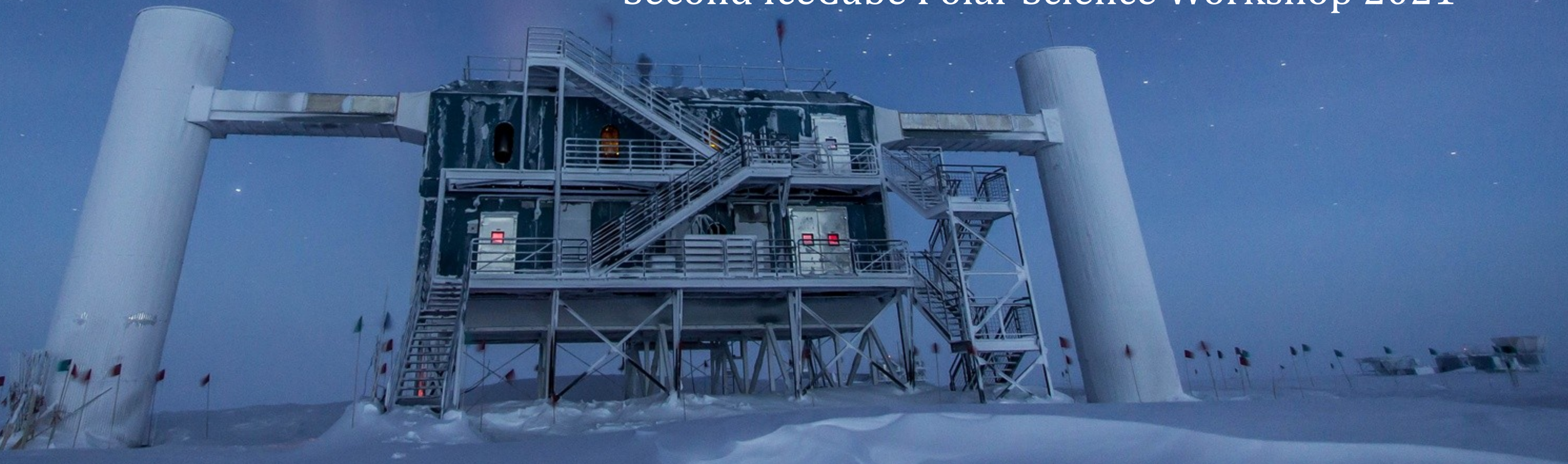
The IceCube ice anisotropy

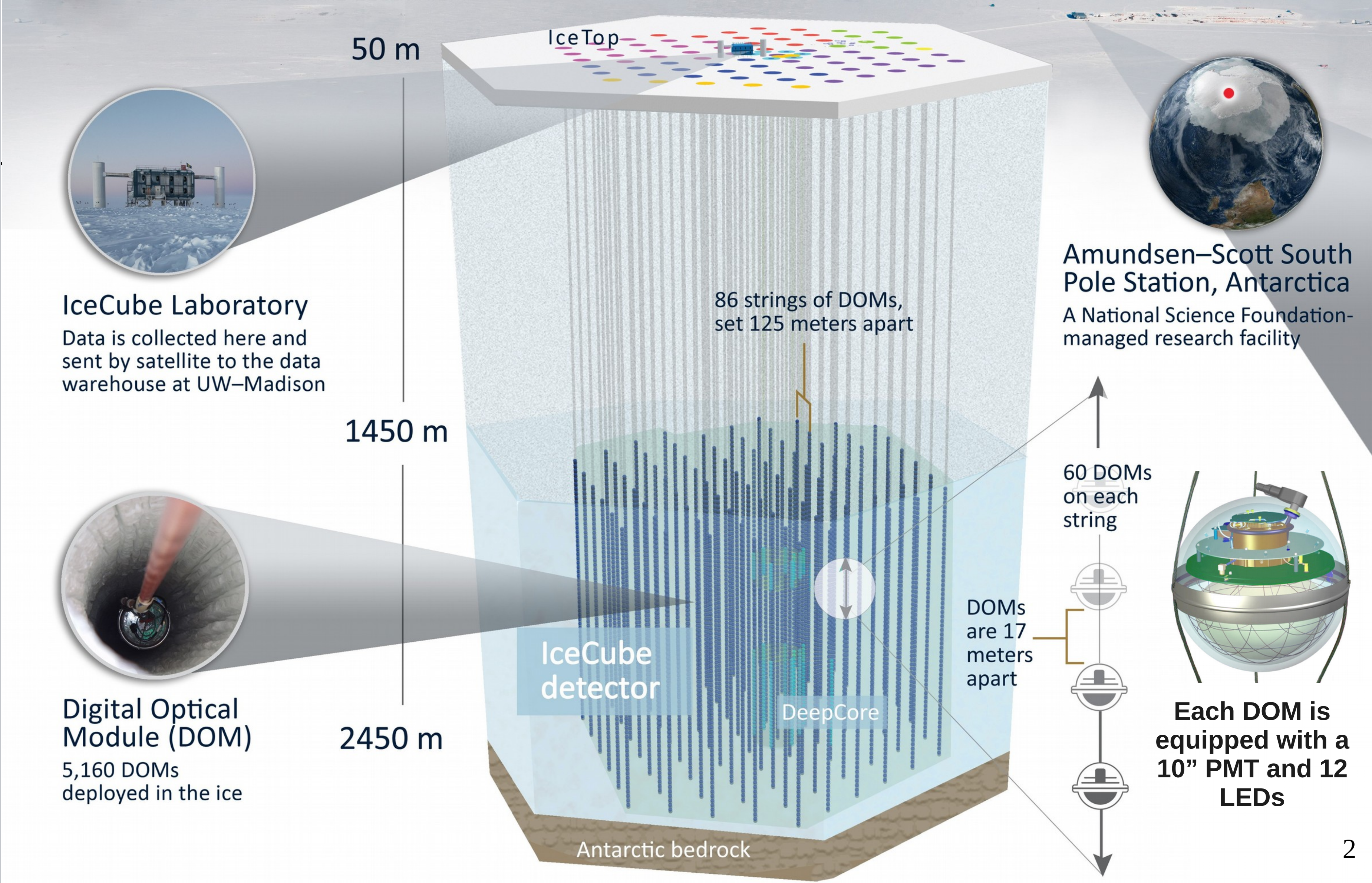
Martin Rongen,
Dmitry Chirkin

Second IceCube Polar Science Workshop 2021



The IceCube Neutrino Observatory

Design and construction



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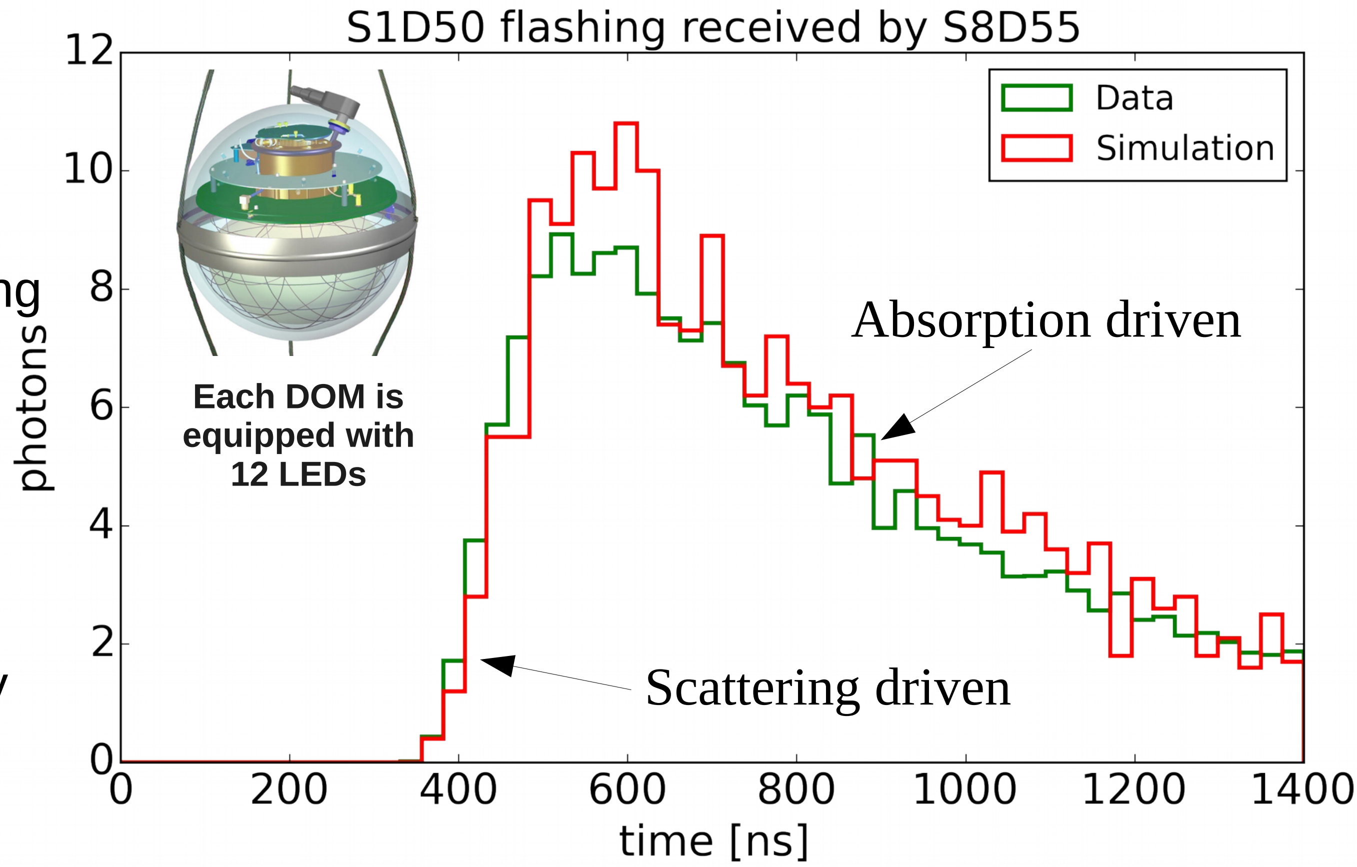
Light curve sensitivity

- Observation of photon arrival time distributions from pulsed light sources, allows for measurement of absolute absorption & scattering lengths

- Normalization independent, but observations at different distances help

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



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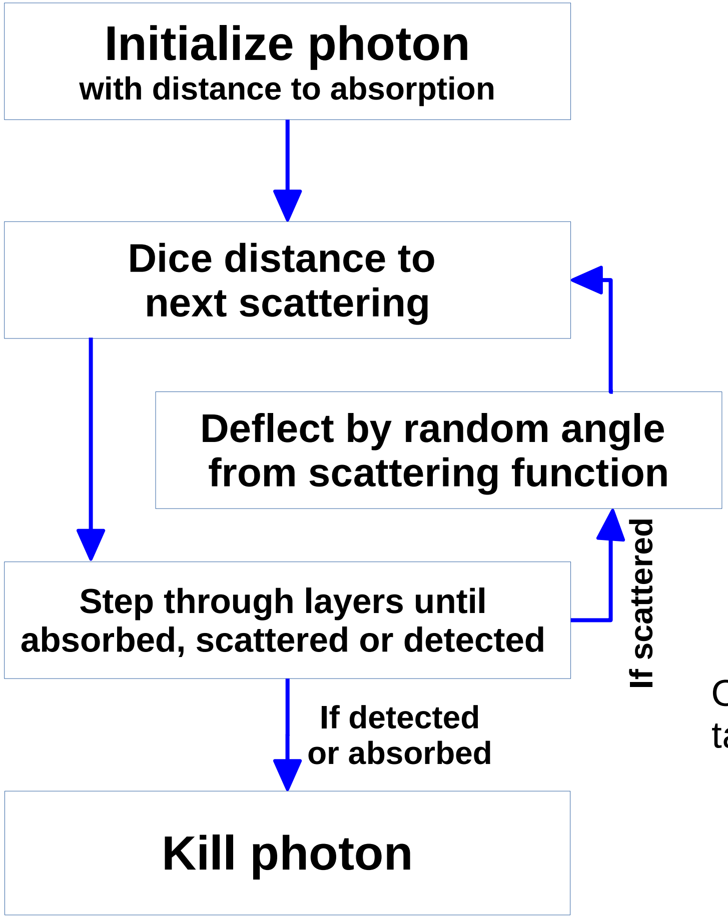

Photon propagator code (PPC)

On GPUs ~250 times faster than CPUs

One full detector simulation takes 200-5000 GPU hours

Layered ice model (SPICE)

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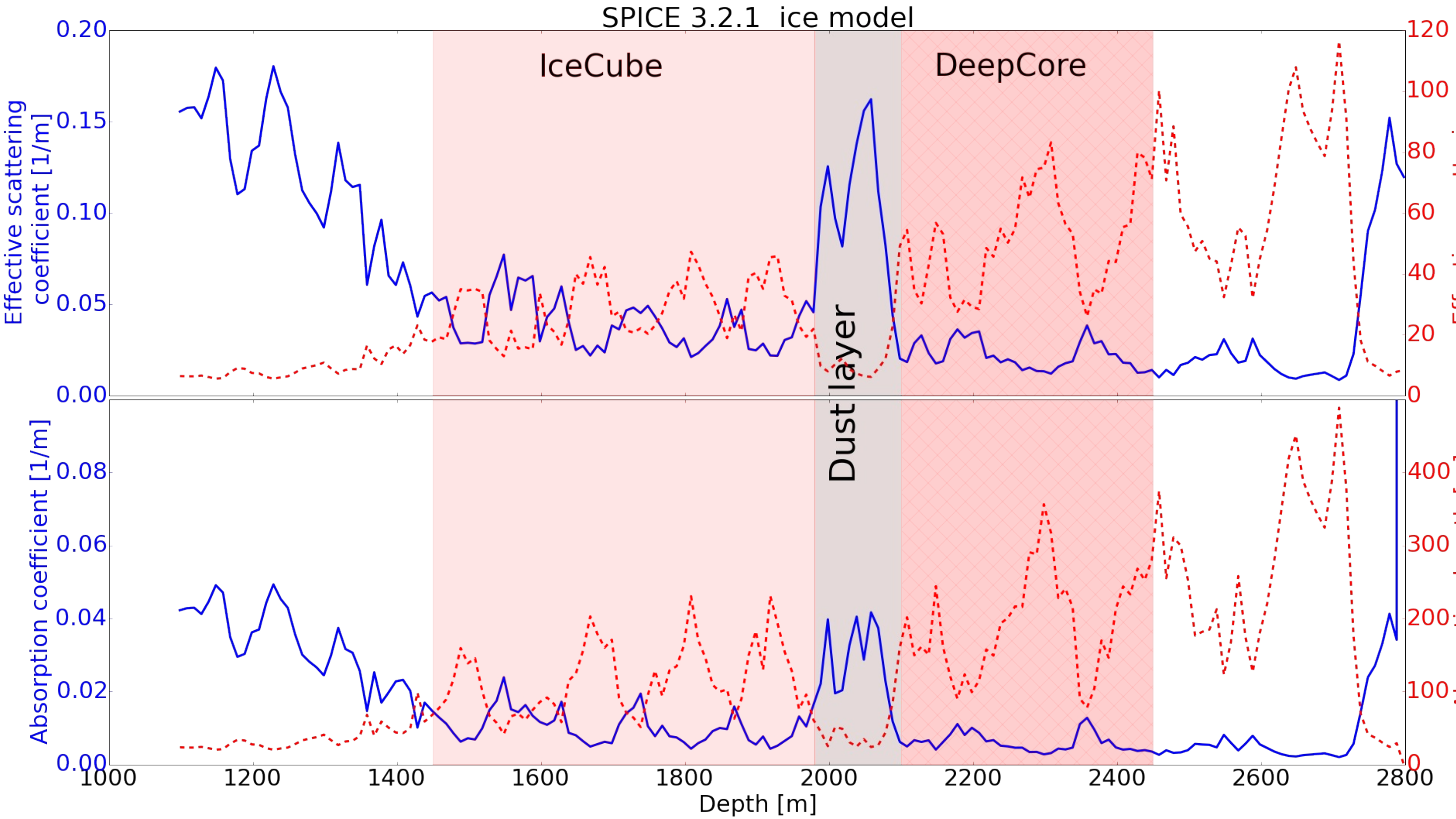

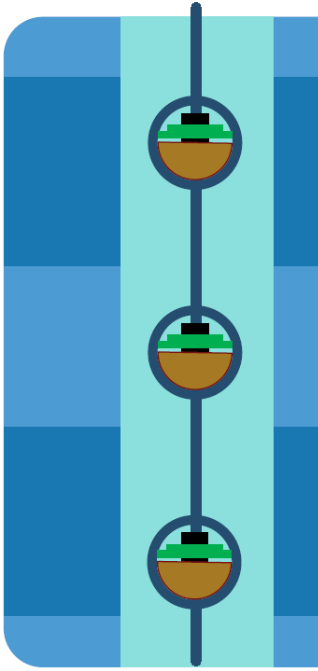

The ice anisotropy effect

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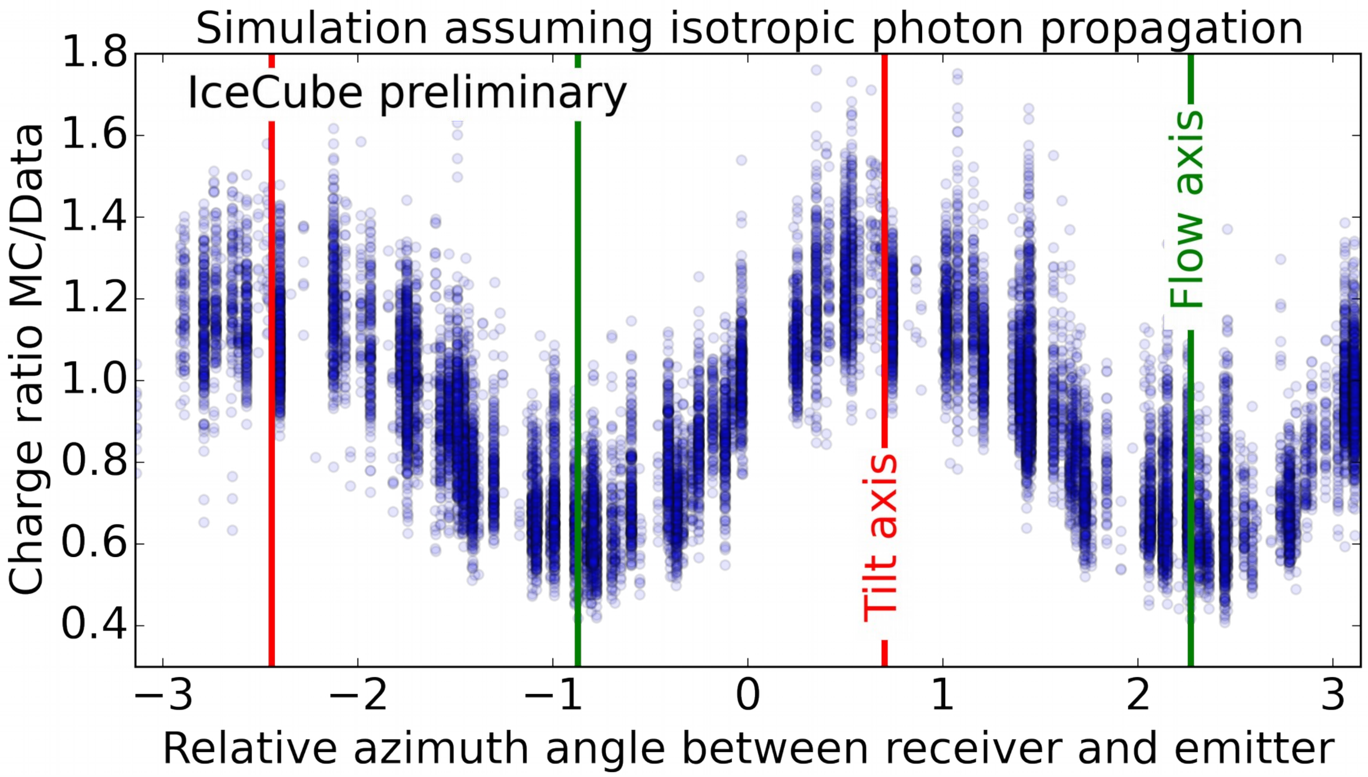
- Observed charge depends on orientation of receiver DOM with respect to emitter DOM
- Most charge seen along the flow axis, least orthogonal to it
- In 2013 implemented as a direction dependent modification of the scattering function



→ less scattering in the flow direction

Timing vs. intensity

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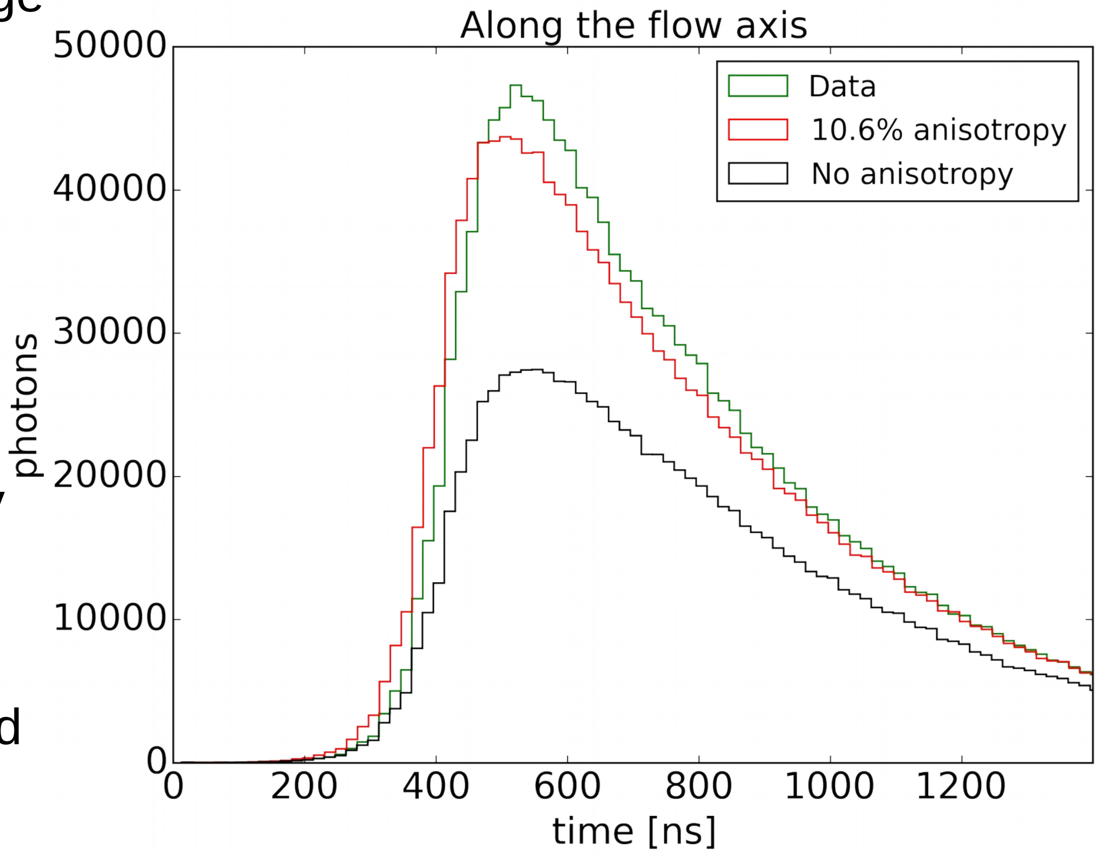
- Best fit does not fully compensate charge
- Compensating the intensity results in too-early rising edge

- Alternative model varying absorption instead of scattering was tested
- Better, but could also not fully match the light curves

- Also found that inhomogenious impurity distributions can never lead to anisotropic Mie scattering
- Anisotropic absorption is possible, but a mechanism leading to the required strength is not understood



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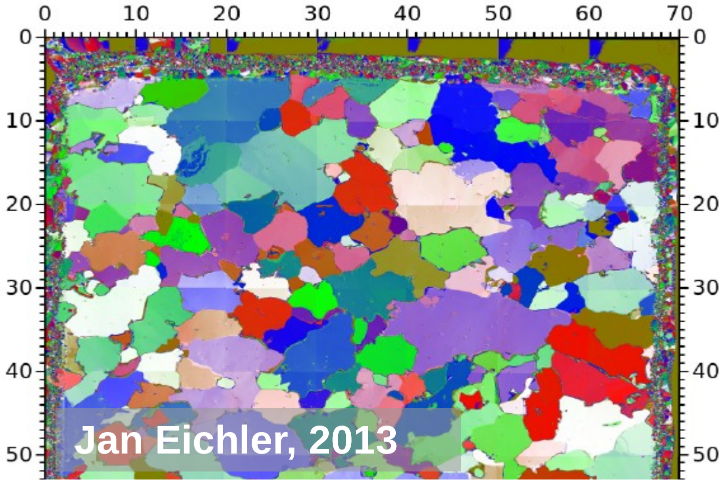
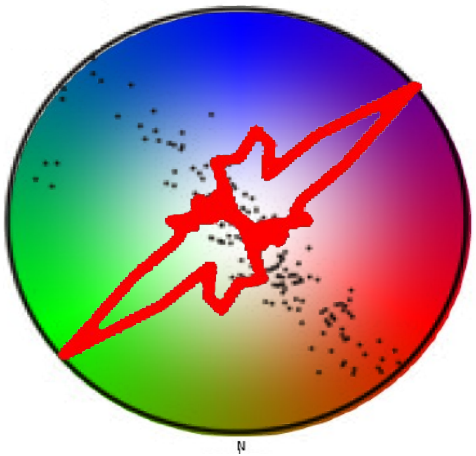
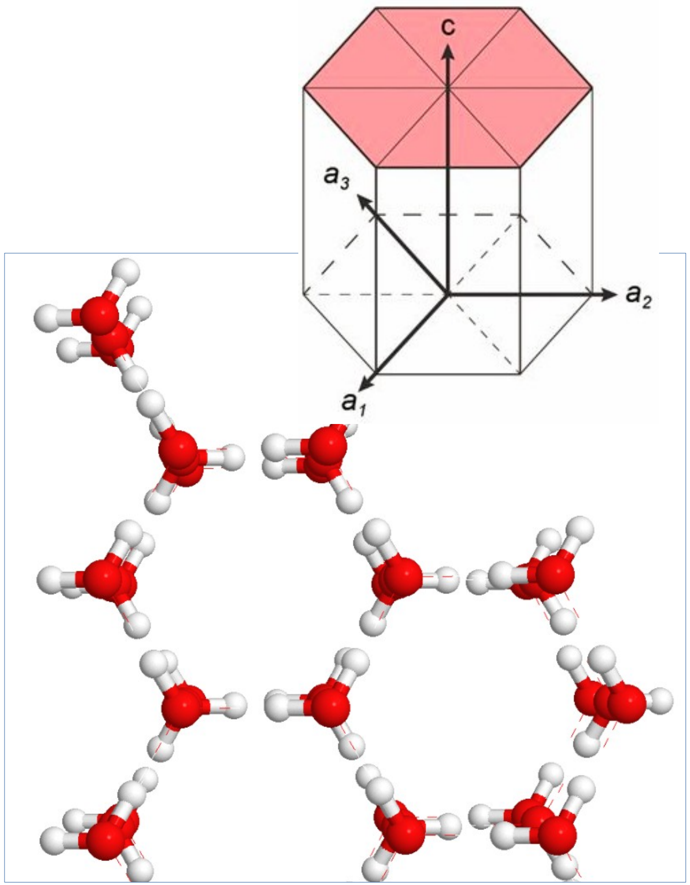
c-axis and elongation

- Due to it’s hexagonal crystal lattice, each grain deforms essentially only by sliding of its basal planes

- An ensemble of grains under stress (such as flow) will elongate with the flow yielding a girdle of c-axes orthogonal to the flow







Birefringence

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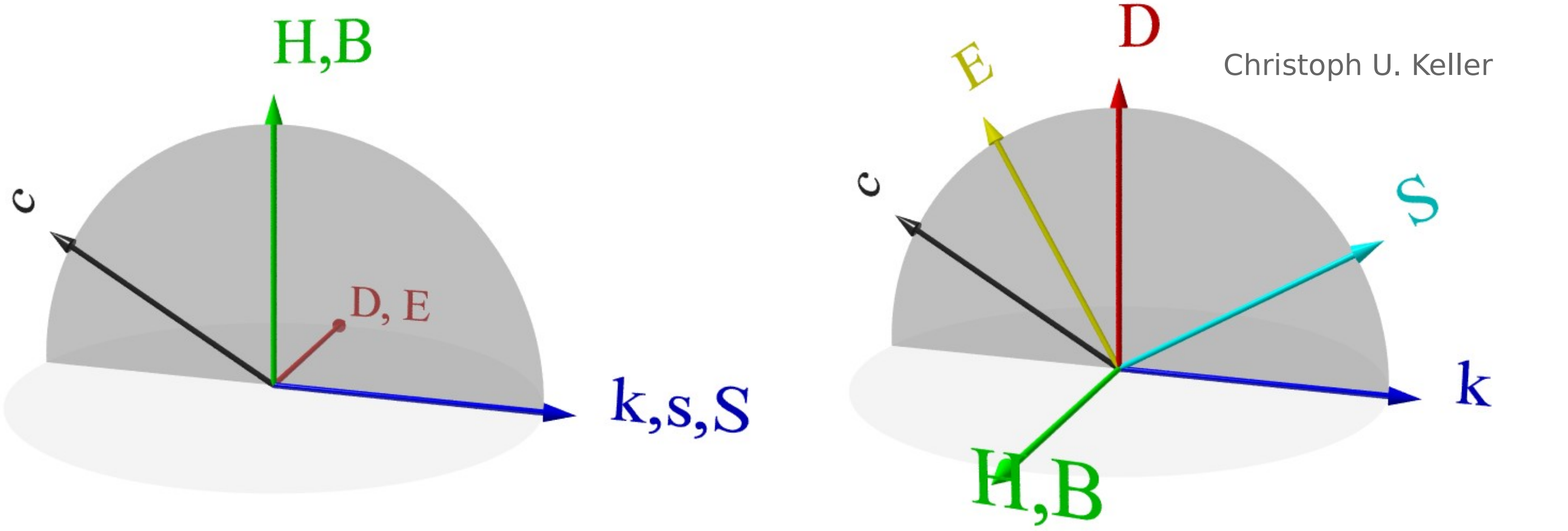

- Ice is a birefringent material:
  Light is split into an ordinary and an extraordinary ray with respect to the c-axis
- The refractive index of the extraordinary ray is direction dependent
- Extraordinary ray exhibits dispersion between the wave and Poynting vectors

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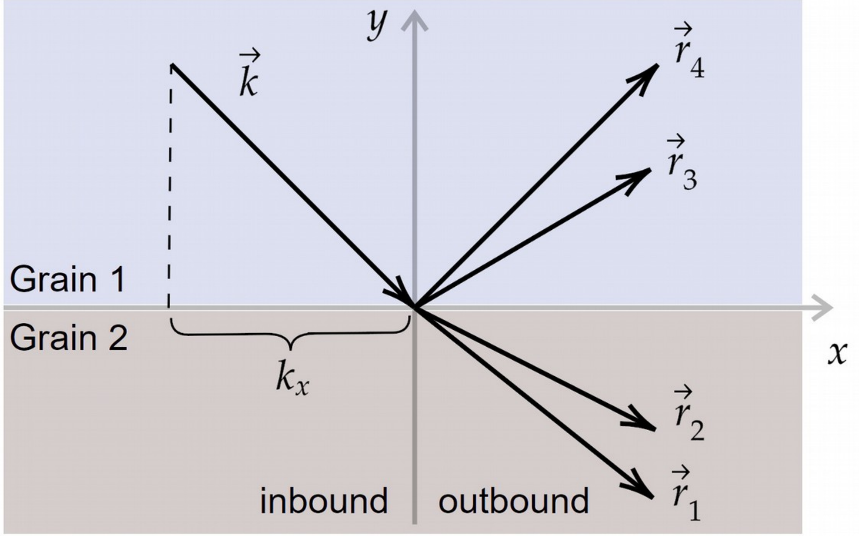
A single grain boundary

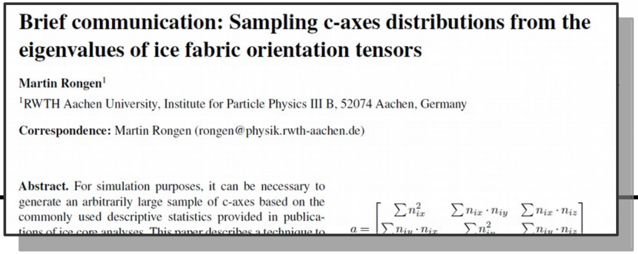
- At each grain boundary every ray is split into two reflected and two refracted rays one ordinary and one extraordinary ray each
- Wave vector component parallel to surface is conserved, norm is proportional to the refractive index
- Poynting vectors are derived from wave vectors and boundary conditions
- Outgoing ray is randomly sampled from Poynting vectors according to Poynting theorem (Poynting vector component through the boundary is conserved)



wavelength λ (nm)	n_o	n_e
405	1.3185	1.3200
436	1.3161	1.3176
492	1.3128	1.3143
546	1.3105	1.3119
624	1.3091	1.3105
691	1.3067	1.3081

Physics of Ice,
Victor F. Petrenko

c-axis sampling



Brief communication: Sampling c-axes distributions from the eigenvalues of ice fabric orientation tensors

Martin Rongen[1]

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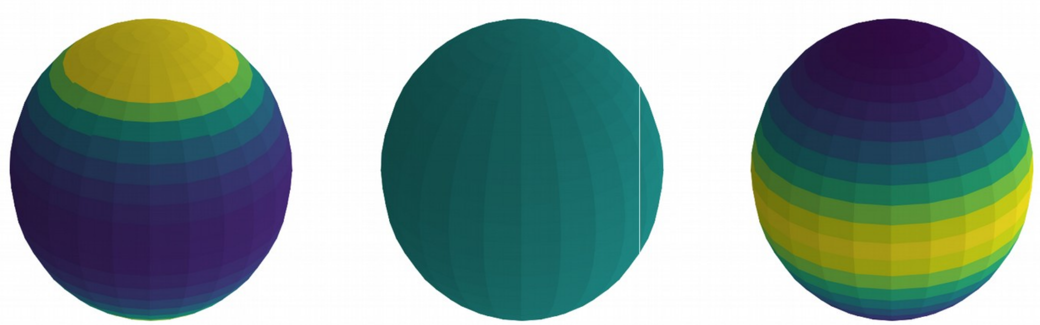
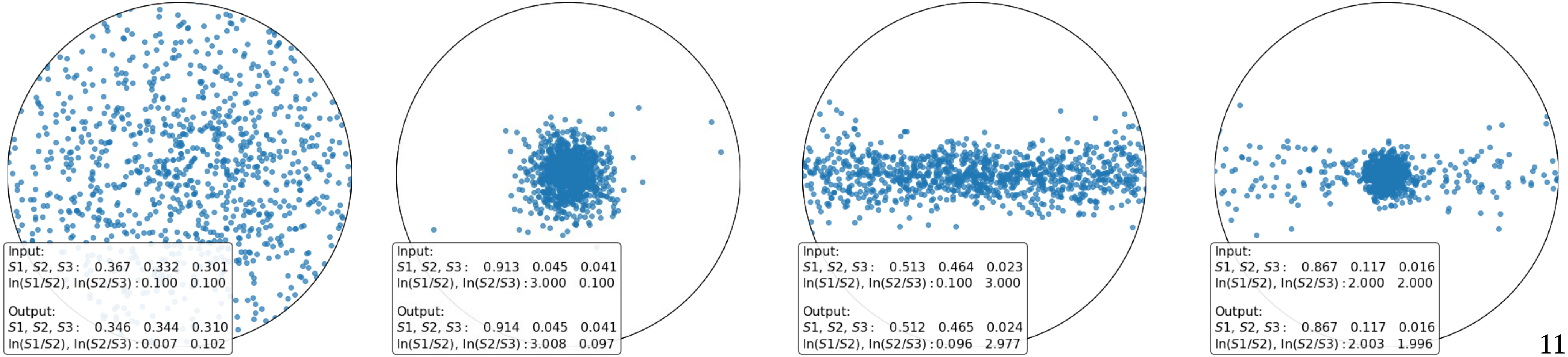
Abstract. For simulation purposes, it can be necessary to generate an arbitrarily large sample of c-axes based on the commonly used descriptive statistics provided in publica-

$$f(\theta, \phi) = C_w \exp(k \cdot \cos^2 \theta) \sin \theta$$

Watson distribution

$$C_w = 1 / \left(4\pi \int_0^1 exp(k \cdot u^2) du \right).$$





Chord and surface orientations

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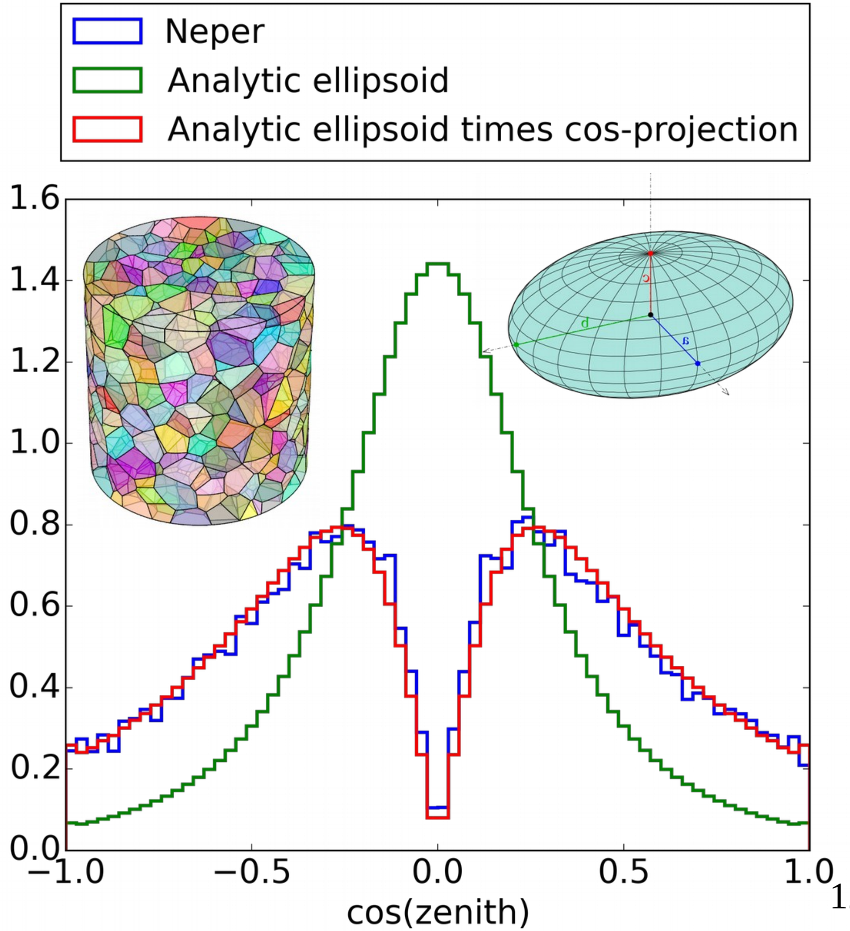
To be able to simulate propagating through a polycrystal we need to further know:

1. The average distance spend in a grain
2. The distribution of boundary orientations

For elongated grains these quantities are direction dependent.

Quantities computed on an average grain shape, assumed to be a triaxial ellipsoid.

Verified by comparison to crystal tessellation software. (Neper: doi:10.1016/j.cma.2011.01.002)



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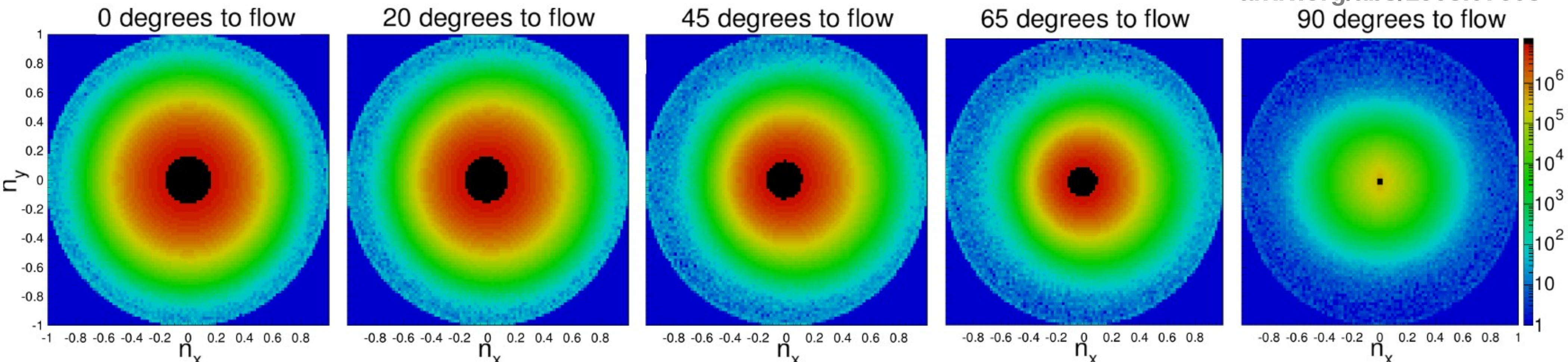
Birefringence Monte Carlo

Running MC simulation with many photons through 1000 grains with ideal girdle fabric shows two effects:

I. Diffusion is largest on flow axis and smallest orthogonal to it
II. Photons on average get deflected towards the flow axis

→ **photons effectively fly a curve towards the flow axis**

arxiv.org/abs/1908.07608



Average photon trajectories

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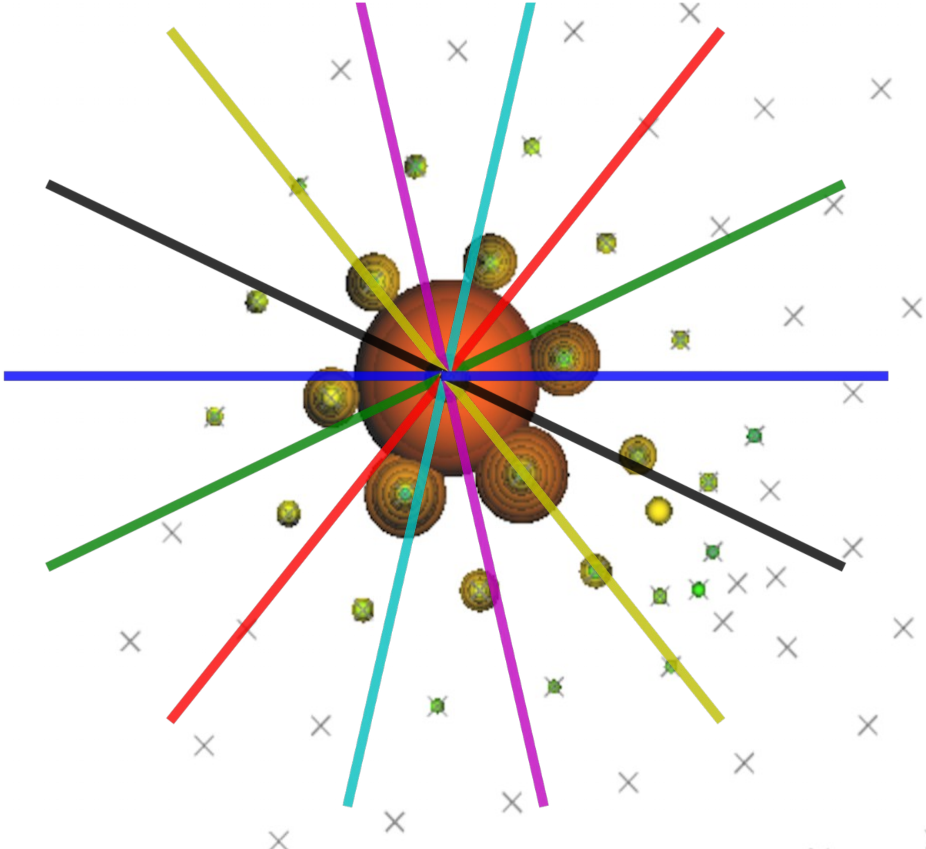
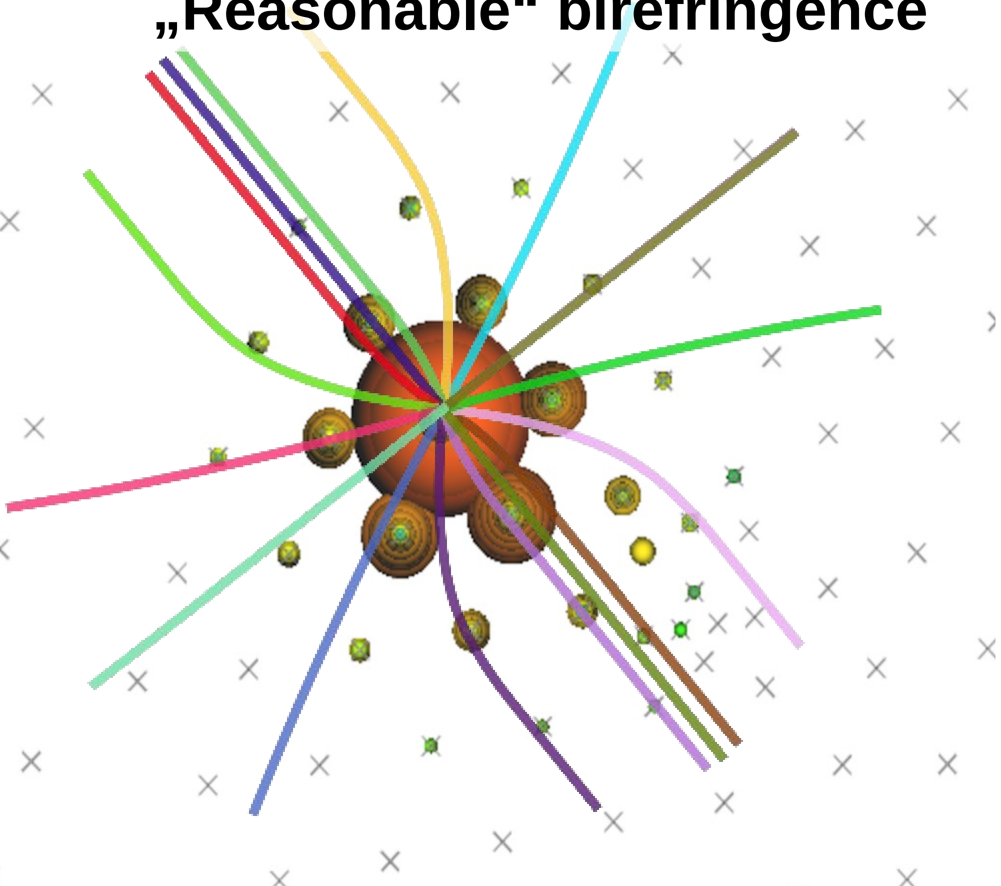
No birefringence



„Reasonable“ birefringence



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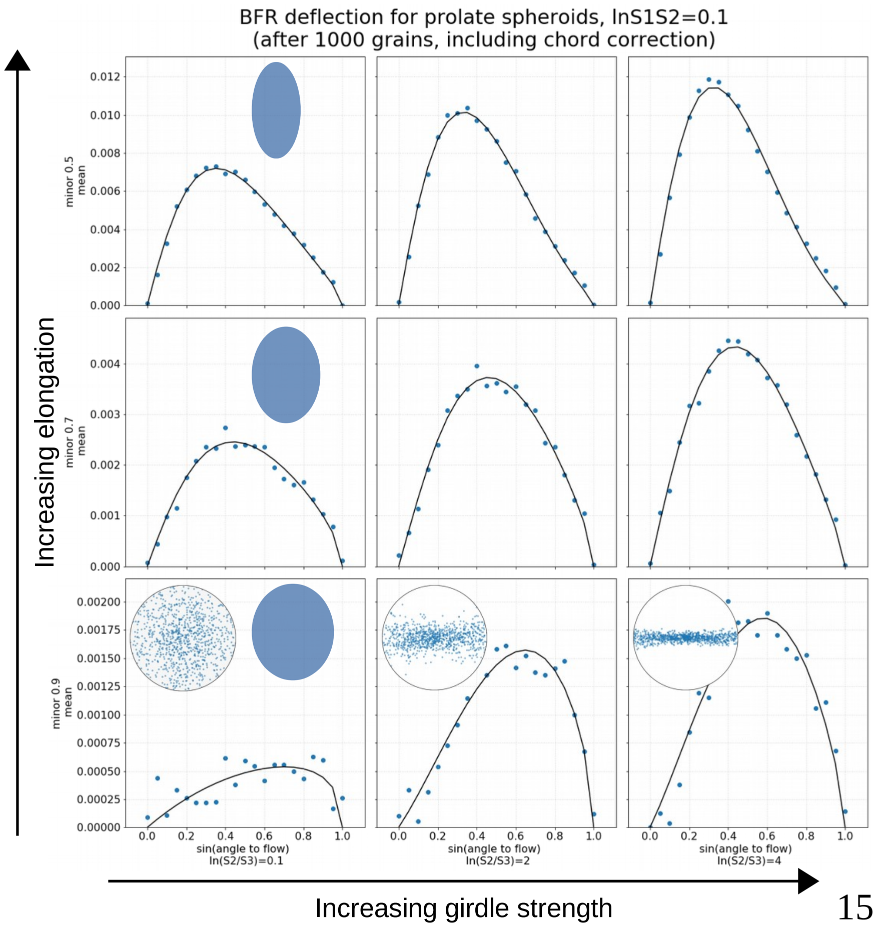
Parametrization

- Can not perform per crystal simulation for full-scale photon propagation
- Parametrize complex patterns using a displaced 2D-Gaussian

- In PPC photons are displaced and deflected at each scattering site (after proper distance scaling) depending on their current angle to the flow

- Elongation has a stronger effect compared to fabric (these in reality are of cause related)

- Free parameters:
  ln(S1/S2), ln(S2/S3), elongation, size
  (+ absorption, scattering & absorption anisotropy)



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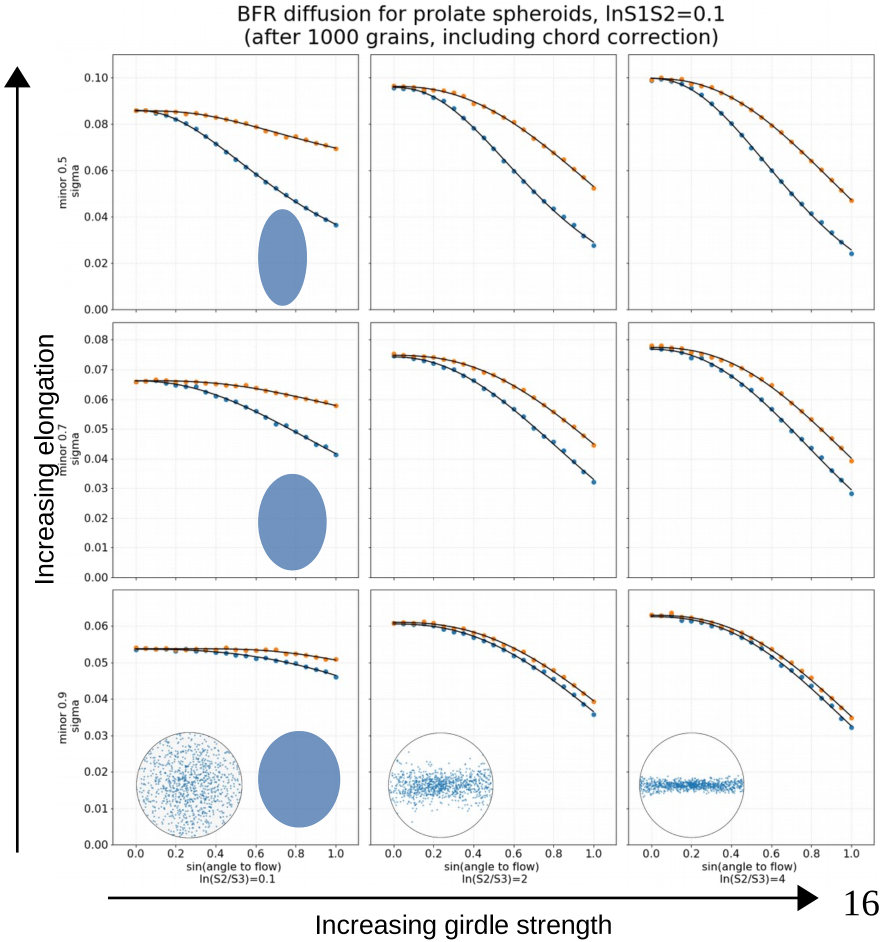

Pre-fits

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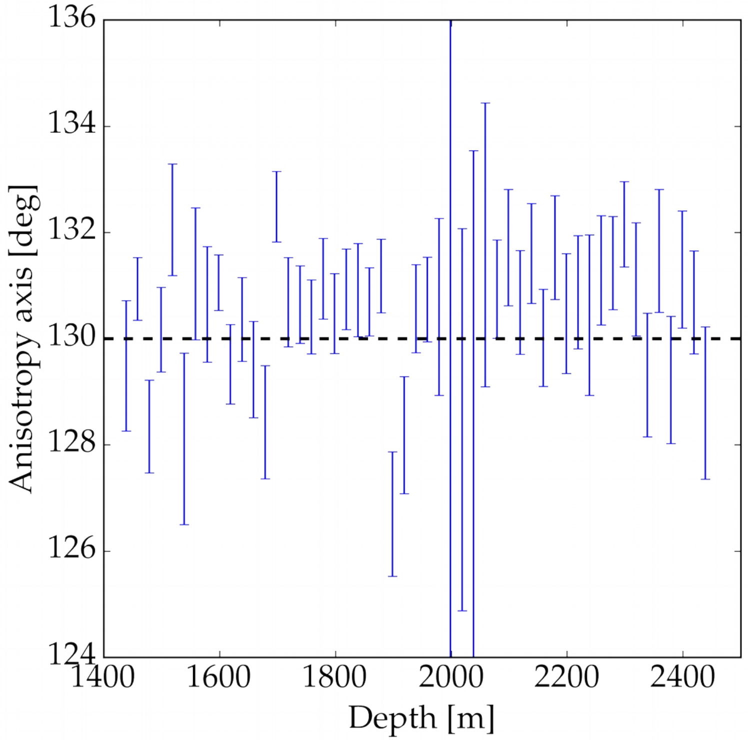
- We can't optimize 9+ dimensions at once, especially as a function of depth…
  → need to find parameters which are less relevant or near constant at all depths

- Spheroids (horizontal = vertical minor axis) strongly preferred over arbitrary ellipsoid

- The anisotropy angle is indistinguishable from 130° at all depths and over the entire surface footprint

- Given a girdle (ln(S2/S3) >> ln(S1/S2)) the actual fabric values are near indistinguishable
  → fixed to ln(S1/S2)=0.1 & ln(S2/S3)=4 at all depth
  (may be problematic in the very deep ice
  where at some point a switch to uni- modal is expected)



Single layer fit example

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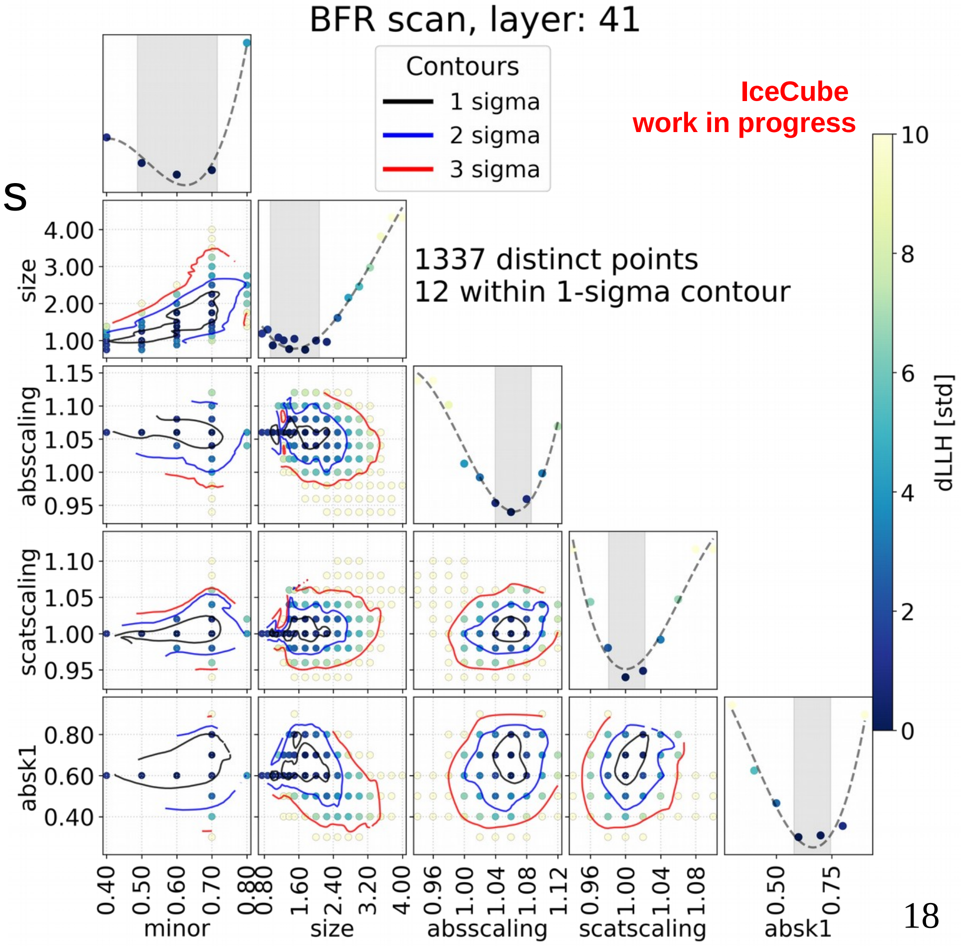
- Size and elongation are strongly correlated
  → data just as well described by small, nearly spherical or large, strongly elongated grains

- Fix minor axes at 0.7 (elongation ~1.4)

- Birefringence only model describes the data better then any previous model
- BUT crystal sizes are unphysically small
- Mixing in additional absorption anisotropy strongly improves data-MC agreement and yields sensible crystal sizes

- Including the scattering based model does not improve the fit (not shown here)



Grain size vs. depth

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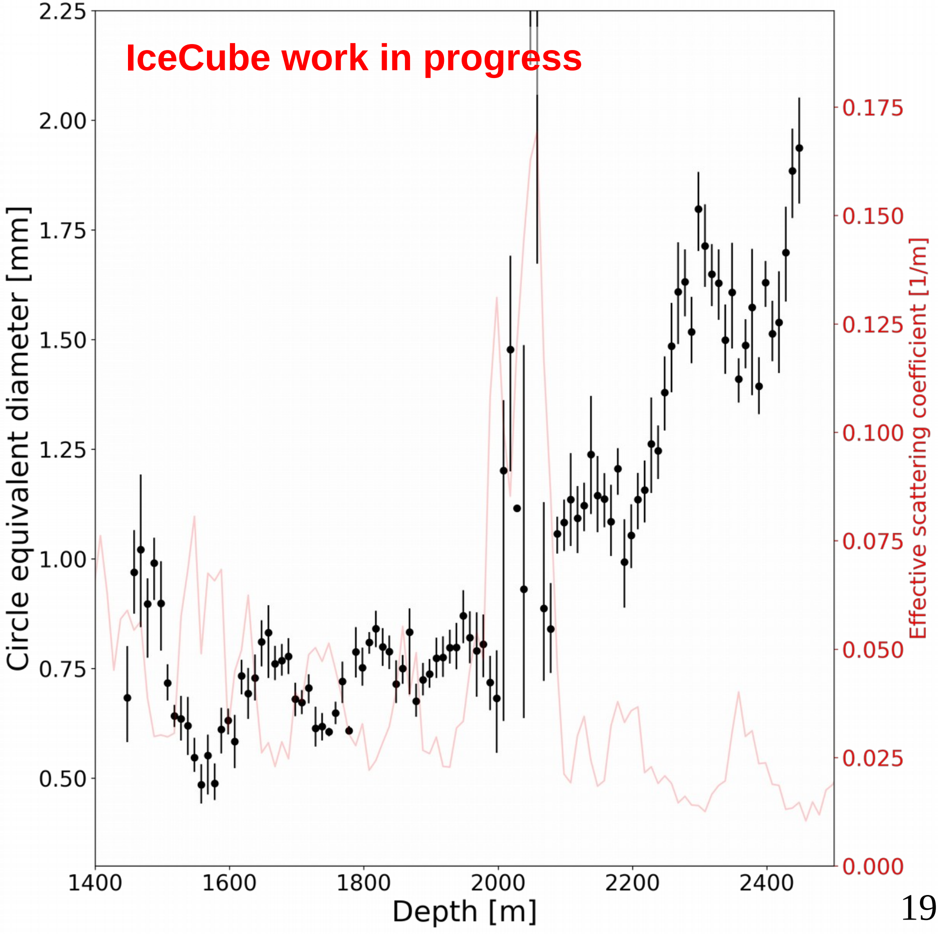
- Due to the assumptions on unconstrained parameters (elongation, absorption anisotropy…) the size has an overall scaling uncertainty
- The fixed parameters (such as fabric) may also bias the result

- Still we see that grain size increases with depth and in particular below the dust layer

- Grain size seems to be anticorrelated to the scattering coefficient → crystals are smaller where scattering is stronger, there are is more dust

Disclaimer: This fit is still ongoing! Best fit values and statistical errors will change.

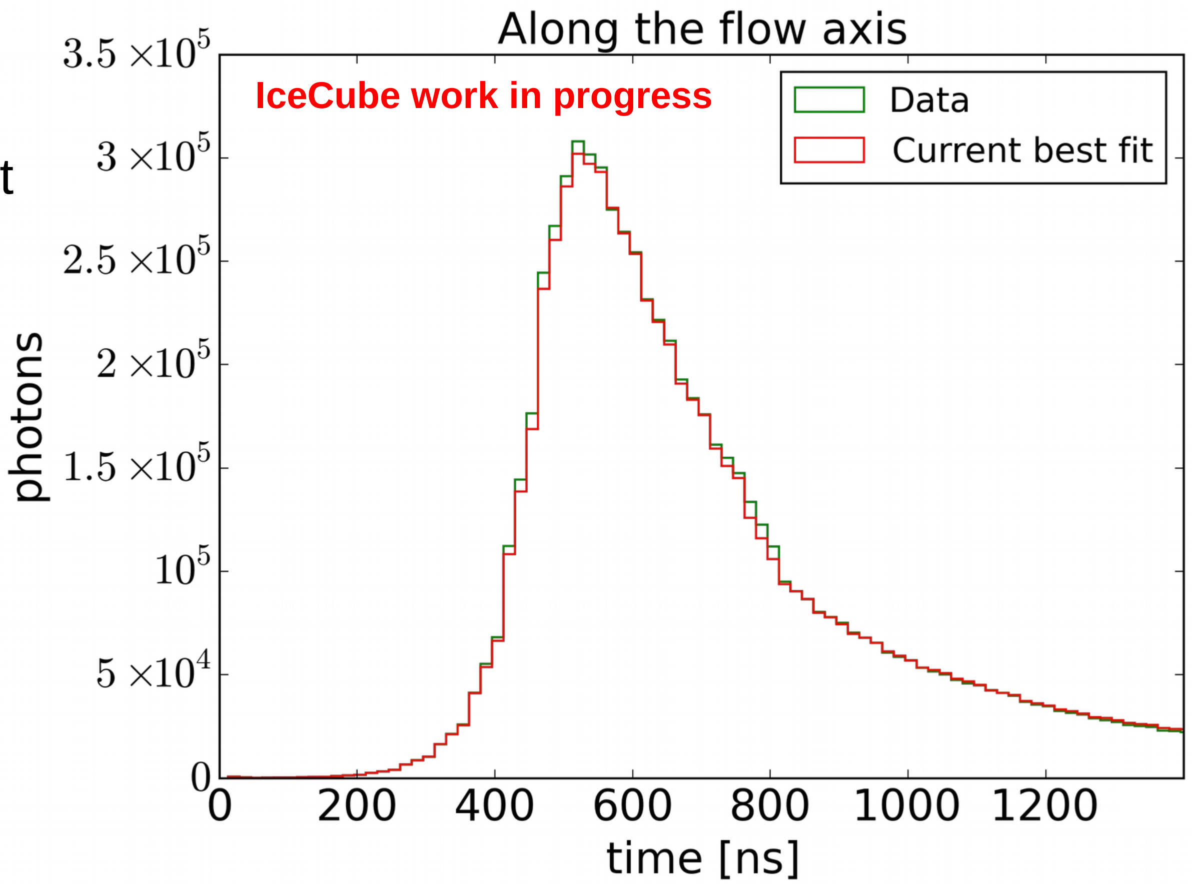


Quality & open issues

- Using the full-model described above, we achieve an unprecedented data-MC agreement

- This allows us to probe crystal properties using only PMT data sampled at 125m intervals
- BUT the LED data is insufficient to unambiguously determine the large number of parameters involved

- And we still require a first principle explanation for what appears to be an absorption anisotropy
  (which may in turn change the birefringence understanding)



Pencil beam in the Upgrade

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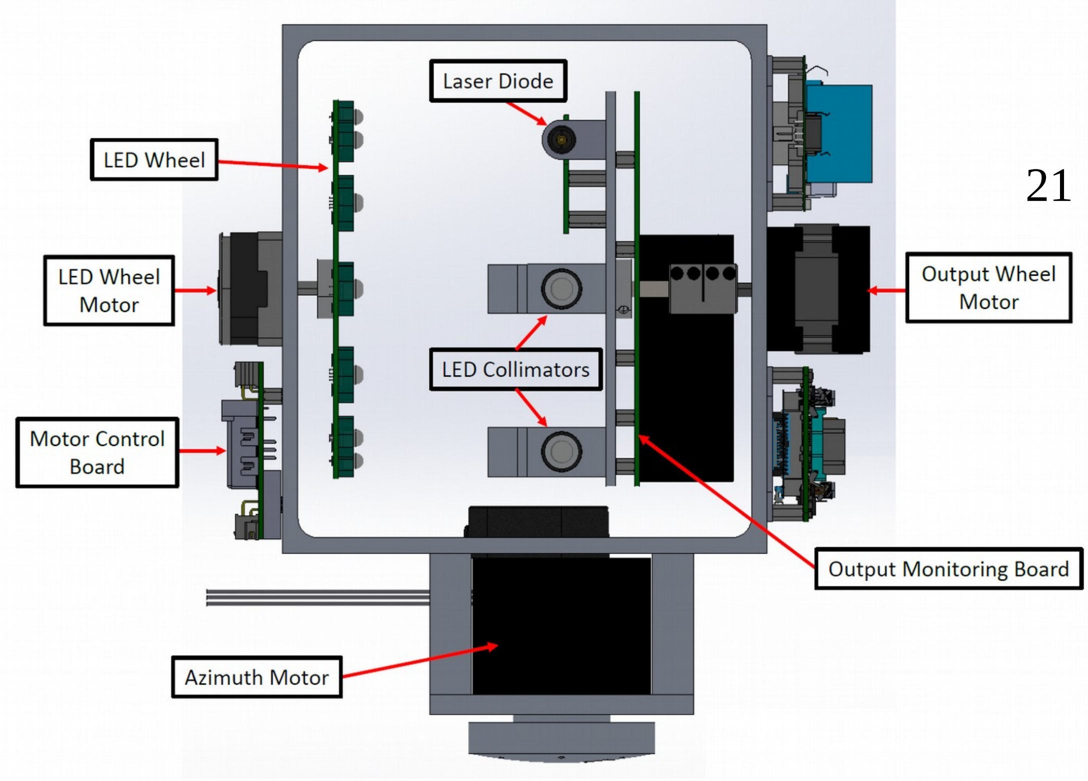
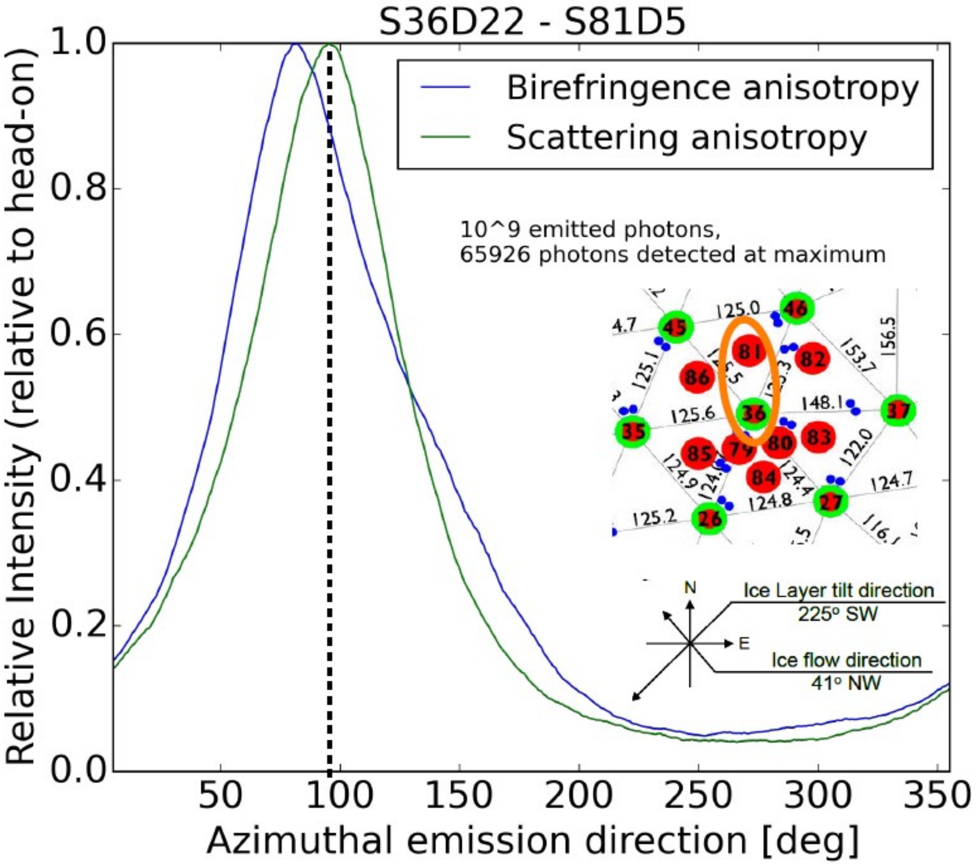
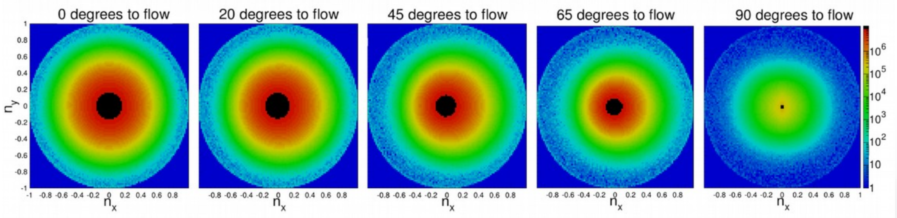


4π steerable, ns, collimated light source



Summary

- IceCube observes anisotropic propagation aligned with the ice flow
- Best best modeling of the effect is achieved through anisotropic absorption (still to be understood) combined with diffusion in birefringent polycrystals with preferential c-axis distribution which results in an average photon deflection
- The resulting ice model achieves and unprecedented data-MC agreement
- In the process IceCube is able to deduce crystal properties based on single photon arrival times sampled at 125m distances

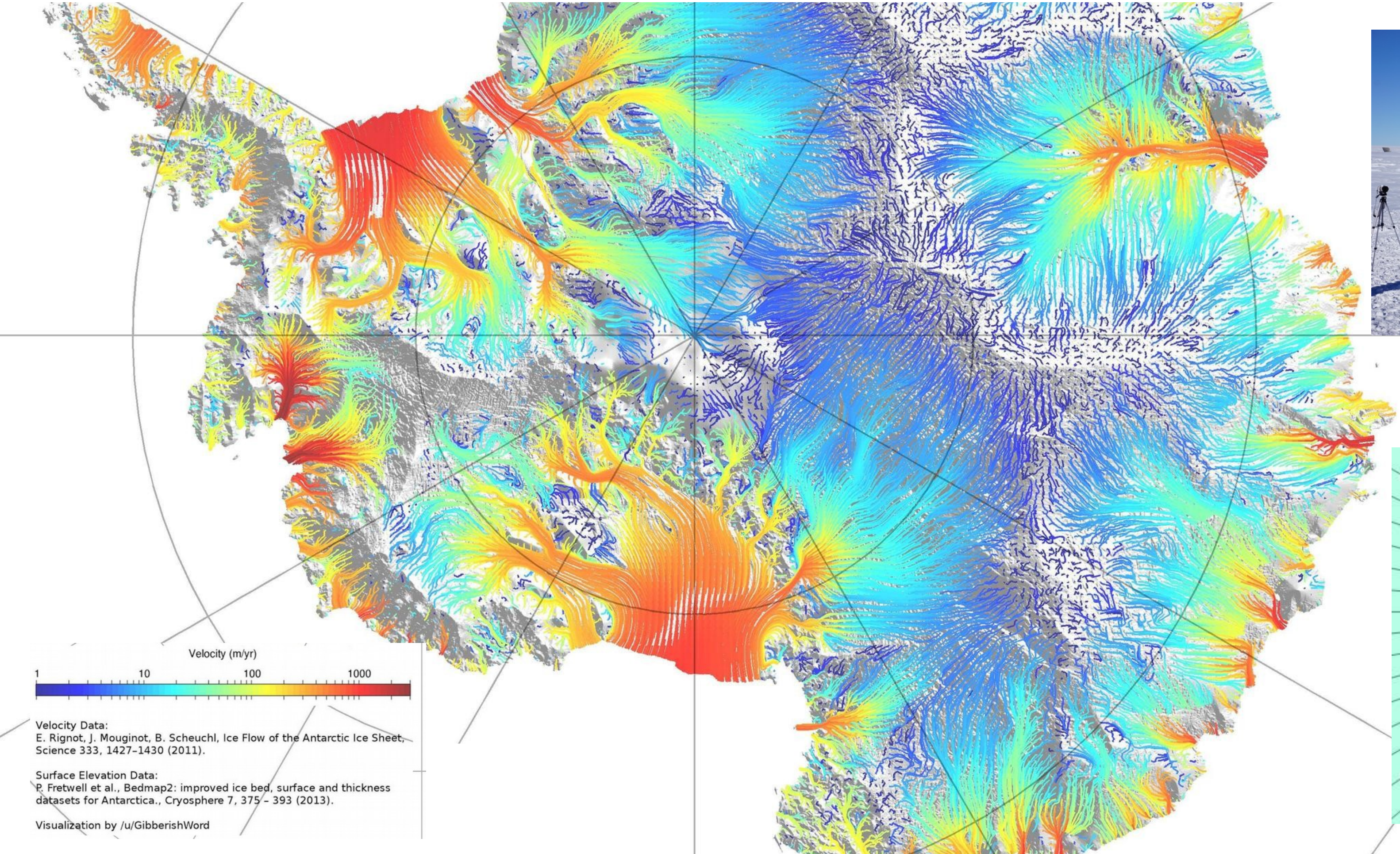


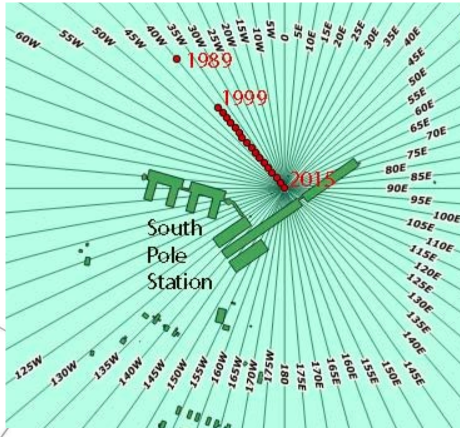
Thank you for your attention!

Questions are welcome

Backup….

Rivers of ice





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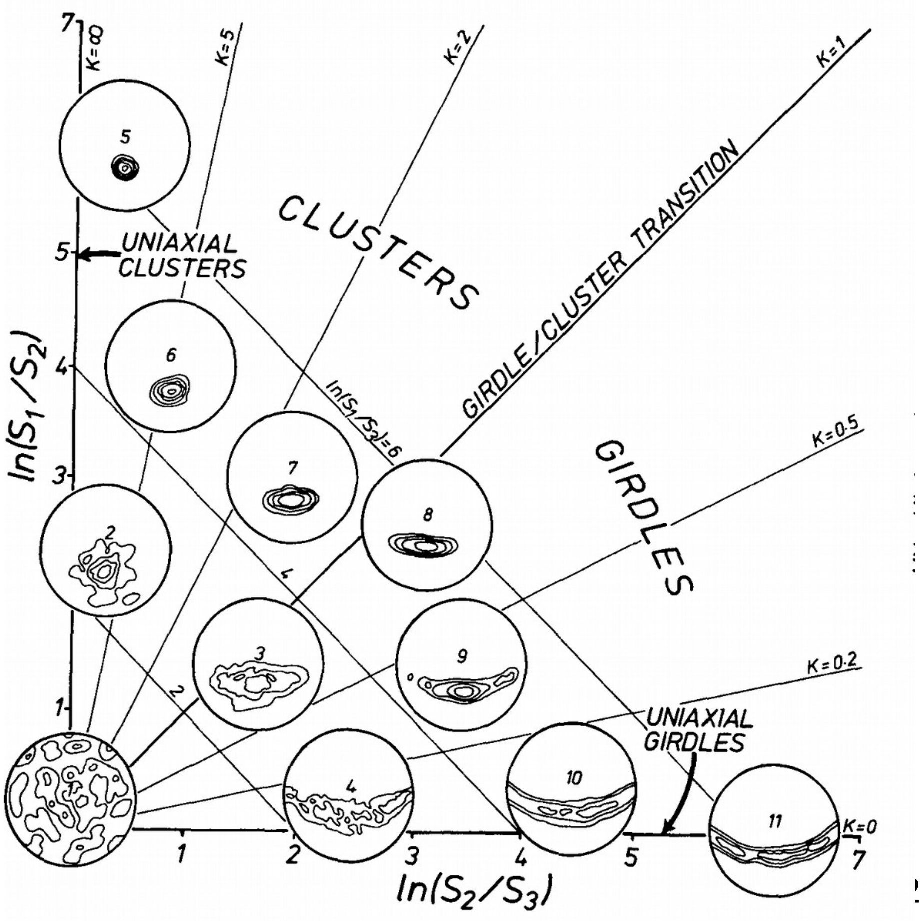
c-axis sampling

We can describe an ensemble of c-axis by their direction vectors n and construct the orientation tensor:

$$a = \begin{bmatrix} \sum n_{ix}^2 & \sum n_{ix} \cdot n_{iy} & \sum n_{ix} \cdot n_{iz} \\ \sum n_{iy} \cdot n_{ix} & \sum n_{iy}^2 & \sum n_{iy} \cdot n_{iz} \\ \sum n_{iz} \cdot n_{ix} & \sum n_{iz} \cdot n_{iy} & \sum n_{iz}^2 \end{bmatrix}$$

This matrix can be diagonalized.
This is equivalently to choosing the coordinate system such that the x-axis is along the axes mean and the other two are orthogonal.

It‘s eigenvectors are then the axes and it has three eigenvalues with: S1>S2>S3



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Circle equivalent diameter

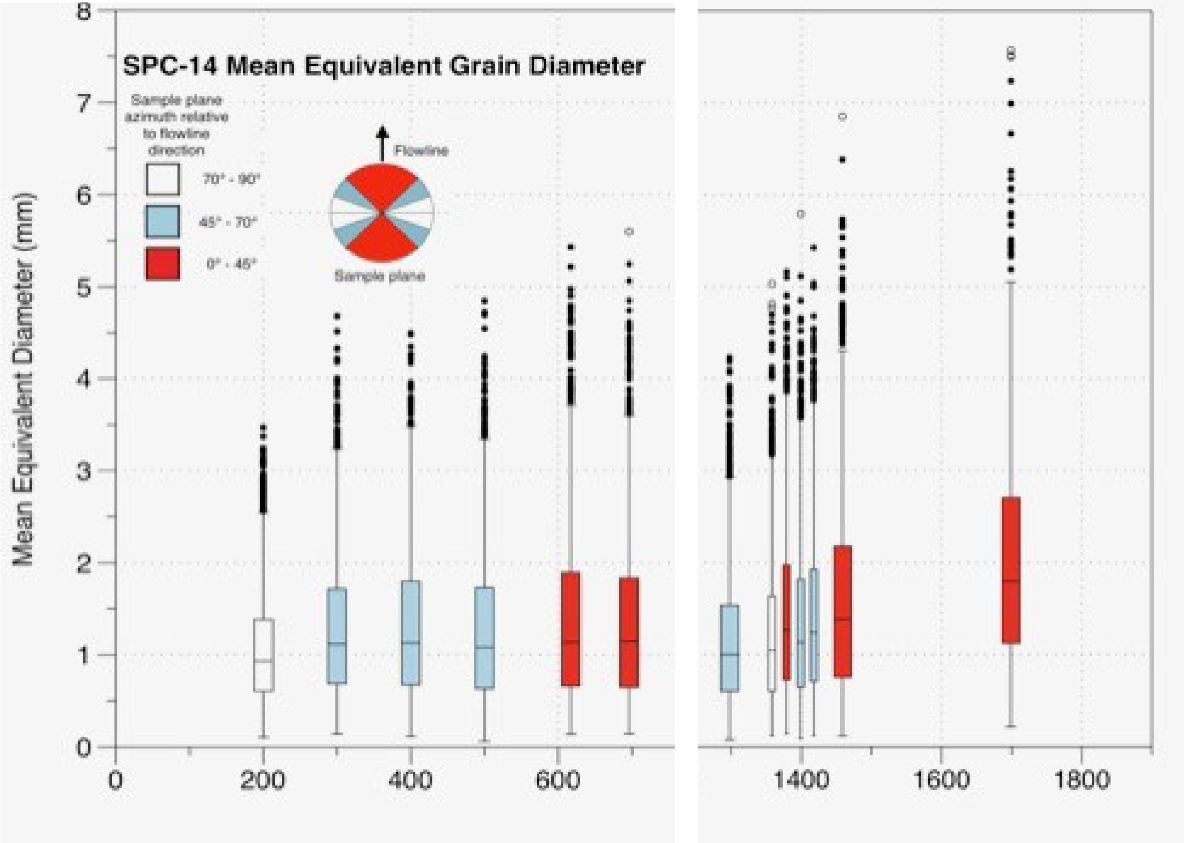
- SPICEcore measures grain size as the circle equivalent diameter
- That is the diameter of a circle with the same area as the grain
- It obtains 1-2mm ⌀ in deep ice

- For an ellipsoid the circle equivalent diameter depends on the cut plane
- In our parametrization the range is between:

$$d\ [mm] = 2\ \sqrt{minor}\ /\ size$$

&

$$d\ [mm] = 2\ minor/\ size$$



Juan Fitzpatrick, private communication