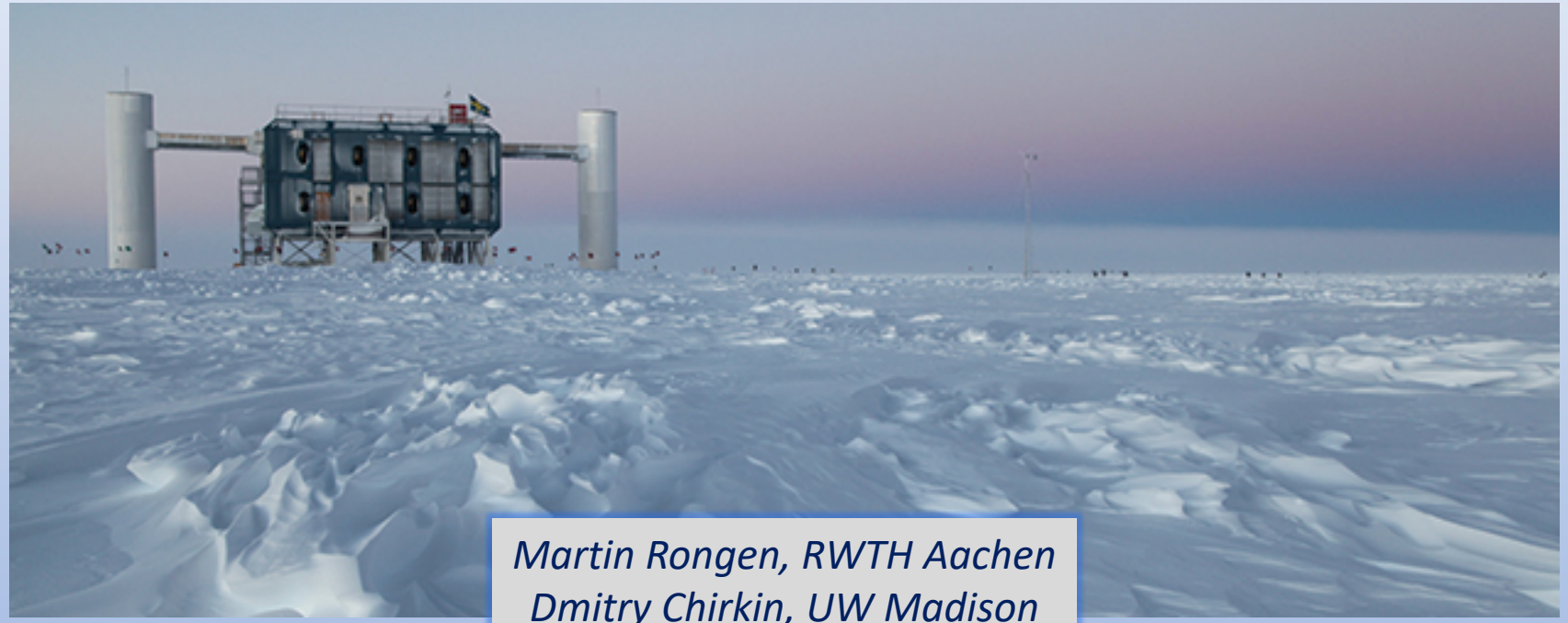
# Light diffusion in birefringent polycrystals and the IceCube ice anisotropy



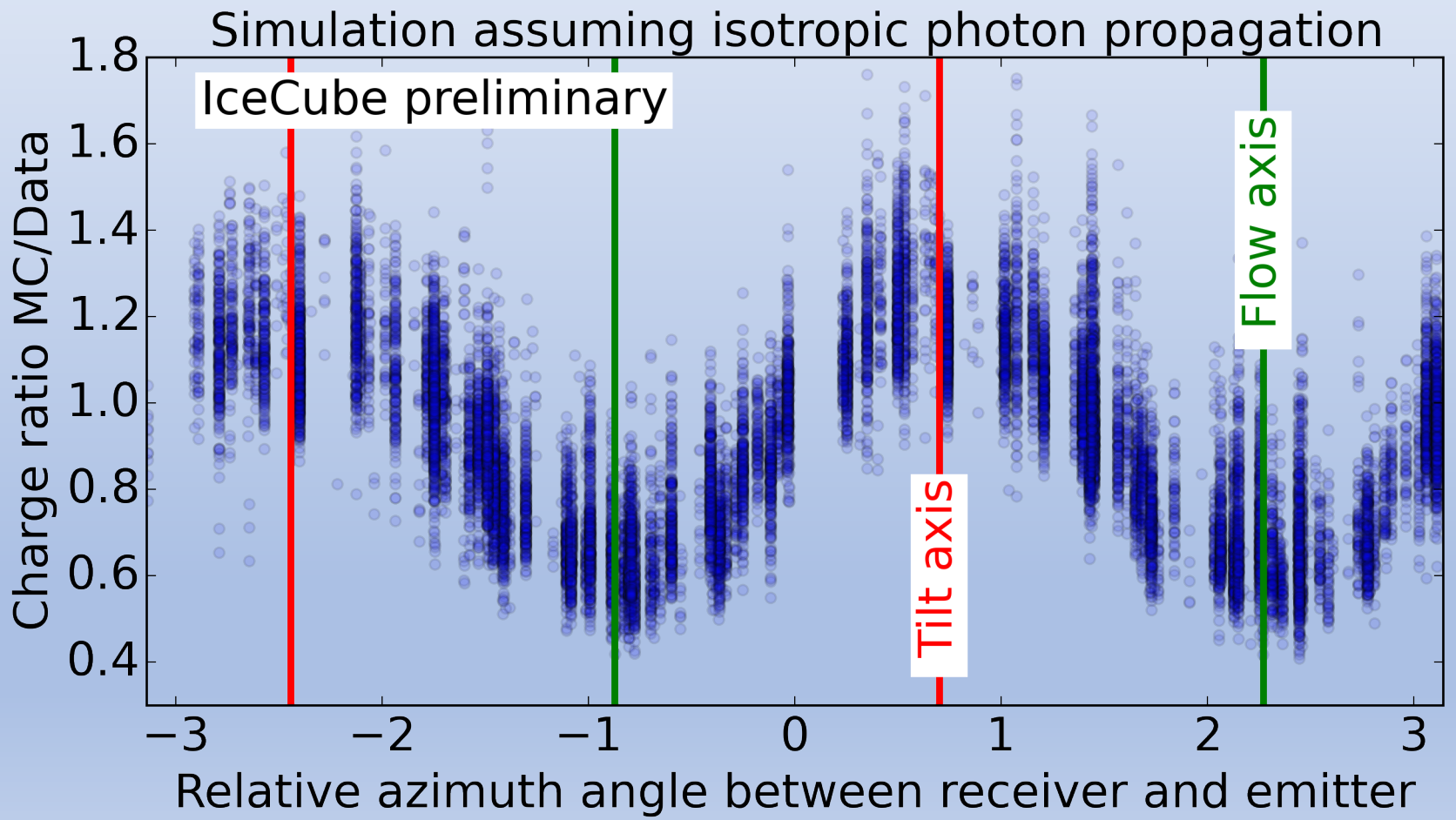
*Martin Rongen, RWTH Aachen*
*Dmitry Chirkin, UW Madison*

III. Physikalisches Institut | RWTH AACHEN UNIVERSITY

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

IceCube
South Pole Neutrino Observatory

# The ice anisotropy effect

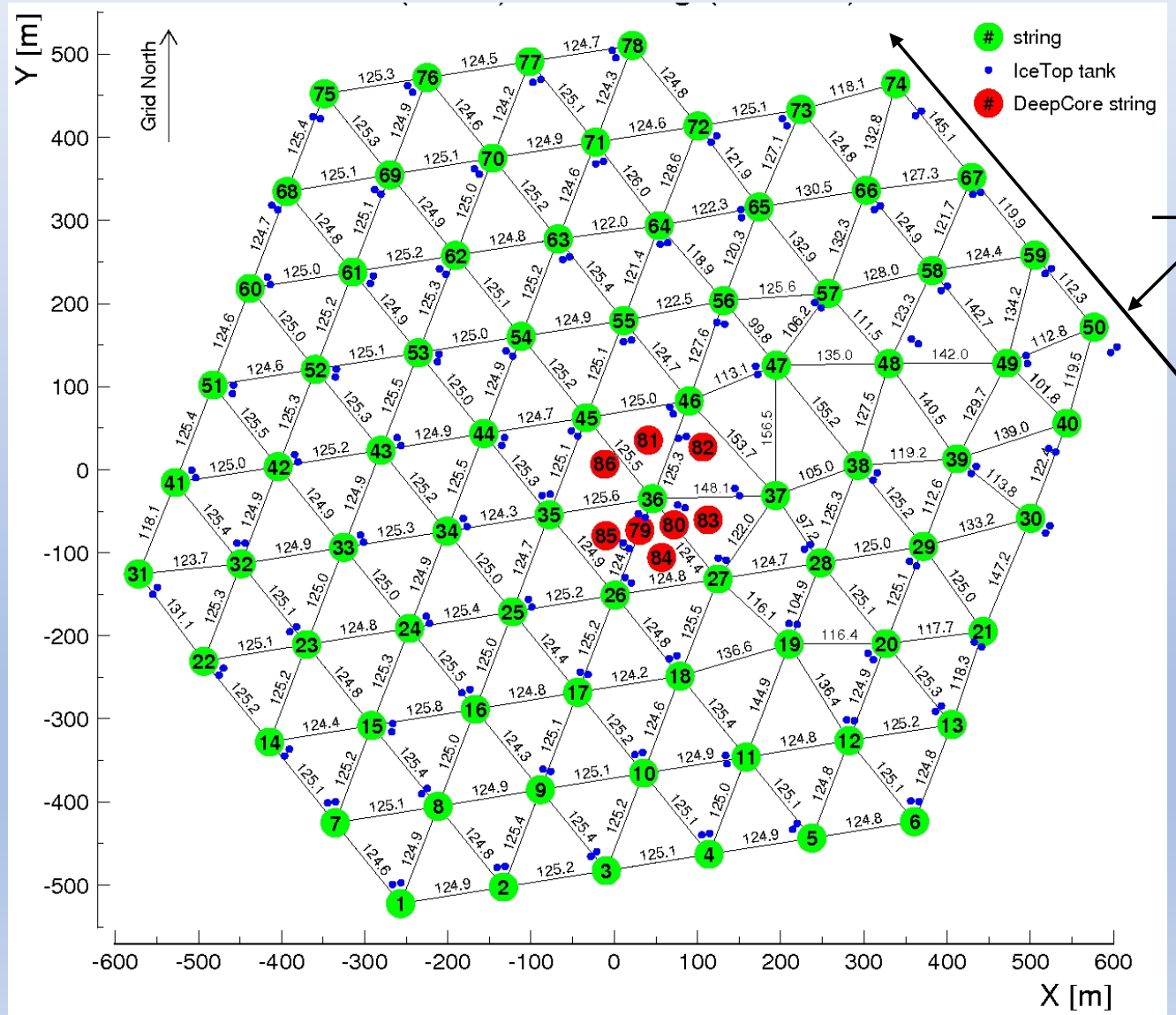



Observed integral charge and light curve depend on orientation of receiver DOM with respect to emitter DOM

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

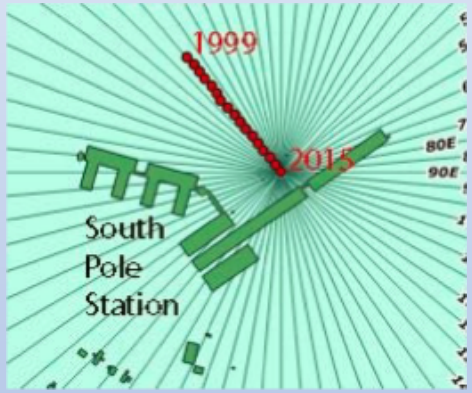
# Glacial ice flow, ice layer tilt at the South Pole



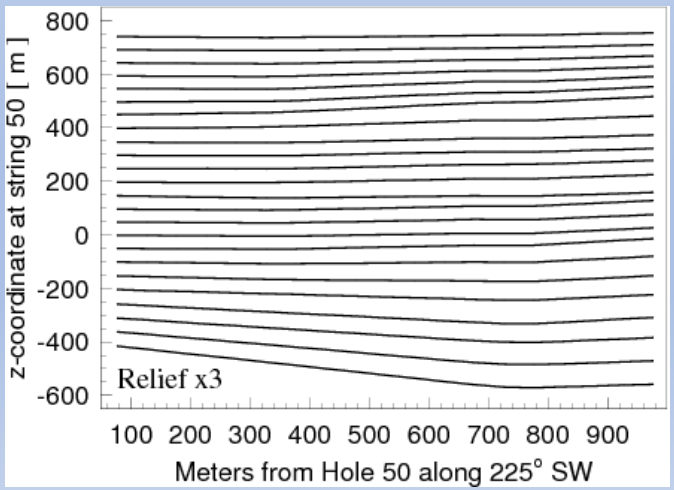

N
E

Ice Layer tilt direction
225° SW

Ice flow direction
41° NW




~8% less scattering
41° NW



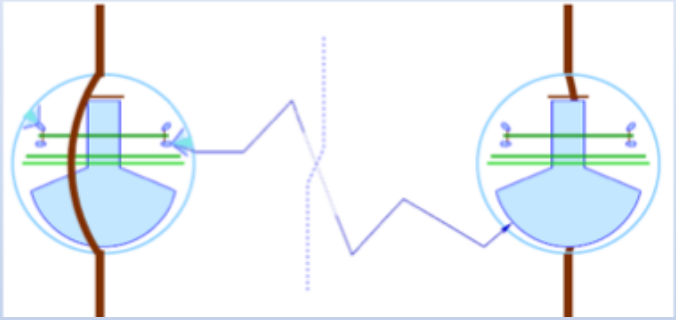
# Models of optical ice anisotropy in IceCube

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

Introduced depth-dependence (2017)

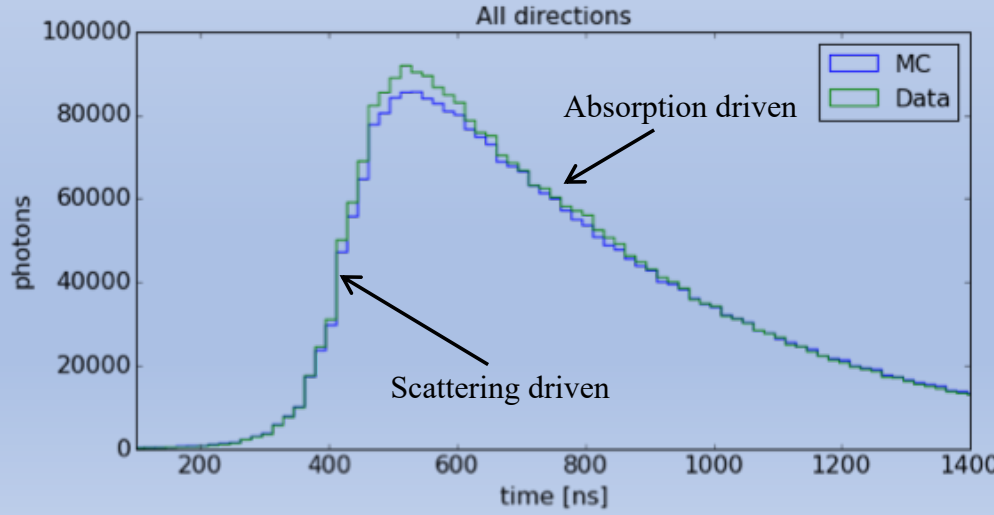
Discrepancies between data and simulation remain

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).



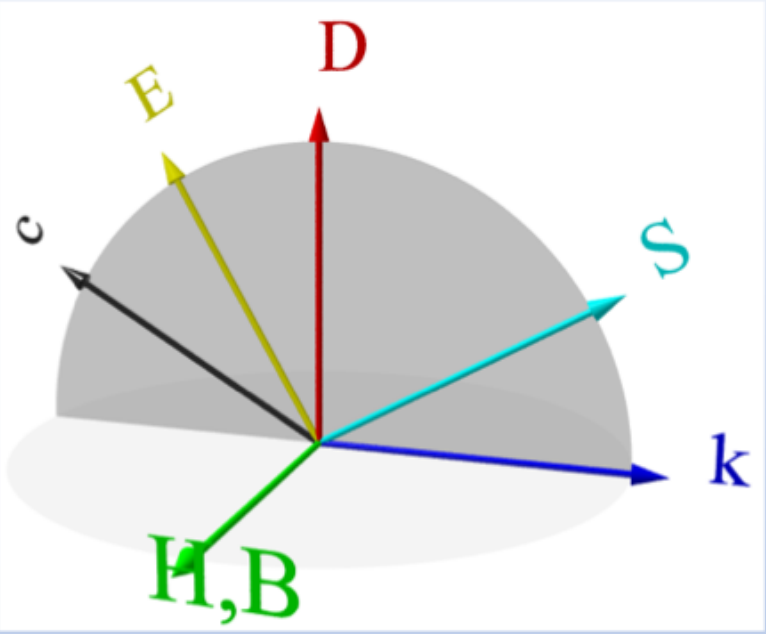
# Birefringence

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

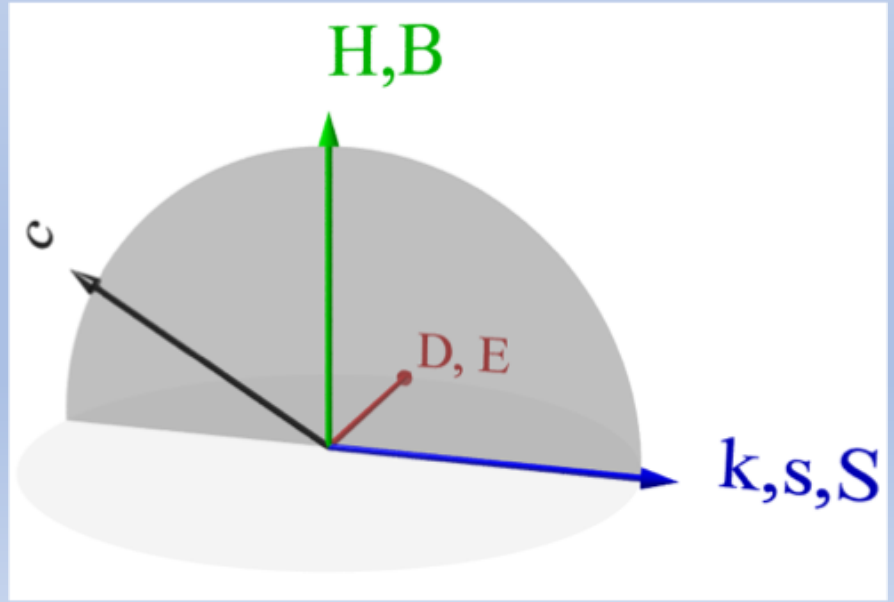
The refractive index of the extraordinary ray is direction dependent

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




| wavelength $\lambda$ (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



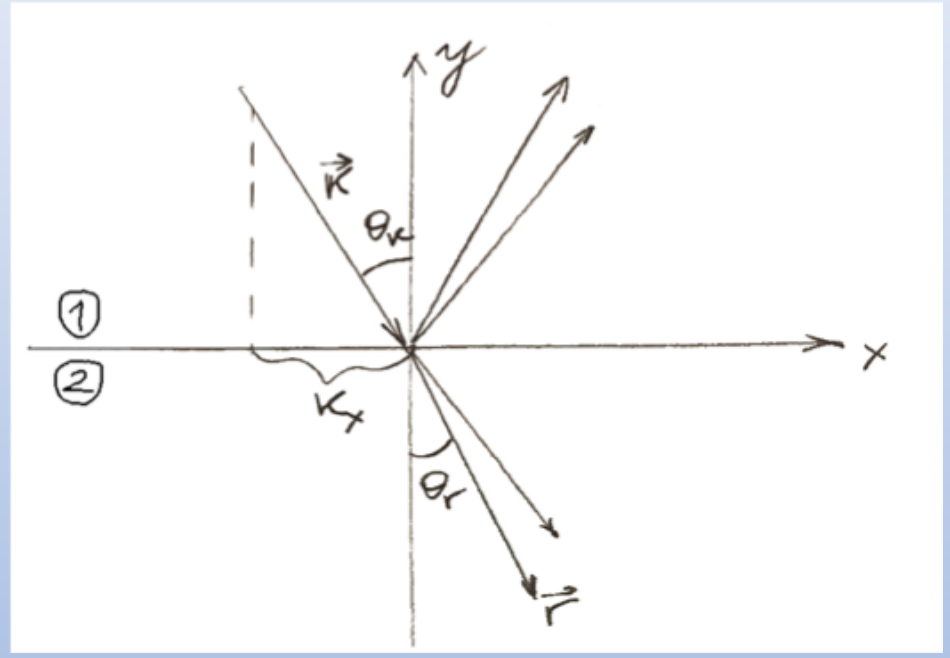
# Birefringence

- 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)




$$\begin{aligned}\hat{n}\cdot\boldsymbol{D}_2 &= \hat{n}\cdot\boldsymbol{D}_1\\ \hat{n}\cdot\boldsymbol{B}_2 &= \hat{n}\cdot\boldsymbol{B}_1\\ \hat{n}\times\boldsymbol{E}_2 &= \hat{n}\times\boldsymbol{E}_1\\ \hat{n}\times\boldsymbol{H}_2 &= \hat{n}\times\boldsymbol{H}_1.\end{aligned}$$

Hence we can make the following observations:

1. Normal components of $\boldsymbol{D}$ and $\boldsymbol{B}$ are continuous across a dielectric interface
2. Tangential components of $\boldsymbol{E}$, $\boldsymbol{H}$ are continuous across a dielectric surface

# Polycrystalline ice

A solid block of ice contains monocrystals (grains)

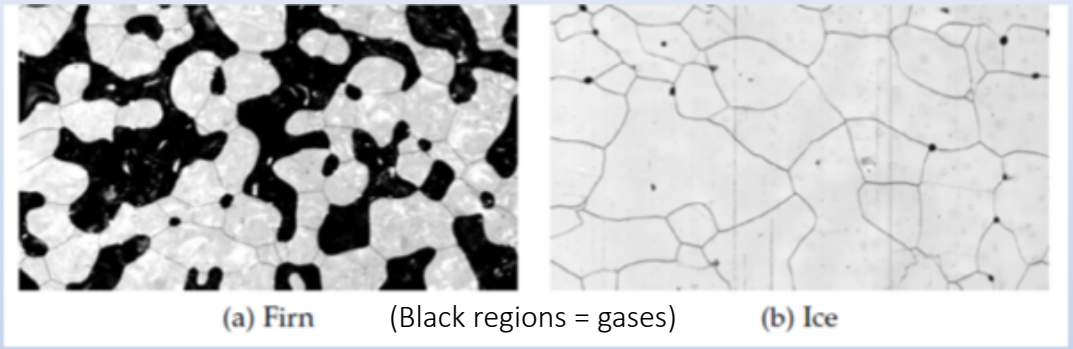
Grains grow independently and the surfaces where they meet form grain boundaries

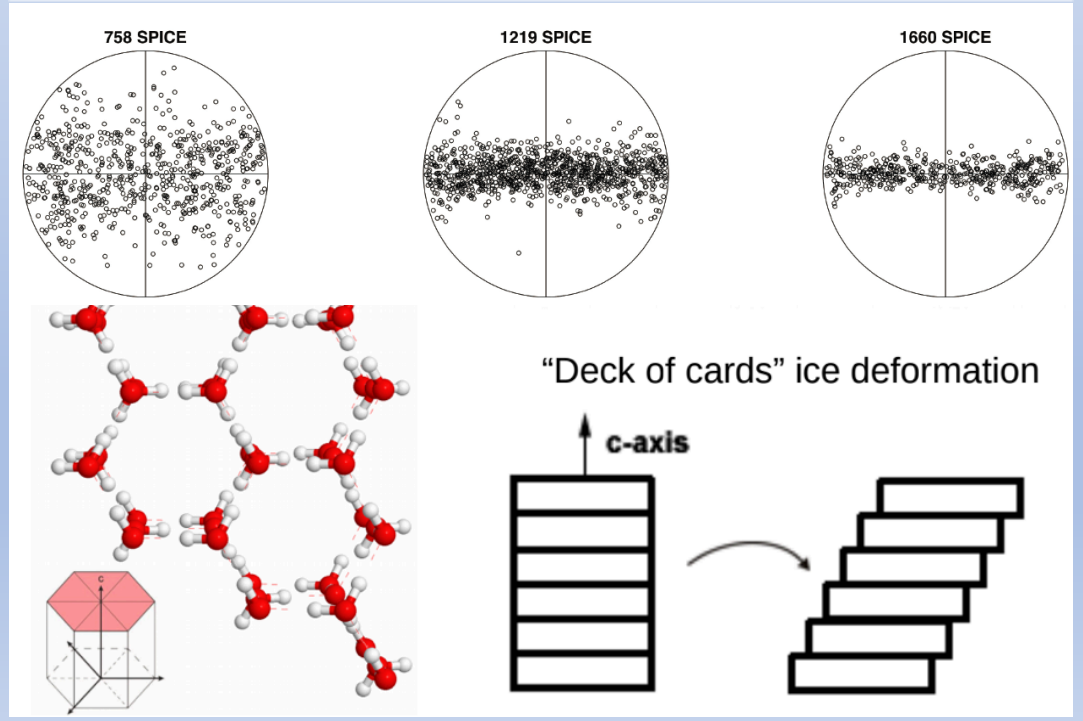
As the surface of an ice core sample sublimates the grain boundaries leave grooves on the surface that can be imaged

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



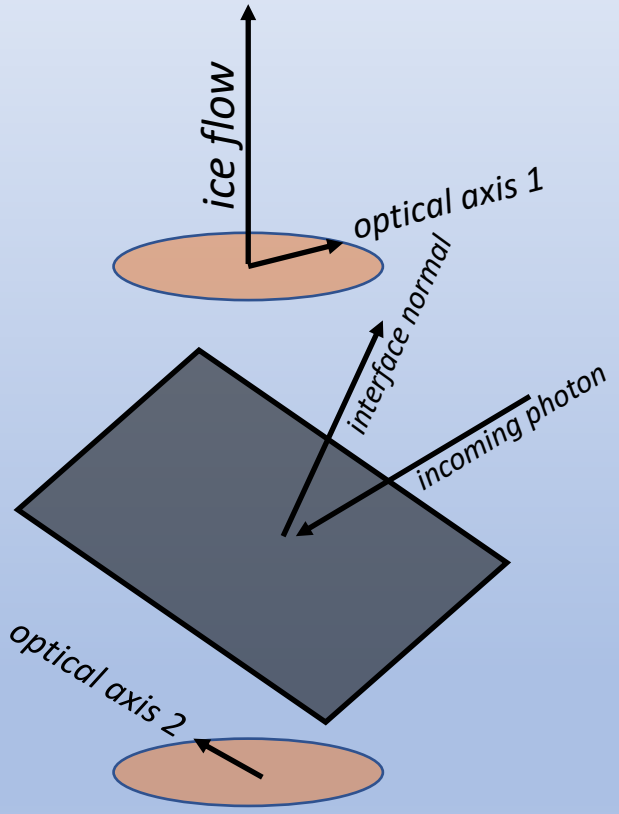
# Simulation setup

Boundary surface chosen randomly from parameterized elongated crystal distribution

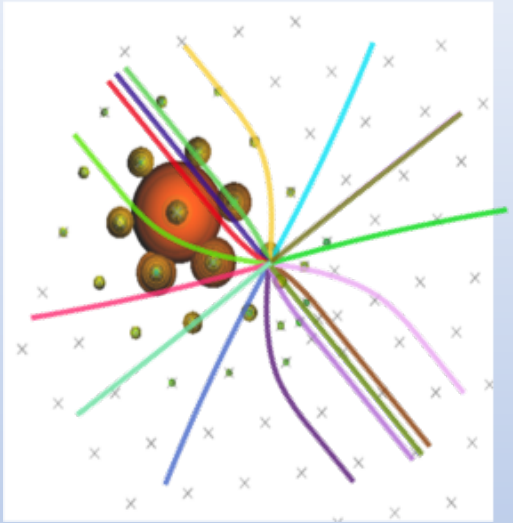
The optical axis of media is chosen randomly from the girdle (or other) fabric distribution

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

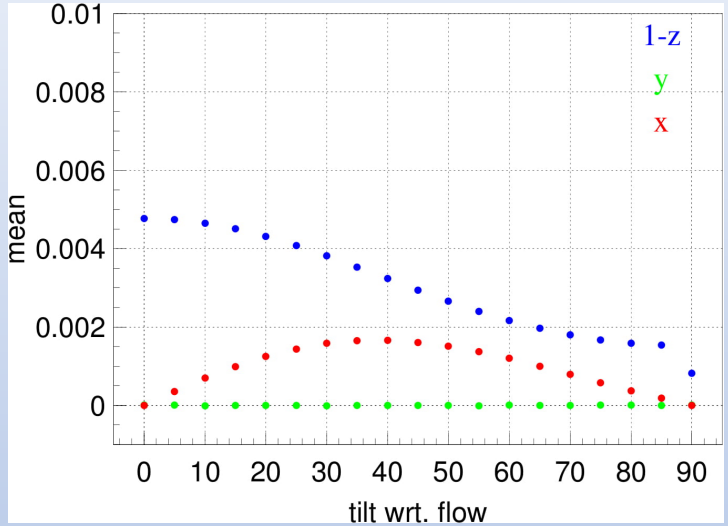


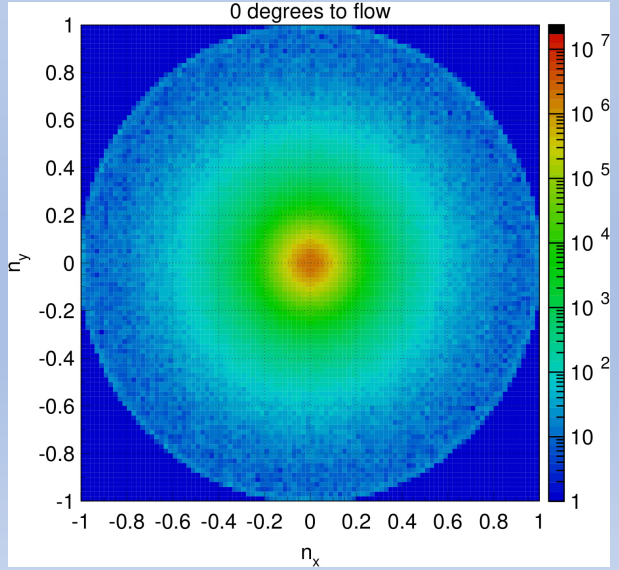
Running MC simulation on many photons in ice with girdle fabric shows two effects:

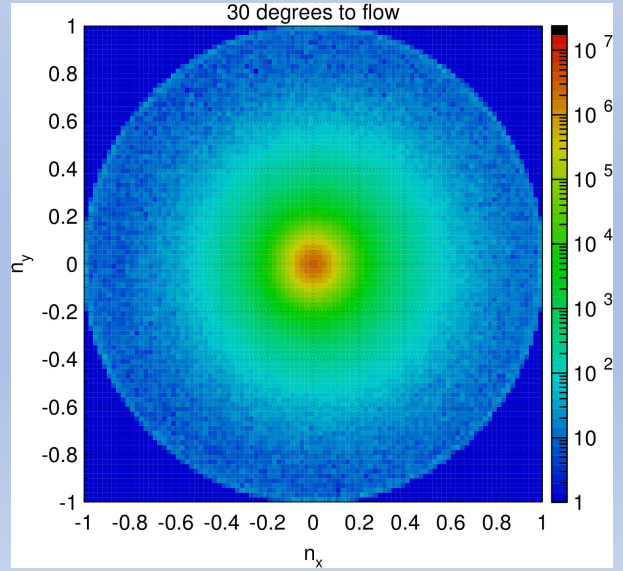
Diffusion is largest on flow axis and smallest orthogonal to it

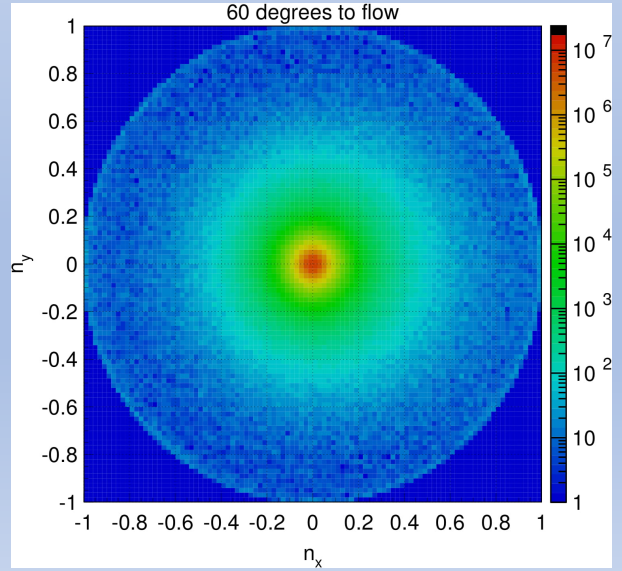
Photons on average get deflected towards the flow axis

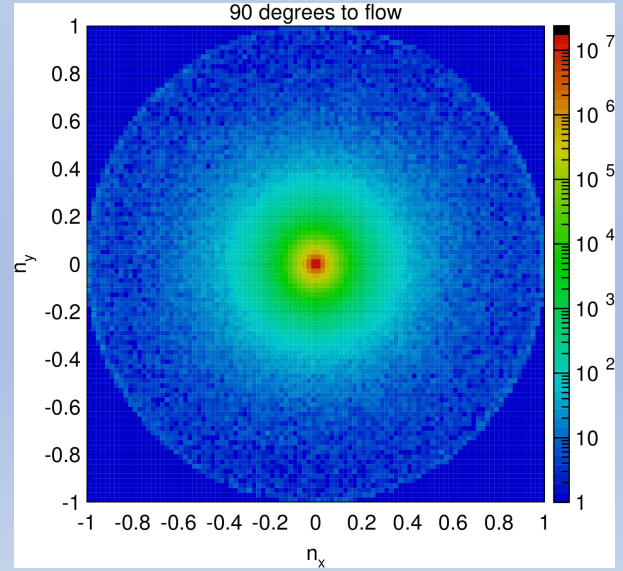
→ photons effectively fly a curve towards the flow axis



# 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