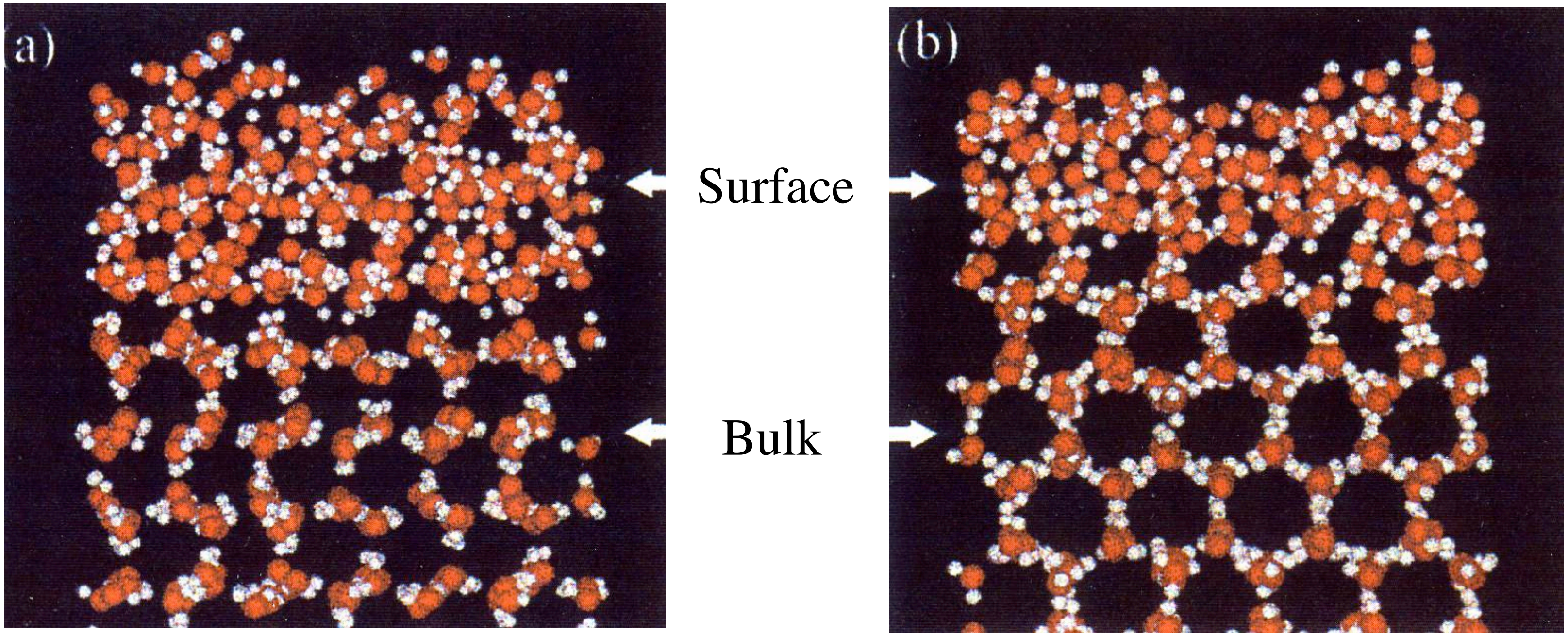
MELTING BELOW ZERO

New research shows how a layer of water on the surface of ice— even at temperatures well below freezing—can account for everything from the slipperiness of a skating rink to the electrification of thunderclouds

by John S. Wettlaufer and J. Greg Dash

Scientific American

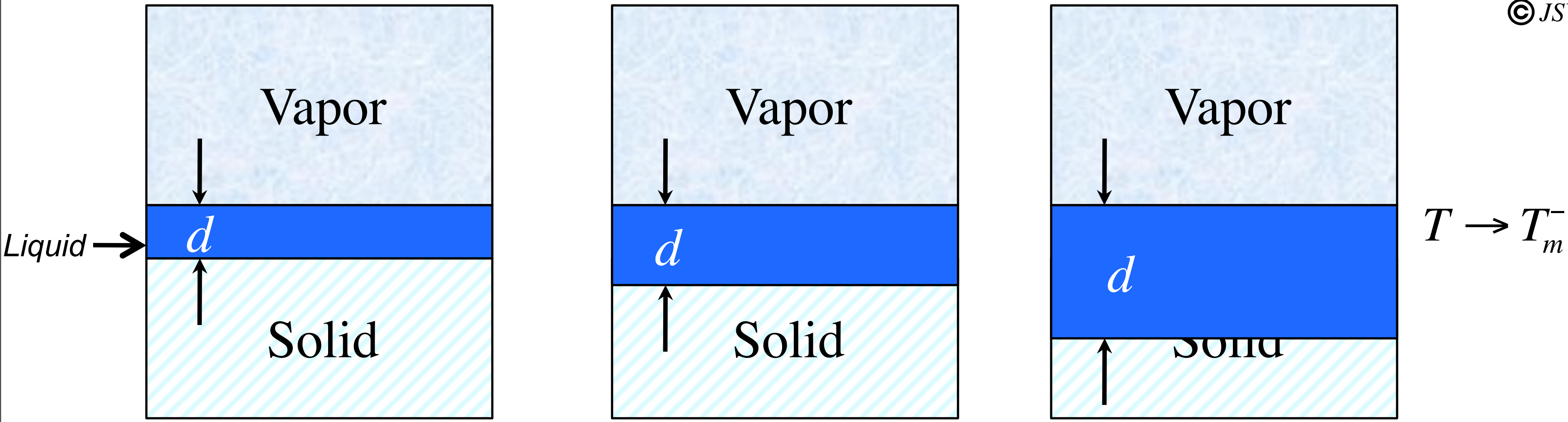
Missing Bonds at the Surface: Greater Vibrational Anharmonicity than in the bulk…

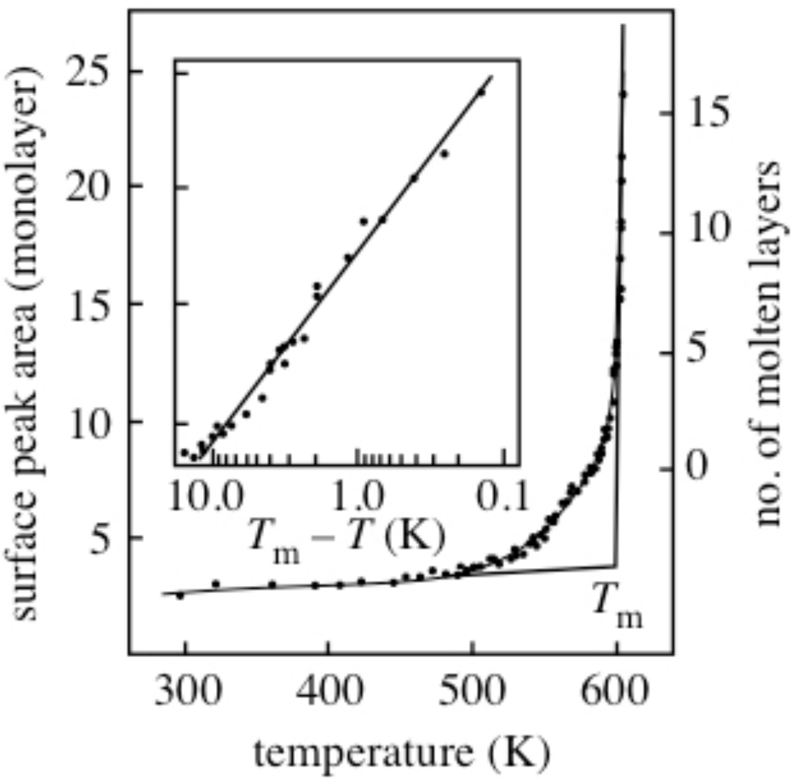


Basal Facet

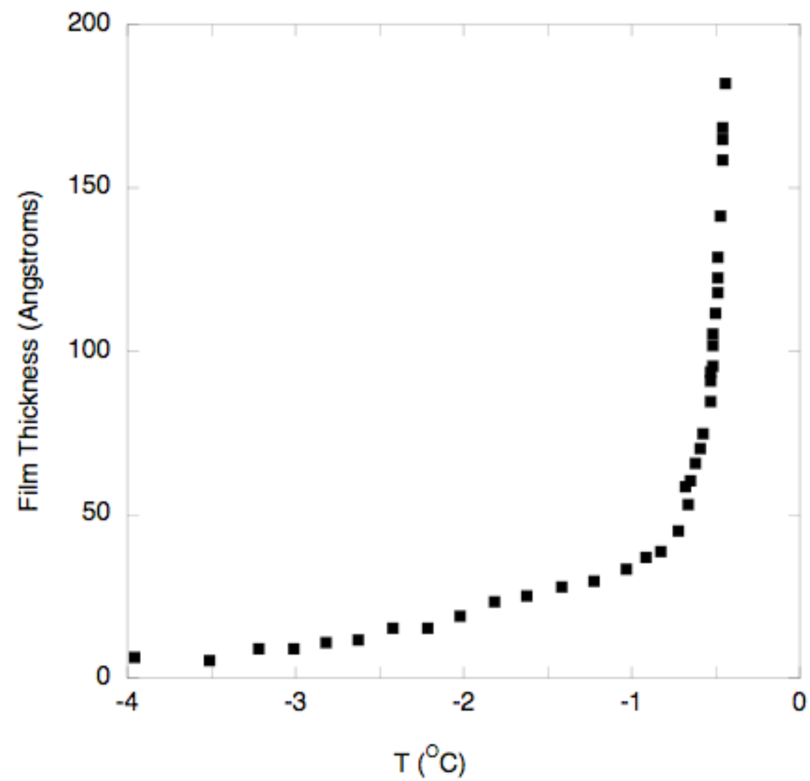
Prism Facet

Nada & Furukawa, *J. Phys. Chem. B* **101** 6163 (1997).

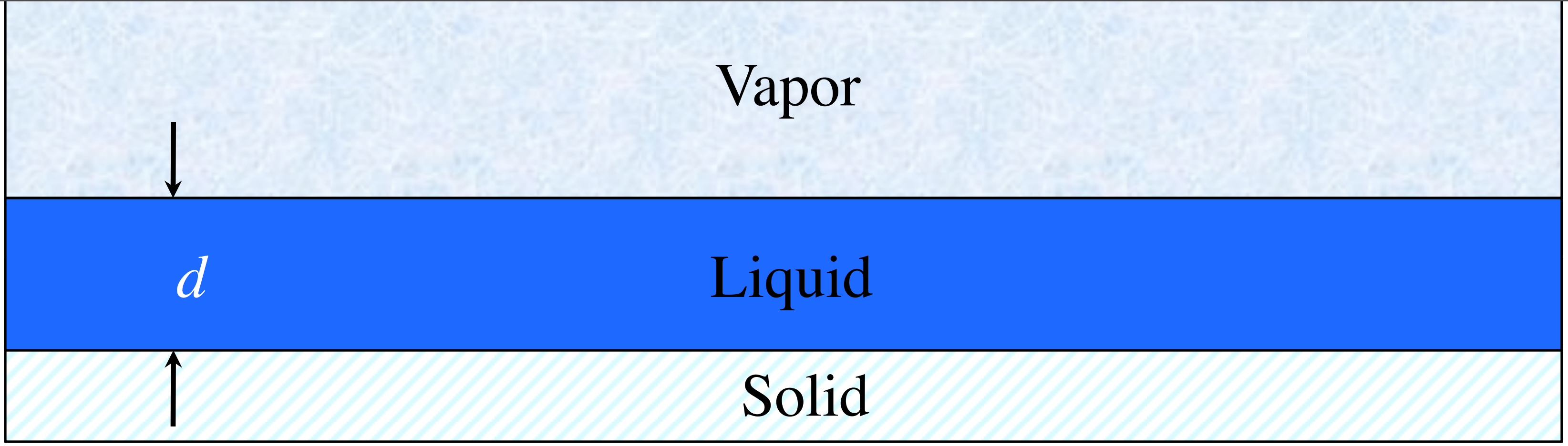




Frenken & van der Veen *Phys Rev Lett* **54**, 134 (1985)

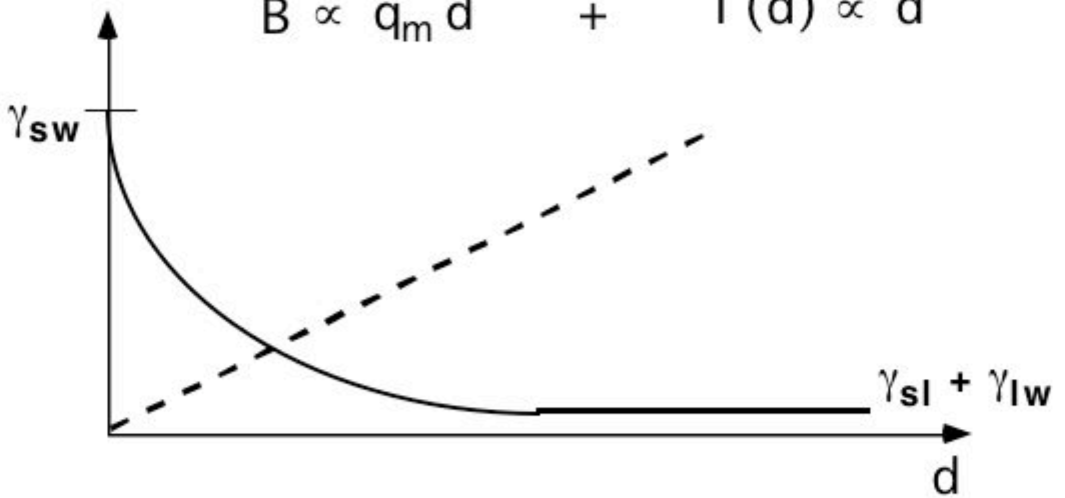


Elbaum, Lipson & Dash *J Cryst Growth* **129**, 491 (1993)



$$\Omega \quad = \quad \text{BULK} \quad + \quad \text{INTERFACIAL}$$

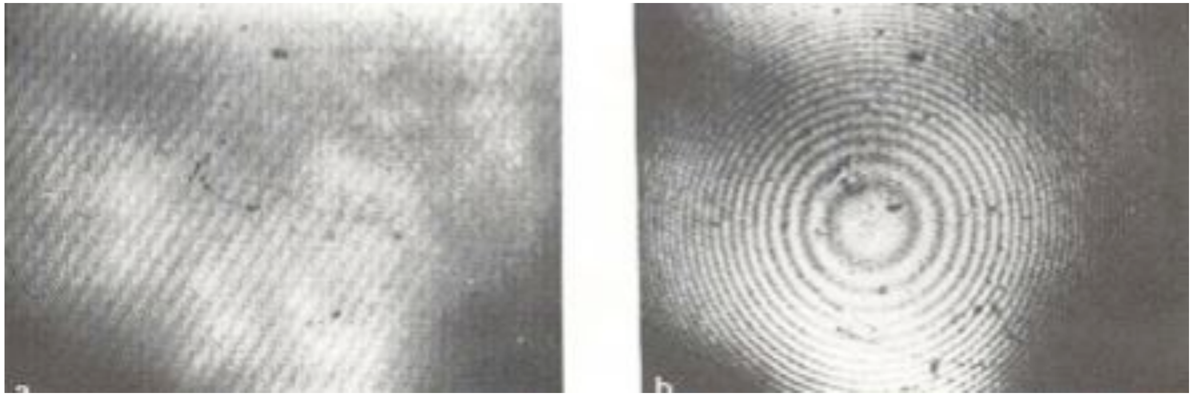
$$B \propto q_m d \quad + \quad I(d) \propto d^{-n}$$

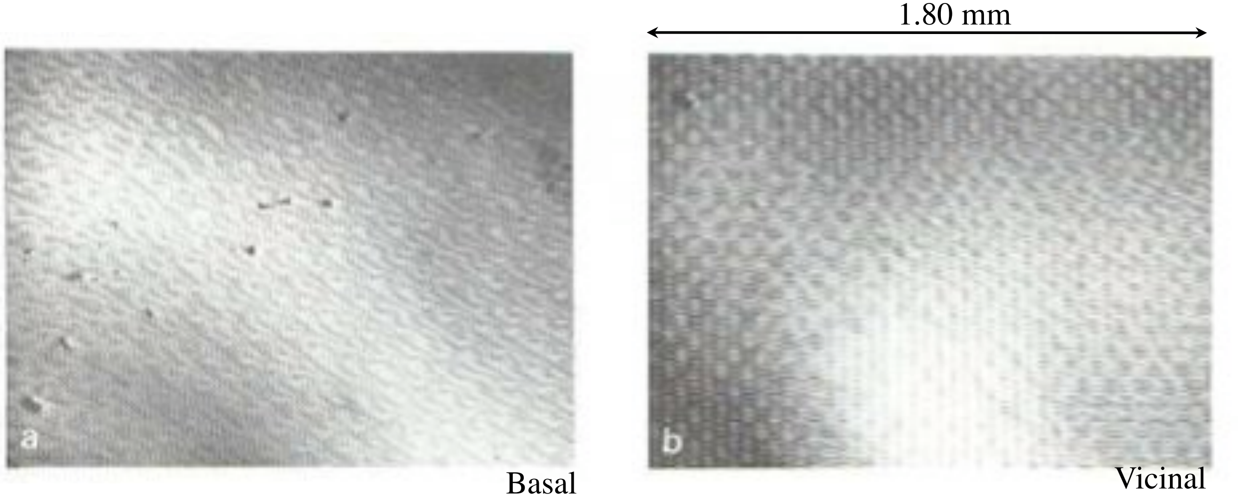


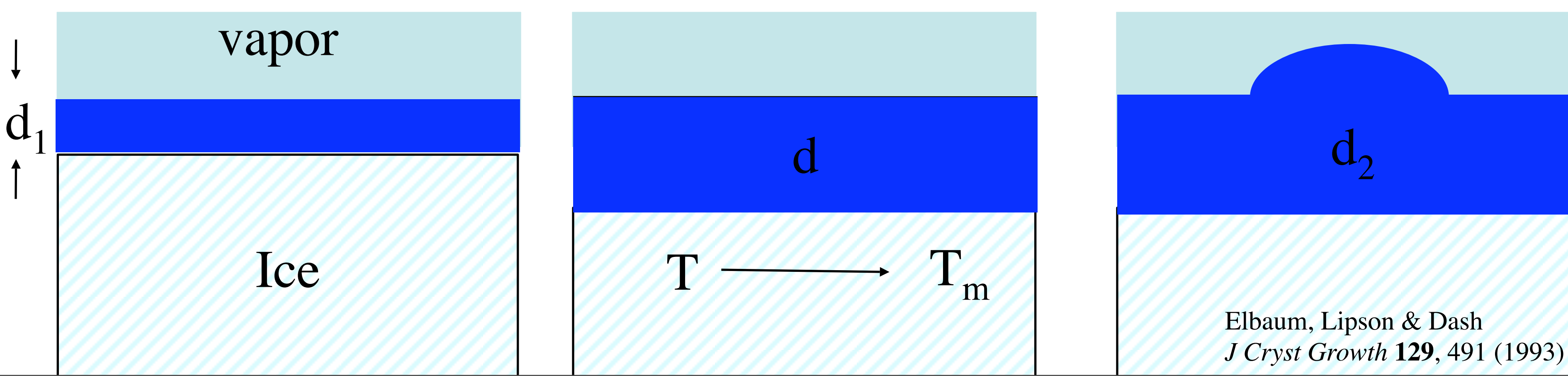
Minimizing Ω

$\Rightarrow$ (1) $P_l - P_s = I'(d)$

(2) $d = \lambda \, (1 - T/T_m)^{\frac{-1}{n+1}}$







Elbaum, Lipson & Dash
J Cryst Growth **129**, 491 (1993)

Mayonnaise, Paint, Gecko's and Vacuum Fluctuations: Casimir, London, Overbeek & Polder (1948)

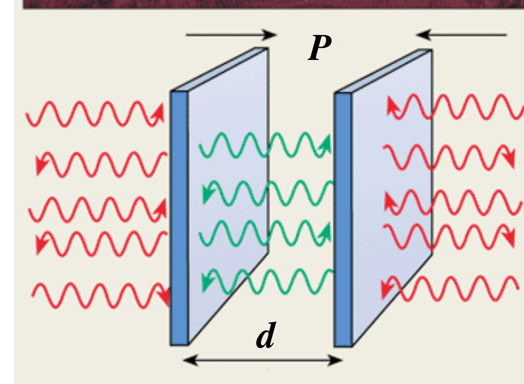
Phys Today
Feb 2007

feature article

Casimir forces: Still surprising after 60 years

Steve K. Lamoreaux

The once startling idea of a connection between quantum fluctuations and forces has by now been applied throughout physics. Nonetheless, experimentalists and theorists alike still find challenges in the Casimir force.



$$V(r) = -\frac{23\alpha_1\alpha_2\hbar c}{4\pi}\frac{1}{r^7}$$

$$\Rightarrow P(d) = \frac{C}{d^4}$$

$$C = 0.16\mu N(cm^4)cm^{-2}$$

d = mm, A= 1 cm^2: F = 10^{-7} N

Dzyaloshinskii, Lifshitz and Pitaevski, *Adv. Phys.* **10**, 165 (1961).

make precise the intuition that a

fluid less polarizable than its solid

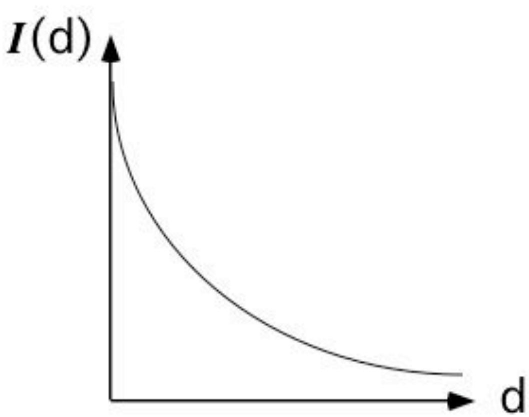
will be attracted to it

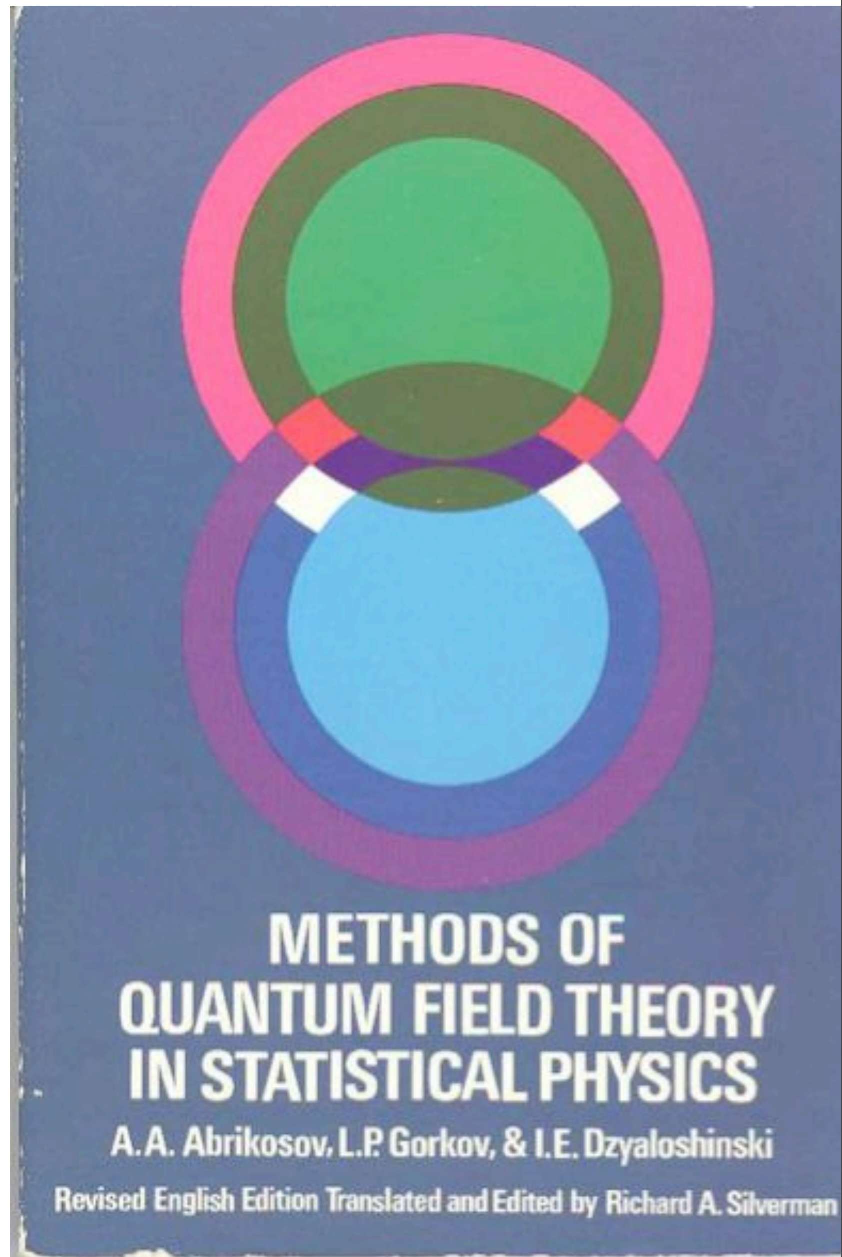
Film growth favored:

$\varepsilon_1 < \varepsilon_2 < \varepsilon_3$

$\varepsilon_1 > \varepsilon_2 > \varepsilon_3$

Embodied in Interfacial Free Energy $I(\mathrm{d})$





$$I(d) = \frac{k_b T}{8\pi d^2} \sum_{n=0}^{\infty} \int_{r_n}^{\infty} \left[\ln\left(1 - \frac{(x - x_i)(x - x_s)}{(x + x_i)(x + x_s)} e^{-x}\right)\right.$$

$$\left. + \ln\left(1 - \frac{(\varepsilon_s x - \varepsilon_w x_s)(\varepsilon_i x - \varepsilon_w x_i)}{(\varepsilon_s x + \varepsilon_w x_s)(\varepsilon_i x + \varepsilon_w x_i)} e^{-x}\right)\right] dx, \qquad \text{where}$$

$$r_n = 2d\sqrt{\varepsilon_w}\,\xi_n / c, \qquad i\xi_n = i(2\pi kT/\hbar)n$$

$$x_j = \left[x^2 - r_n^2\left(1 - \frac{\varepsilon_j}{\varepsilon_w}\right)\right]^{1/2} \qquad \text{with} \qquad j = i, s$$

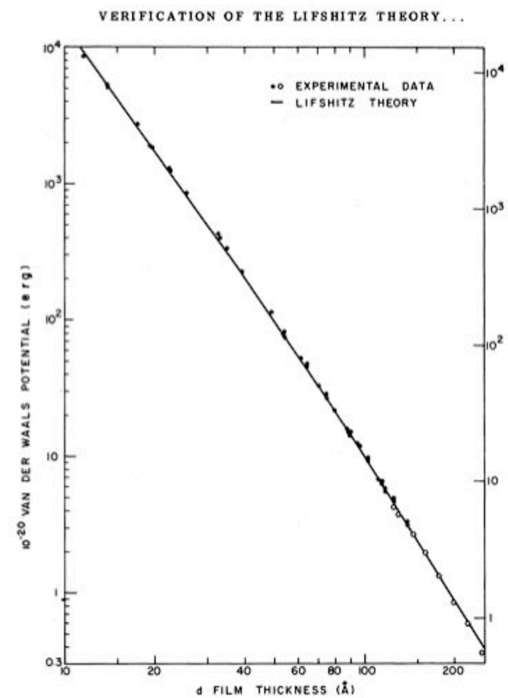
Dielectric functions : damped oscillator model

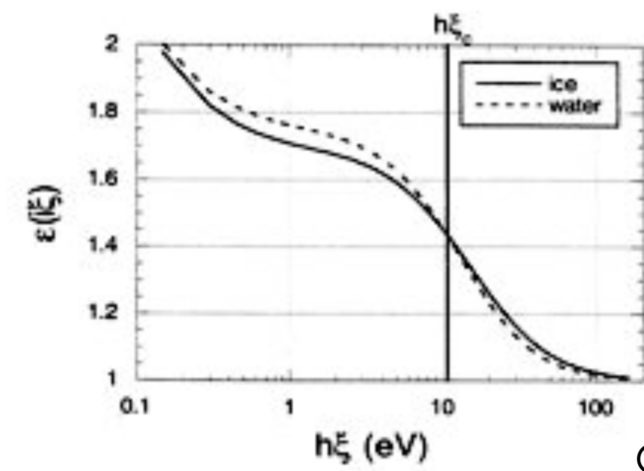
$$\varepsilon(\omega) = 1 + \sum_j \frac{f_j}{e_j^2 - i\hbar\omega g_j - (\hbar\omega)^2}$$

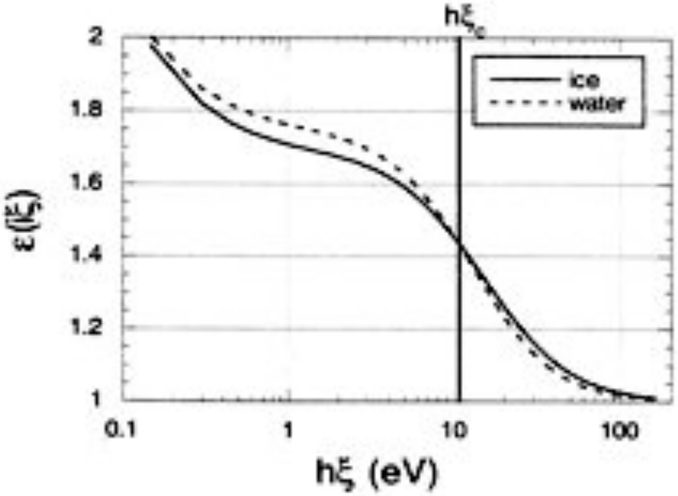
for $\varepsilon_w \approx \varepsilon_i \approx \varepsilon_s \approx 1$

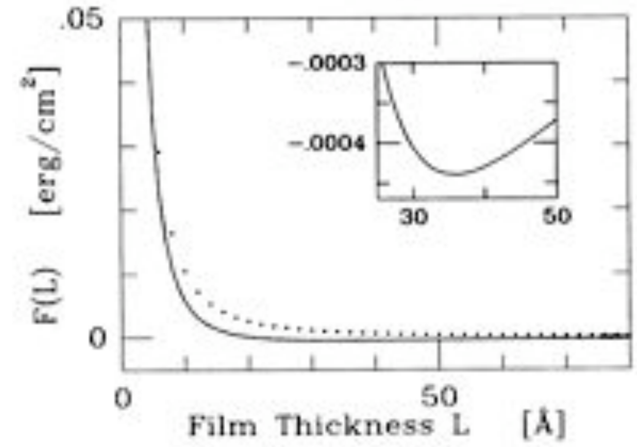
$$I(d) = \frac{k_b T}{8\pi d^2} \sum_{n=0}^{\infty} \left(\frac{\varepsilon_i - \varepsilon_w}{\varepsilon_i + \varepsilon_w}\right)\left(\frac{\varepsilon_w - \varepsilon_s}{\varepsilon_w + \varepsilon_s}\right)(1 + r_n)e^{-r_n}$$

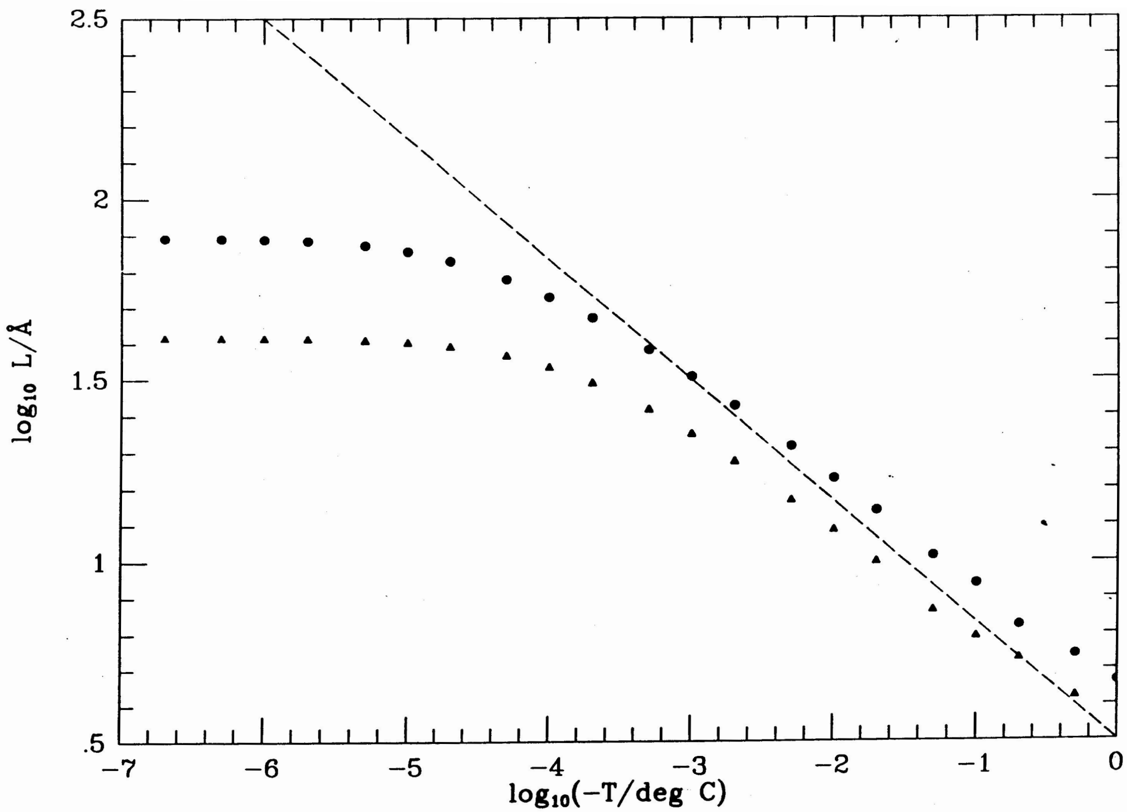
Sabisky & Anderson
Phys Rev Lett **24**, 1049 (1970),
Phys Rev A **7**, 790 (1973).











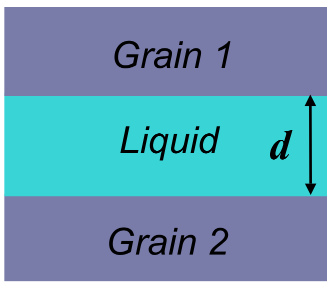
Phys Rev Lett **66** 1713 (1991)
Phys Rev B **52** 12426 (1995)

Yale University
Ice Physics Lab

The Solid-Solid Interface; Incomplete Interfacial (Grain Boundary) Premelting

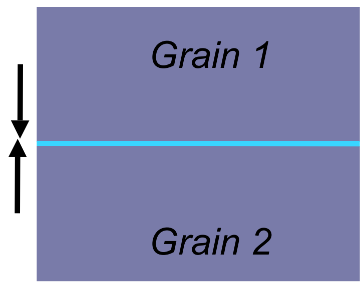
$T \to T_m^-$

?



No

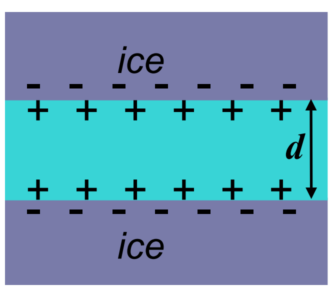
$d \to \delta_O$



$$F_{vdw}(d) = \frac{-A_H}{12\pi d^2}$$

$$A_H > 0$$

System Specificity to impurities…^{4}He has superfluid film influenced by ^{3}He…Olivine by H_2O



… Ice is *sensitive to ionic impurities.*

Repulsive screened Coulomb interactions and attractive dispersion forces compete

Yale University
Ice Physics Lab

Expectations from Theory

Impurity Stimulated

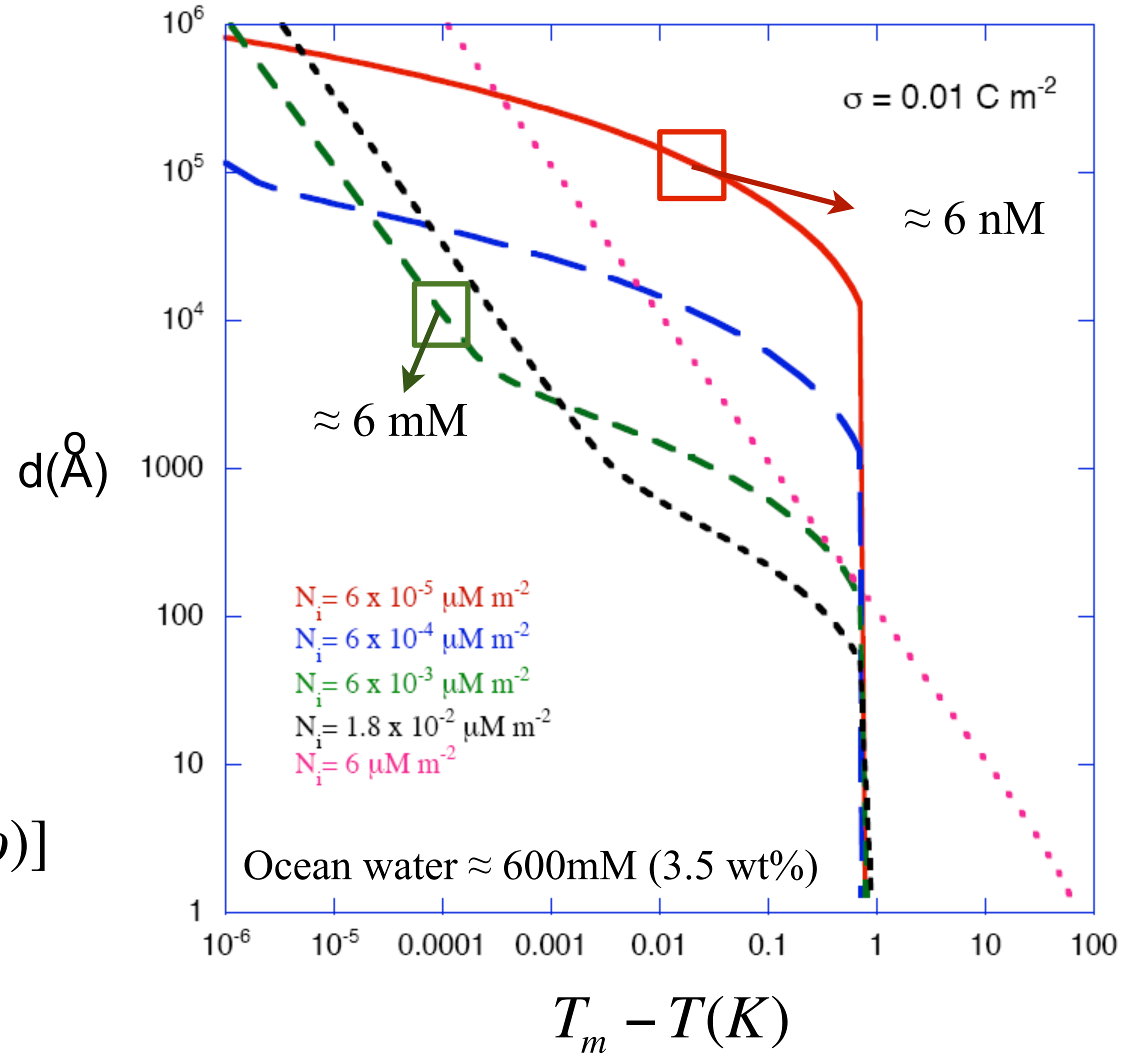
Grain Boundary Melting

$$F_{total}(d) =$$

$$2\gamma_{sl} +$$

$$\frac{2\sigma^2}{\kappa\varepsilon\varepsilon_O}\exp(-\kappa d) +$$

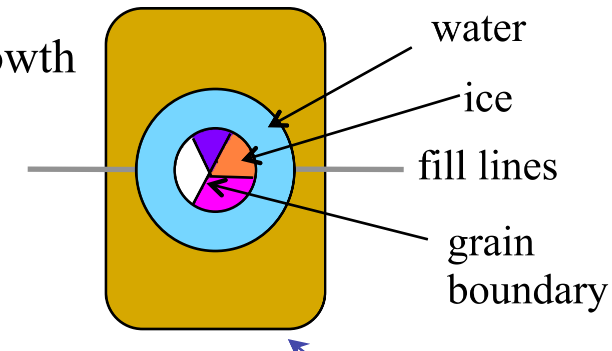
$$\frac{kT}{8\pi d^2}\int d\omega K[\varepsilon_s(\hbar\omega),\varepsilon_l(\hbar\omega)]$$

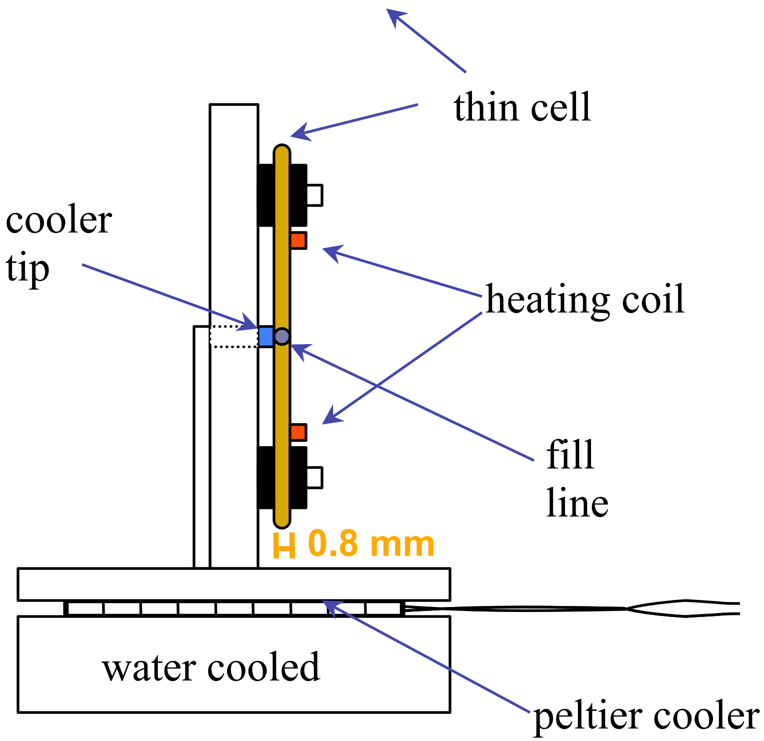


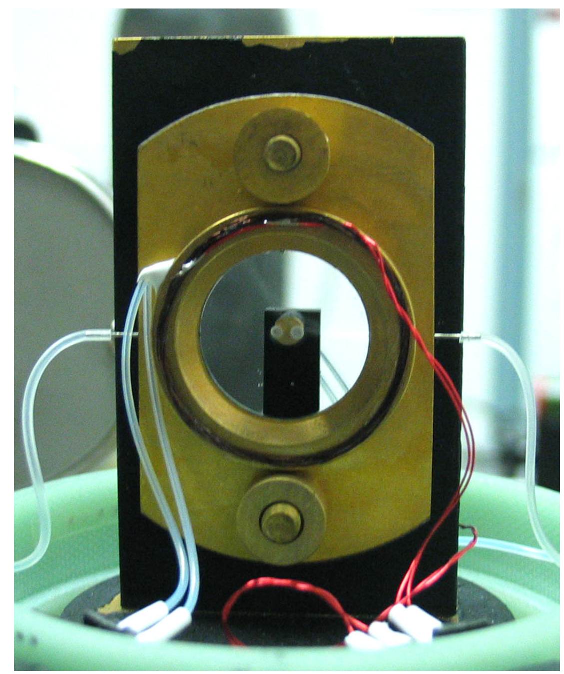
Benatov & JSW, *Phys Rev E,* **70**, 061606 (2004)

Experimental Search for grain boundary melting

Ice Growth Cell :







Dynamics of Unfrozen Films

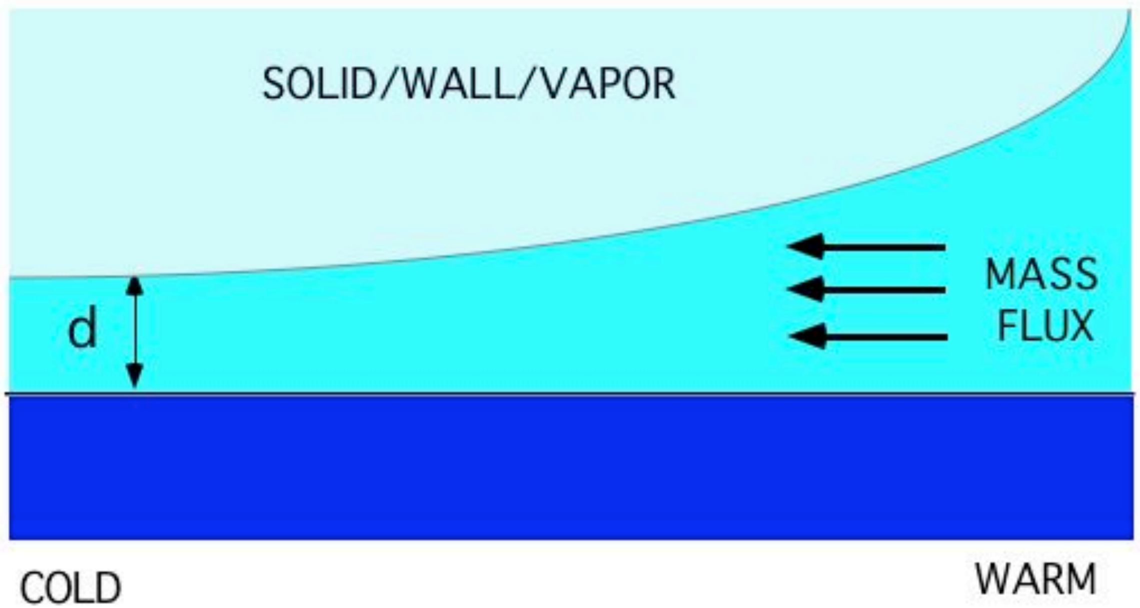
(1) $P_l - P_s = -A\,d^{-3}$

(2) $d = \lambda\, t_r^{-\frac{1}{3}}$

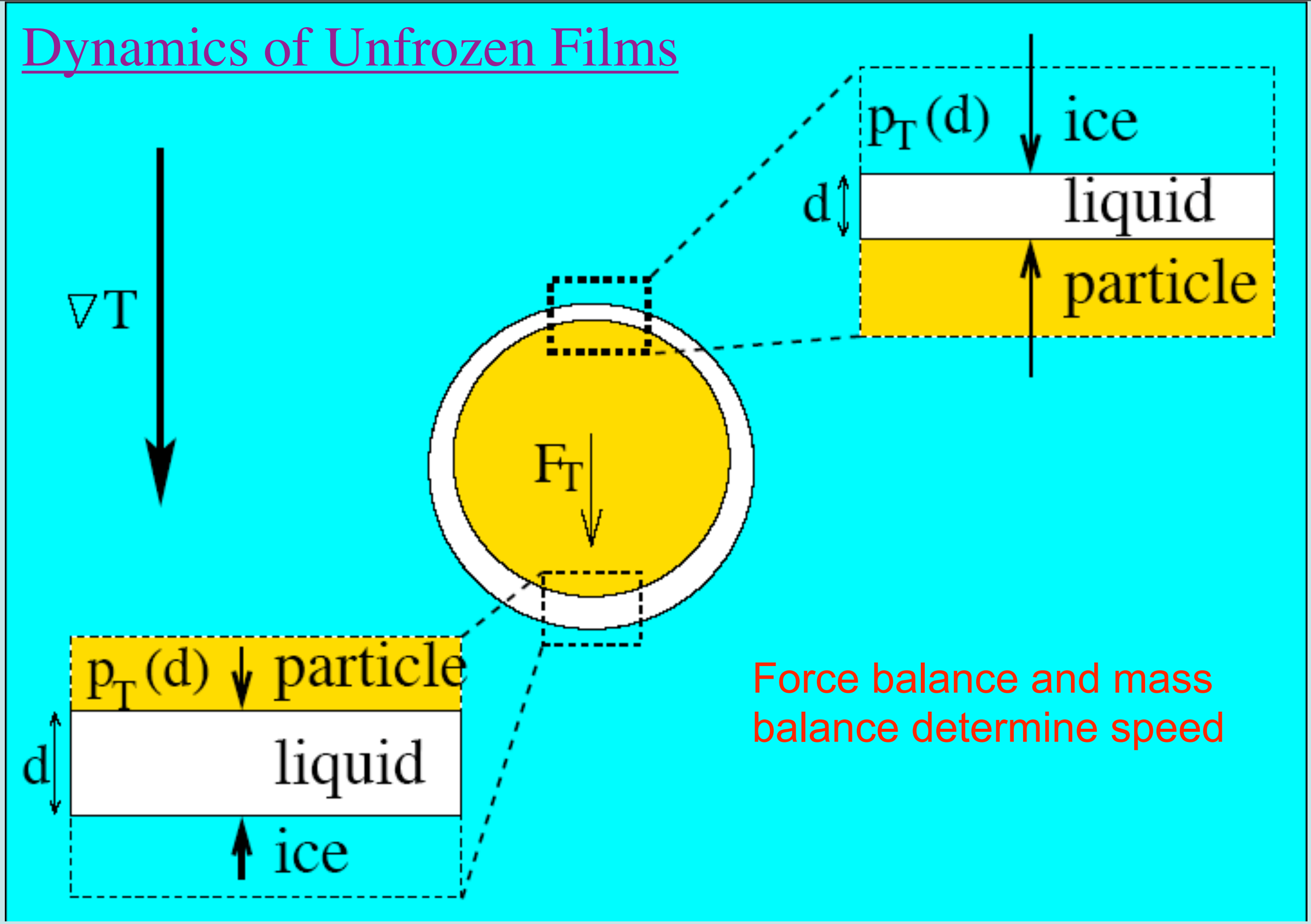
$t_r = (T_m - T)/T_m$

$\Longrightarrow \quad P_l = P_s - \rho_s\, q_m\, t_r$

$$\left(\frac{dP_l}{dT} = \frac{\rho_s q_m}{T_m} = 11\,\text{atm/K}\right)$$



$$Q(x) = -\frac{d^3}{12\mu}\nabla P_l$$



Thermodynamic buoyancy: $F_T = m_s G, \quad G = \frac{q_m}{T_m} \nabla T$

Rempel, JSW, Worster, *Phys Rev Lett* **87**, 088501 (2001).

The surface of ice is wet by a thin film of water below 0 deg C

The surface of ice is wet by a thin film of water below 0 deg C

The unfrozen water moves in temperature gradients

The surface of ice is wet by a thin film of water below 0 deg C

The unfrozen water moves in temperature gradients

There is a large thermomolecular pressure associated with it

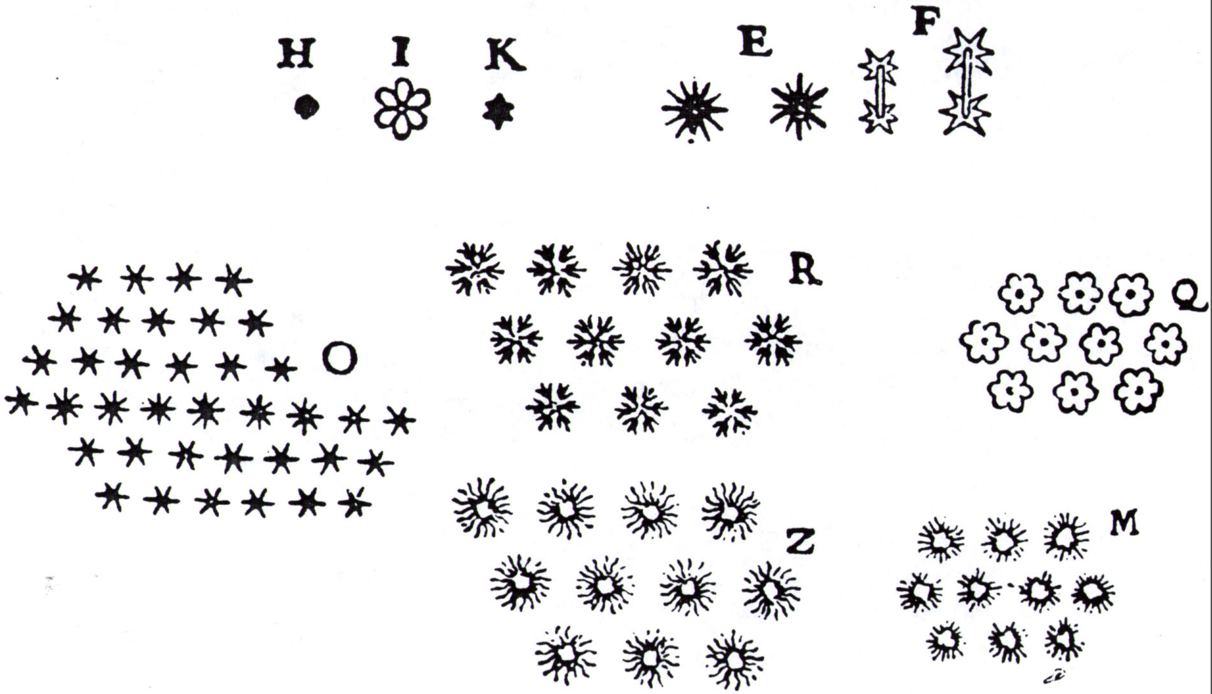
The surface of ice is wet by a thin film of water below 0 deg C

The unfrozen water moves in temperature gradients

There is a large thermomolecular pressure associated with it

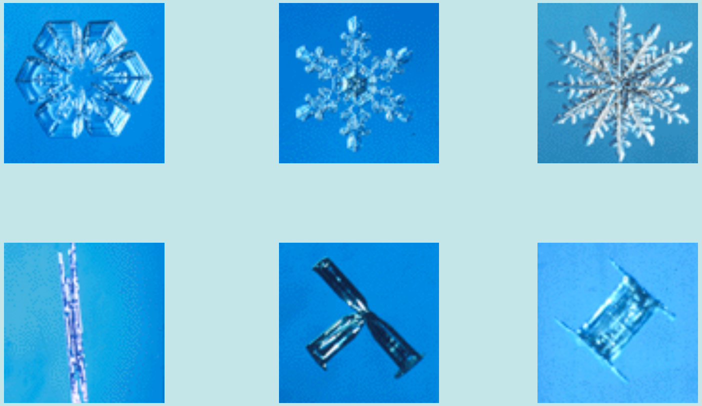
There are many consequences...

"What astonished me the most was that among the grains which fell last I noticed some which had around them six little teeth, like clock-makers' wheels such as you see at ***I***."

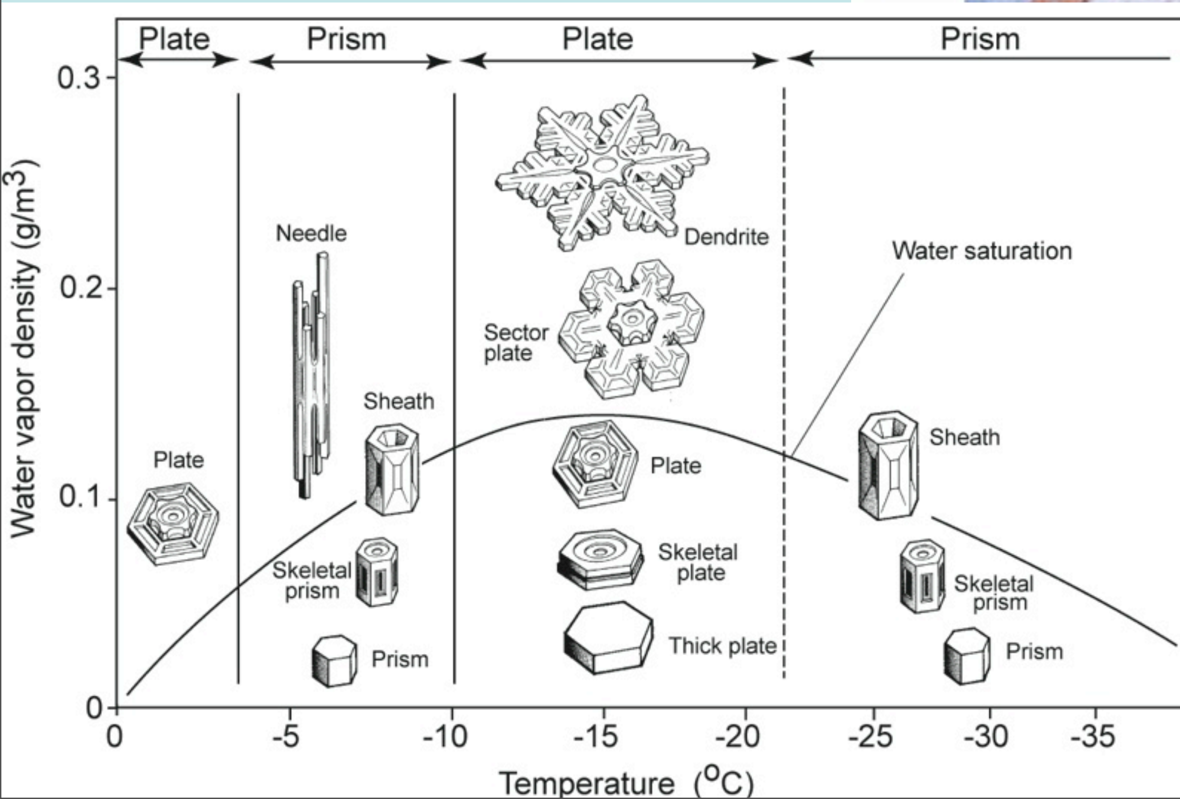


"I only had difficulty to imagine what could have formed and made so exactly symmetrical these six teeth around each grain in the midst of free air and during the agitation of a very strong wind... it is impossible for men to make anything so exact."

R. Descartes, 1637. *Les Météores* (published with) *Discours de la méthode*, Leiden.



The Nakaya Diagram

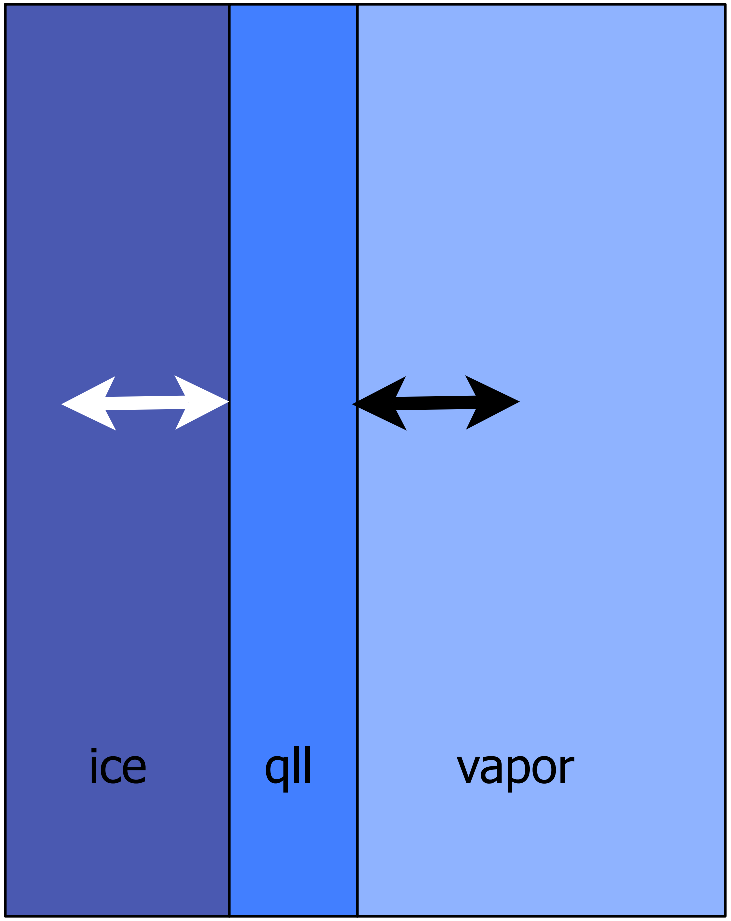


Letters from the Sky

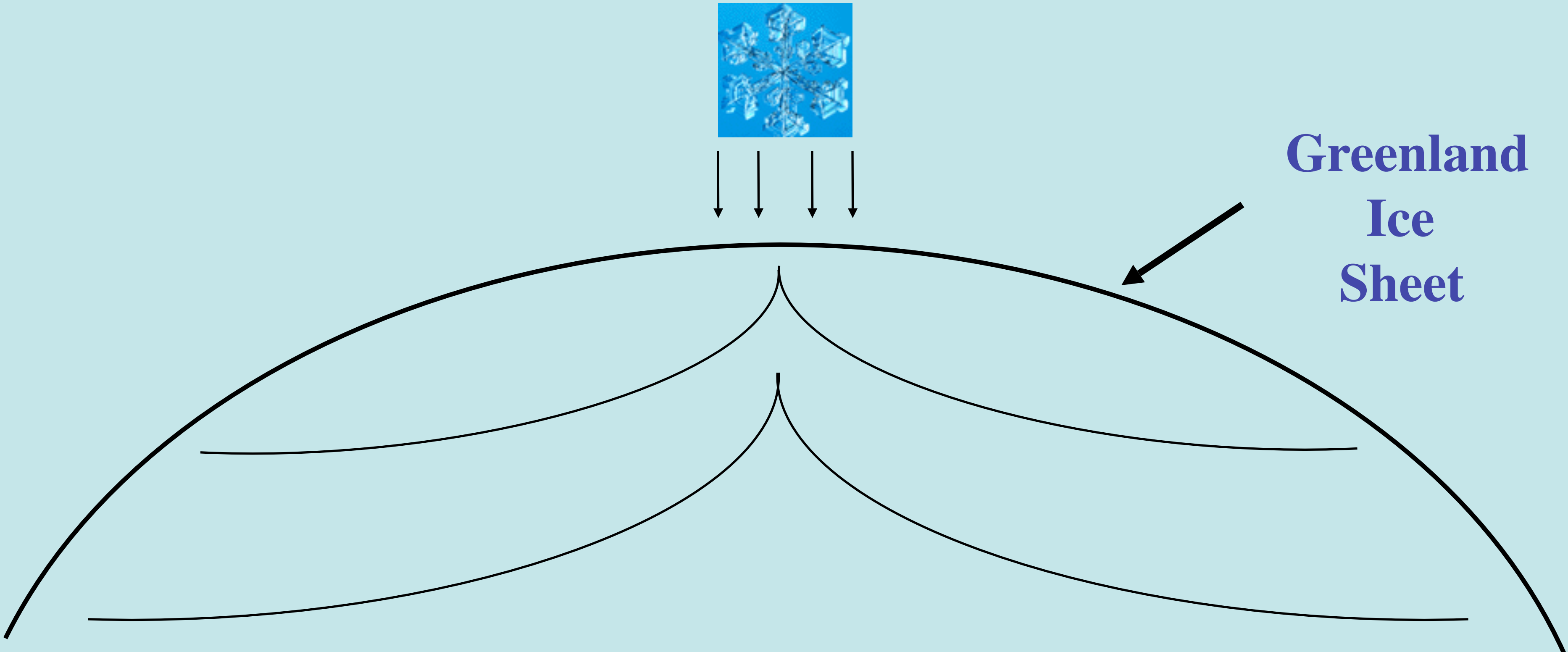
© JSW

Disequilibrium Surface Melting

- Growth into liquid phase plays a role in disequilibrium surface melting
- Solid-vapor interface near the triple point is complicated by quasi-liquid layer (qll)
- One prediction in the literature: film *decreases* thickness during growth
- Issues with proper thermodynamic description and dynamics
- Surface melting suspected to play a key role in the habit change of atmospheric ice crystals



A. Cahoon, PhD thesis



Soluble Impurities

Stable Isotopes

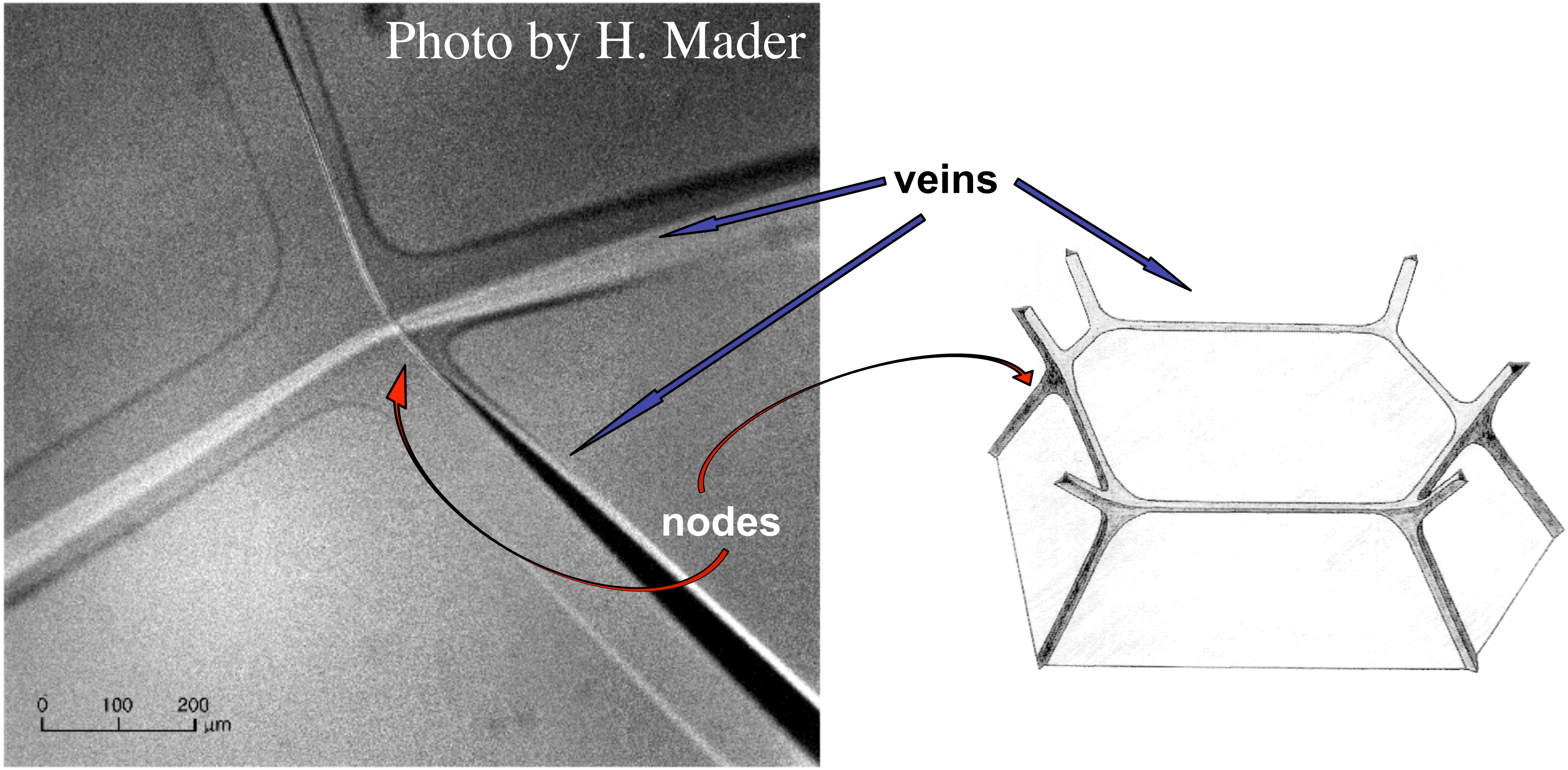
Air Bubbles

Dust Particles

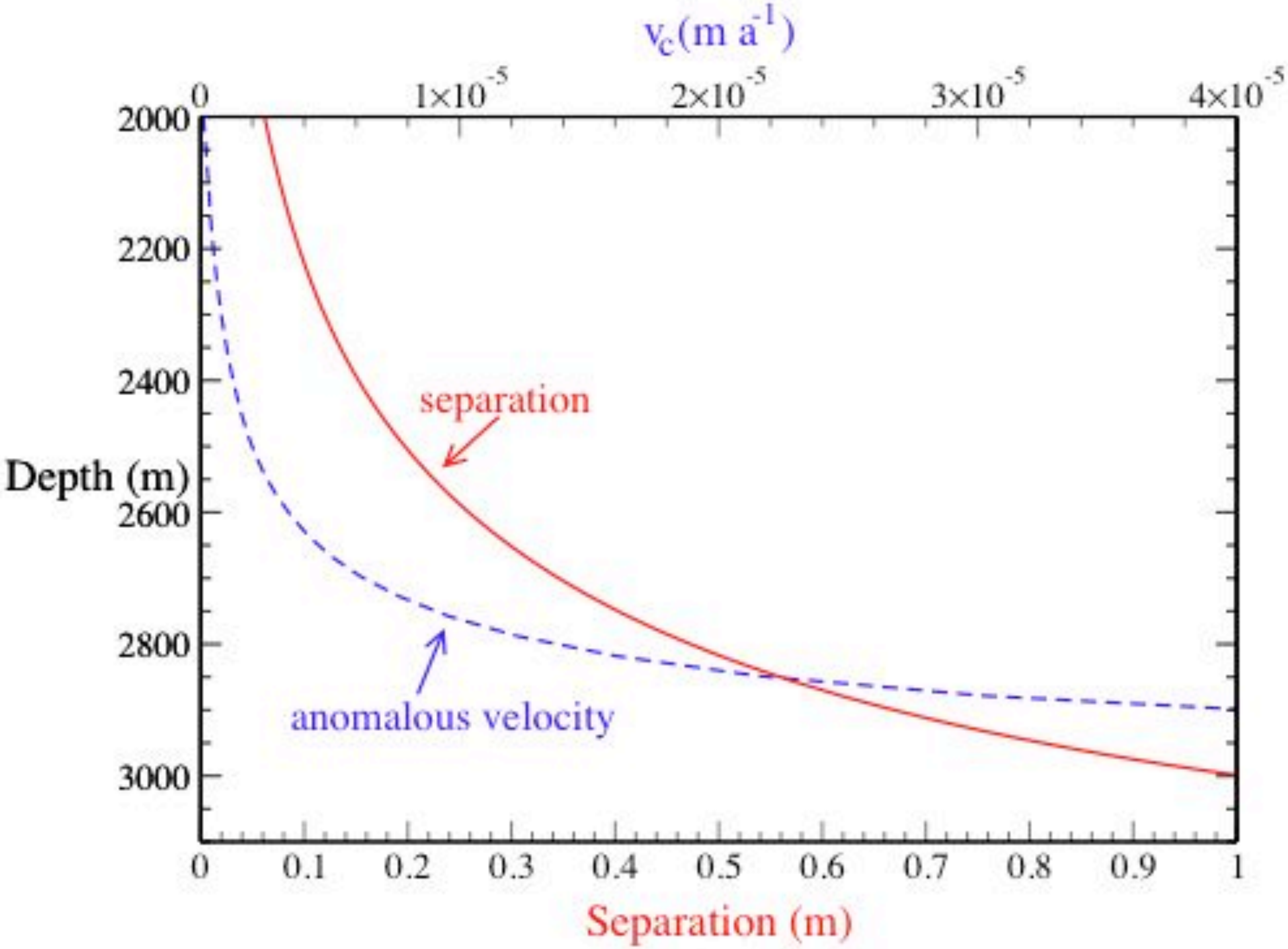
Yale University

Ice Physics Lab

The phase architecture of polycrystalline ice



Defined by the presence of liquid water in thermodynamic equilibrium, below the bulk melting temperature, T_m.



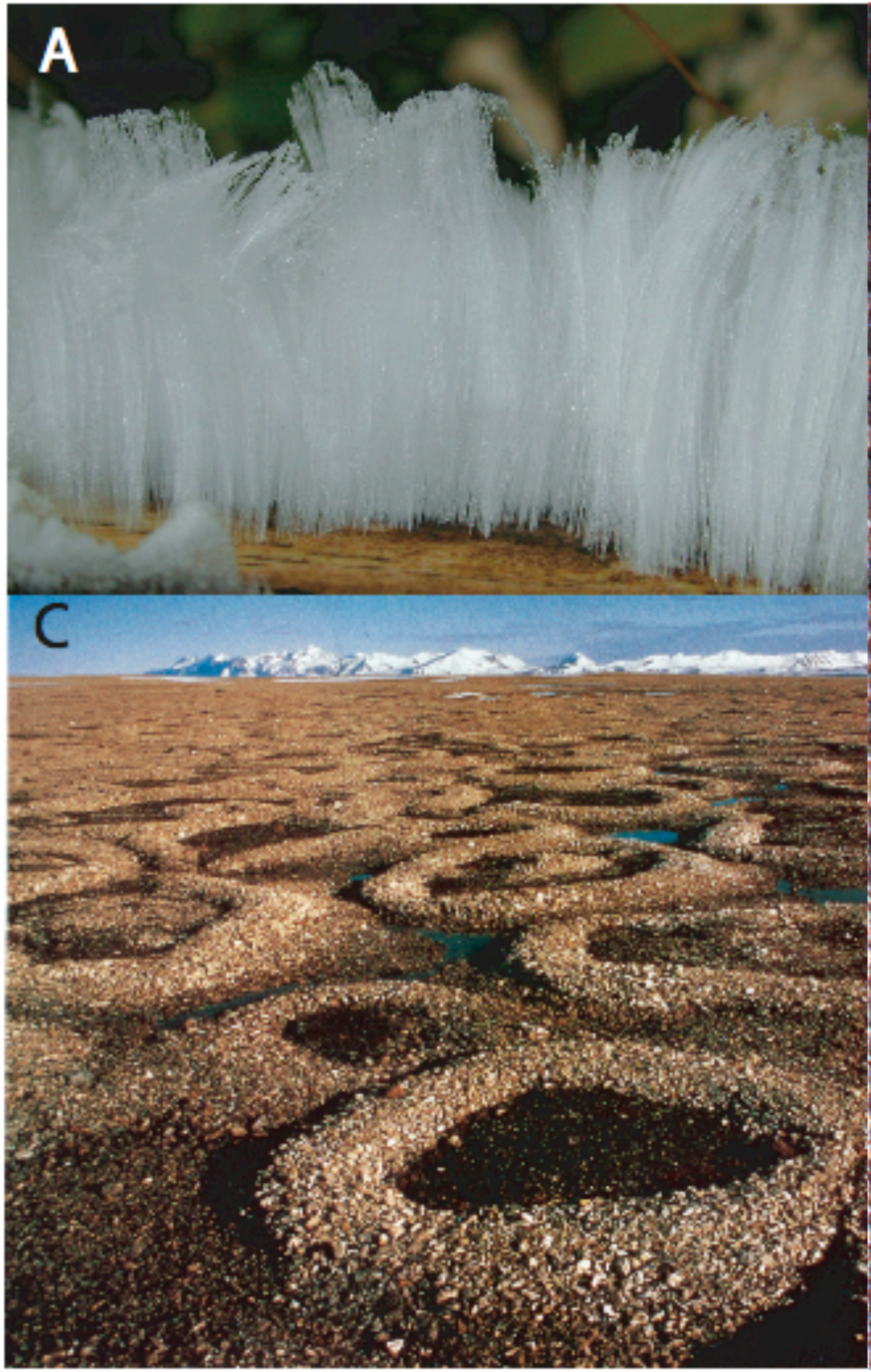
Quantifiable Signal Displacement

Displacement negligible until great depth/age

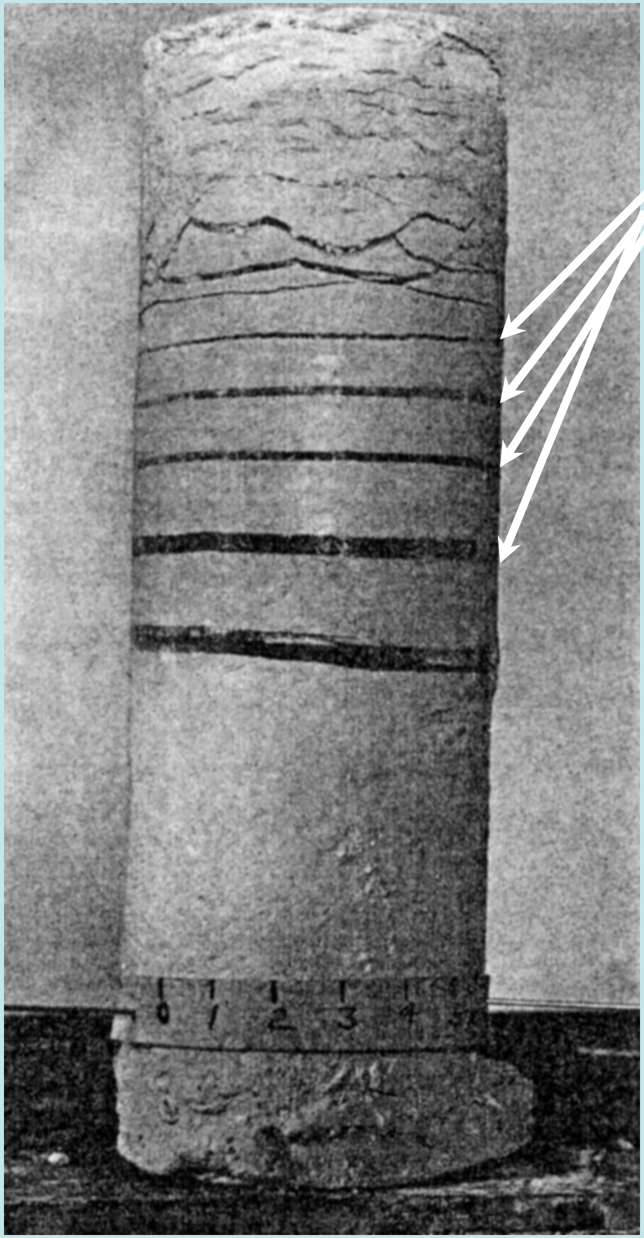
Important for relative timing of old events

Rempel et al. *Nature* **411**, 568 (2001)

The Cold “Hard” Ground...



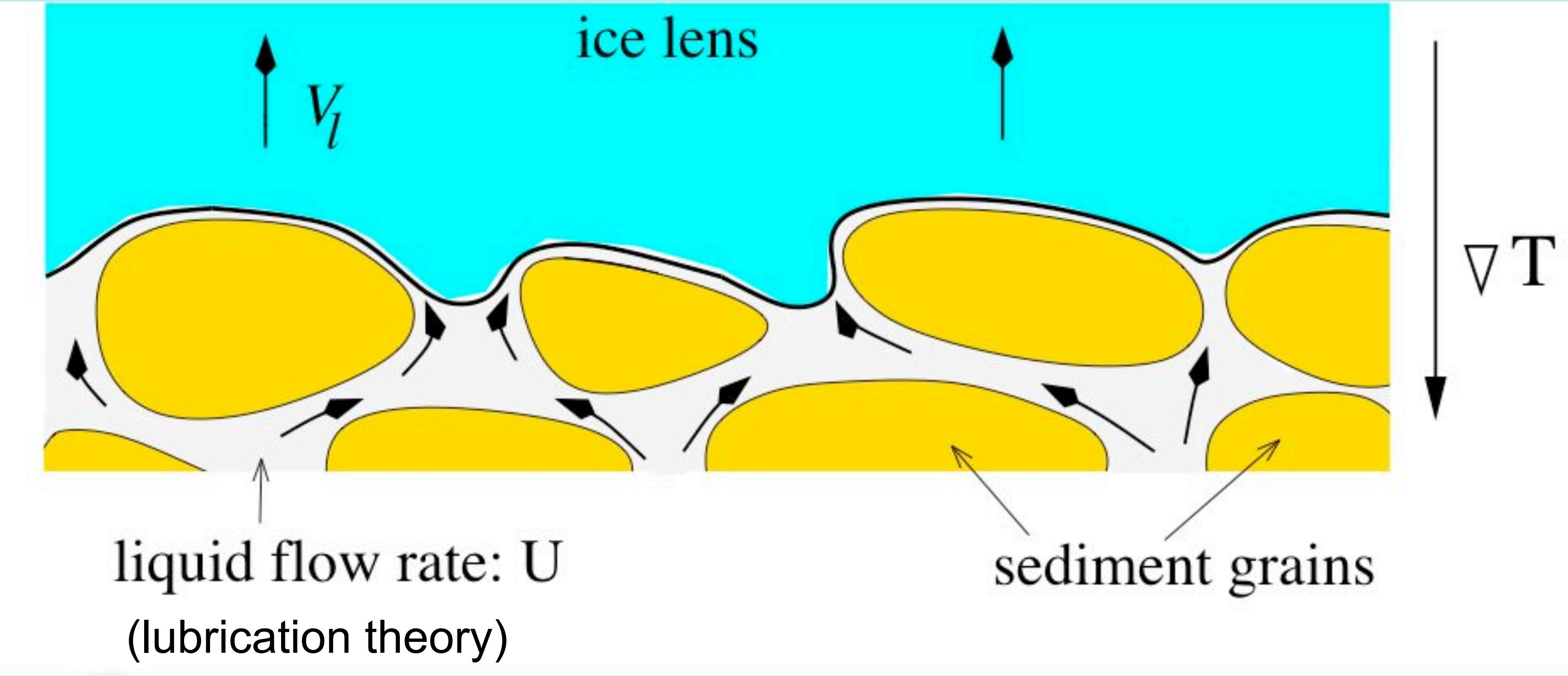
Frost Heave



- prolonged ice growth (days/weeks/months)
- fine-grained materials
- capable of lifting large loads $\left(\frac{dP_l}{dT} = \frac{\rho_s q_m}{T_m} = 11 \text{atm/K} \right)$

Water expands when freezing, but Argon heaves too…*Phys. Rev. Lett*. **85**, 4908 (2000).

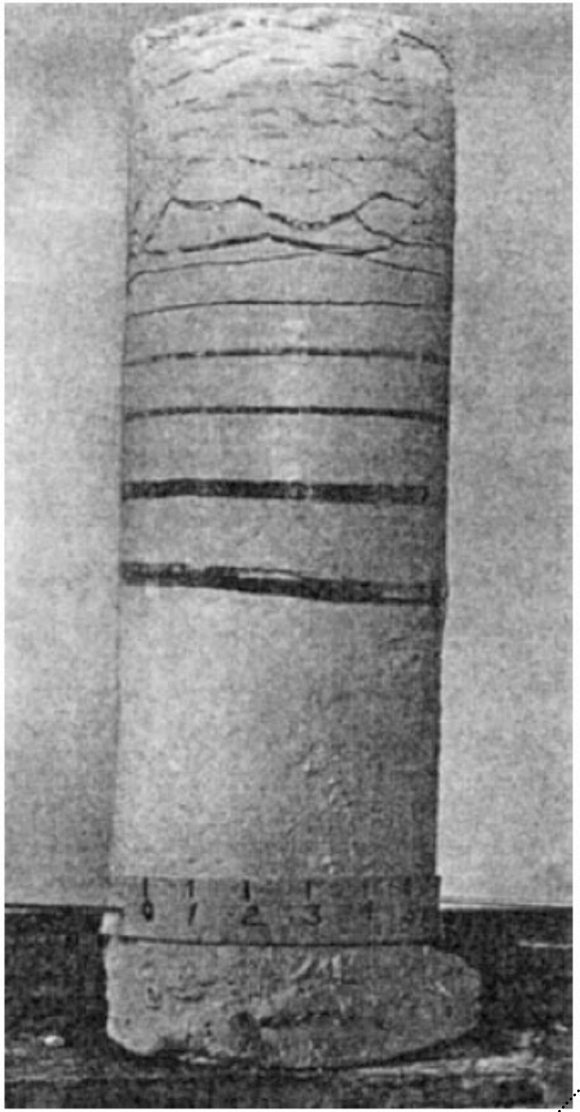
A Growing lens

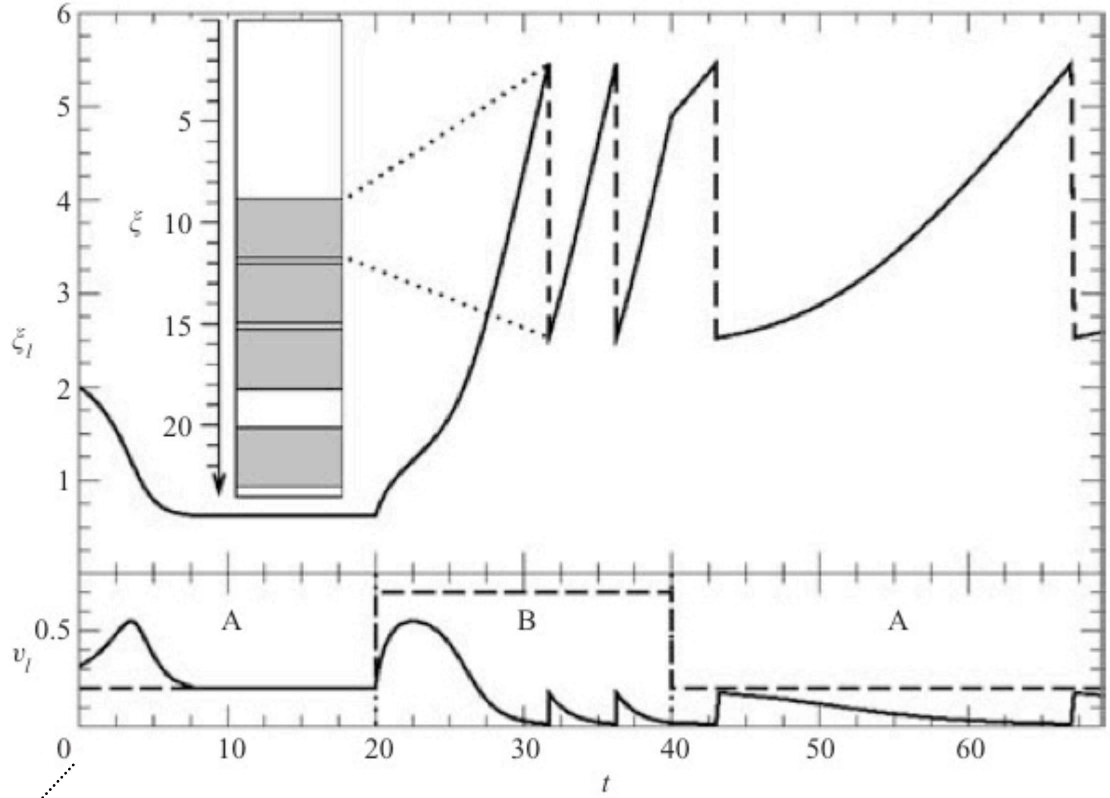


Interface shape satisfies: $$\rho \frac{q_m}{T_m}(T_m - T) = p_T + \gamma_{sl}\kappa$$

Balance of forces, mass and energy control growth rate

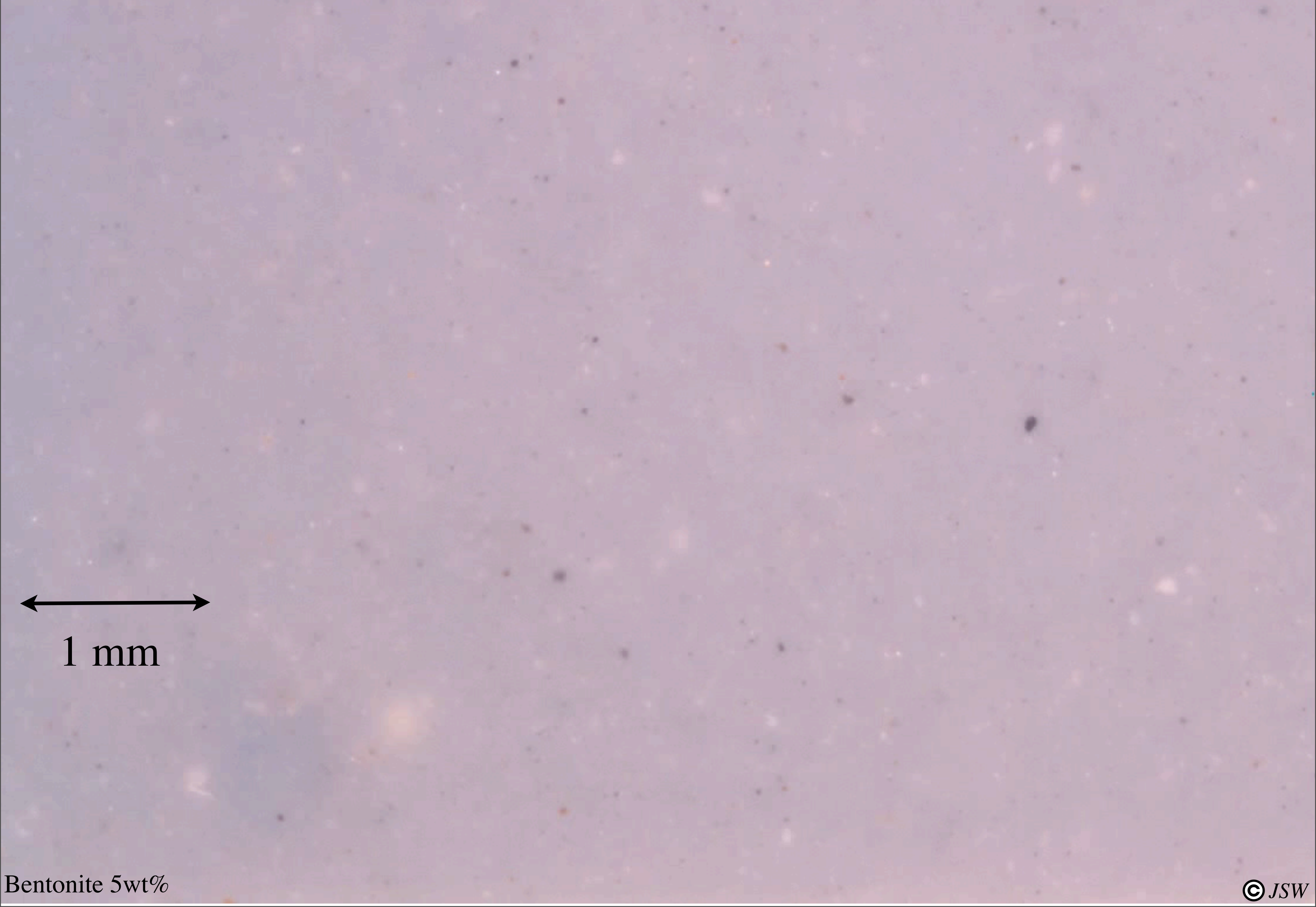
Periodicity Predicted



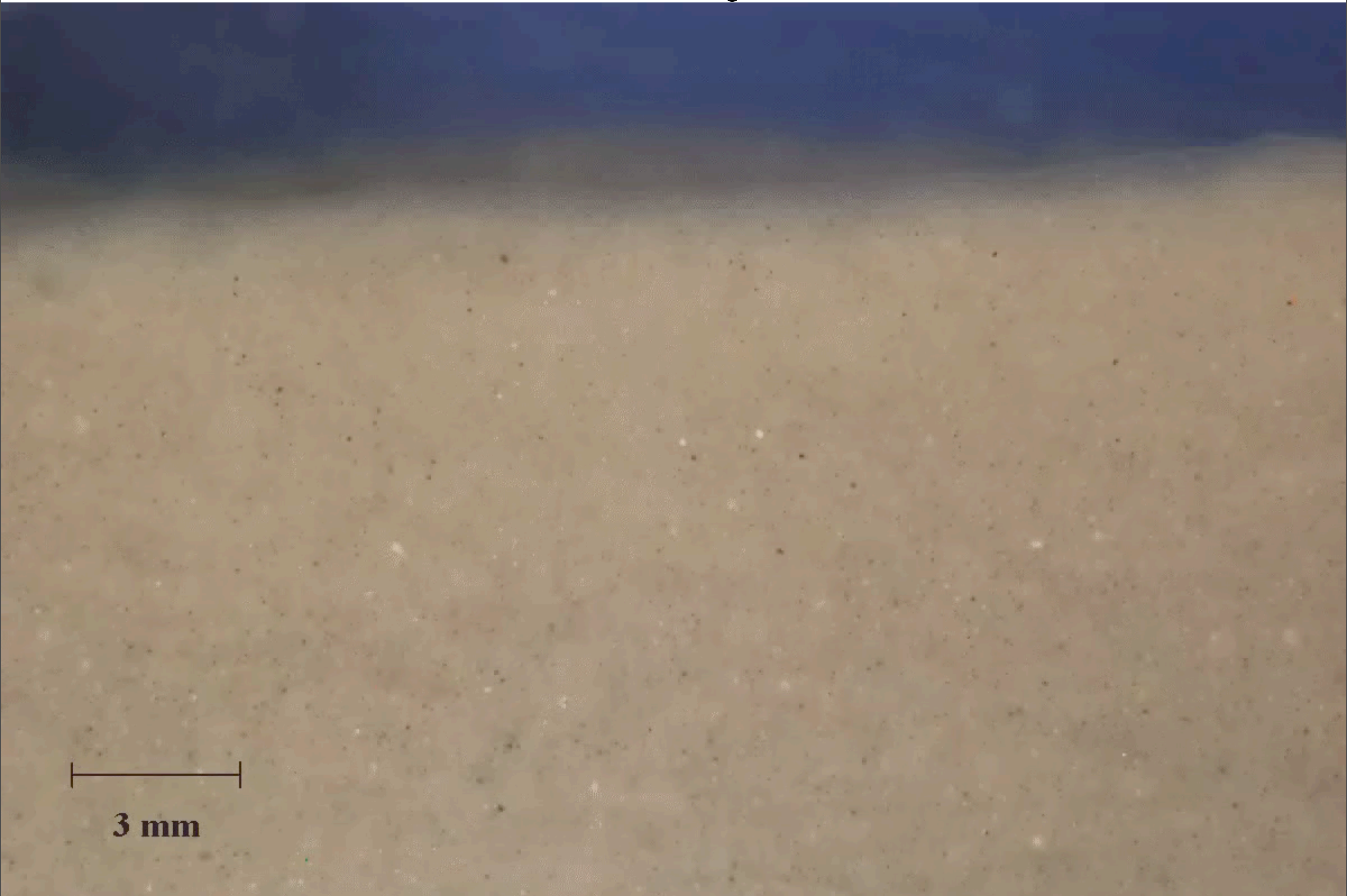


Rempel, JSW, Worster, *J. Fluid Mech*. **498**, 227-44 (2004)

Not so fast...

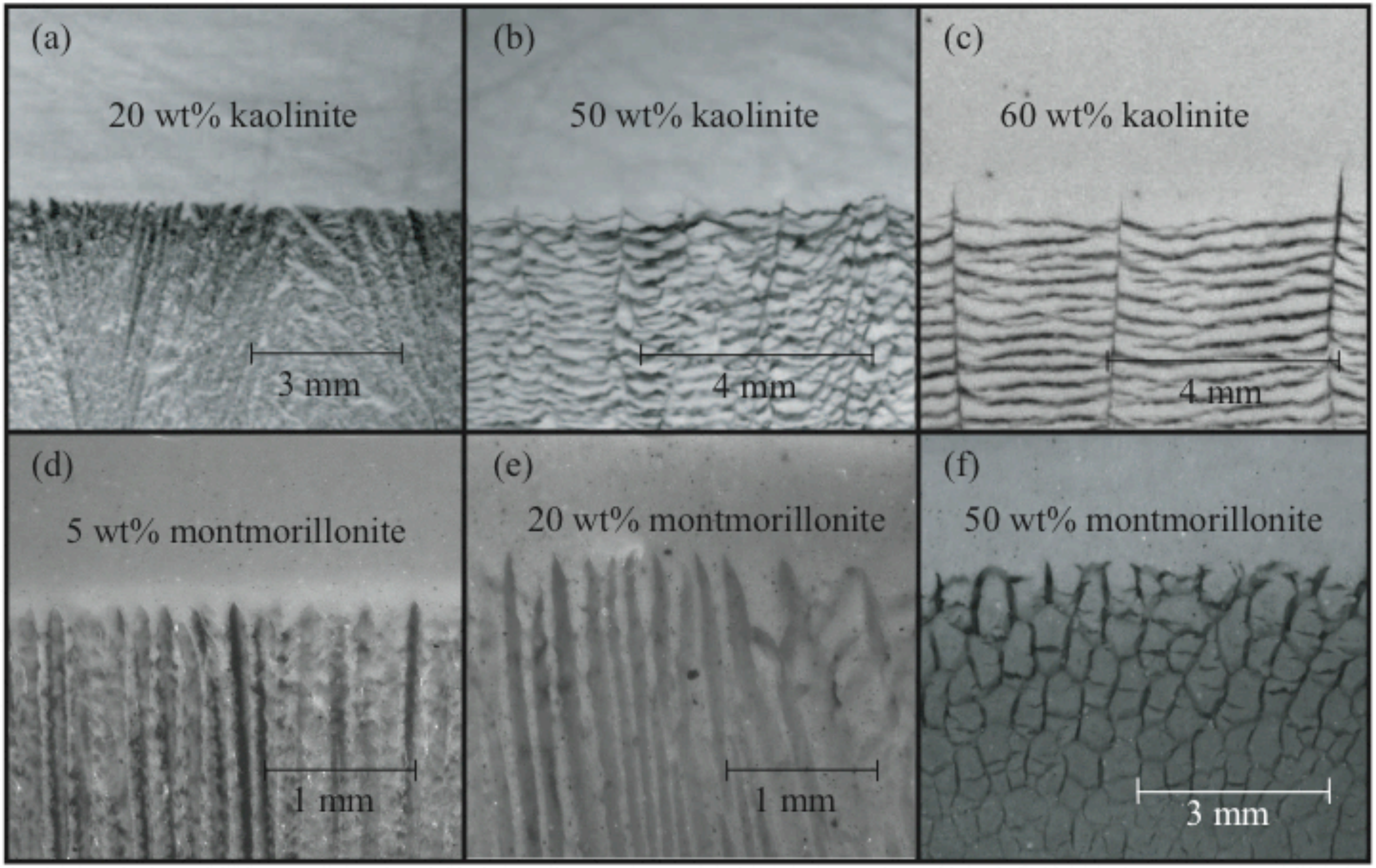


…in reality...

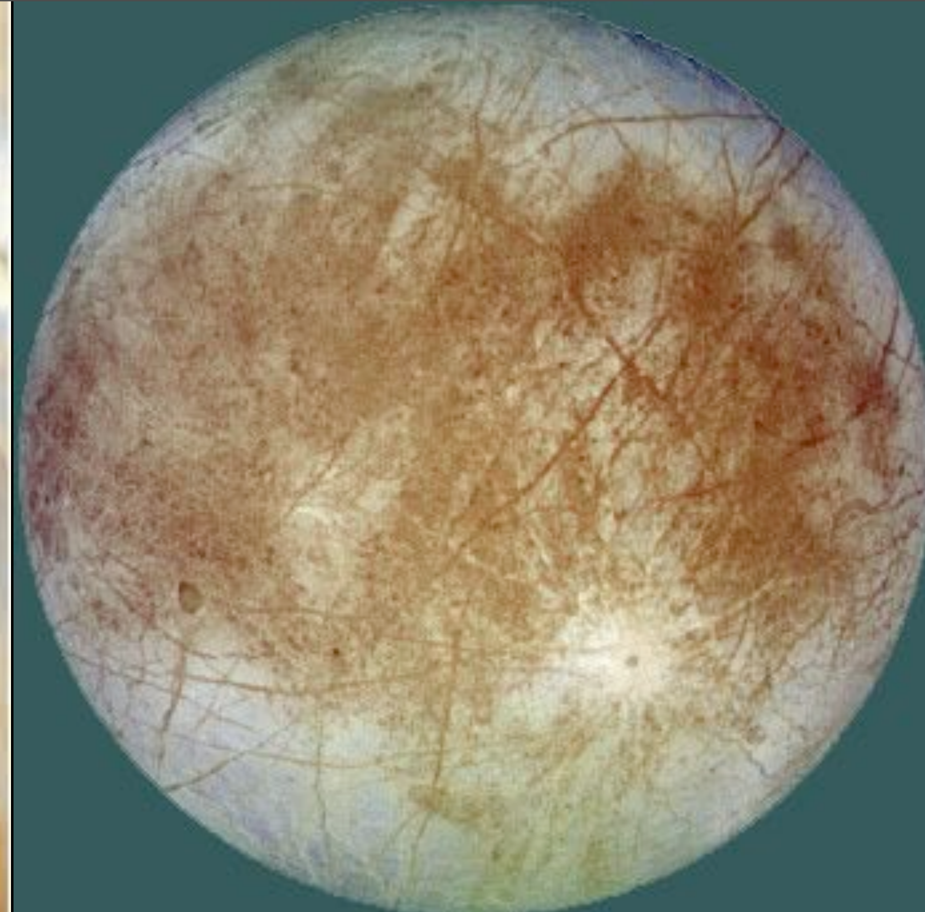
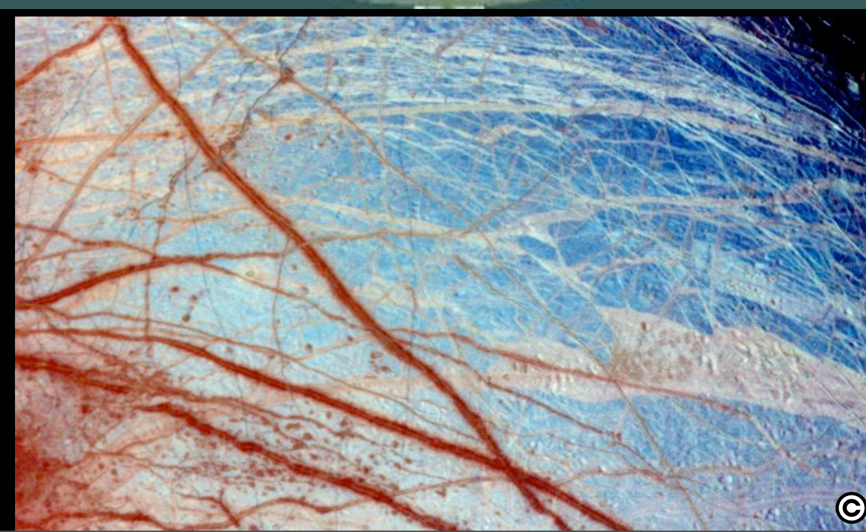


Bentonite 50wt%

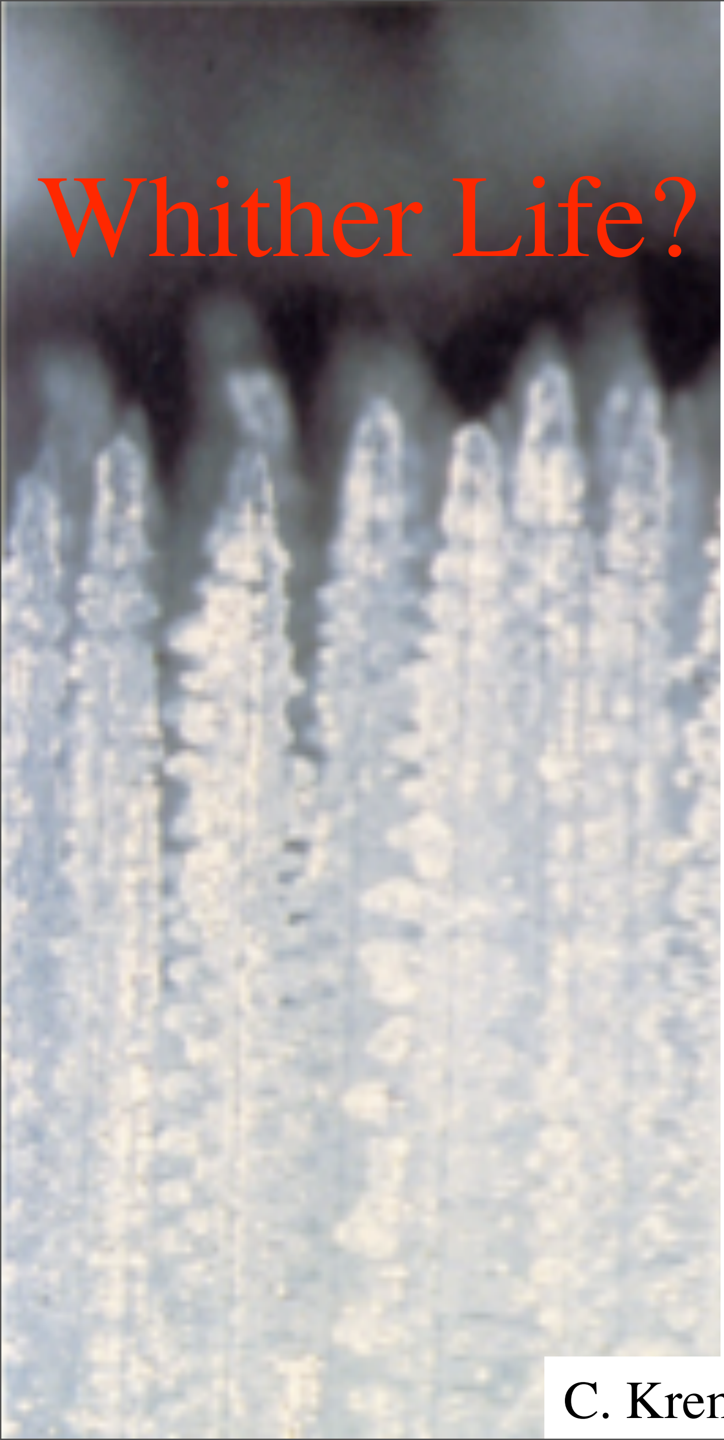
... it's a zoo out there.

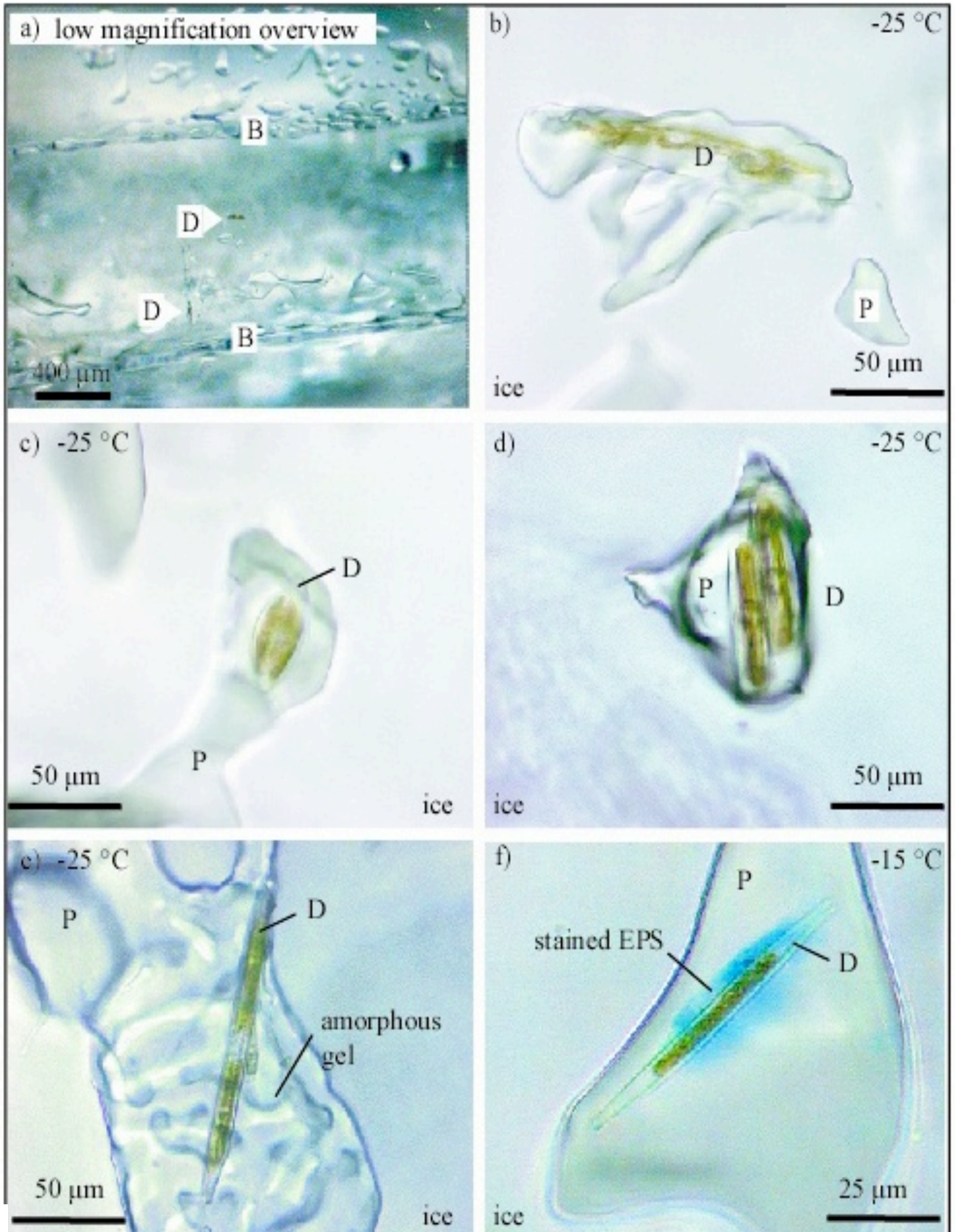


Peppin et al. *J. Fluid Mech*. **554**, 147 (2006); *Proc Roy Soc* **463**, 723 (2007); *Phys Rev Lett* **100**, 238301 (2008)

Whither Life?

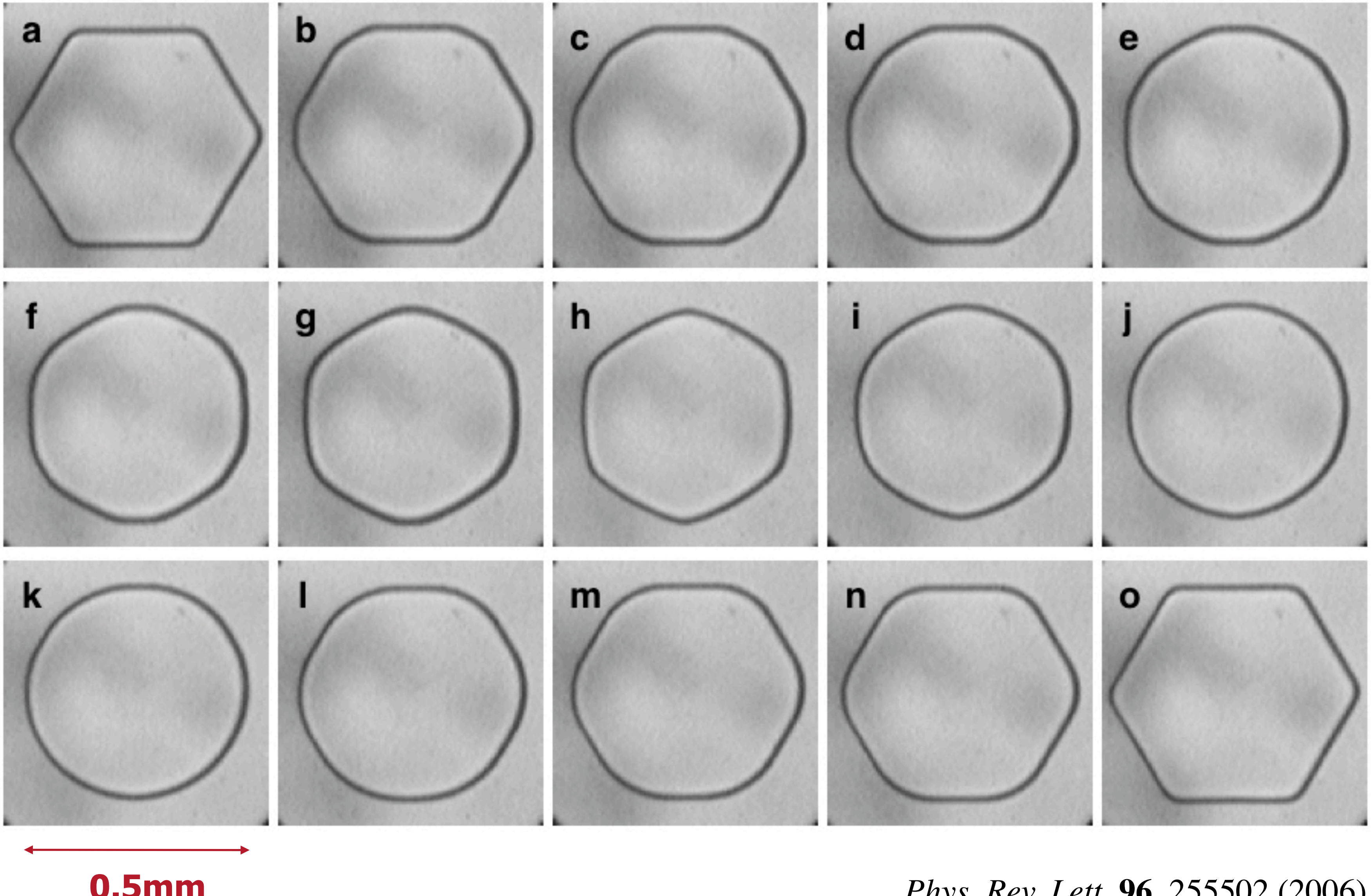




C. Krembs

Pristine Ice Crystal Growth

T = -22 ^{o}C, P = 2000 bar

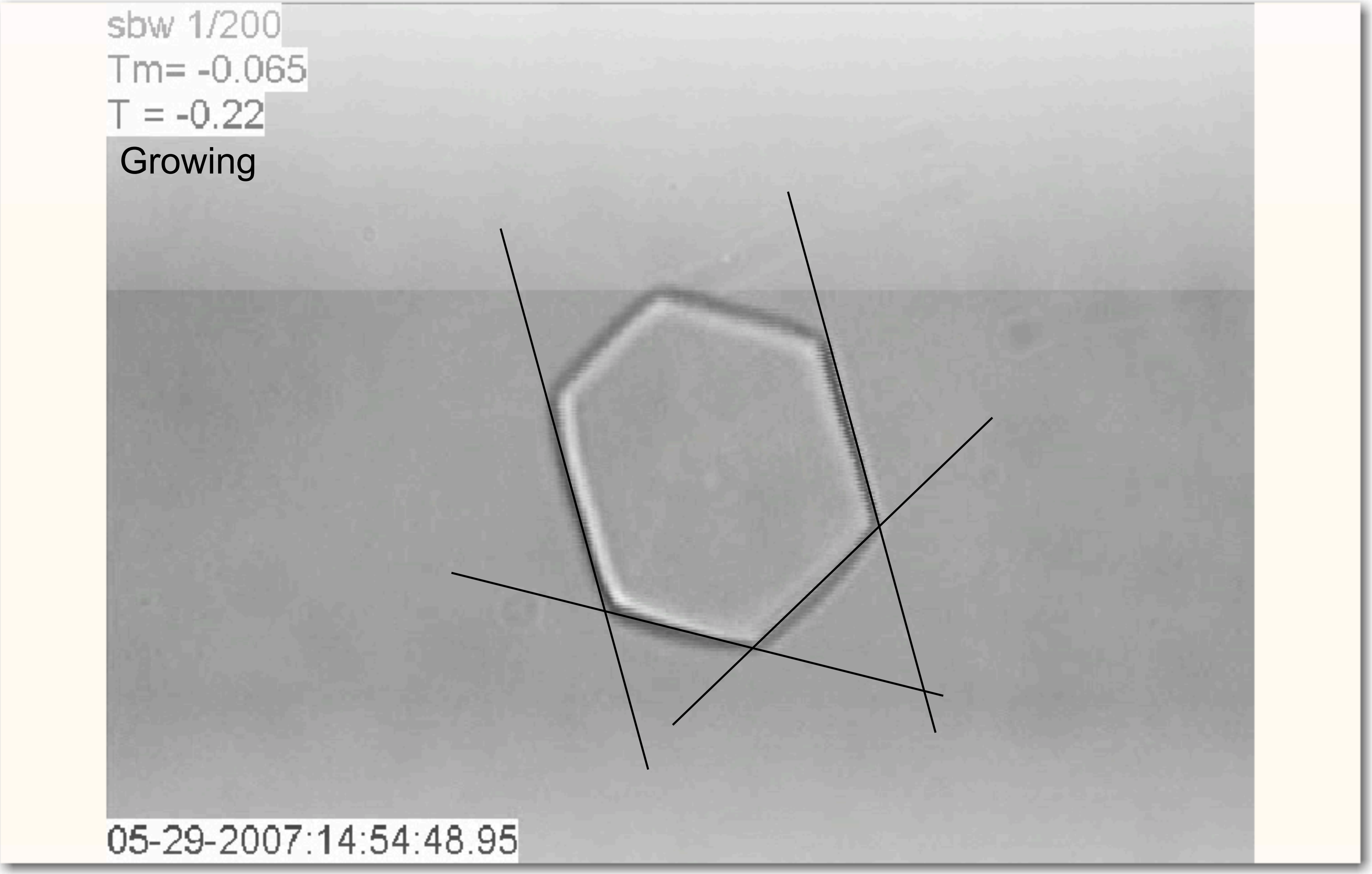


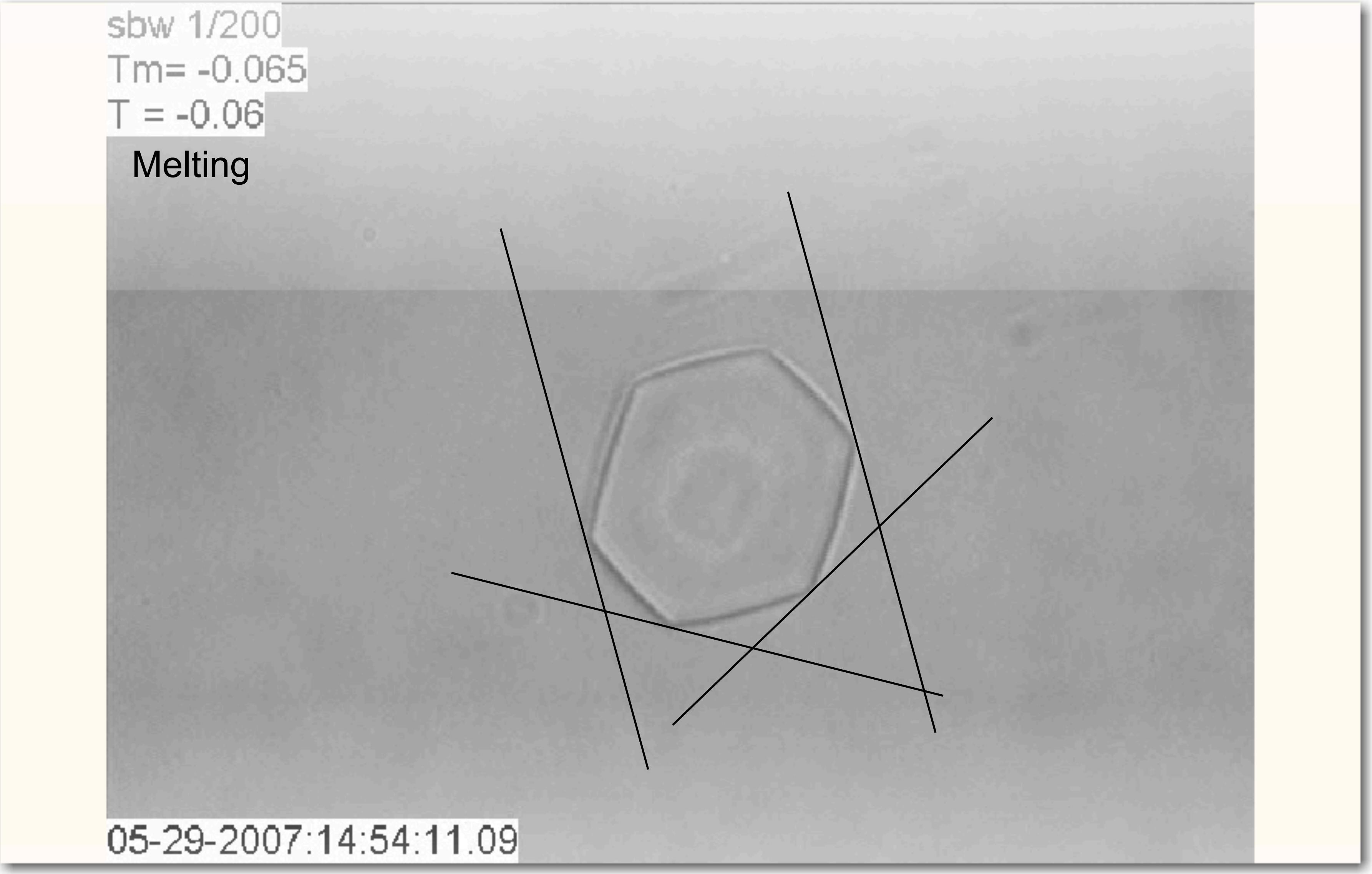
Phys. Rev. Lett. **96**, 255502 (2006).

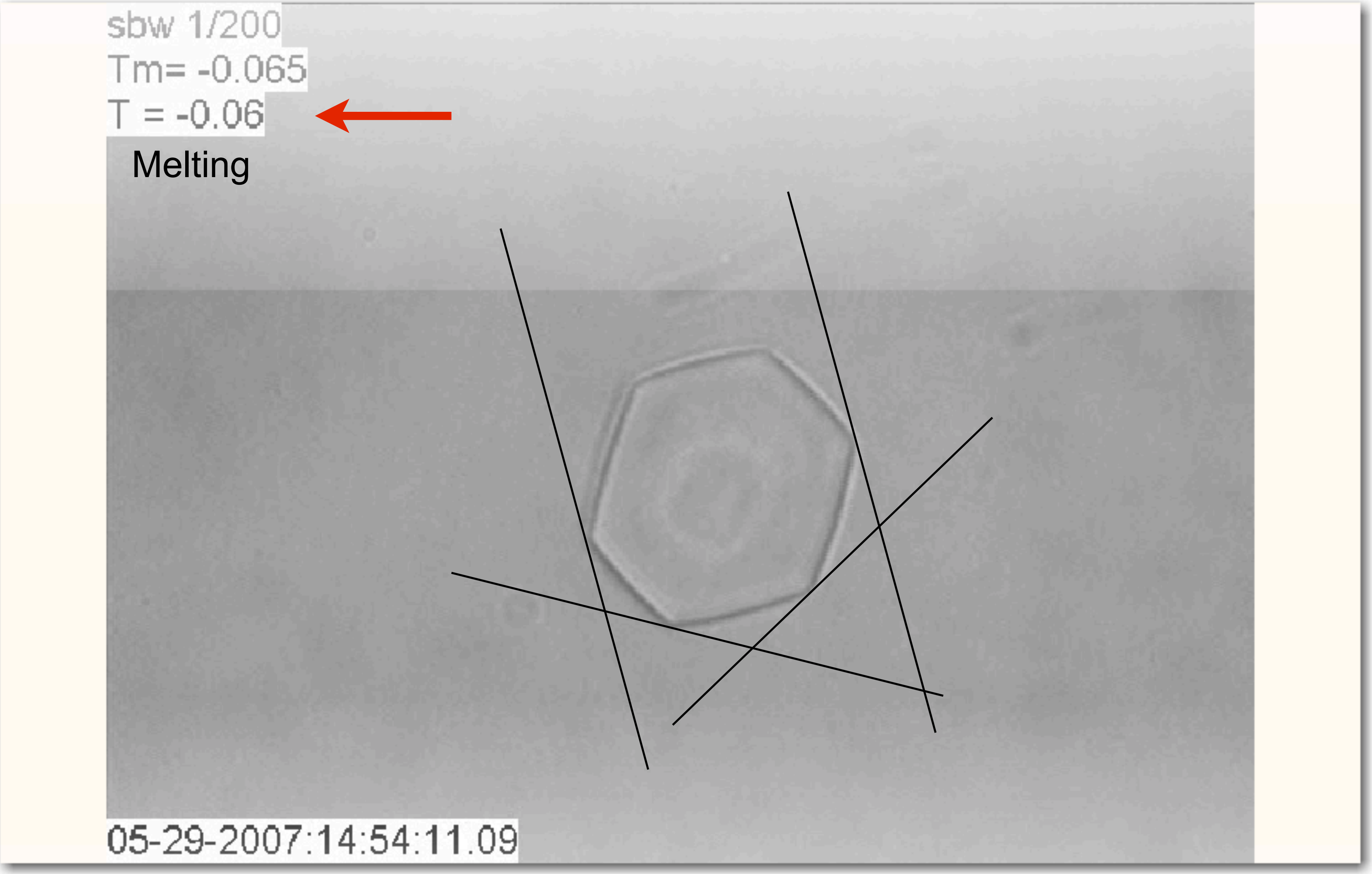
Ice Crystal Growth from sbwAFGP Solution

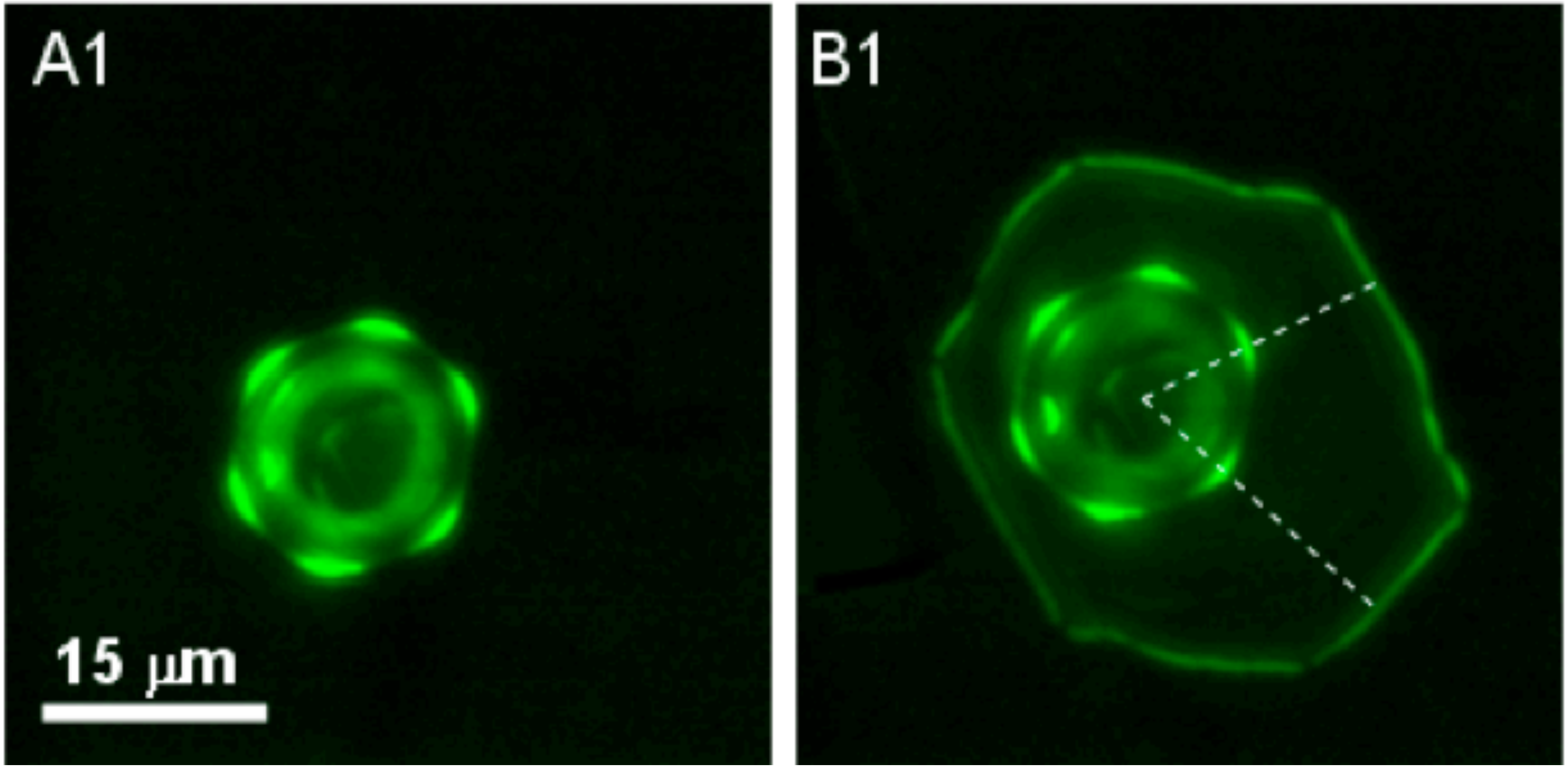
sbwAFP: C=0.01 mg/mL (1.1 µM, TH= 0.02K) to 2 mg/mL (220 µM, TH= 5K)
Buffer 10 mM Tris-HCl, 1mM EDTA, 5 mM Ammonium bicarbonate, pH 8.0

© JSW


sbw 1/200
Tm= -0.065
T = -0.22
Growing
05-29-2007:14:54:48.95


sbw 1/200
Tm= -0.065
T = -0.06
Melting
05-29-2007:14:54:11.09


sbw 1/200
Tm= -0.065
T = -0.06
Melting
05-29-2007:14:54:11.09



Braslavsky *et al*., *Biophys*. *J*. **92**, 3663-73 (2007)   Braslavsky *et al*., *J*. *Phys*. *Cond*. *Matt*. **19**, 42101 (2007)

Problems & Challenges

Access to Interfaces in Thermodynamic Equilibrium

Nature of Structural Information Provided by Probe of Choice

- Nature of Disorder
- Definition of Melting (from Peierls to KTHNY)
- Onset of Premelting…GULF in ignorance across scales

Systematic Study of Impurity Effects

- Nature of Phenomena
- Major Experimental Hurdles
- Manipulation of amplitude and range of interactions
- Applicability across materials systems and disciplines

Emergent Phenomena (Think Natural Phenomena & Manipulation)

- Premelting Dynamics (particle trapping & redistribution)
- Disequilibrium, pattern formation, ...
- Biophysical, Geophysical & Materials Processing

Acknowledgments

J.G. Dash	University of Washington
I. Braslavsky	Ohio University
M. Elbaum	Weizmann Institute
Y. Furukawa	Hokkaido University
M. Maruyama	Osaka City University
J.A. Neufeld	Cambridge University
A.W. Rempel	University of Oregon
M. Schick	University of Washington
L.A. Wilen	Ohio University
M.G. Worster	Cambridge University

Yale Postdocs and Students

L. Benatov
A. Cahoon
S. Peppin
M. Spannuth
E. Thomson

Rev. Mod. Phys. **78**, 695 (2006)
Ann. Rev. Fl. Mech **38**, 427 (2006)
Phys. Today **60**, 70 (2007)

Support
Bosack & Kruger Foundation
NSF, DoE and Yale

"Physics is not just Concerning the Nature of Things, But Concerning the Interconnectedness of all the Natures of Things".

Sir Charles Frank, FRS, upon retirement from Univ. Bristol's Physics Department in 1976.