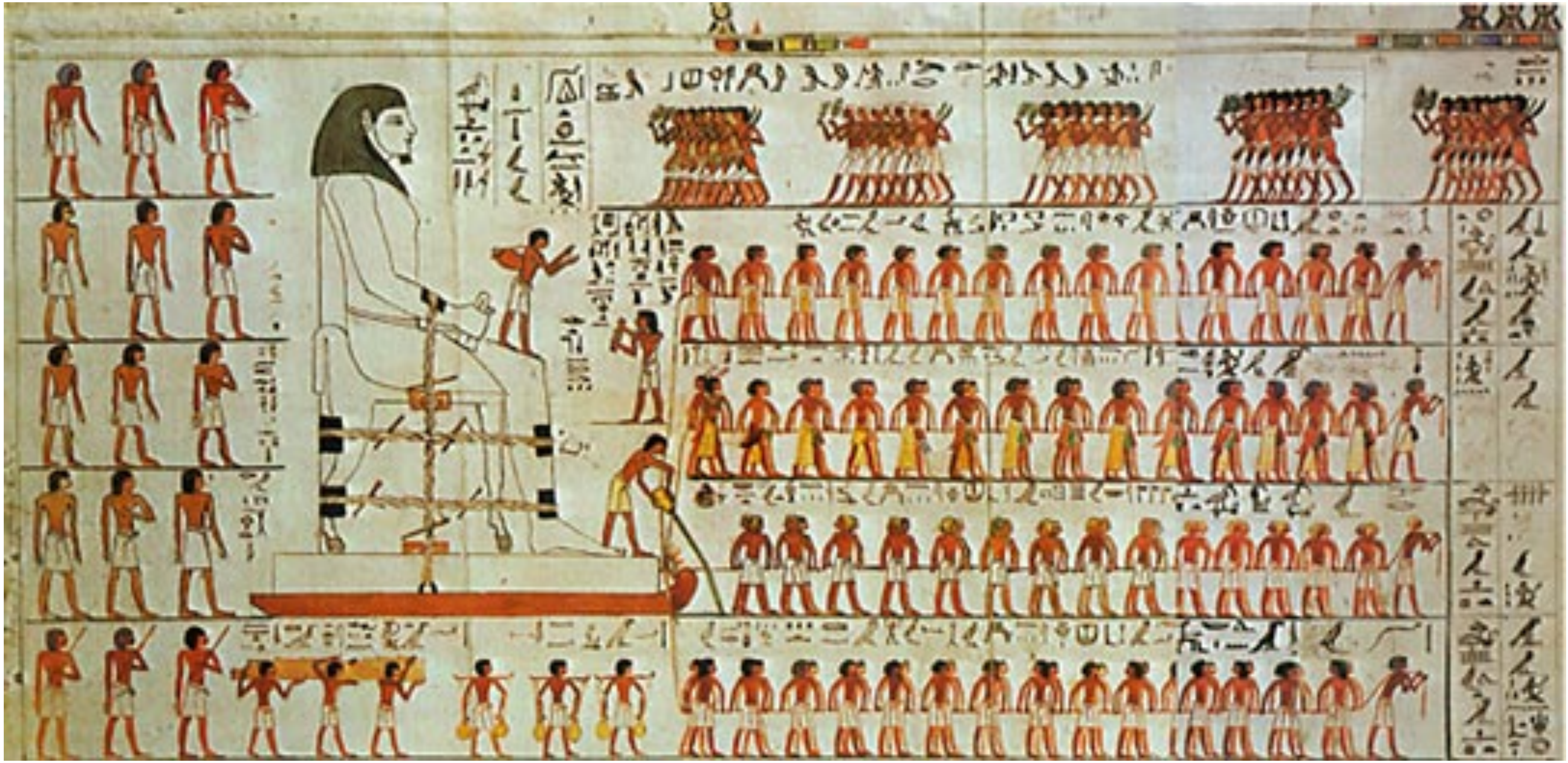
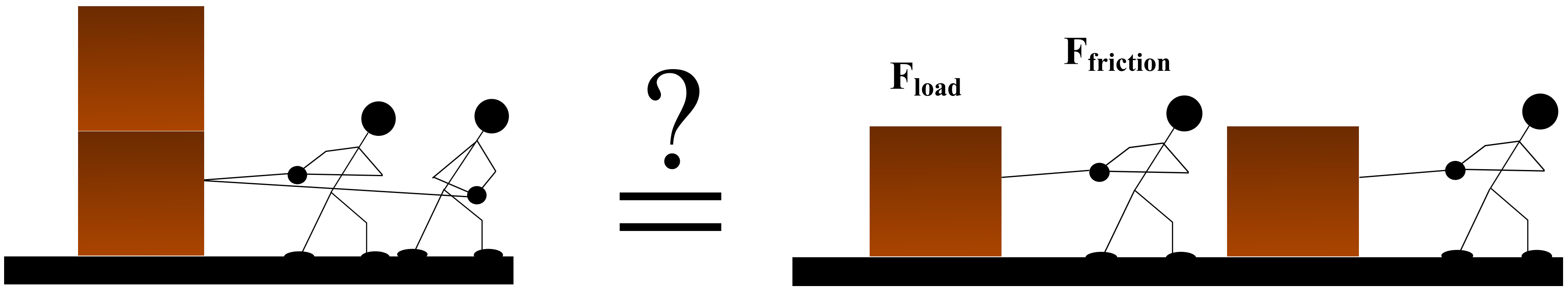
Why study friction? It represents ~20% of the world energy consumption!



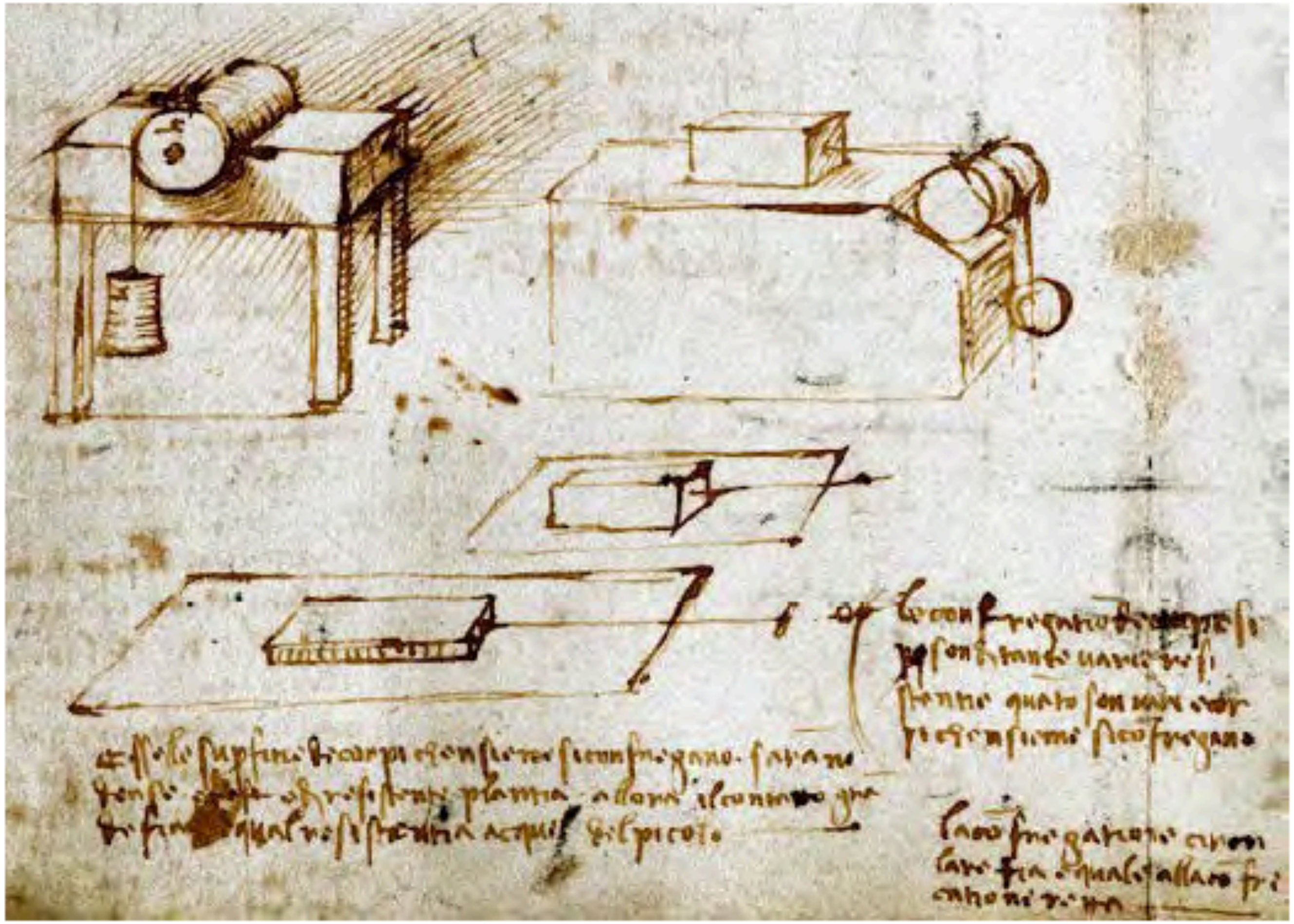
Fall et al. PRL 2014

Looking deeper into friction: Equivalent or not?



Is the friction force independent of the contact area?

Da Vinci



‘Normal and friction force have a constant ratio of ¼’

Ice is much more slippery than that; μ~0.04 for a real ice skate

Rank	Nation	Gold	Total
1	Netherlands	42	121
2	United States	29	68
3	Norway	27	84
4	Soviet Union	24	60
5	Germany	13	38
6	Canada	9	37
7	East Germany	8	29

'Large stone carving': 300 tons transported over ice roads in china

Researchers at Princeton studied how a band of workers moved the enormous block of stone from a quarry 70 kilometers (about 43 miles) by sliding it on a track of wet ice.

Forbidden city, China

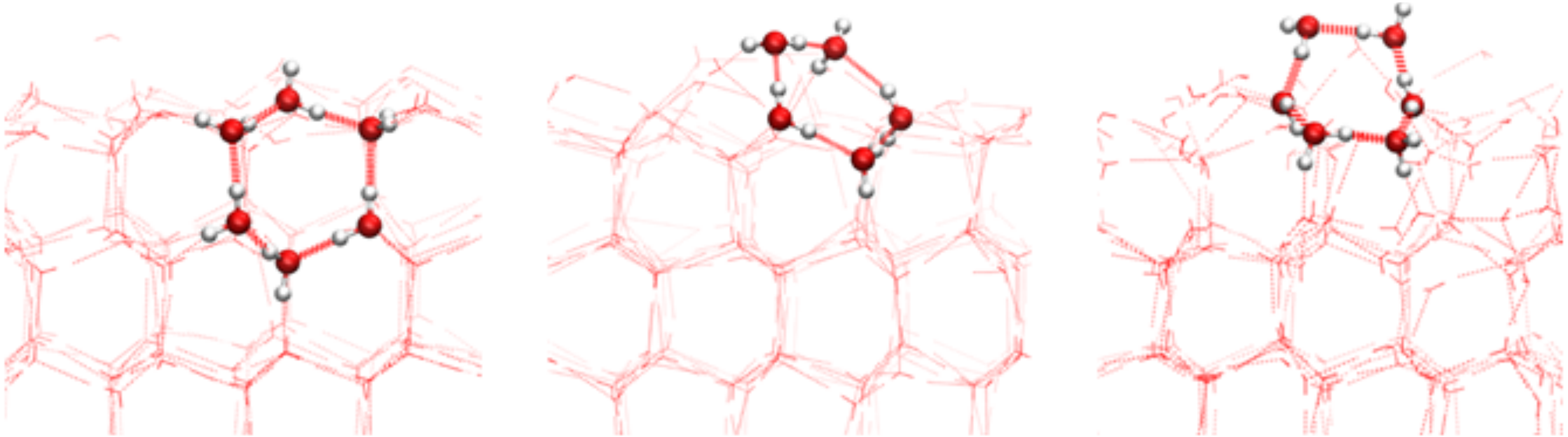
PNAS

Experimental and theoretical evidence for bilayer-by-bilayer surface melting of crystalline ice

M. Alejandra Sánchez[a], Tanja Kling[a], Tatsuya Ishiyama[b], Marc-Jan van Zadel[a], Patrick J. Bisson[c], Markus Mezger[a,d], Mara N. Jochum[a,e], Jenée D. Cyran[a], Wilbert J. Smit[f], Huib J. Bakker[f], Mary Jane Shultz[c], Akihiro Morita[g,h], Davide Donadio[a,i], Yuki Nagata[a], Mischa Bonn[a,1], and Ellen H. G. Backus[a,1]

[a]Max Planck Institute for Polymer Research, 55128 Mainz, Germany; [b]Graduate School of Science and Engineering, University of Toyama, Toyama 930-8555, Japan; [c]Laboratory for Water and Surface Studies, Department of Chemistry, Pearson Laboratory, Tufts University, Medford, MA 02155; [d]Institute of Physics, Johannes Gutenberg University Mainz, 55128 Mainz, Germany; [e]BASF SE, 67117 Limburgerhof, Germany; [f]FOM Institute AMOLF, 1098 XG Amsterdam, The Netherlands; [g]Department of Chemistry, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan; [h]Elements Strategy Initiative for Catalysts and Batteries, Kyoto University, Kyoto 615-8520, Japan; and [i]Department of Chemistry, University of California, Davis, CA 95616

T < -70 °C   -70 °C   -20 °C



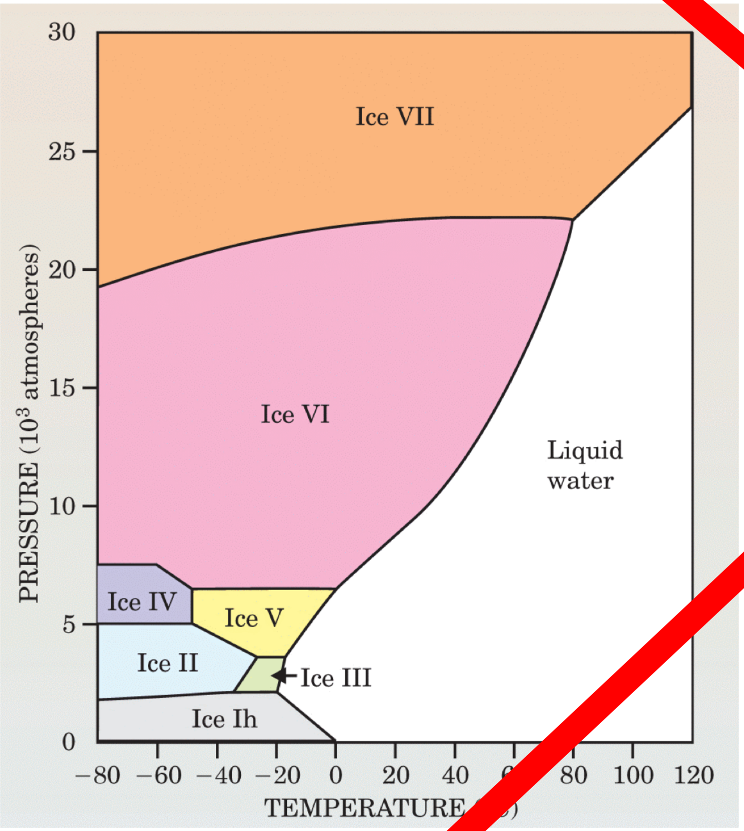
Why is ice slippery?

Bart Weber[1], Rinse Liefferink[1], Yuki Nagata[3], Stefania Ketzetzi[1], Paul Kolpakov[1], Wilbert J. Smit[2], Huib J. Bakker[2], Ellen Backus[3], Mischa Bonn[3] and Daniel Bonn[1]

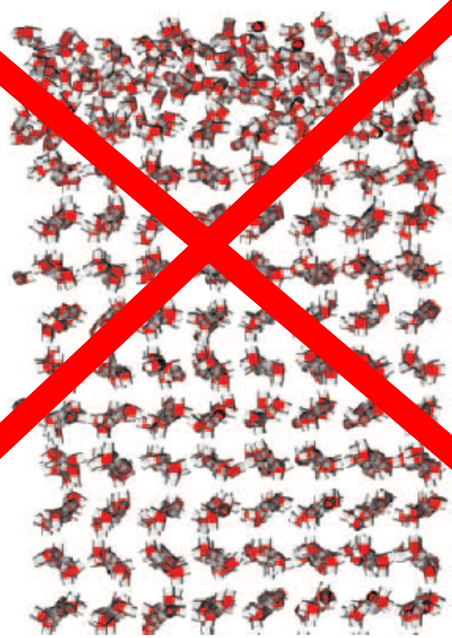
[1]Van der Waals-Zeeman Institute, IoP, University of Amsterdam, The Netherlands
[2]FOM Institute AMOLF, The Netherlands
[3]Max Planck Institute for Polymer Research, Germany

Lubricating water layer created by:

Pressure Melting



Premelting



The thickness of a liquid layer on the free surface of ice as obtained from computer simulation

M. M. Conde,[1] C. Vega,[1,a)] and A. Patrykiejew[2]
[1]*Departamento de Química Física, Facultad de Ciencias Químicas, Universidad Complutense, 28040 Madrid, Spain*
[2]*Faculty of Chemistry, MCS University, 20031 Lublin, Poland*

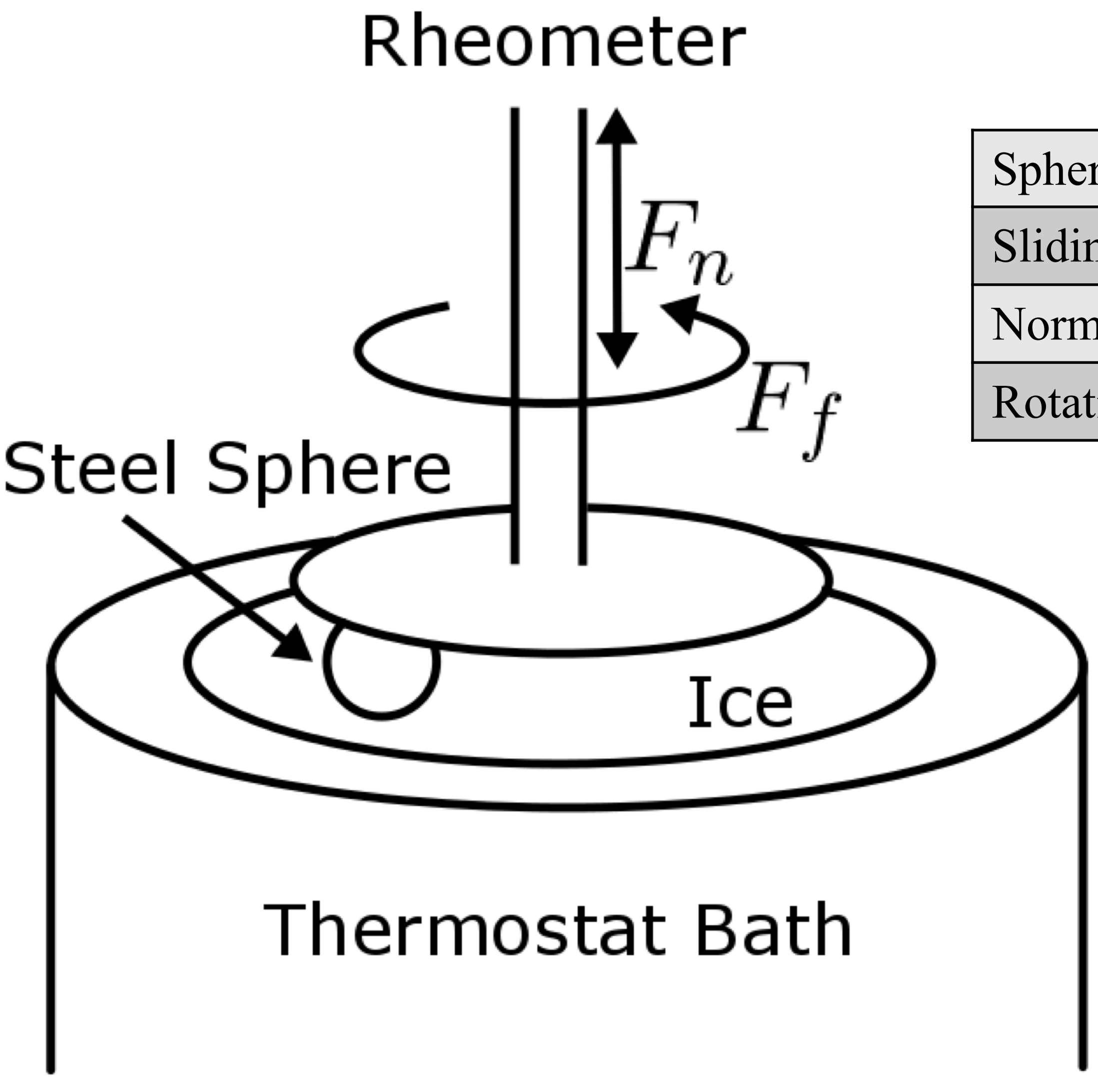
(Received 11 January 2008; accepted 16 May 2008; published online 1 July 2008)

Frictional Heating

Photo taken from globalnews.ca

(what happens here?)

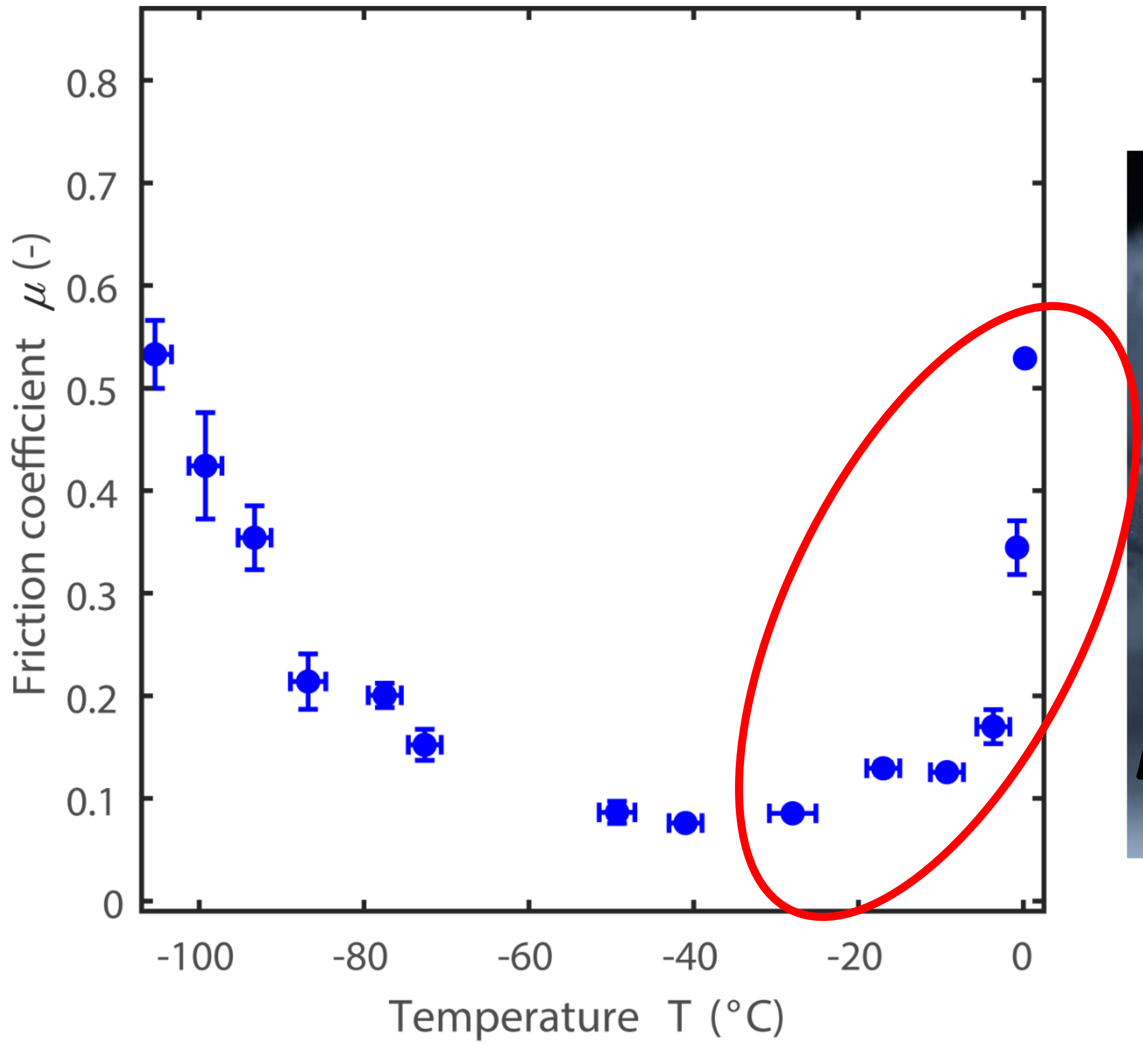
Experiment

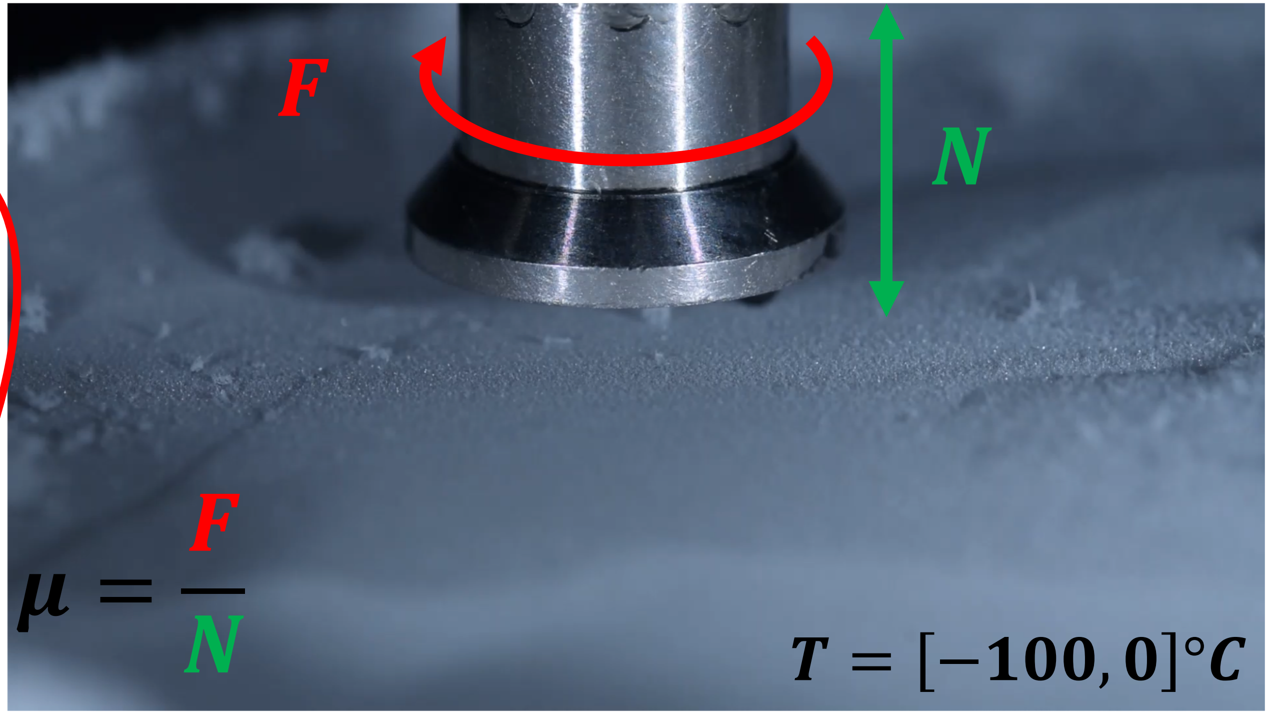


Sphere Radius	2.38 mm
Sliding Speed	0.38 mm/s
Normal Force	1 mN – 5 N
Rotation Radius	9 mm

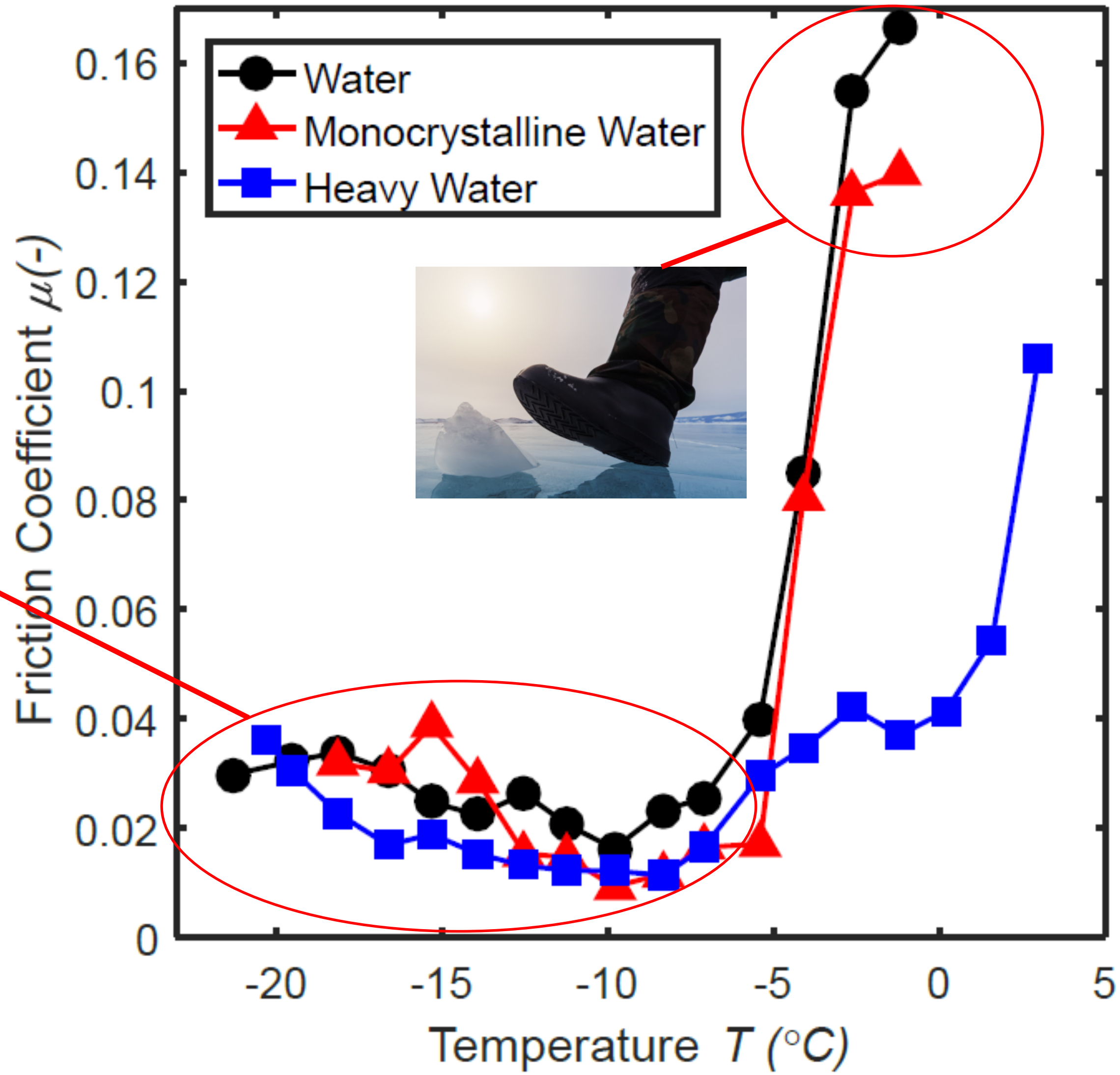
$$\mu = \frac{F_f}{F_n}$$

T- dependence: Ice friction is nonmonotonic!

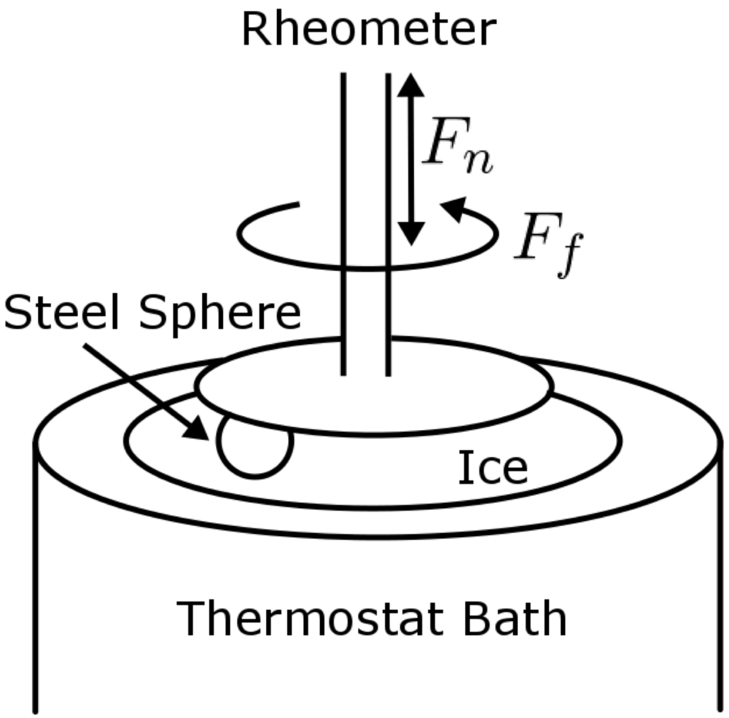


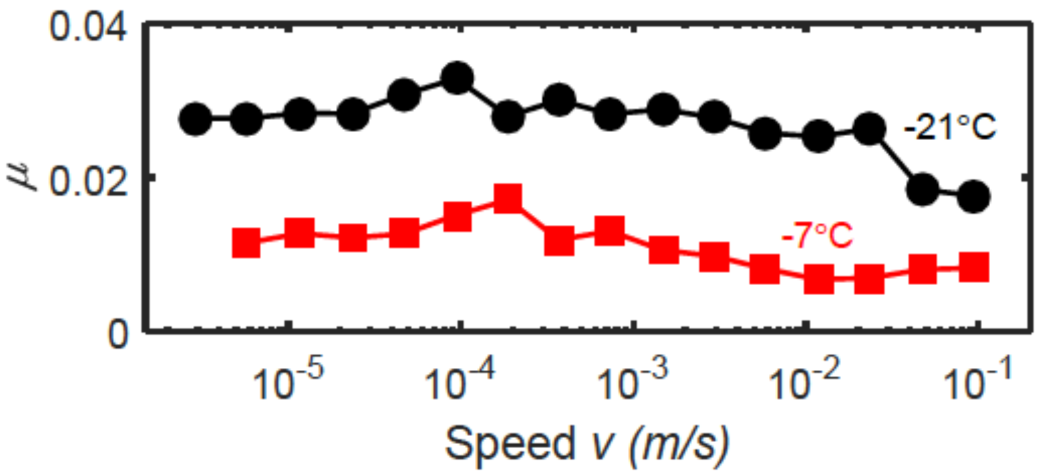


No ice structure dependence



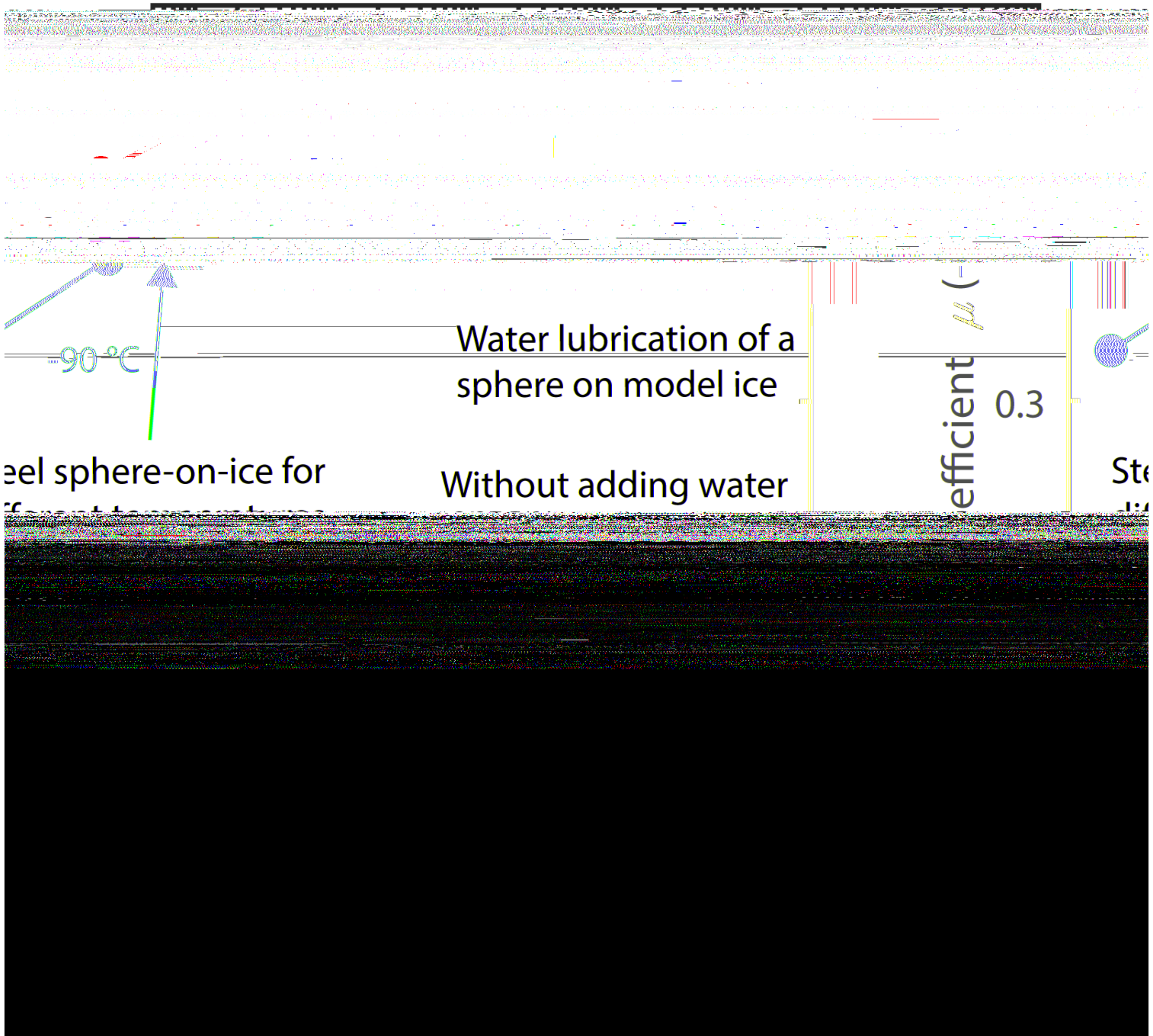
Velocity Dependence





..again, no frictional melting and solid-on solid friction

Velocity dependence, once again

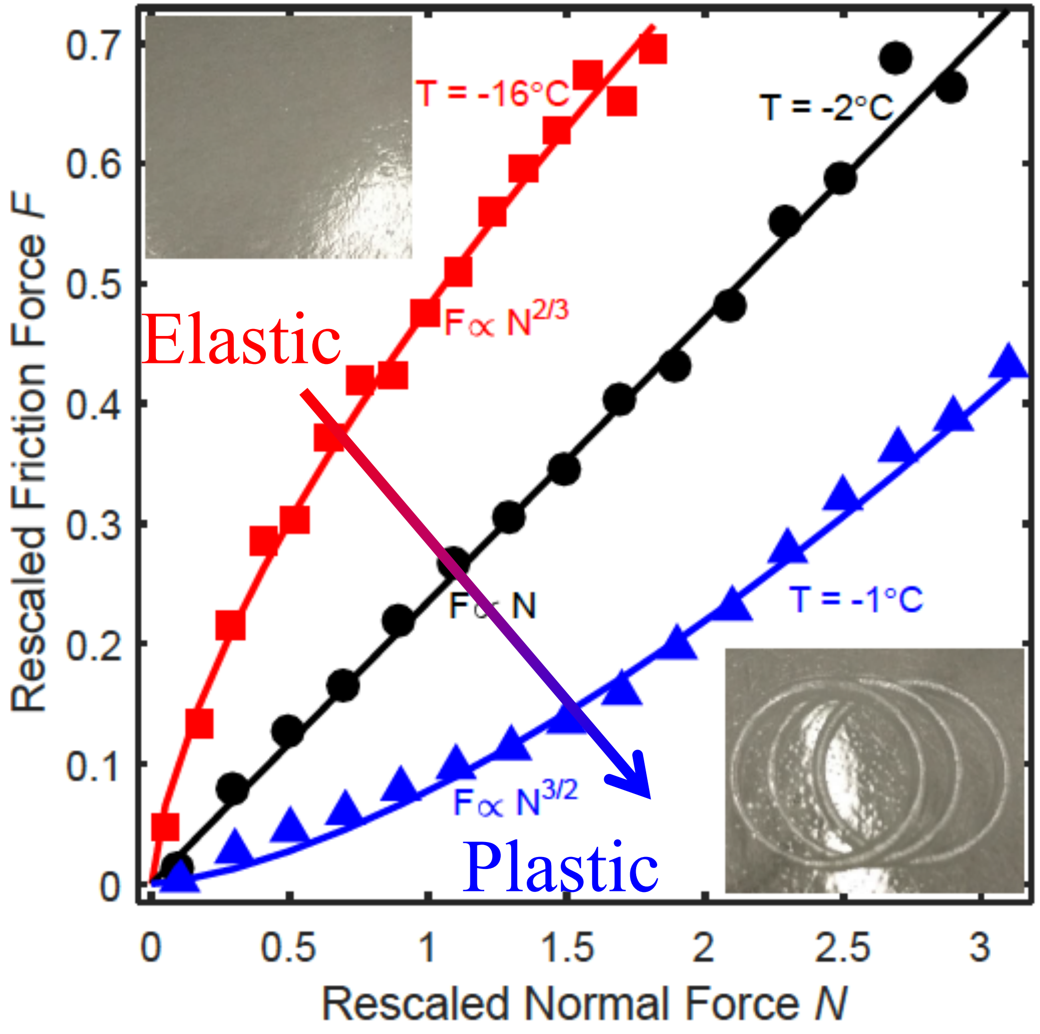


High density PE has the same mechanical properties as ice

Normal Force Dependence

Hertz contact

Usual friction assumption
(Da Vinci, Amontons, Coulomb)

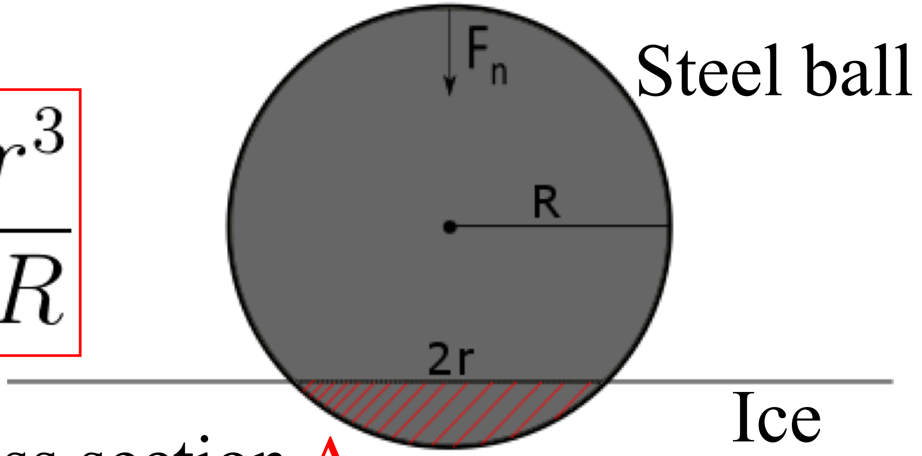


New!

High Temperatures: Calculation of the Ploughing Force

$$F_p = A_p \cdot p_h$$

$$A_p = \frac{2r^3}{3R}$$

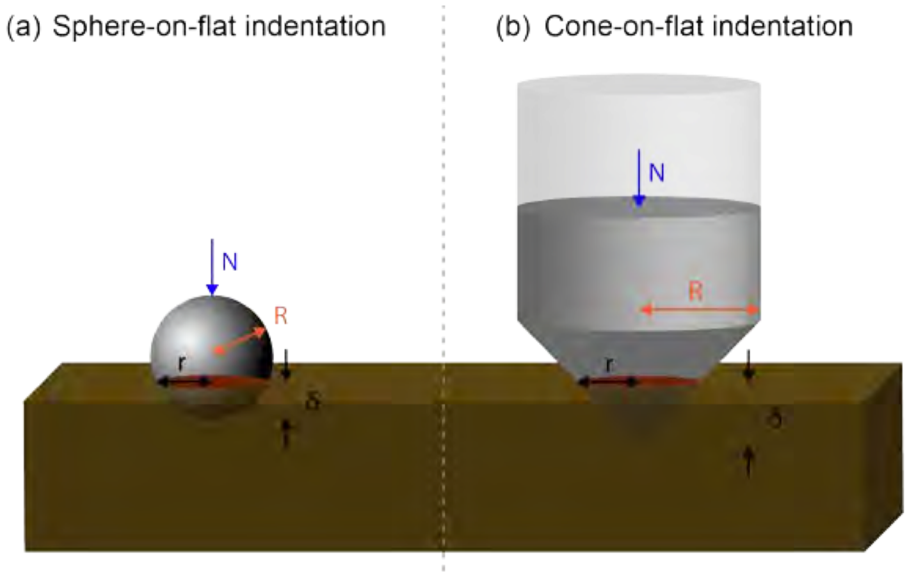


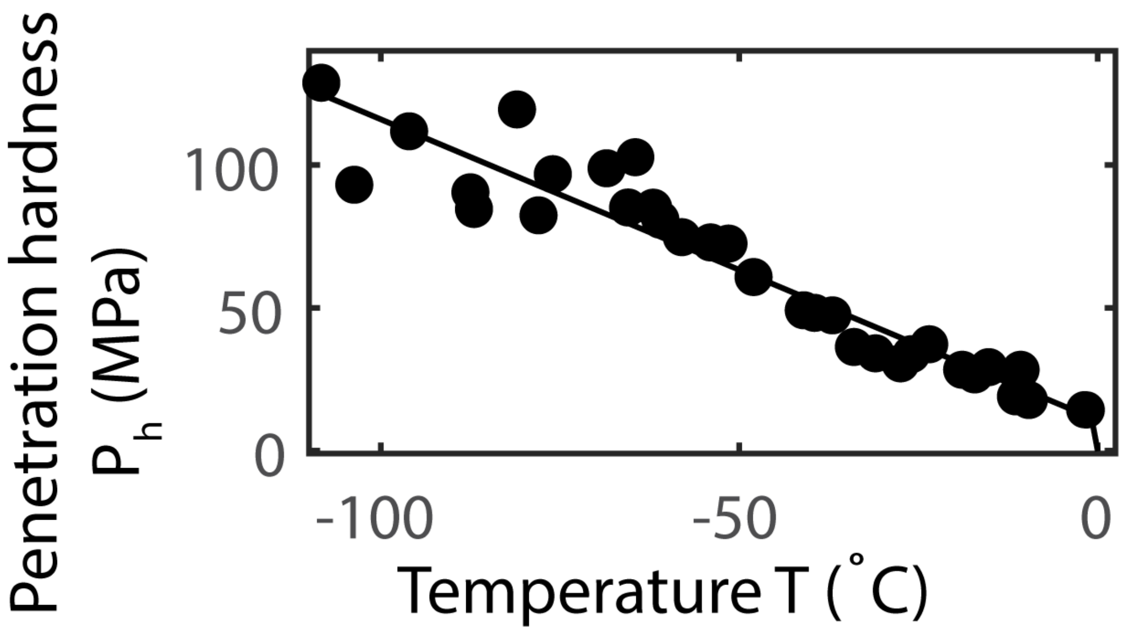
Ploughing cross section A_p

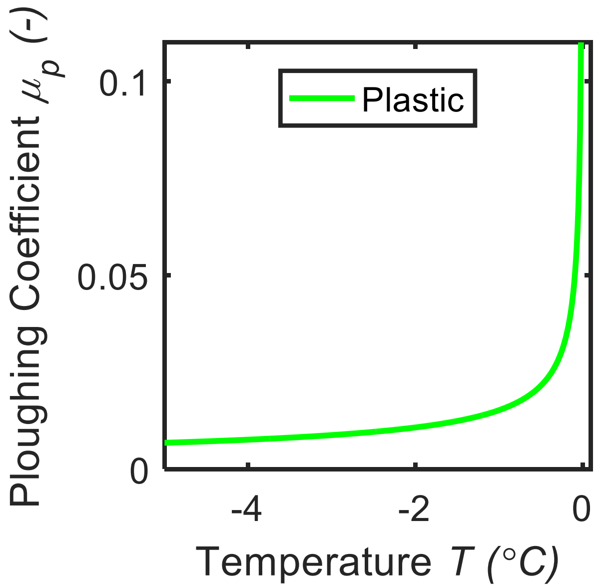
$$r^2 = \frac{F_n}{\pi p_h}$$

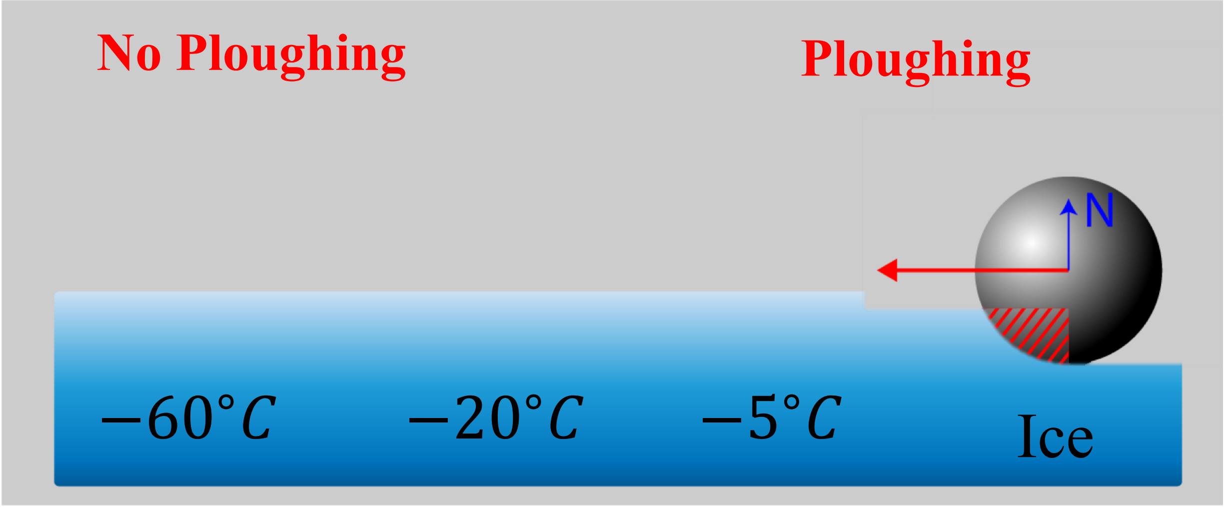
$$F_p = \frac{2}{3\pi^{\frac{3}{2}} R \sqrt{p_h}} F_n^{\frac{3}{2}}$$

Penetration hardness

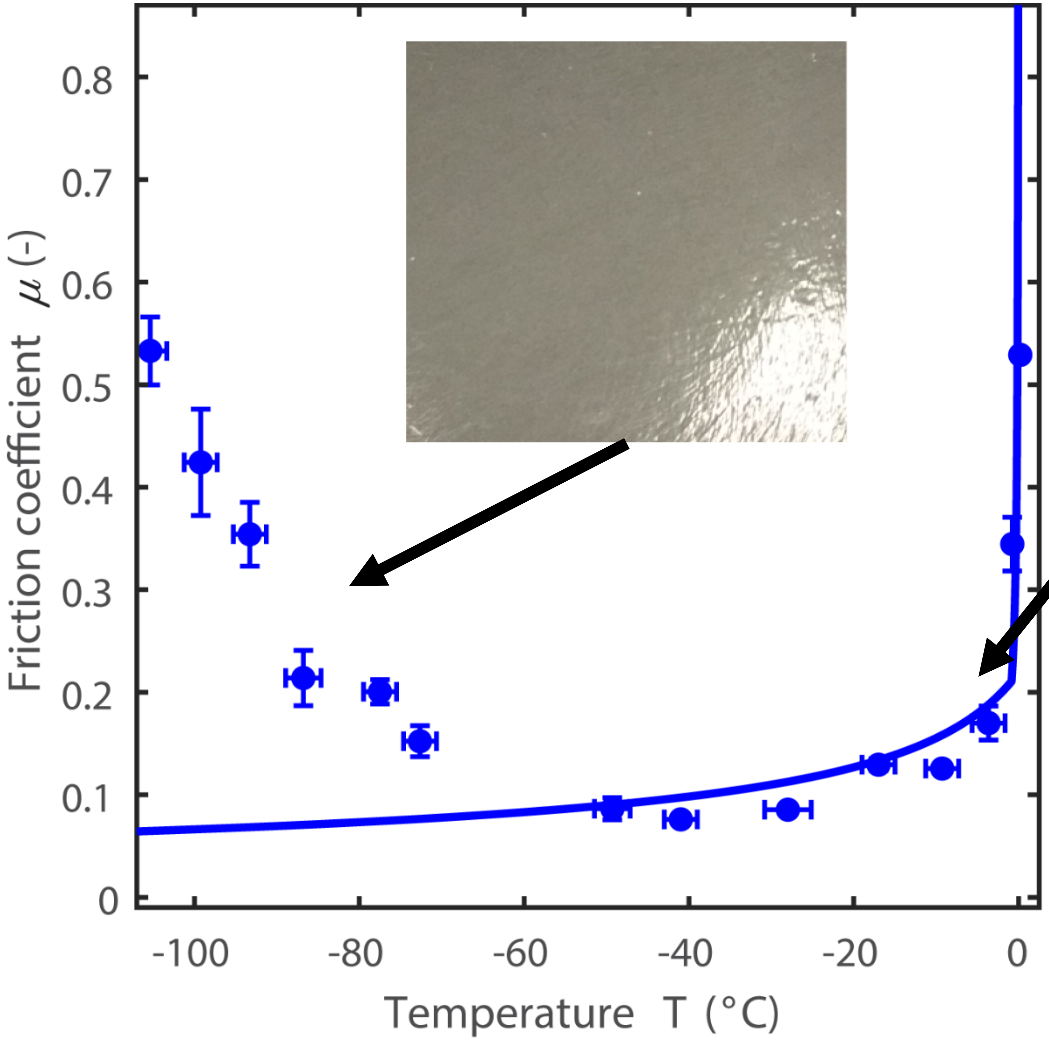


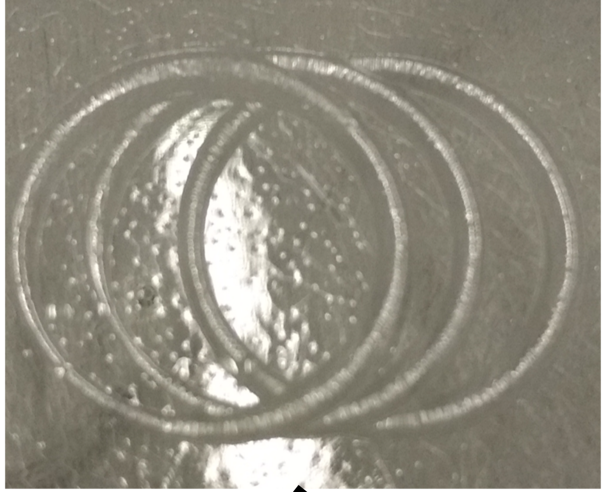






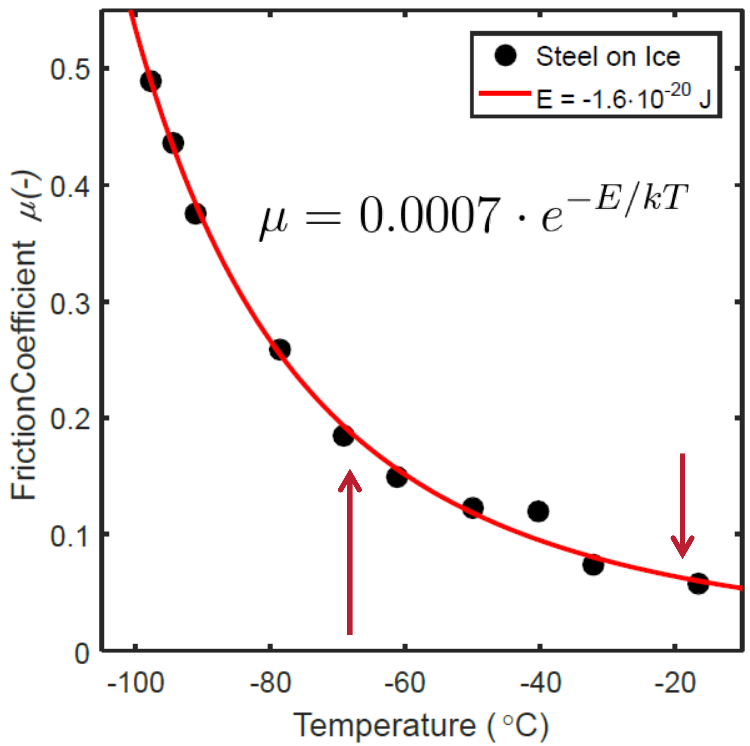
Ploughing friction





$$F_p = \frac{2}{3\pi^{\frac{3}{2}} R \sqrt{p_h}} F_n^{\frac{3}{2}}$$

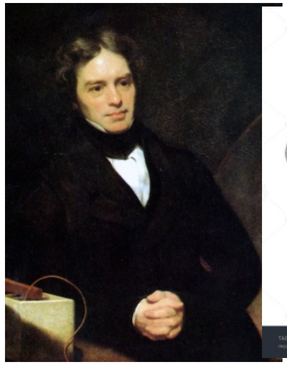
WHAT HAPPENS AT LOW T? NO EFFECT OF 'SURFACE MELTING'!



But an Arrhenius behavior of the friction coefficient, suggesting an activated process is involved…

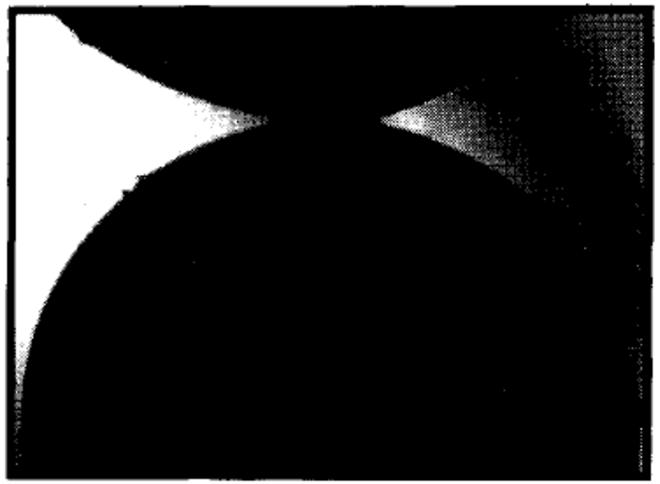
..the first bilayer melts at temperatures as low as -70 ^{o}C, and at -20 ^{o}C a single additional bilayer melts Sanchez (+ M. Bonn) et al, PNAS 2017

Ice sintering: an activated process



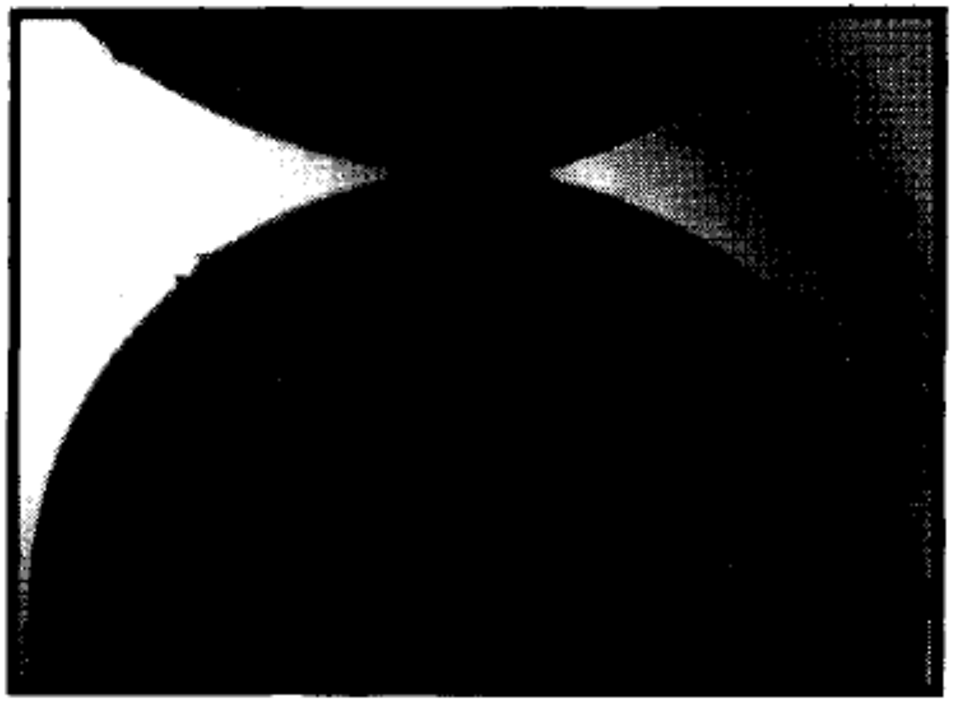
Regelation, Surface Diffusion, and Ice Sintering

W. D. KINGERY
Ice Research Laboratory, Department of Metallurgy, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received October 30, 1959)



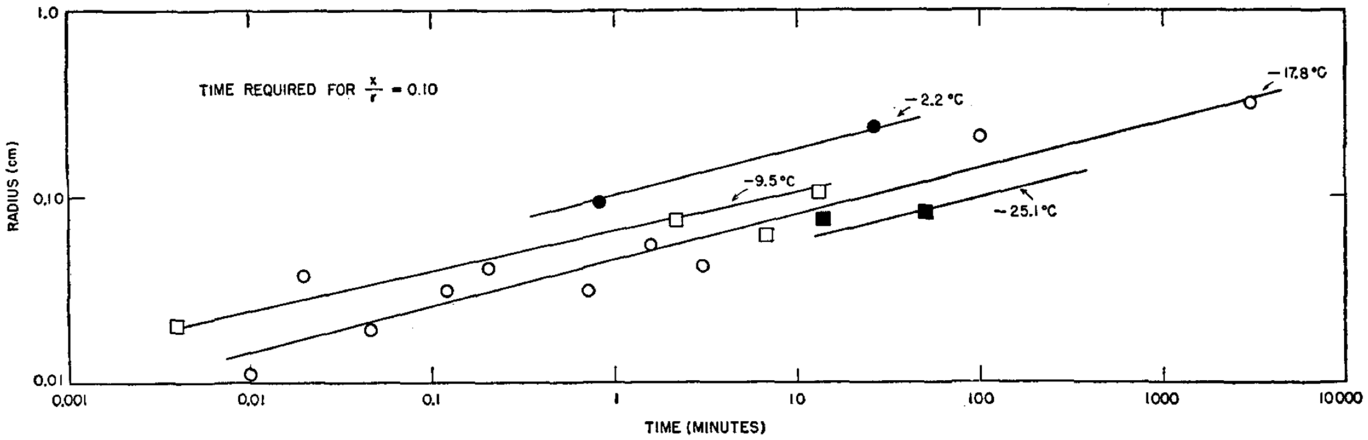
UNIVERSITY OF AMSTERDAM

Faraday experiment revisited: growth of ice bridge between two spheres….



« The welding together of ice particles occurs as a result of surface diffusion, as indicated by the time dependence and particle size dependence for the process. Surface diffusion of H_2O molecules over an ice surface is found to be rapid. »

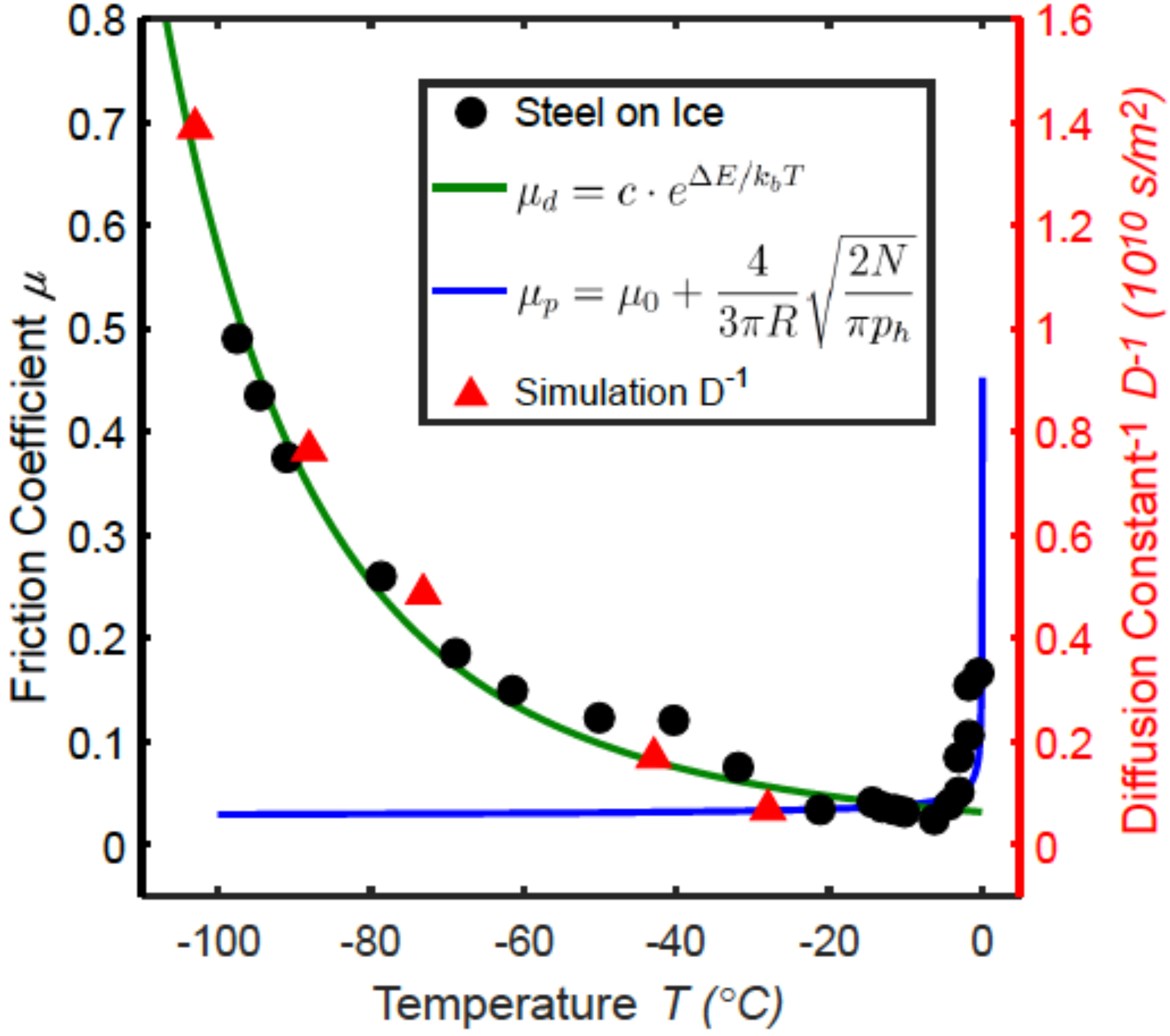
« Since the vapor pressure of ice is quite high the evaporation-condensation process is relatively rapid »



Fast and thermally activated, activation energy a few kT

Just like the friction coefficient! (But not with the correct activation energy for surface diffusion)

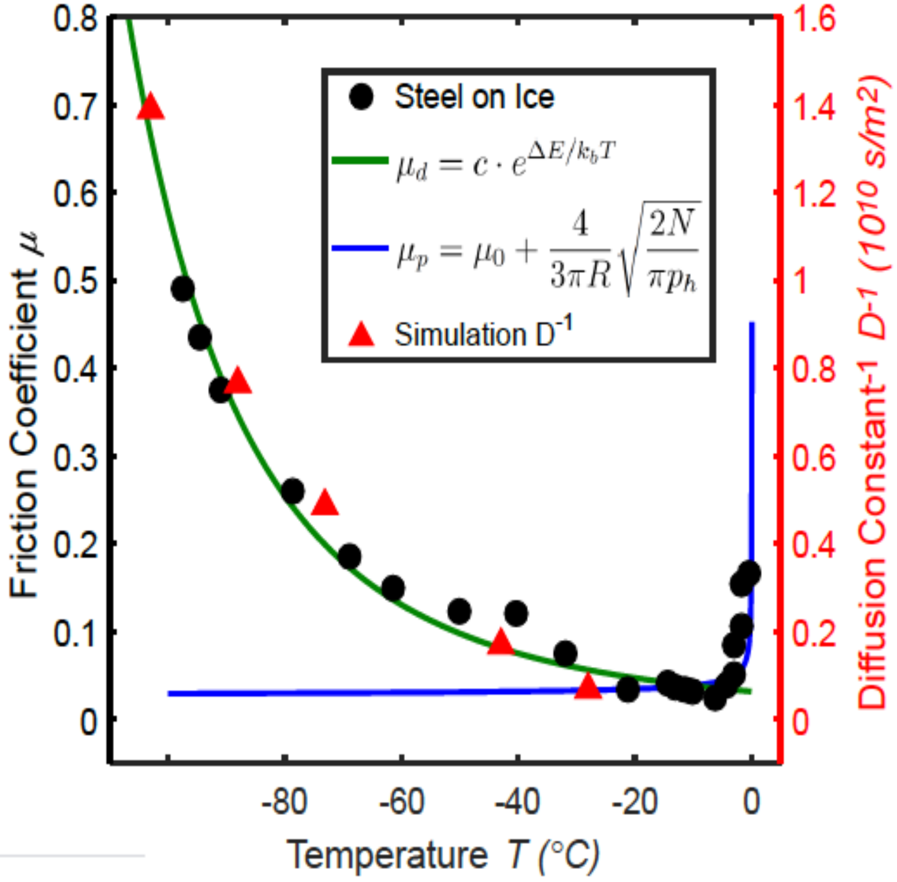
Surface mobility and friction have identical T-dependence



(a)

Intermediate conclusions

- Ice is not slippery because of a water layer, but rather due to a mobile surface layer of ice molecules
- Two regimes, depending on the contact mechanics: there is an optimum skating T of -7 ^{o}C



People also ask

What is the ice temperature in Olympic speed skating?

The ideal temperature for speed skating ice is –5° C to –9° C. During maintenance, the ice

April 26, 1860.

Sir BENJAMIN C. BRODIE, Bart., President, in the Chair.

The following communications were read :—

I. " Note on Regelation." By MICHAEL FARADAY, D.C.L., F.R.S. &c. Received March 13, 1860.

Two pieces of thawing ice, if put together, adhere and become one ; at a place where liquefaction was proceeding, congelation suddenly occurs. The effect will take place in air, or in water, or in vacuo. It will occur at every point where the two pieces of ice touch; but not with ice below the freezing-point, i.e. with dry ice, or ice so cold as to be everywhere in the solid state.

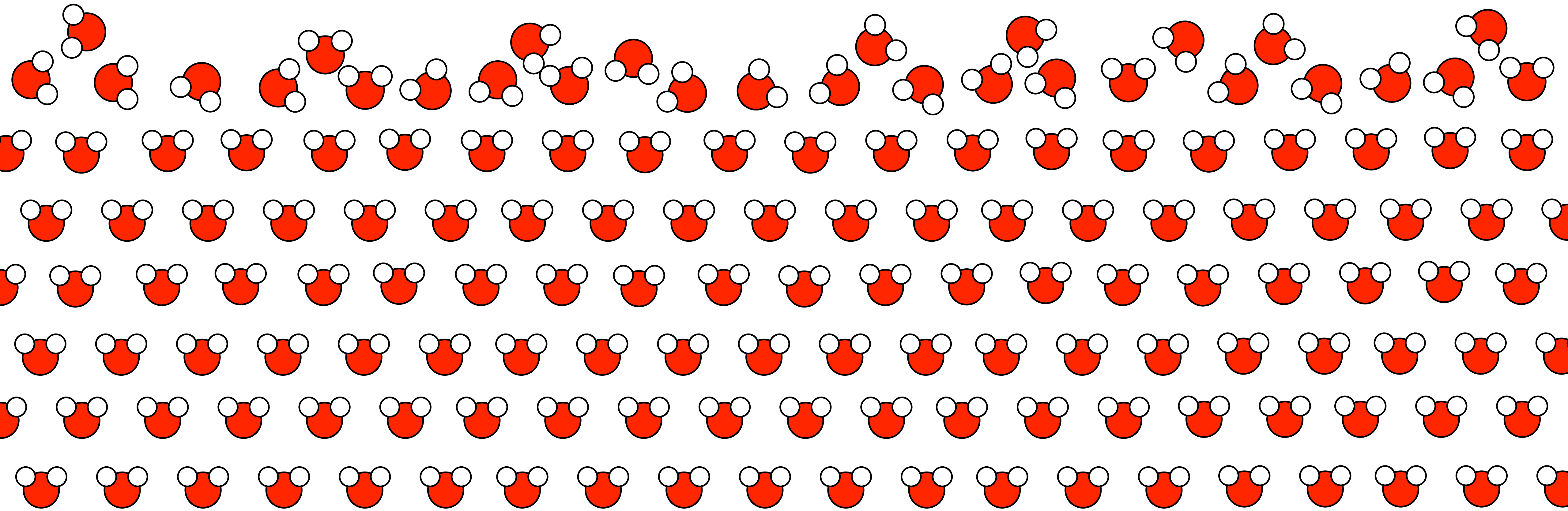
Conclusion: Faraday's observations agree with an Arrhenius behavior, and regelation may be due to the large mobility of molecules at the surface of ice. But what gives this large mobility?

University of Amsterdam

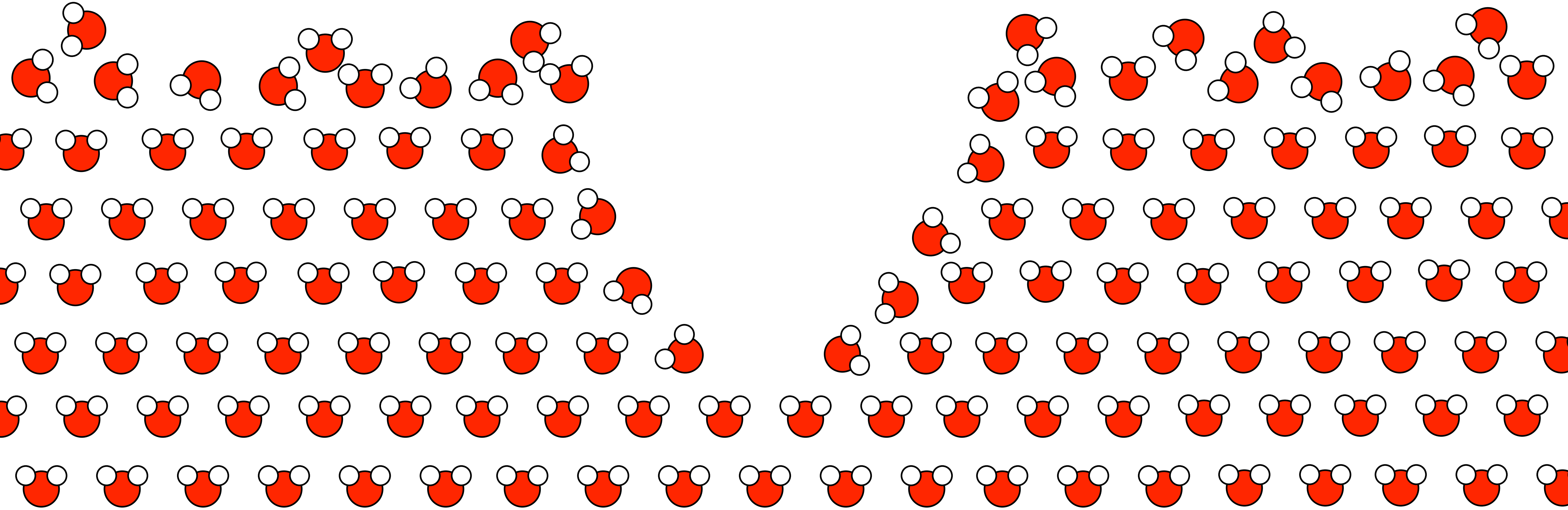
Dynamics of molecules at the surface of ice

Menno Demmenie, Paul Kolpakov,
Yuki Nagata, Sander Woutersen

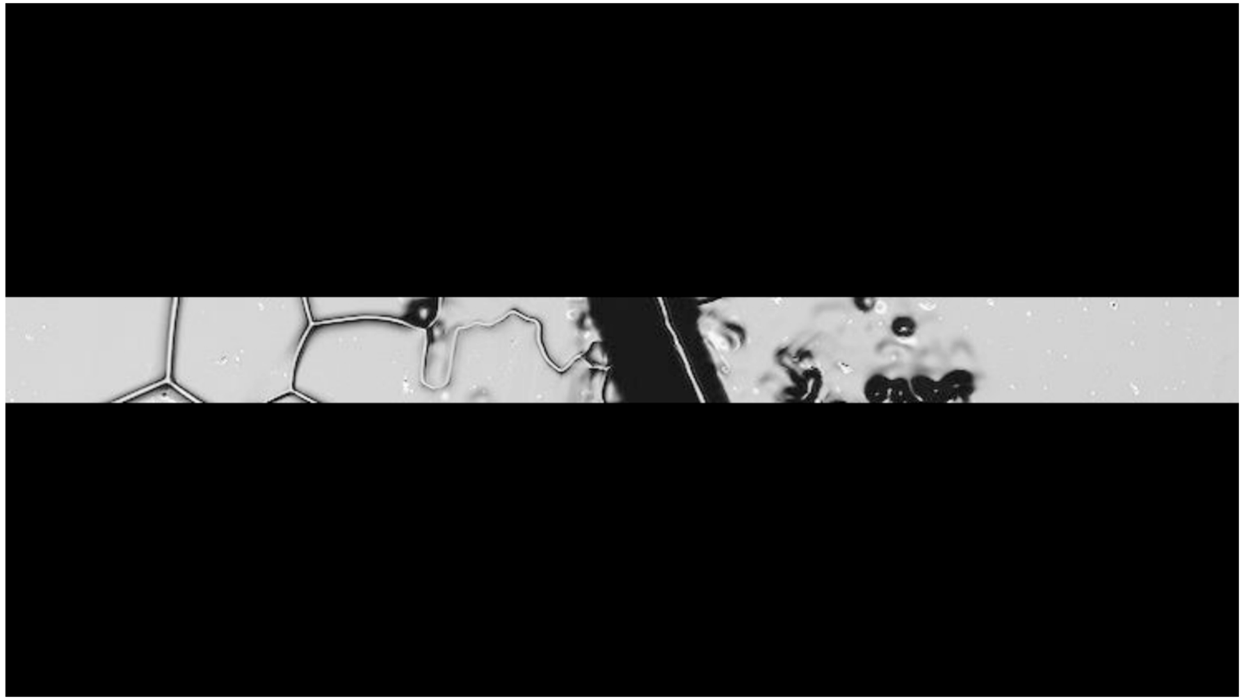
How to investigate the dynamics?

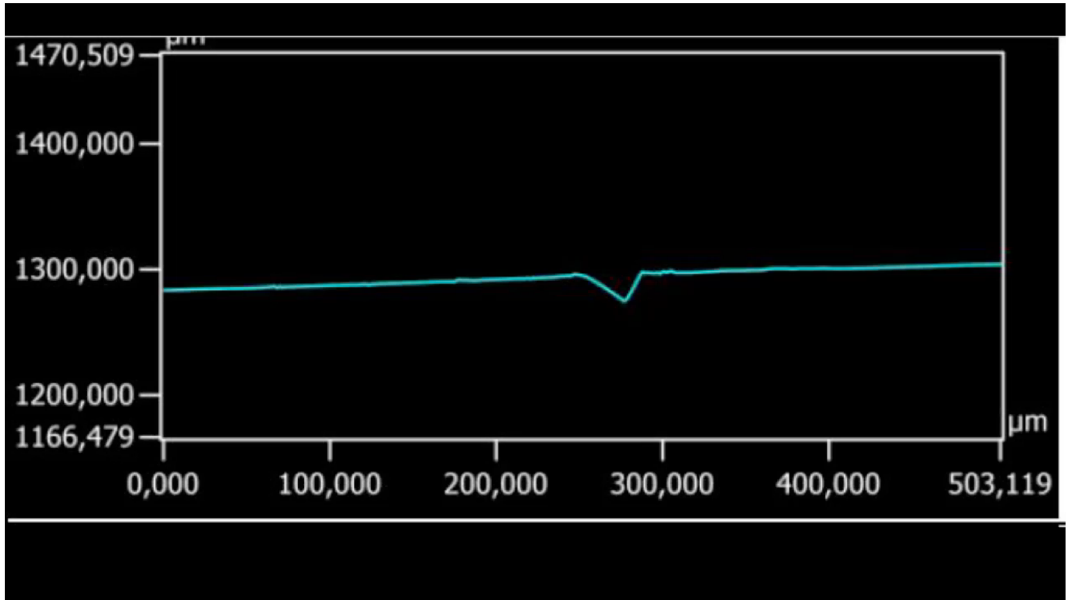


What happens when we cut it?

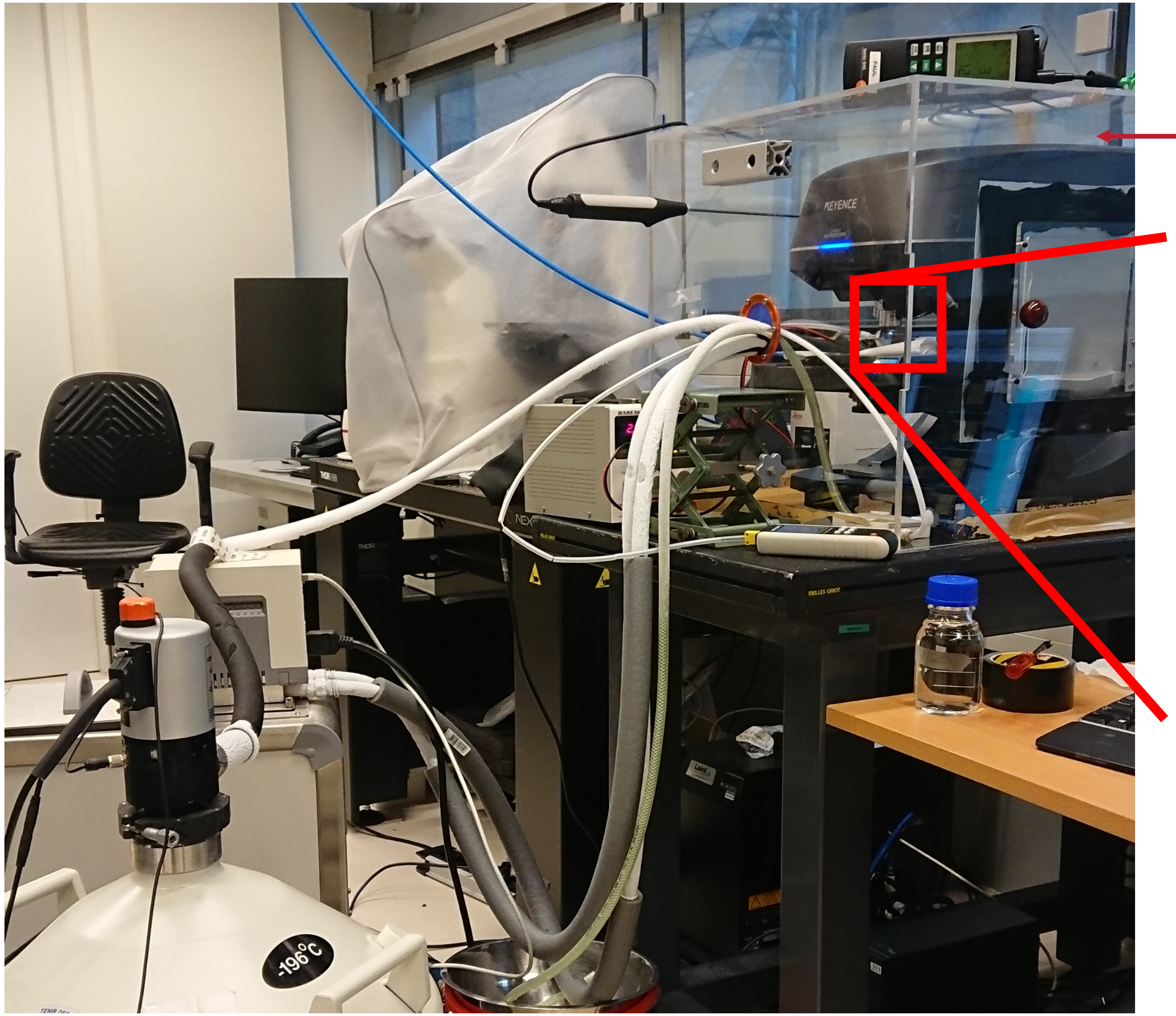


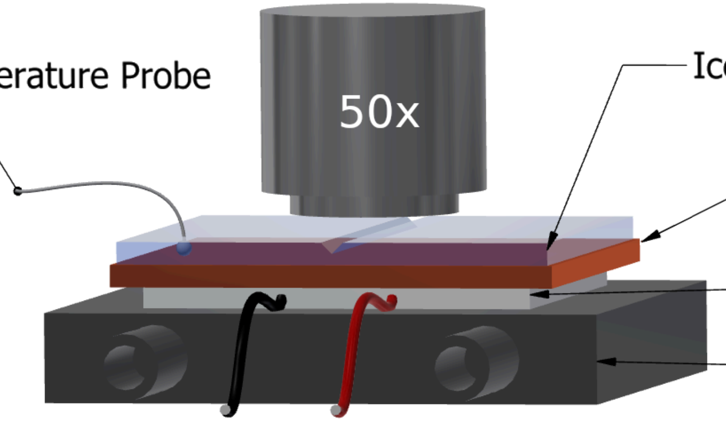
Ice is a self-healing material!





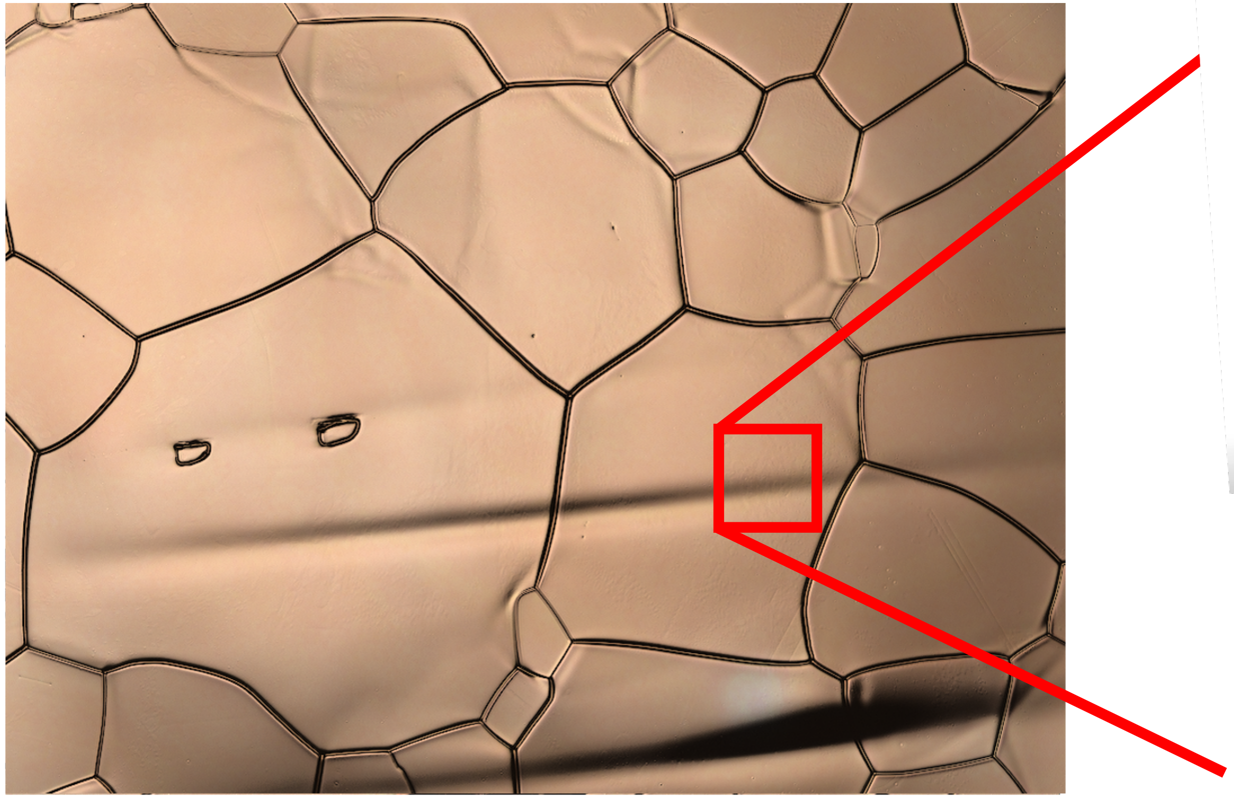
Set up

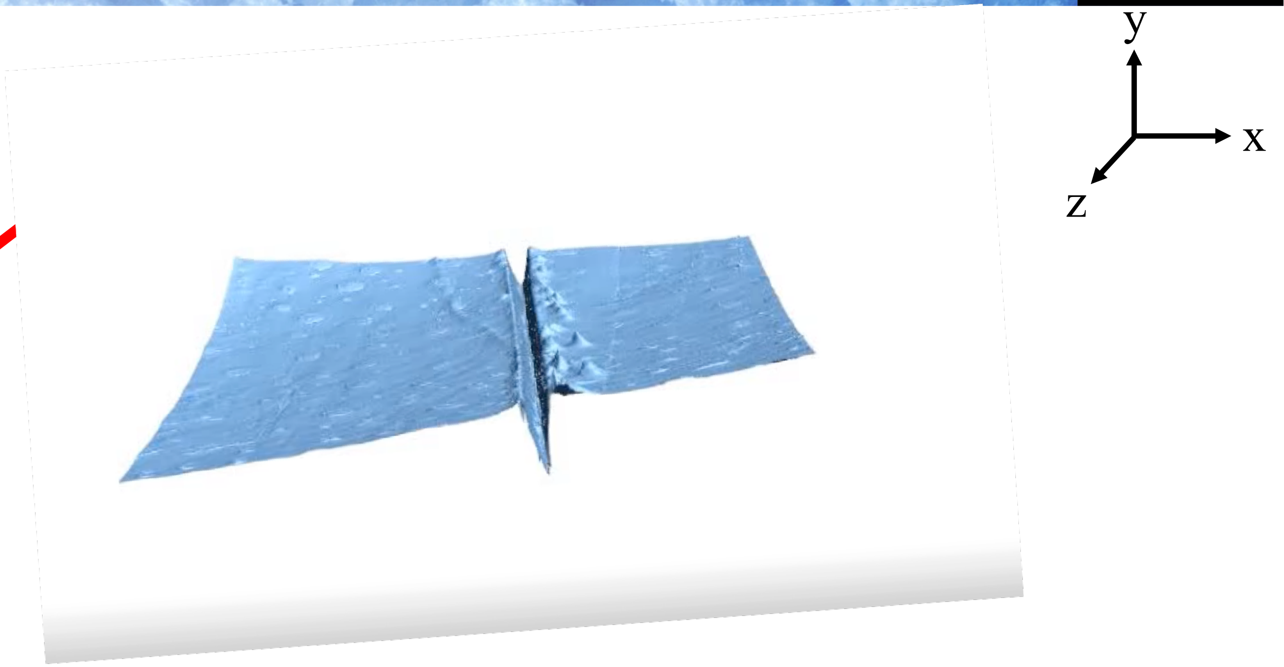

Humidity control

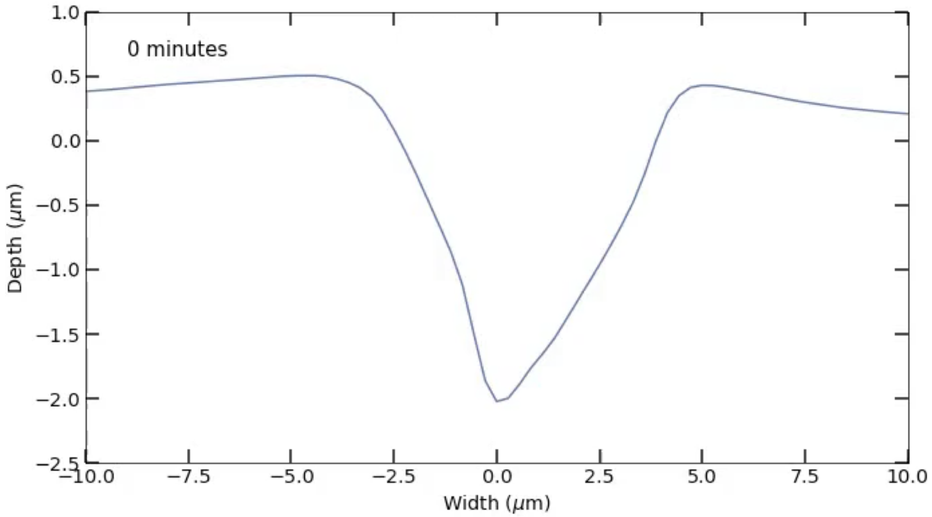

Temperature Probe
50x
Ice
Copper plate
Peltier
Cooling Plate

Scratch disappears

T = 247 K

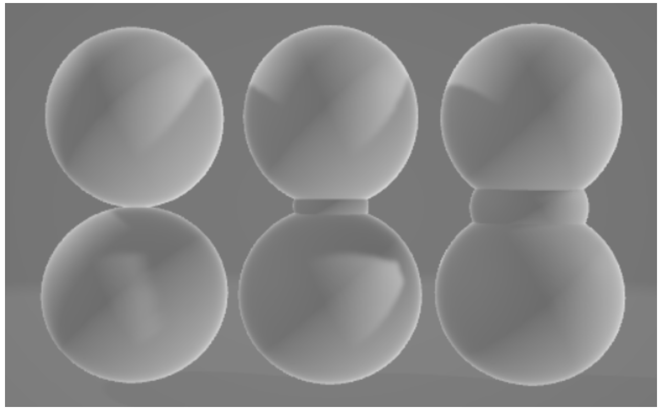


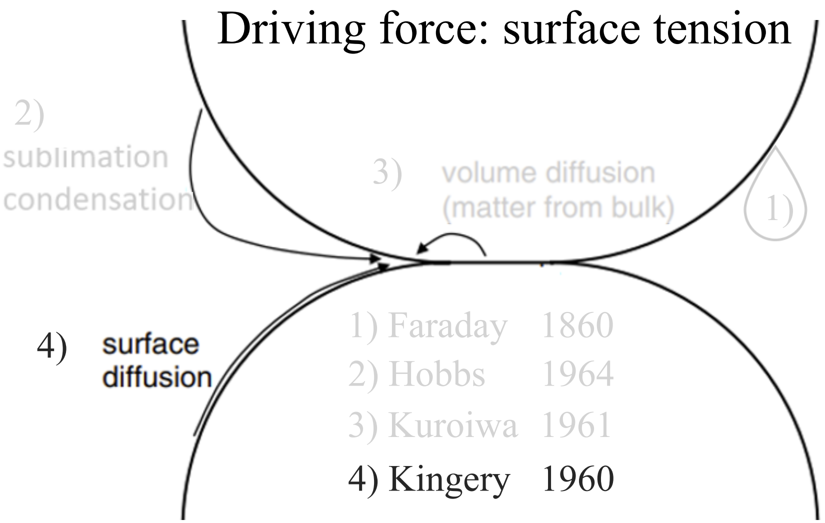




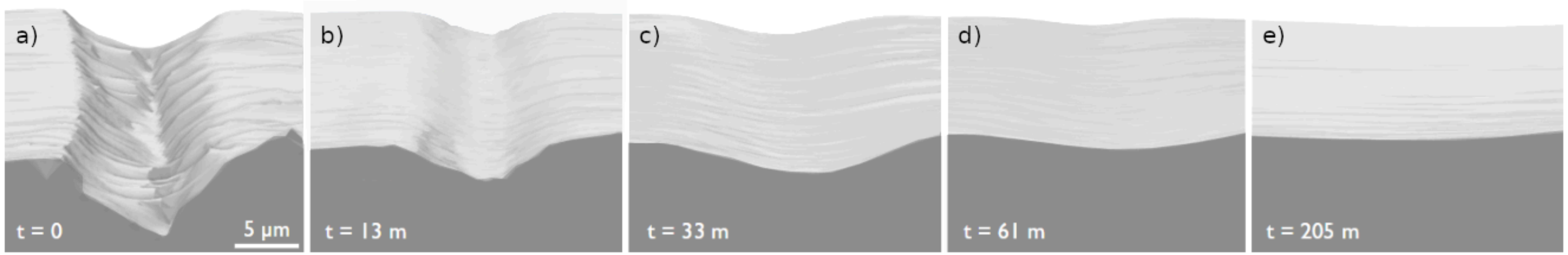
Sintering mechanisms

Sintering mechanisms:

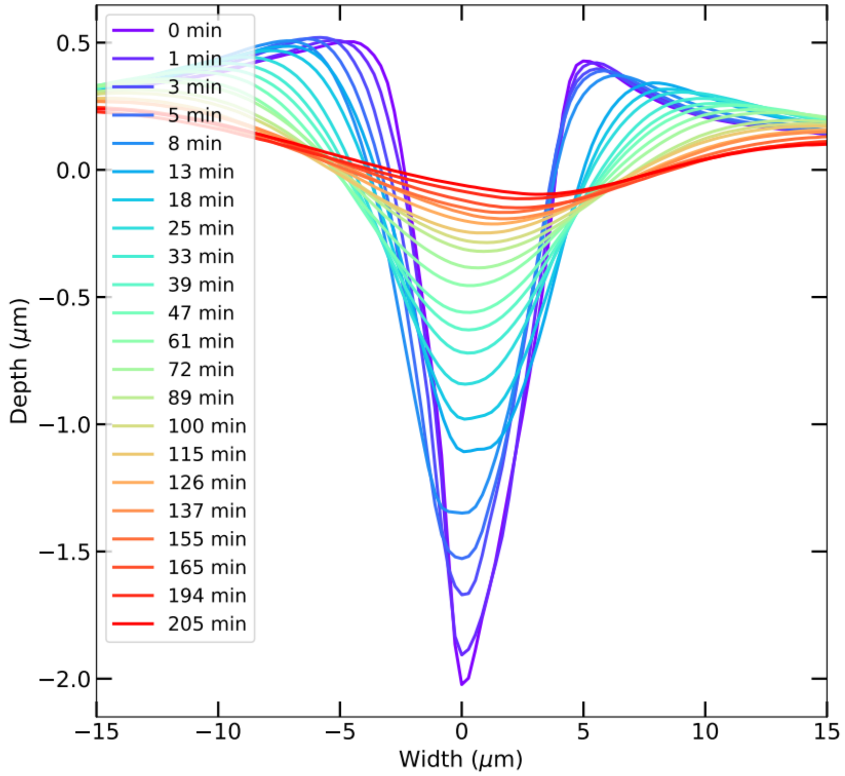


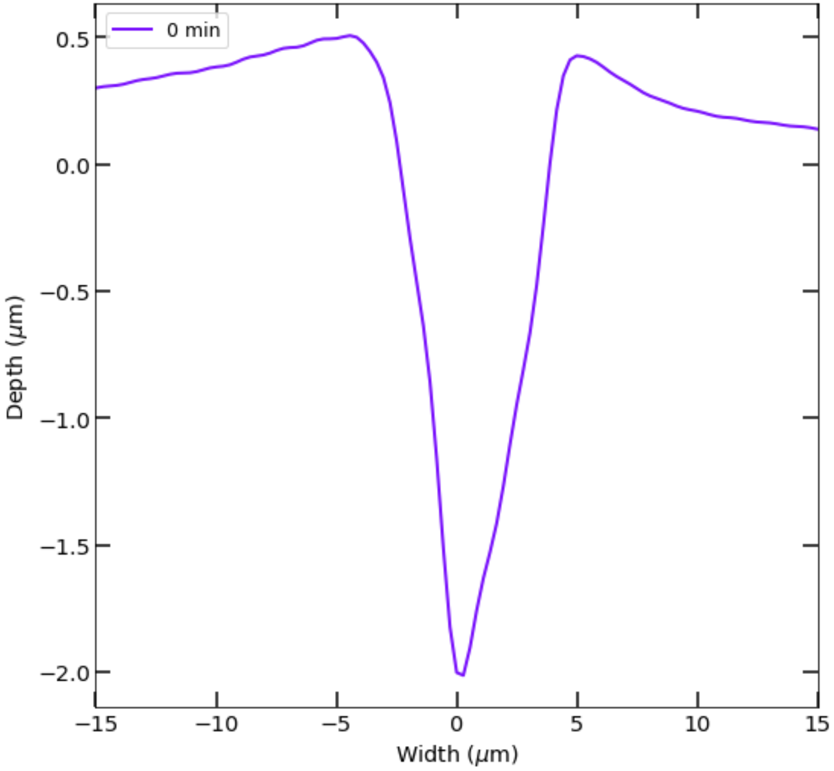


Measurement --> mechanism test



$$s(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[a_n \cos(nx) + b_n \sin(nx)\right]$$





$$\frac{\partial u}{\partial t} = -C_n(T)\left(\frac{2\pi}{\lambda}\right)^n u.$$

n	mechanism
1	Fluid flow
2	Sublimation/condensation
3	Volume diffusion
4	Surface diffusion

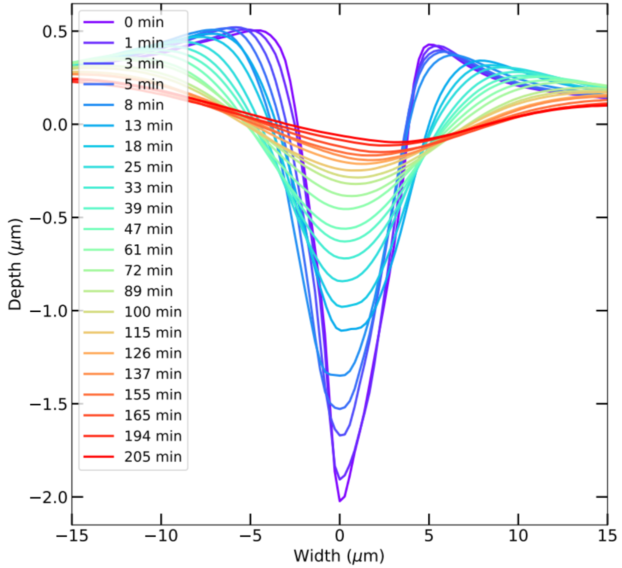
Mullins and co. ~1960's

What mechanism?

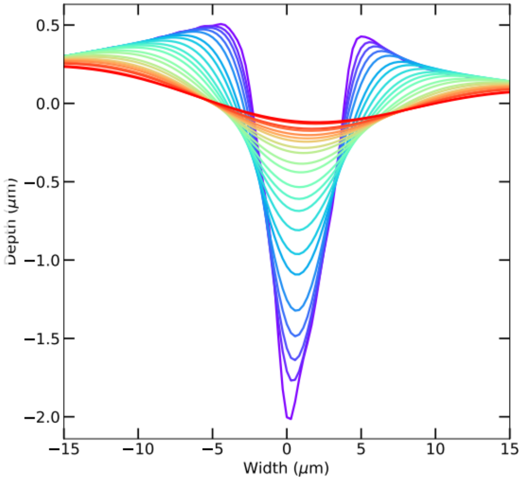
$$\frac{\partial u}{\partial t} = -C_n(T)\left(\frac{2\pi}{\lambda}\right)^n u.$$

$$U(x,t) = u(t)\sin(2\pi x/\lambda),$$

$$s(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left[a_n\cos(nx) + b_n\sin(nx)\right]$$



n = 1 liquid layer

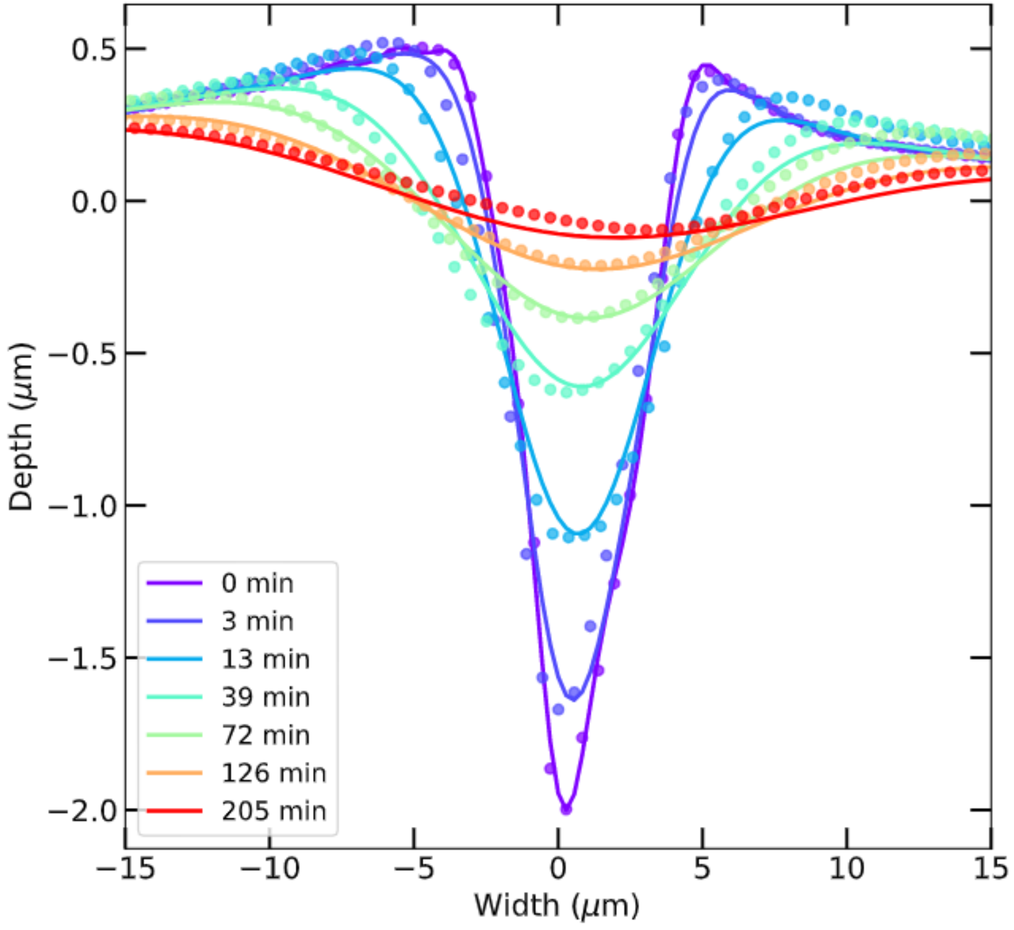


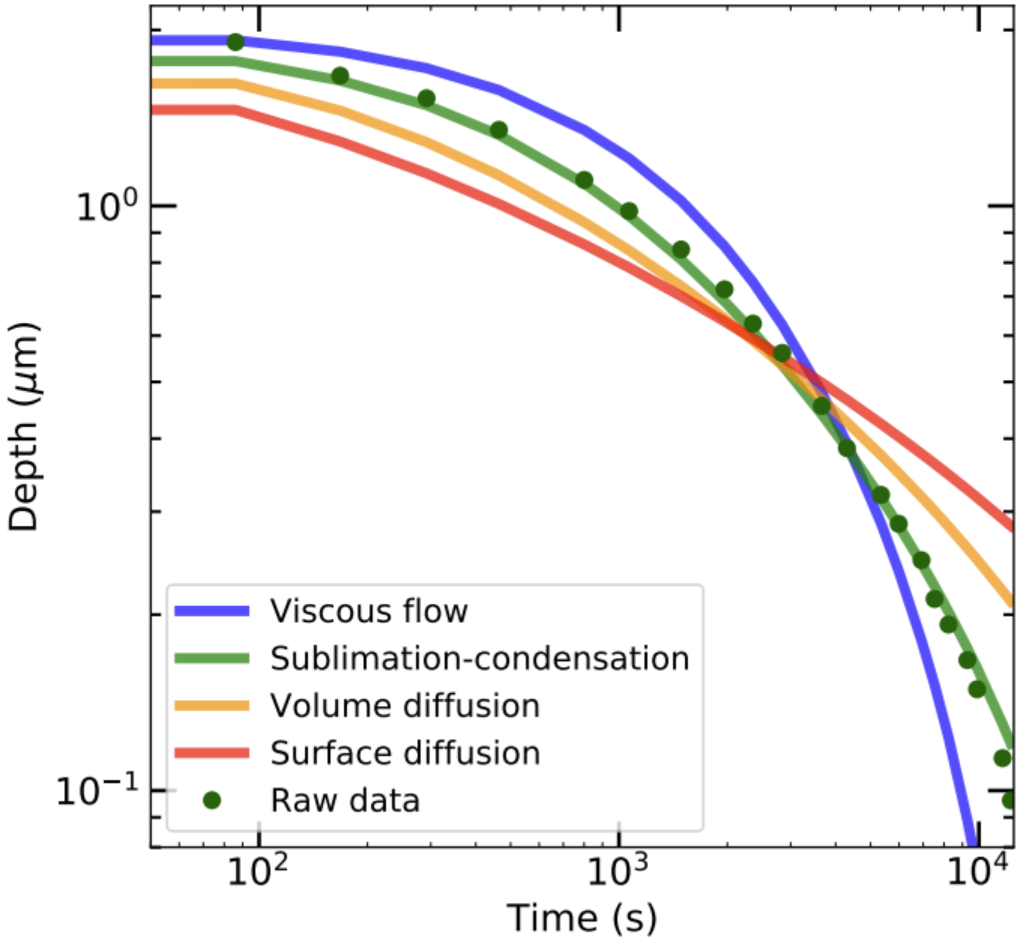
n = 2 sublimation/condensation

n = 3 volume diffusion

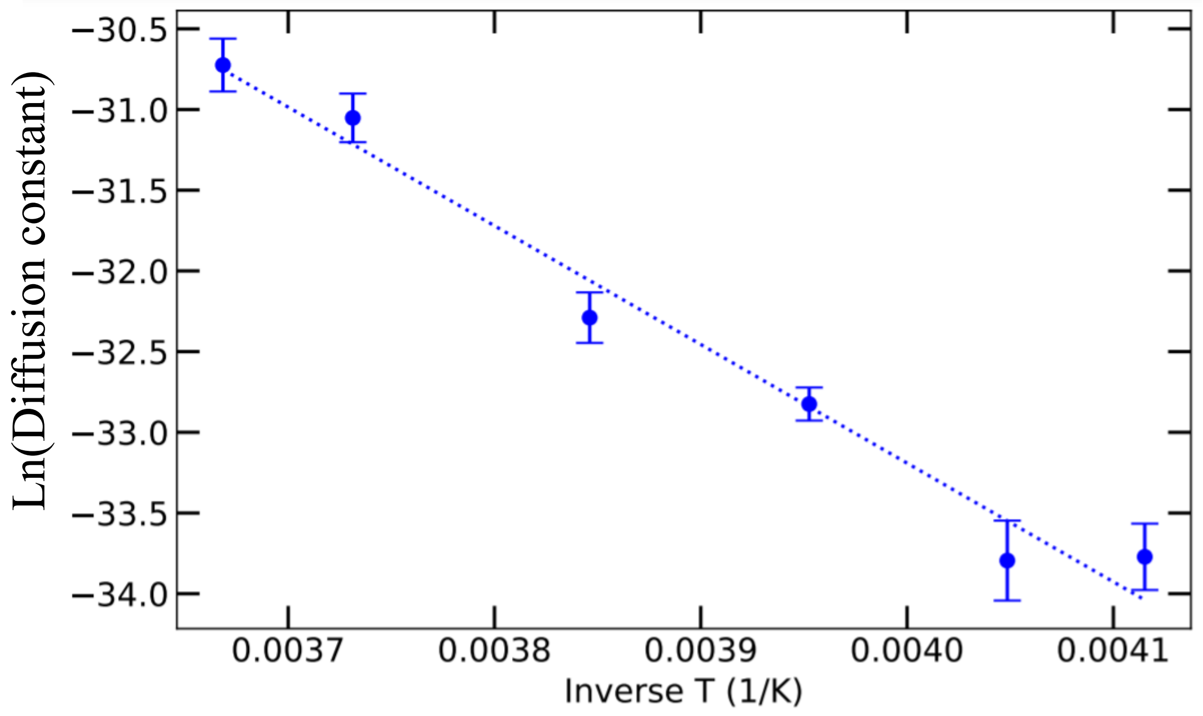
n = 4 surface diffusion

Winner: sublimation-condensation





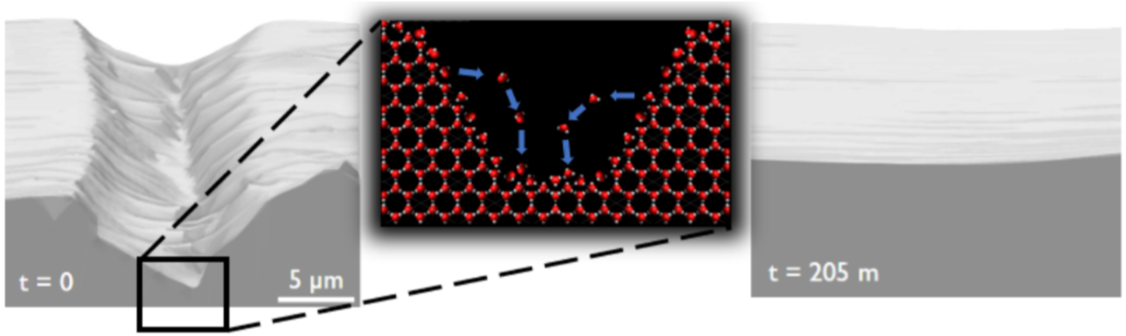
Arrhenius behavior of vapor diffusion constant



$$E_{act} = 58.6 \pm 4.6\ kJ/mole$$

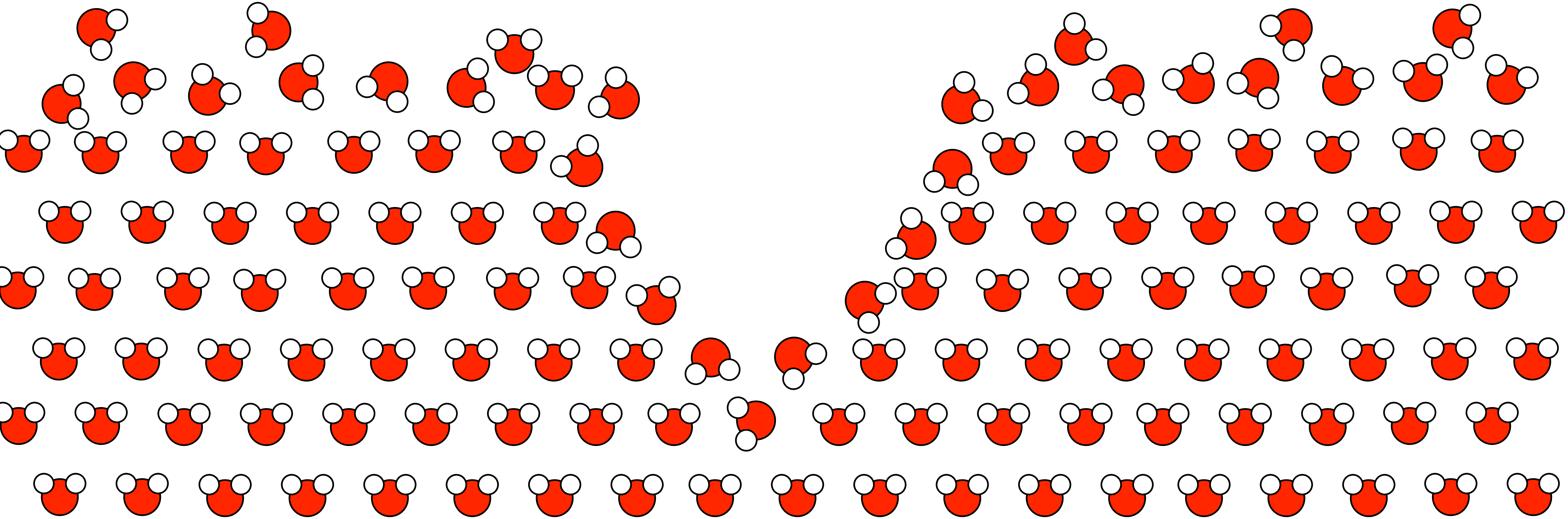
The sublimation activation energy of water was
In the literature: 55 $\pm$ 3 *kJ/mole*

In conclusion:
Local sublimation and condensation is responsible for the self-healing of ice



Incidentally, force-fitting surface diffusion to our data, we get $E_{act}\sim 100\ kJ/mole$, very similar to what Kingery found……

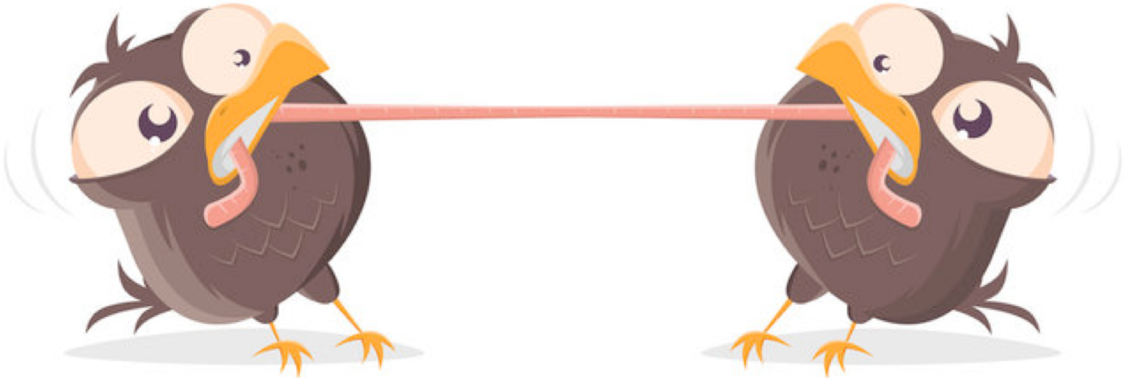
Self-healing by local sublimation and condensation



https://doi.org/10.1021/acs.jpcc.1c09590

J. Phys. Chem. C 2022 – Scratch-Healing Behavior of Ice by Local Sublimation and Condensation

So, can I be reconciled with my brother?



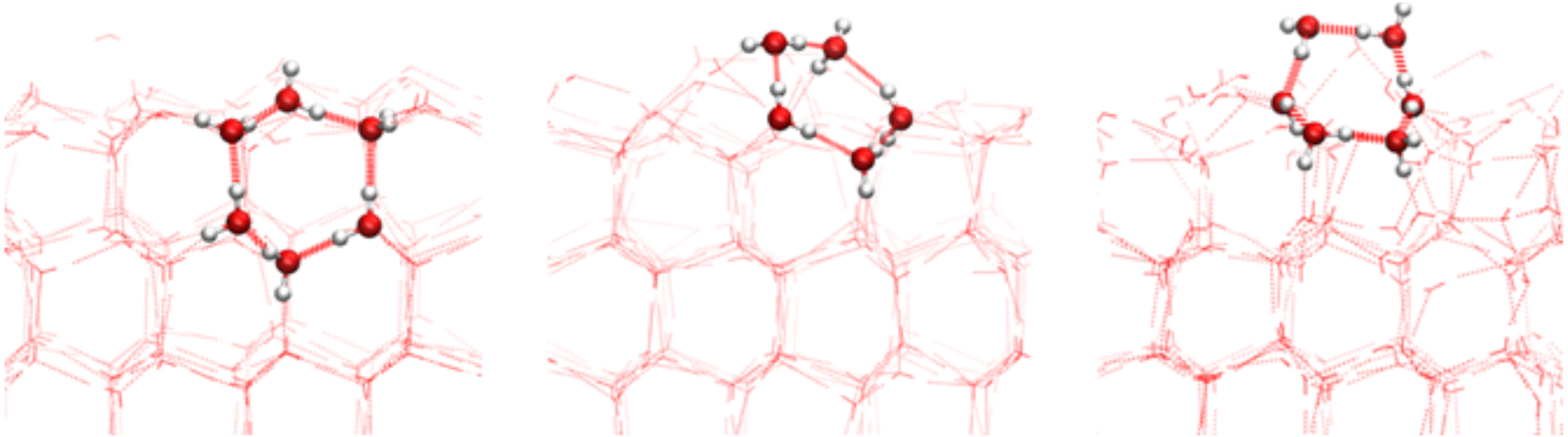
PNAS

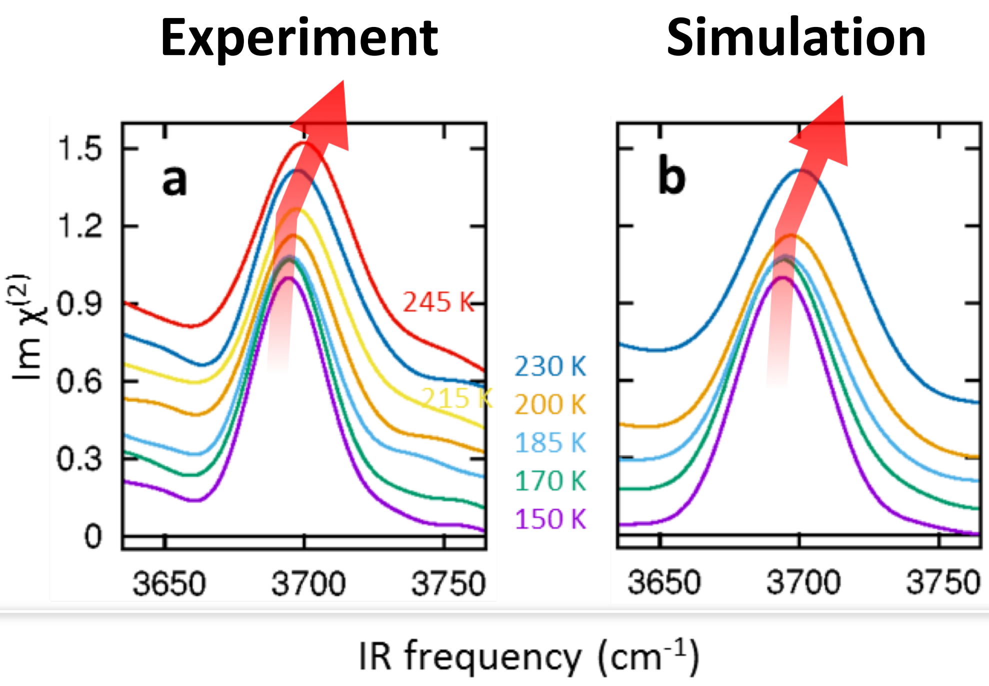
Experimental and theoretical evidence for bilayer-by-bilayer surface melting of crystalline ice

M. Alejandra Sánchez[a], Tanja Kling[a], Tatsuya Ishiyama[b], Marc-Jan van Zadel[a], Patrick J. Bisson[c], Markus Mezger[a,d], Mara N. Jochum[a,e], Jenée D. Cyran[a], Wilbert J. Smit[f], Huib J. Bakker[f], Mary Jane Shultz[c], Akihiro Morita[g,h], Davide Donadio[a,i], Yuki Nagata[a], Mischa Bonn[a,1], and Ellen H. G. Backus[a,1]

[a]Max Planck Institute for Polymer Research, 55128 Mainz, Germany; [b]Graduate School of Science and Engineering, University of Toyama, Toyama 930-8555, Japan; [c]Laboratory for Water and Surface Studies, Department of Chemistry, Pearson Laboratory, Tufts University, Medford, MA 02155; [d]Institute of Physics, Johannes Gutenberg University Mainz, 55128 Mainz, Germany; [e]BASF SE, 67117 Limburgerhof, Germany; [f]FOM Institute AMOLF, 1098 XG Amsterdam, The Netherlands; [g]Department of Chemistry, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan; [h]Elements Strategy Initiative for Catalysts and Batteries, Kyoto University, Kyoto 615-8520, Japan; and [i]Department of Chemistry, University of California, Davis, CA 95616

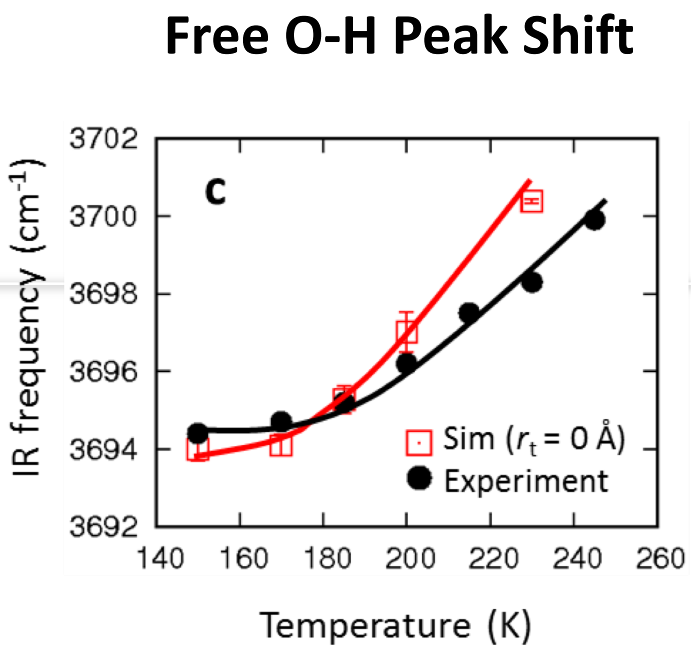
T < -70 ^{o}C | -70 ^{o}C | -20 ^{o}C

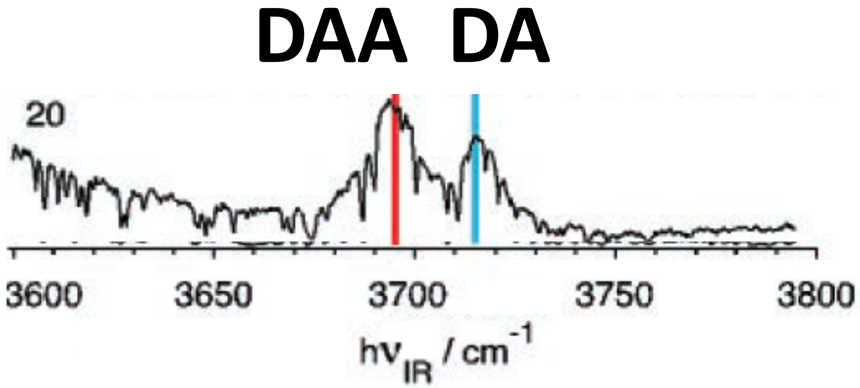




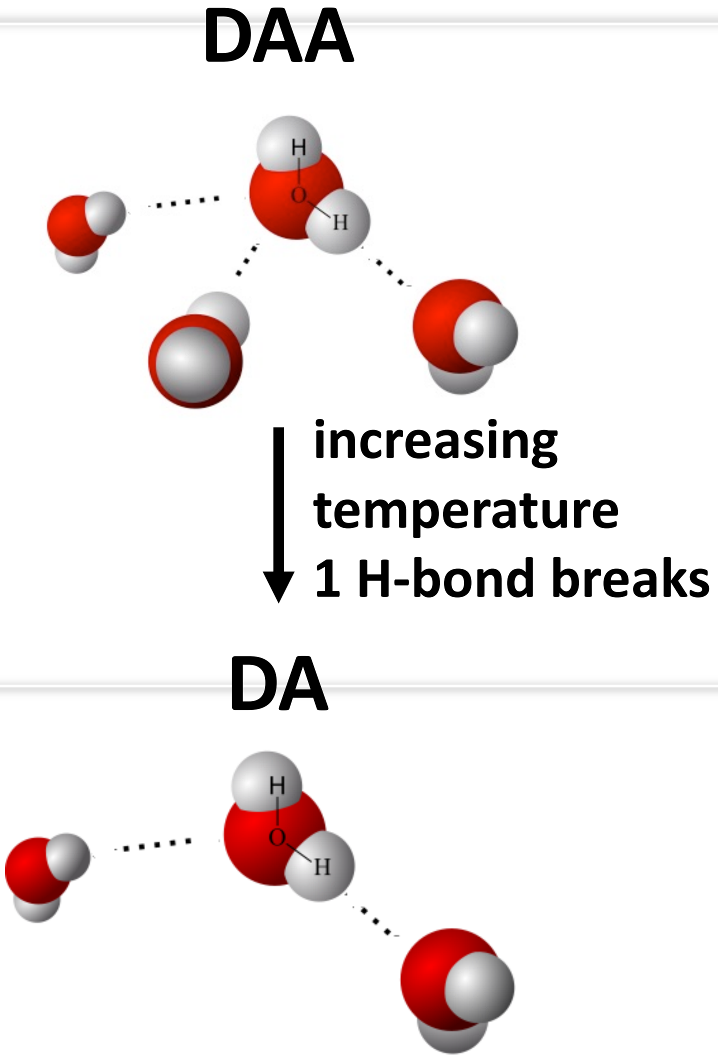
Not changed below 185 K

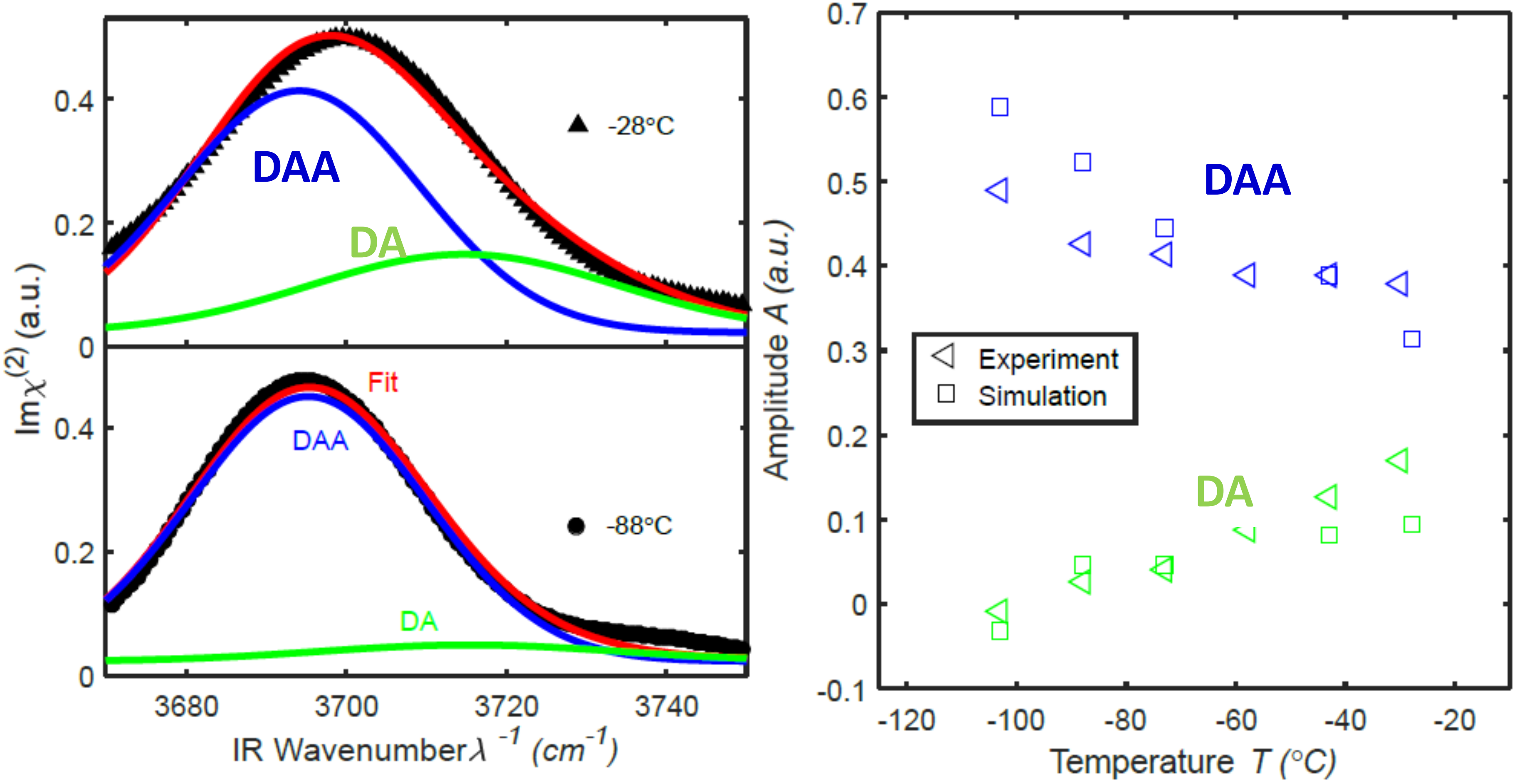
Blue shift above 185 K (with increasing T)





Miyazaki, *et al.*, *Science* **304**, 1135 (2004)



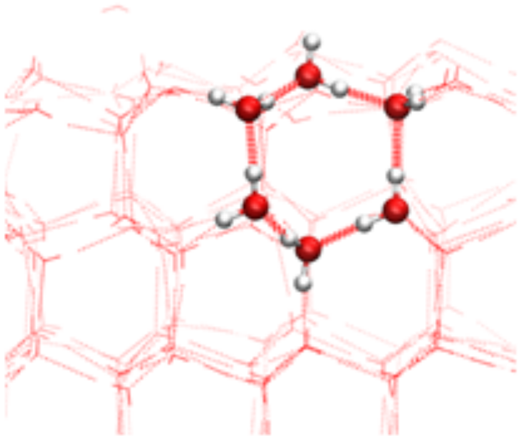


Imχ(2) (a.u.)
0.4
0.2
0
DAA
DA
-28°C
Fit
DAA
-88°C
DA
3680
3700
3720
3740
IR Wavenumber λ -1 (cm-1)
Amplitude A (a.u.)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
DAA
Experiment
Simulation
DA
-120
-100
-80
-60
-40
-20
Temperature T (°C)

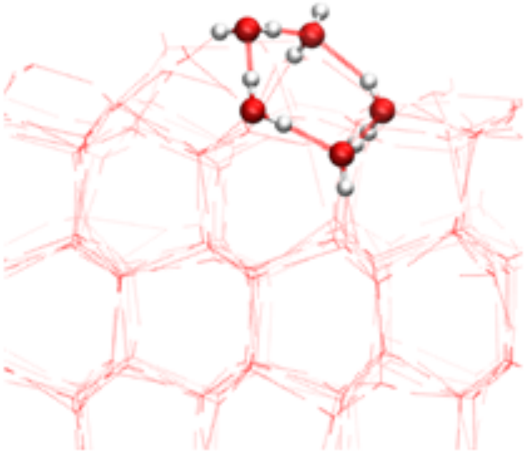
Variation of Ice Structure

More DA water
By breaking H-bonds

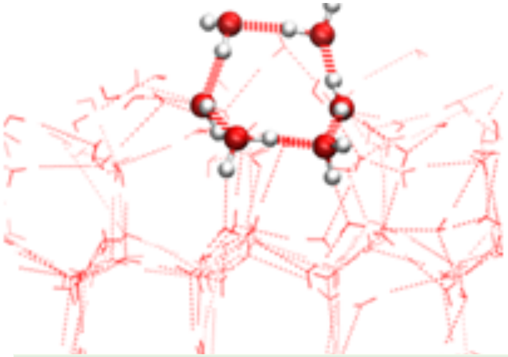
T < -70 ^{o}C



-70 ^{o}C



-20 ^{o}C

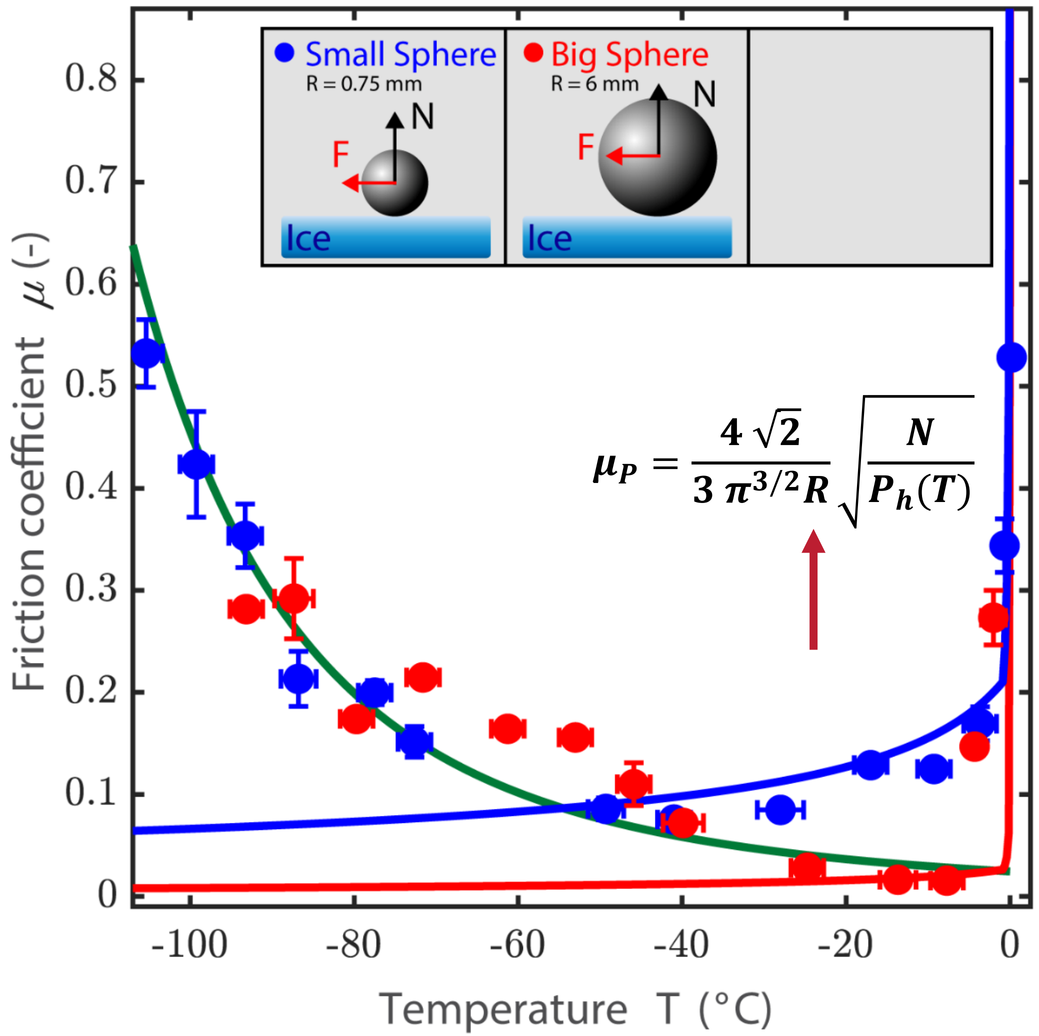


=higher mobility!

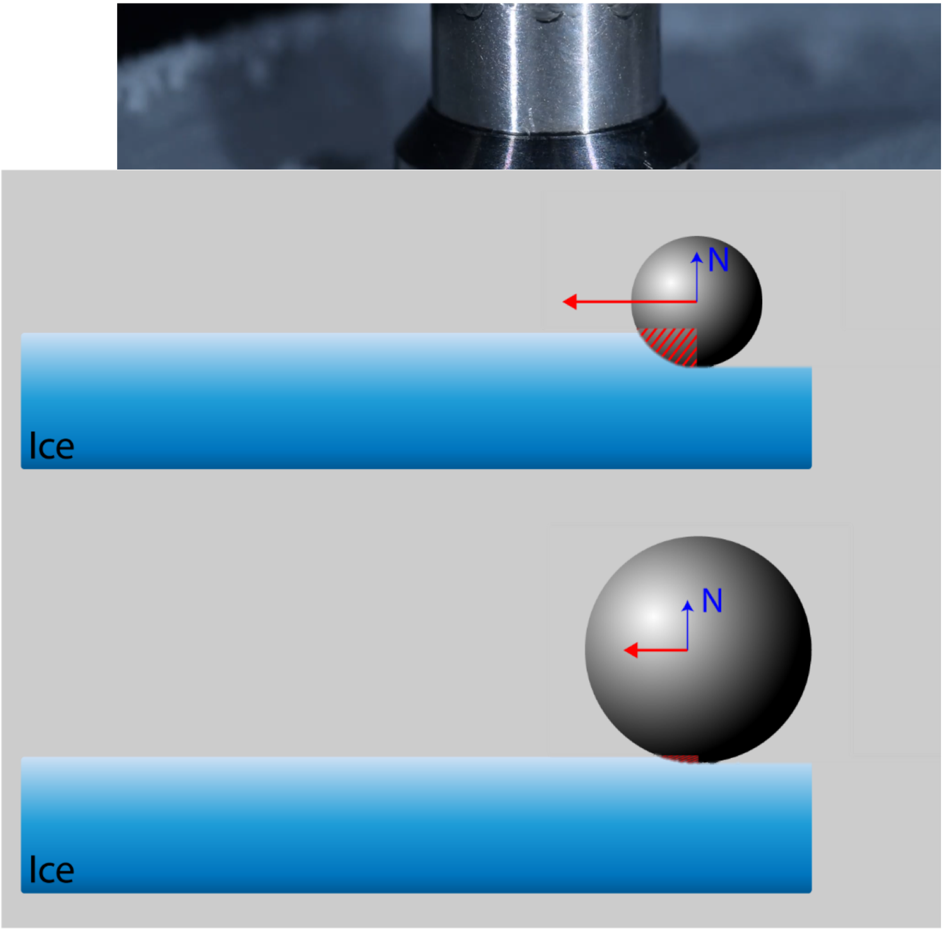
Back to skating: what about the countersurface?

Rinse Liefferink, Bart Weber

What is the best ice skate? Geometry

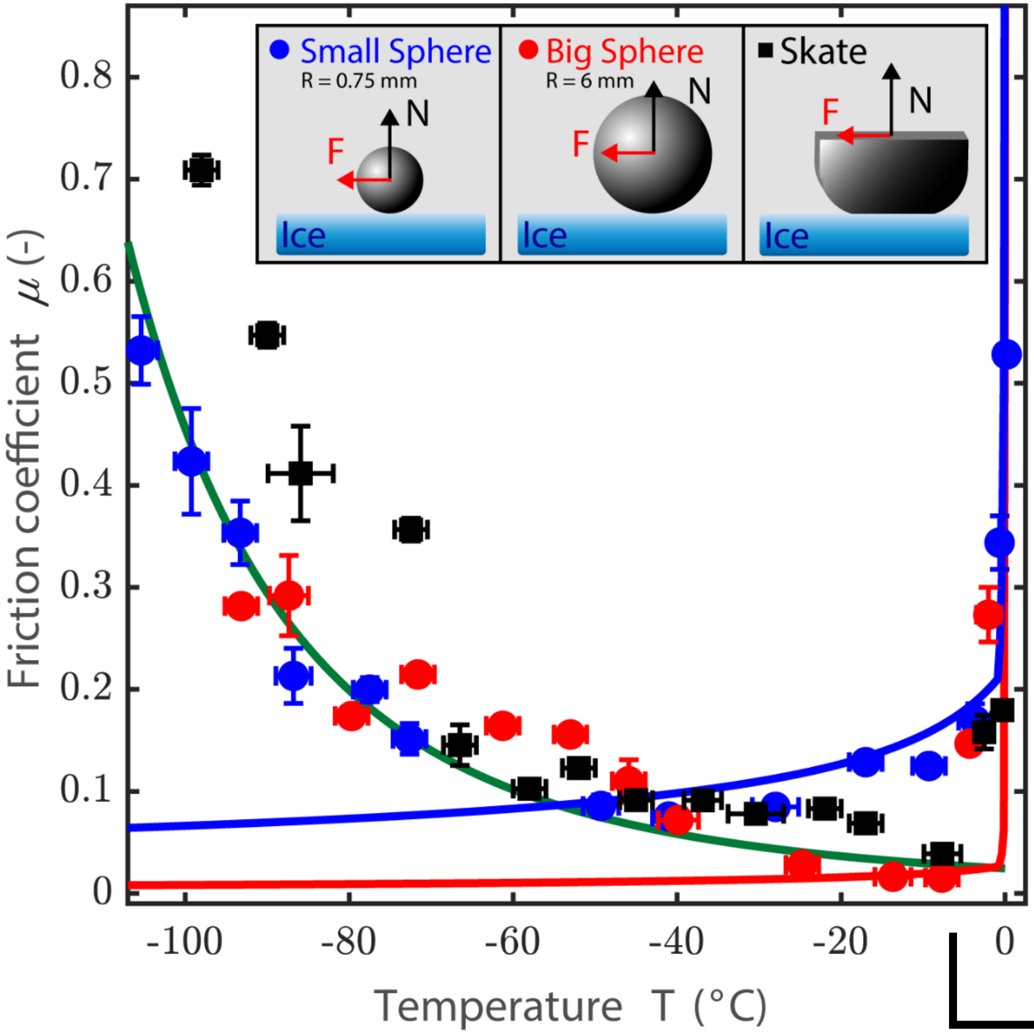


$$\mu_P = \frac{4\sqrt{2}}{3\,\pi^{3/2} R}\sqrt{\frac{N}{P_h(T)}}$$

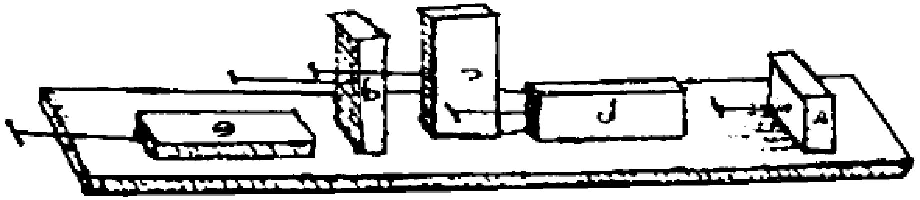


Ploughing force depends on the radius R

What is the best ice skate? **Real skate**



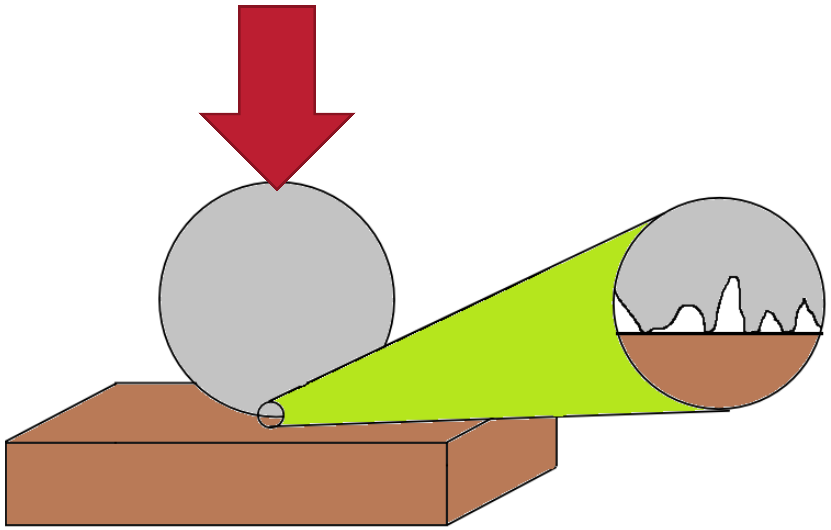
Amontons' first and second Law



In the Codex Atlanticus and the Codex Madrid, Leonardo da Vinci (1452-1519) documented the first systematic experiments on friction

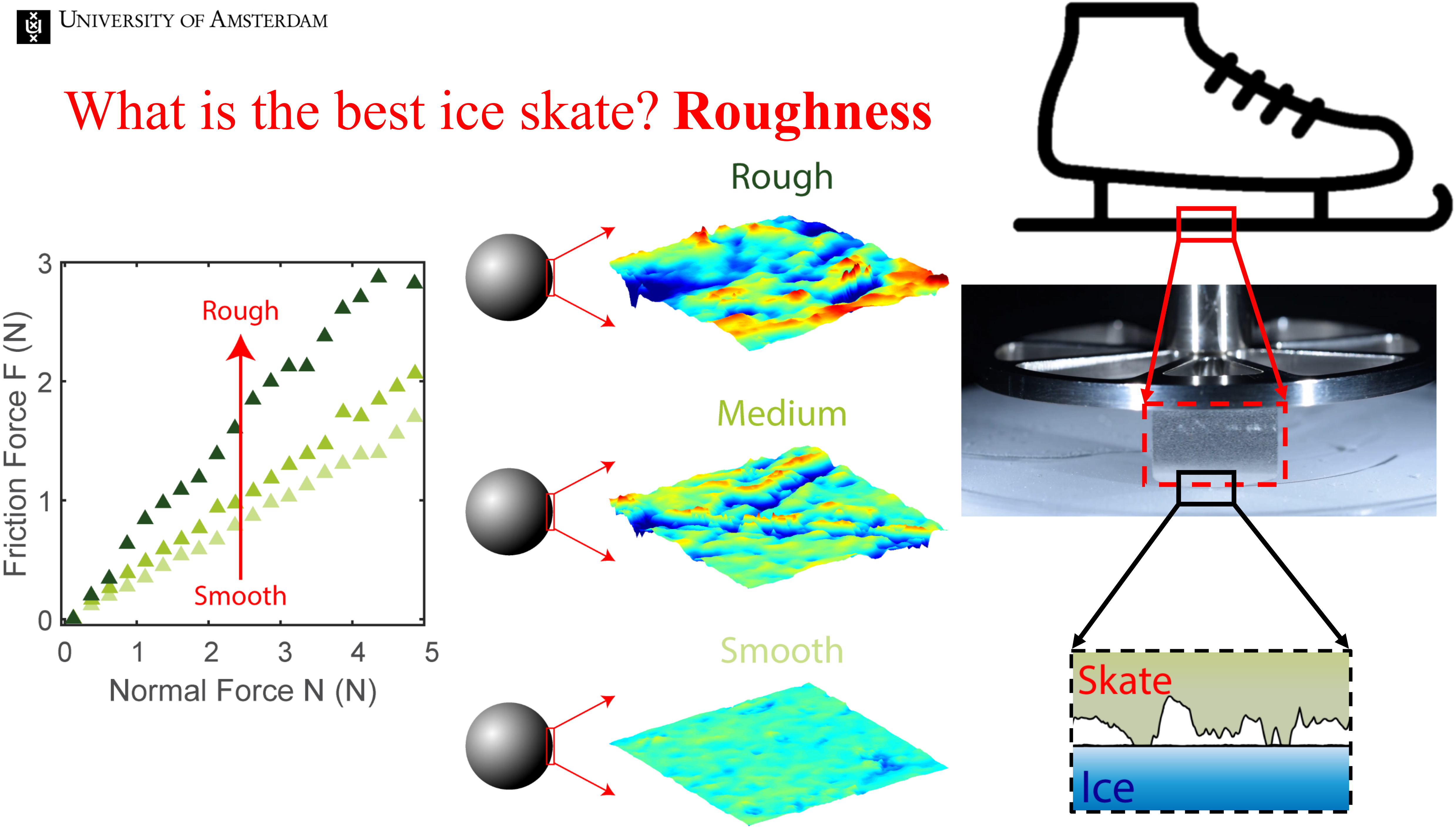
Friction coefficient is independent of the (apparent) contact area

- Real Contact Area ~ Normal Force
- Friction Force~ Real Contact Area

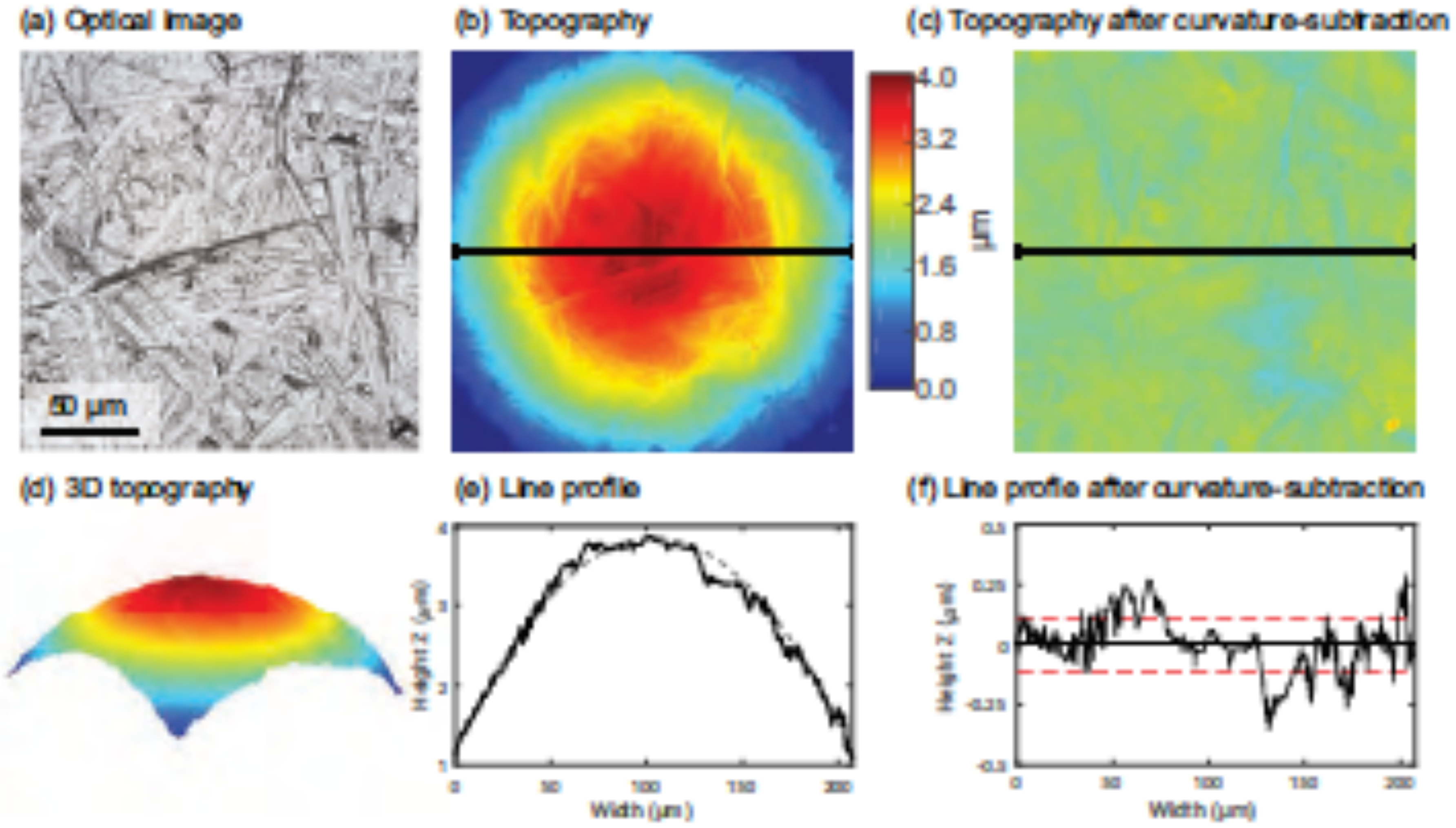


University of Amsterdam

What is the best ice skate? **Roughness**



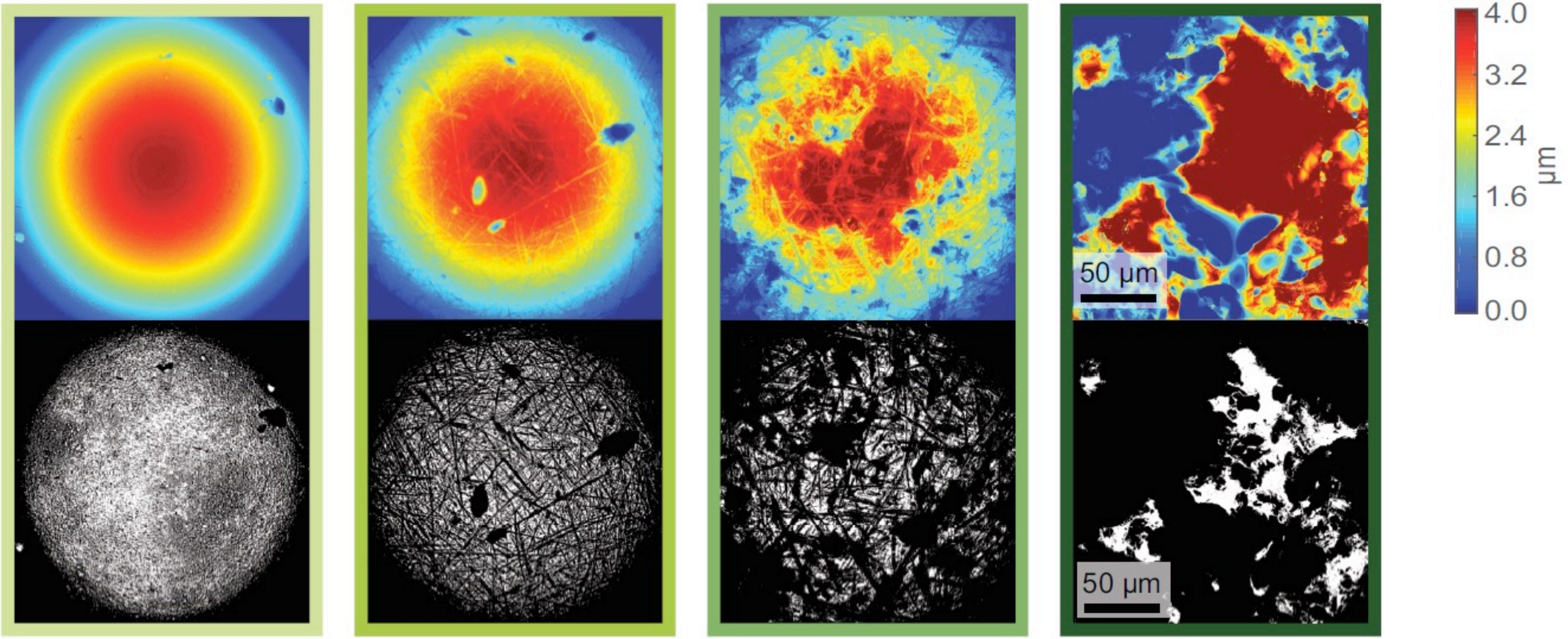
Optical profilometry: measurement of the surface roughness



Ice friction and surface topography: contact calculations

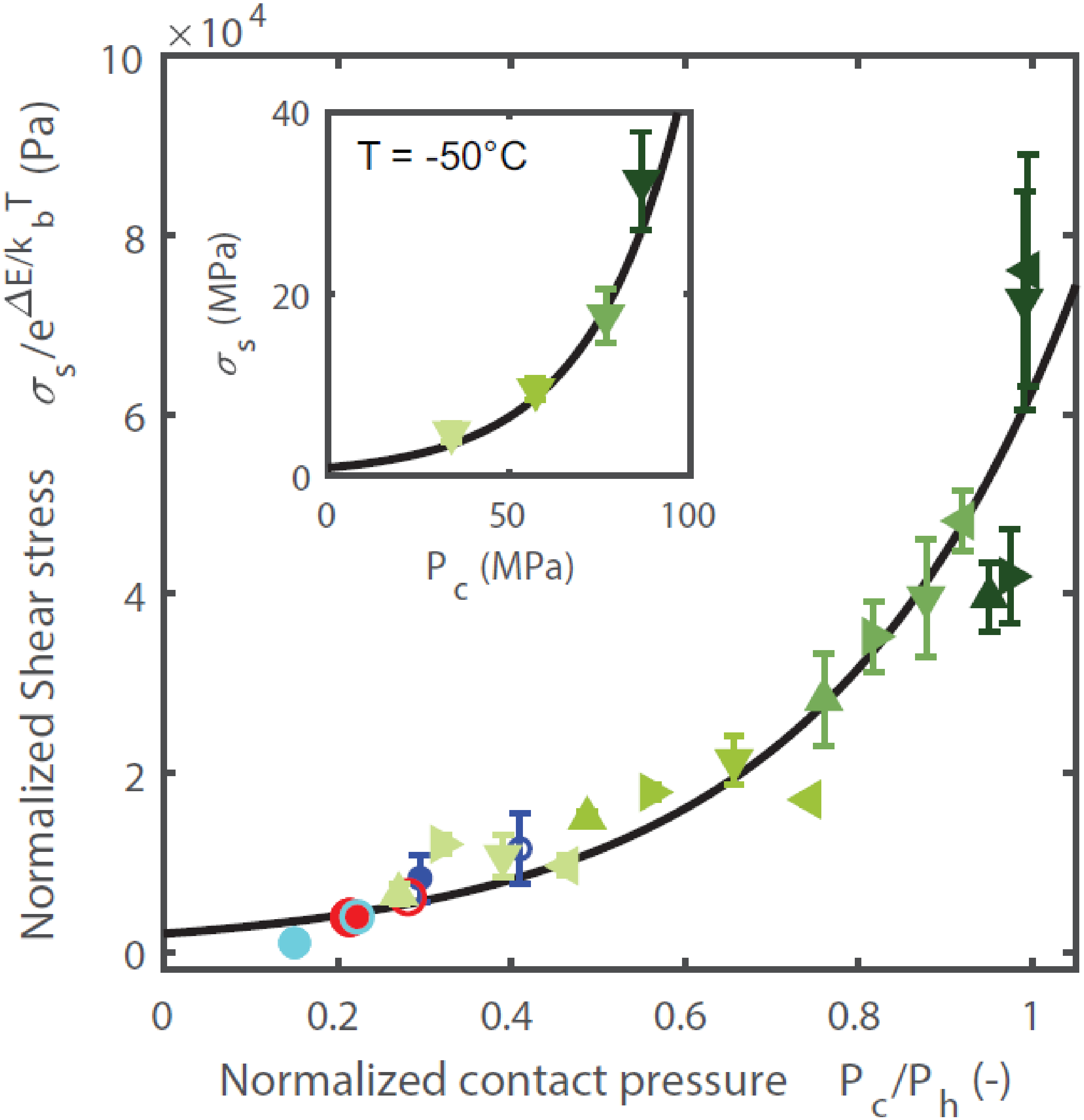
Topography sliders

Area of real contact



Normal Force N	0.5 N
Radius R	1.84 mm
Temperature	$-50°C$
Material	Glass-on-ice

Surface water mobility suppressed by contact pressure

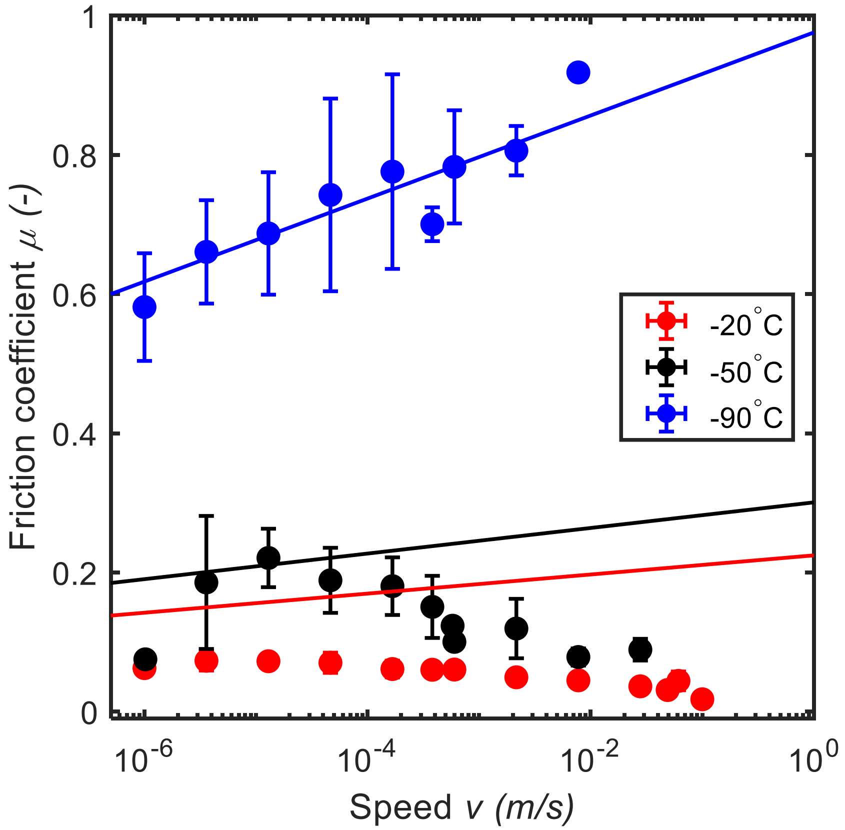


$$\sigma_s = \sigma_0 e^{\frac{\Delta E}{k_B T}} e^{b\frac{P_c}{P_h(T)}}$$

Various sliders, surface roughnesses, and temperatures

Triangles from light green to dark green correspond to glass spheres with a surface roughness 98, 222, 575, and 3077 nm, where upward, right, down, and left-pointing triangles are measurements at T . −90 °C, −70 °C, −50 °C, and −30 °C, respectively. The blue, red, and cyan circles correspond to, respectively, a small SiC (R = 0.75 mm), a large SiC (R = 6 mm), and a sapphire sphere (R = 1.59 mm) at T =−90 °C for closed and −50 °C for open markers.

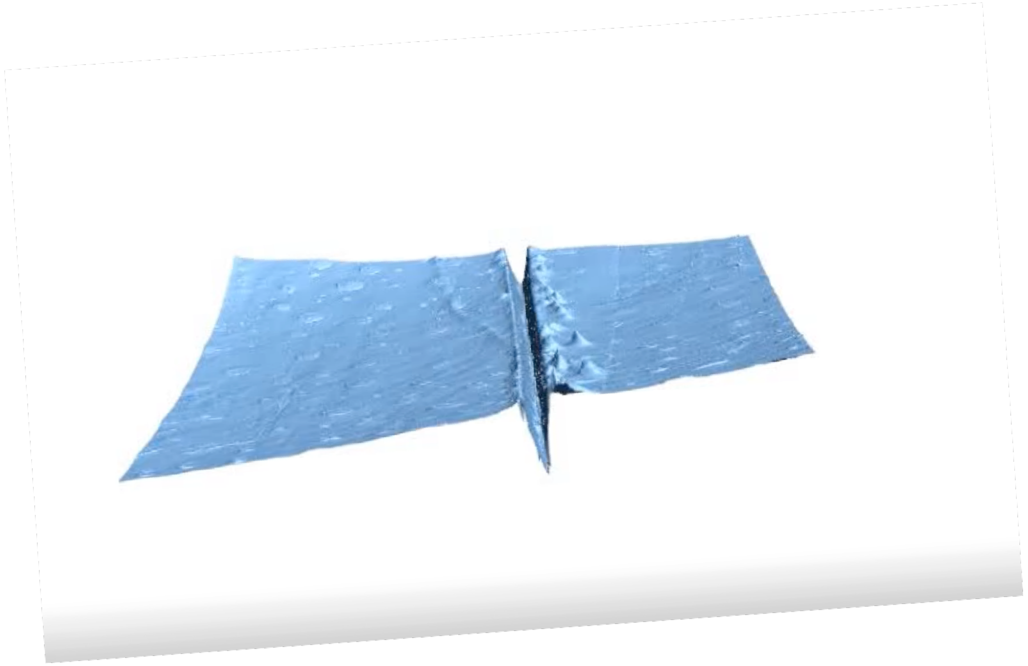
Speed dependence of the friction coefficient



$$\mu = \mu_0 e^{\frac{\Delta E}{k_b T}} e^{b\frac{\sigma_n}{P_h}} \ln(1 + b\, v)$$

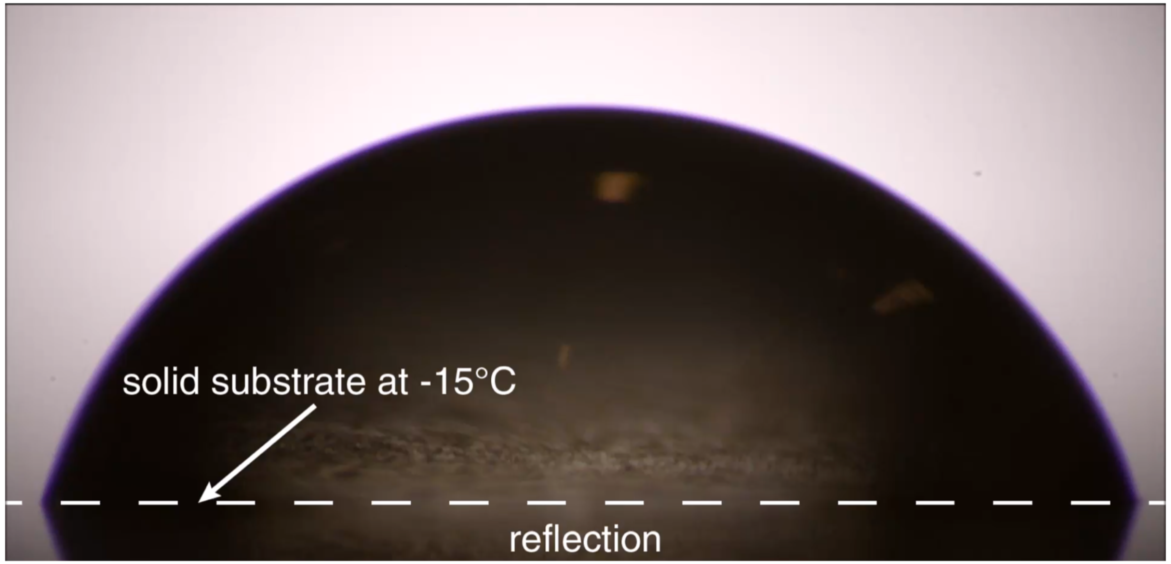
In ‘rough’ agreement

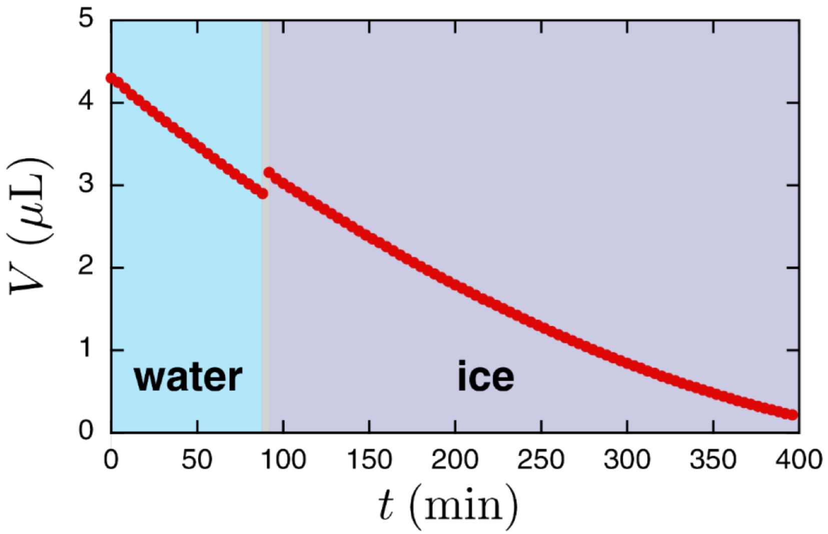
So, what is different between ice and all other materials?



Snow sublimation is very rapid

Water evaporation vs ice sublimation





Same evaporation rate !
Both are limited by diffusion
in the vapor

Jambon-Puillet, Shahidzadeh, DB, Nature Comms 2018

Singular sublimation of snow and ice

Video courtesy of K. Libbrecht

General conclusion

Ice is different from almost all other solids in that it has a high vapor pressure. This makes for a layer of very mobile molecules at the surface that account for self-healing, ice skating…..