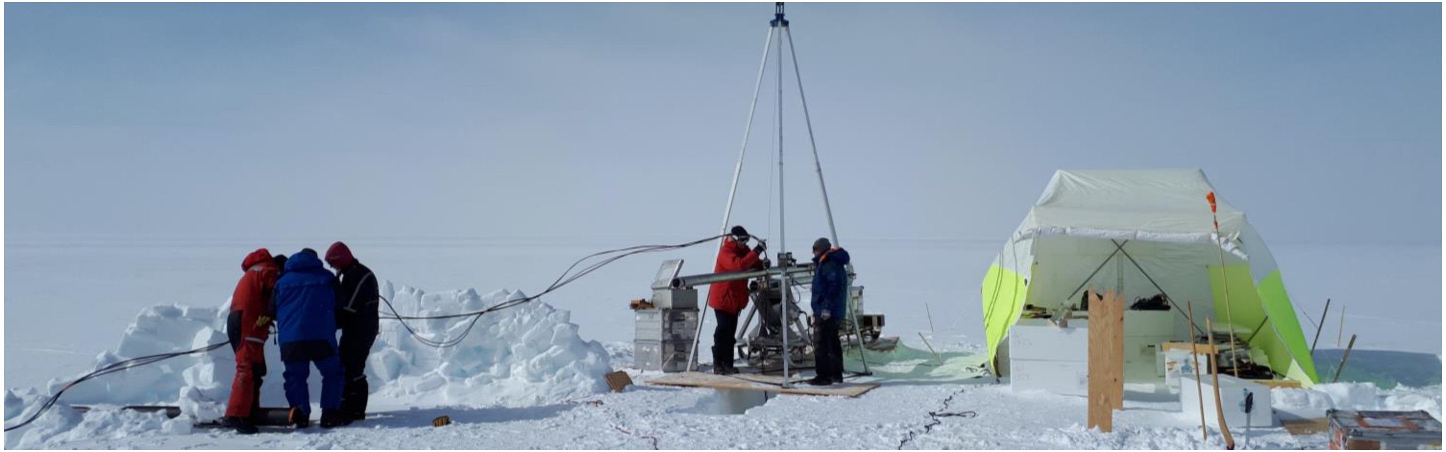
ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

X-ray comuputer tomography of polar firn

How snow transforms to ice



Johannes Freitag

EastGripS6 Greenland 2018
Drill and firn-air pumping site

HOKKAIDO UNIVERSITY

HU-UB-workshop
11th Dec 2023

Universität Bremen

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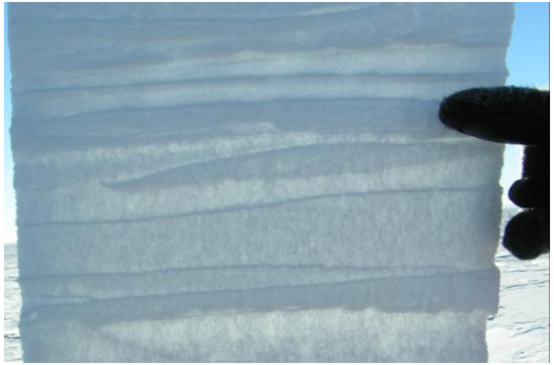
Motivation

- **Surface mass balance/ satellite altimetry**
  - Temporal evolution of firn column heights (**firn densification models, firn microstructure**)

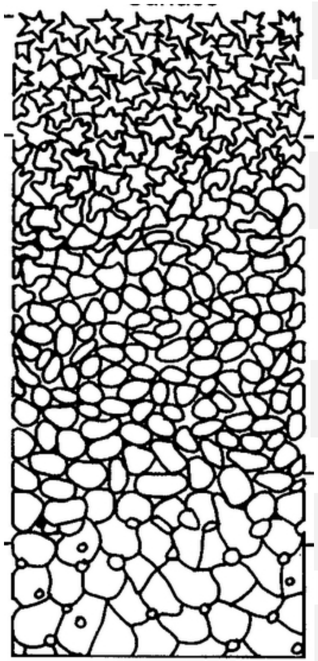
- **Ice as climate archive**
  - Ice core dating:
    - Gas chronology: gas-ice delta age estimates (Parrenin et al. Xxx) (**firn densification models, firn microstructure**)
    - Ice chronology: orbital tuning (Kawamura et al. Xxx) (**firn microstructure**)
  - Temperature reconstruction for Glacial periods (Buizert et al. 2022) (**firn densification models**)

Firnification: isothermal hot pressure sintering



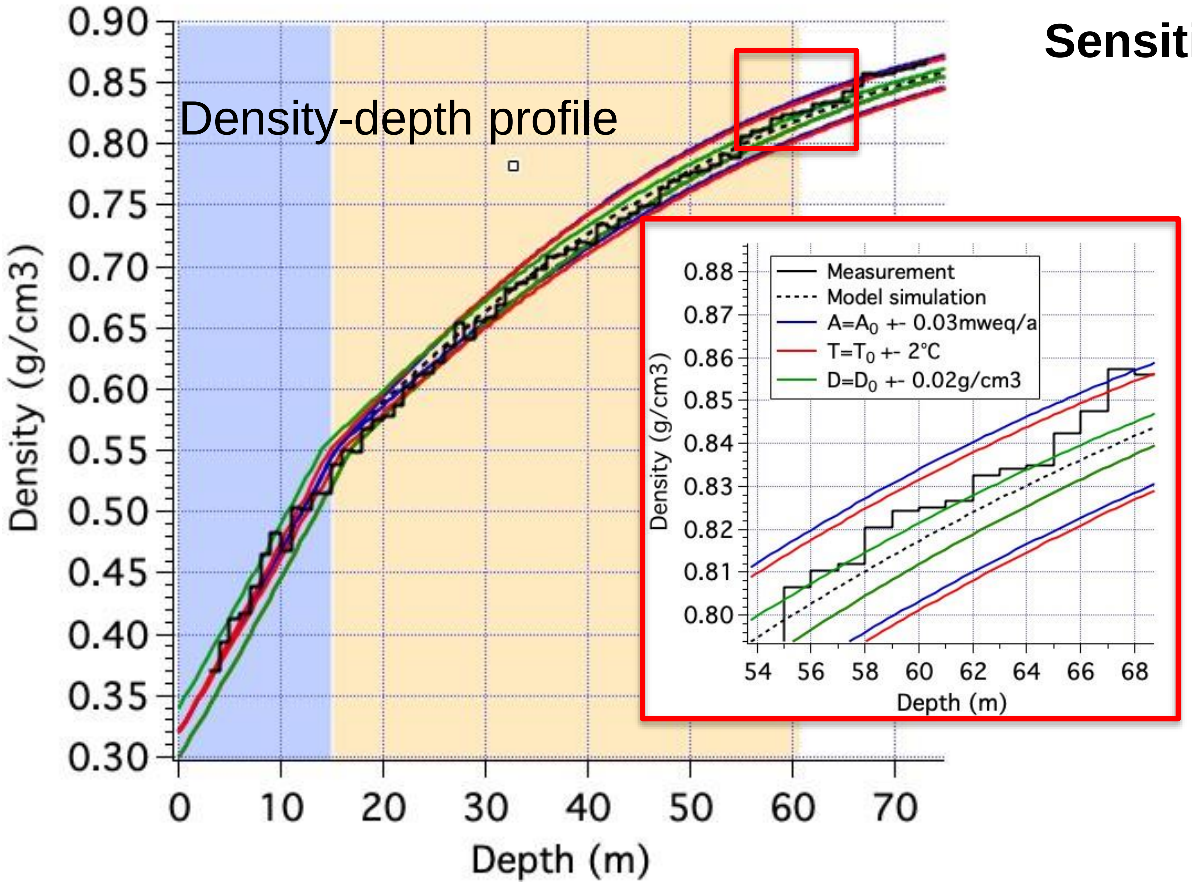
0.3m

layered firn column



Firn Density $\rho = (1 - porosity) * \rho_{ice}$

Firn densification: driving factors



Sensitivity study using empirical Herron-Langway-Model

Data set: Firn core EGRIPS6
density 1m avg,
Nord-East-Greenland

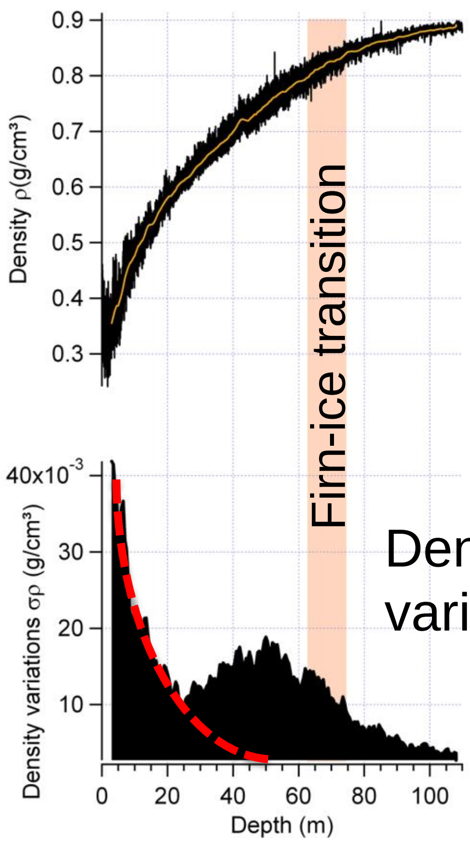
Accumulation rate:
A=0.13m weq/a+- 0.03m weq/a
Δdepth(0.83g/cm³): -+4m

Temperature:
T=-30°C+-2°C
Δdepth(0.83g/cm³): -+4m

Surface density:
D=0.320g/cm³ +-0.02g/cm³
Δdepth(0.83g/cm³): -+1m

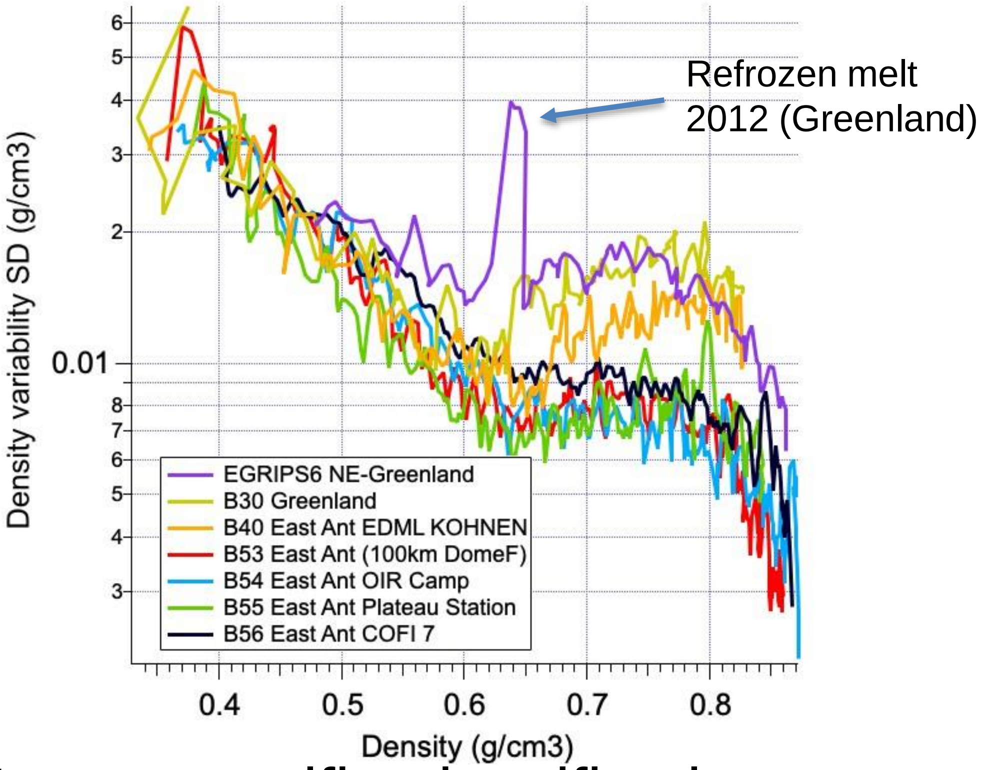
What is the impact of **impurities** and **microstructure** on densification ?

Impurity / microstructure effects – some hints



Density variations

expected

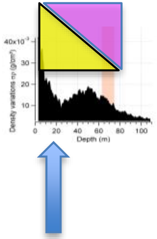


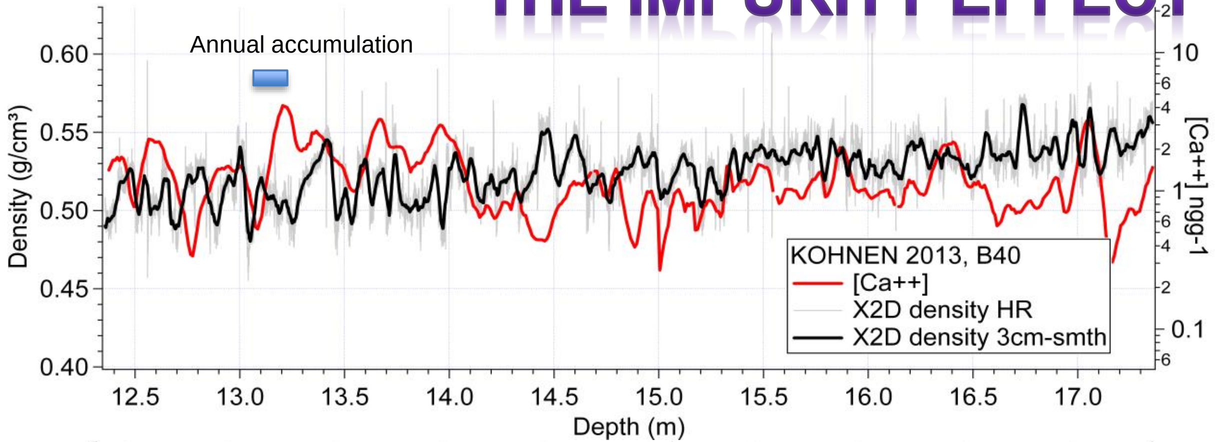
→ Layer specific densification

Synchronisation between Density and [Ca++] with depth

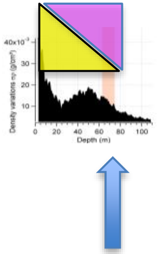
THE IMPURITY EFFECT

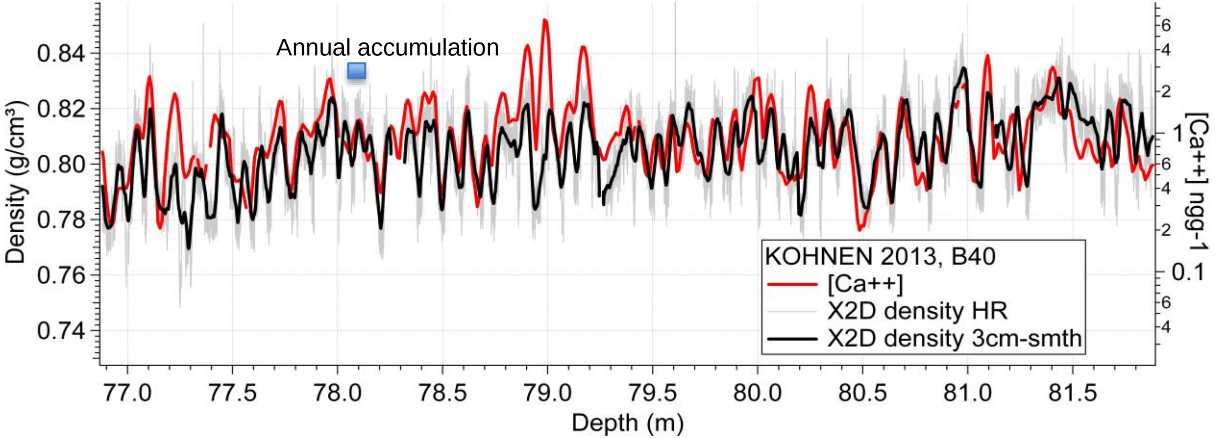
Shallow firn



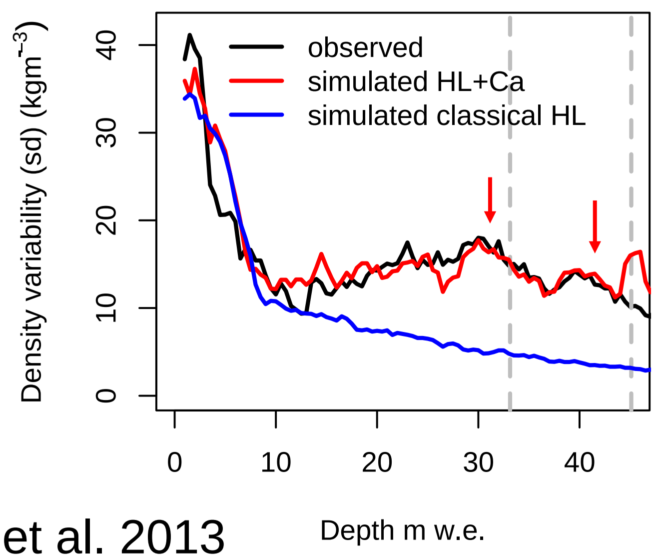


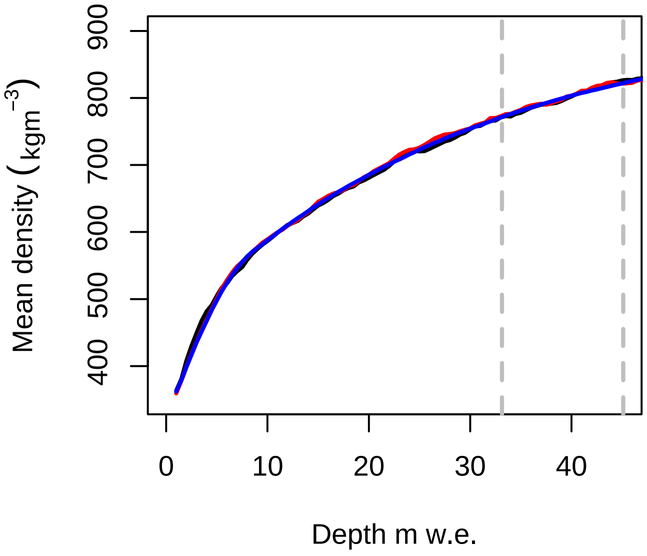
Deep firn



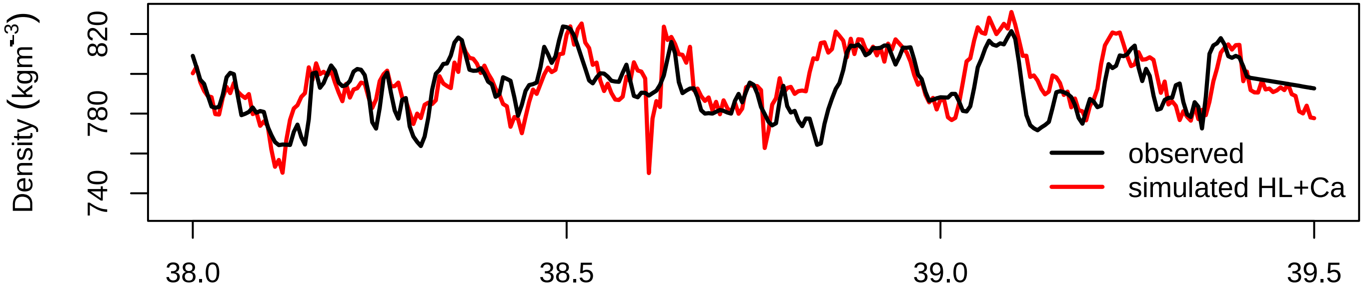


Impurity-controlled firn densification: exHL-model





Freitag et al. 2013



B29
N-Greenland

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Objectives

What is the role of **microstructure** during densification?

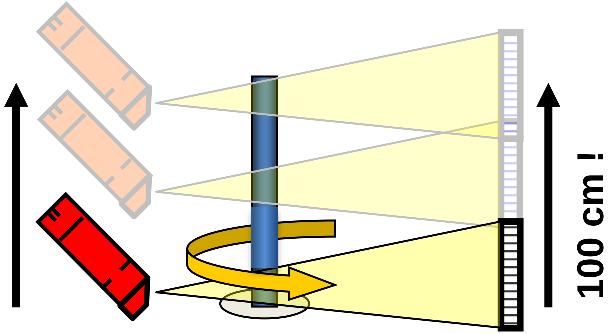
Continuous high-resolution profiles of structure parameters along firn columns (+ impurity and firn air profiles)

Bridging scales from 100 µm to 100 meter (6 orders of magnitude)

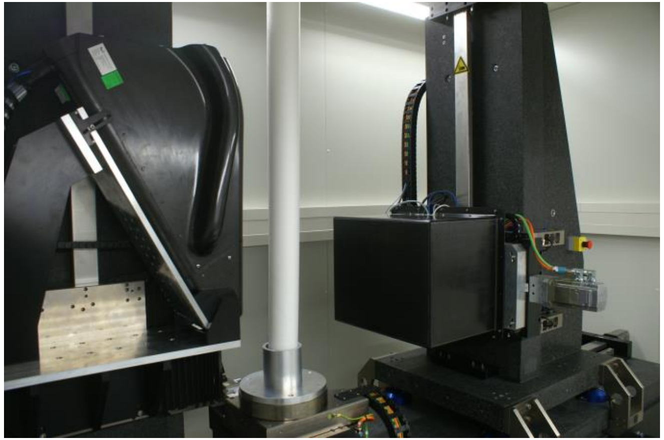
Approach

- fast and efficient X-ray computer tomography
- applicable to (archived) ice cores

AWI-ice storage facility



Schematic of helical x-rayCT



AWI-IceCT

Performance parameters of iceCT

1m core segment (Ø=10cm):

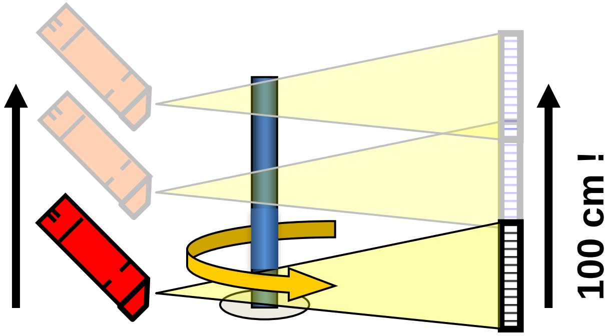
Resolution of 3d-volume reconstruction	Measurement time	Storage consumption of reconstructed volume
120µm	120 min	8 GB
60µm	>=1200 min (>=1day)	64 GB
30µm	>=12000 min (>=8days)	512 GB

Prediction for 140m firn core:

120µm	16800 min (~47 days (3m/day))	800 GB
60µm	>=168000 min (~280 days (1m/2days)	6.4 TB
30µm	>=1680000 min (>=4 years)	51.2 TB

Helical flyby X-ray-CT

Vertical axis source



Vertical axis detector

continuous movement of axes and rotation table during scaning

Performance parameters of iceCT

1m core segment (Ø=10cm):

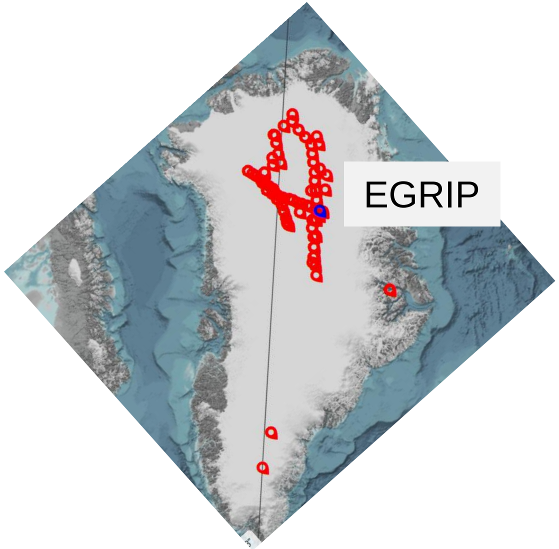
Resolution of 3d-volume reconstruction	Measurement time	Storage consumption of reconstructed volume
120µm	25 min! (<<120min)	8 GB
60µm	>=1200 min (>=1day)	64 GB
30µm	>=12000 min (>=8days)	512 GB

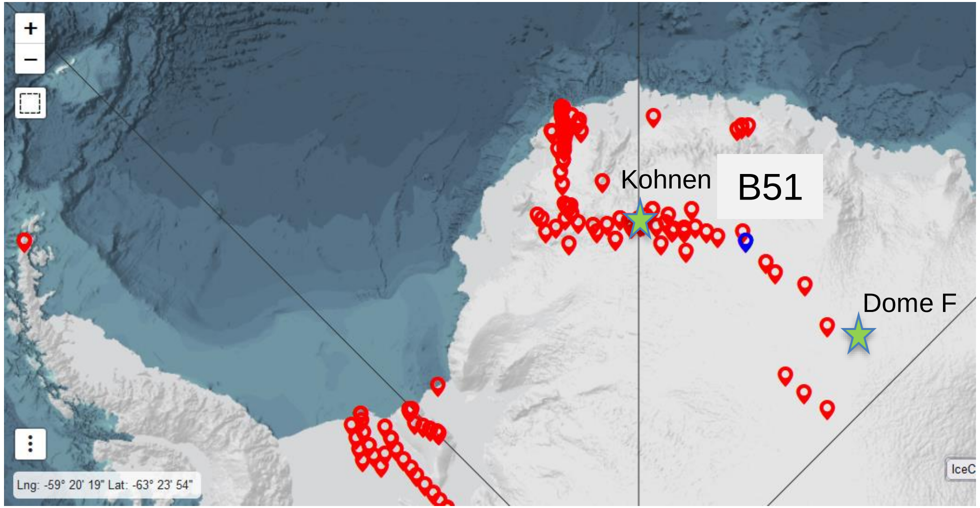
Prediction for 140m firn core:

120µm	3500 min (~14 d)	800 GB
60µm	>=120000 min (>=100days)	6.4 TB
30µm		

Helical flyby X-Ray-CT

Sample selection





EGRIP-S6 (75.6°N, 36°W)
T_{annual} ≈ -30°C
A = 138 mm weq/a
$\rho_{surface}$= 0.335 g/cm3

B51 (75.1°S, 15.4°E)
T_{annual} ≈ -50°C
A ≈ 40 mm weq/a
$\rho_{surface}$ = 0.372 g/cm3

Image processing

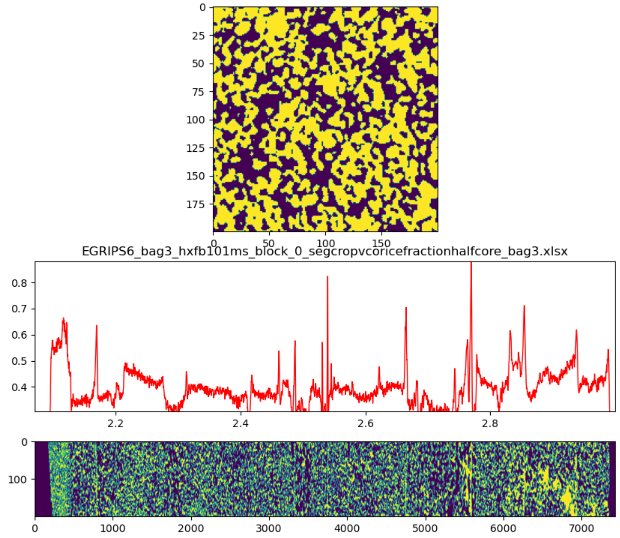
Volume image reconstruction of filtered fan-beam back projections

Correction of beam hardening / intensity gradient

Binarisation / Segmentation

Inspection and depth assignment

Calculation of structure parameters



Comparison of calculated and measured weight

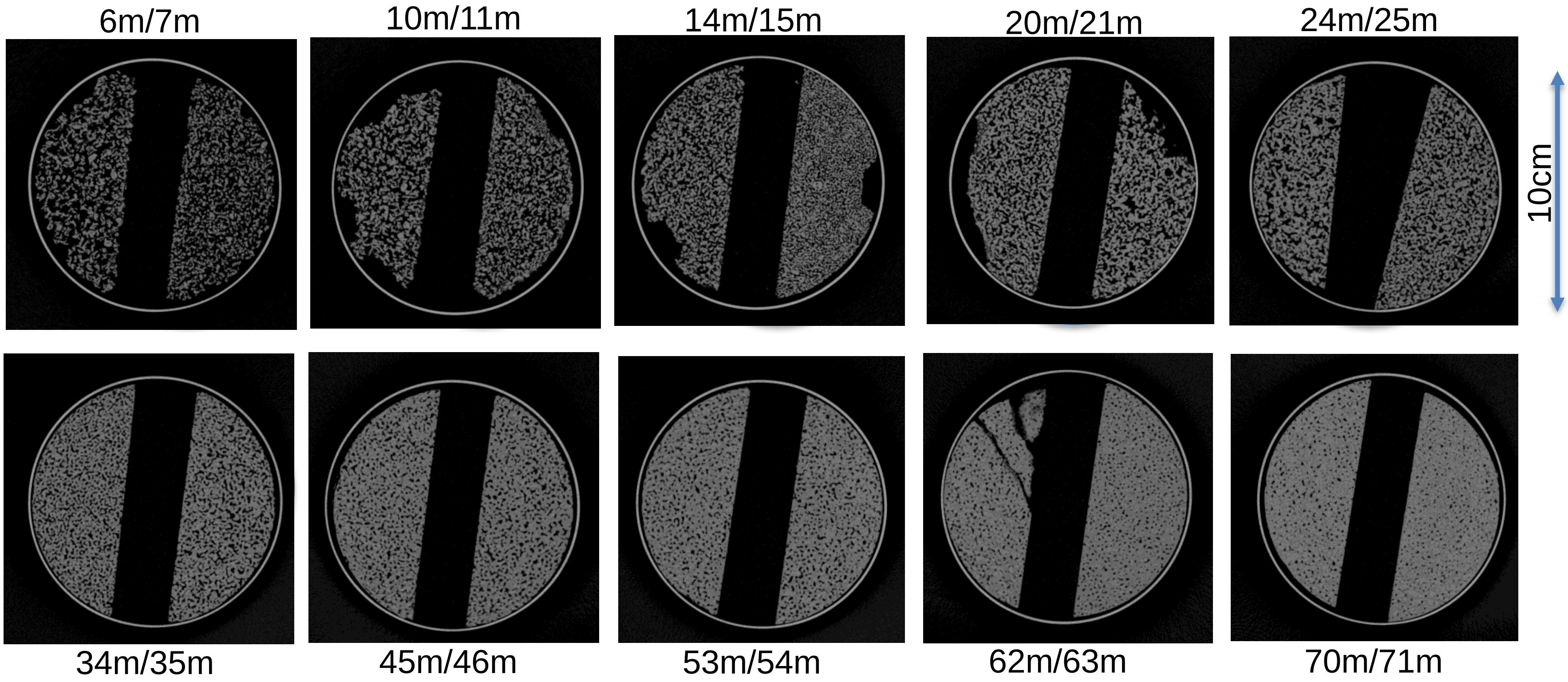
Global thresholding

Ice volume weight calculation

Structure describing parameters

- Porosity, **density**: *n*, *ρ*
- Intercept lengths: l_x, l_y, l_z : averaged dimension of ice phase in x,y,z
- **Anisotropy *a*** $:= (l_x+l_y)/\,2\,l_z$ ***a***==1 (isotrop), ***a***<1 (vertically aligned)
  a>1 (horizontally aligned)
- **Euler number *E*** $:= B-R$: number of isolated objects *B* minus number of redundant connections *R* (measure of connectivity and bubble numbers) ***E***<<0: highly connected pore space, fine grained structures ***E***==0 (Coordination number = 2, independent of B!) ***E***>>0 dominance of isolated objects
- **Spherical cluster size** := volume weighted diameter of spherical elements that maximal fit into the structure (iteratively derived from erosion/dilation-filter applications with increasing element size)

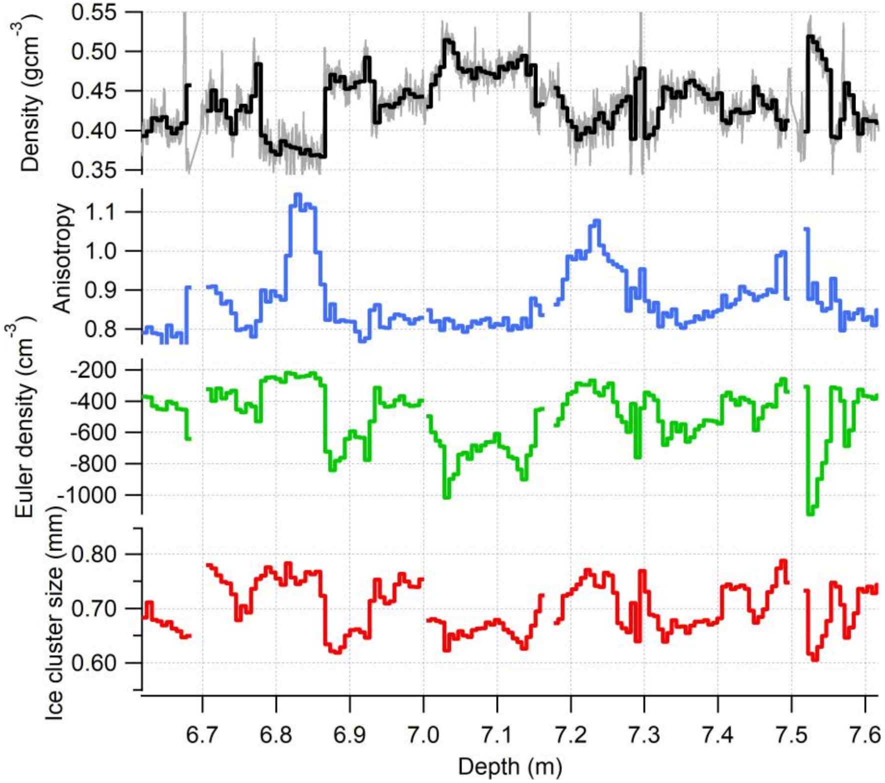
Reconstructed cross sections



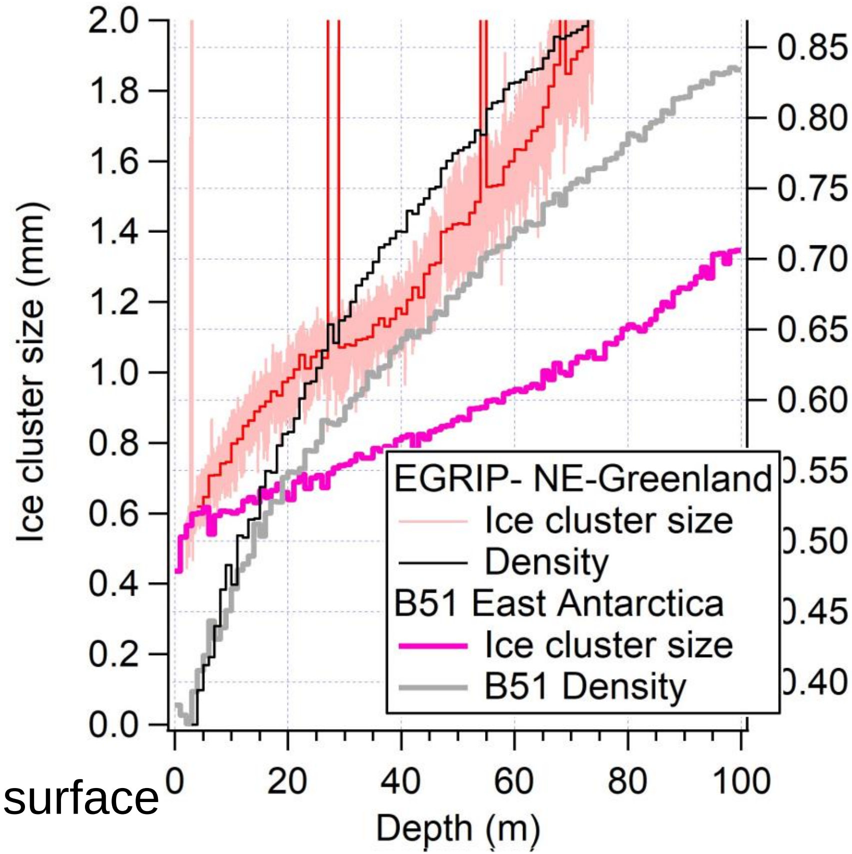
~1 million reconstructed slices per core

1m profile of structure parameters

EGRIPS6 NE-Greenland

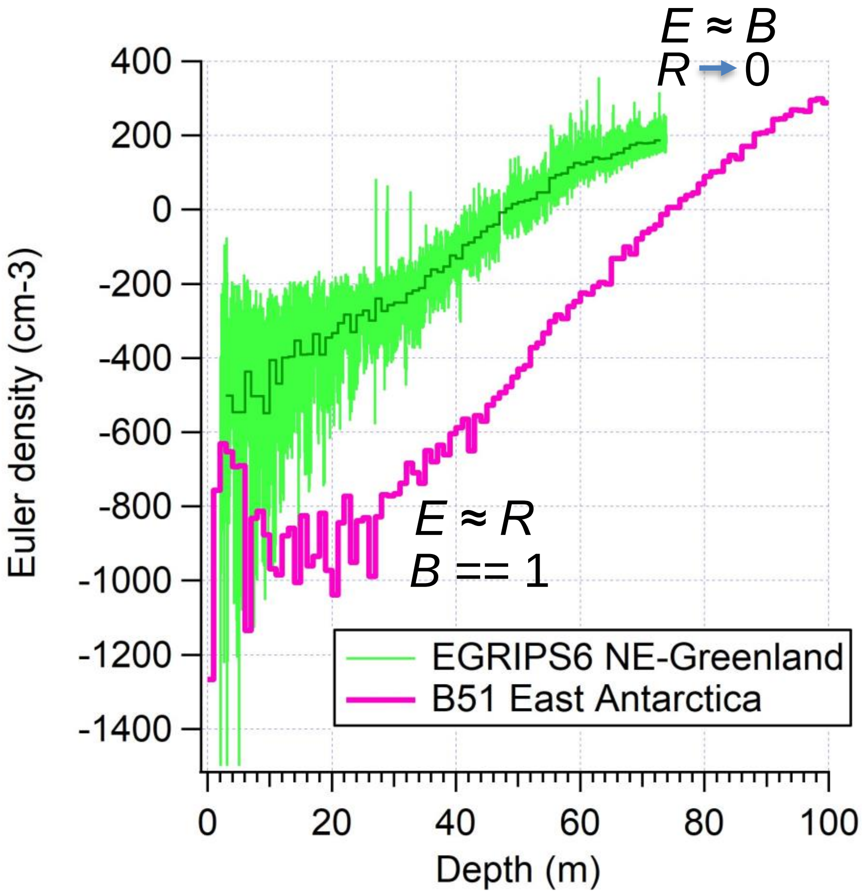


Ice cluster size



surface

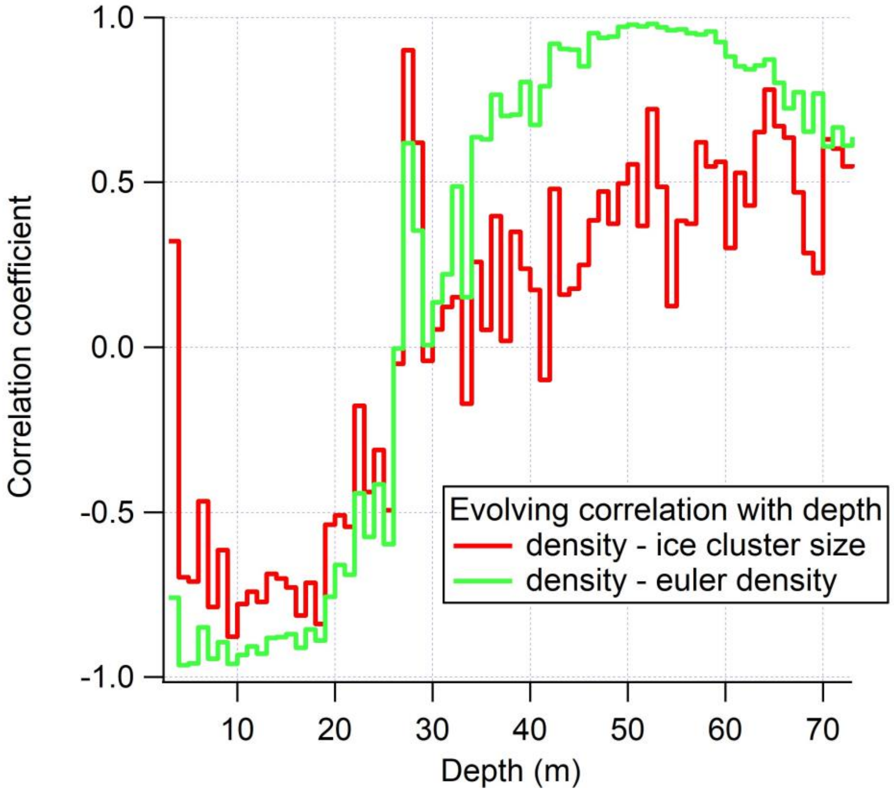
Connectivity



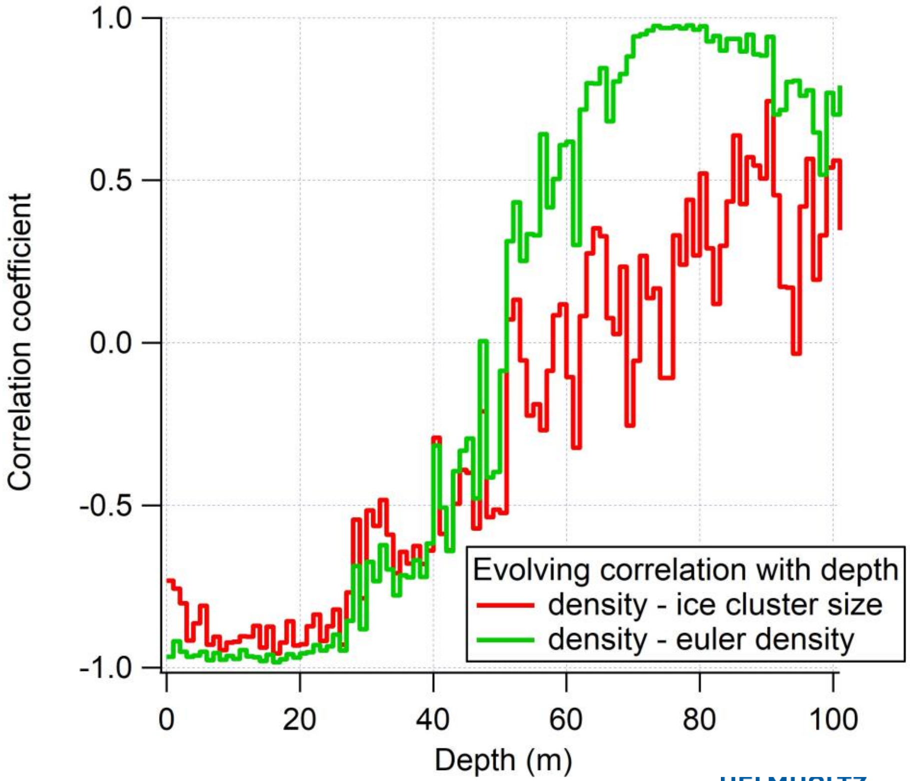
Euler number *E*:= *B*-*R*: number of isolated objects *B* minus number of redundant connections *R* (measure of connectivity and bubble numbers)

Evolving density correlations with depth

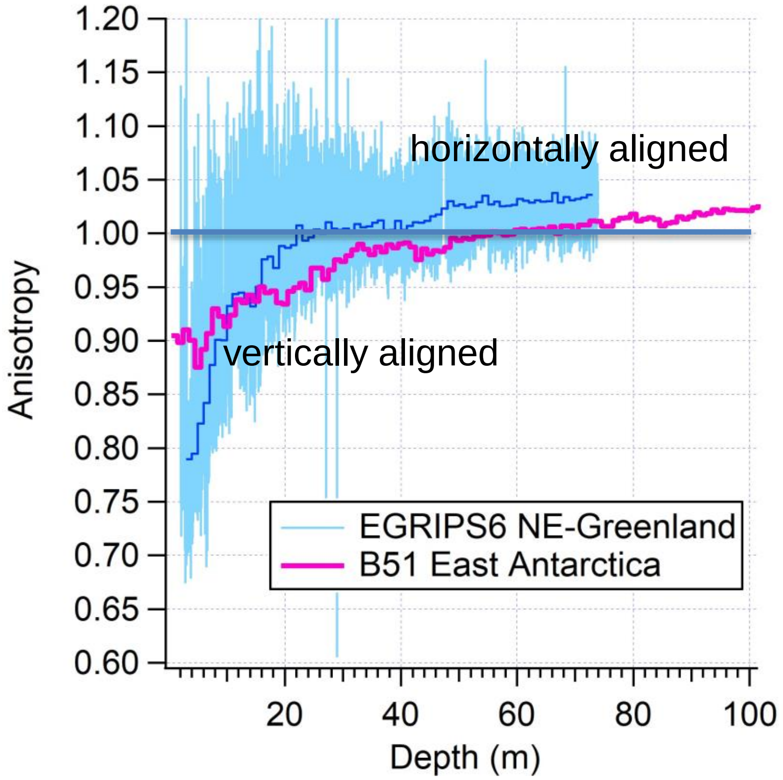
EGRIP S6 NE-Greenland



B51 East Antarctica

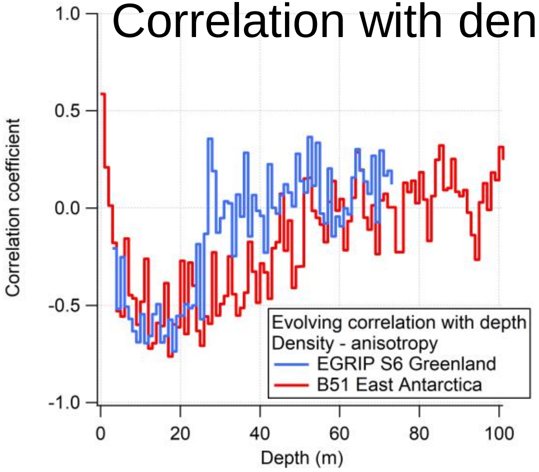


Structural anisotropy



a==1 (isotrop),
a<1 (vertically aligned)
a>1 (horizontally aligned)

Correlation with density



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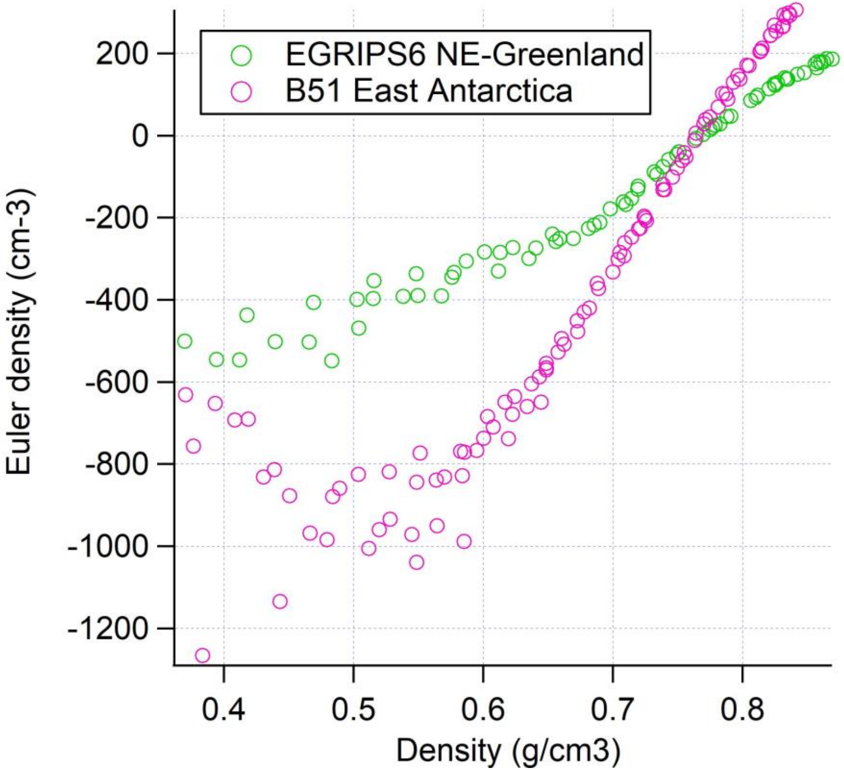
Connectivity vs density



Coordination number Z = 2R/B = 2(E-B)/B
R: redundant connections
B: isolated objects

If E==0 -> Z=2 independent of B

Both curves intersect at E ≈ 0 !
⇒ Close-off at similar densities for different microstructures

Summary

- First data sets of microstructure evolution over firn columns
- Several fundamental relationships:
  - Non-uniform increase of ice cluster size with depth (EGRIP-S6, associated with stage I to stage II transition)
  - Distinct correlation of microstructure and density in shallow firn (stage I)
  - Density-correlation shifts of anisotropy, euler number and ice cluster size with depth
  - Layers of larger cluster sizes show higher densities in deep firn (stage II)
  - Disappearing vertical anisotropy with depth

Outlook

- Invitation of the audience to visit the CT-Lab @ AWI-Bremerhaven

- Compilation of further data sets from further ice cores
- Comparison study with impurity records
- Improvements in CT-segmentation (super resolution)
- Investigation of bubble formation and number in context of initial microstructure

Thank you!