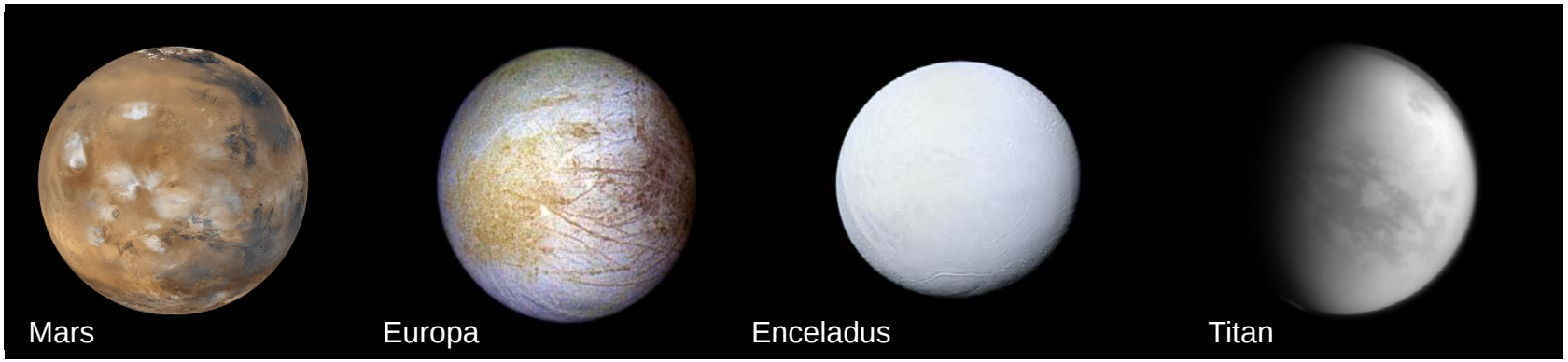


Image Credit: NASA, JPL [14-18]

# A THERMAL SIMULATION TOOL TO SUPPORT ICE-PENETRATING EXPLORATION PROBES

June, 18th 2015 – IPPW12 Cologne

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Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

# Enceladus Explorer Initiative

**The Enceladus Explorer Initiative addresses technological challenges for autonomous subsurface exploration in ice**
**(http://www.dlr.de/rd/EnEx)**

**CAUSE**
**Cognitive Autonomous Subsurface Exploration**
started Feb 2015 at University of Bremen

**RANGE**
**Robust Acoustic Autonomous Navigation in Glacier Ice**
started Feb 2015 at RWTH Aachen University

**DiMIce**
**Directional Melting in Ice**
started April 2015 at RWTH Aachen University

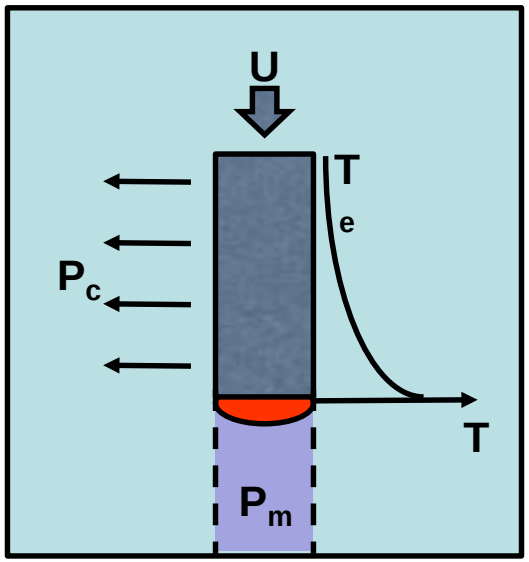
**EnEx-nExT**
**Enceladus Explorer – Environmental Experimental Testing**
started Jun 2015 at FH Aachen University of Applied Sciences

**Others in planning phase …**

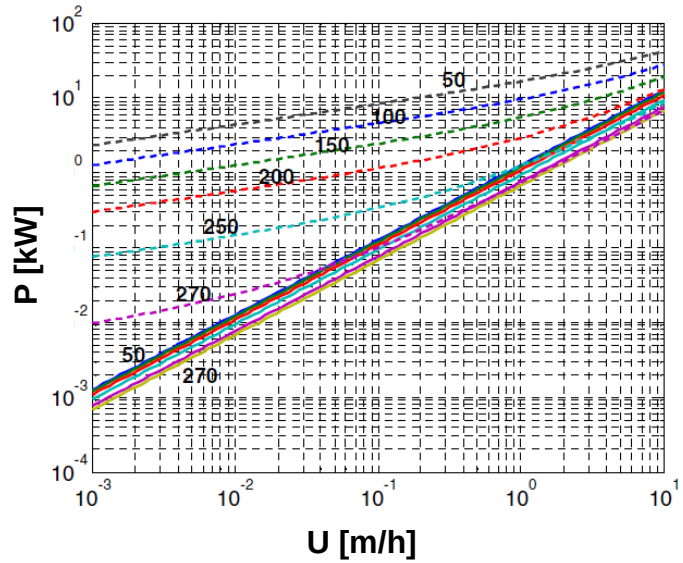
Initiatiated by the DLR Space Administration and supported by the Federal Ministry of Economics and Technology on the basis of a decision by the German Bundestag

# Ice-penetrating probes on Earth

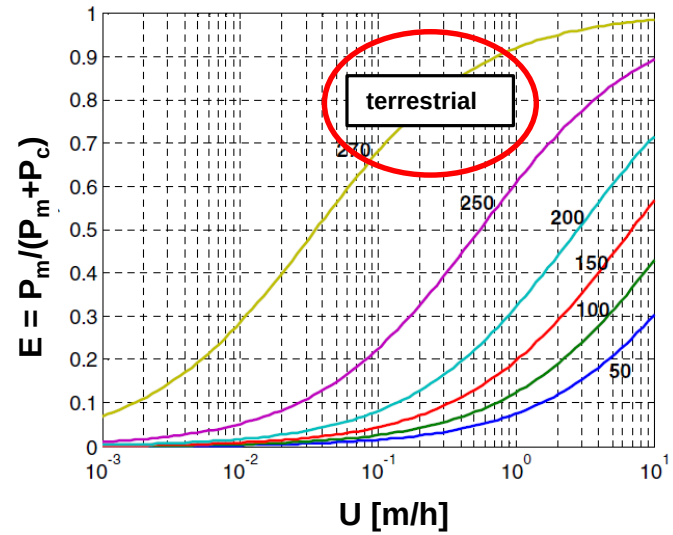
## Classical approach: Aamot theory [1]




**Power vs velocity [2]**




**Efficiency vs velocity [2]**




**Energy balance:**

$$P_m = U\,A\,\rho\,\underbrace{\left(c_p(T_m - T_a) + L_m\right)}_{L_m^*}$$

**Conductive losses (to avoid stall):**

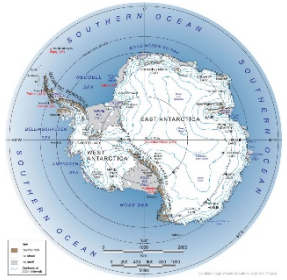
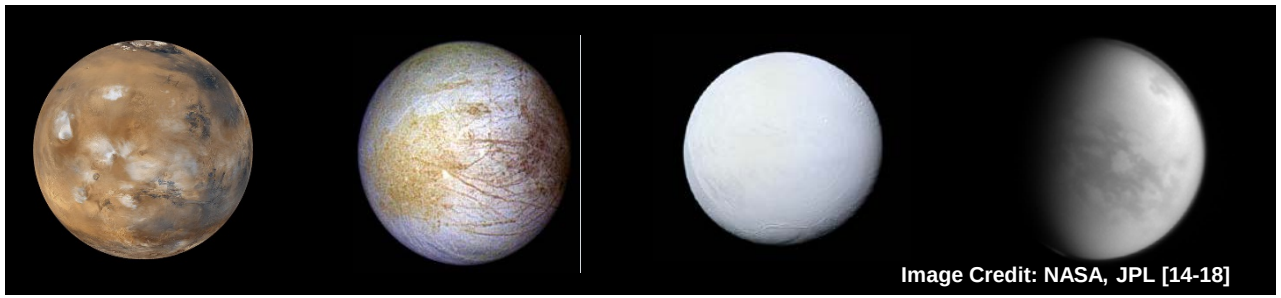
$$P_c = \frac{8\,\alpha\,T_a}{\pi}\int_0^l\int_0^\infty \frac{e^{-\kappa u^2 s/U}}{u\,\left(J_0^2(a\,u) + Y_0^2(a\,u)\right)}\,du\,ds$$

**U**: melting velocity
**A**: crosssection of the probe
**ρ**: density of the ice
$c_p$: specific heat capacity of the ice
$T_m$: melting temperature
$T_a$: temperature of the ambient ice
$L_m$ : melting enthalphy of ice
$L^*_m$ : convention to take ambient temperature into account
**α**: thermal diffusivity
**κ**: thermal conductivity

**Neglected:** radiative losses, variable forces, convective heat transfer in the melting film.

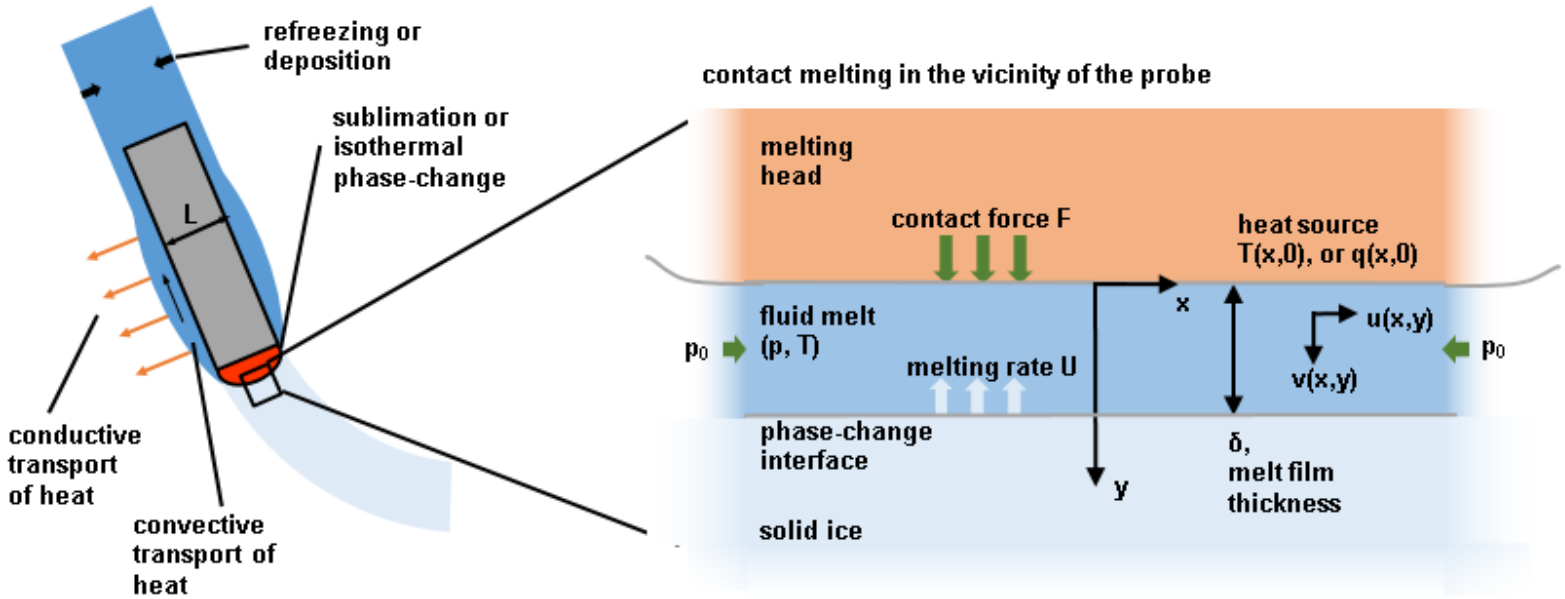
**Critical:** space-resolution? channel evolution? temperature in the ice?

# Ice exploration in our Solar System

| | Earth | Mars | Europa | Enceladus | Titan |
|---|---|---|---|---|---|
| |  |  Image Credit: NASA, JPL [14-18] | | | |
| region of interest | Antarctica, Taylor Glacier | Polar caps | | Tiger Stripes | |
| surface temperature | 250K | 210K | 100K | 145K | 94K |
| composition | $H_2O$ | $H_20$ + seasonal $CO_2$ layer | $H_20$ | $H_20$ | $H_20$ |
| ice density [1] | ~ 920kg/m$^3$ | ~ 925kg/m$^3$ | ~ 934kg/m$^3$ | ~ 932kg/m$^3$ | ~ 935kg/m$^3$ water ice |
| surface pressure | 1bar | 6,7x10$^{-3}$ bar | 10$^{-11}$ bar | 0 bar | 1,5 bar |
| grav. acceleration | 9,8m/s$^2$ | 3,7m/s$^2$ | 1,3m/s$^2$ | 0,1m/s$^2$ | 1,4 m/s$^2$ |
| est. ice sheet thickness | <5km | <5km | 5-20km | 30-40km | 80km |

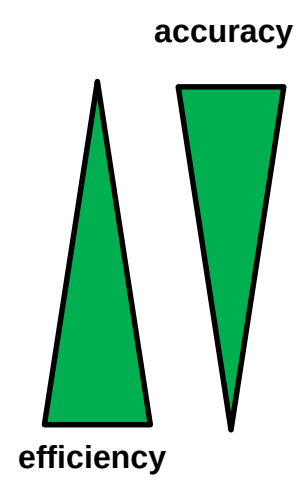
# Contact phase-change in a Nutshell

## Sketch of the physical situation:



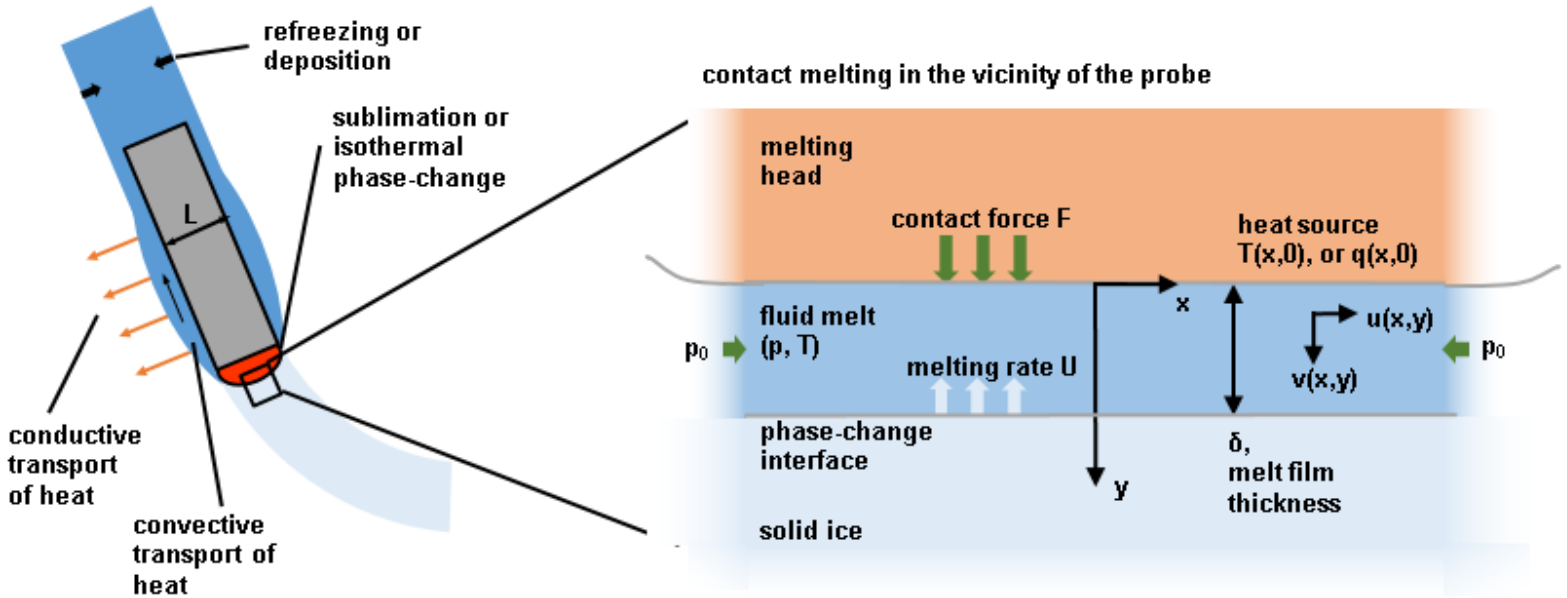

## Key questions are:

- How fast and how efficient can we melt with a specific melting design?
- What is a good geometric scale / shape of the probe?
- Which sequence of configurations is necessary to follow a given path?
- How does the channel geometry evolve in such a scenario?
- Model-based decision support and autonomous control?



# What are the dominant processes?

## Sketch of the physical situation:




**Melt - balance laws in physical units:**

$$\nabla \cdot \mathbf{u} = 0$$

$$\mathbf{u}_t + (\mathbf{u} \cdot \nabla)\,\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu \triangle \mathbf{u}$$

$$T_t + (\mathbf{u} \cdot \nabla)\,T = \alpha \triangle T$$

**Melt - balance laws dimensionless:**

Reynolds number
Peclet numer
thin film parameter

$$\partial_x u + \partial_y v = 0$$

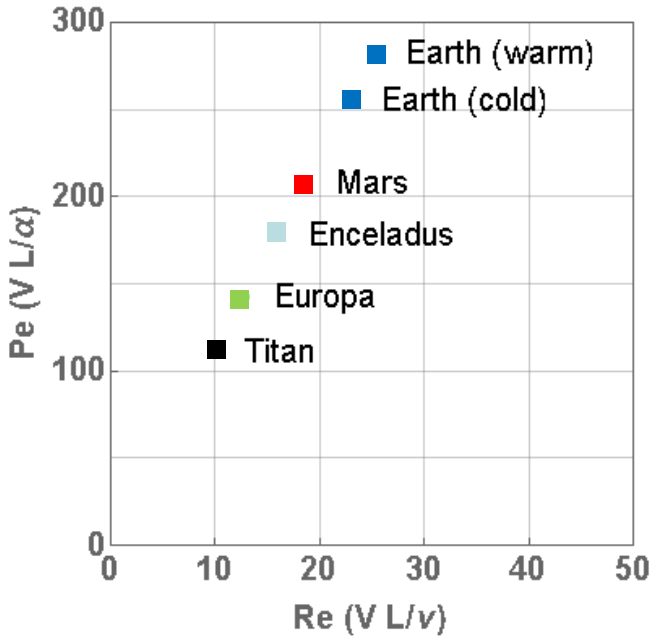
$$\epsilon Re\,(\epsilon \partial_t u + u \partial_x u + v \partial_x u) = -\epsilon d_x p + \epsilon^2 \partial_x^2 u + \partial_y^2 u$$

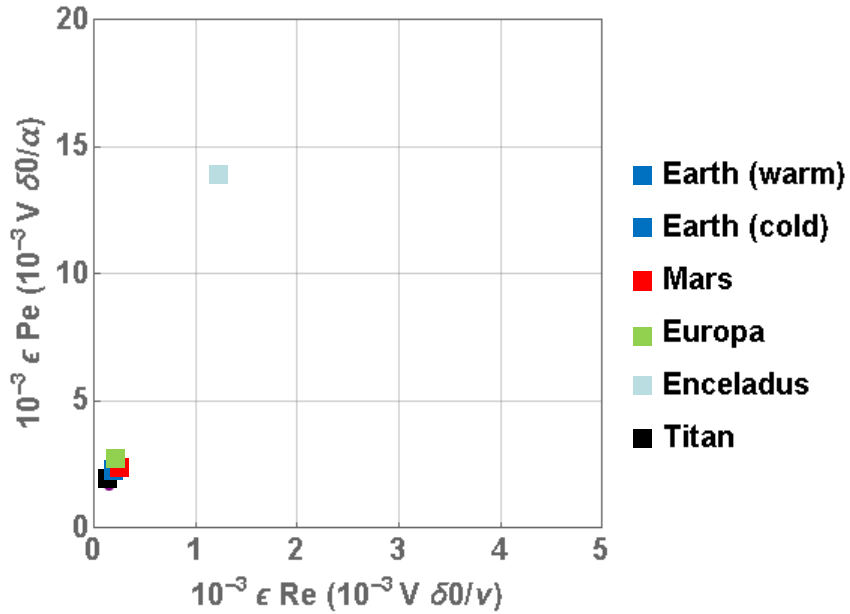
$$\epsilon\, Pe\,(\epsilon \partial_t T + u \partial_x T + v \partial_x T) = \epsilon^2 \partial_x^2 T + \partial_y^2 T$$

In a similar manner the heat equation for the ice and equations that describe boundary, initial and interface conditions can be formulated.
**Unknowns: velocity u=(u,v), pressure p, temperature T, kinematic viscosity v, thermal diffusivity α**
**Model further developed from theory summarized in [4]**

# Space-resolved modeling of contact melting

## Contact melting regime in our Solar System:




## Two possible approaches:

**(1) LUS: Lubrication coupled to an extended Stefan problem (drop terms that scale with $\varepsilon^2$ and $\varepsilon$ Re)**

**advantage: efficiency disadvantage: cannot cover the whole channel**

**(2) STOS: Stokes flow coupled to an extended Stefan problem (drop terms that scale with $\varepsilon^2$)**

**advantage: can be implemented holistically disadvantage: computationally more expensive**

# Implementation(s) of the thermal melting model

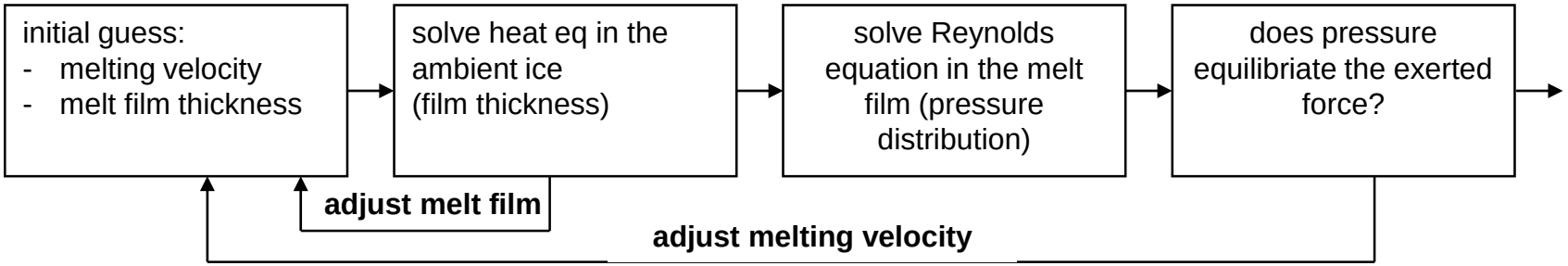
## Boundary conditions:

- No-slip velocity at the probe‘s skin
- Temperature or power constraint
- Ice: initial temperature distribution
- Interface: no-slip, mass influx due to melting rate,melting temperature

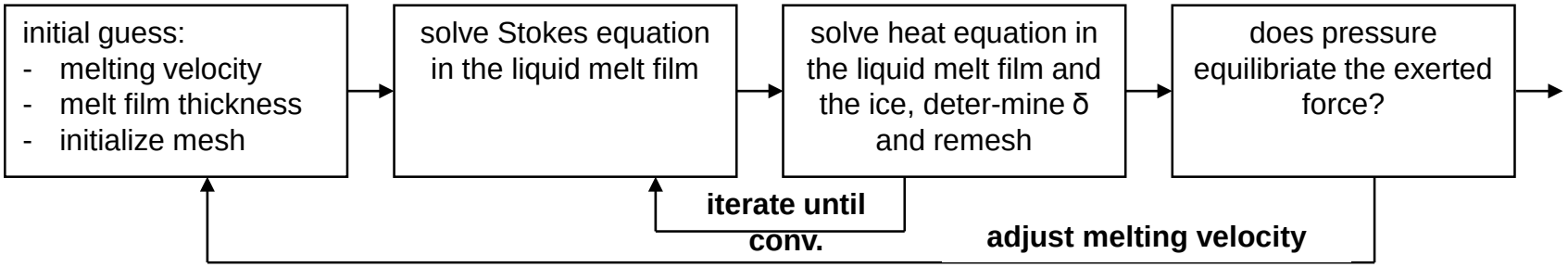
## Closure relations:

- Local enery balance at the phase-change interface (Stefan condition)
- Force-equilibrium (zero order pressure moment equals force)

## LUS: Implemented into ELMER incl. 2d/3d + complex geometries [5,6]



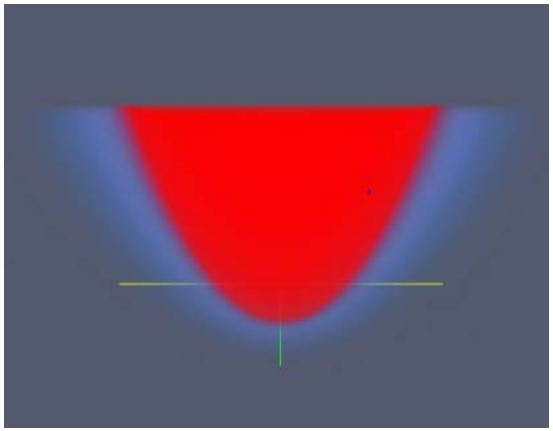

## STOS: Implemented at prototype level[1)] into Matlab (2d) + channel evolution

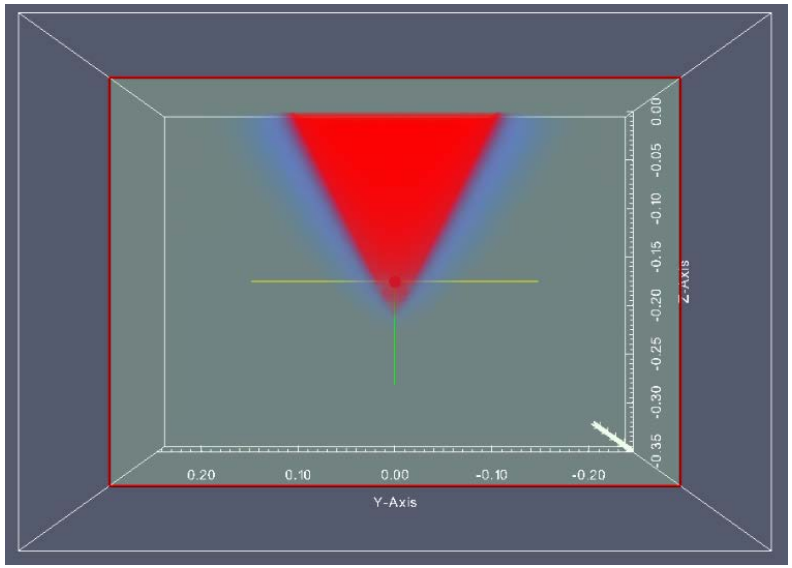


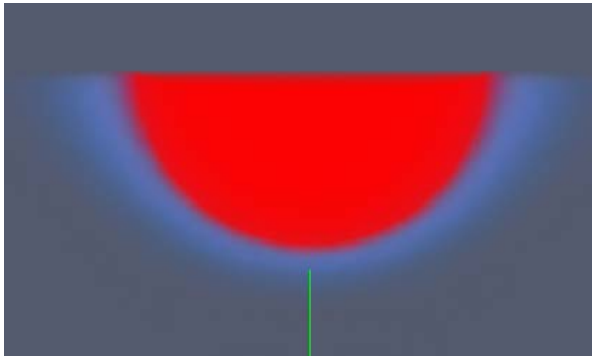

1) same architecture than NGSOLVE

# Shape analysis consistent to literature

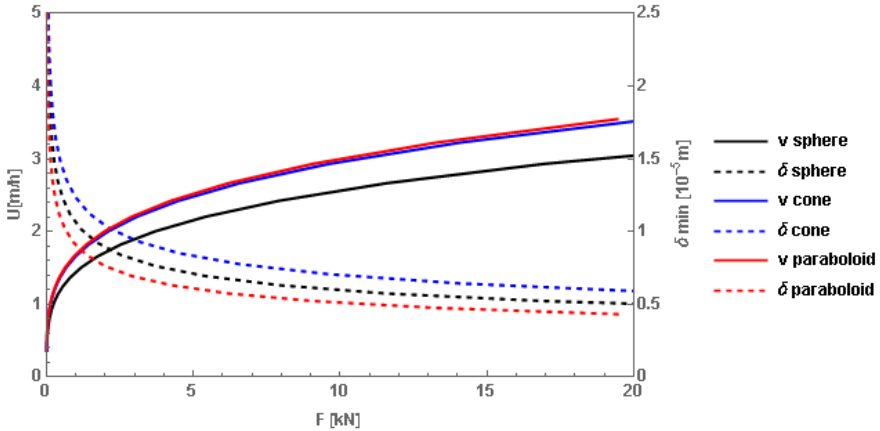
**The LUS model has been applied to different geometries (controlled temp.):**

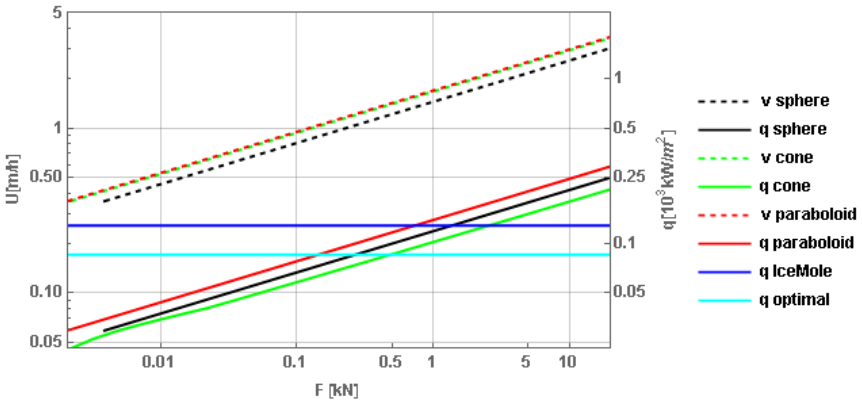




**Consistent to results in the literature [7]**

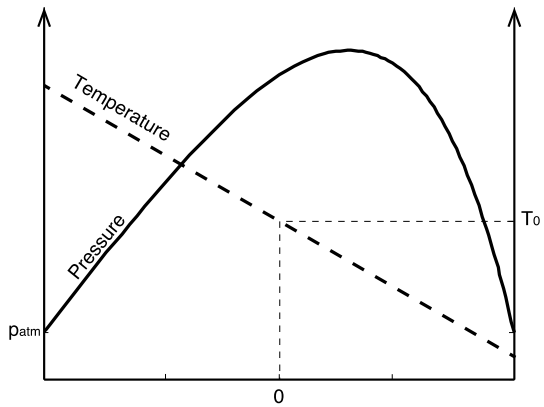


# Curve melting in the lab

# Comparison to the model

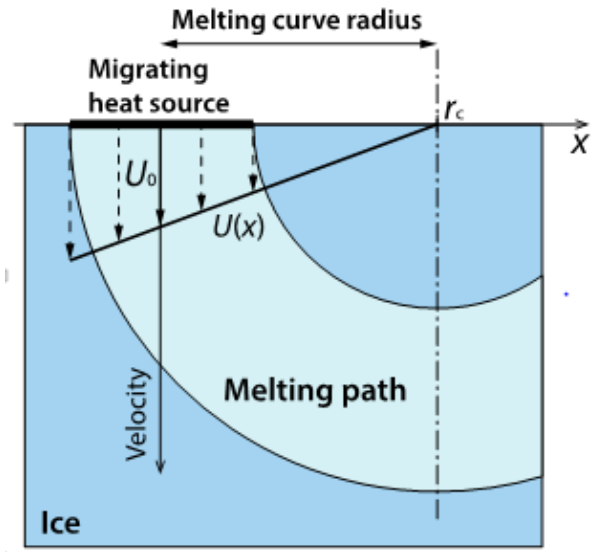
**Temperature gradient induces a curve:**



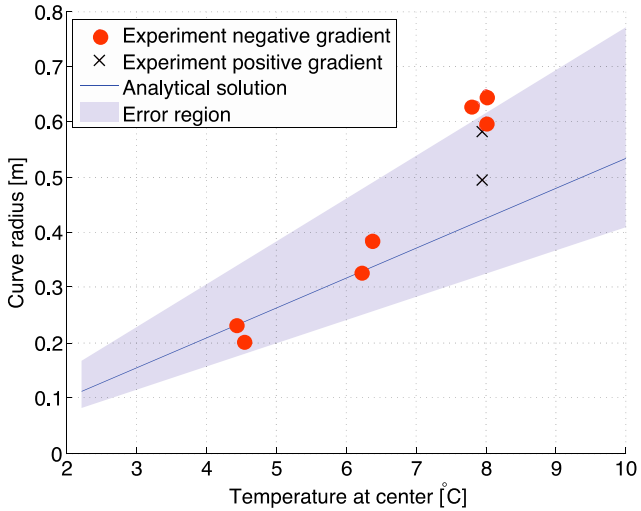

**Idea: Change parametrization of the velocity field**

$$U(x) = U_0 \left(1 - \frac{x}{r_c}\right)$$

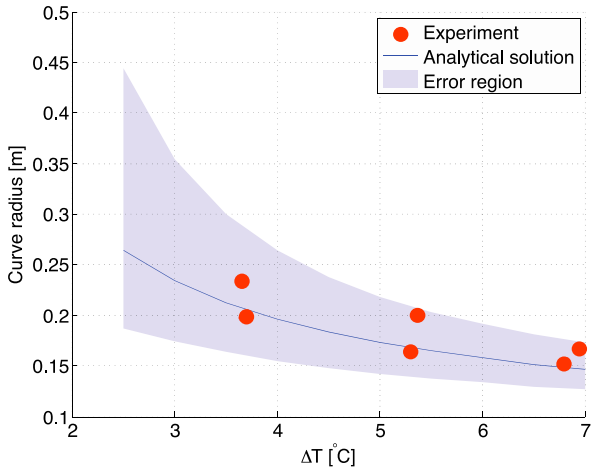
**Closure:**
Vanishing torque




## Comparison to laboratory results [8,9]




**Left:**
Constant temperature difference of 3.27°C
**Right:**
Constant center temperature of 2.57 °C



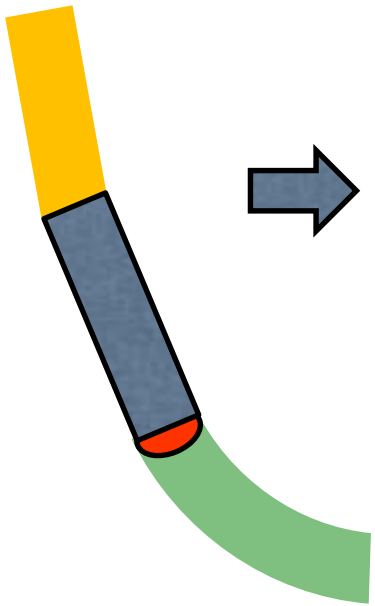
# Towards trajectory planning

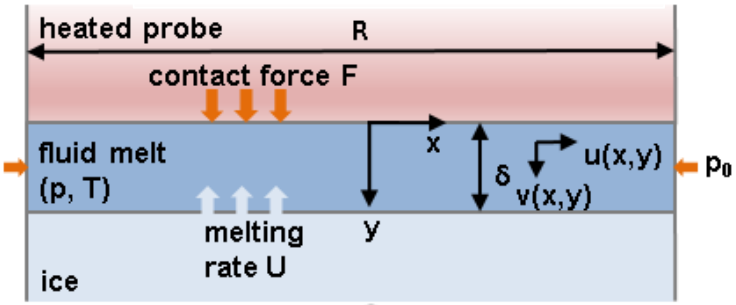
**Assumption: A melting scenario is a sequence of equilibrium melting states[1)]**

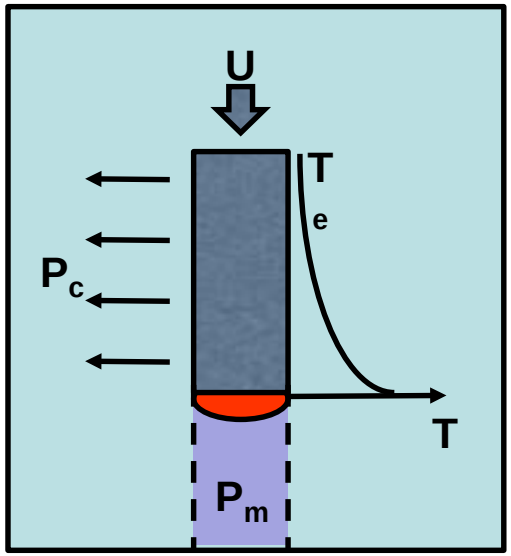
**1) Discrete configuration space:**
A melting scenario can be split into a sequence of specific probe configurations.

**2) For each configuration**
the ambient thermal situation is modeled by taking into account the microscale contact melting regime.

**3) Global efficiency and trajectory parameters**
can be determined by evaluation of the ‚database of melting states'






**4) Intelligent sampling**
of the melting state space will allow model based decision and trajectory control.

1) inspired by the scaling analysis and experiments [10]

# Conclusions & Next Steps

We proposed a thermal simulation tool to analyse melting probe technologies for ice-penetrating exploration under extraterrestrial conditions. The computational model directly resolves the microscale processes within the melting film. It exceeds the level of detail provided by classical power budgets and static analyses.

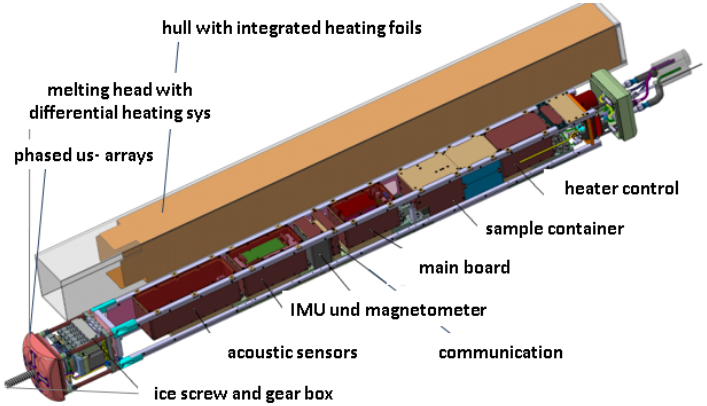
## Next steps

**1) Modeling and Methodology:**
a) Migrate STOS prototype model ino specialized finite element framework
b) Couple to channel evolution
c) Consider isothermal phase-change
d) Consider rarefied situations

**2) Validation:**
a) Existing IceMole data from Antarctica
b) IceDiver data from APL at UW [11]
c) Vacuum chamber experiments EnEx-nExT
d) Model selection and uncertainty quantification

**IceDiver, APL, University of Washington, Image Credit: Dale Winebrenner [11]**

**3) Application:**
a) Leverage the melting state space - CAUSE
b) Derive model based mission constraints
c) Shape optimization




**IceMole, FH Aachen University of Applied Sciences,Image Credit: Marco Feldmann [12,13]**

# Bibliography

## Literature:


[1] Aamot , H.W.C.: Heat transfer and performance analysis of a thermal probe for glaciers, 1967
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[8] Schüller, K. et. al.: (to be submitted) Curvilinear Melting - A Preliminary Experimental and Numerical Study, 2015
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[12] Dachwald, B., et. al.: Icemole: a maneuverable probe for clean in situ analysis and sampling of subsurface ice and subglacial aquatic ecosystems, 2014
[13] Kowalski, J., et. al.: (to be submitted) Navigation Technology for Exploration of Glacier Ice With Maneuverable Melting Probes, 2015


## Other sources:


[14] http://geology.com/world/antarctica-satellite-image.shtml
[15] Image Credit: Mars, NASA/JPL/MSSS, PIA 02653, 1999
[16] Image Credit: Europa, NASA/JPL/University of Arizona, PIA01295, 1998
[17] Image Credit: Enceladus, NASA/JPL-Caltech/Space Science Institute, PIA17182, 2013
[18] Image Credit: Titan, NASA/JPL-Caltech/Space Science Institute, PIA18309, 2015


## Thanks to:


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