

Direct Hole Ice and Cable Shadows

IceCube Photon-Propagator Workshop October 2021

Sebastian Fiedlschuster (@fiedl)

<https://github.com/fiedl/hole-ice-study>

sebastian.fiedlschuster@fau.de

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Erlangen Centre for Astroparticle Physics



Federal Ministry
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SOUTH POLE NEUTRINO OBSERVATORY



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Resources

Thesis (2018-09-05) can be found at:

<https://arxiv.org/abs/1904.08422>

Scripts and resources:

<https://github.com/fiedl/hole-ice-study>

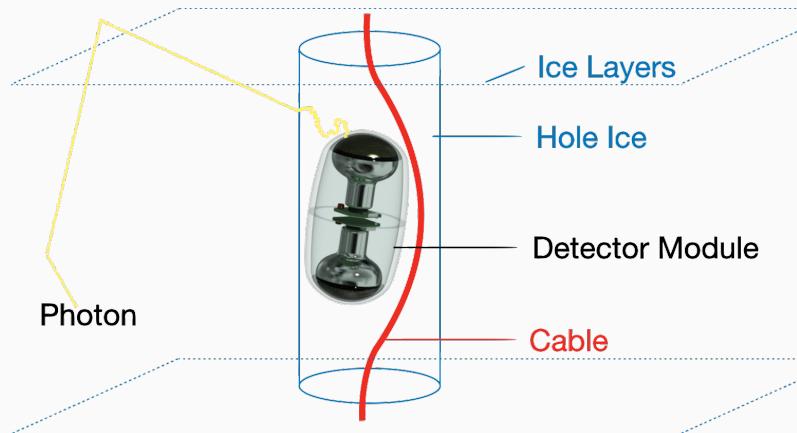
Previous talks on this topic:

<https://github.com/fiedl/hole-ice-talk/releases>

\LaTeX version of these presentation slides:

<https://github.com/fiedl/hole-ice-talk>

Motivation and Scope



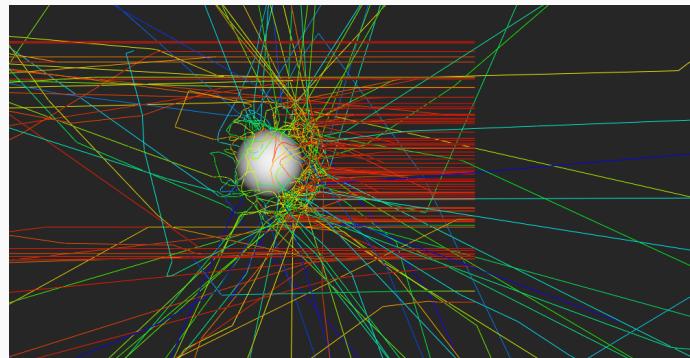
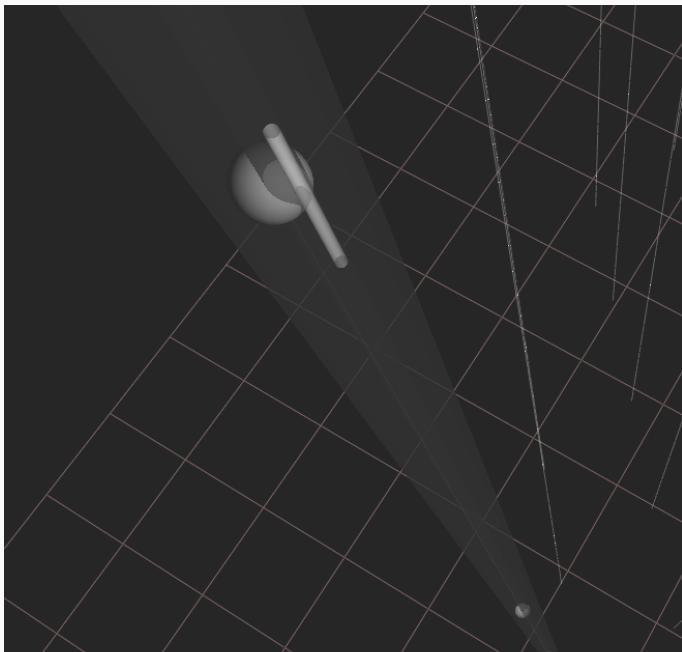
Thesis: <https://arxiv.org/abs/1904.08422>

- Context: Thesis 2018
- Topic: Light-propagation simulation in vicinity of detector modules, considering:
 - ice properties in vicinity, esp. in hole ice
 - opaque cables
 - non-spherical detector modules of variable position
- Usually: Effective modification of module sensitivity
- Here: Direct ray-tracing algorithm in cslim

D-Egg-detector-module image: Pfeiffer, New optical sensors for IceCube-Gen2, 2016

How does it look like?

Hole ice and cables as geometrical objects with optical properties



Animation on youtube:

<https://youtu.be/BhJ6F3B-I1s>

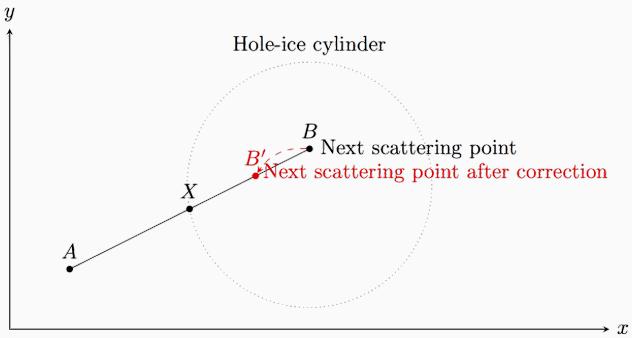
Scattering length $\lambda_{\text{sca},\text{hole-ice}} = 10^{-2} \lambda_{\text{sca},\text{bulk}}$.

Absorption length $\lambda_{\text{abs},\text{hole-ice}} = \lambda_{\text{sca},\text{bulk}}$.

View from top onto a detector module within a hole-ice cylinder. Colors indicate simulation steps, i.e. number of scatterings relative to the total number until absorption. **Red: Photon just created, blue: Photon about to be absorbed.**

Source: <https://github.com/fiedl/hole-ice-study/issues/110>, <https://github.com/fiedl/hole-ice-study/issues/39>

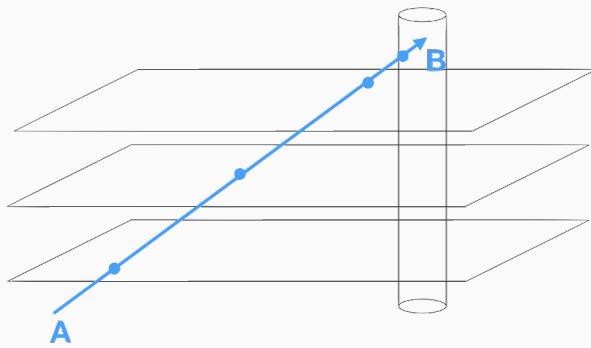
Approach A (naive)



- Minimal extension to existing kernel
- Hole ice as correction for each scattering step
- Pros:
 - Small surface area of implementation
 - Standard `clsim` (well-tested) almost untouched
 - Very testable using unit tests
- Cons:
 - Hole-ice properties relative to bulk ice
 - Does not work with nested cylinders

Source: <https://github.com/fiedl/hole-ice-study/issues/45>

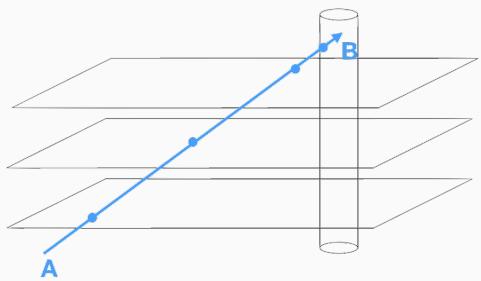
Approach B (the one to go)



- Treat hole ice and cables as media with ice optical properties
- Generalize ice-layer algorithm
- Pros:
 - Supports nested cylinders and cables
- Cons:
 - Needed to rewrite some of the existing propagation kernel
 - i.e. needed lots of statistical cross checks to make sure everything works

Source: <https://github.com/fiedl/hole-ice-study/issues/45>

How approach B work?



Within standard clsim kernel

- Take current photon position
- and properties of ice layers
- Loop over layers
- Calculate physical distance to next interaction



Replace with: apply_propagation_through_media

- Take current photon position
- Define arrays:
 - distances_to_medium_changes
 - local_scattering_lengths
 - local_absorption_lengths
- Add ice layers to these arrays
- Add hole-ice and cable cylinders to these arrays
- Sort arrays by ascending distance from photon
- Loop over arrays
- and calculate physical distance to next interaction

Source:
<https://github.com/fiedl/clsim/tree/sf/hole-ice-2018/resources/kernels/lib>

Can this be used today?

- Kernel helper function can be used in today's kernel
- Rewrite has changed interface → Need to **pass additional parameters** to kernel
- But: **no birefringence** (BFR)
- Cave: Ice tilt

Source code on github:

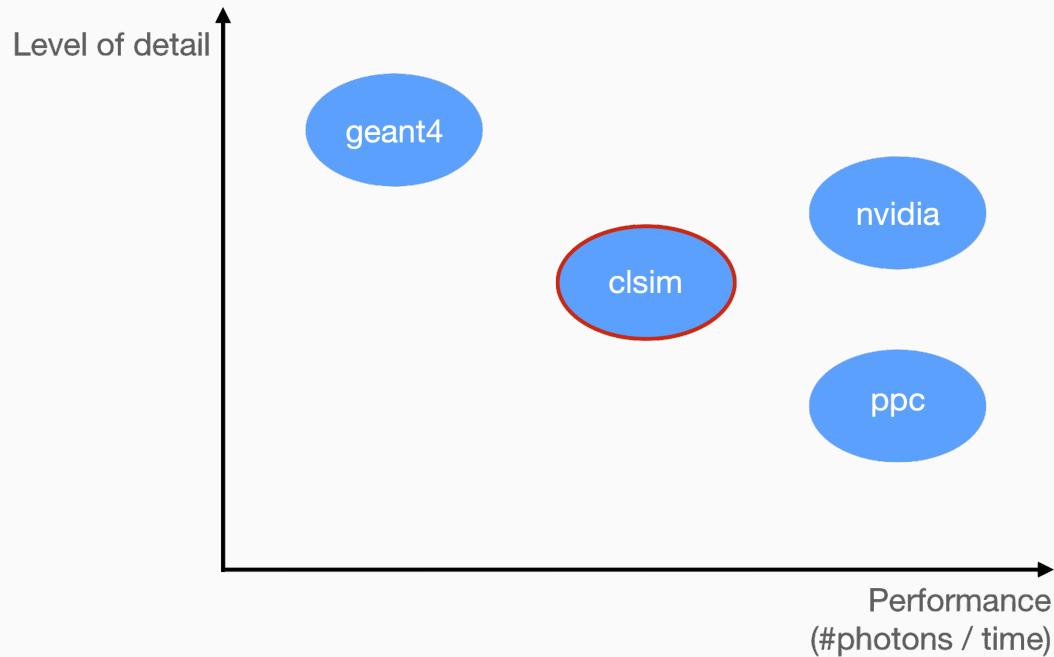
<https://github.com/fiedl/clsim/blob/sf/hole-ice-2018/resources/kernels/lib>

Can this help us today?

Apply this to Upgrade/Gen2 problems?

- Strength: Propagation through different media with sharp boundaries
- Arbitrary shapes as long as we can calculate the intersection points with the photon ray
- Interactions: Scatter, Absorb, plus: Detect
- Performance:
 - When running the same scenario, simulation performance is the same as before. ✓
 - When running scenarios with more scattering, simulation time increases accordingly as expected.
 - In comparison to other tools, compromise of performance and level of detail

Where does this tool fit in?



Thanks for your attention!

Any input you might have is welcome:

<https://github.com/fiedl/hole-ice-study/issues>

Slack: @fiedl sebastian.fiedlschuster@fau.de

Video illustration of a simple example:

<https://youtu.be/BhJ6F3B-I1s>



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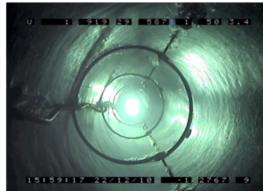
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FAU

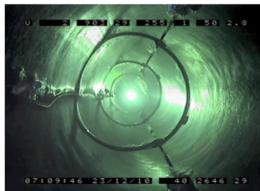
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Backup slides

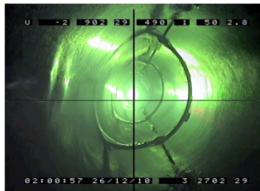
Hole ice



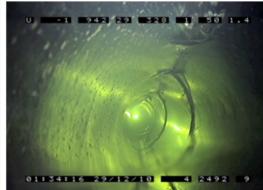
(a)



(b)



(c)



(d)



(e)



(f)



(g)



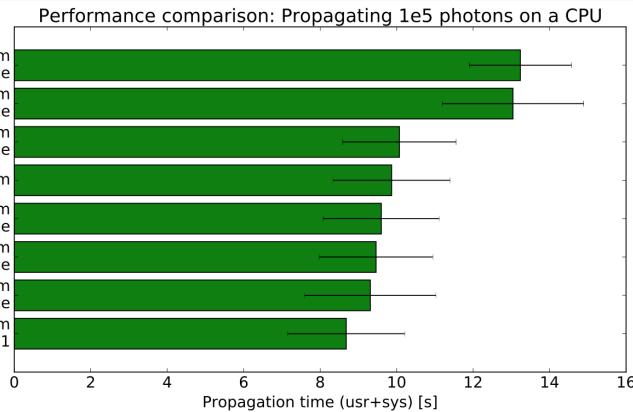
(h)

- Hole ice is the refrozen water in the drill holes around the detector modules
- possibly different optical properties than surrounding bulk ice
- special kinds:
drill-hole ice
bubble column

Images (a) to (g) show a time series of the freeze-in process. Image (h) shows has been taken several years after the freeze-in process.
Image sources: Resconi, Rongen, Krings: The Precision Optical Calibration Module for IceCube-Gen2: First Prototype, 2017. Finley et al.: Freezing in the IceCube camera in string 80, 22 Dec - 1st Jan. 2011. Rongen: The 2018 Sweden Camera run — light at the end of the ice, 2018.

Performance

Time measurement: Propagating 10^5 photons on CPU

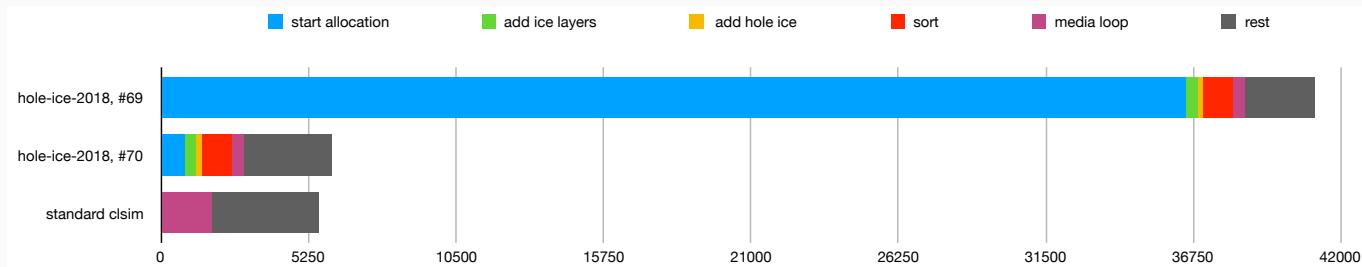


```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
time ./run.rb --distance=1.0 --number-of-runs=1 --number-of-parallel-runs=1 --cpu --angle=45 --plane-wave
↪ --number-of-photons=1e5
```

- Medium propagation features (hole ice, layers) have no measurable performance impact for scattering lengths comparable to bulk-ice scattering ($\lambda_s = 20$ m).
- Performance drop can be seen when lowering the scattering length, i.e. increasing the number of simulation steps ($\lambda_s = 3$ mm).

Performance on GPU

Performance of one simulation step depends on optimizations:



Total performance depends on number of scatters:

Standard clsim with hole-ice approximation: 11 mins

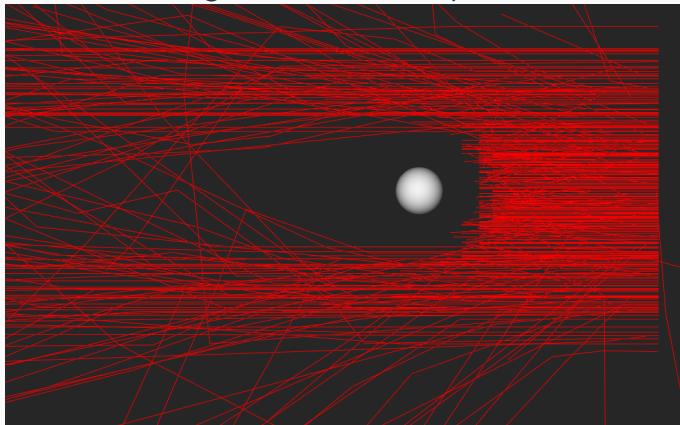
New algorithm, no hole ice: 10 mins

New algorithm, about H2 hole ice: 15 mins

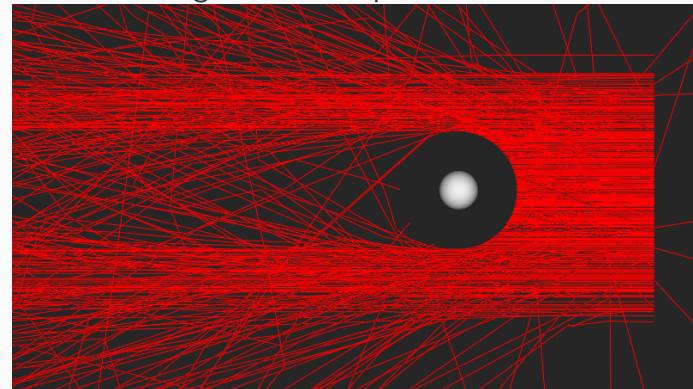
Coordinates-vs-vectors bug

Scenario: Instant absorption. Top view. Mathematics of intersection calculations and starting conditions are the same in both figures.

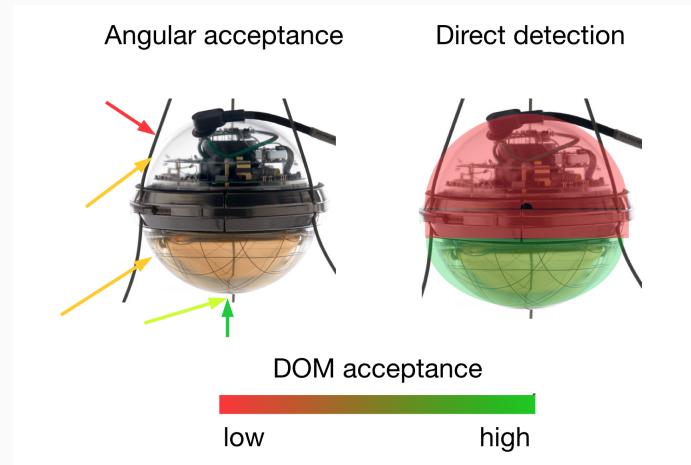
Before: Treating coordinates as separate variables



After: Treating vectors as opencl-native vectors



Direct detection

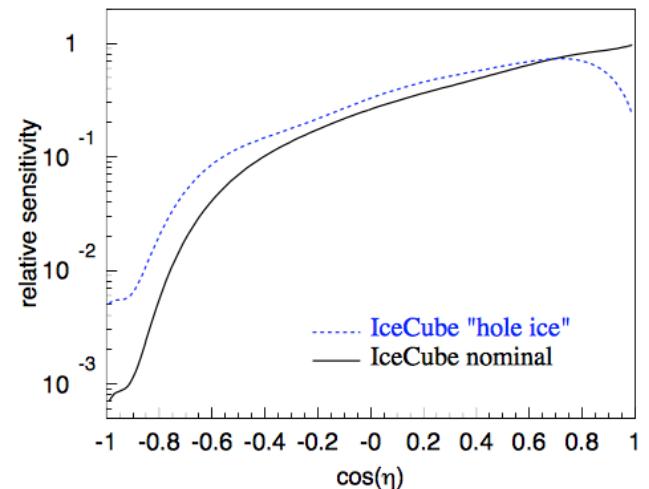
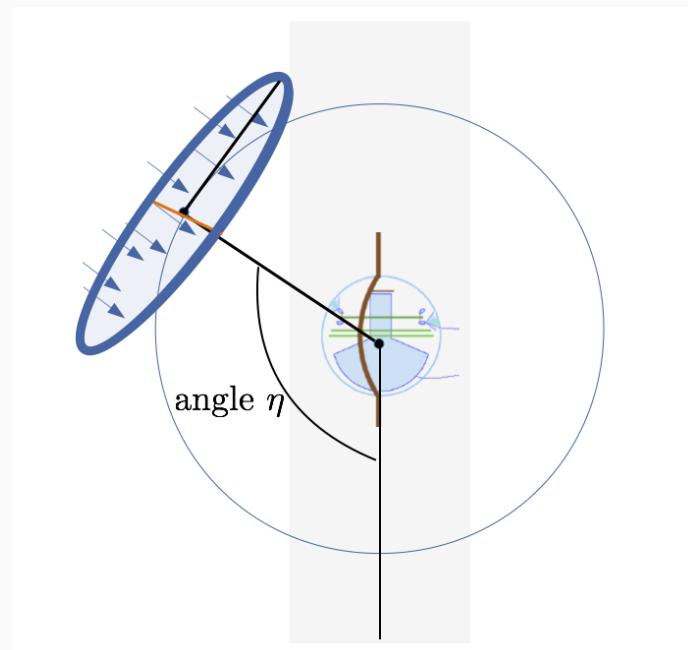


- The DOM looks downwards by design
- Currently, the hit position is not used when determining DOM acceptance, just the photon direction when hitting the DOM (*DOM angular acceptance*)
- Direct detection: Accept all hits below the waist band, reject all others
- Direct detection is easy with clsim
 - Hit position is known and guaranteed to be on the DOM sphere
 - Idea: Accept hits depending on z of the hit position
 - Patch is a couple of lines:
`fiedl/clsim@96a2e3f`
- Still work to be done:
 - Implement a switch for direct detection vs. DOM angular acceptance

Source: Image: Martin Rongen, *Status and future of SpiceHD DARD*, 2017, Slide 17,
See also: <https://github.com/fiedl/hole-ice-study/issues/32>

Angular acceptance

For each angle η , shoot photons onto the DOM and count hits.



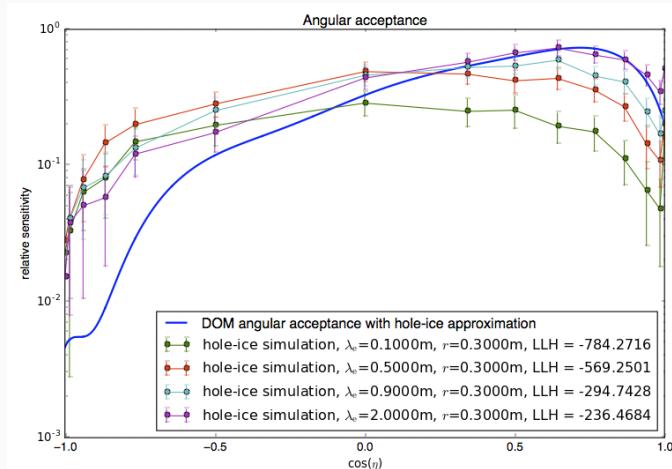
Angular acceptance *reference curves*. The nominal model is based on lab measurement, the hole ice curve on previous simulations.

Source: Image: Martin Rongen, Calibration Call 2015-11-06, DARD Update, Slide 9

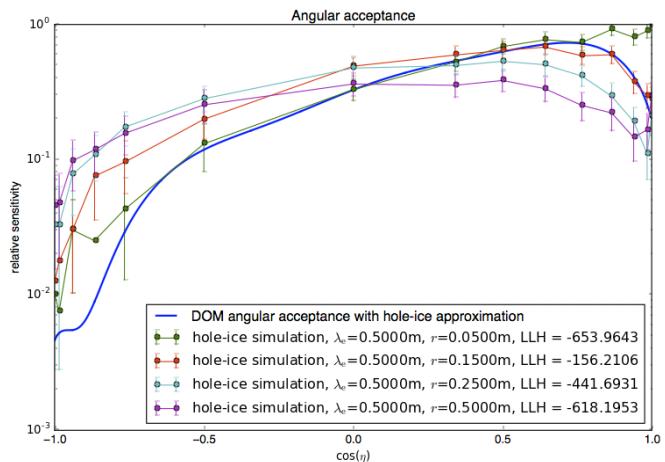
Plot: Measurement of South Pole ice transparency with the IceCube LED calibration system, 2013, figure 7. See also: <https://github.com/fiedl/hole-ice-study/issues/10>

Angular acceptance for different hole-ice parameters

Vary hole-ice scattering length:



Vary hole-ice radius:



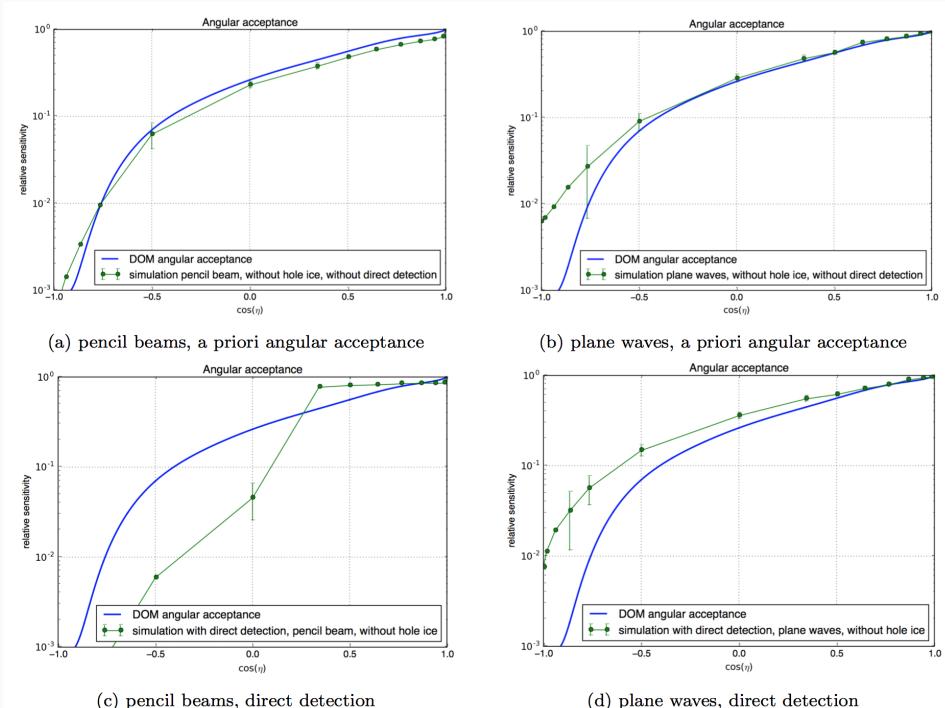
Systematics:

For direct detection + plane waves, increased number of photons for $\cos \eta < 0$.

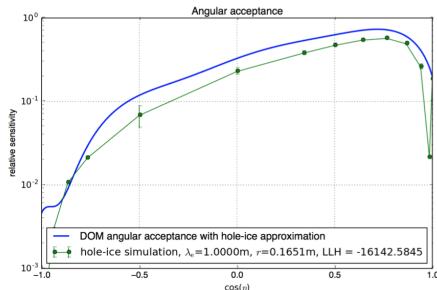
plane extent 1 m, starting distance 1 m

non-perfect bulk-ice properties

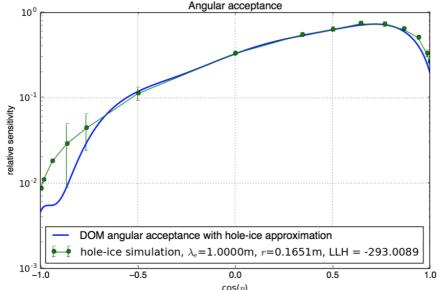
Angular acceptance: Sources and acceptance criteria



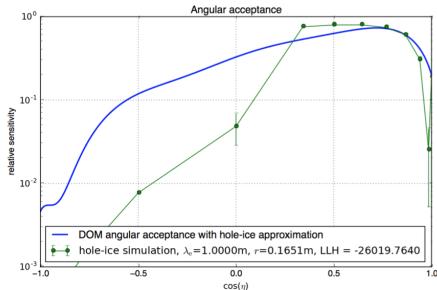
Angular acceptance: Sources and acceptance criteria



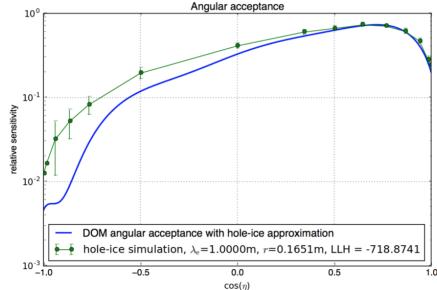
(a) pencil beams, a priori angular acceptance



(b) plane waves, a priori angular acceptance

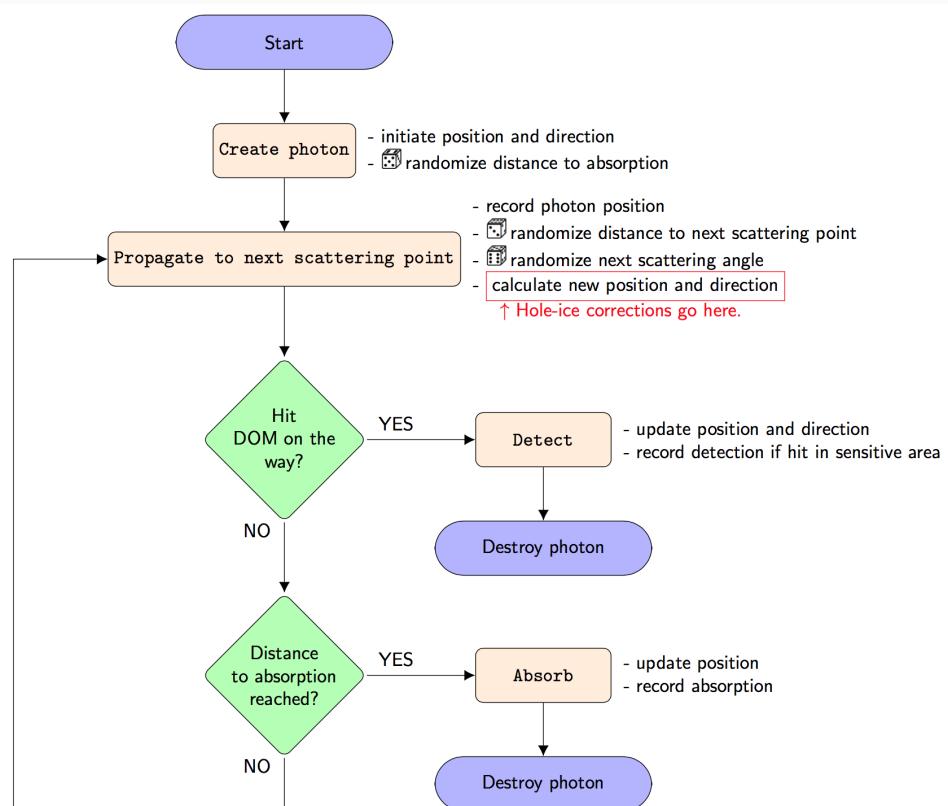


(c) pencil beams, direct detection



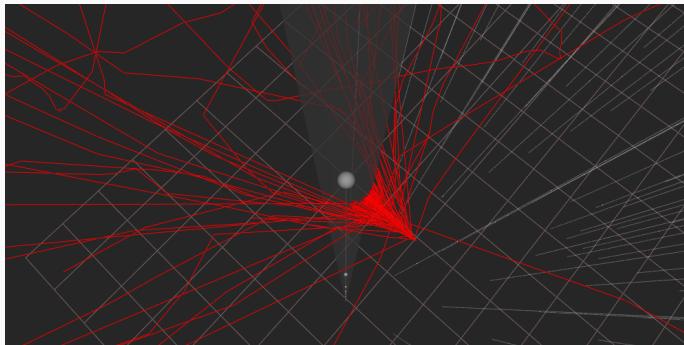
(d) plane waves, direct detection

Simplified simulation-step flow chart



Instant absorption

Visualizing instant absorption with clsim and steamshovel. DOM radius: 10 cm, hole ice radius: 30 cm

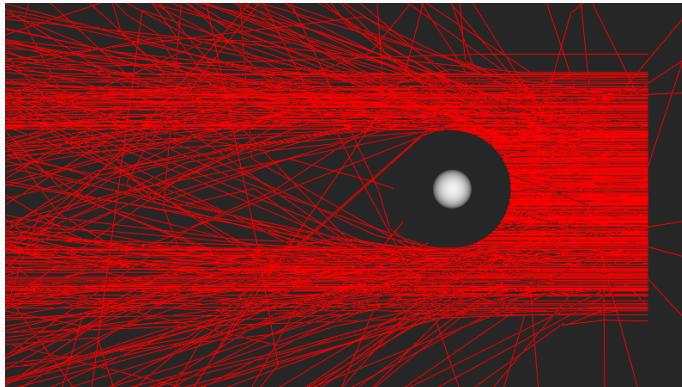


Photon point source, 3d view

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/FiringRange
./run.rb \
    --scattering-factor=1.0 --absorption-factor=0.0 \
    --distance=1.0 \
    --number-of-photons=1e3 --angle=90 \
    --number-of-runs=1 --number-of-parallel-runs=1 \
    --save-photon-paths --cpu
steamshovel tmp/propagated_photons.i3
```

Instant absorption

Visualizing instant absorption with clsim and steamshovel. DOM radius: 10 cm, hole ice radius: 30 cm

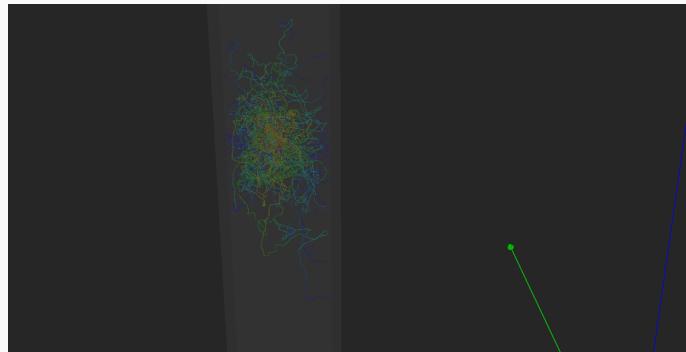


Plane wave photon source, top view

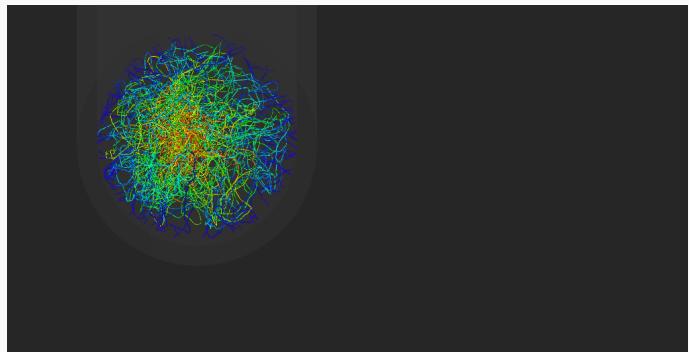
```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/FiringRange
./run.rb \
    --scattering-factor=1.0 --absorption-factor=0.0 \
    --distance=1.0 --plane-wave \
    --number-of-photons=1e3 --angle=90 \
    --number-of-runs=1 --number-of-parallel-runs=1 \
    --cpu --save-photon-paths
steamshovel tmp/propagated_photons.i3
```

Instant absorption with nested cylinders

The inner cylinder is configured for small scattering length, the outer cylinder for instant absorption.



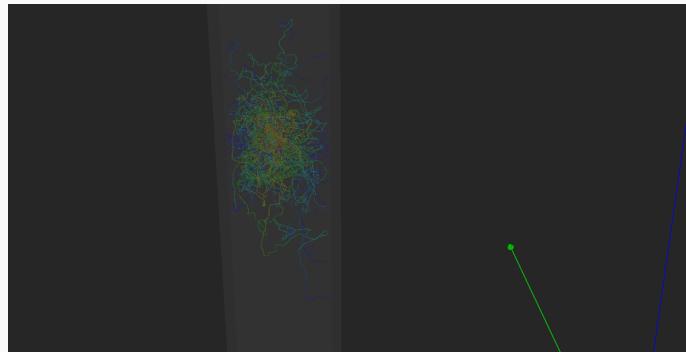
With outer cylinder configured for instant absorption



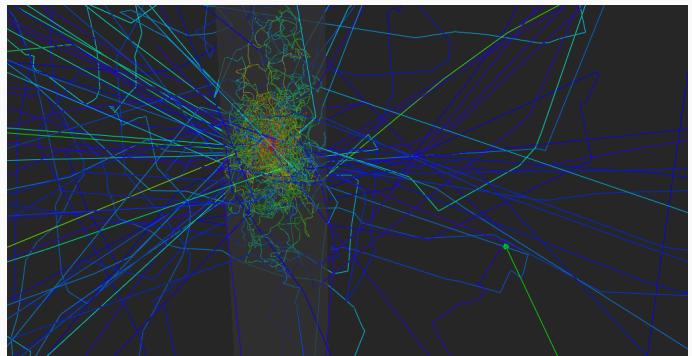
Top view

Instant absorption with nested cylinders

The inner cylinder is configured for small scattering length, the outer cylinder for instant absorption.

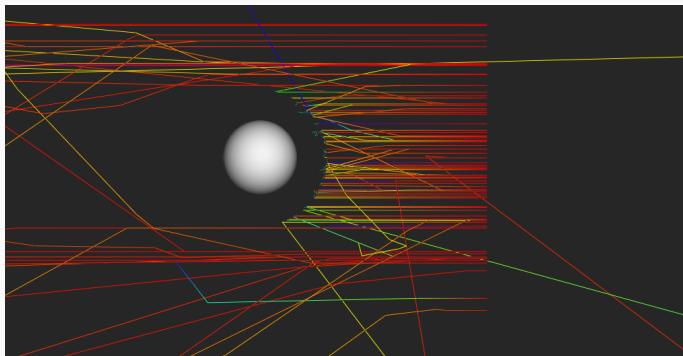


With outer cylinder configured for instant absorption



Without the outer cylinder

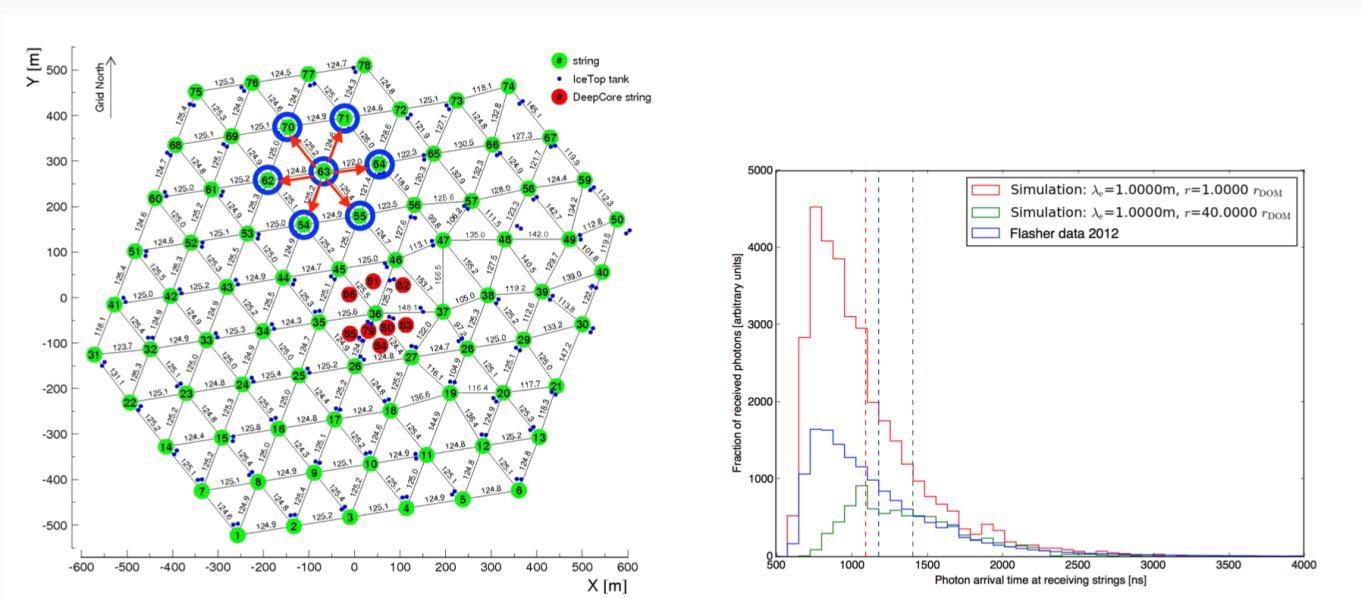
Scattering example



- Hole-ice absorption length: about 5 cm
- Hole-ice scattering length factor: 0.001

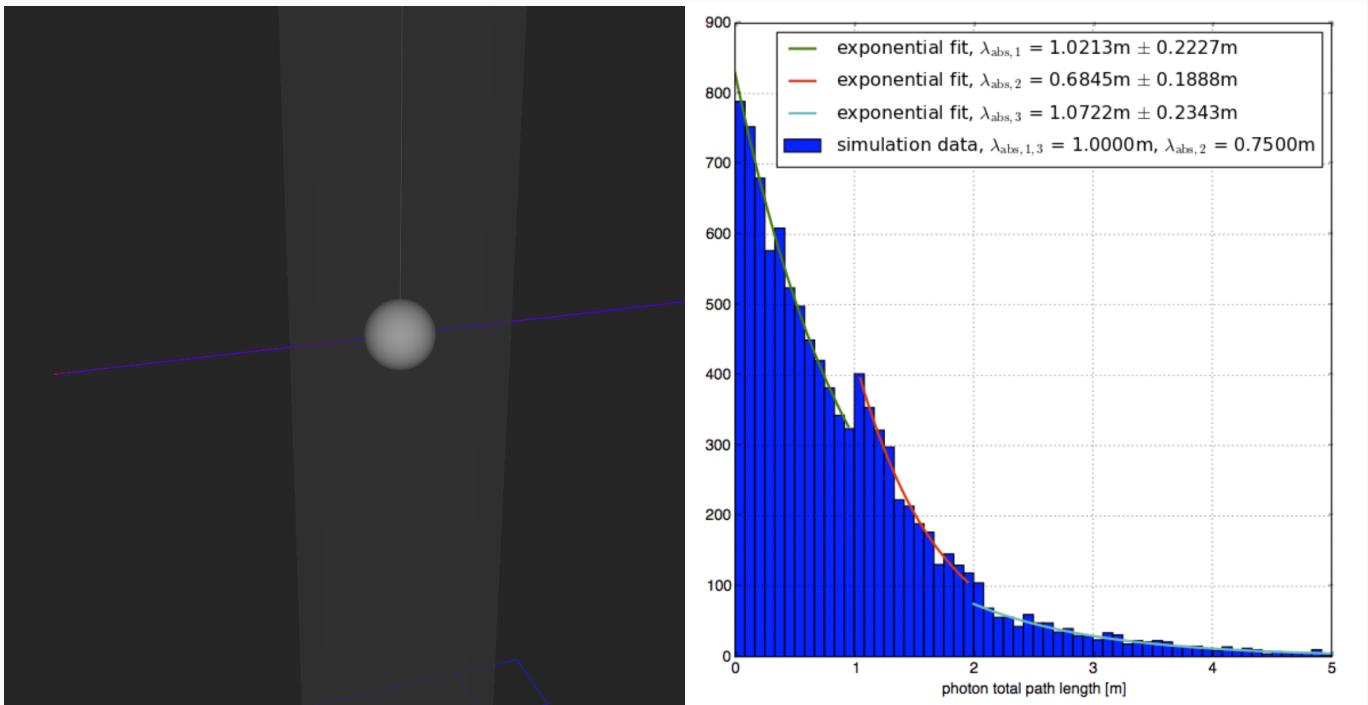
```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/FiringRange
./run.rb --scattering-factor=0.001 --absorption-factor=0.00033 --distance=1.0
--number-of-photons=100 --number-of-runs=1 --number-of-parallel-runs=1
--save-photon-paths --cpu --plane-wave
steamshovel tmp/propagated_photons.i3
```

Cross checks: Arrival-time distributions

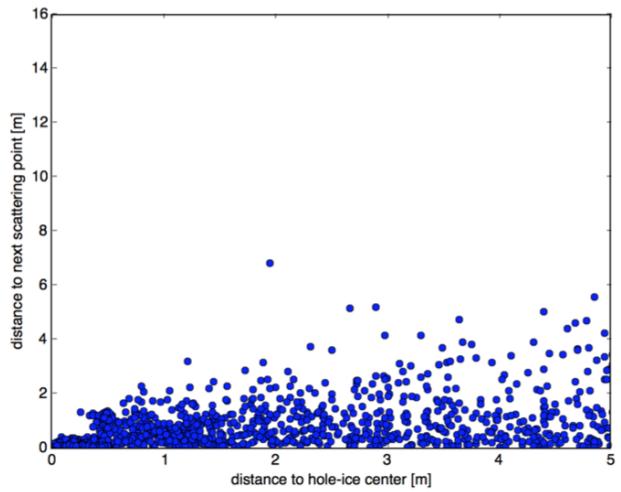


Source: <https://github.com/fiedl/hole-ice-study/issues/91>. Image based on <https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg>.

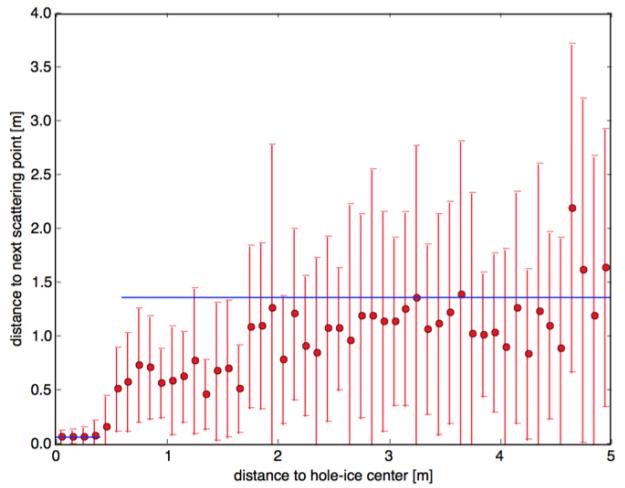
Cross checks: Path-length distributions



Cross checks: Distance to next scattering point vs. dst. from hole-ice center

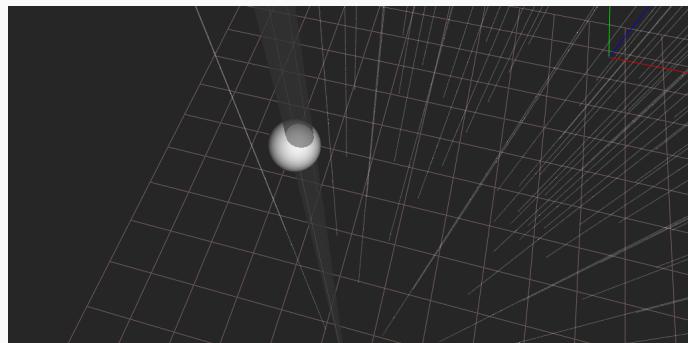


(a) All data points



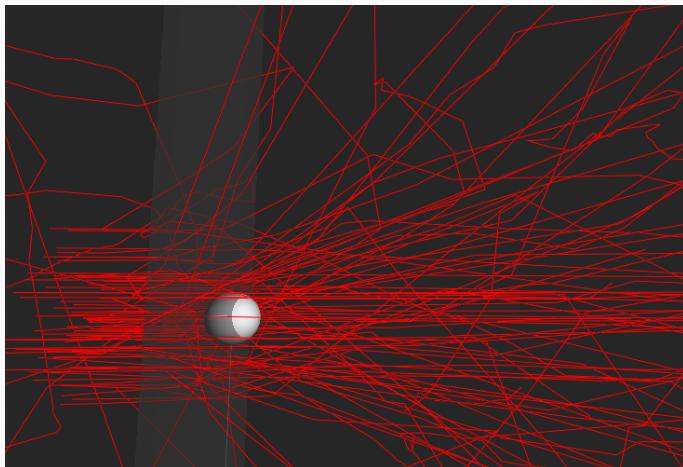
(b) Averaged for bins of a width of 10 cm

Separate hole-ice cylinder positions



- Each string can have its own hole-ice cylinder configuration
 - cylinder position
 - cylinder radius
 - scattering length within cylinder
 - absorption length within cylinder
 - DOM positions — DOMs may not be perfectly centred relative to the hole ice

Asymmetry example



For angle $\eta = \pi/2$, shoot photons from planes onto the DOM and count hits.

Hole-ice radius: 30 cm

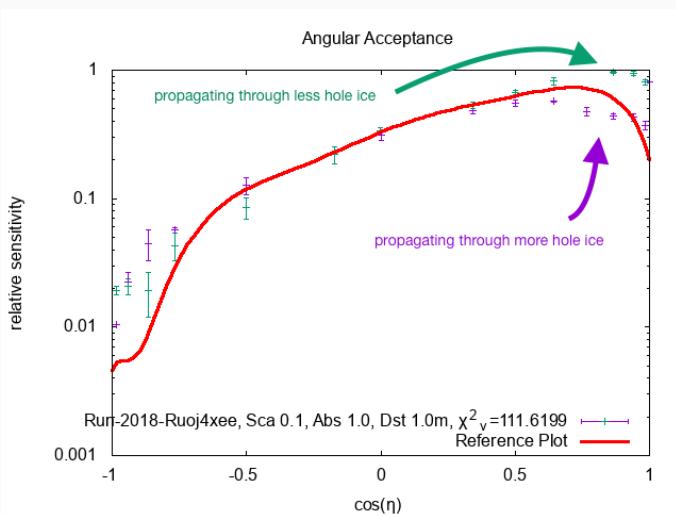
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$

$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

The **hole-ice is shifted in x-direction against the DOM position by 20 cm.**

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.1 --absorption-factor=1.0
↪ --distance=1.0 --plane-wave --number-of-photons=1e2
↪ --cylinder-shift=0.2 --save-photon-paths --cpu
steamshovel tmp/propagated_photons.i3
```

Asymmetry example



For each angle $\eta \in [0; 2\pi]$, shoot photons from planes onto the DOM and count hits.

Hole-ice radius: 30 cm

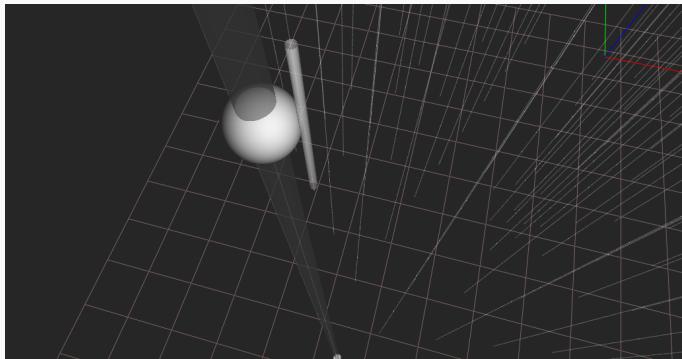
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \lambda_{\text{sca,bulk}}$$

$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

The **hole-ice is shifted in x-direction against the DOM position by 20 cm.**

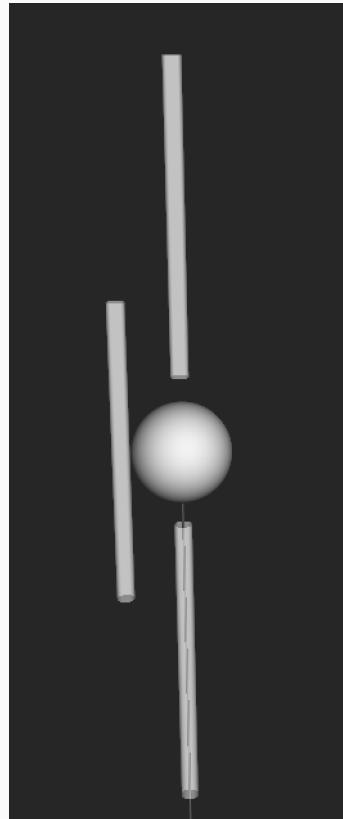
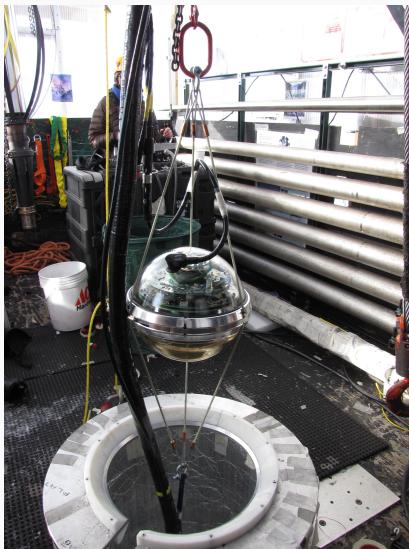
```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.1 --absorption-factor=1.0 --distance=1.0
--plane-wave --number-of-photons=1e5
--angles=0,10,20,30,40,50,60,70,90,120,140,150,160,170,190,200,210,220,
240,260,270,290,300,310,320,330,340,350 --number-of-runs=2
--number-of-parallel-runs=2 --cylinder-shift=0.2
open results/current/plot_with_reference.png
```

Cable shadows



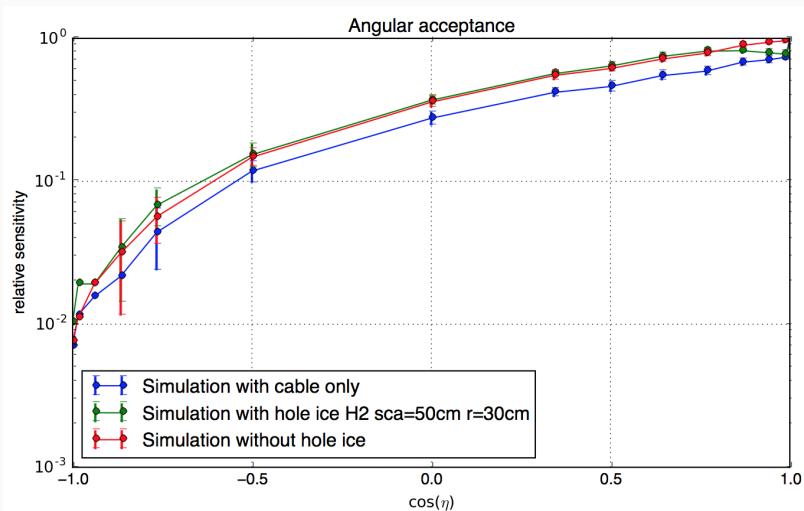
- Cables can be modelled as separate cylinders
 - for each DOM separate position
 - 1 m height
 - configured for instant absorption
- This image:
 - DOM radius: 16.5 cm
 - bubble-column radius: 8.0 cm
 - cable radius: 2.0 cm

Direct cable simulation: Angular acceptance

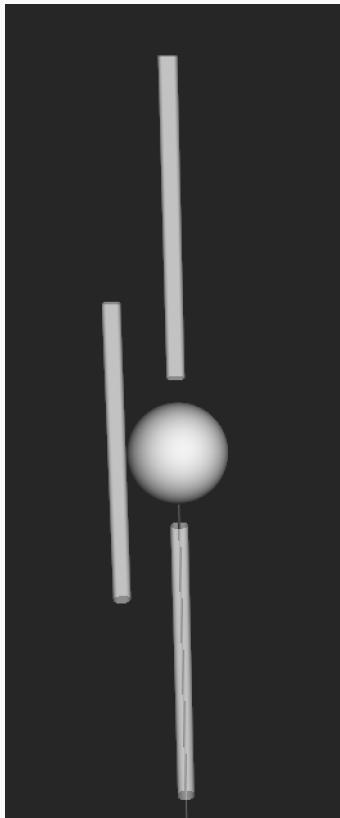


Source: <https://github.com/fiedl/hole-ice-study/issues/101>. Images: <https://icecube.wisc.edu/gallery/view/153>, <https://gallery.icecube.wisc.edu/internal/v/GraphicRe/graphics/arraygraphics2011/sketchup/DOMCloseUp.jpg.html>

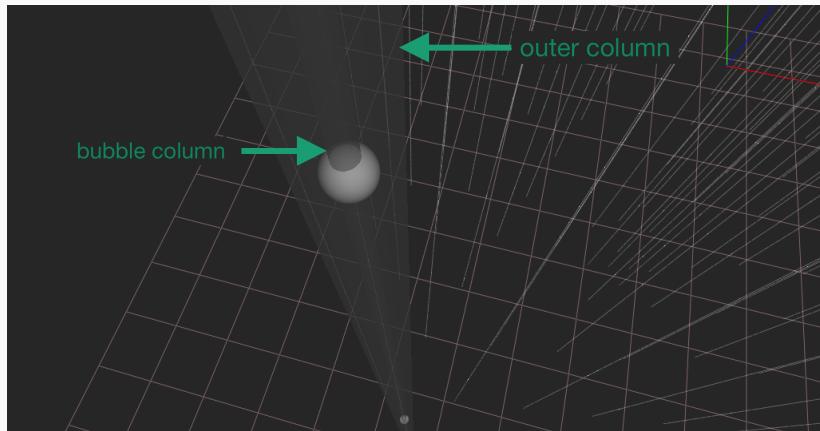
Direct cable simulation: Angular acceptance



The azimuthal starting angle is such that the cable shadow is maximal.

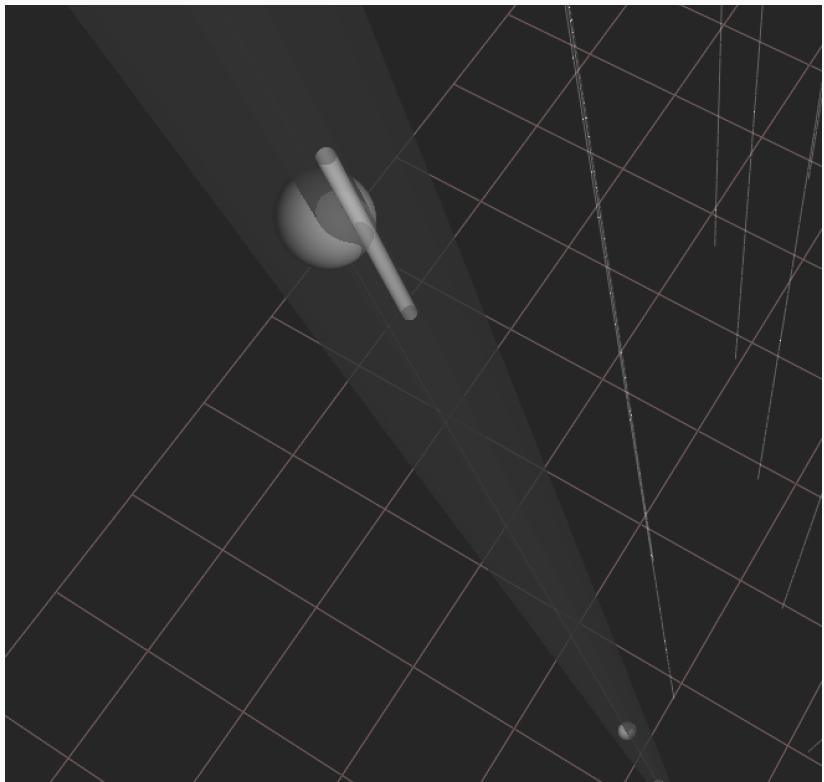


Nested hole-ice cylinders



- Hole-ice cylinders can be nested
 - for each string separate positions
 - for each string and each column separate radii
- This image:
 - DOM radius: 16.5 cm
 - bubble-column radius: 8.0 cm
 - outer-column radius: 30.0 cm

Realistic simulation scenario

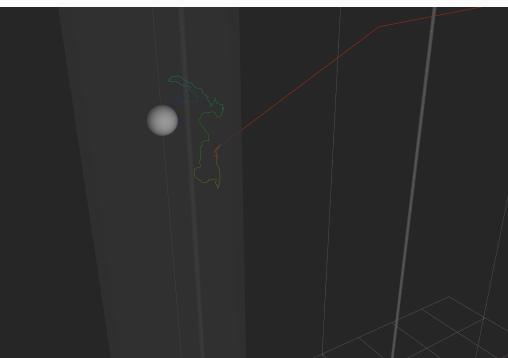
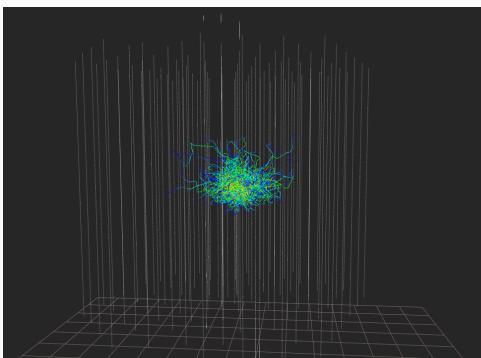
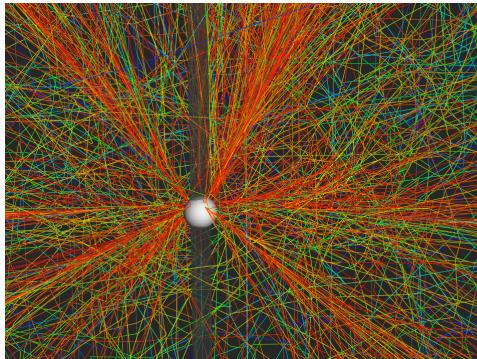
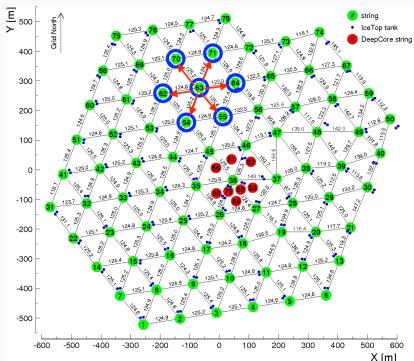


- DOM: radius 16.5 cm, shifted by 12.0 cm against the center of the bore hole
- bubble column: radius 8.0 cm
- drill-hole column: radius 30.0 cm
- cable: radius 3.0 cm, placed next to the DOM, partially within the bubble column

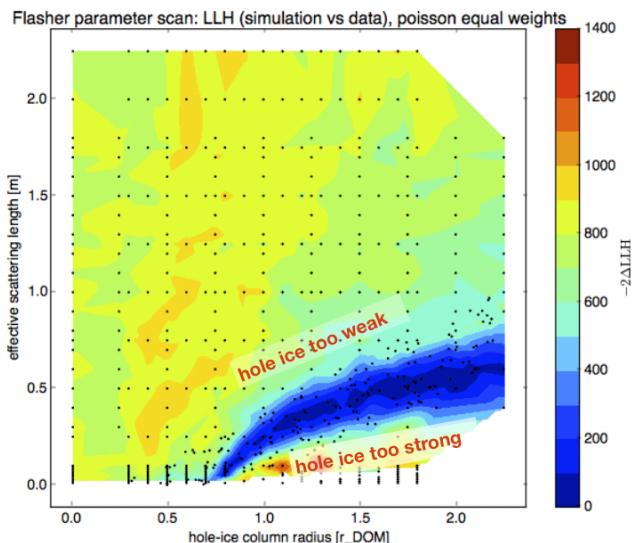
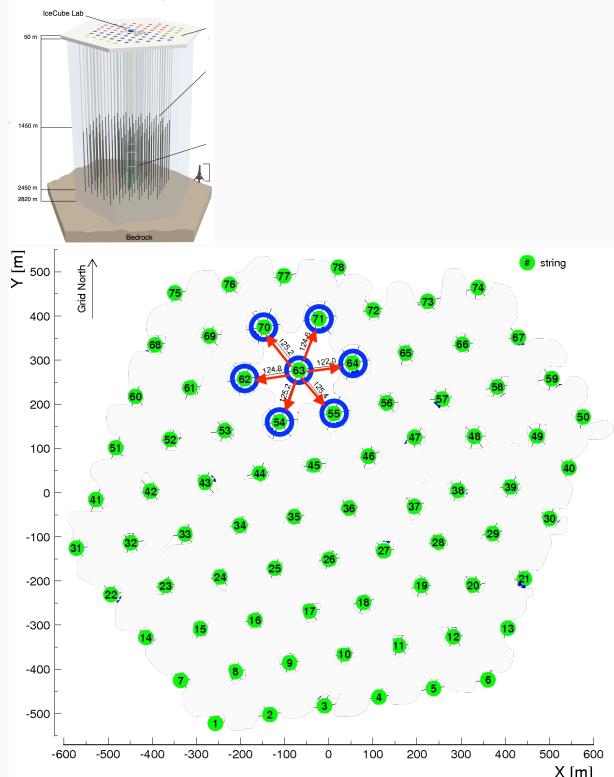
See also: <https://github.com/fiedl/hole-ice-study/issues/110>

Flasher-simulation example

Calibration: Find out the properties of the hole ice by comparing simulations with different properties to data of IceCube's LED-flasher-calibration system.

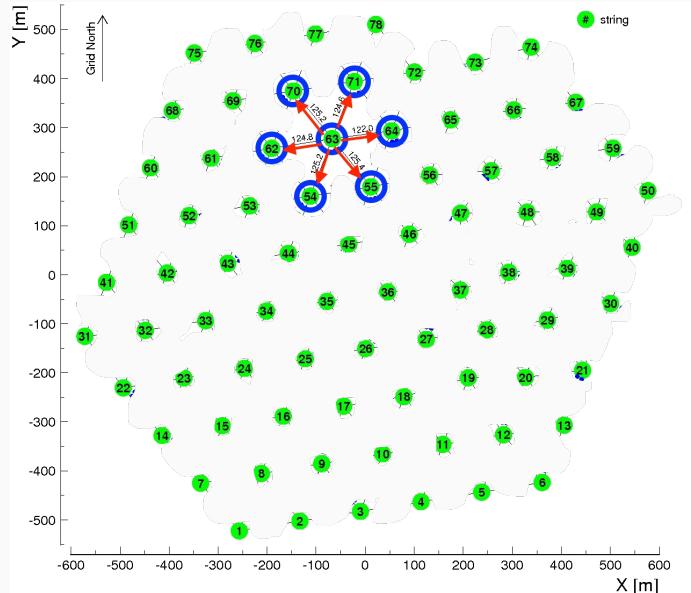


Example scan for best hole-ice parameters based on calibration data



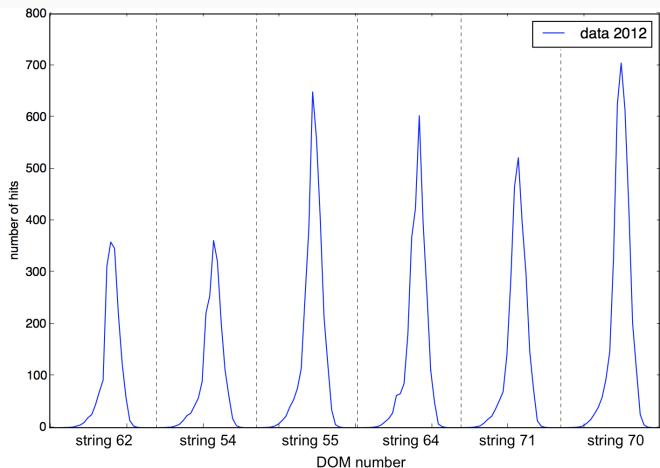
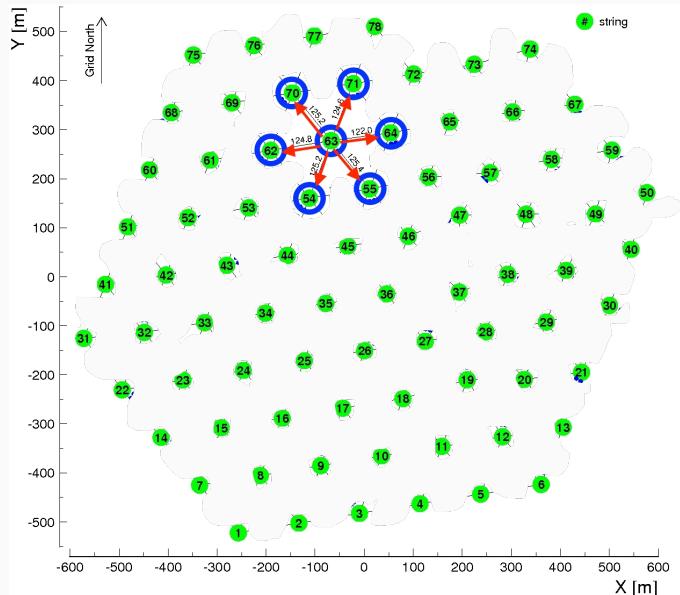
Source: <https://github.com/fiedhl/hole-ice-study/issues/59>. Footprint based on <https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg>. Image: Aartsen et al., The IceCube Neutrino Observatory: Instrumentation and online systems, 2017.

Early results: Calibration data suggest asymmetric shielding by hole ice

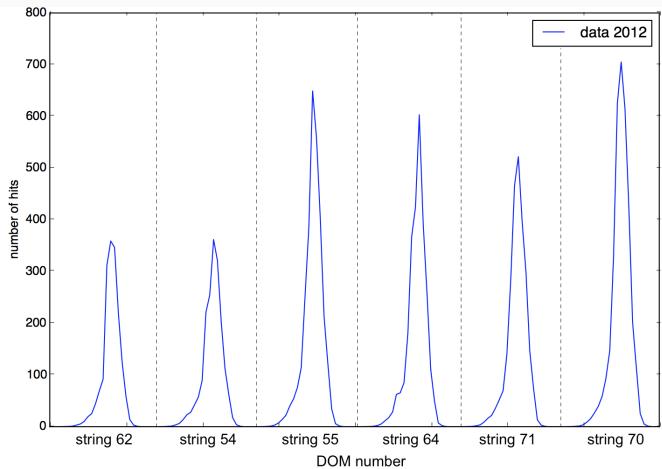
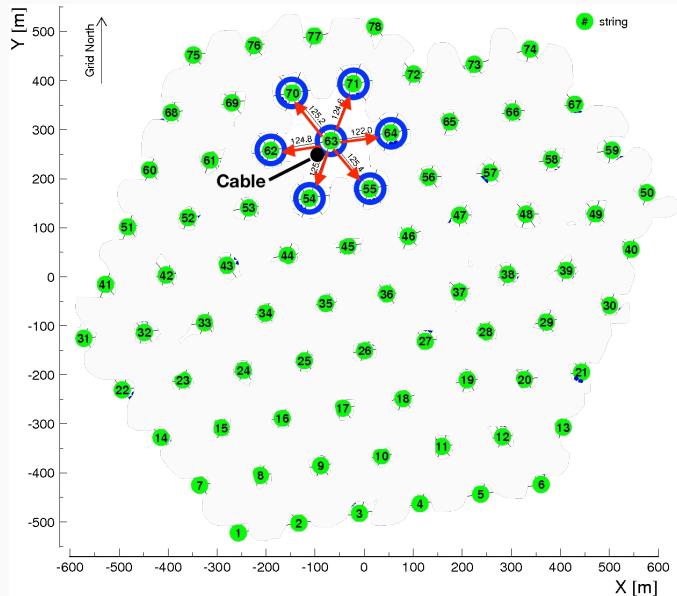


Source: <https://github.com/fiedl/hole-ice-study/issues/97>. Image based on <https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg>.

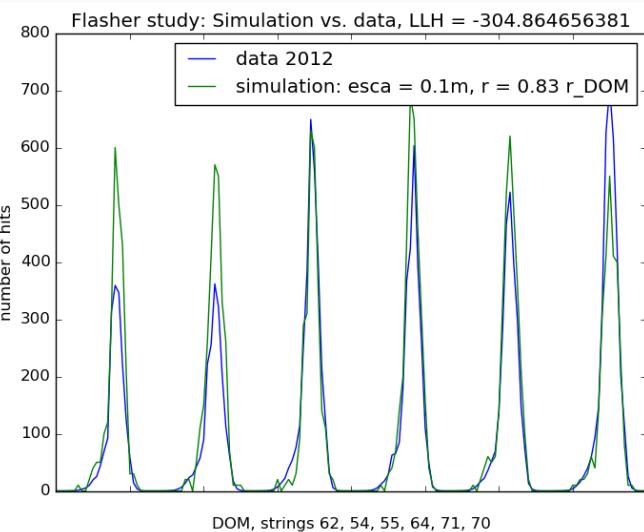
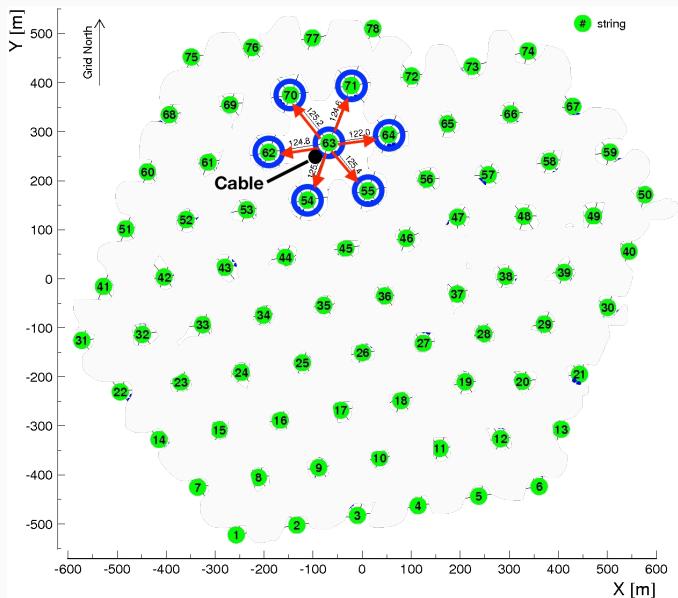
Early results: Calibration data suggest asymmetric shielding by hole ice



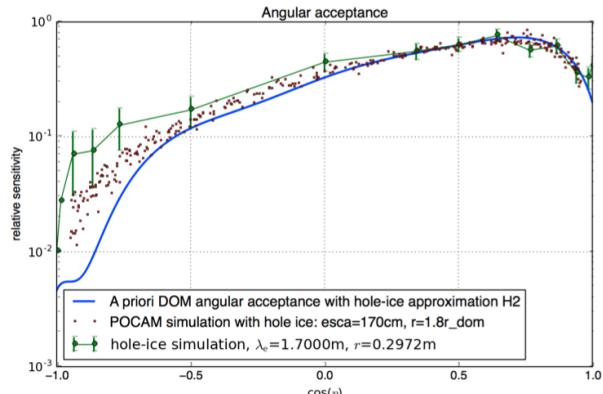
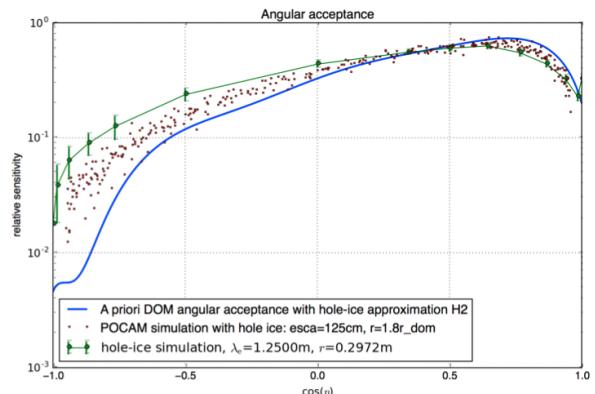
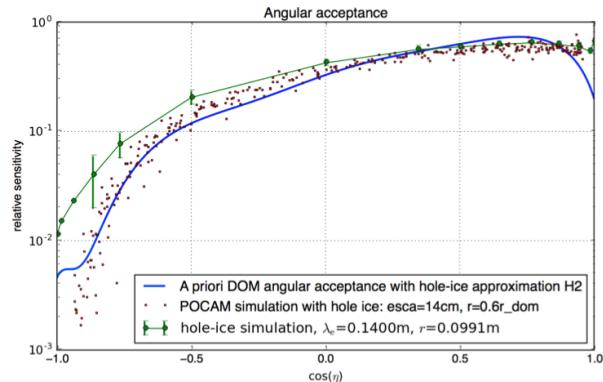
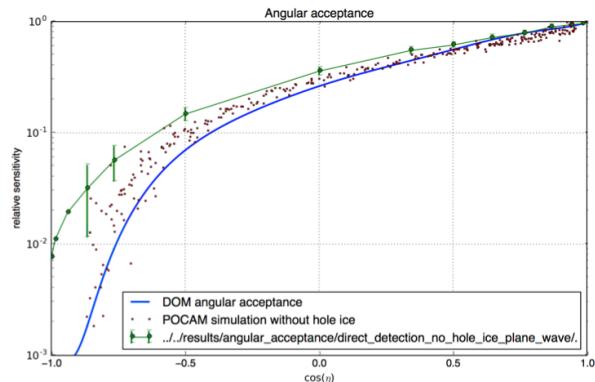
Early results: Calibration data suggest asymmetric shielding by hole ice



Early results: Calibration data suggest asymmetric shielding by hole ice

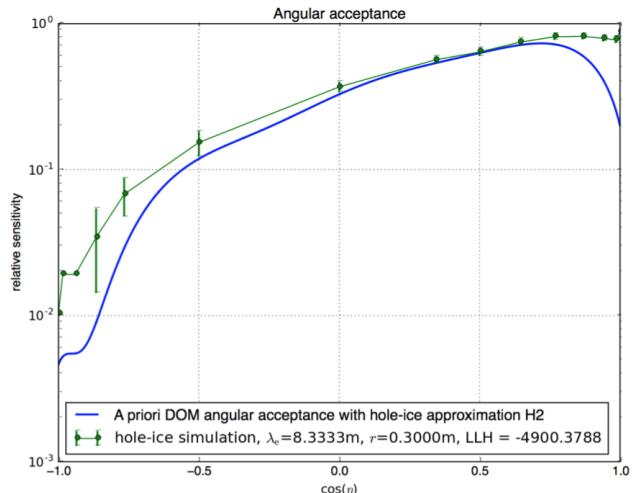


Comparison to ppc simulation

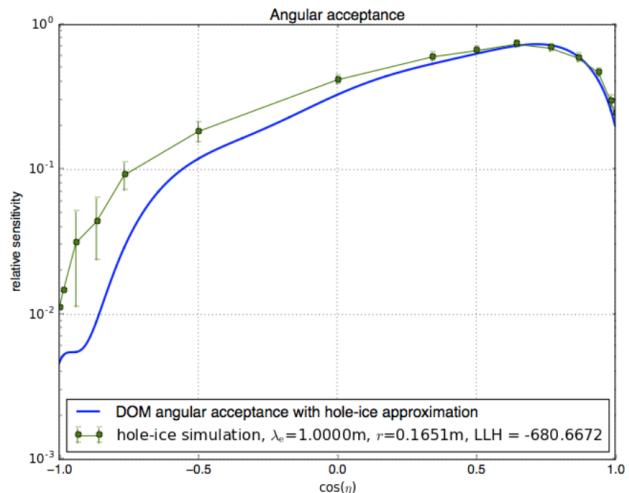


Source: <https://github.com/fiedl/hole-ice-study/issues/4>, POCAM ppc data source: Resconi, Rongen, Krings: The Precision Optical CALibration Module for IceCube-Gen2: First Prototype, 2017.

Comparison to H2 hole-ice model

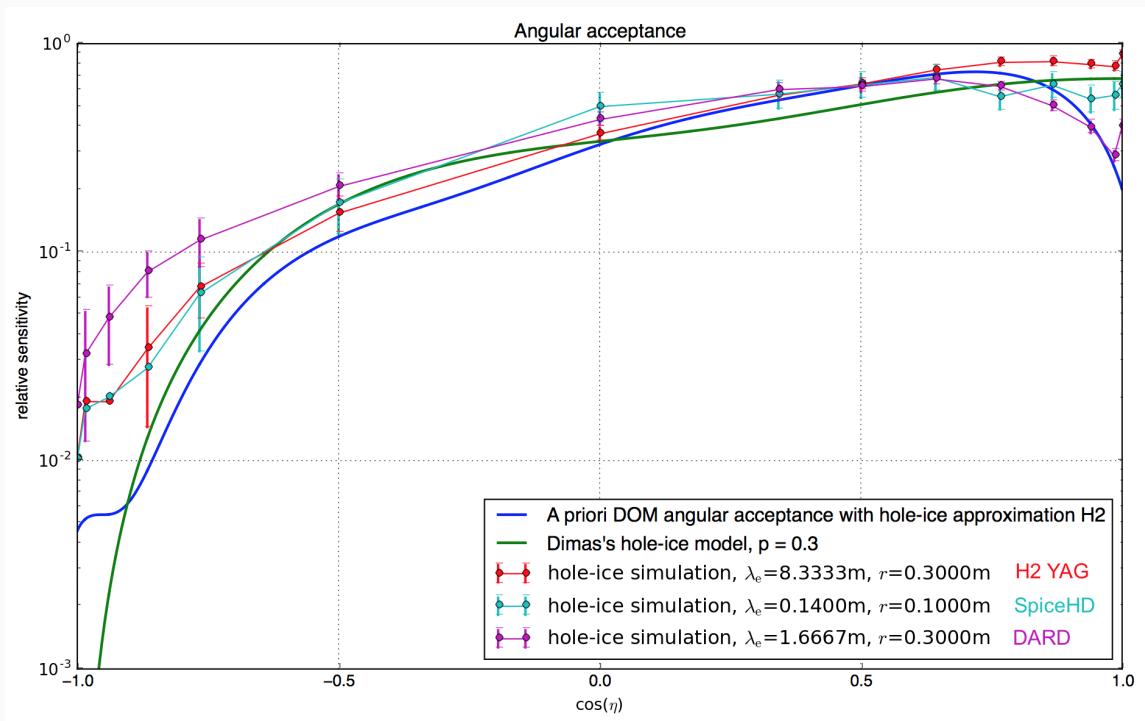


(a) CLSIM simulation with H2 hole-ice parameters:
 $r = 30\text{ cm}$, $\lambda_{\text{sca}}^{\text{H}} = 50\text{ cm}$, $\lambda_{\text{sca}}^{\text{H}} = 8.33\text{ m}$



(b) CLSIM simulation with parameters
 $r = r_{\text{DOM}} = 0.1651\text{ m}$, $\lambda_{\text{sca}}^{\text{H}} = 6\text{ cm}$, $\lambda_{\text{e}}^{\text{H}} = 1.0\text{ m}$

Comparison of parameters from calibration measurements



Source: <https://github.com/fiedl/hole-ice-study/issues/104> H2 YAG: <https://github.com/fiedl/hole-ice-study/issues/80>. Karle, Hole Ice Studies with YAG, <http://icecube.berkeley.edu/kurt/interstring/hole-ice/yak.html>, 1998. SpiceHD: <https://github.com/fiedl/hole-ice-study/issues/87>. Rongen, Status and future of SpiceHD and DARD, Calibration Workshop August 2017. DARD: <https://github.com/fiedl/hole-ice-study/issues/105>. Rongen, Measuring the optical properties of IceCube drill holes, 2016. Rongen, DARD Update, Calibration Call 2015-11-06.