Direct Hole Ice and Cable Shadows

IceCube Photon-Propagator Workshop October 2021

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Erlangen Centre for Astroparticle Physics

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`

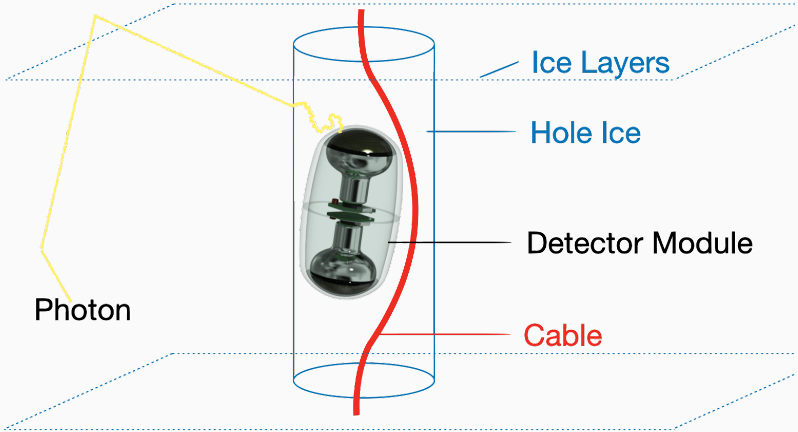
Previous talks on this topic:

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

LaTeX version of these presentation slides:

`https://github.com/fiedl/hole-ice-talk`

Motivation and Scope



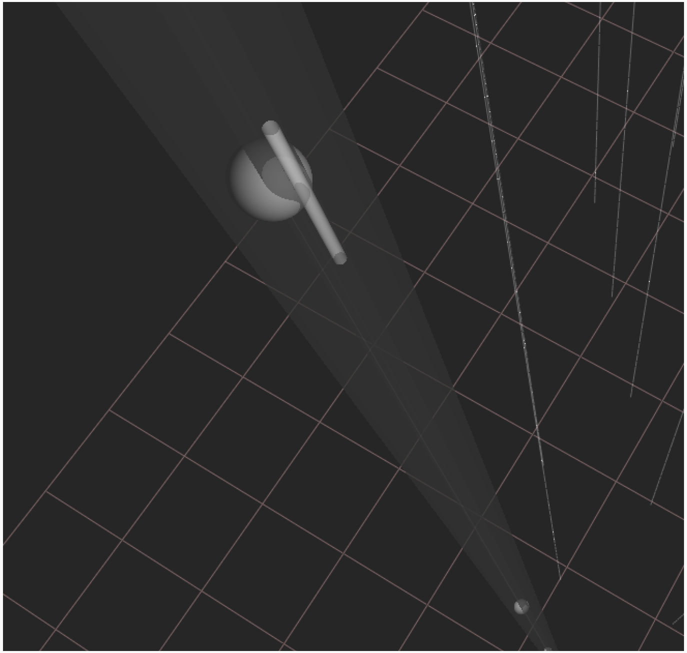
Thesis: `https://arxiv.org/abs/1904.08422`

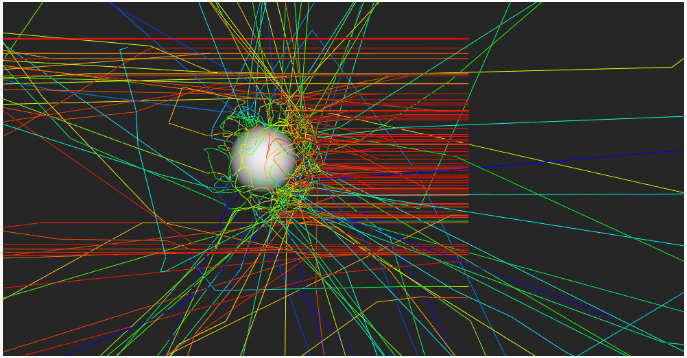
- Context: Thesis 2018
- Topic: Light-propagation simulation in vicinity of detector modules, considering:
  - ice properties in vicinity, esp. in hole ice
  - opaque cables
  - non-spherical detector modules of variable position
- Usually: Effective modification of module sensitivity
- Here: Direct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

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:

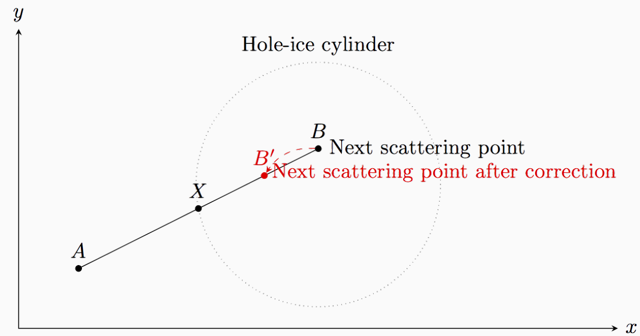
`https://youtu.be/BhJ6F3B-I1s`

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

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`

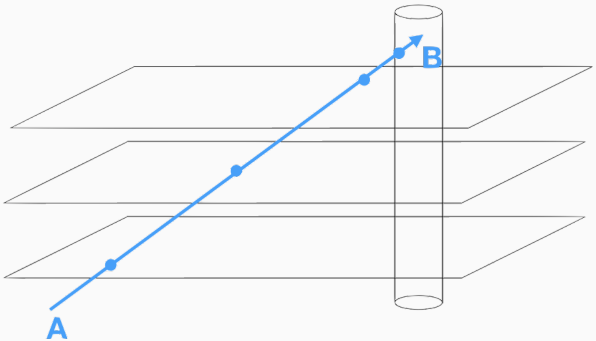
Approach A (naive)



- 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

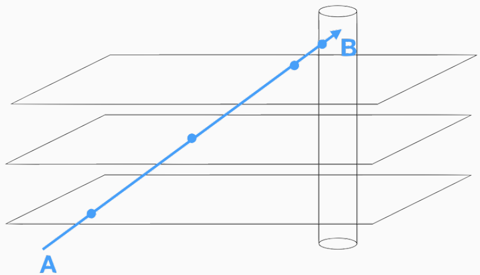
Approach B (the one to go)



- 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?



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

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

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:

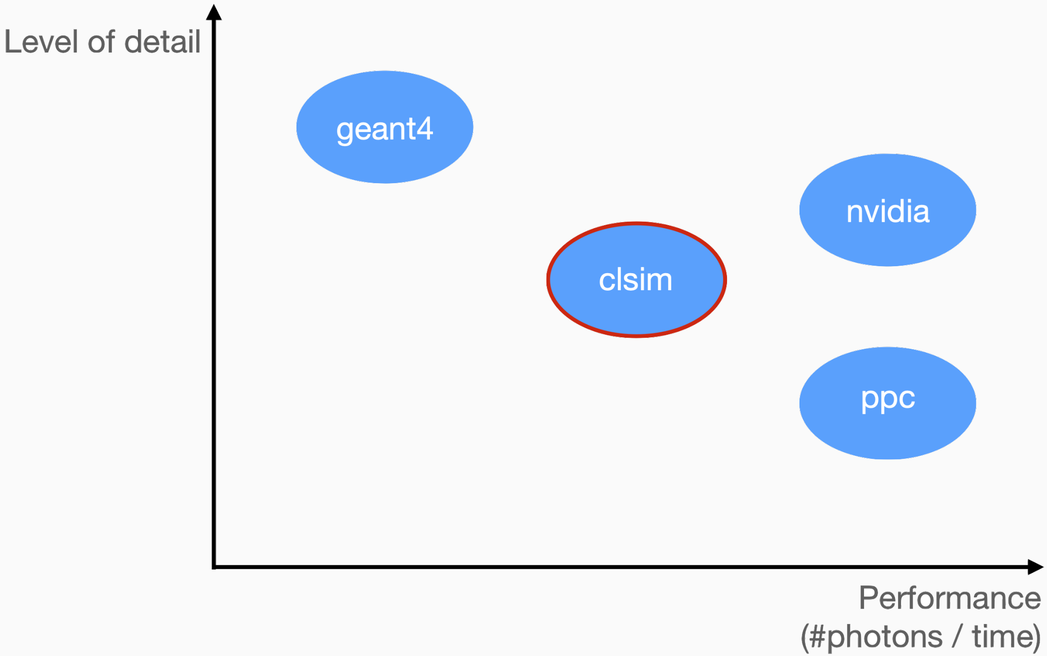
`https://github.com/fiedl/clsim/blob/sf/hole-ice-2018/resources/kernels/lib`

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 calcualte 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`

Federal Ministry of Education and Research

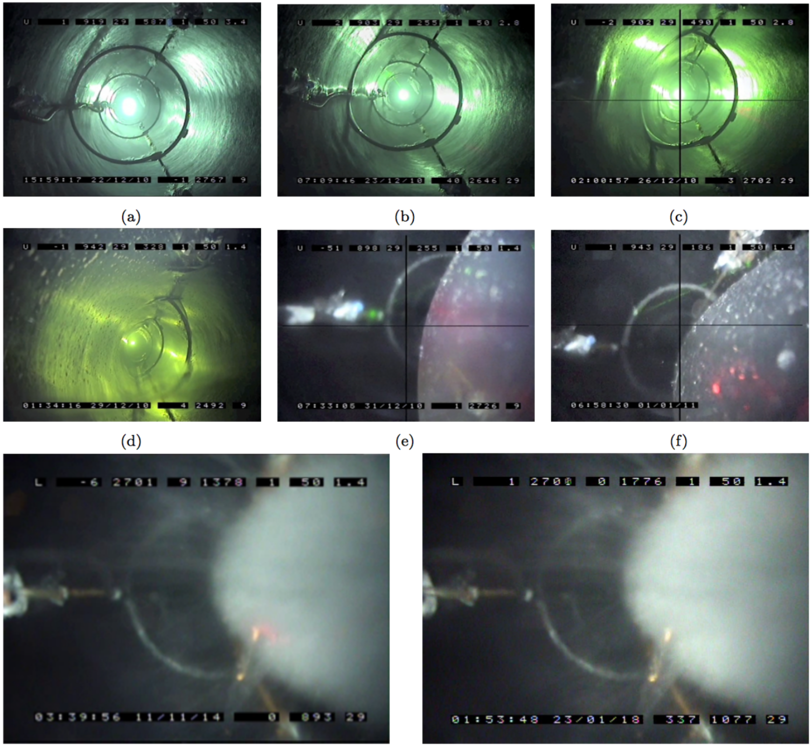
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Friedrich-Alexander-Universität Erlangen-Nürnberg

Backup slides

Hole ice



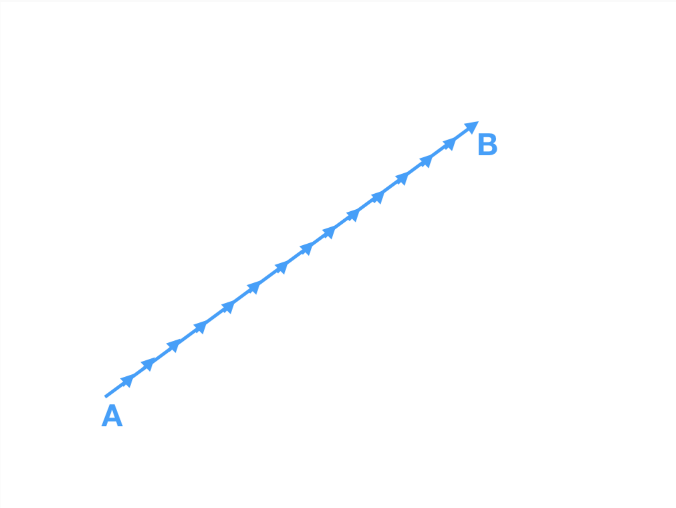
(a) (b) (c) (d) (e) (f) (g) (h)

- 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.

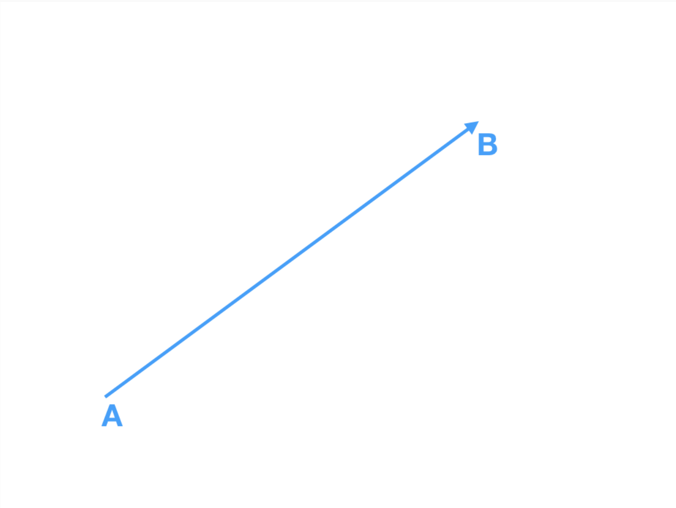
Photon-Propagation Algorithm

How does it work?



- Photon scattering points A and B
- Naive algorithm: Propagate photon small distance δx in each simulation step and randomize whether the photon will scatter in this step (easy to implement local properties)
- Faster algorithm: Randomize geometric distance to next scattering point and propagate from A to B in one simulation step
- Ice layers with different optical properties: Randomize number of scattering lengths between A and B as budget and calculate geometric distance by spending the budget over the ice layers
- New: Generalize budget algorithm to support cylinders and possibly other shapes with distinct scattering and absorption lengths and detection probabilities.

How does it work?



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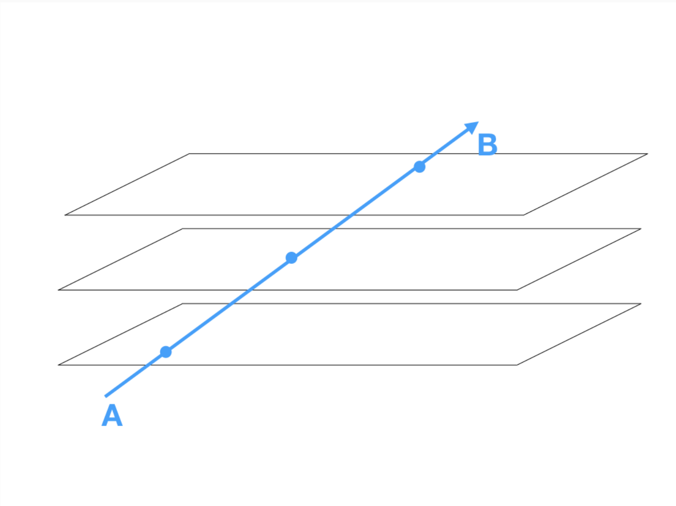

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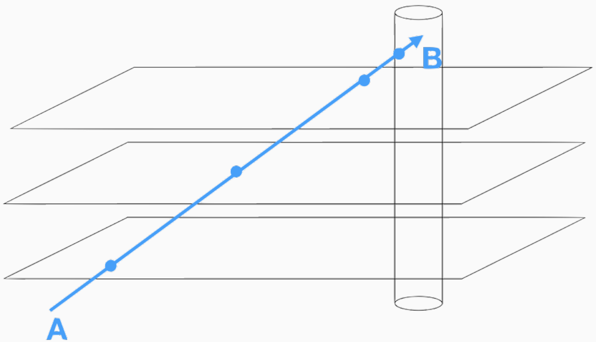

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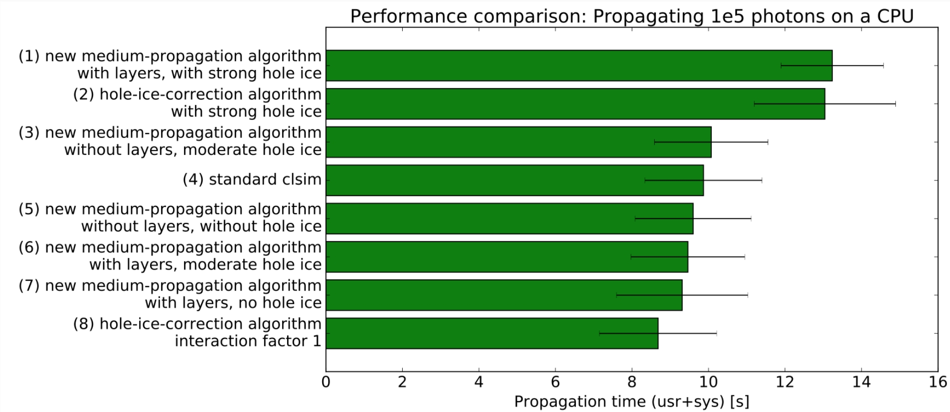
Performance

Time measurement: Propagating 10^5 photons on CPU



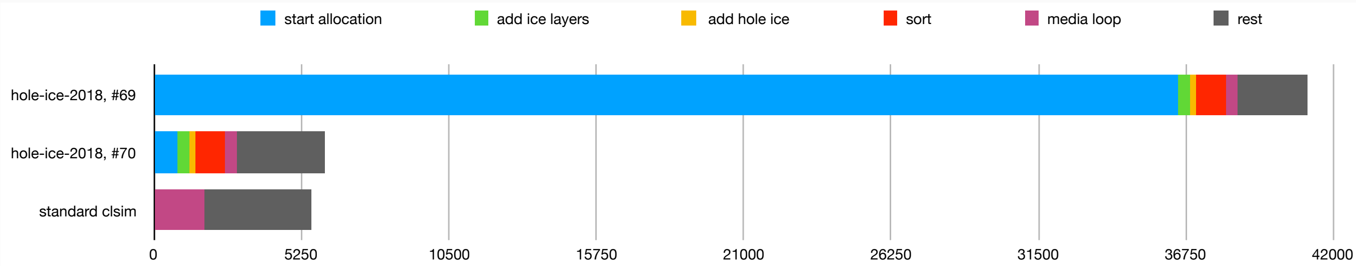

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
time ./run.rb --distance=1.0 --number-of-runs=1 --number-of-parallel-runs=1 --cpu --angle=45 --plane-wave
↪  --number-of-photons=1e5
```

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

Source: https://github.com/fiedl/hole-ice-study/issues/49

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

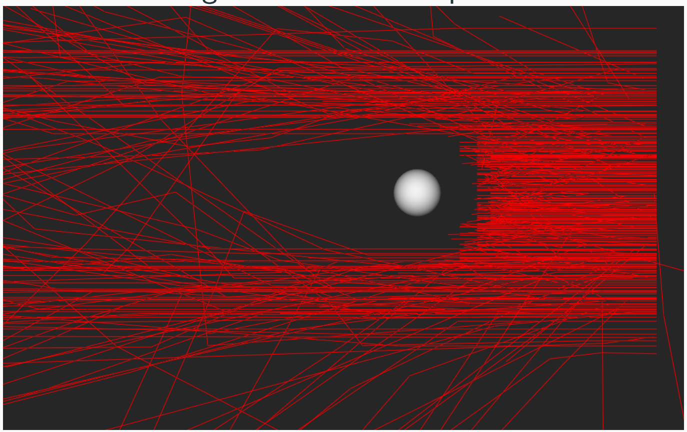
New algorithm, about H2 hole ice: 15 mins

Source: `https://github.com/fiedl/hole-ice-study/issues/69`

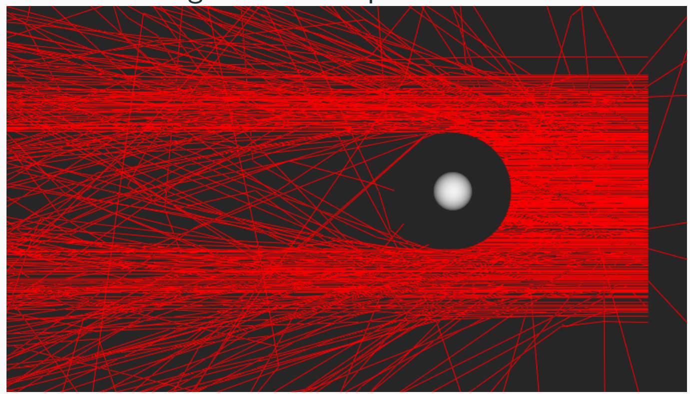
Coordinates-vs-vectors bug

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

Before: Treating coordinates as separate variables

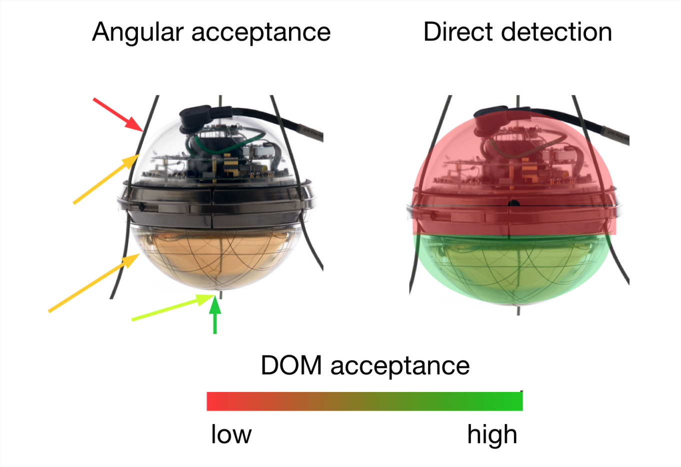


After: Treating vectors as opencl-native vectors



Source: `https://github.com/fiedl/hole-ice-study/issues/28`

Direct detection



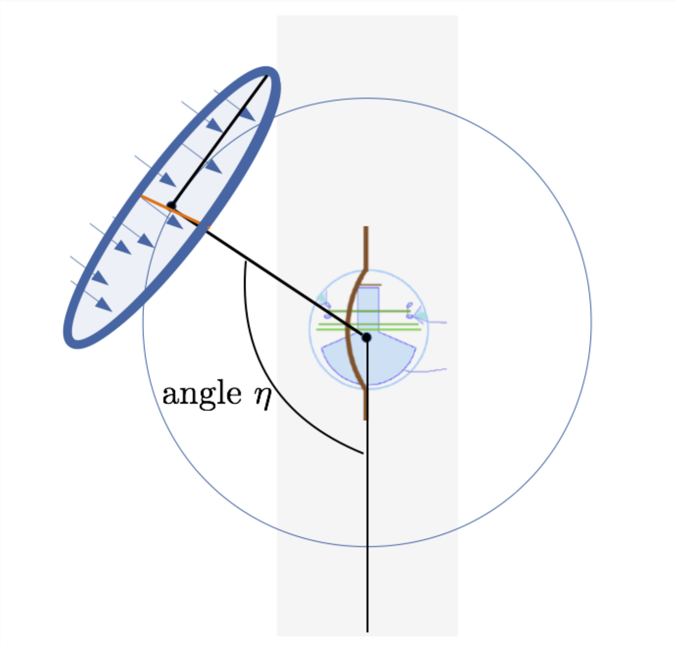
Source: Image: Martin Rongen, *Status and future of SpiceHD DARD*, 2017, Slide 17,
See also: `https://github.com/fiedl/hole-ice-study/issues/32`

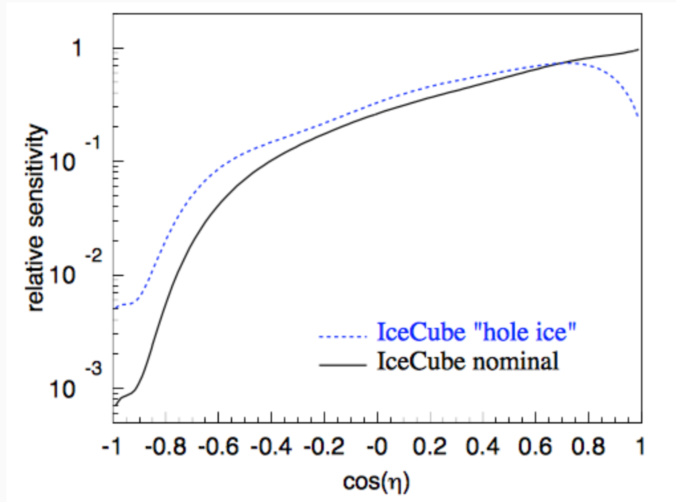
- The DOM looks downwards by design
- Currently, the hit position is not used when determining DOM acceptance, just the photon direction when hitting the DOM (*DOM angular acceptance*)
- Direct detection: Accept all hits below the waist band, reject all others
- Direct detection is easy with clsim
  - 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

`https://github.com/fiedl/hole-ice-study/issues/32`

Angular acceptance

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



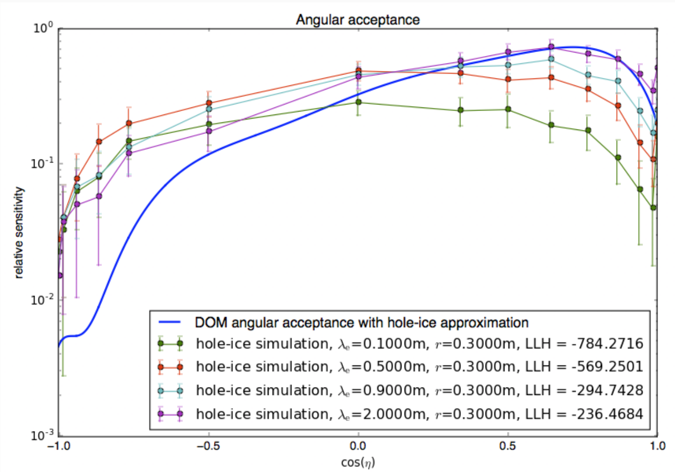


Angular acceptance *reference curves*. The nominal model is based on lab measurement, the hole ice curve on previous simulations.

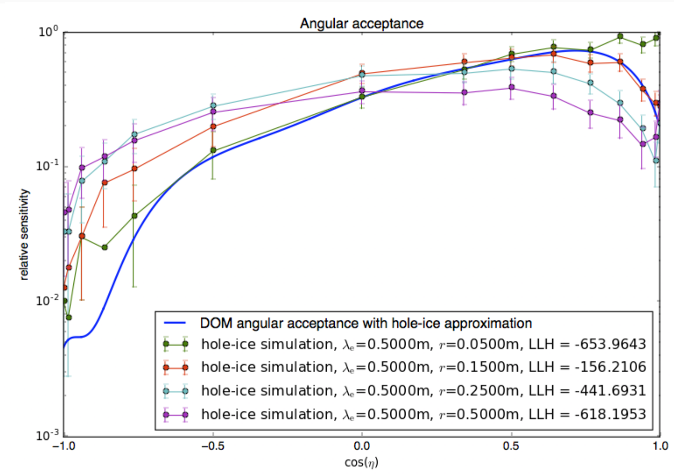
Source: Image: Martin Rongen, Calibration Call 2015-11-06, DARD Update, Slide 9
Plot: Measurement of South Pole ice transparency with the IceCube LED calibration system, 2013, figure 7. See also: `https://github.com/fiedl/hole-ice-study/issues/10`

Angular acceptance for different hole-ice parameters

Vary hole-ice scattering length:



Vary hole-ice radius:



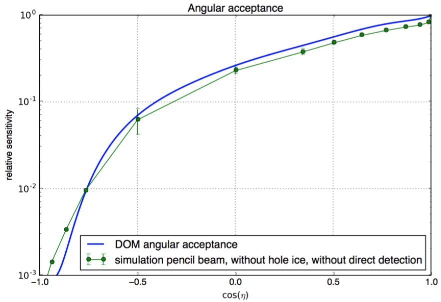
Systematics:

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

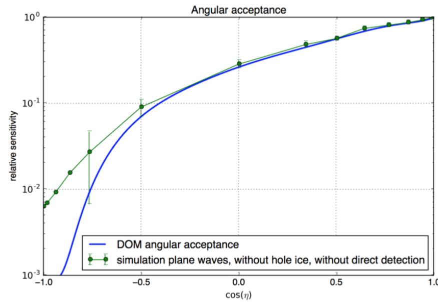
plane extent 1 m, starting distance 1 m

non-perfect bulk-ice properties

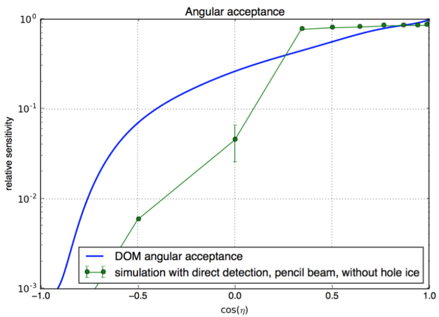
Angular acceptance: Sources and acceptance criteria



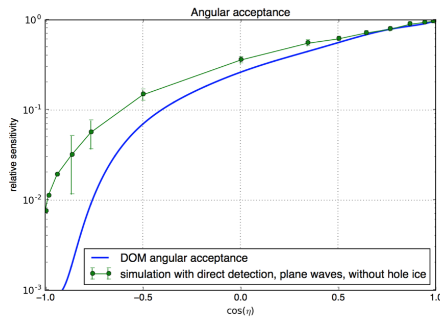
(a) pencil beams, a priori angular acceptance



(b) plane waves, a priori angular acceptance



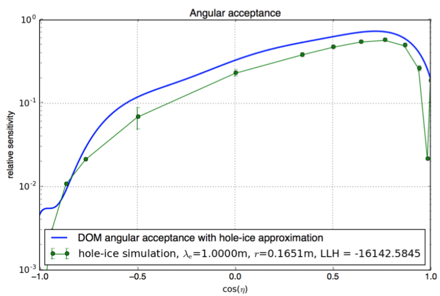
(c) pencil beams, direct detection



(d) plane waves, direct detection

Source: `https://github.com/fiedl/hole-ice-study/issues/98` **and** `https://github.com/fiedl/hole-ice-study/issues/99`

Angular acceptance: Sources and acceptance criteria



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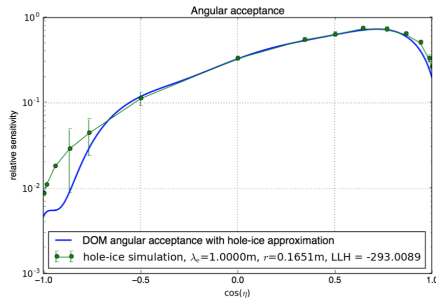
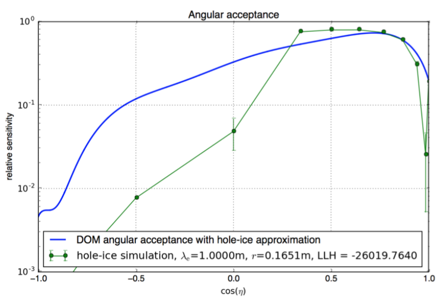
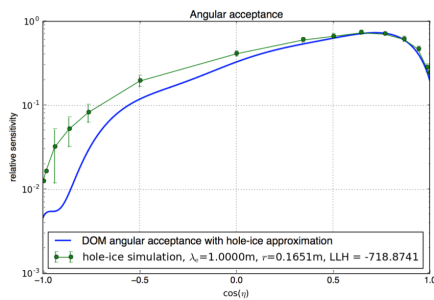


(b) plane waves, a priori angular acceptance



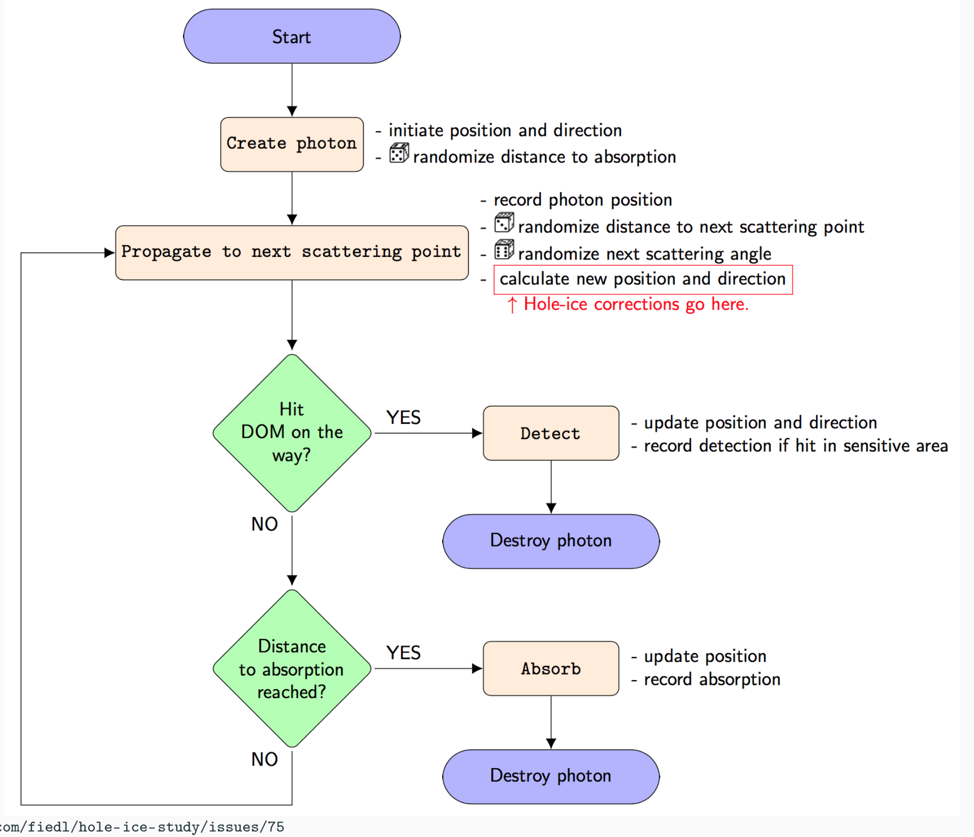
(c) pencil beams, direct detection



(d) plane waves, direct detection

Source: `https://github.com/fiedl/hole-ice-study/issues/98` **and** `https://github.com/fiedl/hole-ice-study/issues/99`

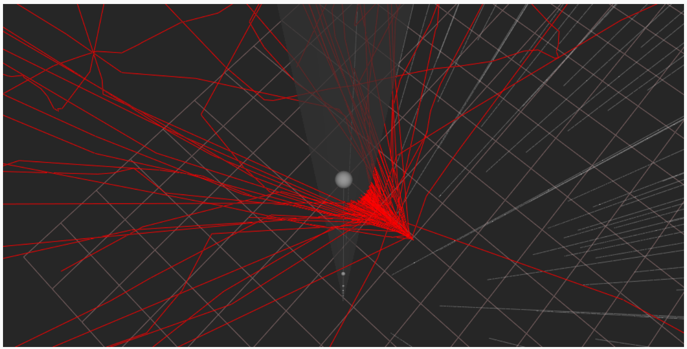
Simplified simulation-step flow chart



Source: `https://github.com/fiedl/hole-ice-study/issues/75`

Instant absorption

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



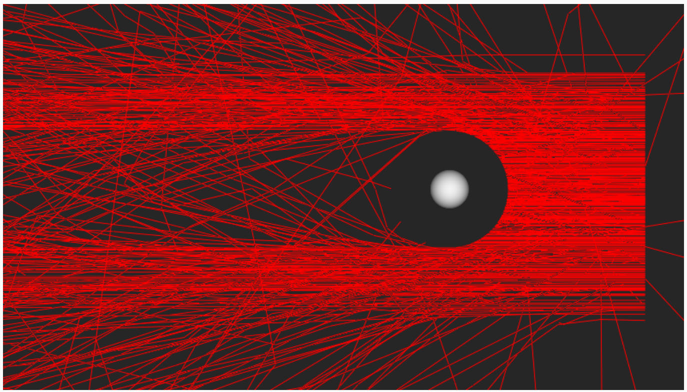
Photon point source, 3d view

```
$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
```

Source: https://github.com/fiedl/hole-ice-study/issues/22

Instant absorption

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



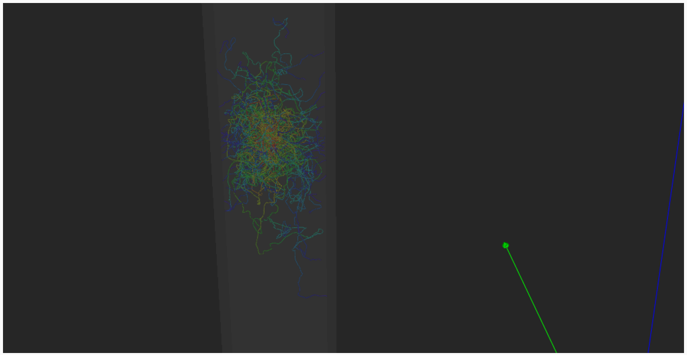
Plane wave photon source, top view

```
$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-paralle-runs=1 \
    --cpu --save-photon-paths
steamshovel tmp/propagated_photons.i3
```

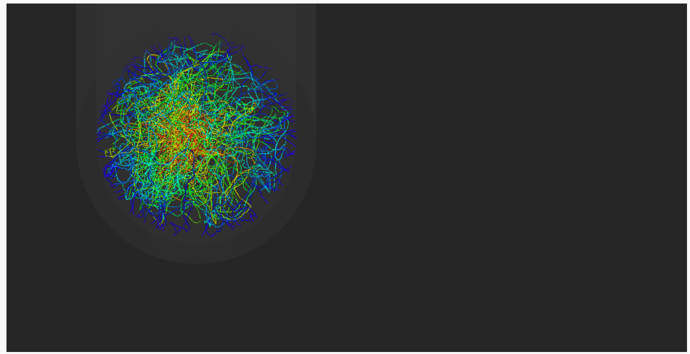
Source: https://github.com/fiedl/hole-ice-study/issues/22

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

Source: `https://github.com/fiedl/hole-ice-study/issues/47`

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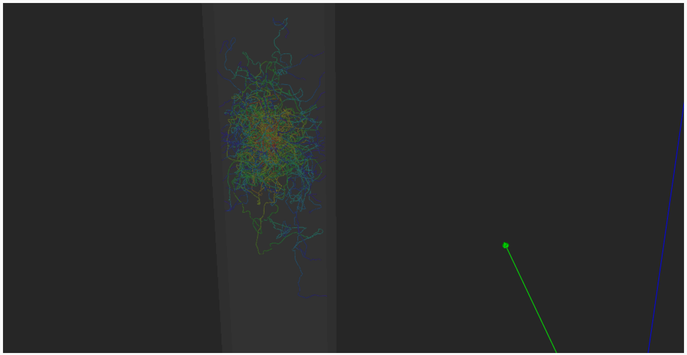

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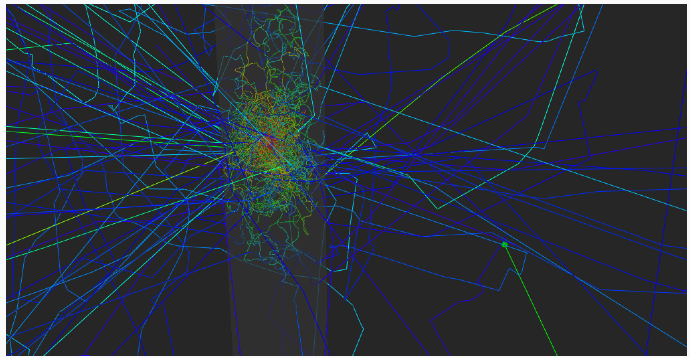
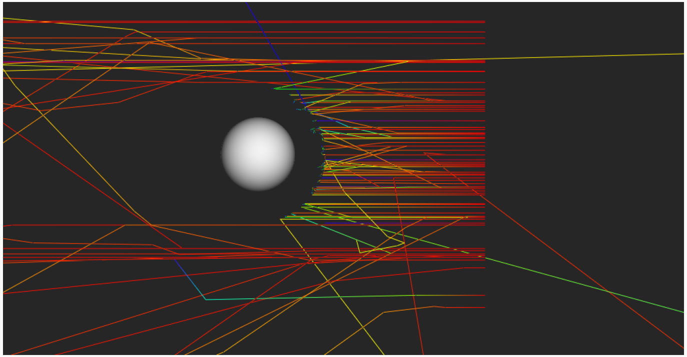


Without the outer cylinder

Source: `https://github.com/fiedl/hole-ice-study/issues/47`

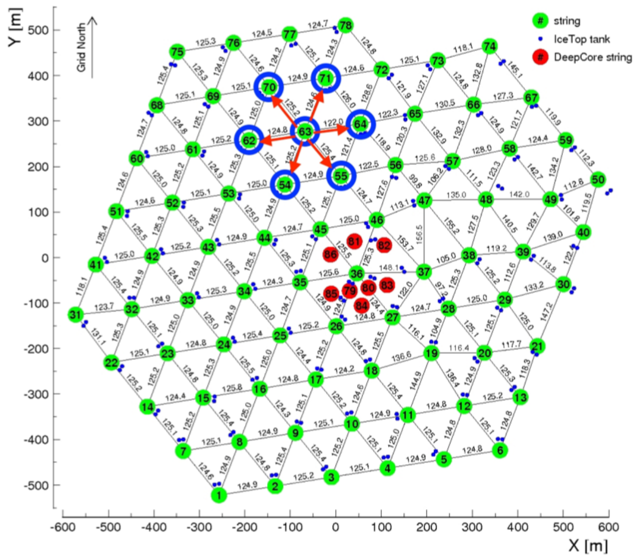
Scattering example

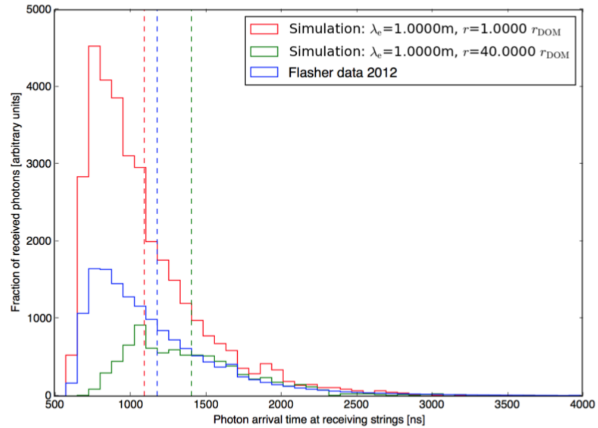


- Hole-ice absorption length: about 5 cm
- Hole-ice scattering length factor: 0.001

```
$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
```

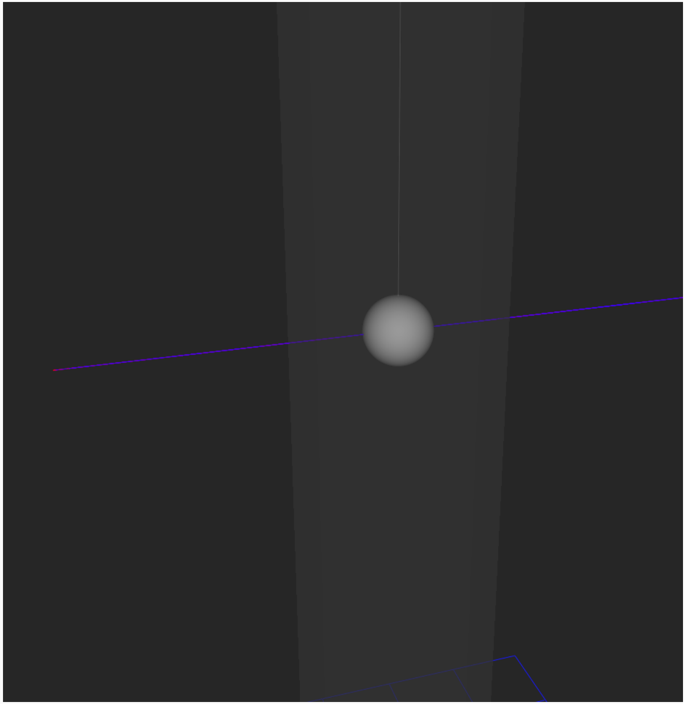
Cross checks: Arrival-time distributions

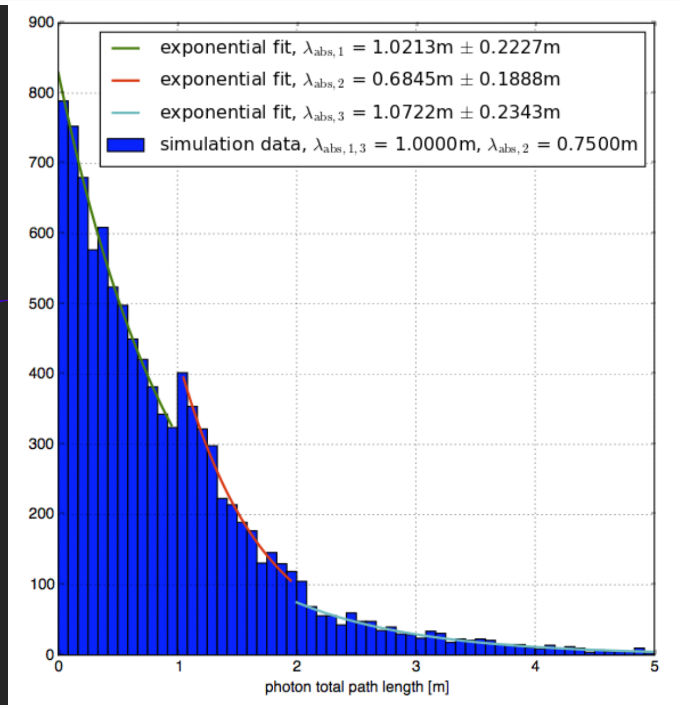




Source: `https://github.com/fiedl/hole-ice-study/issues/91`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

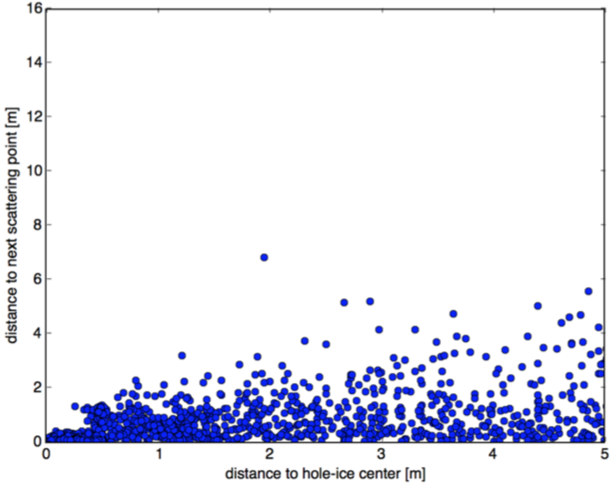
Cross checks: Path-length distributions



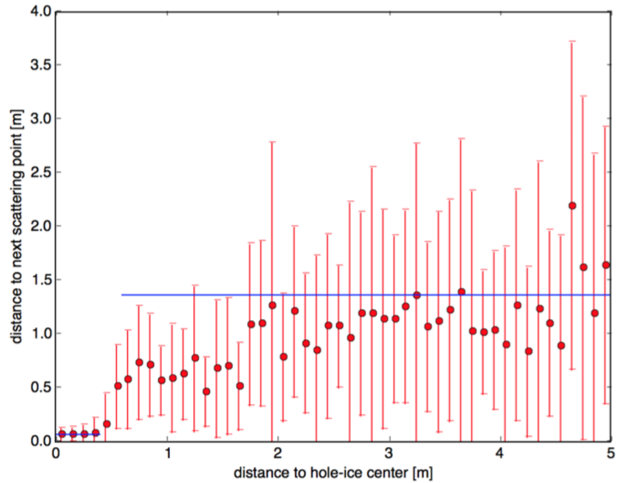


Source: `https://github.com/fiedl/hole-ice-study/issues/66`

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



(a) All data points

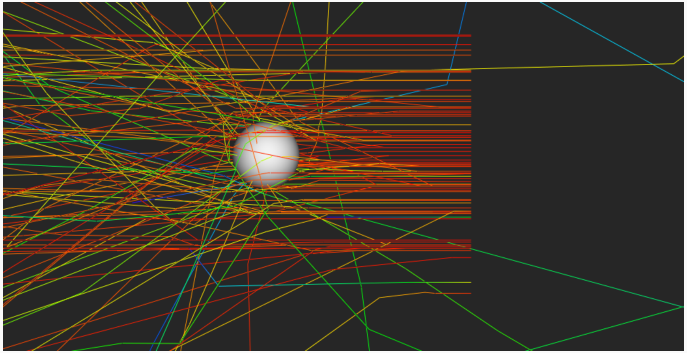


(b) Averaged for bins of a width of 10 cm

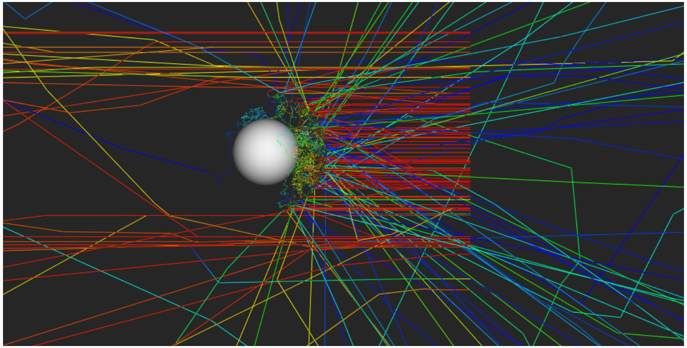
Source: `https://github.com/fiedl/hole-ice-study/issues/71`

Trying out different hole-ice scattering lengths

The exact optical properties of the hole ice are unknown. With the simulation, one can try out different properties, e.g. scattering length.



Scattering length $\lambda_{\text{sca,hole-ice}} = 10^{-1}\,\lambda_{\text{sca,bulk}}$.
Absorption length $\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$.



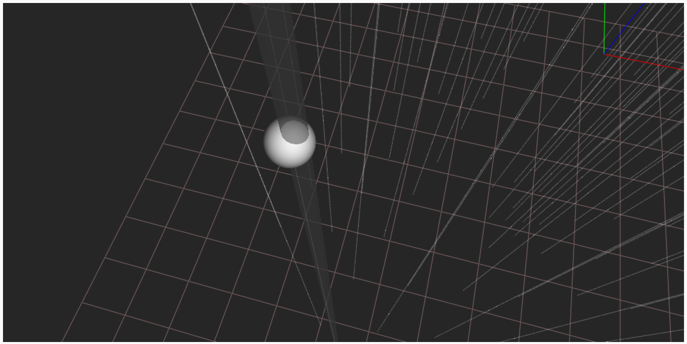
Scattering length $\lambda_{\text{sca,hole-ice}} = 10^{-3}\,\lambda_{\text{sca,bulk}}$.
Absorption length $\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$.

Animation on youtube: `https://youtu.be/BhJ6F3B-I1s`

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.

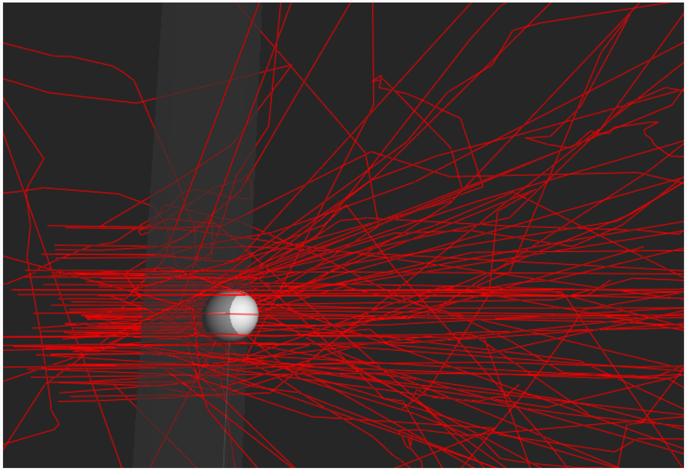
Source: `https://github.com/fiedl/hole-ice-study/issues/39`

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

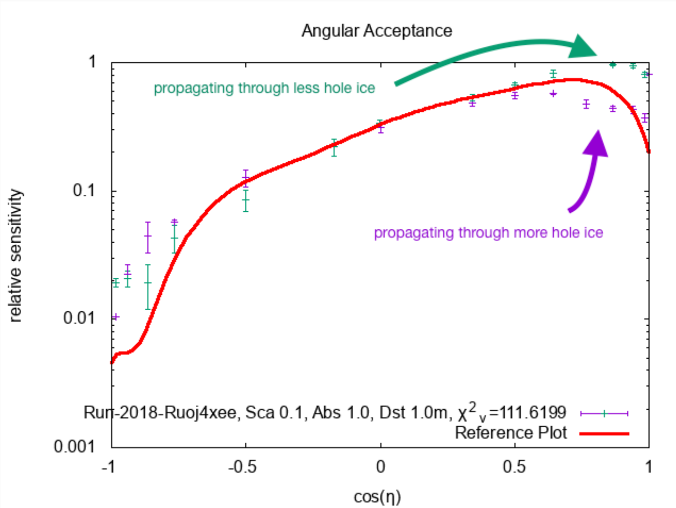
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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
```

Source: https://github.com/fiedl/hole-ice-study#asymmetry-example, https://github.com/fiedl/hole-ice-study/issues/8

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

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

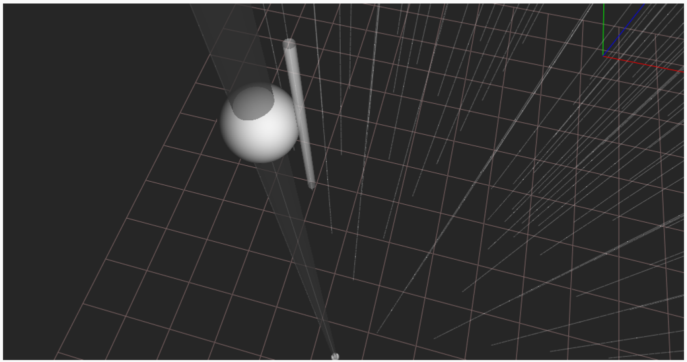
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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
```

Source: https://github.com/fiedl/hole-ice-study#asymmetry-example, https://github.com/fiedl/hole-ice-study/issues/8

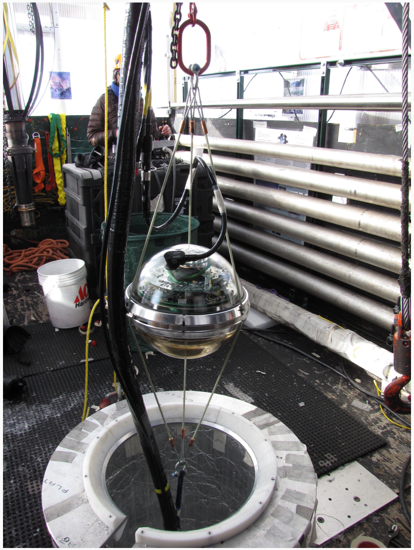
Cable shadows

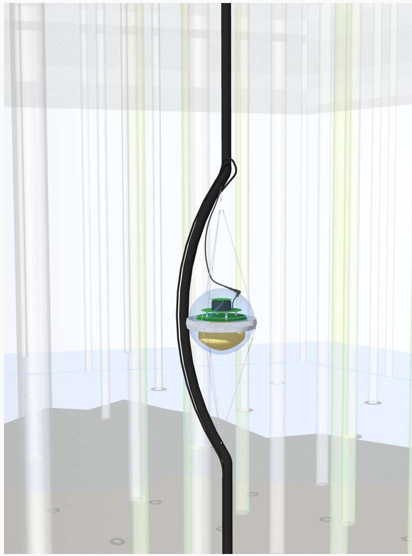


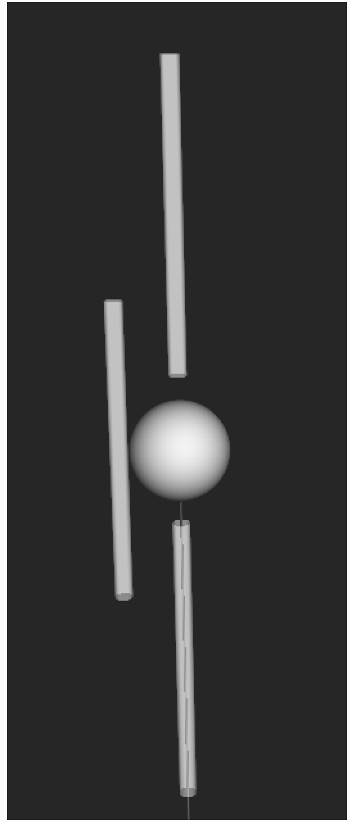
- Cables can be modelled as separate cylinders
  - for each DOM separate position
  - 1 m height
  - configured for instant absorption
- This image:
  - DOM radius: 16.5 cm
  - bubble-column radius: 8.0 cm
  - cable radius: 2.0 cm

Source: `https://github.com/fiedl/hole-ice-study/issues/35`

Direct cable simulation: Angular acceptance

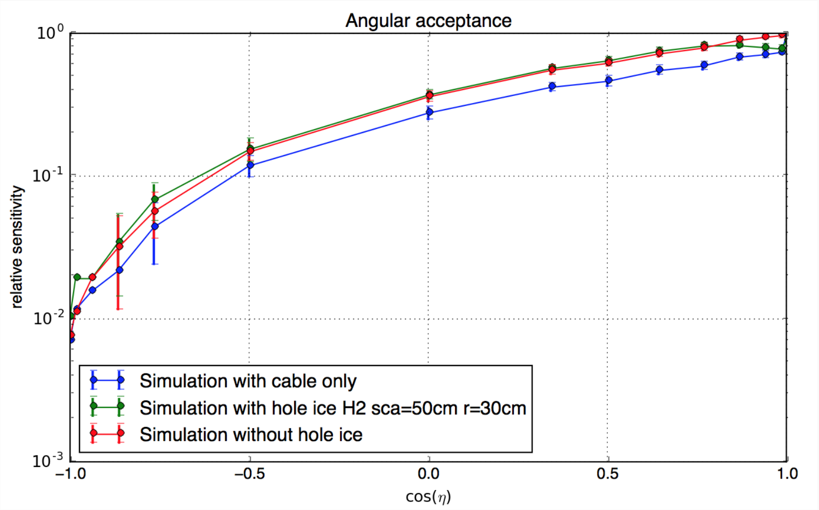


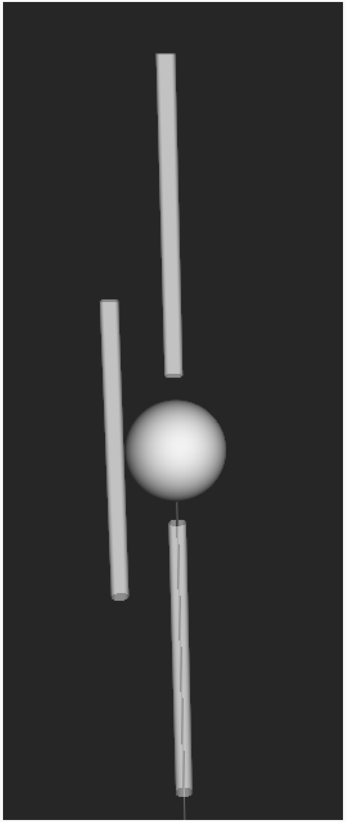




Source: https://github.com/fiedl/hole-ice-study/issues/101. Images: https://icecube.wisc.edu/gallery/view/153, https://gallery.icecube.wisc.edu/internal/v/GraphicRe/graphics/arraygraphics2011/sketchup/DOMCloseUp.jpg.html

Direct cable simulation: Angular acceptance

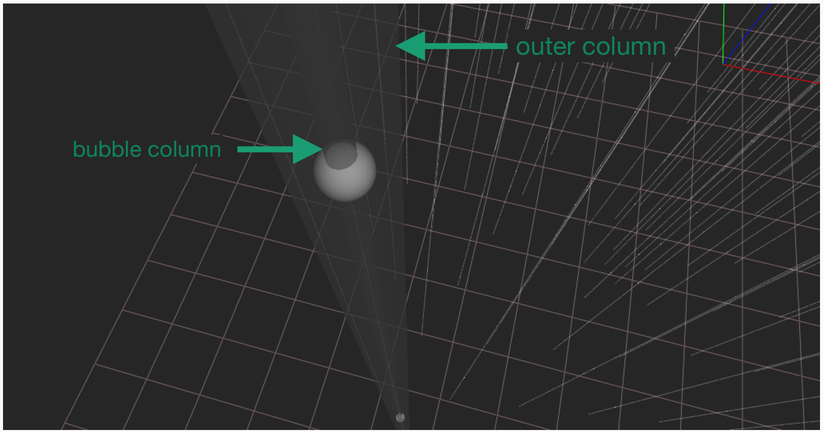




The azimuthal starting angle is such that the cable shadow is maximal.

Source: https://github.com/fiedl/hole-ice-study/issues/101.

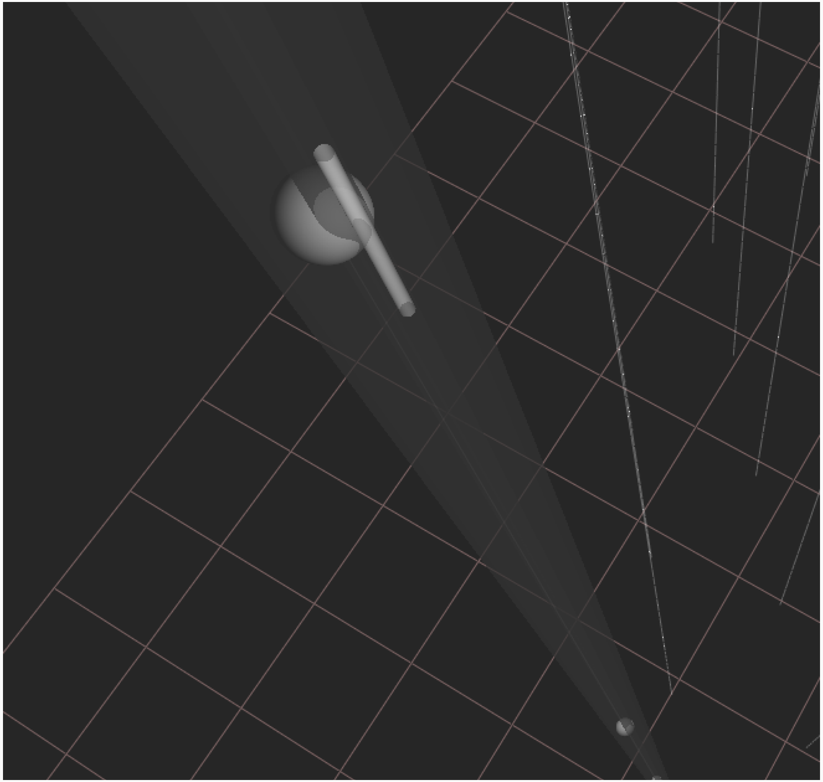
Nested hole-ice cylinders



- 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

Source: `https://github.com/fiedl/hole-ice-study/issues/7`

Realistic simulation scenario

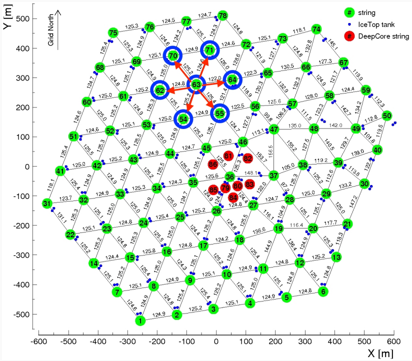


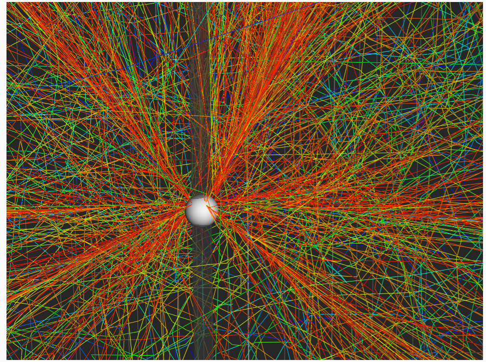
- DOM: radius 16.5 cm, shifted by 12.0 cm against the center of the bore hole
- bubble column: radius 8.0 cm
- drill-hole column: radius 30.0 cm
- cable: radius 3.0 cm, placed next to the DOM, partially within the bubble column

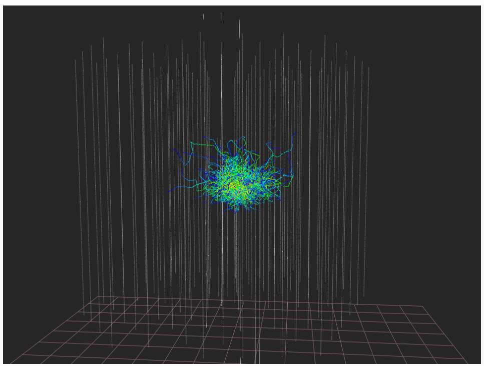
See also: `https://github.com/fiedl/hole-ice-study/issues/110`

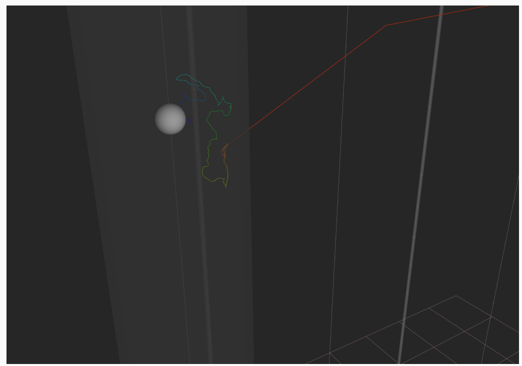
Flasher-simulation example

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



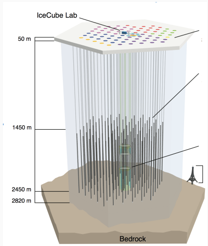


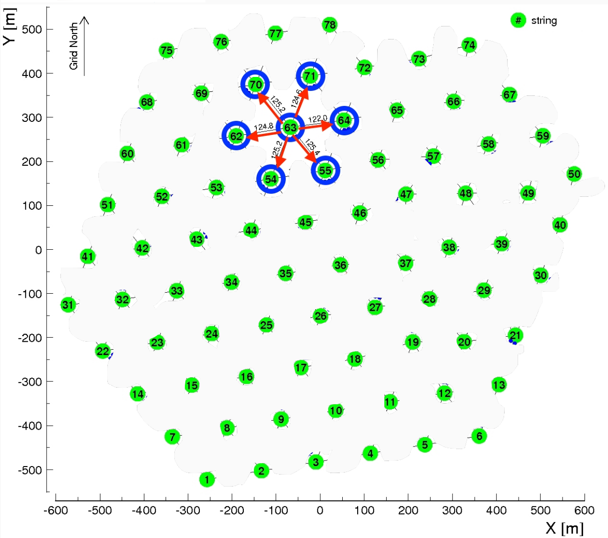


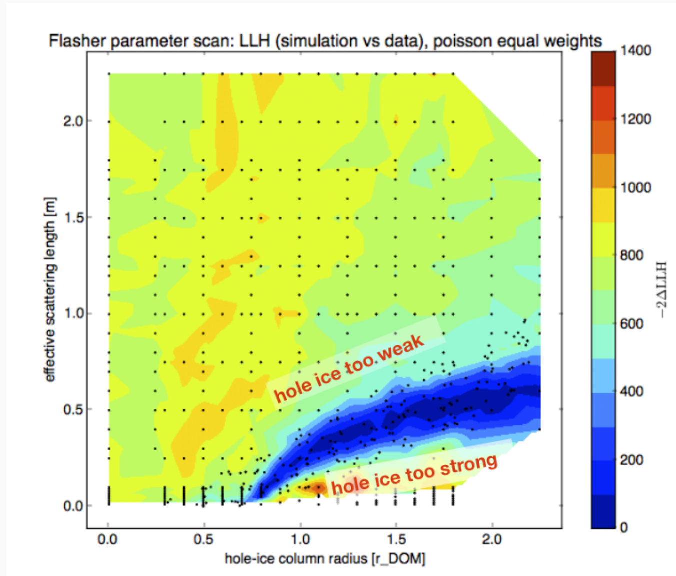


See `https://github.com/fiedl/hole-ice-study/issues/107`

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

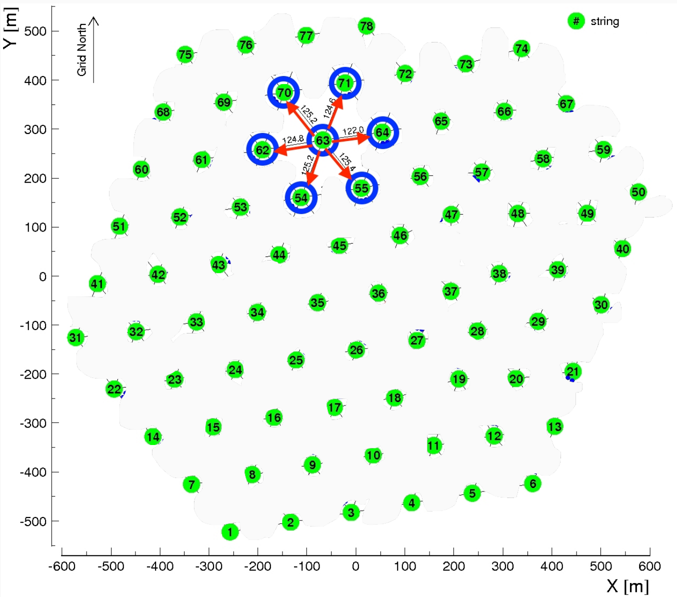






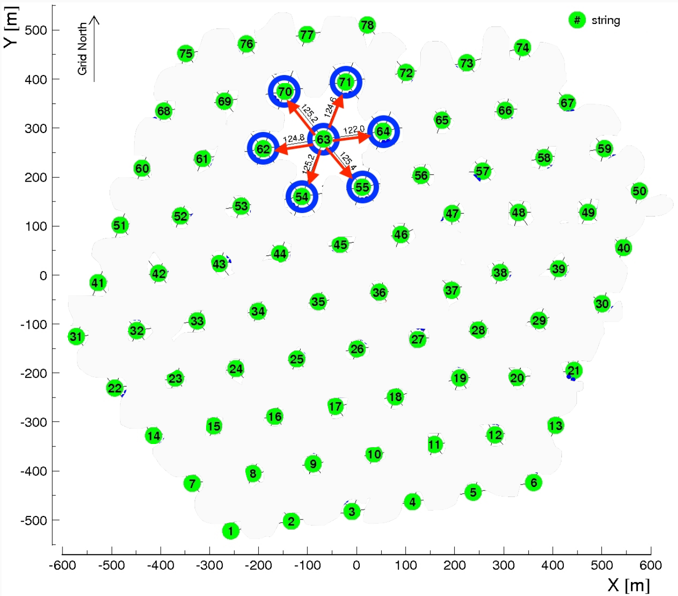
Source: `https://github.com/fiedl/hole-ice-study/issues/59`. Footprint based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`. Image: Aartsen et al., The IceCube Neutrino Observatory: Instrumentation and online systems, 2017.

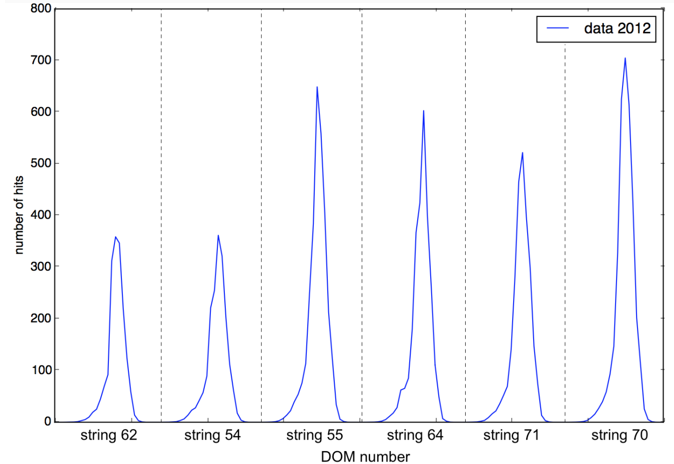
Early results: Calibration data suggest asymmetric shielding by hole ice



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

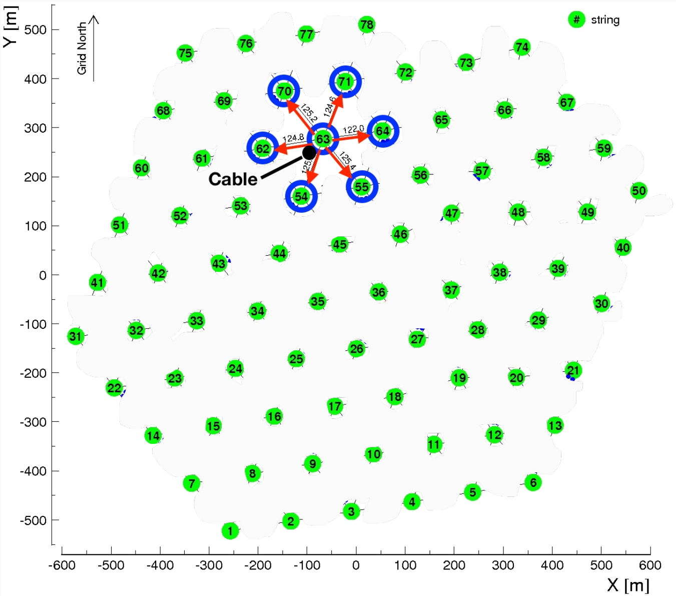
Early results: Calibration data suggest asymmetric shielding by hole ice

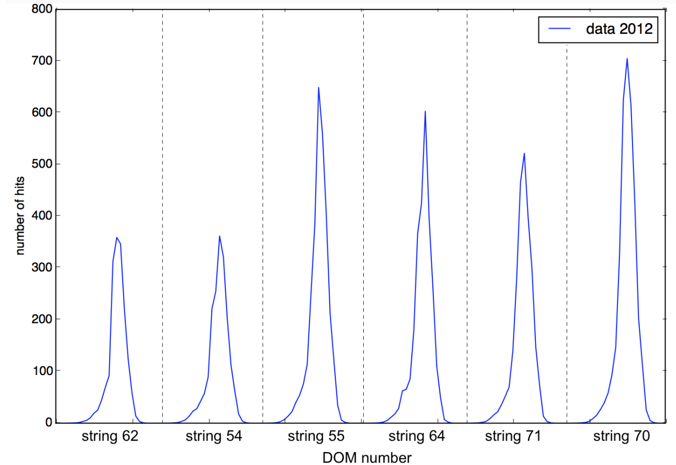




Source: `https://github.com/fiedl/hole-ice-study/issues/97`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

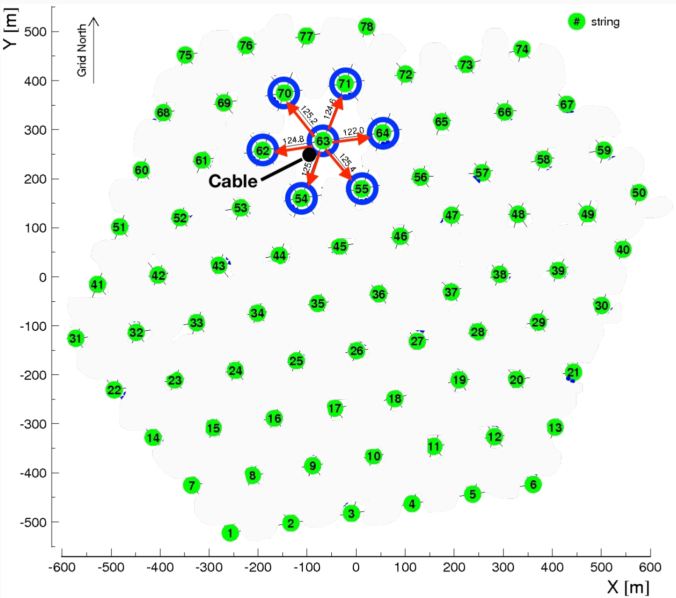
Early results: Calibration data suggest asymmetric shielding by hole ice

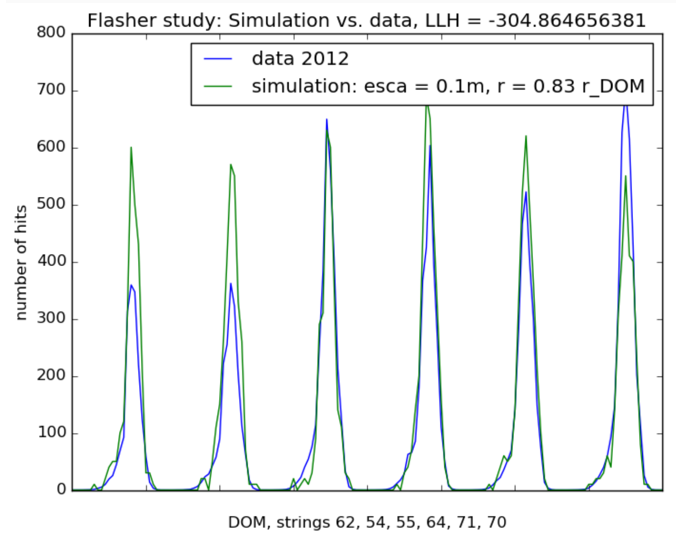




Source: `https://github.com/fiedl/hole-ice-study/issues/97`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

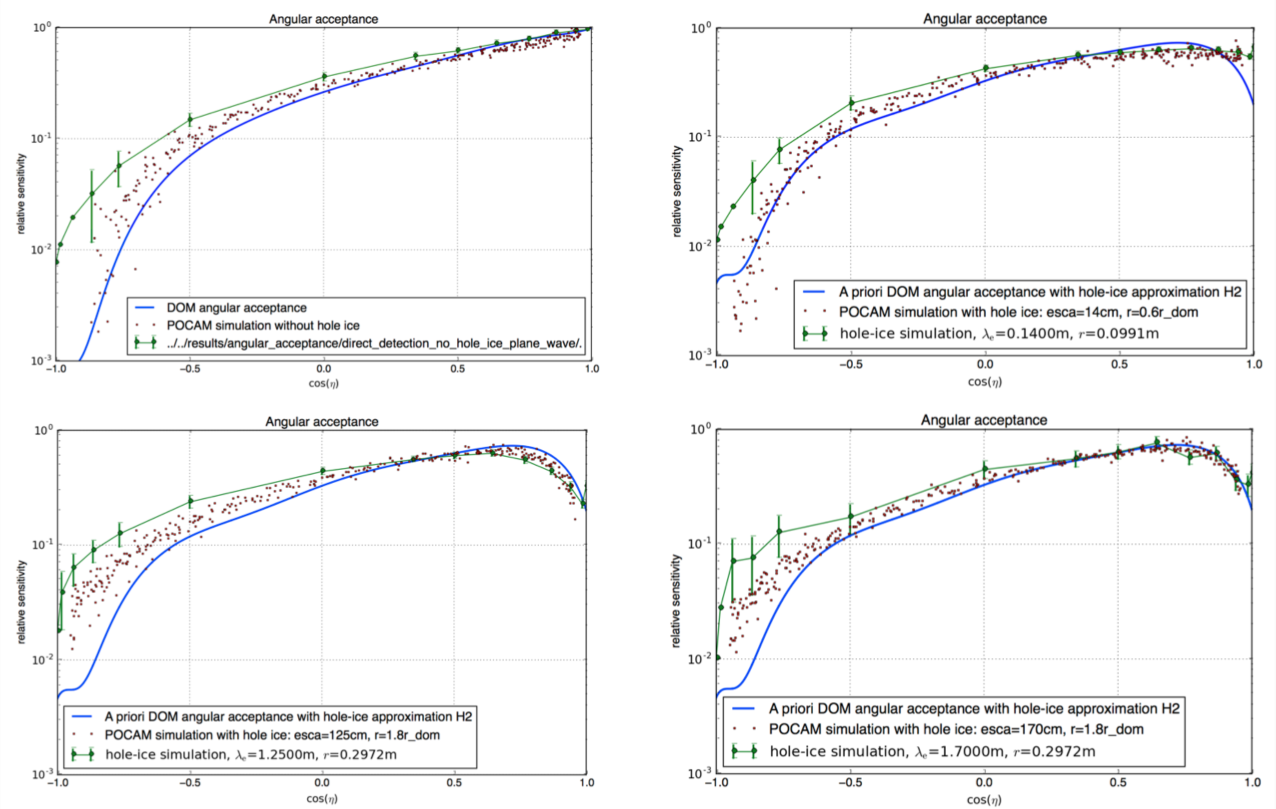
Early results: Calibration data suggest asymmetric shielding by hole ice





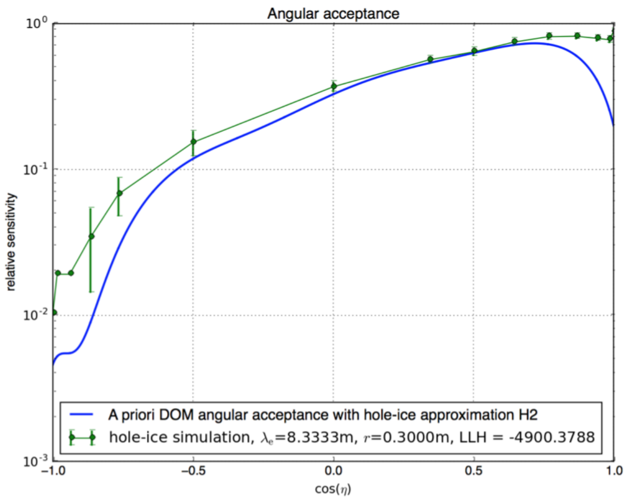
Source: `https://github.com/fiedl/hole-ice-study/issues/97`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

Comparison to ppc simulation

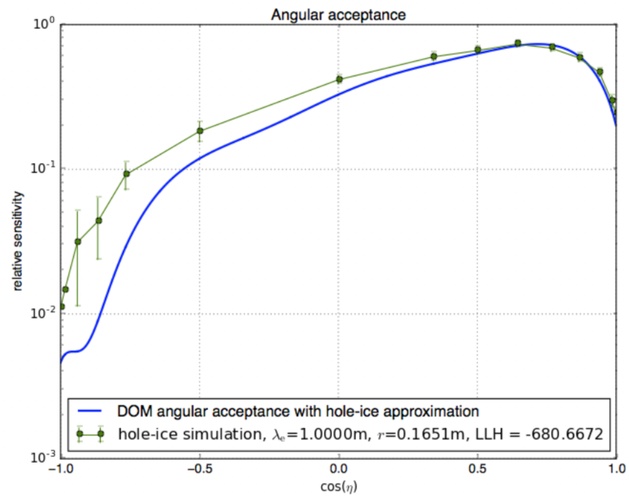


Source: `https://github.com/fiedl/hole-ice-study/issues/4`, POCAM ppc data source: Resconi, Rongen, Krings: The Precision Optical CAlibration Module for IceCube-Gen2: First Prototype, 2017.

Comparison to H2 hole-ice model



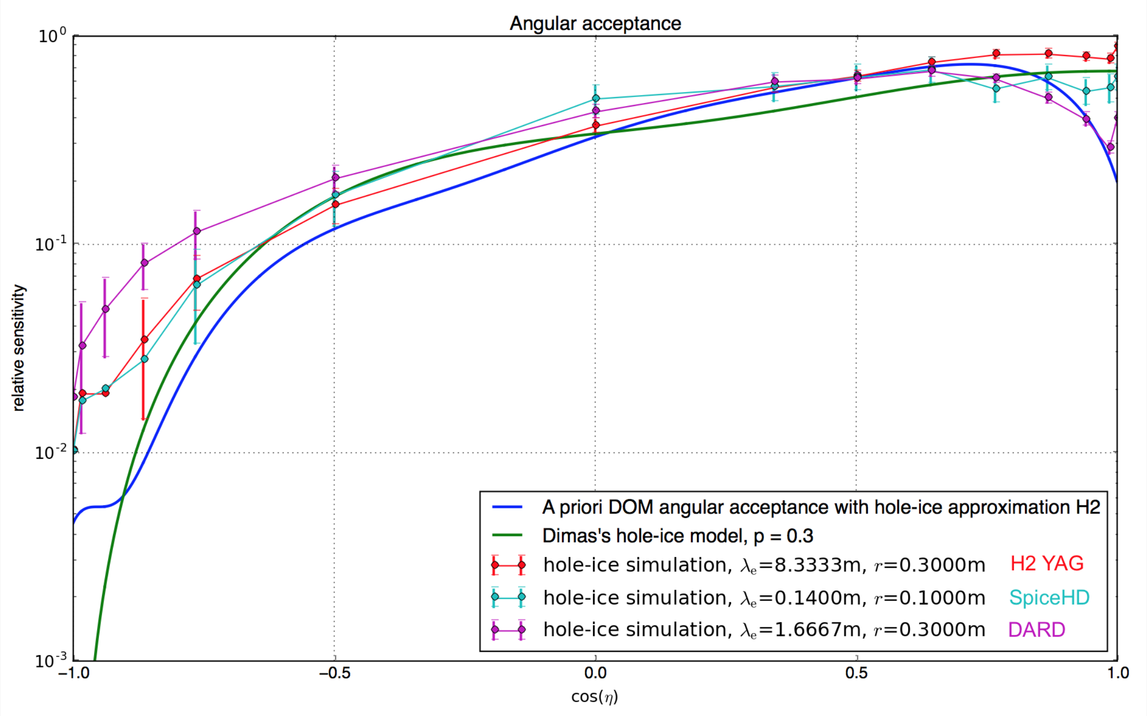
(a) Clsim simulation with H2 hole-ice parameters: $r = 30\,\text{cm}, \lambda^{\text{H}}_{\text{sca}} = 50\,\text{cm}, \lambda^{\text{H}}_{\text{sca}} = 8.33\,\text{m}$



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

Source: https://github.com/fiedl/hole-ice-study/issues/80. H2 curve source: IceCube Collaboration et al. Measurement of South Pole ice transparency with the IceCube LED calibration system. 2013. H2 parameter source: Albrecht Karle. Hole Ice Studies with YAG. http://icecube.berkeley.edu/kurt/interstring/hole-ice/yak.html. 1998.

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.