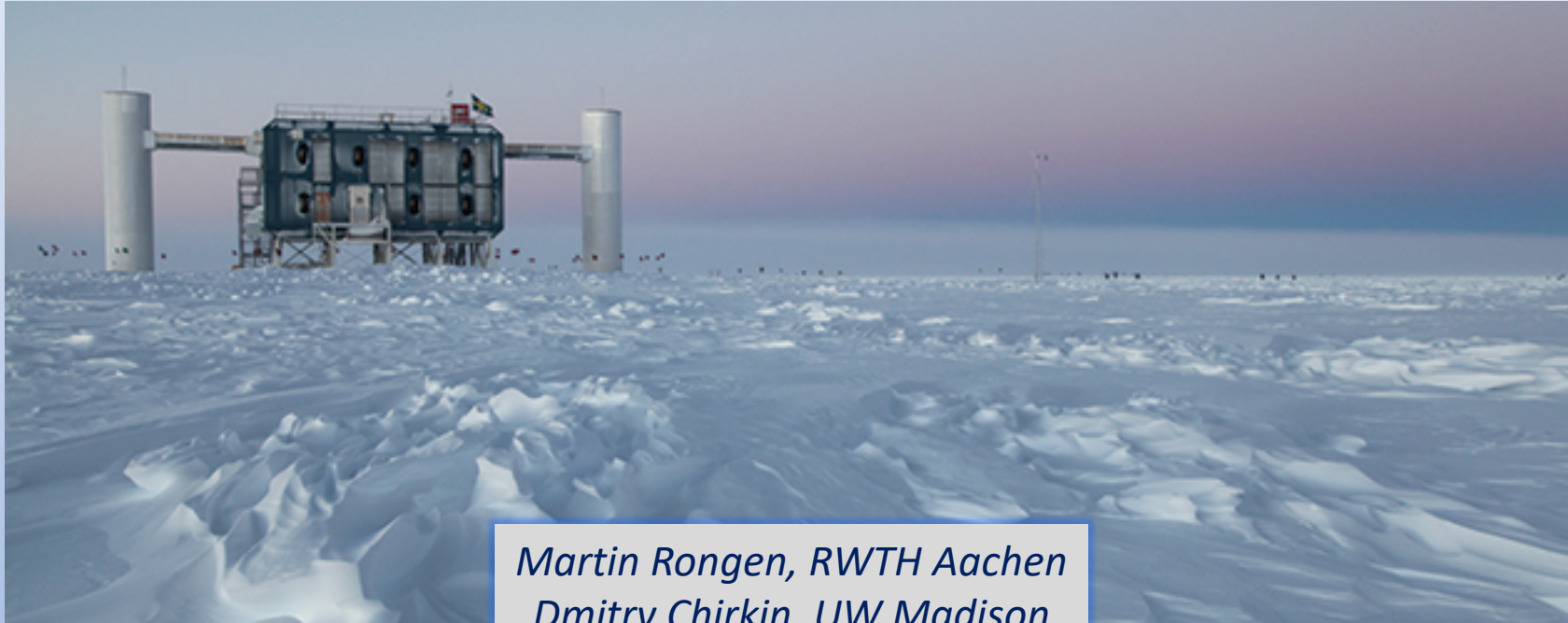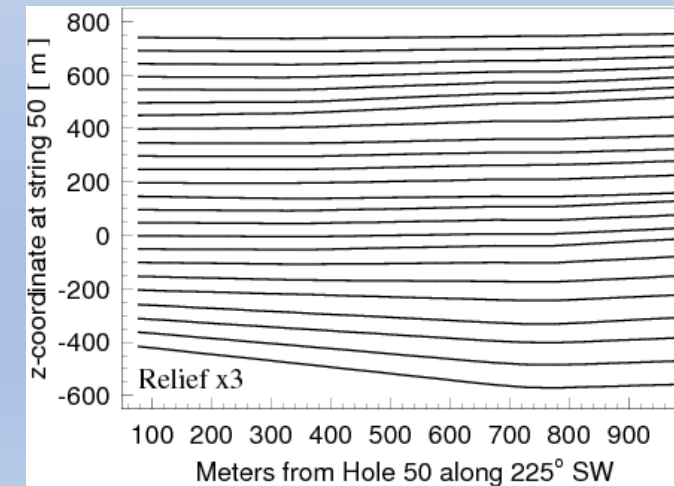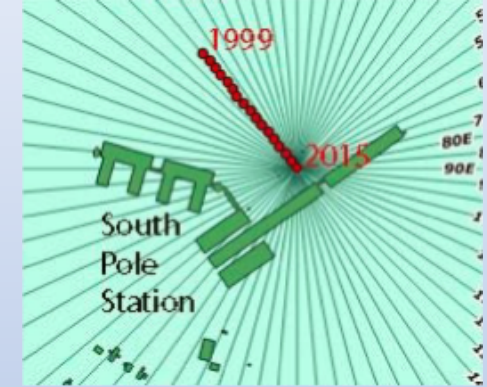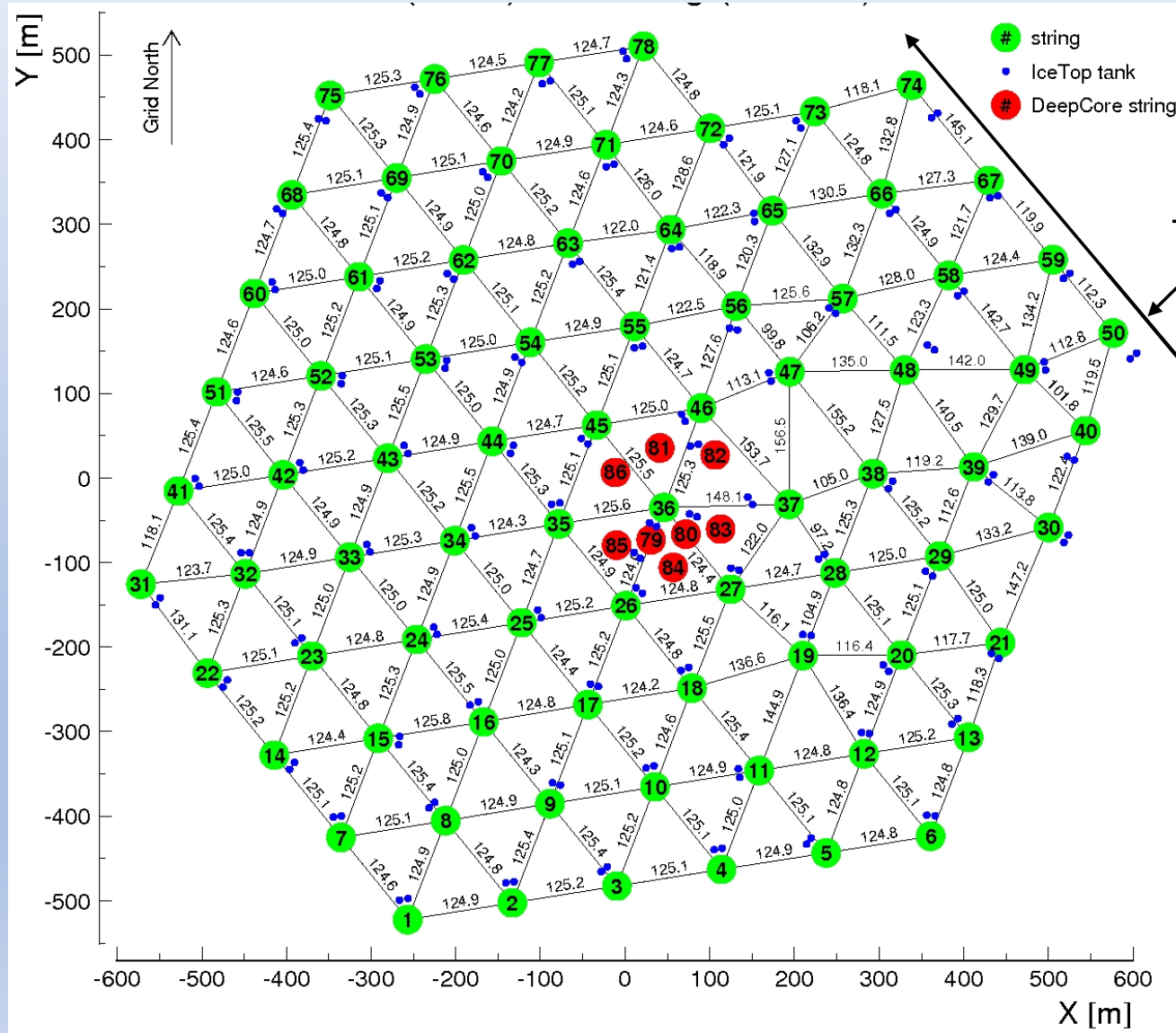# Light diffusion in birefringent polycrystals and the IceCube ice anisotropy

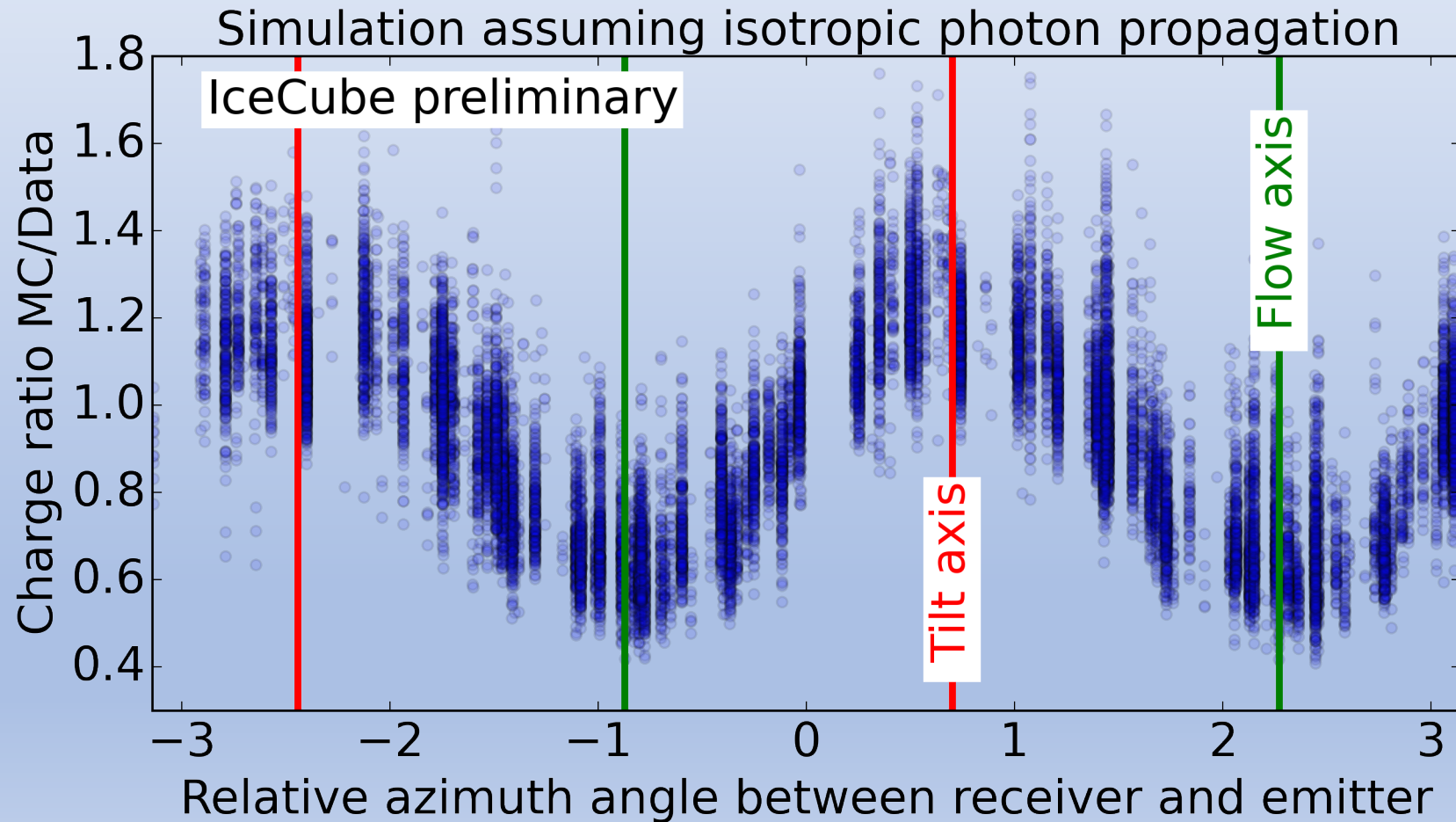*Martin Rongen, RWTH Aachen*
Dmitry Chirkin, UW Madison

Glacial ice flow, ice layer tilt at the South Pole

Ice moves about 10 m/year at South Pole along the 40° west longitude line

~8% less scattering 41° NW

Layers of ice of similar optical properties slowly change depth along gradient direction

The ice anisotropy effect

Simulation assuming isotropic photon propagation

IceCube preliminary

Charge ratio MC/Data — Relative azimuth angle between receiver and emitter

Tilt axis

Flow axis

Observed integral charge and light curve depend on orientation of receiver DOM with respect to emitter DOM

Most charge seen along the flow axis, least orthogonal to it

First observed in 2013 and described by direction dependent scattering function, re-evaluation started in 2017 with depth dependent strength fit

Models of optical ice anisotropy in IceCube

1. Scattering (mainly): direction dependent scattering function (ICRC 2013)
2. Absorption (mainly): direction dependent absorption (studied in 2017)

Introduced depth-dependence (2017)

Discrepancies between data and simulation remain

Cannot simultaneously fit total charge and
arrival time distribution to statistical precision

Ice has small amount of intrinsic absorption, but most of absorption and all of scattering has been assumed to be due to impurities (according to Mie scattering theory).

Here we explore scattering of light in pure ice, due to a small difference in refractive index of ordinary and extraordinary waves in ice (birefringence).
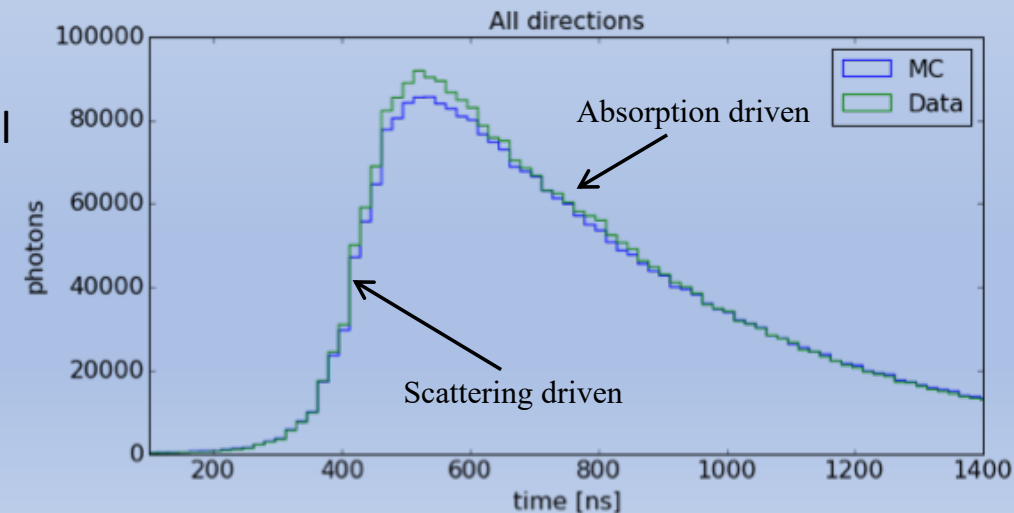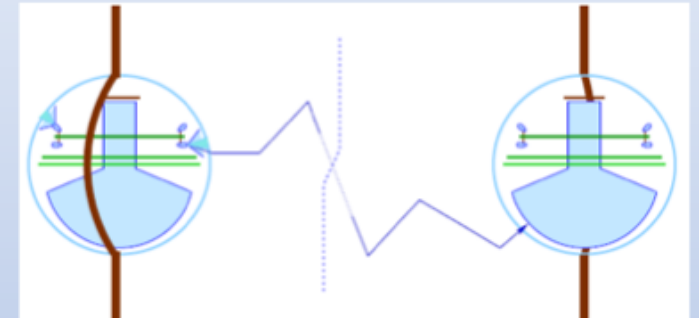
Birefringence

Ice is a birefringent material:

Light is split into an ordinary and an extraordinary rays with respect to the (optical) c-axis, these have orthogonal polarizations

The refractive index of the extraordinary ray is direction dependent

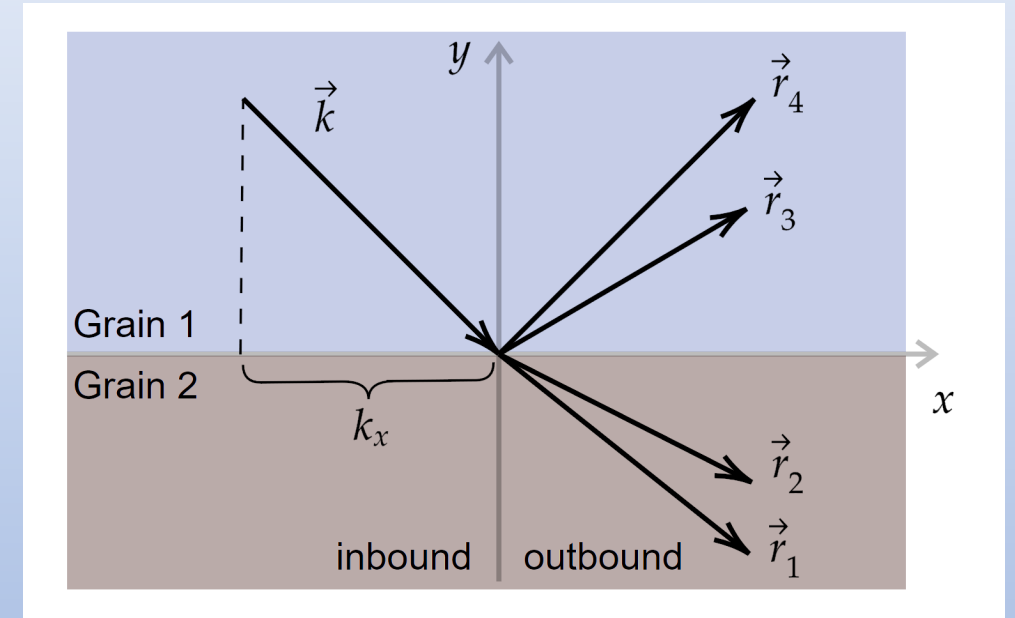The extraordinary ray exhibits dispersion between the wave vector and the Poynting vector

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
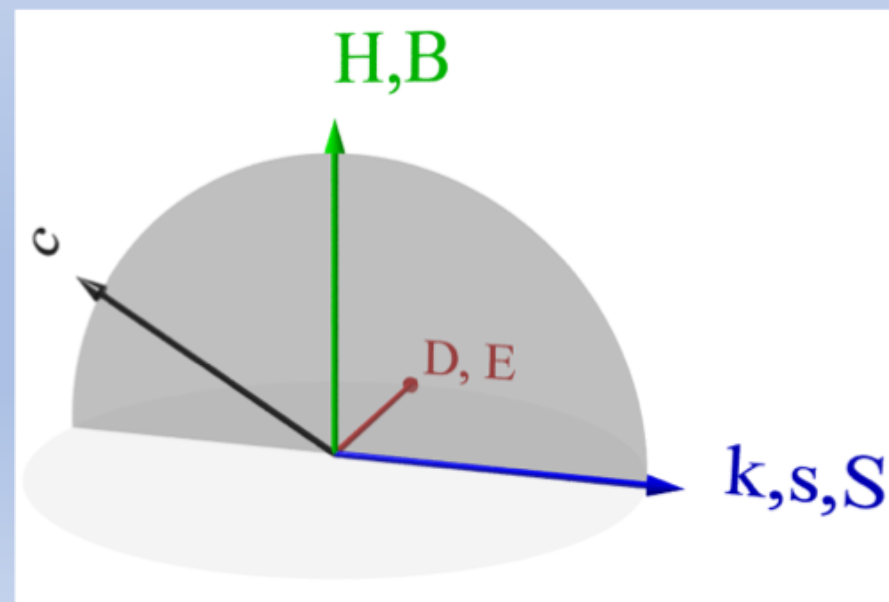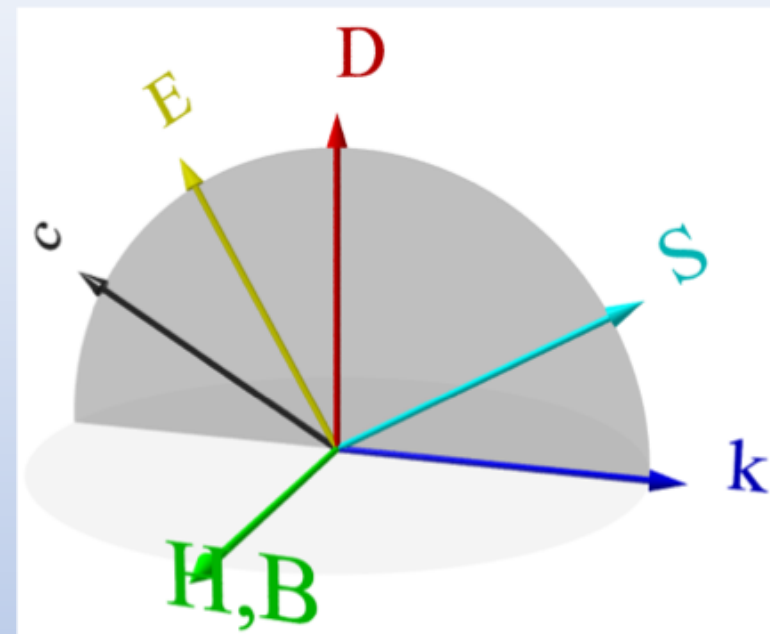
Birefringence

- 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 plane is conserved)

$$\hat{n} \cdot \mathbf{D}_2 = \hat{n} \cdot \mathbf{D}_1$$
$$\hat{n} \cdot \mathbf{B}_2 = \hat{n} \cdot \mathbf{B}_1$$
$$\hat{n} \times \mathbf{E}_2 = \hat{n} \times \mathbf{E}_1$$
$$\hat{n} \times \mathbf{H}_2 = \hat{n} \times \mathbf{H}_1.$$

Hence we can make the following observations:

1. Normal components of $\mathbf{D}$ and $\mathbf{B}$ are continuous across a dielectric interface

2. Tangential components of $\mathbf{E}$, $\mathbf{H}$ are continuous across a dielectric surface

Polycrystalline ice

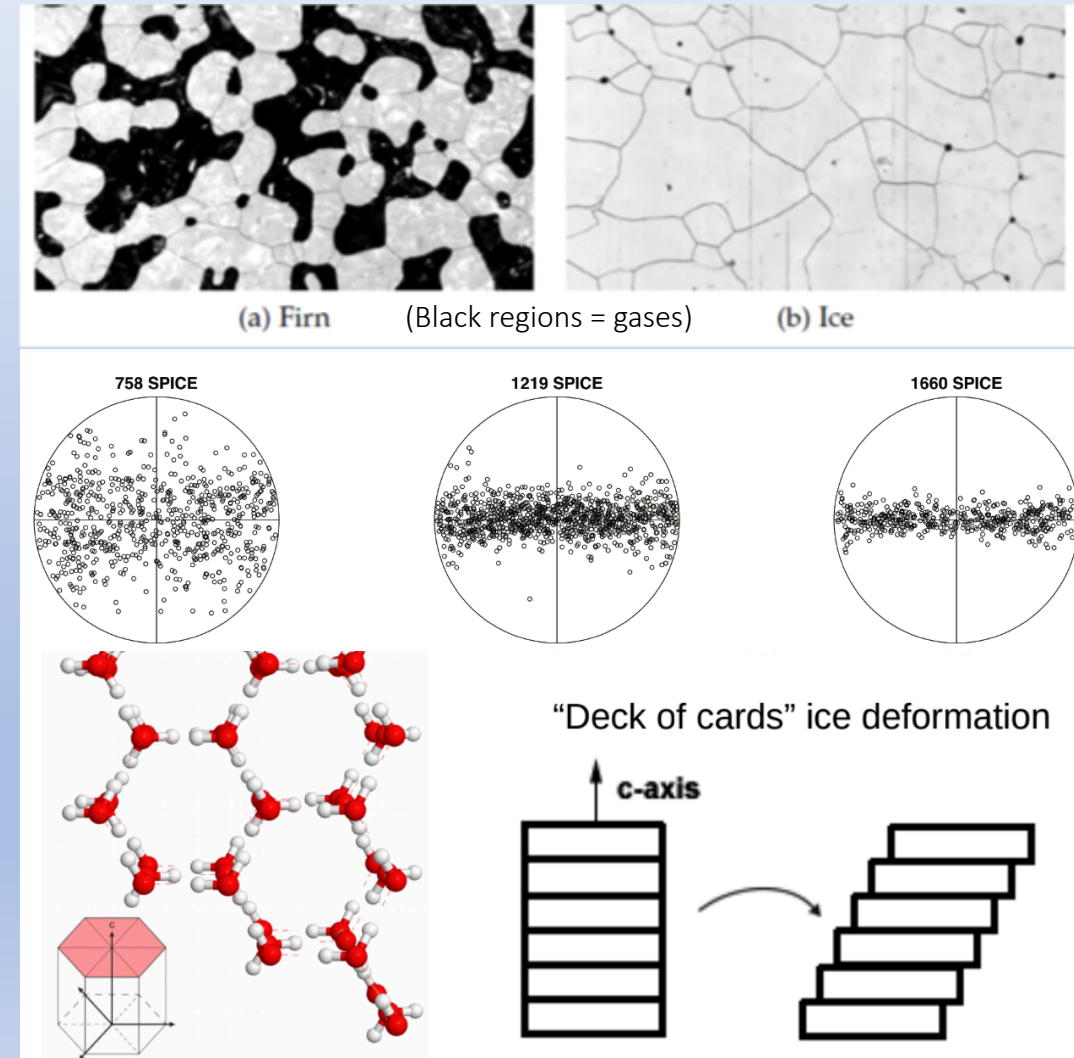A solid block of ice contains monocrystals (grains)

Grains grow independently and the surfaces where they meet form grain 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-mm² to thousands of mm² with aspect ratios between 1 and 1.8 → elongated

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

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

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

758 SPICE   1219 SPICE   1660 SPICE

"Deck of cards" ice deformation

c-axis

Simulation setup

Boundary surface chosen randomly from parameterized elongated crystal distribution

The optical axis of media is chosen randomly from the girdle (or other) fabric distribution

If the photon is reflected the current medium axis is unchanged

Outgoing photon is chosen at random weighting choices with normal component of Poynting vectors
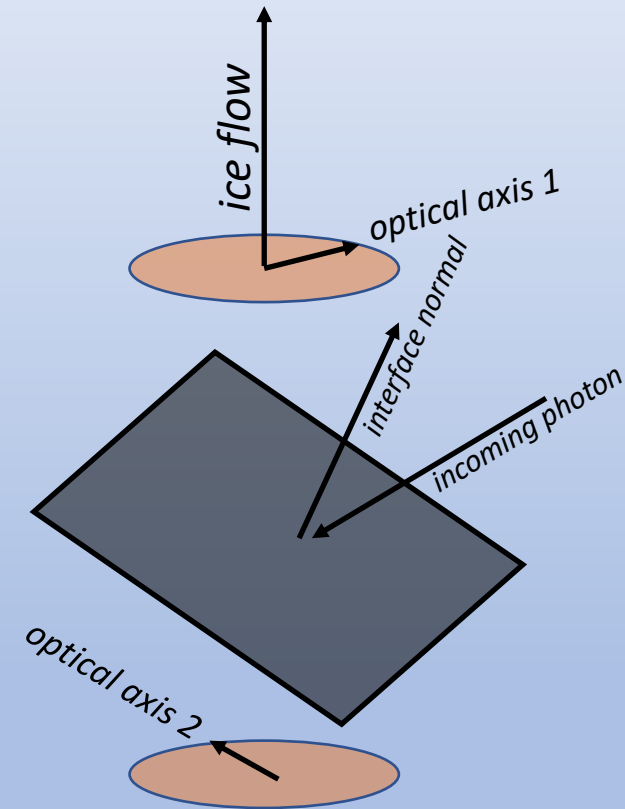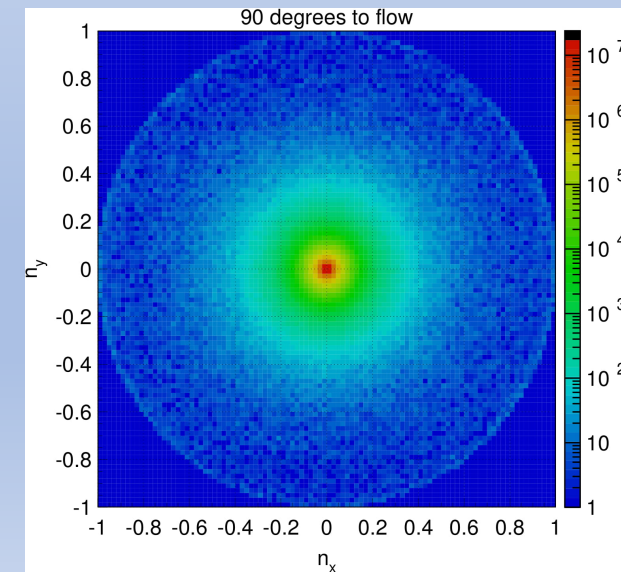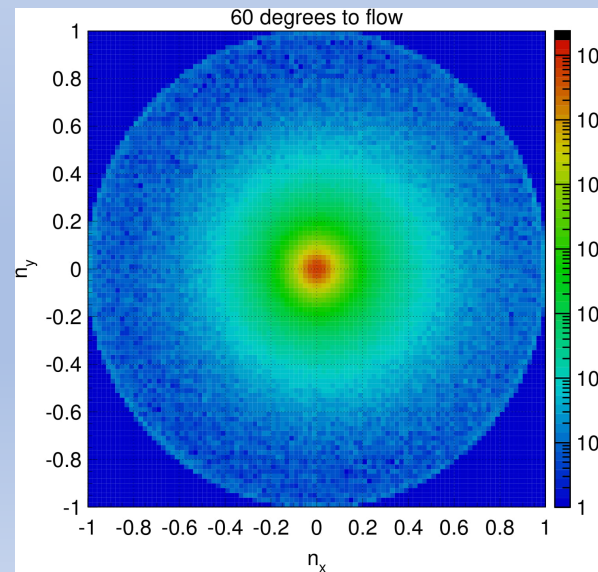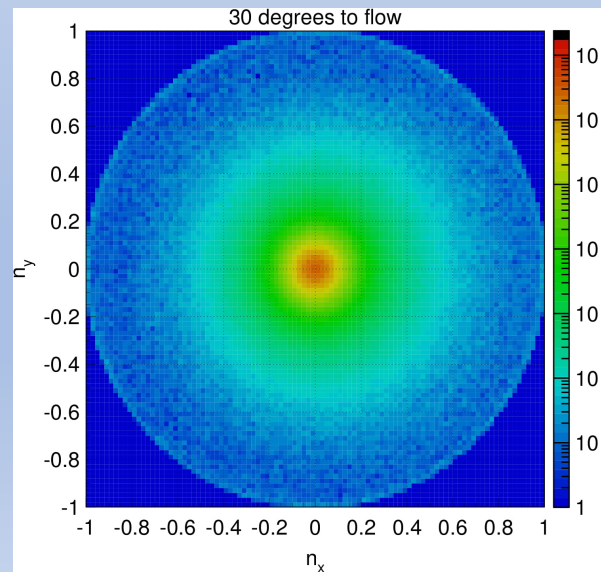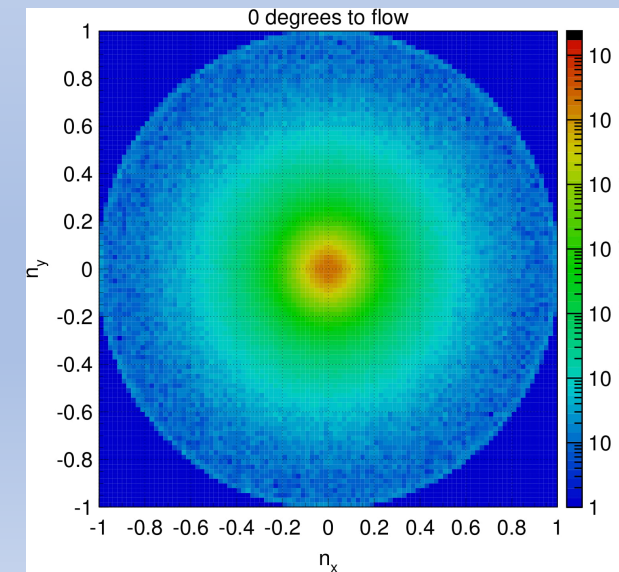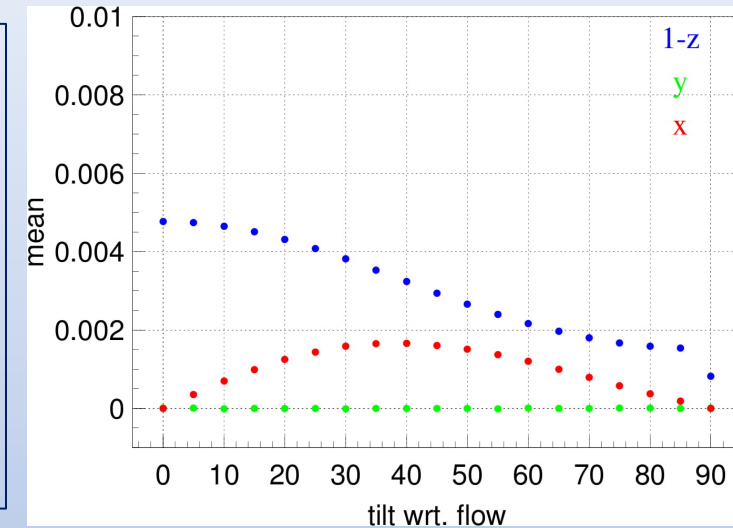
Birefringence Monte Carlo
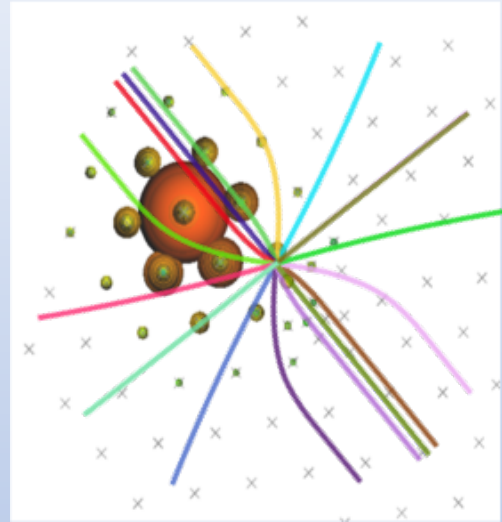
Running MC simulation on many photons in ice with girdle fabric shows two effects:

Diffusion is largest on flow axis and smallest orthogonal to it

Photons on average get deflected towards the flow axis

→ photons effectively fly a curve towards the flow axis

Summary and outlook

IceCube observes an anisotropic propagation effect aligned with the ice flow

Modeling through absorption or scattering on impurities appears to be insufficient

The current mismatch is a major source of uncertainties in the description of IceCube ice

Diffusion in birefringent polycrystals with preferential c-axis distribution yields average photon deflection and effective scattering that is intrinsic to ice

Simulation tool at crystal level and some preliminary parametrizations have been developed

Fitting of the effect with this new hypothesis is ongoing