Hole-ice simulation in clsim

Icecube calibration call, 2018-03-02

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Erlangen Centre for Astroparticle Physics

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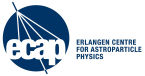


Motivation and Scope

- 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)

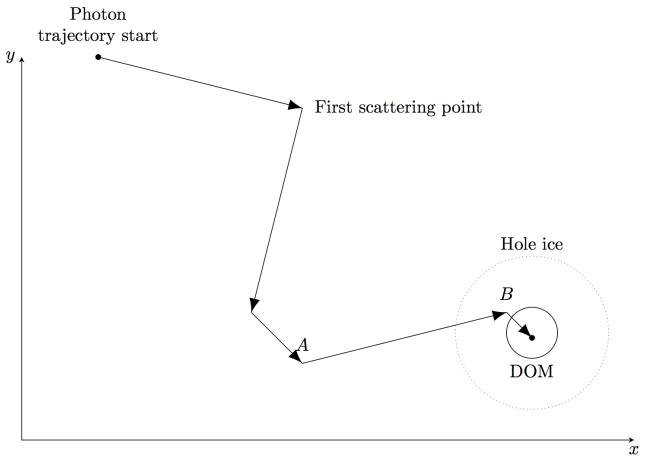
Resources

Usage examples can be found on github:

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

Contents

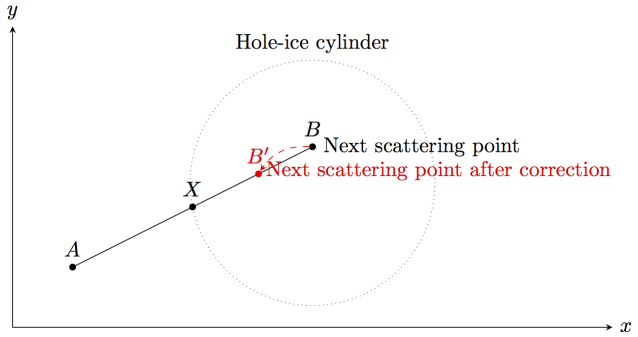
How does it work?



- 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?



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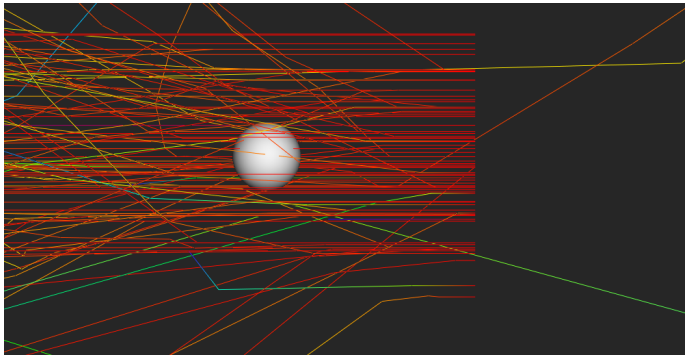
Source: `https://github.com/fiedl/hole-ice-study#how-does-it-work`

Scattering example



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

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

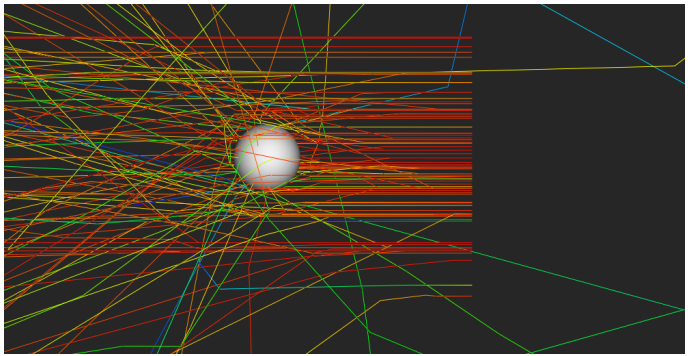
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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.

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

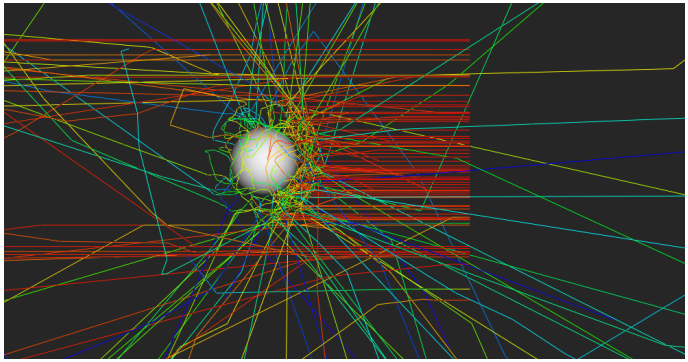
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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=0.1 --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.

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

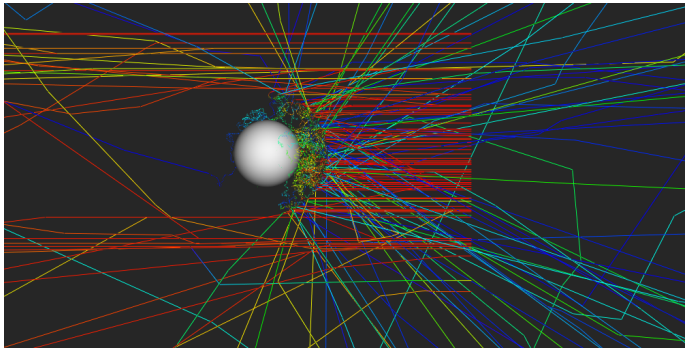
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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=0.01 --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-I1s

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

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

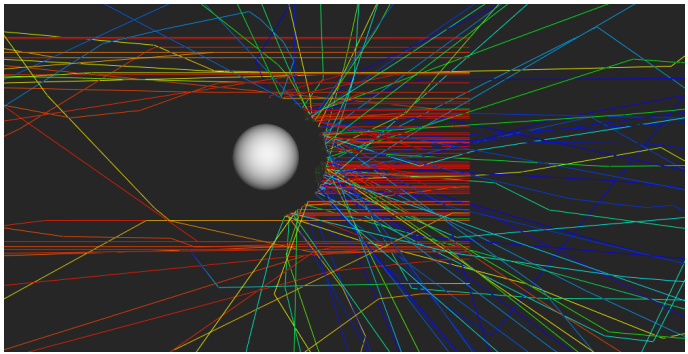
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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=0.001 --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.

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

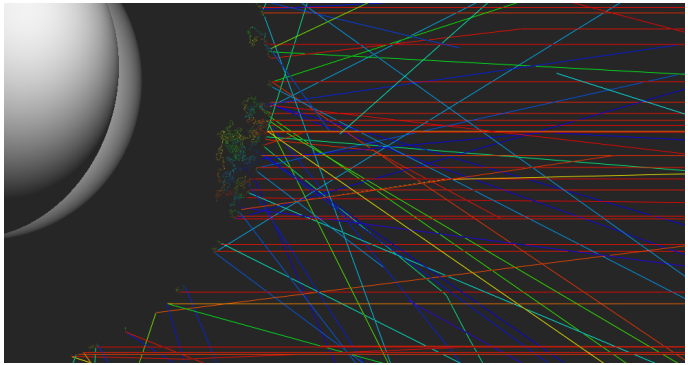
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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
```

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

Scattering example



(Magnification)

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

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

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

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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$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
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steamshovel tmp/propagated_photons.i3
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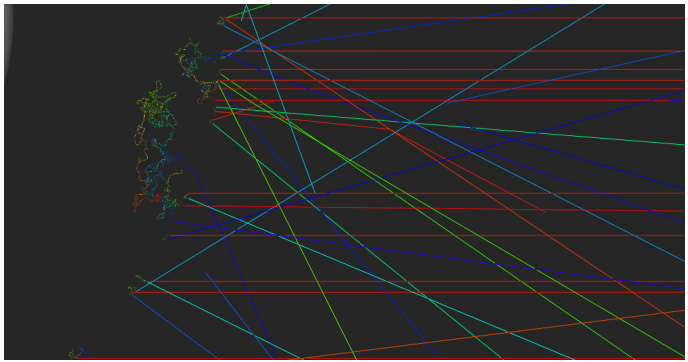
Scattering example



(Magnification)

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

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

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

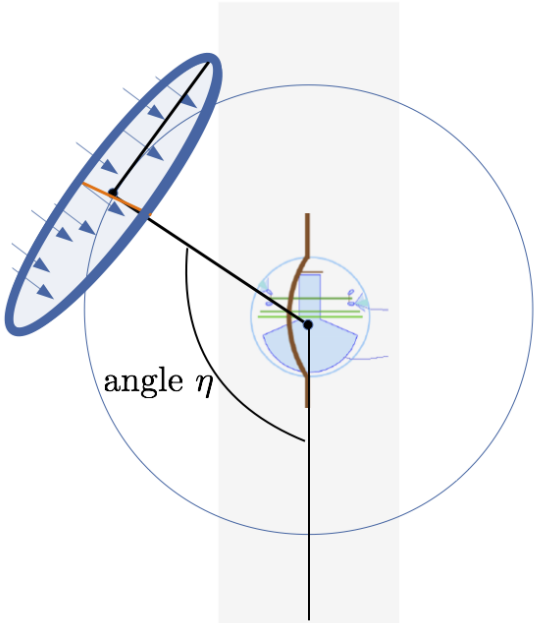
Colors indicate simulation steps, i.e. number of scatterings relative to the total number until absorption. Red: Photon just created, blue: Photon about to be absorbed.

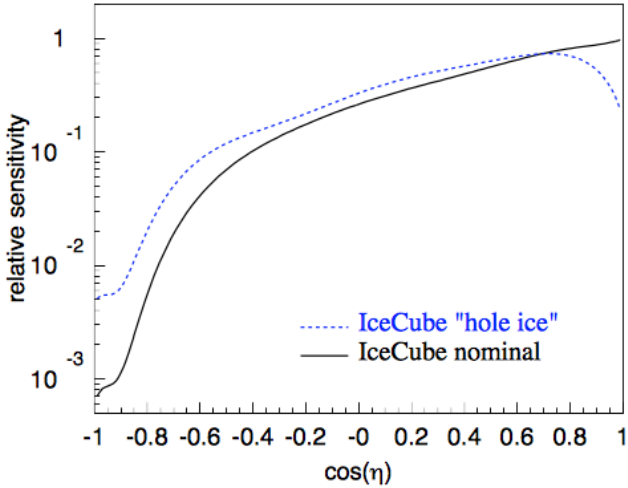
```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.0001 --absorption-factor=1.0 --distance=1.0
↪  --plane-wave --number-of-photons=1e2 --number-of-runs=1
↪  --number-of-parallel-runs=1 --save-photon-paths --cpu
steamshovel tmp/propagated_photons.i3
```

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

Angular acceptance

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



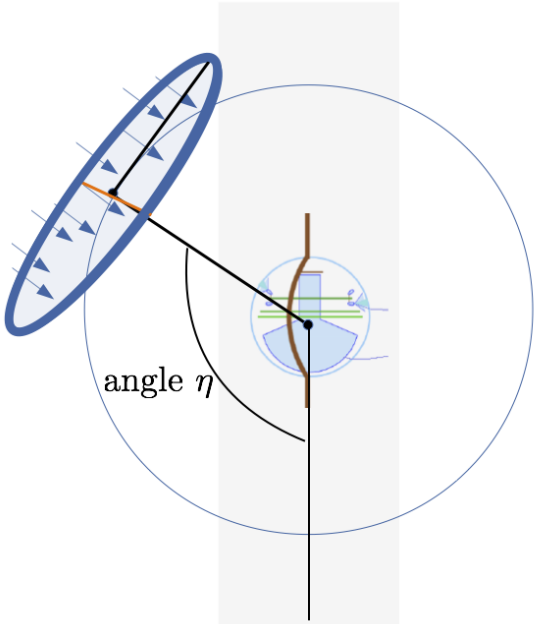


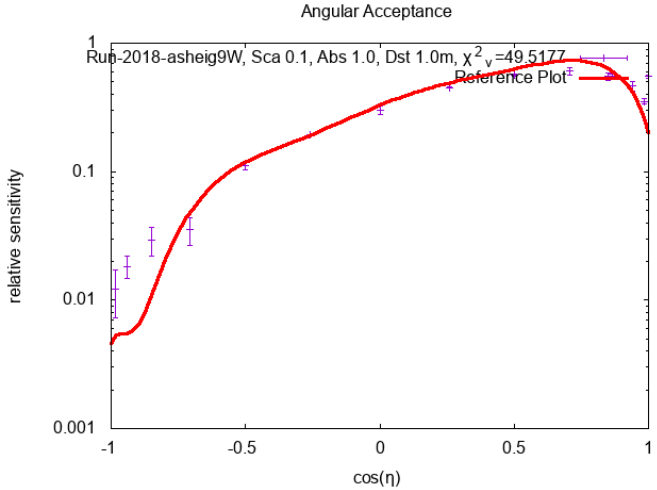
Angular acceptance *reference curves*. The nominal model is based on lab measurement, the hole ice curve on previous simulations.

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.



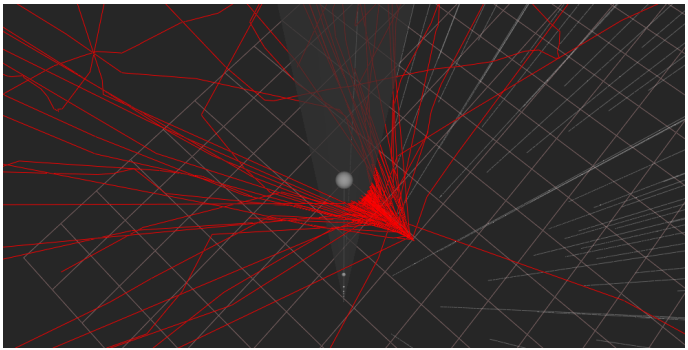



```
$ICESIM/env-shell.sh; cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.1 --absorption-factor=1.0 --distance=1.0
↪  --plane-wave --number-of-photons=1e5
↪  --angles=0,10,20,30,32,45,60,75,90,105,120,135,148,160,170,180]
↪  --number-of-runs=2 --number-of-parallel-runs=2
open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

Instant absorption

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



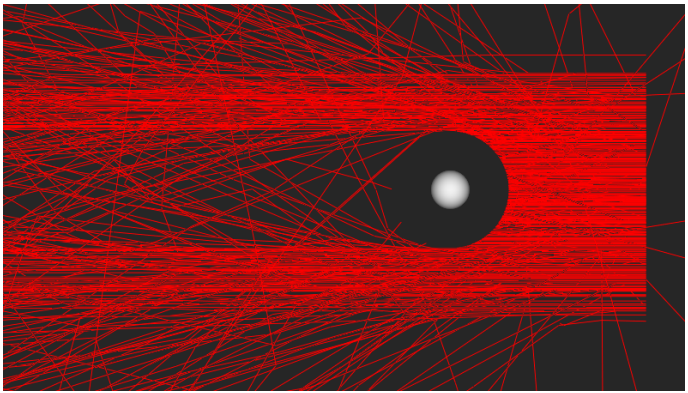
Photon point source, 3d view

```
$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

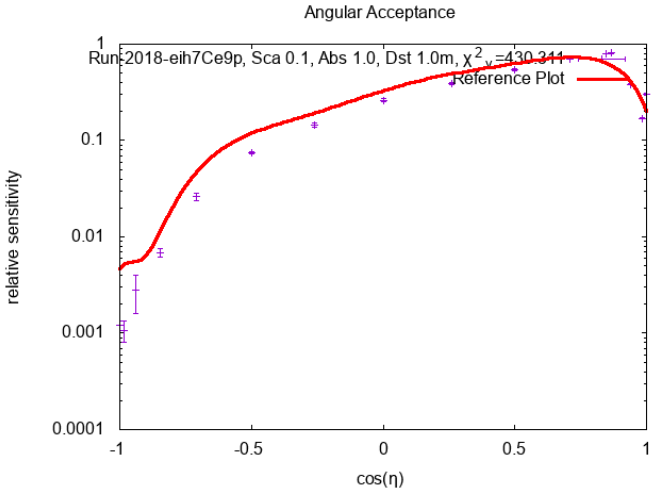


Plane wave photon source, top view

```
$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

Fixed source example



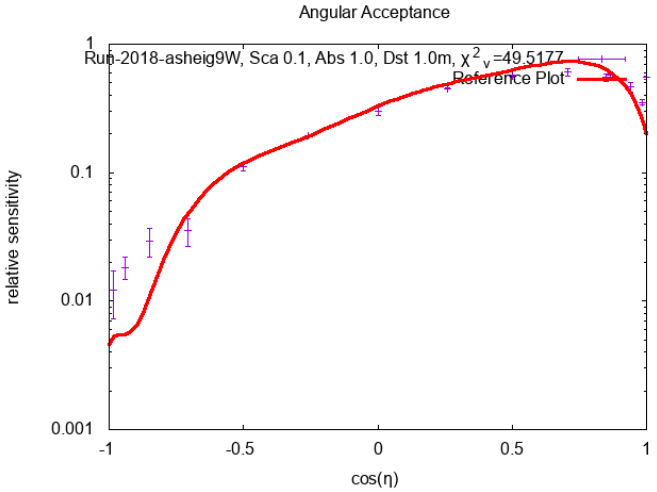
For each angle η, shoot photons **from a fixed point** onto the DOM and count hits. Hole-ice radius: 30 cm

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

```
$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



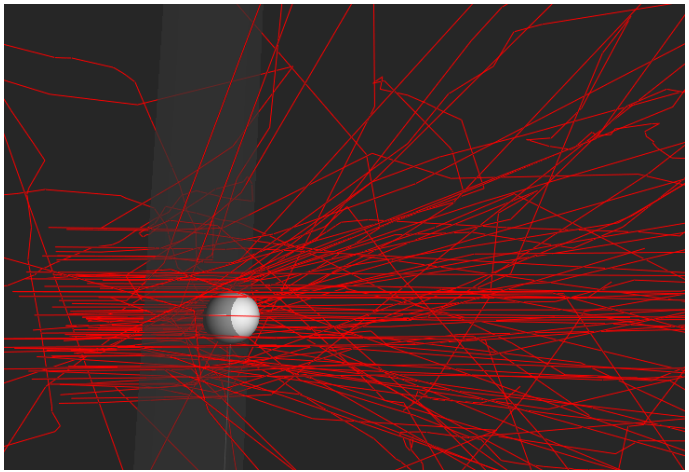
For each angle η, shoot photons **from planes** onto the DOM and count hits. Hole-ice radius: 30 cm

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

```
$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

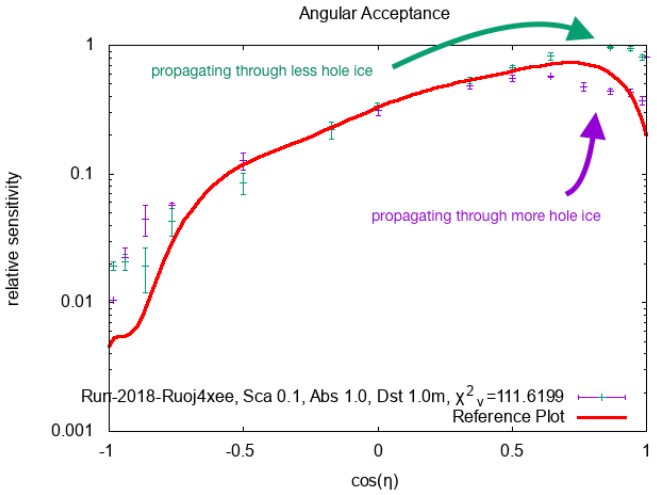
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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

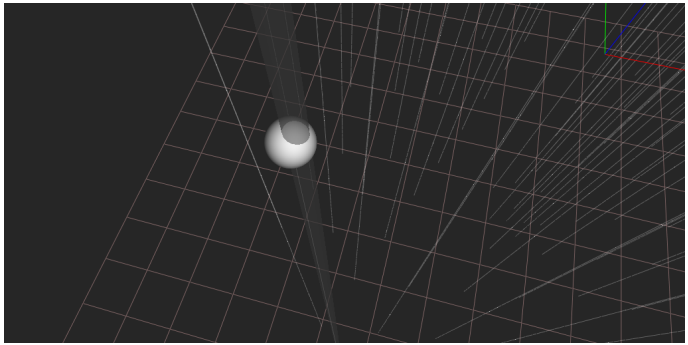
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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
```

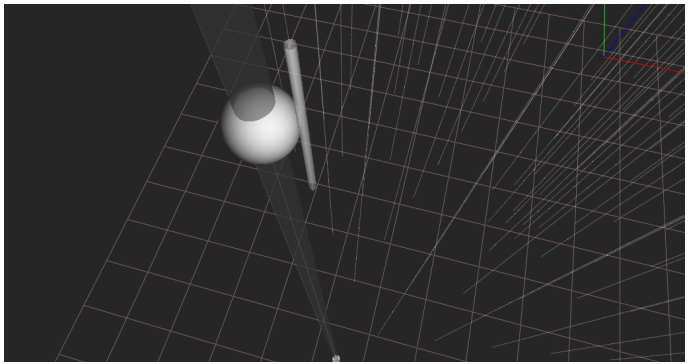
Source: https://github.com/fiedl/hole-ice-study#asymmetry-example, https://github.com/fiedl/hole-ice-study/issues/8

Separate hole-ice cylinder positions



- Each string can have its own hole-ice cylinder configuration
  - cylinder position
  - cylinder radius
  - DOM positions — DOMs may not be perfectly centred relative to the hole ice
- Currently configurable in Geometry frame. **Q: Is there a better place to configure this?**
- Still work to be done:
  - Ice properties need to be configurable for each cylinder: `https://github.com/fiedl/hole-ice-study/issues/9`

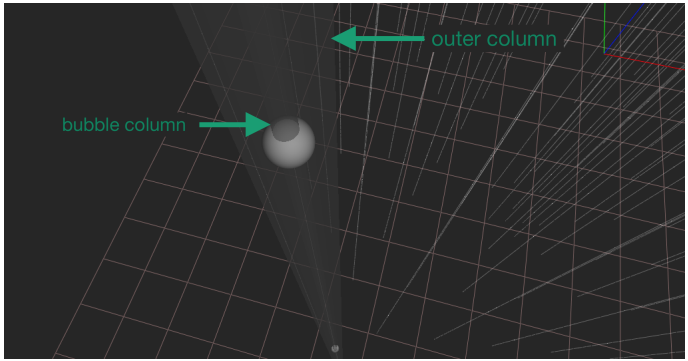
Cable shadows



- 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:
  - Ice properties need to be configurable for each cylinder: https://github.com/fiedl/hole-ice-study/issues/9
  - 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

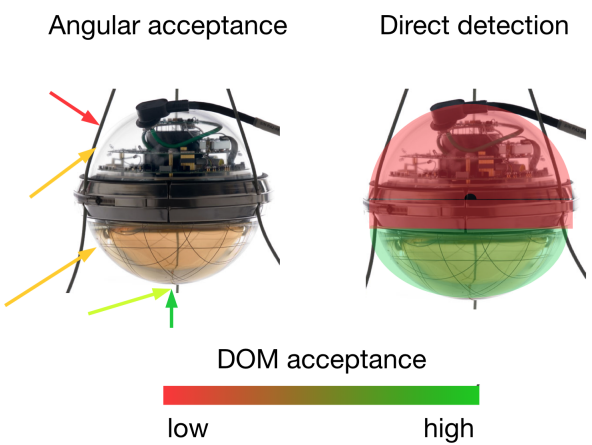
Nested hole-ice cylinders



- 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
- Still work to be done:
  - Ice properties need to be configurable for each cylinder: `https://github.com/fiedl/hole-ice-study/issues/9`

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@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`

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

- Absolute ice properties in hole ice rather than relative to respective bulk ice layers
- Separate ice properties for each cylinder
- 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	✓		✓	yes
Cable shadows using cylinder parts	✓		✓	yes
Direct detection	✓		✓	yes
Absolute scattering and absorption lengths in hole ice (more physical than relative properties)	✓			?
Vertical gradient of scattering length in bubble column	✓			no

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

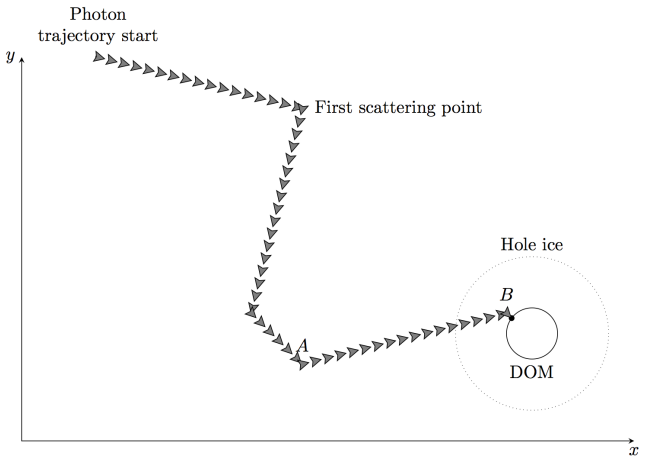
Thanks for your attention!

Any input you might have is welcome:

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

Slack: `@fiedl`

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

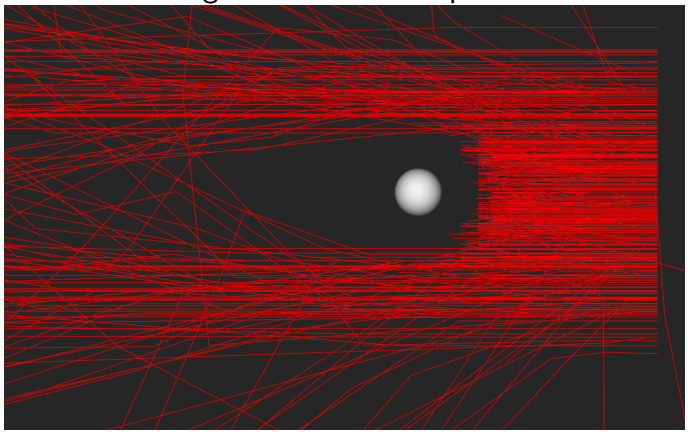
→ **Hole ice is easy** because all ice properties can be locally evaluated

→ But **performance is bad** because there are lots of simulation steps even for long distances without interaction

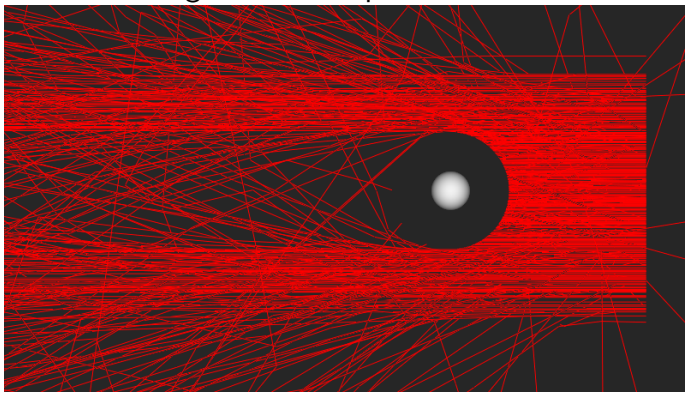
Coordinates-vs-vectors bug

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

Before: Treating coordinates as separate variables

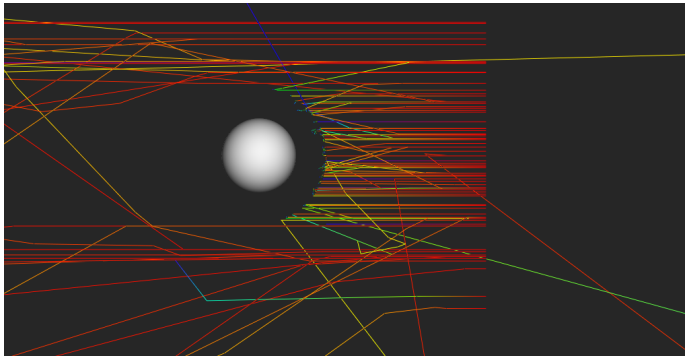


After: Treating vectors as opencl-native vectors



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
```