Simulation of Light Propagation Through Hole Ice for the IceCube Experiment

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Session T11 Neutrino Astronomy I

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Erlangen Centre for Astroparticle Physics

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Introduction: IceCube Detector

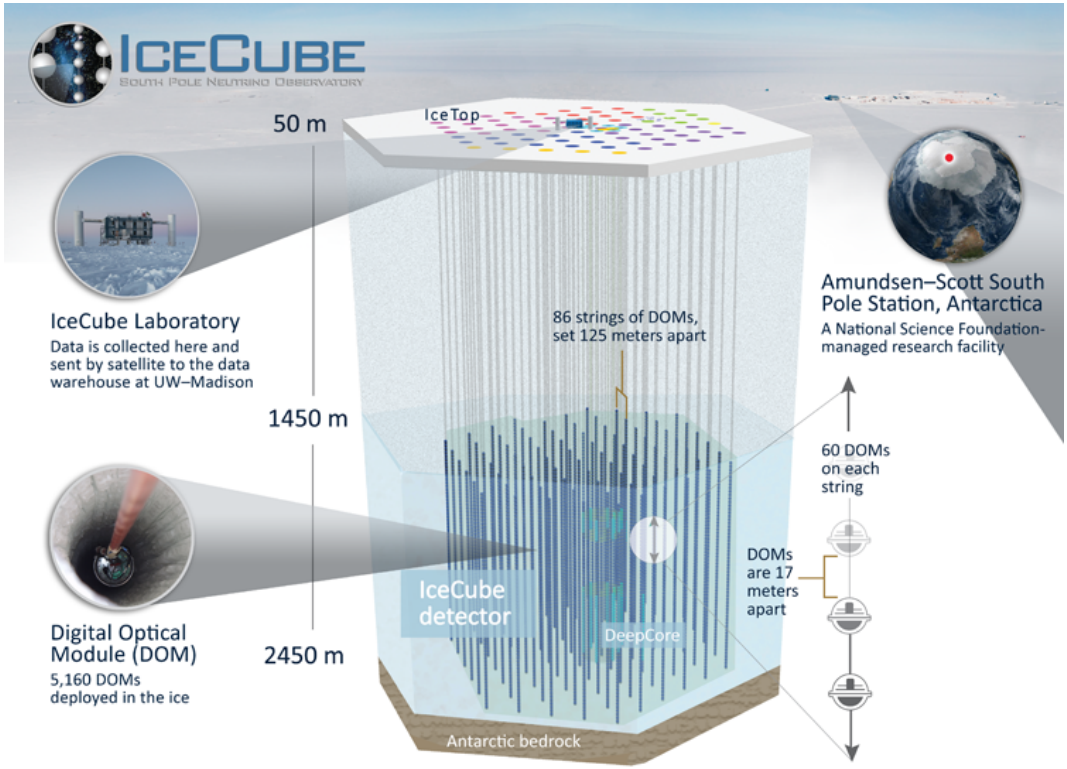
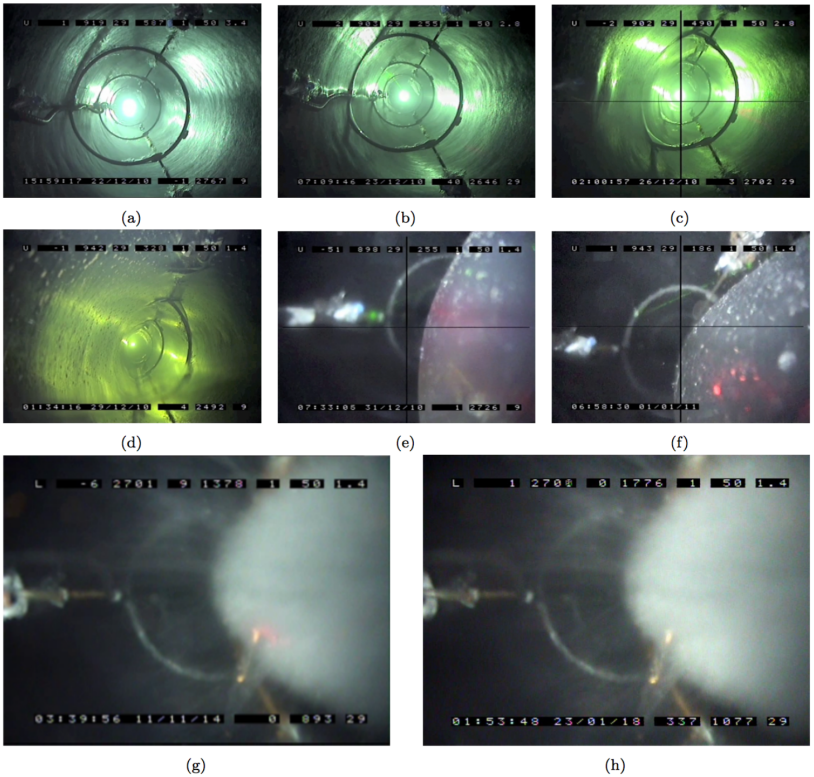


Image source: https://icecube.wisc.edu/icecube/static/science/images/icecube_detector_sm.png

Motivation and Scope



- **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

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.

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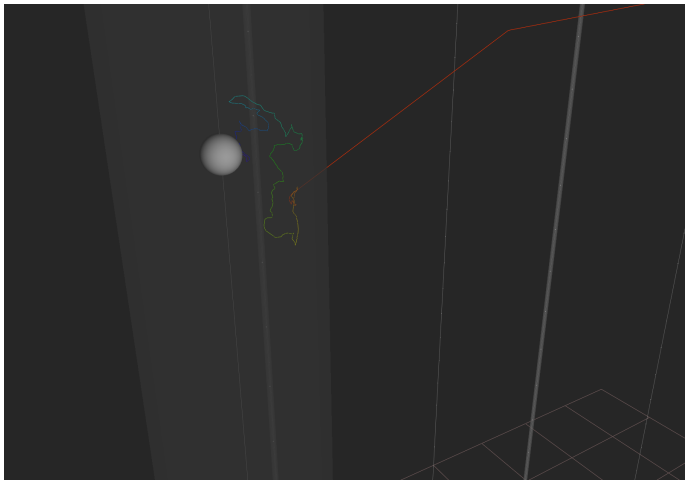


Simulation: Incoming photon (red) hits a large hole-ice cylinder with small scattering length

- No direct hole-ice simulation in standard clsim only angular sensitivity approximation
  - $\rightarrow$ No asymmetries possible, e.g. DOM position relative to hole ice
- implement direct hole-ice simulation in clsim

Resources

Usage examples can be found on github:

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

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

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

Previous talks on this topic:

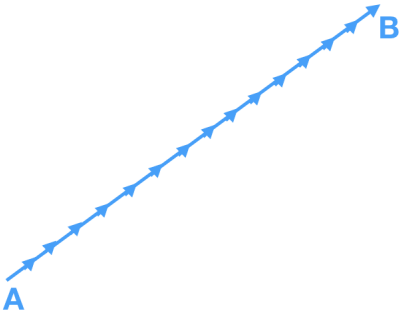
`https://github.com/fiedl/hole-ice-talk/releases`

LaTeX version of these presentation slides:

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

Contents

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 in clsim**: Randomize number of scattering lengths between A and B as budget and calculate geometric distance by spending the budget over the ice layers
- **New: Hole ice** in clsim: Generalize budget algorithm to support cylinders (with distinct scattering and absorption lengths) in addition to ice layers.

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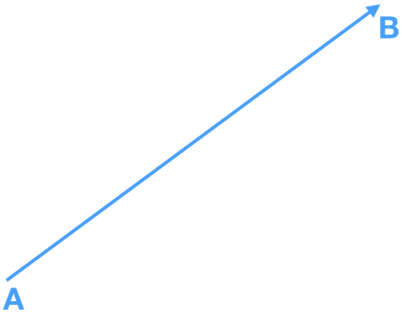

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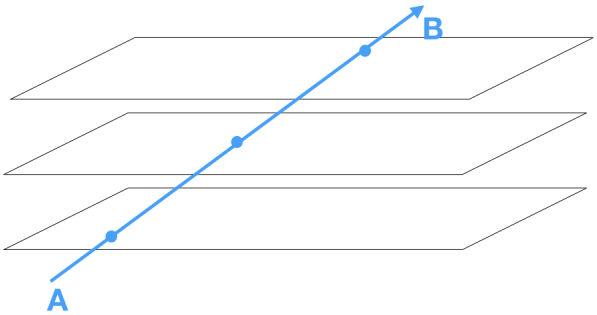

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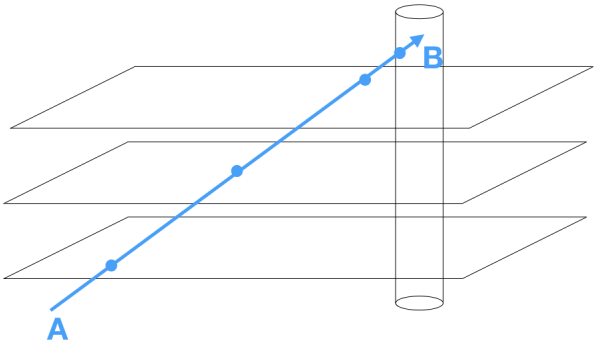

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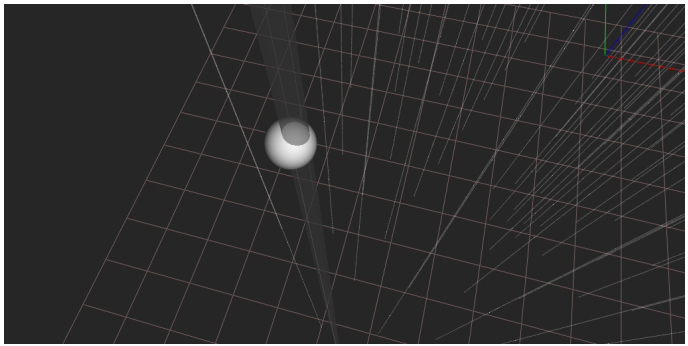
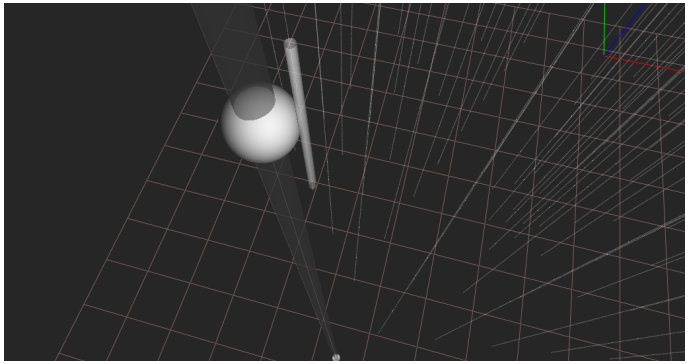
Separate hole-ice cylinder positions



- 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

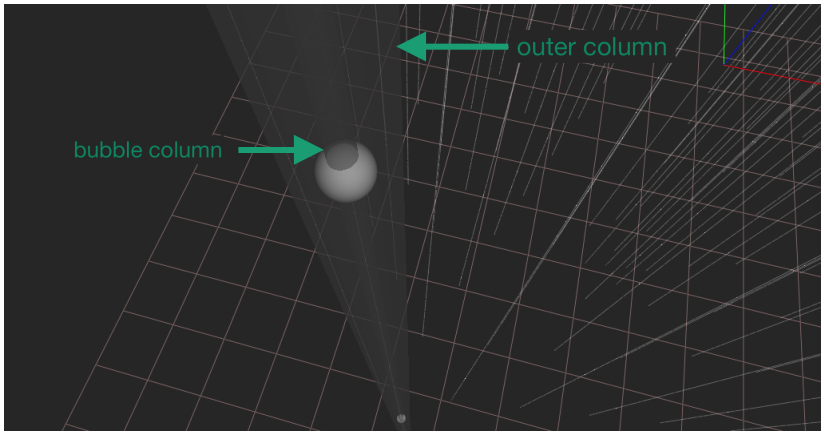
Cable shadows



- 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

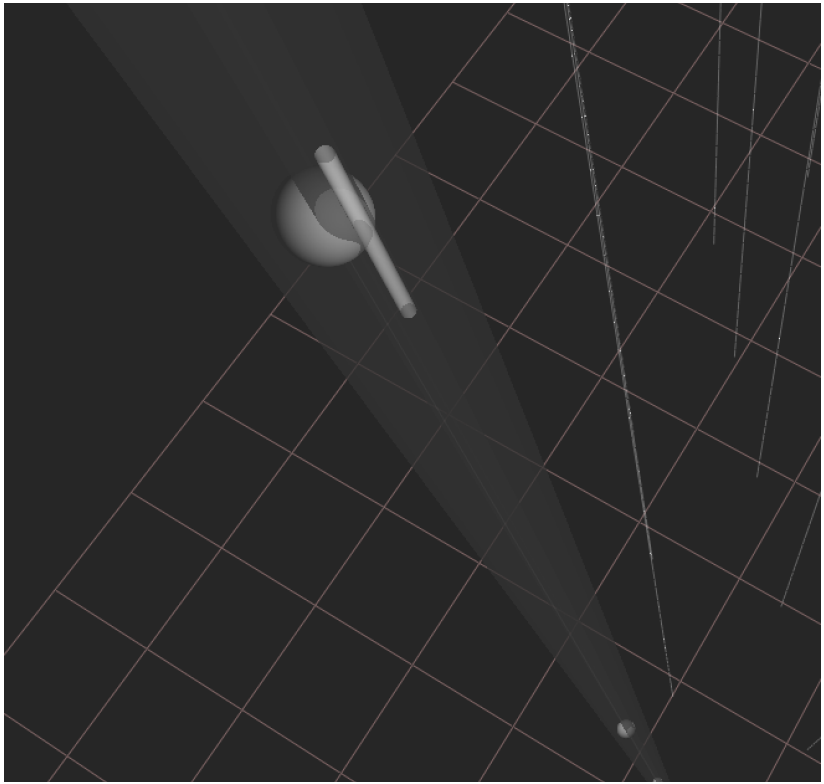
Nested hole-ice cylinders



- 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`

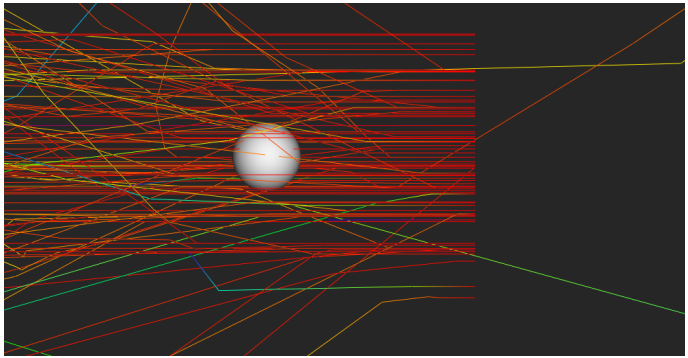
Nested shifted cylinders and cable



- This image:
  - DOM: radius 16.5 cm, shifted by 12.0 cm
  - bubble column: radius 8.0 cm
  - droll-hole column: radius 30.0 cm
  - cable: radius 3.0 cm, placed next to the DOM, partially within the bubble column

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

Scattering example



Shoot photons onto the DOM. Top view.
No hole ice at all.

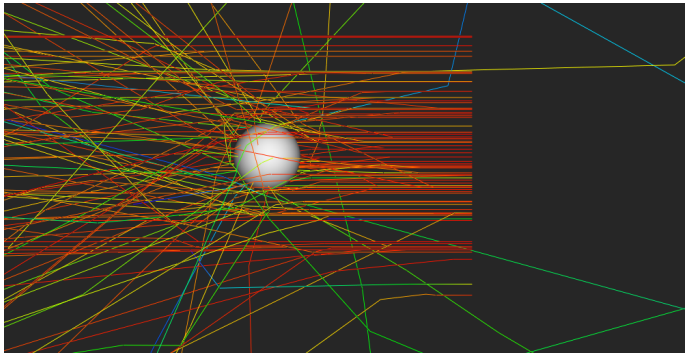
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{1} \quad \lambda_{\text{sca,bulk}}$$

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

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`

Scattering example



Shoot photons onto the DOM. Top view.
Change the scattering length inside the hole ice to be 1/10 of the scattering length outside.

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

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

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.

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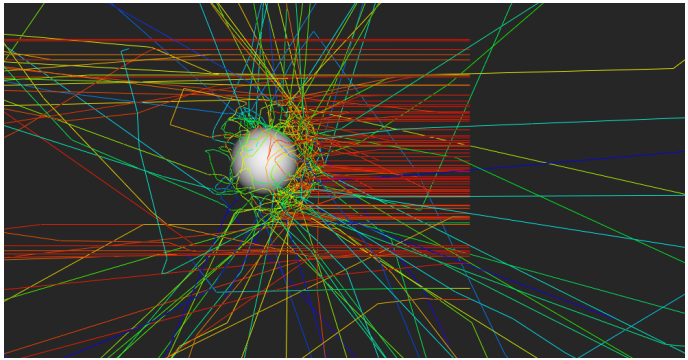
Scattering example



Shoot photons onto the DOM. Top view.
Change the scattering length inside the hole ice to be 1/100 of the scattering length outside.

$$\lambda_{\text{sca,hole-ice}} = \frac{1}{100} \quad \lambda_{\text{sca,bulk}}$$

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

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.

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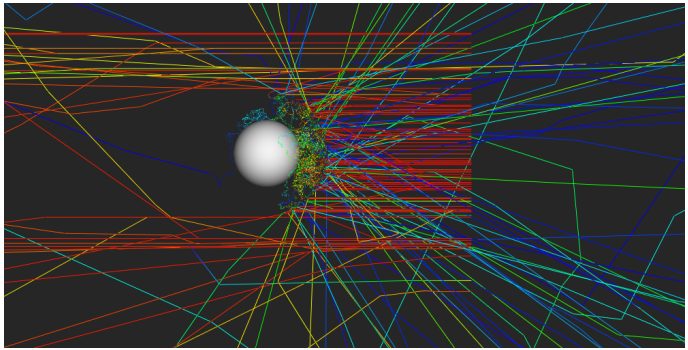

Animation on youtube: `https://youtu.be/BhJ6F3B-I1s`

Shoot photons onto the DOM. Top view.
Change the scattering length inside the hole ice to be 1/1 000 of the scattering length outside.

$$\lambda_{\text{sca,hole-ice}} = \frac{1}{1\,000} \quad \lambda_{\text{sca,bulk}}$$

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

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.

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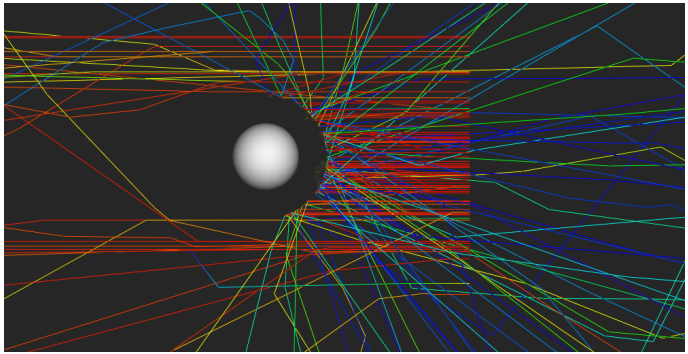

Shoot photons onto the DOM. Top view.
Change the scattering length inside the hole ice to be 1/10 000 of the scattering length outside.

$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10\,000} \quad \lambda_{\text{sca,bulk}}$$

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

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.

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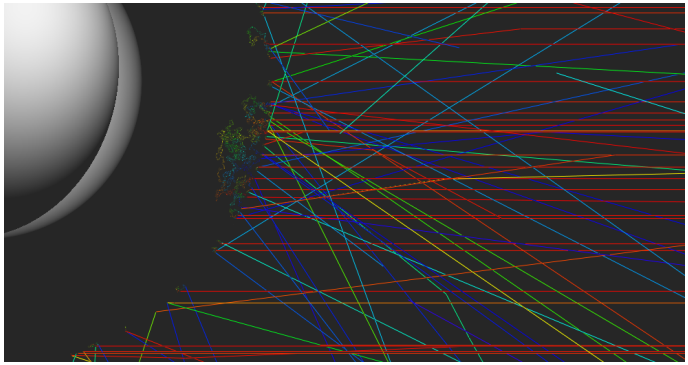

(Magnification)

Shoot photons onto the DOM. Top view.
Change the scattering length inside the hole ice to be 1/10 000 of the scattering length outside.

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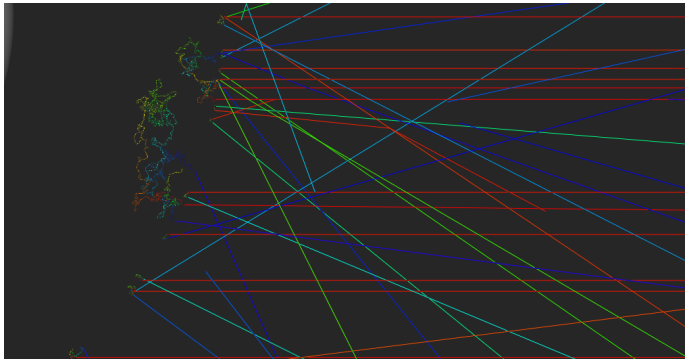

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Shoot photons onto the DOM. Top view.
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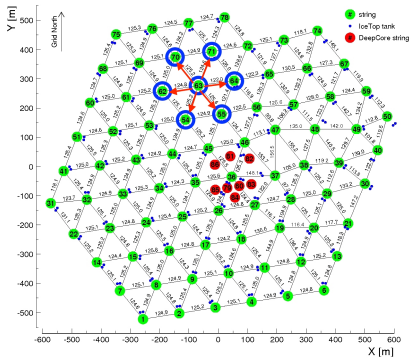
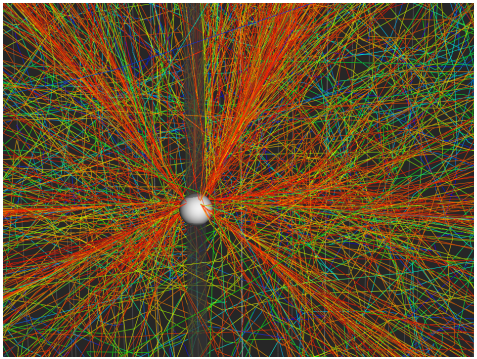
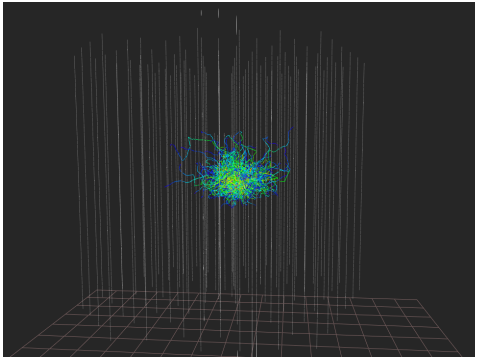
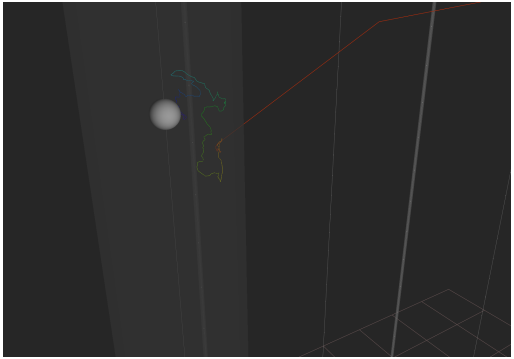
Flasher-simulation example





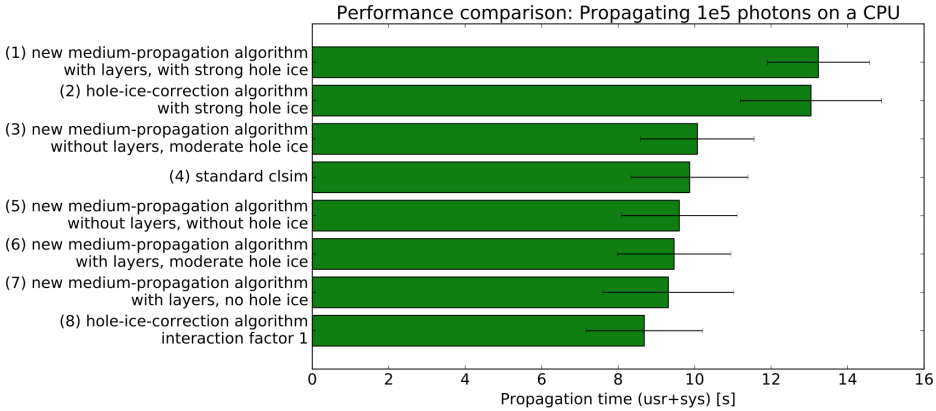




See https://github.com/fiedl/hole-ice-study/issues/107

Performance

Time measurement: Propagating 10^5 photons on CPU

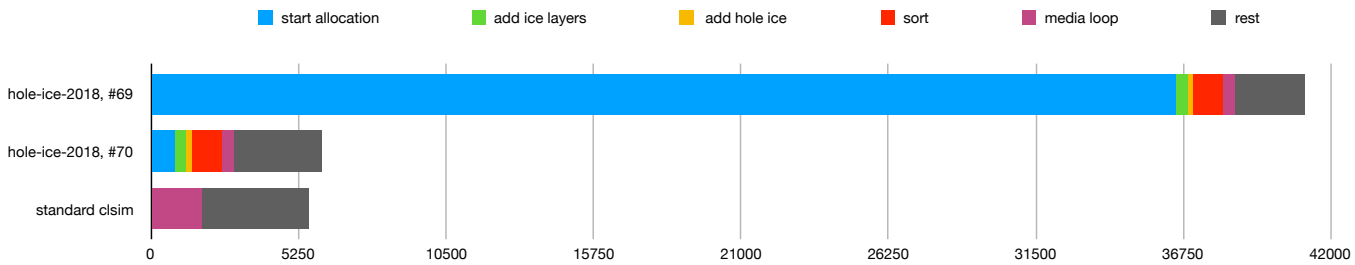


- Medium propagation features (hole ice, layers) have no measurable performance impact for scattering lengths comparable to bulk-ice scattering ($\lambda_s = 20\,\mathrm{m}$).
- Performance drop can be seen when lowering the scattering length, i.e. increasing the number of simulation steps ($\lambda_s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

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

Performance on GPU

Performance of one simulation step depends on optimizations:

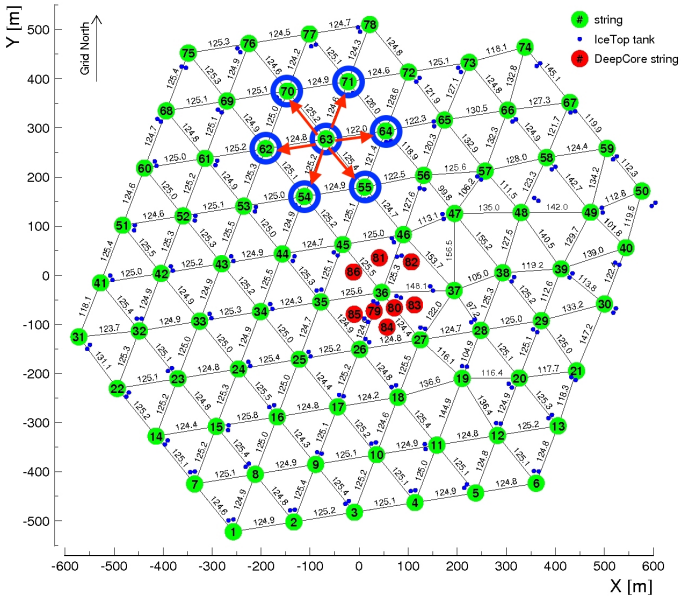


Total performance depends on number of scatters:

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`

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.

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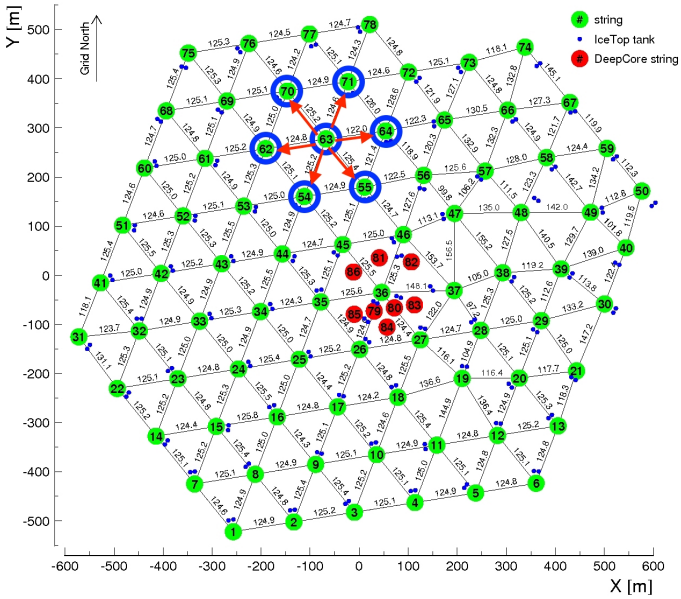

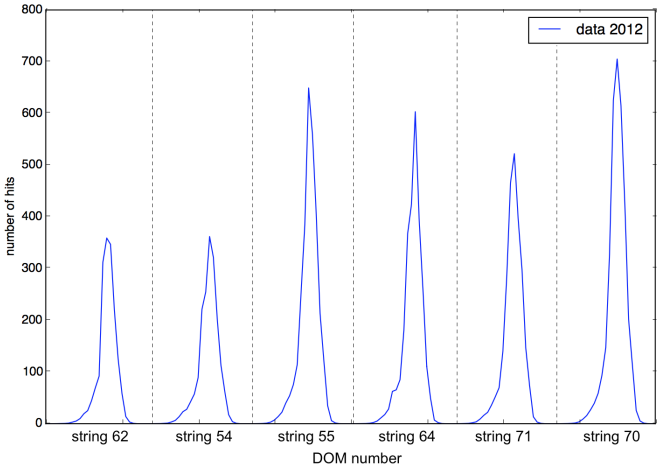

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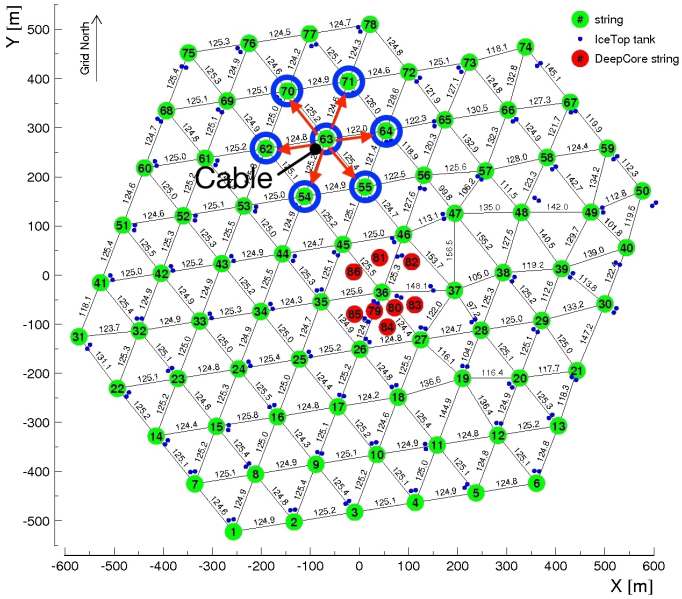

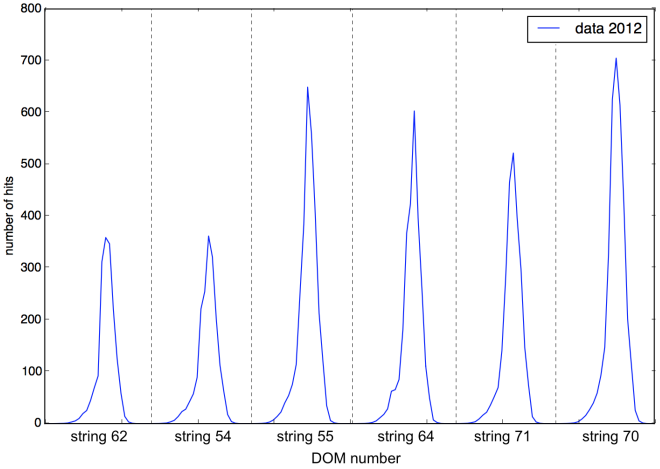

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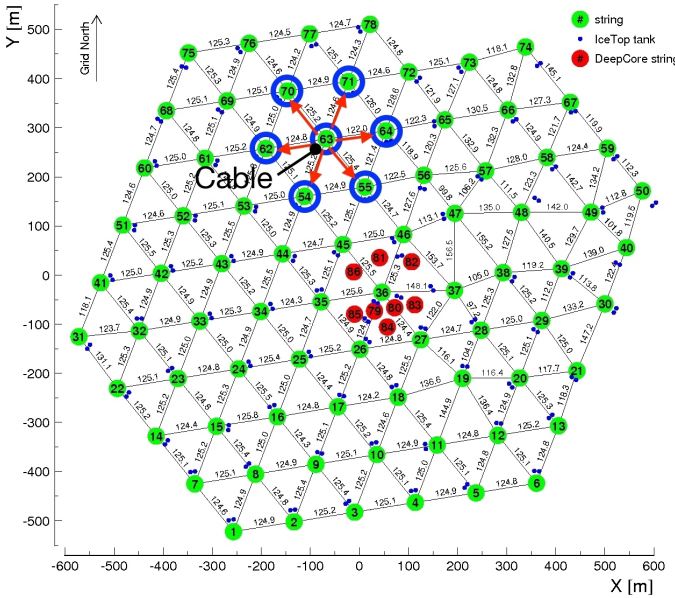
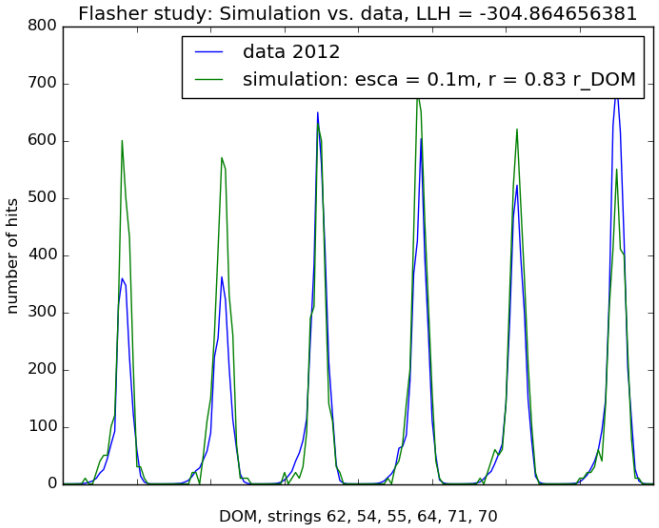
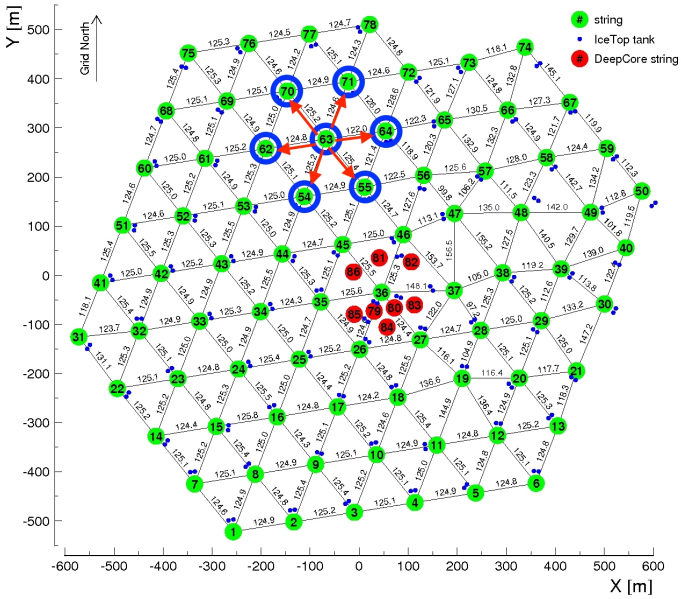
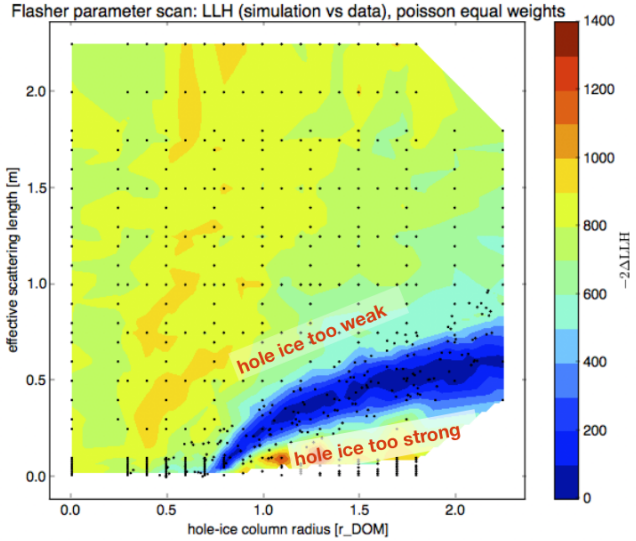




Source: https://github.com/fiedl/hole-ice-study/issues/97. Image based on https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg.

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





Source: https://github.com/fiedl/hole-ice-study/issues/59. Image based on https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg.

Outlook: Next Steps

- Bring the new hole-ice simulation into IceCube's main simulation framework
- Study impact of hole ice on low-energy systematics
- Find best hole-ice parameters (radius, scattering length) with calibration data
- Provide new approximation for use with high-energy studies, where a direct simulation would be too expensive
- Study calibration scenarios for upcoming IceCube Upgrade

Thanks for your attention!

Any input you might have is welcome:

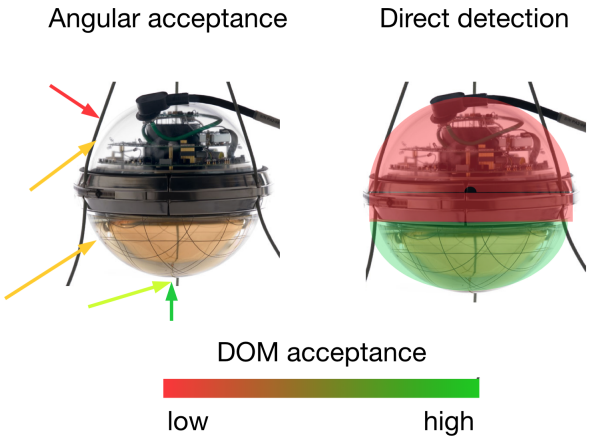
`https://github.com/fiedl/hole-ice-study/issues`

sebastian.fiedlschuster@fau.de

Video illustration of a simple example:
`https://youtu.be/BhJ6F3B-I1s`

Backup Slides

Direct detection

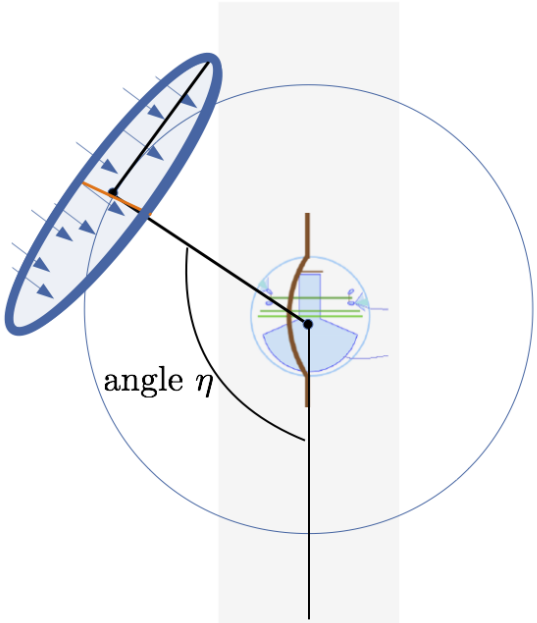


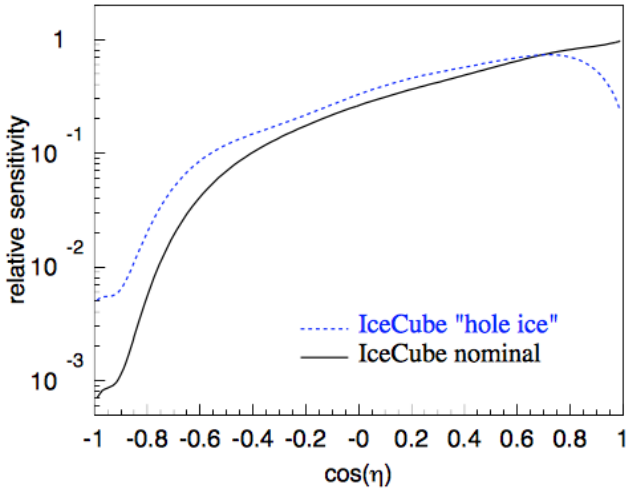
Source: Image: Martin Rongen, *Status and future of SpiceHD DARD*, 2017, Slide 17,
See also: https://github.com/fiedl/hole-ice-study/issues/32

- 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.

Angular acceptance

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



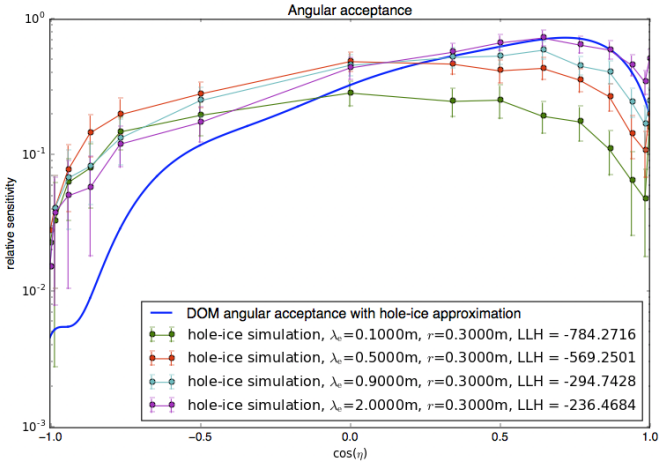


Angular acceptance *reference curves*. The nominal model is based on lab measurement, the hole ice curve on previous simulations.

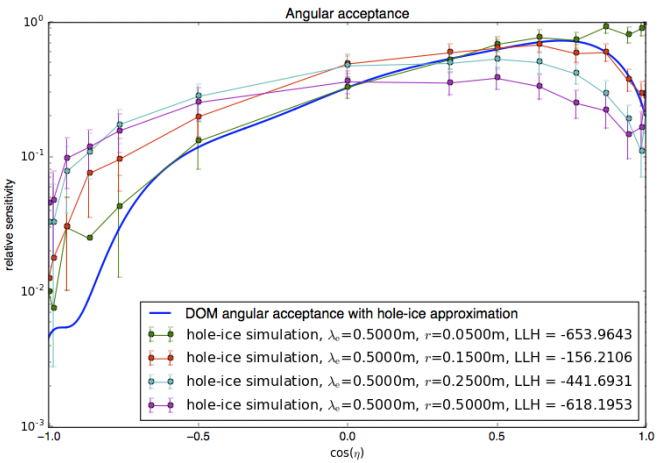
Source: Image: Martin Rongen, Calibration Call 2015-11-06, DARD Update, Slide 9
Plot: Measurement of South Pole ice transparency with the IceCube LED calibration system, 2013, figure 7. See also: `https://github.com/fiedl/hole-ice-study/issues/10`

Angular acceptance for different hole-ice parameters

Vary hole-ice scattering length:



Vary hole-ice radius:



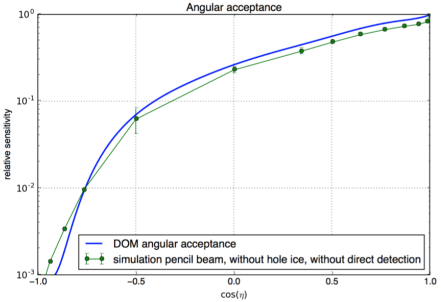
Systematics:

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

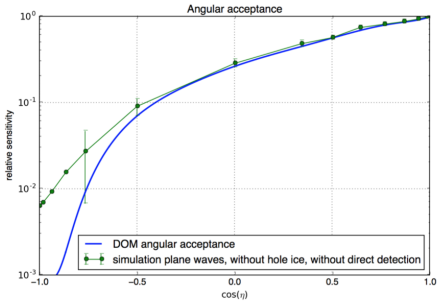
plane extent 1 m, starting distance 1 m

non-perfect bulk-ice properties

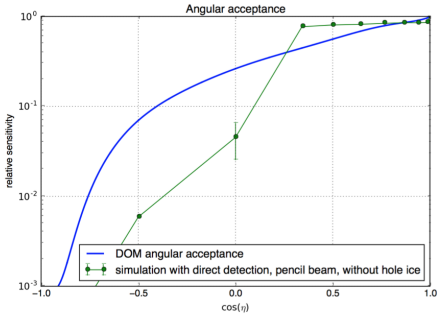
Angular acceptance: Sources and acceptance criteria



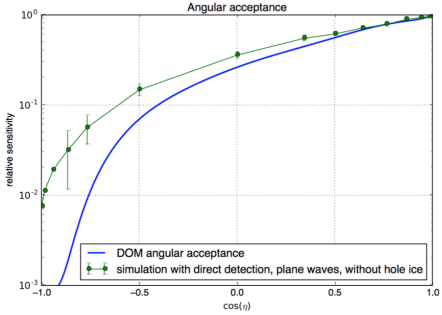
(a) pencil beams, a priori angular acceptance



(b) plane waves, a priori angular acceptance



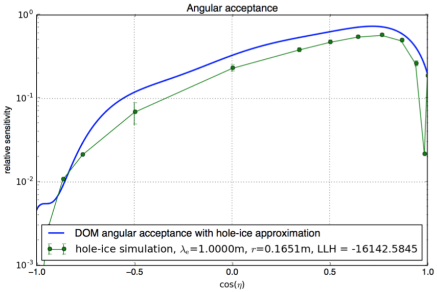
(c) pencil beams, direct detection



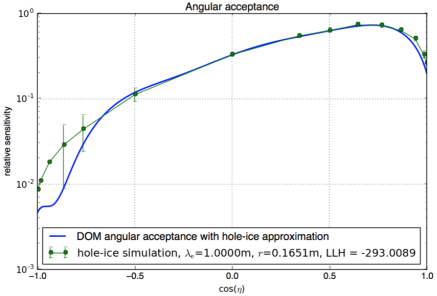
(d) plane waves, direct detection

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

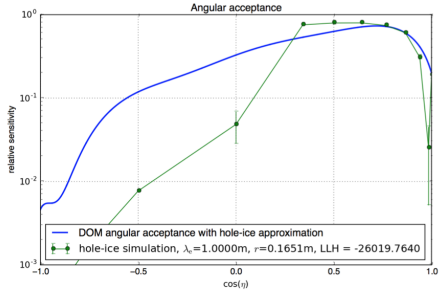
Angular acceptance: Sources and acceptance criteria



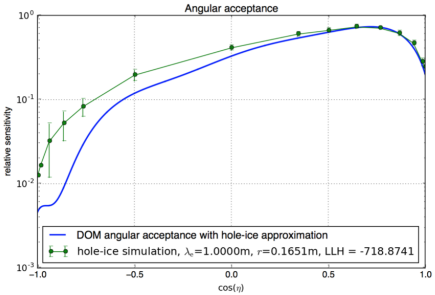
(a) pencil beams, a priori angular acceptance



(b) plane waves, a priori angular acceptance



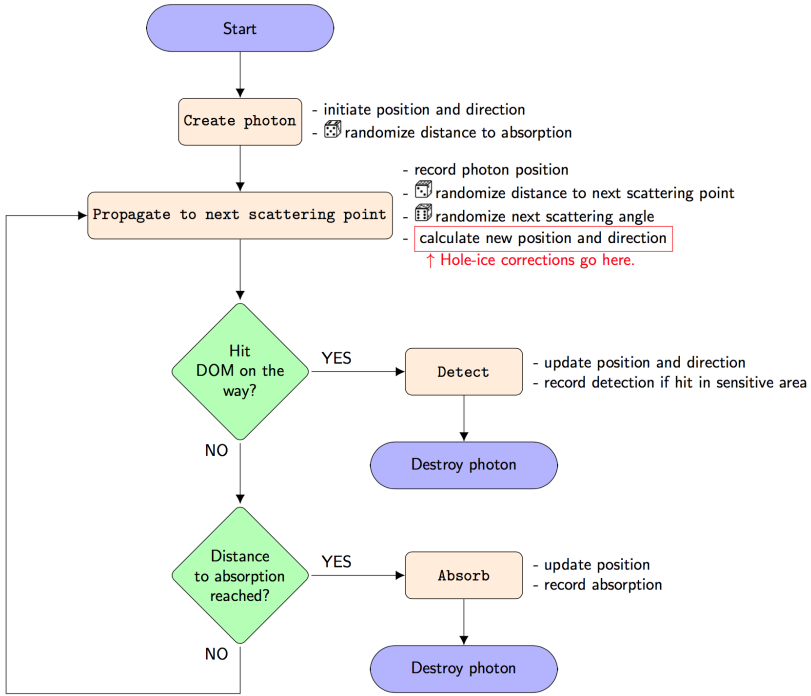
(c) pencil beams, direct detection



(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`

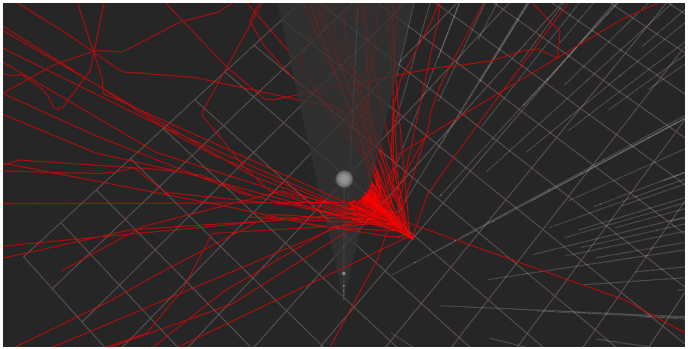
Simplified simulation-step flow chart



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

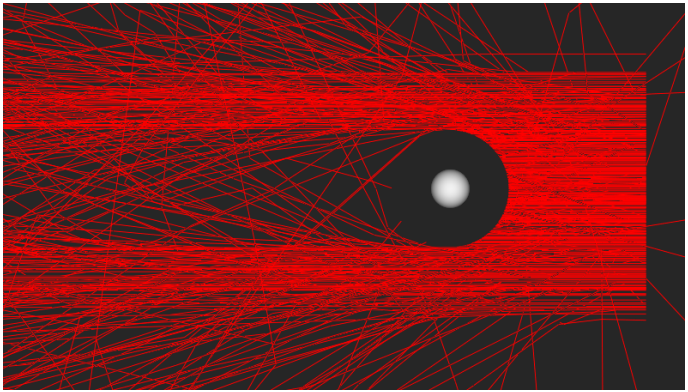


Photon point source, 3d view

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

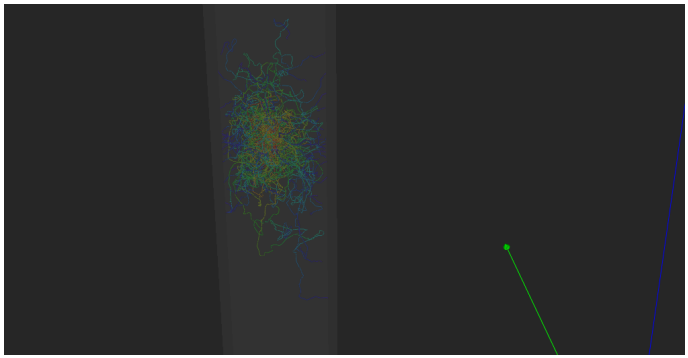


Plane wave photon source, top view

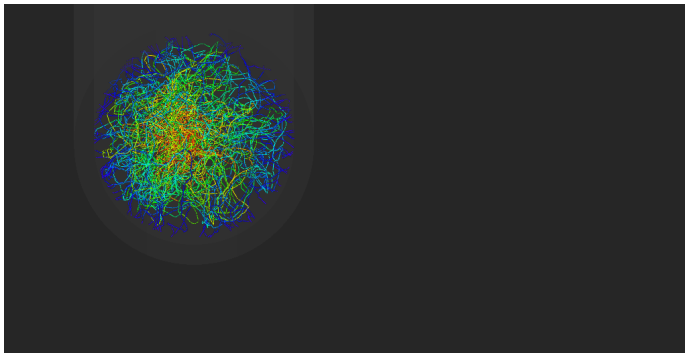
Source: `https://github.com/fiedl/hole-ice-study/issues/22`

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

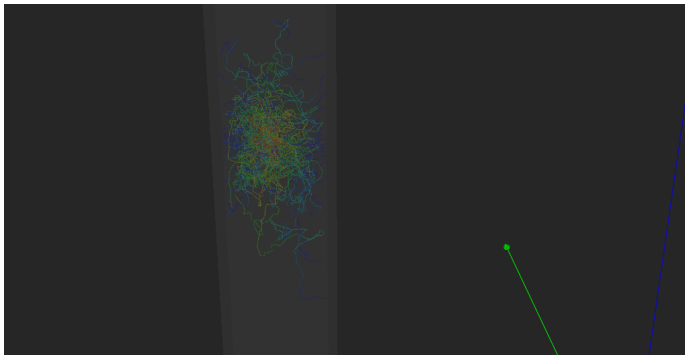


Top view

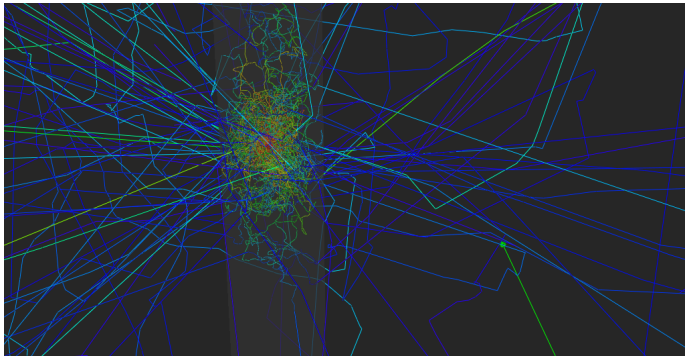
Source: https://github.com/fiedl/hole-ice-study/issues/47

Instant absorption with nested cylinders

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



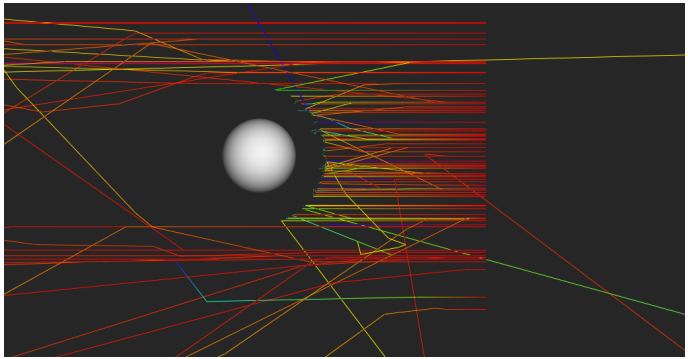
With outer cylinder configured for instant absorption



Without the outer cylinder

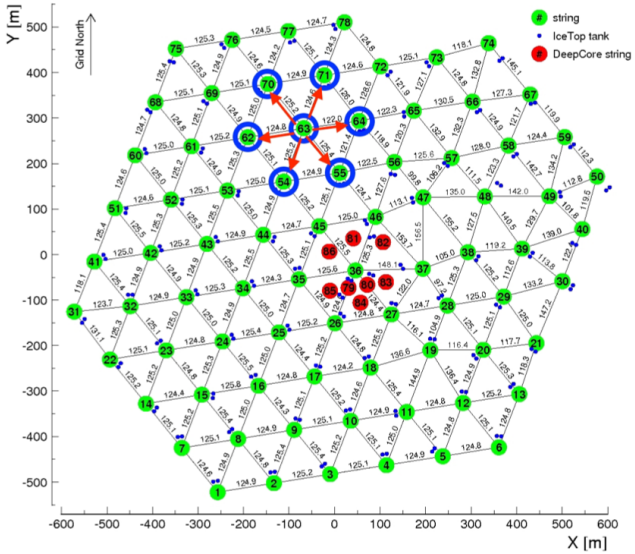
Source: `https://github.com/fiedl/hole-ice-study/issues/47`

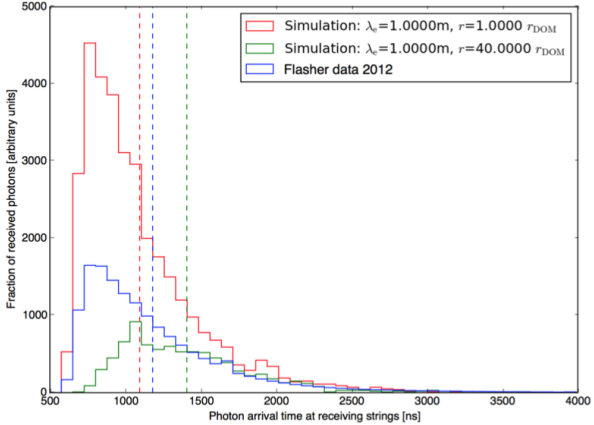
Scattering example



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

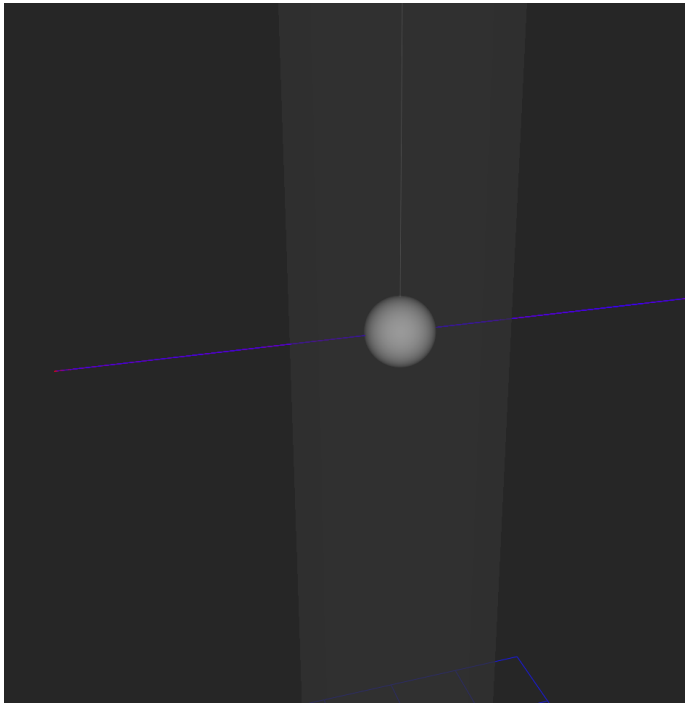
Cross checks: Arrival-time distributions

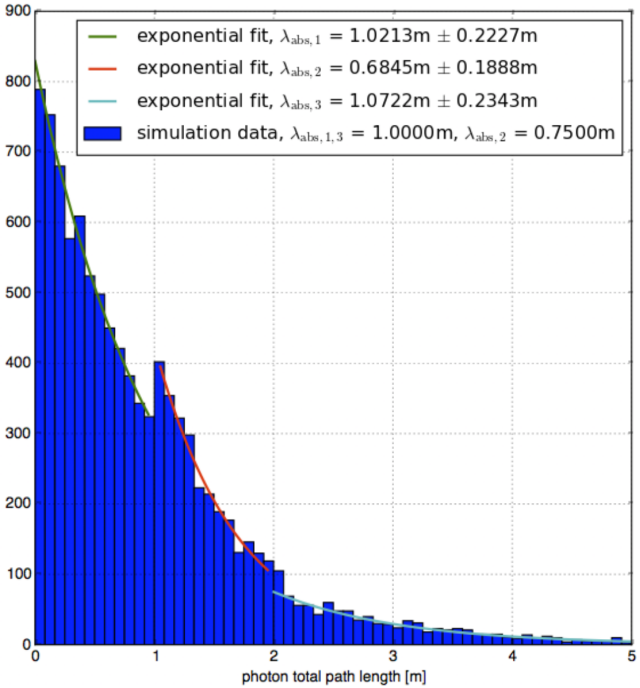




Source: https://github.com/fiedl/hole-ice-study/issues/91. Image based on https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg.

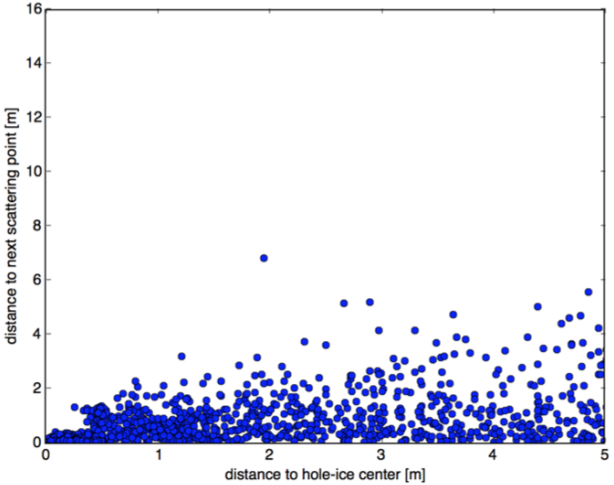
Cross checks: Path-length distributions



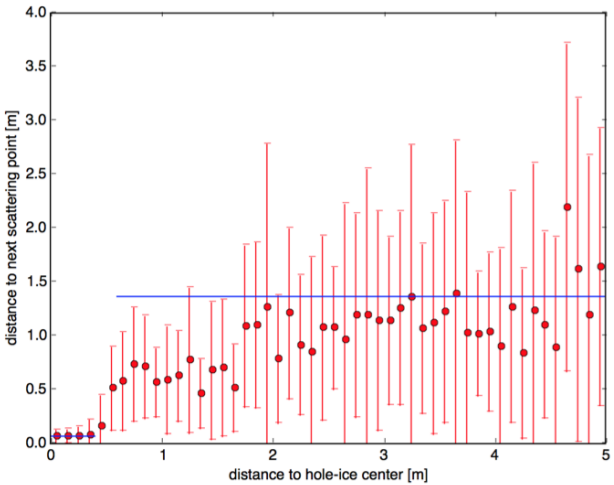


Source: https://github.com/fiedl/hole-ice-study/issues/66

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



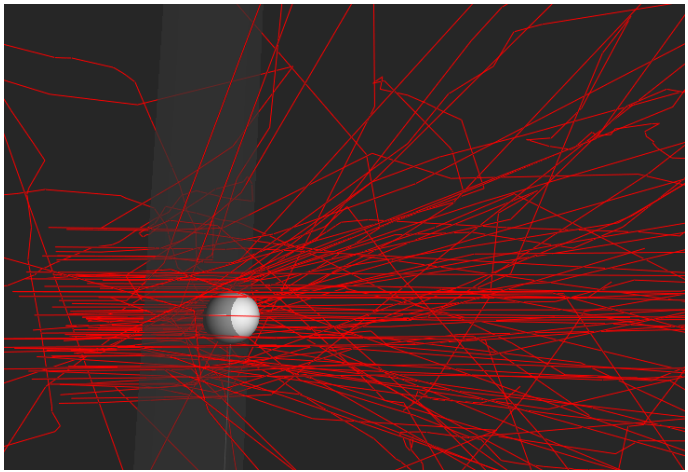
(a) All data points



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

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

Asymmetry example



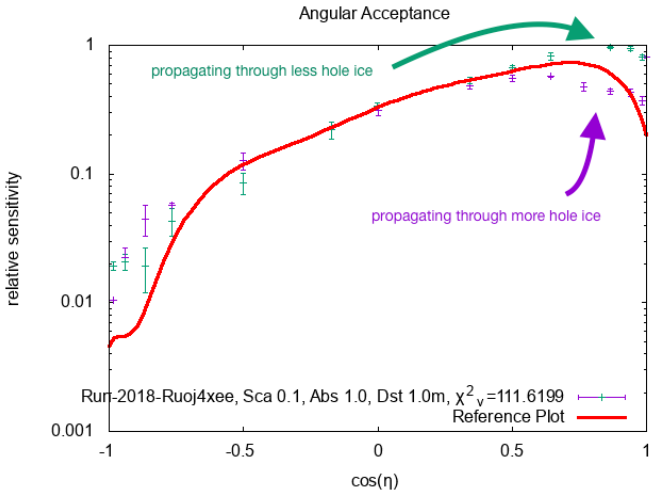
For angle $\eta = \pi/2$, shoot photons from planes onto the DOM and count hits.
Hole-ice radius: 30 cm

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

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

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

Asymmetry example



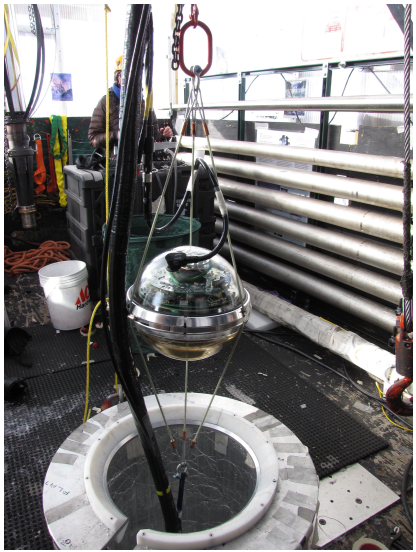
For each angle $\eta \in [0; 2\,\pi[$, shoot photons from planes onto the DOM and count hits.
Hole-ice radius: 30 cm

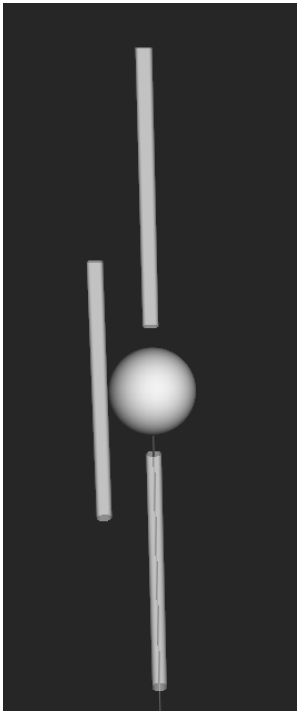
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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

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

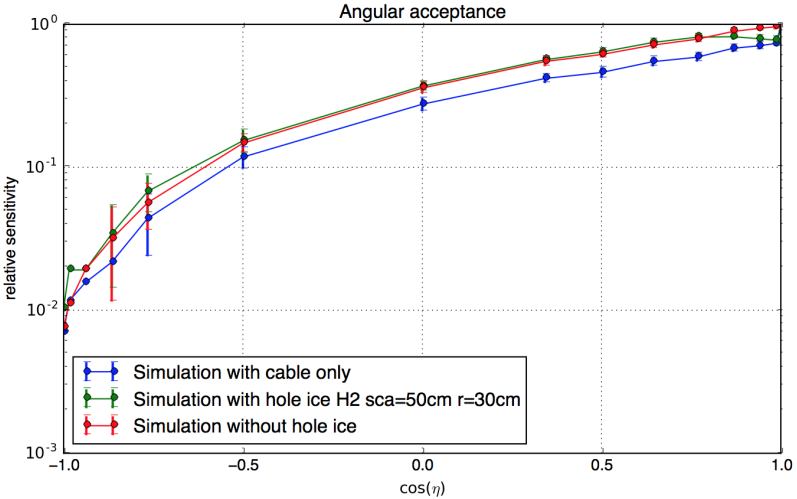
Direct cable simulation: Angular acceptance



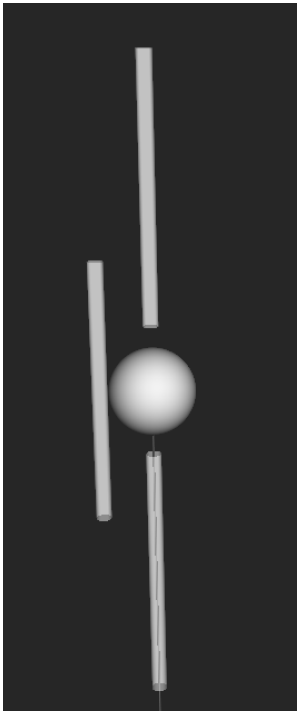


Source: https://github.com/fiedl/hole-ice-study/issues/101. **Images**: https://icecube.wisc.edu/gallery/view/153, https://gallery.icecube.wisc.edu/internal/v/GraphicRe/graphics/arraygraphics2011/sketchup/DOMCloseUp.jpg.html

Direct cable simulation: Angular acceptance



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

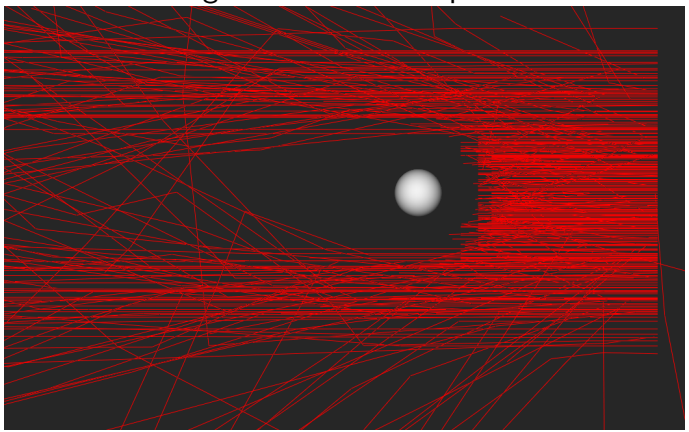


Source: https://github.com/fiedl/hole-ice-study/issues/101.

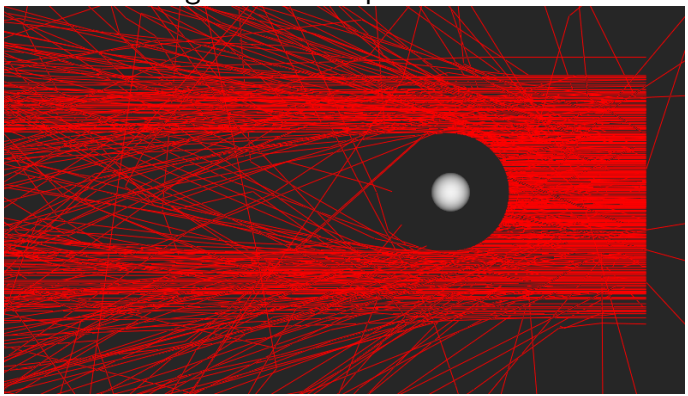
Coordinates-vs-vectors bug

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