Hole Ice, Cables, and Non-Spherical Detector Modules in Light-Propagation Simulations for the IceCube Experiment

DPG Conference Dortmund 2021 (Virtual)

Session T22 Experimental techniques in astroparticle physics I

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2021-03-15

Document 2021-voXoo3zo

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

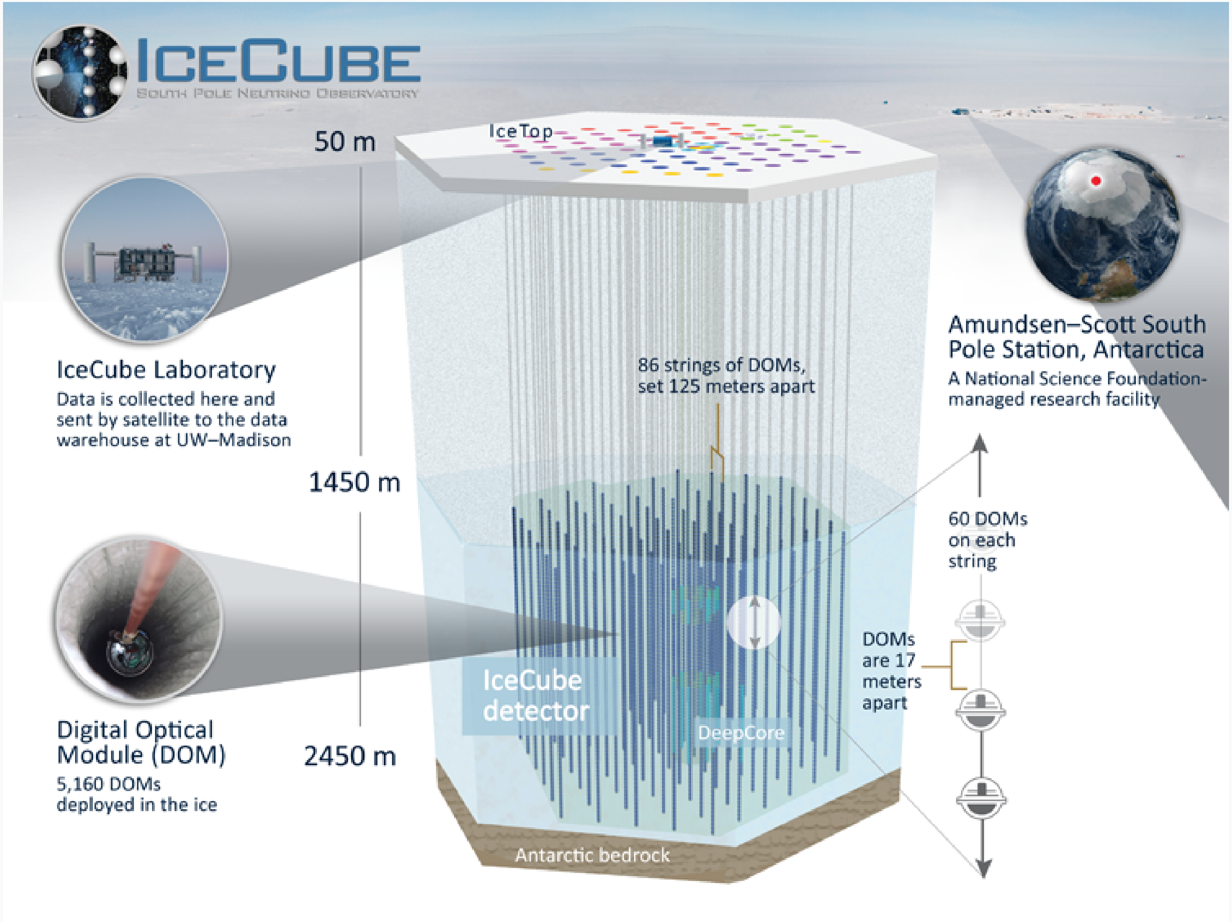
Previous talks on this topic:

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

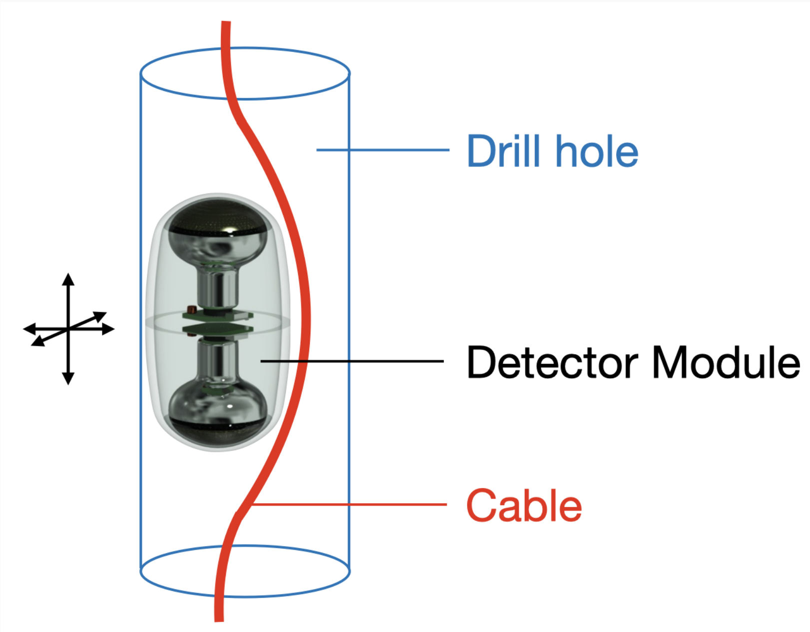
LaTeX version of these presentation slides:

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

Introduction: IceCube Detector



Motivation and Scope

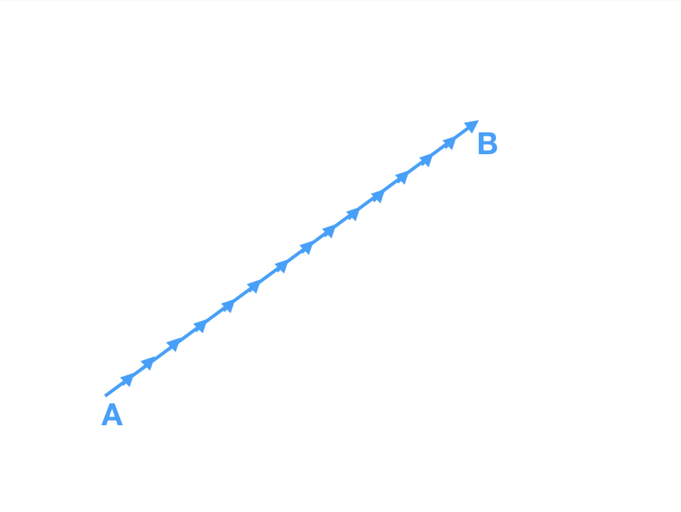


- Topic: Light-propagation simulation in vicinity of detector modules, considering:
  - ice properties in vicinity, esp. in drill hole
  - opaque cables
  - non-spherical detector modules of variable position
- Usually: Effective modification of module sensitivity
- Here: Direct ray-tracing algorithm

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

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.

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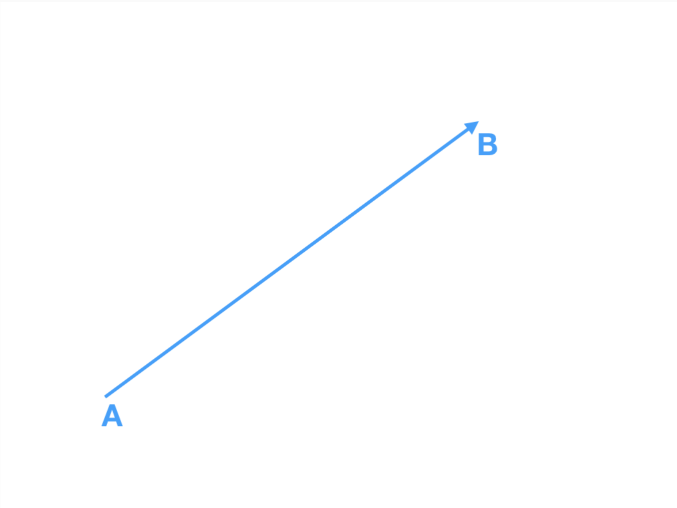

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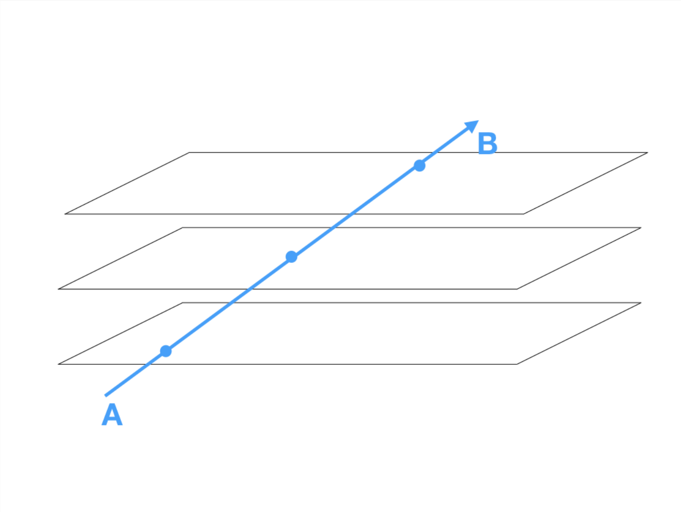

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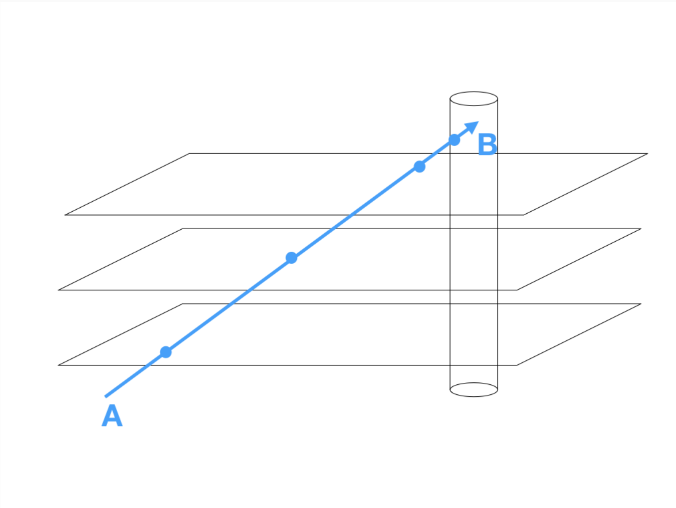

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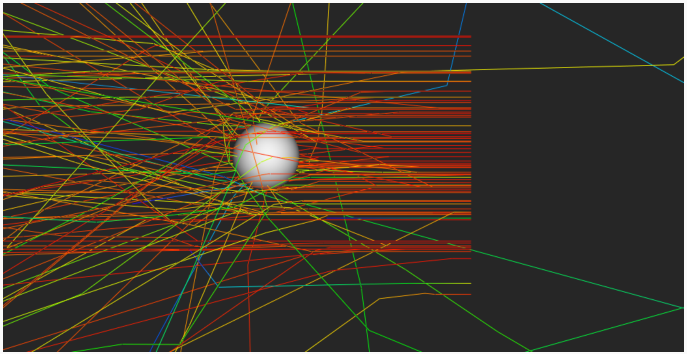
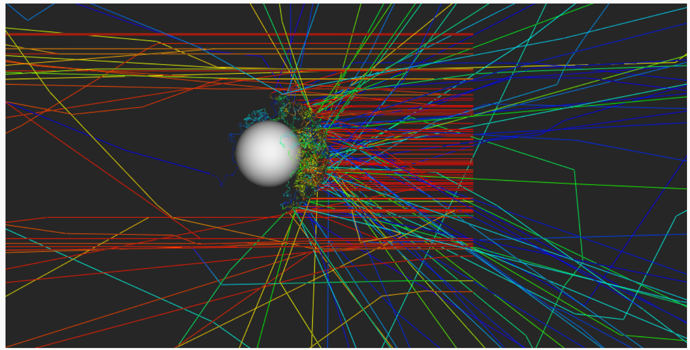
Examples of Application

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



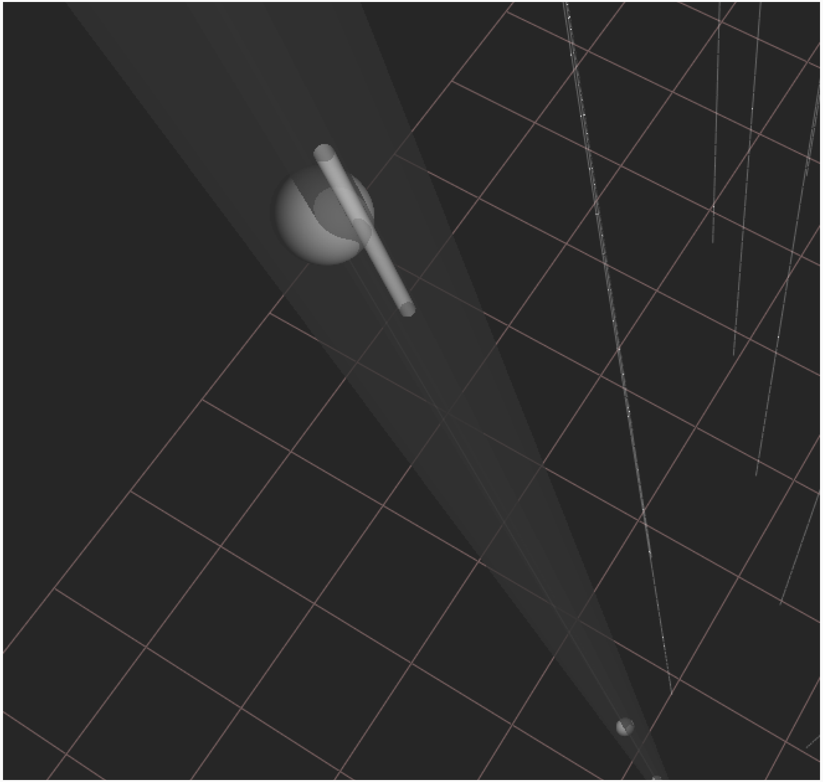
Scattering length $\lambda_{\text{sca,hole-ice}} = 10^{-3}\,\lambda_{\text{sca,bulk}}$.
Absorption length $\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$.

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`

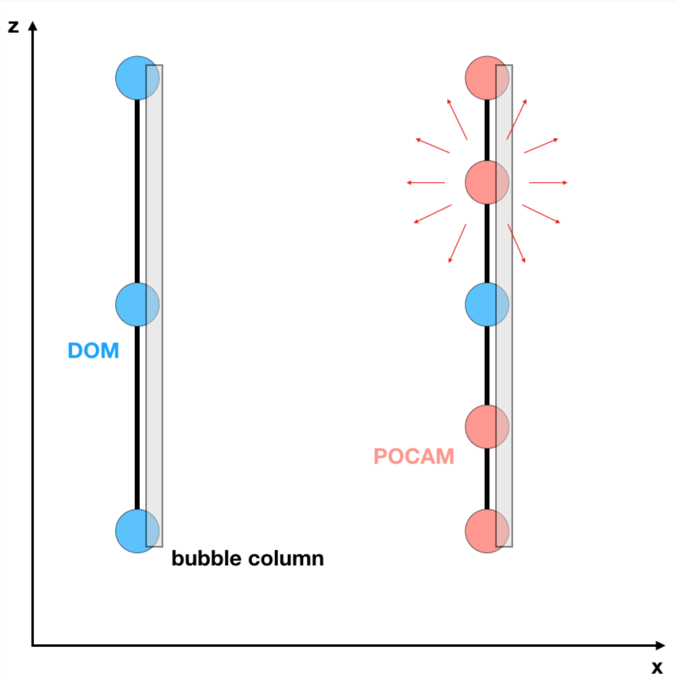
Realistic simulation scenario



- 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

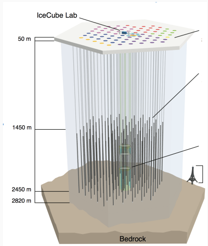
See also: `https://github.com/fiedl/hole-ice-study/issues/110`

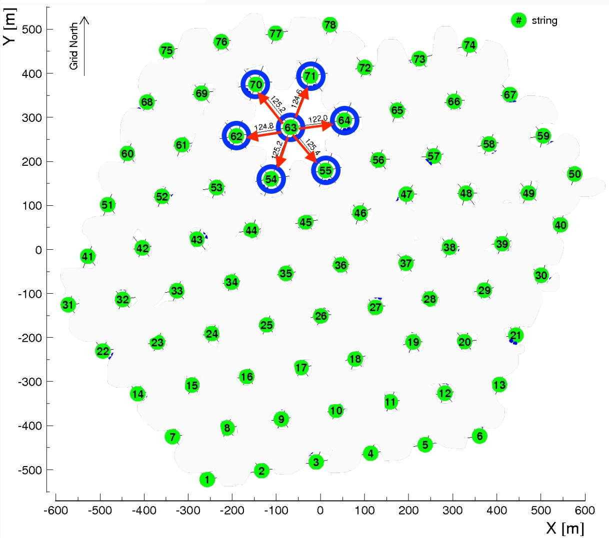
POCAM Simulation

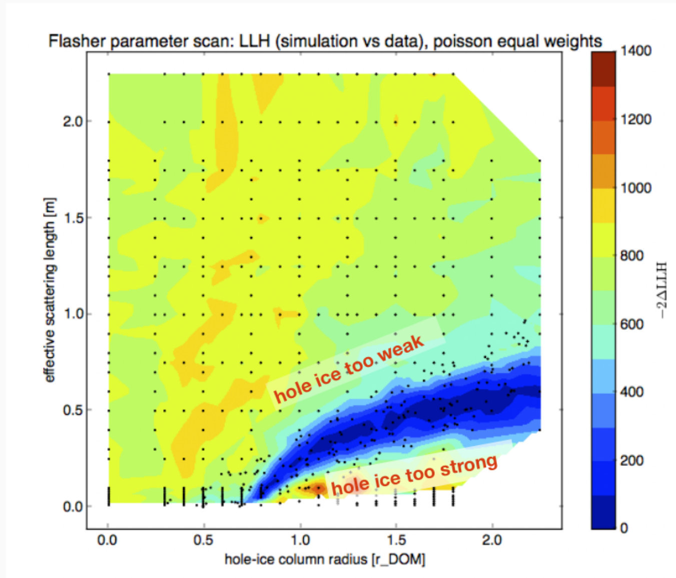


- Study scenarios with POCAM calibration devices, which emit light isotropically:
- Expected hits with ideal parameters (perfect symmetry, no cables, ...)
- Bubble-column parameters
- Cable-shadow parameters

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

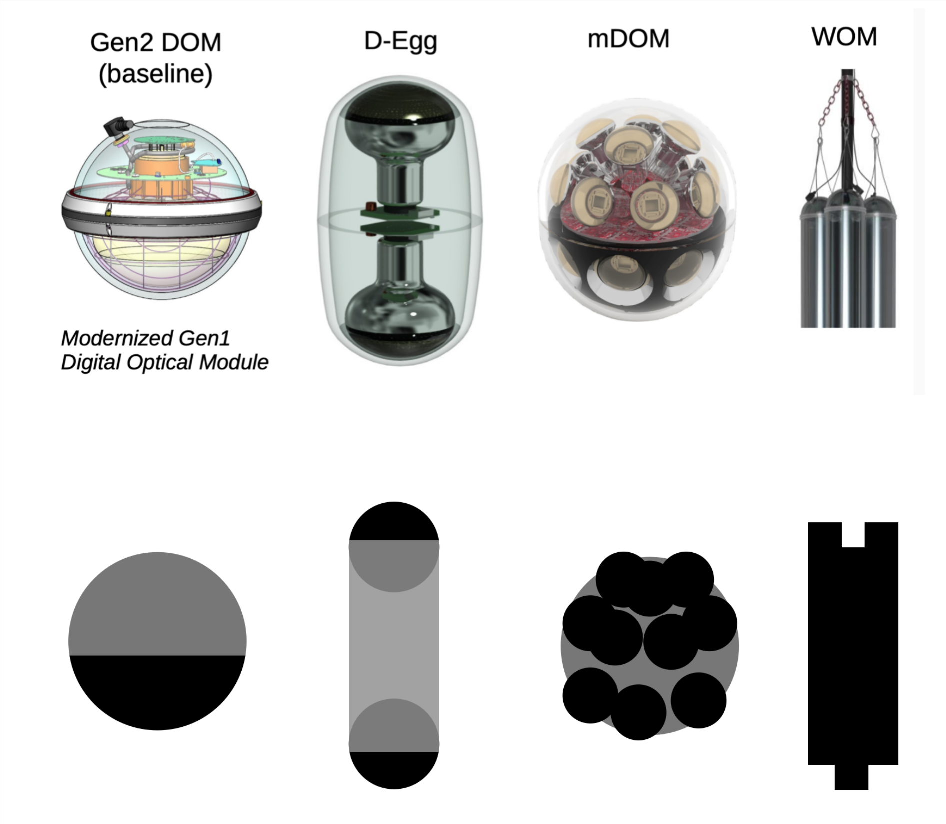






Source: `https://github.com/fiedl/hole-ice-study/issues/59`. Footprint based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`. Image: Aartsen et al., The IceCube Neutrino Observatory: Instrumentation and online systems, 2017.

Detector-Module Types



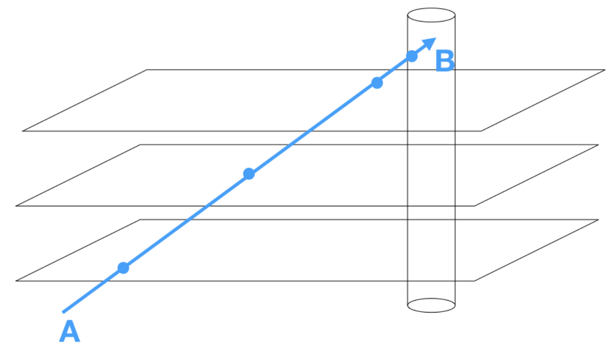
- Detector-module types with different:
  - Size
  - Shape
  - Photo-sensitive areas
- Direct simulation of:
  - Sensitivity profile
  - Hole ice, relative position, and orientation of the modules
  - Cable shadows

Image based on: Pfeiffer, New optical sensors for IceCube-Gen2, 2016

Status

Project status

- ✓ Implement new ray-tracing algorithm
- ✓ Implement hole ice and cables
- ✓ Verify plausibility with examples
- ✓ Verify with statistical cross checks
- ✓ Compare to effective descriptions
- ⇒ Fix compatibility issues with
  - ⇒ server-client-architecture rewrite
  - ☐ ice anisotropy
  - ☐ Unit-test framework
- ☐ Implement detection-probability property
- ☐ Provide ready-to-use mDOM and D-Egg
- ☐ Provide example scripts for python 3



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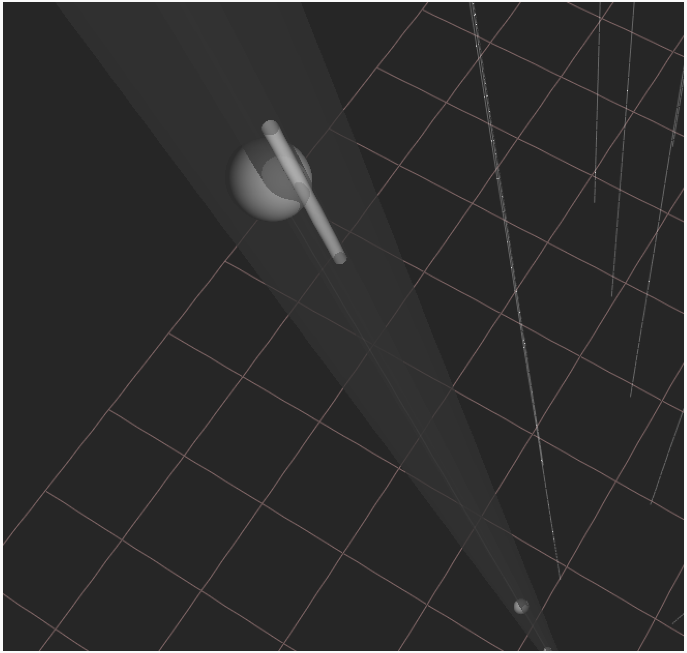

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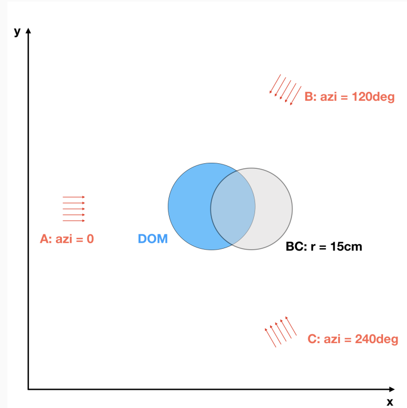

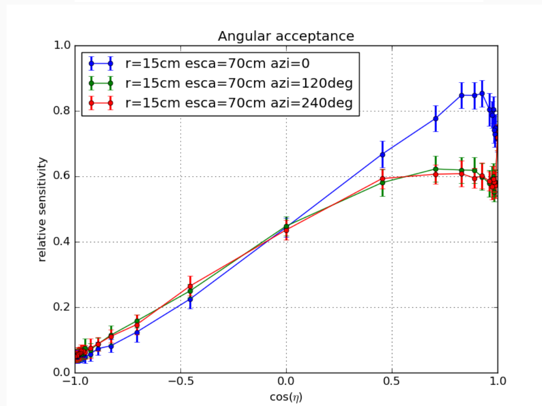

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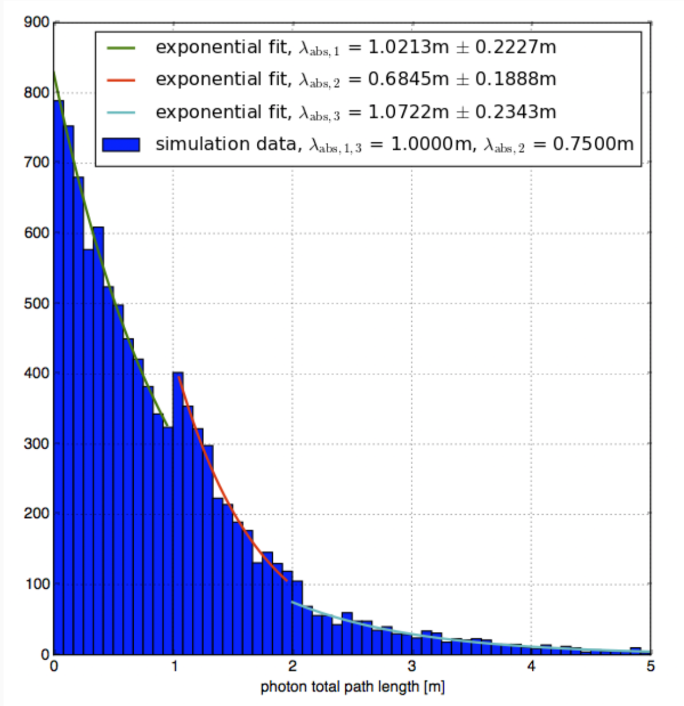

See also: `https://github.com/fiedl/hole-ice-study/issues/66`

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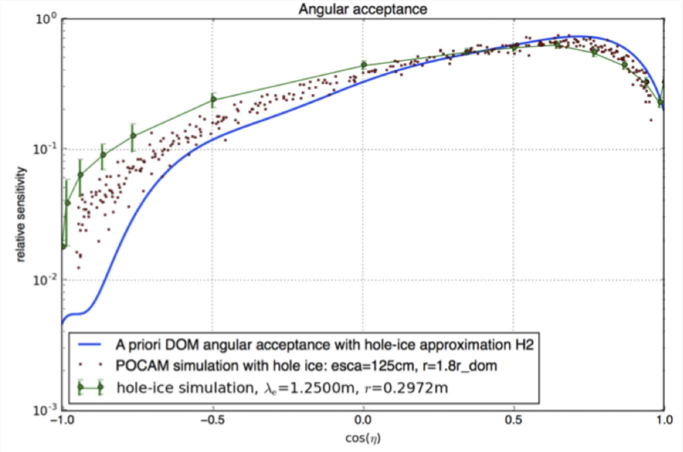

See also: https://github.com/fiedl/hole-ice-study/issues/4, https://github.com/fiedl/hole-ice-study/labels/comparison

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Currently resolving technical issues due to major rewrite of the underlying tool.

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Next step: For ray-tracing, each geometric object (cylinders, spheres, . . .) can have a probability to detect the photon on interaction (absorption, scattering). This can be used to model the photo-sensitive areas of a detector module.

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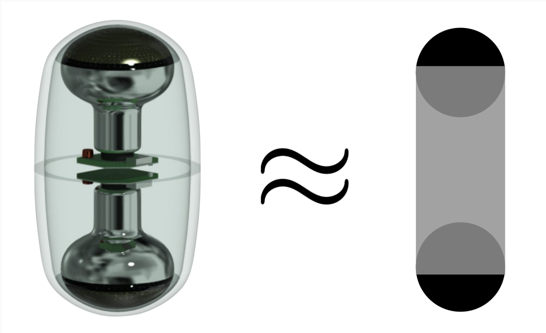
Next step: For ray-tracing, each geometric object (cylinders, spheres, . . .) can have a probability to detect the photon on interaction (absorption, scattering). This can be used to model the photo-sensitive areas of a detector module. Then:

Read detector-module type from simulation configuration and place corresponding preset at the position of the module.



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Results

Results

- Statistical cross checks and intuitive scenarios indicate that the new algorithm yields expected results. ✓
- With the corresponding settings, the new algorithm is backwards compatible to the previous one. ✓
- 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.

Thanks for your attention!

Any input you might have is welcome:

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

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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

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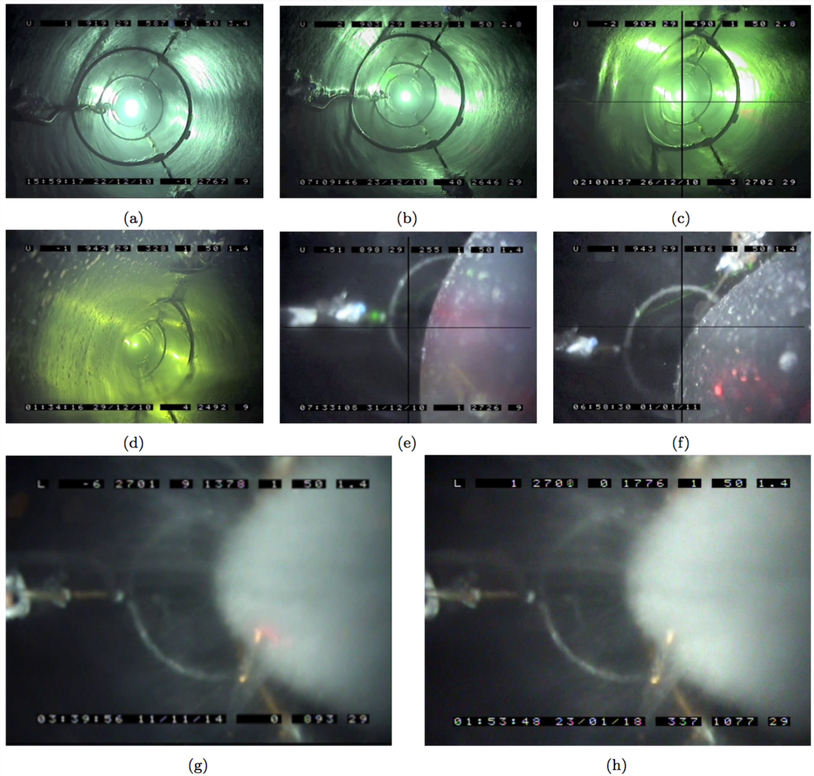
Backup slides

Hole ice



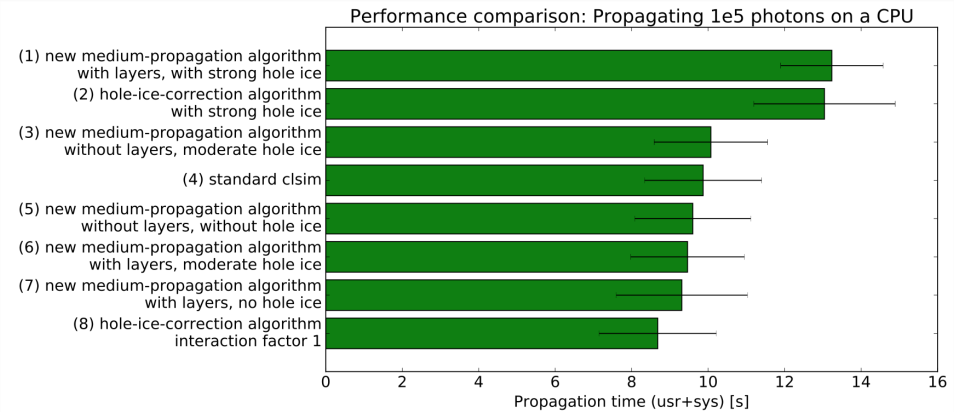
(a) (b) (c) (d) (e) (f) (g) (h)

- 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



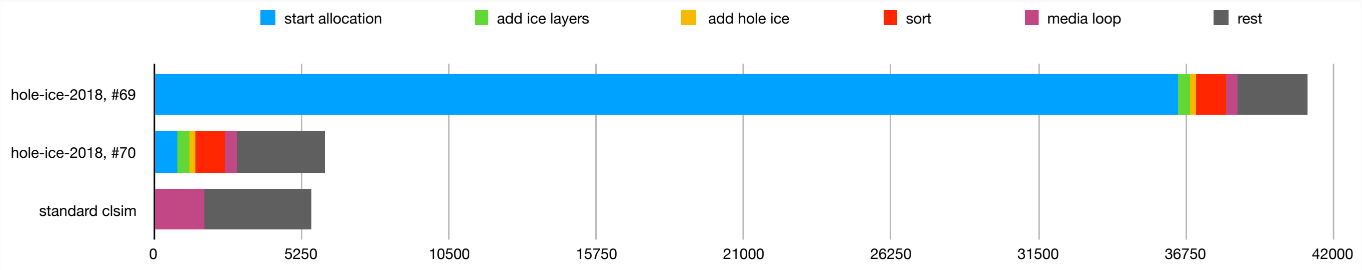

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
time ./run.rb --distance=1.0 --number-of-runs=1 --number-of-parallel-runs=1 --cpu --angle=45 --plane-wave
↪  --number-of-photons=1e5
```

- Medium propagation features (hole ice, layers) have no measurable performance impact for scattering lengths comparable to bulk-ice scattering ($\lambda_s = 20\,\mathrm{m}$).
- 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

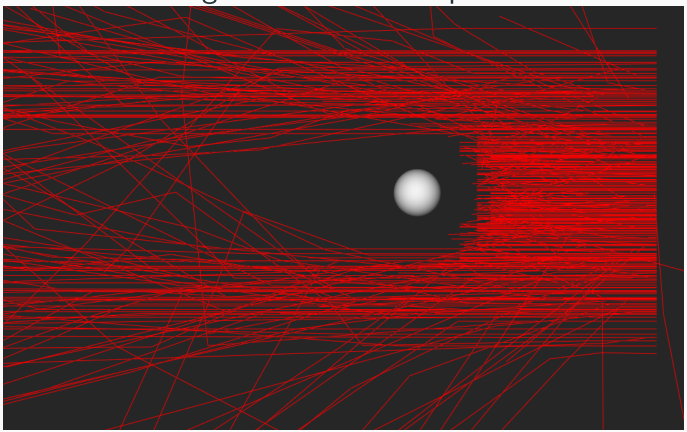
New algorithm, about H2 hole ice: 15 mins

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

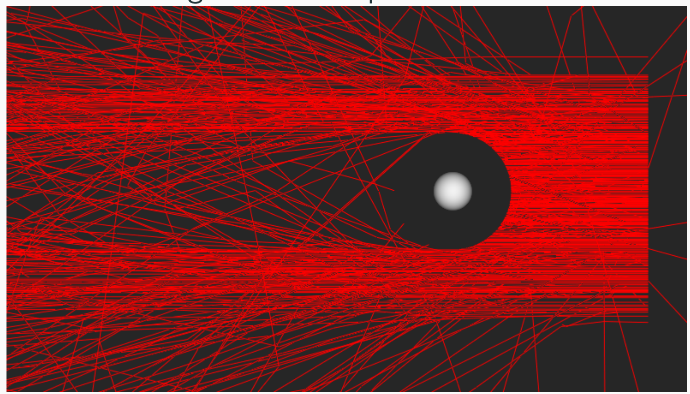
Coordinates-vs-vectors bug

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

Before: Treating coordinates as separate variables

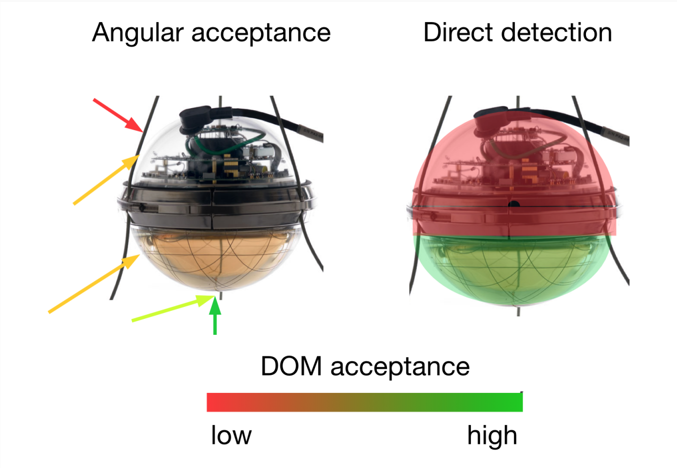


After: Treating vectors as opencl-native vectors



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

Direct detection



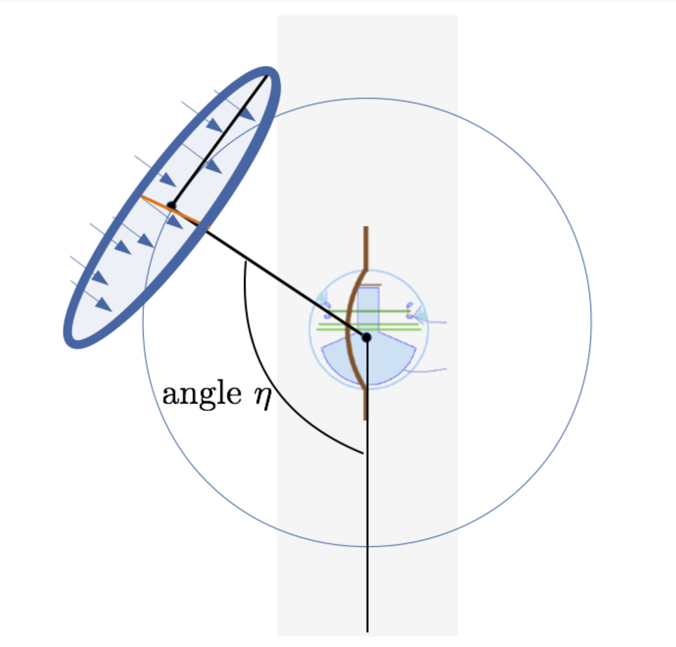
Source: Image: Martin Rongen, *Status and future of SpiceHD DARD*, 2017, Slide 17, See also: `https://github.com/fiedl/hole-ice-study/issues/32`

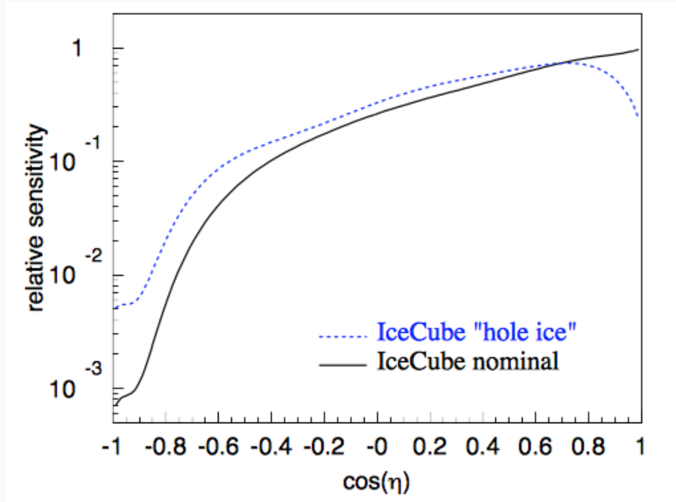
- The DOM looks downwards by design
- Currently, the hit position is not used when determining DOM acceptance, just the photon direction when hitting the DOM (*DOM angular acceptance*)
- Direct detection: Accept all hits below the waist band, reject all others
- Direct detection is easy with clsim
 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



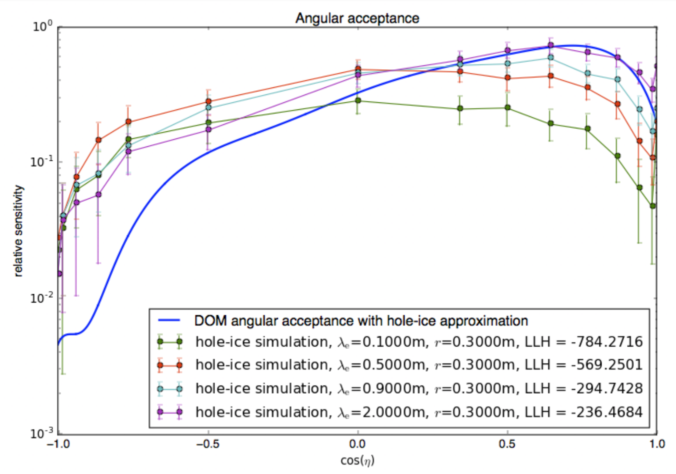


Angular acceptance *reference curves*. The nominal model is based on lab measurement, the hole ice curve on previous simulations.

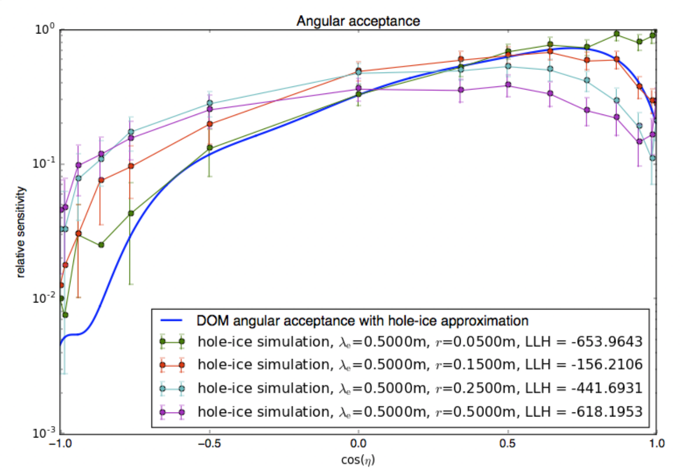
Source: Image: Martin Rongen, Calibration Call 2015-11-06, DARD Update, Slide 9
Plot: Measurement of South Pole ice transparency with the IceCube LED calibration system, 2013, figure 7. See also: `https://github.com/fiedl/hole-ice-study/issues/10`

Angular acceptance for different hole-ice parameters

Vary hole-ice scattering length:



Vary hole-ice radius:



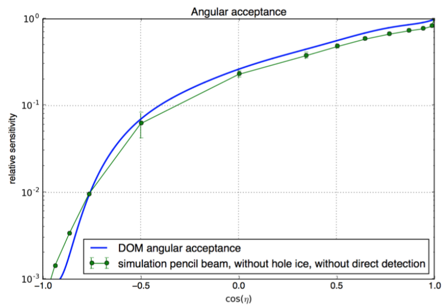
Systematics:

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

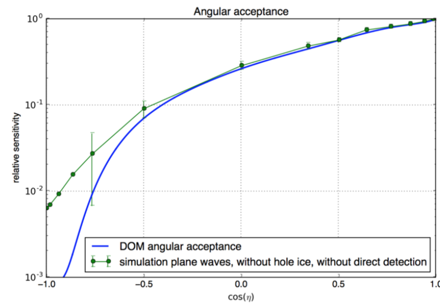
plane extent 1 m, starting distance 1 m

non-perfect bulk-ice properties

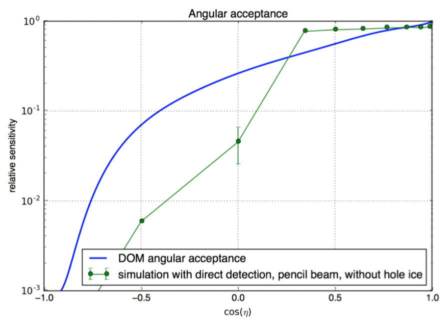
Angular acceptance: Sources and acceptance criteria



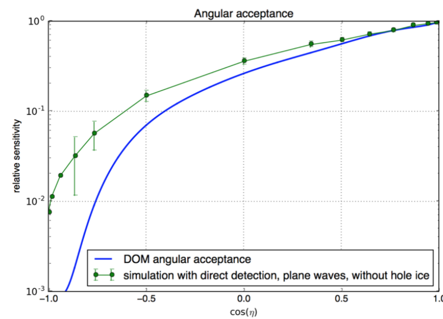
(a) pencil beams, a priori angular acceptance



(b) plane waves, a priori angular acceptance



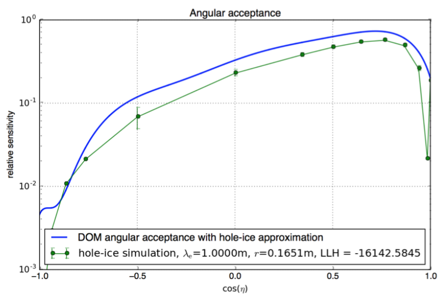
(c) pencil beams, direct detection



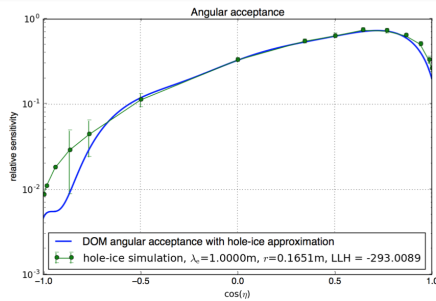
(d) plane waves, direct detection

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

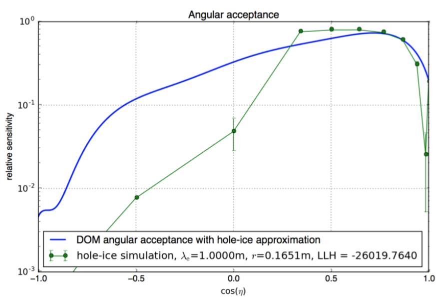
Angular acceptance: Sources and acceptance criteria



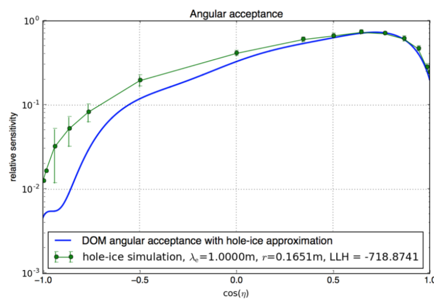
(a) pencil beams, a priori angular acceptance



(b) plane waves, a priori angular acceptance



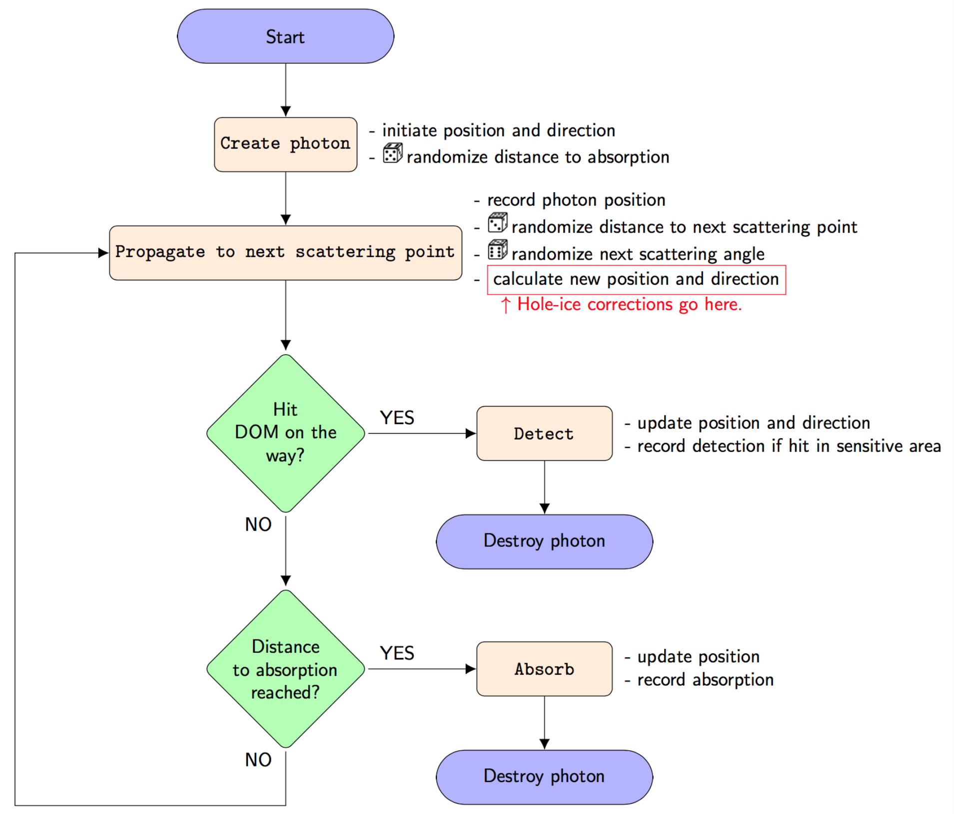
(c) pencil beams, direct detection



(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`

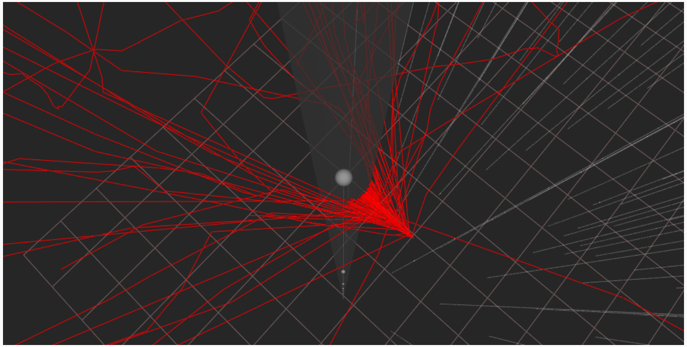
Simplified simulation-step flow chart



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



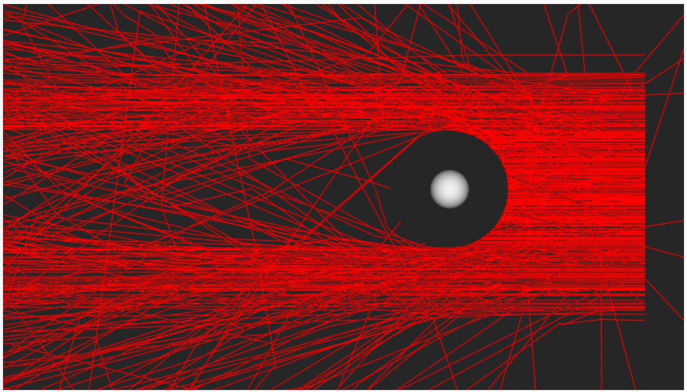
Photon point source, 3d view

```
$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



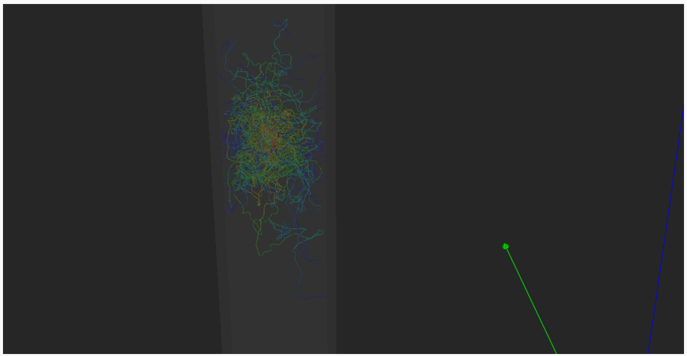
Plane wave photon source, top view

```
$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
```

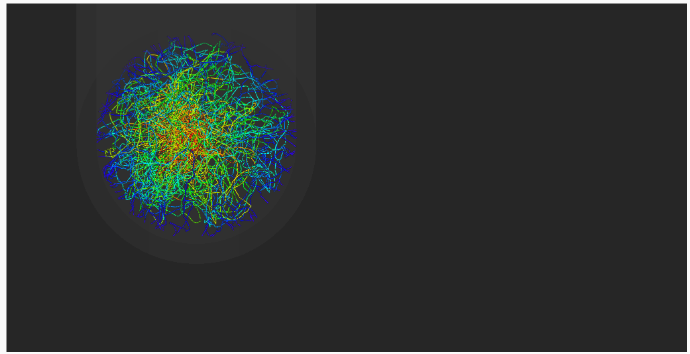
Source: https://github.com/fiedl/hole-ice-study/issues/22

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

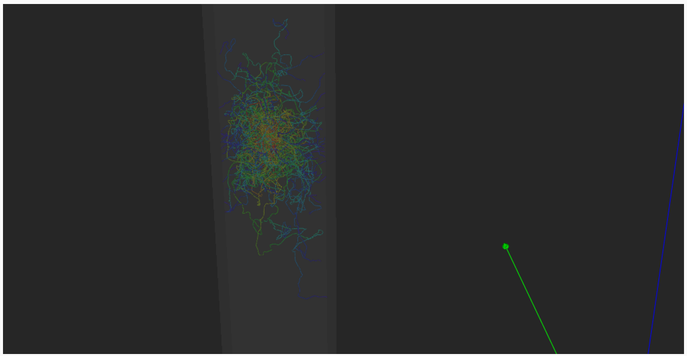


Top view

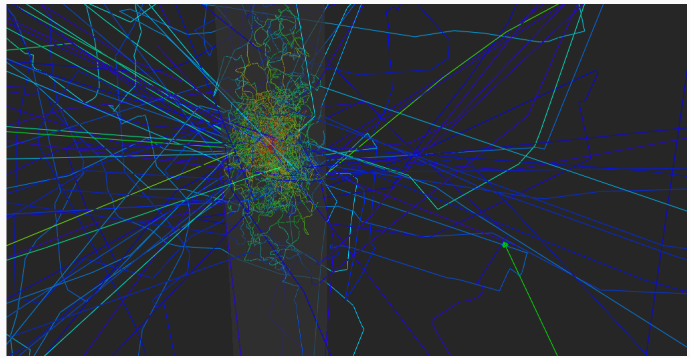
Source: `https://github.com/fiedl/hole-ice-study/issues/47`

Instant absorption with nested cylinders

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



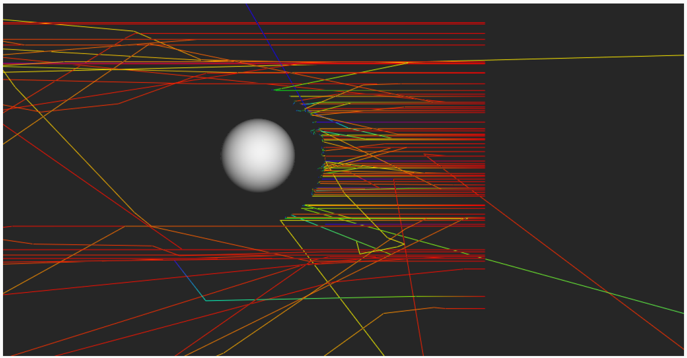
With outer cylinder configured for instant absorption



Without the outer cylinder

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

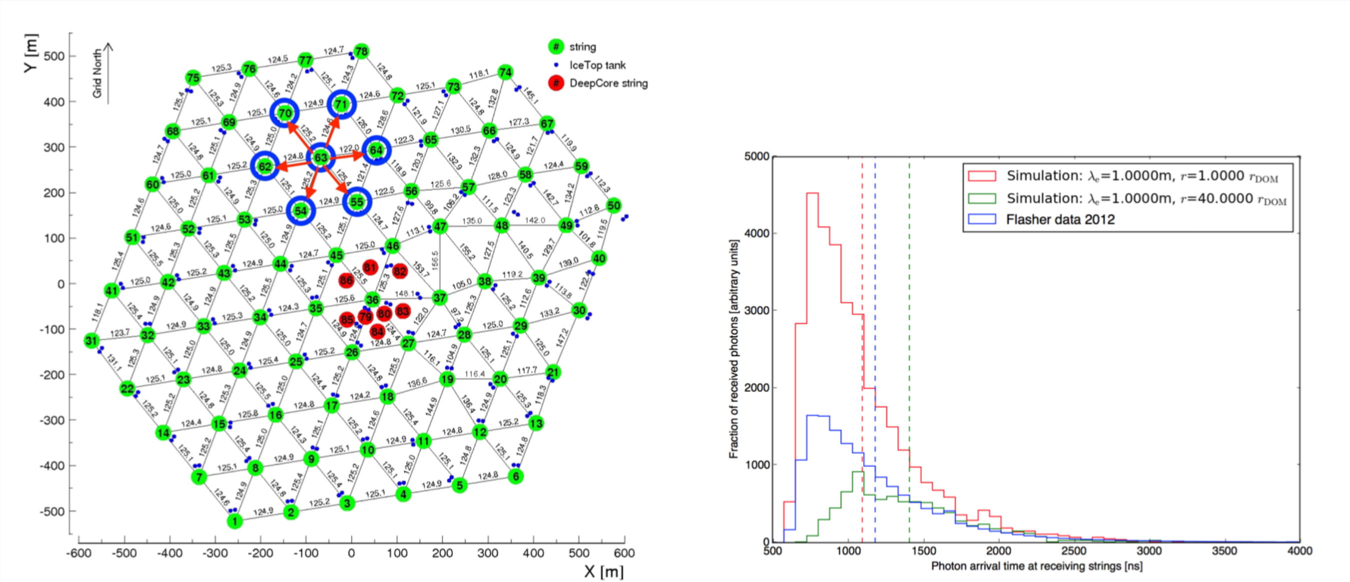
Scattering example



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

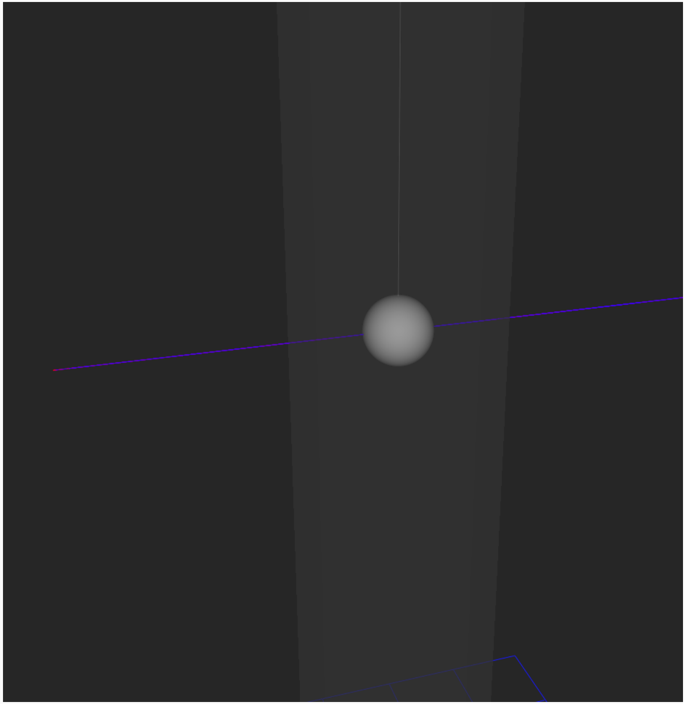
```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/FiringRange
./run.rb --scattering-factor=0.001 --absorption-factor=0.00033 --distance=1.0
↪  --number-of-photons=100 --number-of-runs=1 --number-of-parallel-runs=1
↪  --save-photon-paths --cpu --plane-wave
steamshovel tmp/propagated_photons.i3
```

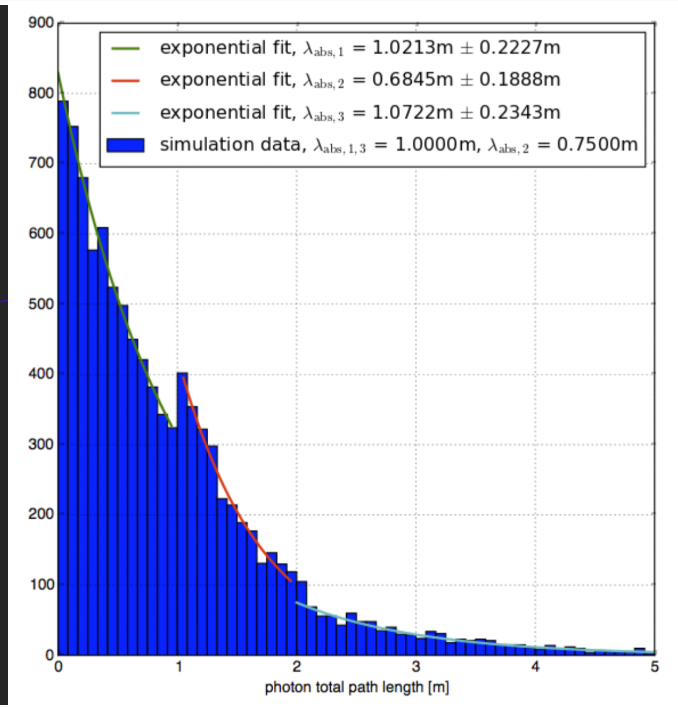
Cross checks: Arrival-time distributions



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

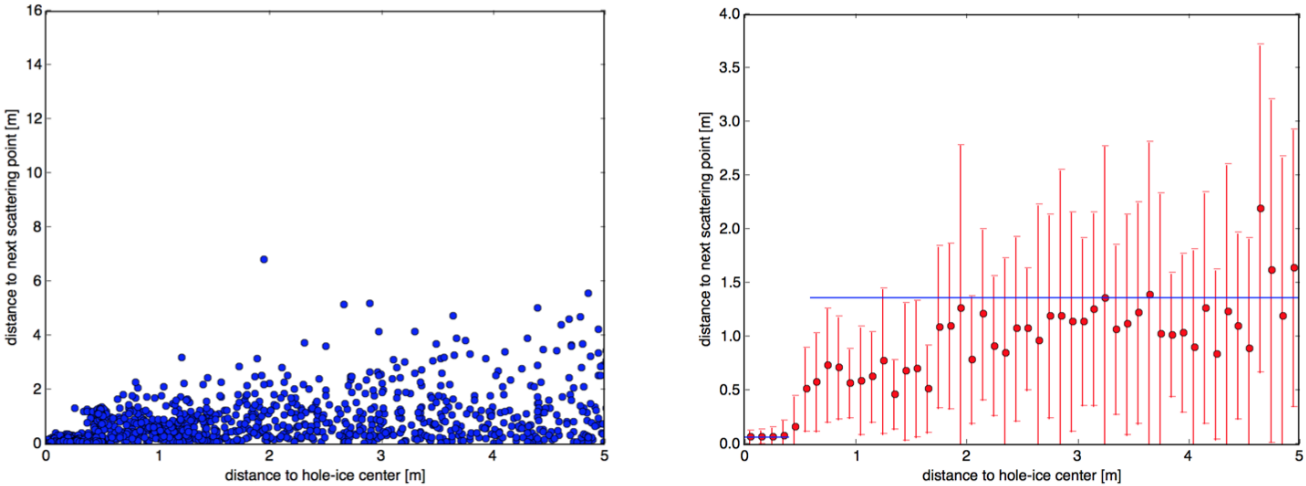
Cross checks: Path-length distributions





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

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

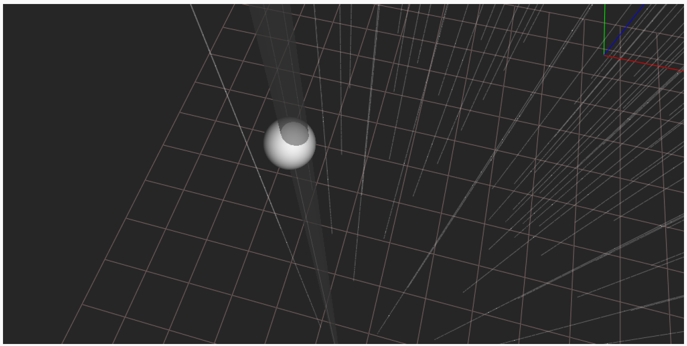


(a) All data points

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

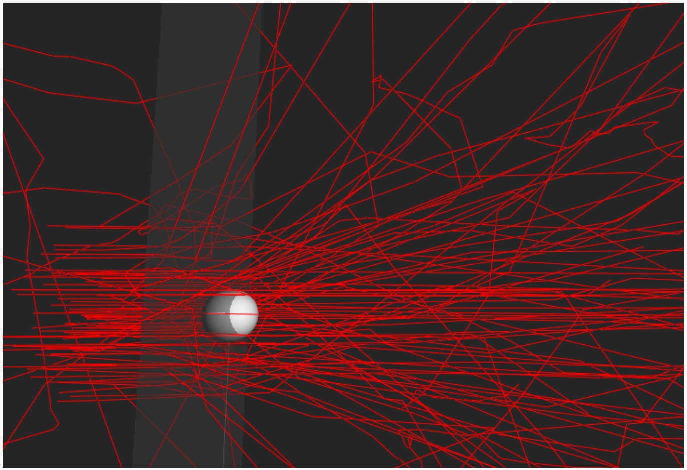
Source: `https://github.com/fiedl/hole-ice-study/issues/71`

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

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

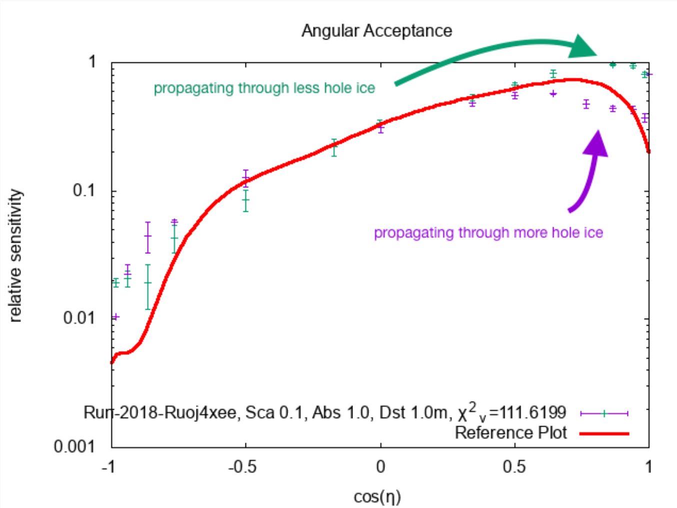
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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

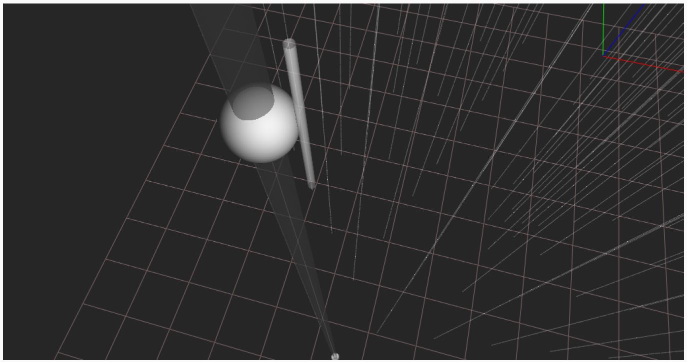
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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=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

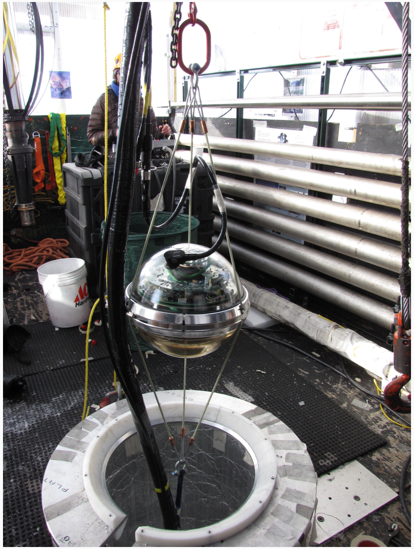
Cable shadows

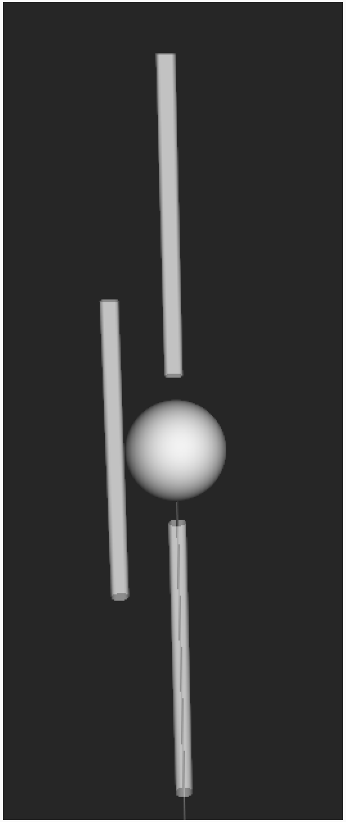


- Cables can be modelled as separate cylinders
  - for each DOM separate position
  - 1 m height
  - configured for instant absorption
- This image:
  - DOM radius: 16.5 cm
  - bubble-column radius: 8.0 cm
  - cable radius: 2.0 cm

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

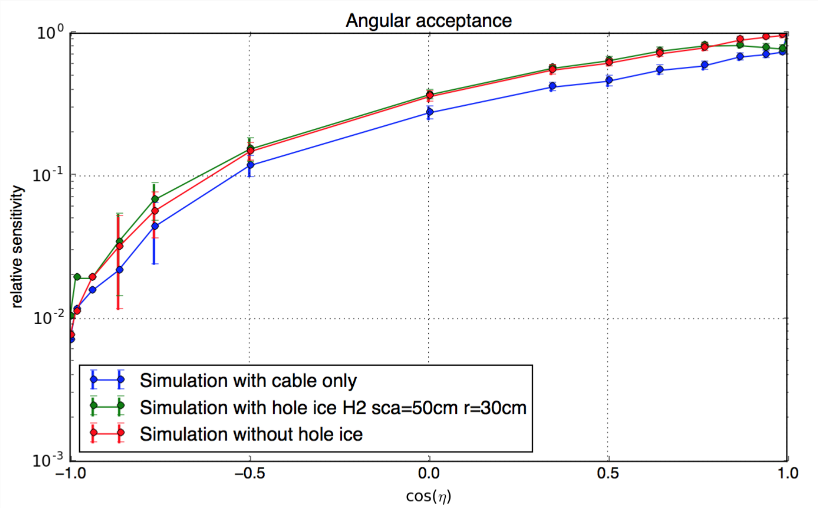
Direct cable simulation: Angular acceptance



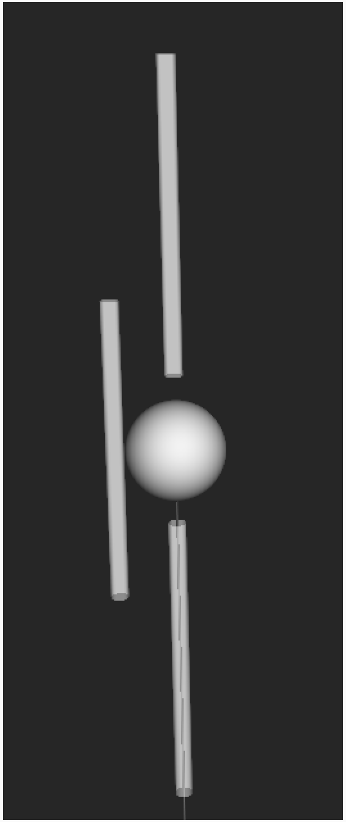


Source: https://github.com/fiedl/hole-ice-study/issues/101. Images: https://icecube.wisc.edu/gallery/view/153, https://gallery.icecube.wisc.edu/internal/v/GraphicRe/graphics/arraygraphics2011/sketchup/DOMCloseUp.jpg.html

Direct cable simulation: Angular acceptance

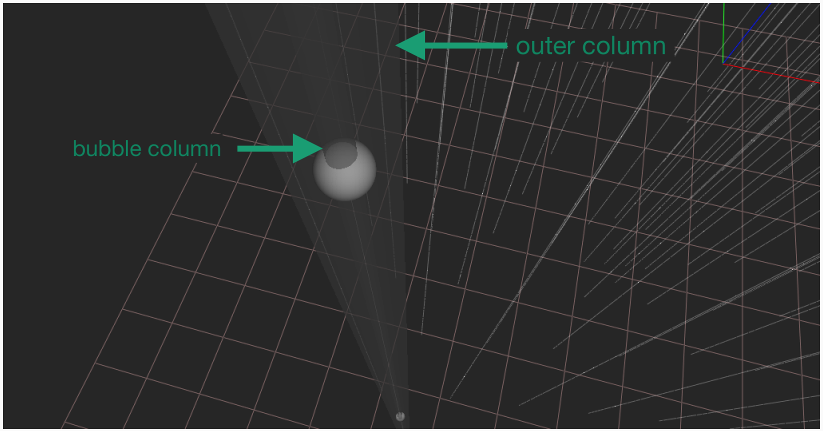


The azimuthal starting angle is such that the cable shadow is maximal.



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

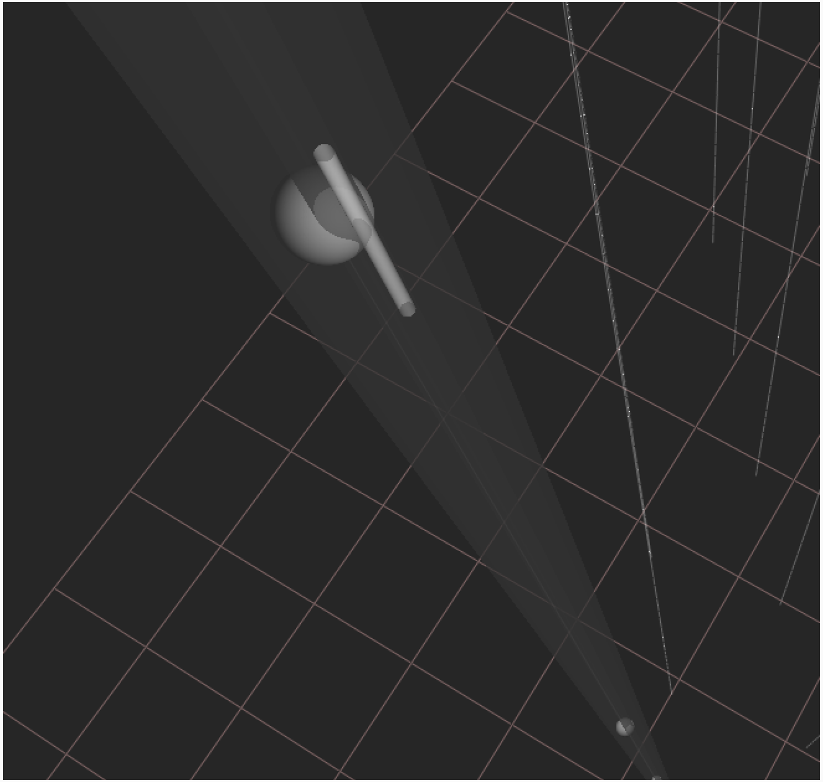
Nested hole-ice cylinders



- 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

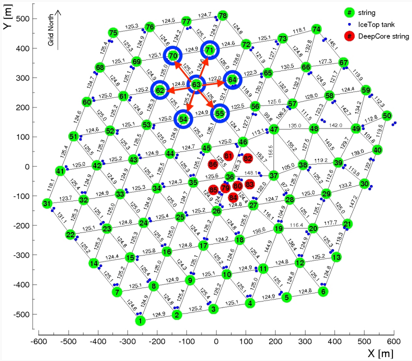


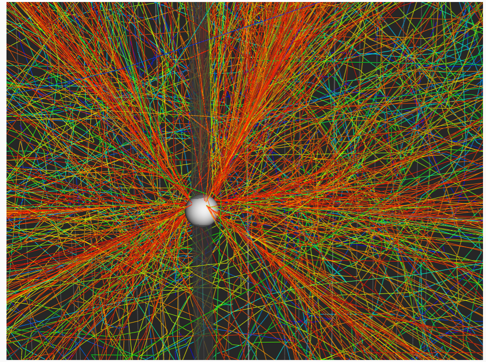
- DOM: radius 16.5 cm, shifted by 12.0 cm against the center of the bore hole
- bubble column: radius 8.0 cm
- drill-hole column: radius 30.0 cm
- cable: radius 3.0 cm, placed next to the DOM, partially within the bubble column

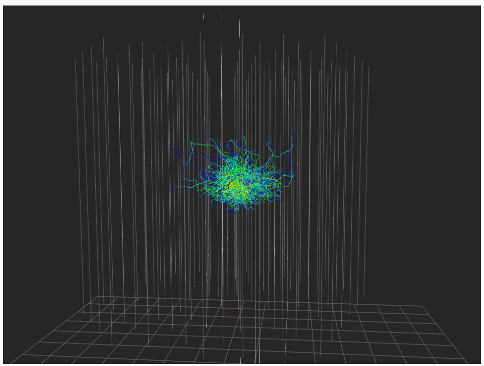
See also: `https://github.com/fiedl/hole-ice-study/issues/110`

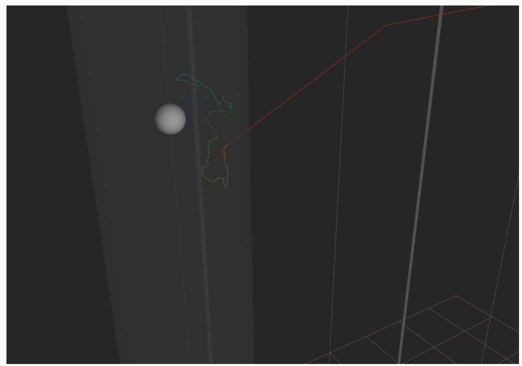
Flasher-simulation example

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



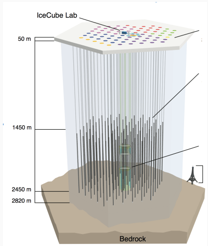


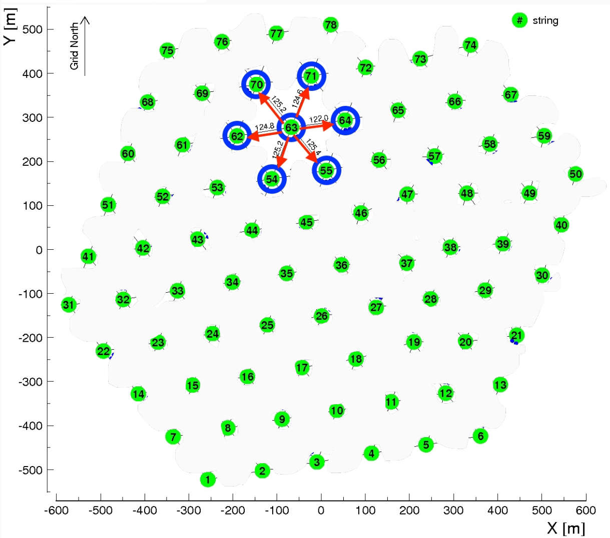


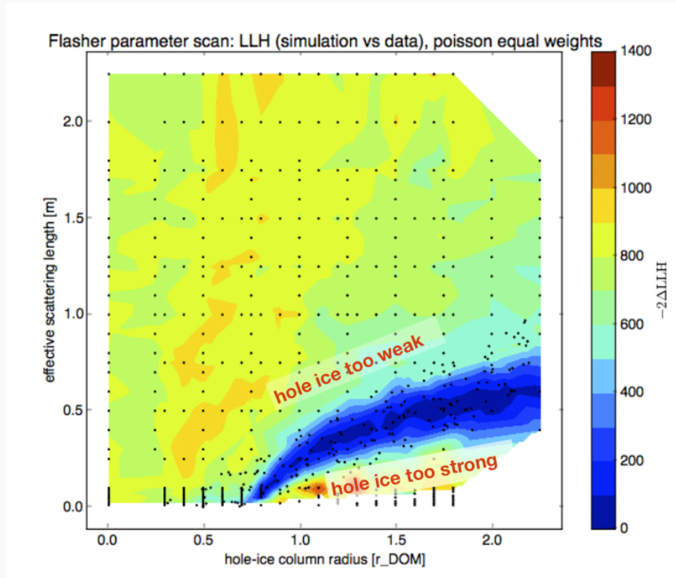


See `https://github.com/fiedl/hole-ice-study/issues/107`

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

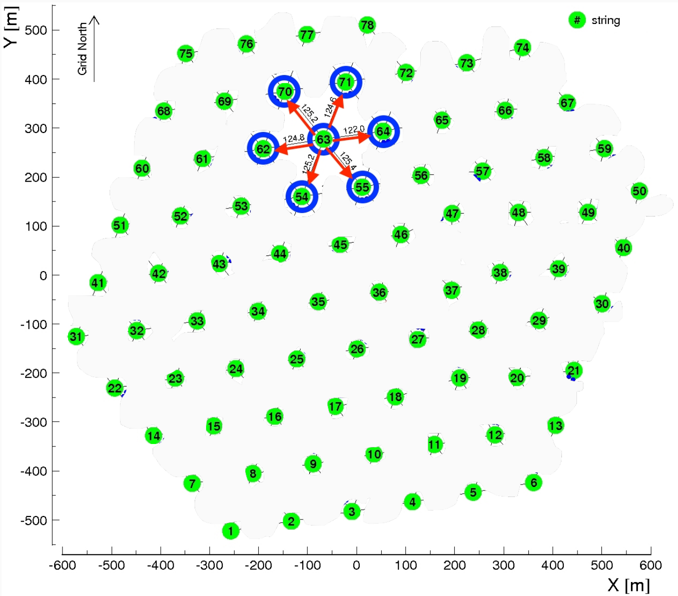






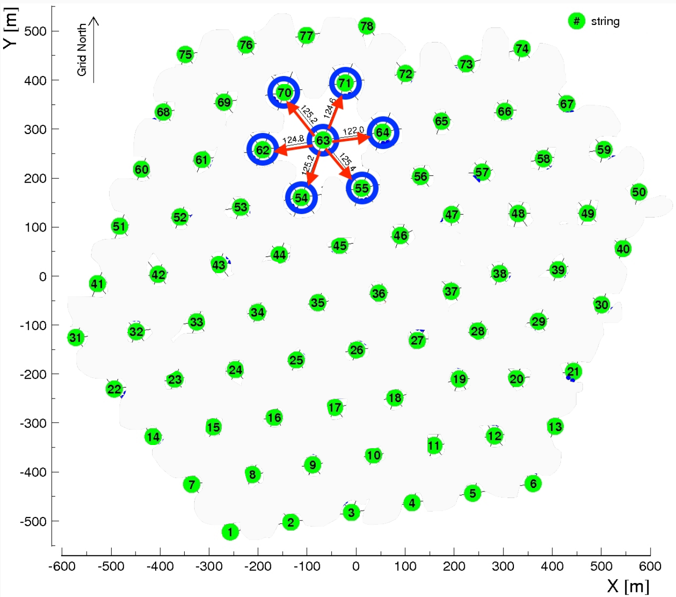
Source: `https://github.com/fiedl/hole-ice-study/issues/59`. Footprint based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`. Image: Aartsen et al., The IceCube Neutrino Observatory: Instrumentation and online systems, 2017.

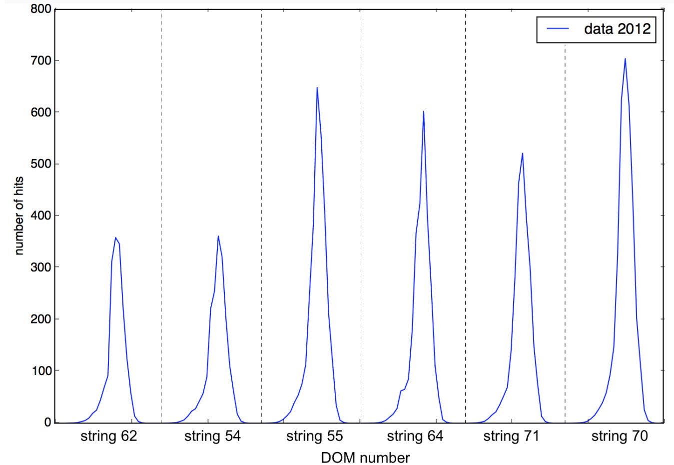
Early results: Calibration data suggest asymmetric shielding by hole ice



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

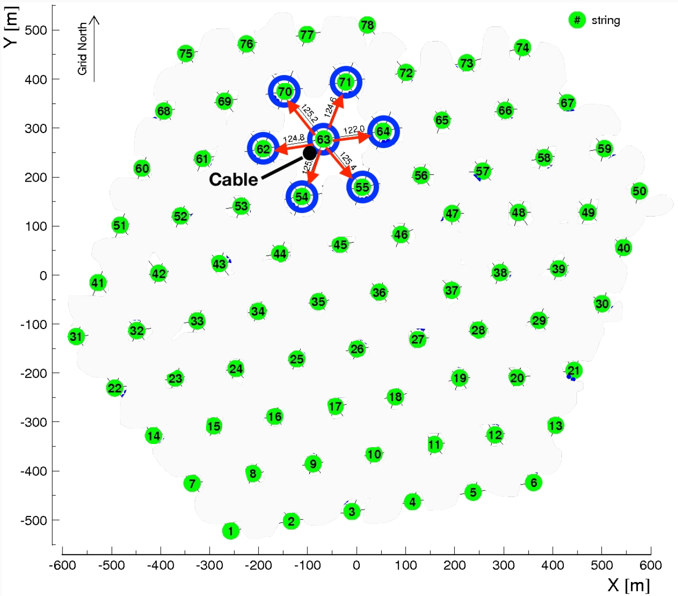
Early results: Calibration data suggest asymmetric shielding by hole ice

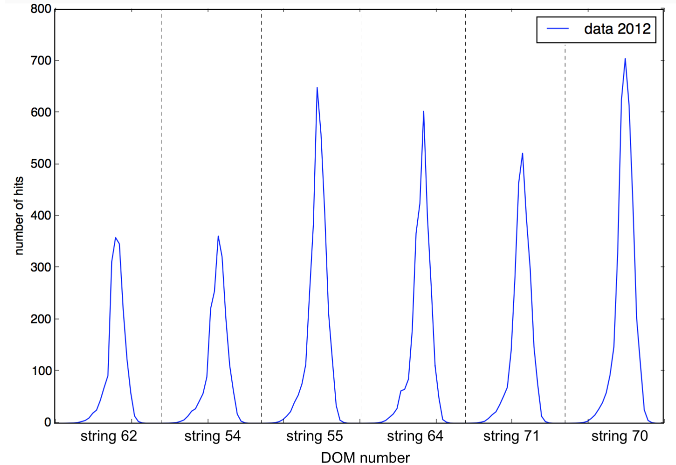




Source: `https://github.com/fiedl/hole-ice-study/issues/97`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

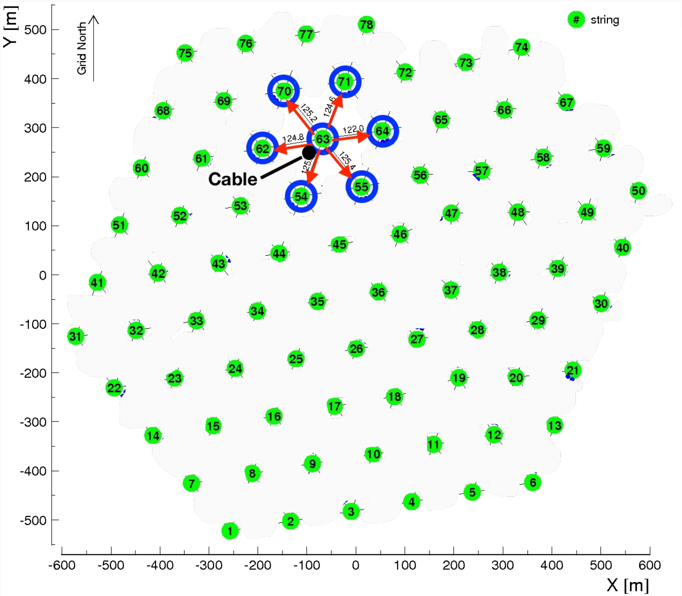
Early results: Calibration data suggest asymmetric shielding by hole ice

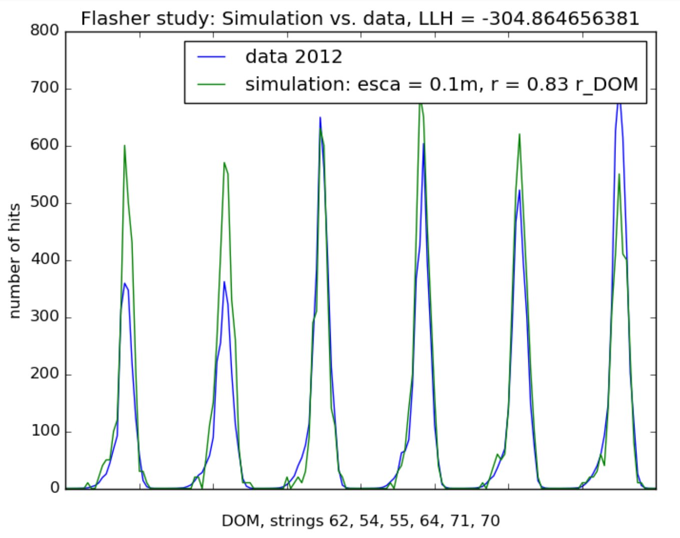




Source: `https://github.com/fiedl/hole-ice-study/issues/97`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

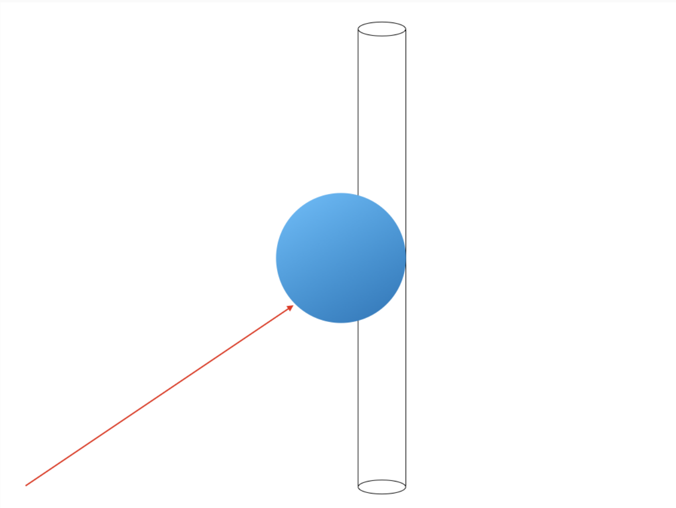
Early results: Calibration data suggest asymmetric shielding by hole ice





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

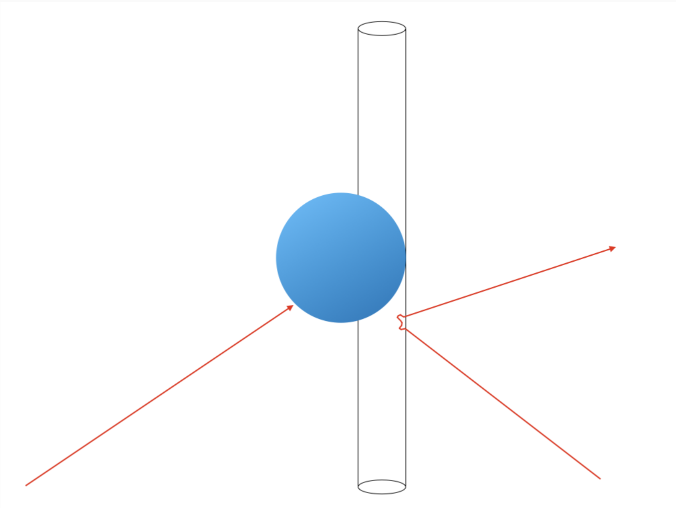
DOM oversizing with hole ice?



Source: `https://github.com/fiedl/hole-ice-study/issues/116`

- Consider a DOM displaced relative to the bubble column, such that
  - a photon from one direction would hit the DOM,
  - a photon from another direction might be deflected by the bubble column.
- Consider a sphere with arbitrary radius, e.g. 5 m or 10 m.
- In detailled simulations with direct propagation, record impact position, impact direction, hole-ice displacement, hole-ice azimuthal position, and count hits.
- In simulations without direct propagation, just intersect the outer sphere and use the hit probability from the table.

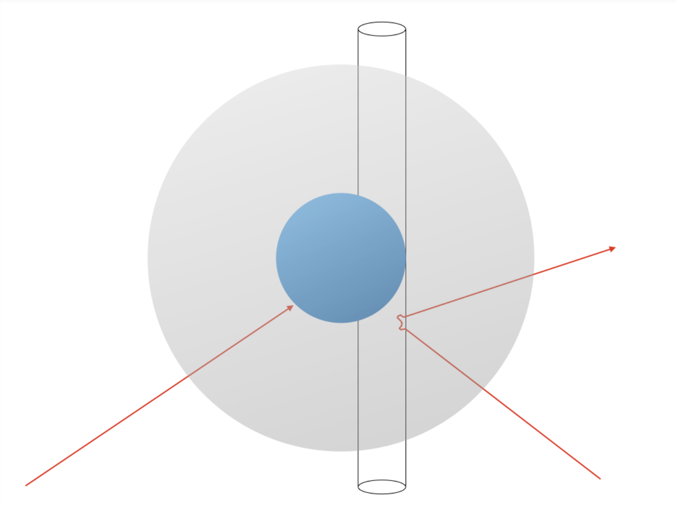
DOM oversizing with hole ice?



Source: `https://github.com/fiedl/hole-ice-study/issues/116`

- Consider a DOM displaced relative to the bubble column, such that
  - a photon from one direction would hit the DOM,
  - a photon from another direction might be deflected by the bubble column.
- Consider a sphere with arbitrary radius, e.g. 5 m or 10 m.
- In detailled simulations with direct propagation, record impact position, impact direction, hole-ice displacement, hole-ice azimuthal position, and count hits.
- In simulations without direct propagation, just intersect the outer sphere and use the hit probability from the table.

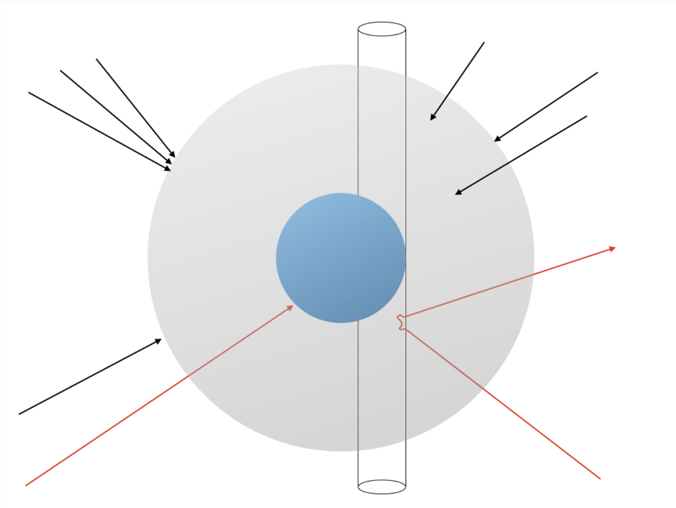
DOM oversizing with hole ice?



Source: `https://github.com/fiedl/hole-ice-study/issues/116`

- Consider a DOM displaced relative to the bubble column, such that
  - a photon from one direction would hit the DOM,
  - a photon from another direction might be deflected by the bubble column.
- Consider a sphere with arbitrary radius, e.g. 5 m or 10 m.
- In detailled simulations with direct propagation, record impact position, impact direction, hole-ice displacement, hole-ice azimuthal position, and count hits.
- In simulations without direct propagation, just intersect the outer sphere and use the hit probability from the table.

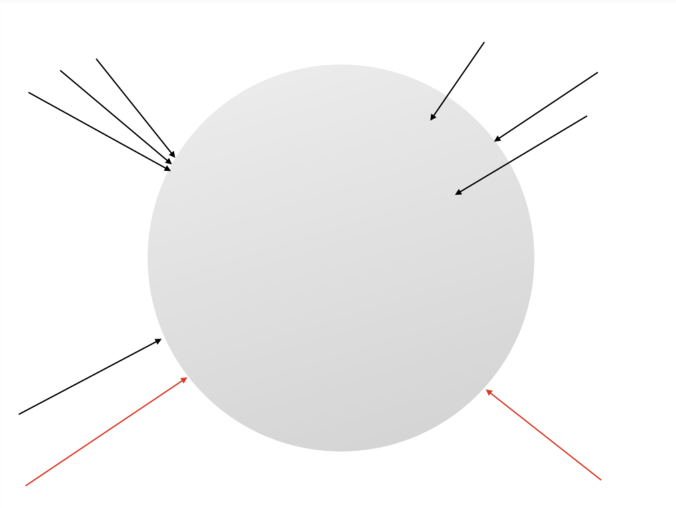
DOM oversizing with hole ice?



Source: `https://github.com/fiedl/hole-ice-study/issues/116`

- Consider a DOM displaced relative to the bubble column, such that
  - a photon from one direction would hit the DOM,
  - a photon from another direction might be deflected by the bubble column.
- Consider a sphere with arbitrary radius, e.g. 5 m or 10 m.
- In detailled simulations with direct propagation, record impact position, impact direction, hole-ice displacement, hole-ice azimuthal position, and count hits.
- In simulations without direct propagation, just intersect the outer sphere and use the hit probability from the table.

DOM oversizing with hole ice?



Source: https://github.com/fiedl/hole-ice-study/issues/116

- Consider a DOM displaced relative to the bubble column, such that
  - a photon from one direction would hit the DOM,
  - a photon from another direction might be deflected by the bubble column.
- Consider a sphere with arbitrary radius, e.g. 5 m or 10 m.
- In detailled simulations with direct propagation, record impact position, impact direction, hole-ice displacement, hole-ice azimuthal position, and count hits.
- In simulations without direct propagation, just intersect the outer sphere and use the hit probability from the table.

Simulation scenario

For each angle polar and azimuthal angle, shoot photons onto the DOM, possibly propagate through the bubble column, and count hits.

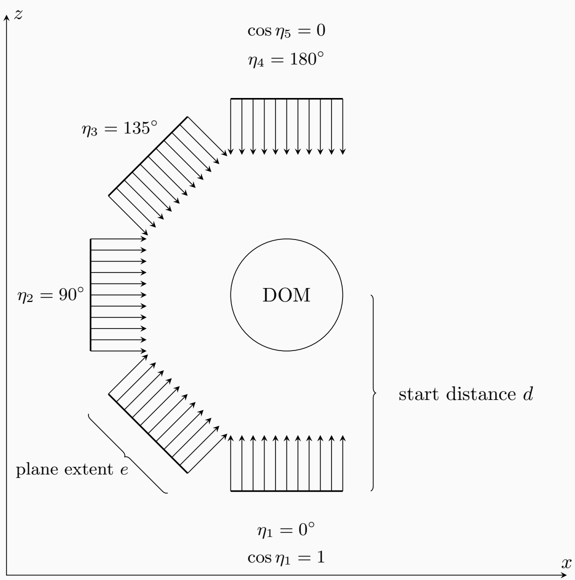


Figure 1: View from the side. Shooting photons from different polar angles.

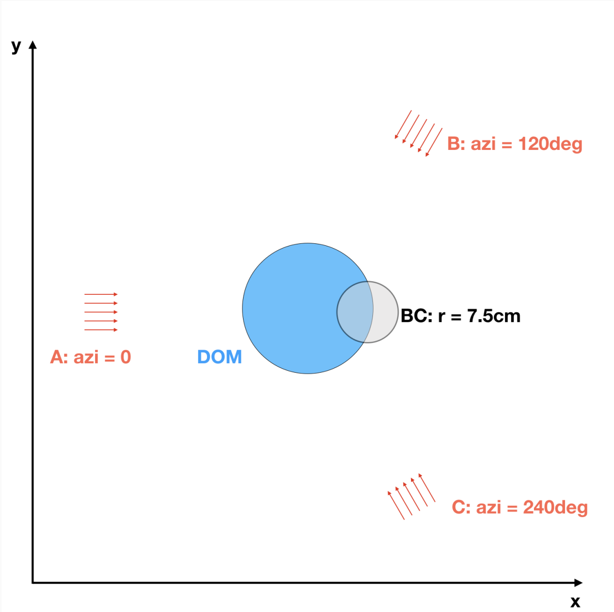
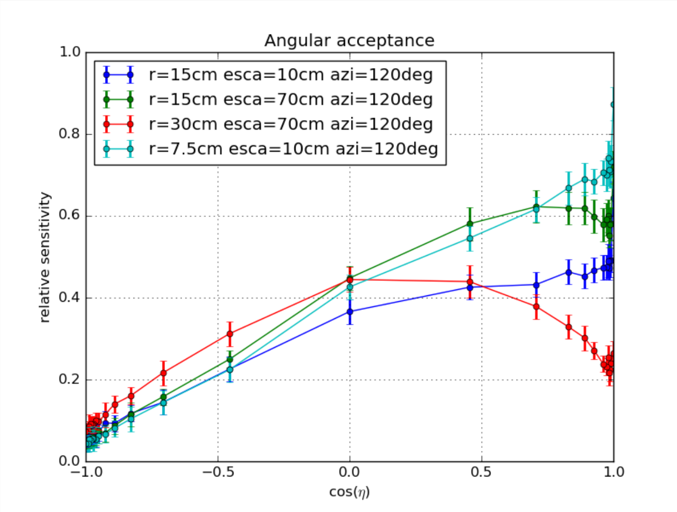
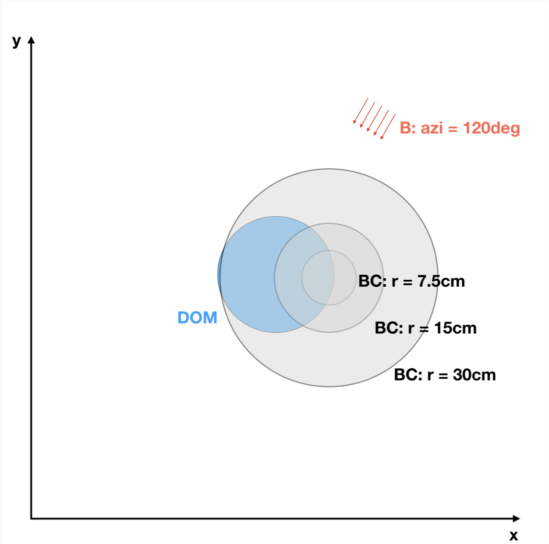


Figure 2: View from above. Shooting photons from different azimuthal angles.

New simulation results



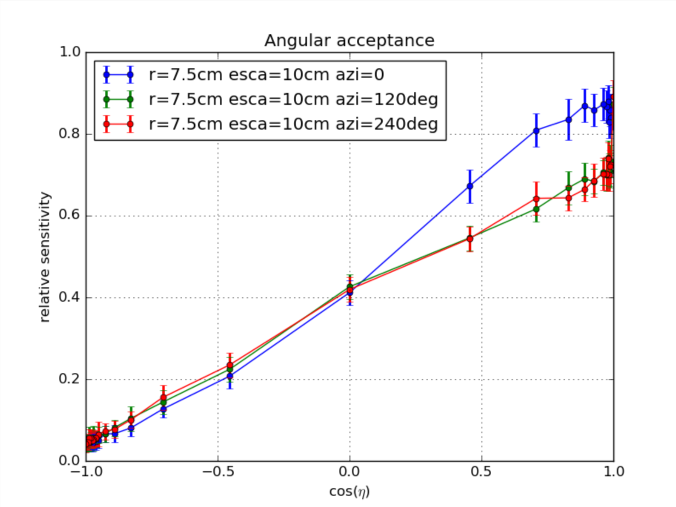


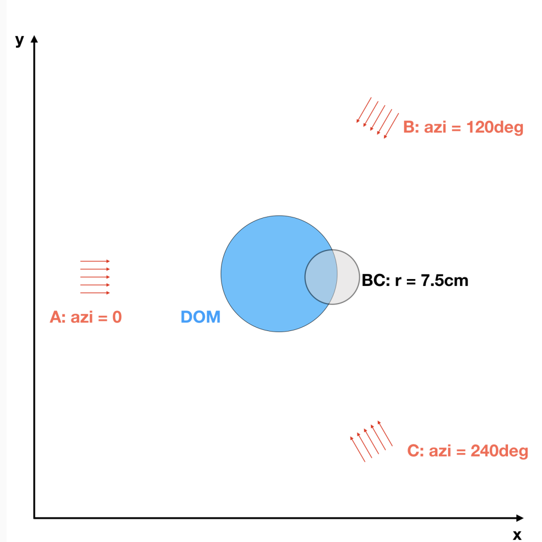
Configuration: Starting distance 3 m, plane-wave extent 3 m, bulk-ice geometric scattering length 130 cm.

Comparing different bubble columns for the same direction of incoming photons.

- Effective scattering length $\lambda_\mathrm{e} = \frac{\lambda_\mathrm{sca}}{(1-\langle\cos\theta\rangle)}$, $\langle\cos\theta\rangle = 0.94$, $\lambda_\mathrm{sca} = 0.06\,\lambda_\mathrm{e}$
- For stronger hole ice (e.g. $\lambda_\mathrm{e} = 10\,\mathrm{cm}$, i.e. $\lambda_\mathrm{sca} = 0.6\,\mathrm{cm}$), the hole-ice radius does matter. ✓
- For a stronger or larger bubble column, the hole-ice effect for lower angles should increase. ✓

New simulation results: Different azimuthal directions



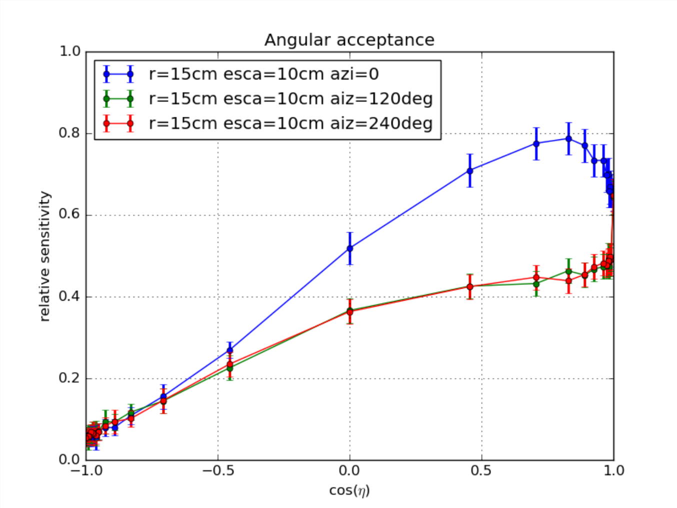


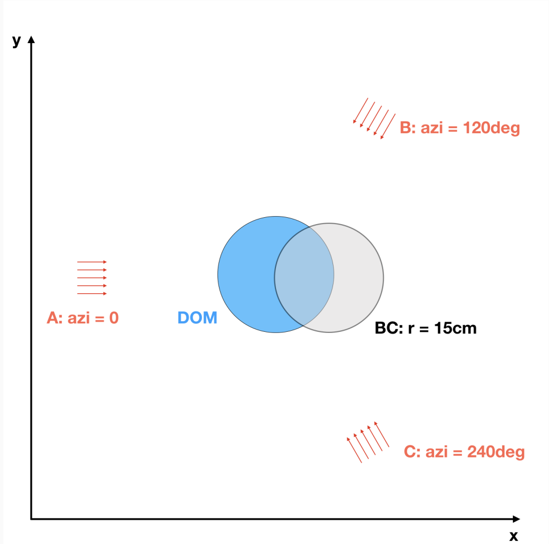
Total photon hit count: 118441 / 1e7

Configuration: Starting distance 3 m, plane-wave extent 3 m, bubble-column geometric scattering length 10 cm, bulk-ice geometric scattering length 130 cm.

- For lower polar angles ($\cos\eta \approx 1$), less photons should arrive from azimuths B and C as from azimuth A as the DOM's PMTs look downwards and photons from B and C are more likely to cross the bubble-column cylinder. ✓
- From azimuths B and C, the same number of photons should arrive due to the symmetry of the scenario (right image). ✓

New simulation results: Different azimuthal directions



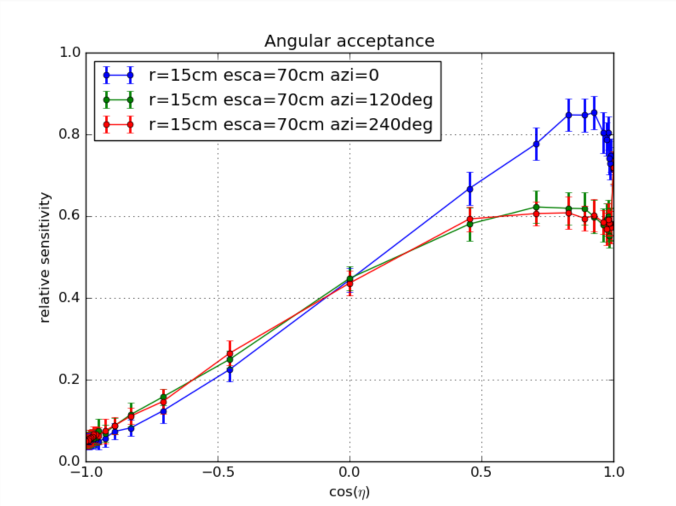


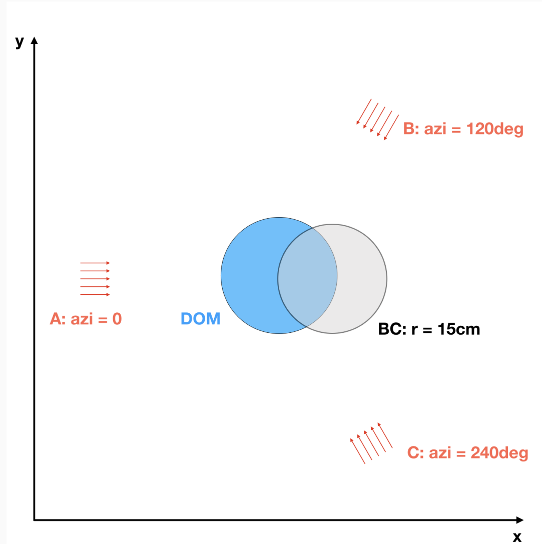
Total photon hit count: 94866 / 1e7

Configuration: Starting distance 3 m, plane-wave extent 3 m, bubble-column geometric scattering length 10 cm, bulk-ice geometric scattering length 130 cm.

- For a larger bubble column with same scattering length, the effect should increase. ✓
- For photons coming from below, the blue curve should see a stronger effect as well. ✓

New simulation results: Different azimuthal directions



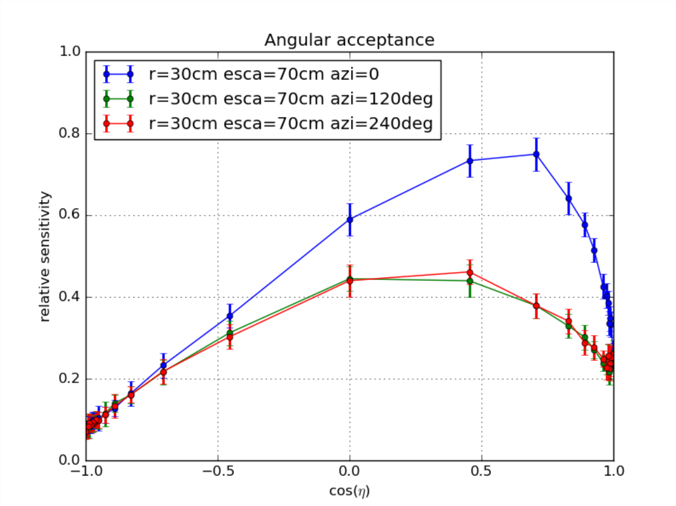


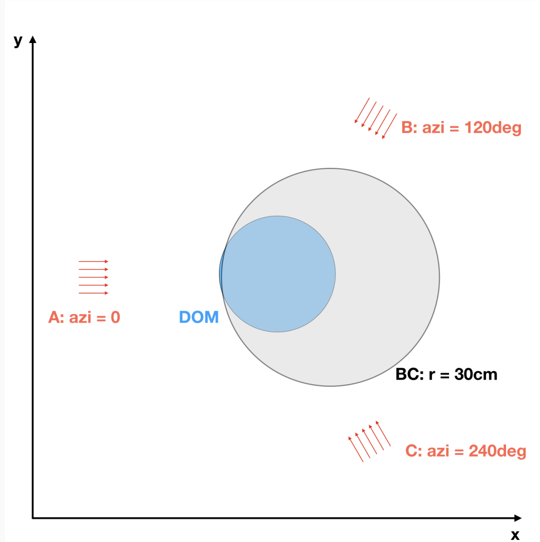
Total photon hit count: 108198 / 1e7

Configuration: Starting distance 3 m, plane-wave extent 3 m, bubble-column geometric scattering length 70 cm, bulk-ice geometric scattering length 130 cm.

- For a larger scattering length (weaker bubble column), the effect should decrease. ✓

New simulation results: Different azimuthal directions





Total photon hit count: 72595 / 1e7

Configuration: Starting distance 3 m, plane-wave extent 3 m, bubble-column geometric scattering length 70 cm, bulk-ice geometric scattering length 130 cm.

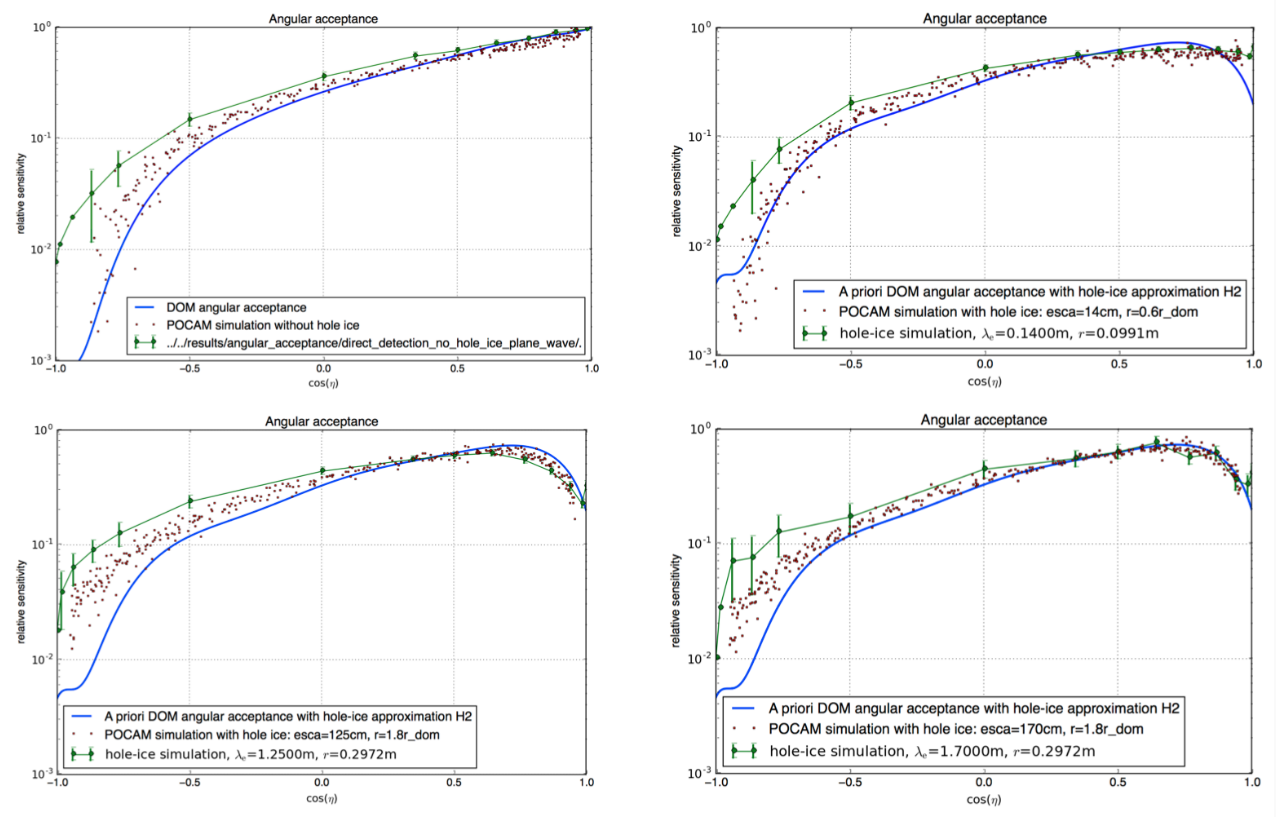
- For a larger bubble column, the effect should increase. ✓
- Less photons should arrive in total as the whole DOM is now shielded by the hole ice. ✓

Two hole-ice algorithms

	Algorithm (a)	**Algorithm (b)**
Approach	Leave clsim medium propagation as it is and add **hole-ice effects as correction** afterwards	Unify clsim medium propagation through layers and hole ice: Treat them as **generic medium changes**
Hole-ice properties	defined relative to bulk-ice properties	defined absolute
Pros	+ Small surface area of hole-ice code, i.e. well testable through unit tests + Standard clsim almost untouched	+ Supports nested cylinders and cables
Cons	– Current understanding of hole-ice suggests defining hole-ice properties absolute rather than relative	– Needed rewrite of clsim's medium-propagation code – Ice tilt and ice anisotropy not re-implemented, yet (Issue #48)

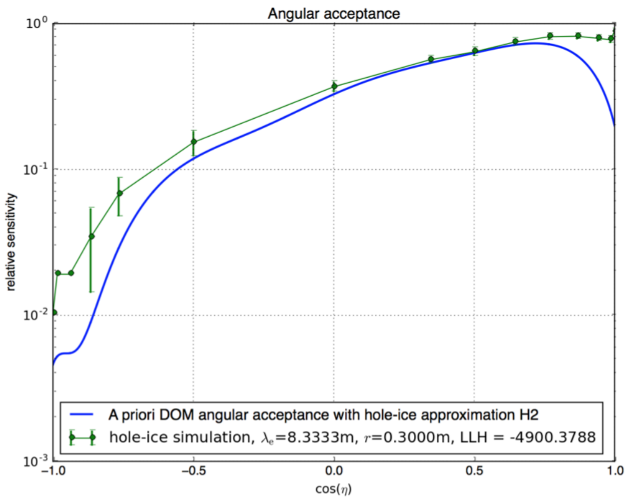
Source: https://github.com/fiedl/hole-ice-study/issues/45

Comparison to ppc simulation

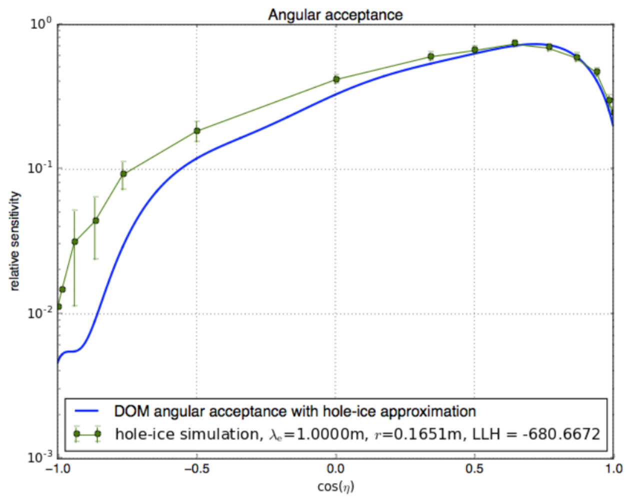


Source: `https://github.com/fiedl/hole-ice-study/issues/4`, POCAM ppc data source: Resconi, Rongen, Krings: The Precision Optical CAlibration Module for IceCube-Gen2: First Prototype, 2017.

Comparison to H2 hole-ice model



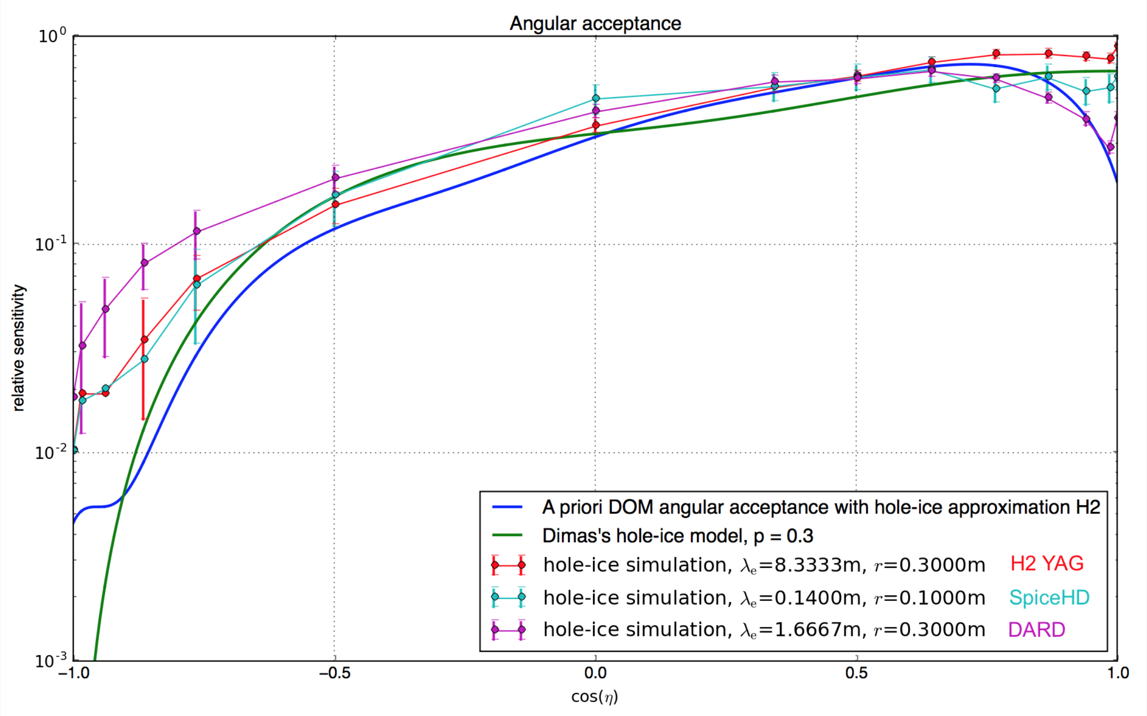
(a) Clsim simulation with H2 hole-ice parameters: $r = 30\,\mathrm{cm}, \lambda_{\mathrm{sca}}^{\mathrm{H}} = 50\,\mathrm{cm}, \lambda_{\mathrm{sca}}^{\mathrm{H}} = 8.33\,\mathrm{m}$



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

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.