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

ICRC 2021 presentation:
https://docushare.icecube.wisc.edu/dsweb/Get/Document-89231/ICRCiceAnisotropy.pdf

The following are relevant slides from my SCAR 2022 presentation

Links from Francis:
https://icecube.wisc.edu/news/research/2022/10/newly-discovered-optical-effect-allows-icecube-to-deduce-ice-crystal-properties/
https://phys.org/news/2022-10-newly-optical-effect-icecube-neutrino.html

Birefringence paper:
https://tc.copernicus.org/preprints/tc-2022-174/tc-2022-174.pdf

Birefringence slides for Vladimir

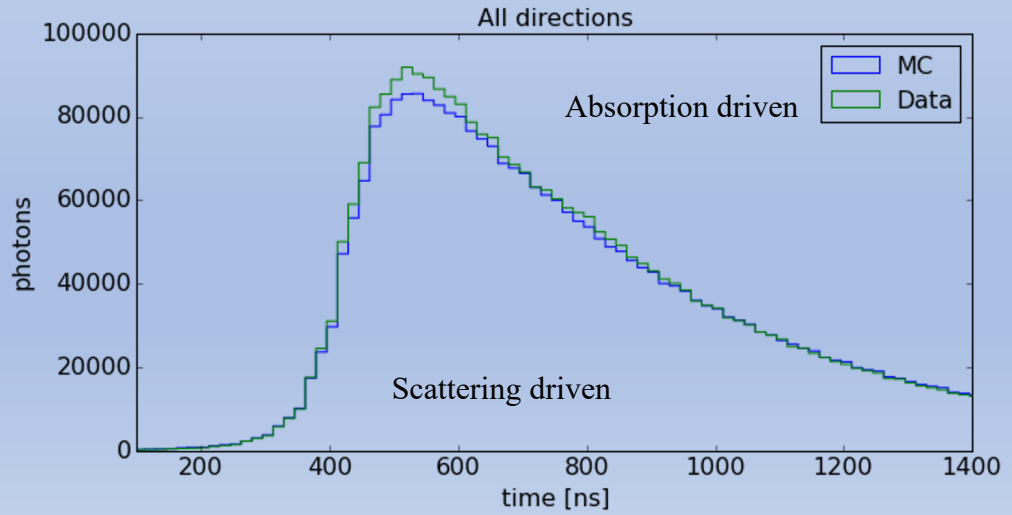
Models of optical ice anisotropy in IceCube

1. Scattering (mainly): direction dependent scattering function (ICRC 2013)
2. Absorption (mainly): direction dependent absorption (studied in 2018)

Introduced depth-dependence (2017)

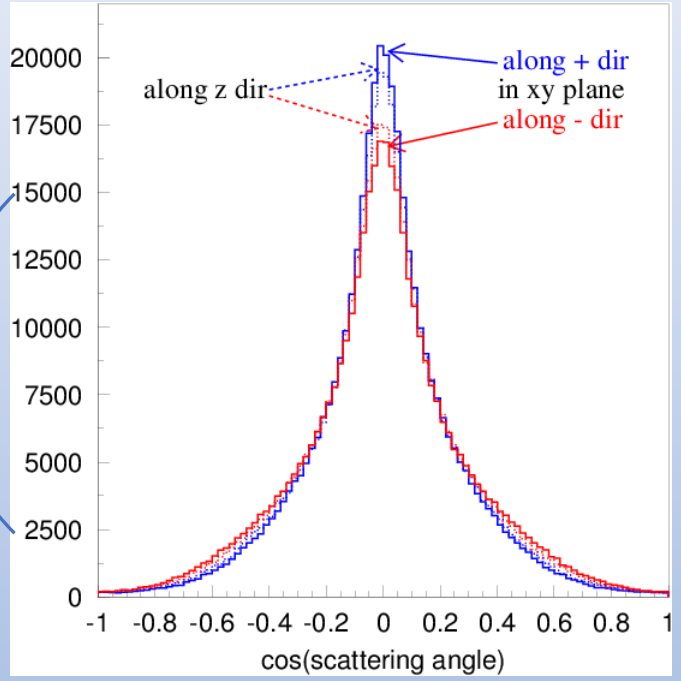
Discrepancies between data and simulation remain

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



scattering-based

SPICE Lea, 3.2.x

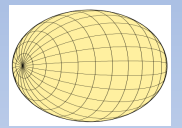


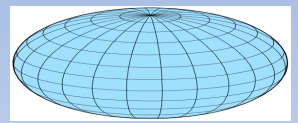
absorption-based

SPICE EMRM

prolate

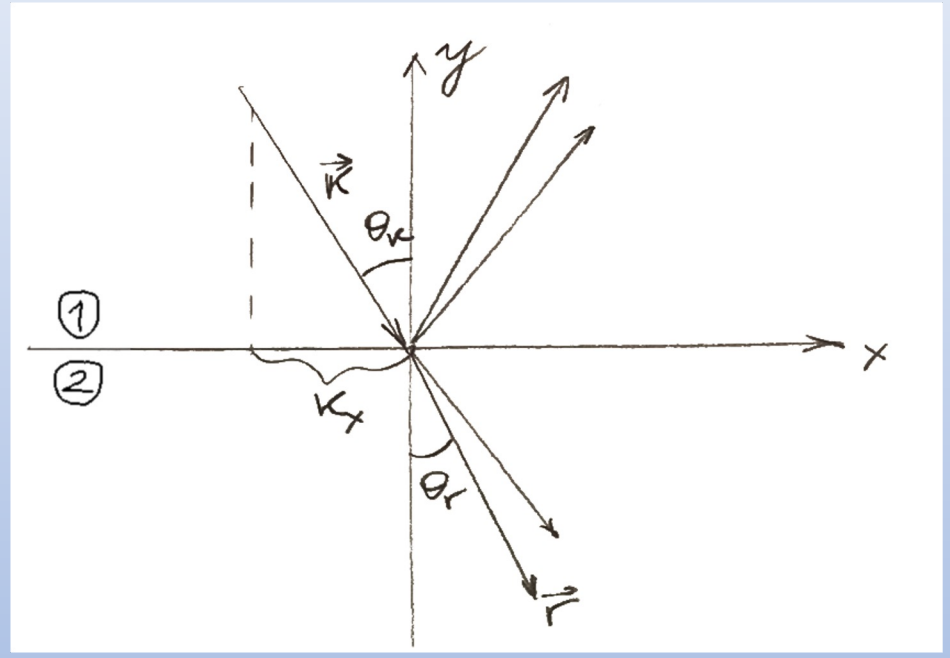
oblate





Birefringence

- Ice is a birefringent material with n_e-n_o=0.0015. This tiny difference builds to a macroscopic effect due to 1000s of ice crystal boundaries crossed per meter of traveled distance
- 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)



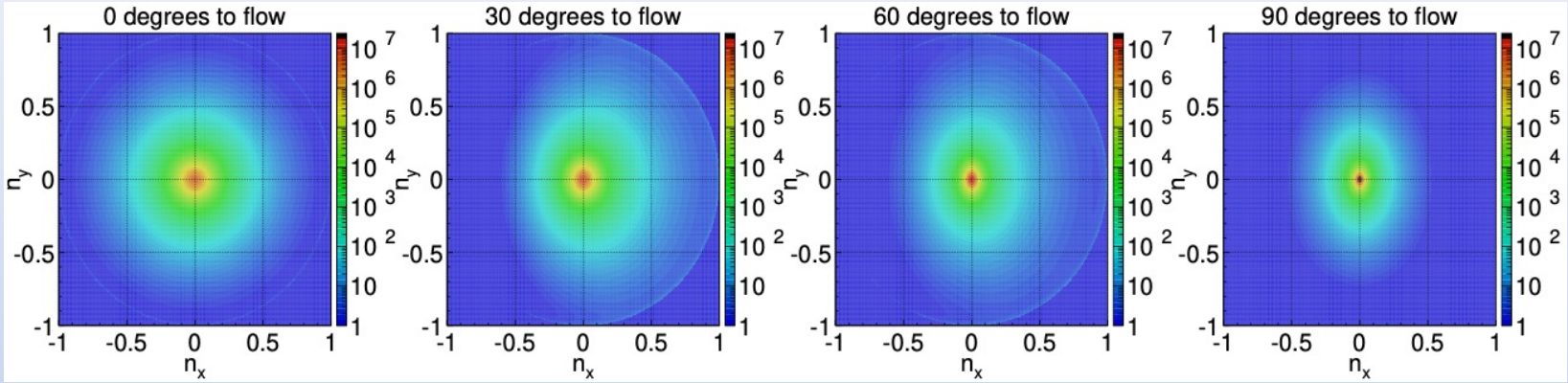
$$\begin{aligned}
\hat{n} \cdot \boldsymbol{D}_2 &= \hat{n} \cdot \boldsymbol{D}_1 \\
\hat{n} \cdot \boldsymbol{B}_2 &= \hat{n} \cdot \boldsymbol{B}_1 \\
\hat{n} \times \boldsymbol{E}_2 &= \hat{n} \times \boldsymbol{E}_1 \\
\hat{n} \times \boldsymbol{H}_2 &= \hat{n} \times \boldsymbol{H}_1.
\end{aligned}$$

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

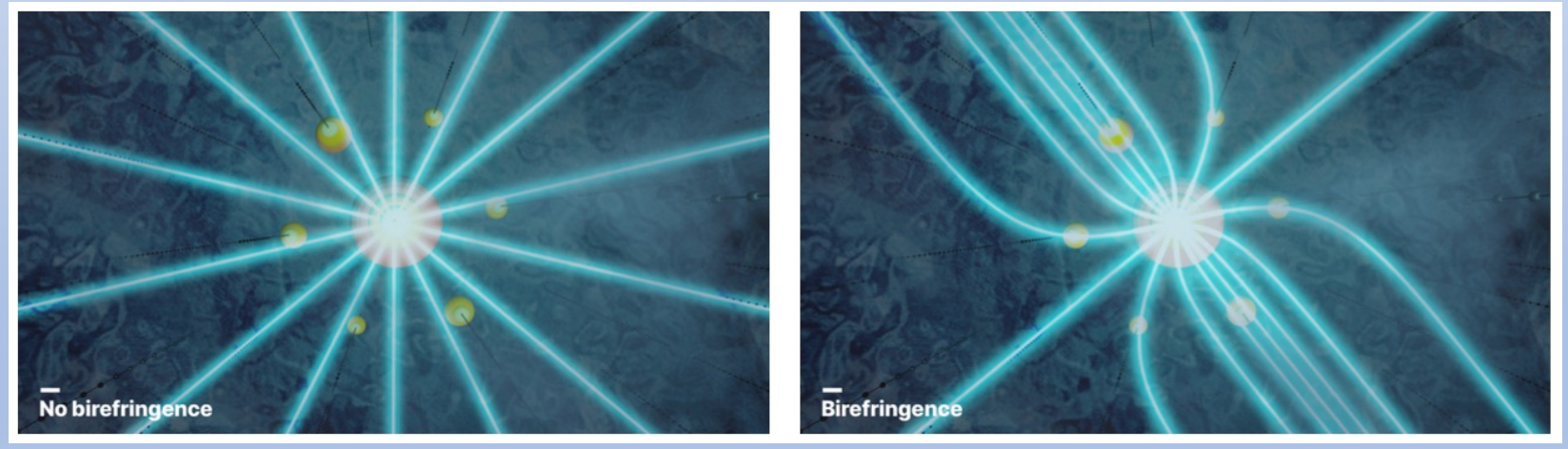
Scattering patterns birefringent ice

along flow



orthogonal to flow

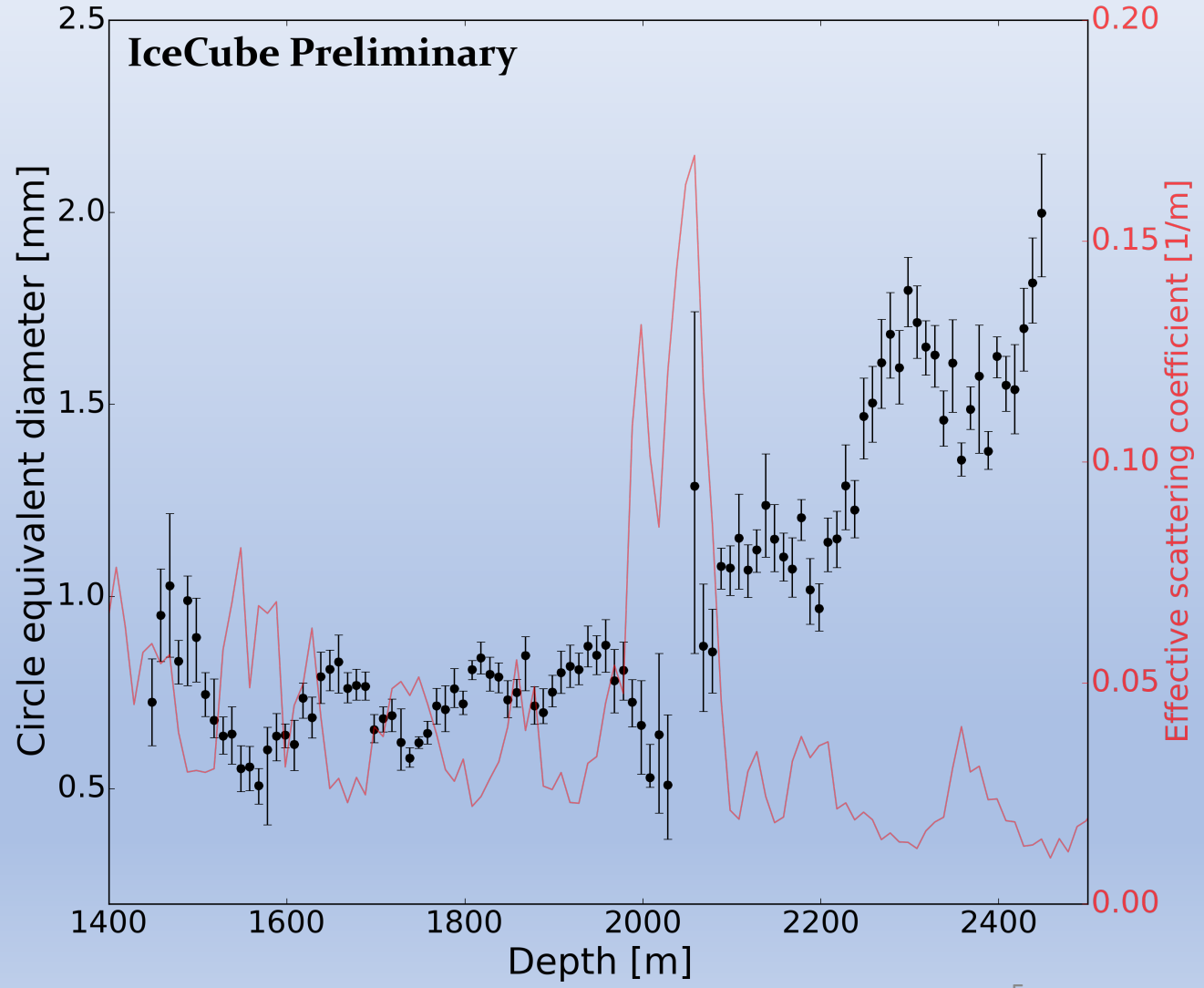
diffusion patterns after photon propagation through 1000 crystals (roughly equivalent to 1 m)



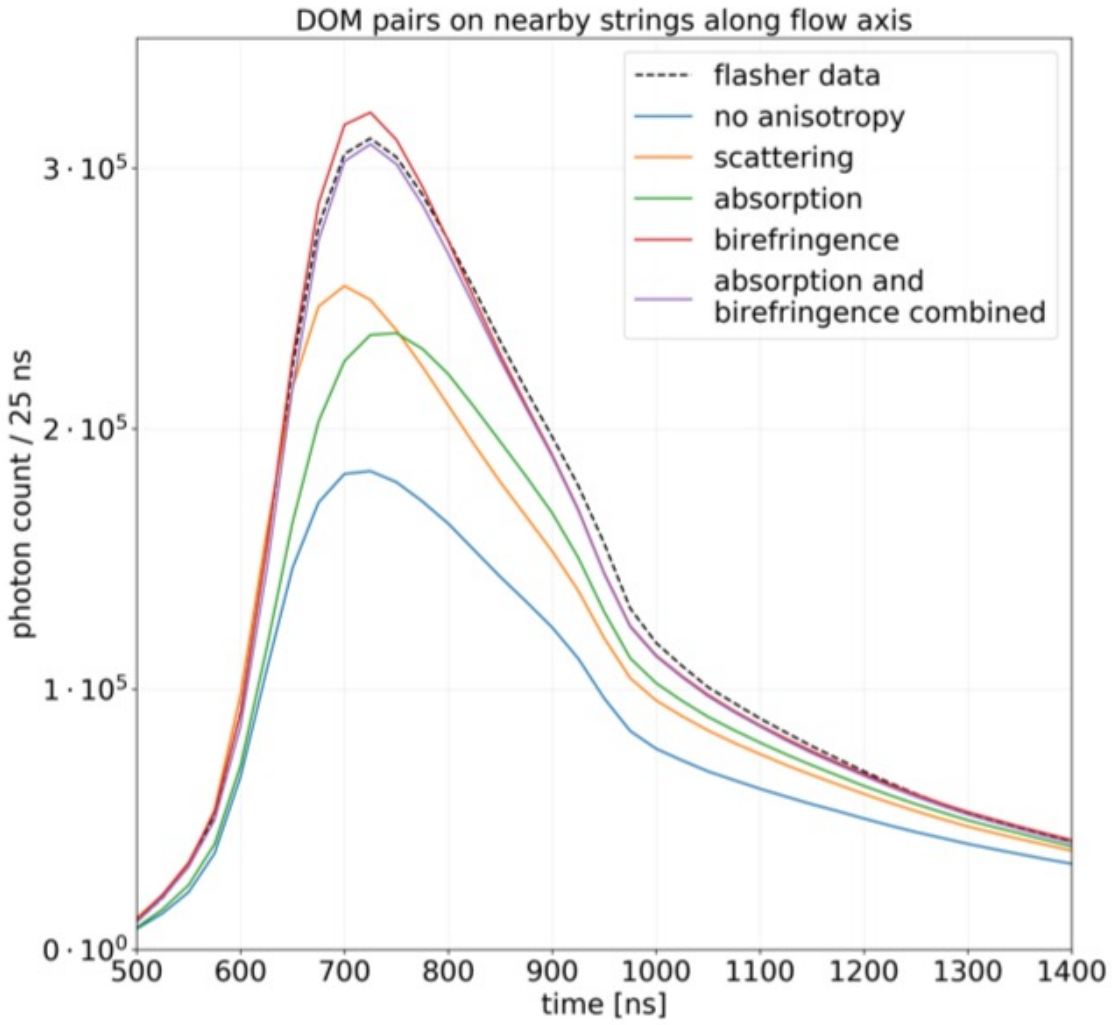
Artist illustration visualizing the deflection concept. Without birefringence light streams out radially from an isotropic light source. With birefringence rays get slowly deflected towards the flow axis. (The effects of scattering and diffusion are not shown. The hexagonal pattern of the IceCube array around the light source is shown

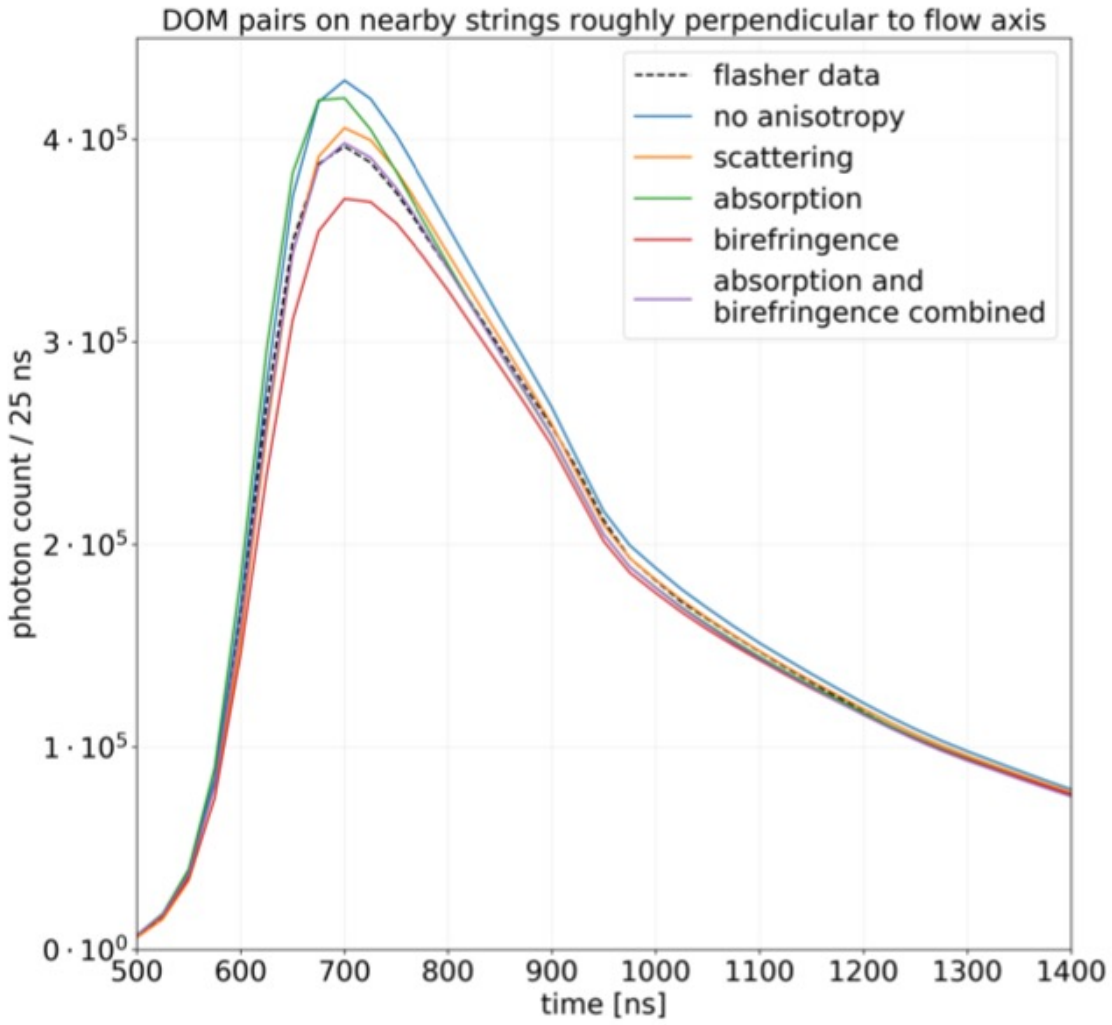
Ice crystal grain size vs. depth

- 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



Average photon arrival time distributions for DOM pairs along and perpendicular to the ice flow





Our chosen model of ice anisotropy (birefringence with absorption) yields an almost perfect description of the average arrival time distribution simultaneously both along and perpendicular to ice flow

Ice anisotropy with Pencil Beam

- IceCube upgrade to be deployed in 2025/26
- Will contain new calibration devices including several pencil beam devices
- Laser-like beam can sweep over a range of directions, allowing to distinguish models of anisotropy and measure the scattering function directly.

