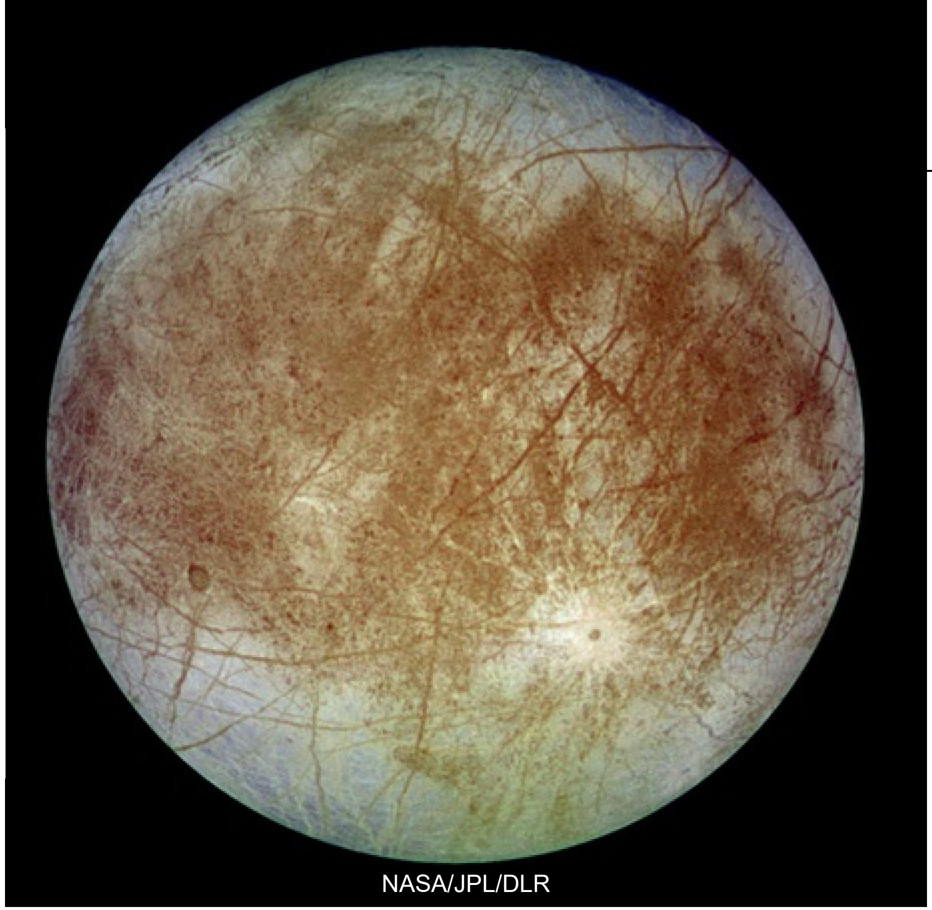
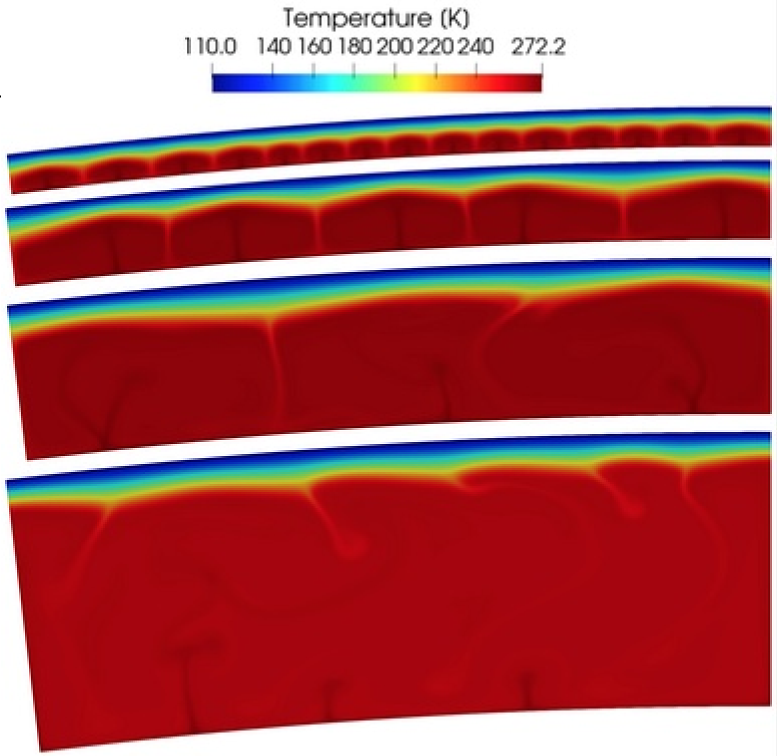




Concepts to utilize planetary analogue studies for icy moon exploration missions

M. S. Boxberg, F. Baader, L. Boledi, Q. Chen, B. Dachwald, G. Francke, J. Kerch, A-C. Plesa, A. Simson, J. Kowalski

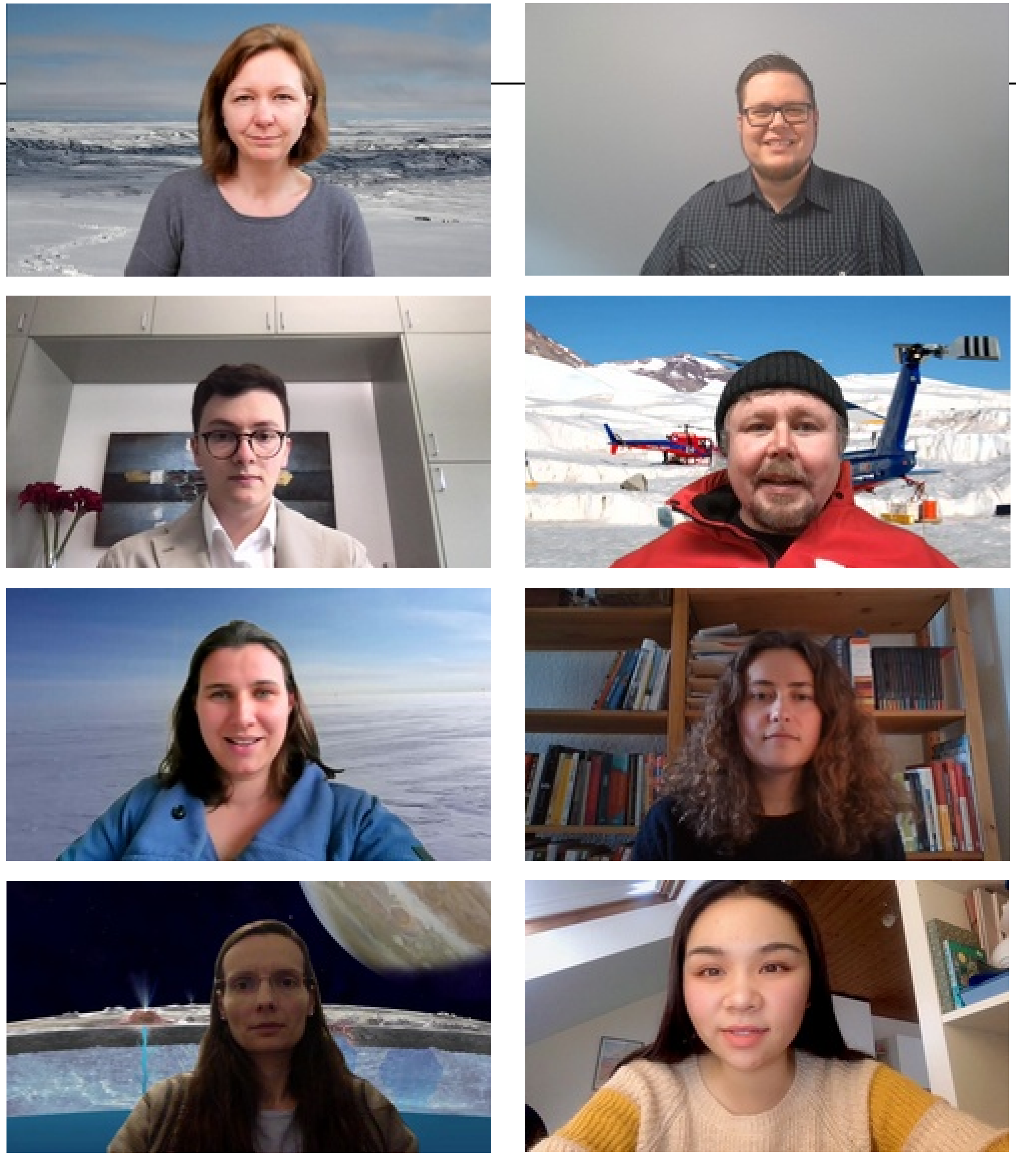
EGU21-13052

View talk at:
https://youtu.be/MPDJMMOVE8A

DLR FH AACHEN UNIVERSITY OF APPLIED SCIENCES GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN AICES Aachen Institute for Advanced Study in Computational Engineering Science RWTH AACHEN UNIVERSITY

Outline

1. Introduction
   - Europa
   - TRIPLE mission concept
2. Virtual cryobot testbed
   - Trajectory modeling
   - EnEx-IceMole
   - Field tests
   - Ice Data Hub
   - Validation
   - Terrestrial analouge mission planning
3. Extraterrestrial scenarios
   - Models for Europa
   - Melting probe trajectories for Europa mission planning
4. Summary

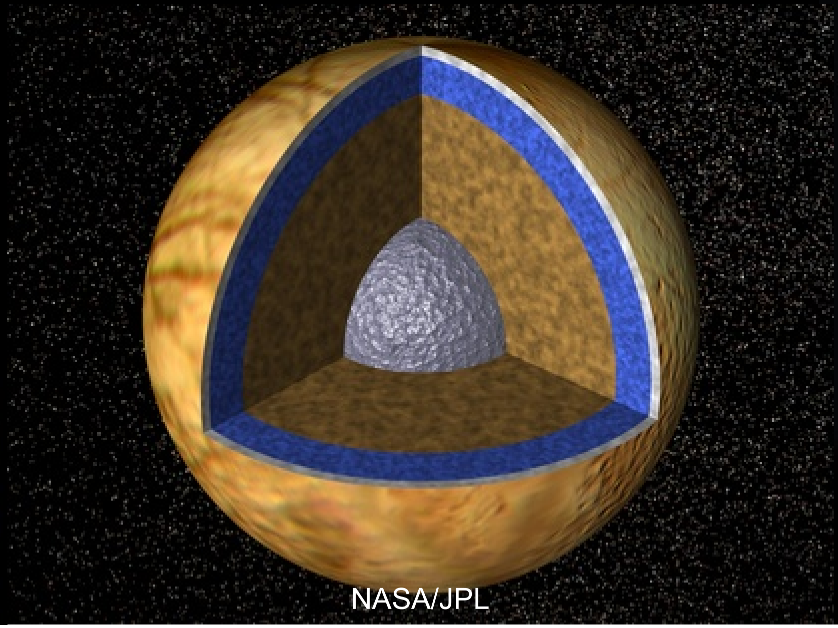


DLR FH AACHEN UNIVERSITY OF APPLIED SCIENCES GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN AICES Aachen Institute for Advanced Study in Computational Engineering Science RWTH AACHEN UNIVERSITY

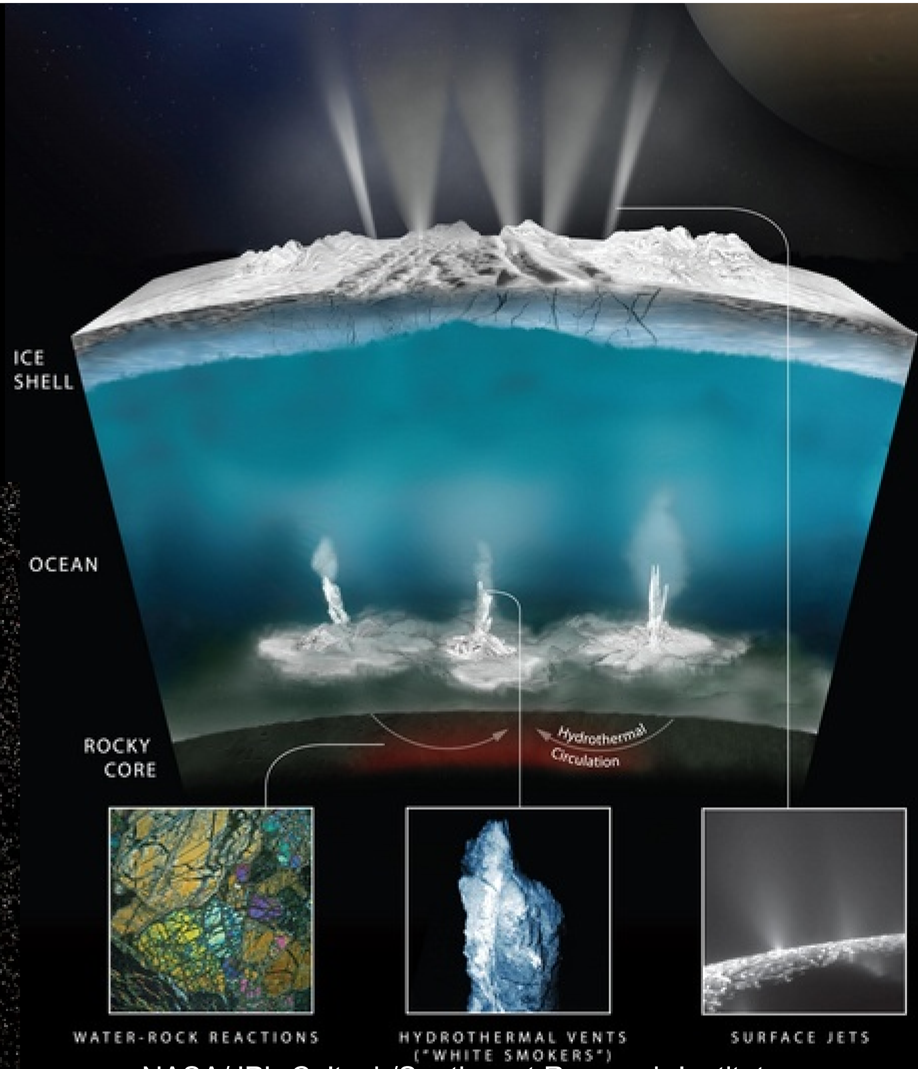
Jovian moon Europa could be habitable

- Icy crust and global salty ocean below
- Water in contact with rocky mantle
  - Source for minerals and salts
- Tidal heating prevents ocean from freezing
- Life (as we know it) could most likely survive in the ocean of Europa

NASA/JPL



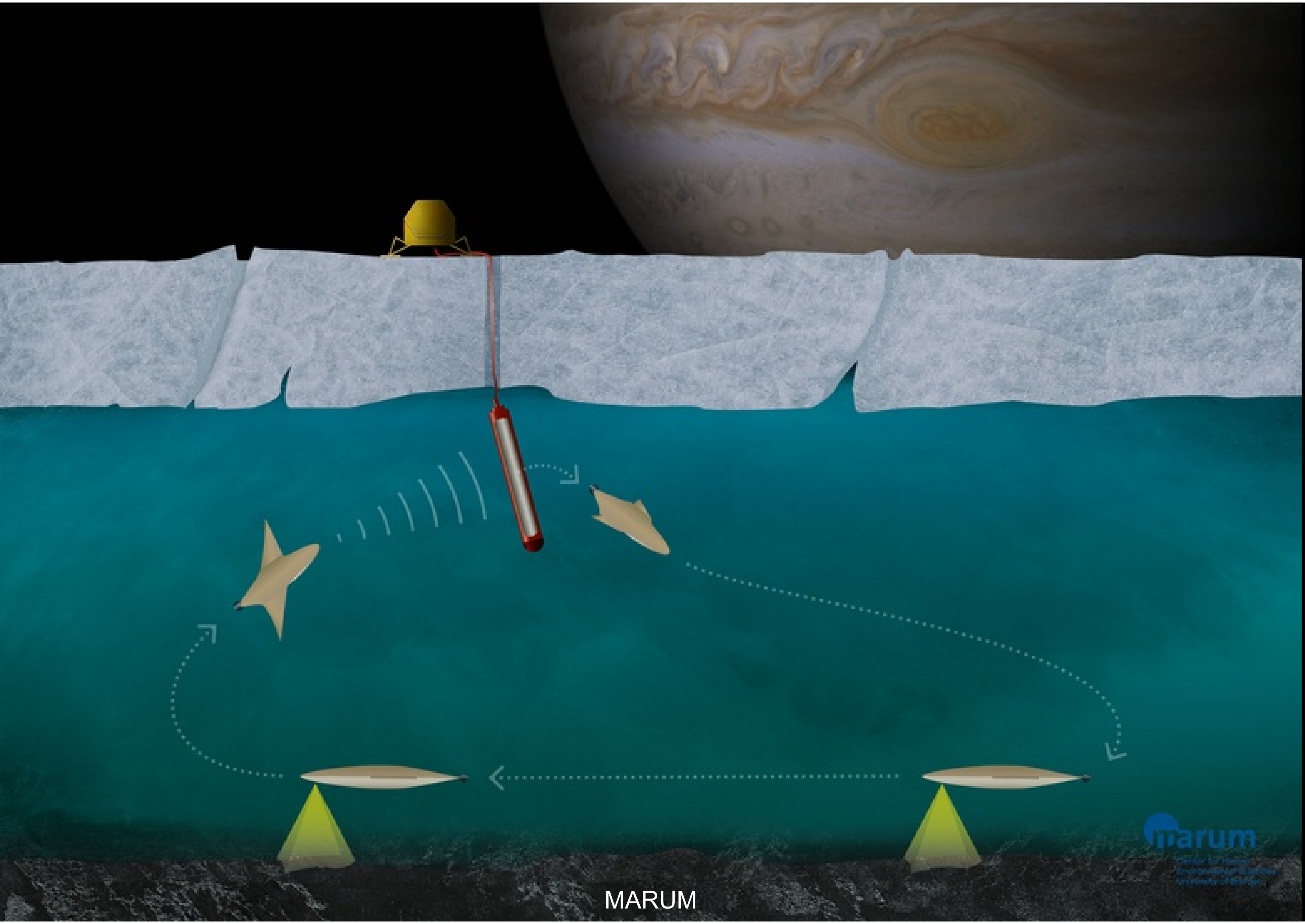
NASA/JPL



NASA/JPL-Caltech/Southwest Research Institute

DLR | FH Aachen University of Applied Sciences | Georg-August-Universität Göttingen | AICES Aachen Institute for Advanced Study in Computational Engineering Science | RWTH Aachen University

German mission concept using a cryobot and a hydrobot



TRIPLE Mission Concept (DLR):

1. Melting Probe: traverse through the ice
2. nanoAUV: small autonomous underwater vehicle to explore the subglacial ocean
3. AstroBioLab: Instruments for analyzing samples taken by the nanoAUV

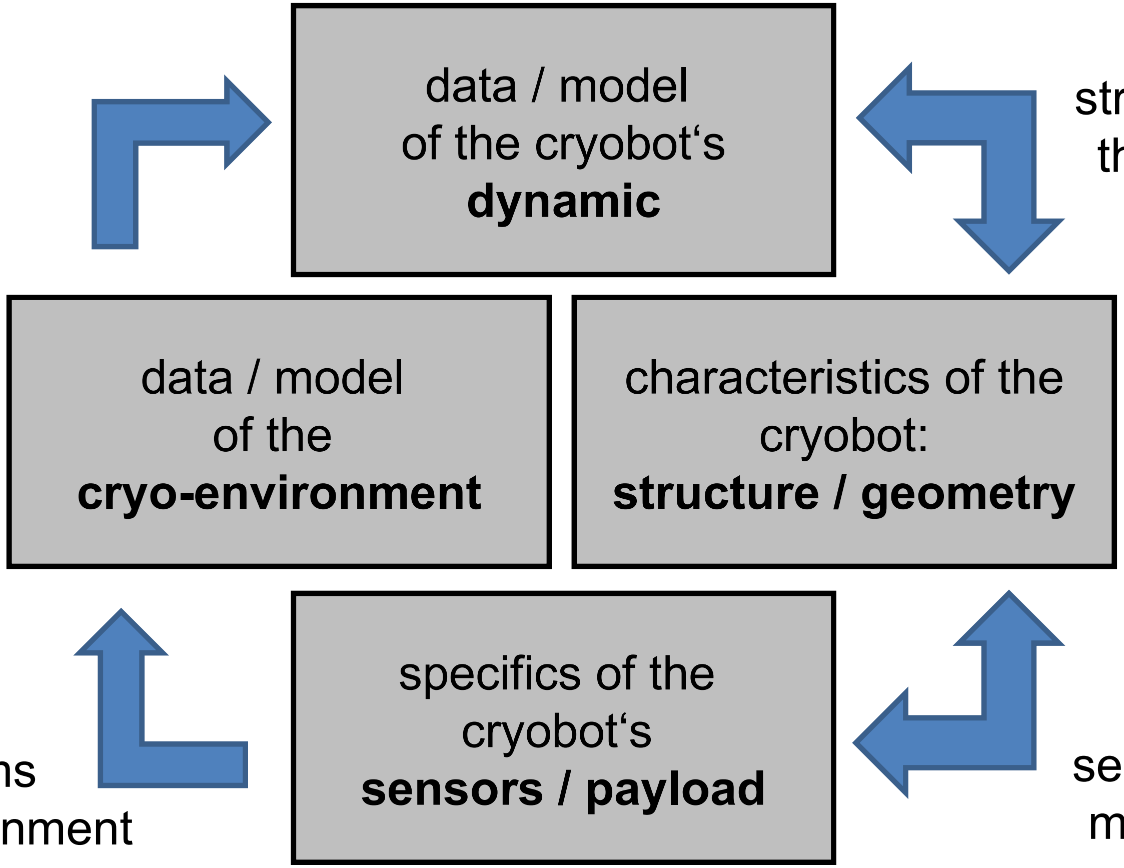
https://triple-project.net/

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Building blocks of a virtual cryobot testbed and their interplay

cryo-environment determines the cryobot dynamics

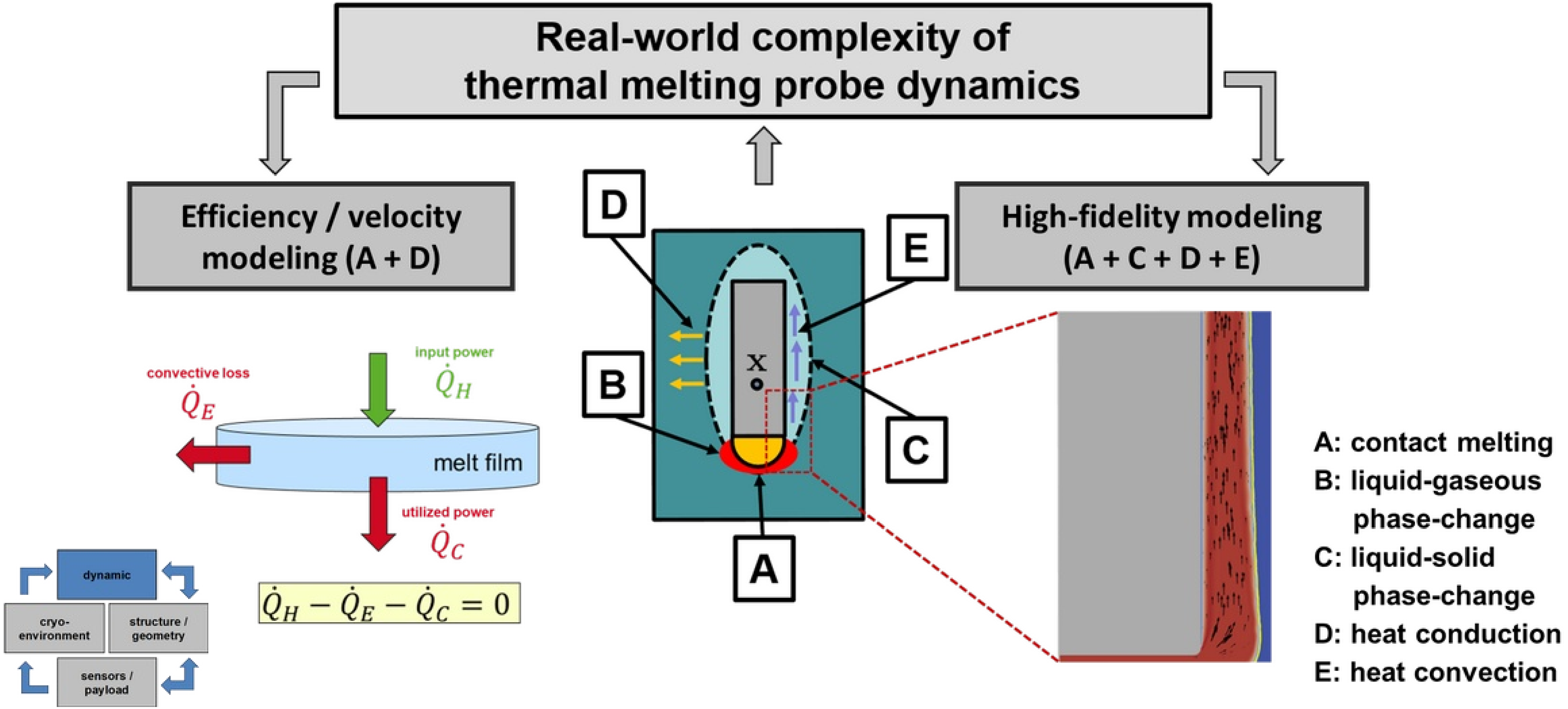
structure and geometry determine the cryobot‘s dynamic, and may in return be opimized for performance



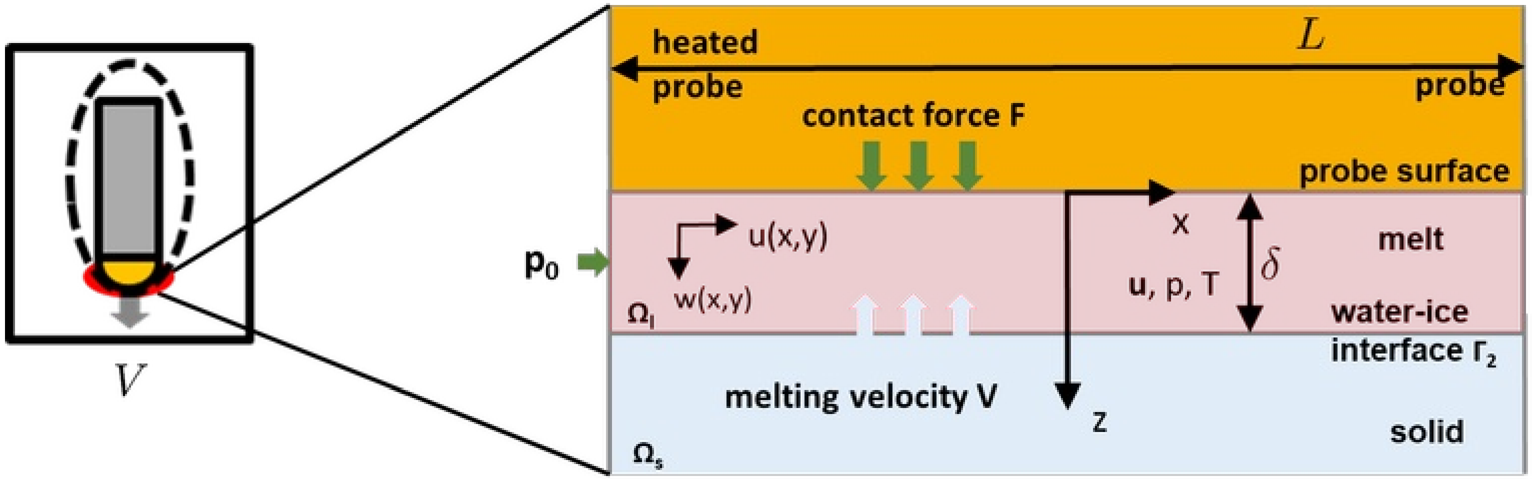
sensor / payload informs on the ambient cryo-environment

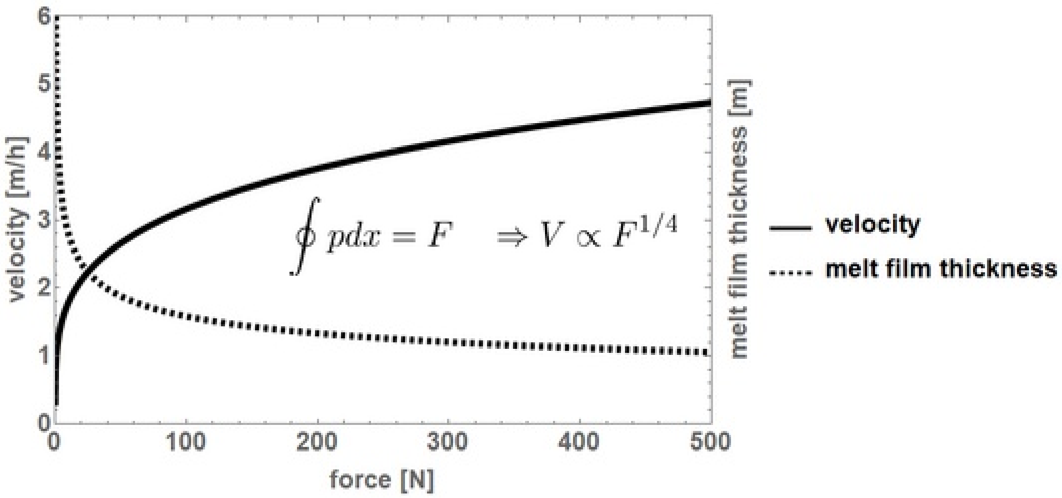
sensor / payload implementation is mutually dependant on structual / geometric design

Trajectory modeling – predicting the dynamics of a cryobot



Efficiency and velocity modeling



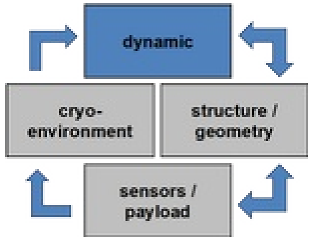


Water-ice interface:

- no-slip
- melting inflow
- melting temperature
- Stefan condition

Probe surface:

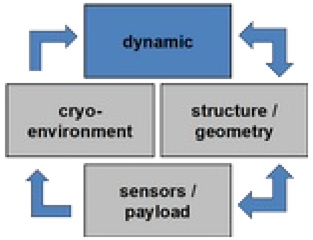
- no-slip / no inflow
- **temperature-driven (classical contact melting)** or heat flux-driven
- Newton‘s third law



Model inspired data acquisition for phase-change processes

Many challenges to be considered:

- Phase change (C)
- Moving domain
- Close contact melting (A)
- Flow field (C)
- Convection-coupled temperature evolution in both phases (D+E)



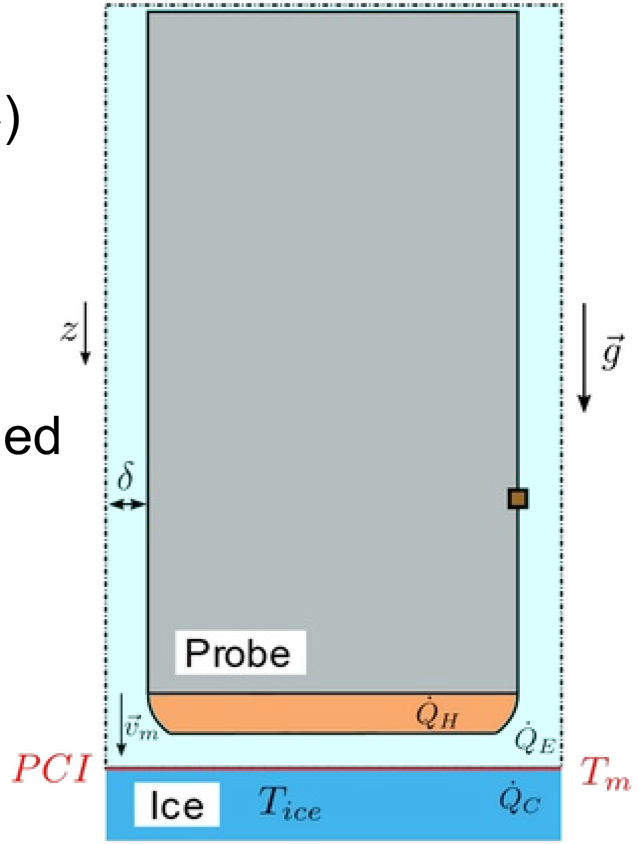
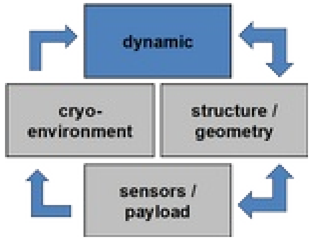


Fig.: Sketch of the problem setup (not drawn to scale)

Model inspired data acquisition for phase-change processes

Many challenges to be considered:

- Phase change
- Moving domain
- Close contact melting
- Flow field
- Convection-coupled temperature evolution in both phases



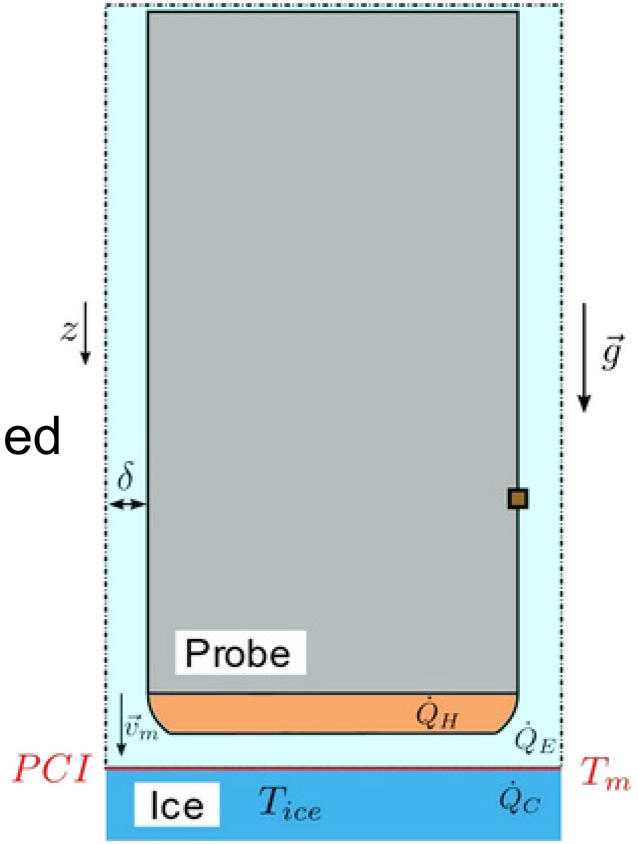


Fig.: Sketch of the problem setup (not drawn to scale)

We can simulate convection-coupled melting processes:

- In-house space-time FE solver
- A level-set method tracks the phase interface
- The local propagation velocity of the interface is modelled as the Stefan condition
- A ghost cell approach is used to retrieve heat-flux jumps at the interface

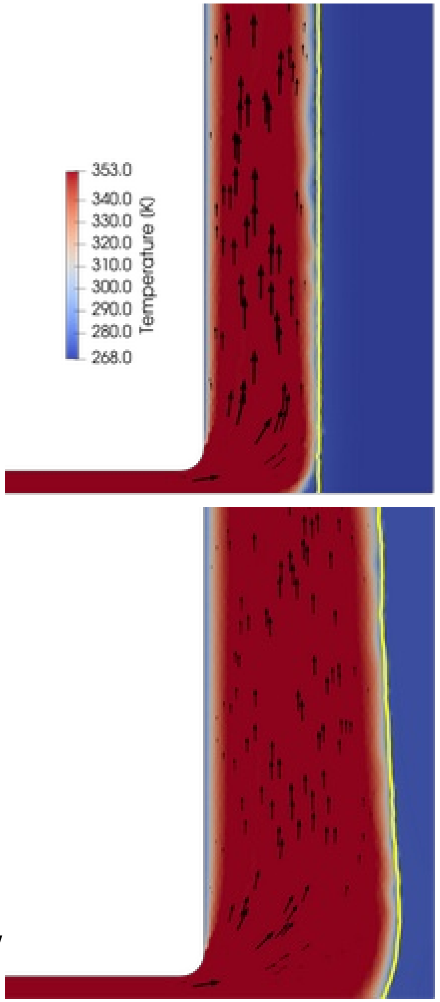
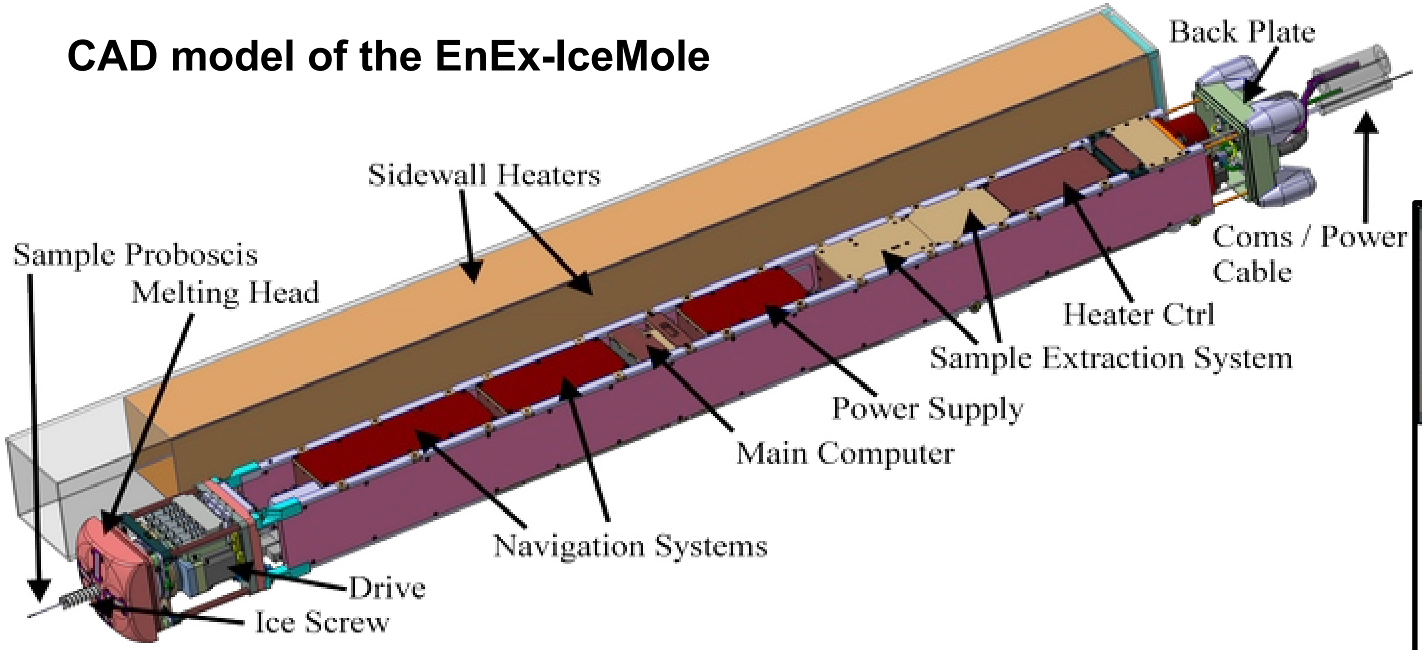
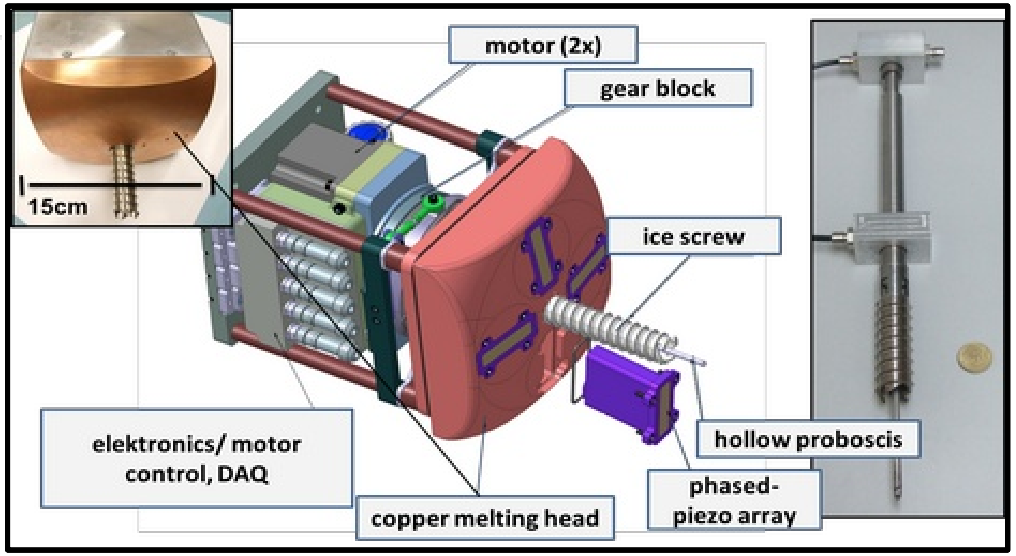


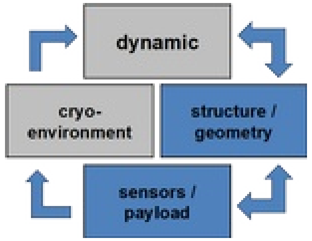
Fig.: Evolving 2D corner flow

Structure, geometry and payload of the IceMole

CAD model of the EnEx-IceMole







Enex-IceMole *, 2m long

Photo: C. Espe

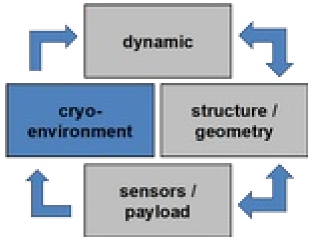
Selected field tests and terrestrial deployment scenarios

Morteratsch. Photo: J. Kowalski

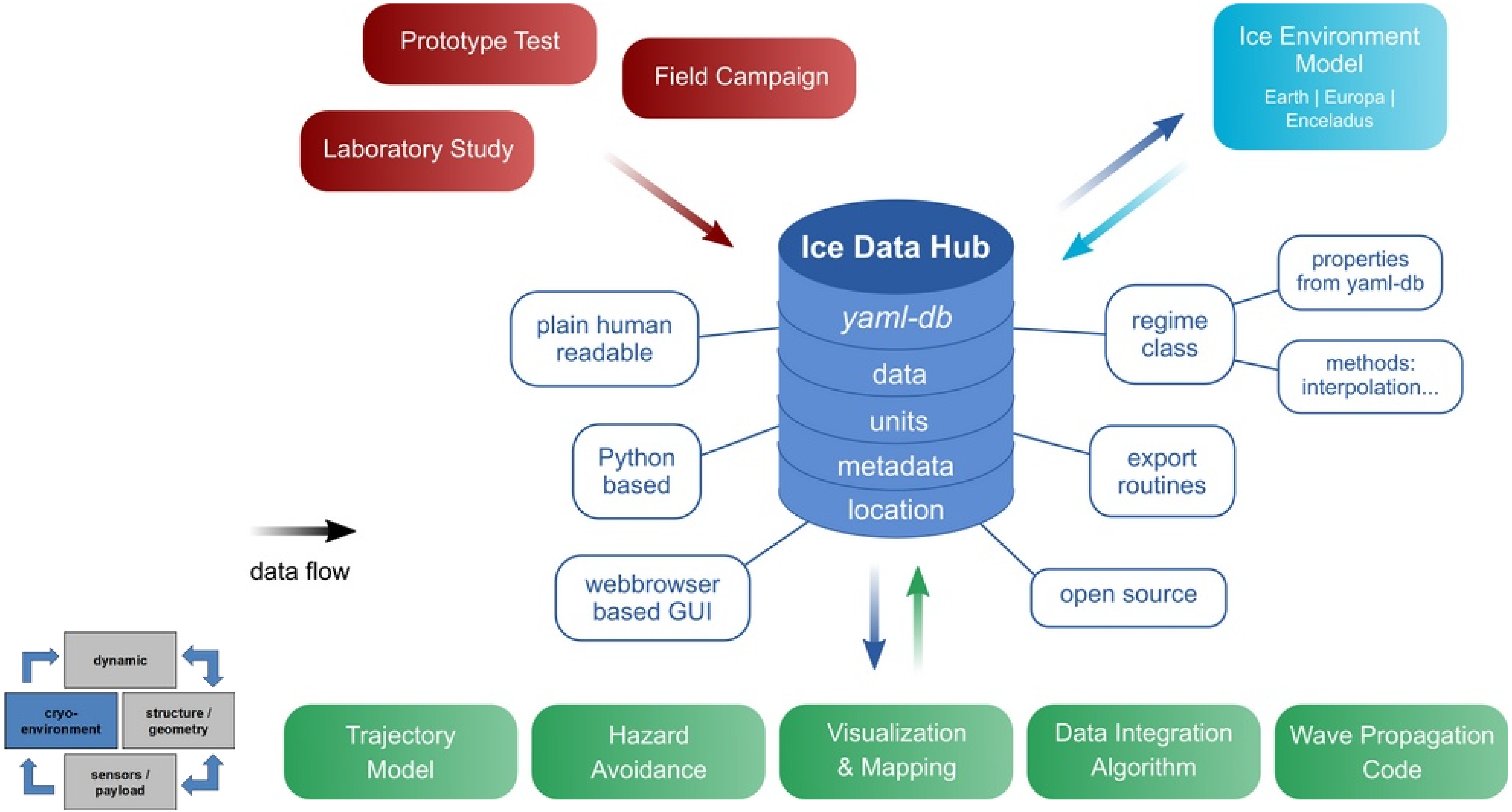
Hofsjkúll. Photo: J. Kowalski

Blood Falls. Photo: C. Espe

Langenferner. Photo: D. Heinen



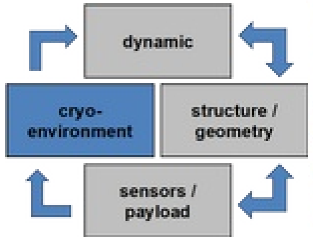
Ice Data Hub



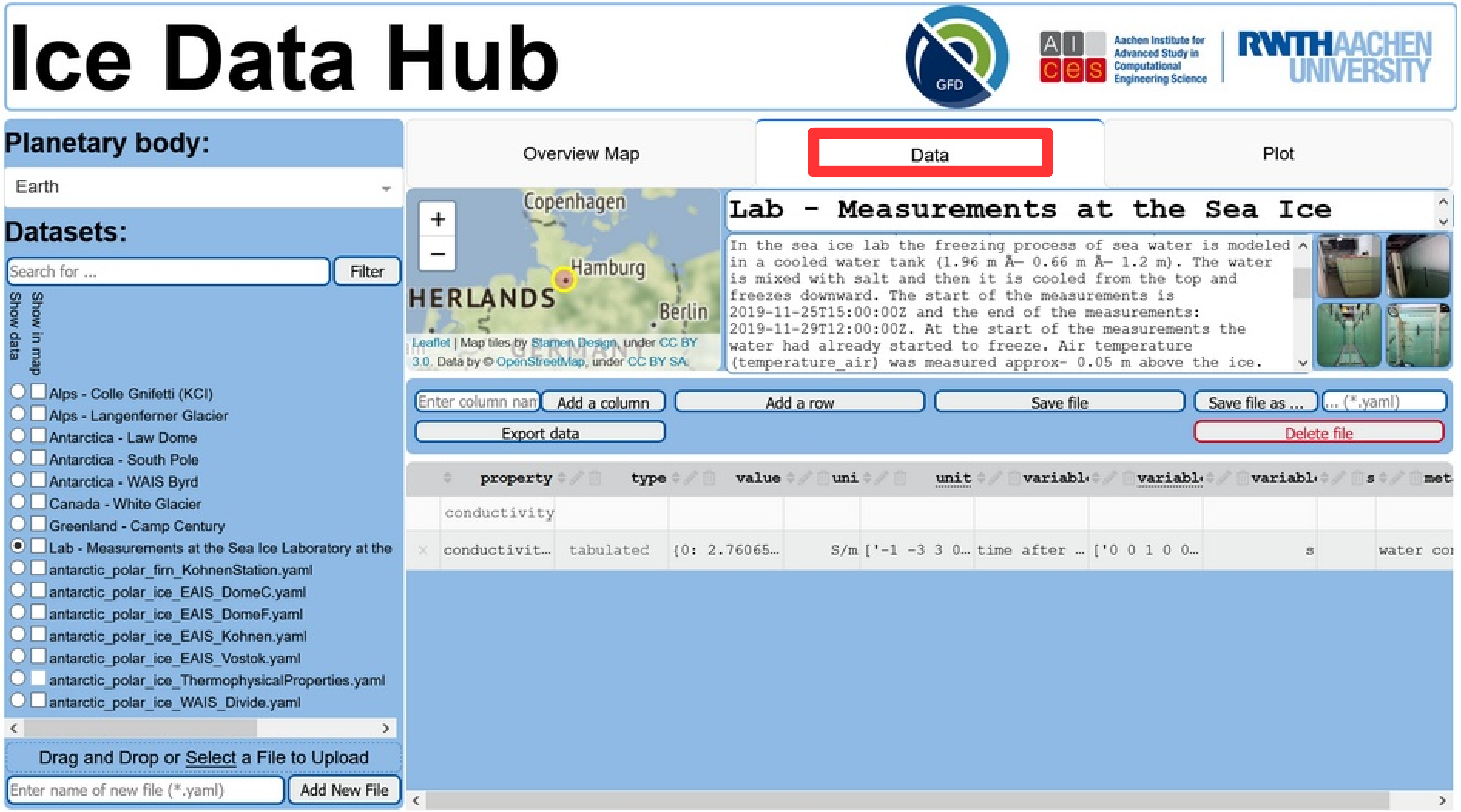
Prototype Test
Field Campaign
Laboratory Study
Ice Environment Model
Earth | Europa | Enceladus
Ice Data Hub
yaml-db
data
units
metadata
location
plain human readable
Python based
webbrowser based GUI
regime class
properties from yaml-db
methods: interpolation...
export routines
open source
data flow
dynamic
cryo-environment
structure / geometry
sensors / payload
Trajectory Model
Hazard Avoidance
Visualization & Mapping
Data Integration Algorithm
Wave Propagation Code

Ice Data Hub

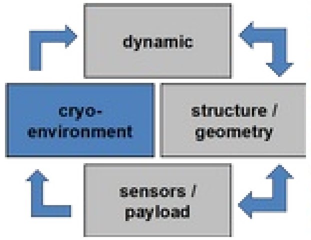

Ice Data Hub
GFD
Aachen Institute for Advanced Study in Computational Engineering Science
RWTH AACHEN UNIVERSITY
Planetary body:
Earth
Datasets:
Search for ...
Filter
Show data
Show in map
Alps - Colle Gnifetti (KCI)
Alps - Langenferner Glacier
Antarctica - Law Dome
Antarctica - South Pole
Antarctica - WAIS Byrd
Canada - White Glacier
Lab - Measurements at the Sea Ice Laboratory at the
antarctic_polar_ice_EAIS_DomeC.yaml
antarctic_polar_ice_EAIS_DomeF.yaml
antarctic_polar_ice_EAIS_Kohnen.yaml
antarctic_polar_ice_EAIS_Vostok.yaml
antarctic_polar_ice_ThermophysicalProperties.yaml
antarctic_polar_ice_WAIS_Divide.yaml
Drag and Drop or Select a File to Upload
Enter name of new file (*.yaml)
Add New File
Overview Map
Data
Plot
Asia
North America
Europe
Africa
South America
Australia
Antarctica
Leaflet | Map tiles by Stamen Design, under CC BY 3.0. Data by © OpenStreetMap, under CC BY SA.


dynamic
cryo-environment
structure / geometry
sensors / payload

Ice Data Hub

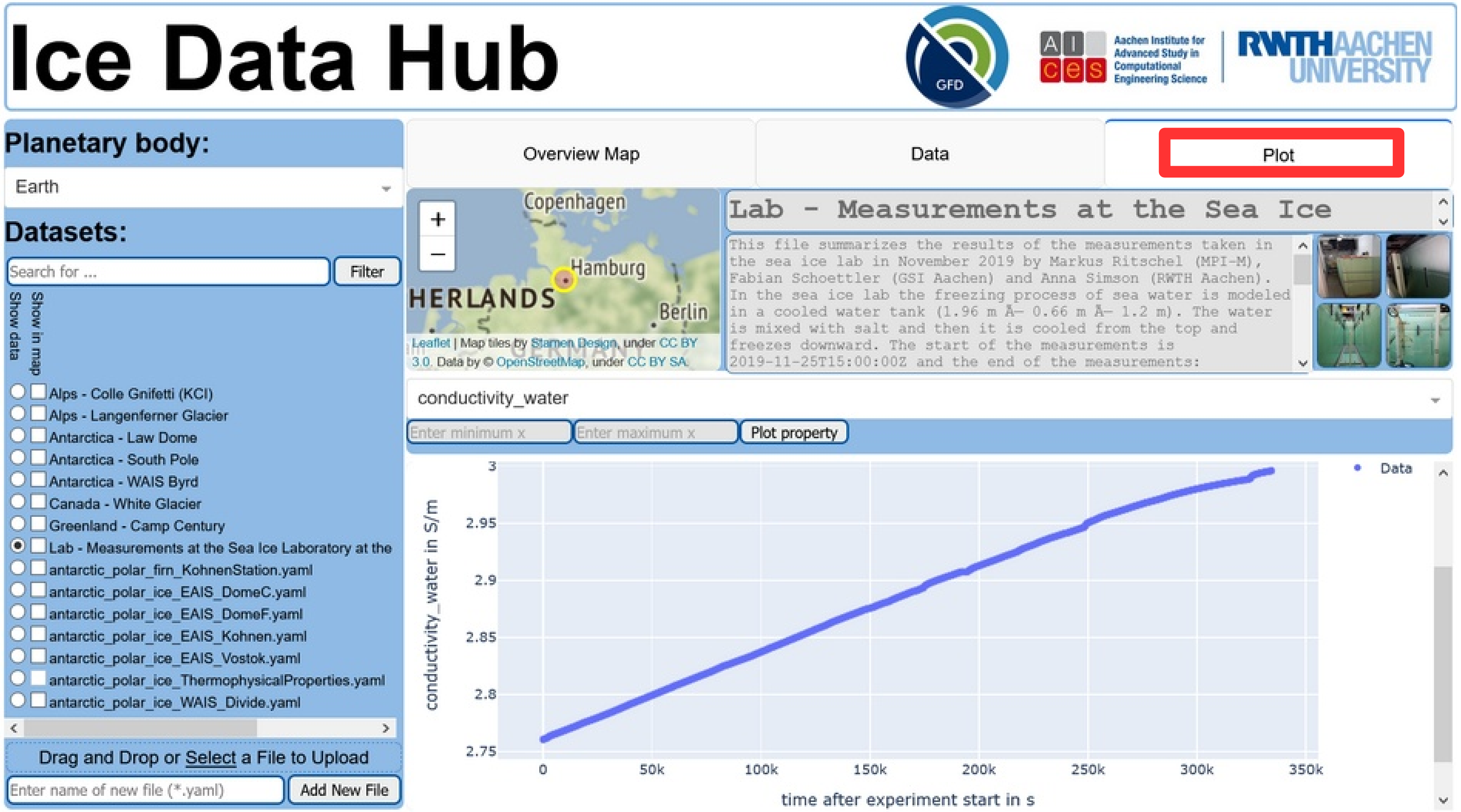


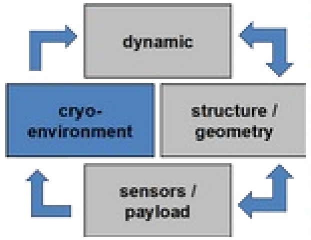
Ice Data Hub
Aachen Institute for Advanced Study in Computational Engineering Science
RWTH AACHEN UNIVERSITY
Planetary body:
Earth
Datasets:
Search for ...
Filter
Show data
Show in map
Alps - Colle Gnifetti (KCI)
Alps - Langenferner Glacier
Antarctica - Law Dome
Antarctica - South Pole
Antarctica - WAIS Byrd
Canada - White Glacier
Greenland - Camp Century
Lab - Measurements at the Sea Ice Laboratory at the
antarctic_polar_firn_KohnenStation.yaml
antarctic_polar_ice_EAIS_DomeC.yaml
antarctic_polar_ice_EAIS_DomeF.yaml
antarctic_polar_ice_EAIS_Kohnen.yaml
antarctic_polar_ice_EAIS_Vostok.yaml
antarctic_polar_ice_ThermophysicalProperties.yaml
antarctic_polar_ice_WAIS_Divide.yaml
Drag and Drop or Select a File to Upload
Enter name of new file (*.yaml)
Add New File
Overview Map
Data
Plot
Copenhagen
Hamburg
Berlin
HERLANDS
Leaflet | Map tiles by Stamen Design, under CC BY 3.0. Data by © OpenStreetMap, under CC BY SA.
Lab - Measurements at the Sea Ice
In the sea ice lab the freezing process of sea water is modeled in a cooled water tank (1.96 m Ã— 0.66 m Ã— 1.2 m). The water is mixed with salt and then it is cooled from the top and freezes downward. The start of the measurements is 2019-11-25T15:00:00Z and the end of the measurements: 2019-11-29T12:00:00Z. At the start of the measurements the water had already started to freeze. Air temperature (temperature_air) was measured approx- 0.05 m above the ice.
Enter column nan
Add a column
Add a row
Save file
Save file as ...
... (*.yaml)
Export data
Delete file
property
type
value
uni
unit
variabl
variabl
variabl
s
met
conductivity
conductivit...
tabulated
{0: 2.76065...
S/m
['-1 -3 3 0...
time after ...
['0 0 1 0 0...
s
water co



dynamic
cryo-environment
structure / geometry
sensors / payload

Ice Data Hub





GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Ice Data Hub


```yaml
# Data from sea ice lab Hamburg
# measurement start: 2019-11-25T15:00:00Z
# measurement end: 2019-11-29T12:00:00Z
# Anna Simson @ RWTH, September 2020
#
# name:
#   - type                          # [ scalar, array, tabulated, expression ]
#   - value                         # float
#   - dev_pdf                       # Gauss or other parametrized or tabulated PDF
#   - dev_value                     # hyperparameters of PDF or array
#   - unit_str                      # standard string to inidate unit
#   - unit  [ kg m s K A mol cd ]   # unit in systematically documented SI units
#   - variable                      # function argument
#   - variable_unit  [ kg m s K A mol cd ]  # unit in systematically documented SI units
#   - variable_unit_str             # standard string to indicate variable_unit
#   - source [ string ]             # data source
#   - meta_sys [ string ]           # meta data from systematic databases, e.g. NASA database
#   - meta_free [ string]           # free text meta data

name: "Lab - Measurements at the Sea Ice Laboratory at the MPI-M and Uni Hamburg"
description: "This file summarizes the results of the measurements taken in the sea ice lab in November 2019
Air temperature (temperature_air) was measured approx- 0.05 m above the ice. Water temperature (temperature_
8 temperature sensors are vertically aligned (0.02 m spacing) along a so called 'measurement harp'. 2 measur

location:
  type: coordinate
  value: {'N': 53.568033, 'E': 9.974234}
  source: Google Maps
  meta_free: The sea ice lab is located at the Geomatikum at Uni Hamburg

temperature_water:
  type: tabulated
  value: {0: 271.2196, 30: 271.2191, 60: 271.2191, 90: 271.2192, 120: 271.2186, 150: 271.2188, 180: 271.2189
  unit_str: K
  unit: [ 0 0 0 1 0 0 0 ]
  variable: time after experiment start
  variable_unit_str: s
  variable_unit: [ 0 0 1 0 0 0 0 ]
  meta_free: water temperature values, measured with CTD Seabird CTD SBE 37SM MicroCat

salinity_water:
  type: tabulated
  value: {0: 0.03530, 30: 0.03530, 60: 0.03530, 90: 0.03530, 120: 0.03530, 150: 0.03530, 180: 0.03530, 210:
  unit_str: '-'
  unit: [ 0 0 0 0 0 0 0 ]
  variable: time after experiment start
  variable_unit_str: s
  variable_unit: [ 0 0 1 0 0 0 0 ]
  meta_free: water salinity values as ratio ((parts per thousand) / 1000),  measured with CTD Seabird CTD SB

conductivity_water:
  type: tabulated
  value: {0: 2.76065, 30: 2.76066, 60: 2.76066, 90: 2.76071, 120: 2.76071, 150: 2.76074, 180: 2.76077, 210:
  unit_str: S/m
  unit: [ -1 -3 3 0 2 0 0 ]
  variable: time after experiment start
  variable_unit_str: s
  variable_unit: [ 0 0 1 0 0 0 0 ]
  meta_free: water conductivity,  measured with CTD Seabird CTD SBE 37SM MicroCat
```


emacs@[redacted]

File Edit Options Buffers Tools Python Help

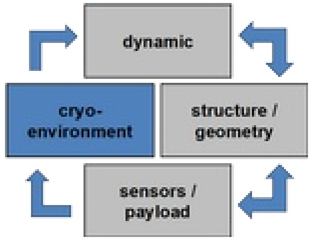
Save Undo

```python
# code using data from ice data hub

from ice_data_hub.library.ice_regimes import Regime

scenario = Regime()
scenario.load_ice_props('lab_hamburg_Nov2019.yaml')
time = 180 # sec
temperature_water = scenario.get_scalar_prop_value(name_props='temperature_water', variable=time)
salinity_water = scenario.get_scalar_prop_value(name_props='salinity_water', variable=time)
conductivity_water = scenario.get_scalar_prop_value(name_props='conductivity_water', variable=time)
```

U:**- code_snippet_RegimeClass2.py   All L10   (Python ElDoc)

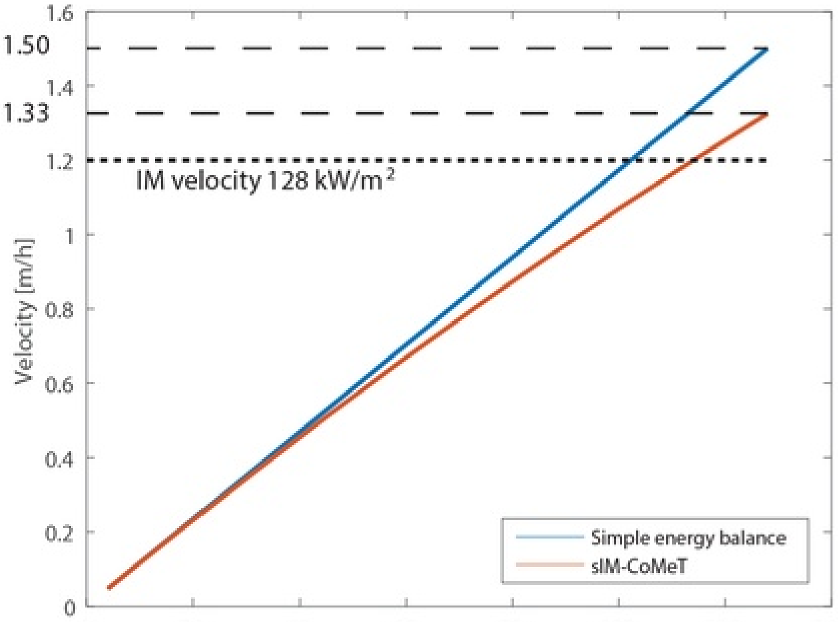


Validation of the computational dynamics prediction

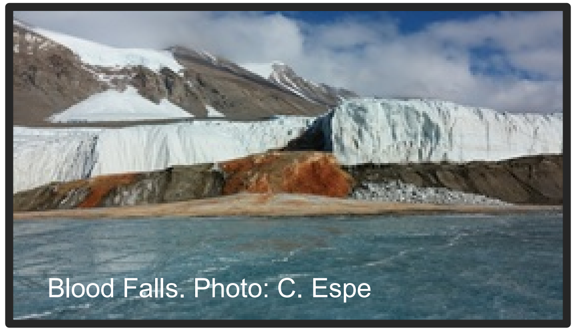
Lab-based validation:

Schueller, Kowalski, Raback, 2016, Int. J. Heat and Mass

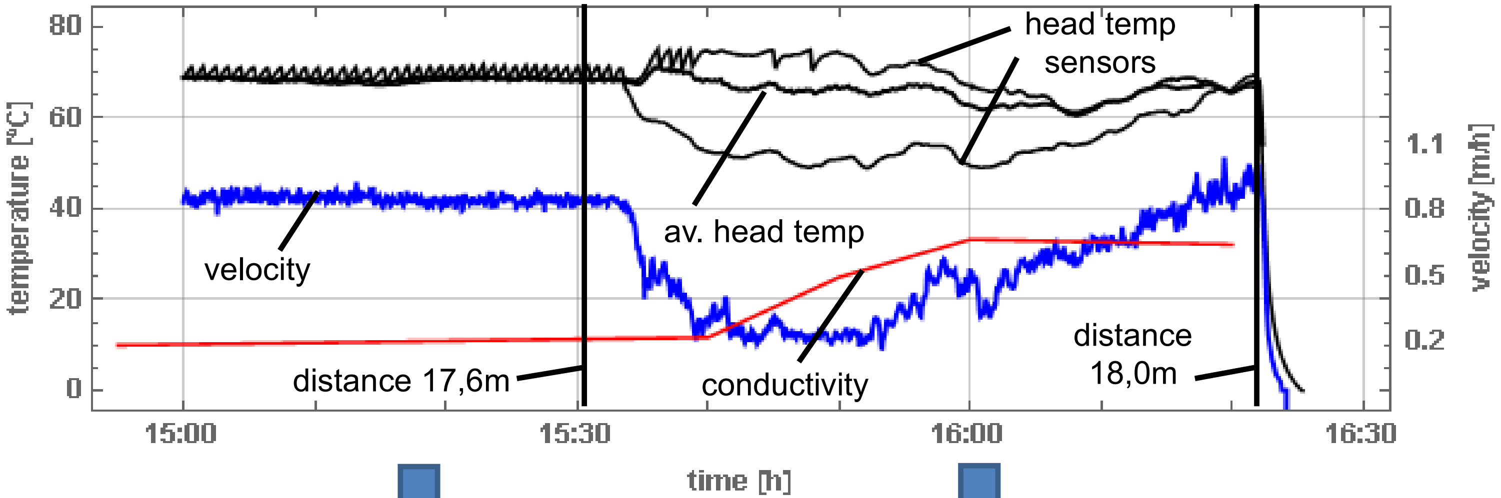
Field-based validation:



convective losses explain part of the efficiency losses as observed in the field



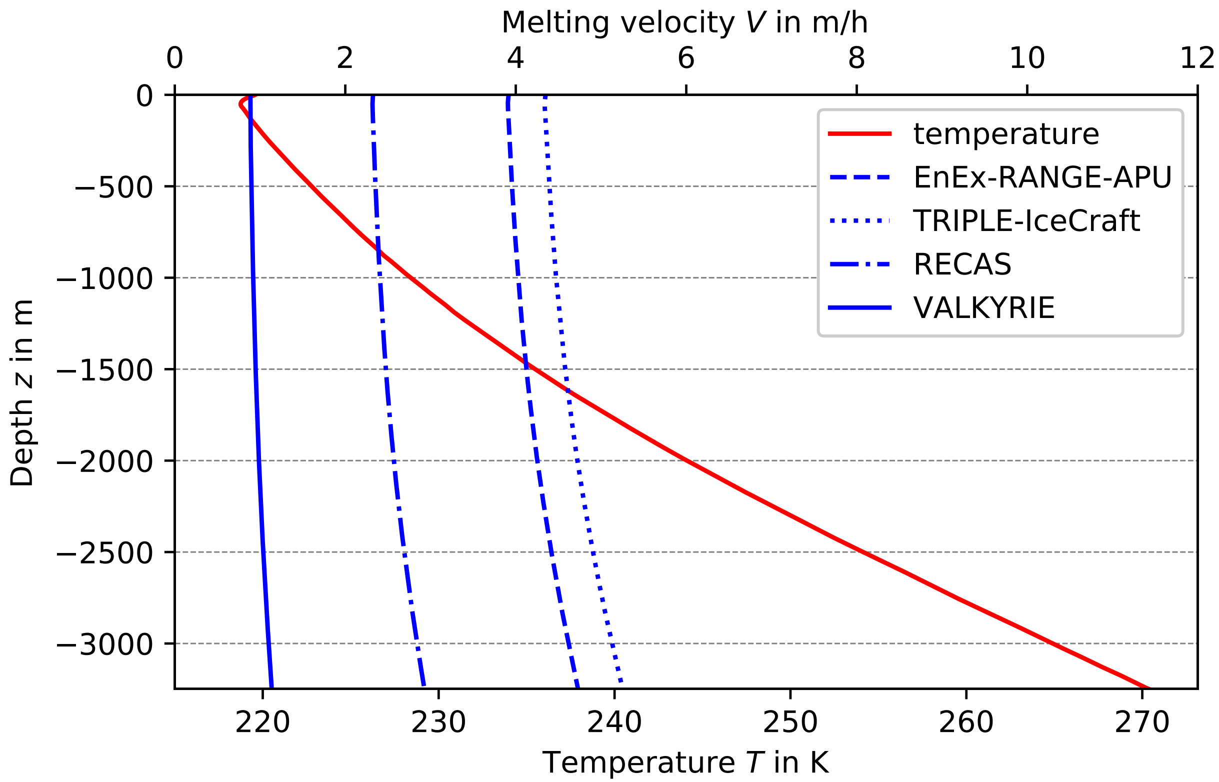
Next steps:

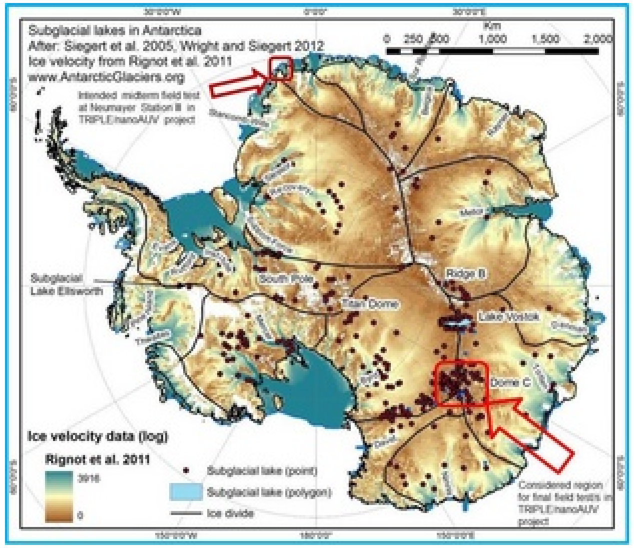


- **equilibrium contact melting**
- **penetration of a water reservoir**

DLR
FH AACHEN UNIVERSITY OF APPLIED SCIENCES
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN
AICES Aachen Institute for Advanced Study in Computational Engineering Science
RWTH AACHEN UNIVERSITY

Terrestrial analogue studies to prepare for space mission





DomeC

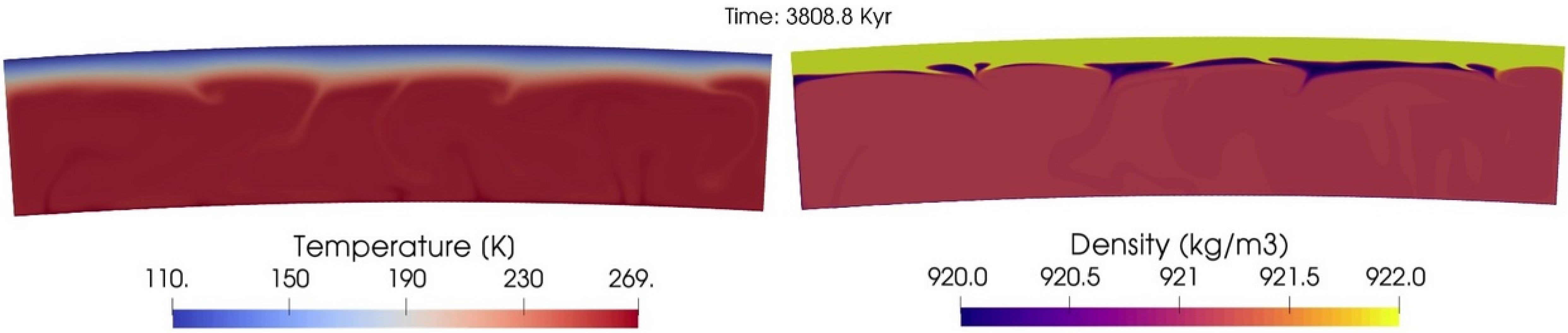
TRIPLE analogue mission planned for 2026

Boxberg et al., 2021, 10.23689/fidgeo-3968

Dome C Antarctica	**Transit time in d**	**Total required energy in MWh**	**Average energy per meter of ice in kWh/m**
EnEx-RANGE APU	32.3	2.230	0.686
RECAS	53.5	6.425	1.978
TRIPLE-IceCraft	29.1	13.944	4.293
VALKYRIE	139.6	16.749	5.157

Europa Ice Shell Dynamics, Heat Transport & Mixing

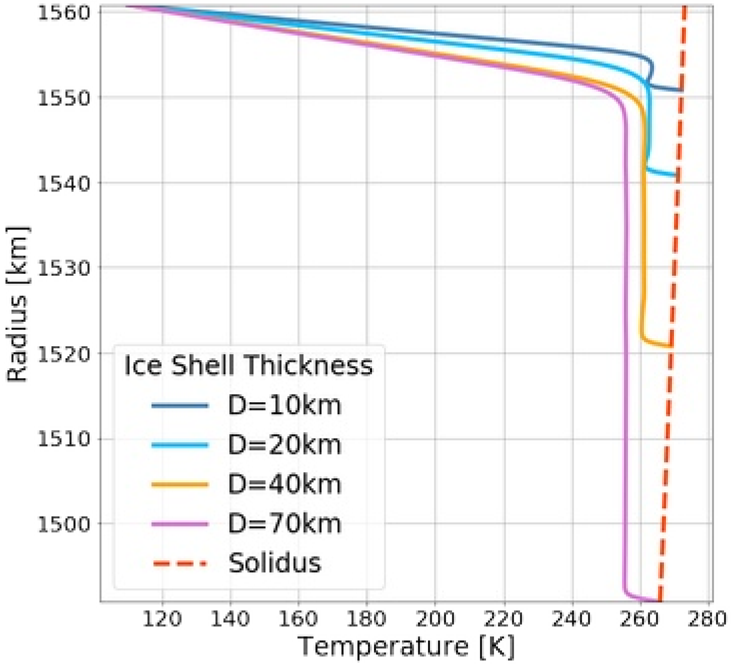
- We use the geodynamics code GAIA to model the heat transport and mixing of impurities in Europa‘s ice shell
- Density variations due to salinity are modeled using tracer particles
- The simulation shows a model with an ice shell thickness of 40 km and a density contrast of 23 kg/m^3, corresponding to 5% density increase due to salinity
- A high salt concentration remains trapped in the stagnant layer that forms close to the surface due to the low temperature, and hence high viscosity



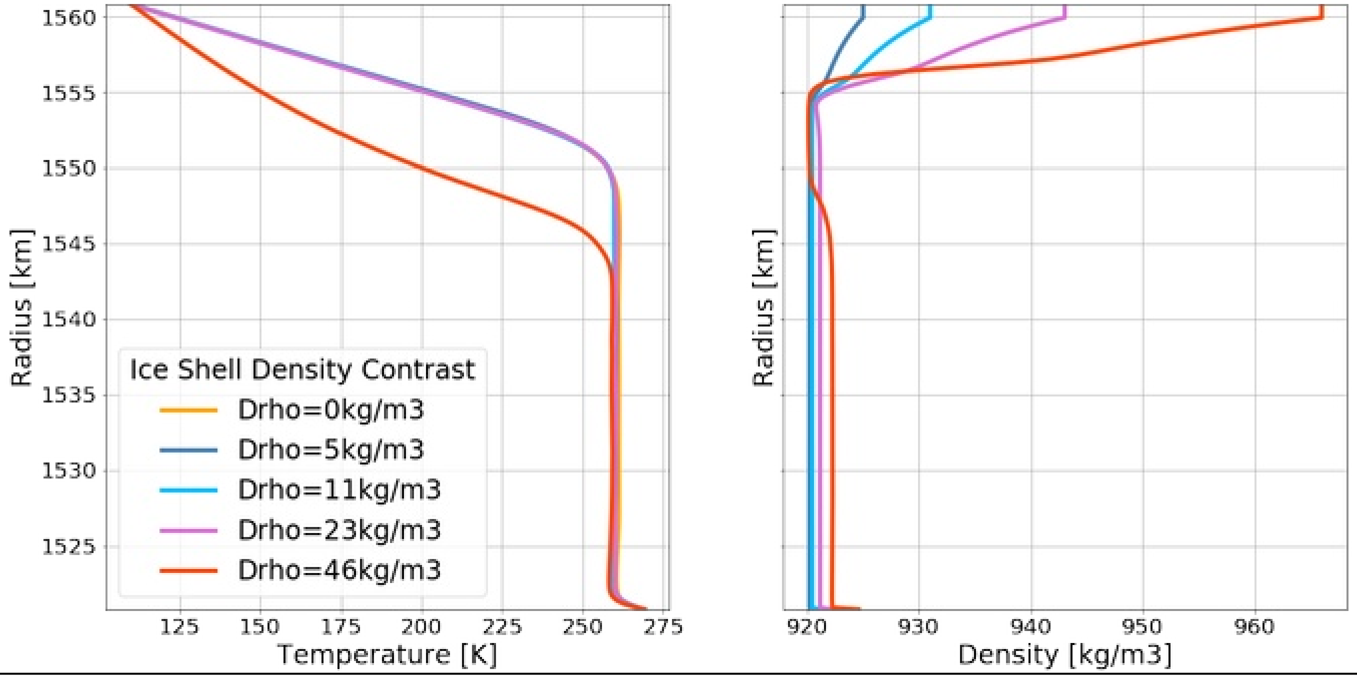
Europa Ice Shell Models

- We test various scenarios to evaluate the temperature distribution in the ice shell of Europa
- Since the thickness of the ice shell is poorly known, we test the effects of 10 – 70 km ice shell thickness on the efficiency of heat transport and hence on the thermal state of the ice shell
- The amount of impurities (e.g. salts) has been varied to test the effect of 0.5 to 5% density variations due to salinity on the temperature distribution.

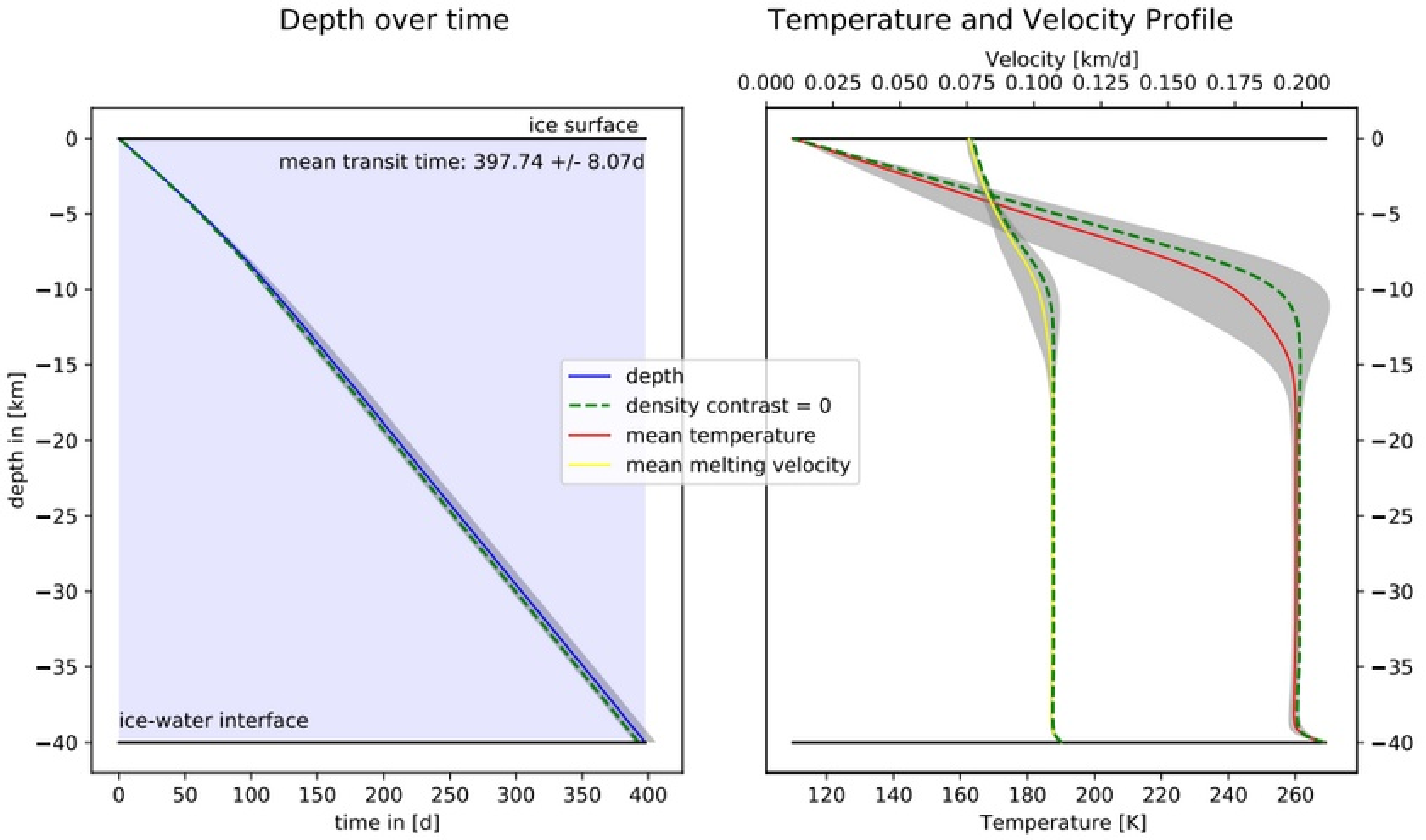
Effects of the ice shell thickness



Effects of compositional variations due to salts



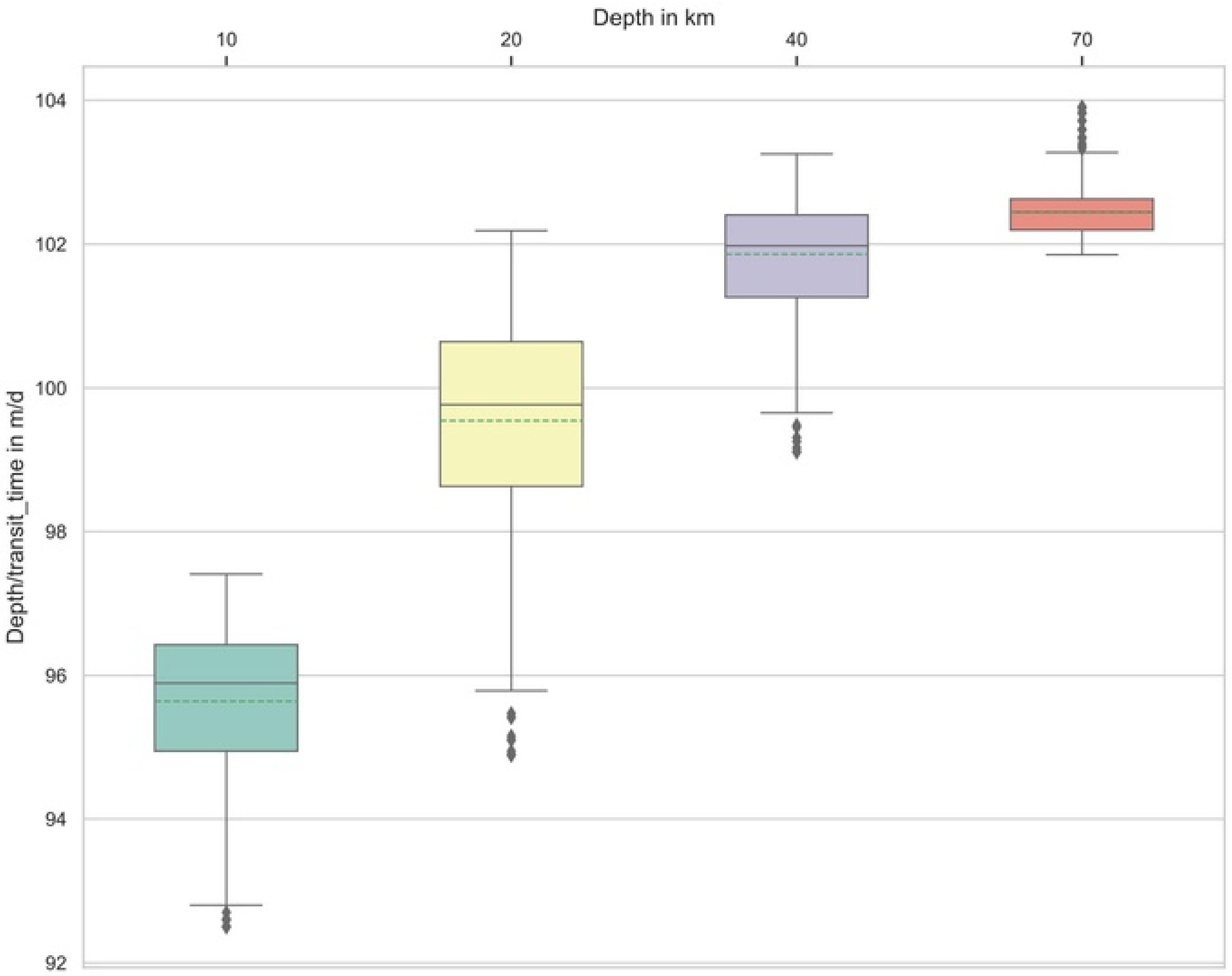
Melting Probe Trajectories on Europa



Boxberg et al., in prep.

DLR | FH Aachen University of Applied Sciences | Georg-August-Universität Göttingen | Aachen Institute for Advanced Study in Computational Engineering Science | RWTH Aachen University

Melting Probe Trajectories on Europa



Boxberg et al., in prep.

Summary

- Europa is a promising candidate to search for extraterrestrial life
- Cryobots can be used to access the ocean below the ice
- Trajectories can be modeled in terms of
  - Efficiency / velocity modeling
  - High-fidelity modeling
- Ice Data Hub was developed to store any data related to ice and provide interfaces to any kind of modeling software
- The ice of Europa is poorly constrained, but models are available to make some predictions

Our trajectory models can be used to provide mission parameters like transit time and energy consumption to prepare terrestrial analogue missions as well as future extraterrestrial missions.

NASA/JPL-Caltech/SETI Institute

Thank you for your attention!

AICES Aachen Institute for Advanced Study in Computational Engineering Science

RWTH AACHEN UNIVERSITY

FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

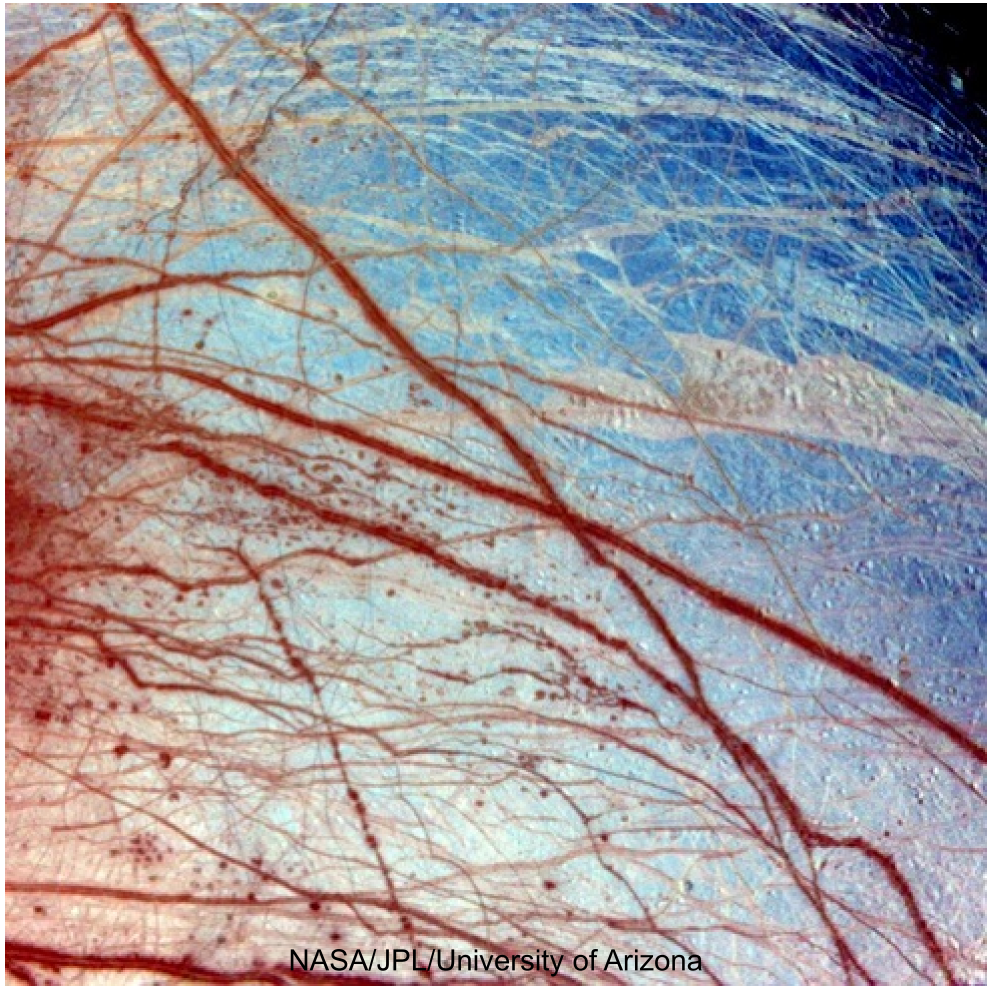
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

DLR

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages


NASA/JPL/University of Arizona