III. Physikalisches Institut
RWTH AACHEN UNIVERSITY

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

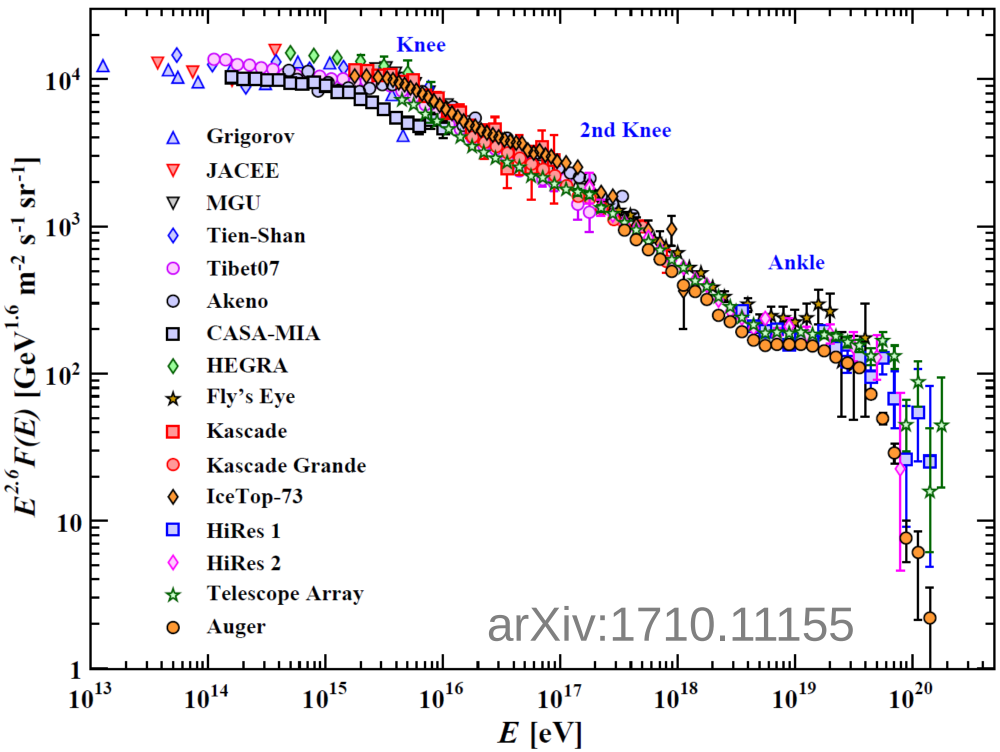
The IceCube Neutrino Observatory as an Instrument for Glaciology

Martin Rongen

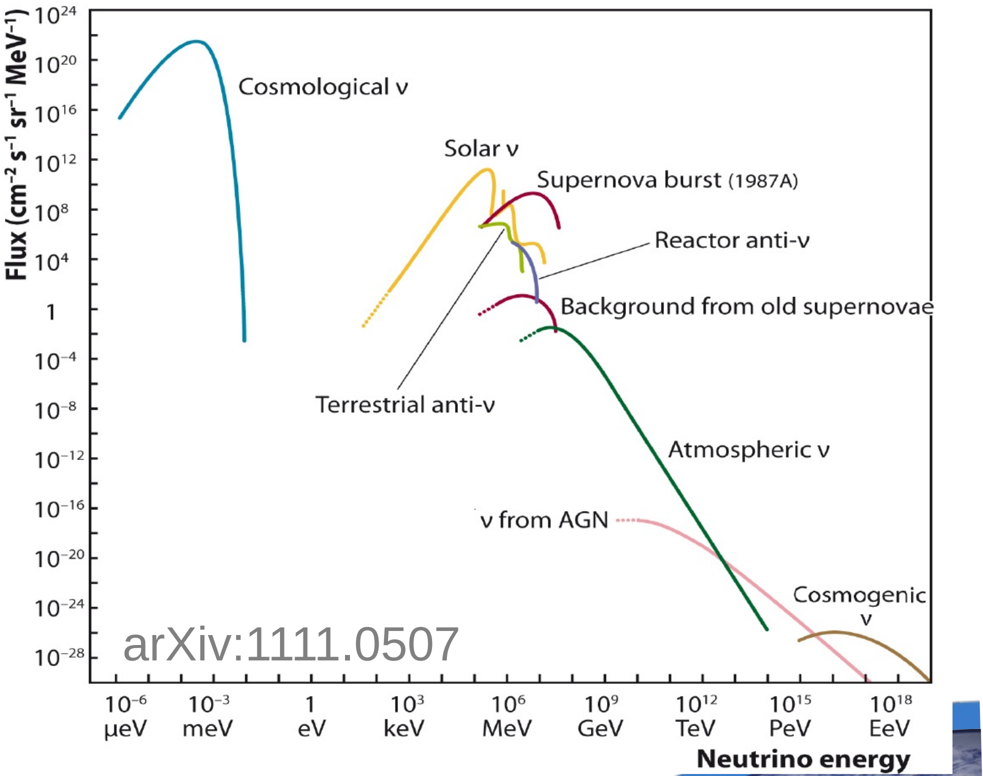
VUB IIHE Seminar
28th March 2018

The need for a km^3 detector

Martin Rongen
IIHE Seminar
March 2018



arXiv:1710.11155



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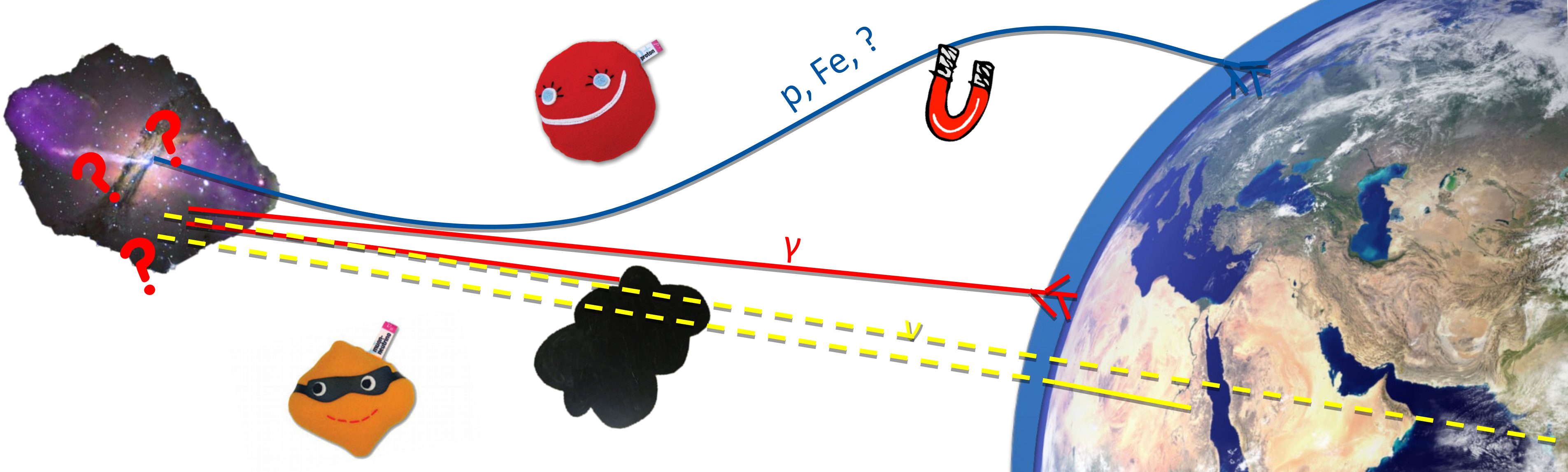

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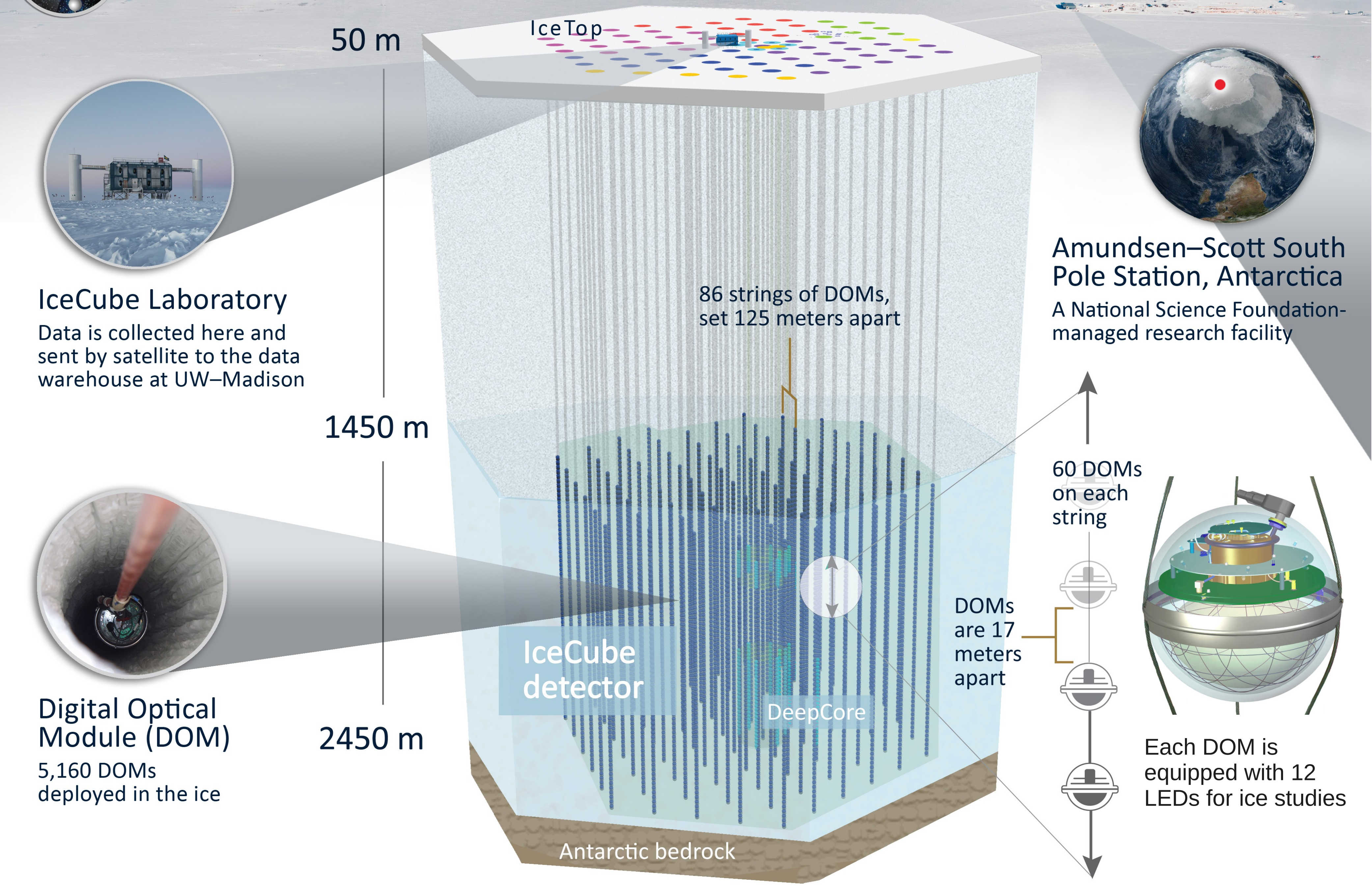
SOUTH POLE NEUTRINO OBSERVATORY



IceCube Laboratory

Data is collected here and
sent by satellite to the data
warehouse at UW–Madison

Digital Optical Module (DOM)

5,160 DOMs
deployed in the ice

86 strings of DOMs,
set 125 meters apart

Amundsen–Scott South Pole Station, Antarctica

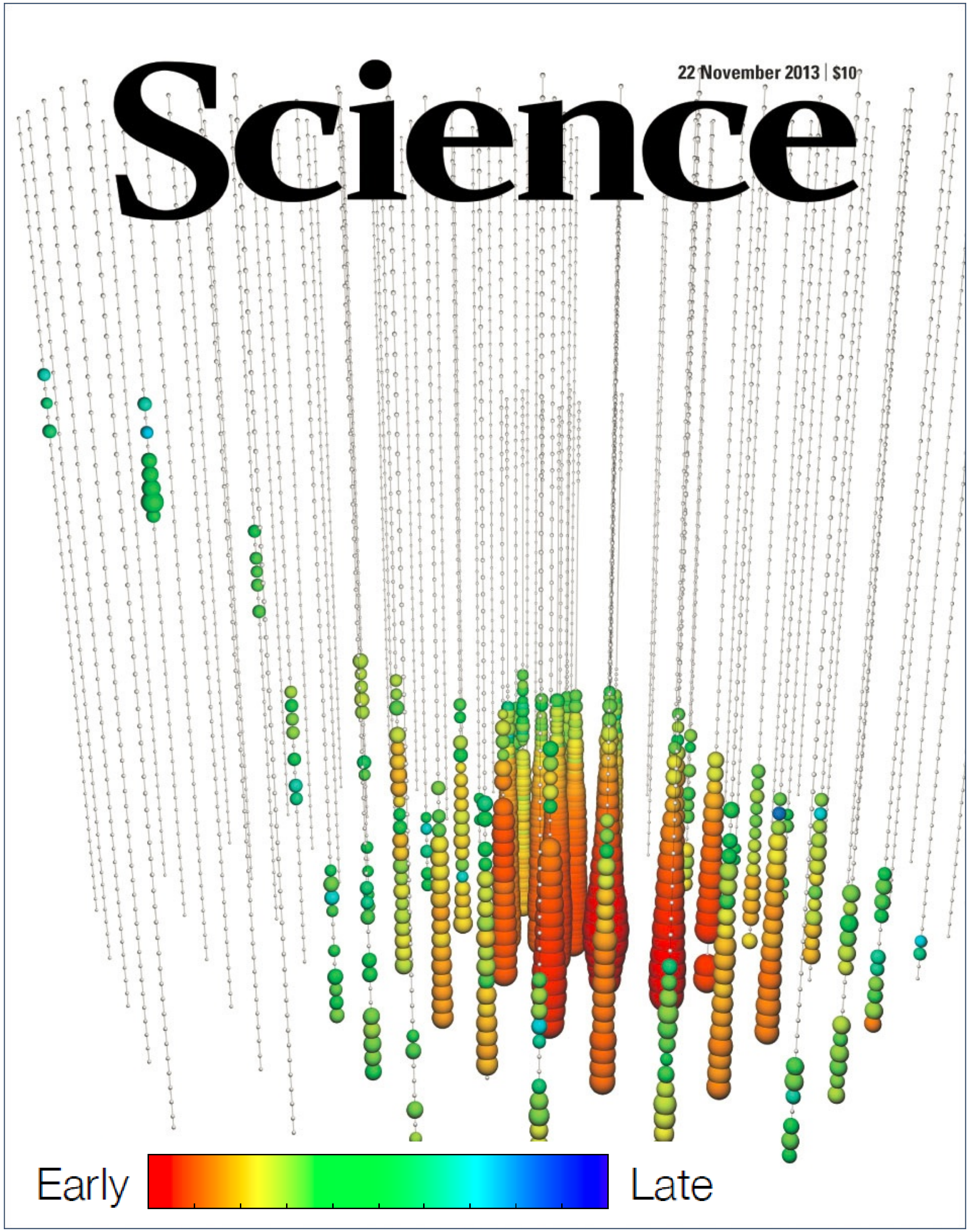
A National Science Foundation-
managed research facility

60 DOMs
on each
string

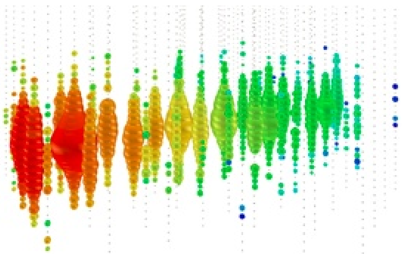
DOMs
are 17
meters
apart

Each DOM is
equipped with 12
LEDs for ice studies

Event signatures

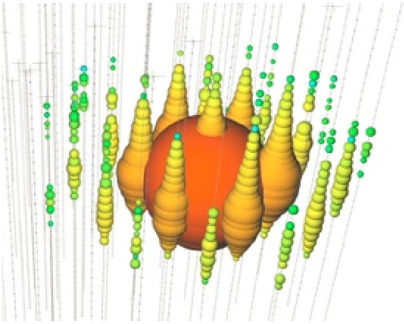


Charged current ν_μ



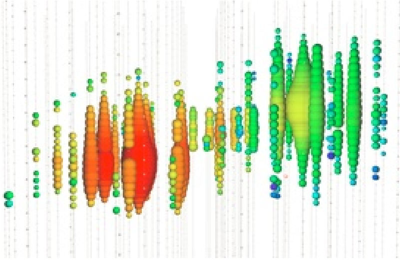
- Factor ~2 energy resolution
- <1° angular resolution

Neutral current, Charged current ν_e



- 15% resolution on the deposited energy
- 10° angular resolution (above 100 TeV)

Double Bang ν_τ



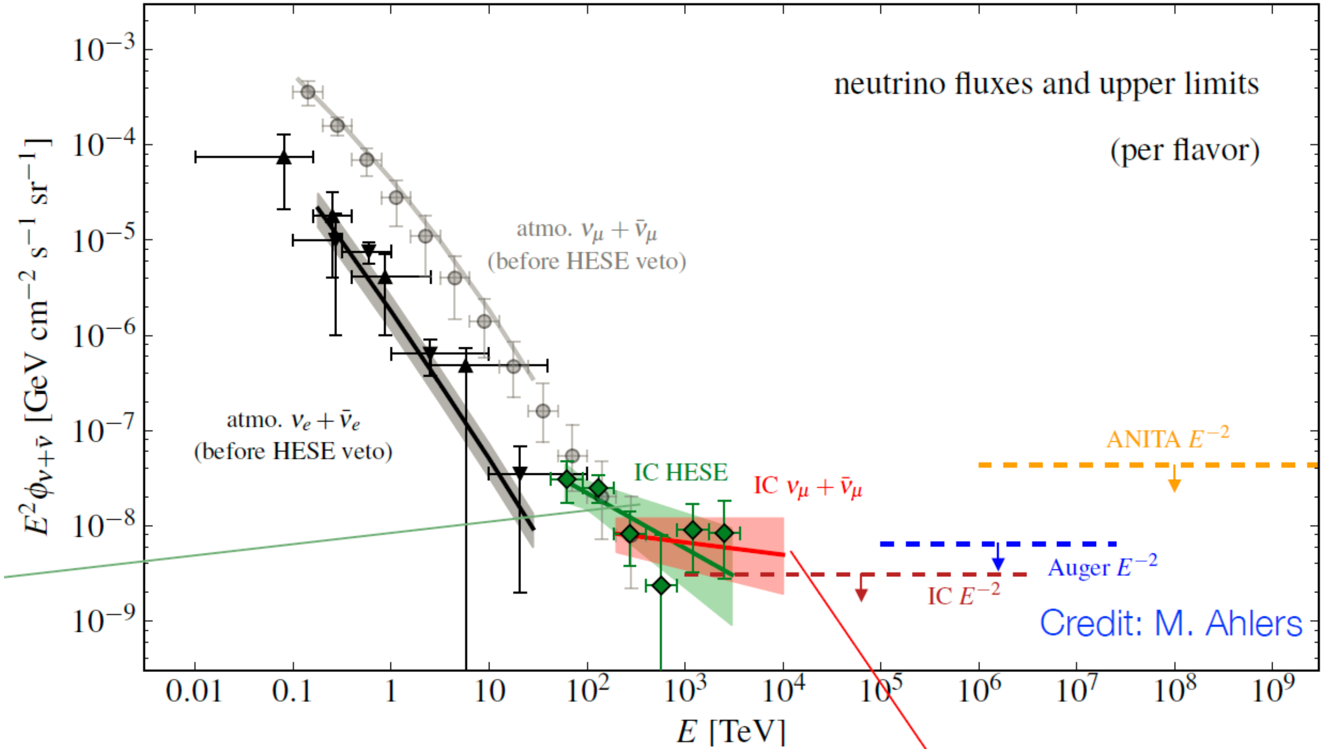
- Vertex separation ~50m/PeV
- Not yet observed

Astrophysical neutrinos

High-Energy Starting Events

7 yrs observation ➛ 8σ
80 events (all flavor)

Spectral index: 2.92



Credit: M. Ahlers

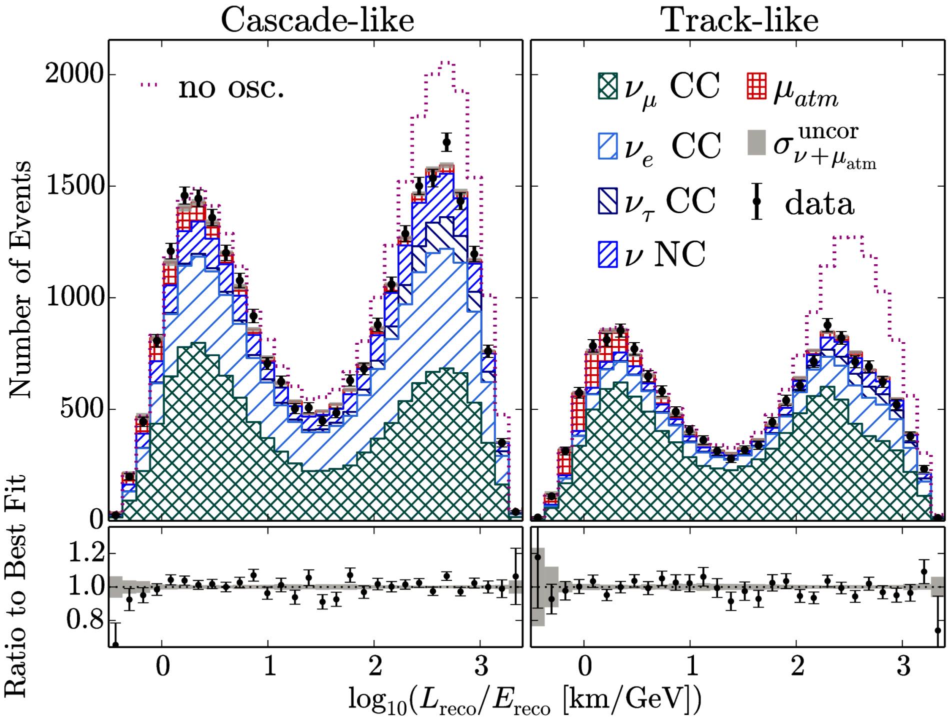
- Observation confirmed in independent channels
- Potential hardening of the spectrum at high energies hinting at feature
- Fluxes are compatible in the common energy range
- Sources remain to be seen

Up-going Muon Tracks

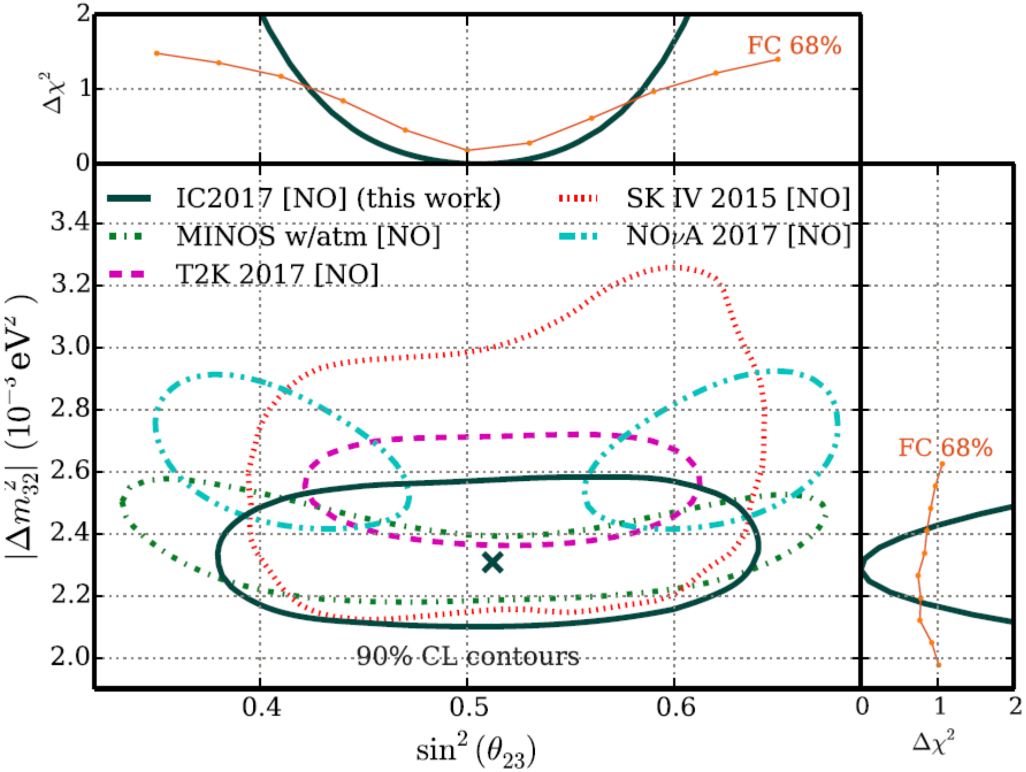
8 years observation ➛ 6.7σ
~ 500 astrophysical neutrinos

Spectral index: 2.19

Neutrino physics

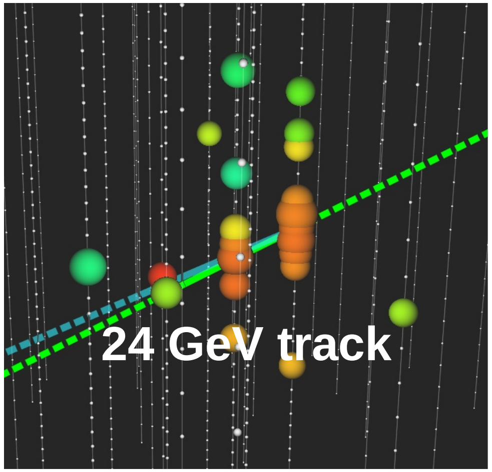


IceCube, PRL 2018



- DeepCore sub-detector lowers energy threshold to ~5GeV
- Measurements of muon neutrino disappearance
- Range of baselines up to the diameter of the Earth

→ competitive neutrino oscillation experiment



IceCube: An instrument for glaciology?

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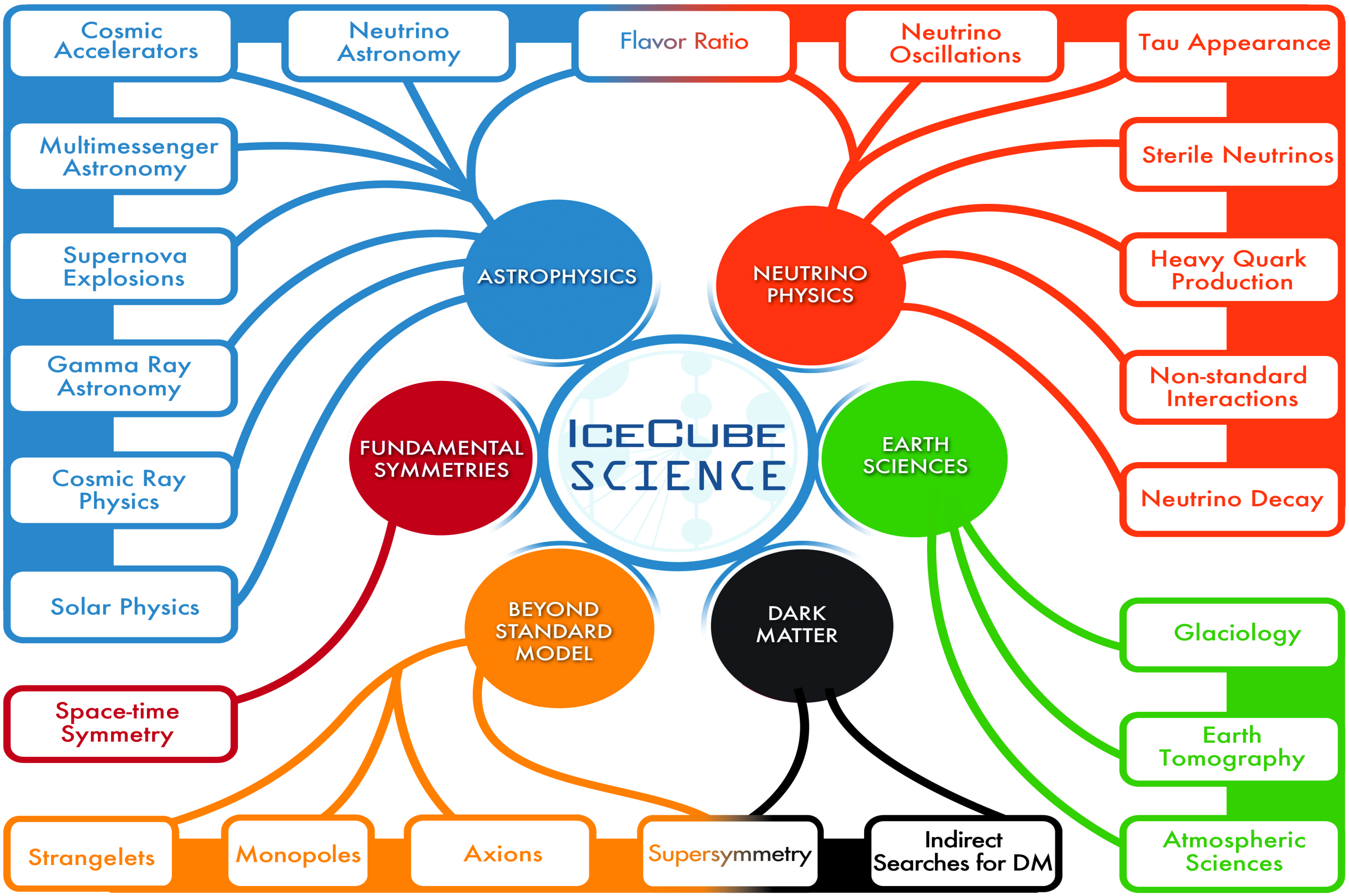
IIHE Seminar
March 2018



ICECUBE SCIENCE

ASTROPHYSICS
- Cosmic Accelerators
- Neutrino Astronomy
- Flavor Ratio
- Multimessenger Astronomy
- Supernova Explosions
- Gamma Ray Astronomy
- Cosmic Ray Physics
- Solar Physics

NEUTRINO PHYSICS
- Flavor Ratio
- Neutrino Oscillations
- Tau Appearance
- Sterile Neutrinos
- Heavy Quark Production
- Non-standard Interactions
- Neutrino Decay

FUNDAMENTAL SYMMETRIES
- Space-time Symmetry

BEYOND STANDARD MODEL
- Strangelets
- Monopoles
- Axions
- Supersymmetry

DARK MATTER
- Supersymmetry
- Indirect Searches for DM

EARTH SCIENCES
- Glaciology
- Earth Tomography
- Atmospheric Sciences

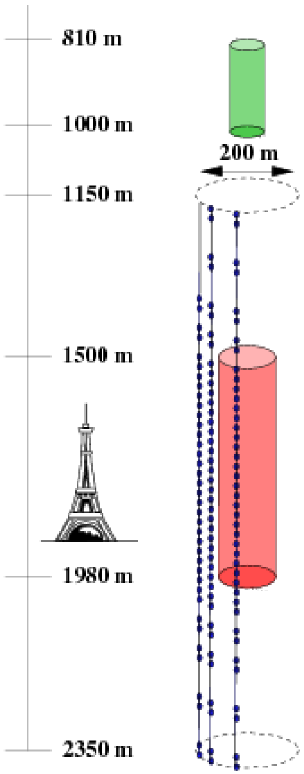
Glacial ice as detection medium

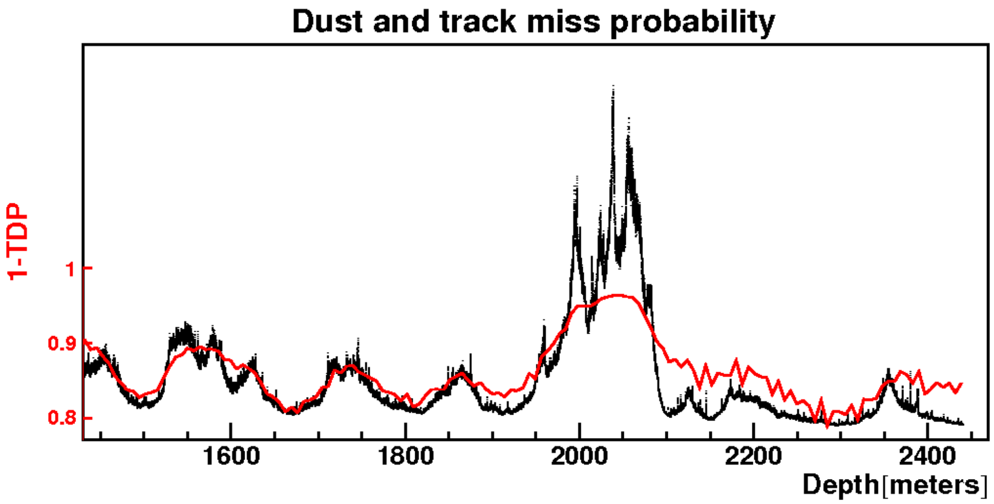
- In particle physics we usually design and build our detection medium with great care

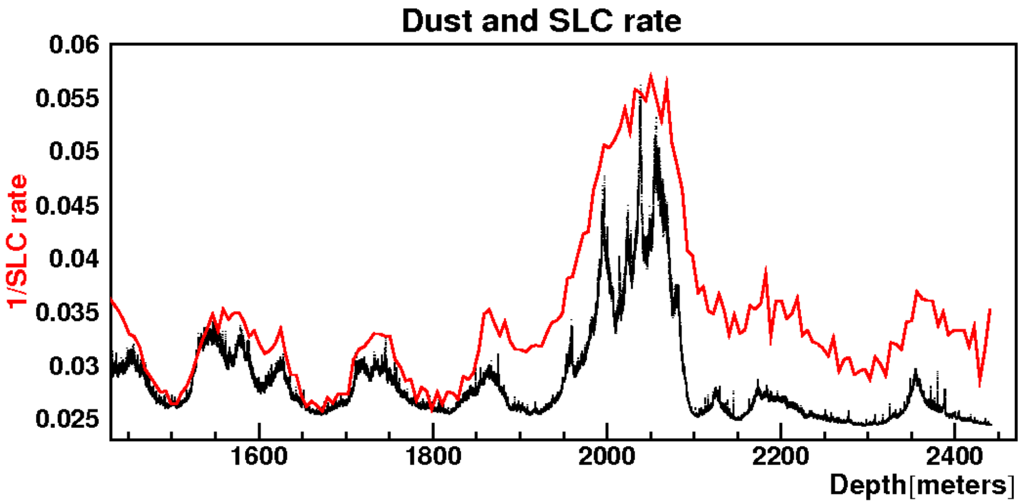
- Deploying into natural glacial ice we don‘t have that luxury
  (AMANDA-A failed because the optical properties at 1km were over-predicted)

- The optical scattering & absorption properties directly impact physics performance
  - Trigger performance, angular reconstruction, energy reconstruction, particle identification, ...

→ we need to in-situ calibrate the detection medium





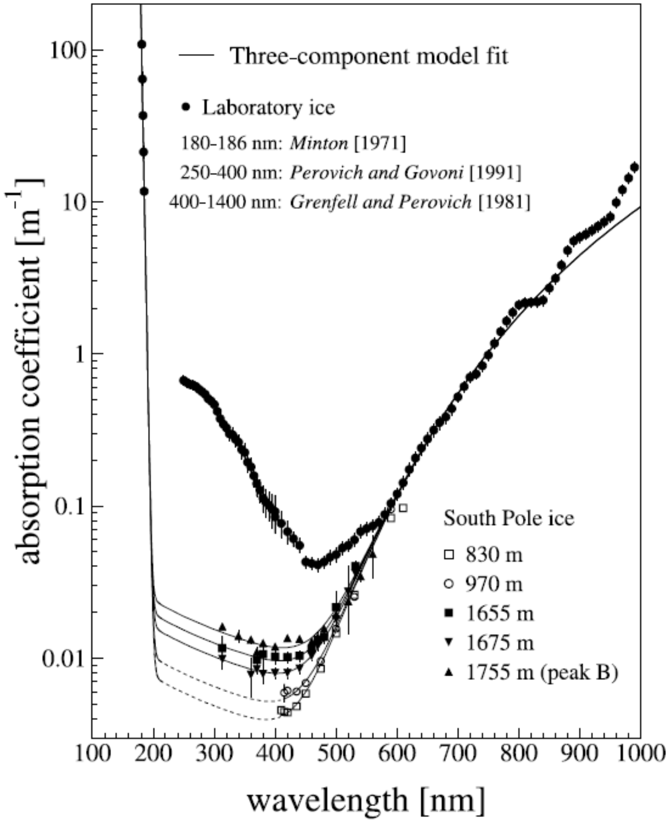


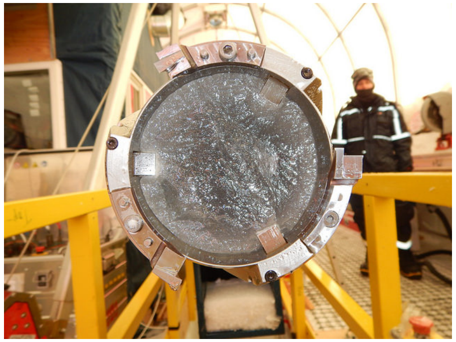
The Antarctic Glacier

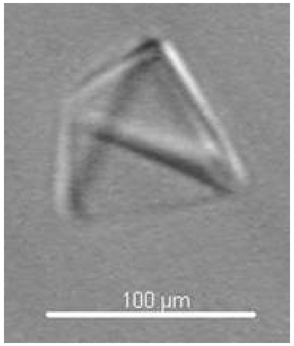
- Compacted snow up to 100'000 years old (Antarctica frozen for ~35 Ma)
- *Absorption* (~100m) better then any other solid on Earth

- Above ~1300m air bubbles dominate *scattering*
- Below ~1300m air bubbles get incorporated into crystal structure (craigite), *scattering* (~20m eff.) dominated by dust and volcanic ash correlated to absorption

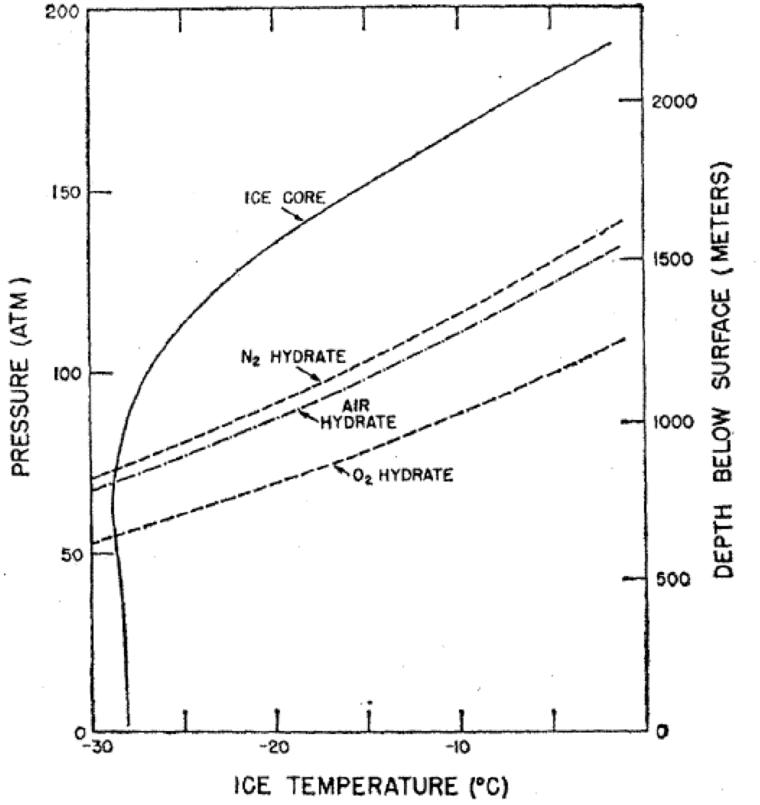
JGR 111 D13203







Nature 298, 548 - 550

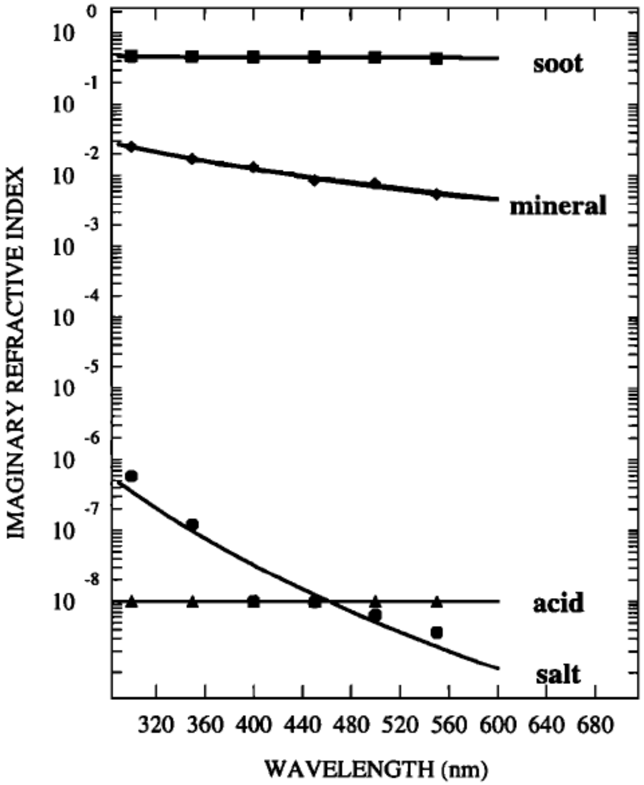


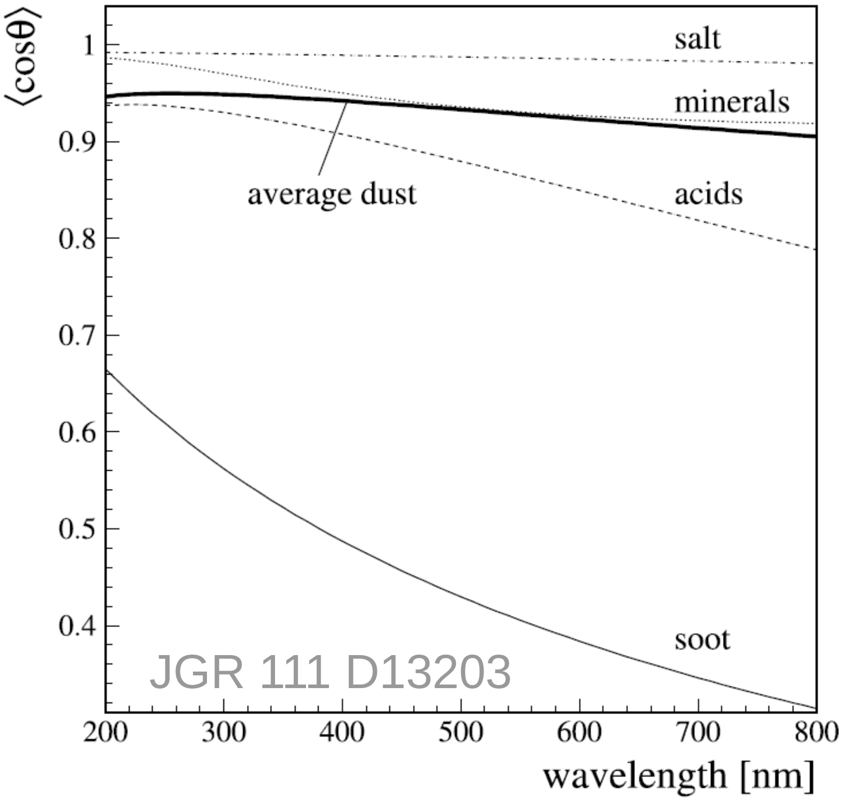
Impurity constituents

- Four main impurity components identified:
  - Soot (~10nm) being highly absorptive and acting as Rayleigh scatterer
  - Mineral grains (dust) also being absorptive but acting as Mie scatterers
  - Sea salty crystals (~400nm) only acting as Mie scatterers
  - Liquid (sulfuric) acid droplets also only acting as Mie scatterers

→ combined properties give overall optical characteristics

DOI: 10.1029/98JD01643

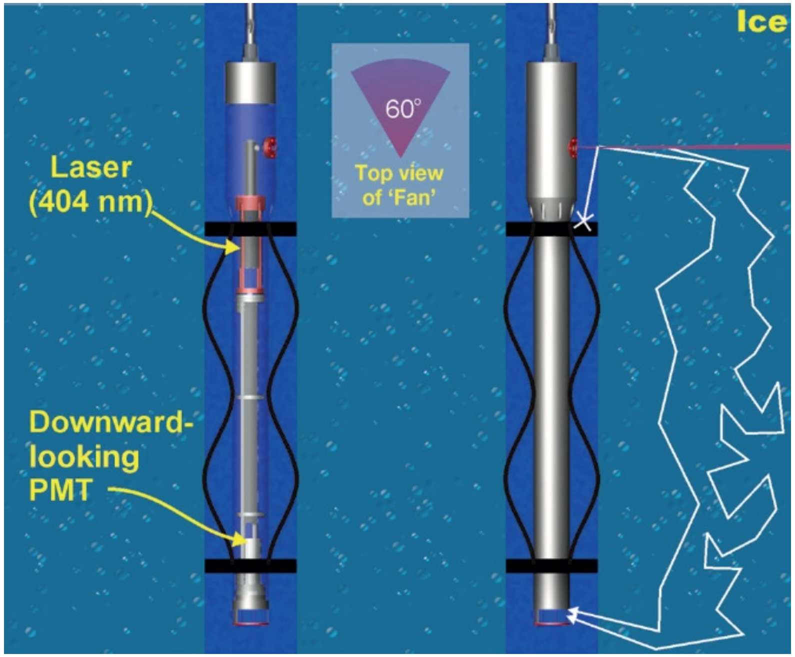


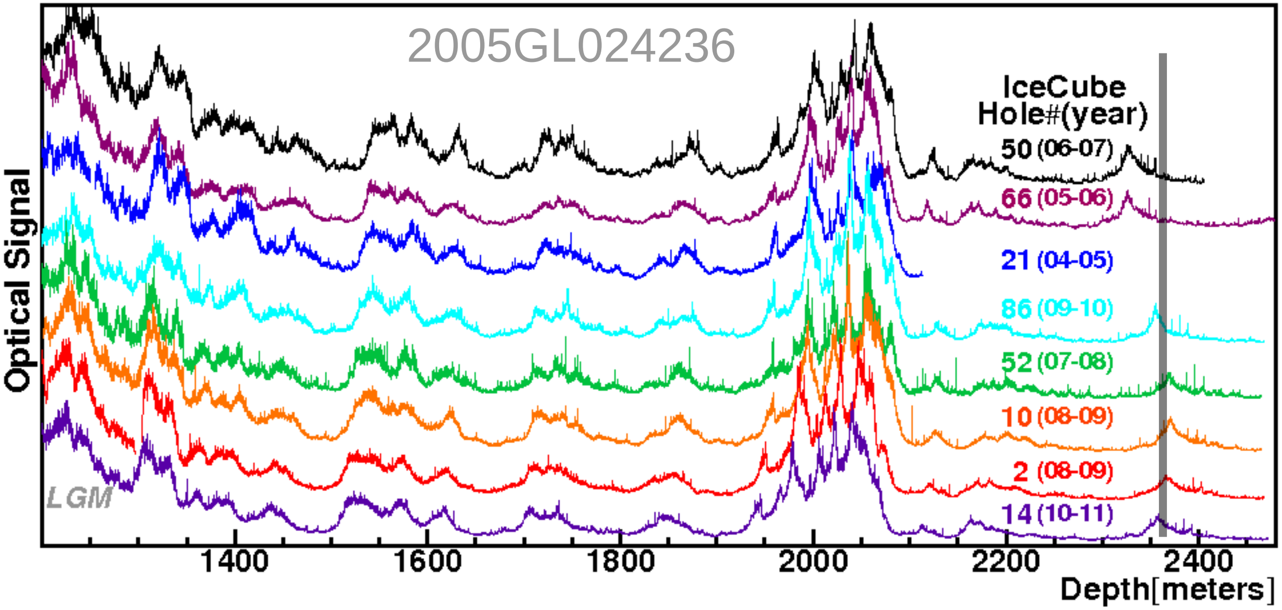


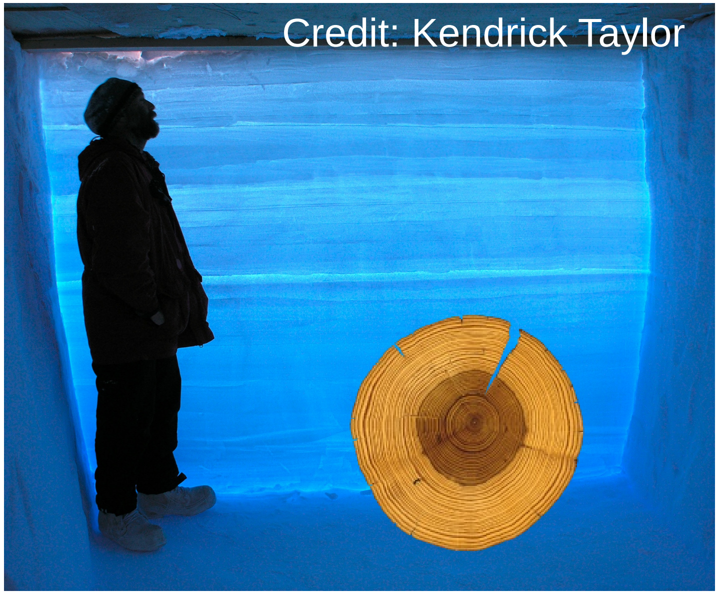
JGR 111 D13203

The DustLogger

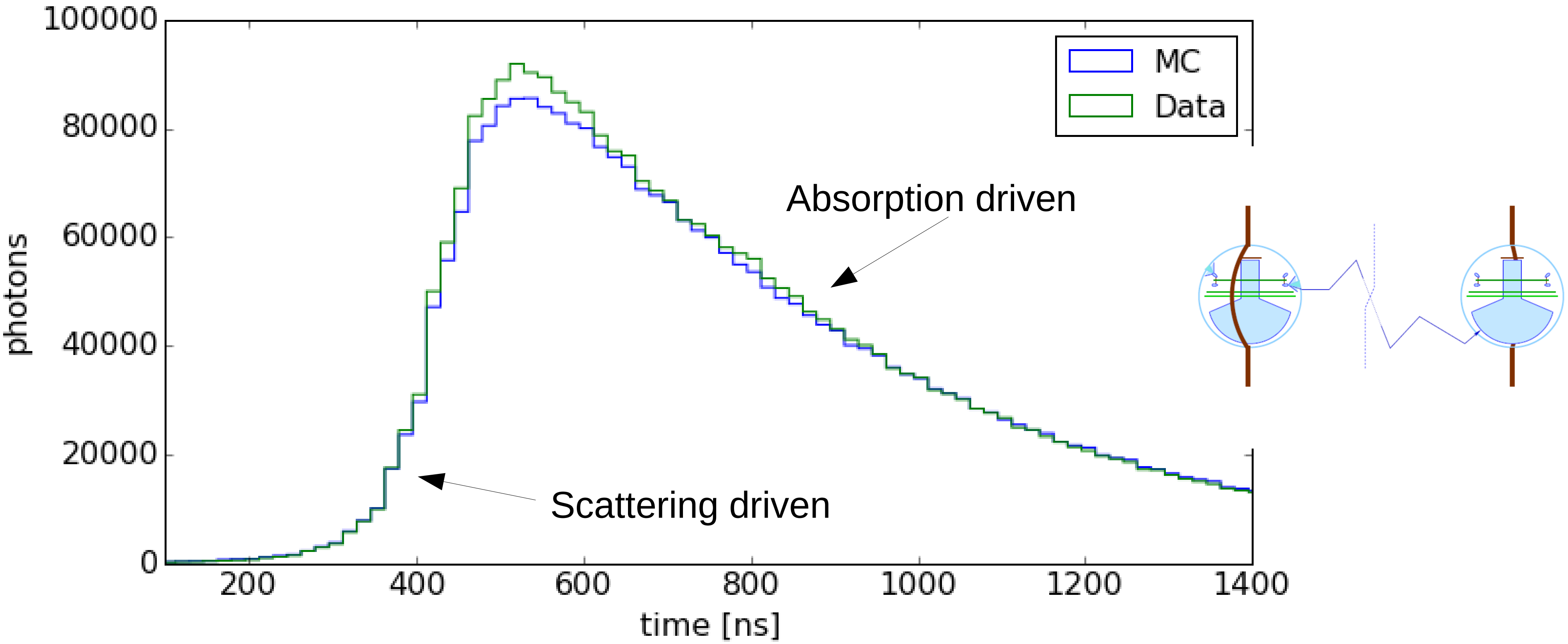
- Horizontal fan of light emitted into ice
- Scattering centers can deflect light into PMT shielded from direct light
  → Signal at photon counter proportional to density of scattering centers
- Yields high resolution depth profile but not absolute absorption and scattering lengths






Credit: Kendrick Taylor

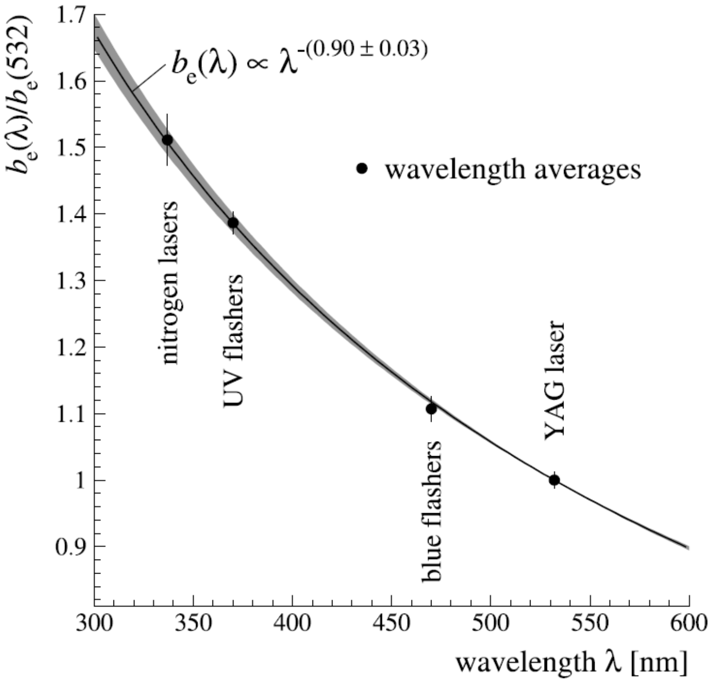
Light curve sensitivity



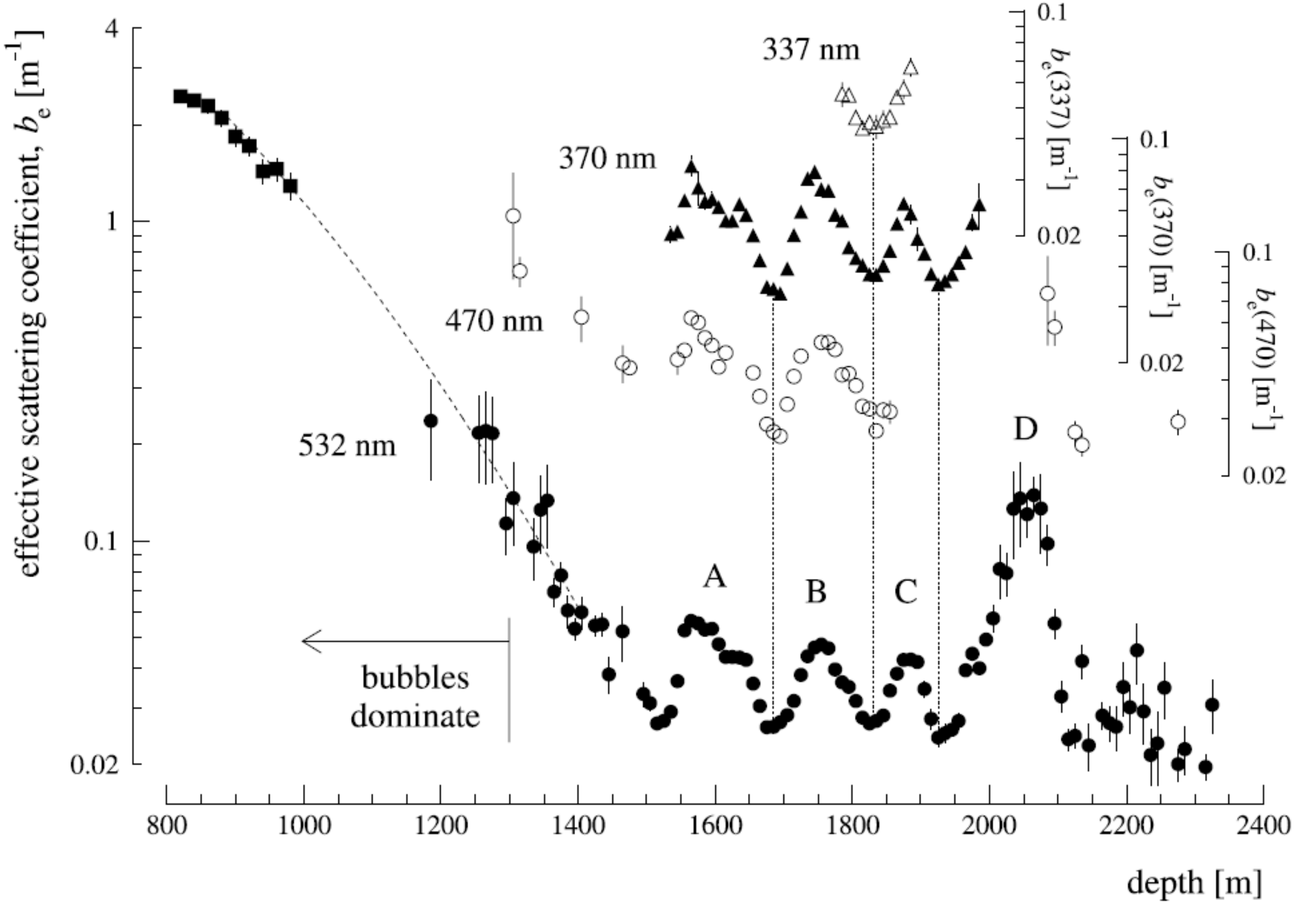
- Observation of photon arrival time distributions from pulsed light sources allows determination of absolute absorption & scattering lengths
- Independent from normalization, but observations at different distances help

- Distributions badly modeled by analytic random walk → full simulation needed

Layered ice model



doi:10.1029/2005JD006687



- AMANDA (shown here) and recently IceCube fits yield absolute optical properties over a wide range of depths (800-2500m) and wavelengths (350-550nm)

- 10m layering driven by sampling distance and computational limitations → mm-sized volcanic lines neglected

Analytic modeling

$$a(\lambda) = \sum_j N_j \int_{r_{max}}^{r_{min}} dr \left[A_j(r, \lambda, m_j) \frac{df_j}{dr} \right]$$

Absorption length to be obtained

Summing over impurity densities

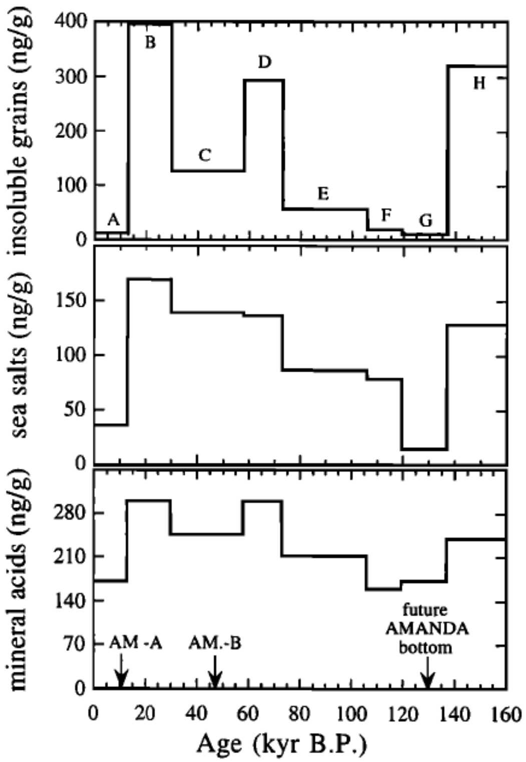
Per component size distribution

Per component Mie cross sections

- Given the number densities, size distributions and complex refractive indices of all impurities the:
  - Absorption length
  - Scattering length and angular deflection function
  - And their scaling with wavelength

  can be calculated from first principle Mie theory

- Concept proven in 1998 by Price and He comparing vague ice core data to the AMANDA ice model
  → update desperately needed

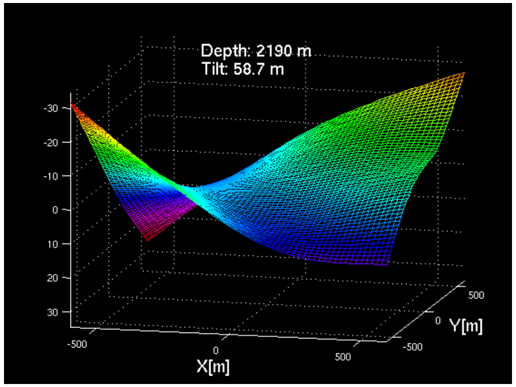


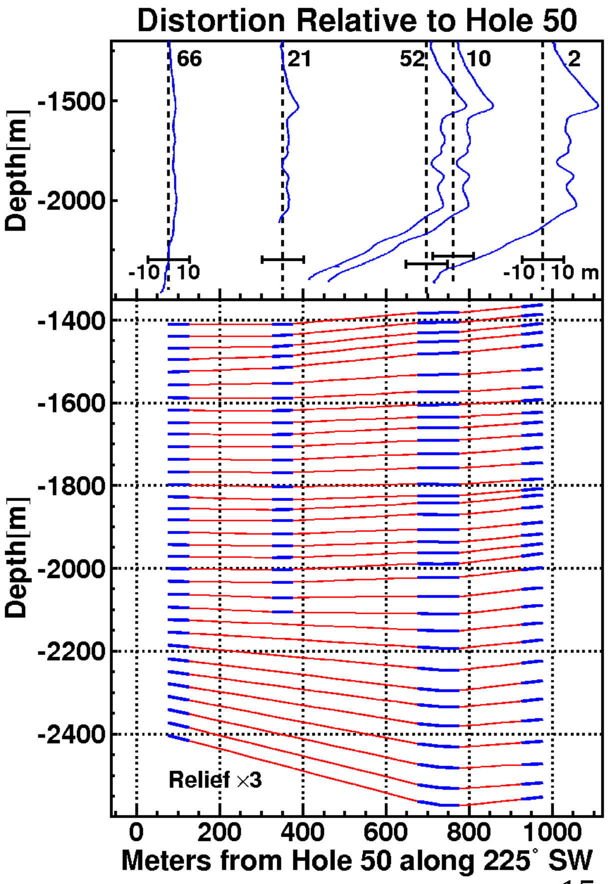
DOI: 10.1029/98JD01643

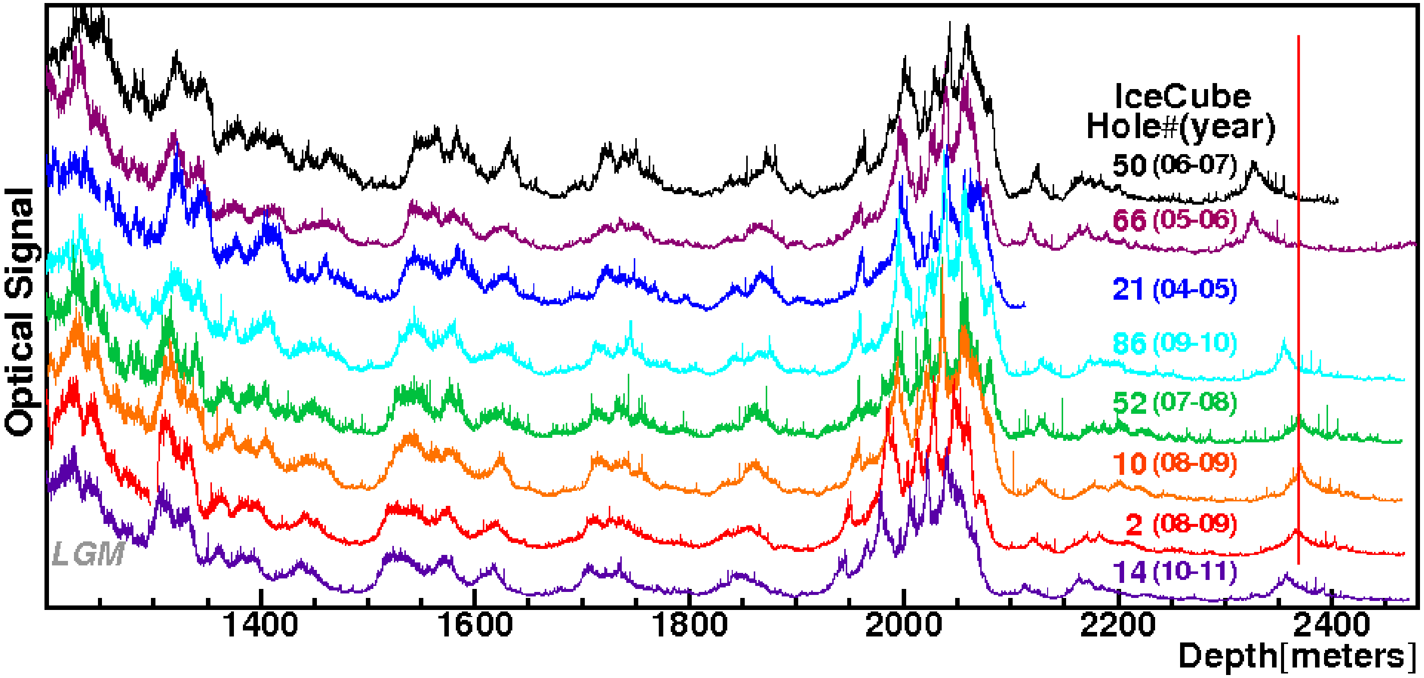
The ice tilt

- While the ice surface appears flat,
  the underlying terrain is fairly mountainous
  (as surveyed by BEDMAP2)

- Valleys only filled in gradually
  → ice layers at great depth are offset / tilted







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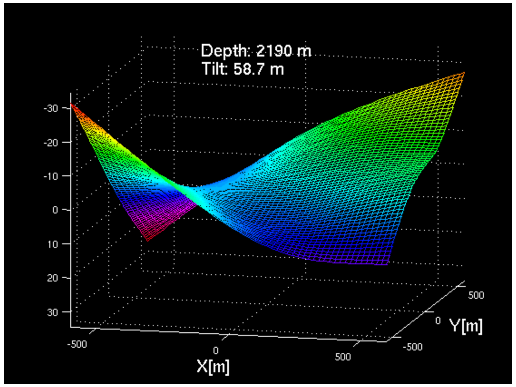

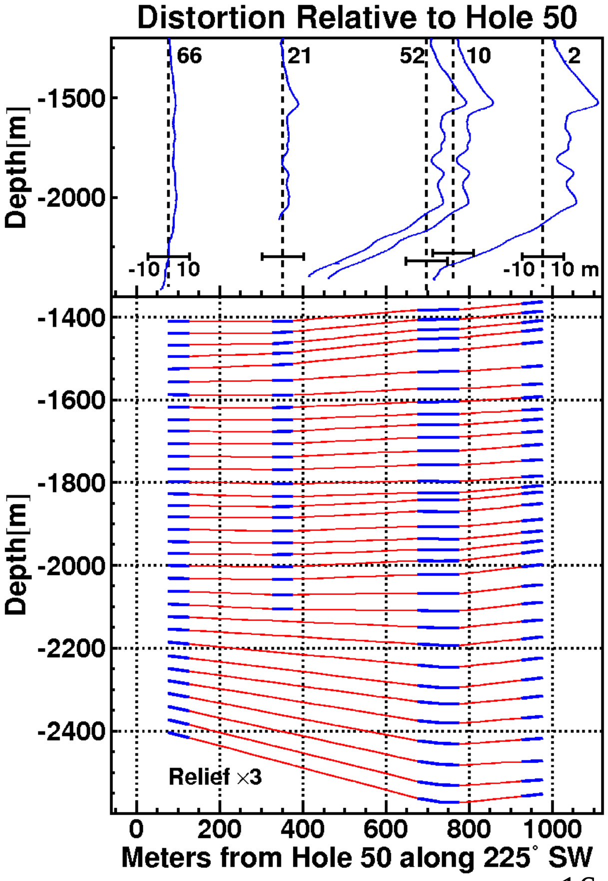

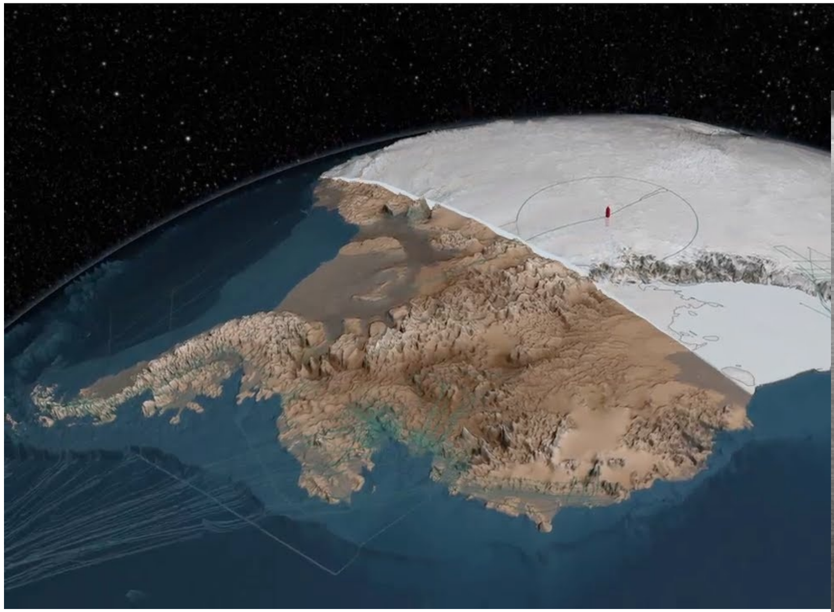

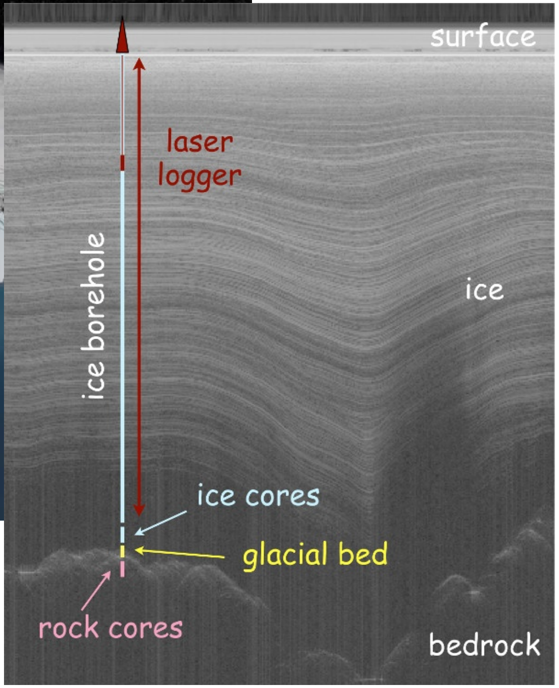

Rivers of ice

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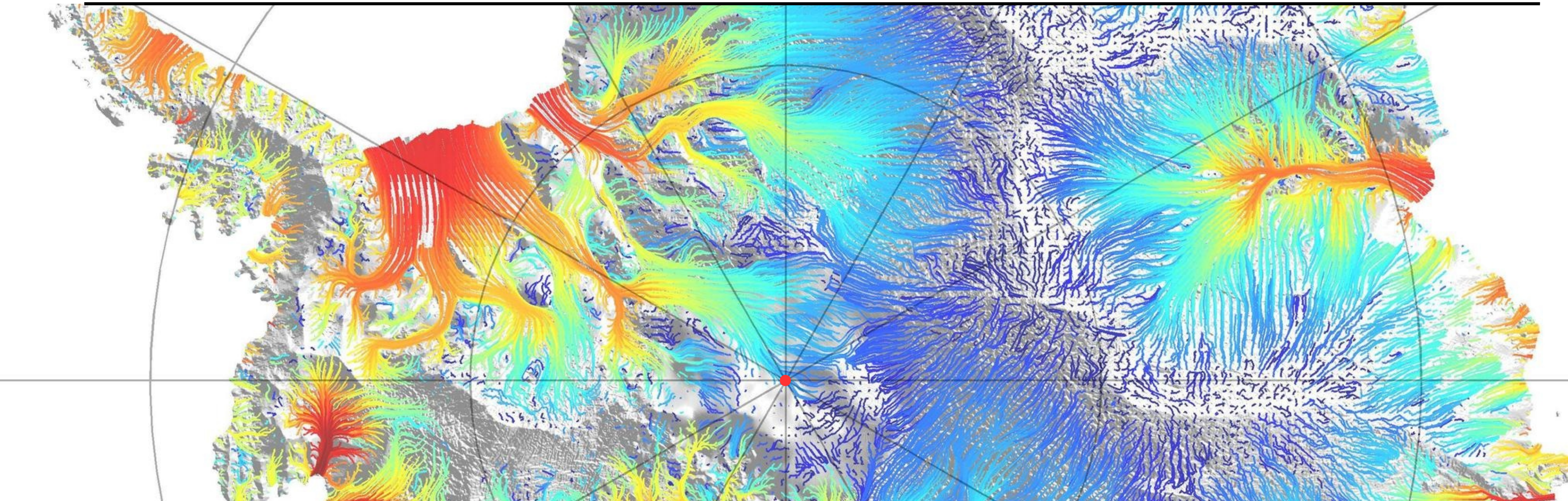
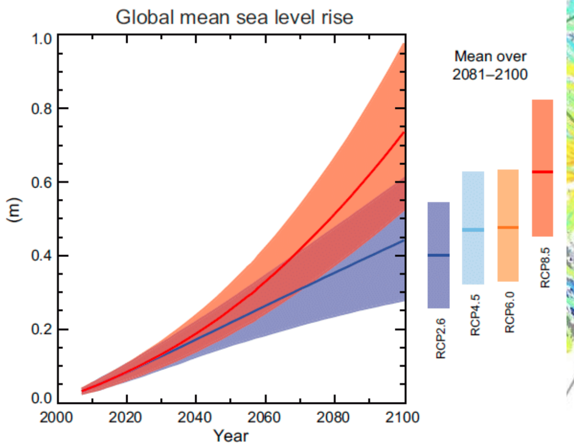
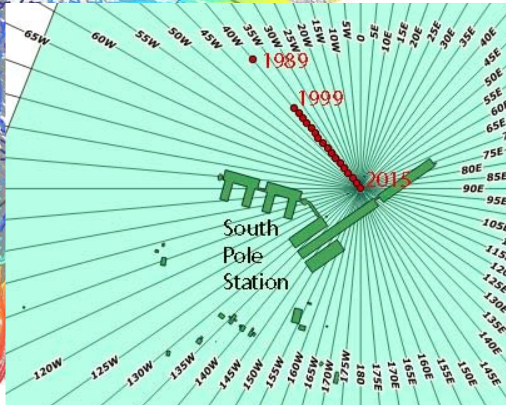


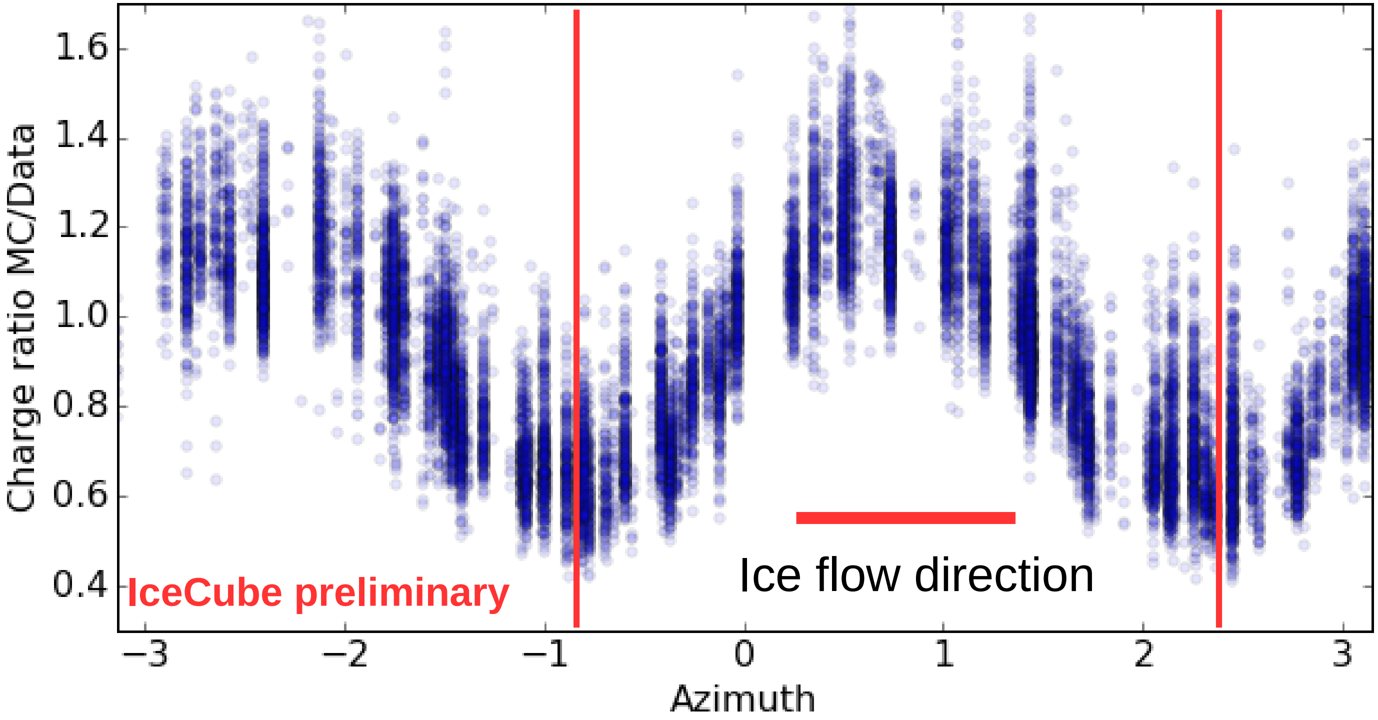


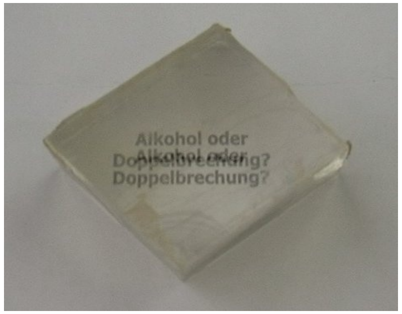


Velocity Data:
E. Rignot, J. Mouginot, B. Scheuchl, Ice Flow of the Antarctic Ice Sheet, Science 333, 1427–1430 (2011).

Credit: Devyn Rysewyk

The ice anisotropy





- Anisotropy: exhibiting properties with different values when measured in different directions

- Light traveling along the flow axis is less attenuated than light propagating orthogonal (along the tilt)

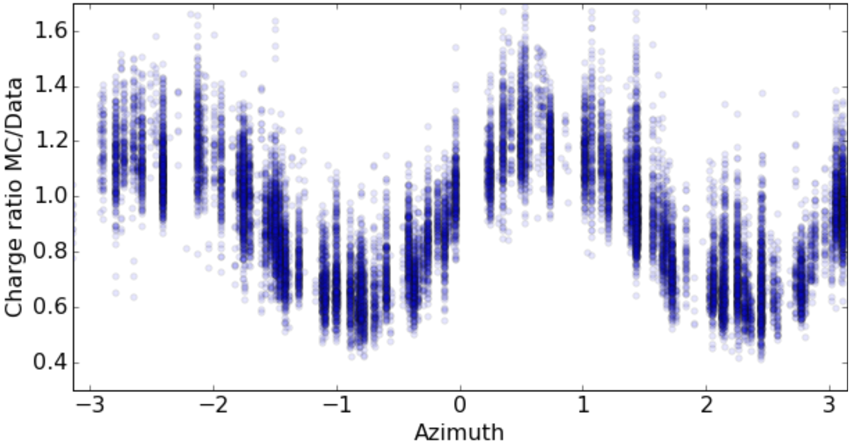
- Leads to an effective birefringence, mimicking the double bang signature of tau neutrinos

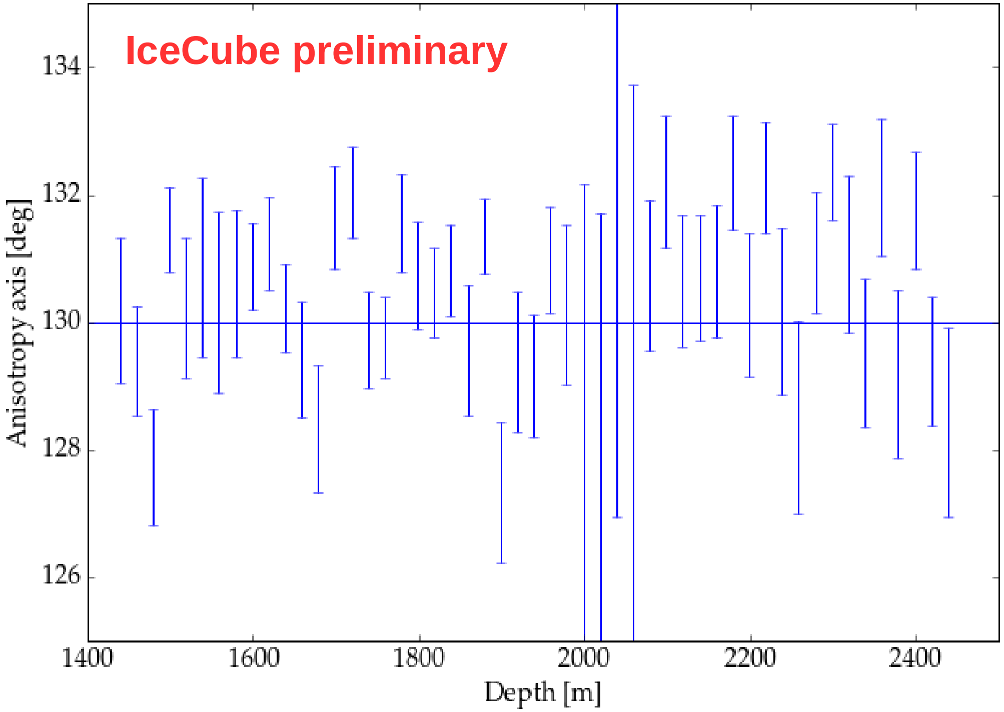
Anisotropy axis

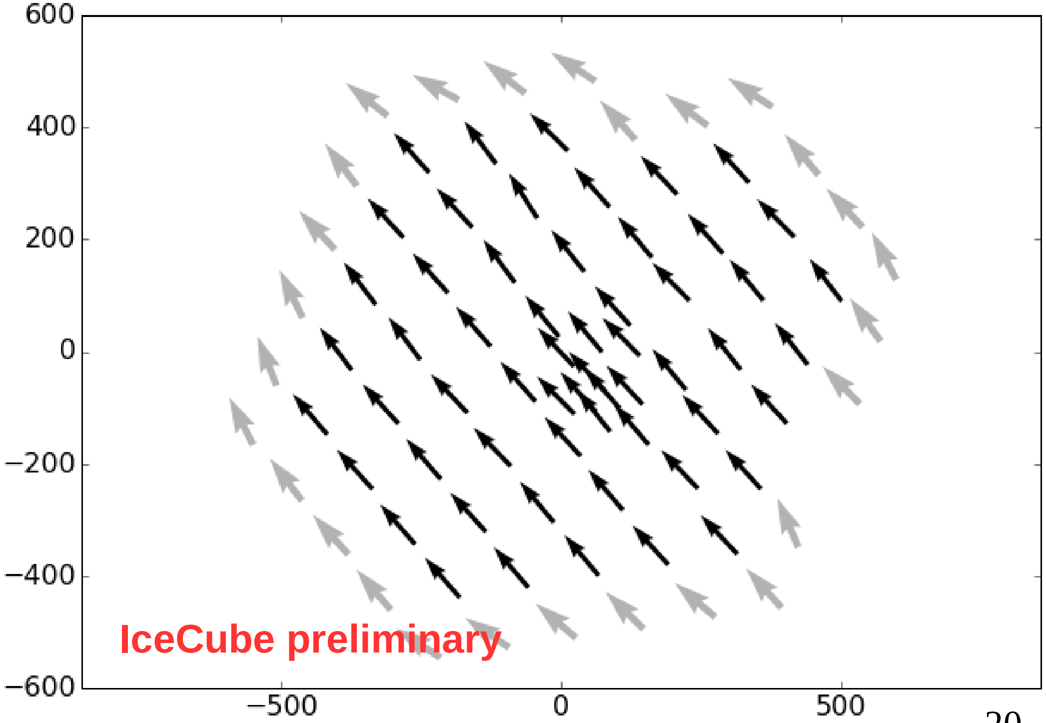
- Fit the phase of the intensity modulation to determine the anisotropy axis with the detector sliced in depth or by cable

- Axis appears to be constant over the face of the detector and versus depth

→ assumed to be constant at 130°







Original parametrization

- Assuming homogeneous impurity distributions 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*

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

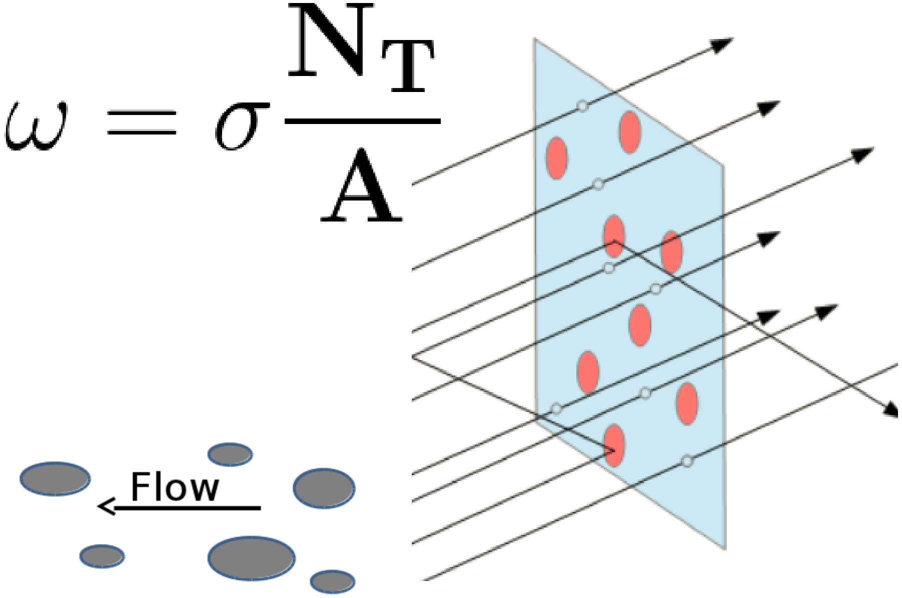
$$A = \begin{pmatrix} \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \gamma \end{pmatrix} = \exp\begin{pmatrix} \kappa_1 & 0 & 0 \\ 0 & \kappa_2 & 0 \\ 0 & 0 & \kappa_3 \end{pmatrix}$$

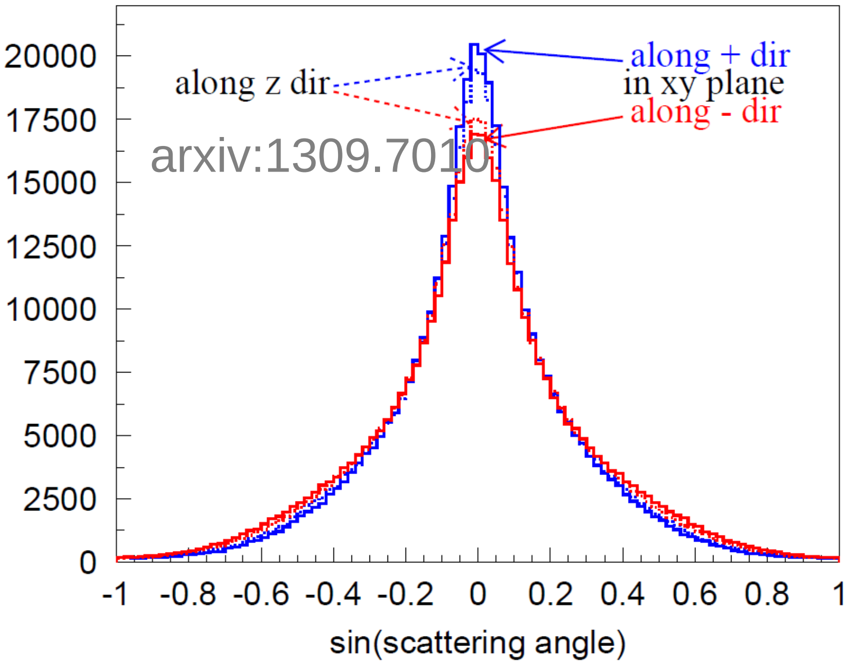
- Evaluated against a coordinate system aligned with the direction of largest scattering in the xy-plane → the anisotropy axis

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

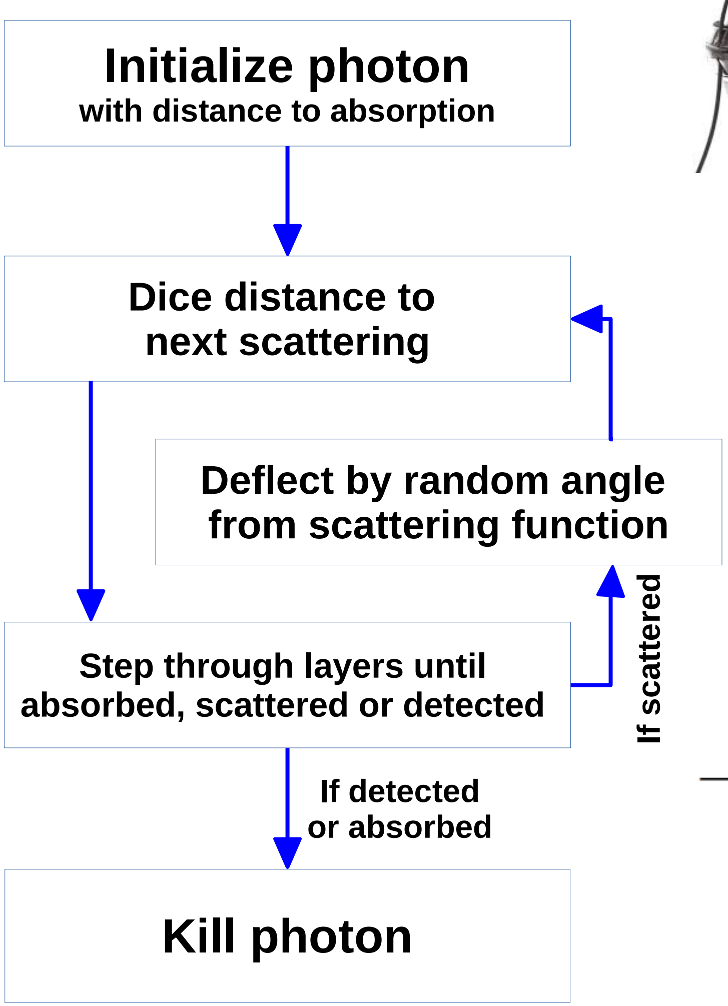
→ 3 free parameters (axis, kappa1, kappa2)

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





Photon propagation & likelihood analysis



Initialize photon
with distance to absorption

Dice distance to next scattering

Deflect by random angle from scattering function

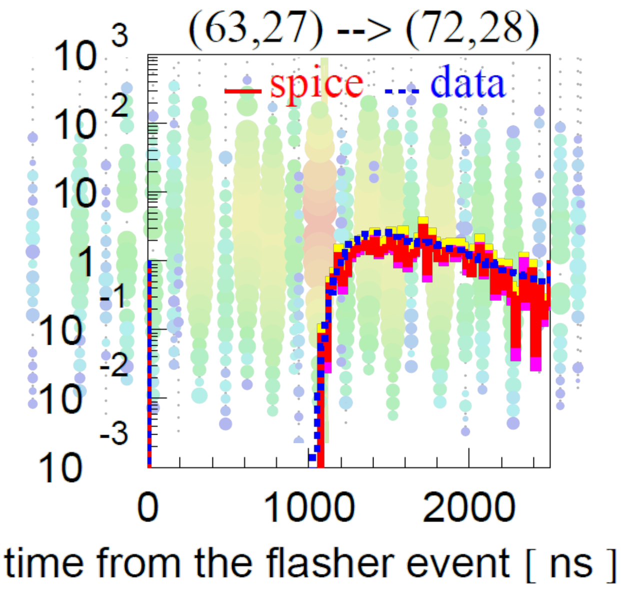
Step through layers until absorbed, scattered or detected

If scattered

If detected or absorbed

Kill photon

On GPUs ~250 times faster than CPUs



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

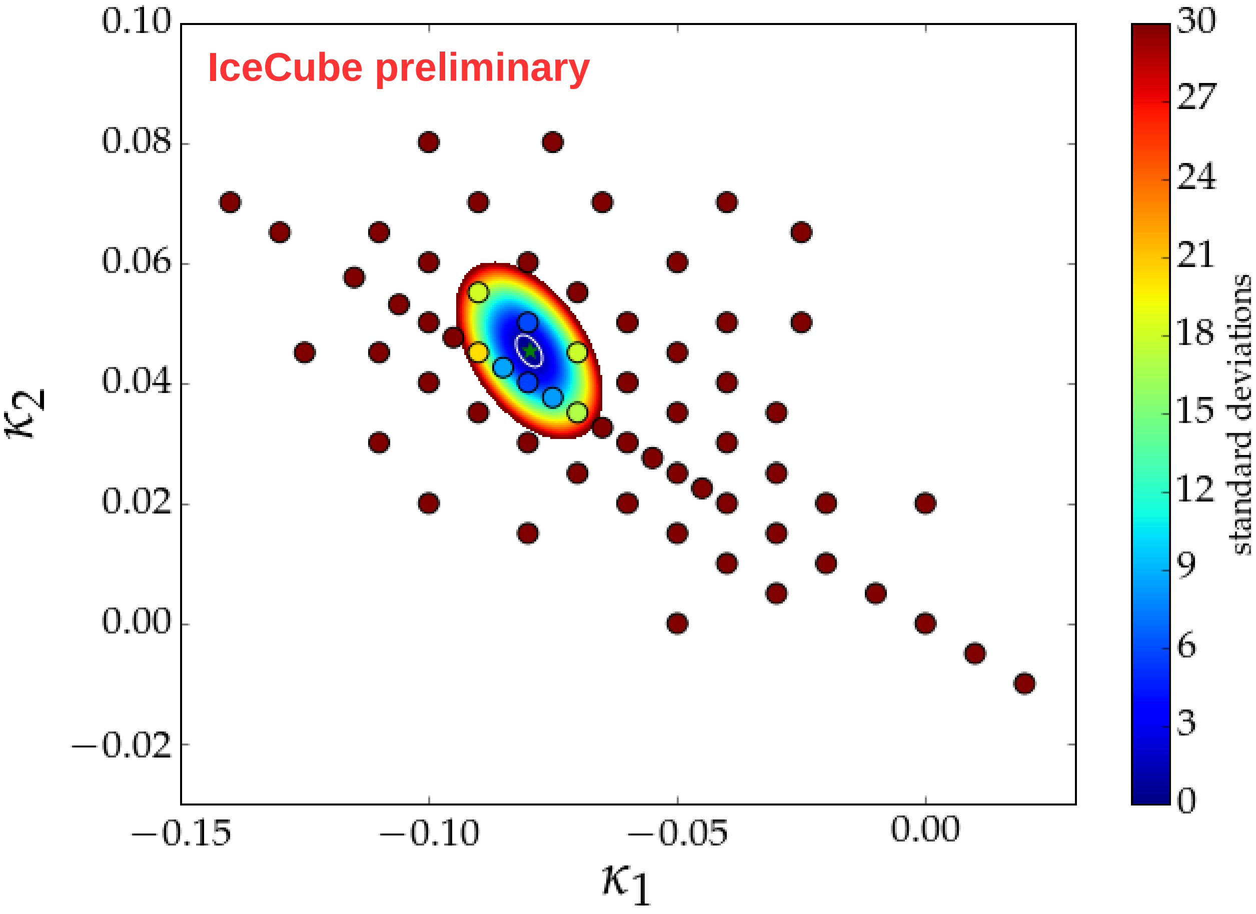
$$-\ln\mathcal{L} = \sum_i \left[s_i \ln \frac{s_i/n_s}{\mu_s^i} + d_i \ln \frac{d_i/n_d}{\mu_d^i} + \frac{1}{2\sigma^2} \ln^2 \frac{\mu_d^i}{\mu_s} \right]$$

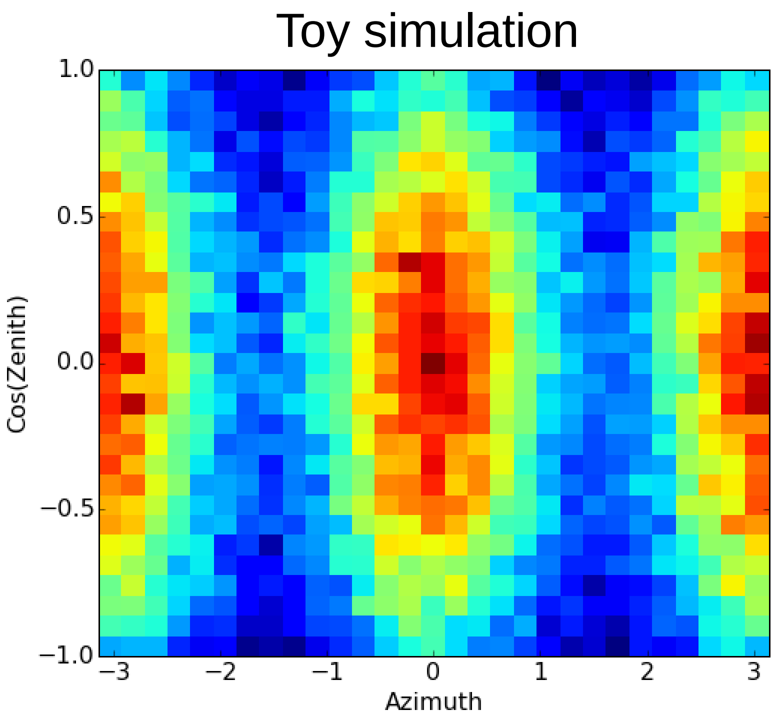
i sums over all emitting & receiving DOMs and their time bins

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

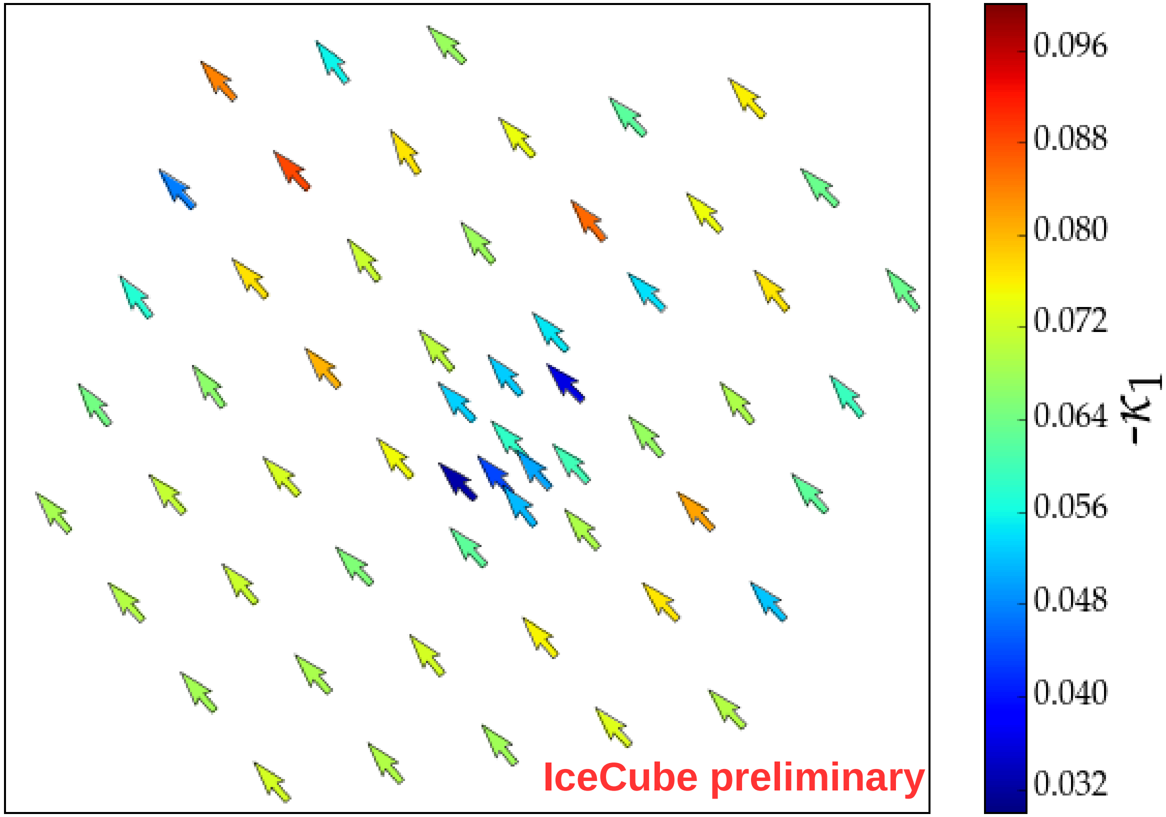
Detector average strength

- 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 affects propagation as a function of zenith





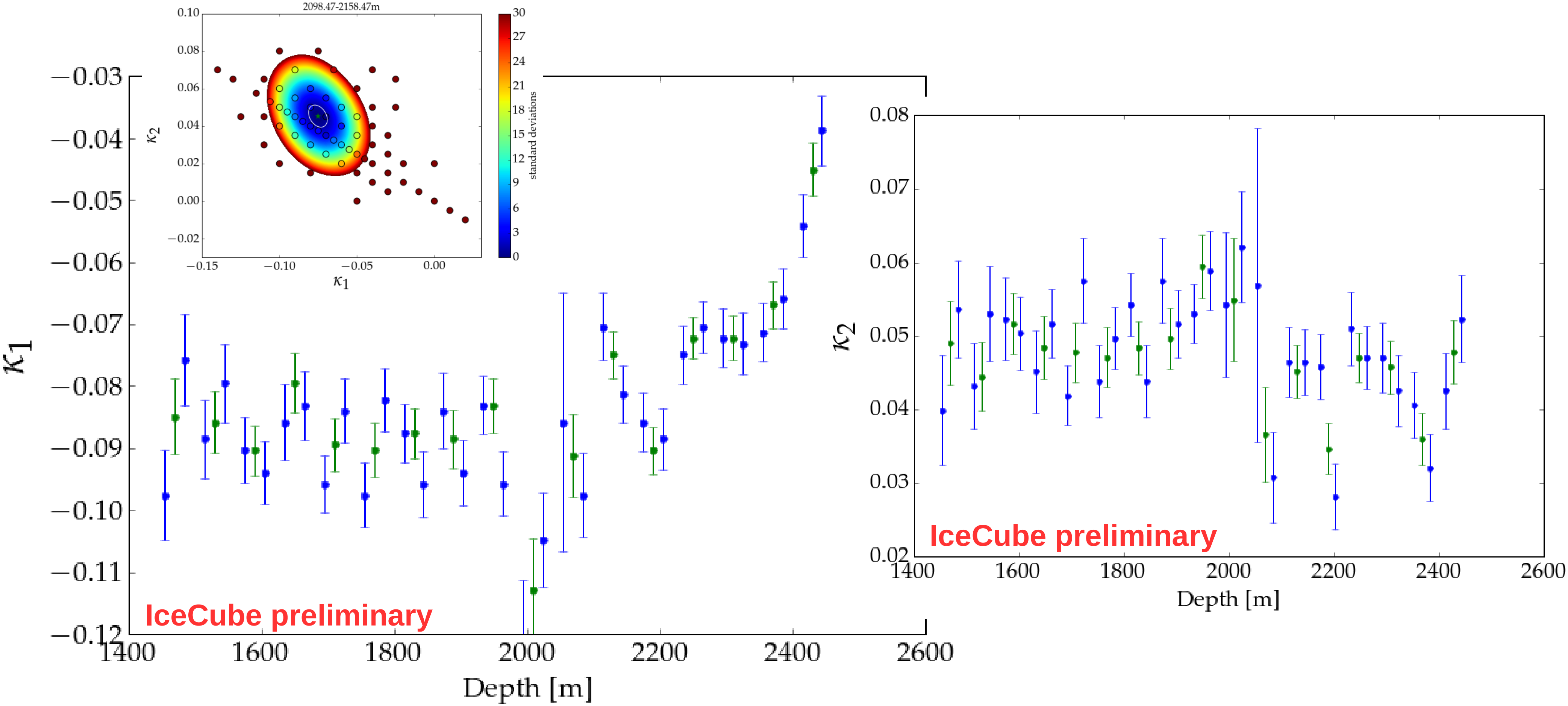
Anisotropy strength over the array



- 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

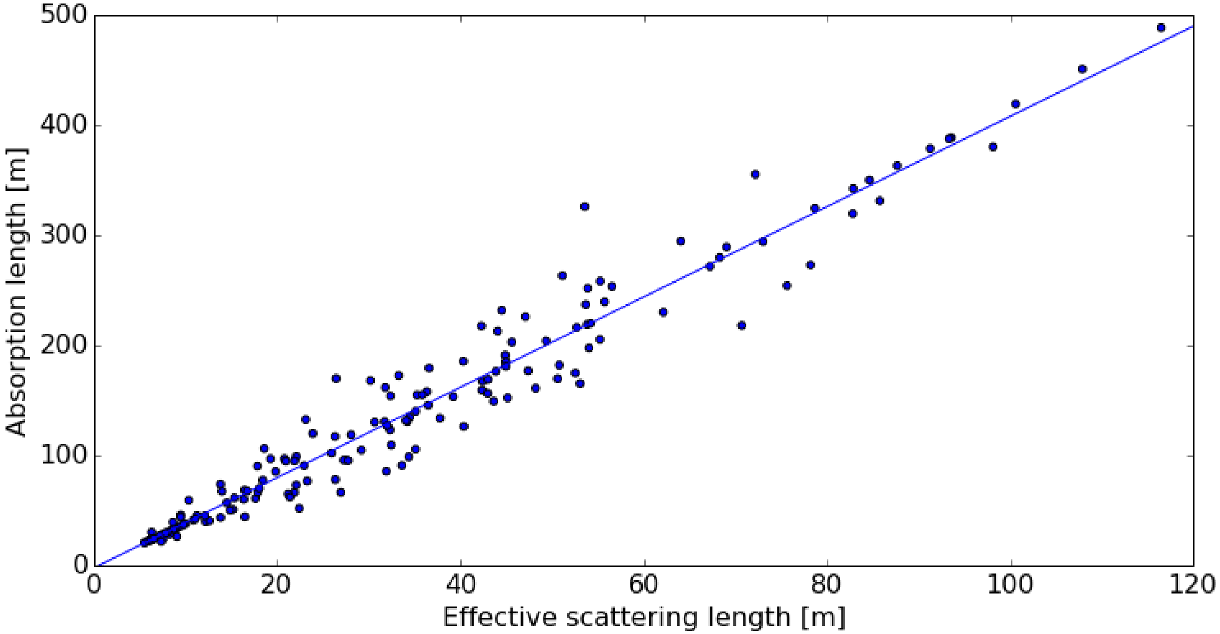
Anisotropy strength vs. depth



- 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



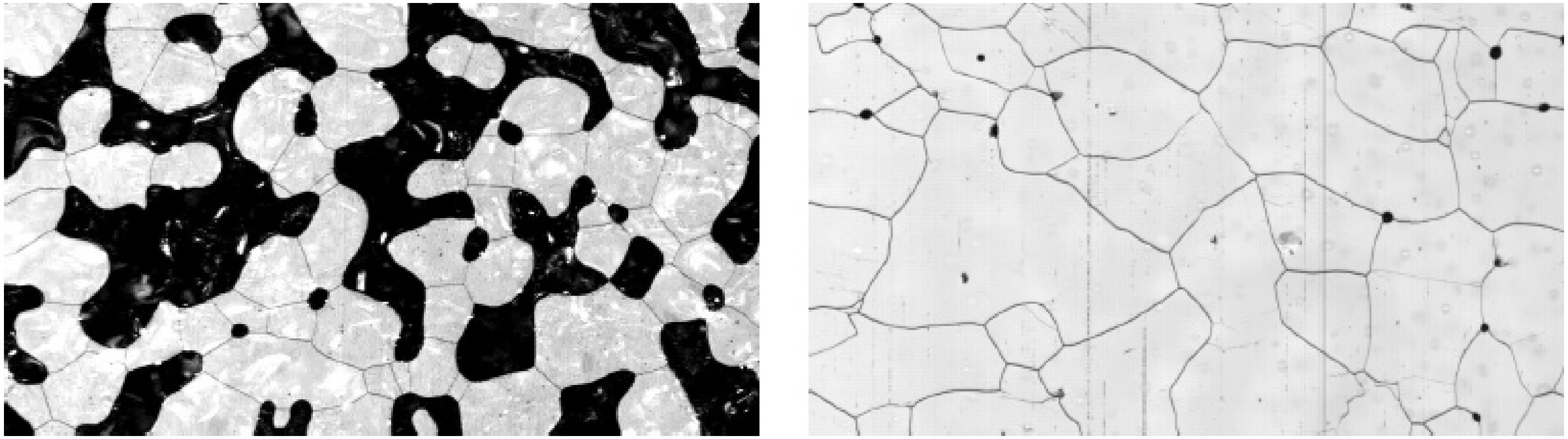
- While modifying the scattering function is an elegant solution, it is hard to motivate
- Rotation of dust particles has been proposed,
  but is hard to explain on the microscale

- 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 function is the underlying cause

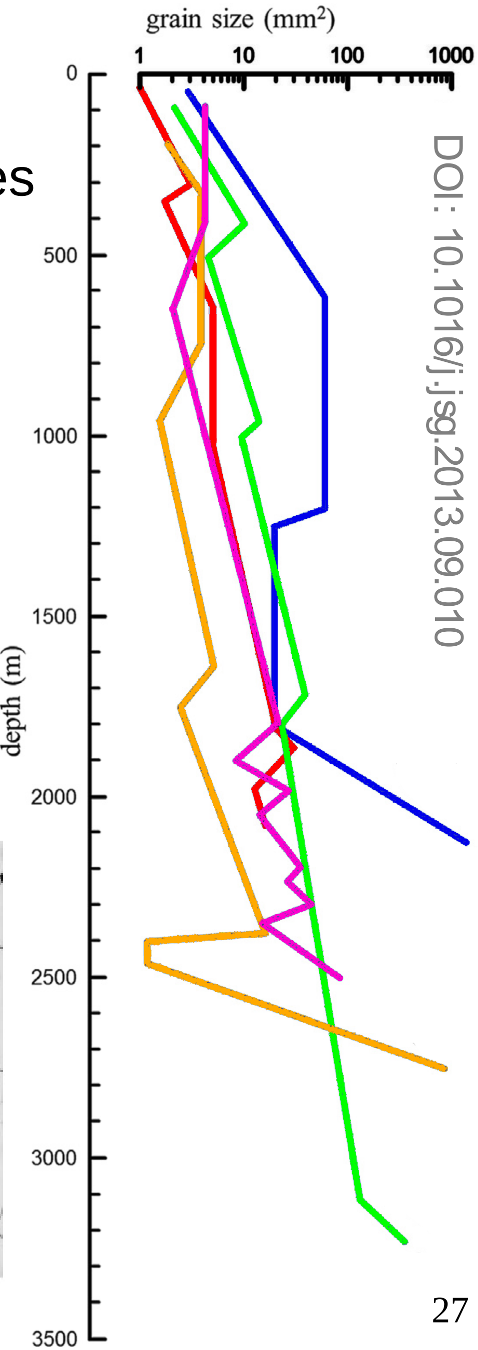
→ **let‘s turn to ice cores to motivate a more physical parametrization**

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 an ice core sample sublimates the grain boundaries leave grooves on the surface that can be imaged
- Ice grain sizes range from sub-mm^2 to thousands of mm^2 with aspect ratios between 1 and 1.8 → elongated
- Ice is a HOT material
  → the lattice undergoes constant re-crystallization
  which shifts the grain boundaries or bends and breaks grains

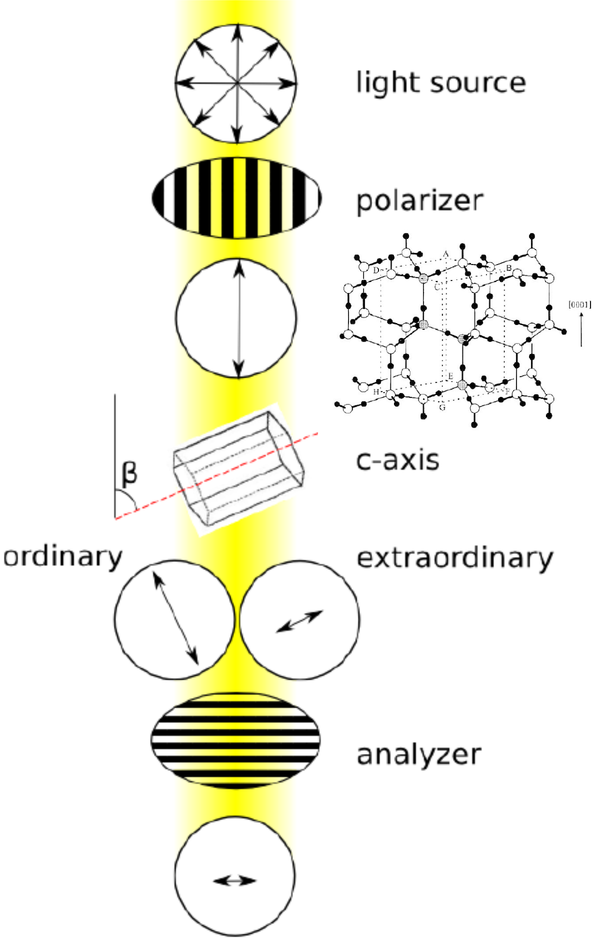


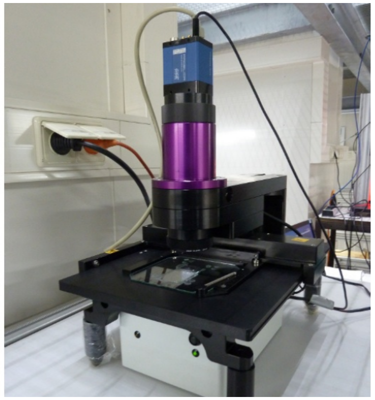
(a) Firn (Black regions = gases) (b) Ice



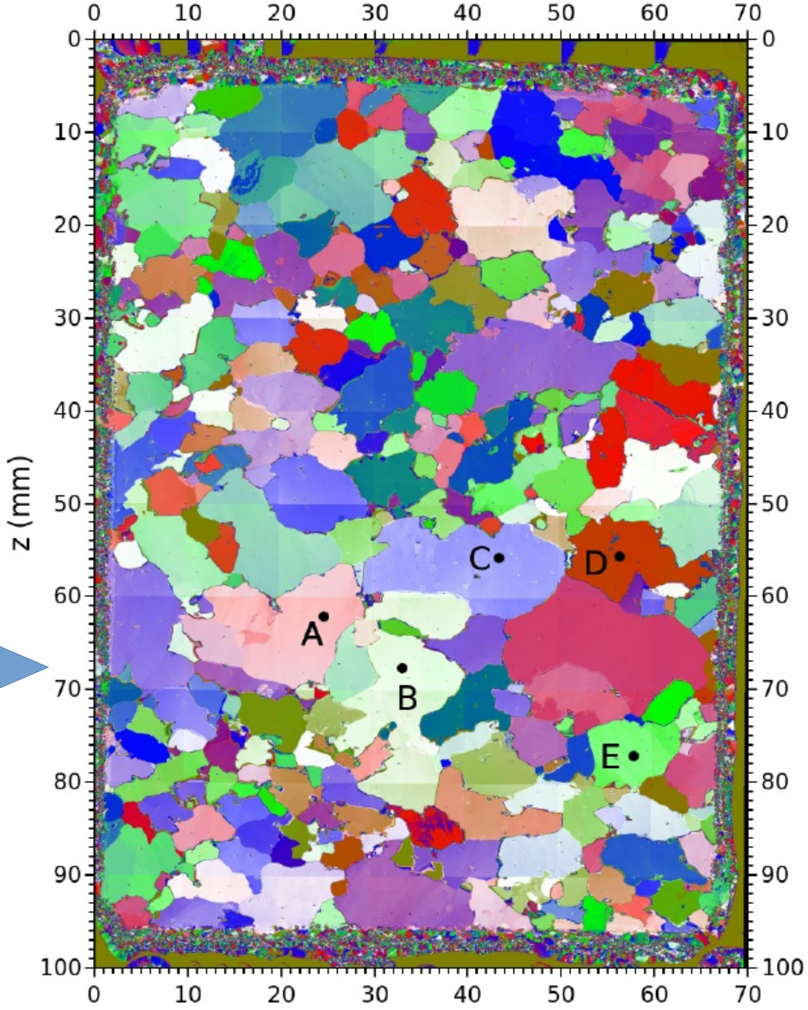
DOI: 10.1016/j.jsg.2013.09.010

C-axis orientation

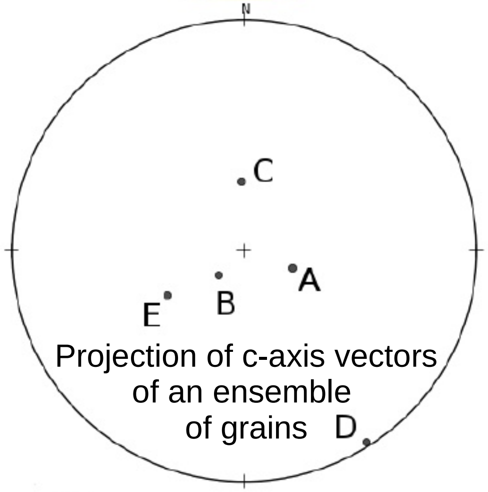




- Monocrystaline ice (a grain) is a birefringent material
- Using imaging polarization analyzers (fabric analyzer), a false color image showing the c-axis vector of each grain can be produced and their population can be studied



Jan Eichler, 2013



Projection of c-axis vectors of an ensemble of grains

The woodcock parameter

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:

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

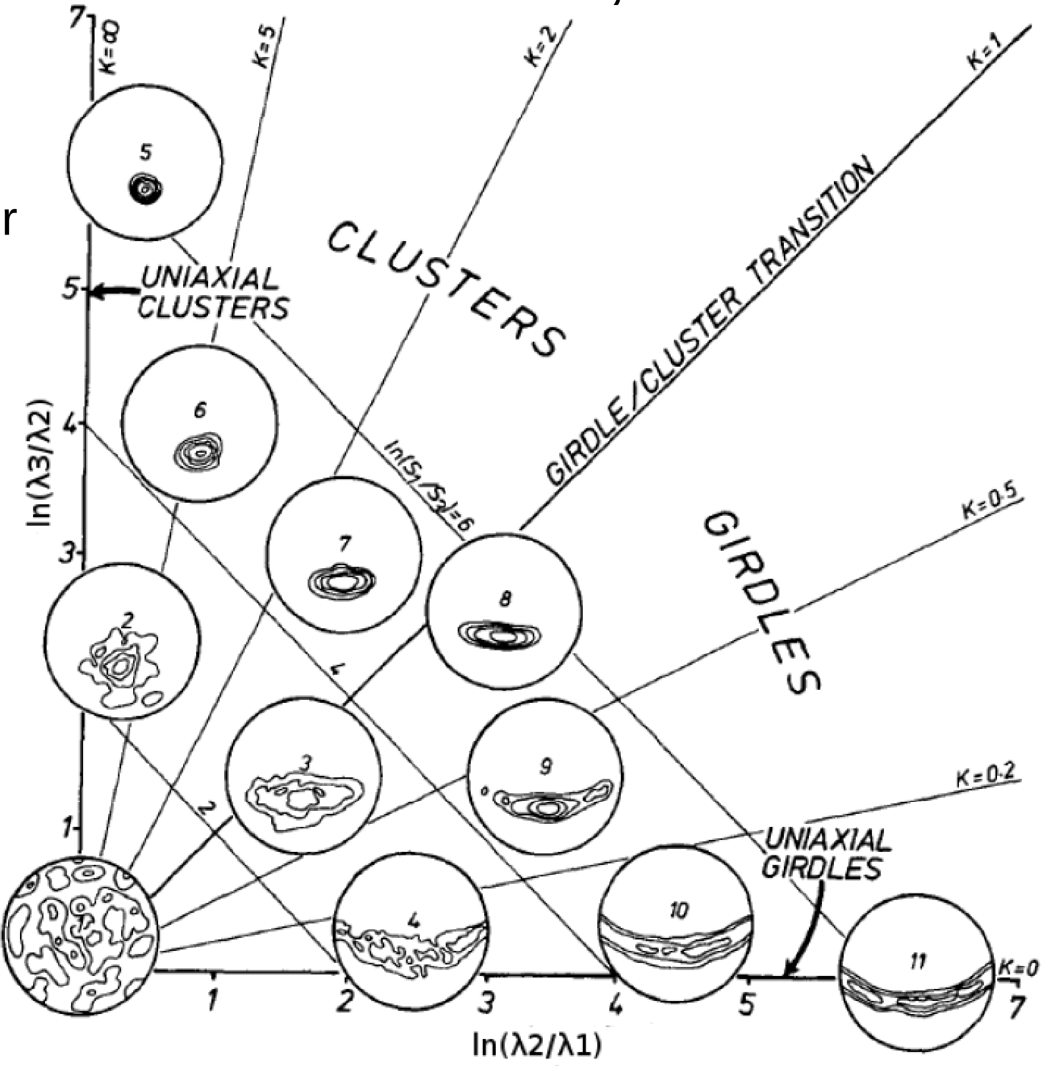
which give the lengths of the shape of the scatter plots with respect to a set of eigenvectors.

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

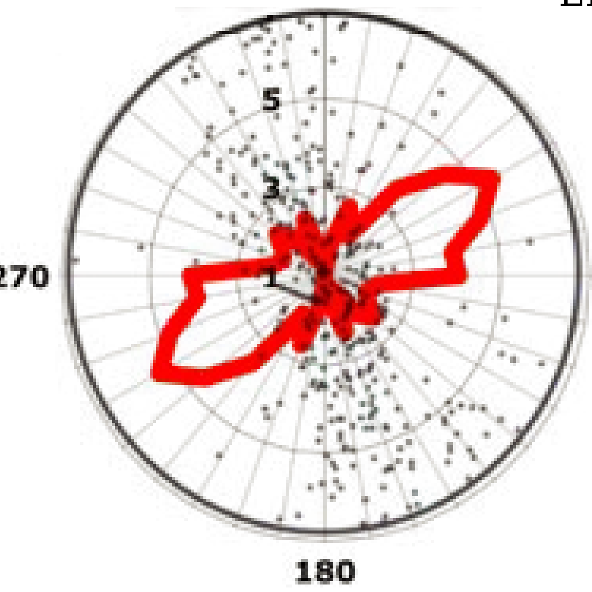


Ice grains & c-axis vs. depth

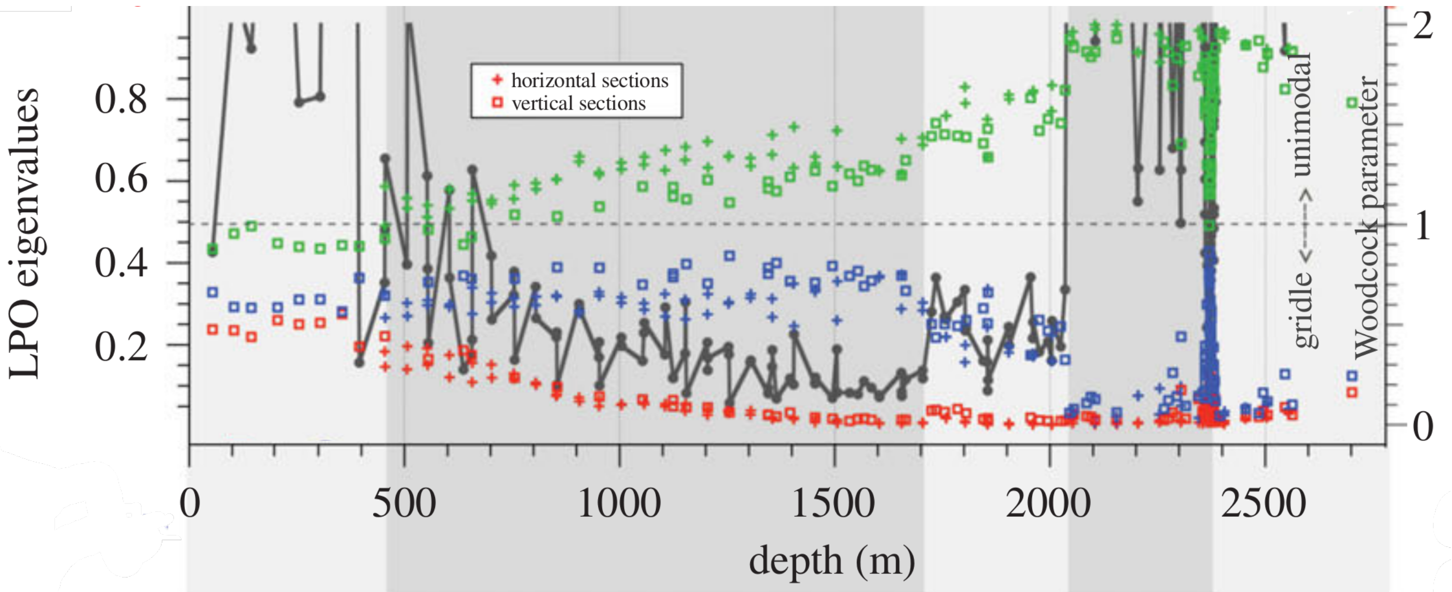
- Deep glacial ice shows a girdle fabric
  (c-axis preferentially horizontally aligned)

- In a girdle fabric the grain elongation-axis 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

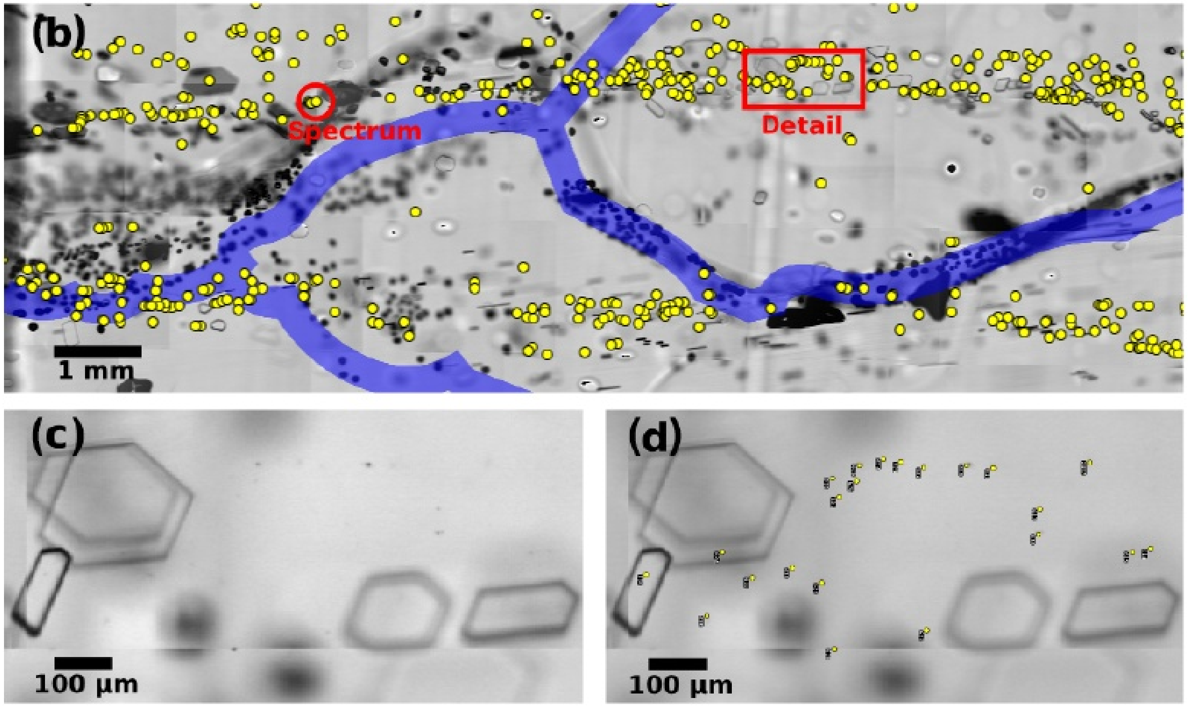


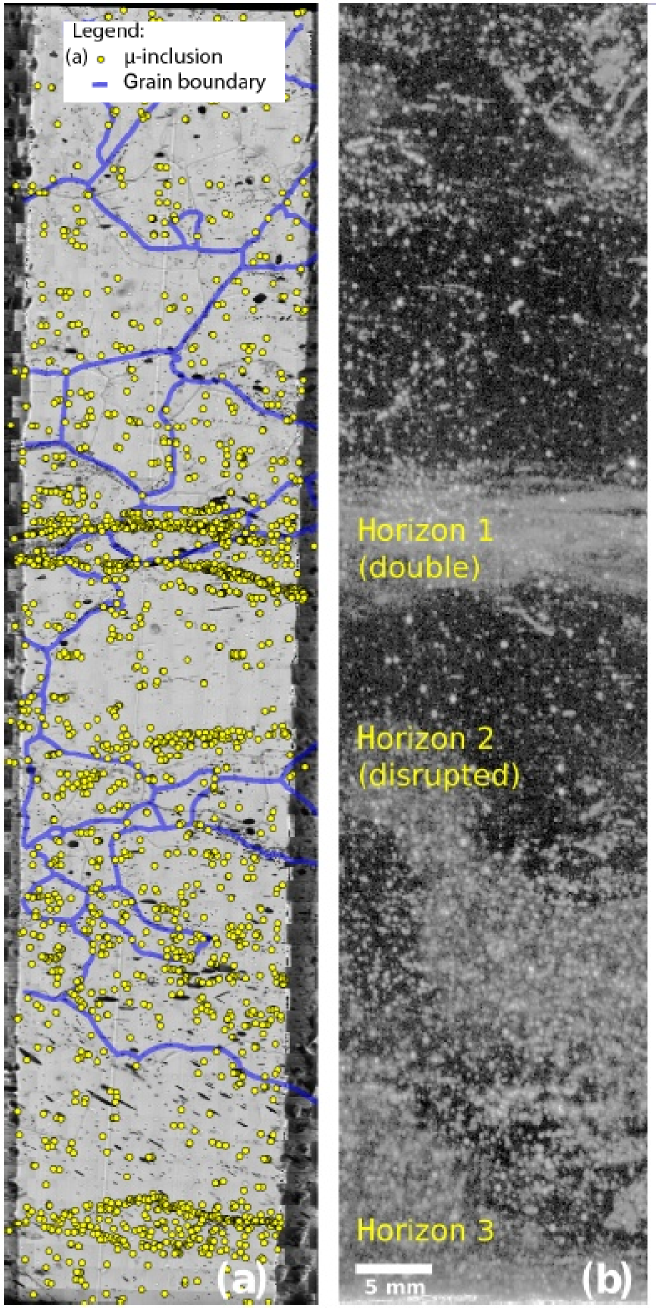
EDML ice core; dx.doi.org/10.1098/rsta.2015.0347



Micro inclusions

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



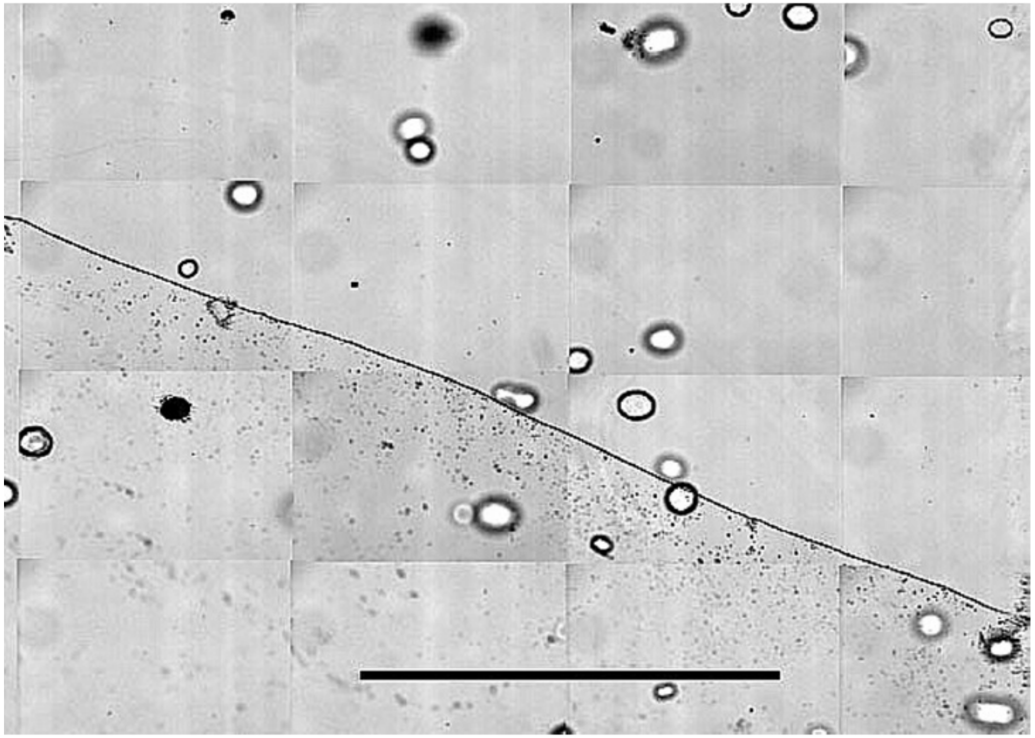


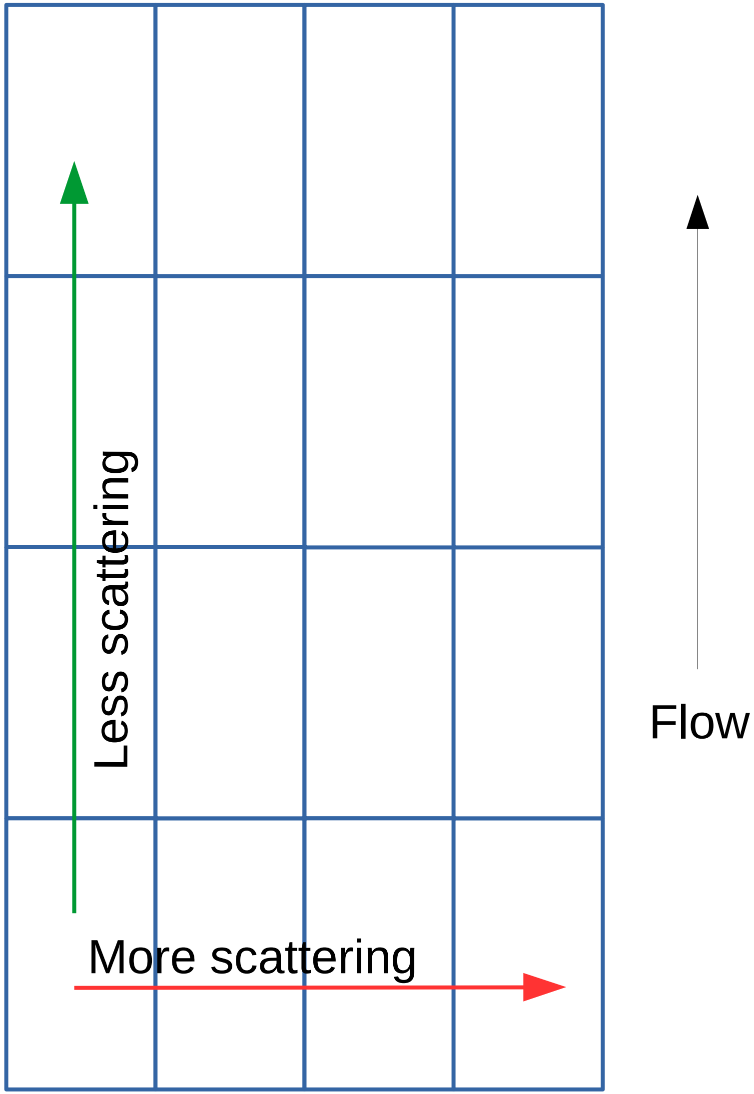
- Glaciologists see pointlike dark inclusions below the surface, which are speculated to be dust or gas
  (doesn't really matter to us because they act as optical impurities anyway)
- Distribution in vertical slices is highly inhomogeneous
- Horizontal slices are not yet sufficiently studied

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 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

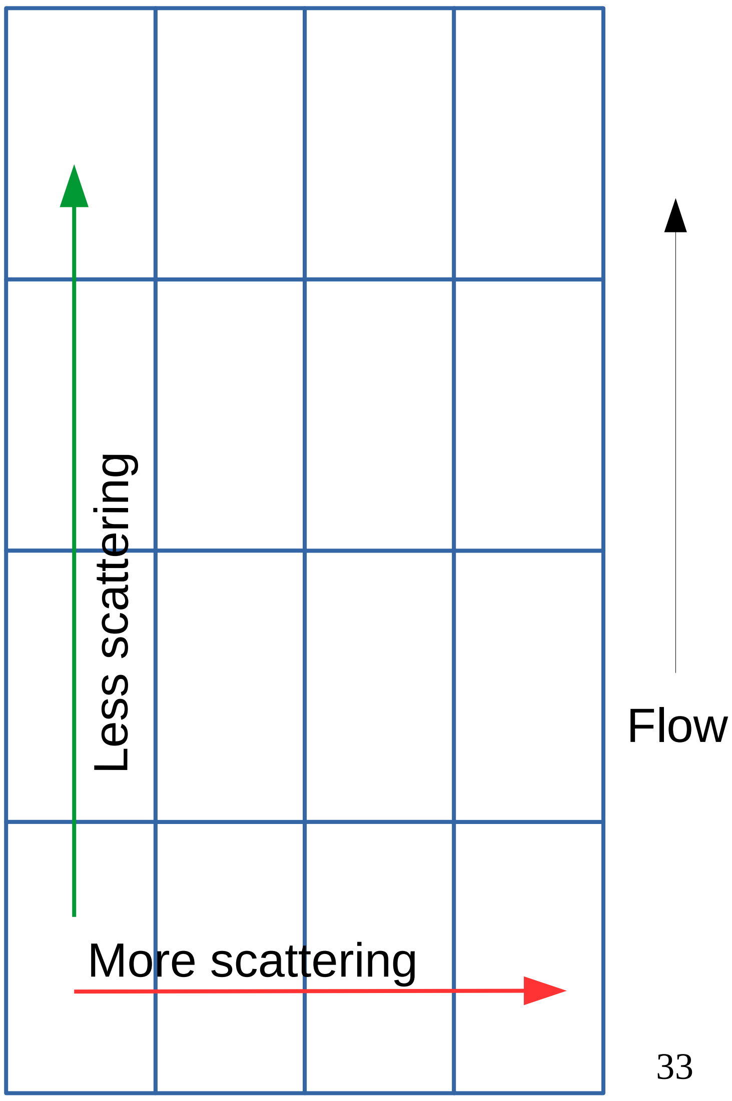
$$\omega = \sigma \frac{\mathbf{N_T}}{\mathbf{A}}$$

- 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:

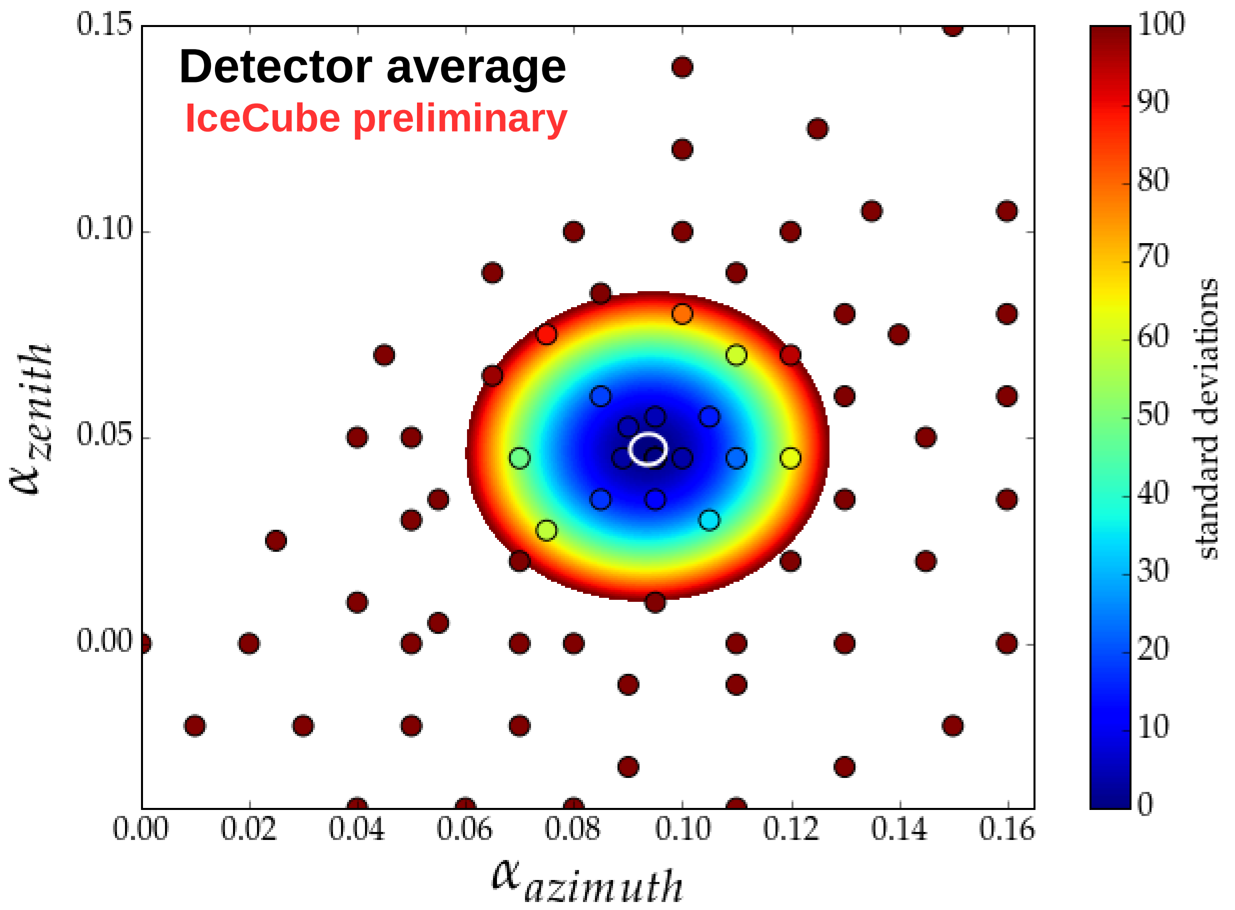
$$l(\theta,\phi) = l \cdot (1 + \alpha_\phi \cos(2 \cdot (\phi - 130^\circ))) \\ \cdot (1 + \alpha_\theta \cos(2 \cdot (\theta - 90^\circ)))$$

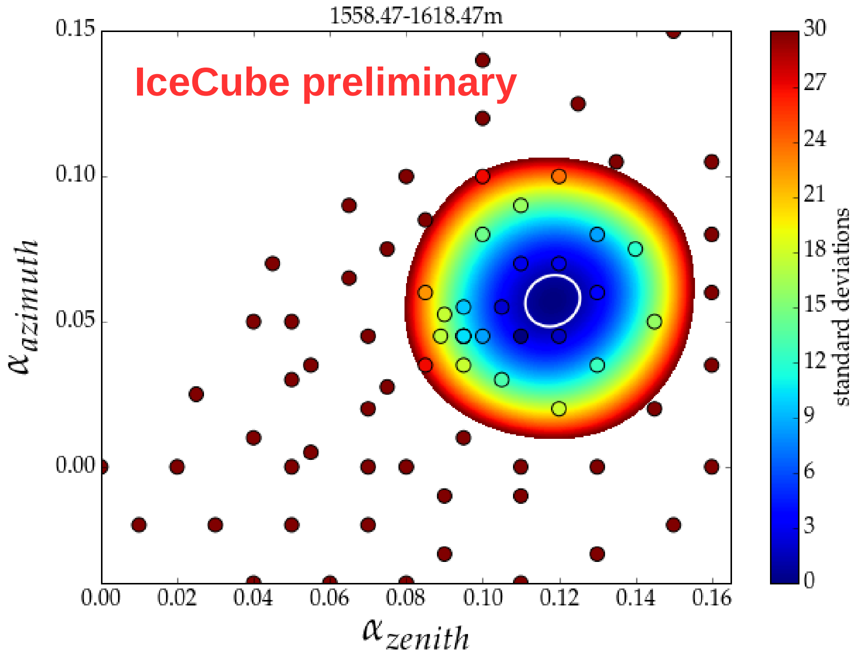
where $\alpha_{\theta/\phi}$ are the zenith and azimuth strength

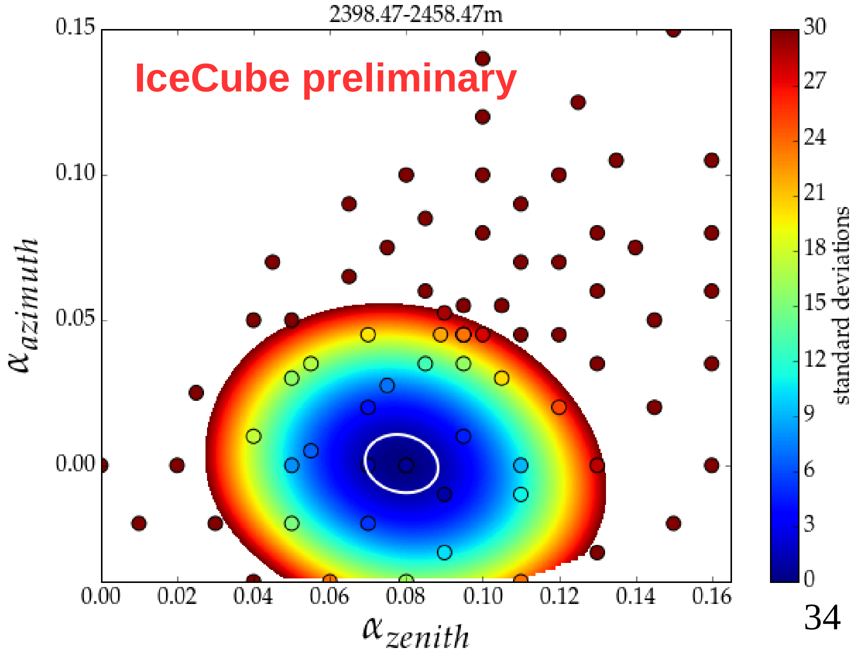
- BUT aggregation on the grain boundary is not fully experimentally accepted in glaciology especially as the sizes of most impurities is below the optical detection threshold



Fitting the new parametrization



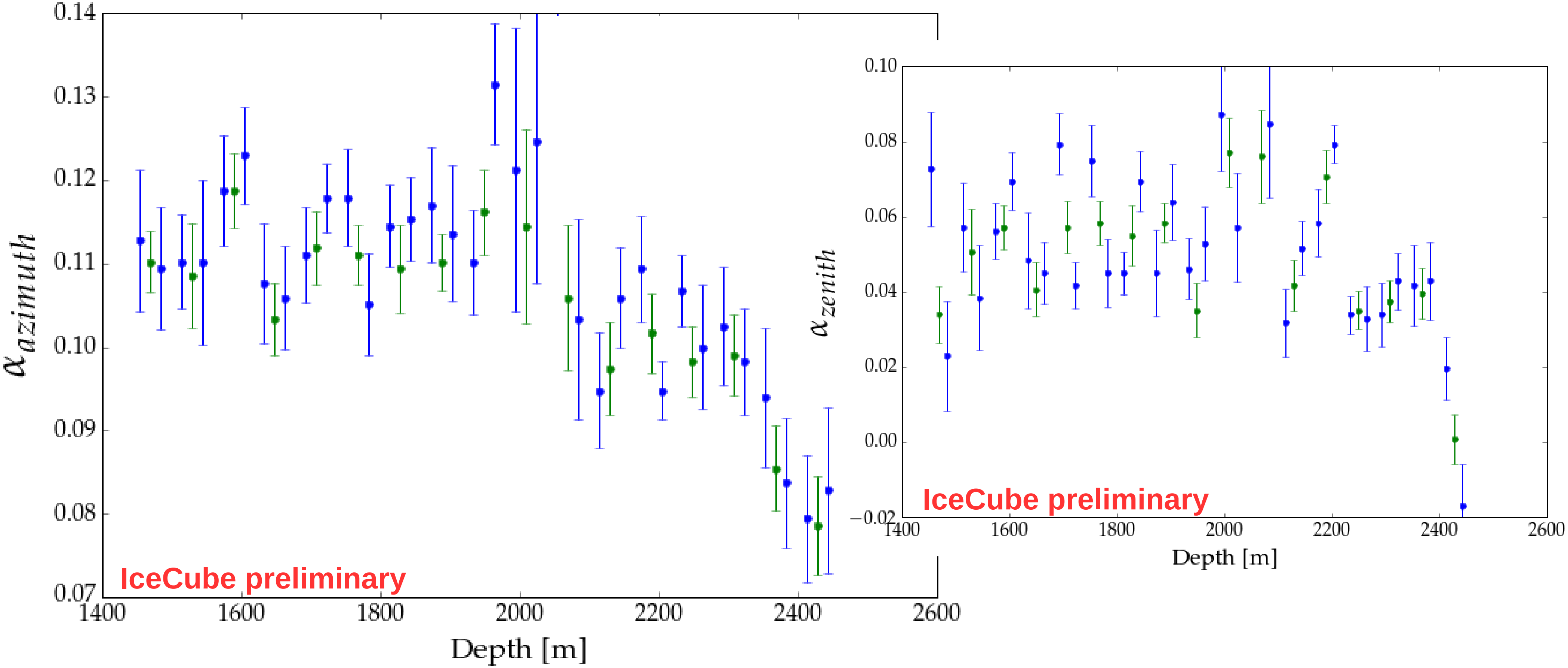




For the new parametrization a complete 2D scan has been performed, for the average detector, 30m & 60m layers.

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

Fitting the new parametrization

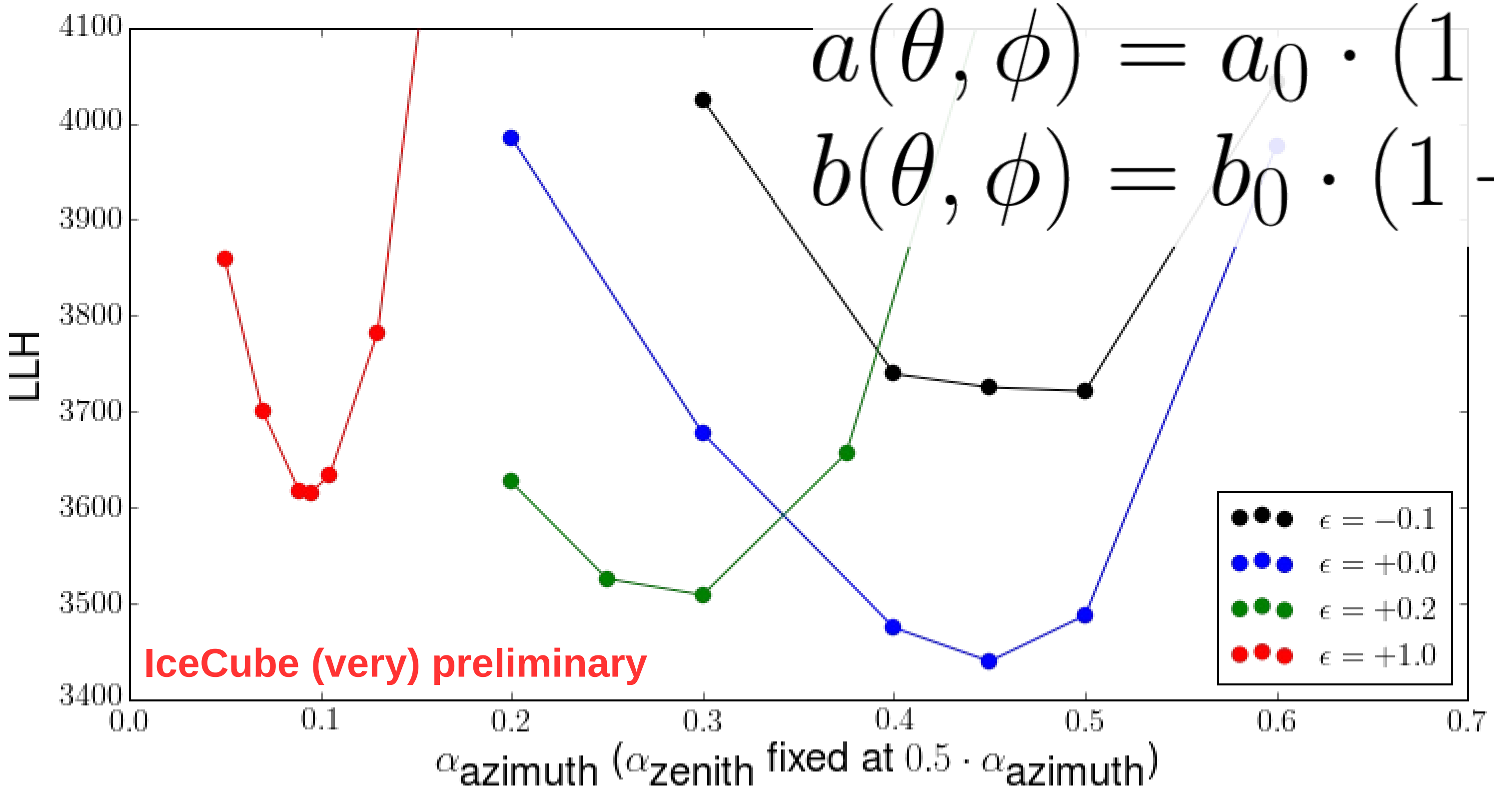


- Zenith & azimuth anisotropy appear constant above 2000m, and exhibit a slight weakening between 2000-2300m
- In the very deep ice the azimuth anisotropy weakens by ~30% while the zenith anisotropy vanishes completely (and potentially reverses)
- Overall the new parametrization achieves the same quality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

Absorption generalization

$$a(\theta, \phi) = a_0 \cdot (1 + \quad \alpha_\phi \cos(\ldots$$

$$b(\theta, \phi) = b_0 \cdot (1 + \epsilon \cdot \alpha_\phi \cos(\ldots$$



- Taking into account the different impurity types it is not natural to assume that the anisotropy should be equivalent in absorption and scattering
- Introducing the mixture as a free parameter,
  a model with anisotropy only in the absorption is preferred

Idea: Glaciological modeling

$$a(\lambda) = \sum_j N_j \int_{r_{\rm min}}^{r_{\rm max}} dr \left[A_j(r, \lambda, m_j) \frac{df_j}{dr} \right]$$

Summing over impurity densities

- Given the probability of each impurity type to be on the grain boundary, elongated grains and a girdle fabric N_j is a direction dependent quantity

- The boundary aggregation probabilities have not been successfully determined, while the fabric and elongation are easily accessible

- BUT observing a certain absorption/scattering anisotropy mixture the probabilities can be inferred from IceCube data, as the different impurity constituents contribute differently (e.g. salt not absorbing)

→ infer microscopic impurity locations from macroscopic IceCube data (cross check against azimuth/zenith strength)

Outlook I: SpiceCore data

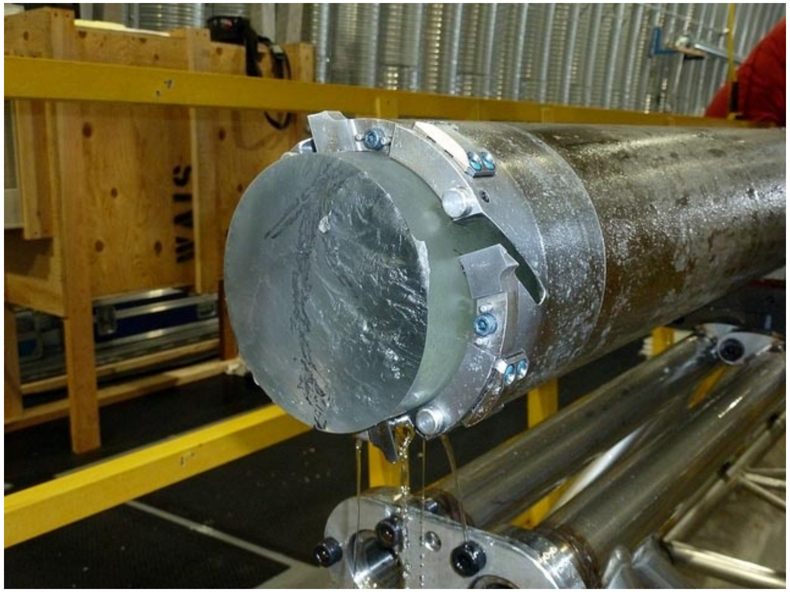
- 1.75km ice core drilled 2014-2016 about 2km from IceCube

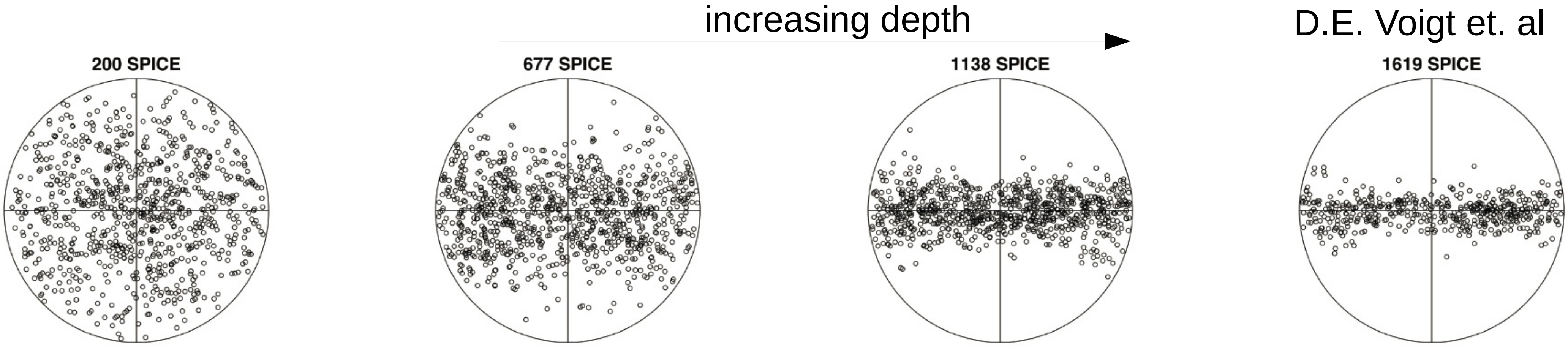
- First modern deep ice core on a flank side
  → Very pronounced c-axis distributions

- Most analyses still ongoing

- Mainly targeted at climatological gas record
- But impurity contents and size distributions and grain elongations will (hopefully) also be available

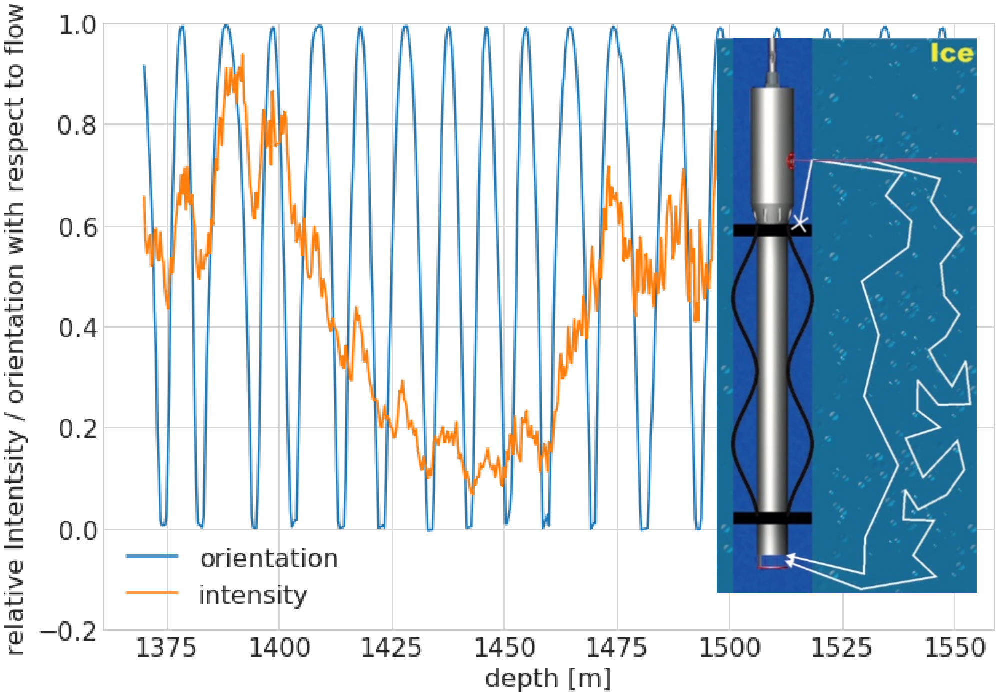
- Can be input for analytic modeling of IceCube optical (anisotropy) properties

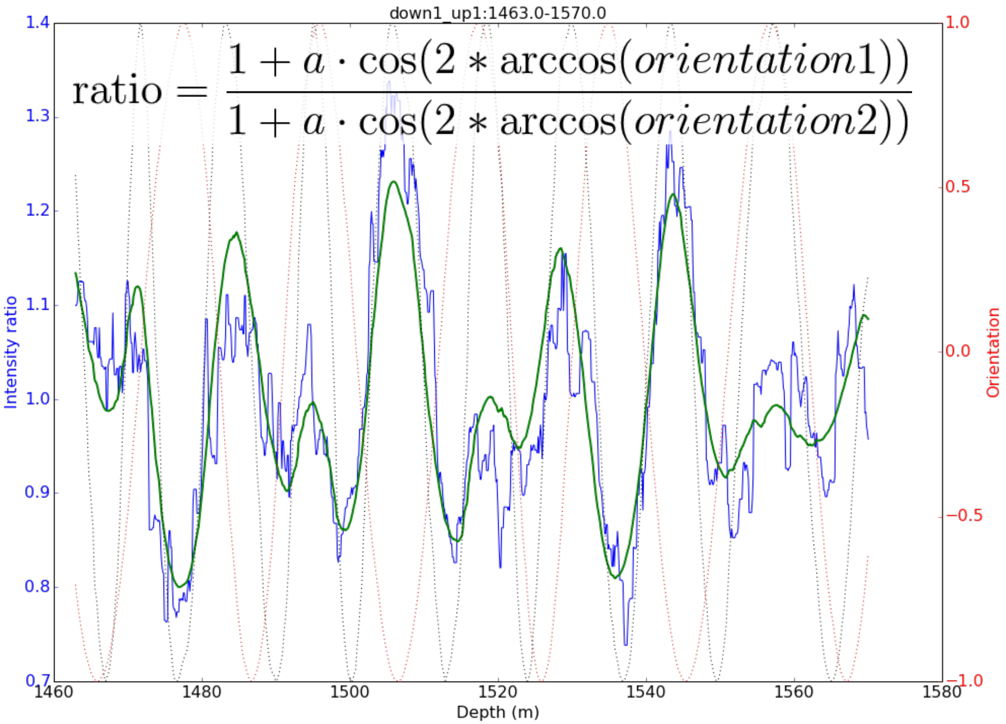




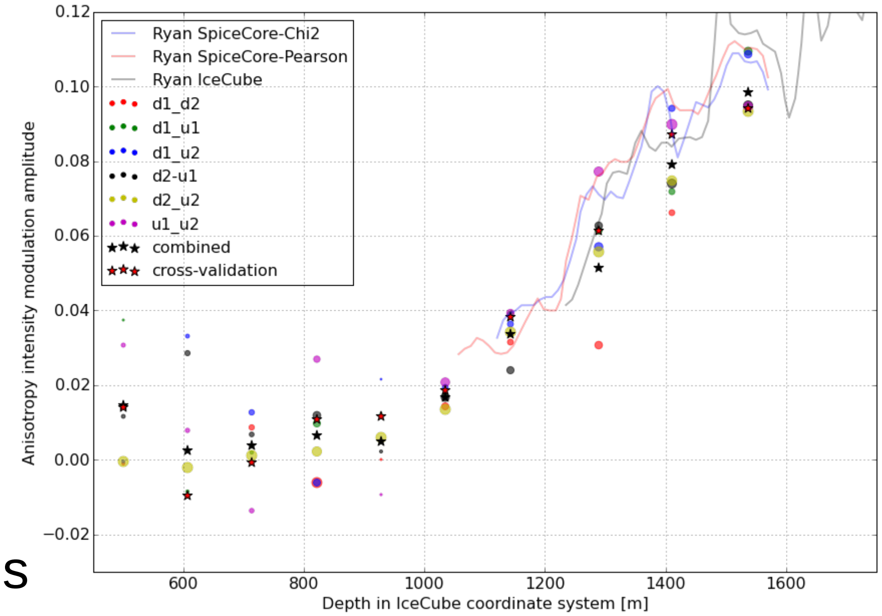
D.E. Voigt et. al

Outlook II: Oriented DustLogger



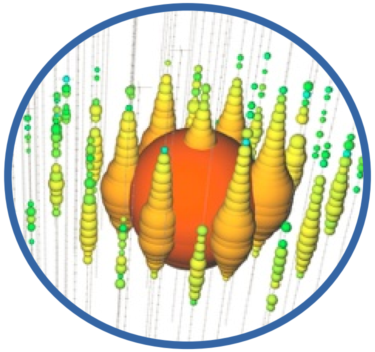


- A new DustLogger with orientation sensors has been deployed in SpiceCore
- Anisotropy seen in ratios of logs as modulation proportional to relative orientation
- Data quality currently insufficient
  → new logging next season
- Back-scattering sensitive to Rayleigh impurities



Outlook III: Big picture

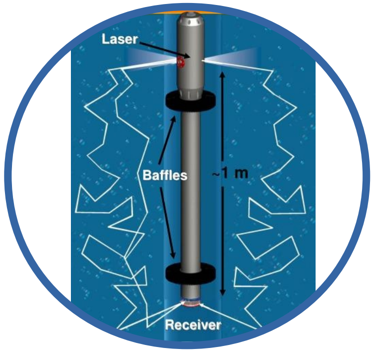
IceCube



Time resolved forward propagation anisotropy
→ absorption vs. scattering

Consistency check

DustLogger

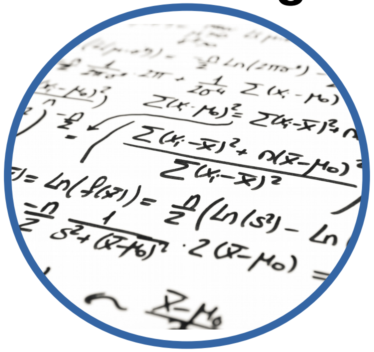


Integral backward propagation anisotropy

Modeling tested against measurements

Measurements inform modeling

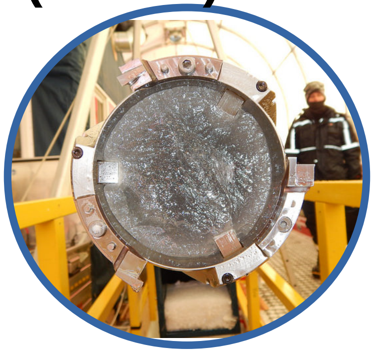
Modeling



- Calculation of absolute absorption and scattering
- Wavelength dependence
- Absorption strength
- **Infer on impurity location**

Input for

(SPICE) core

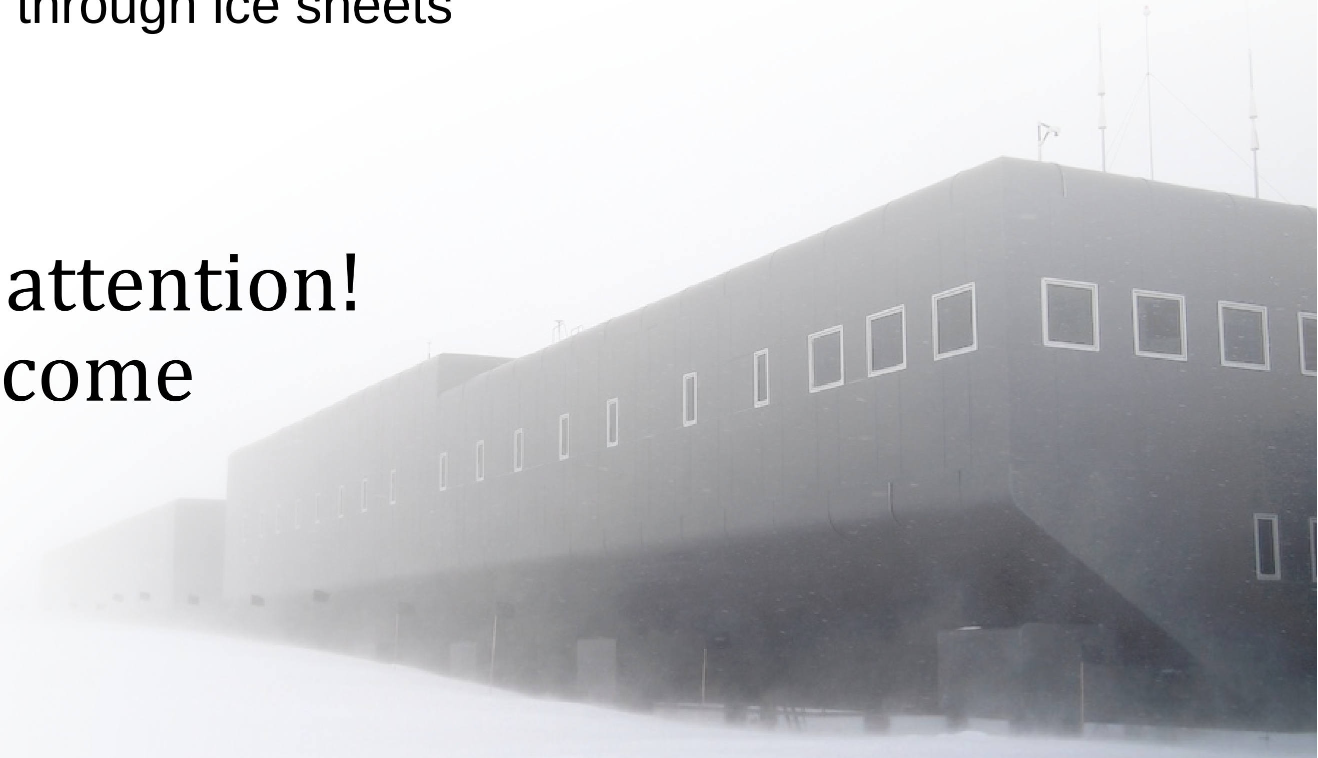


- Impurity concentrations
- Size distributions
- Grain elongation
- C-axis distributions

→ **Improve IceCube MC and deduce glacial flow properties**

Summary

- IceCube Neutrino Observatory is also a kilometer sized instrument to study the optical properties of deep, slowly flowing ice
- IceCube observes anisotropic extinction aligned with the ice flow
- The depth dependency hints at the crystal fabric being the underlying cause
- Combining data from IceCube, the DustLogger and ice cores can help to test models regarding the distribution of impurities in the ice fabric
  → predict sea level rise through ice sheets



Thank you for your attention!
Questions are welcome