Hole-ice simulation in clsim

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Motivation and Scope

- No explicit hole-ice simulation included in clsim, yet only angular sensitivity approximation
  - $\rightarrow$ 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

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

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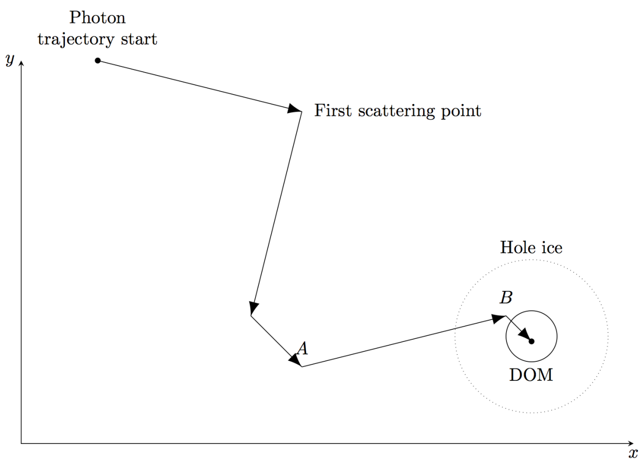
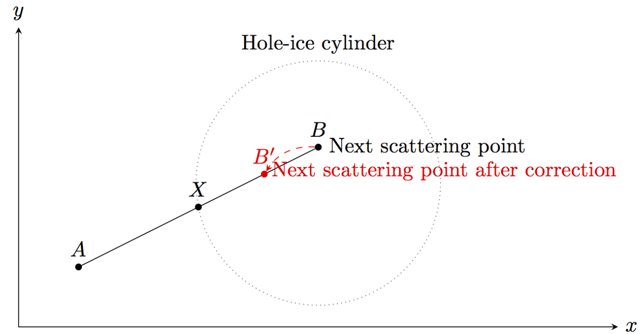
How does it work?



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

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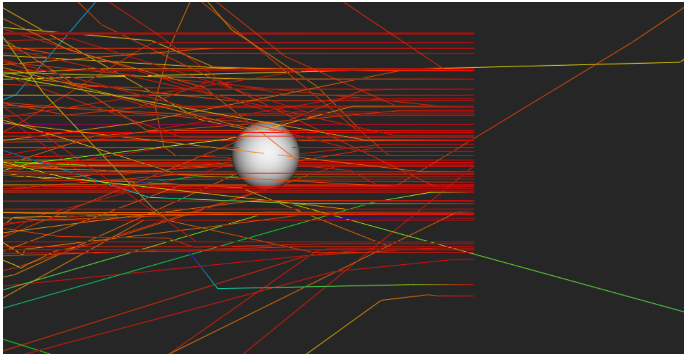
Source: https://github.com/fiedl/hole-ice-study#how-does-it-work

Two hole-ice algorithms

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

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

Scattering example



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

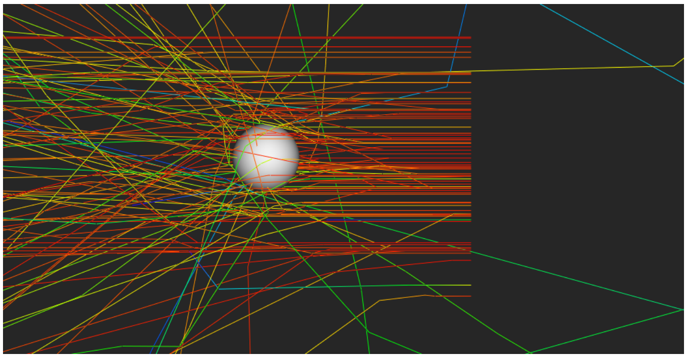
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{1} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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.

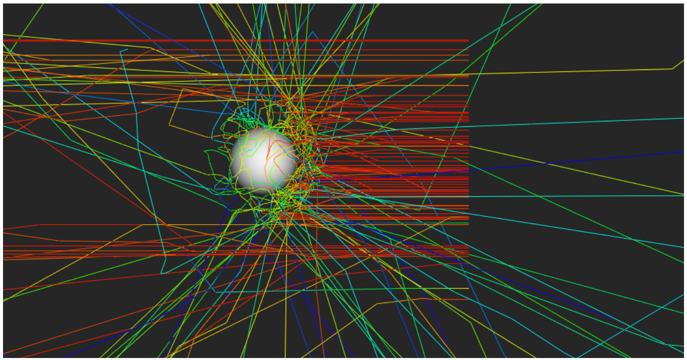
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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.

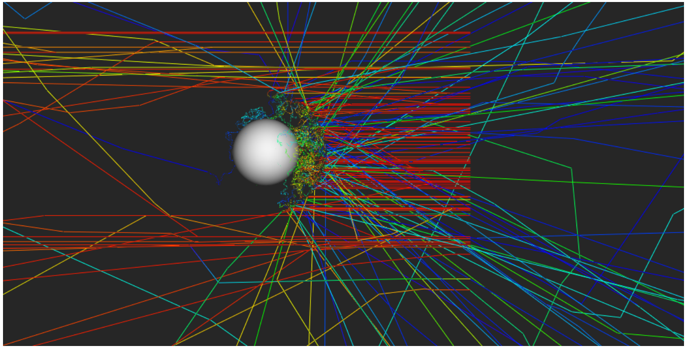
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{100} \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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-I1s`

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

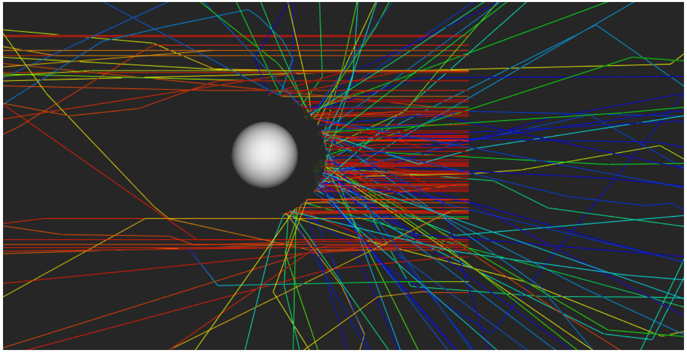
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{1\,000} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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.

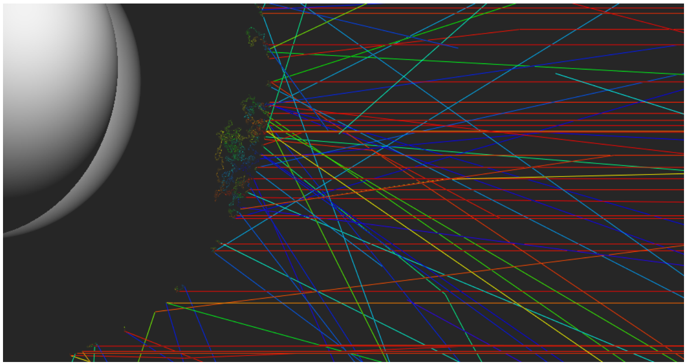
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10\,000} \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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

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.

$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10\,000} \quad \lambda_{\text{sca,bulk}}$$
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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
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Source: `https://github.com/fiedl/hole-ice-study/issues/39`

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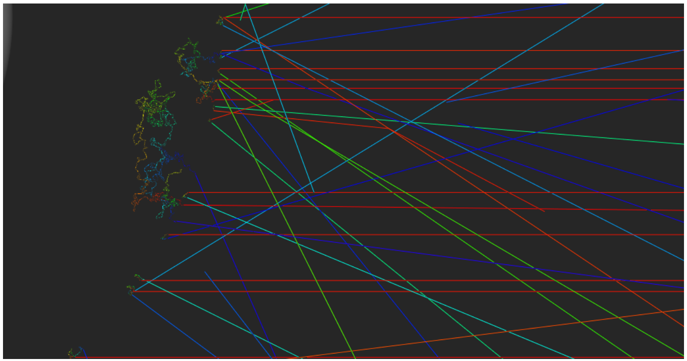

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Shoot photons onto the DOM. Top view.
Change the scattering length inside the hole ice to be 1/10 000 of the scattering length outside.

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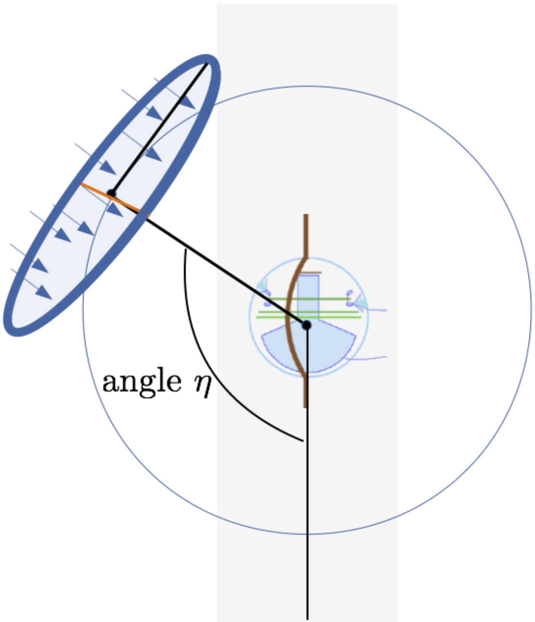
Colors indicate simulation steps, i.e. number of scatterings relative to the total number until absorption. Red: Photon just created, blue: Photon about to be absorbed.

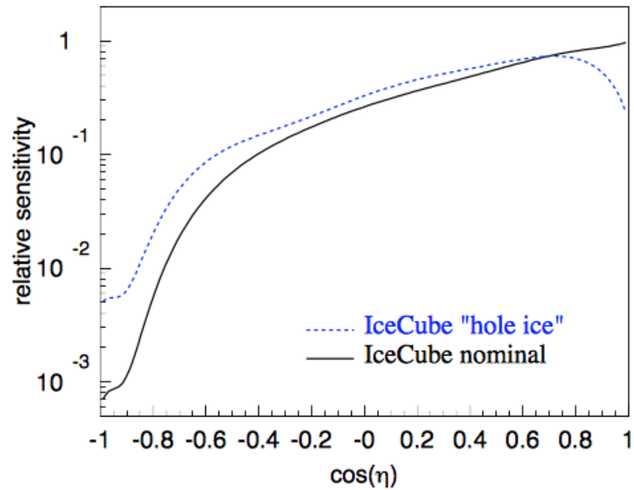
```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.0001 --absorption-factor=1.0 --distance=1.0
↪   --plane-wave --number-of-photons=1e2 --number-of-runs=1
↪   --number-of-parallel-runs=1 --save-photon-paths --cpu
steamshovel tmp/propagated_photons.i3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

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

Angular acceptance

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



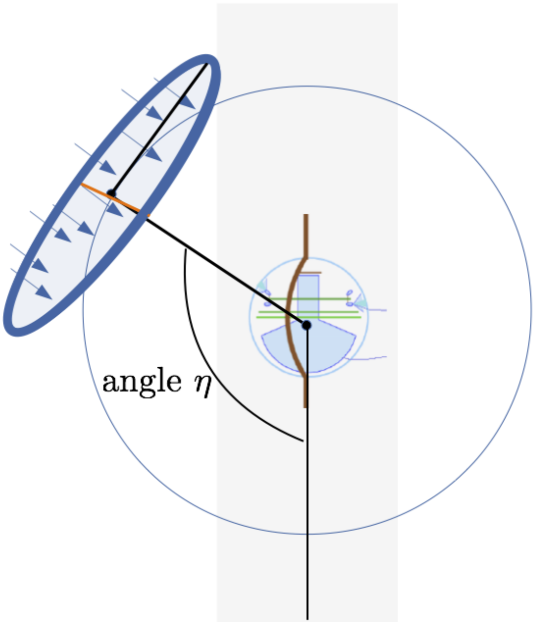


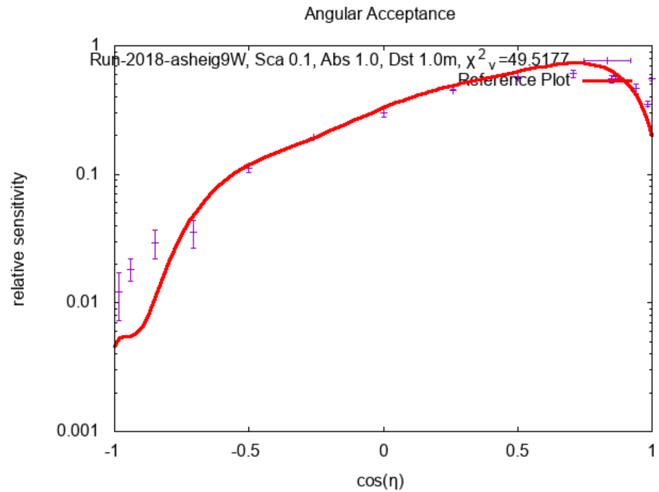
Angular acceptance *reference curves*. The nominal model is based on lab measurement, the hole ice curve on previous simulations.

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.



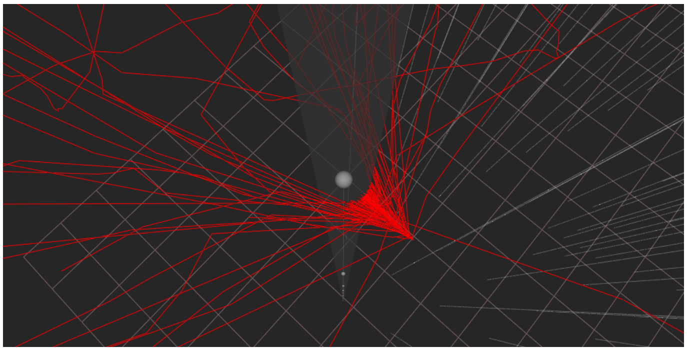



```
$ICESIM/env-shell.sh; cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
./run.rb --scattering-factor=0.1 --absorption-factor=1.0 --distance=1.0
↪   --plane-wave --number-of-photons=1e5
↪   --angles=0,10,20,30,32,45,60,75,90,105,120,135,148,160,170,180]
↪   --number-of-runs=2 --number-of-parallel-runs=2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



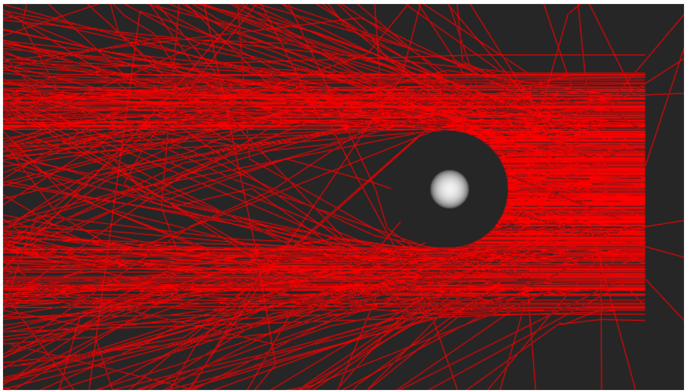
Photon point source, 3d view

```
$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



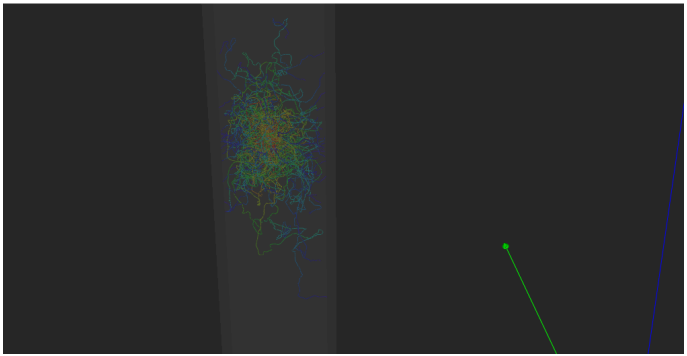
Plane wave photon source, top view

```
$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
```

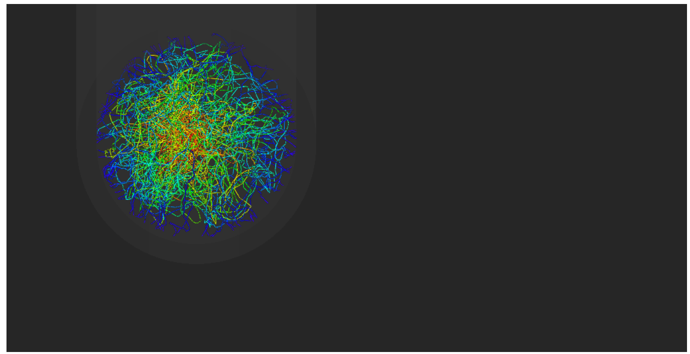
Source: `https://github.com/fiedl/hole-ice-study/issues/22`

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

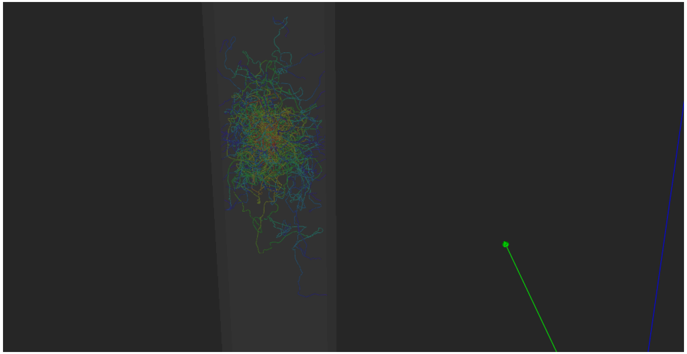


Top view

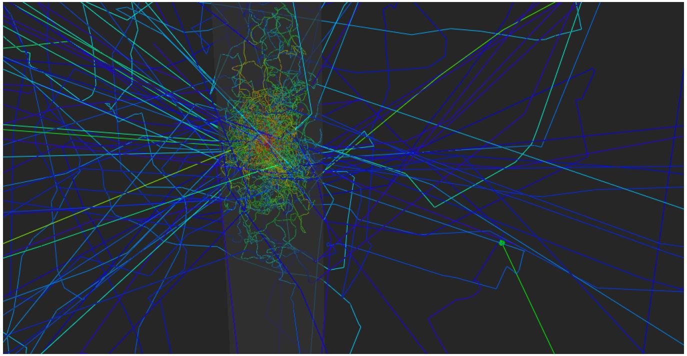
Source: `https://github.com/fiedl/hole-ice-study/issues/47`

Instant absorption with nested cylinders

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



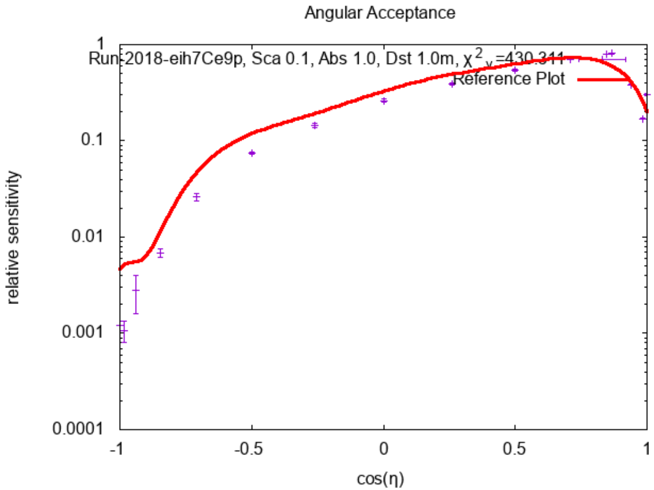
With outer cylinder configured for instant absorption



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

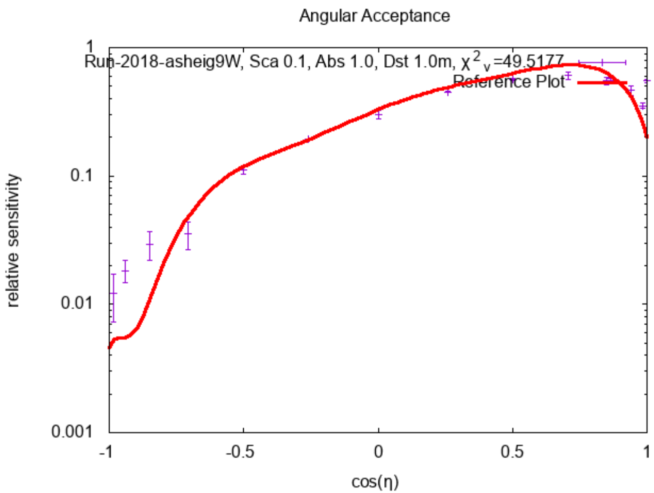
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \lambda_{\text{sca,bulk}}$$

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

```
$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



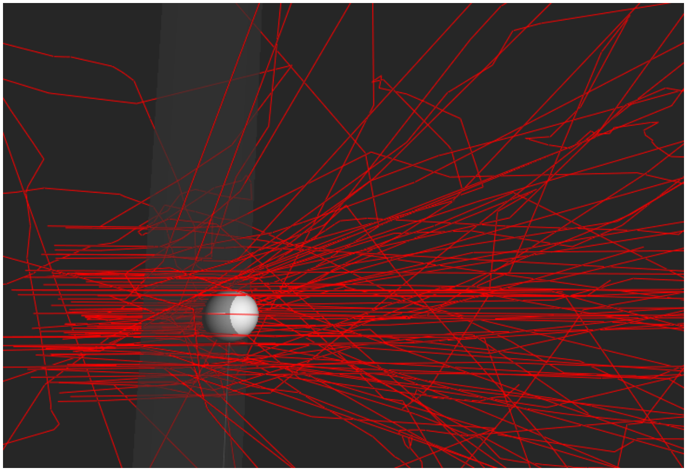
For each angle η, shoot photons **from planes** onto the DOM and count hits. Hole-ice radius: 30 cm

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

```
$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

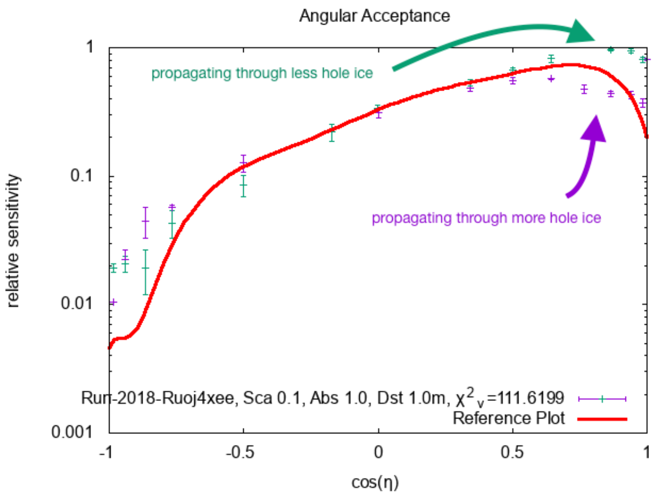
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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

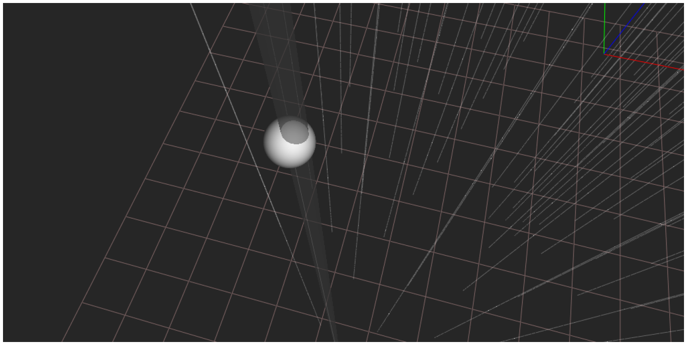
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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
```

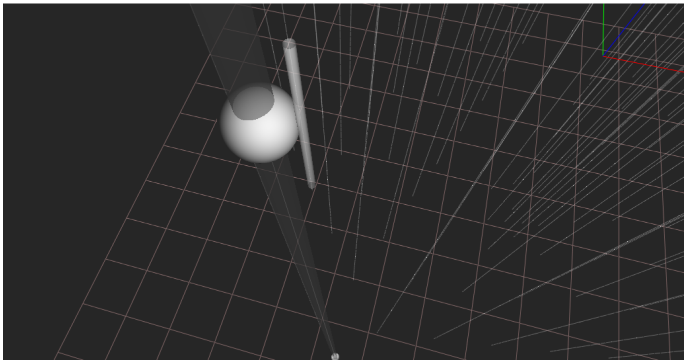
Source: https://github.com/fiedl/hole-ice-study#asymmetry-example, https://github.com/fiedl/hole-ice-study/issues/8

Separate hole-ice cylinder positions



- Each string can have its own hole-ice cylinder configuration
  - cylinder position
  - cylinder radius
  - 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

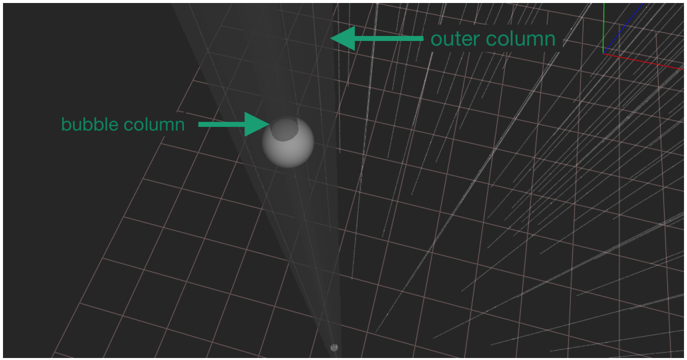
Cable shadows



- 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`

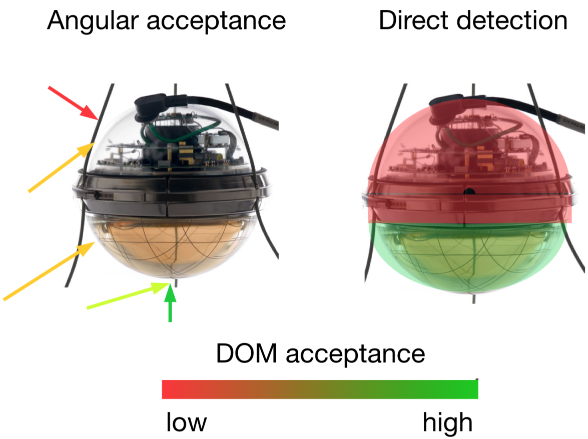
Nested hole-ice cylinders



- 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



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

- The DOM looks downwards by design
- Currently, the hit position is not used when determining DOM acceptance, just the photon direction when hitting the DOM (*DOM angular acceptance*)
- Direct detection: Accept all hits below the waist band, reject all others
- Direct detection is easy with clsim
  - Hit position is known and guaranteed to be on the DOM sphere
  - Idea: Accept hits depending on z of the hit position
  - Patch is a couple of lines: fiedl/clsim@96a2e3f
- Still work to be done:
  - Implement a switch for direct detection vs. DOM angular acceptance
    https://github.com/fiedl/hole-ice-study/issues/32
  - Consider DOM orientation
    https://github.com/fiedl/hole-ice-study/issues/53

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`

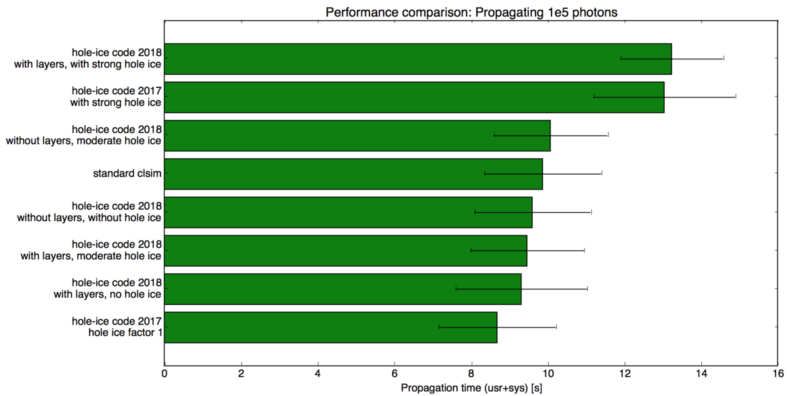
Slack: `@fiedl`

Video illustration of a simple example:

`https://youtu.be/BhJ6F3B-I1s`

Performance

Time measurement: Propagating 10^5 photons on CPU



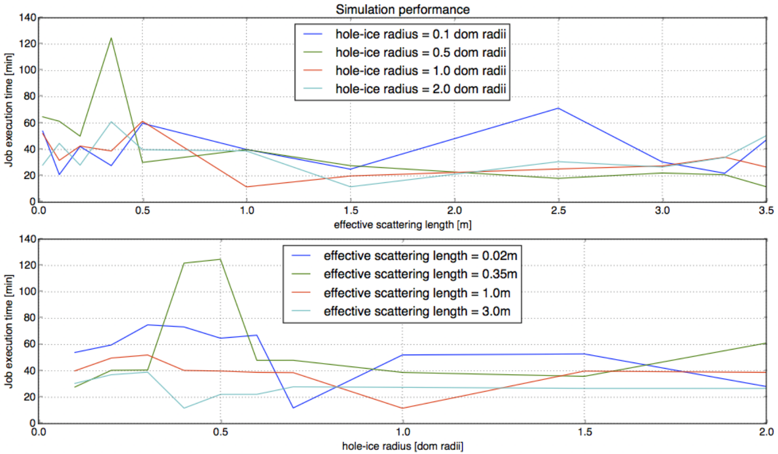

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
time ./run.rb --distance=1.0 --number-of-runs=1 --number-of-parallel-runs=1 --cpu --angle=45
↪   --plane-wave --number-of-photons=1e5
```

- 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 ($\lambda_s = 20\,\mathrm{m}$).
- Performance drop can be seen when lowering the scattering length, i.e. increasing the number of simulation steps ($\lambda_s = 3\,\mathrm{mm}$).

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

Performance

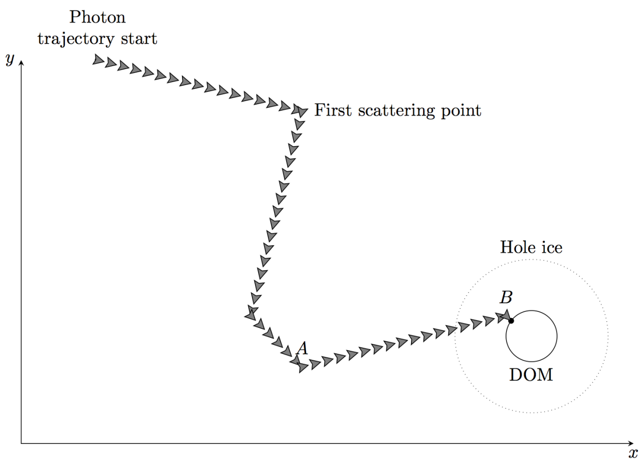
Time measurement: Propagating $30 \cdot 10^5$ photons on GPU.



- 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

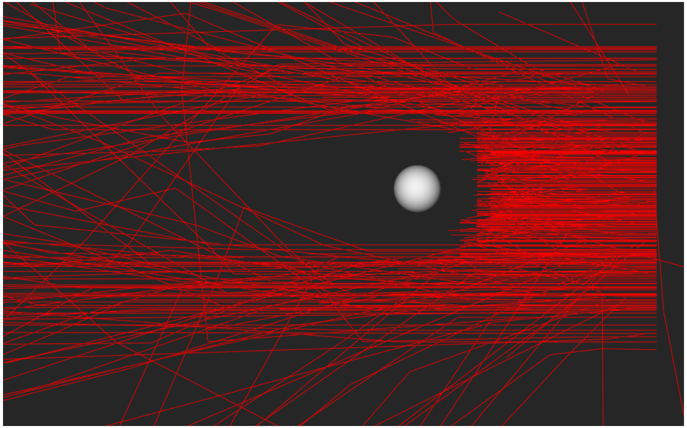
→ **Hole ice is easy** because all ice properties can be locally evaluated

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

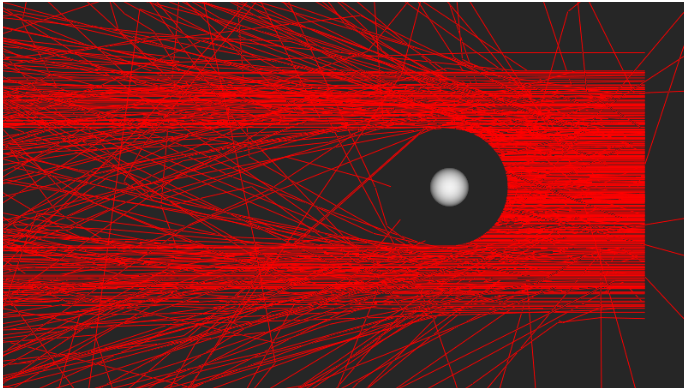
Coordinates-vs-vectors bug

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

Before: Treating coordinates as separate variables

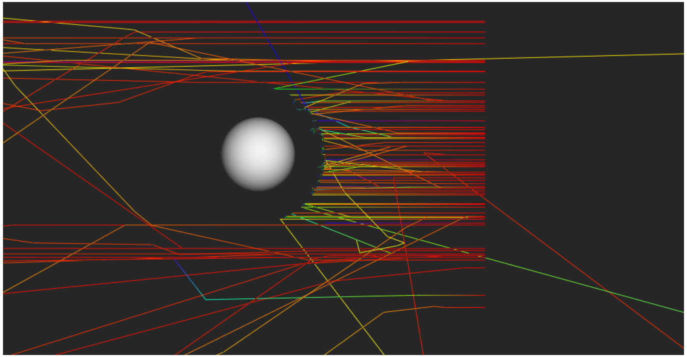


After: Treating vectors as opencl-native vectors



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
```