

Hole-ice simulation in cslim

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Motivation and Scope

- No explicit hole-ice simulation included in `clsim`, yet only angular sensitivity approximation
 - No asymmetries possible, e.g. DOM position relative to hole ice
- Master thesis (ending Aug 2018)

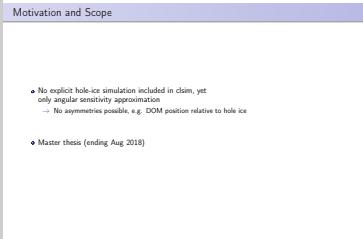


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Hole-ice simulation in clsim

└ Introduction

└ Motivation and Scope



1. clsim approximates hole ice using a convolution function for the angular acceptance.
2. e.g. photons hitting a dom from below are made more unlikely to be detected.
3. but no actual simulation of the changed ice properties.
4. i.e. we can't have asymmetries like shifted DOM positions relative to the hole ice.
5. that's why I'm trying to implement propagation through cylinders with changed ice properties in clsim.

Resources

Usage examples can be found on github:

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



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Contents

1 Introduction

2 What has been done

- How does it work
- How does it look like
- How to compare it

3 Examples

- Instant absorption
- Fixed source vs. plane wave source
- Asymmetry: Shift hole ice vs DOM

4 Outlook

- Separate cylinder positions
- Cable shadows
- Nested cylinders
- Direct detection
- Work to be done



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Hole-ice simulation in clsim

└ Introduction

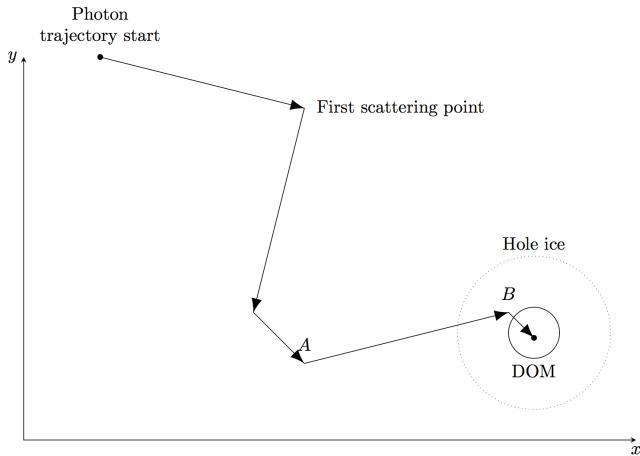
└ Contents

Contents

- ➊ Introduction
 - ➋ What has been done
 - ▶ How does it work
 - ▶ How does it look like
 - ▶ How to compare it
 - ➌ Examples
 - ▶ Instant description
 - ▶ Point source vs. plane wave source
 - ▶ Asymmetry: Shift hole ice vs DOM
 - ➍ Outlook
 - ▶ Separate cylinder positions
 - ▶ Cable shadows
 - ▶ Model finders
 - ▶ Direct detection
 - ▶ Work to be done

- In this presentation, I'll show you what I've been working on
- some examples with images and plots
- point out some features that will be possible with this tool

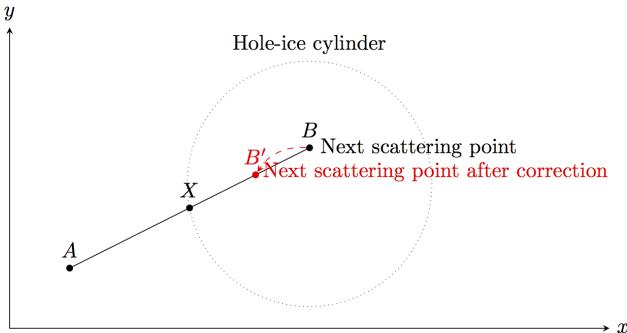
How does it work?



- In current photon propagation simulation, one simulation step consists of everything between two scatterings, i.a.
 - randomizing the distance to the next scattering point
 - randomizing the scattering angle
 - moving the photon to the next scattering point
 - checking for absorption
 - checking for detection at a DOM
- Hole ice simulation adds another task to each simulation step:
 - Calculate the portion of the photon trajectory in the step that runs through hole ice
 - Correct the distance to the next scattering point for the changed ice properties within the hole ice
 - Correct the distance to absorption as well

Source: <https://github.com/fiedl/hole-ice-study#how-does-it-work>

How does it work?



- In current photon propagation simulation, one simulation step consists of everything between two scatterings, i.a.
 - randomizing the distance to the next scattering point
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- Hole ice simulation adds another task to each simulation step:
 - Calculate the portion of the photon trajectory in the step that runs through hole ice
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 - Correct the distance to absorption as well

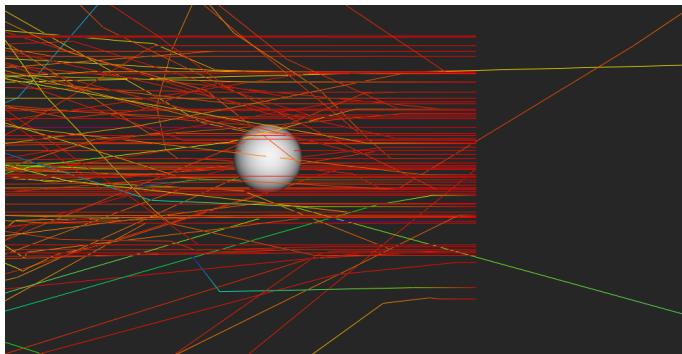
Source: <https://github.com/fiedl/hole-ice-study#how-does-it-work>

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 <ul style="list-style-type: none">+ Small surface area of hole-ice code, i.e. well testable through unit tests+ Standard clsim almost untouched	defined absolute <ul style="list-style-type: none">+ Supports nested cylinders and cables
Pros		
Cons	<ul style="list-style-type: none">- Current understanding of hole-ice suggests defining hole-ice properties absolute rather than relative	<ul style="list-style-type: none">- Needed rewrite of clsim's medium-propagation code- Ice tilt and ice anisotropy not re-implemented, yet (<small>Issue #48</small>)

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

Scattering example



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

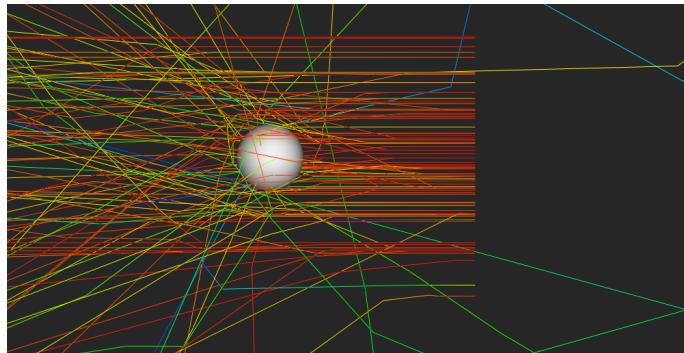
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{1} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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.

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=1.0 --absorption-factor=1.0 --distance=1.0
    --plane-wave --number-of-photons=1e2 --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/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.

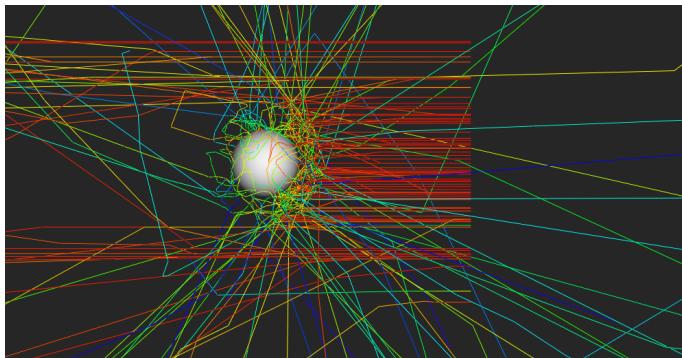
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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.

```
$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 --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/39>

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.

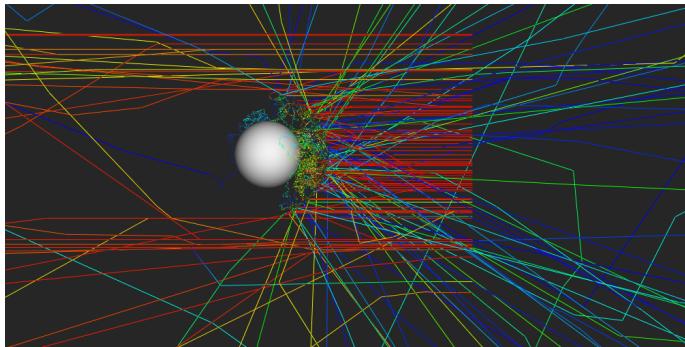
$$\lambda_{\text{sca, hole-ice}} = \frac{1}{100} \quad \lambda_{\text{sca, bulk}}$$
$$\lambda_{\text{abs, hole-ice}} = \lambda_{\text{sca, bulk}}$$

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.

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.01 --absorption-factor=1.0 --distance=1.0
↔ --plane-wave --number-of-photons=1e2 --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/39>

Scattering example



Animation on youtube: <https://youtu.be/BhJ6F3B-IIis>

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.

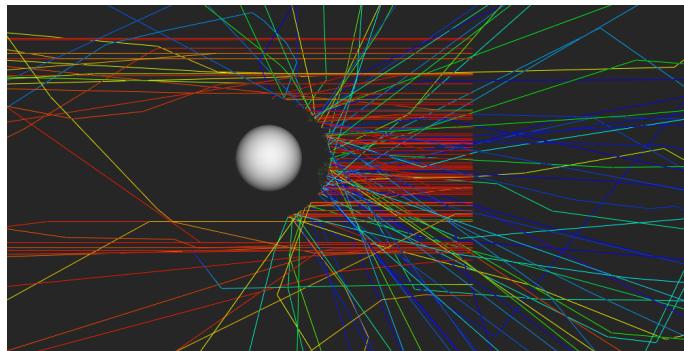
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{1\,000} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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.

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.001 --absorption-factor=1.0 --distance=1.0
↔ --plane-wave --number-of-photons=1e2 --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/39>

Scattering example



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.

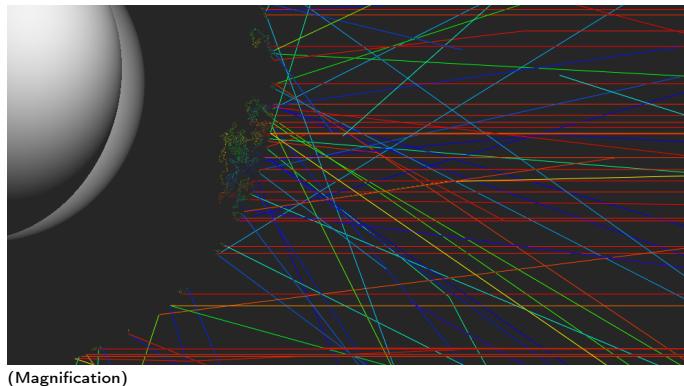
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10\,000} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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.

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.0001 --absorption-factor=1.0 --distance=1.0
↔ --plane-wave --number-of-photons=1e2 --number-of-runs=1
↔ --number-of-parallel-runs=1 --save-photon-paths --cpu
steamshovel tmp/propagated_photons.i3
```

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Scattering example



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.

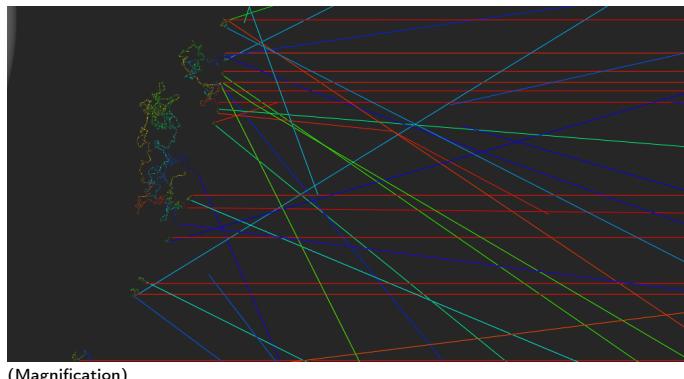
$$\lambda_{\text{sca, hole-ice}} = \frac{1}{10\,000} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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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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 1/10 000 of the scattering length outside.

$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10\,000} \quad \lambda_{\text{sca,bulk}}$$
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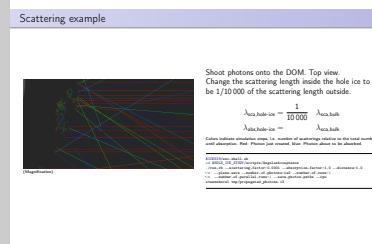
Colors indicate simulation steps, i.e. number of scatterings relative to the total number until absorption. Red: Photon just created, blue: Photon about to be absorbed.

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.0001 --absorption-factor=1.0 --distance=1.0
← --plane-wave --number-of-photons=1e2 --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/39>

Hole-ice simulation in clsim

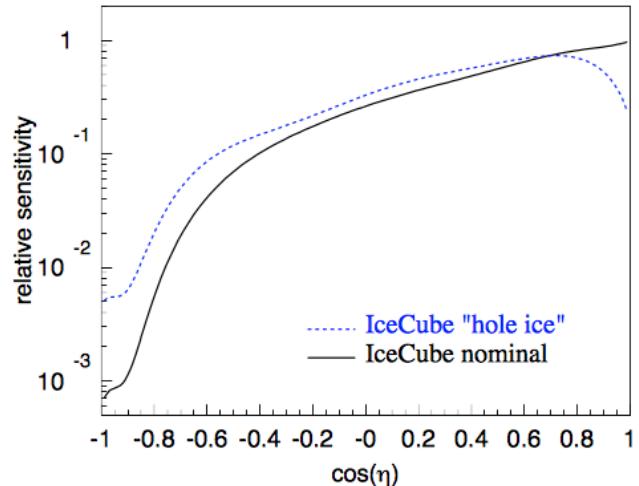
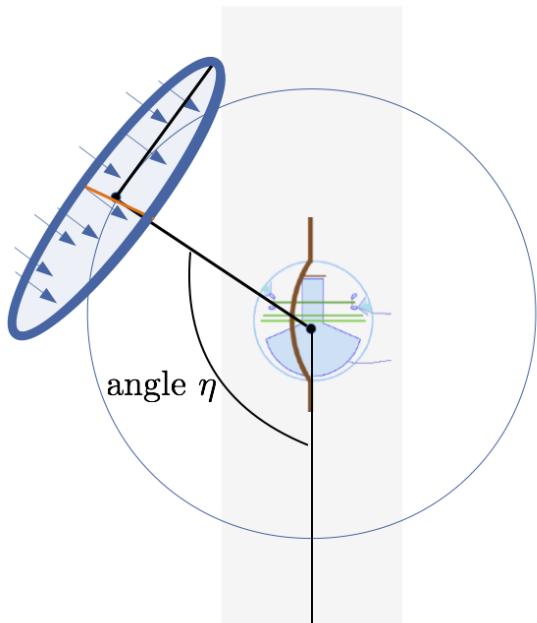
- └ What has been done
 - └ How does it look like
 - └ Scattering example



- Photon wave length: 340 nm (UV)
 - DOM position: $(-256.02301025390625, -521.281982421875, 500.0)$
 - Scattering length in bulk ice at this DOM: $1.78 \text{ m} \pm 1.79 \text{ m}$
 - Absorption length in bulk ice at this DOM: about 150 m
 - The last example is rather extreme. No sharp border in current understanding of hole ice. But I don't know the correct ice properties of the hole ice.
 - Need a way to compare these simulations to other studies.
 - e.g. Angular acceptance plots

Angular acceptance

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



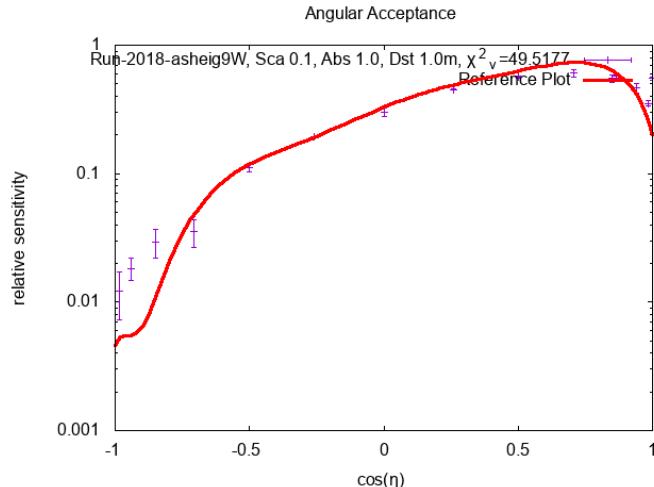
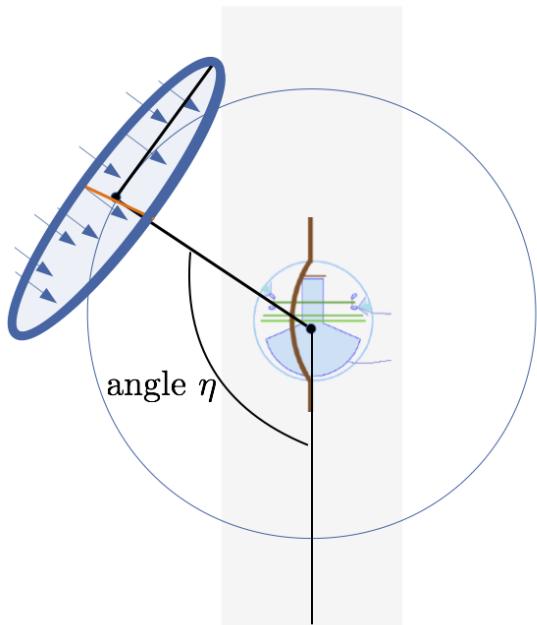
Angular acceptance *reference curves*. The nominal model is based on lab measurement, the hole ice curve on previous simulations.

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



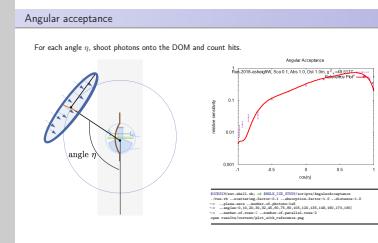
```
$ICESIM/env-shell.sh; cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.1 --absorption-factor=1.0 --distance=1.0
--plane-wave --number-of-photons=1e5
--angles=0,10,20,30,32,45,60,75,90,105,120,135,148,160,170,180]
--number-of-runs=2 --number-of-parallel-runs=2
open results/current/plot_with_reference.png
```

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>

Hole-ice simulation in clsim

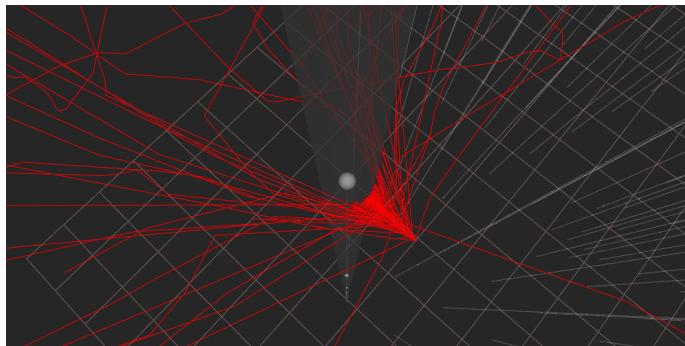
- └ What has been done
 - └ How to compare it
 - └ Angular acceptance



- One way to compare the new simulation to existing results, is to plot angular-acceptance curves.
 - I.e. for each angle η , which is the angle between the starting direction of the photon and the column axis, shoot photons onto the DOM, propagate them in simulation and count hits.
 - The current hole-ice approximations are convolutions onto the DOM angular acceptance.
 - This is an example using the new hole-ice simulation with arbitrary ice parameters (data points) compared to the old reference curve (red).

Instant absorption

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



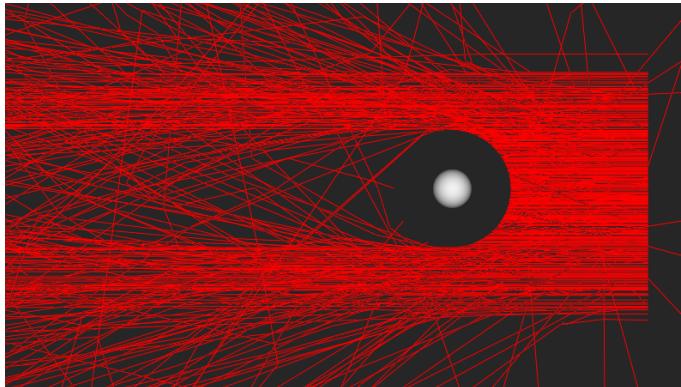
Photon point source, 3d view

```
$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



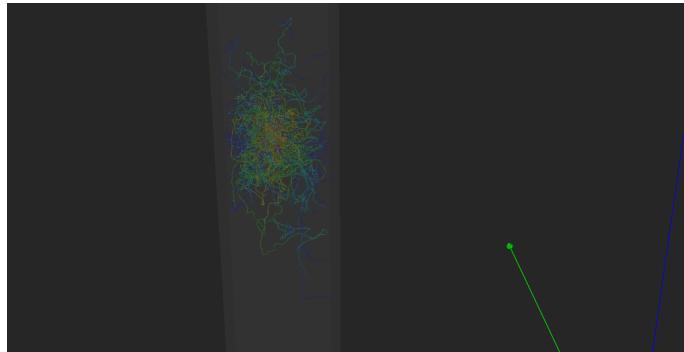
Plane wave photon source, top view

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

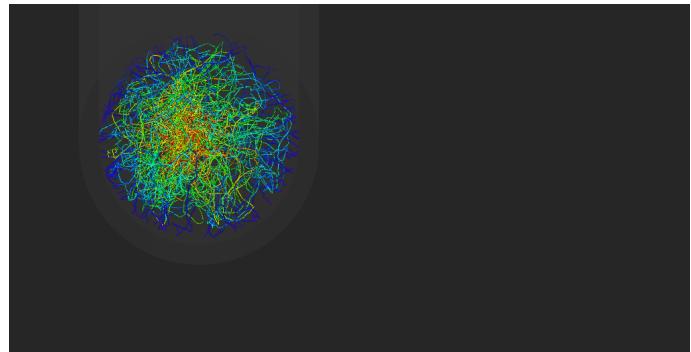
Source: <https://github.com/fiedl/hole-ice-study/issues/22>

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

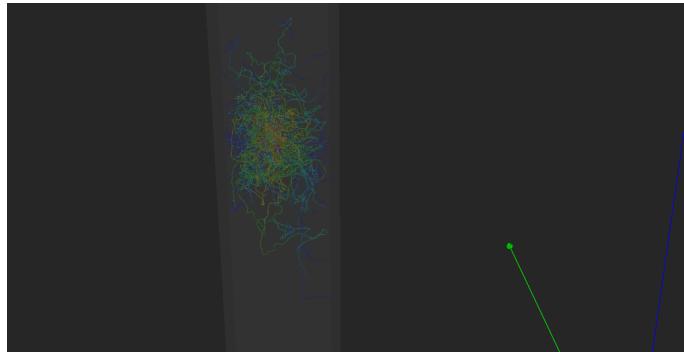


Top view

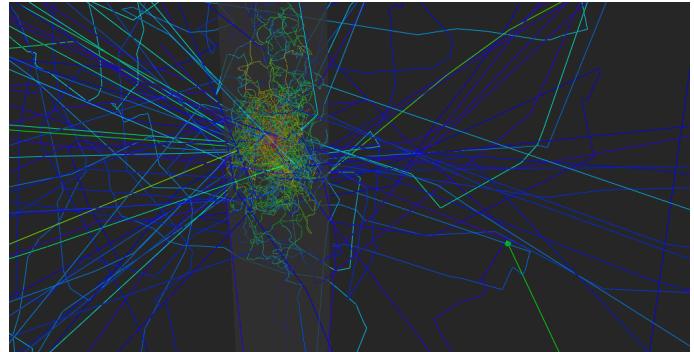
Source: <https://github.com/fiedl/hole-ice-study/issues/47>

Instant absorption with nested cylinders

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



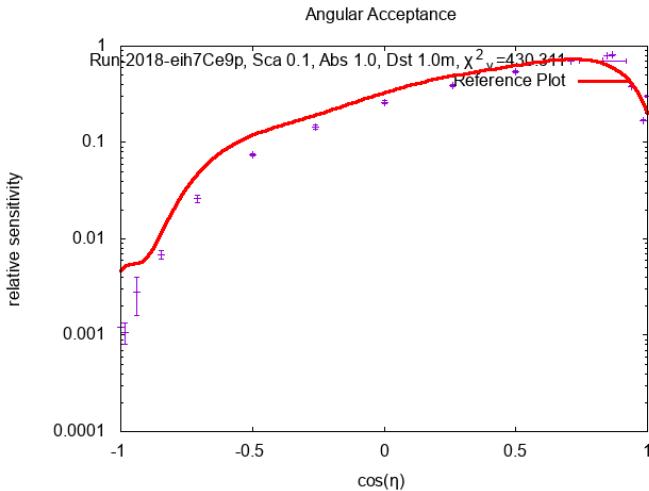
With outer cylinder configured for instant absorption



Without the outer cylinder

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

Fixed source example



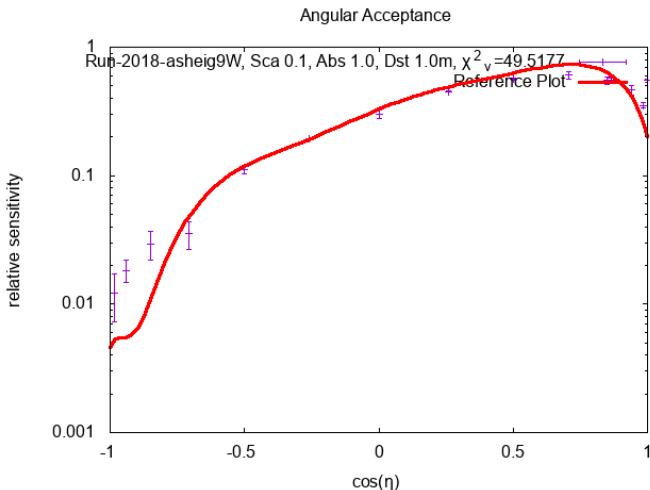
For each angle η , shoot photons **from a fixed point** onto the DOM and count hits. Hole-ice radius: 30 cm

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

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.1 --absorption-factor=0.1 --distance=1.0
    --number-of-photons=1e5
    --angles=0,10,20,30,32,45,60,75,90,105,120,135,148,160,170,180]
    --number-of-runs=2 --number-of-parallel-runs=2
open results/current/plot_with_reference.png
```

Source: <https://github.com/fiedl/hole-ice-study#angular-acceptance-example>

Plane wave example



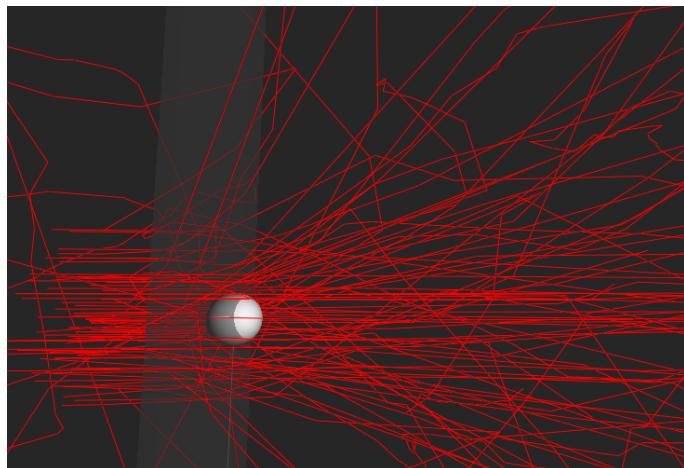
For each angle η , shoot photons **from planes** onto the DOM and count hits. Hole-ice radius: 30 cm

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

```
$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=0,10,20,30,32,45,60,75,90,105,120,135,148,160,170,180
--number-of-runs=2 --number-of-parallel-runs=2
open results/current/plot_with_reference.png
```

Source: <https://github.com/fiedl/hole-ice-study#plane-wave-example>

Asymmetry example



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

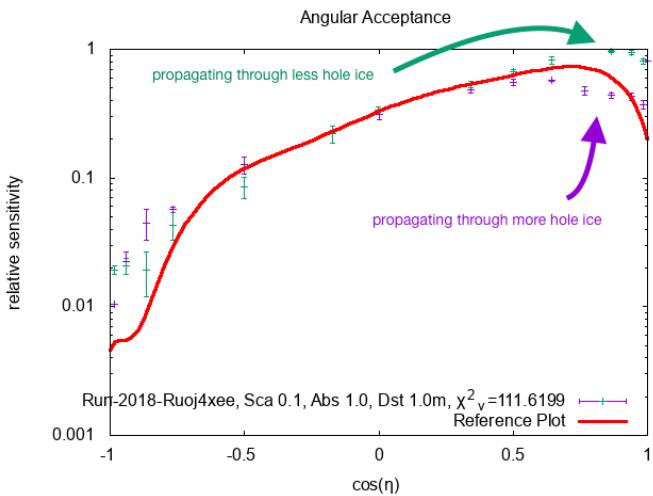
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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

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

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

Asymmetry example



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

Hole-ice radius: 30 cm

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

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

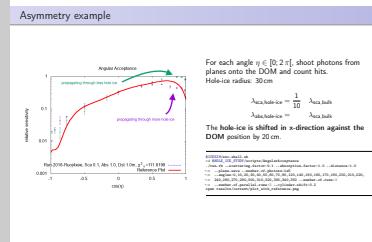
The hole-ice is shifted in x-direction against the DOM position by 20 cm.

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

Hole-ice simulation in clsim

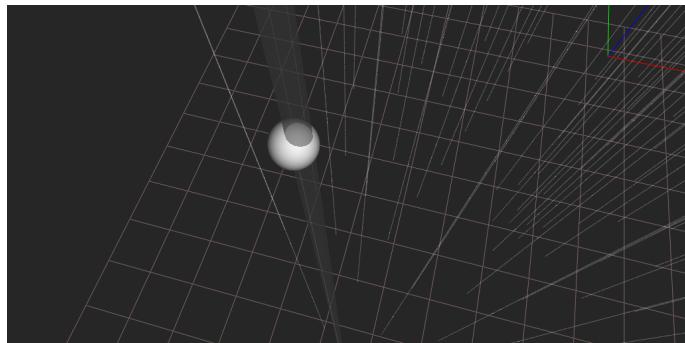
Examples

- Asymmetry: Shift hole ice vs DOM
 - Asymmetry example



- In data points, one sees upper curve and lower curve.
- Because of the asymmetry, on one way, the distance through the hole ice is smaller, on the other way, larger.

Separate hole-ice cylinder positions



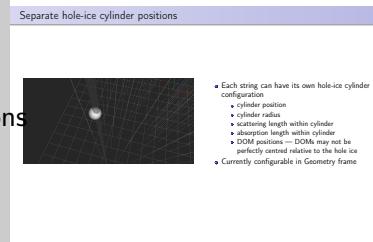
- Each string can have its own hole-ice cylinder configuration
 - cylinder position
 - cylinder radius
 - scattering length within cylinder
 - absorption length within cylinder
 - DOM positions — DOMs may not be perfectly centred relative to the hole ice
- Currently configurable in Geometry frame

Hole-ice simulation in clsim

└ Outlook

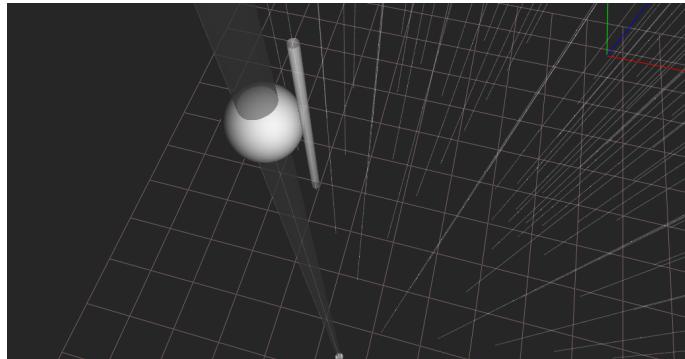
└ Separate cylinder positions

└ Separate hole-ice cylinder positions



Cylinder configuration needs to be accessible by the steamshovel artist.

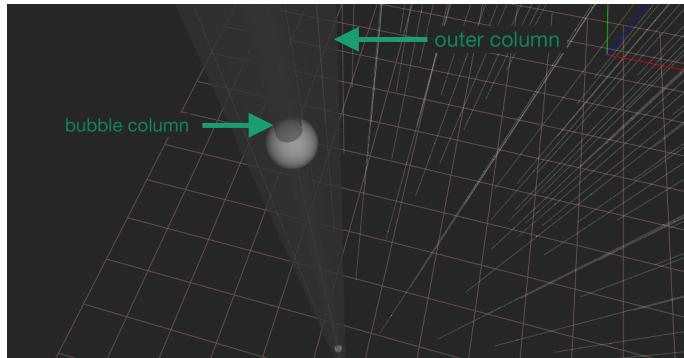
Cable shadows



- 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
- Still work to be done:
 - z-range needs to be implemented in hole-ice code: <https://github.com/fiedl/hole-ice-study/issues/34>

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

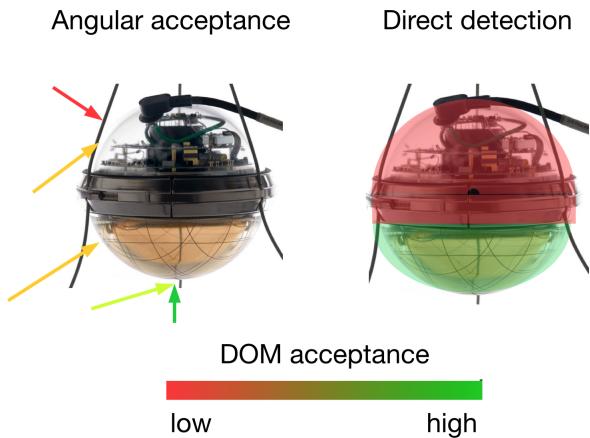
Nested hole-ice cylinders



- 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>

Direct detection



- The DOM looks downwards by design
- Currently, the hit position is not used when determining DOM acceptance, just the photon direction when hitting the DOM (*DOM angular acceptance*)
- Direct detection: Accept all hits below the waist band, reject all others
- Direct detection is easy with clsim
 - Hit position is known and guaranteed to be on the DOM sphere
 - Idea: Accept hits depending on z of the hit position
 - Patch is a couple of lines: `fiedl/clsim@096a2e3f`
- Still work to be done:
 - Implement a switch for direct detection vs. DOM angular acceptance

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

- Consider DOM orientation

<https://github.com/fiedl/hole-ice-study/issues/53>

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

Outlook: What is still missing

- Re-implement ice tilt and ice anisotropy
- Comparison to ppc results
- Grid scan to find best match with reference plot
- Study performance impact
- See also: <https://github.com/fiedl/hole-ice-study/issues>

Martin's wish list

Feature	Possible	Done	In progress	Will be done by me
Separate hole-ice positions for each string	✓	✓		
Nested cylinders: Bubble column and outer column	✓	✓		
Cable shadows using cylinder parts	✓		✓	yes
Direct detection	✓		✓	yes
Absolute scattering and absorption lengths in hole ice (better description of current understanding of hole ice than relative properties)	✓		✓	yes
Bring tilt and anisotropy back	✓			?
Vertical gradient of scattering length in bubble column	✓			no

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

Thanks for your attention!

Any input you might have is welcome:

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

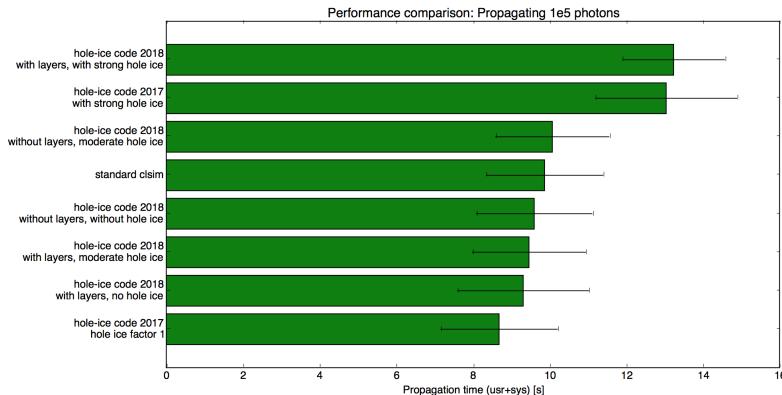
Slack: @fiedl

Video illustration of a simple example:

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

Performance

Time measurement: Propagating 10^5 photons on CPU



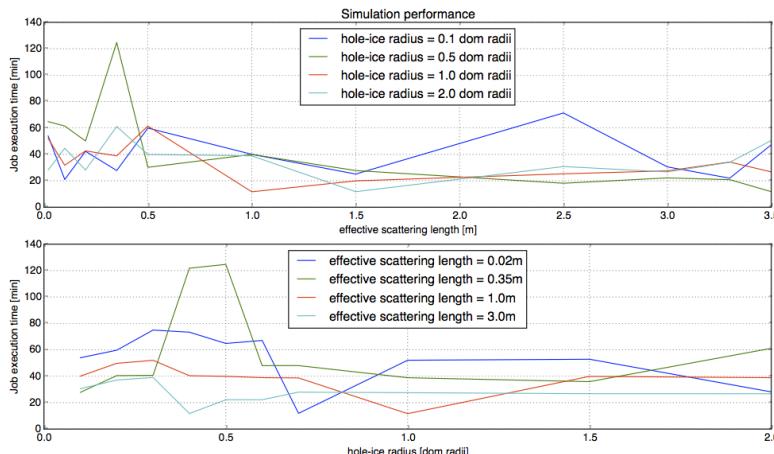
```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
time ./run.rb --distance=1.0 --number-of-runs=1 --number-of-parallel-runs=1 --cpu --angle=45
↪ --plane-wave --number-of-photons=1e5
```

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

- Medium propagation features (hole ice, layers) have no measurable performance impact.
- Hole-ice-2017 and hole-ice-2018 algorithms have no measurable performance impact for scattering lengths comparable to bulk-ice scattering ($\lambda_s = 20$ m).
- Performance drop can be seen when lowering the scattering length, i.e. increasing the number of simulation steps ($\lambda_s = 3$ mm).

Performance

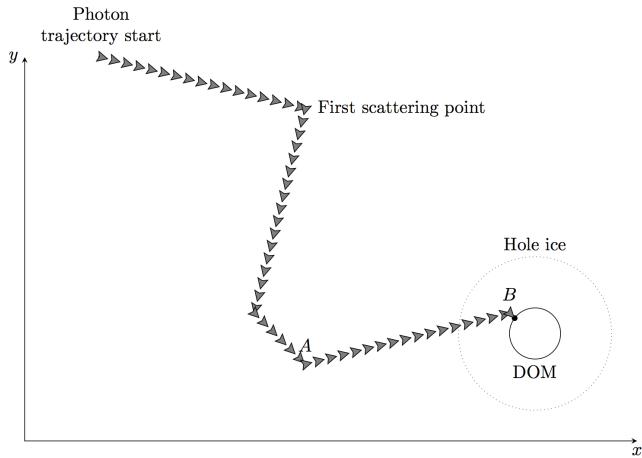
Time measurement: Propagating $30 \cdot 10^5$ photons on GPU.



- Expectation: Simulation time increases with more demanding hole-ice properties, i.e. larger hole-ice radius and shorter scattering length.
- Observation: The GPU cluster node appears to determine the leading factor rather than the hole-ice parameters.

Source: <https://github.com/fiedl/hole-ice-study/issues/12issuecomment-373406819>

Naive propagation algorithm



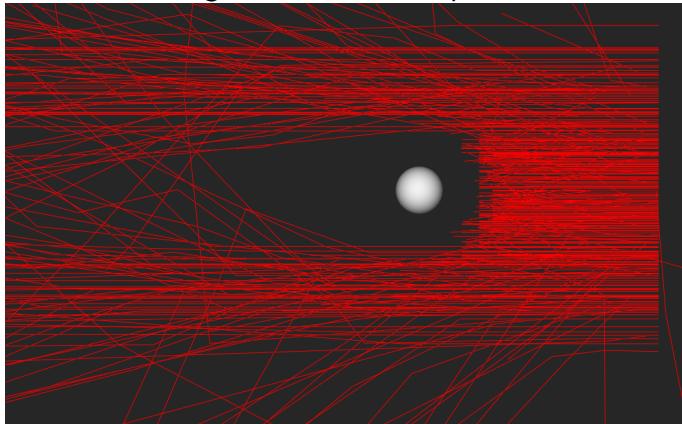
Naive algorithm:

- Propagate photon a tiny distance
 - At current position:
 - Check for random scattering
 - Check for random absorption
 - Check for collision with DOM
- **Hole ice is easy** because all ice properties can be locally evaluated
- **But performance is bad** because there are lots of simulation steps even for long distances without interaction

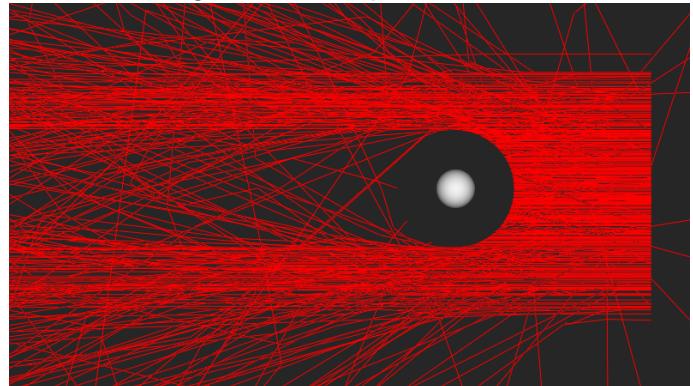
Coordinates-vs-vectors bug

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

Before: Treating coordinates as separate variables

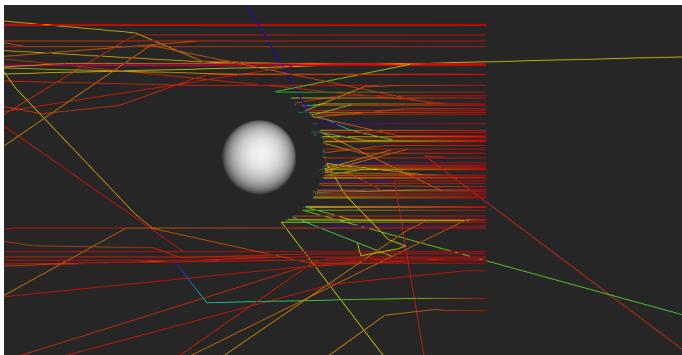


After: Treating vectors as opencl-native vectors



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

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
```
