Simulation of Light Propagation Through Hole Ice for the IceCube Experiment

DPG Conference Aachen 2019
Session T11 Neutrino Astronomy I

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Erlangen Centre for Astroparticle Physics

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Federal Ministry of Education and Research

ICECUBE South Pole Neutrino Observatory

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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`

Introduction: IceCube Detector

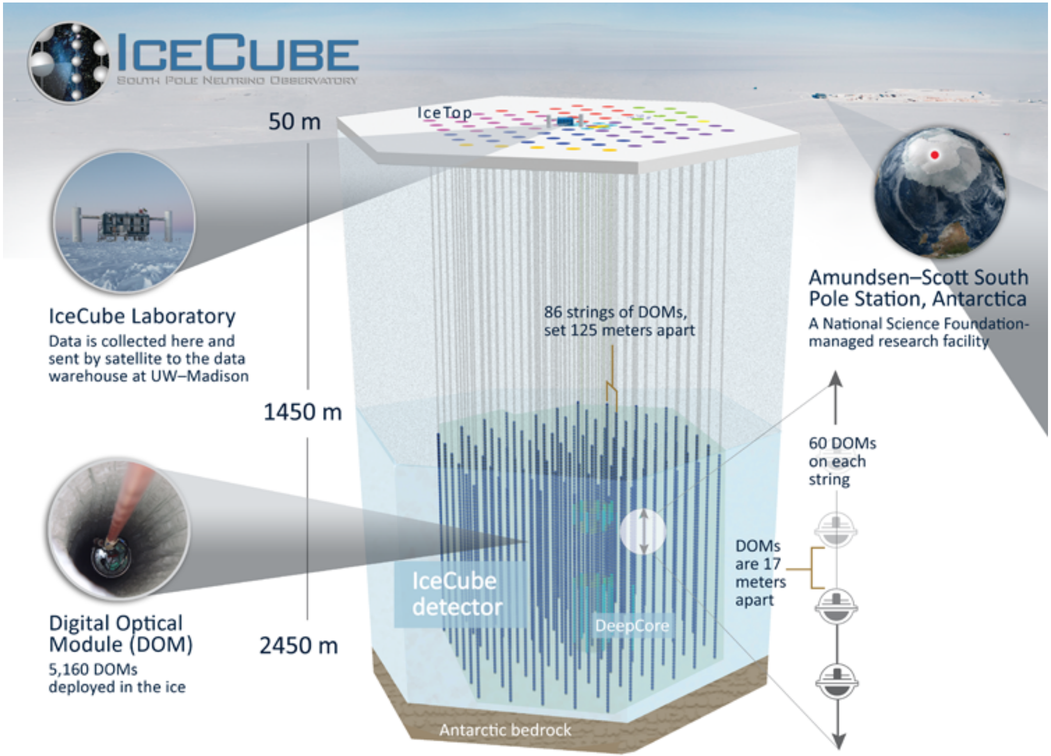
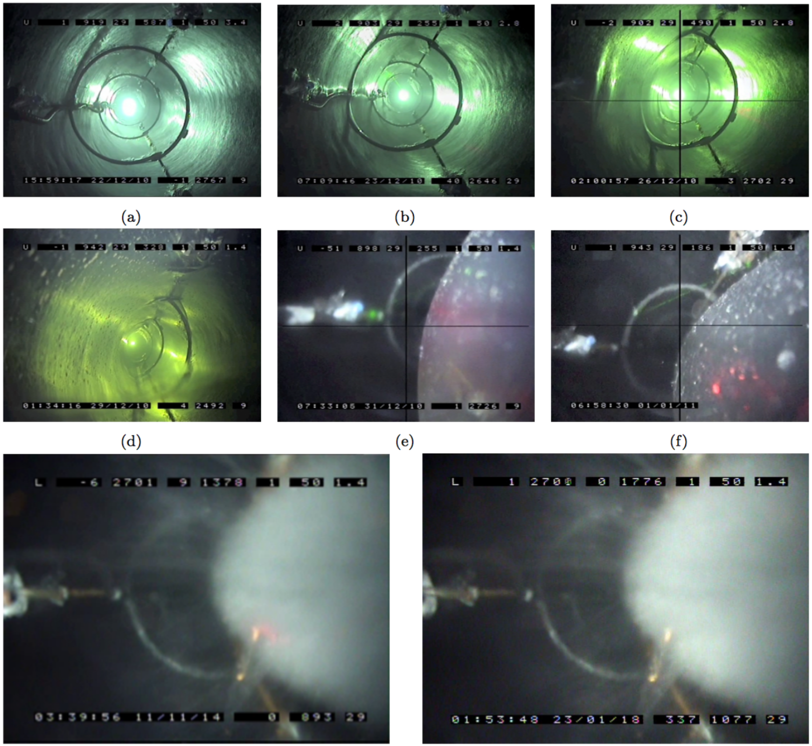


Image source: `https://icecube.wisc.edu/icecube/static/science/images/icecube_detector_sm.png`

Motivation and Scope

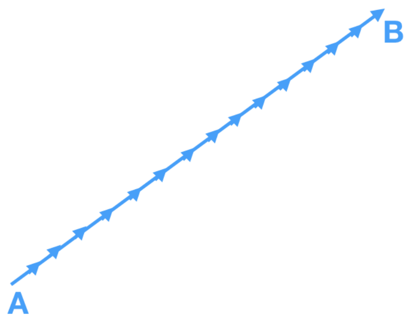


(a) (b) (c) (d) (e) (f) (g) (h)

- **Hole ice** is the refrozen water in the drill holes around the detector modules
- possibly **different optical properties** than surrounding bulk ice
- Implement **hole ice in photon-propagation simulation** in order to improve detector calibration

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.

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: Hole ice**: Generalize budget algorithm to also support cylinders (with distinct scattering and absorption lengths).

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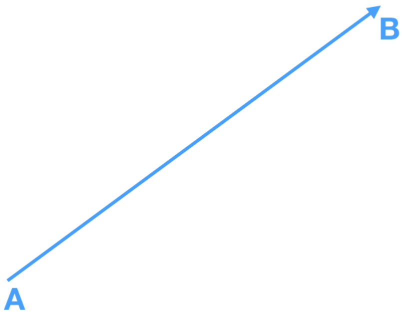

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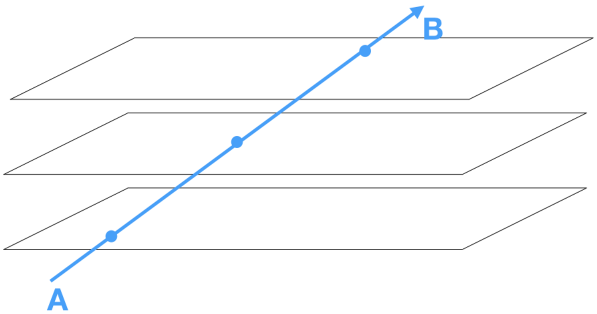

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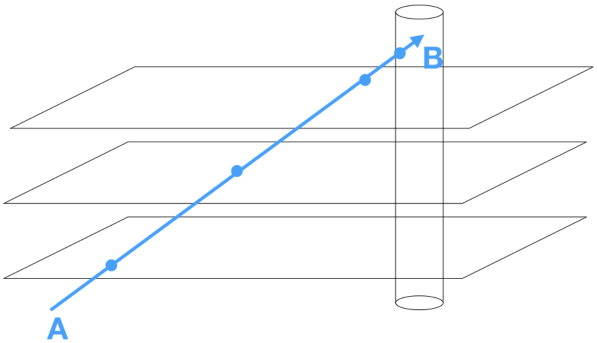

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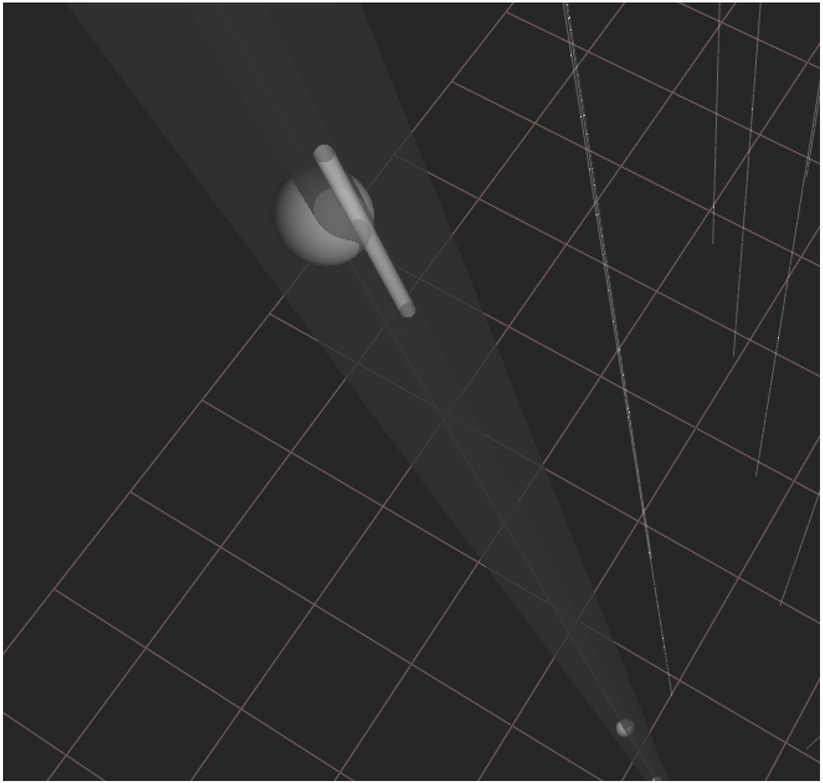
Realistic simulation scenario

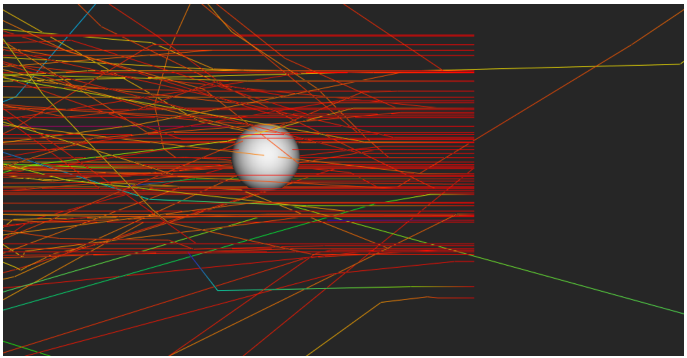


- DOM: radius 16.5 cm, shifted by 12.0 cm against the center of the bore hole
- bubble column: radius 8.0 cm
- droll-hole column: radius 30.0 cm
- cable: radius 3.0 cm, placed next to the DOM, partially within the bubble column

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

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.



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`

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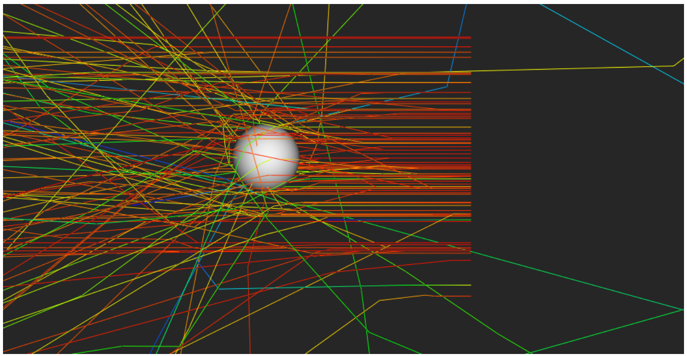

Shoot photons onto the DOM. Top view.
Change the scattering length inside the hole ice to be 1/10 of the scattering length outside.

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

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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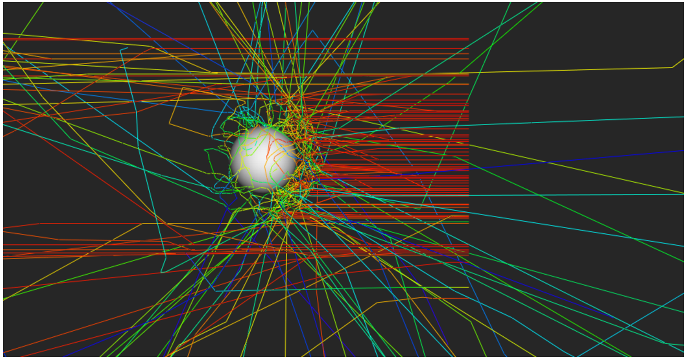

Shoot photons onto the DOM. Top view.
Change the scattering length inside the hole ice to be 1/100 of the scattering length outside.

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

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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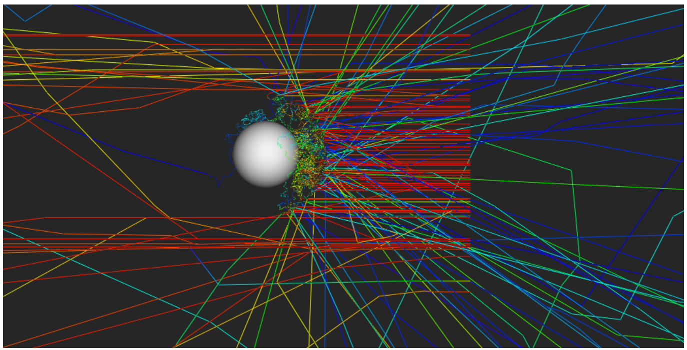

Animation on youtube: `https://youtu.be/BhJ6F3B-I1s`

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.

$$\begin{aligned}\lambda_{\text{sca,hole-ice}} &= \frac{1}{1\,000}\,\lambda_{\text{sca,bulk}}\\ \lambda_{\text{abs,hole-ice}} &= \lambda_{\text{sca,bulk}}\end{aligned}$$

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`

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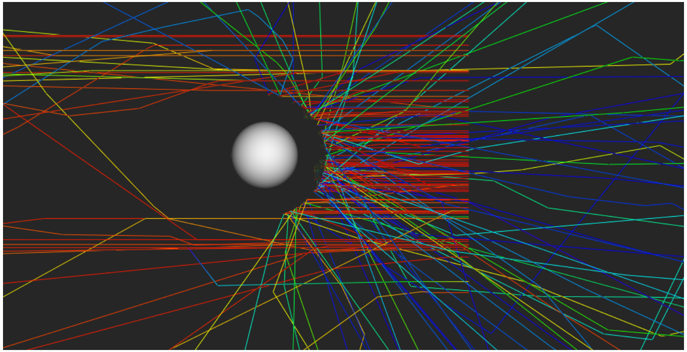

Shoot photons onto the DOM. Top view.
Change the scattering length inside the hole ice to be 1/10 000 of the scattering length outside.

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

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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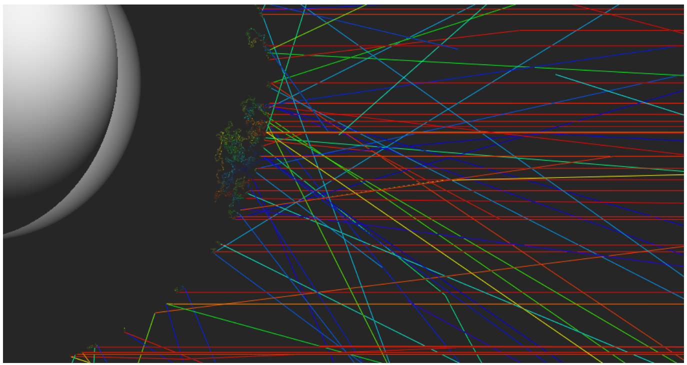

(Magnification)

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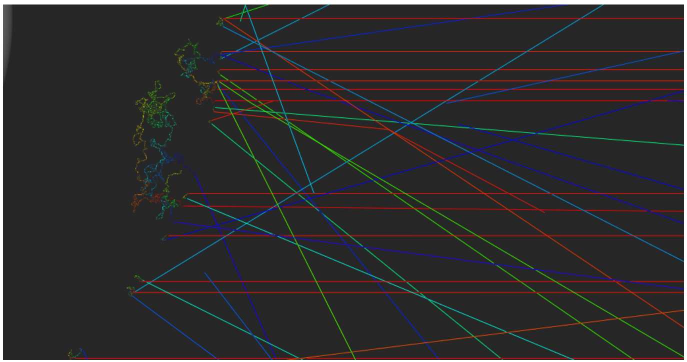

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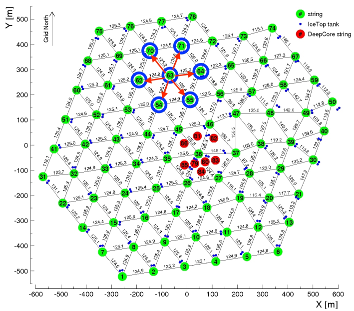
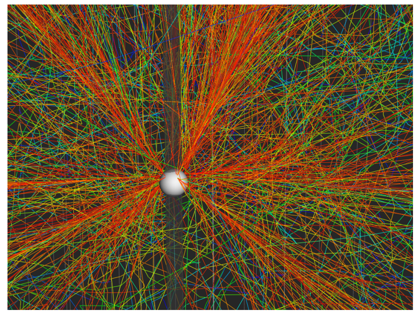
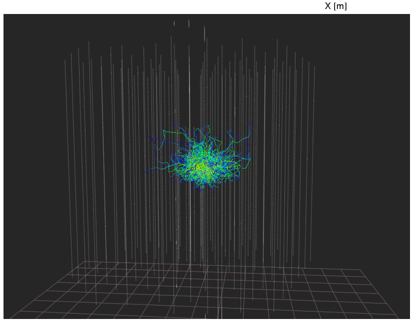
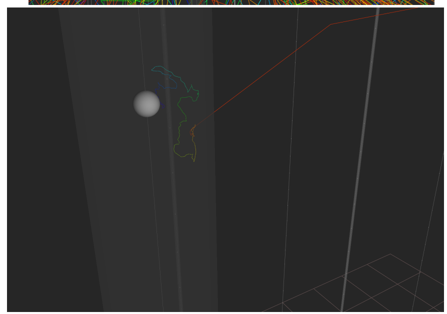
Flasher-simulation example

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



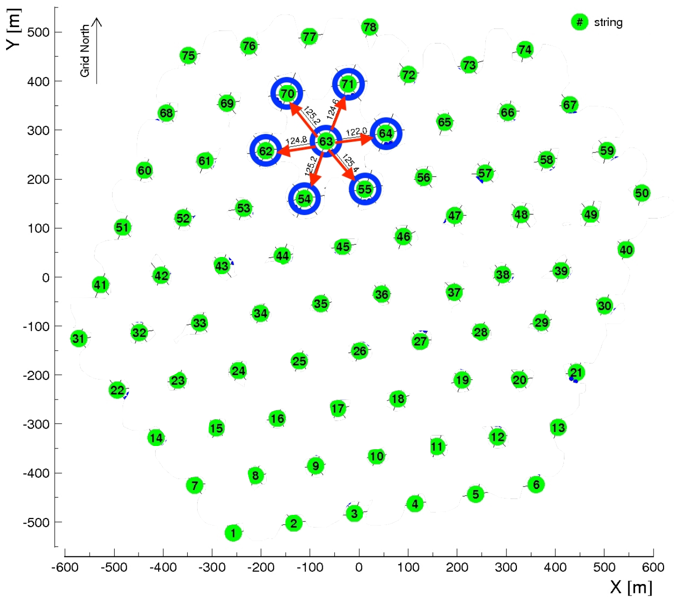


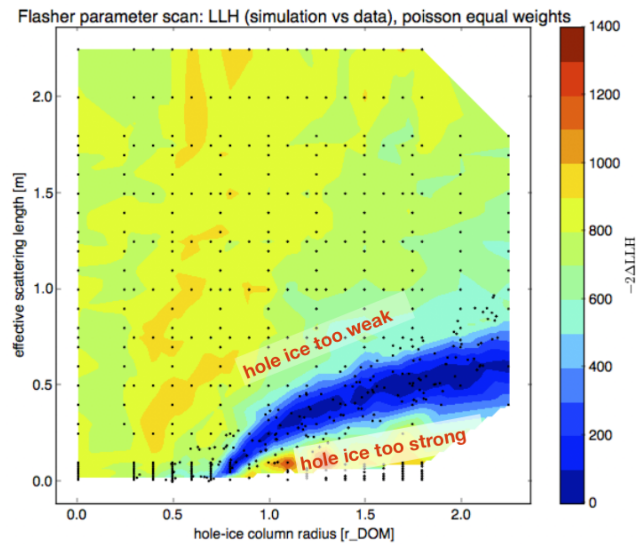




See `https://github.com/fiedl/hole-ice-study/issues/107`

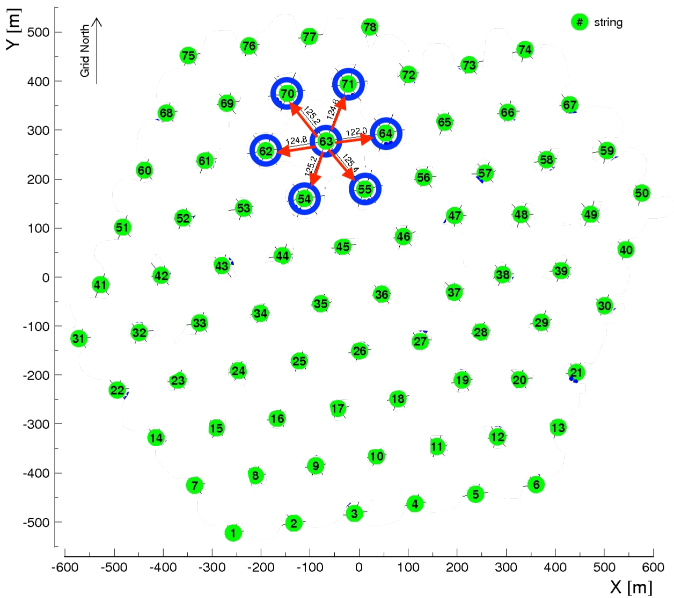
Early results: Example scan for best hole-ice parameters based on calibration data





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

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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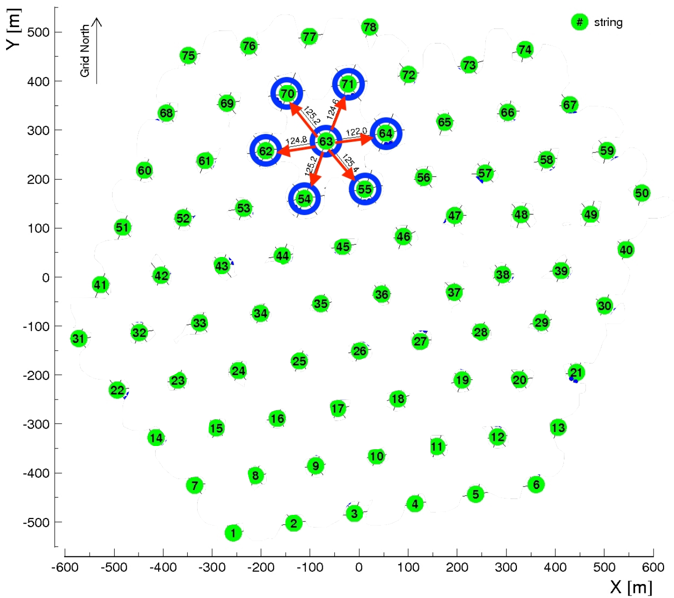

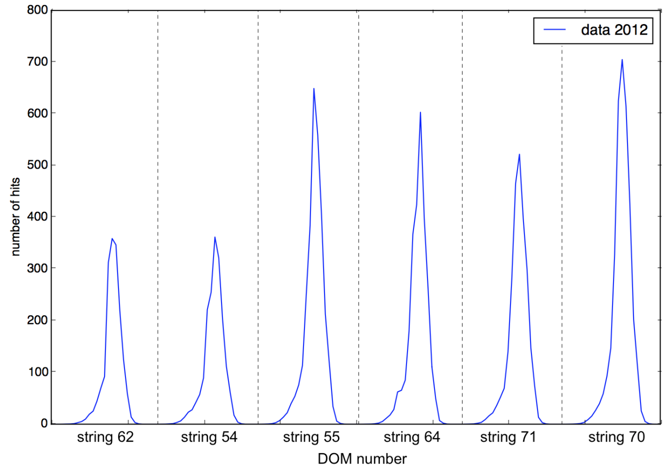

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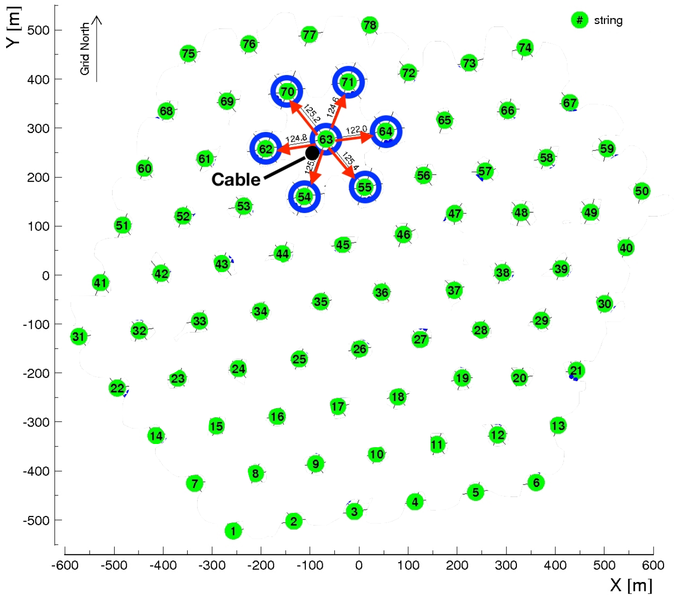

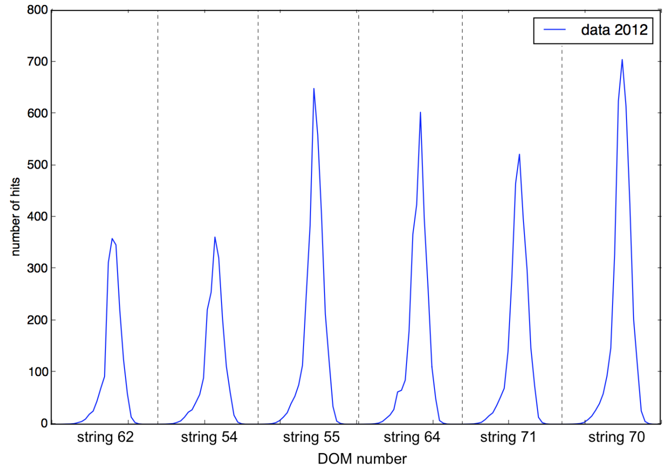

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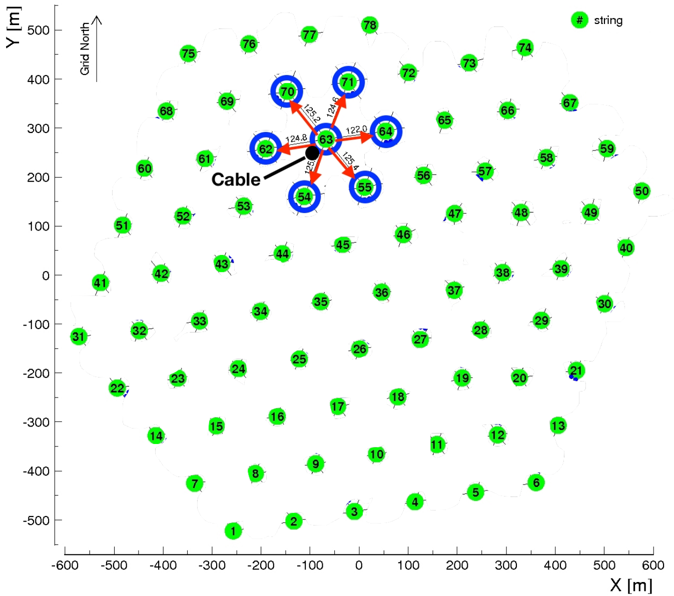
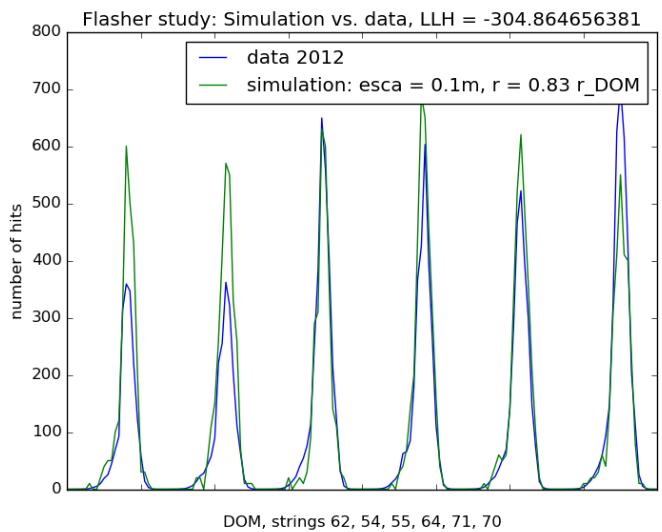




Source: `https://github.com/fiedl/hole-ice-study/issues/97`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

Outlook: Next Steps

- Bring the new hole-ice simulation into IceCube's main simulation framework
- 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`

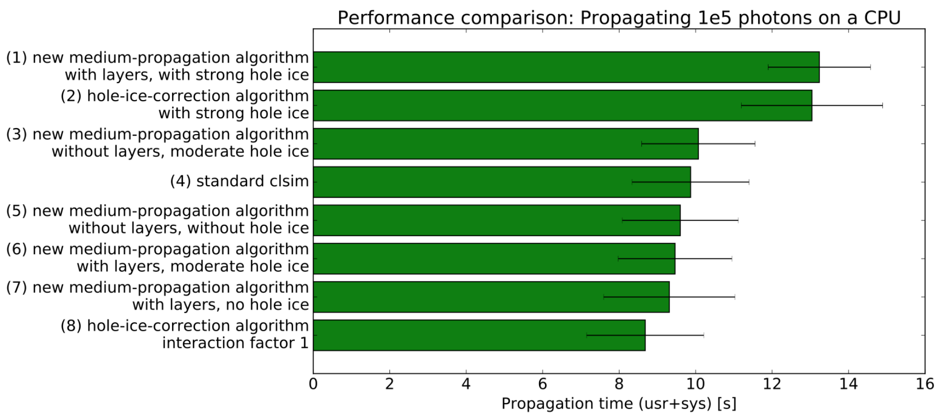
sebastian.fiedlschuster@fau.de

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

Backup Slides

Performance

Time measurement: Propagating 10^5 photons on CPU

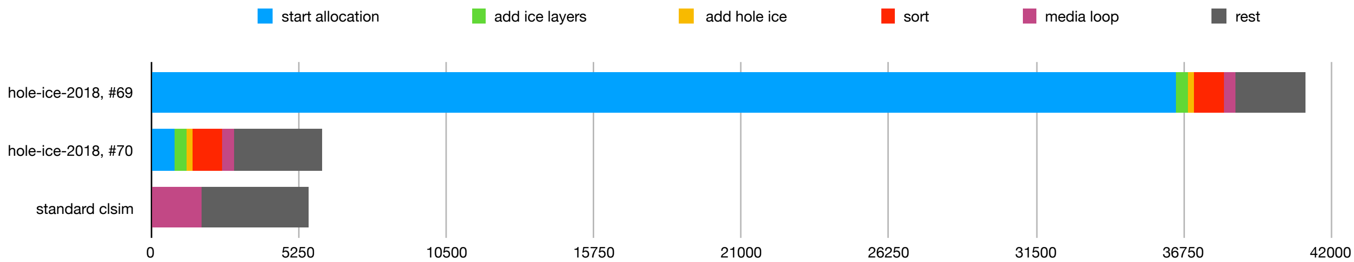


- Medium propagation features (hole ice, layers) have no measurable performance impact for scattering lengths comparable to bulk-ice scattering ($\lambda_s = 20\,\text{m}$).
- Performance drop can be seen when lowering the scattering length, i.e. increasing the number of simulation steps ($\lambda_s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

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:

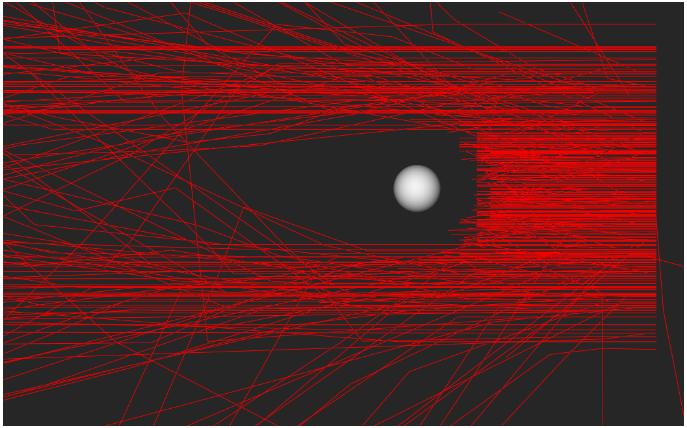
Standard clsim with hole-ice approximation: 11 mins
New algorithm, no hole ice: 10 mins
New algorithm, about H2 hole ice: 15 mins

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

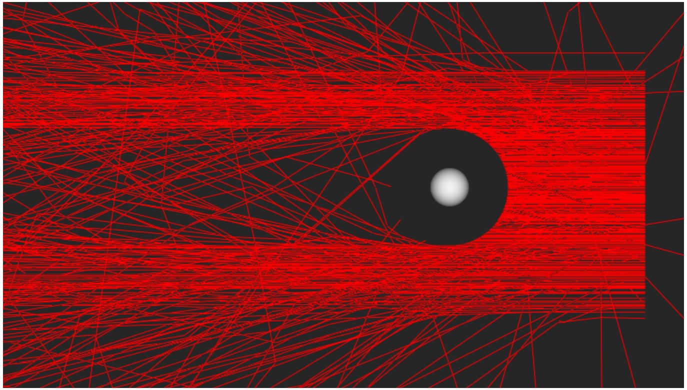
Coordinates-vs-vectors bug

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

Before: Treating coordinates as separate variables

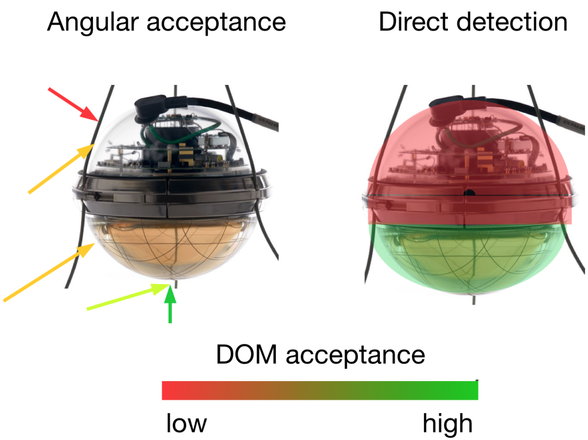


After: Treating vectors as opencl-native vectors



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

Direct detection

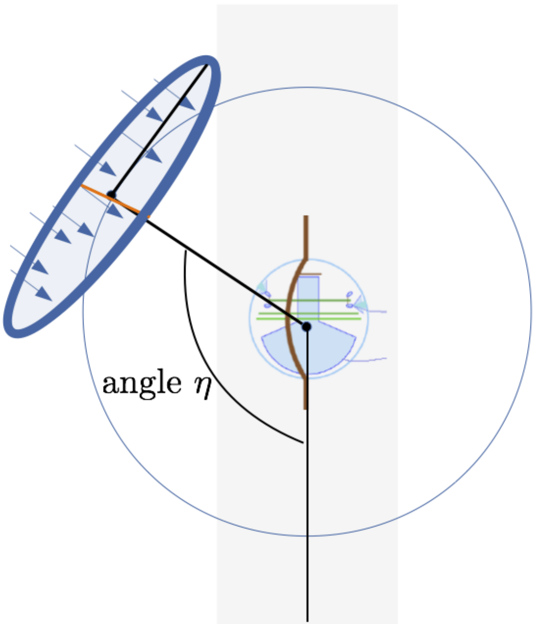


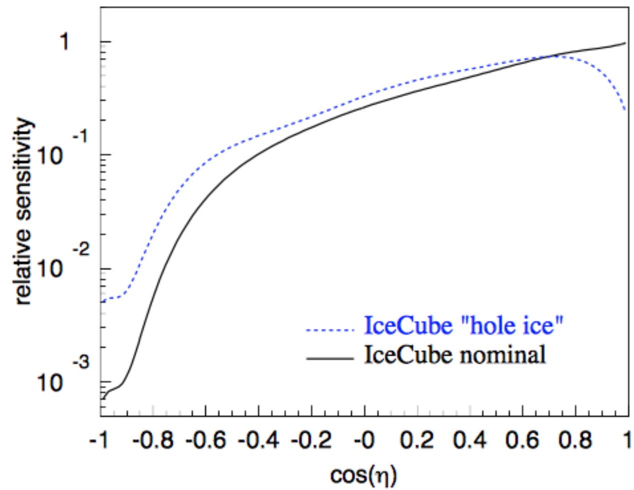
Source: Image: Martin Rongen, *Status and future of SpiceHD DARD*, 2017, Slide 17,
See also: `https://github.com/fiedl/hole-ice-study/issues/32`

- 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.

Angular acceptance

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



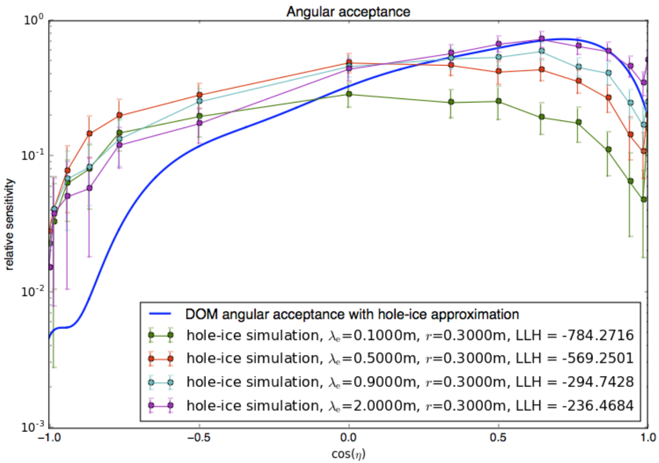


Angular acceptance *reference curves*. The nominal model is based on lab measurement, the hole ice curve on previous simulations.

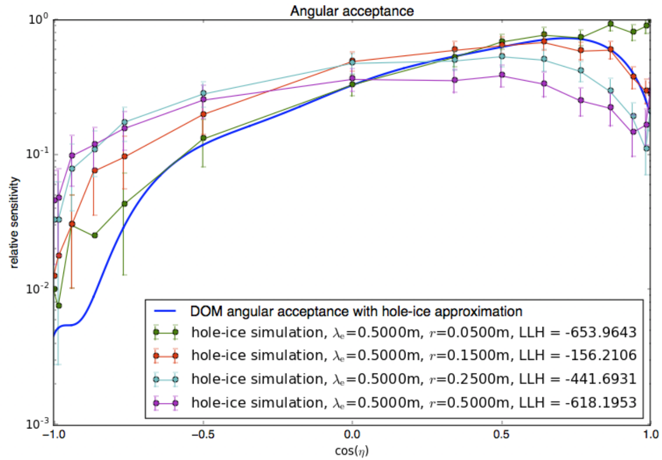
Source: Image: Martin Rongen, Calibration Call 2015-11-06, DARD Update, Slide 9
Plot: Measurement of South Pole ice transparency with the IceCube LED calibration system, 2013, figure 7. See also: `https://github.com/fiedl/hole-ice-study/issues/10`

Angular acceptance for different hole-ice parameters

Vary hole-ice scattering length:

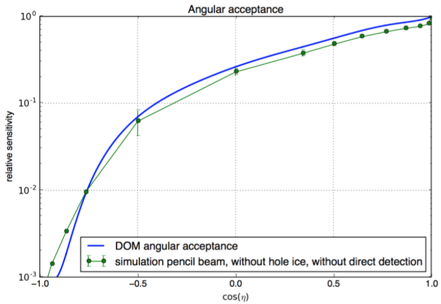


Vary hole-ice radius:

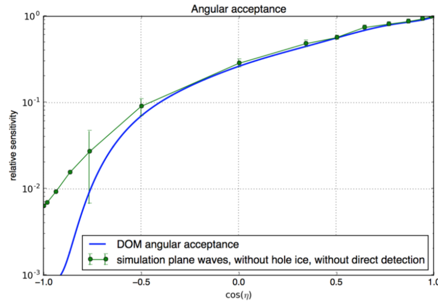


Systematics:
For direct detection + plane waves, increased number of photons for $\cos\eta < 0$.
plane extent 1 m, starting distance 1 m
non-perfect bulk-ice properties

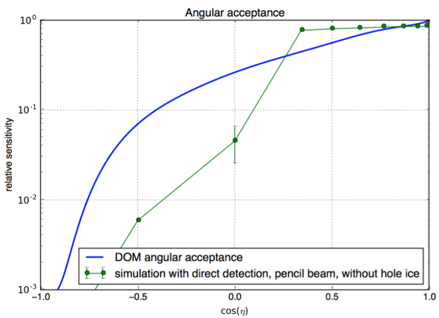
Angular acceptance: Sources and acceptance criteria



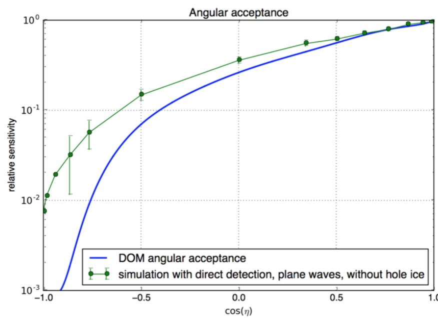
(a) pencil beams, a priori angular acceptance



(b) plane waves, a priori angular acceptance



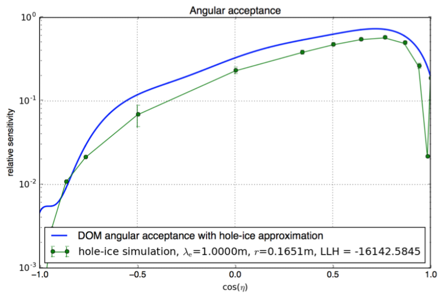
(c) pencil beams, direct detection



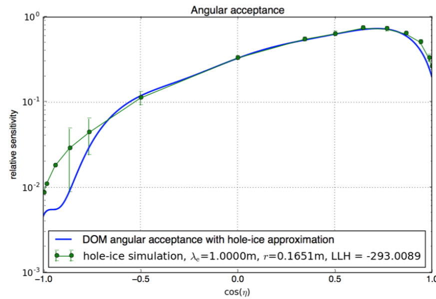
(d) plane waves, direct detection

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

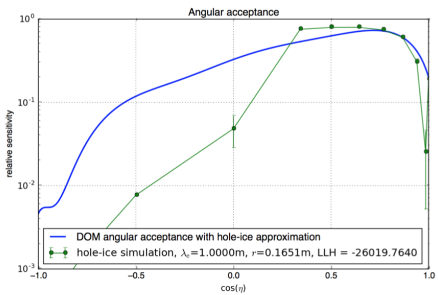
Angular acceptance: Sources and acceptance criteria



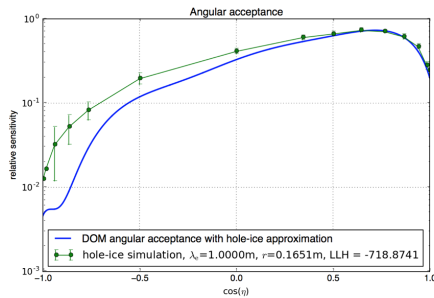
(a) pencil beams, a priori angular acceptance



(b) plane waves, a priori angular acceptance



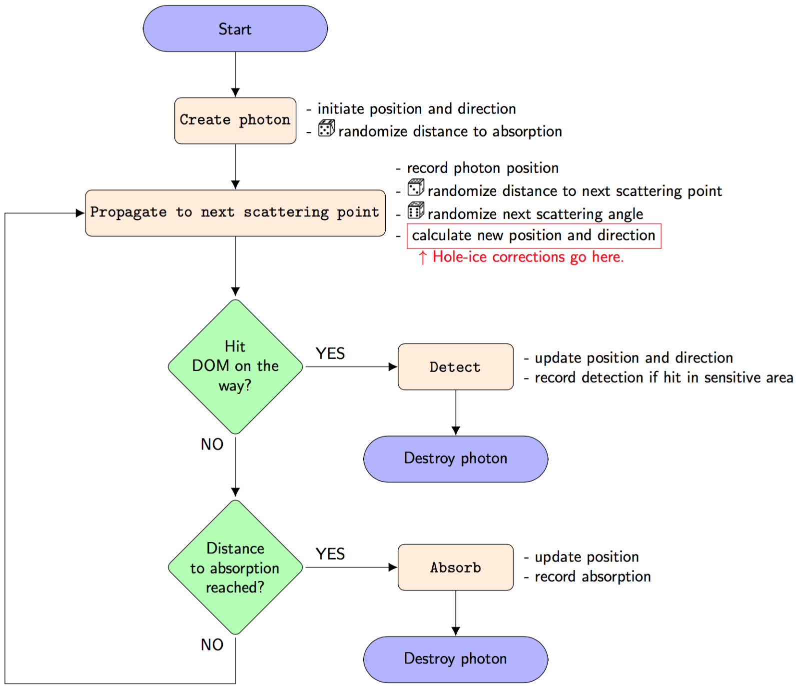
(c) pencil beams, direct detection



(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`

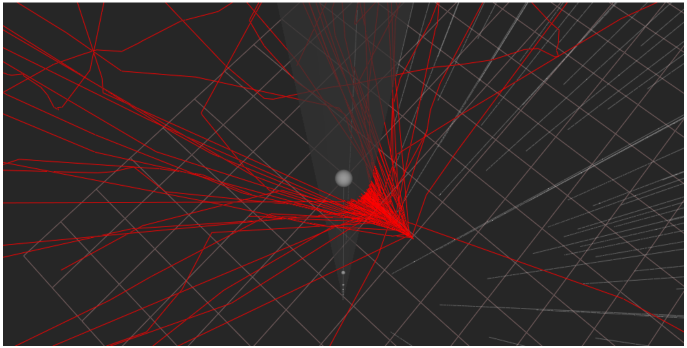
Simplified simulation-step flow chart



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

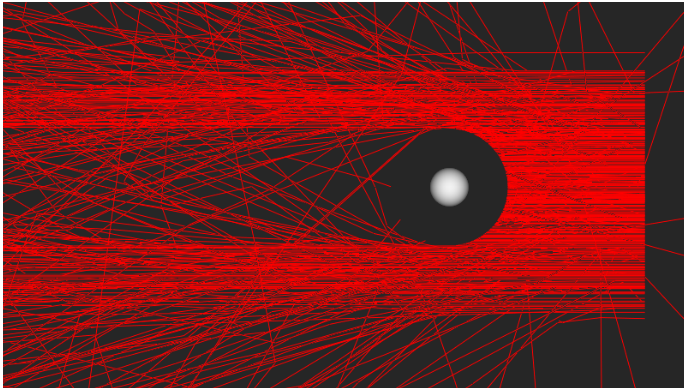


Photon point source, 3d view

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

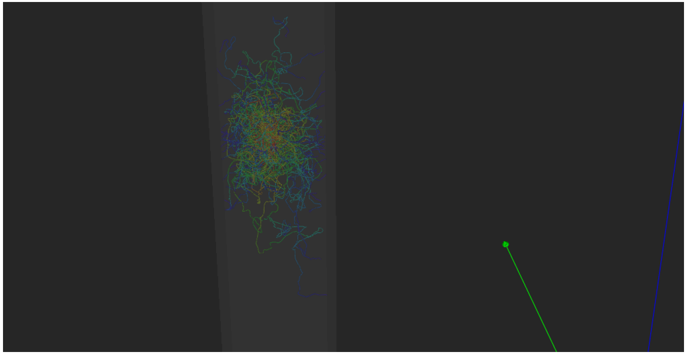


Plane wave photon source, top view

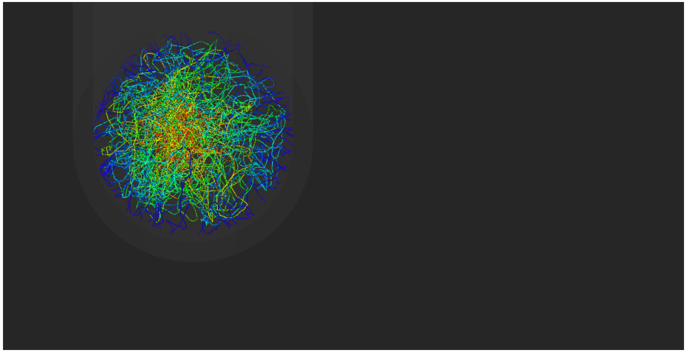
Source: `https://github.com/fiedl/hole-ice-study/issues/22`

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

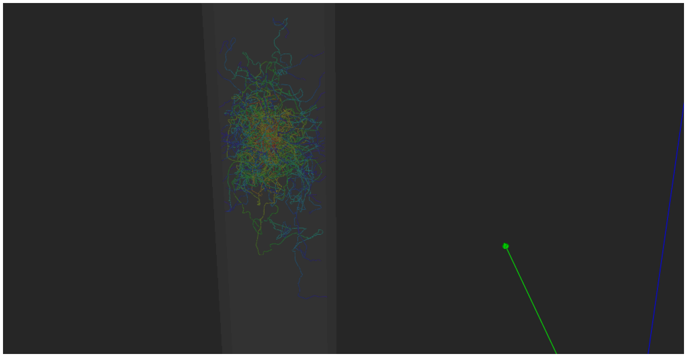


Top view

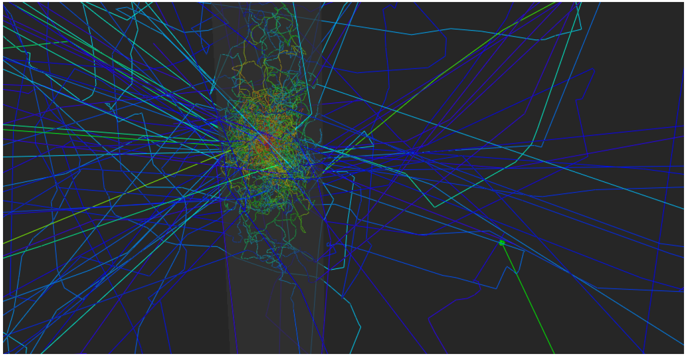
Source: `https://github.com/fiedl/hole-ice-study/issues/47`

Instant absorption with nested cylinders

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



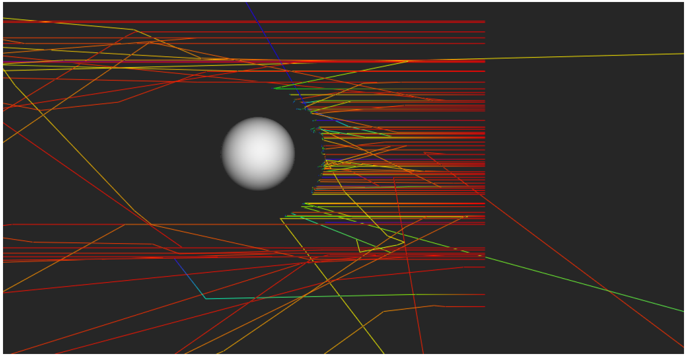
With outer cylinder configured for instant absorption



Without the outer cylinder

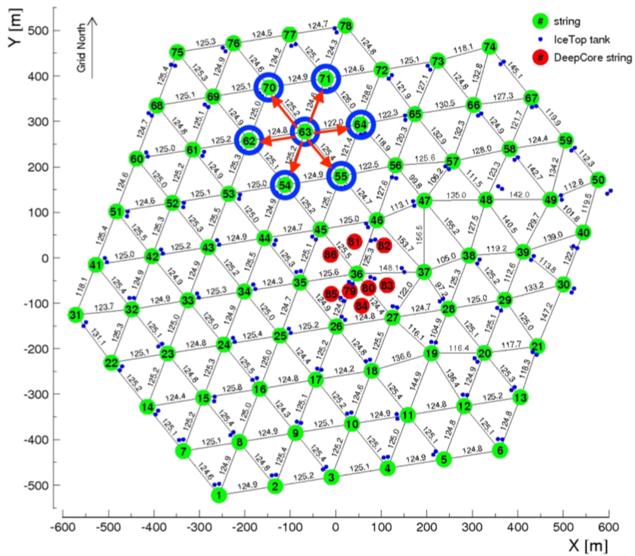
Source: `https://github.com/fiedl/hole-ice-study/issues/47`

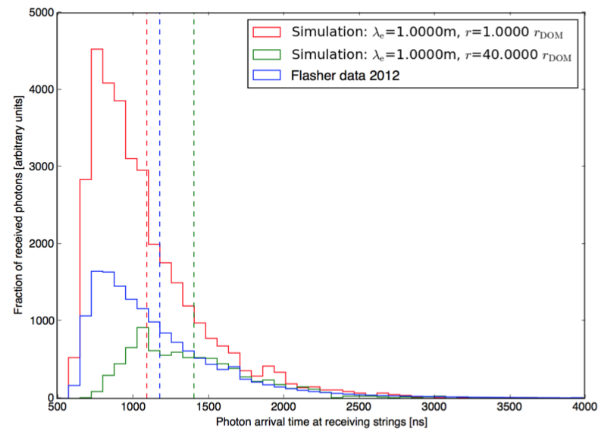
Scattering example



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

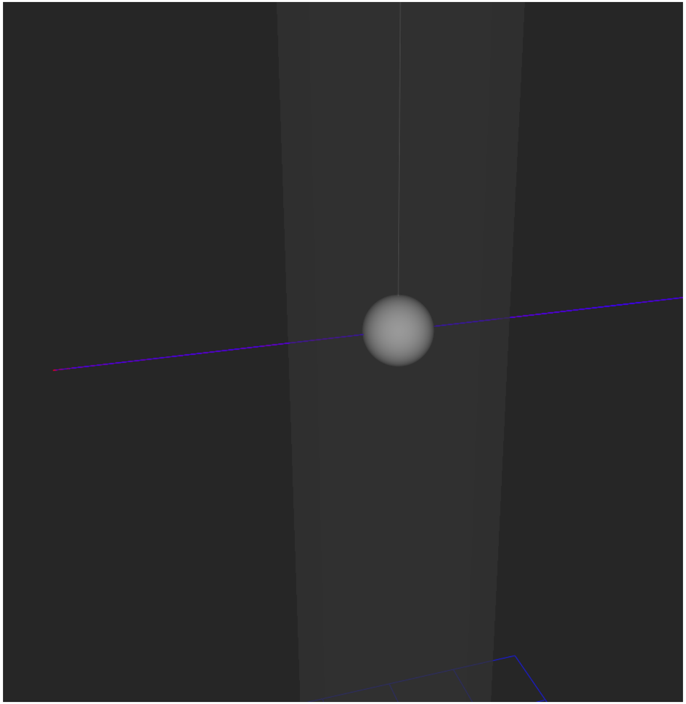
Cross checks: Arrival-time distributions

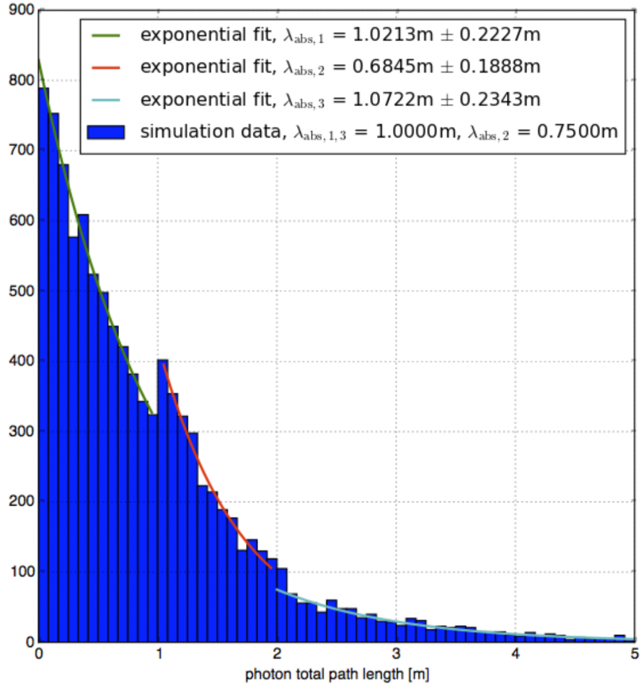




Source: `https://github.com/fiedl/hole-ice-study/issues/91`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

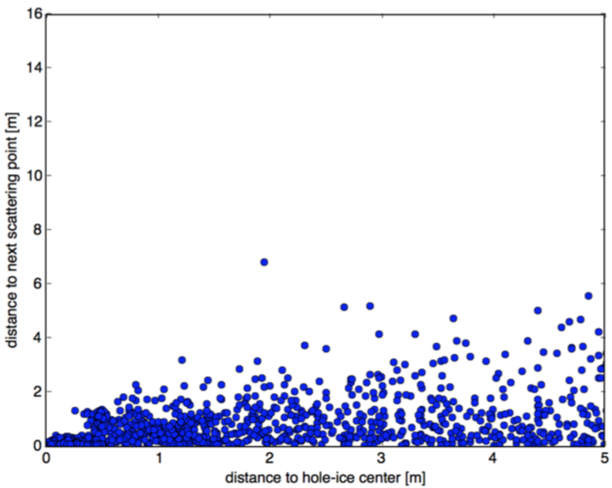
Cross checks: Path-length distributions



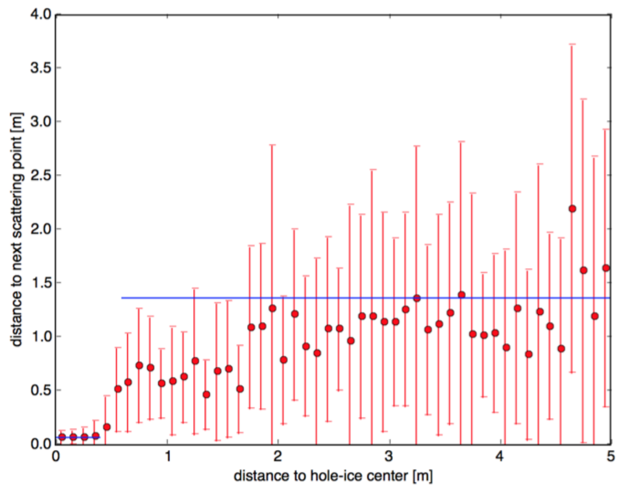


Source: `https://github.com/fiedl/hole-ice-study/issues/66`

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



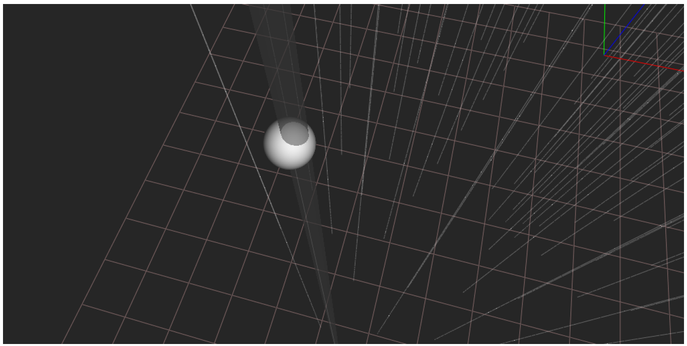
(a) All data points



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

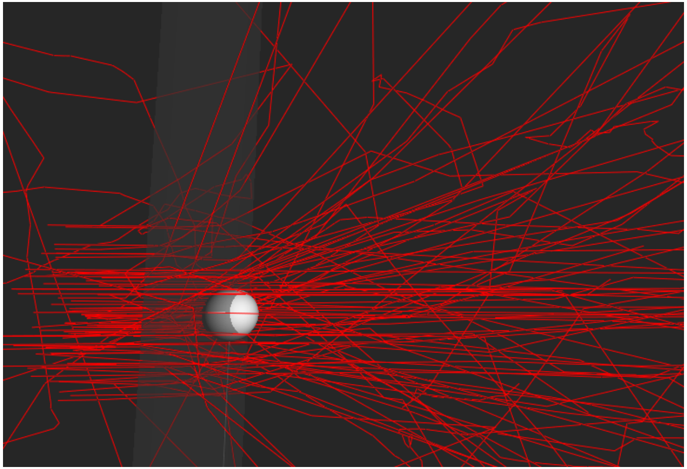
Source: `https://github.com/fiedl/hole-ice-study/issues/71`

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



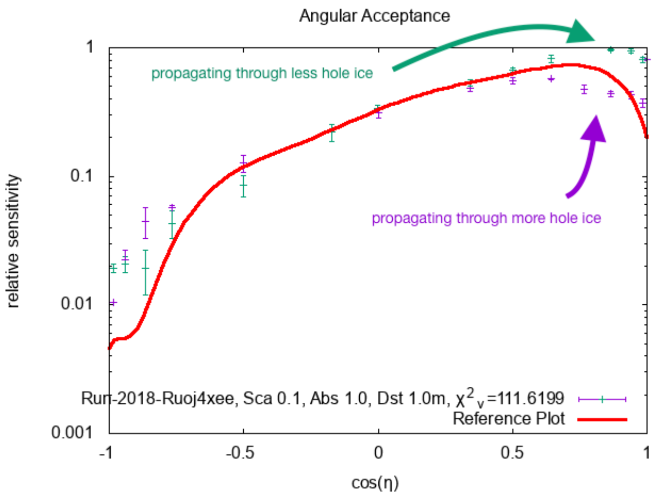
For angle $\eta = \pi/2$, shoot photons from planes onto the DOM and count hits.
Hole-ice radius: 30 cm

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

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

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

Asymmetry example



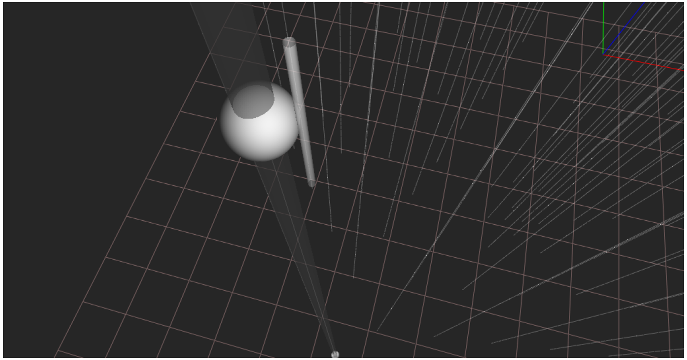
For each angle $\eta \in [0; 2\,\pi[$, shoot photons from planes onto the DOM and count hits.
Hole-ice radius: 30 cm

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

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`

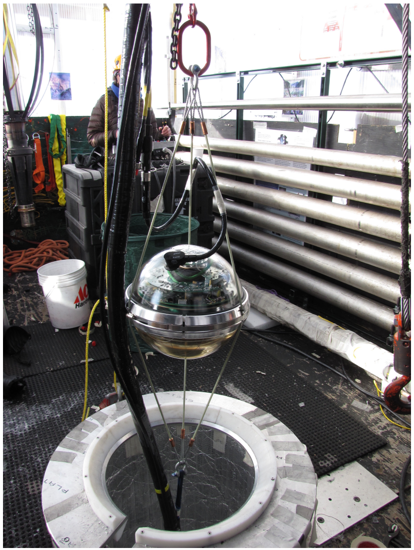
Cable shadows

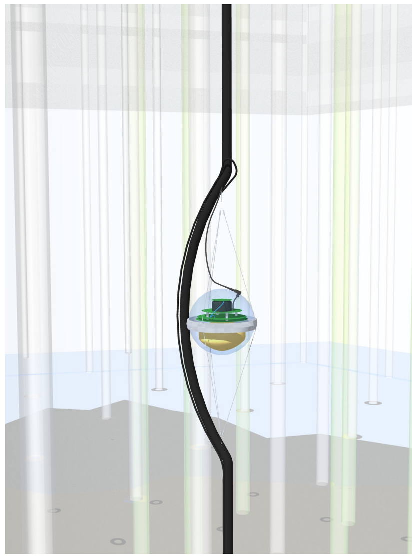


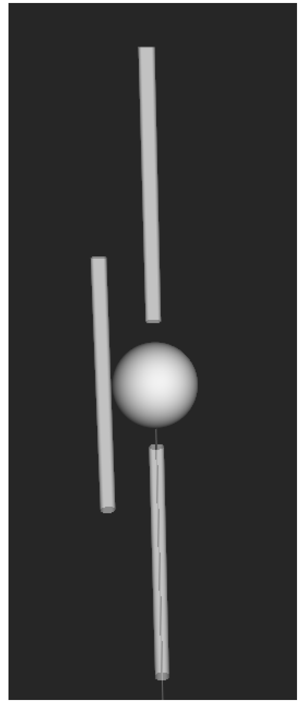
- Cables can be modelled as separate cylinders
  - for each DOM separate position
  - 1 m height
  - configured for instant absorption
- This image:
  - DOM radius: 16.5 cm
  - bubble-column radius: 8.0 cm
  - cable radius: 2.0 cm

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

Direct cable simulation: Angular acceptance

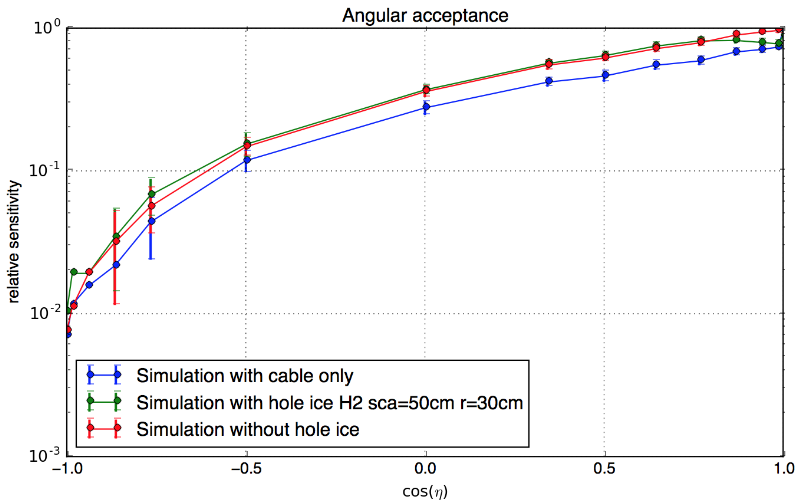


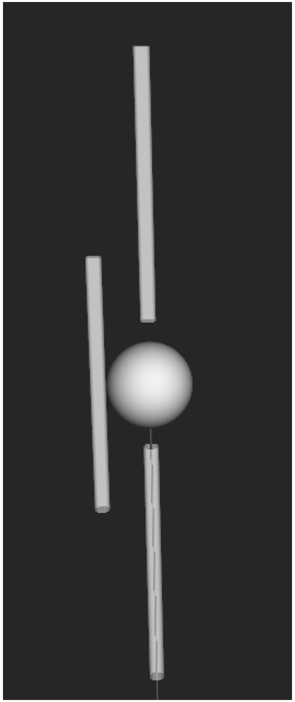




Source: `https://github.com/fiedl/hole-ice-study/issues/101`. **Images**: `https://icecube.wisc.edu/gallery/view/153`, `https://gallery.icecube.wisc.edu/internal/v/GraphicRe/graphics/arraygraphics2011/sketchup/DOMCloseUp.jpg.html`

Direct cable simulation: Angular acceptance

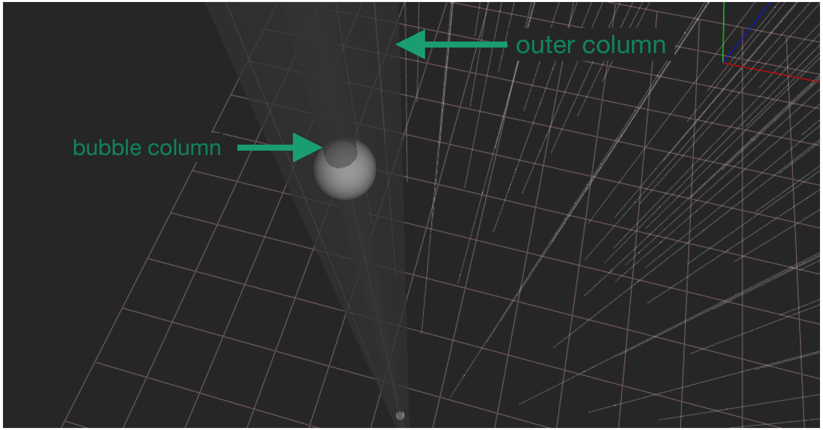




The azimuthal starting angle is such that the cable shadow is maximal.

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

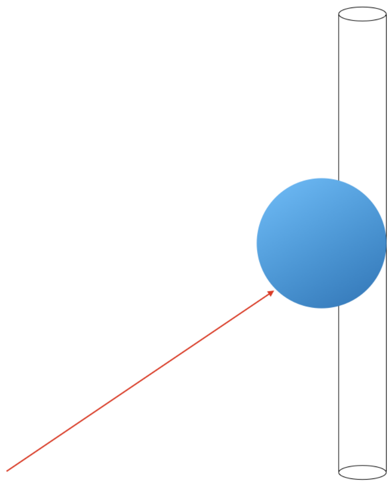
Nested hole-ice cylinders



- 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`

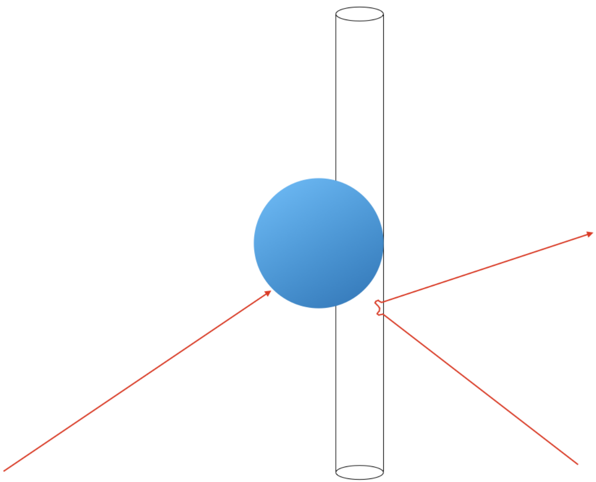
DOM oversizing with hole ice?



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.

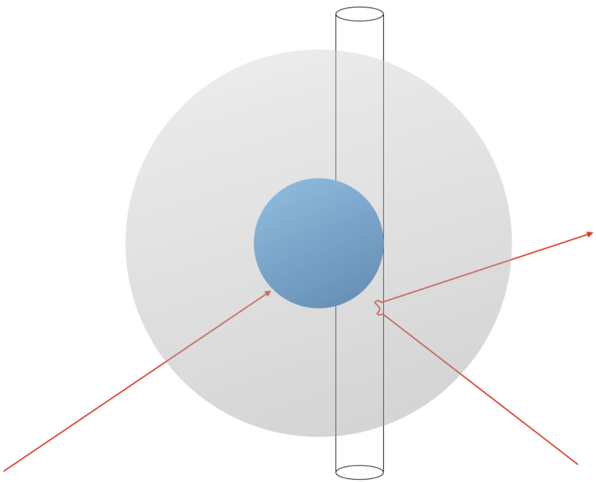
DOM oversizing with hole ice?



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.

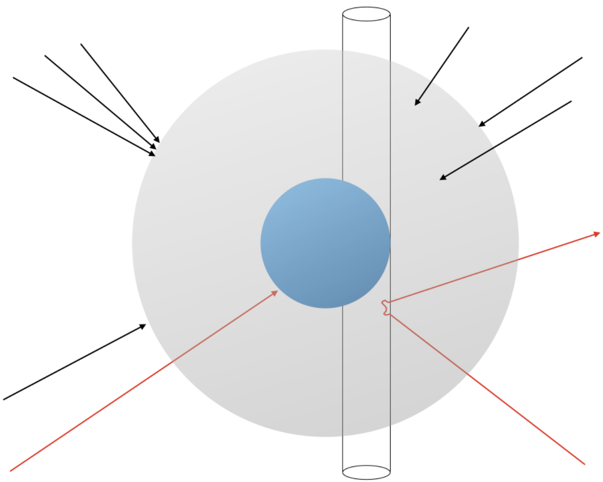
DOM oversizing with hole ice?



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.

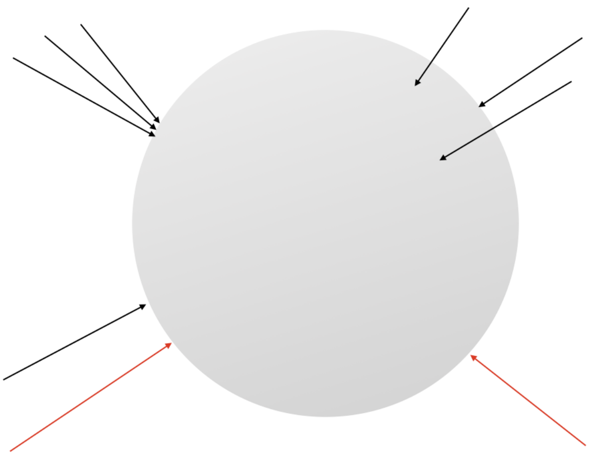
DOM oversizing with hole ice?



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.

Resources

Scripts and plots for this talk:

https://github.com/fiedl/hole-ice-study/issues/117

YouTube video with Steamshovel visualization:

https://youtu.be/Wiu8CpVQn14

Thesis (2018-09-05) with more info on direct hole-ice simulation:

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

Previous talks:

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

LaTeX version of these presentation slides:

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

Simulation scenario

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

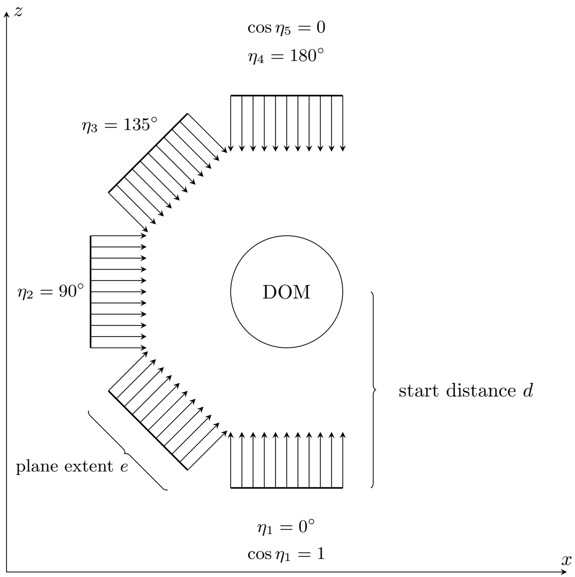


Figure: View from the side. Shooting photons from different polar angles.

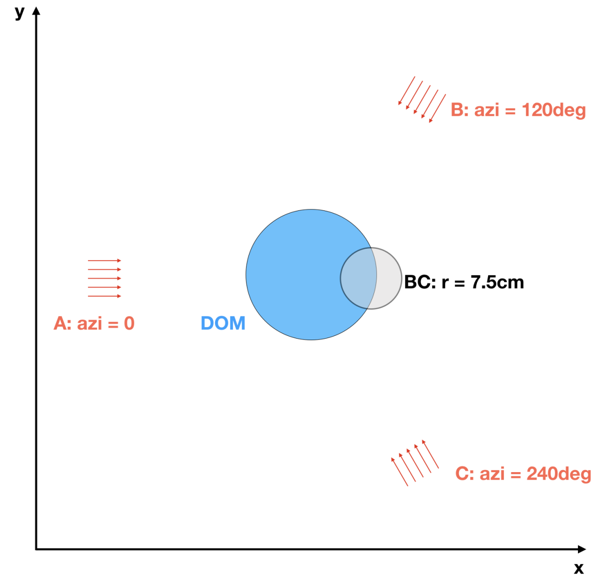
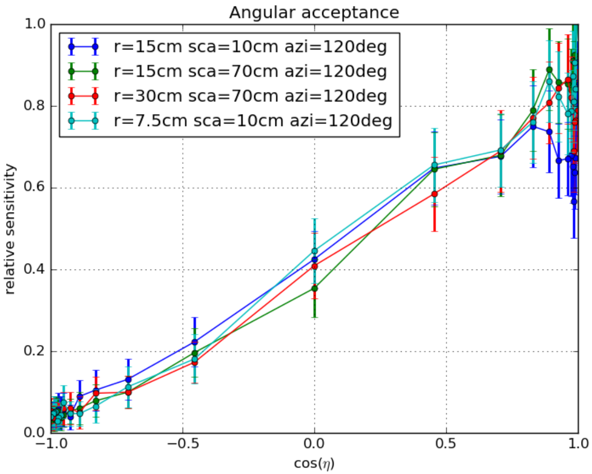
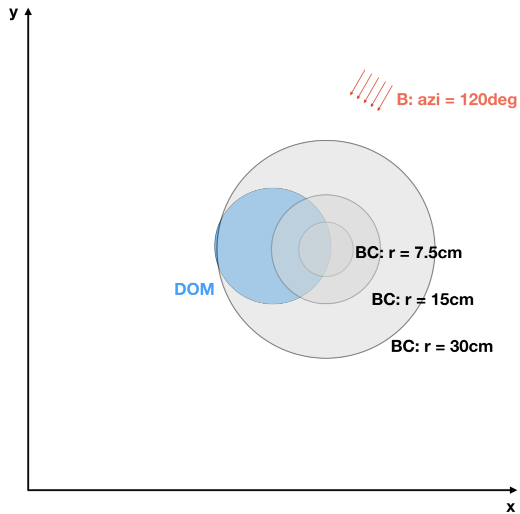


Figure: View from above. Shooting photons from different azimuthal angles.

Previous talk (2018-10-19)

https://github.com/fiedl/hole-ice-talk/releases/download/v1.4/2018-10-19.Direct.hole.ice.simulations.with.Upgrade-like.geometry.Blot.Fiedlschuster.pdf



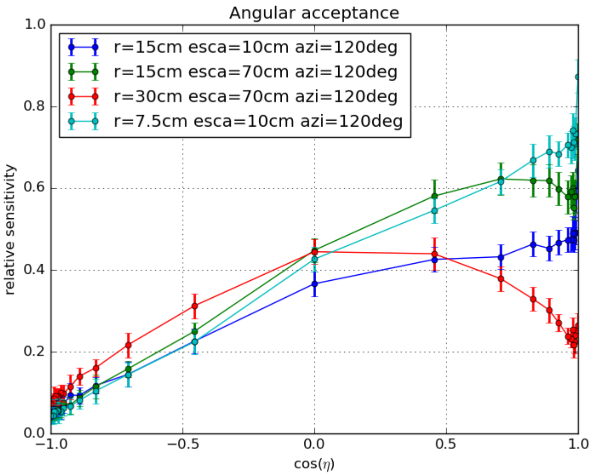


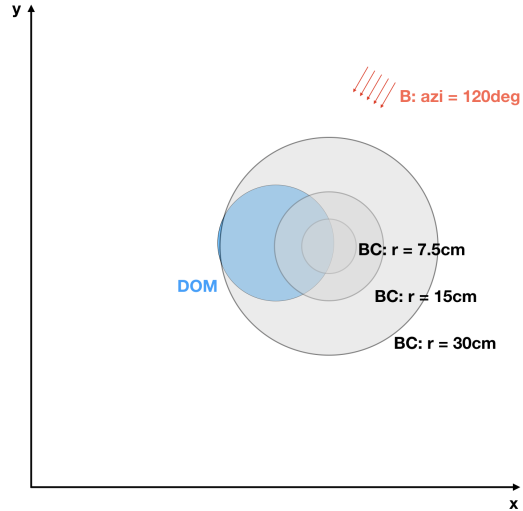
Configuration: Starting distance 3 m, plane-wave extent 3 m, bulk-ice geometric scattering length 130 cm.

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

- In preparation of the last call, we had some misunderstanding regarding the values of the geometric vs. effective scattering length of the hole ice.
- For weak hole as (e.g. geometric $\lambda_{\text{sca}} = 10\,\text{cm}$), as shown in the last call, the angular-acceptance curves do not look that different for different hole-ice radii.

New simulation results



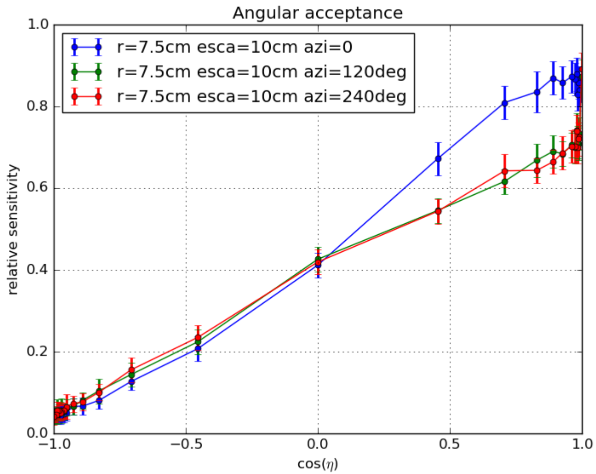


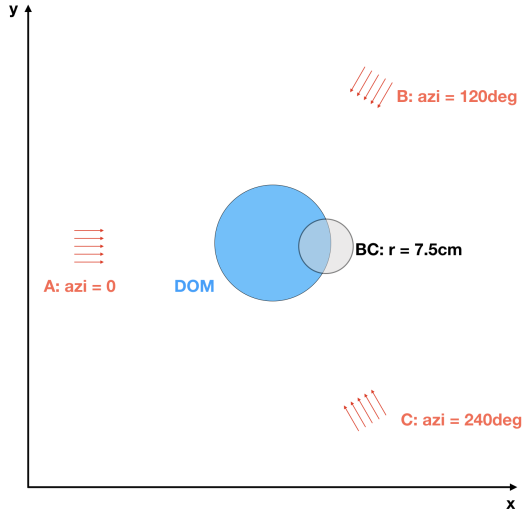
Configuration: Starting distance 3 m, plane-wave extent 3 m, bulk-ice geometric scattering length 130 cm.

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

- Effective scattering length $\lambda_\text{e} = \frac{\lambda_\text{sca}}{(1-\langle\cos\theta\rangle)}$, $\langle\cos\theta\rangle = 0.94$, $\lambda_\text{sca} = 0.06\,\lambda_\text{e}$
- For stronger hole ice (e.g. $\lambda_\text{e} = 10\,\text{cm}$, i.e. $\lambda_\text{sca} = 0.6\,\text{cm}$), 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



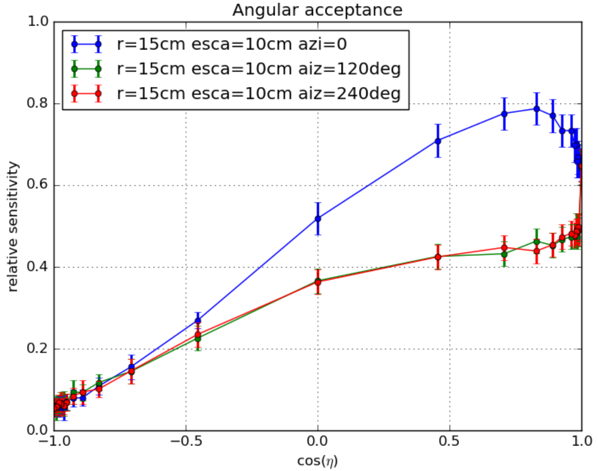


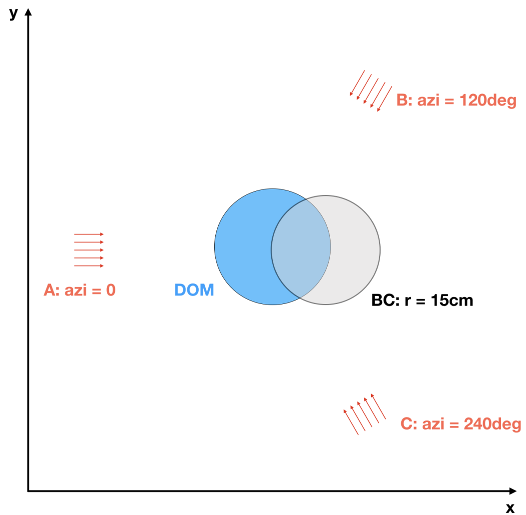
Total photon hit count: 118441 / 1e7

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



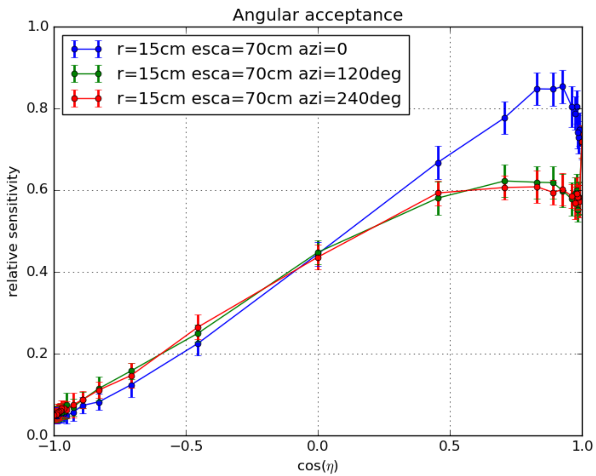


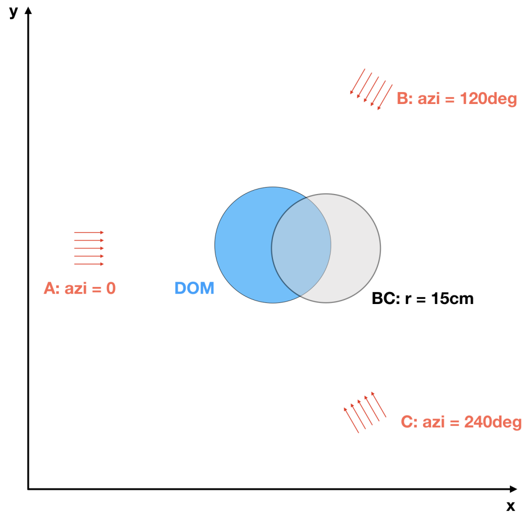
Total photon hit count: 94866 / 1e7

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



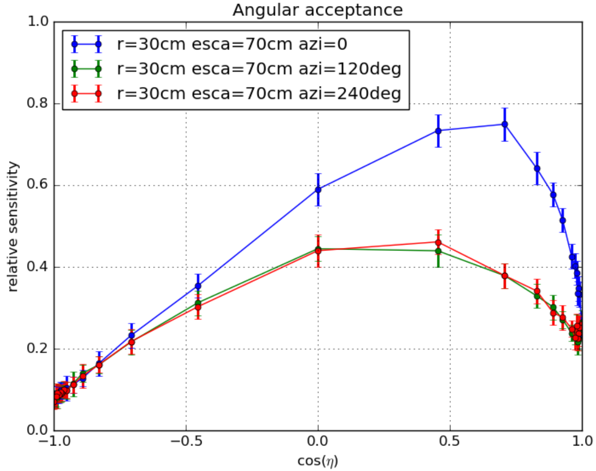


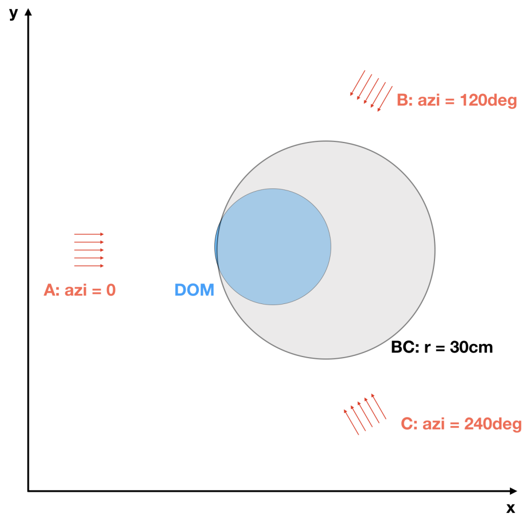
Total photon hit count: 108198 / 1e7

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





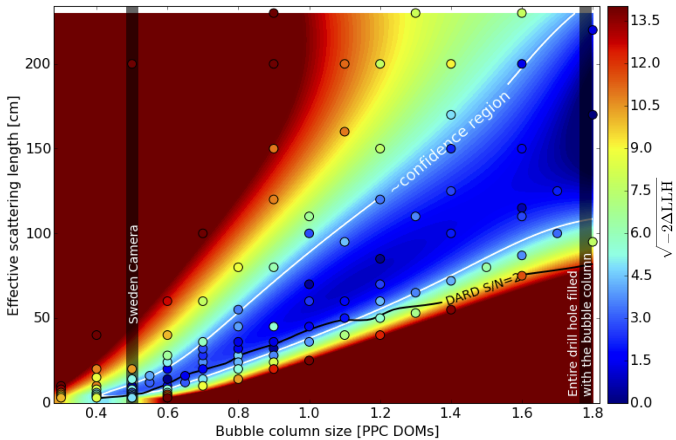
Total photon hit count: 72595 / 1e7

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. ✓

Facit & questions

- The method is sensitive to the bubble-column position.
- The method is sensitive to the bubble-column radius or scattering length if the other is known.
- **Question:** Is there an independent method of determining bubble-column radius or scattering length in the Upgrade?

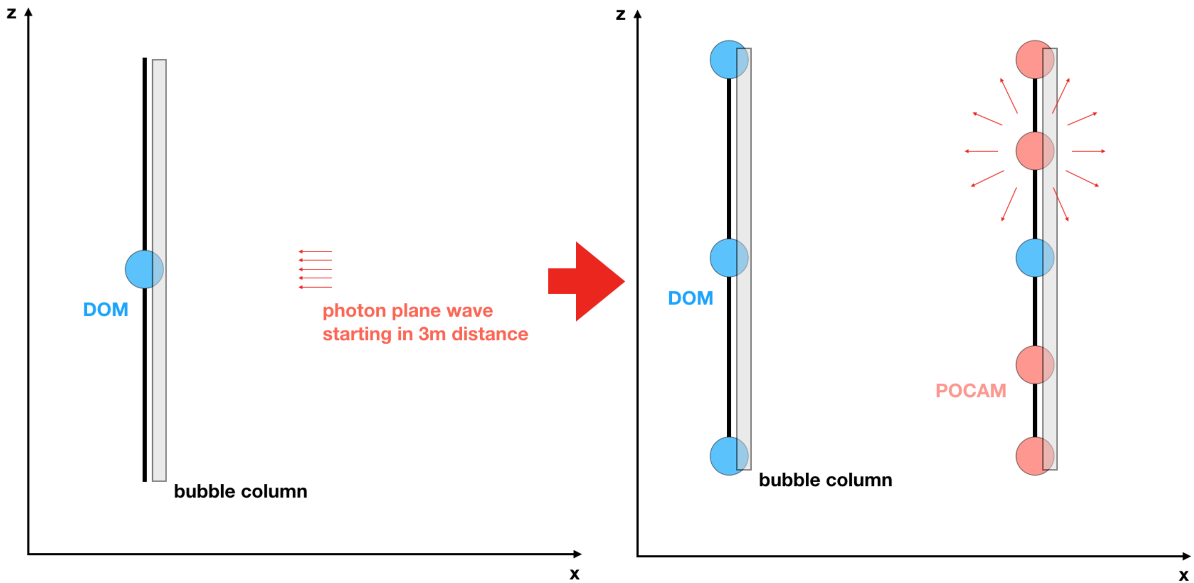


SpiceHD study using direct hole-ice propagation, fitting the size and scattering length of the bubble column and the position of the optical modules relative to the column. Source: Rongen. Status and future of SpiceHD and DARD, Calibration Workshop August 2017.

Swedish-camera images from 2018 still show a diffuse bubble column. Source: Resconi, Rongen, Krings. The Precision Optical CAlibration Module for IceCube-Gen2: First Prototype. 2017.

Next step: More realistic simulation scenario

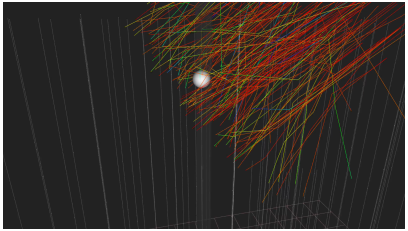
- New scenario: Still count hits at receiving DOM and check if sensitive to the bubble-column position and strength, but start photons from near POCAMs rather than from plane waves.
- **Question**: Is there a POCAM photon source in IceTray?
- **Question**: Where can I get the coordinates of the proposed POCAMs?



Thanks for your attention!

Any input you might have is welcome:

https://github.com/fiedl/hole-ice-study/issues/117
https://github.com/fiedl/hole-ice-study/issues/118
Slack: @fiedl



YouTube video of the simulation:
https://youtu.be/Wiu8CpVQn14