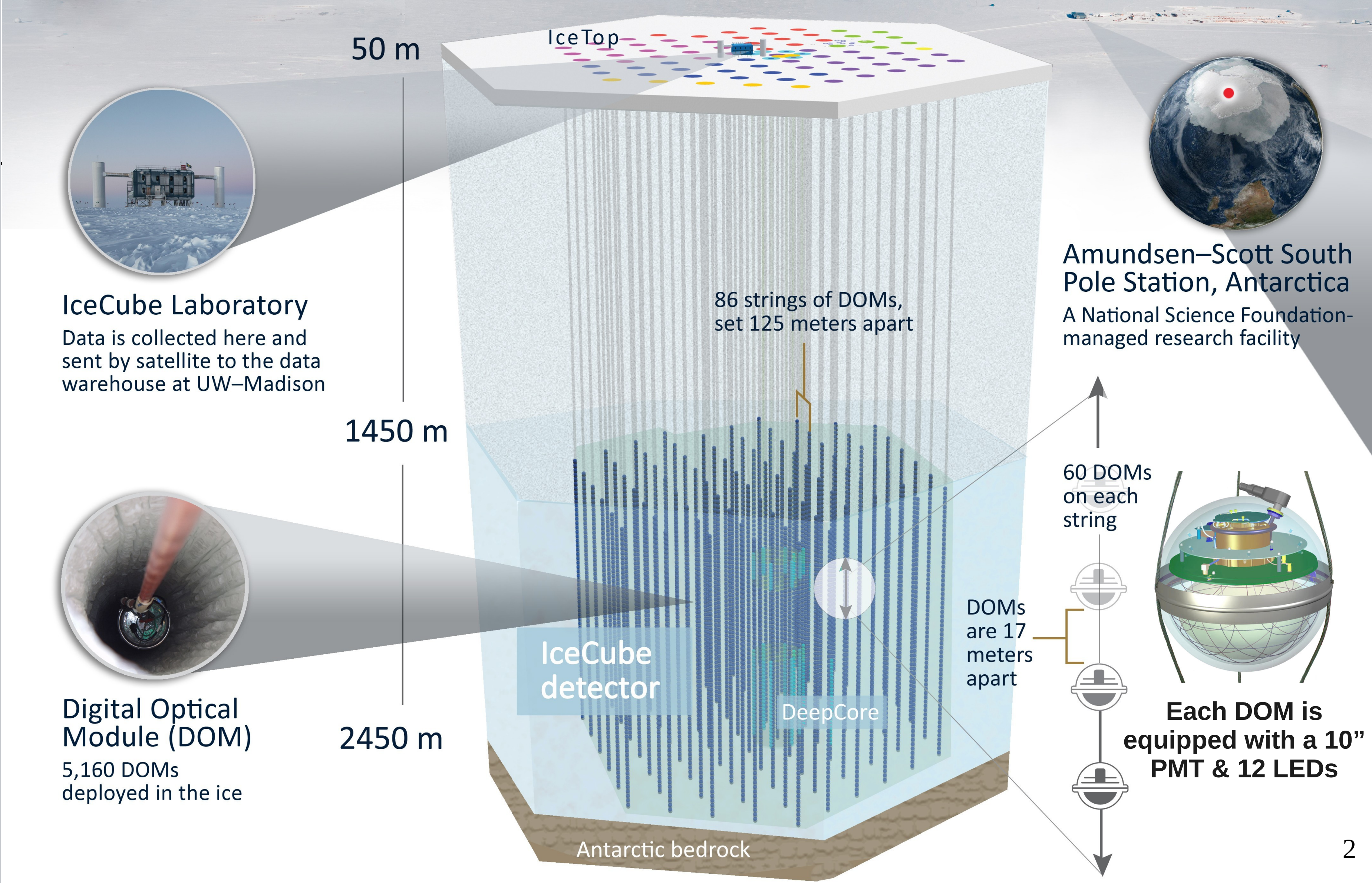
A novel microstructure-based model to explain the IceCube ice anisotropy

Martin Rongen & Dmitry Chirkin for the IceCube collaboration

ICRC July 2021

The IceCube Neutrino Observatory

Design and construction

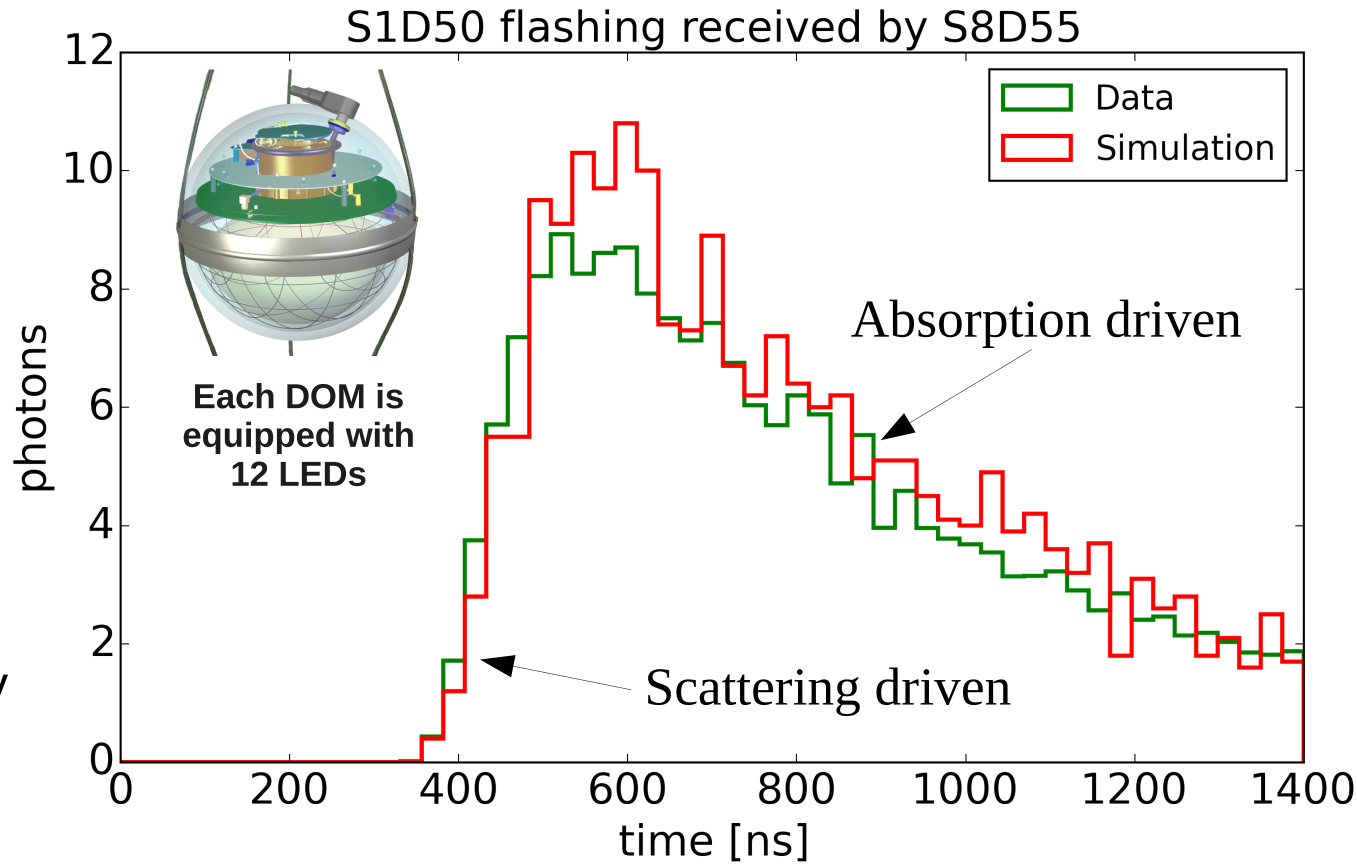


Light curve sensitivity

- 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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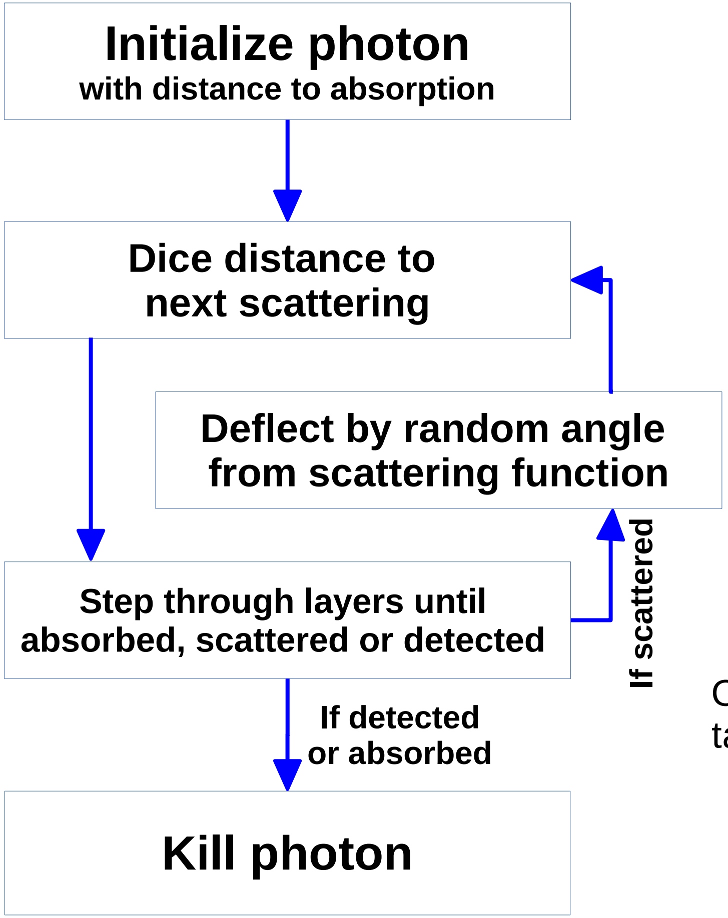

Photon propagator code (PPC)

On GPUs ~250 times faster than CPUs

One full detector simulation takes 200-5000 GPU hours

Layered ice model (SPICE)

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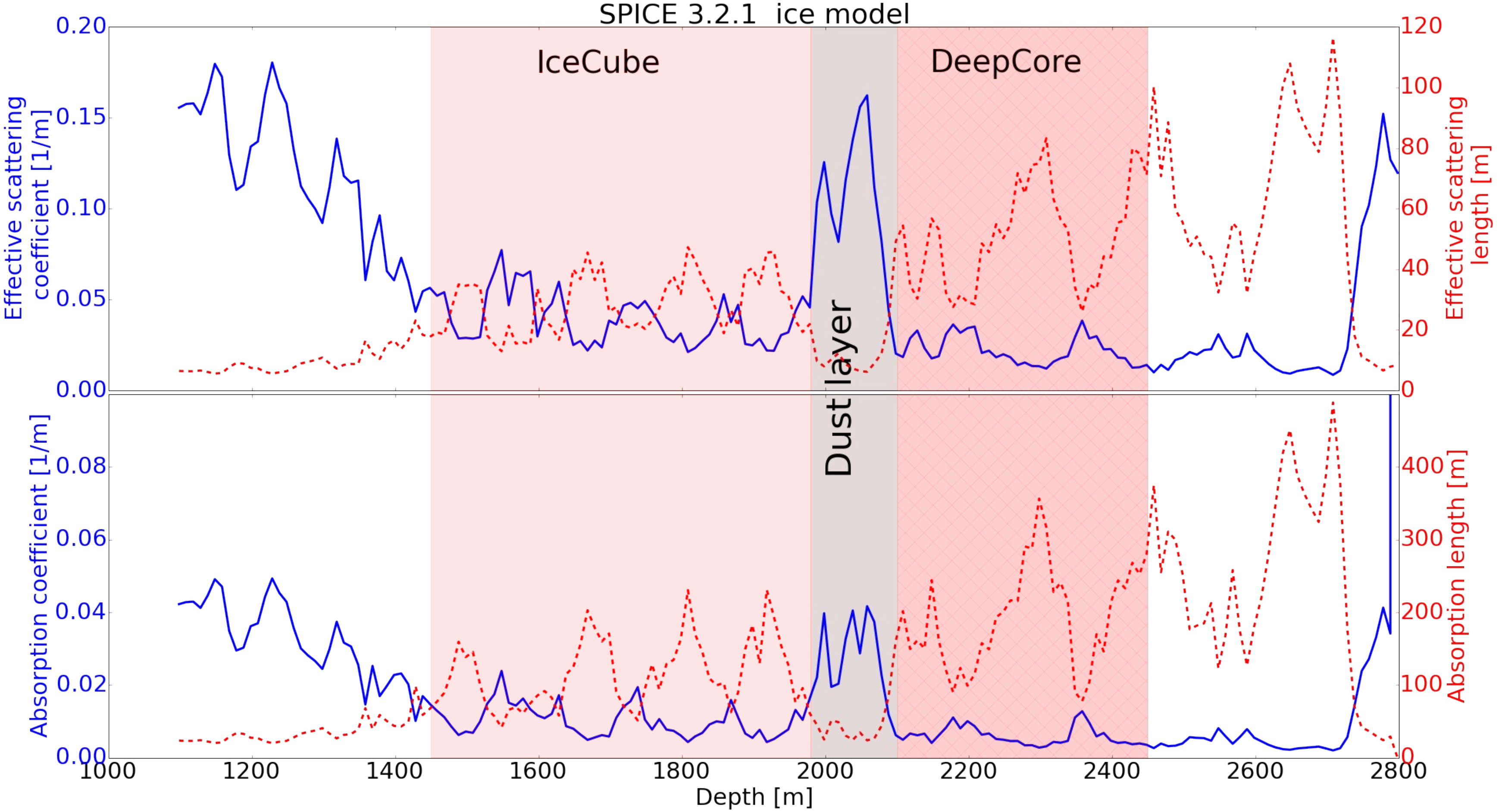

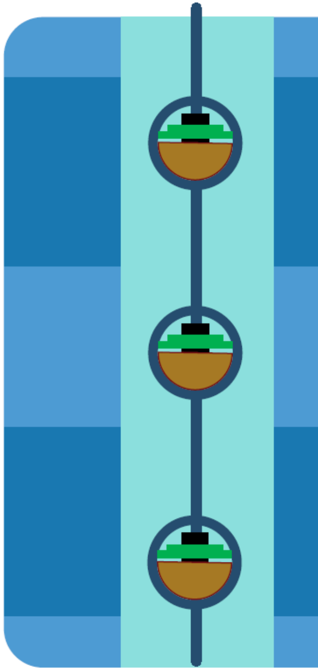

The ice anisotropy effect

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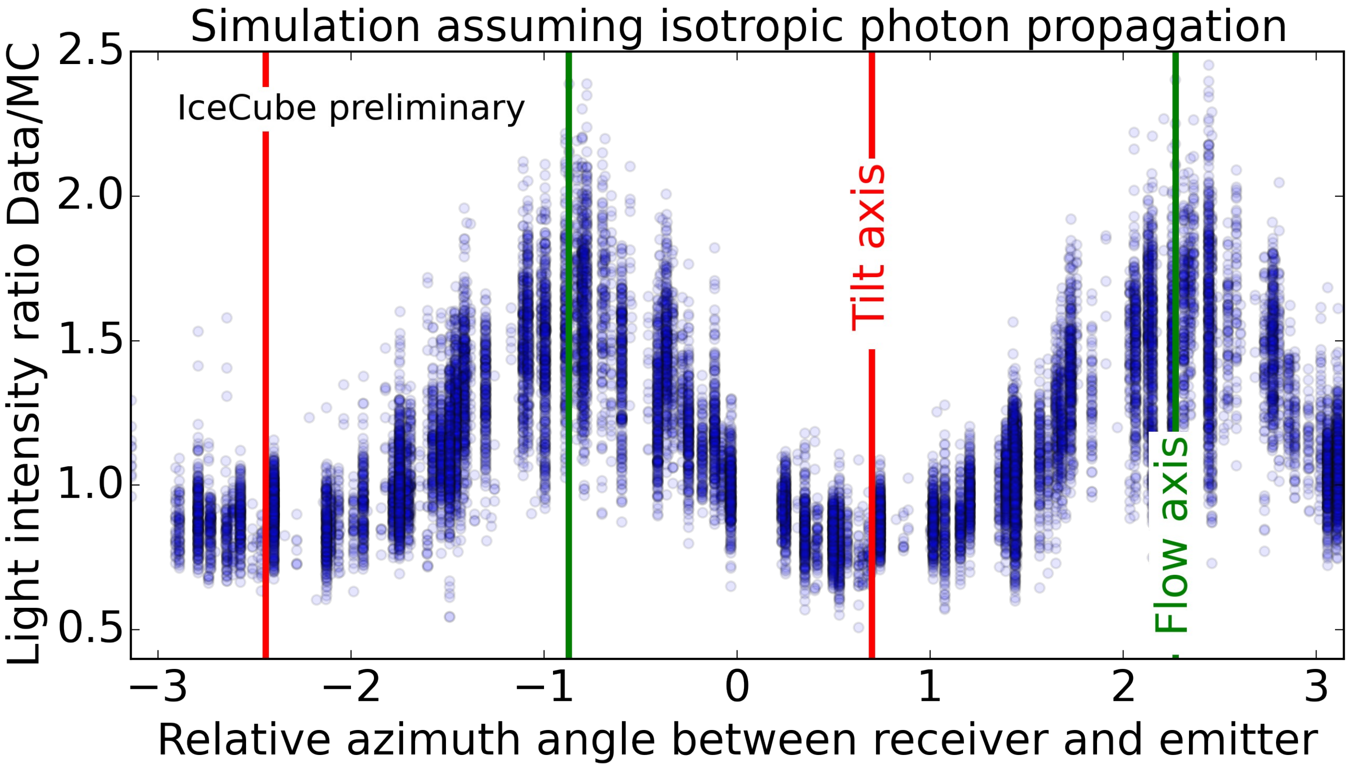
- Observed charge depends on orientation of receiver DOM with respect to emitter DOM

- Most charge seen along flow axis, least orthogonal

- In 2013 implemented as a direction dependent modification of the scattering function



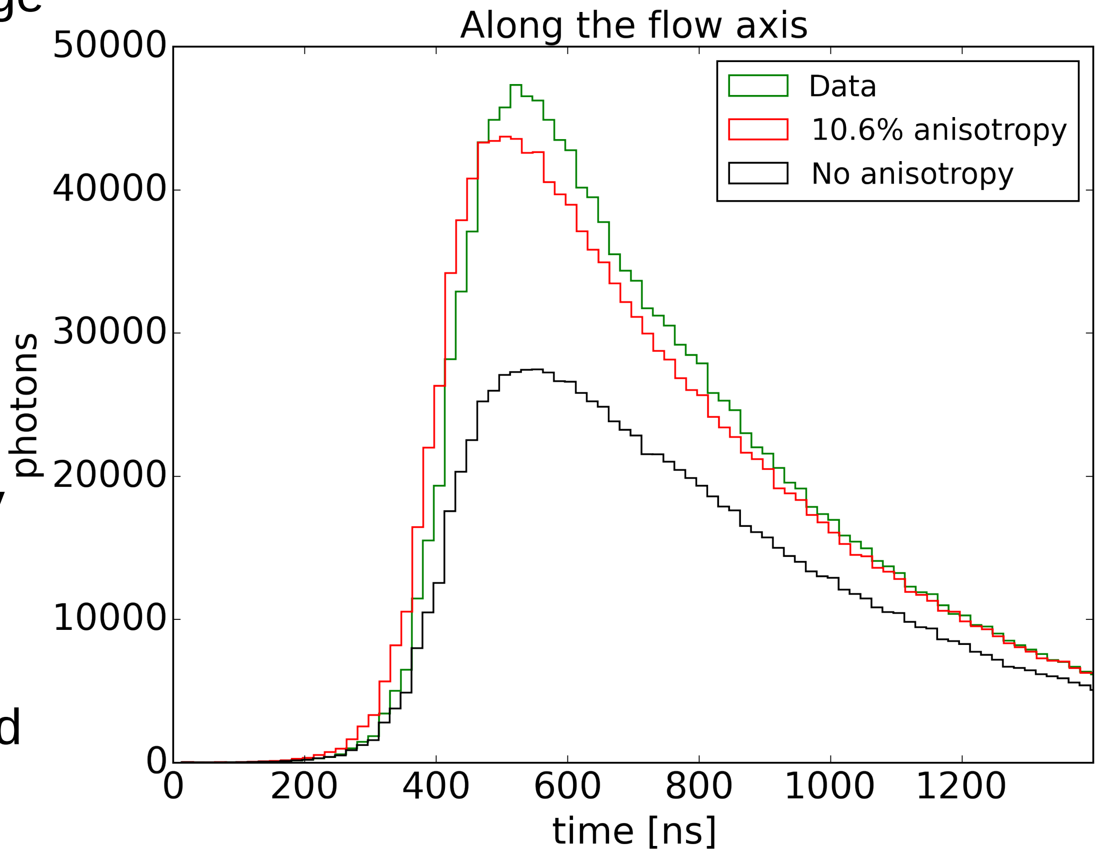
→ less scattering in the flow direction

Timing vs. intensity

- 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

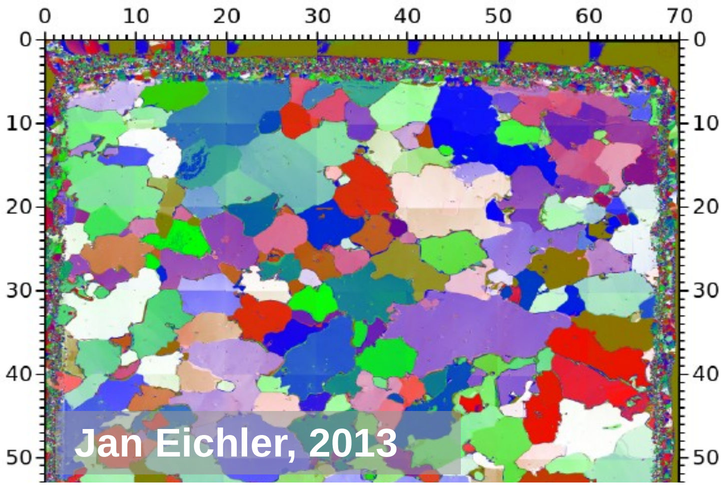
- Also found that inhomogenious impurity distributions can not lead to anisotropic Mie scattering
- Anisotropic absorption is possible, but a mechanism leading to the required strength is not understood

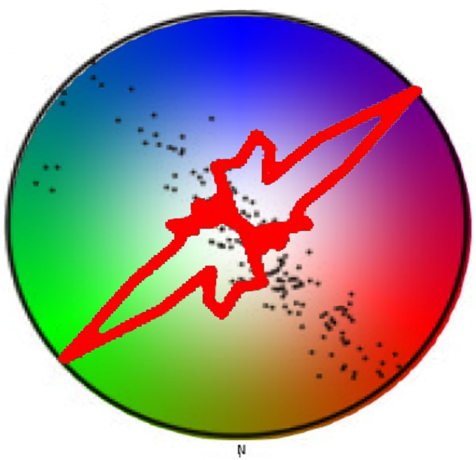


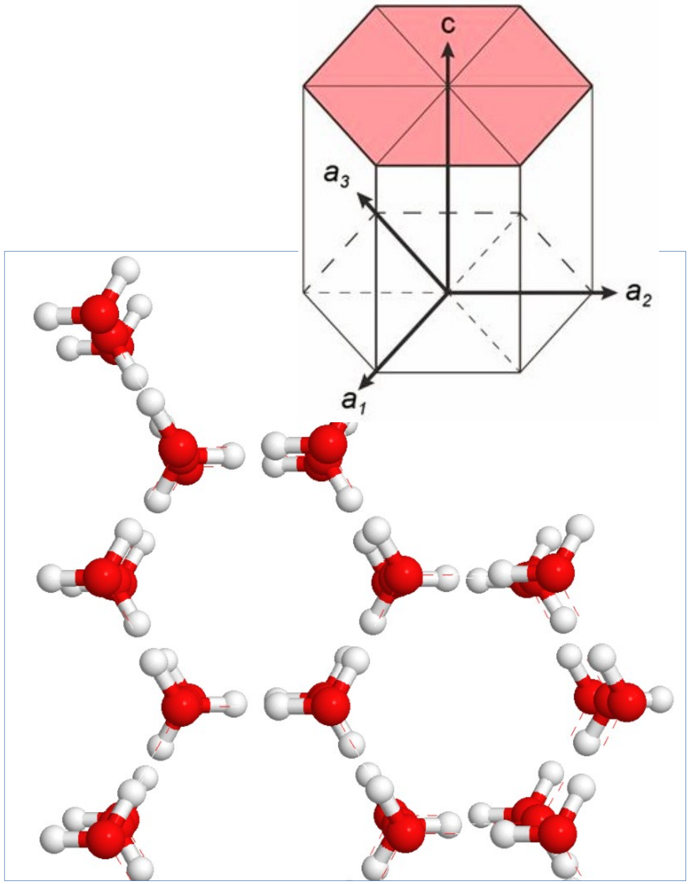
c-axis and elongation

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

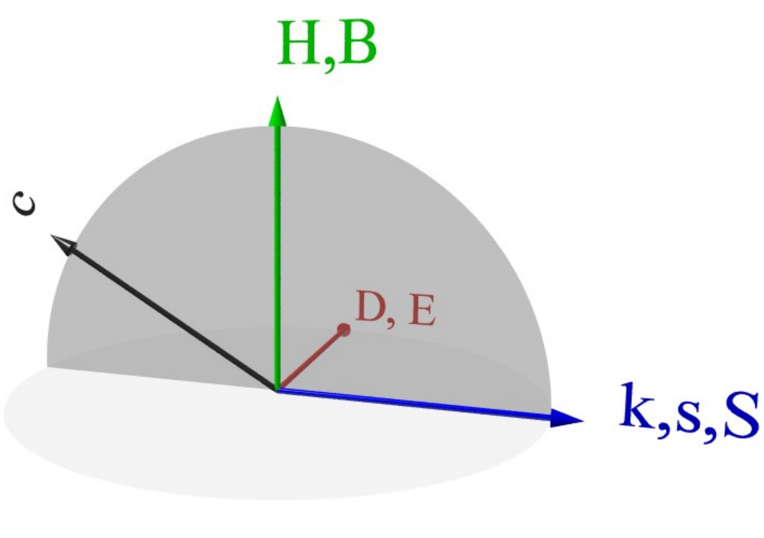
- An ensemble of grains under stress (such as flow) will elongate with the flow yielding a girdle of c-axes orthogonal to the flow







Birefringence



Christoph U. Keller

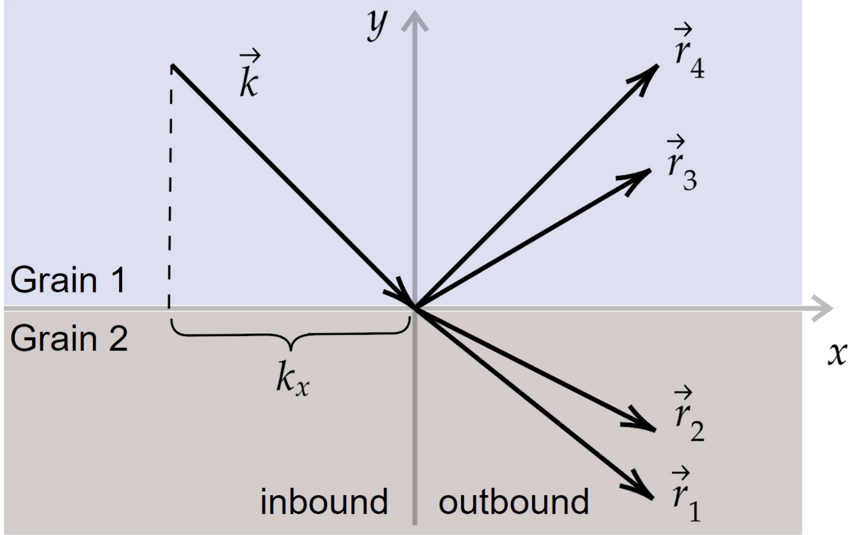
- Ice is a birefringent material:
  Light is split into an ordinary and an extraordinary ray with respect to the c-axis

- The refractive index of the extraordinary ray is direction dependent

- Extraordinary ray exhibits dispersion between the wave and Poynting vectors

A single grain boundary

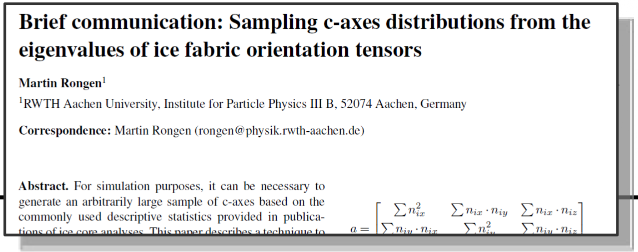
- At each grain boundary every ray is split into two reflected and two refracted rays one ordinary and one extraordinary ray each
- Wave vector component parallel to surface is conserved, norm is proportional to the refractive index
- Poynting vectors are derived from wave vectors and boundary conditions
- 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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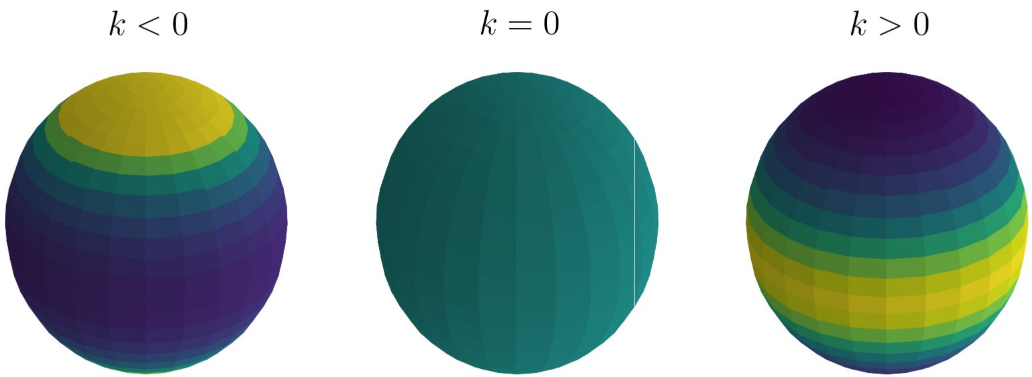
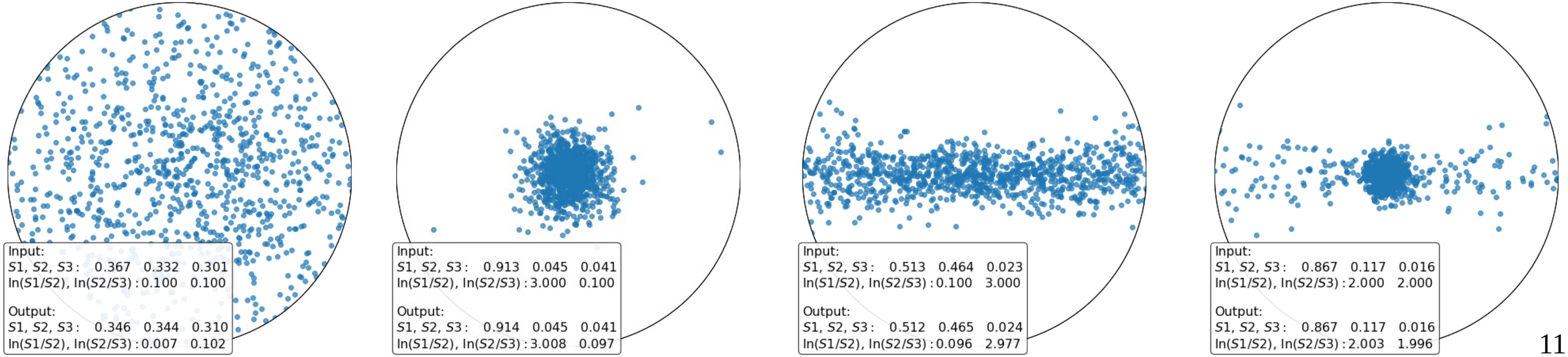
Abstract. For simulation purposes, it can be necessary to generate an arbitrarily large sample of c-axes based on the commonly used descriptive statistics provided in publica-

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

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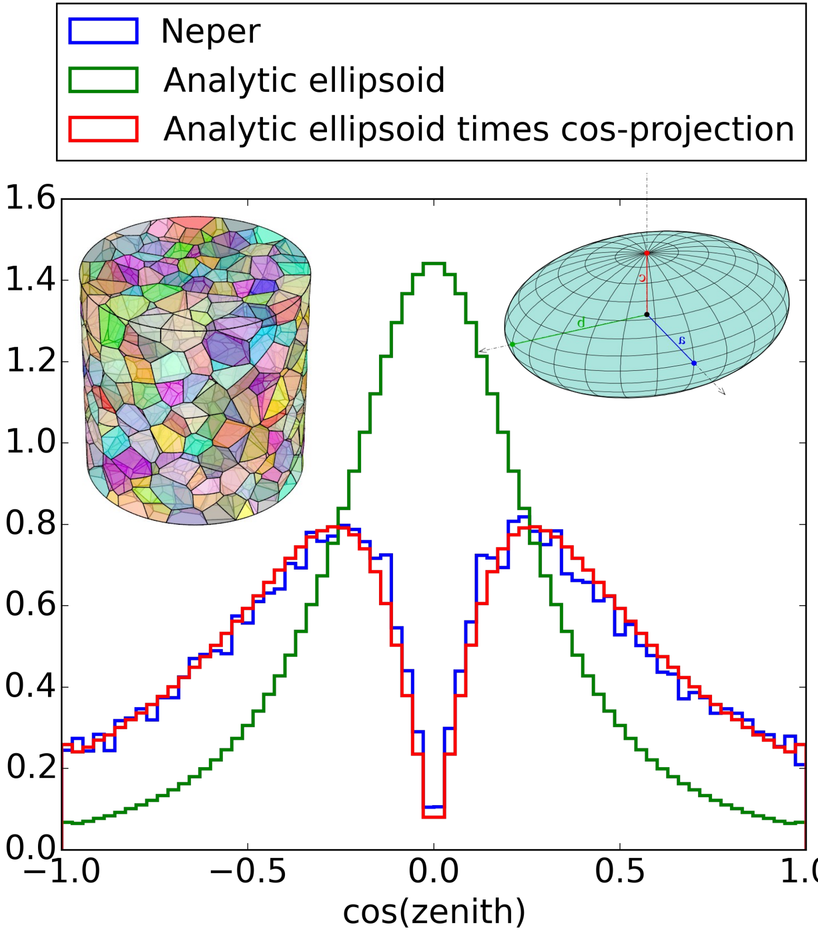
To be able to simulate propagating through a polycrystal we need to further know:

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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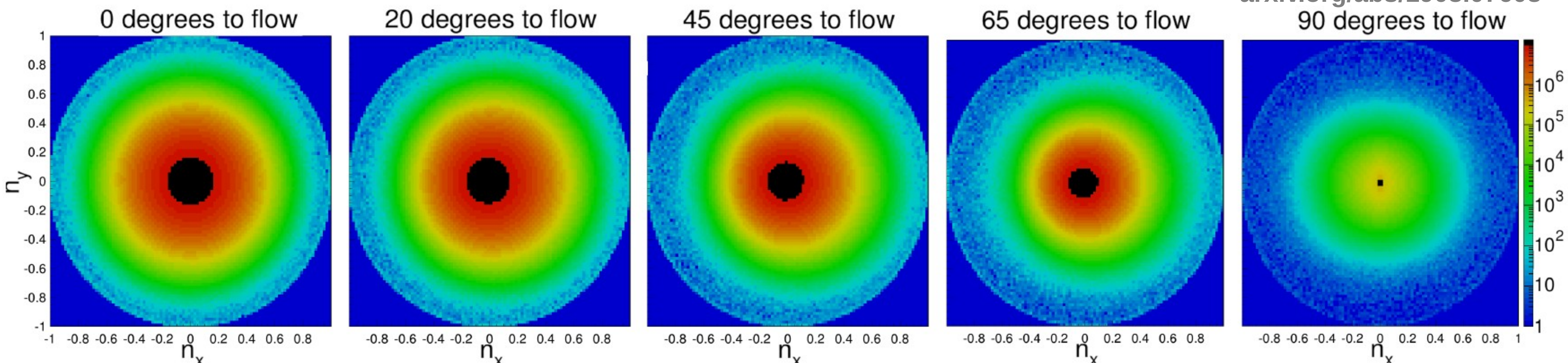
Birefringence Monte Carlo

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



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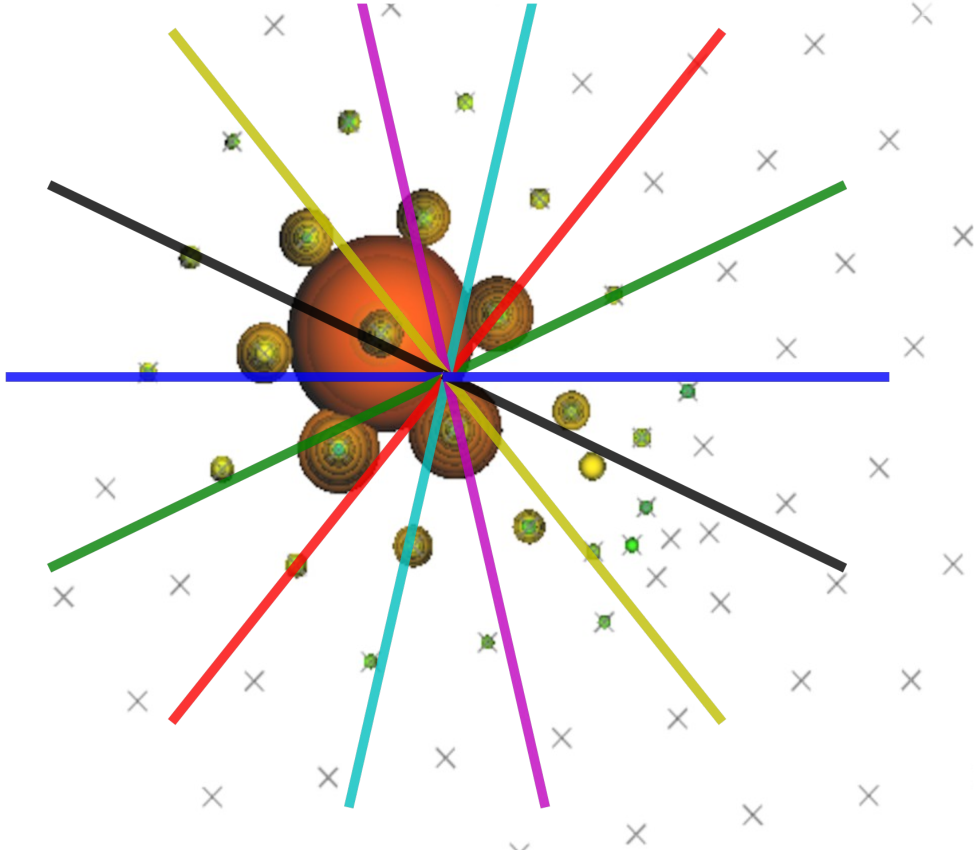
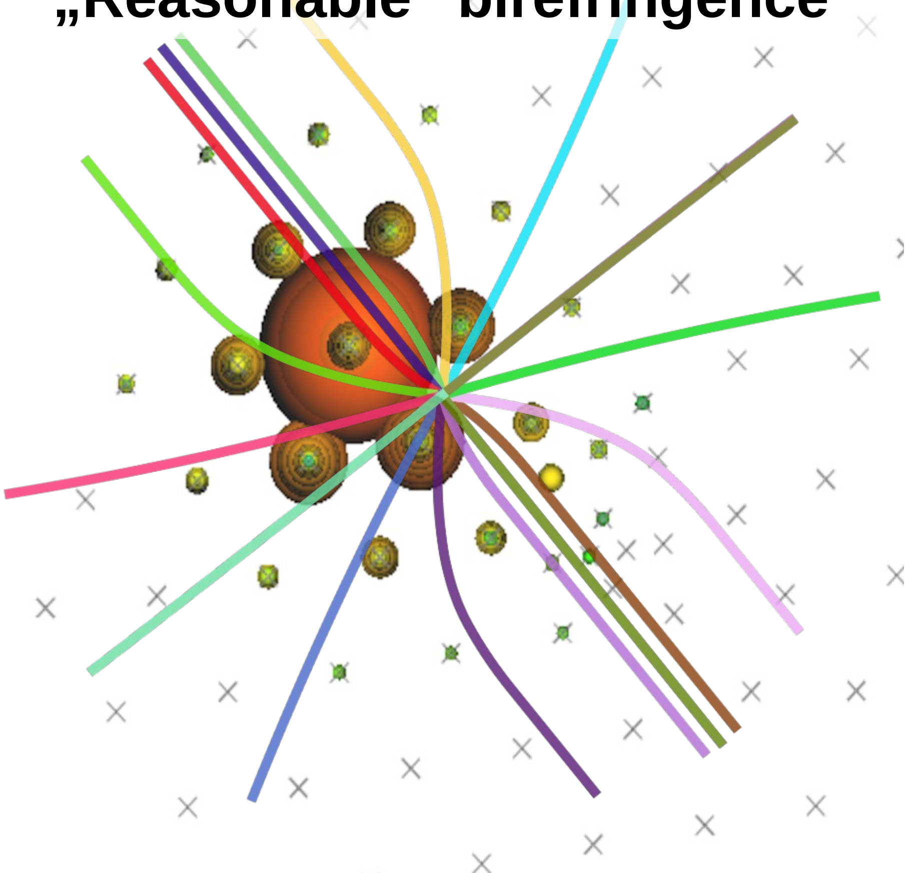
Average photon trajectories

No birefringence



„Reasonable“ birefringence



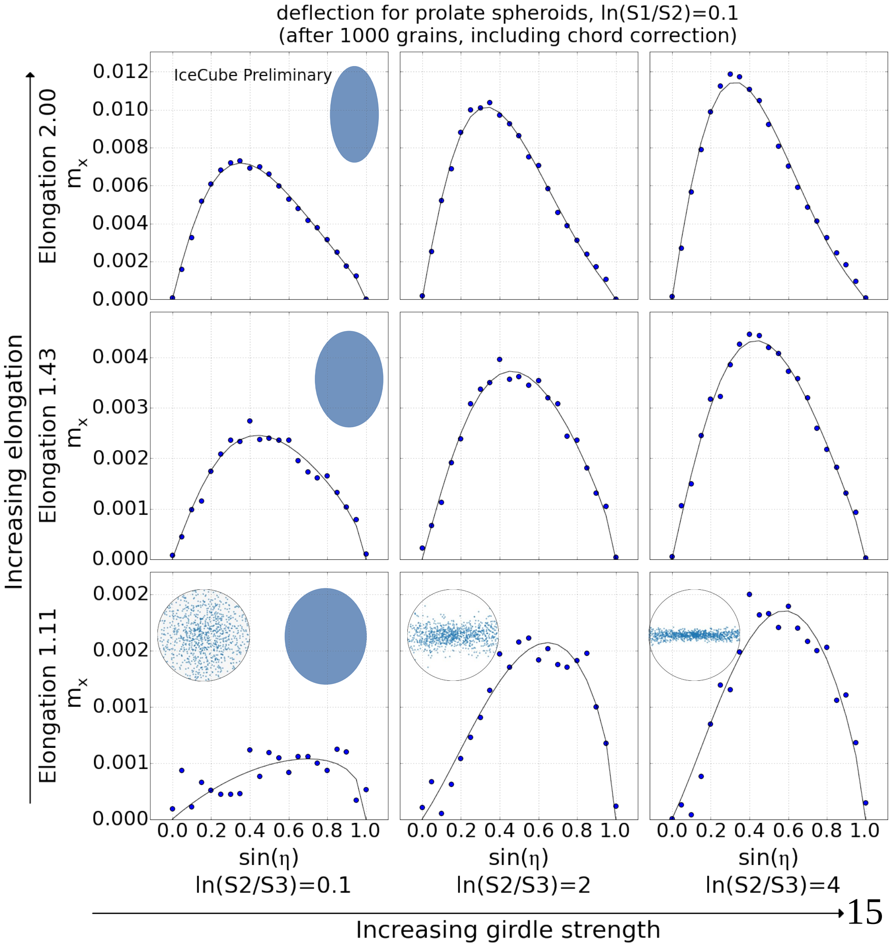
Parametrization

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

- In PPC photons are displaced, deflected & diffused at each scattering site (after distance scaling) depending on their angle to the flow

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

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



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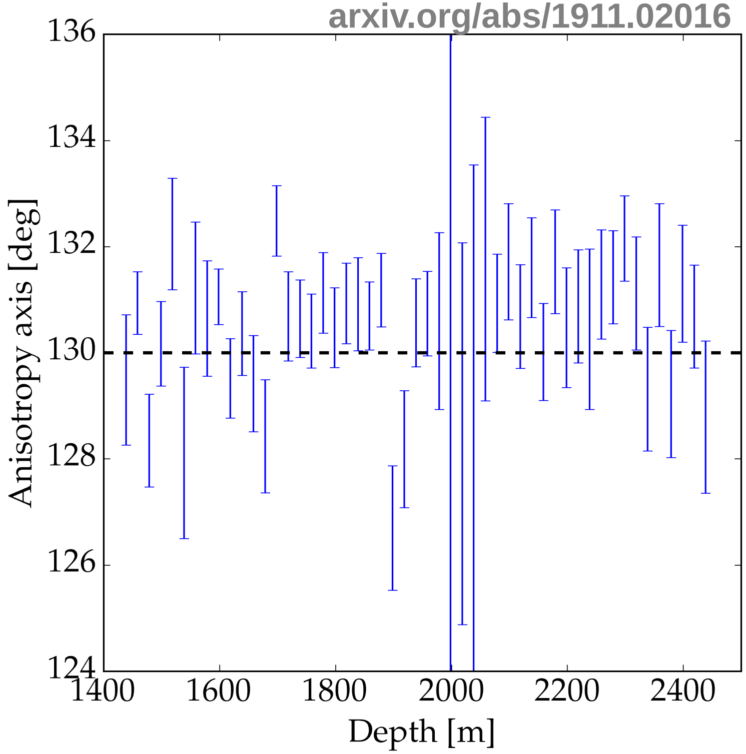
Pre-fits

- We can't optimize all parameters 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

arxiv.org/abs/1911.02016



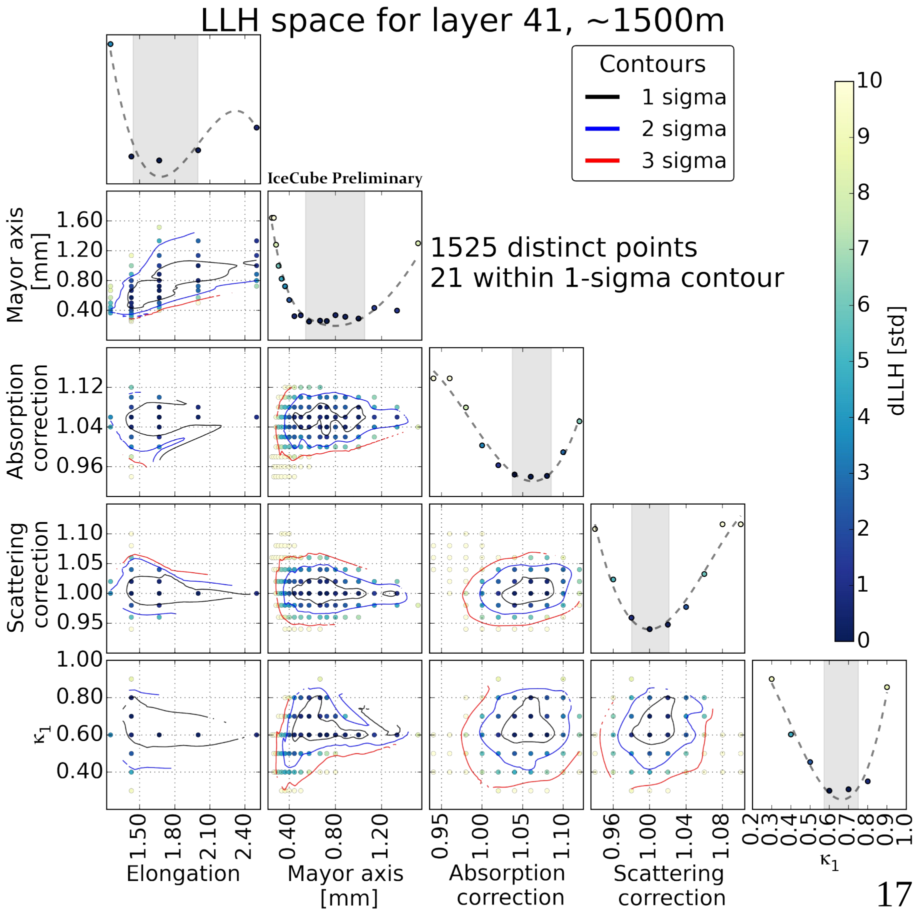
Single layer fit example

- 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)



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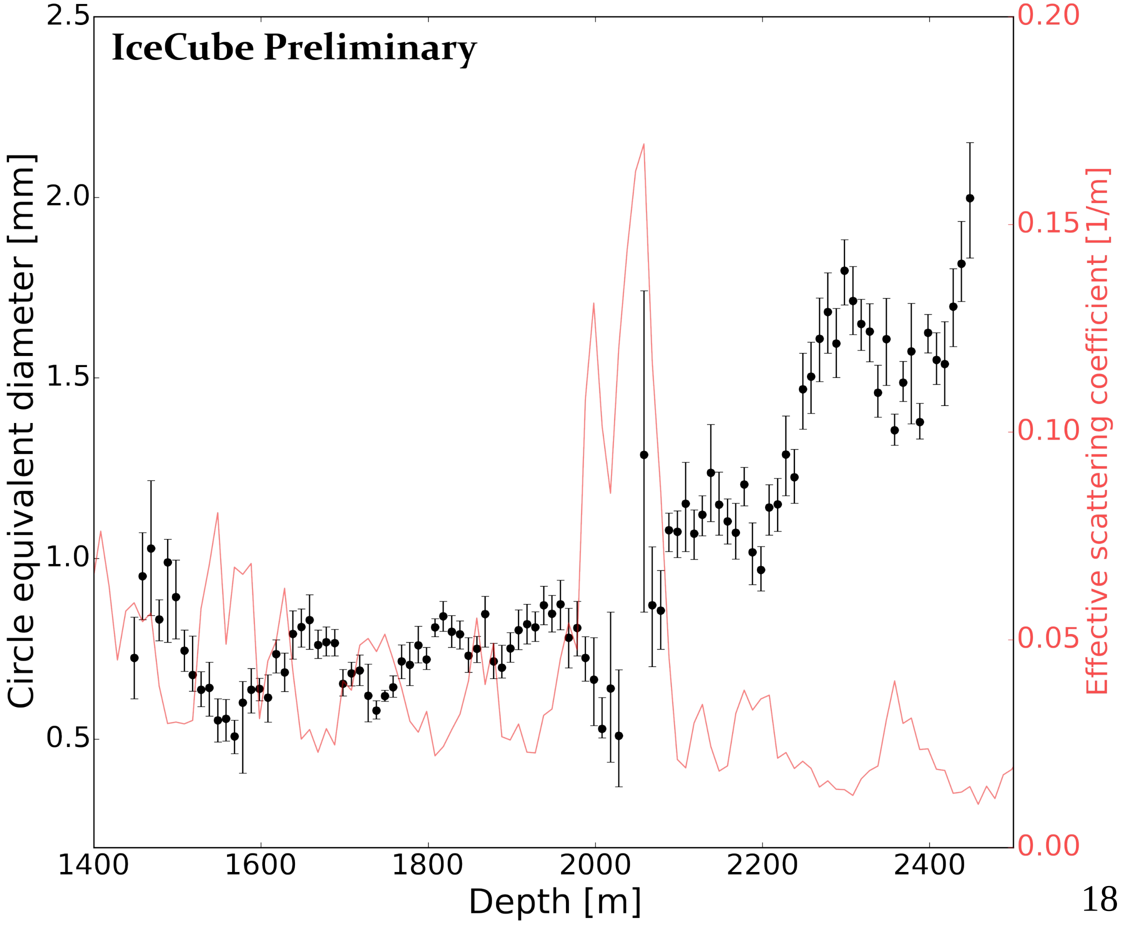
Grain size vs. depth

- 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 scattering
  → crystals are smaller where scattering is stronger, i.e. where there is more dust



Quality & open issues

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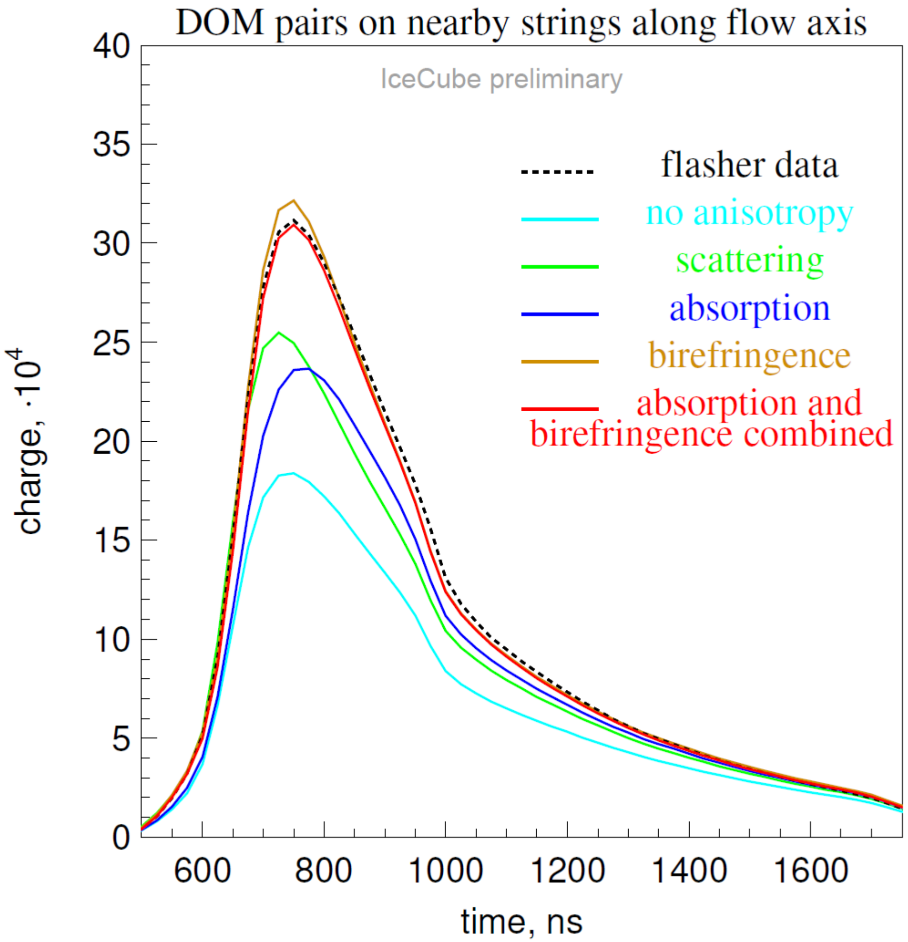
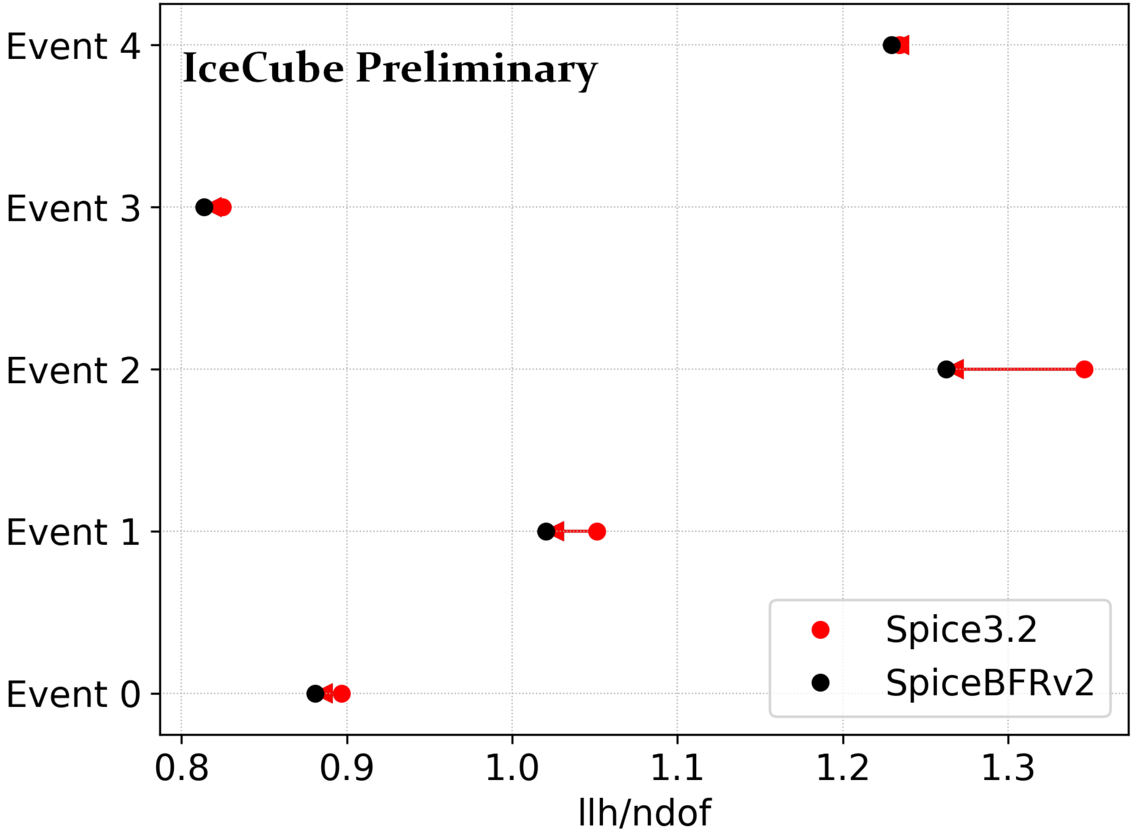
- Using the full-model described above, we achieve an unprecedented data-MC agreement
- Allows us to probe crystal properties using only PMT data sampled at 125m intervals
- BUT the LED data is insufficient to unambiguously determine the large number of parameters involved
- And we still require a first principle explanation for what appears to be an absorption anisotropy
  (which may in turn change the birefringence understanding)



Application in simulation & reconstruction

- New ice model released for use in simulation production
- Wide application requires large scale MC production
- In the meantime first tests using “direct fit” (LLH based reconstruction for individual events using resimulation)
- Confirms that new model yields consistently better data description
  → less reconstruction biases



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

- See proceedings for more details

Thank you for your attention!

Questions are welcome