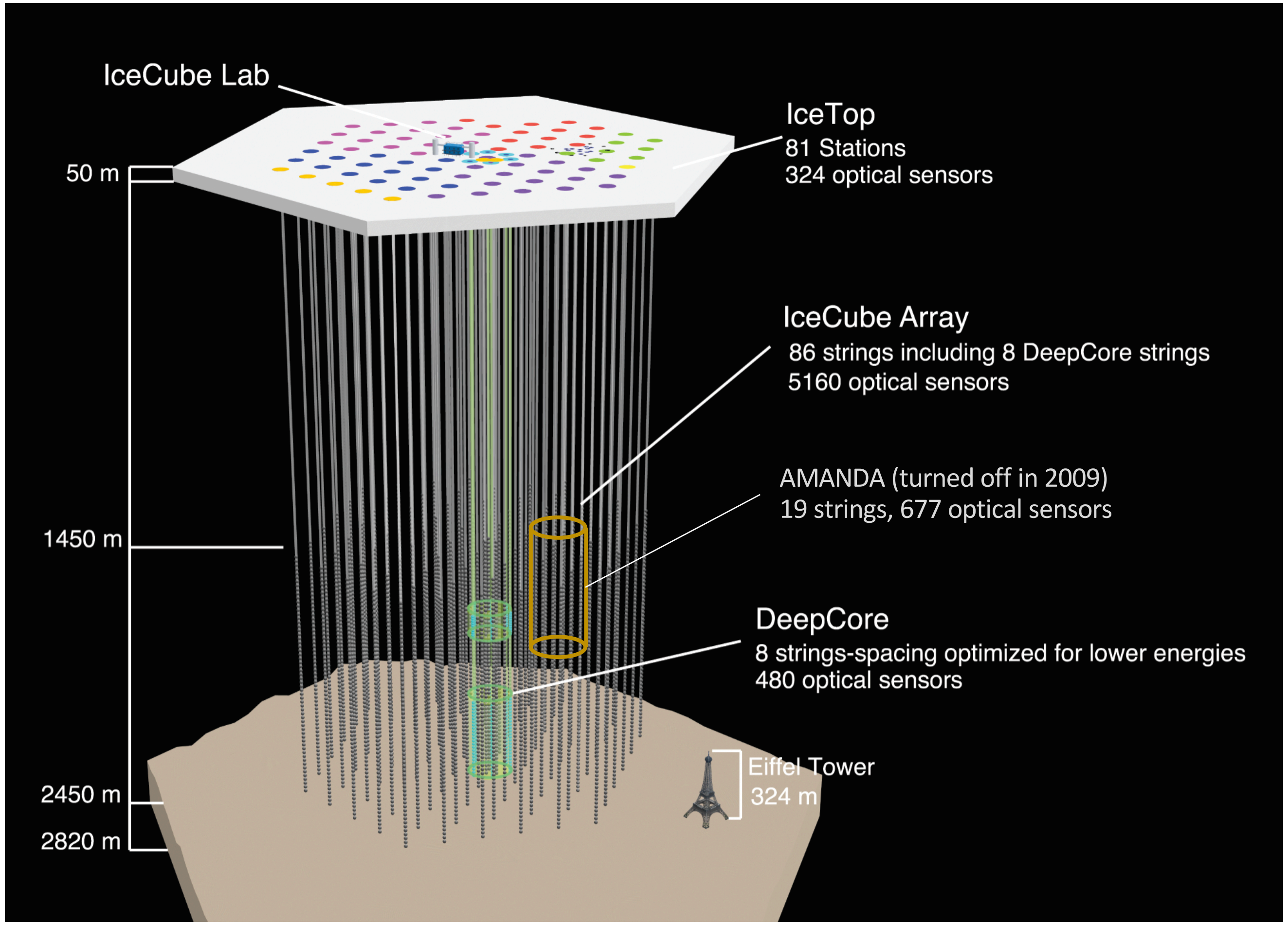
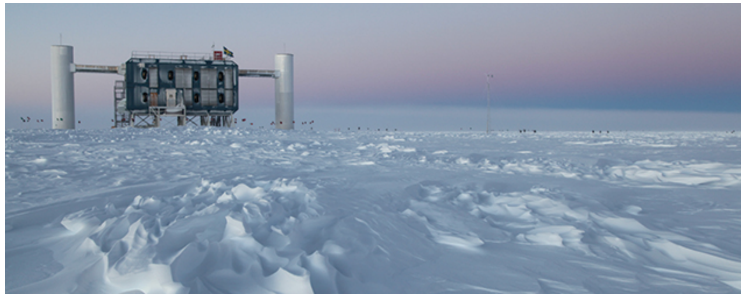
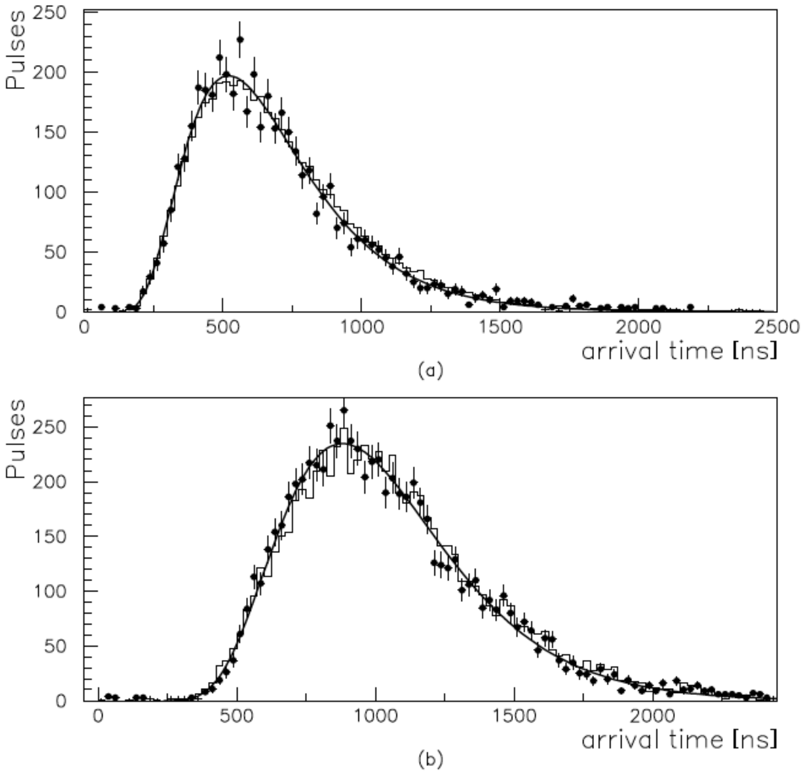
The IceCube optical ice model





Dmitry Chirkin, UW Madison
Martin Rongen, U. Mainz

AMANDA-A: scattering on air bubbles!

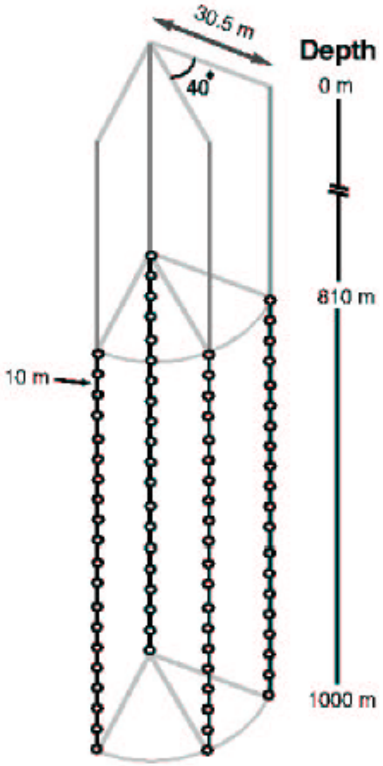


astro-ph/9412028 08 Dec 1994

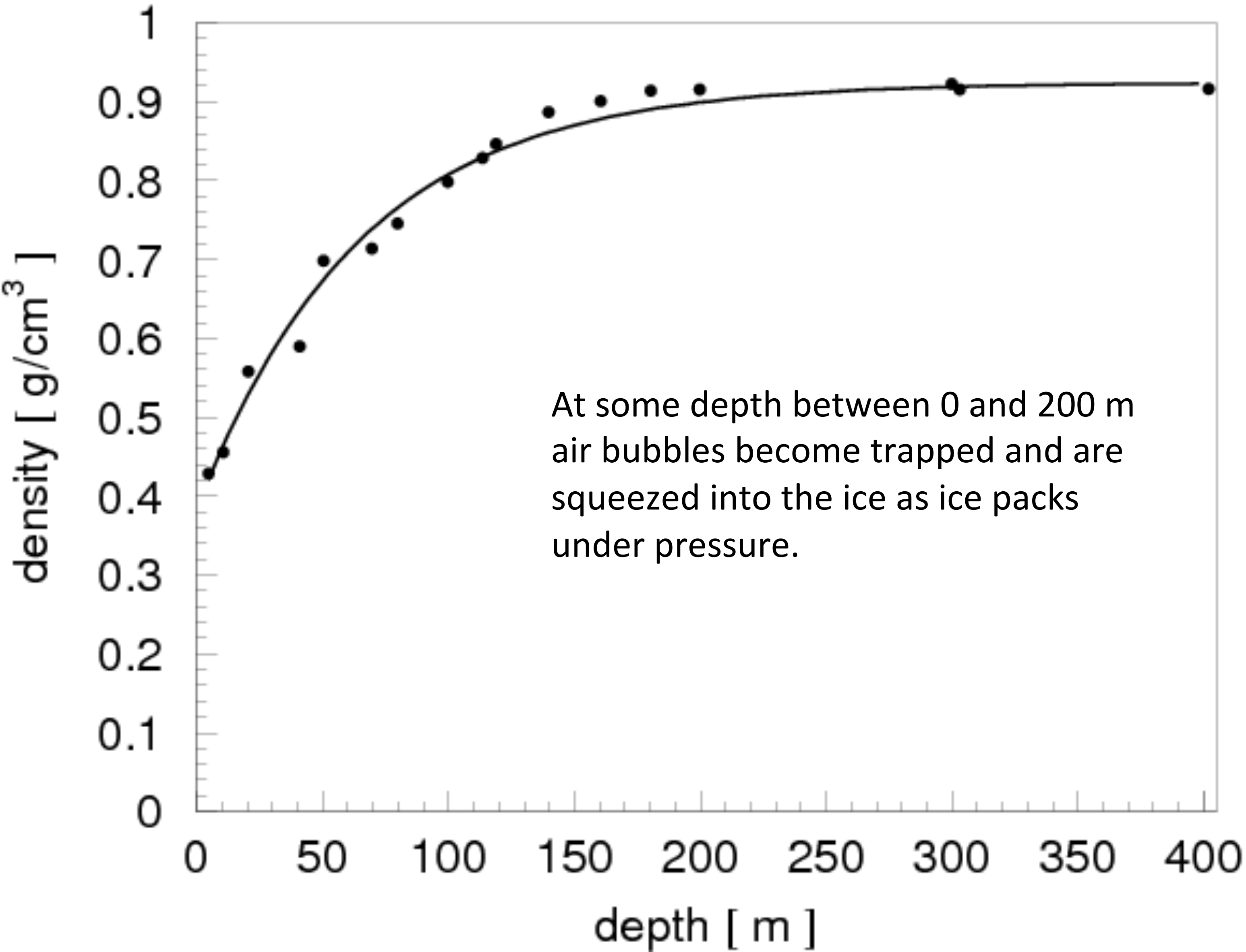
Optical Properties of the South Pole Ice
at Depths Between 0.8 and 1 km

P. Askebjer[*], S.W. Barwick[†], L. Bergström[*], A. Bouchta[*], S. Carius[‡], A. Coulthard[§], K. Engel[§], B. Erlandsson[*], A. Goobar[*], L. Gray[§], A. Hallgren[‡], F. Halzen[§], P.O. Hulth[*], J. Jacobsen[§], S. Johansson[*¶], V. Kandhadai[§], I. Liubarsky[§], D. Lowder[||], T. Miller[||**], P.C. Mock[†], R. Morse[§], R. Porrata[†], P.B. Price[||], A. Richards[||], H. Rubinstein[‡], E. Schneider[†], Q. Sun[*], S. Tilav[§], C. Walck[*] & G. Yodh[†]

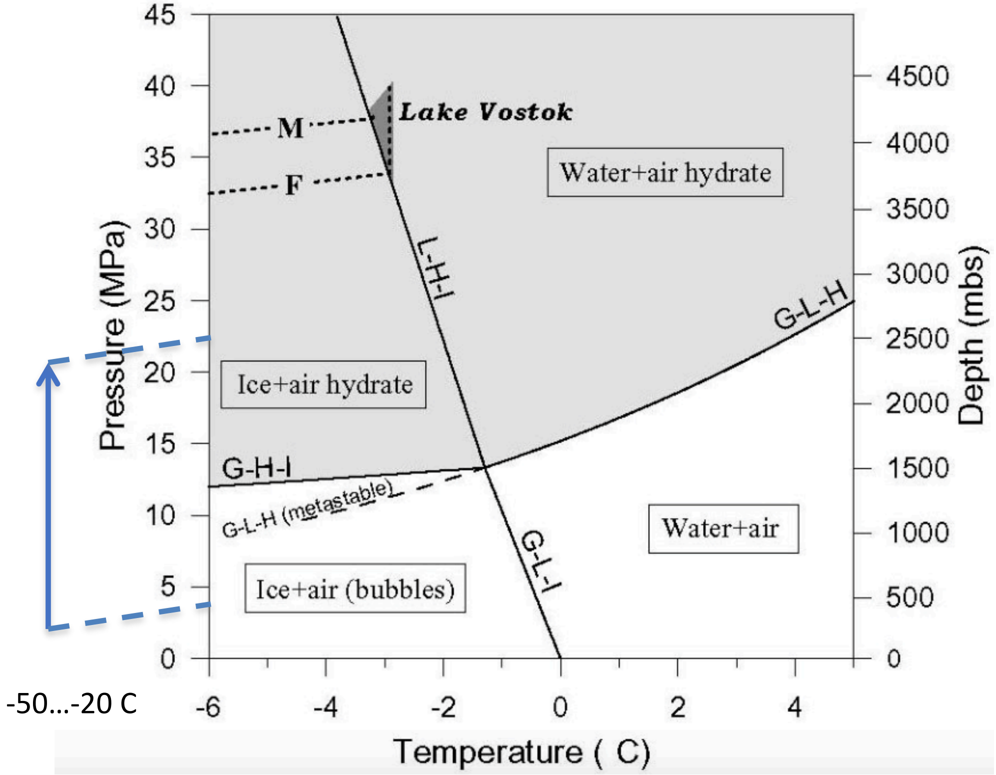
The optical properties of the ice at the geographical South Pole have been investigated at depths between 0.8 and 1 kilometers. The absorption and scattering lengths of visible light (~515 nm) have been measured *in situ* using the laser calibration setup of the AMANDA neutrino detector. The ice is intrinsically extremely transparent. The measured absorption length is 59 ± 3 meters, comparable with the quality of the ultra-pure water used in the IMB and Kamiokande proton-decay and neutrino experiments and more than two times longer than the best value reported for laboratory ice. Due to a residual density of air bubbles at these depths, the trajectories of photons in the medium are randomized. Assuming bubbles are smooth and spherical, the average distance between collisions at 1 km depth is about 25 cm. The measured inverse scattering length on bubbles decreases linearly with increasing depth in the volume of ice investigated.



Trapped air bubbles



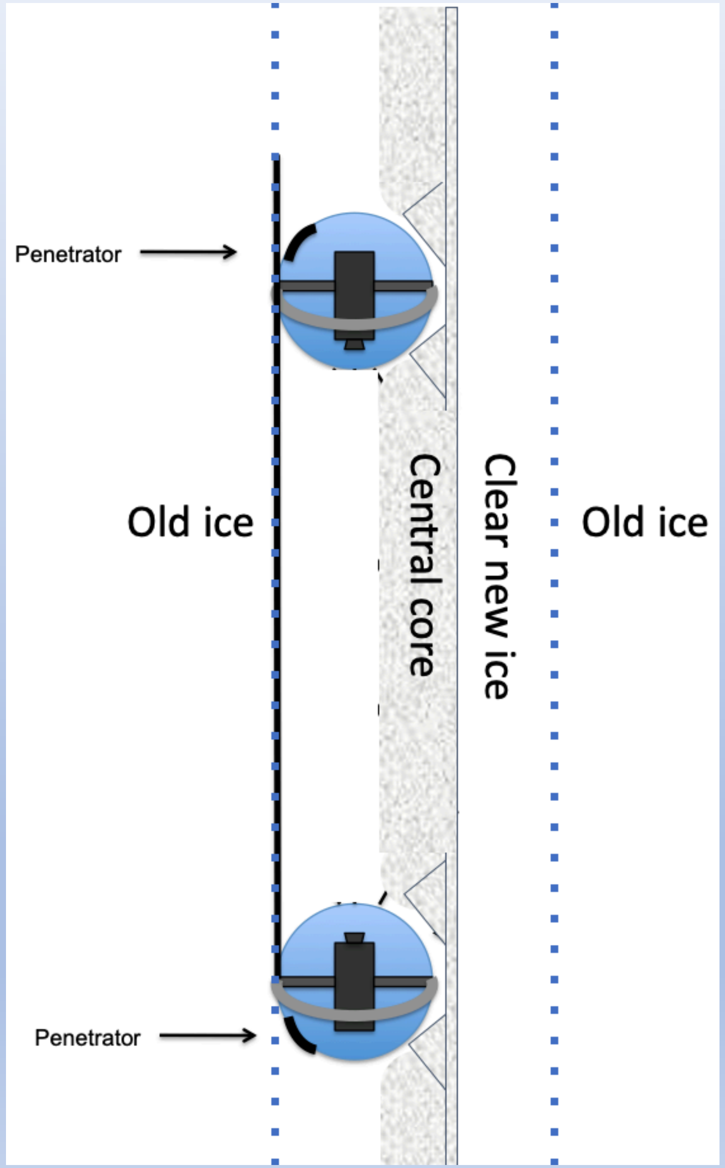
At some depth between 0 and 200 m air bubbles become trapped and are squeezed into the ice as ice packs under pressure.



are converted into air hydrates

(at around 1350 m depth)

Refrozen hole ice is more complex than thought before the Swedish Camera took its pictures

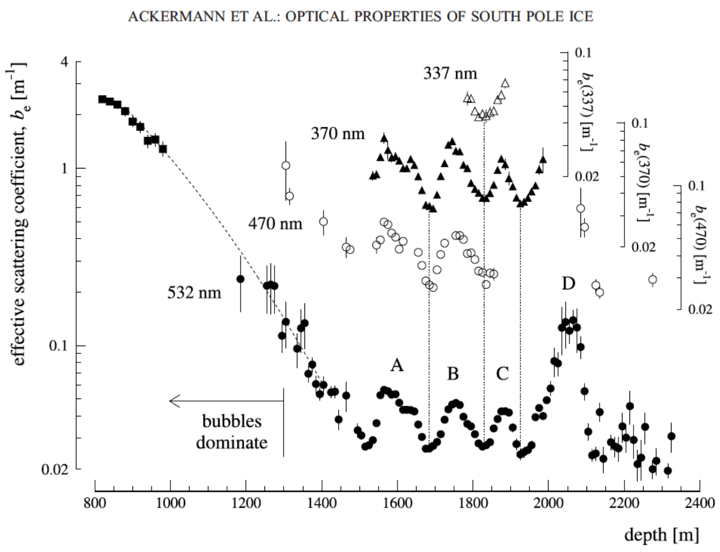


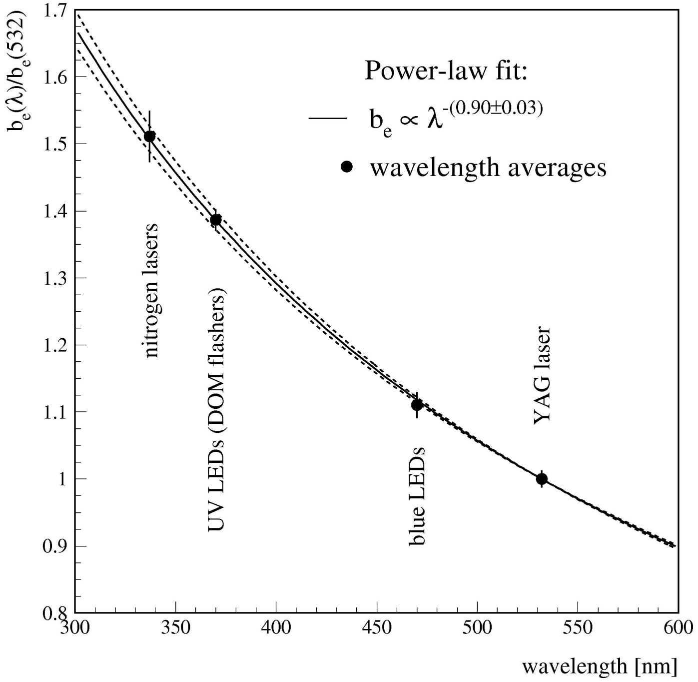
We find:

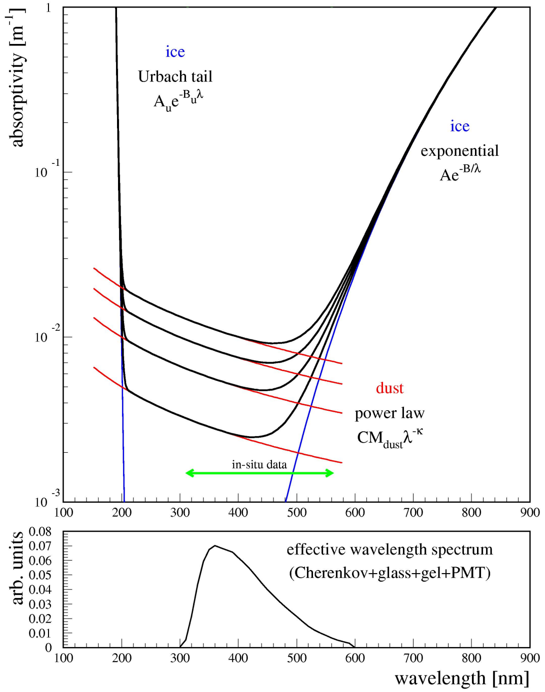
DOM touches the hole wall, is 2/3 of the hole diameter

Most of the HI is transparent, except for the milky central column centered in the hole and 1/3 of hole diameter (referred to as HI in the following, starting with the next line)

HI diameter is ½ of DOM diameter



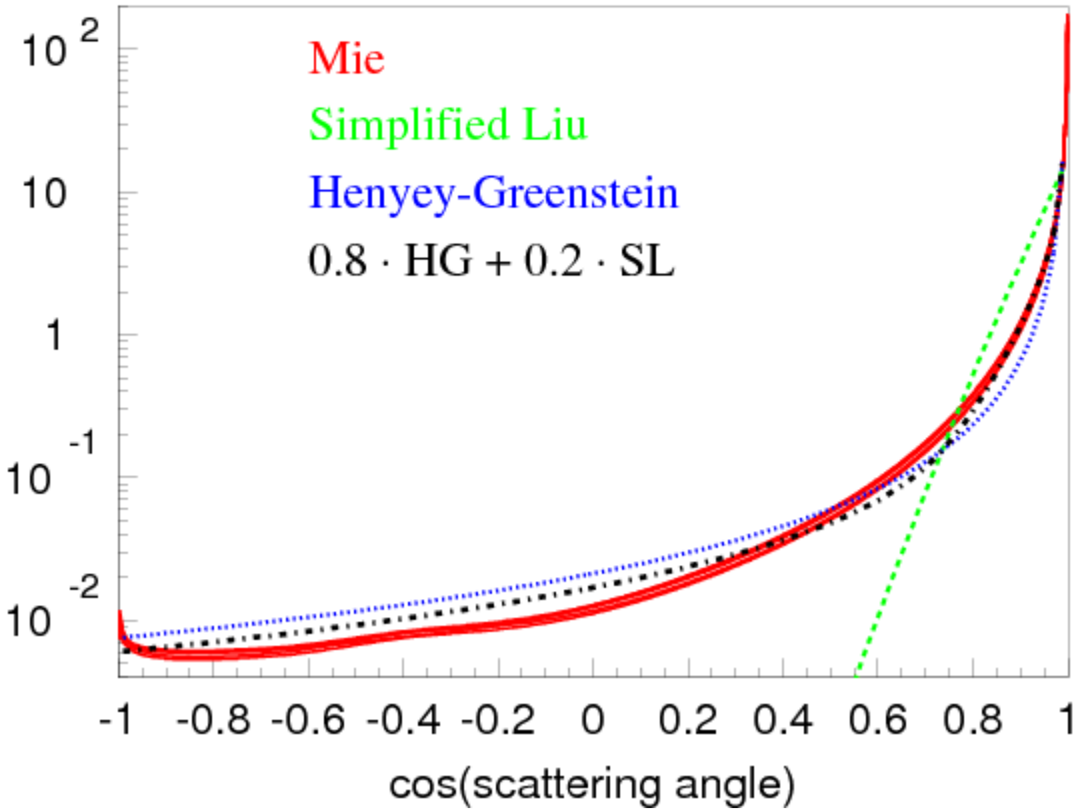




AMANDA-II: comprehensive layered ice model incl. wavelength dependence, identified dust contribution

Ice is extremely transparent between 200 nm and 500 nm
Scattering and absorption are determined by dust concentration
Wavelength dependence of dust scattering and absorption follow power law

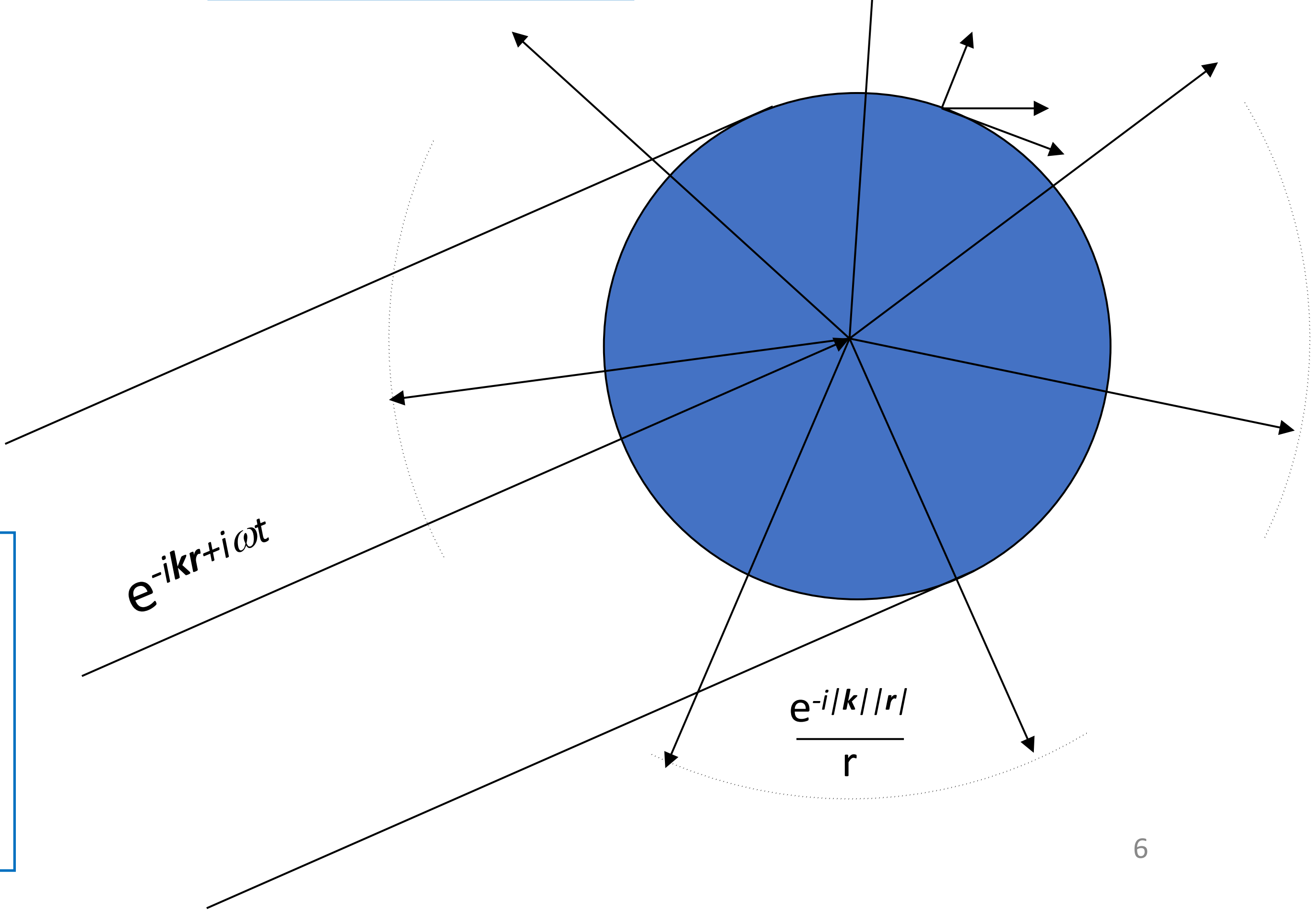
Mie scattering theory



Can be solved for spherically symmetric particles

Need to know:
- refractive index
- size distribution

Continuity in E, H: boundary conditions in Maxwell equations

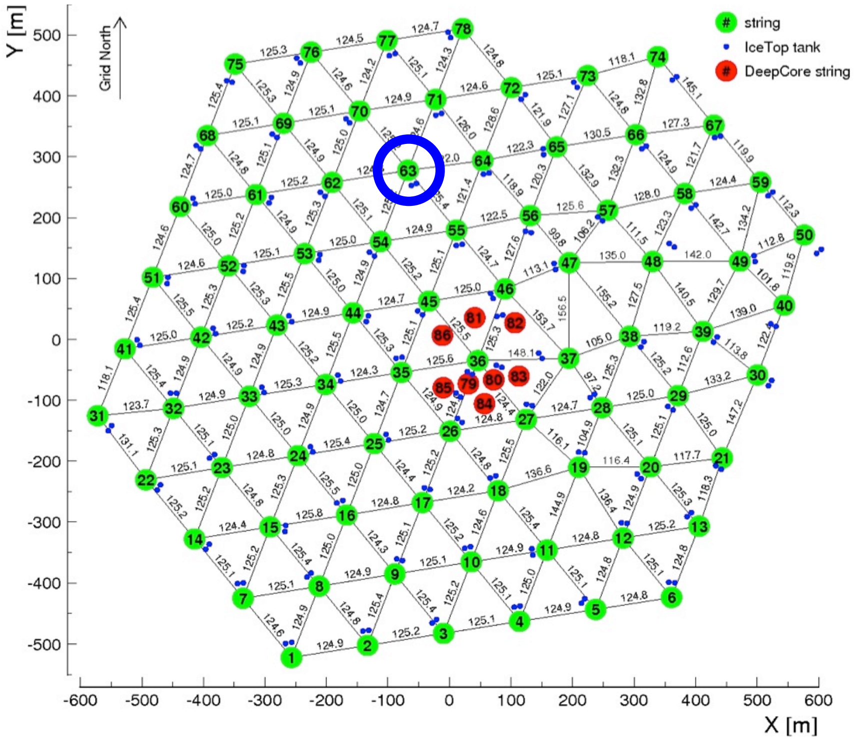


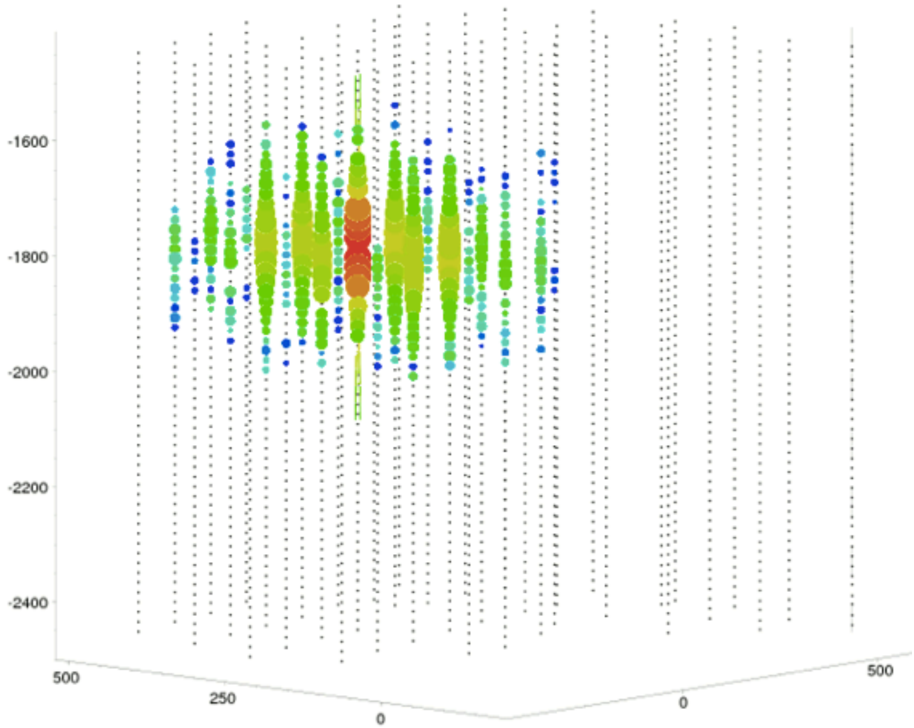
We approximate and fit data with a mixture of:

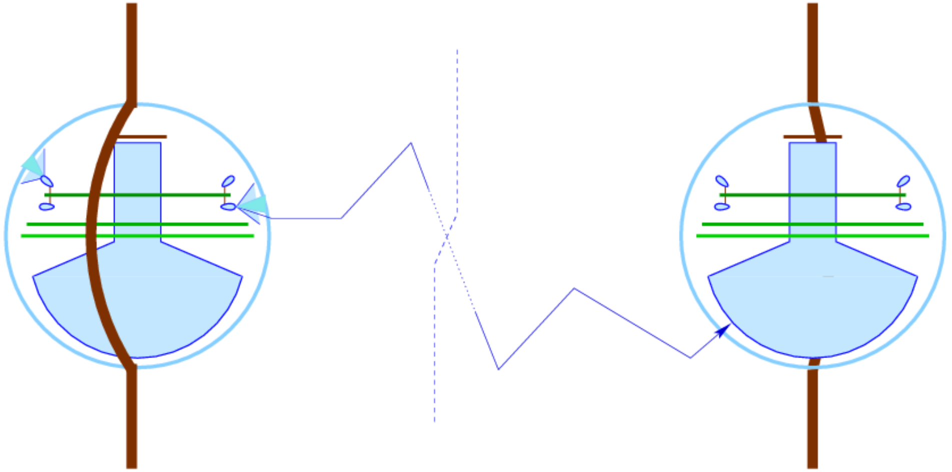
Simplified Liu: $p(\cos\theta) \sim (1+\cos\theta)^{\alpha}, \quad \text{with} \quad \alpha = \frac{2g}{1-g}$

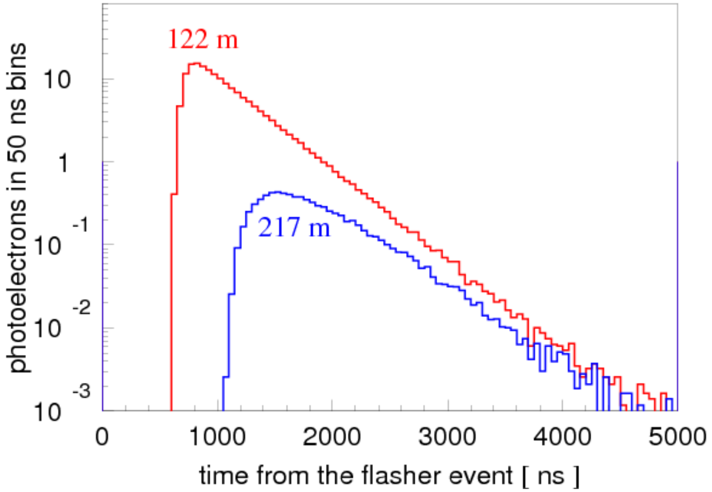
Henyey-Greenstein: $p(\cos\theta) = \frac{1}{2}\frac{1-g^2}{[1+g^2-2g\cdot\cos\theta]^{3/2}}$

Fitting ice to in-situ data

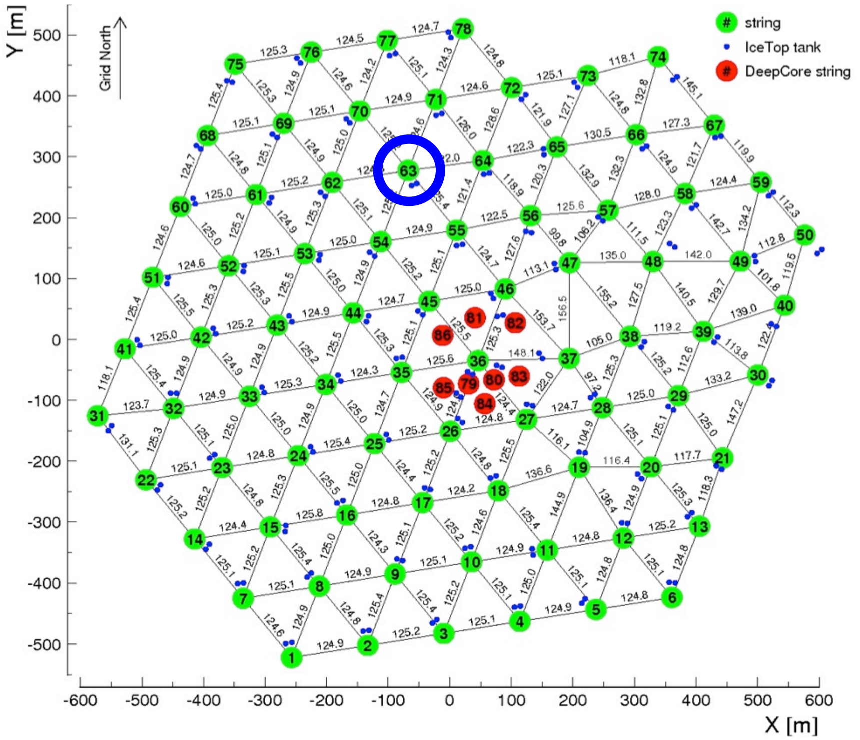


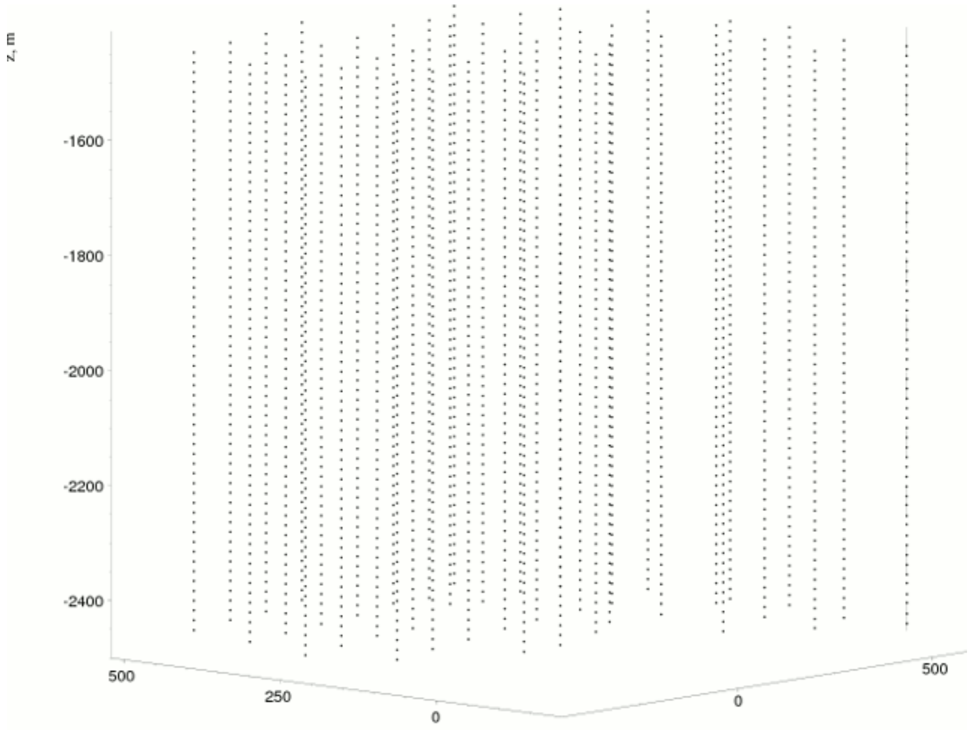


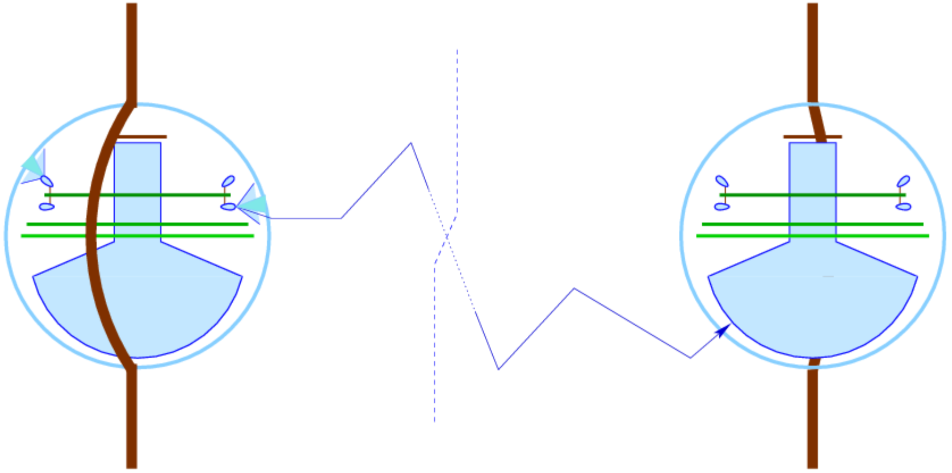


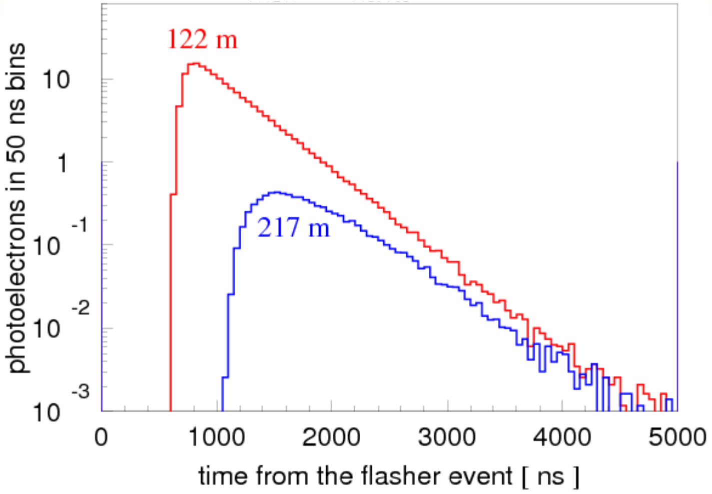


Fitting ice to in-situ data

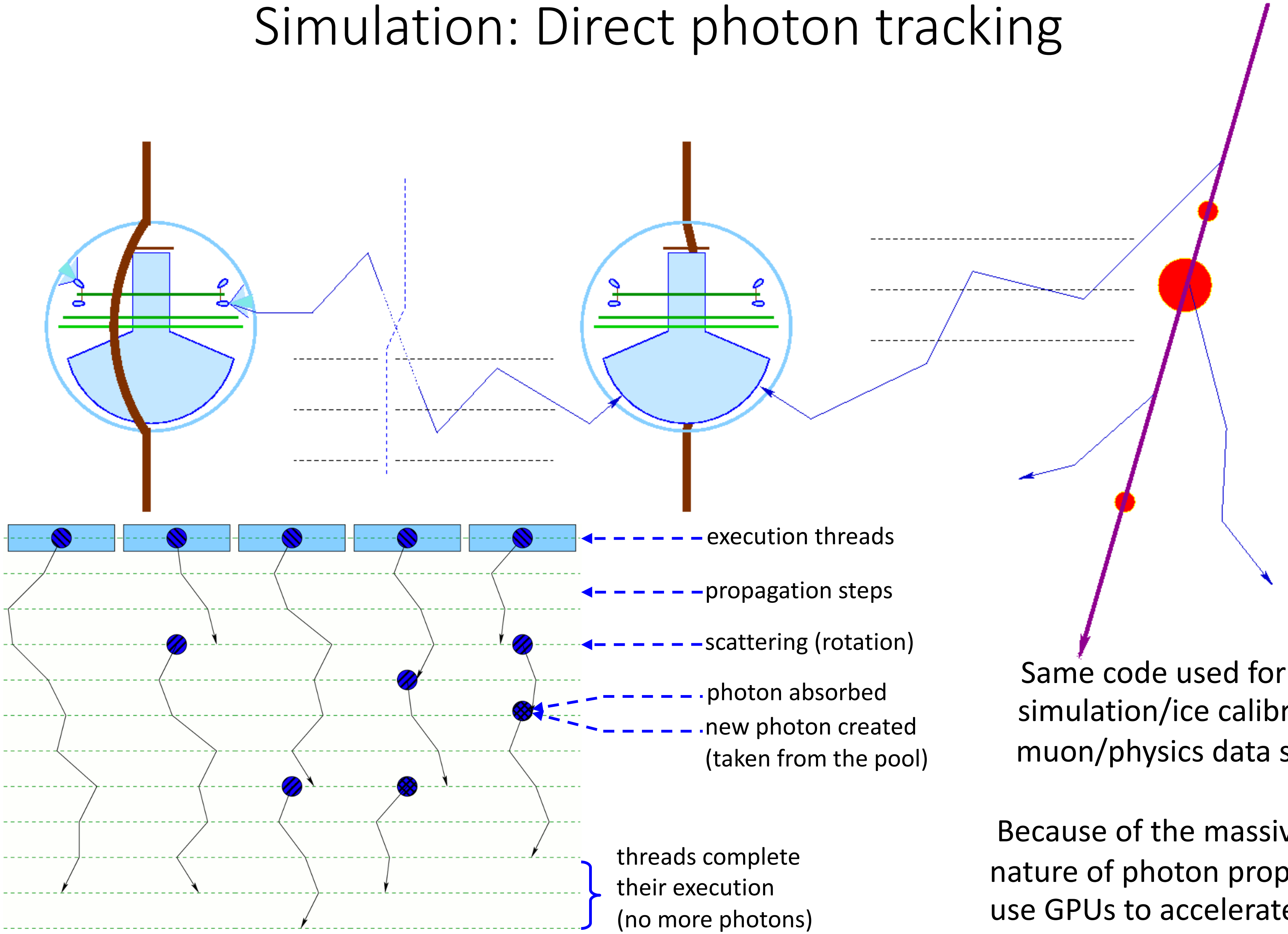








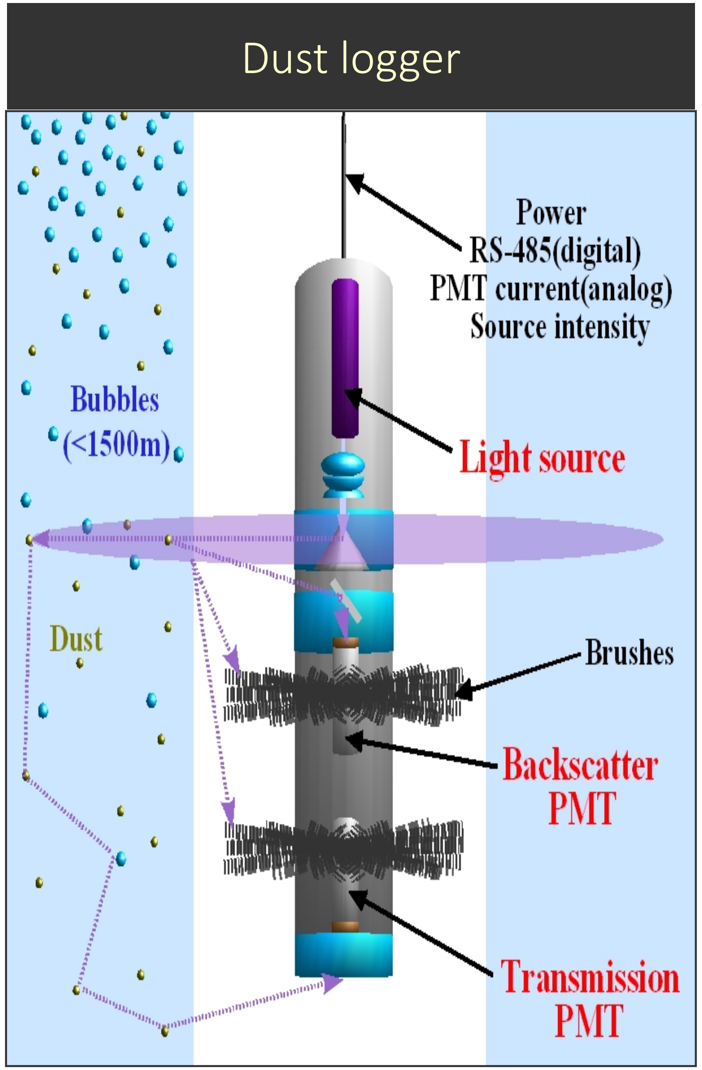
Simulation: Direct photon tracking

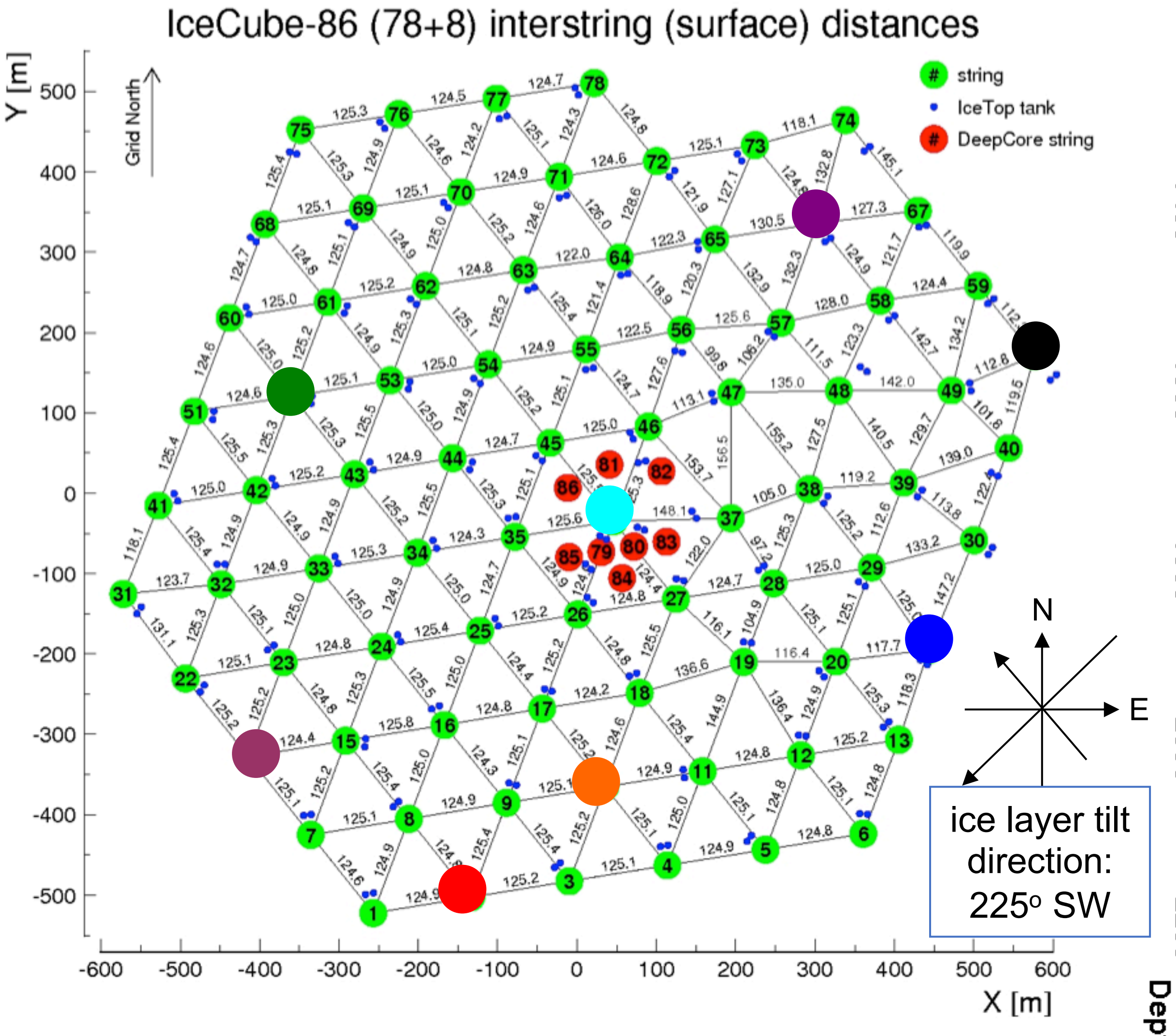


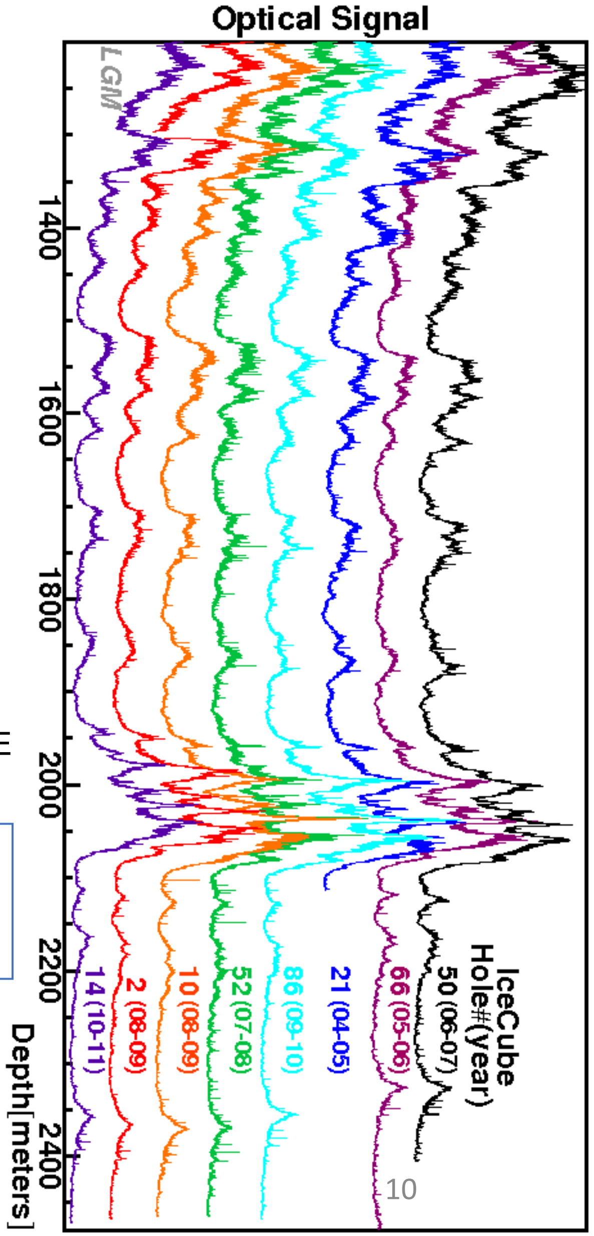
Same code used for both LED simulation/ice calibration and muon/physics data simulation

Because of the massively parallel nature of photon propagation, we use GPUs to accelerate simulation

Dust logger discovers ice tilt

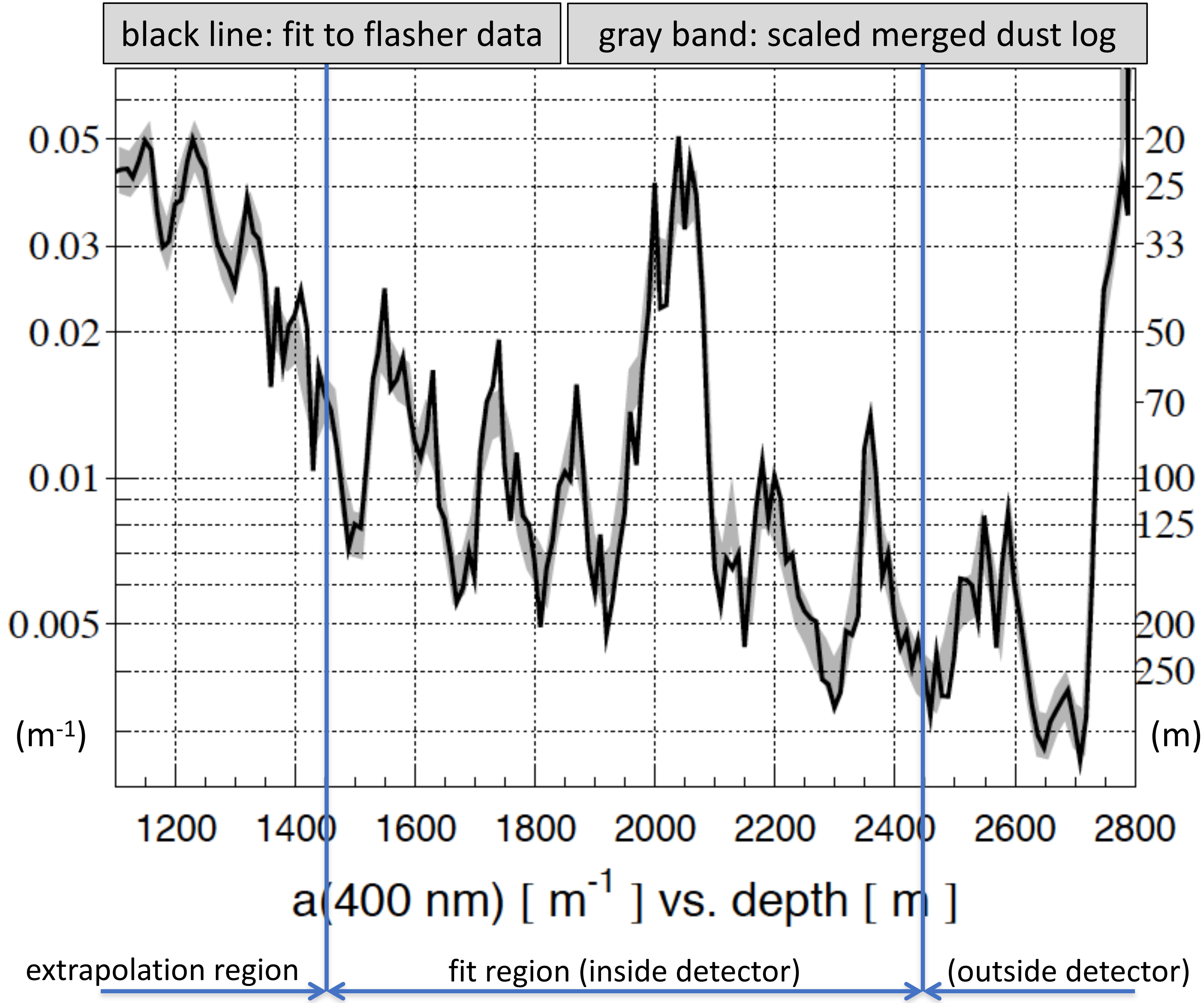


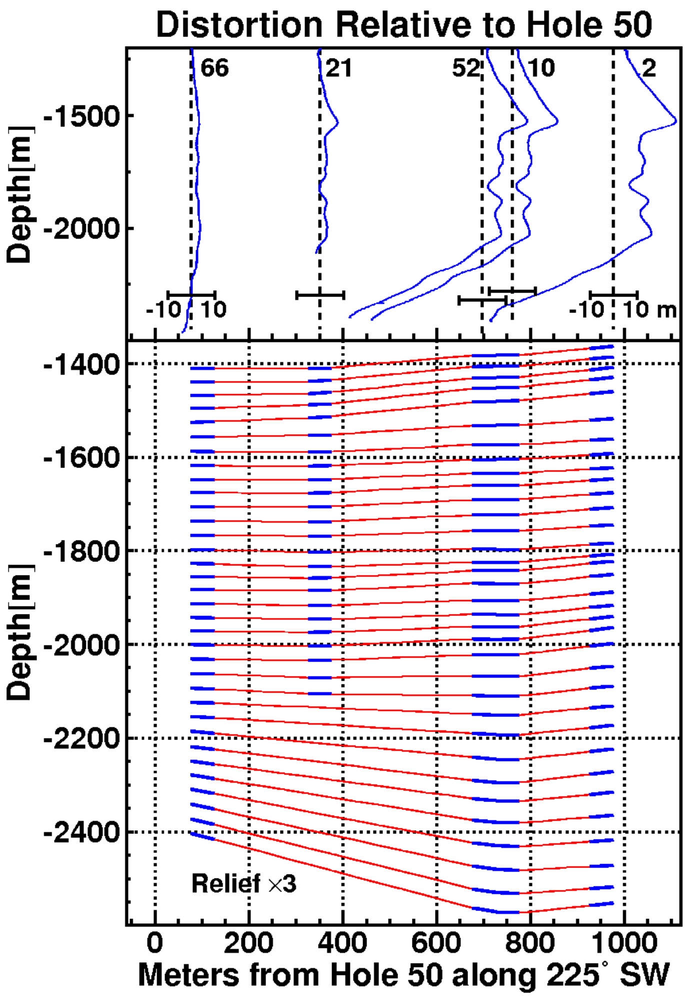




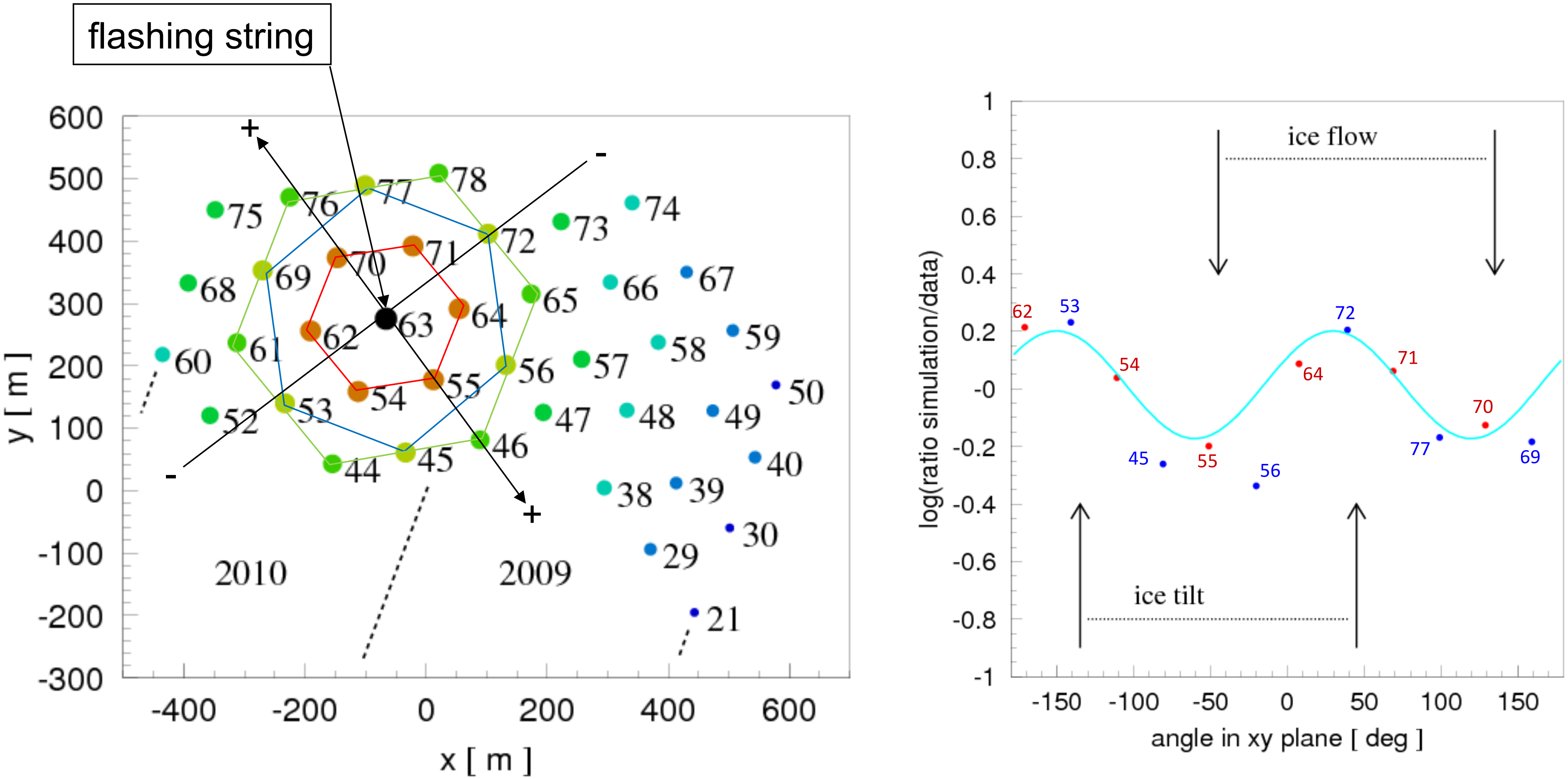
The ice layers (i.e. layers of ice with similar optical properties) change in depth by as much as 60 m when going from NE to SW corners of the detector

Correlation of fitted optical properties with dust logger data





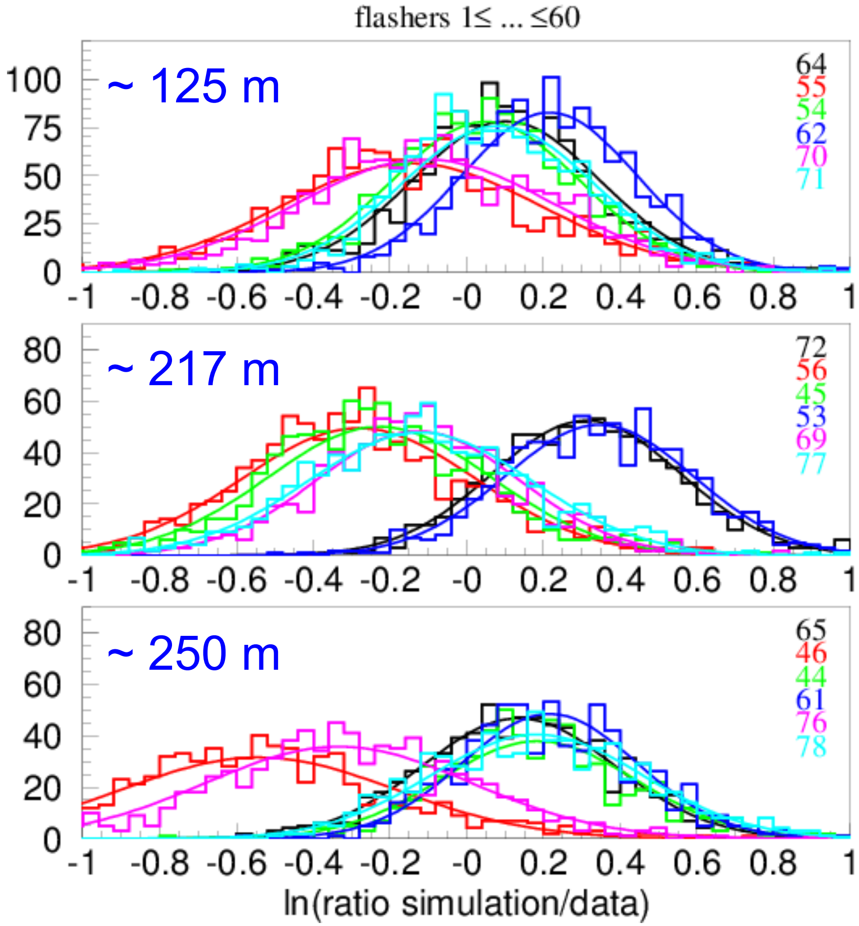
Ice anisotropy (ICRC 2013)

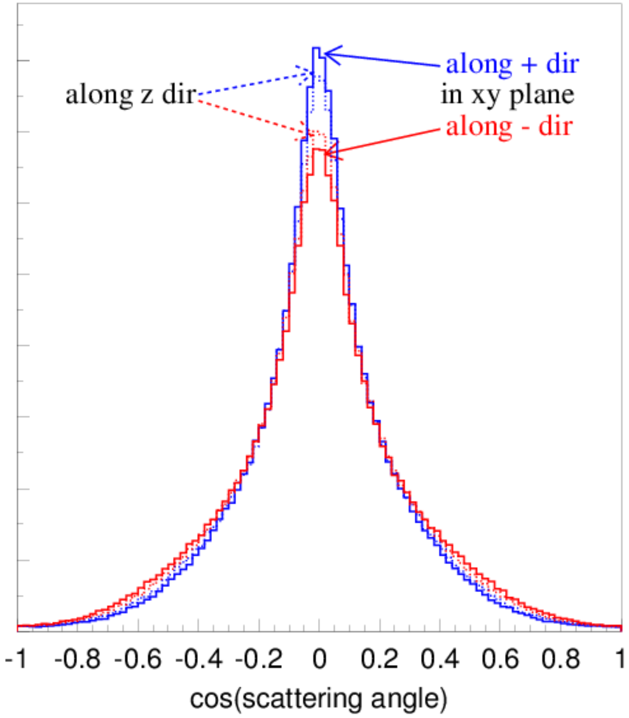


10-20% per 100 m azimuth modulation in charge observed!

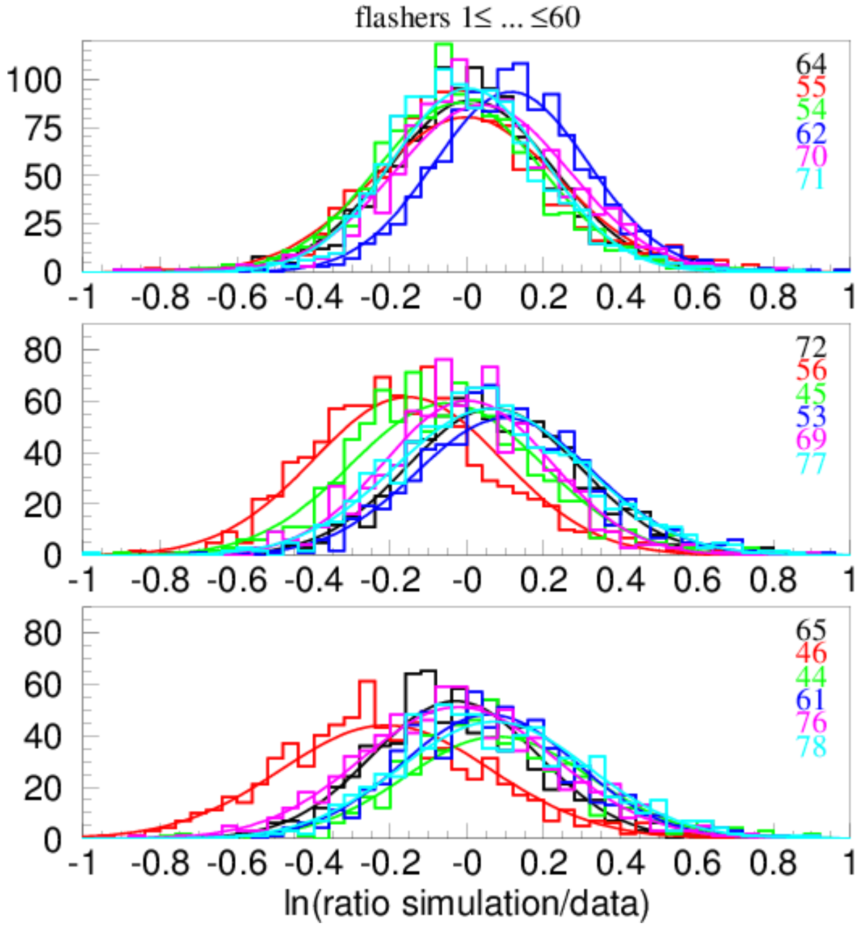
Charge variation vs. distance

SPICE Mie [SPICE Paper]





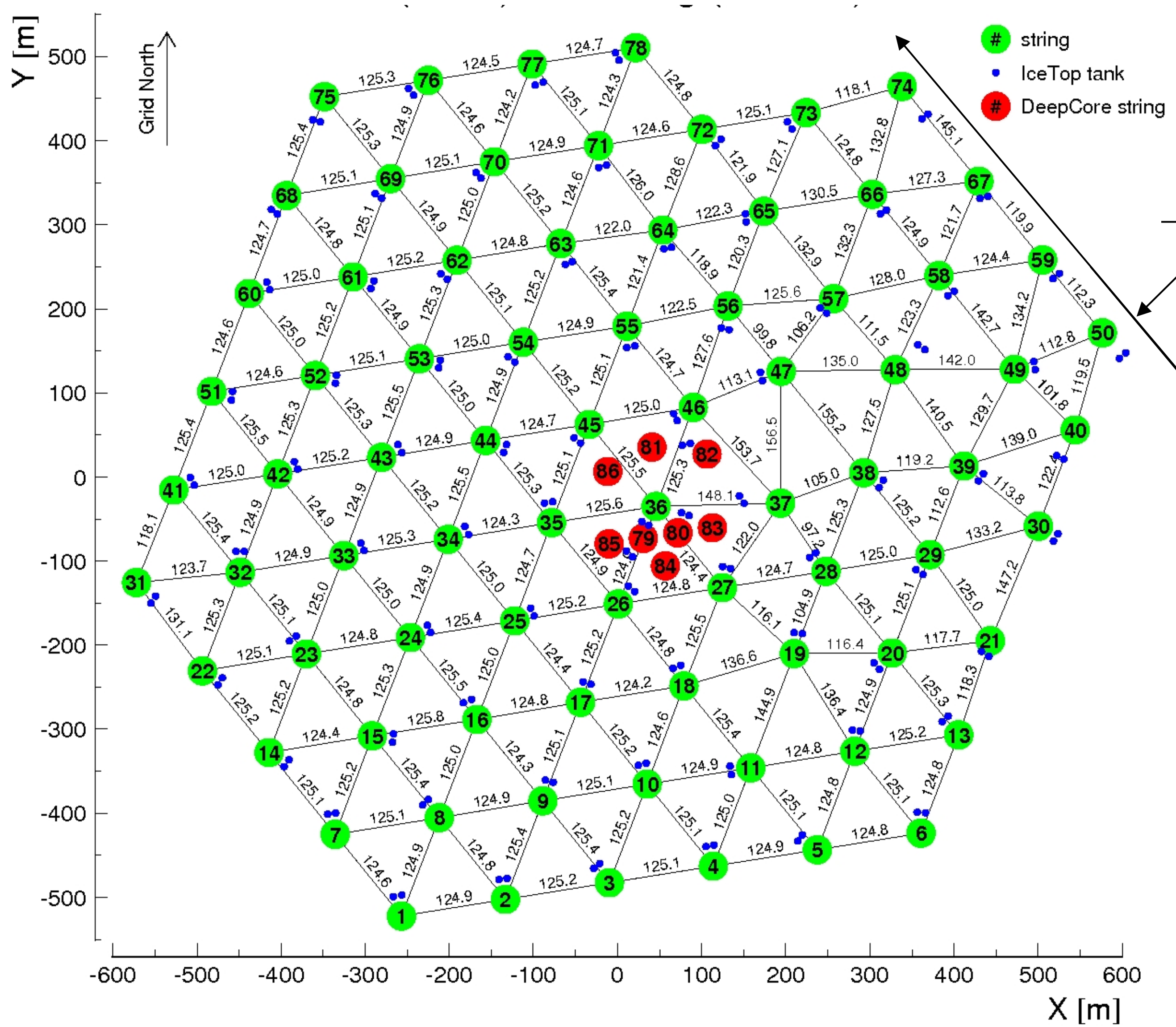
SPICE Lea

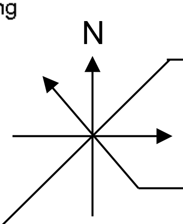


<u>*Scattering function:*</u>

$$f(\vec{n_i} \cdot \vec{n_o}) \rightarrow f(\vec{k_i} \cdot \vec{k_o}), \quad \vec{k}_{i,o} = \frac{A\vec{n}_{i,o}}{|A\vec{n}_{i,o}|}$$

Glacial ice flow, ice layer tilt at the South Pole

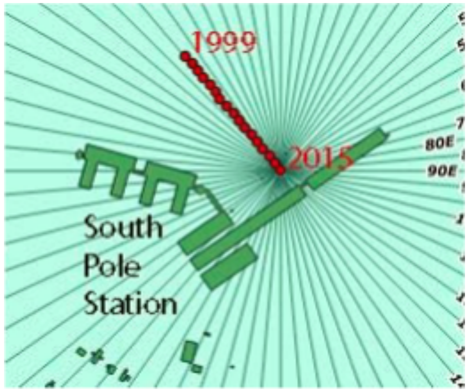


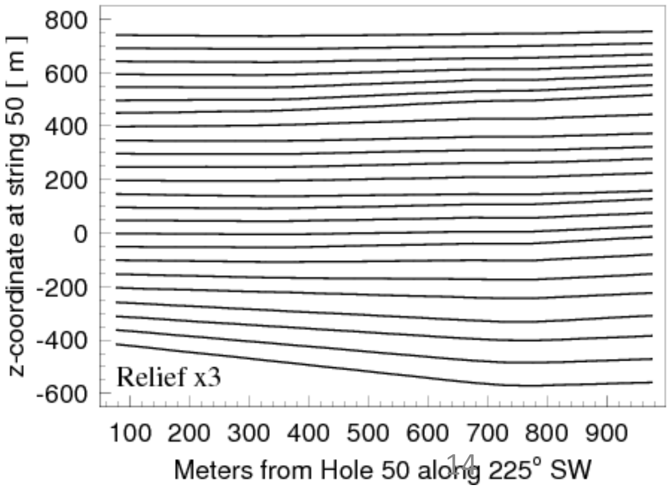


Ice Layer tilt direction
225° SW

Ice flow direction
41° NW

Less attenuation
41° NW





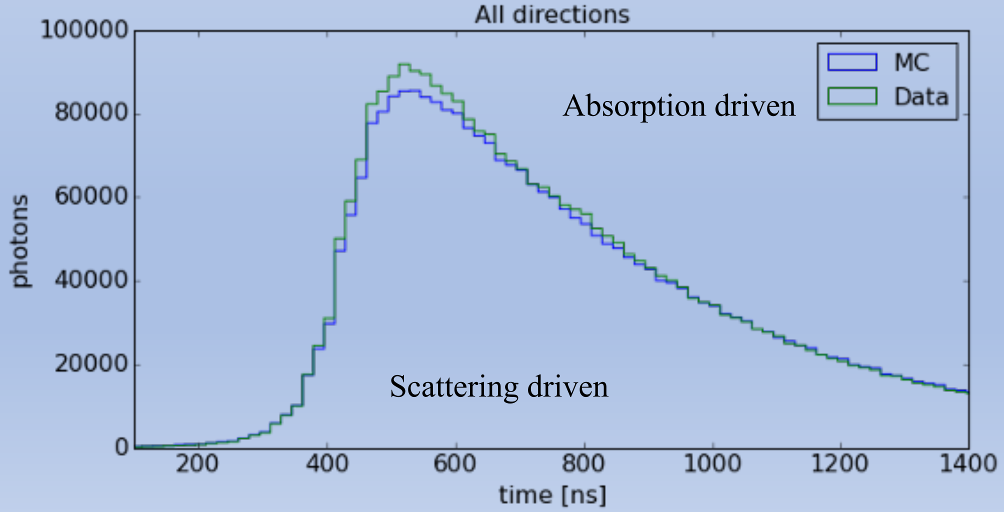
Models of optical ice anisotropy in IceCube

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

Introduced depth-dependence (2017)

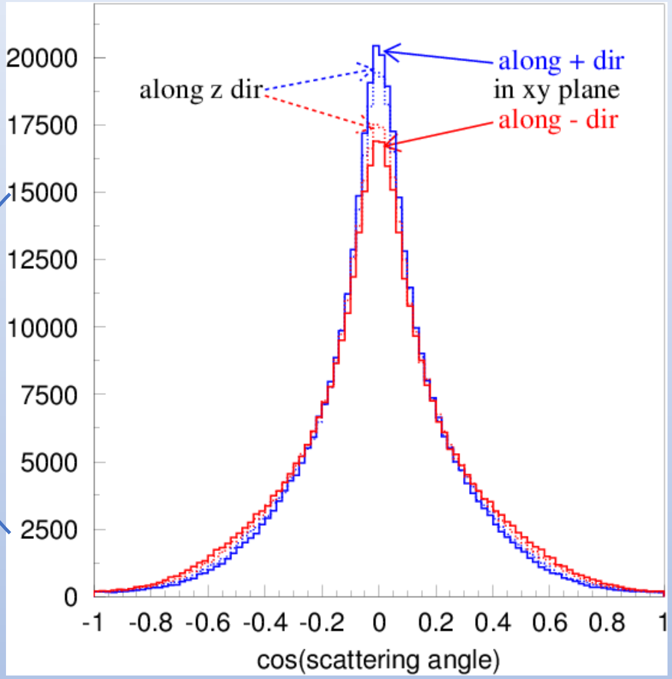
Discrepancies between data and simulation remain

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



scattering-based

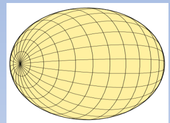
SPICE Lea, 3.2.x



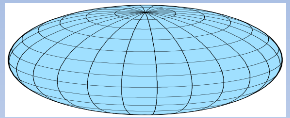
absorption-based

SPICE EMRM

prolate

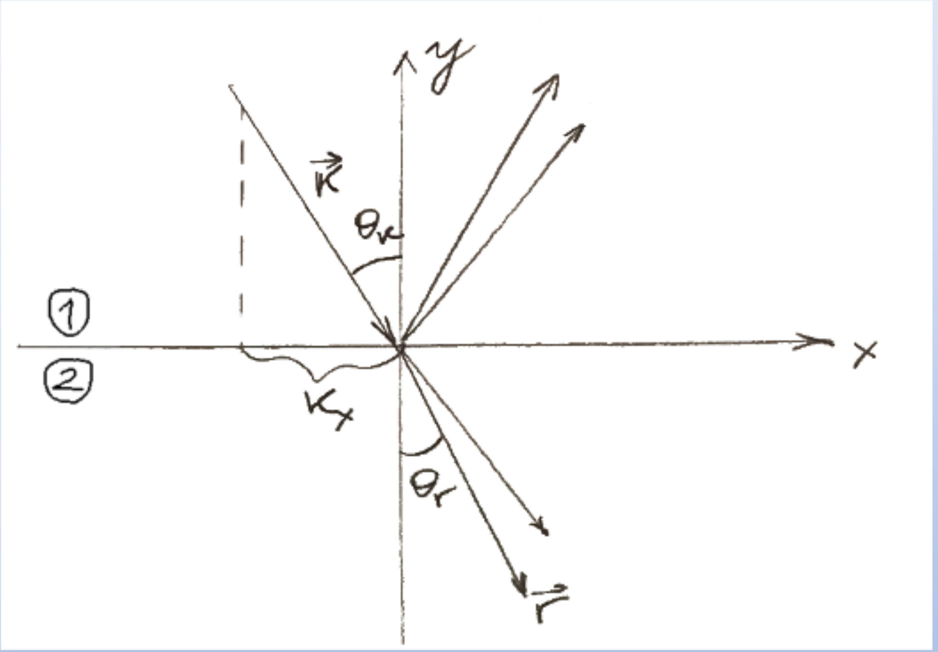


oblate



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

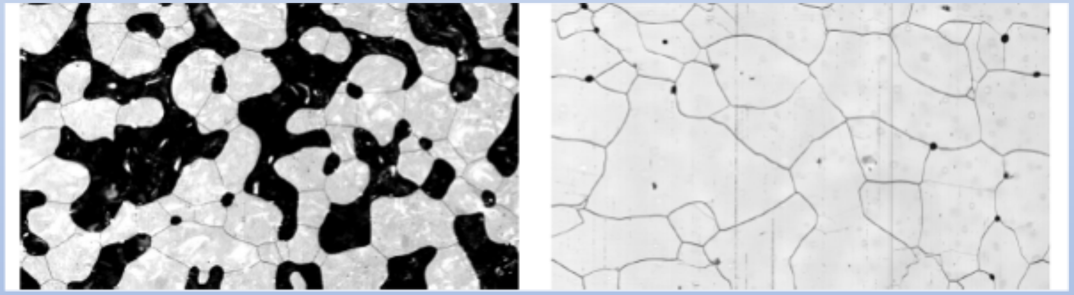
Scattering patterns birefringent ice

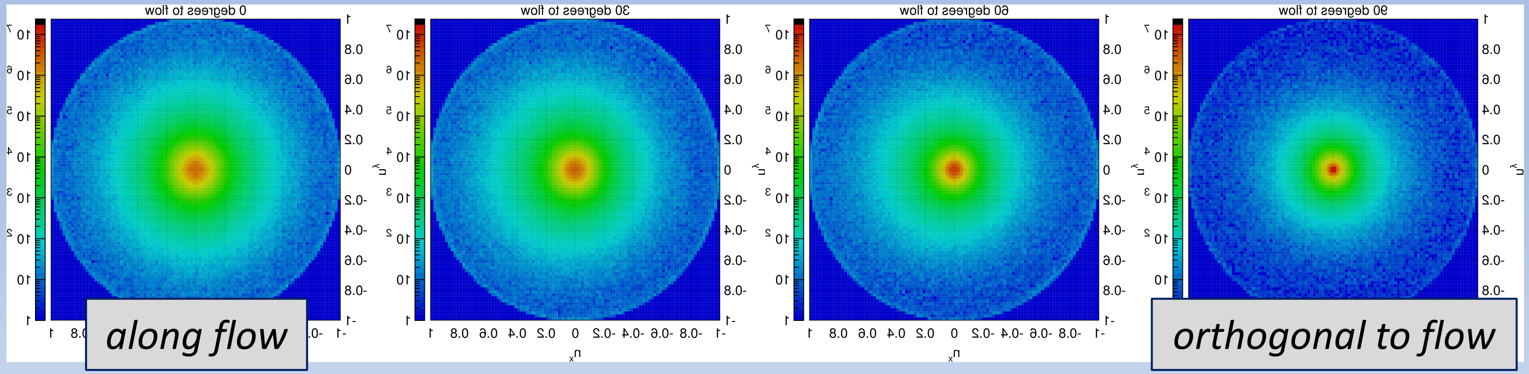
Running MC simulation with realistic crystal size, elongation, and orientation distributions (correlated to flow direction):

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

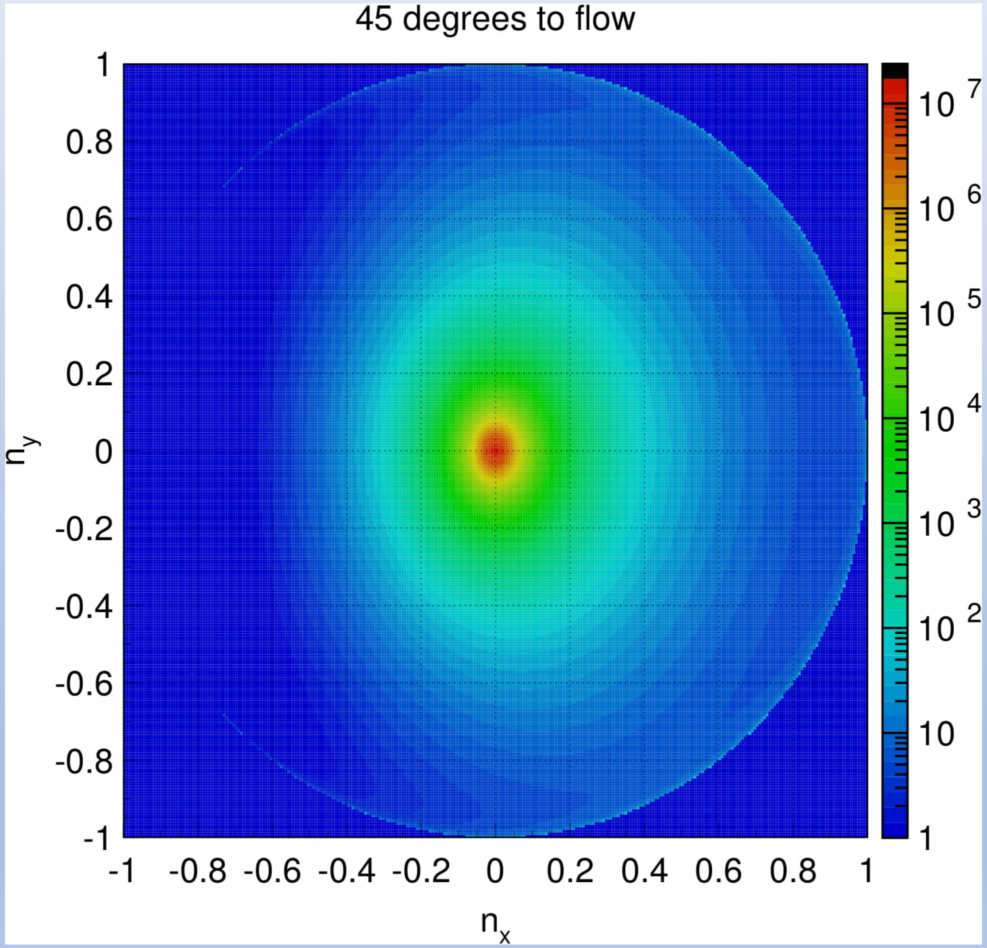




along flow

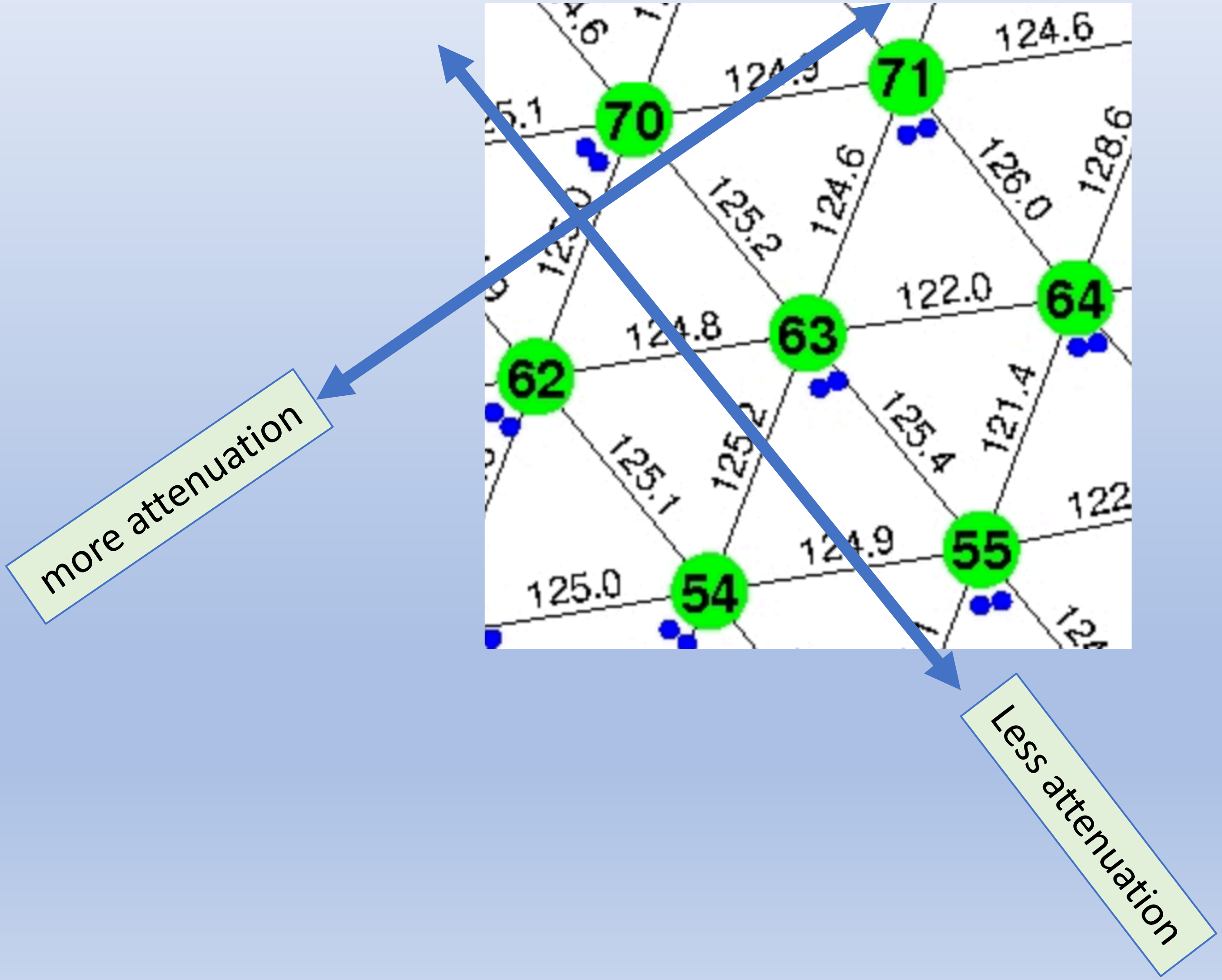
orthogonal to flow

after ~ 1 m of propagation:



towards flow

Our best tool to gauge the quality of our description of anisotropy



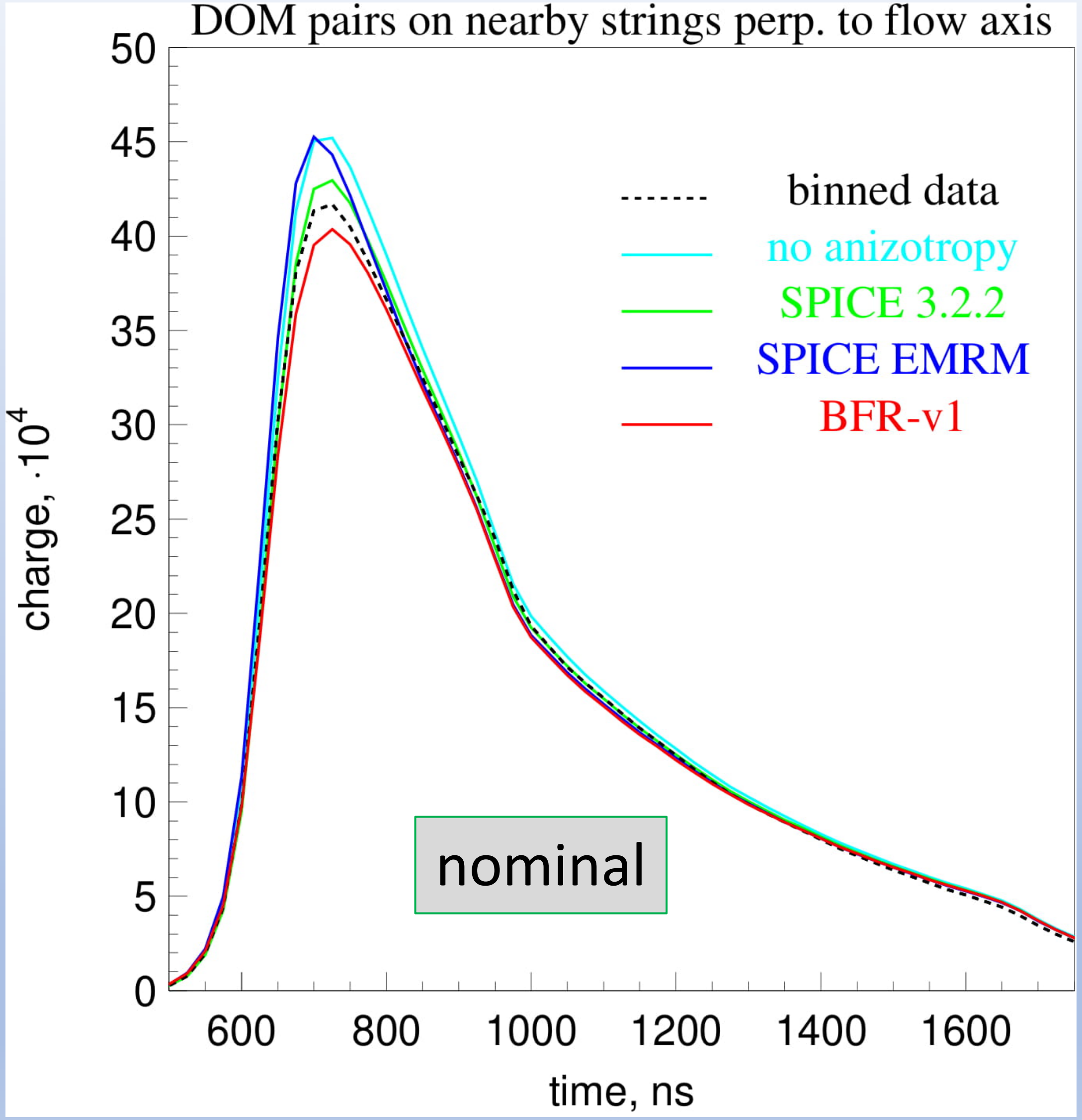
Next slide shows average waveform for nearby emitter-receiver DOM pairs aligned with the two directions (along and perpendicular to ice flow).

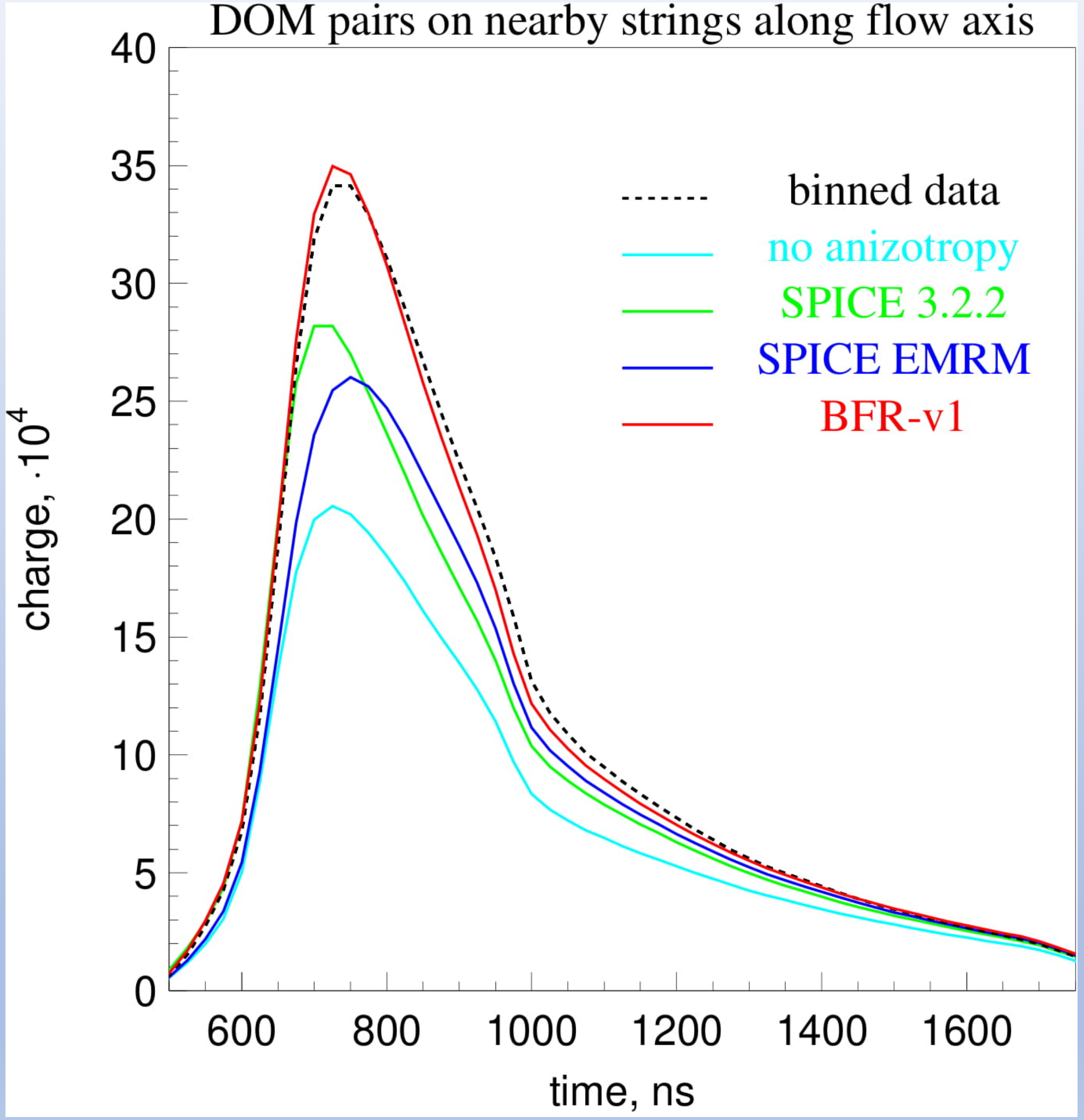
This might be the best tool to rank ice models on how well they describe the anisotropy

Here used string pairs one ~125 m spacing away (excludes DeepCore and far distances)

134 string pairs along flow
272 string pairs perpendicular to flow

Using DOM pairs at the same position (depth)


DOM pairs on nearby strings perp. to flow axis
charge, ·10^4
time, ns
binned data
no anizotropy
SPICE 3.2.2
SPICE EMRM
BFR-v1
nominal
0
5
10
15
20
25
30
35
40
45
50
600
800
1000
1200
1400
1600


DOM pairs on nearby strings along flow axis
charge, ·10^4
time, ns
binned data
no anizotropy
SPICE 3.2.2
SPICE EMRM
BFR-v1
0
5
10
15
20
25
30
35
40
600
800
1000
1200
1400
1600

other metrics of ice model comparison

nominal

Ice model	No anisotropy	SPICE 3.2.2	SPICE EMRM	Birefringence 1
Saturated llh (ndof=60848)	73334	64006	59418	57546
Model error (10 … 500 p.e.)	27.0%	17.2%	16.2%	15.6%

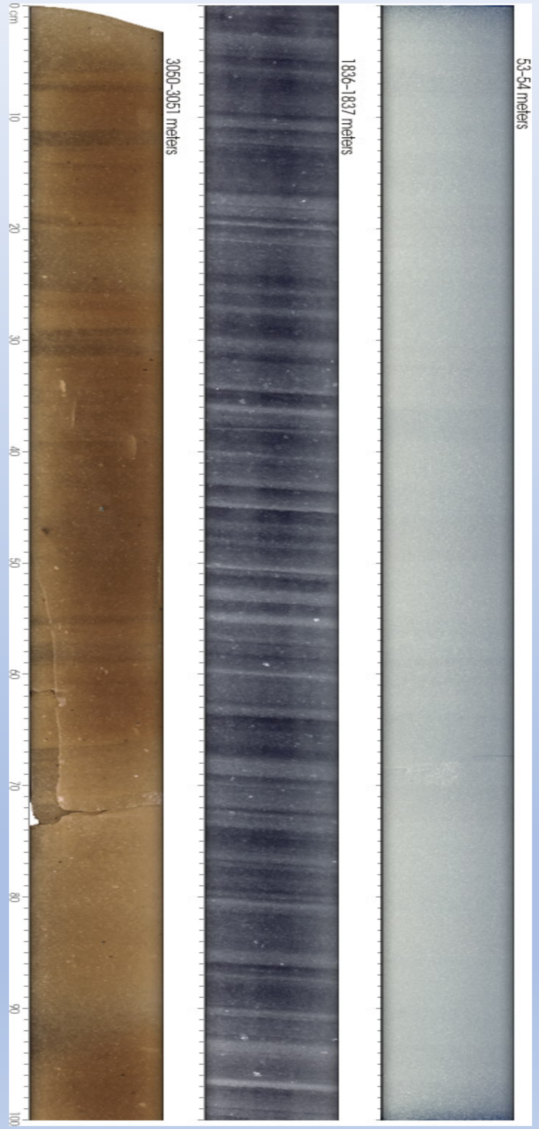
All numbers shown here calculated with 10 simulated flasher events per configuration, 60848 configurations (5160 DOMs x 12 flasher LEDs minus dead DOMs/broken LEDs)

Used:

lab measured angular emission profile (no pattern unfolding)
single LED orientations previously fitted with SPICE 3.2.2
nominal cable shadow (between LEDs 11 and 12) and no DOM tilt
nominal RDEs (relative DOM efficiencies)

So, the numbers might be higher than shown elsewhere, but compare to each other

Timeline



			model error
AMANDA ice models:			
bulk, f125, mam, mamint, stdkurt, sudkurt, kgm, …			
millennium (published 2006) → AHA (2007)			55%
IceCube ice models:			
WHAM	(2011)		42%
SPICE 1	(2009)		29%
SPICE 2, 2+, 2x, 2y	(2010)	added ice layer tilt	
SPICE Mie	(2011)	fit to scattering function	29%
SPICE Lea	(2012)	fit to scattering anisotropy	20%
SPICE (Munich)	(2013)	7-string, LED unfolding	17%
$SPICE^3$ (CUBE)	(2014)	llh fixes, DOM sensitivity fits	11%
SPICE 3.0	(2015)	improved RDE, ang. sens. fits	10%
SPICE 3.1, 3.2	(2016)	85-string, correlated model fit	<10%
SPICE HD, 3.2.2	(2017)	direct HI and DOM sens., cable, DOM tilt	
SPICE EMRM	(2018)	absorption-based anisotropy	*single*
SPICE BFR	(2020)	birefringence-based anisotropy	*LEDs*

Model error (precision in charge prediction): <10%
Extrapolation uncertainty: 13% (sca) / 15% (abs)
Linearity: < 2% in range 0.1 … 500 p.e.

Remarks

Our understanding of optical properties of the South Pole ice has come a long way in the last 30 years! Studied with fixed in-situ light-emitting devices and with special-purpose dust loggers in AMANDA-A, AMANDA-II, and IceCube detectors, and being an important part of the science plan for the future extensions. We were also allowed to lower several devices into the nearby SPICECORE hole to study anisotropy, UV-response, and fluorescence of ice.

Scattering and absorption of ice come from intrinsic ice and impurity contributions.

The entire ice is moving (flowing) downhill at 10 m/year sheet (at all depths relevant to IceCube). This likely is the source of interesting effects that we discovered over the years, in particular the tilt of the ice layers and anisotropy.

We have gone through several models that all describe the anisotropy effect, to various degrees of success. Scattering-based, and absorption-based, and now thought to be due to birefringence.

Birefringence-based model of anisotropy is well grounded on the known ice structure. Albeit individual photon direction changes are tiny, 1000s of crystal boundary crossings happen per every meter of photon path, resulting in a measurable macroscopic effect.

DOM orientations, hole ice, etc.

backup slides

Birefringence

Ice is a birefringent material:

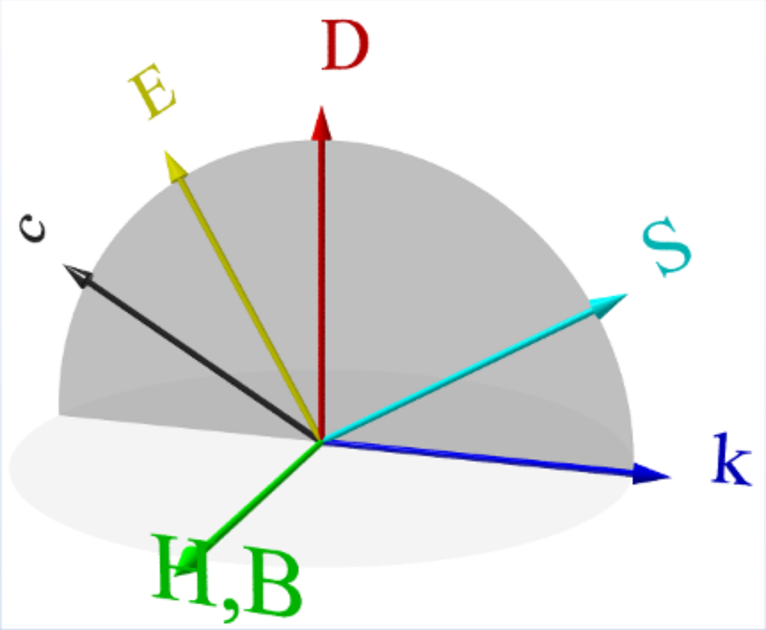
Light is split into an ordinary and an extraordinary rays with respect to the (optical) c-axis, these have orthogonal polarizations

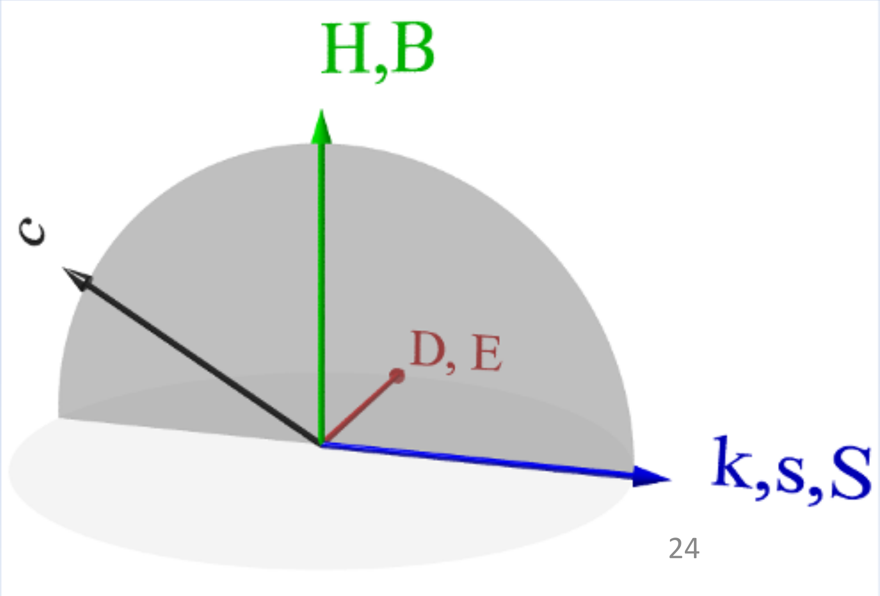
The refractive index of the extraordinary ray is direction dependent

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

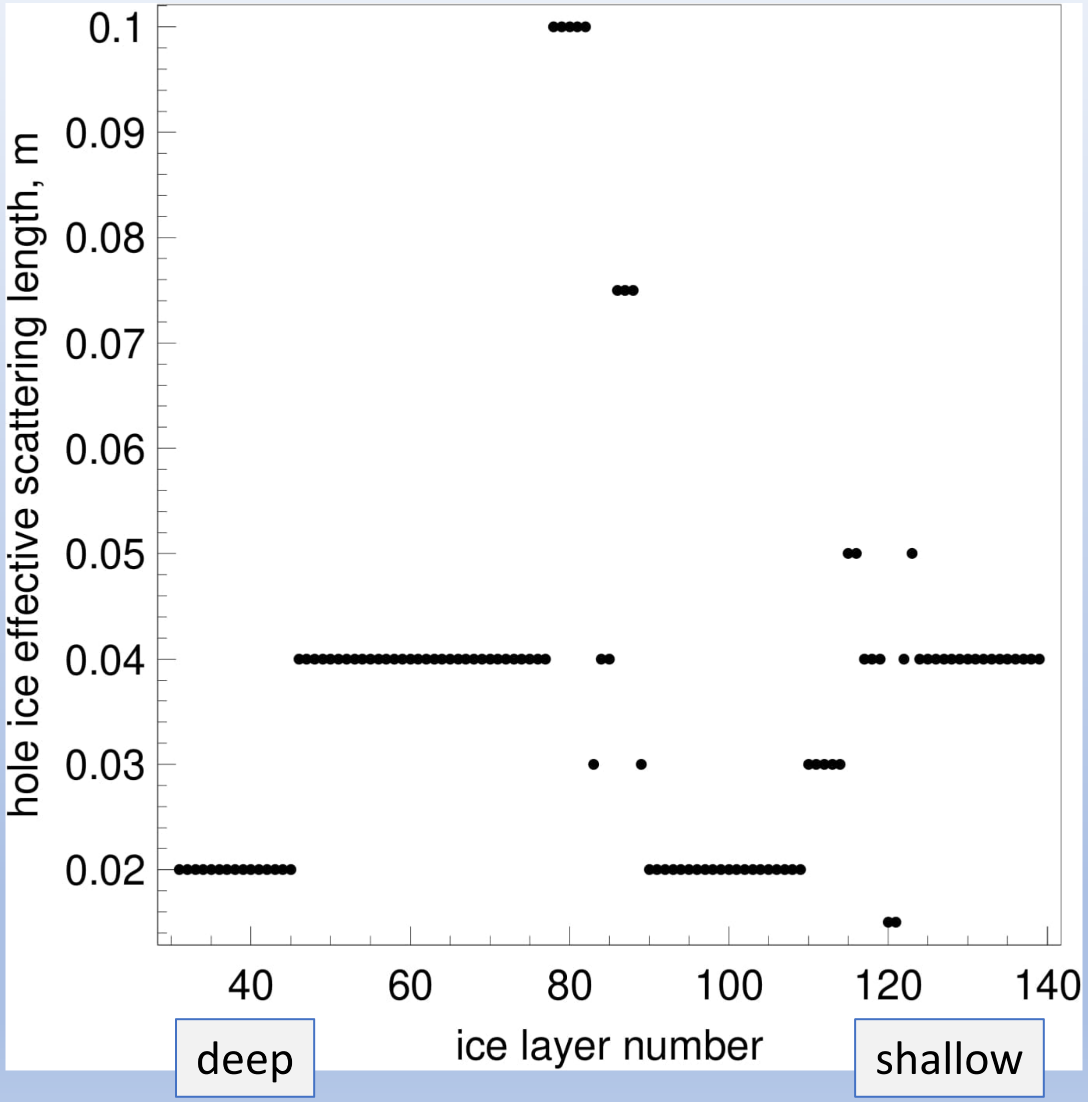
wavelength λ (nm)	n_o	n_e
405	1.3185	1.3200
436	1.3161	1.3176
492	1.3128	1.3143
546	1.3105	1.3119
624	1.3091	1.3105
691	1.3067	1.3081

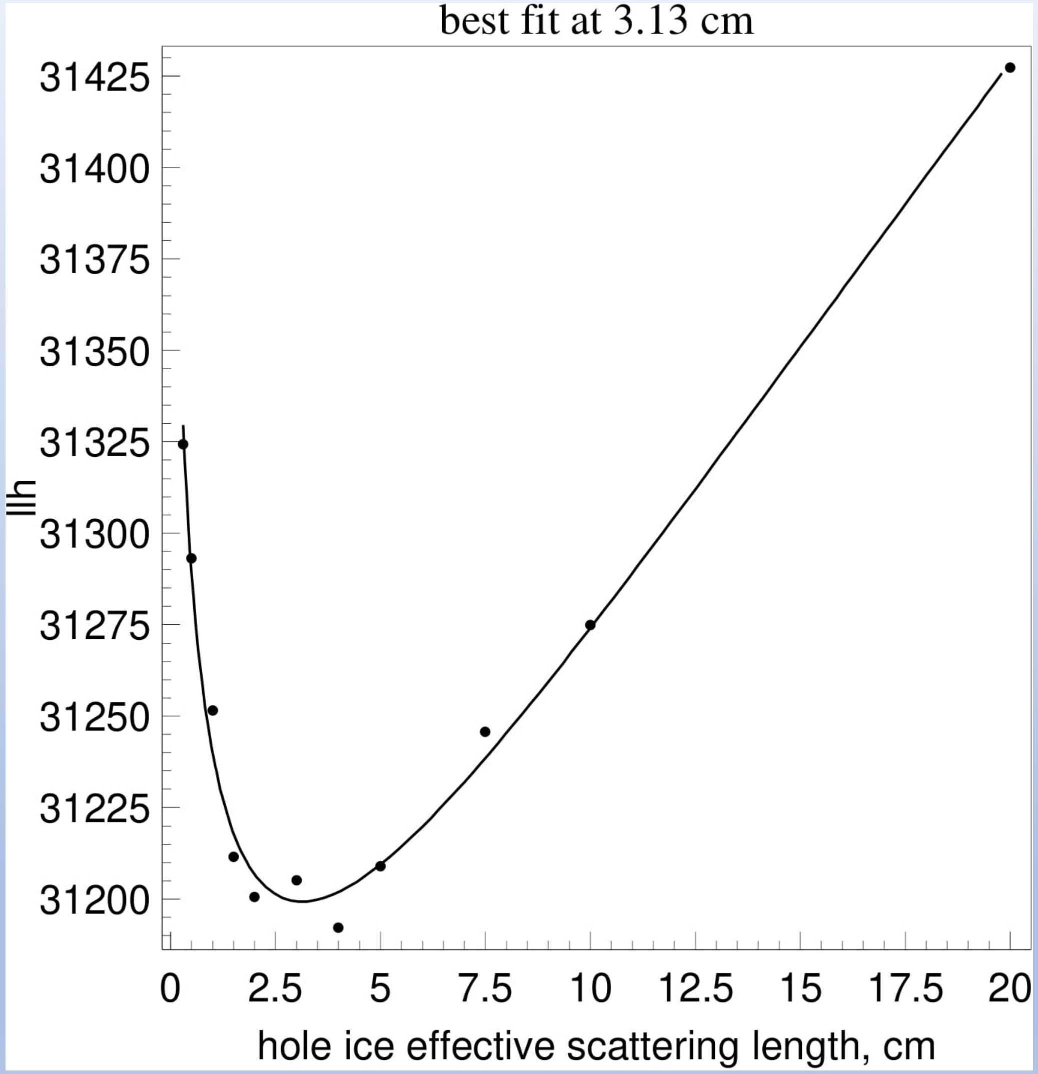
Physics of Ice, Victor F. Petrenko





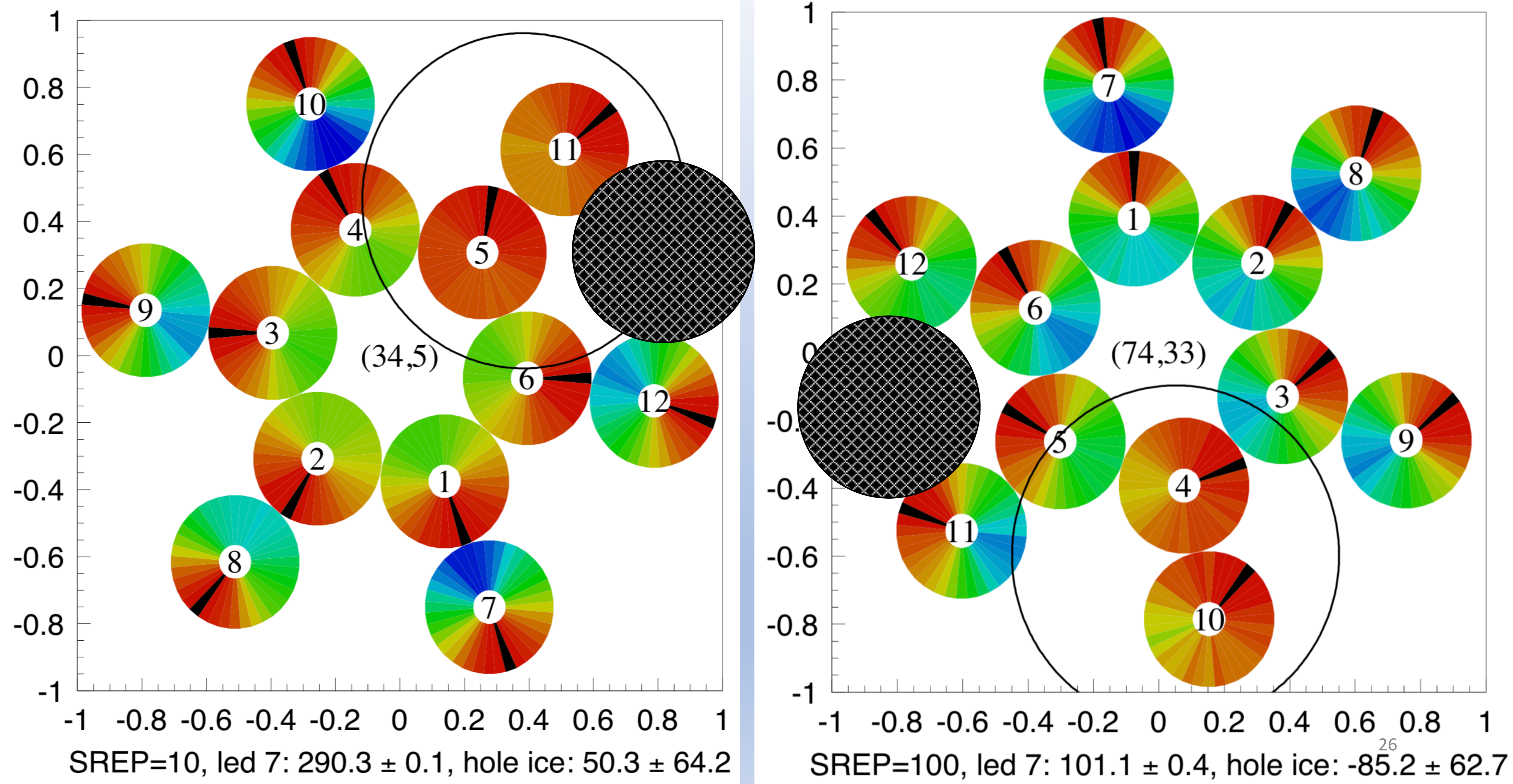
Depth-dependent fit to the effective scattering length of the hole ice



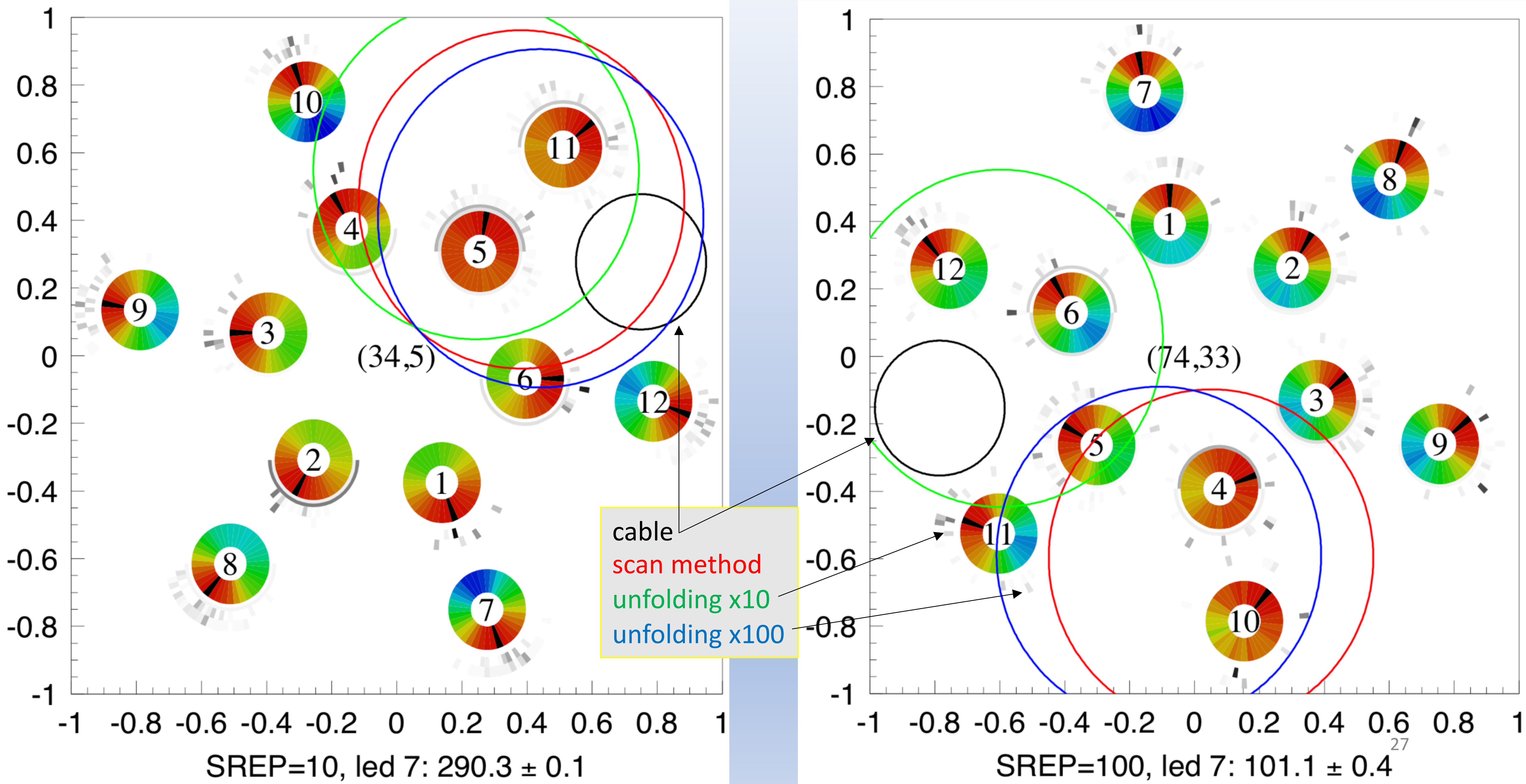


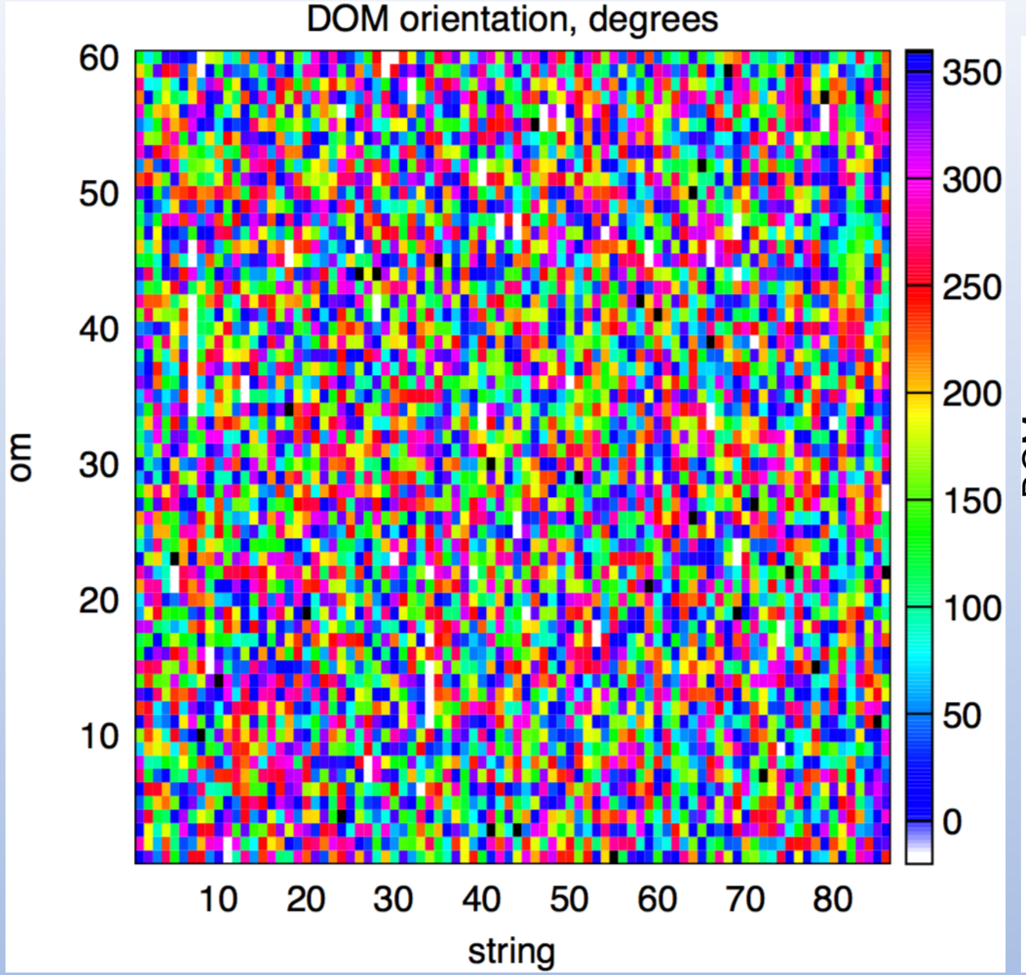
Very little depth dependence!

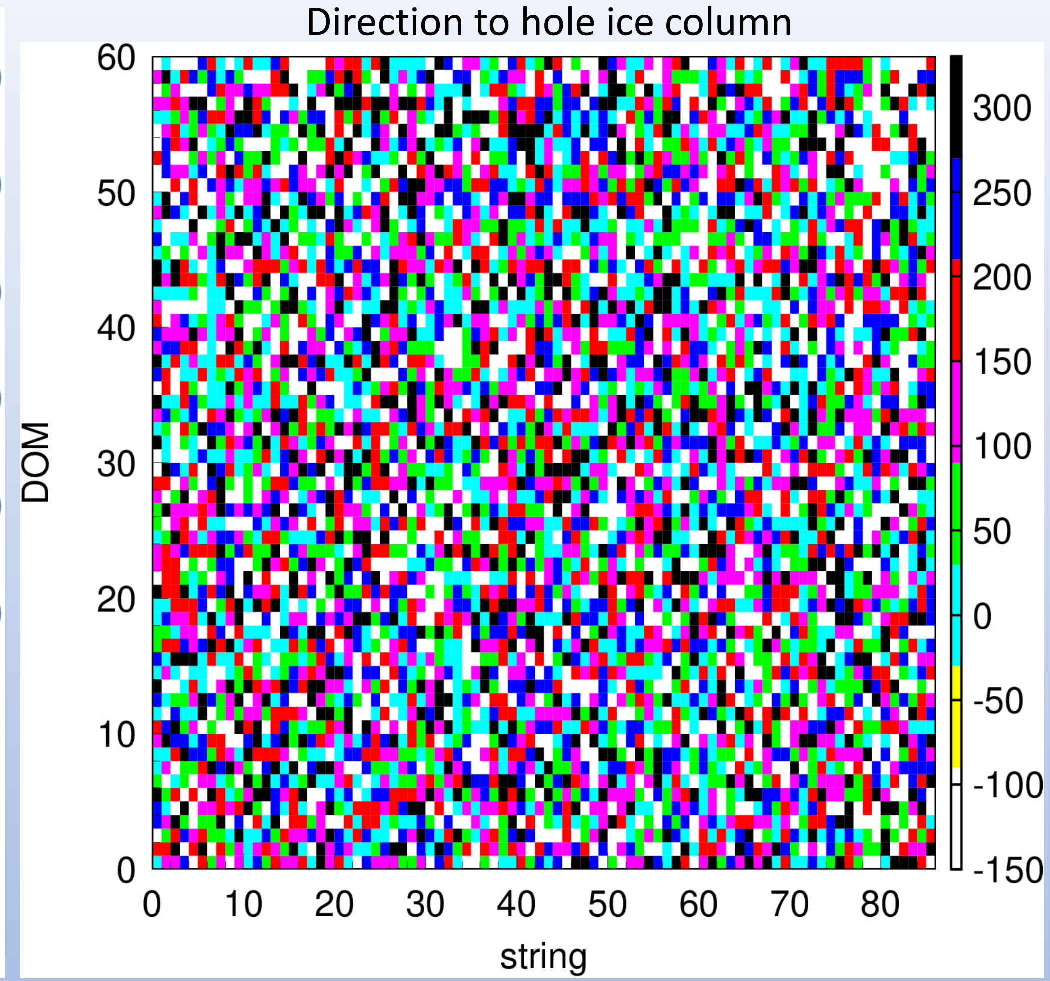
Identifying a problem region



Identifying a problem region: using unfolded profiles







DOM orientations and hole ice positions