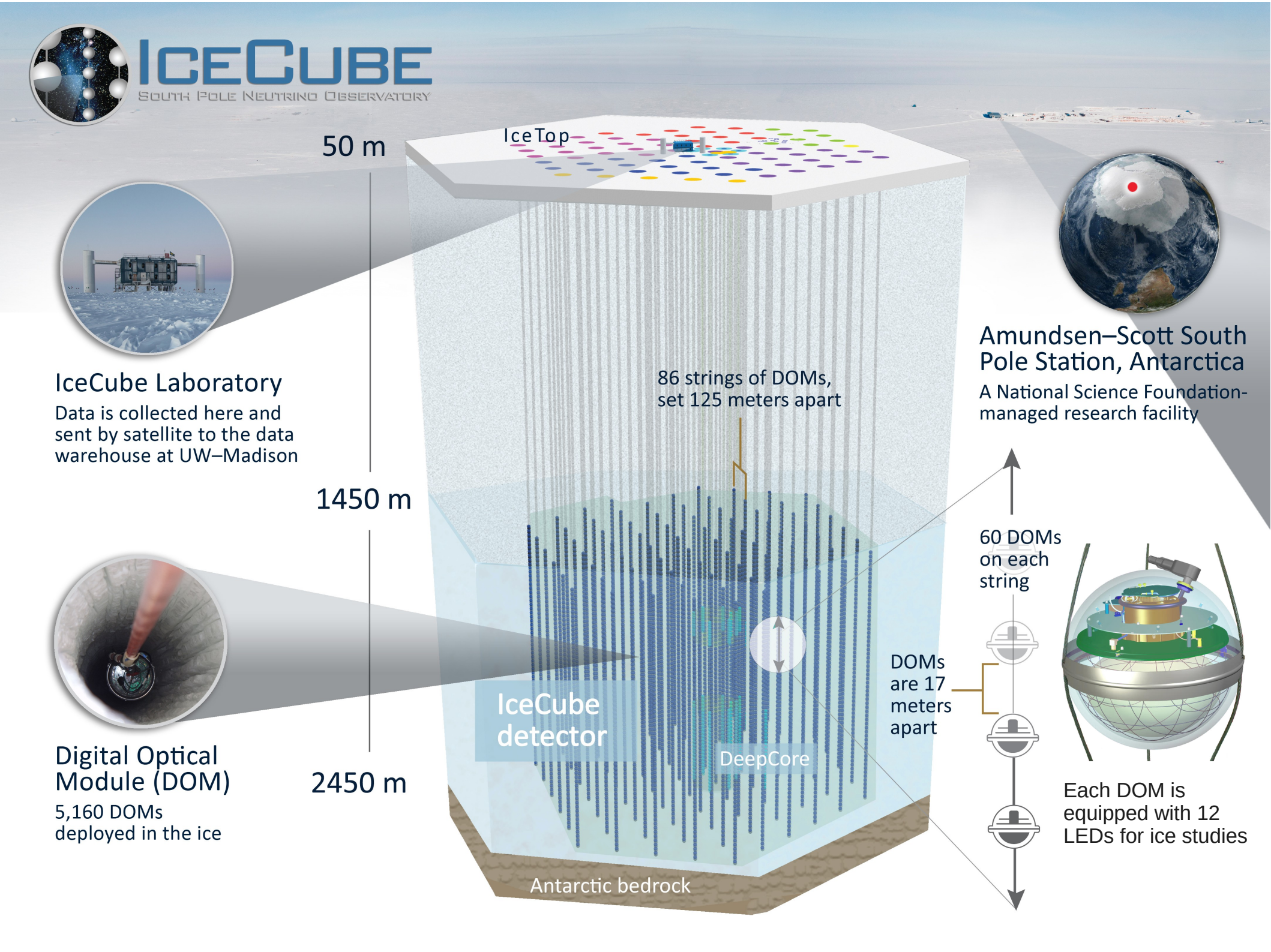
III. Physikalisches Institut

RWTH AACHEN UNIVERSITY

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

The ice anisotropy:
Connecting IceCube's large scale observations to the microstructure of ice cores

Martin Rongen
Polar Science Workshop
September 2017


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
1450 m
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock
Each DOM is equipped with 12 LEDs for ice studies

Highlights of ice calibration

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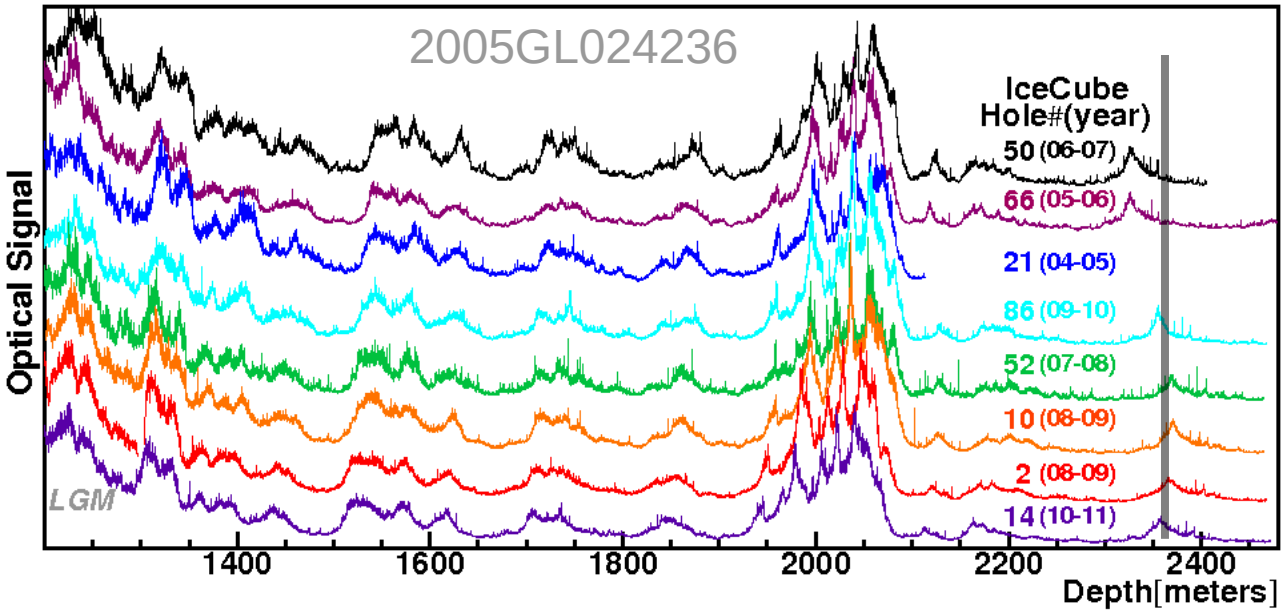
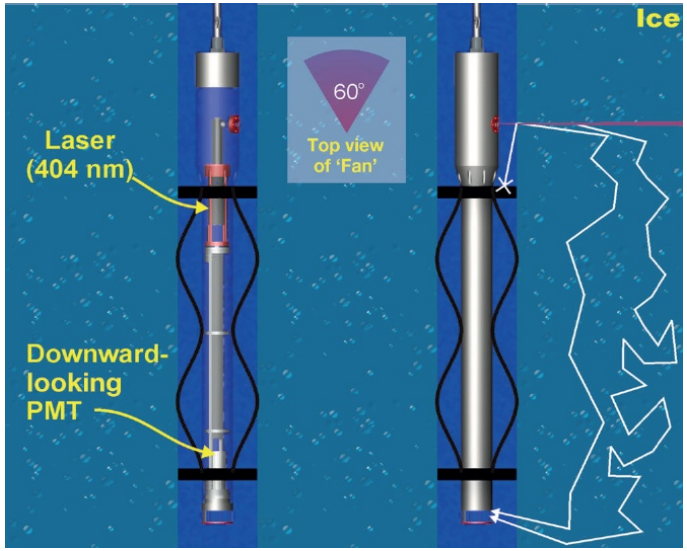
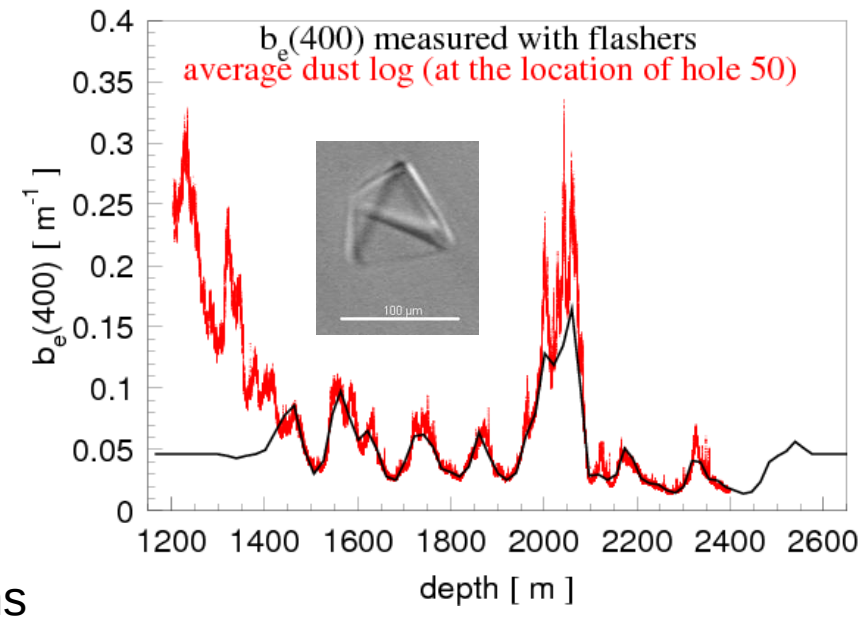




- 8 IceCube holes dust logged by Ryan Bay
  → high resolution image of the relative concentration of optical impurities
- Below 1500m near perfect optical properties as air bubbles get incorporated into ice fabric (craigite)
- Depth offset between logs shows ice tilt, distortion of ice layers due to underlying bedrock
- Combination of dust logger data and LED analysis yields absolute absorption / scattering length in 10m bins



Rivers of ice

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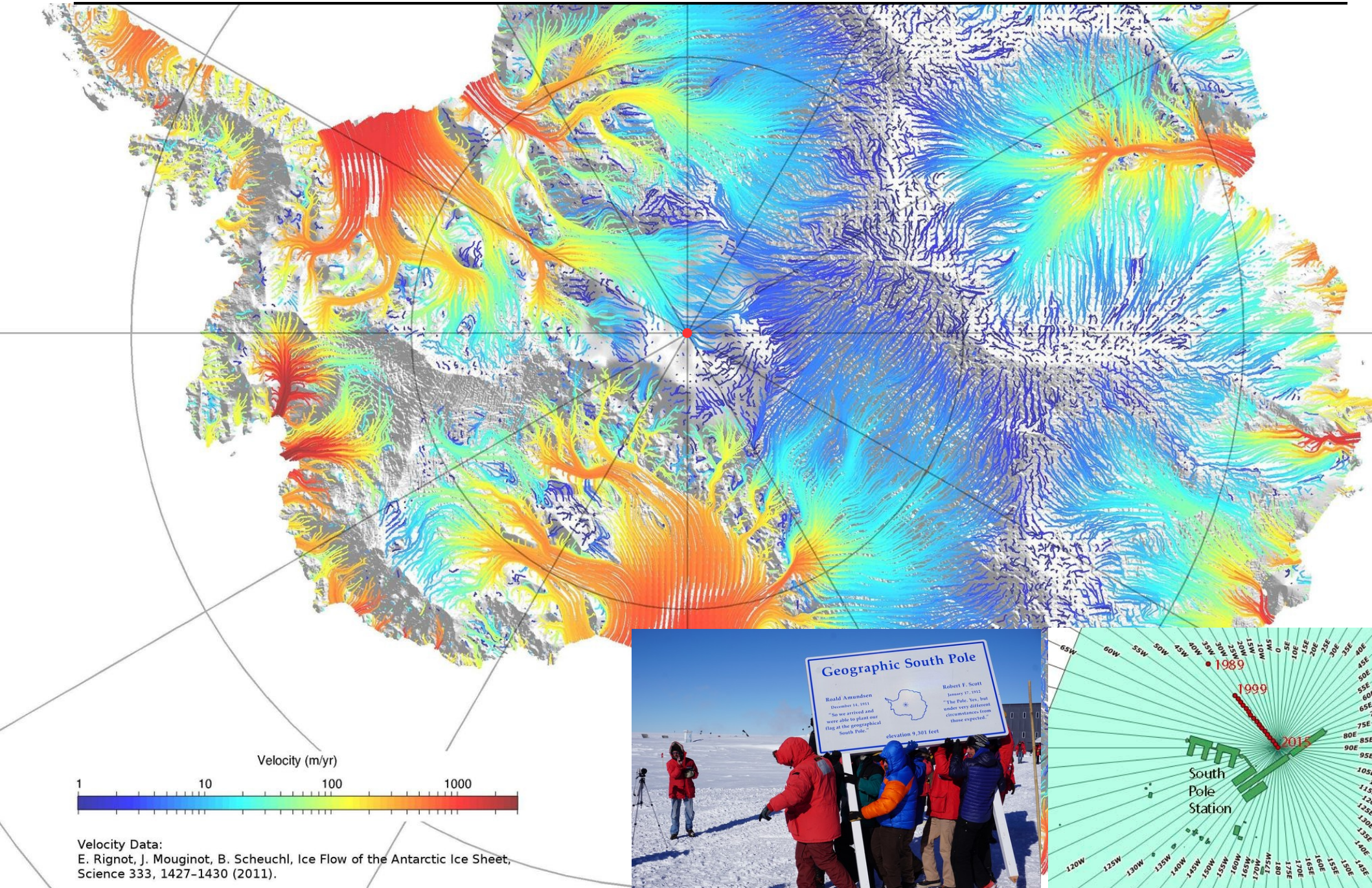

The ice anisotropy

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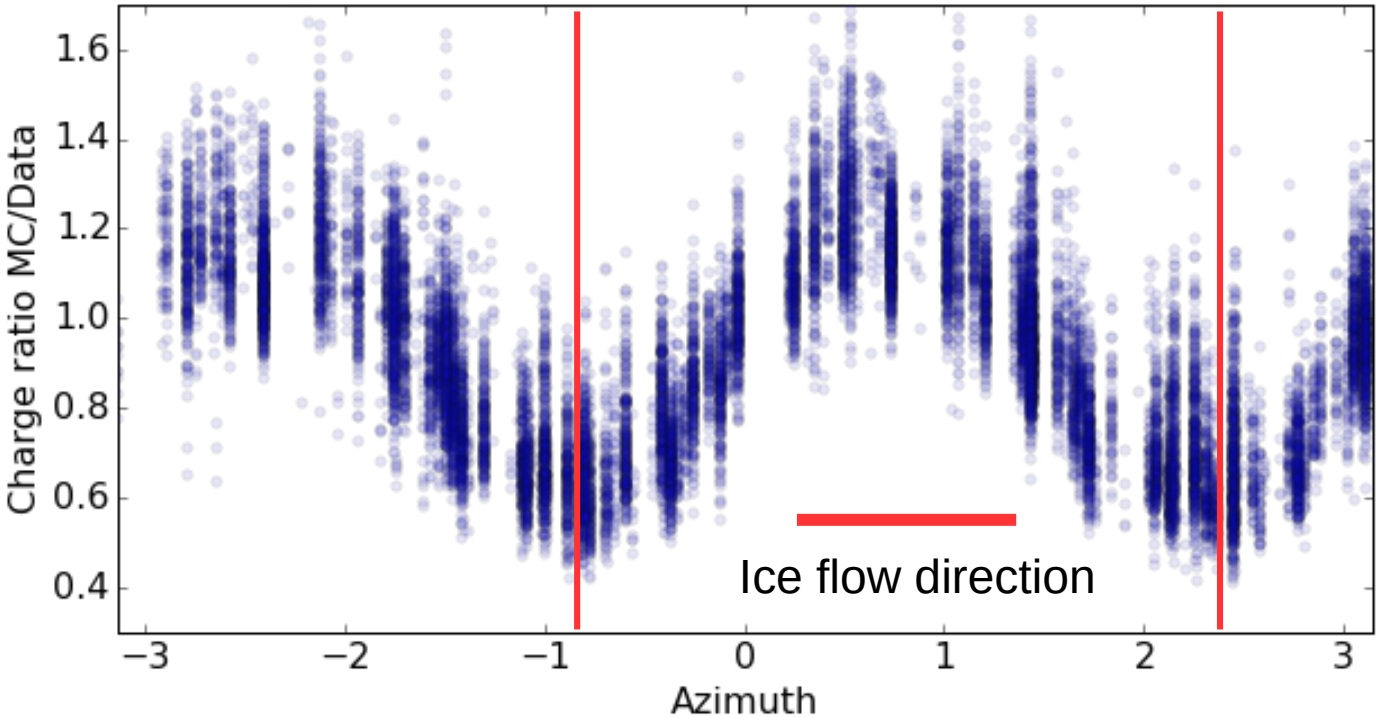

- Anisotropy: exhibiting properties with different values when measured in different directions
- Light traveling along the flow axis is scattered less then light propagating along the tilt → on the flow axis more light, on average arrives earlier
- It is not a subtle effect!

Original parametrization

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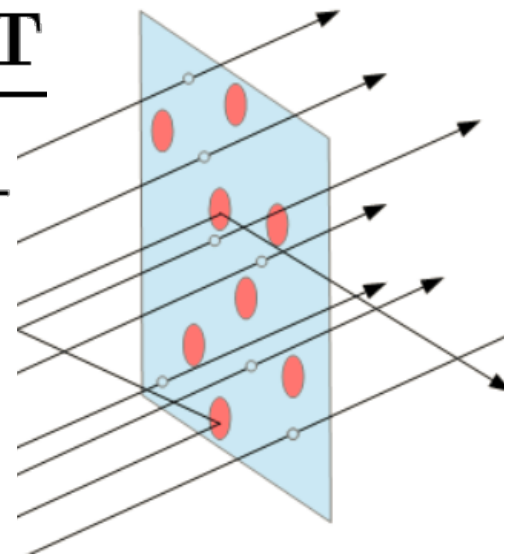
$$\omega = \sigma \frac{\mathbf{N_T}}{\mathbf{A}}$$



- Simply scaling the scattering length would violate the time- and space-reversal symmetries of the scattering cross sections
  → the anisotropy is implemented as an angular modification of the scattering function f

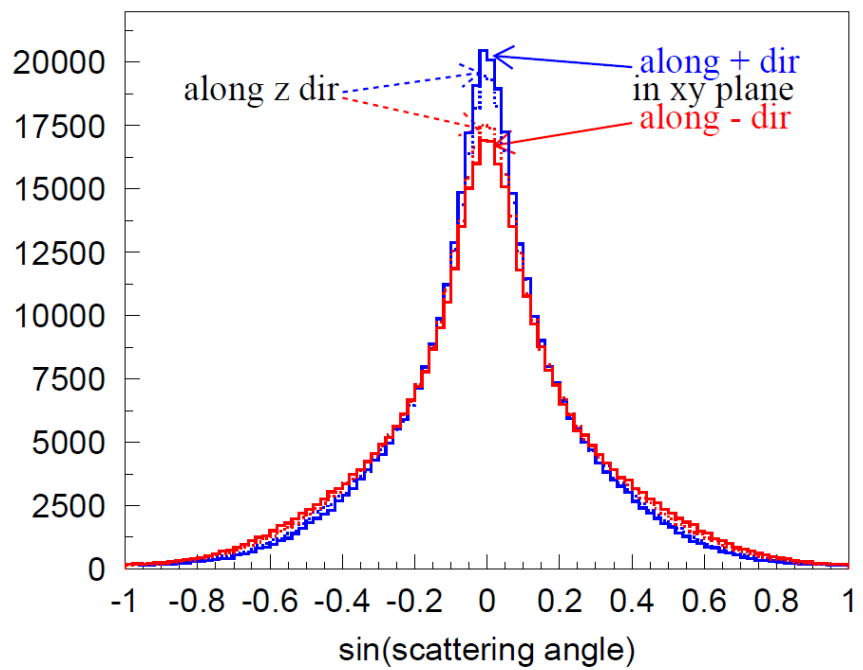
$$f(\vec{n}_i \cdot \vec{n}_o) \rightarrow f(\vec{k}_i \cdot \vec{k}_o), \quad \vec{k}_{i,o} = \frac{A\vec{n}_{i,o}}{|A\vec{n}_{i,o}|}$$

$$A = \begin{pmatrix} \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \gamma \end{pmatrix} = \exp \begin{pmatrix} \kappa_1 & 0 & 0 \\ 0 & \kappa_2 & 0 \\ 0 & 0 & \kappa_3 \end{pmatrix}$$

- Evaluated against a coordinate system aligned with the direction of largest scattering in the xy-plane → the anisotropy axis

- To conserve the overall scattering length we demand: $\kappa_1 + \kappa_2 + \kappa_3 = 0$

→ 3 free parameters (axis, kappa1, kappa2)



Photon propagation & likelihood analysis

Initialize photon
with distance to absorption

↓

Dice distance to next scattering

↓

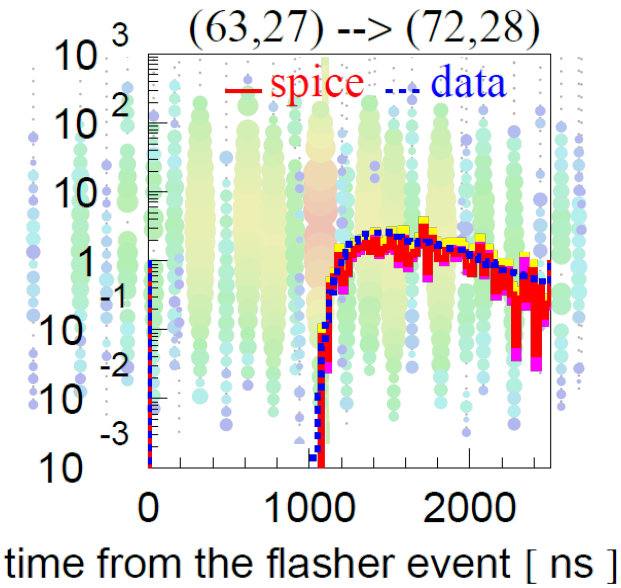
Step through layers until absorbed, scattered or detected

If scattered → **Deflect by random angle from scattering function** → **Dice distance to next scattering**

If detected or absorbed ↓

Kill photon

On GPUs ~250 times faster then CPUs



An event contains average binned waveforms
→ This is compared against MC simulation

$$-\ln \mathcal{L} = \sum_i \left[s_i \ln \frac{s_i/n_s}{\mu_s^i} + d_i \ln \frac{d_i/n_d}{\mu_d^i} + \frac{1}{2\sigma^2} \ln^2 \frac{\mu_d^i}{\mu_s} \right]$$

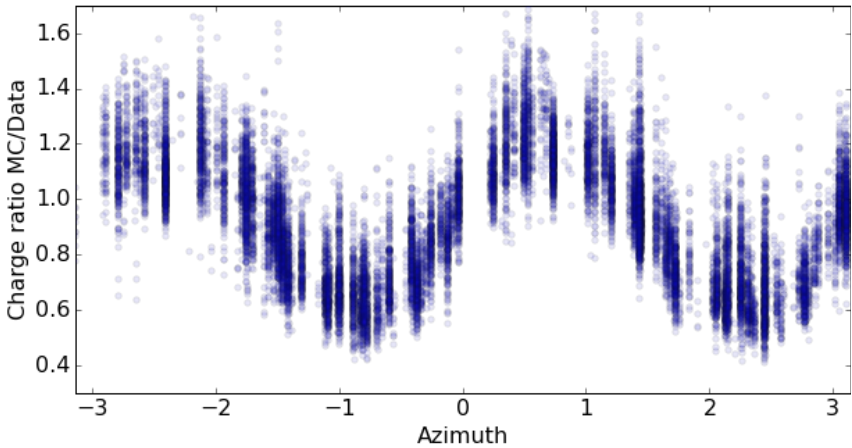
i sums over all emitting & receiving DOMs and their time bins

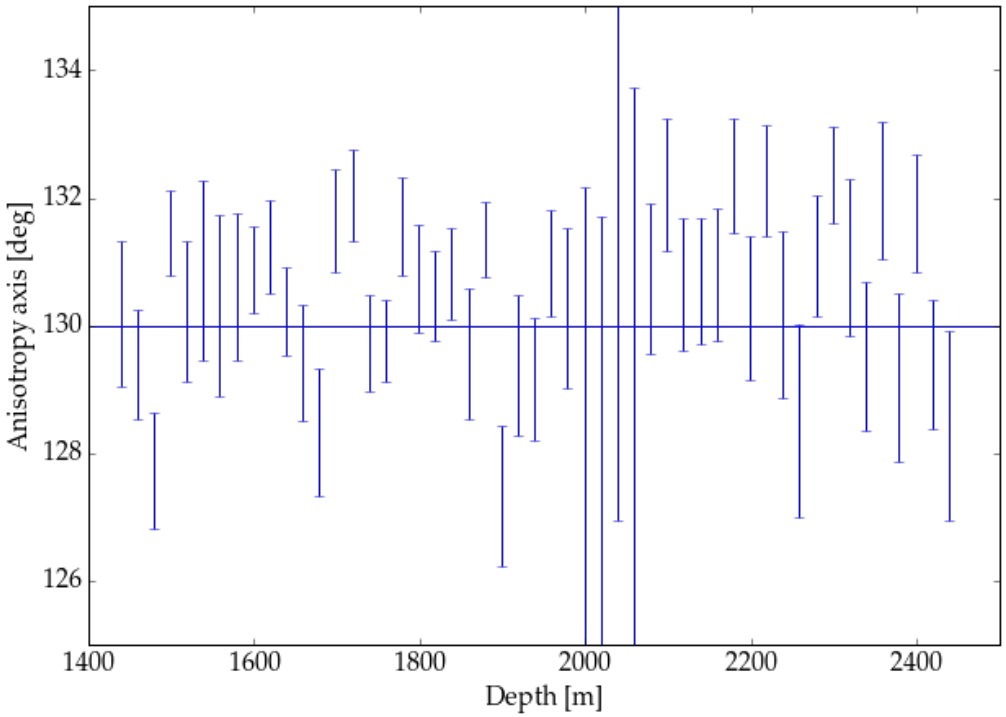
The fit minimizes the GOF (or other observables).
One simulation takes (200-5000 GPU hours)
→ can't use a minimizer (pick by hand)

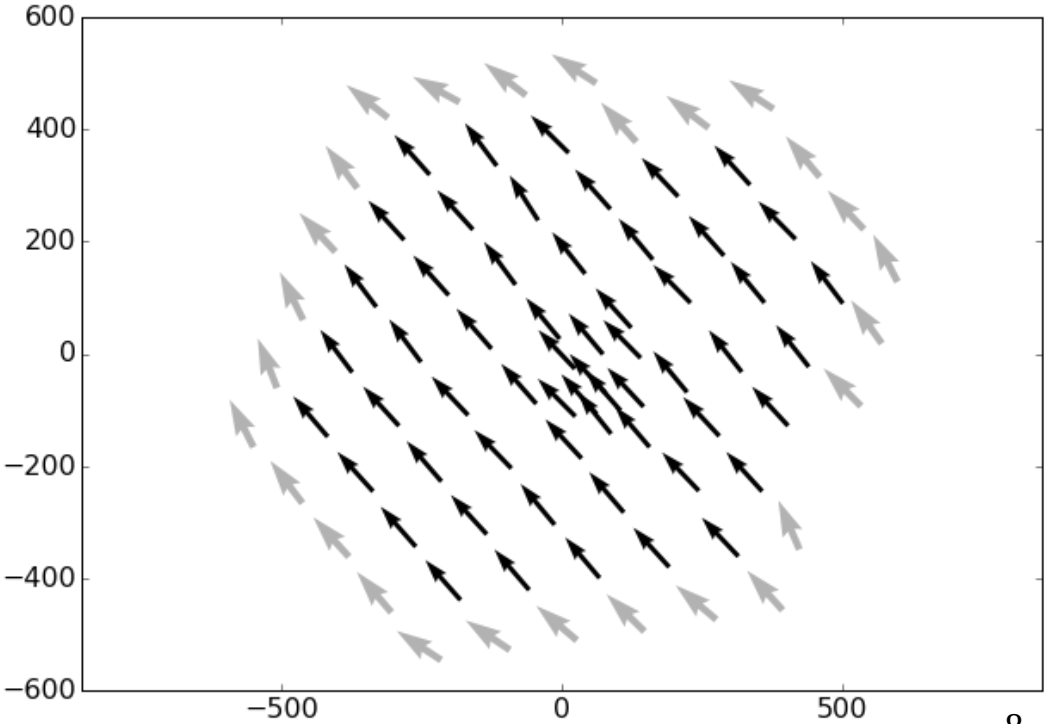
Anisotropy axis over the array

- Fit the phase of the intensity modulation to determine the anisotropy axis with the detector slided in depth or by cable
- Axis appears to be constant over the face of the detector and versus depth

  → assumed to be constant at 130°





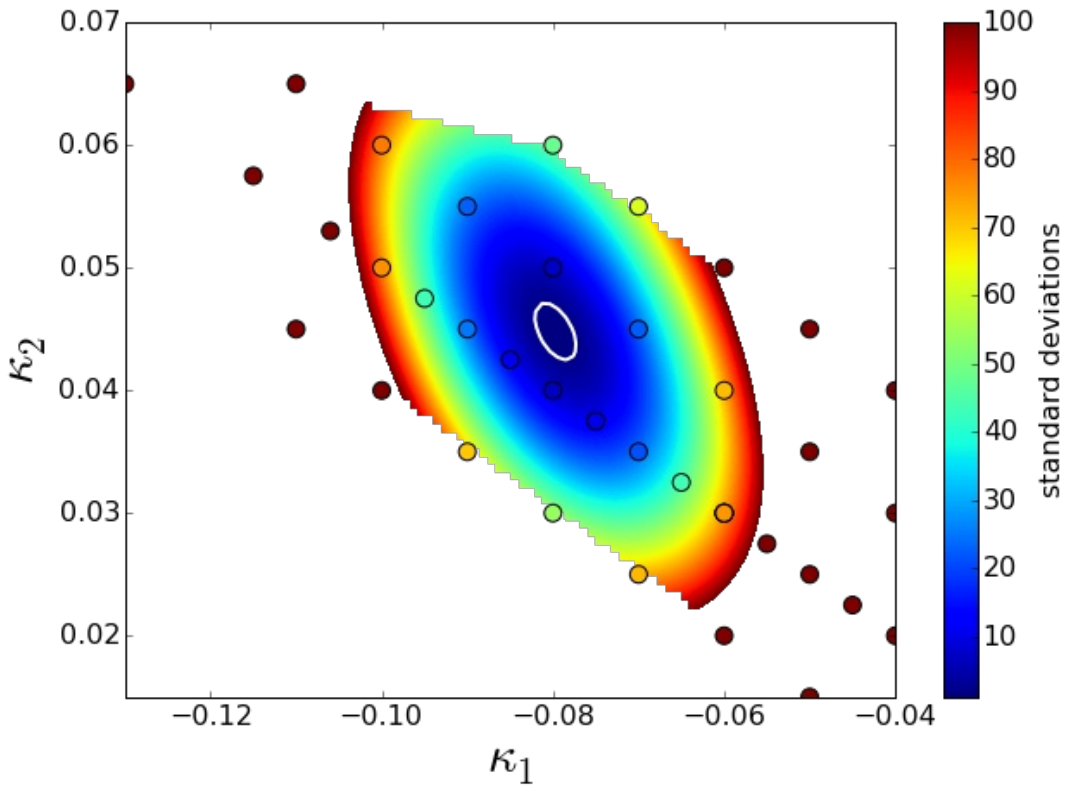


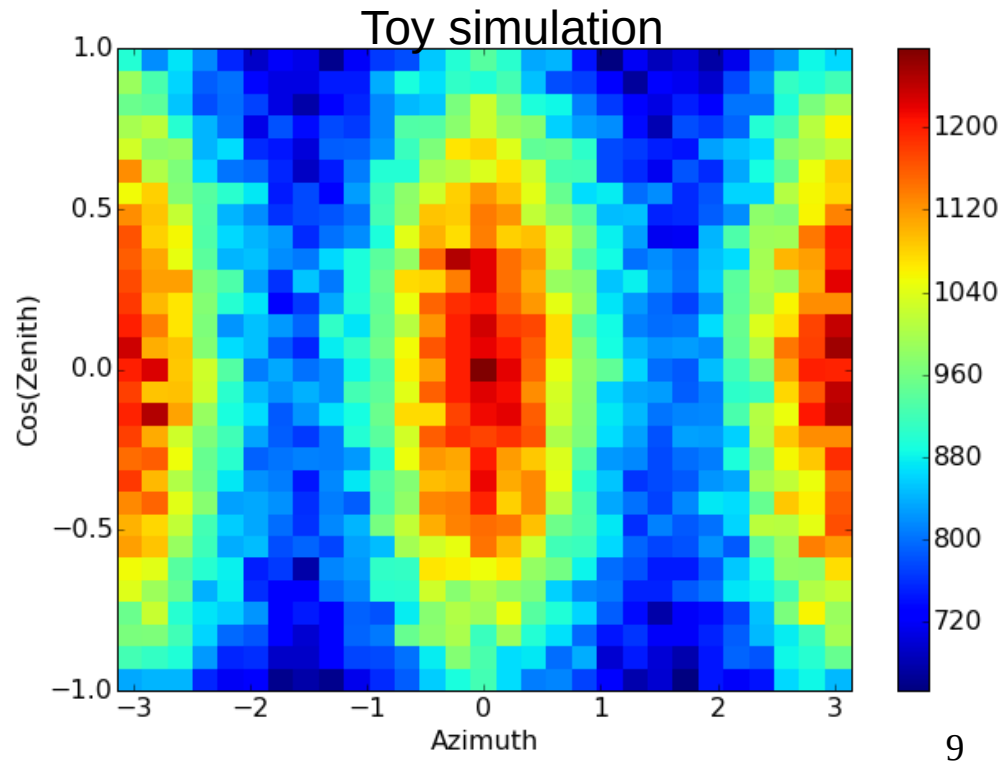
Detector average strength

- The average anisotropy strength has been evaluated in a full 2D parameter scan

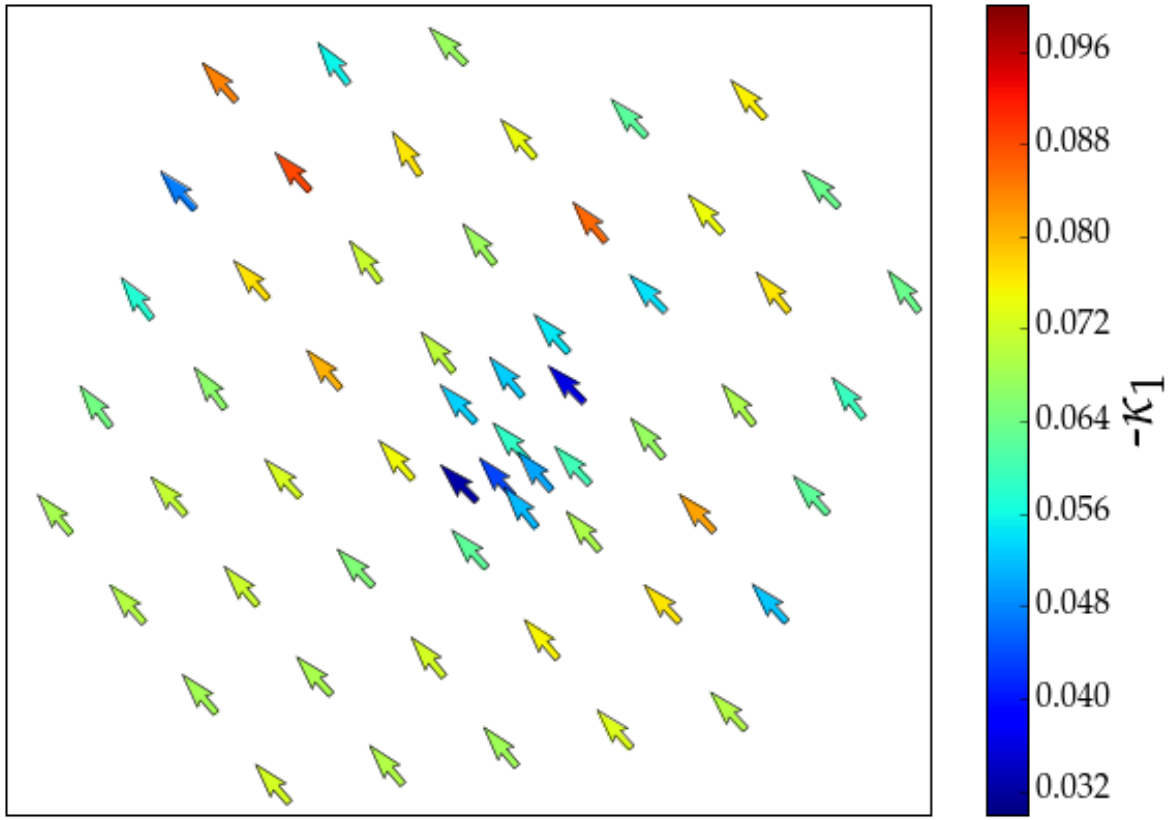
- kappa2 ~ -0.5 kappa1 → kappa3 ≠ 0
  → the anisotropy is not purely azimuthal, but also effects propagation as a function of zenith

- As the 2D scan is not yet finished for all depth bins, assume for now that kappa2 = -0.5 kappa1 holds at all depths





Anisotropy strength over the array



- Averaging along individual String, the anisotropy looks to be fairly homogeneous over the surface of the detector
- Only DeepCore Strings, which are on average deeper, have a systematically weaker anisotropy

→ study the depth dependence averaged over the entire detector area

Anisotropy strength vs. depth

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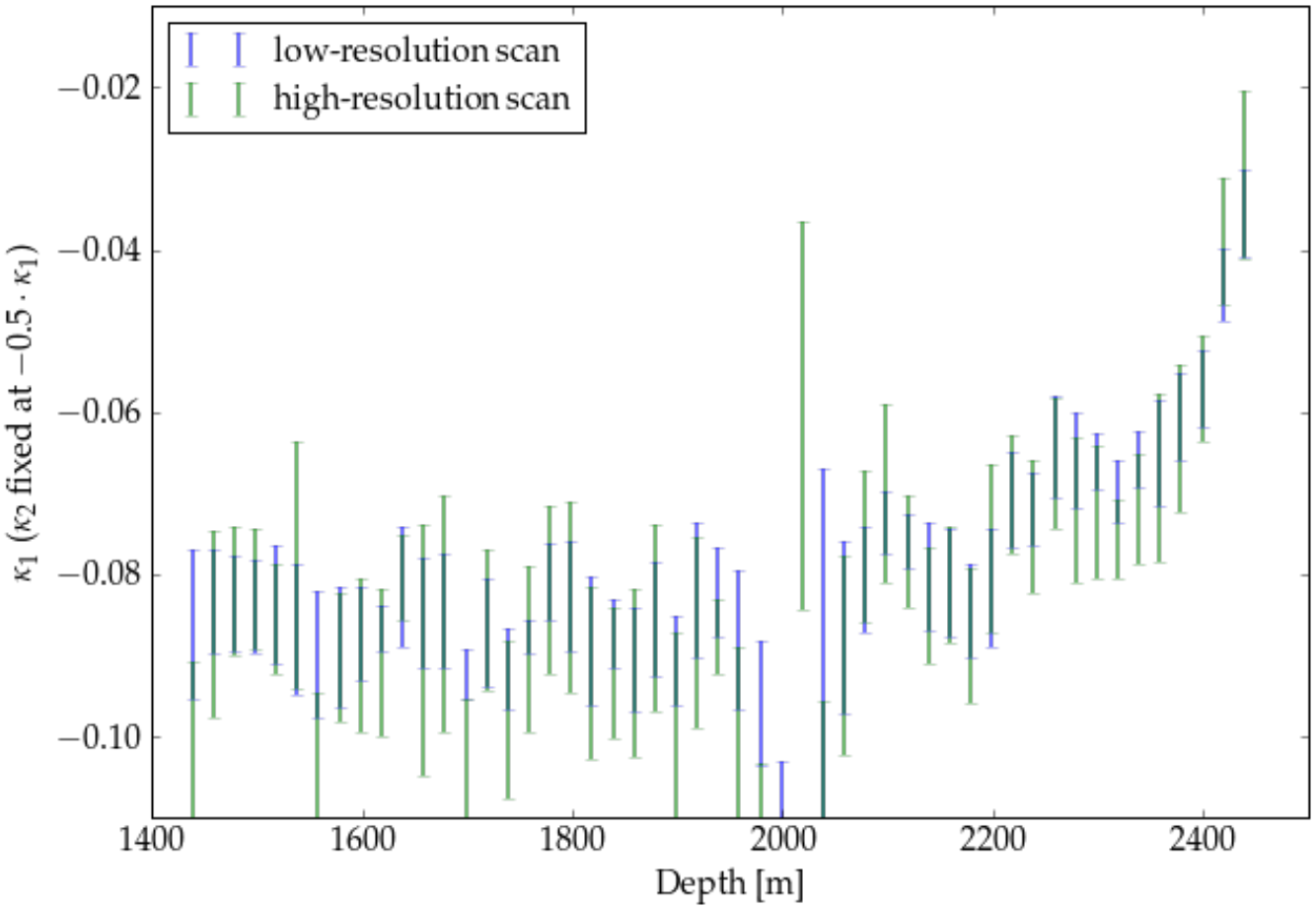
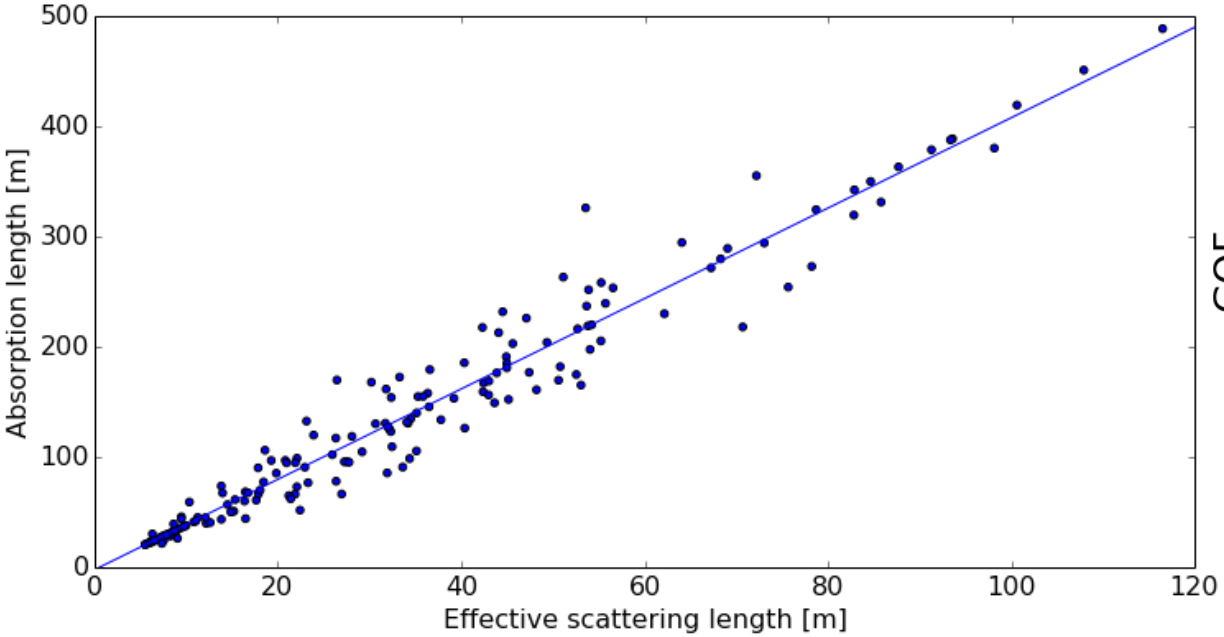
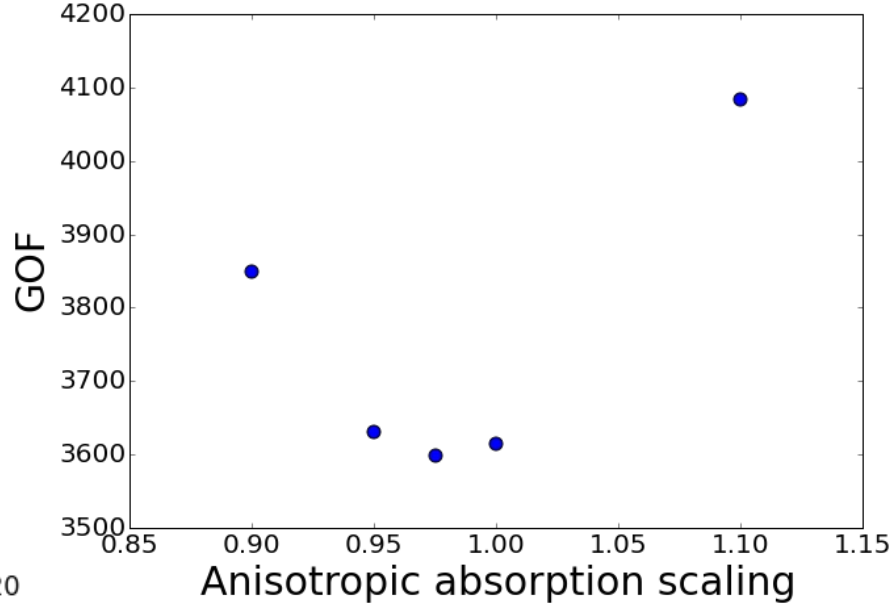


- The anisotropy strength appears constant above 2000m, is badly constrained in the dust layer and exhibit a slight weakening between 2000-2300m
- In the very deep ice the azimuth anisotropy suddenly nearly vanishes

Questioning the approach





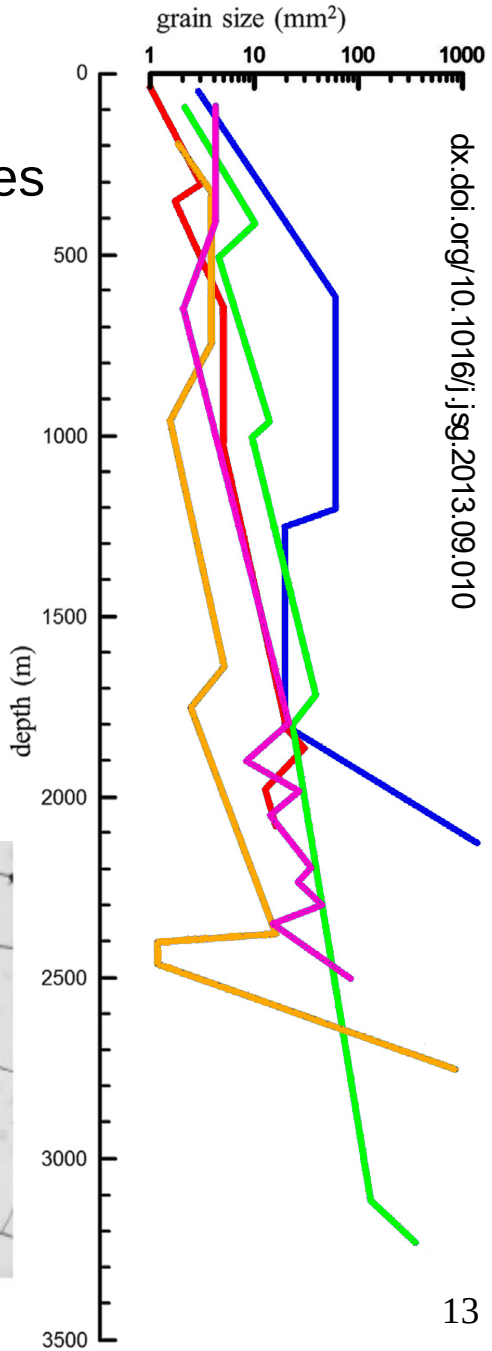
- While modifying the scattering function is an elegant solution, it is hard to motivate
- Rotation of dust particles has been proposed,
  but is hard to explain on the microscale

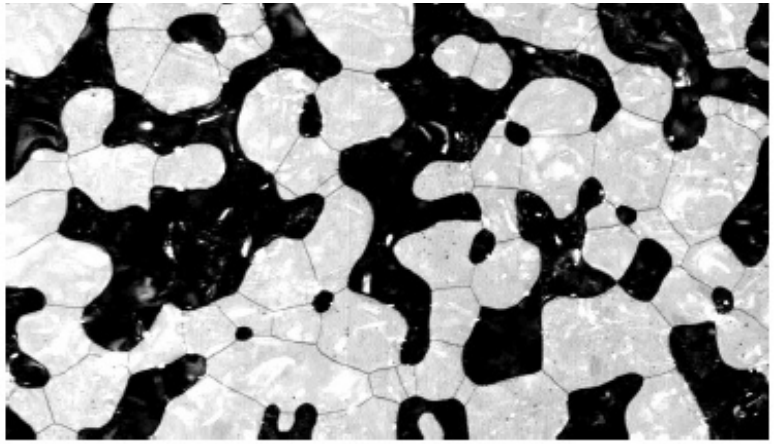
- In addition it was found that a better data description is achieved when treating the absorption with the same anisotropy measured for the scattering
- This does not make sense if the scattering probability is not the underlying cause

→ **let‘s turn to ice cores to motivate a more physical parametrization**

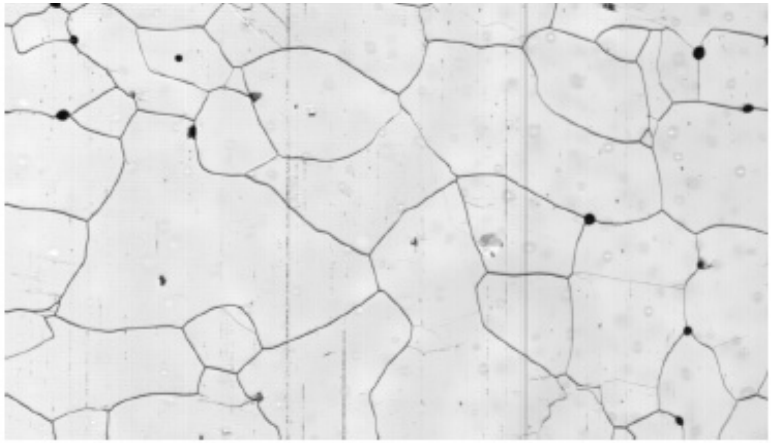
Ice grains

- A solid block of ice contains monocrystals (grains), that grow independently, the surfaces where they met are called boundaries
- As the surface of a ice core sample sublimates the grain boundaries leave grooves on the surface which can be imaged
- Ice grain sizes range from sub-mm2 to thousands of mm2 with aspect ratios between 1 and 1.8 → elongated
- Ice is a HOT material
  → the lattice undergoes constant recrystallization
  which shifts the grain boundaries or bends and breaks grains





(a) Firn (Black regions = gases)



(b) Ice

Ice grains and c-axis orientation

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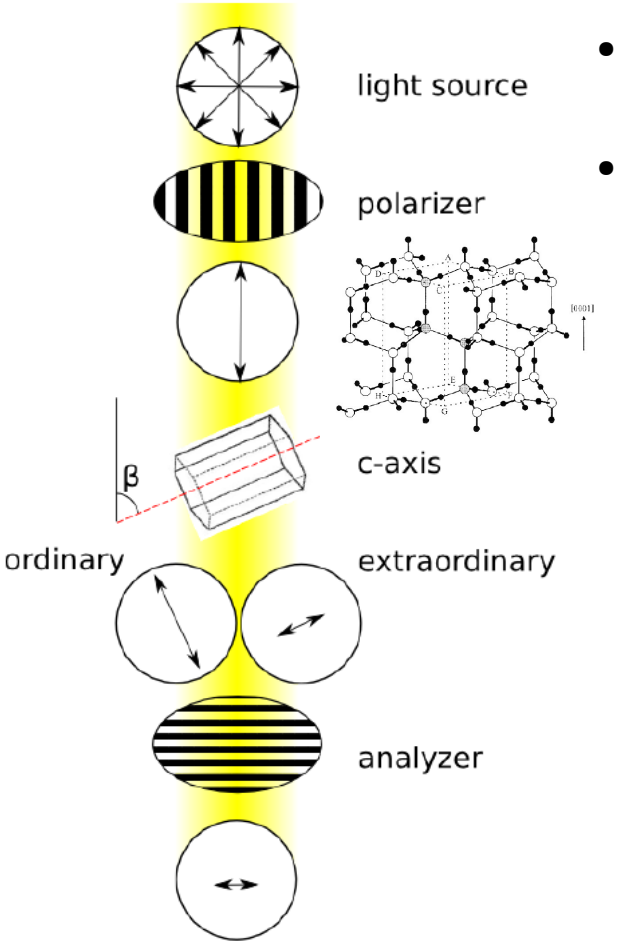
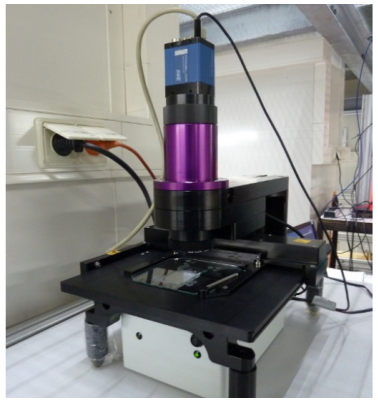
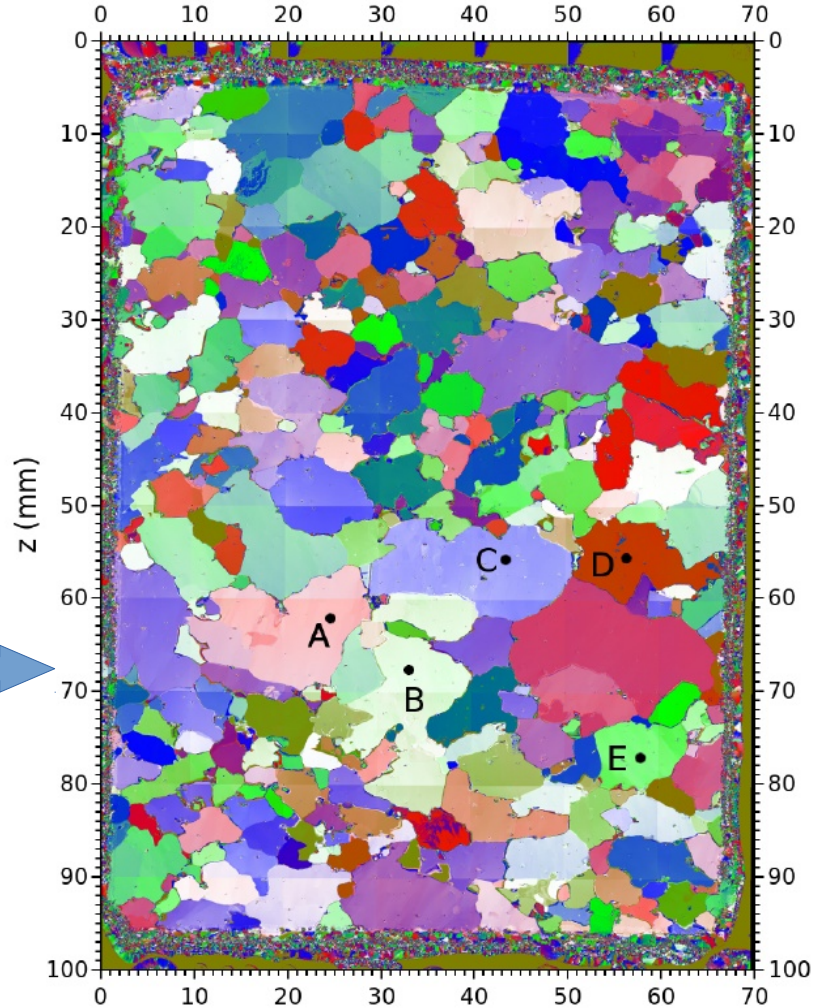
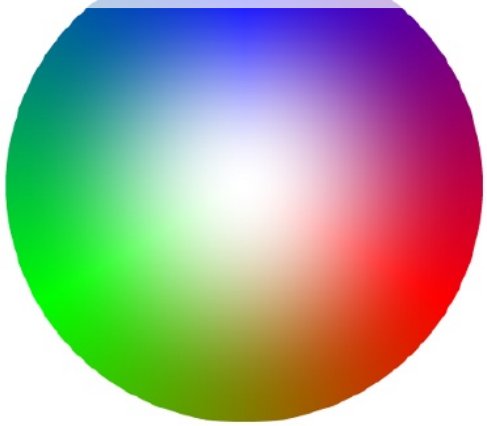


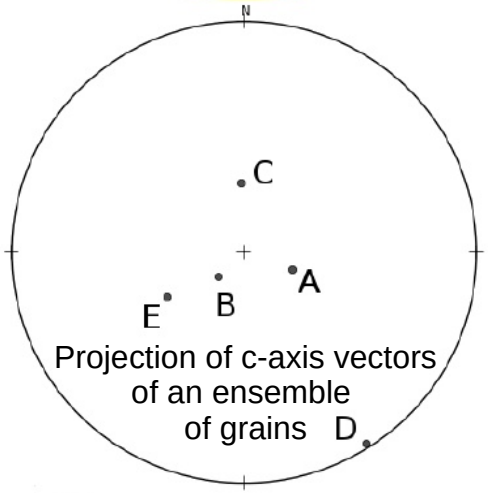
- Monocrystaline ice (a grain) is a birefringent material
- Using imaging polarization analyzers (fabric analyzer) a false color image showing the c-axis vector of each grain can be produced and their population can be studied





Jan Eichler, 2013





Projection of c-axis vectors of an ensemble of grains

The woodcock parameter

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General orientation tensor (k^{th} order):

$$\mathbf{A}^{(k)} = \frac{1}{n}\sum_{i=1}^{n} \mathbf{c}_i^{\otimes k} = \sum_{i=1}^{n} \underbrace{\mathbf{c}_i \otimes \mathbf{c}_i \otimes \ldots \otimes \mathbf{c}_i}_{k}$$

Second order gives matrix with unity trace and:

$$\textit{eigenvalues}\ \lambda_1, \lambda_2, \lambda_3$$

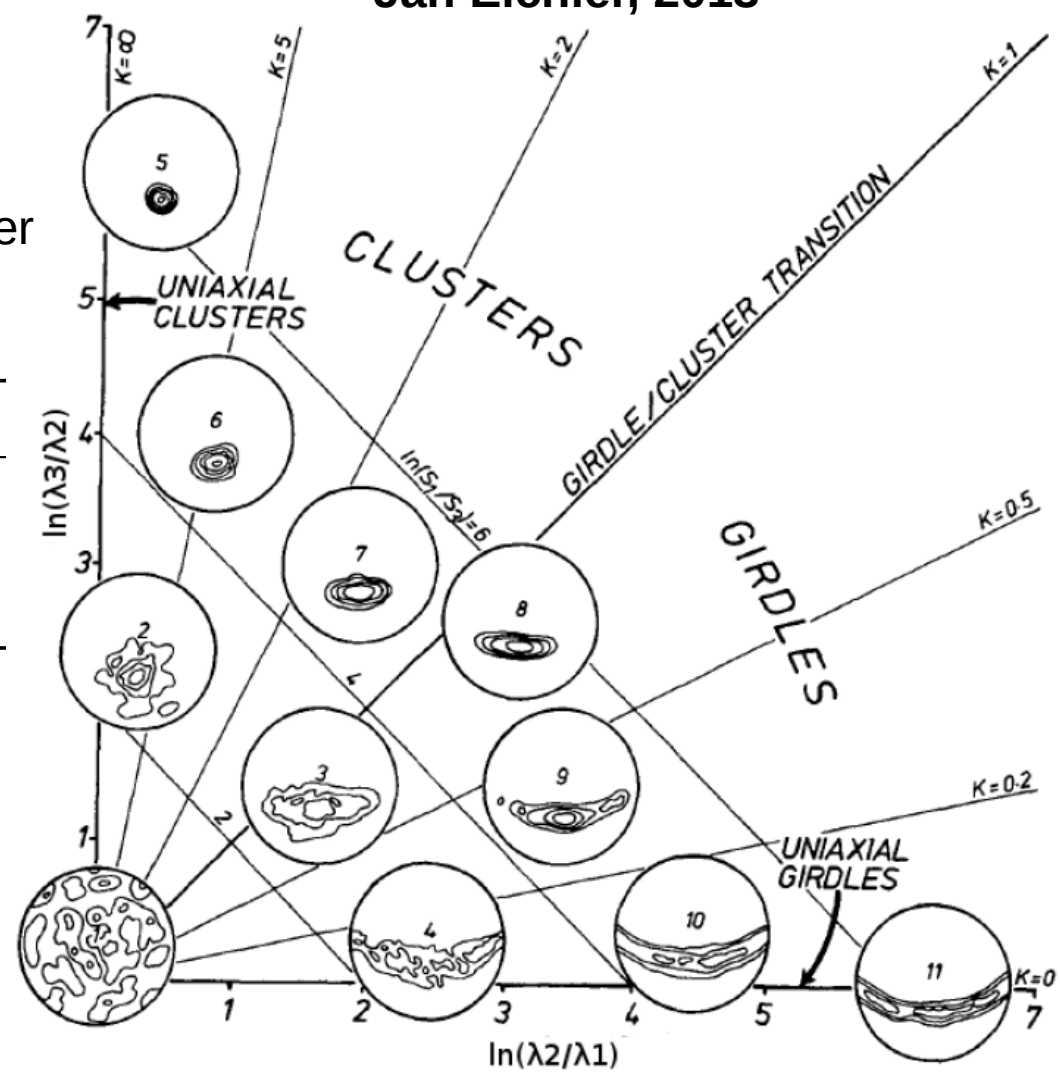
which give the lengths of the shape of the scatter plots with respect to a set of eigenvectors.

eigenvalues	inertia shape	distribution
$\lambda_1 = \lambda_2 = \lambda_3 = 1/3$	sphere	uniform distribution
$\lambda_1 = \lambda_2 < \lambda_3$	prolate ellipsoid	unimodal cluster
$\lambda_1 < \lambda_2 = \lambda_3$	oblate ellipsoid	girdle fabric

Woodcock parameter:

$$\kappa = \frac{\ln(\lambda_3/\lambda_2)}{\ln(\lambda_2/\lambda_1)}$$

Jan Eichler, 2013



Ice grains & c-axis vs. depth

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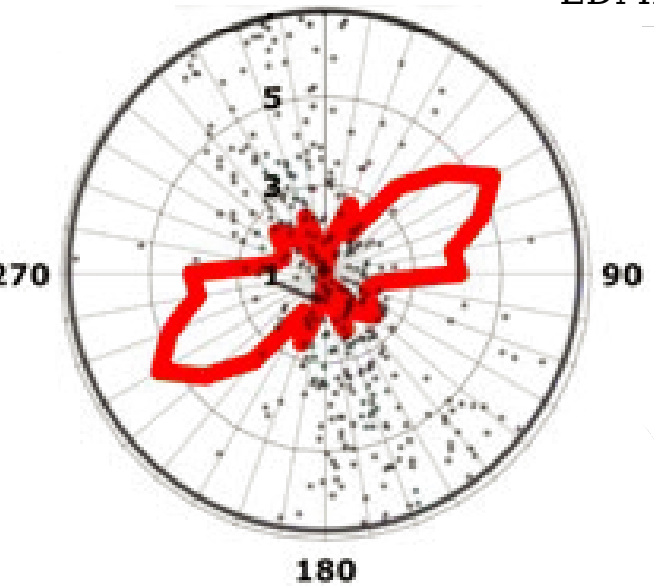
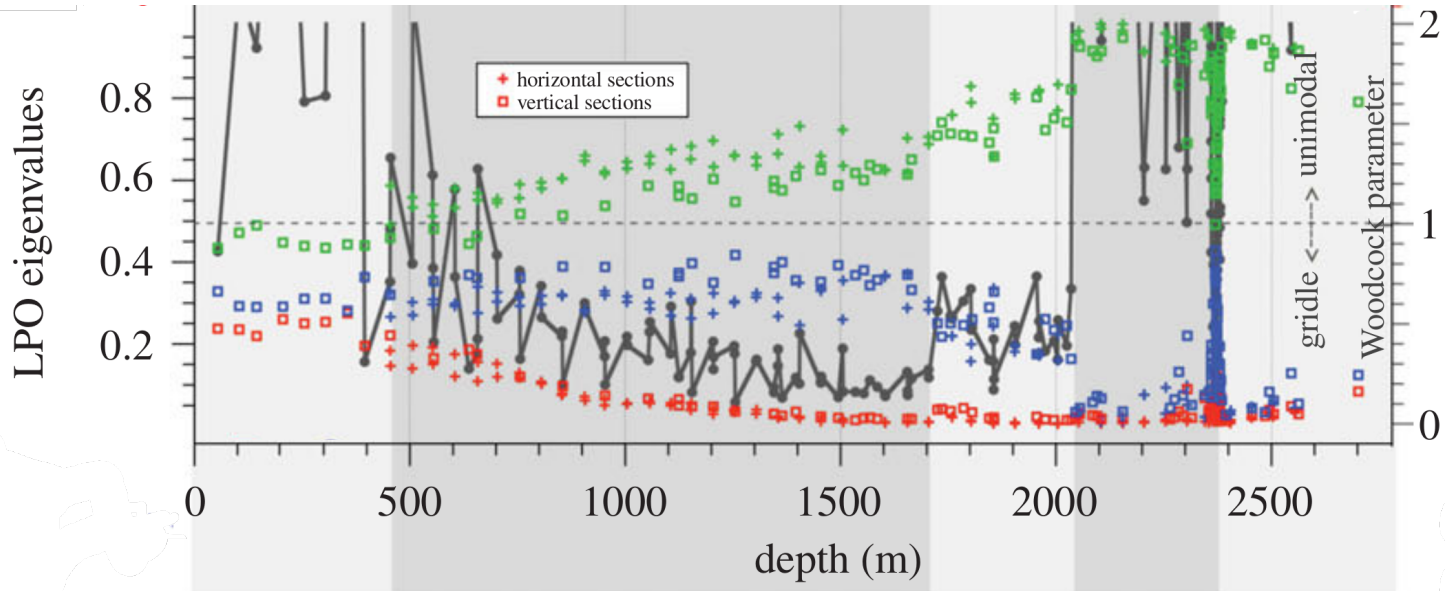
- Deep glacial ice shows a girdle fabric
  (c-axis preferentially horizontally aligned)

- In a girdle fabric the grain elongation- and c-axis are correlated
  → use LPO diagrams as high statistics, 3D tool for elongation alignment

- BUT for still not fully understood reasons nearly all glaciers show the fabric suddenly turning unimodal in the bottom 10% of the ice

EDML ice core; dx.doi.org/10.1098/rsta.2015.0347





Micro inclusions

The Cryosphere, 11, 1075–1090, 2017
www.the-cryosphere.net/11/1075/2017/
doi:10.5194/tc-11-1075-2017

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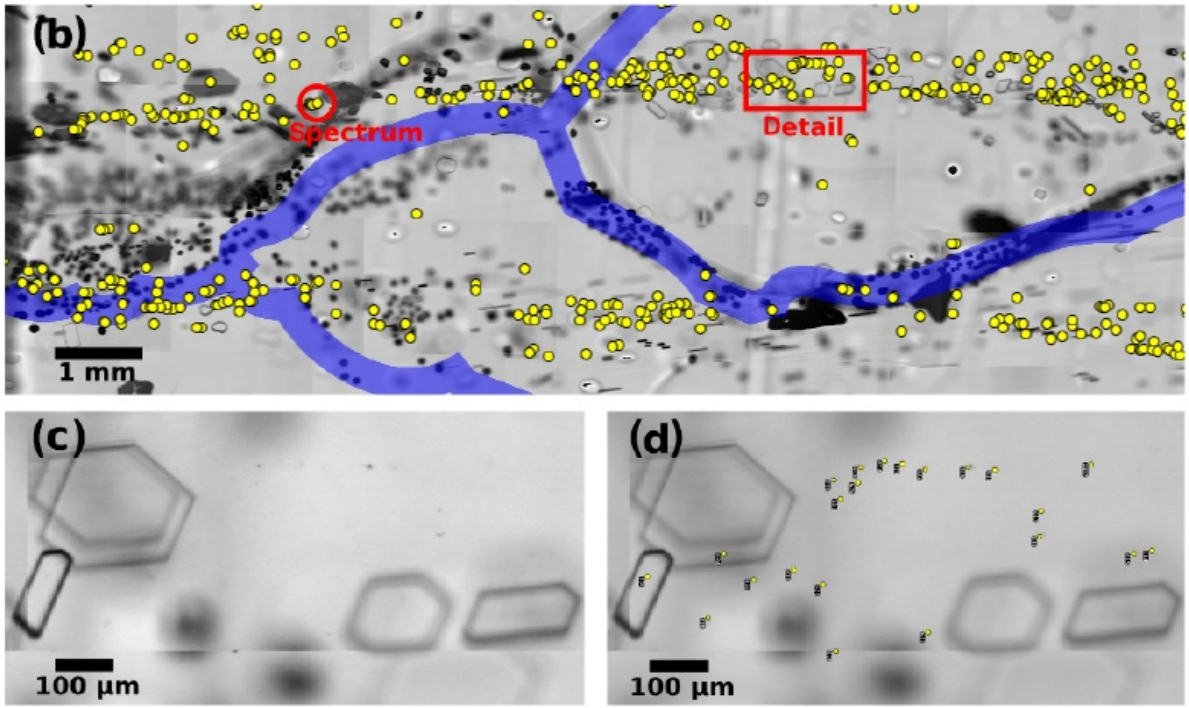
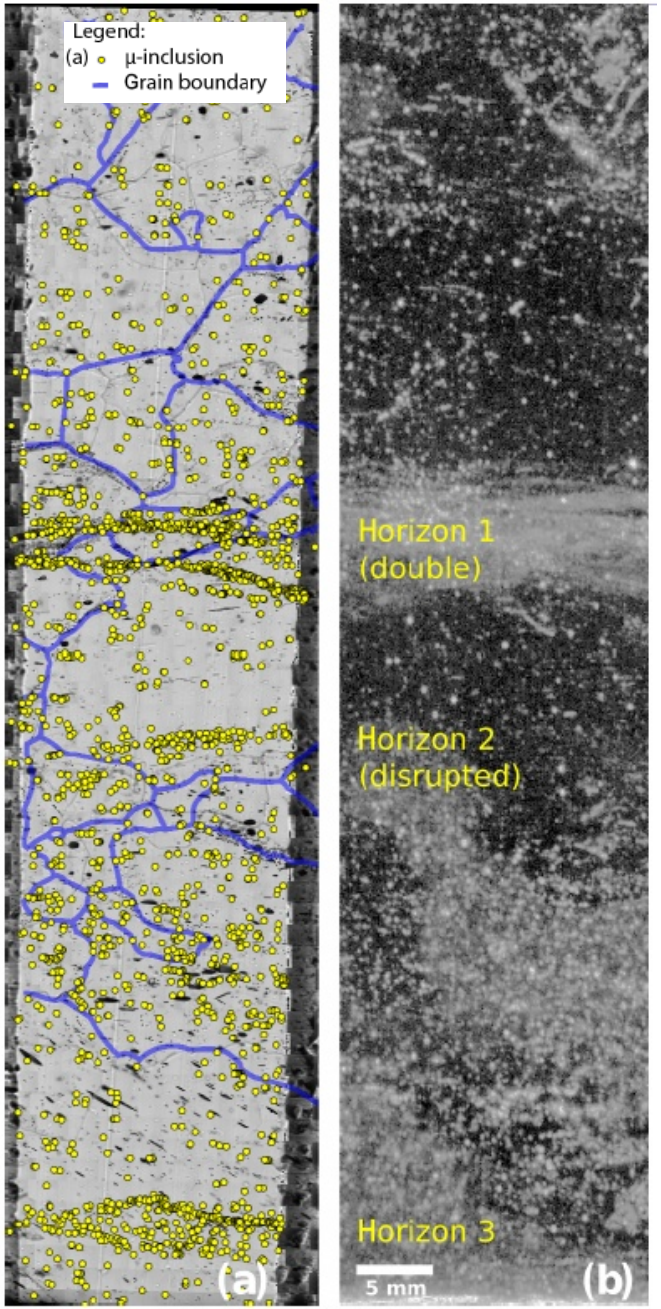


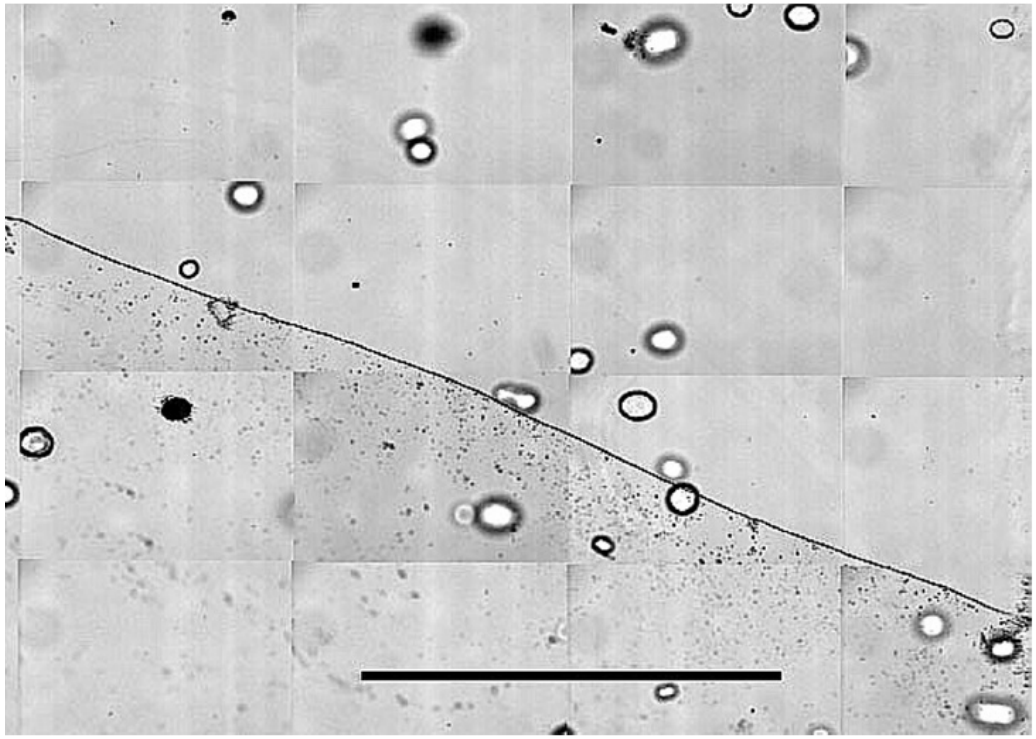


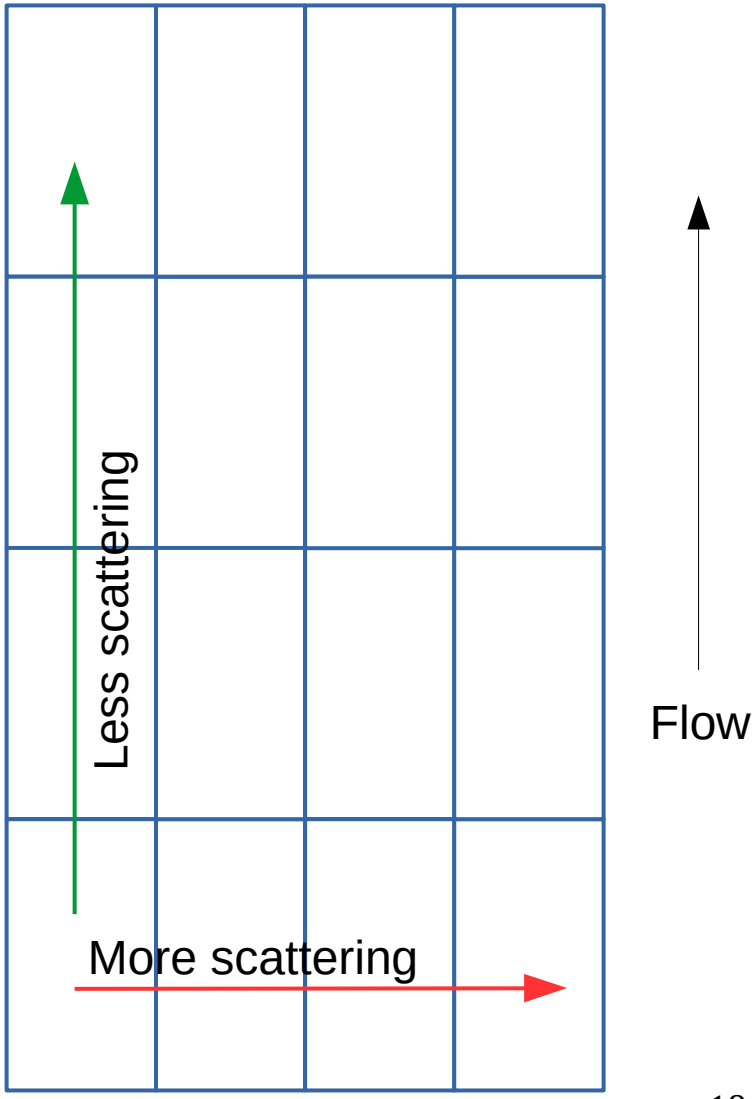
- Glaciologists see point like dark inclusions below the surface, these are speculated to be dust or gas
  (doesn't really matter to us because they act as Mie scattering centers anyway)
- Distribution in vertical slices is highly inhomogeneous
- Horizontal slices are not yet sufficiently studied

Impurity aggregation

- It is suggested that refreezing grain boundaries can drag along or be pinned by impurities, leading to a distribution which is non-homogenous

- grains are elongated and that their long axis is aligned with the flow
  → dust filaments preferentially aligned with flow
  → on the macro-scale:
  less scattering parallel,
  more diagonal to the flow





New parametrization

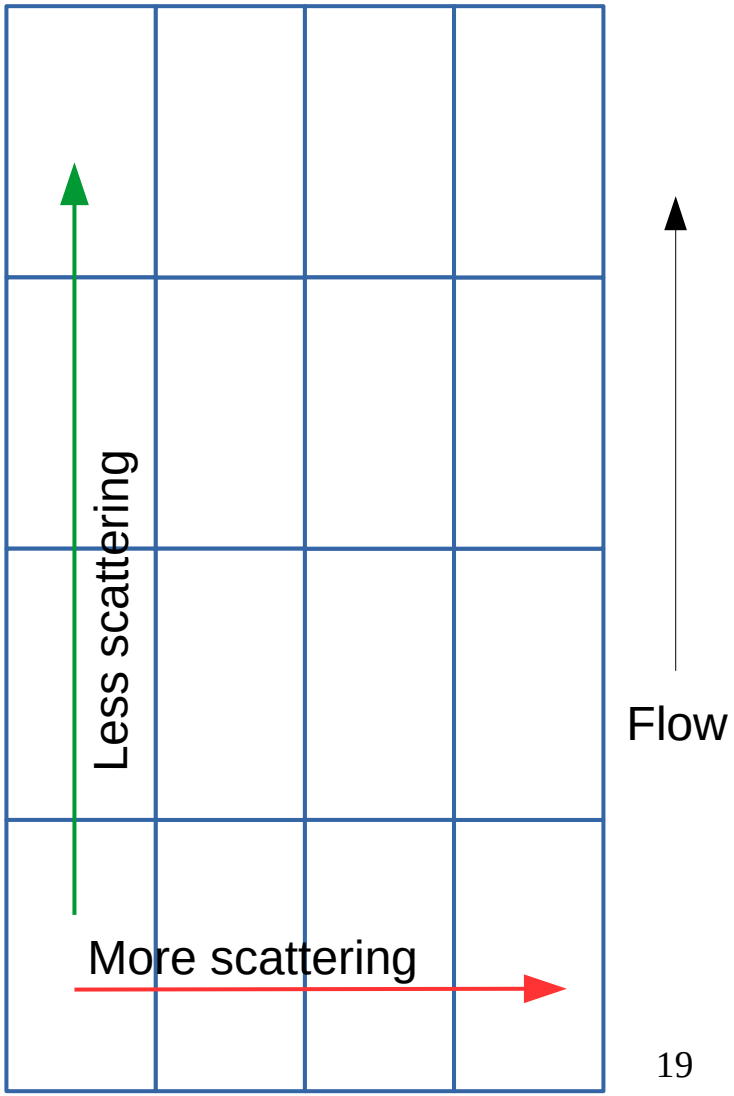
$$\omega = \sigma \frac{\mathbf{N_T}}{\mathbf{A}}$$

- Assuming non-homogeneous dust distributions, scaling the scattering length does not violate symmetry requirements
- Given the evidence from ice cores non-homogeneous dust seems very plausible
- As such modify the absorption & scattering length:

$$l(\theta, \phi) = l \cdot (1 + \alpha_\phi \sin(2 \cdot \phi + 130°)) \cdot (1 + \alpha_\theta \sin(2 \cdot \theta - 90°))$$

where $\alpha_{\theta/\phi}$ are the zenith and azimuth strength

- This parametrization has the added advantage of accounting for the local anisotropy during the entire propagation and not only at the the photon source (absorption anisotropy) and the scattering vertices



Fitting the new parametrization

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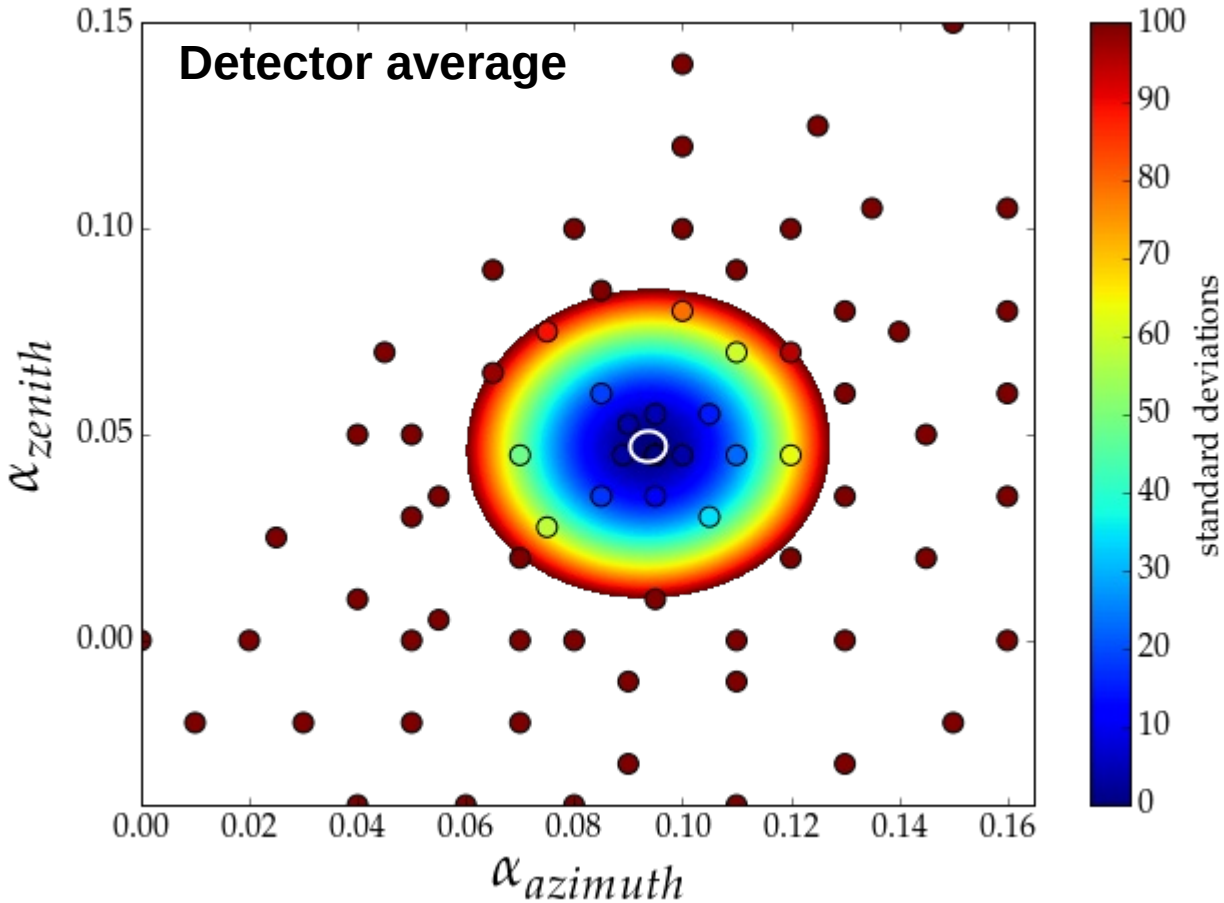

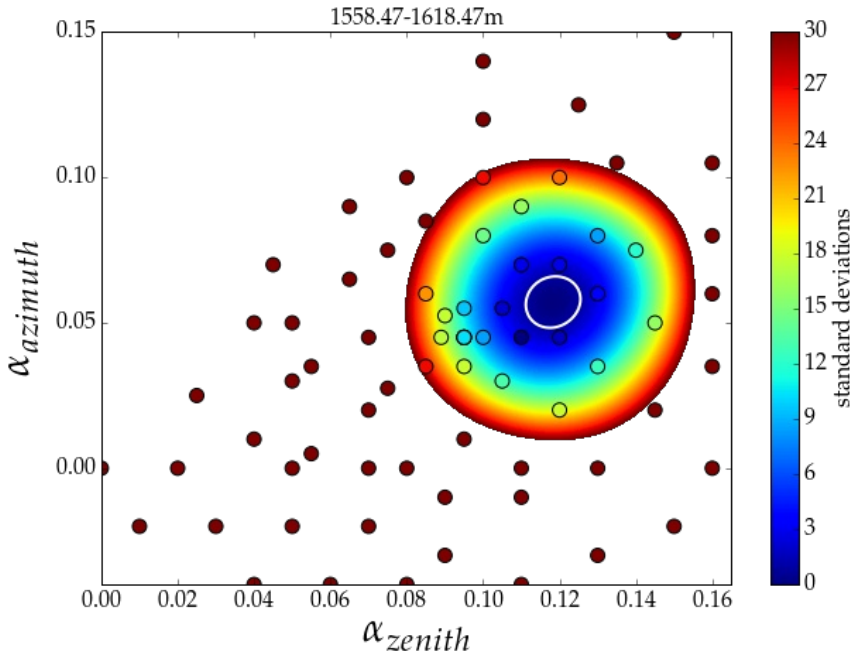

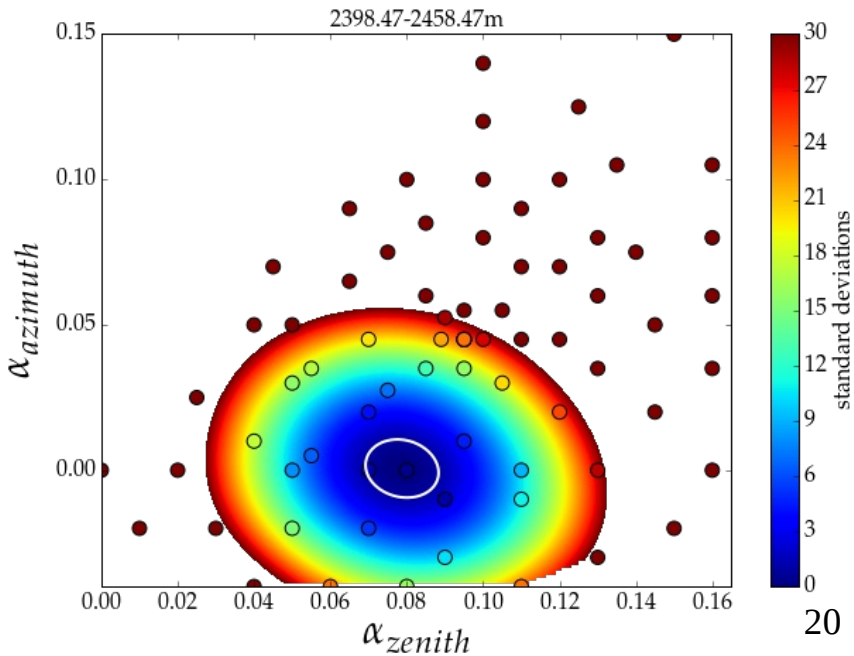

For the new parametrization a complete 2D scan has been performed, for the average detector, 30m & 60m layers.

Positive zenith anisotropy = average grain aspect ratio is larger in the azimuth then in the zenith plane

Fitting the new parametrization

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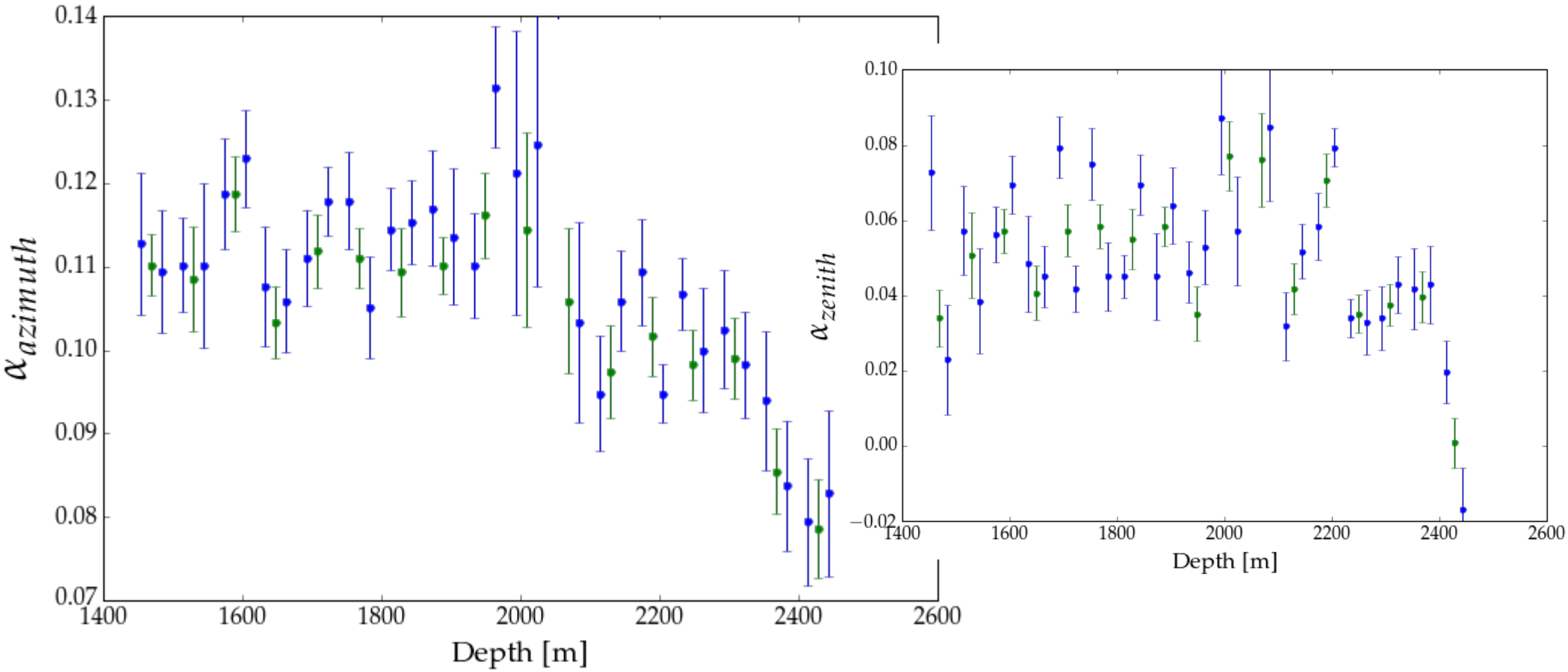


- Zenith & azimuth anisotropy appear constant above 2000m, and exhibit a slight weakening between 2000-2300m
- In the very deep ice the azimuth anisotropy weakens by ~30% while the zenith anisotropy vanishes completely (and potentially reverses)
- Overall the new parametrization achieves the same quality of data description

Glaciological predictions

Why is the new parametrization exciting?

<u>In the context of impurity aggregation it yields predictions on the fabric:</u>

- Assuming all impurities to be on grain boundaries,
  α_{zenith} and $\alpha_{azimuth}$ are the average grain elongation in the respective planes

  BUT: That assumption is stupid & the grain elongation can already be measured,
  the impurity distribution on the other hand is hard to measure....

- Given elongation information from SpiceCore we can deduce the fraction of impurities on the grain boundaries

- As this should in first order be independent of the plane,
  azimuth and zenith can be used as cross-checks

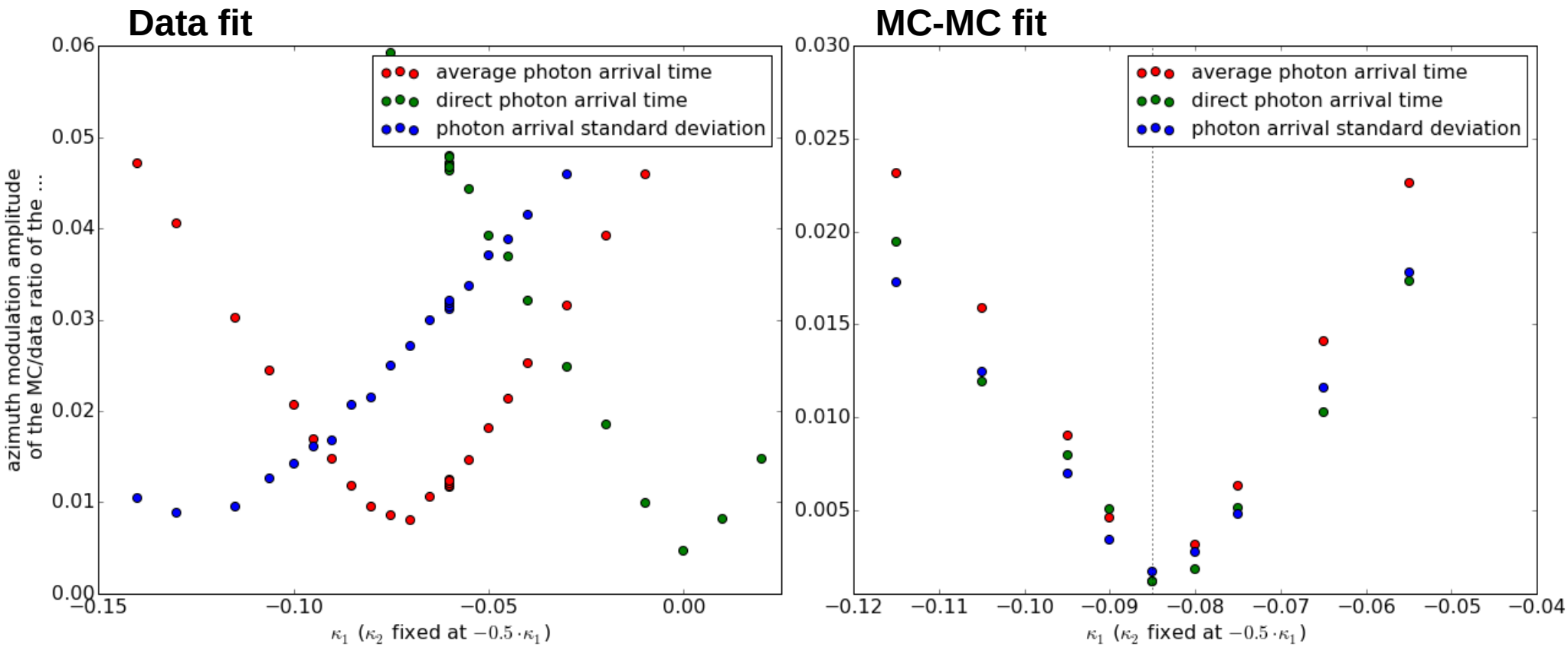
  → better understanding of ice flow characteristics

Summary

- IceCube Neutrino Observatory is also a kilometer seized instrument to study the optical properties of deep, slowly flowing ice
- IceCube observes anisotropic scattering and absorption aligned with the ice flow
- It can be equally well parametrized by a modification of the scattering function OR a directional dependent scattering length
- While the modification of the scattering function is hard to motivate /interpret, a directional scattering length can be understood by impurities aggregating on elongated grain boundaries
- Combining data from IceCube and ice cores can help test models regarding the distribution of impurities in the ice fabric

Thank you for your attention!
Questions are welcome

The timing caveat



- While the likelihood optimizes the overall light curves, we can also check individual timing & charge observables

- Timing observables are known to be wonky
  → only minimize azimuthal modulation, still does not recover common truth

- Things checked so far: Oversizing, g, f_{sl}, absorption scaling, global scattering/absorption, parametrization