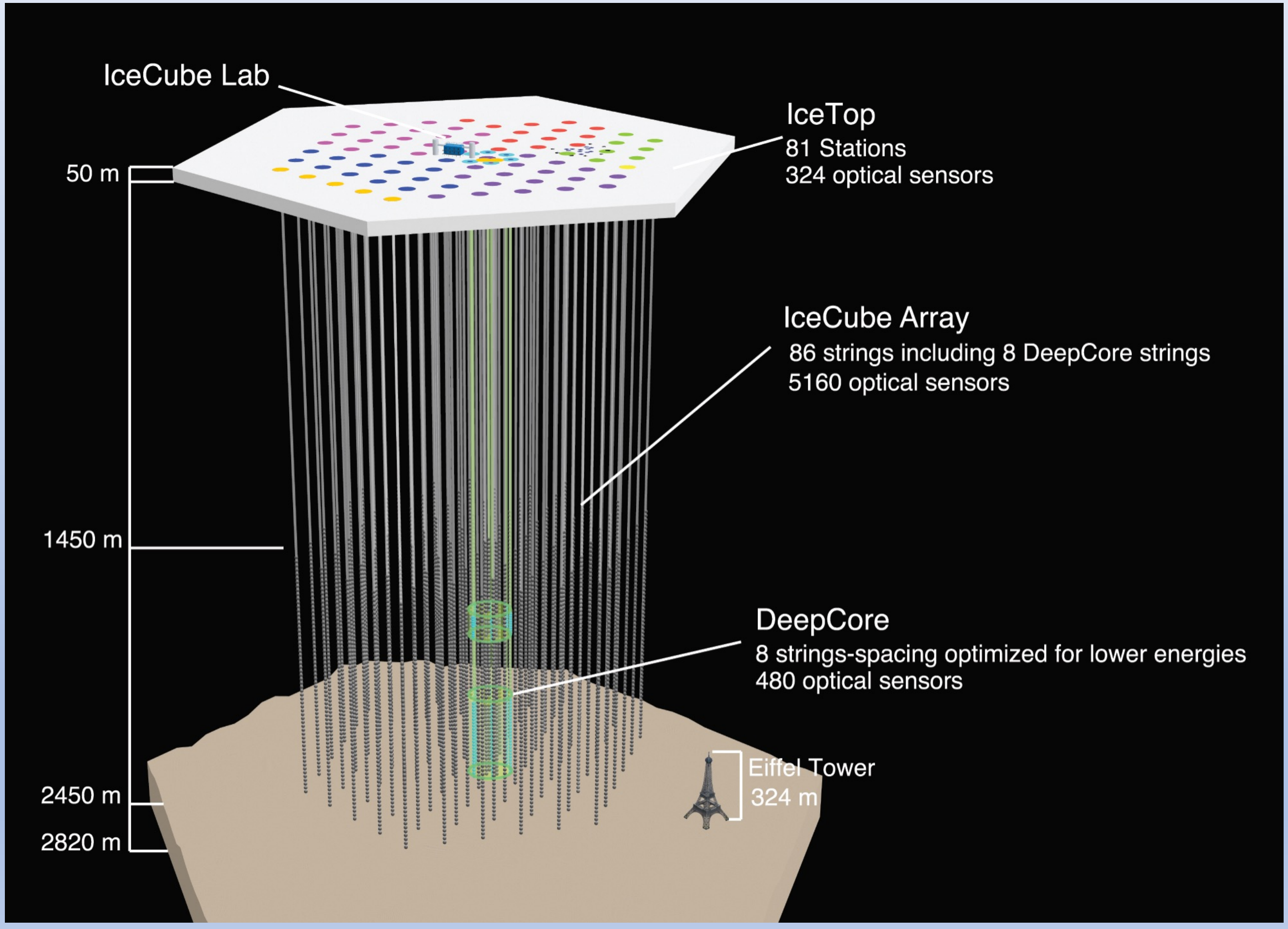
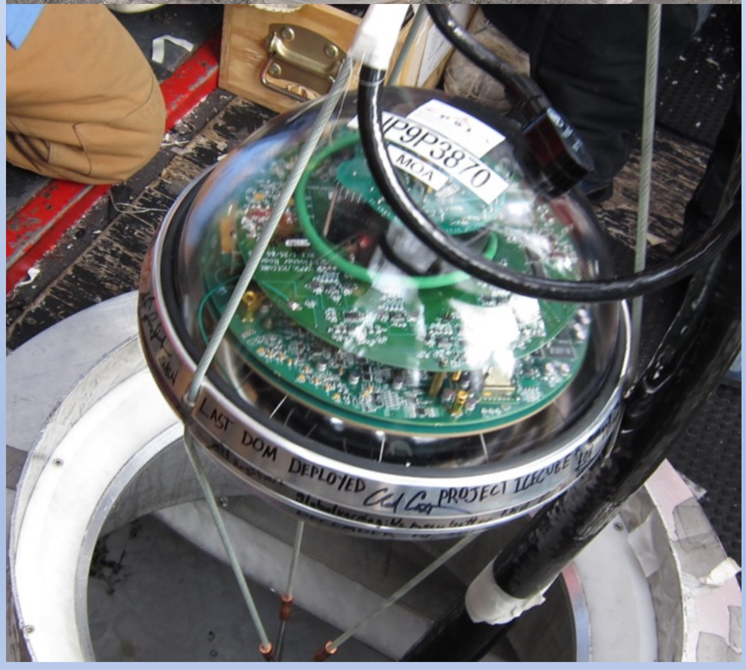
A calibration study of local ice and optical sensor properties in IceCube





Dmitry Chirkin, UW-Madison, for the IceCube collaboration

In-situ light calibration datasets

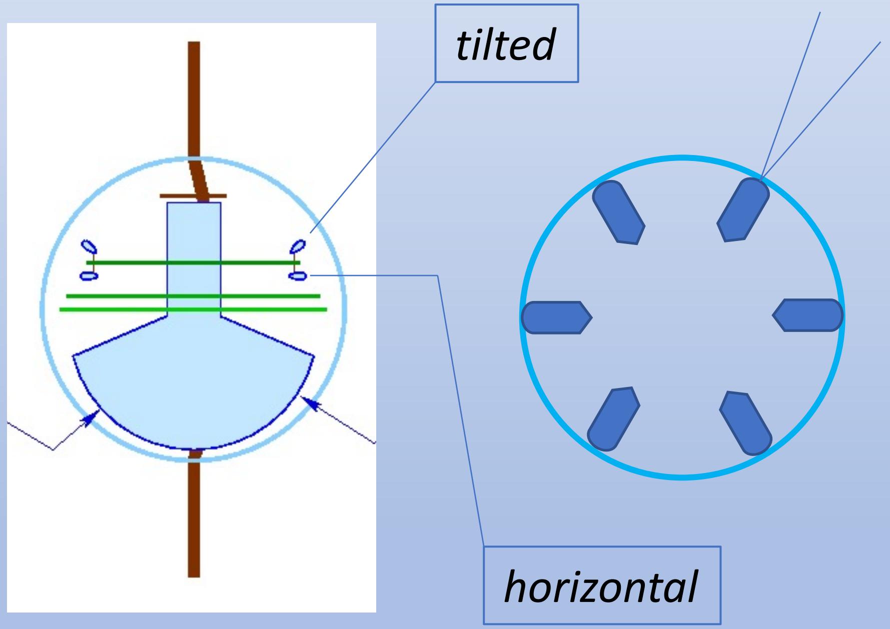
All-purpose data set: all 6 horizonal LEDs used simultaneously, approximating a cylindrically-symmetric emission pattern

> *Was used without orientation data, or with unfolding of the emitted light pattern to the data*

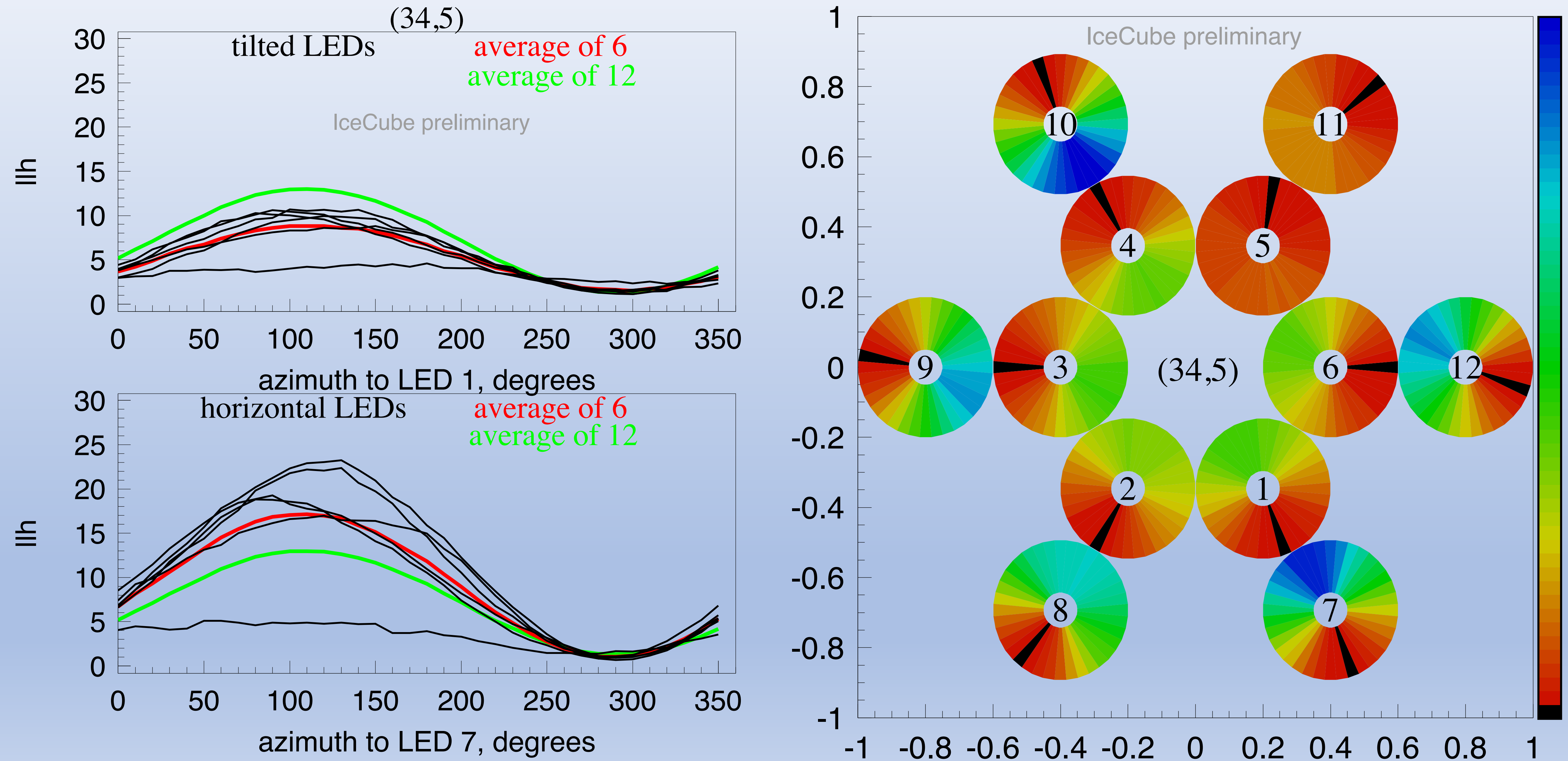
Single-LED data set: each of 6 tilted (LEDs 1-6) and 6 horizontal (7-12) LEDs were emitting light individually.

> *This is a more reach data set, but requires knowing the azimuthal orientation of all DOMs*

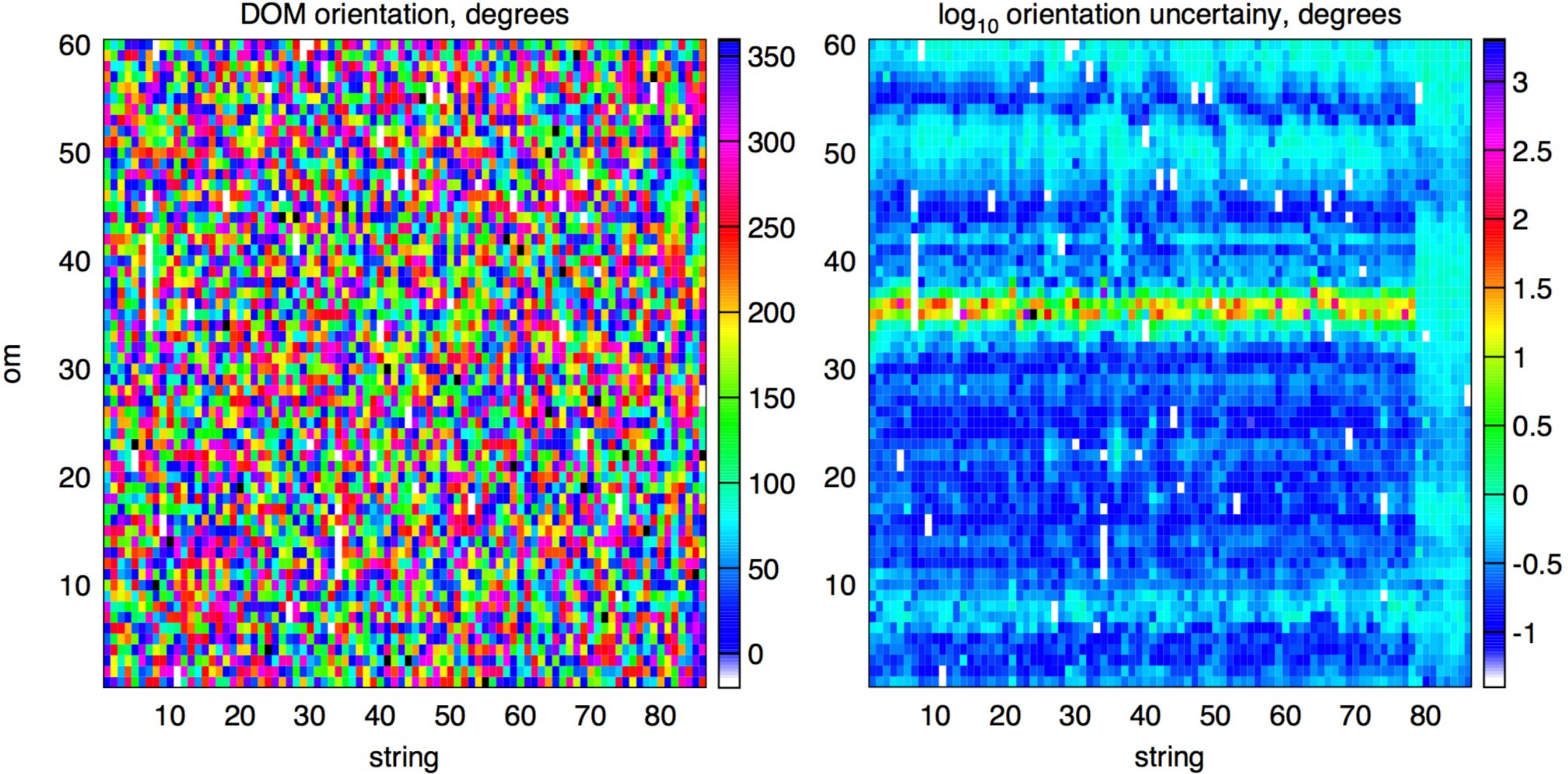
We carried out a simulation campaign to reconstruct azimuthal orientation of all DOMs in the detector



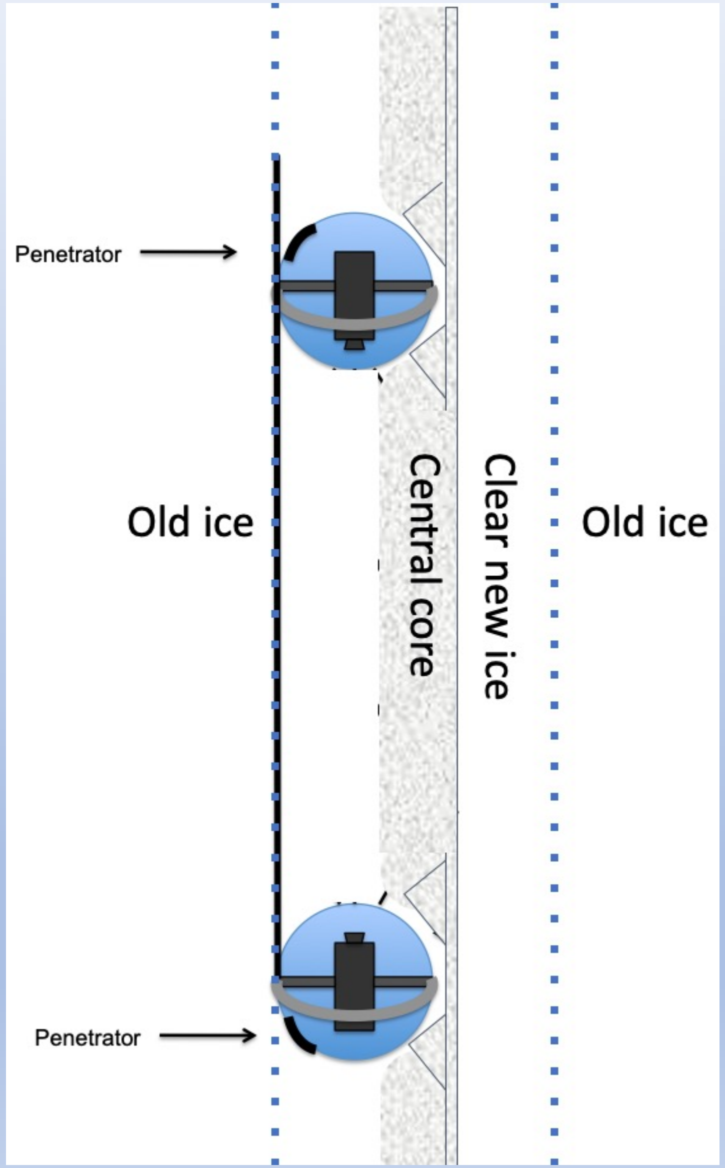
simulating azimuthal directions in 10° increments



DOM azimuthal orientations



Model of the Hole Ice from the Swedish Camera

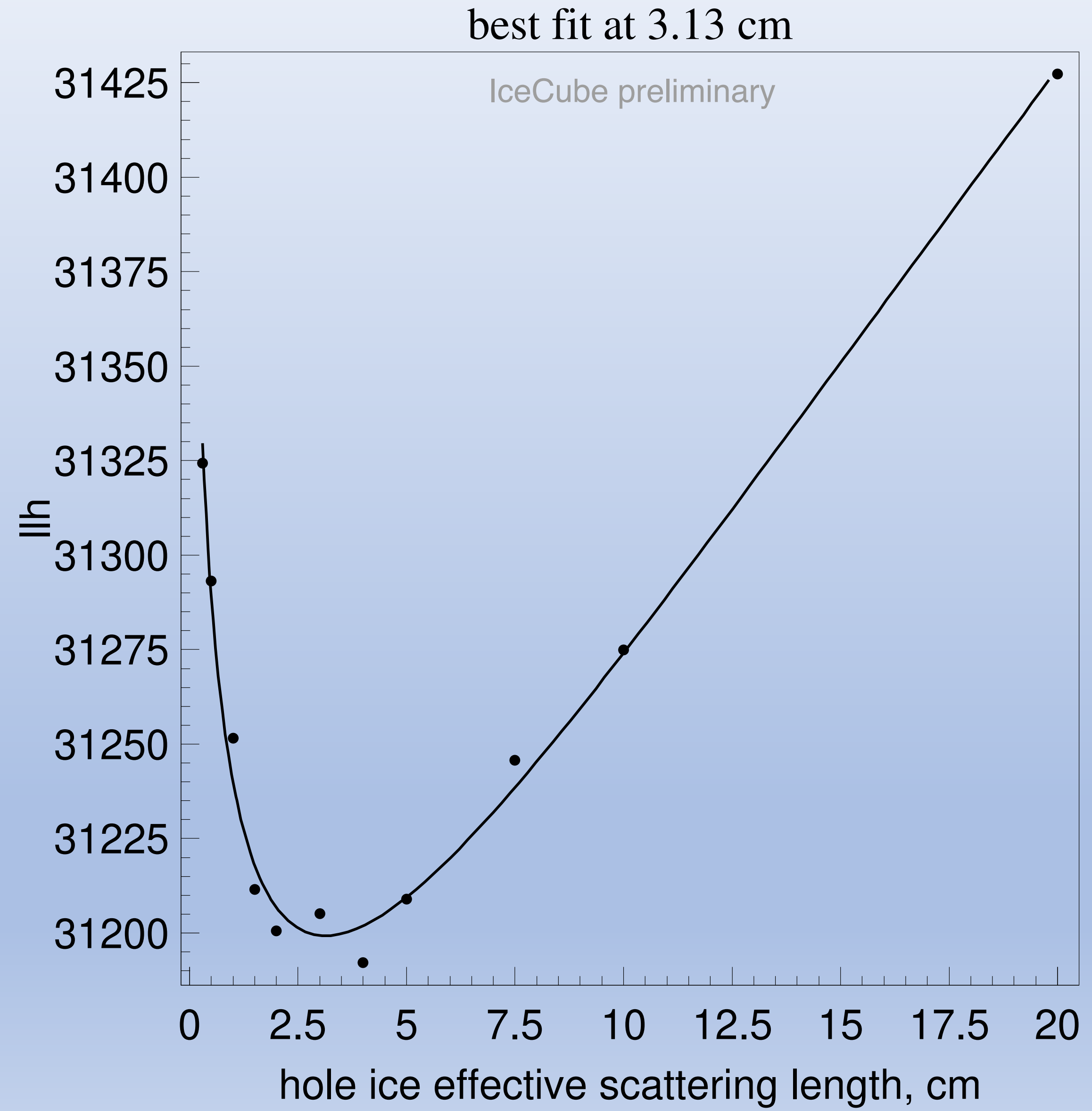


DOM touches the hole wall, is 2/3 of the hole diameter

Most of the hole ice is transparent, except for the milky column centered in the hole, 1/3 of hole diameter wide

Milky column of the hole ice diameter is ½ of DOM diameter

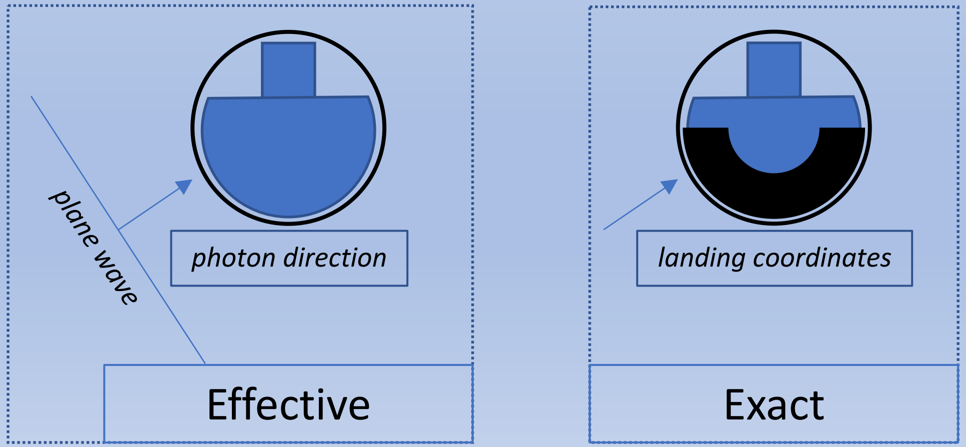
Fitting the scattering length of the hole ice column



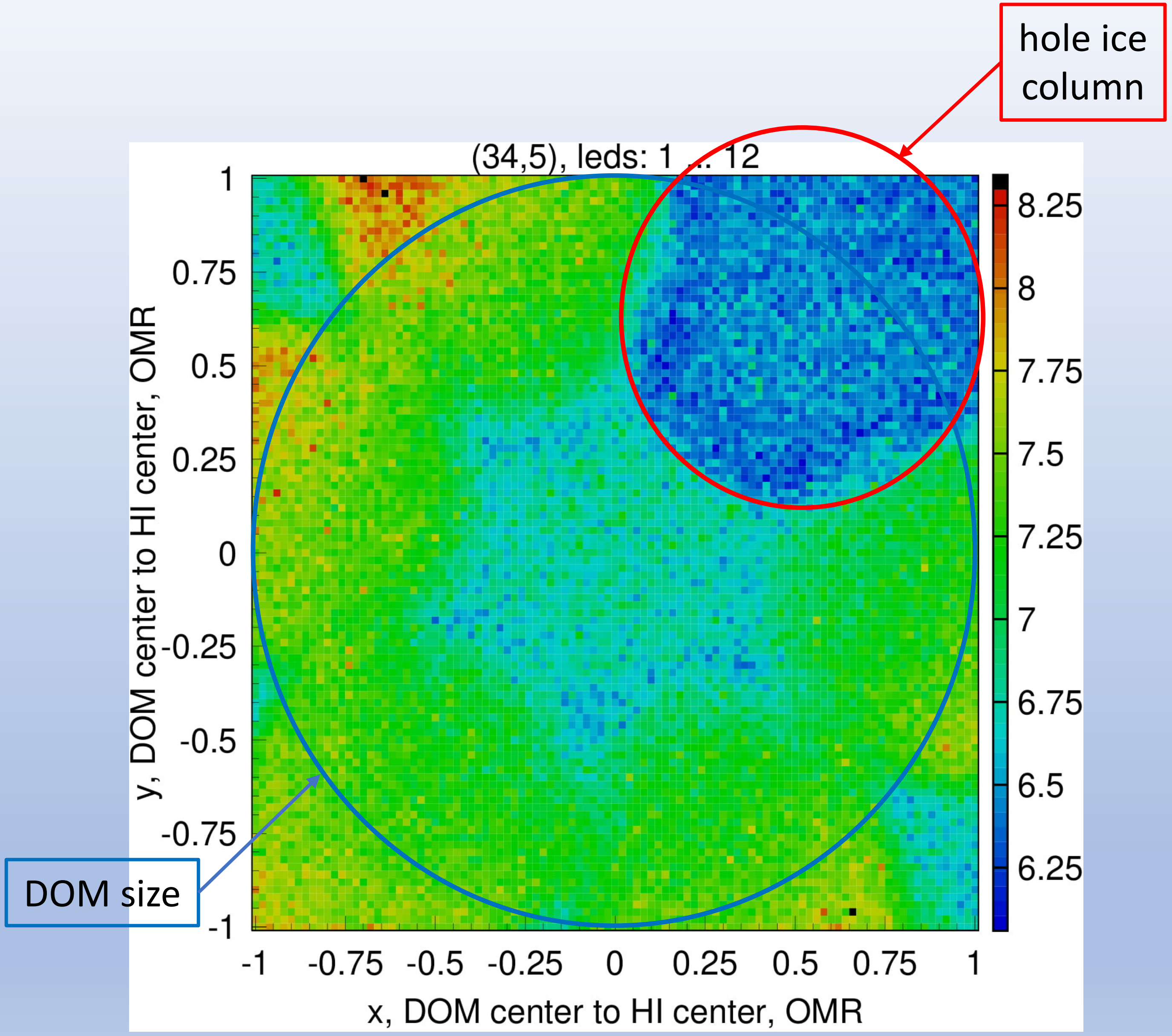
Fitting scattering in hole ice with nominal-size DOMs and exact angular sensitivity model.

Hole ice diameter is fixed at 0.5 that of DOM.

Here the hole ice column is perfectly centered on each string, and the bubbly column of the hole ice is only simulated *at receiver* DOMs



Hole Ice Position Fits



Emitter-side fits:

- shift the DOMs around the hole ice column near the emitters
- only simulate hole ice column for young photons (of age less than 20 ns)
- can simulate oversized DOMs with the *effective* angular sensitivity description

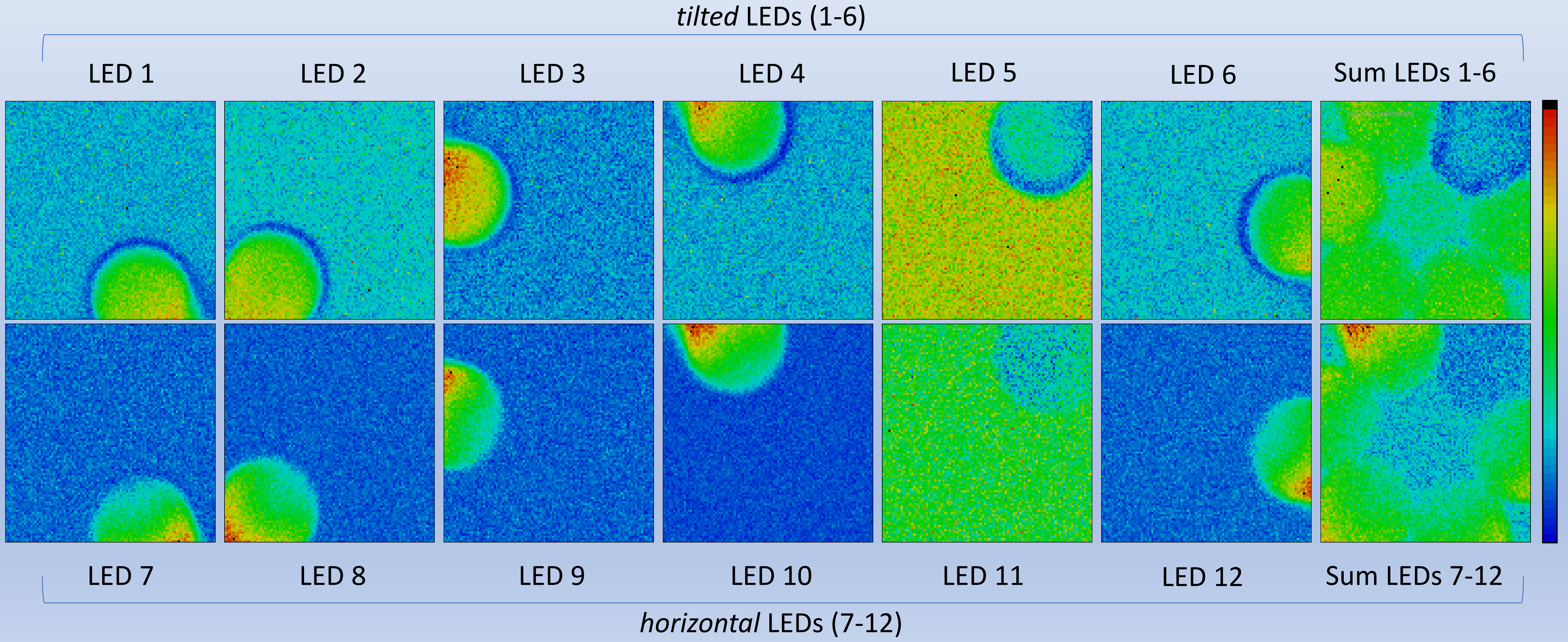
Receiver-side fits:

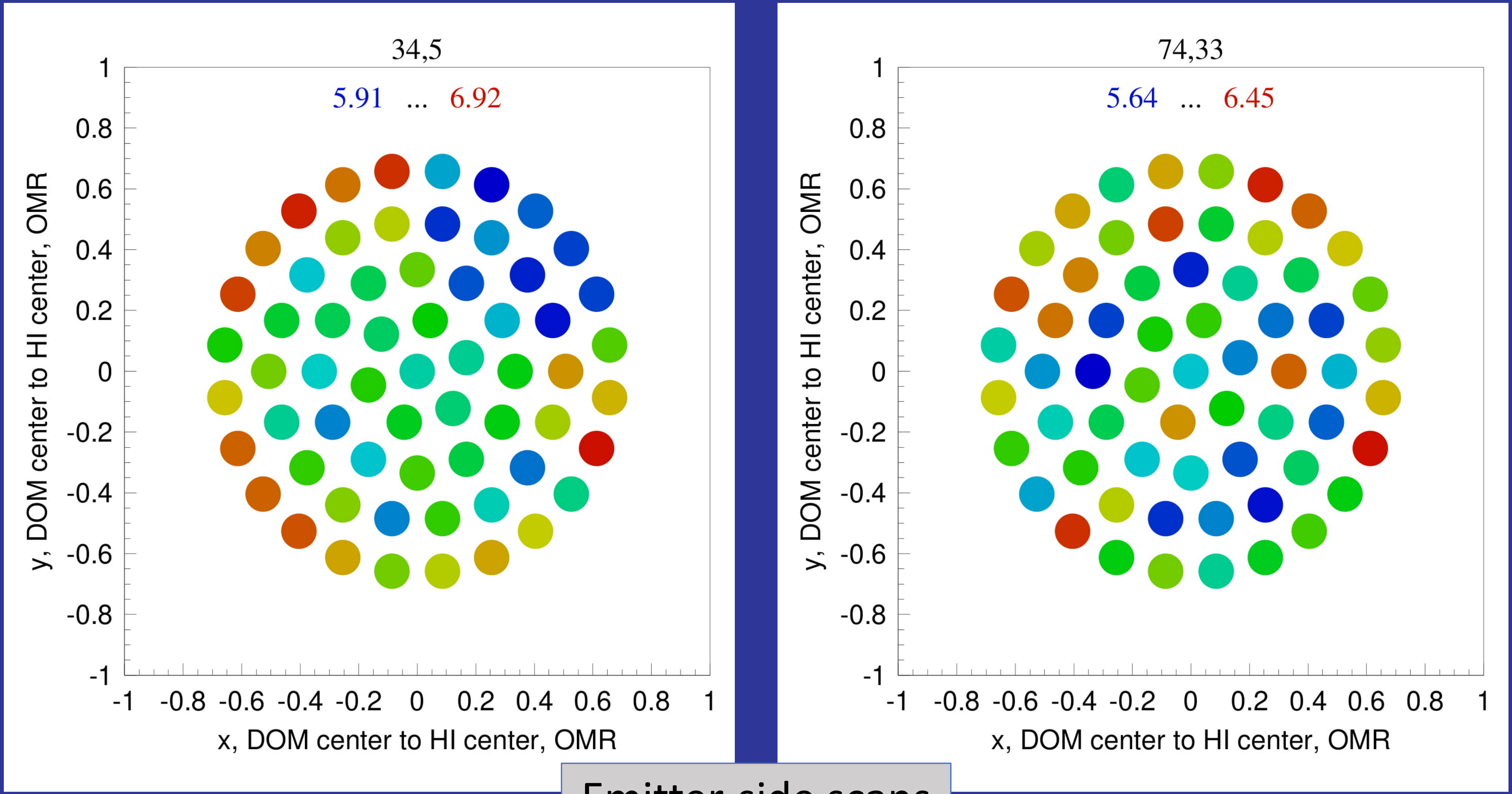
- shift the DOMs around the hole ice column near the receivers
- only simulate hole ice column for older photons (of age greater than 20 ns)
- need to simulate nominal-size DOMs and *exact* angular sensitivity description

Using 61-point grid (uniform packing on a circle)

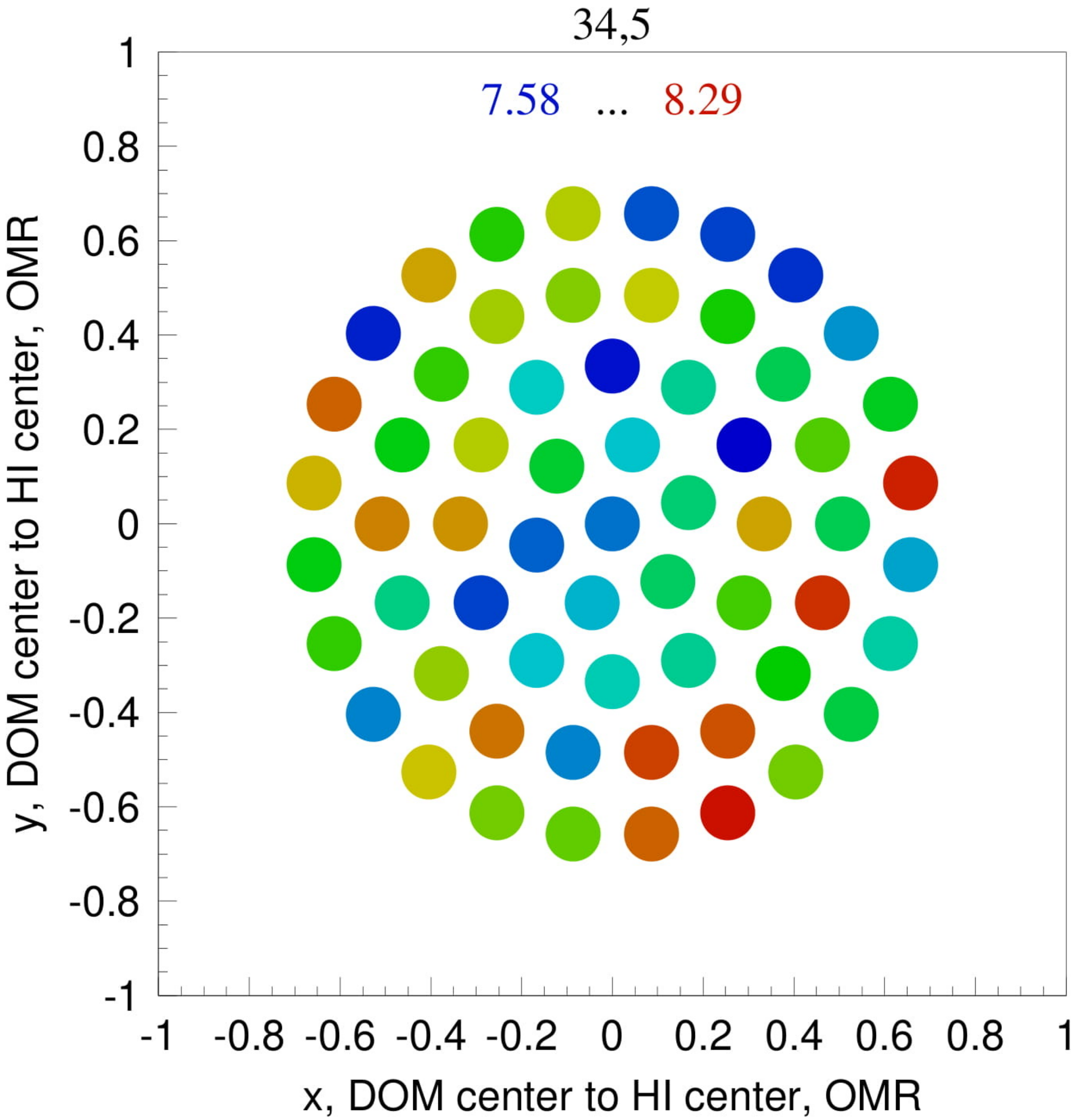
High-resolution hole ice scans for DOM 34,5

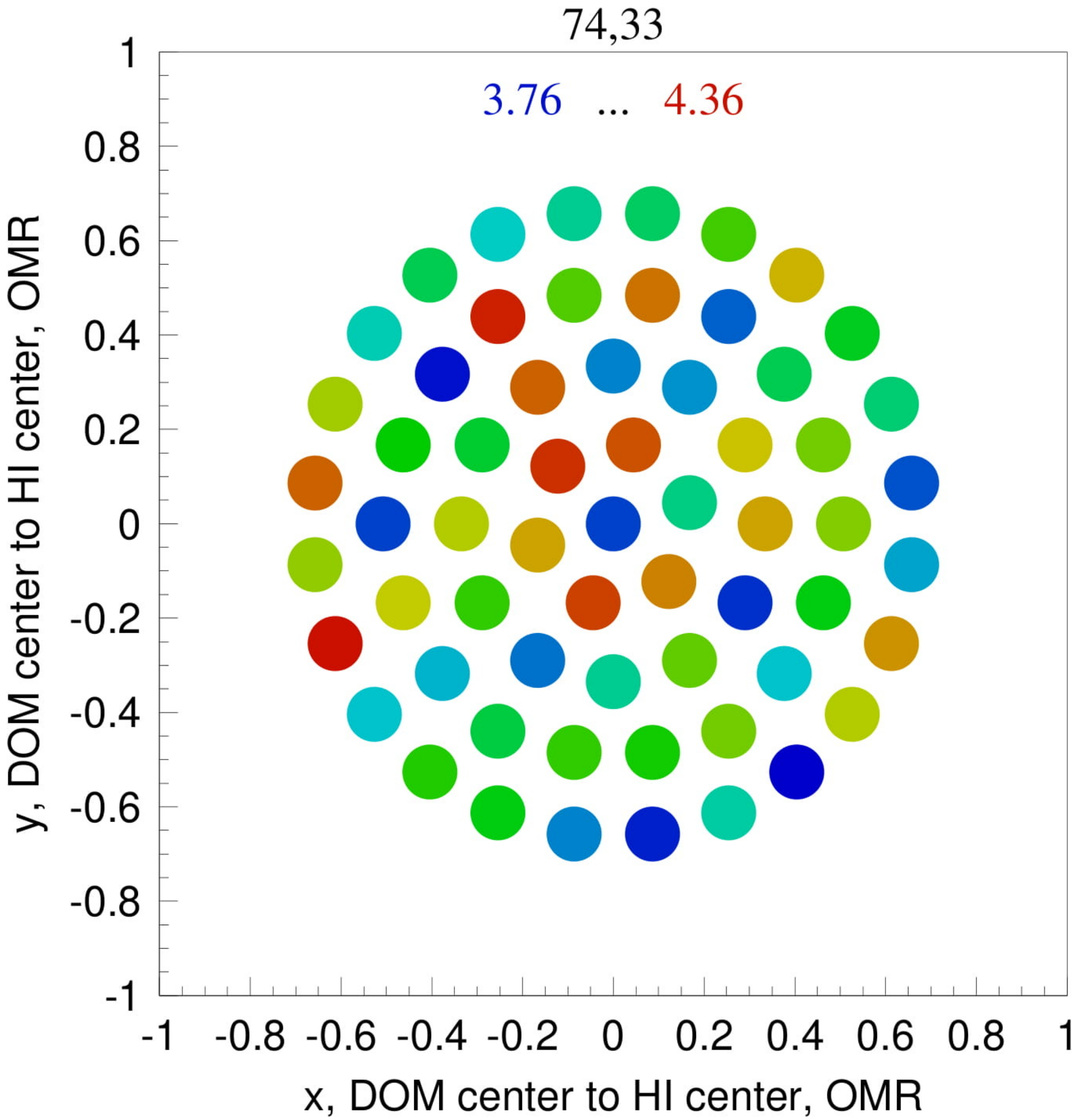
<u>*emitter-side* fits</u>



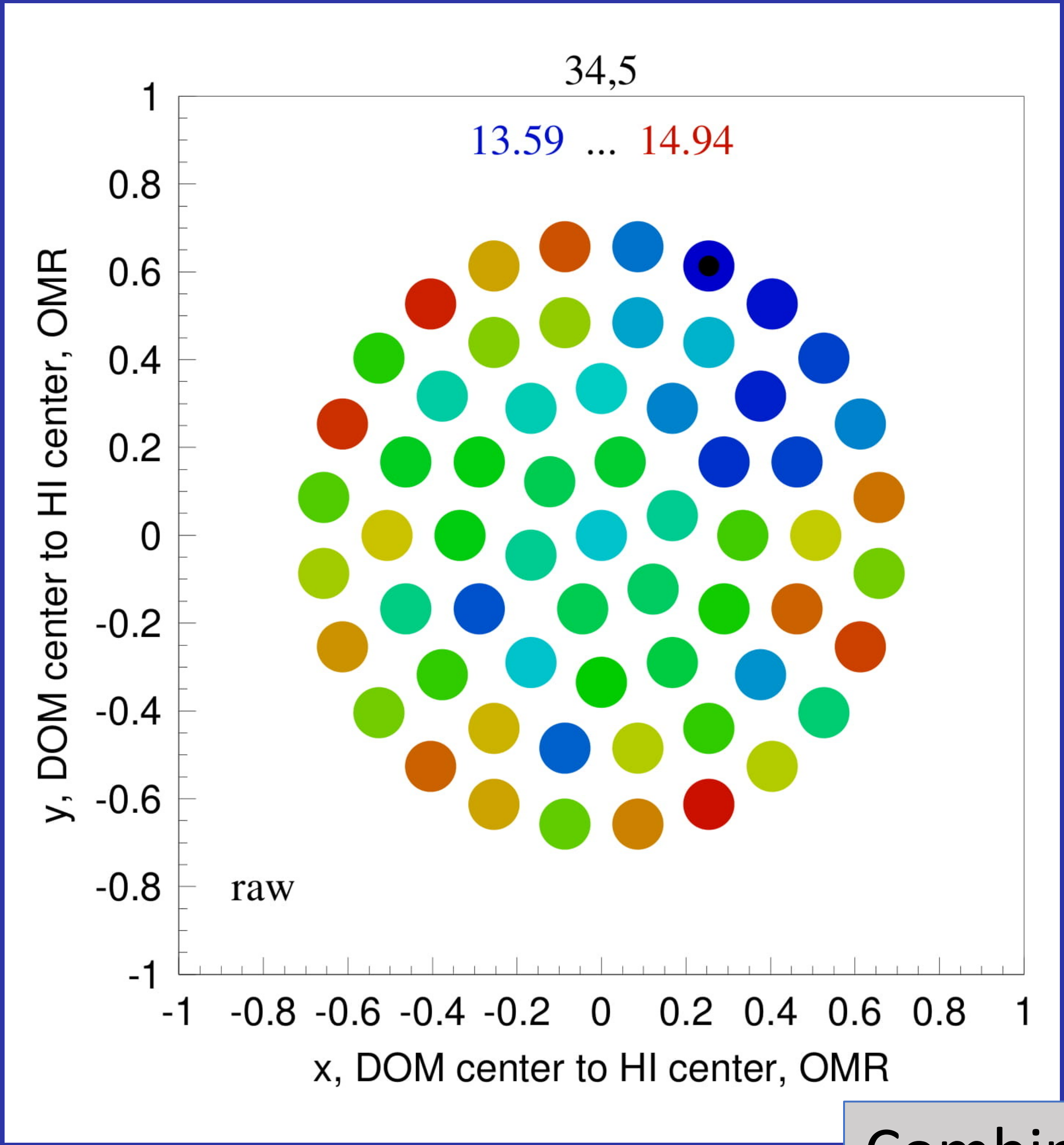


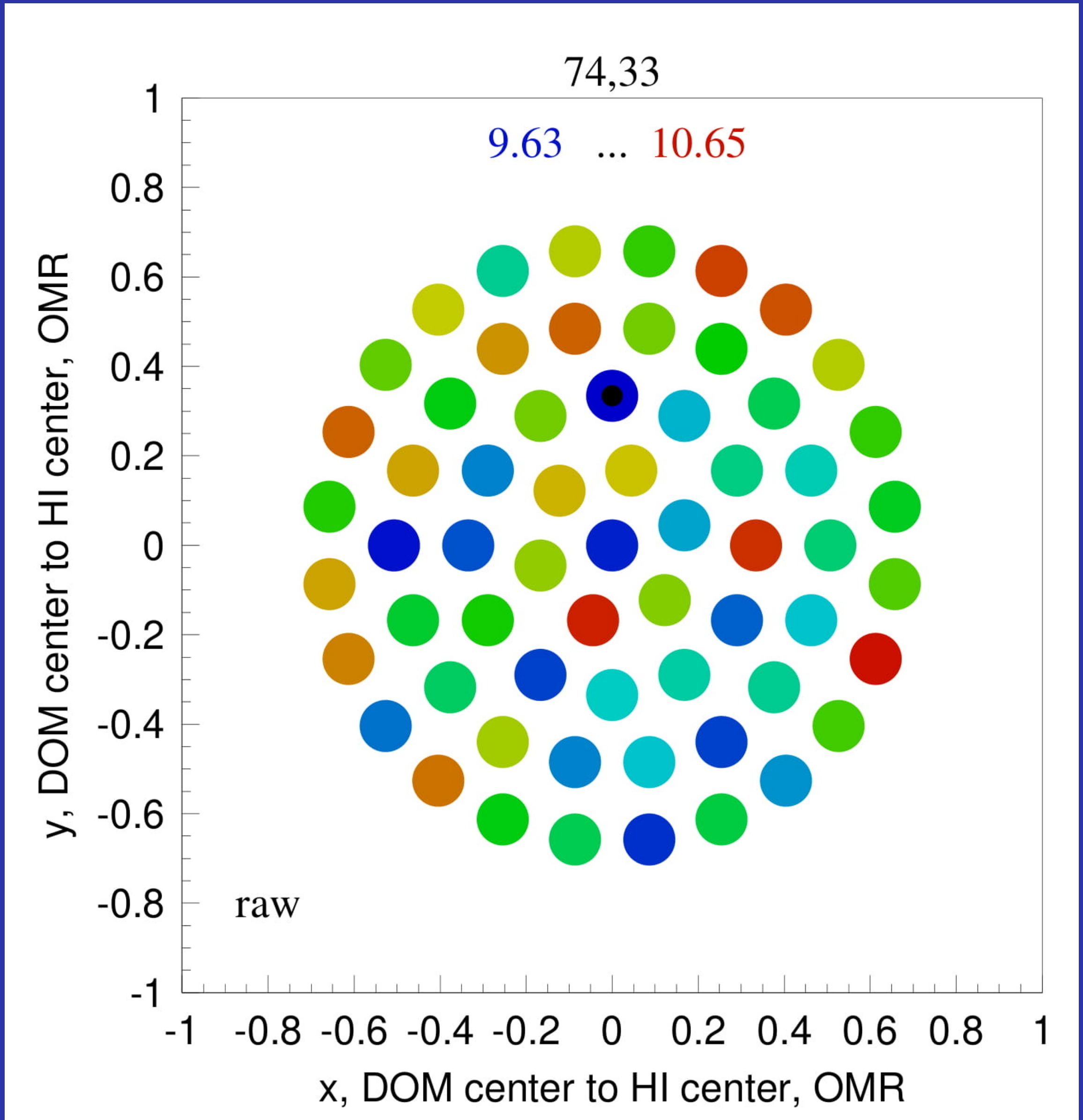
Emitter-side scans



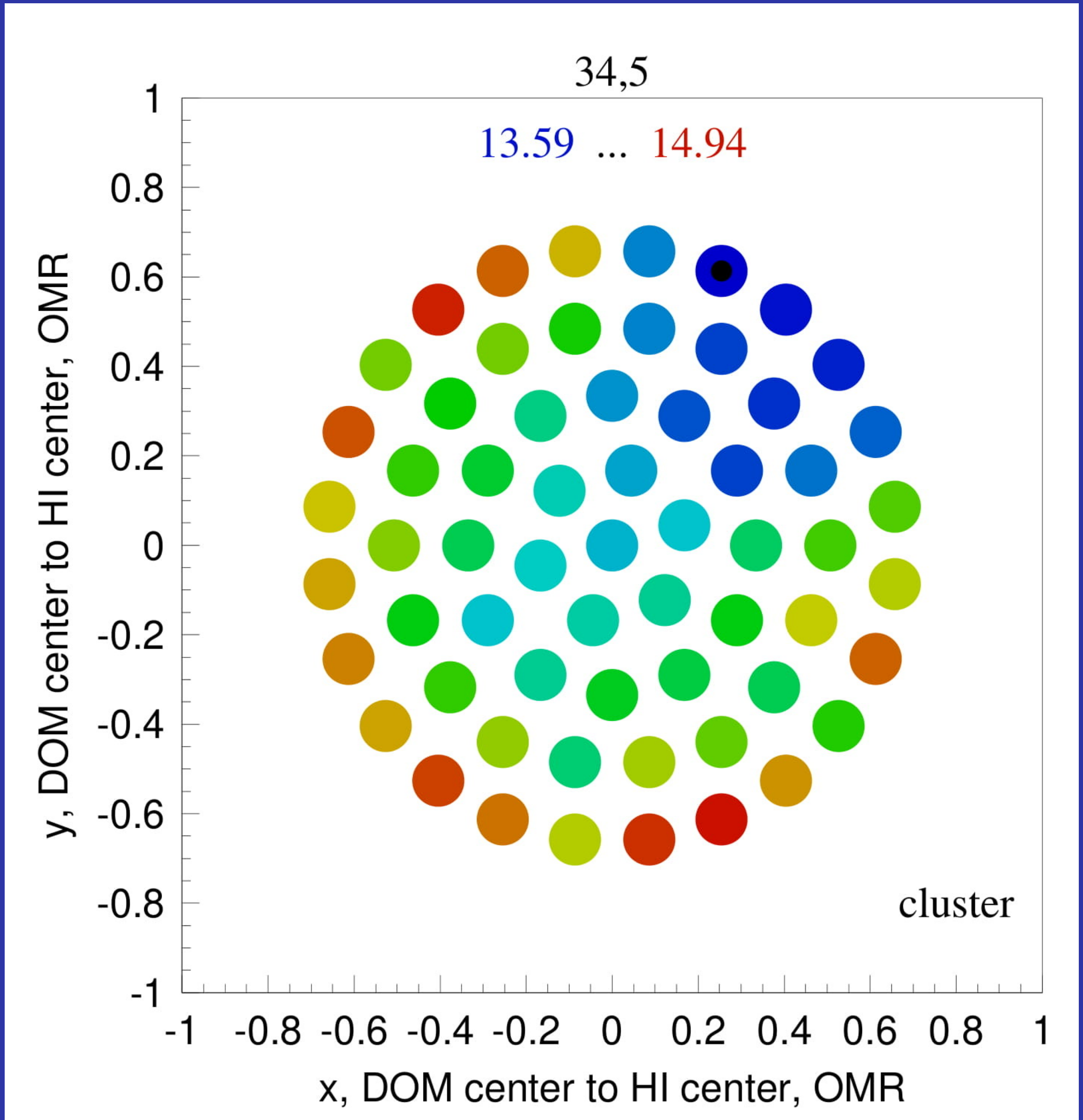


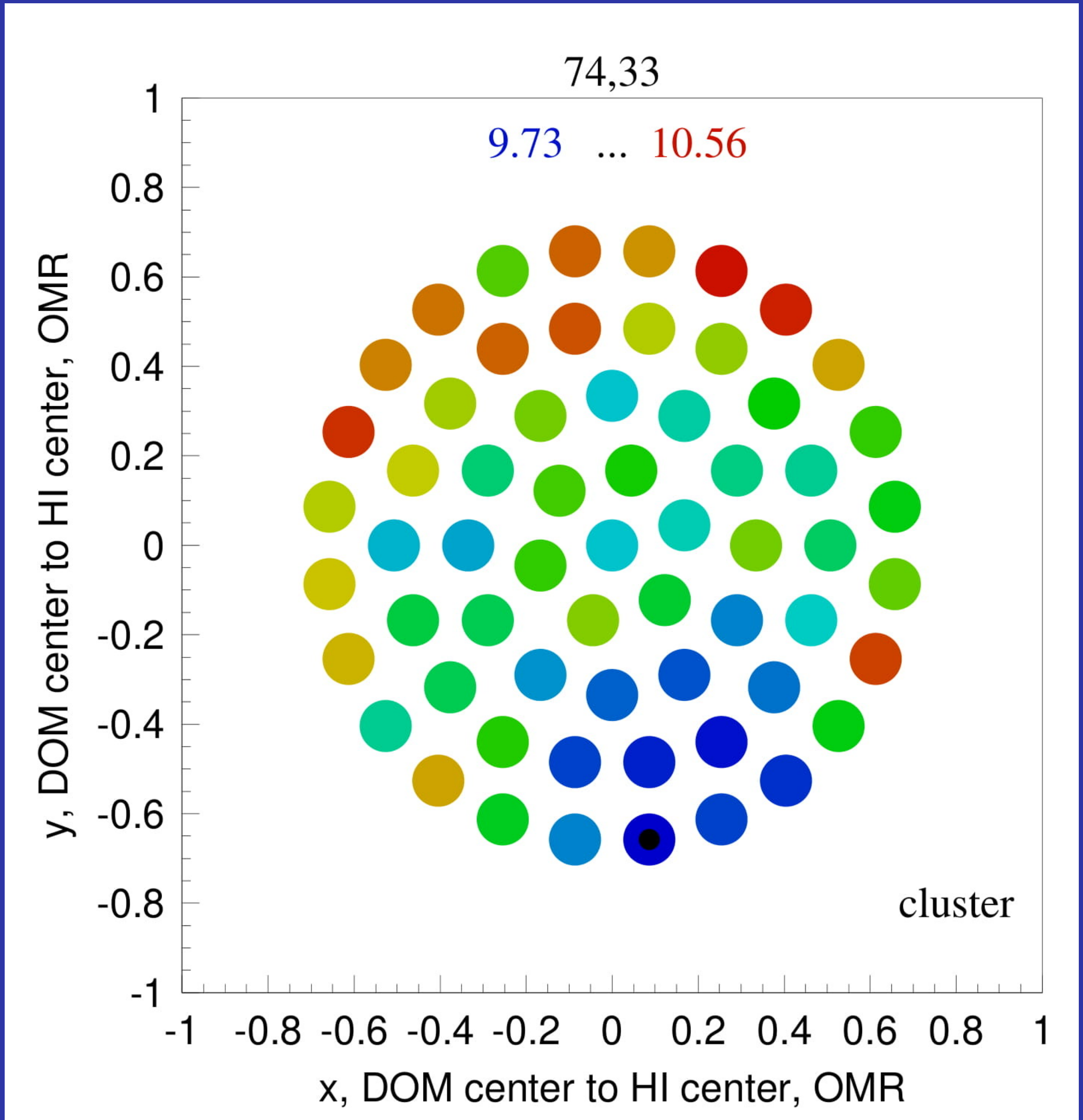
Receiver-side scans





Combined scans



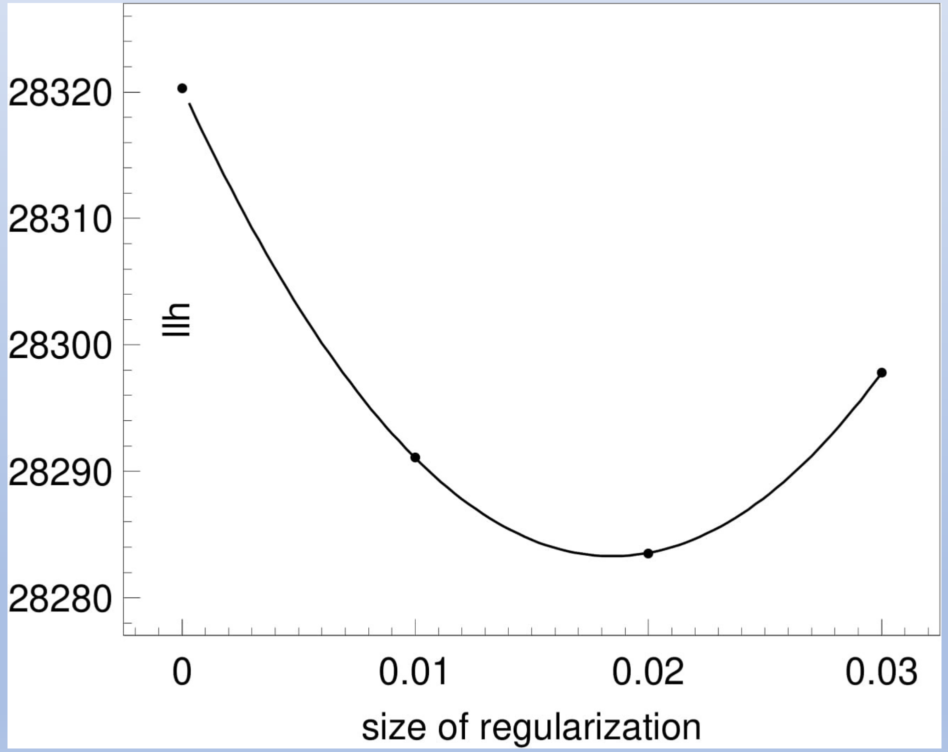


Cluster/smoothed scans

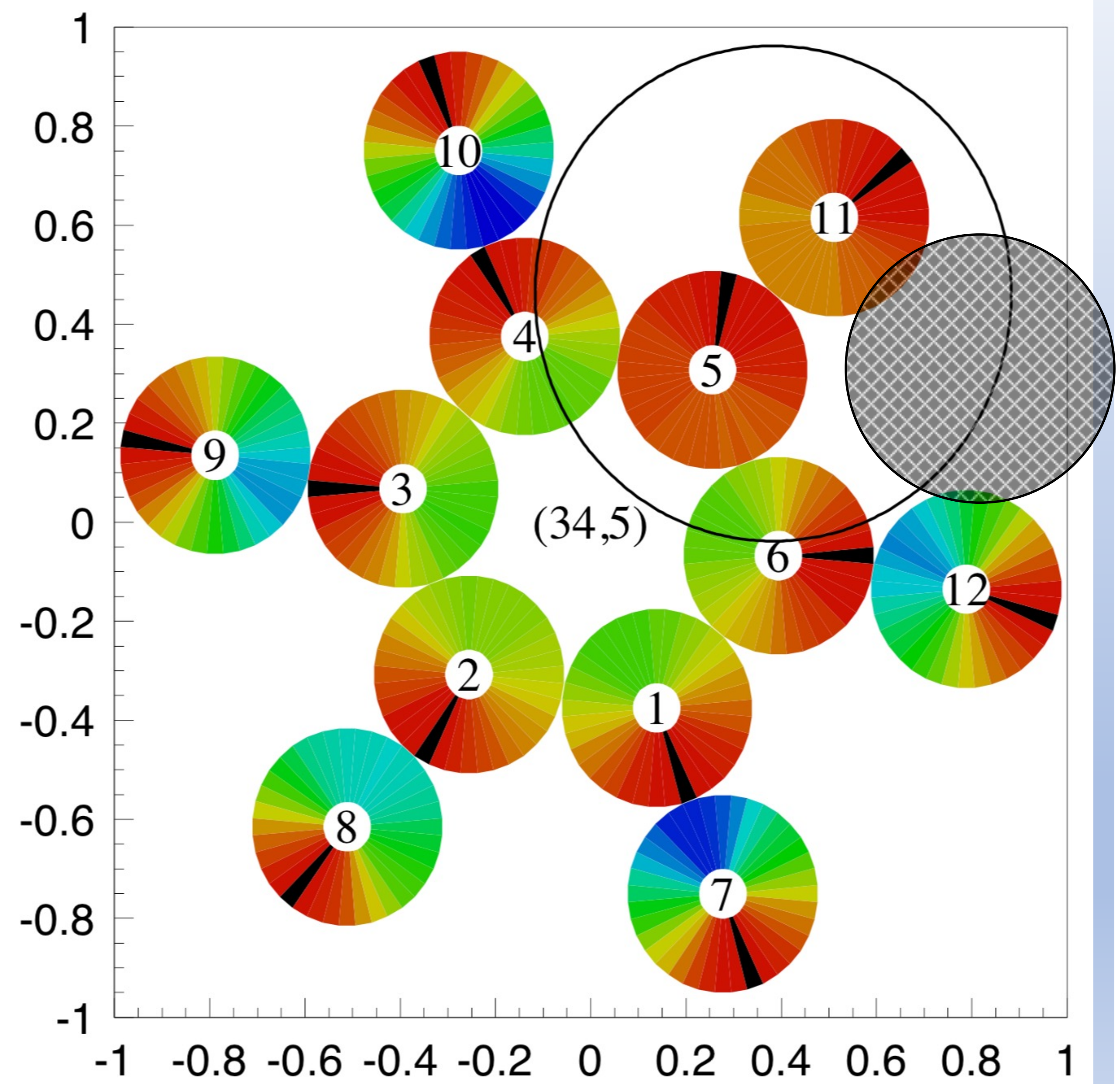
Cluster-search

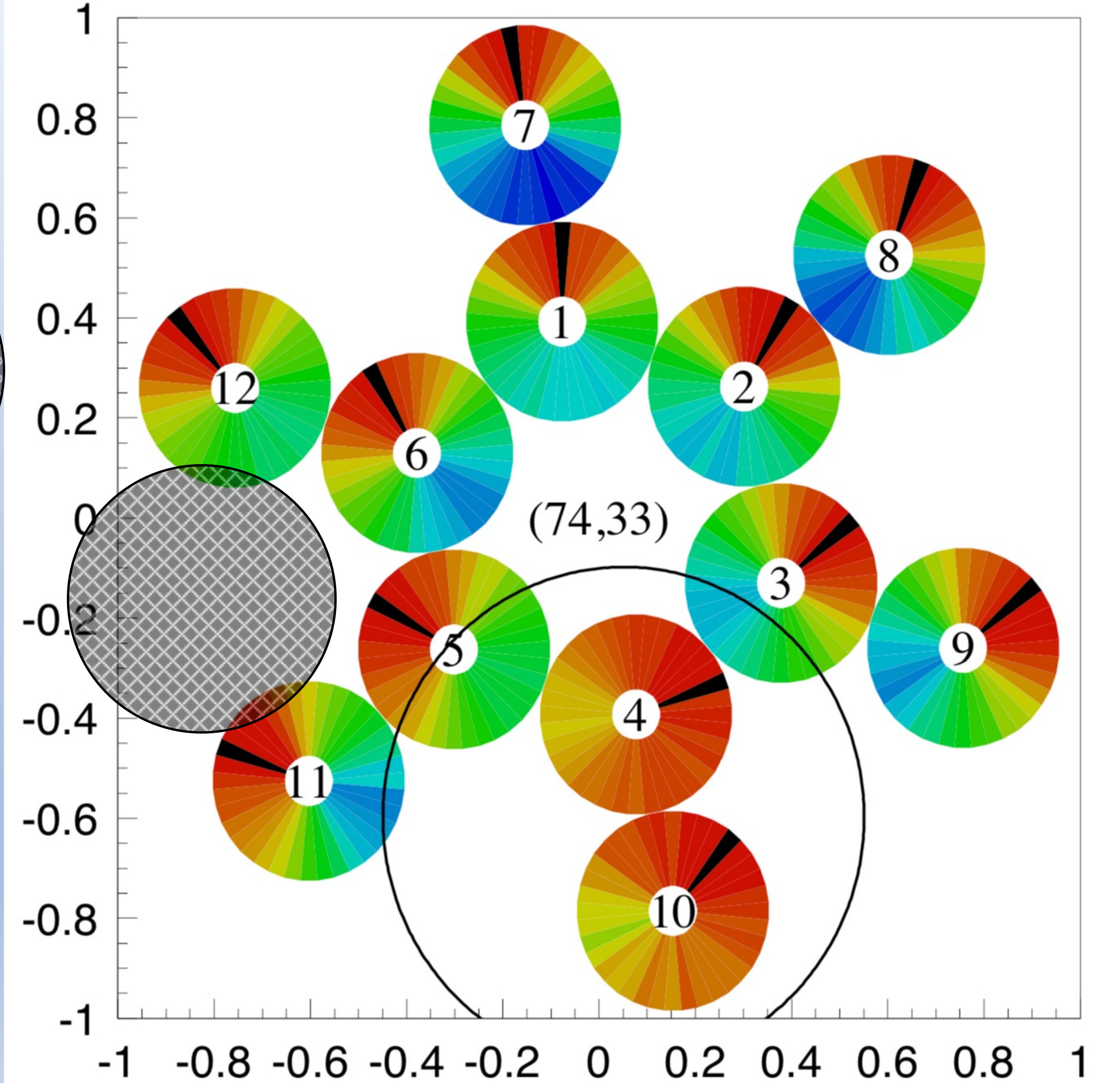
Developed a smoothing algorithm:

- *llh* value at each point is averaged over the entire grid with weights $1/(r^2+a^2)$. Here r^2 is distance squared to the weighted point
- Value of a^2 is optimized. $a^2=0$ corresponds to no smoothing (i.e., original combined map)
- $a^2=0.02$ is chosen for best result



Previously found anomalies in the azimuthal orientation study: related to hole ice?





Fitting relative in-ice DOM sensitivities

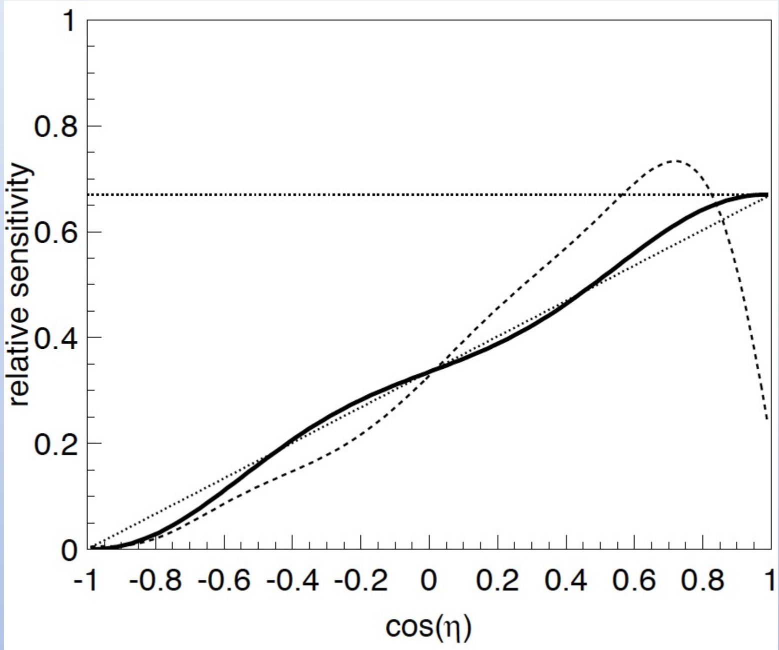
Starting with nominal values:

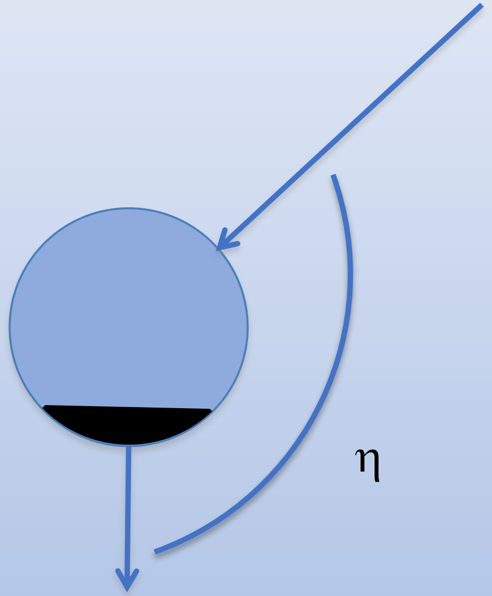
1. Produce high-statistics simulation
   → *the number of emitted photons is fitted for each LED*
   → *fitted RDEs are constrained to lie the 1/1.5 … 1.5 range*

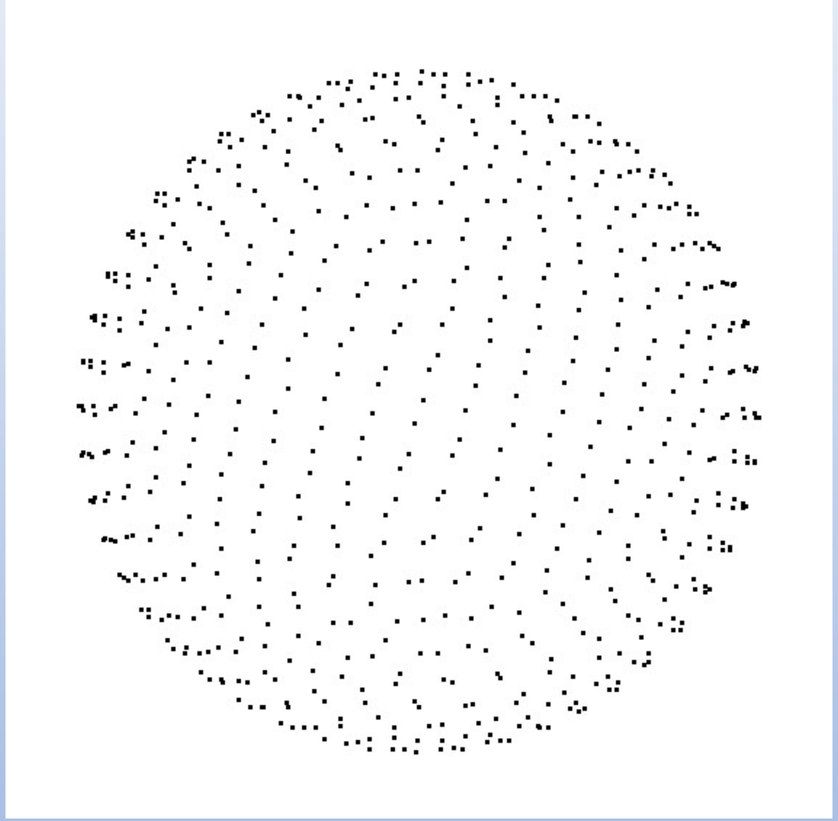
2. For each receiving DOM (individually), fit for the best RDE value

3. Repeat from step 1 with new RDE values

Fitting DOM orientations (tilt)

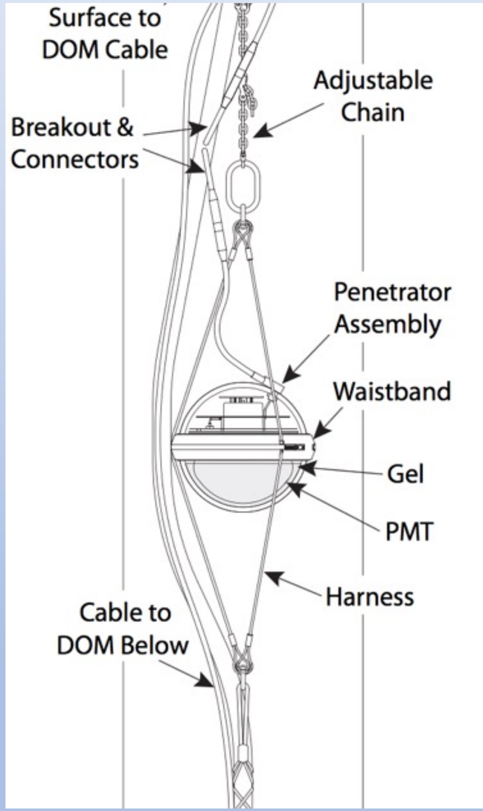






The chosen DOM angular sensitivity model is applied wrt. a set of directions.
Average of several best directions is chosen as the DOM “tilt”.
This ”tilt” is perceived mainly a tool to approximate the effect of the hole ice column.

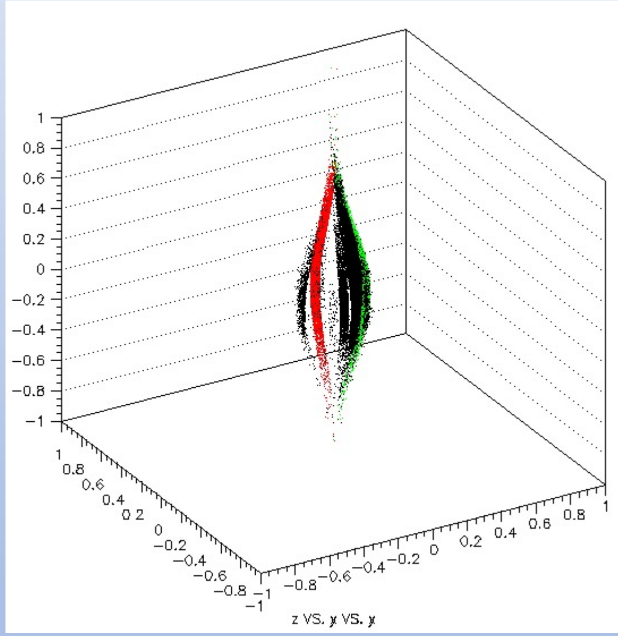
Direct fit of cable positions



Similar procedure to tilt fit, except choose from 360 possible azimuthal arrangements

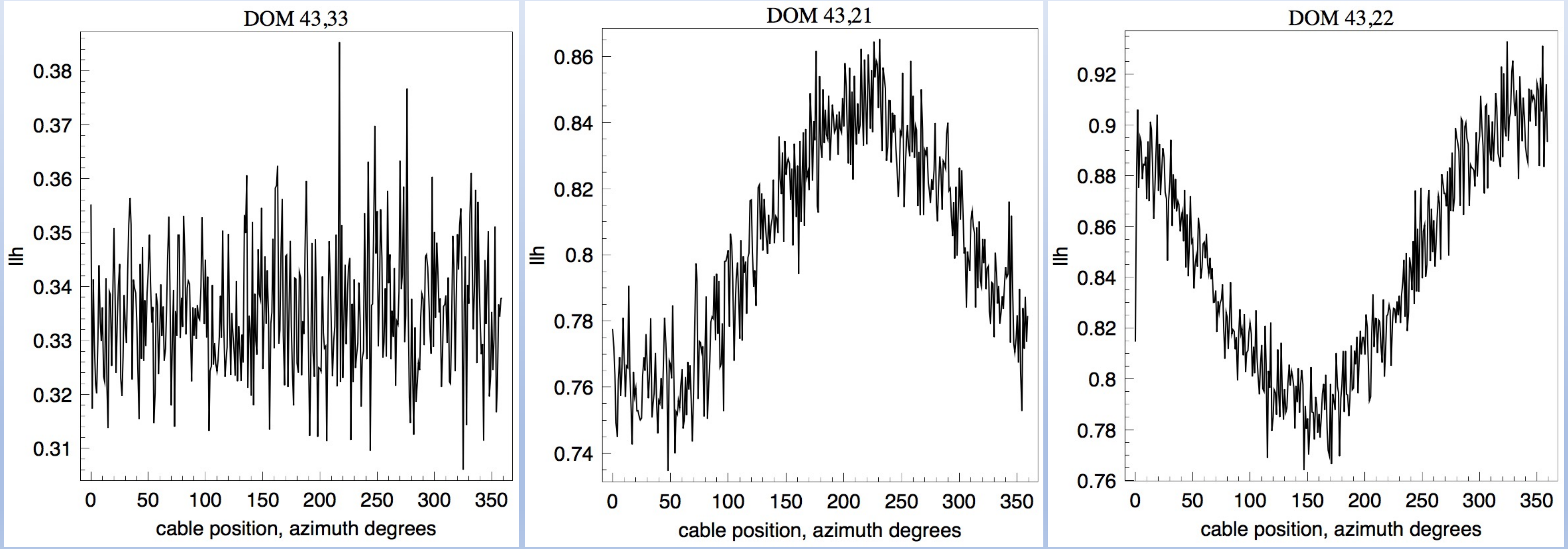
The photons are backtracked from the DOM surface to see if they intersect with the cable, and thrown out if they do

Simulation can be done with oversized DOMs, and photon hit coordinates extrapolated to standard-radius DOM surface, while keeping the photon direction at hit point.

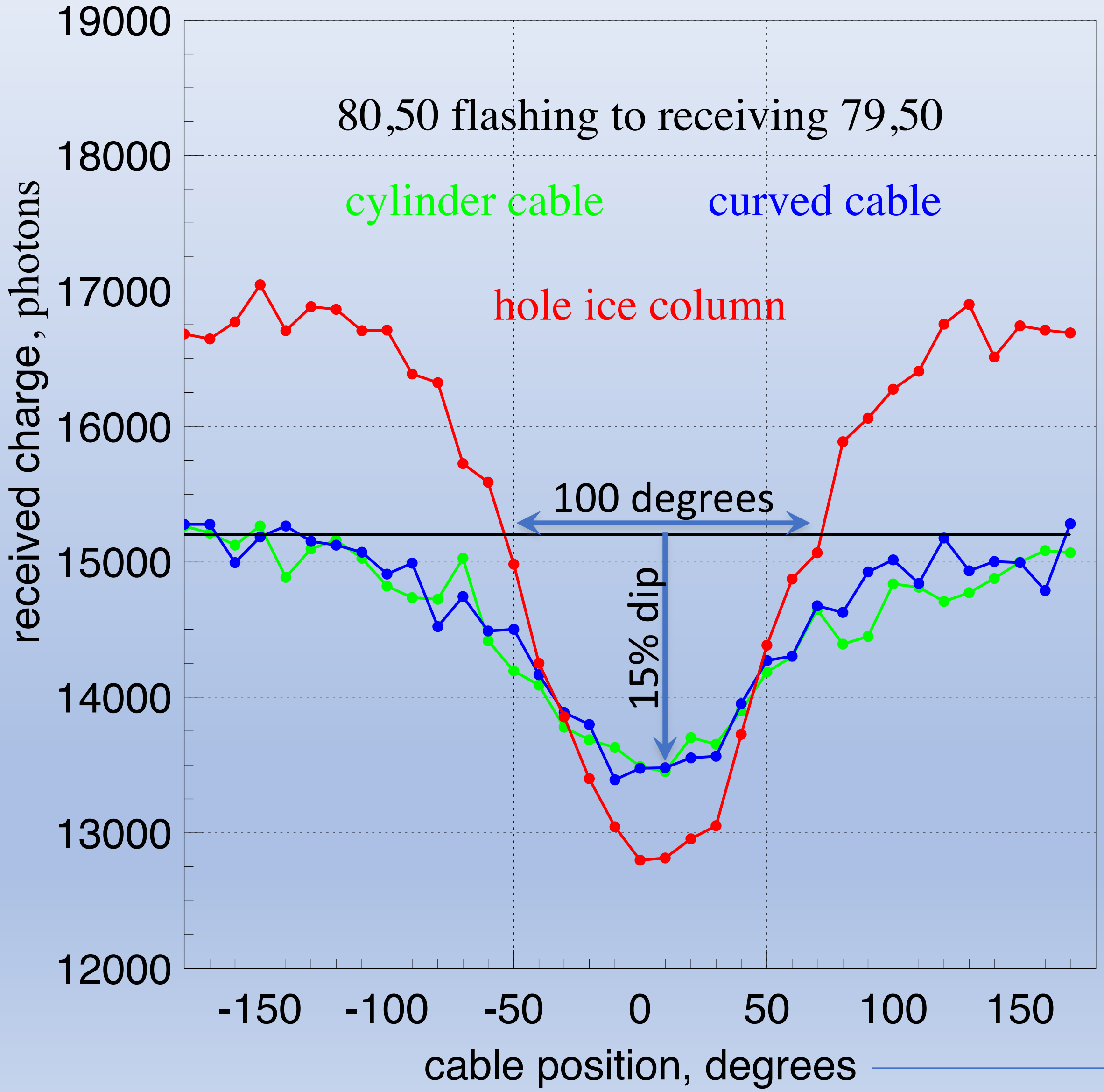


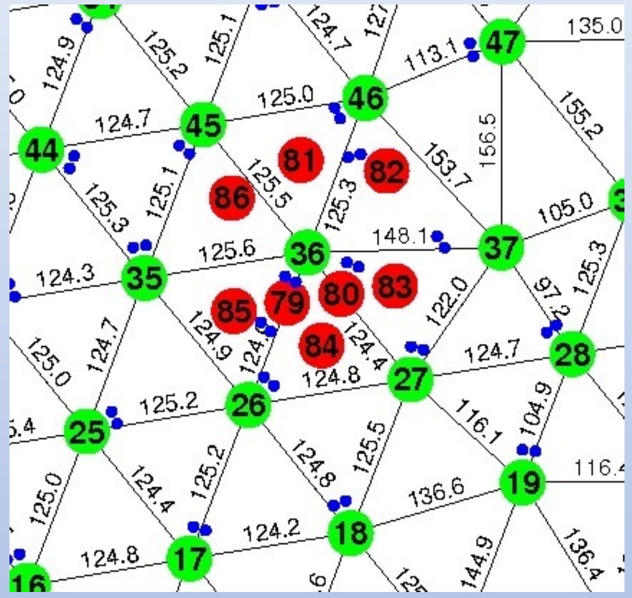
Coordinates of photon path intersection points with cable for different cable azimuthal orientations

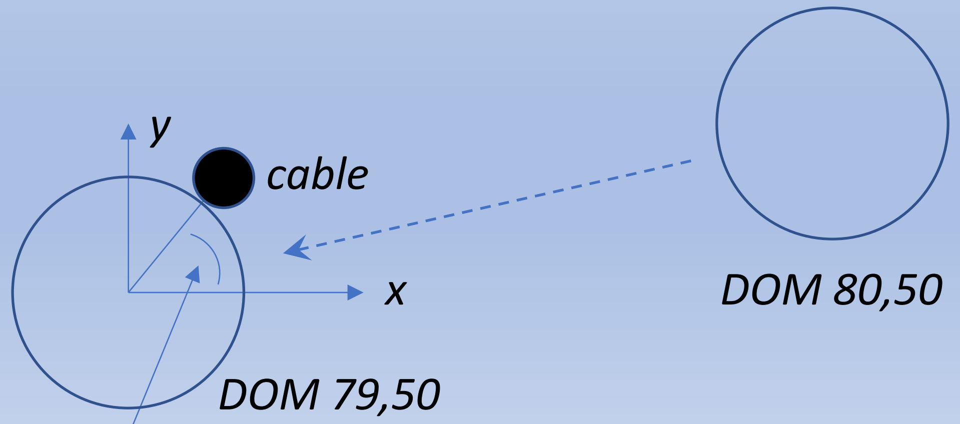
Fitting cable positions

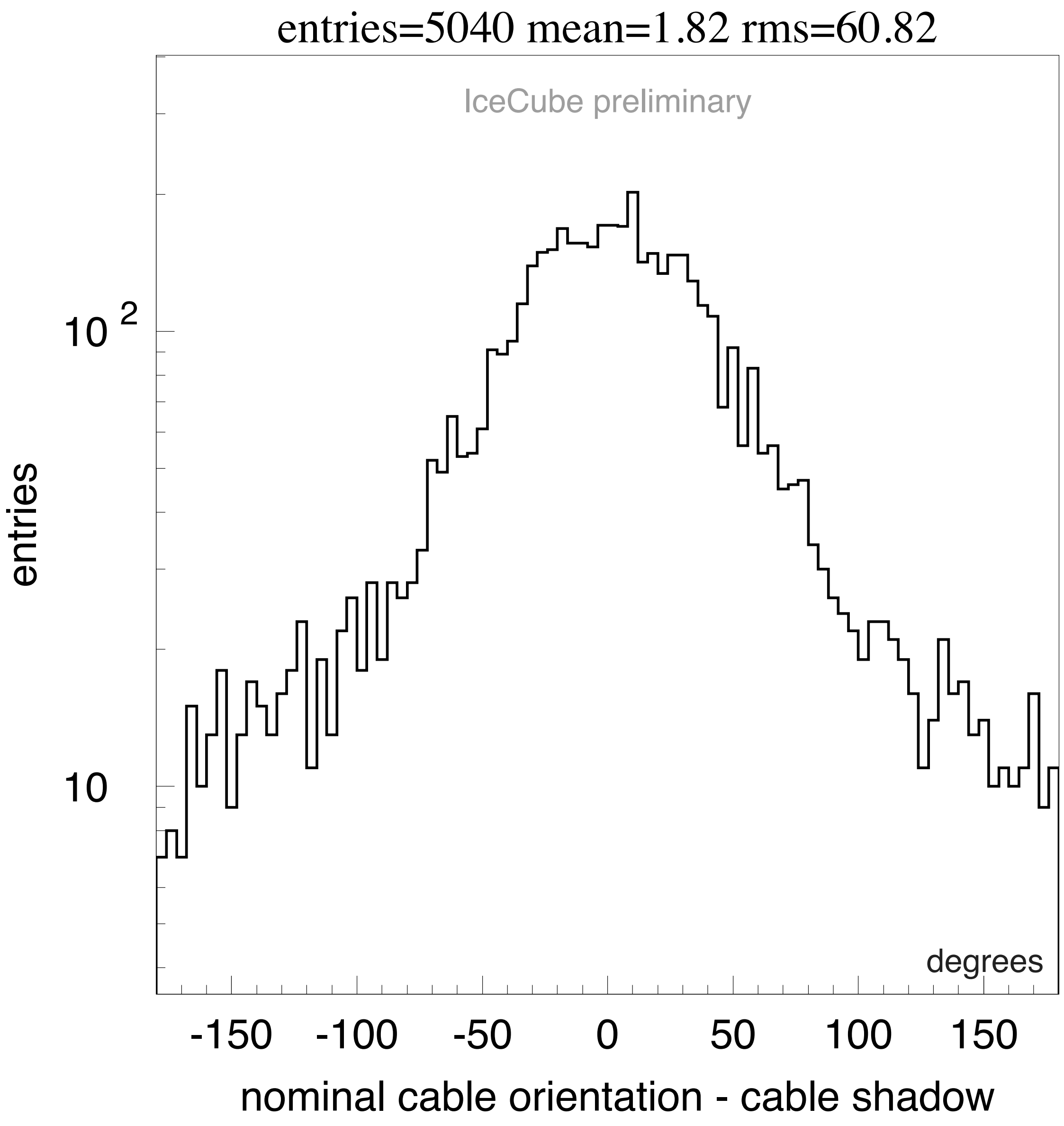


Size of the effect: hole ice and cable shadow



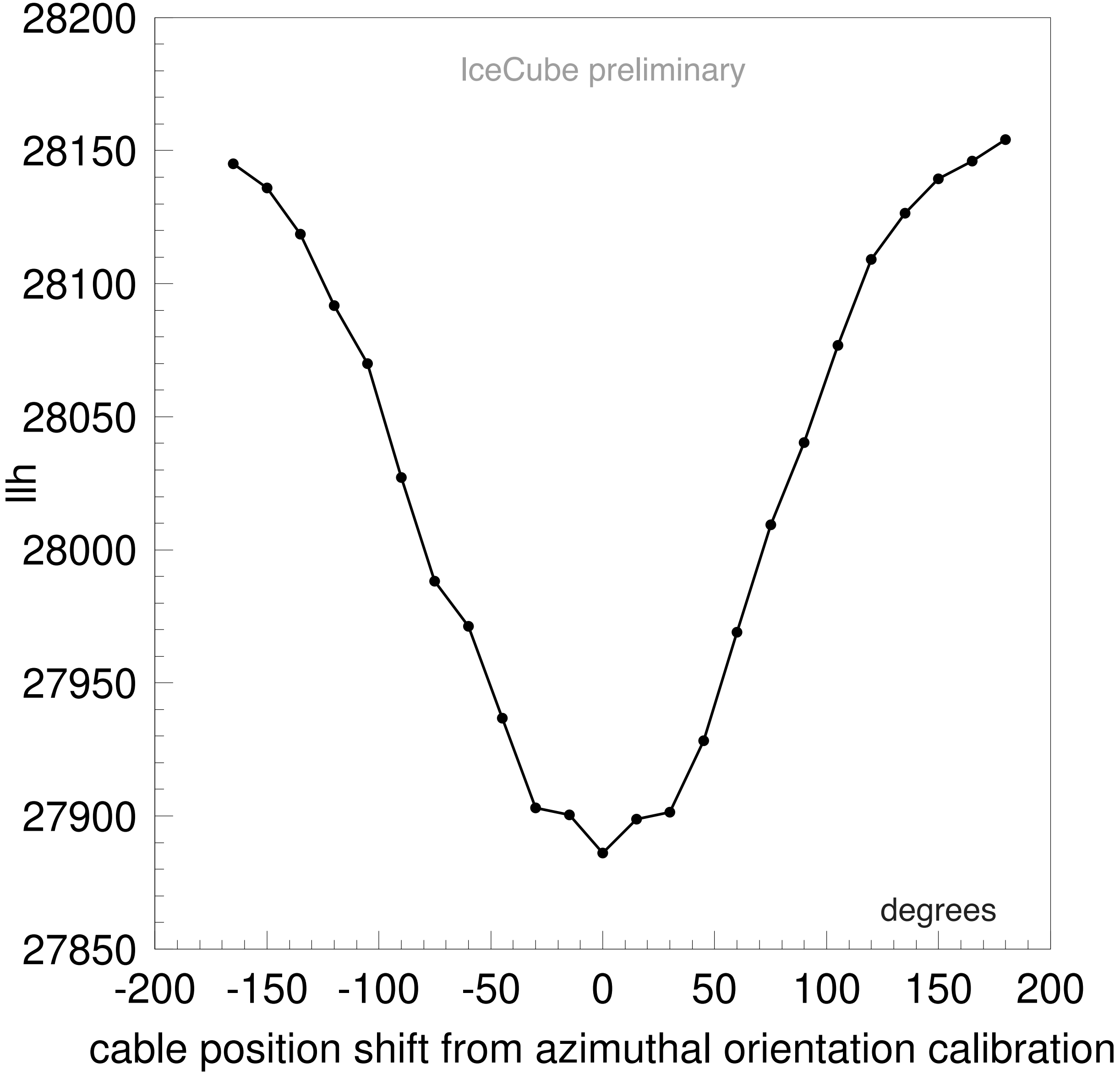






Cable is positioned nominally between LEDs 11 and 12. We have this for all DOMs since the DOM azimuthal orientation study (with sub-1 degree accuracy).

This plot compares cable position obtained from the cable shadow (i.e., direct cable position reconstruction due to shadow on the receiver DOM) study with the nominal cable position.



Cable is positioned nominally between LEDs 11 and 12. We have this for all DOMs since the DOM azimuthal orientation study (with sub-1 degree accuracy).

This plot confirms that indeed, shifting all cable positions off from the nominal orientation (by uniform amount) leads to worse descriptions of the flasher data.

The best description is achieved when the cable positions are at their nominal values.

Summary of improvements

model	*llh*	*model error*
Starting model	28472	14.1%
+ hole ice	28307	13.6%
+ DOM in-ice sensitivities	27892	10.0%
+ DOM tilt	27644	9.9%
+ precise nominal DOM	27542	9.8%

llh is minus log likelihood summed over ~60000 LEDs (12 per DOM, around 5000 DOMs)
statistical + numerical uncertainty in *llh* estimate is ~12

model error is our estimate of how well total per-DOM charge in data agrees with simulation calculated with enough statistics in both to significantly exceed purely statistical expectation

Summary

Azimuthal orientations of all DOMs in the ice were fitted with the *single-LED* in-situ light calibration data set (in most cases with a better than 1 degree resolution).

Hole ice was fitted to a model with bubbly central column of half-DOM diameter as observed with the Swedish camera. The DOM positions relative to the HI column were fitted using both effects at the emitter and receiver side. These positions often correspond to the anomalies observed in the azimuthal orientation study.

Azimuthal position of cable (relying on its shadow effect) can be fitted directly with around 60 degrees uncertainty (when compared to nominal placement).

DOM tilt can also be fitted for best description of data at the receiver side. It is yet unclear if this is just an effective way of describing the position of DOMs within the hole ice or, at least in some cases, corresponds to the actual tilt of the DOM in ice.

Relative in-ice OM Sensitivities, with hole ice as fitted here and cable shadow at the nominal position were simulated with the best ice model (presented at this conference). A model error of 10% is achieved.