Hole-ice simulation in clsim

IceCube Stockholm Collaboration Meeting 2018
Reconstruction/Systematics Session 2

Sebastian Fiedlschuster
https://github.com/fiedl/hole-ice-study
sebastian@fiedlschuster.de

Erlangen Centre for Astroparticle Physics

2018-09-27

Document 2018-gumee8Ai

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:

2018-09-26 calibration session Stockholm:

`https://events.icecube.wisc.edu/contributionDisplay.py?contribId=225&confId=102`

2018-03-02 calibration call:

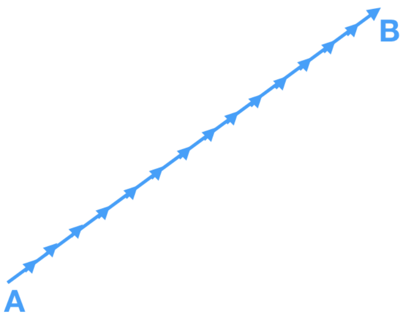
`https://docushare.icecube.wisc.edu/dsweb/View/Collection-15039`

LaTeX version of these presentation slides:

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

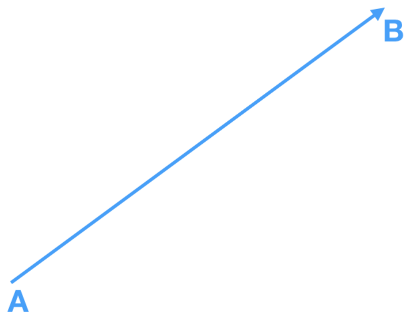
Contents

How does it work?



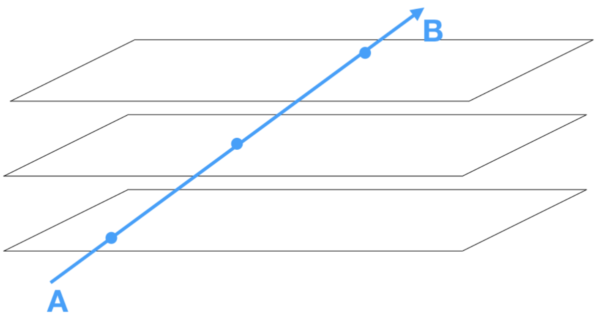
- Photon scattering points A and B
- **Naive algorithm**: Propagate photon small distance δx in each simulation step and randomize whether the photon will scatter in this step (easy to implement local properties)
- **Faster algorithm**: Randomize geometric distance to next scattering point and propagate from A to B in one simulation step
- **Ice layers in clsim**: 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** in clsim: Generalize budget algorithm to support cylinders (with distinct scattering and absorption lengths) in addition to ice layers.

How does it work?



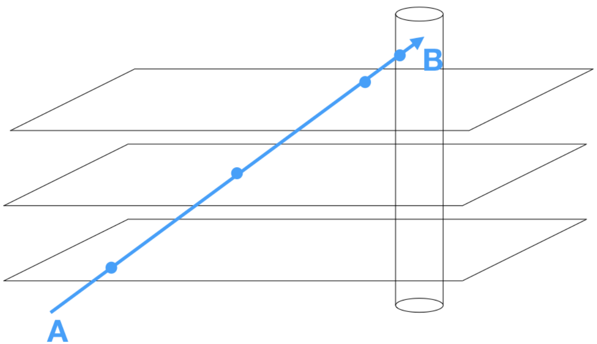
- Photon scattering points A and B
- **Naive algorithm**: Propagate photon small distance δx in each simulation step and randomize whether the photon will scatter in this step (easy to implement local properties)
- **Faster algorithm**: Randomize geometric distance to next scattering point and propagate from A to B in one simulation step
- **Ice layers in clsim**: 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** in clsim: Generalize budget algorithm to support cylinders (with distinct scattering and absorption lengths) in addition to ice layers.

How does it work?



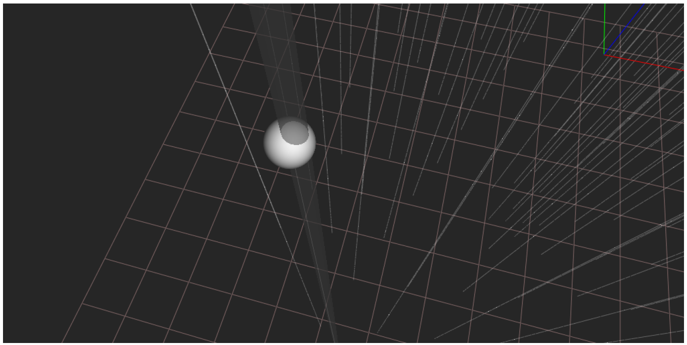
- Photon scattering points A and B
- **Naive algorithm**: Propagate photon small distance δx in each simulation step and randomize whether the photon will scatter in this step (easy to implement local properties)
- **Faster algorithm**: Randomize geometric distance to next scattering point and propagate from A to B in one simulation step
- **Ice layers in clsim**: 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** in clsim: Generalize budget algorithm to support cylinders (with distinct scattering and absorption lengths) in addition to ice layers.

How does it work?



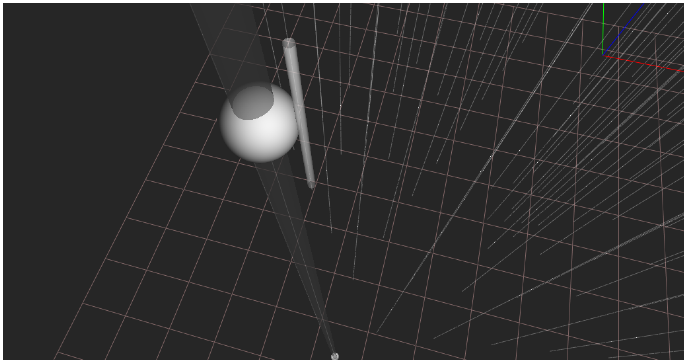
- Photon scattering points A and B
- **Naive algorithm**: Propagate photon small distance δx in each simulation step and randomize whether the photon will scatter in this step (easy to implement local properties)
- **Faster algorithm**: Randomize geometric distance to next scattering point and propagate from A to B in one simulation step
- **Ice layers in clsim**: 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** in clsim: Generalize budget algorithm to support cylinders (with distinct scattering and absorption lengths) in addition to ice layers.

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

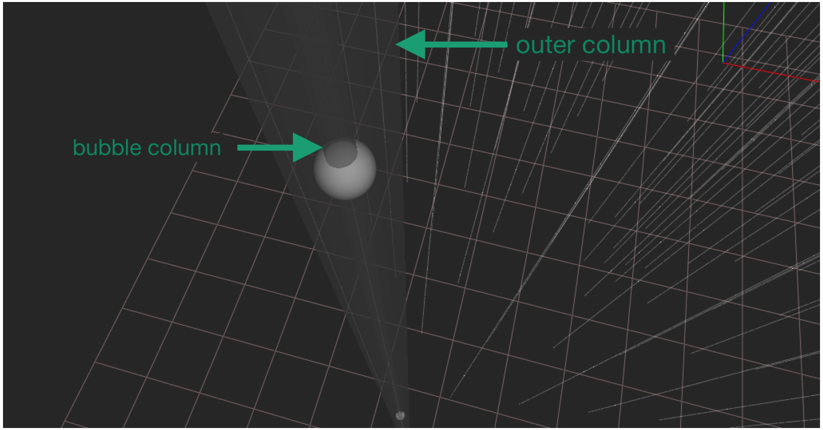
Cable shadows



- 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

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

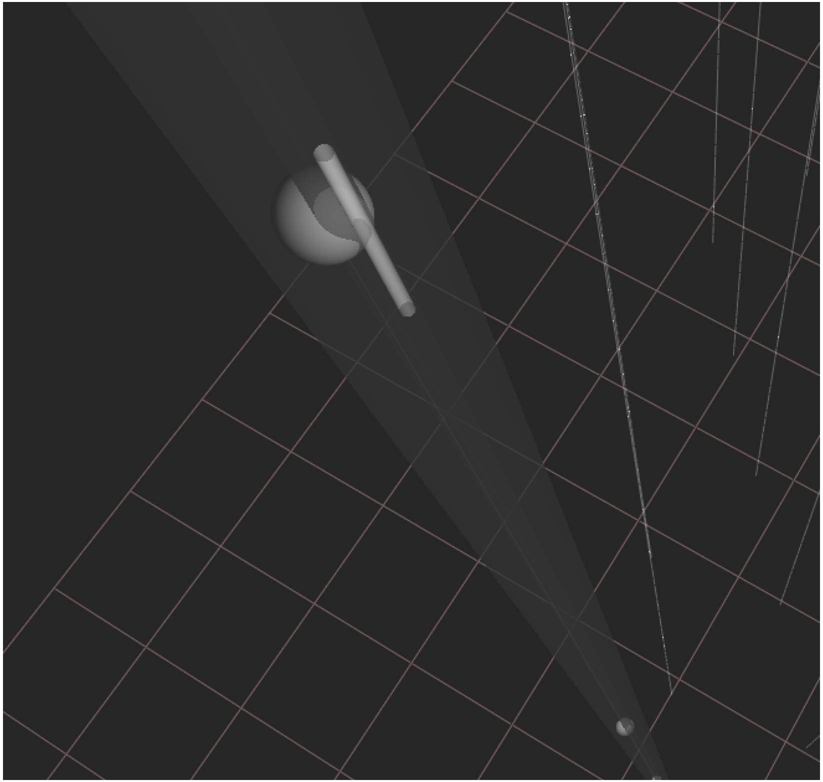
Nested hole-ice cylinders



- 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`

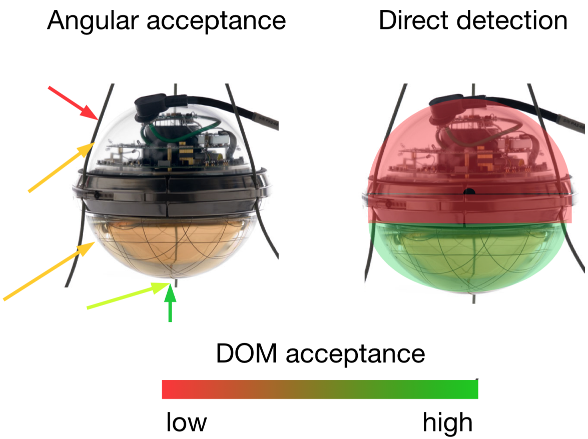
Nested shifted cylinders and cable



- This image:
  - DOM: radius 16.5 cm, shifted by 12.0 cm
  - 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

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

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`

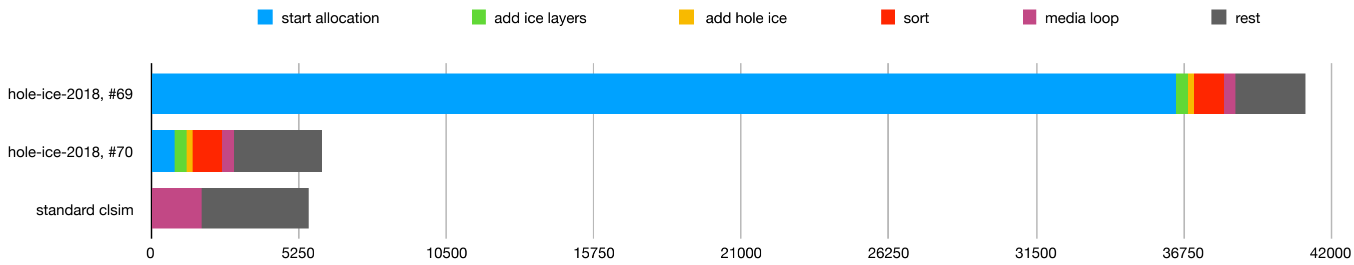
- The DOM looks downwards by design
- Currently, the hit position is not used when determining DOM acceptance, just the photon direction when hitting the DOM (*DOM angular acceptance*)
- Direct detection: Accept all hits below the waist band, reject all others
- Direct detection is easy with clsim
 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

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`

Outlook: What is still missing

Next steps:

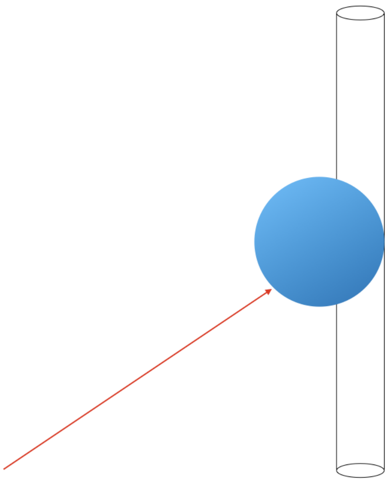
- Re-implement ice tilt and ice anisotropy
- Implement direct-detection switch
- Merge it to icecube-simulation trunk
- Time frame: late 2018 / early 2019

Follow-up ideas:

- tapered cylinders (bore holes are larger at the bottom)
- bent cylinders (cables)
- DOM oversizing for complex scenarios

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

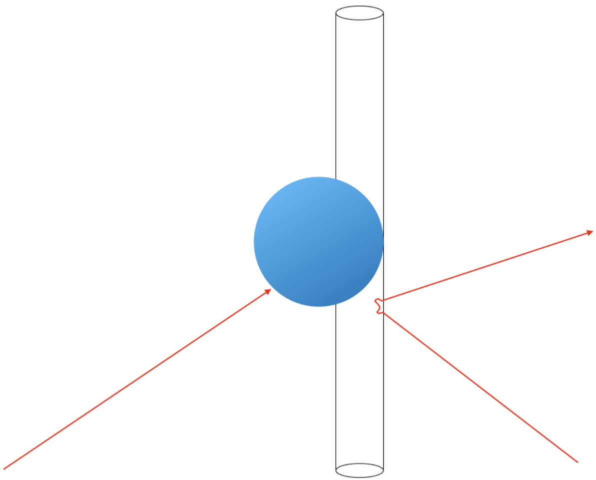
DOM oversizing with hole ice?



- 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.

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

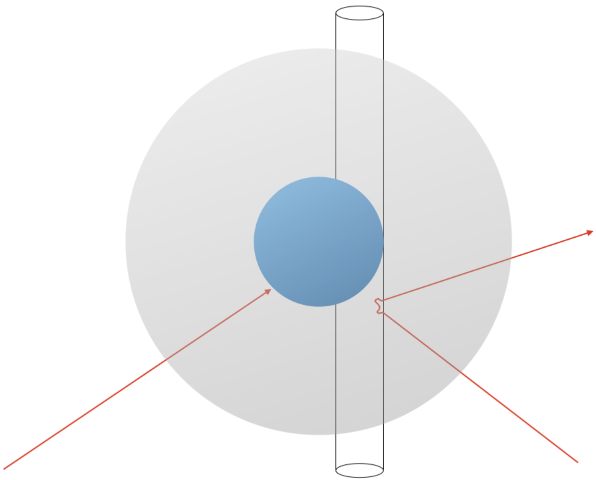
DOM oversizing with hole ice?



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.

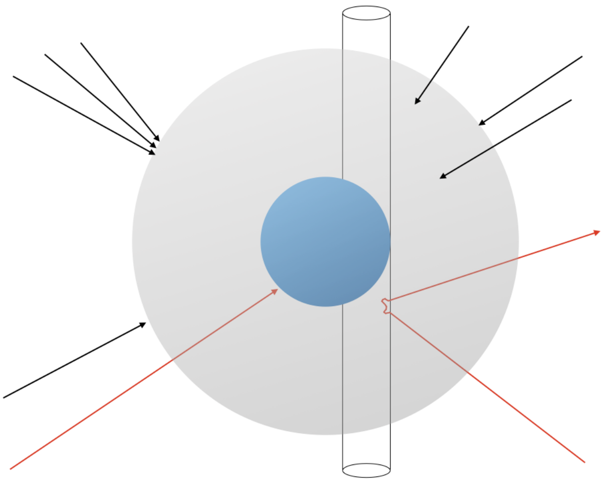
DOM oversizing with hole ice?



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.

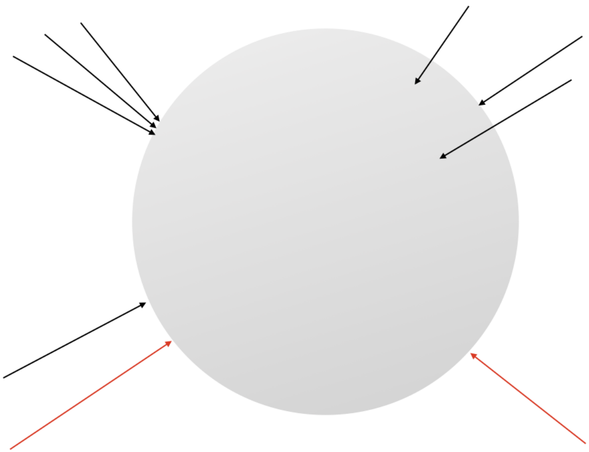
DOM oversizing with hole ice?



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.

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`

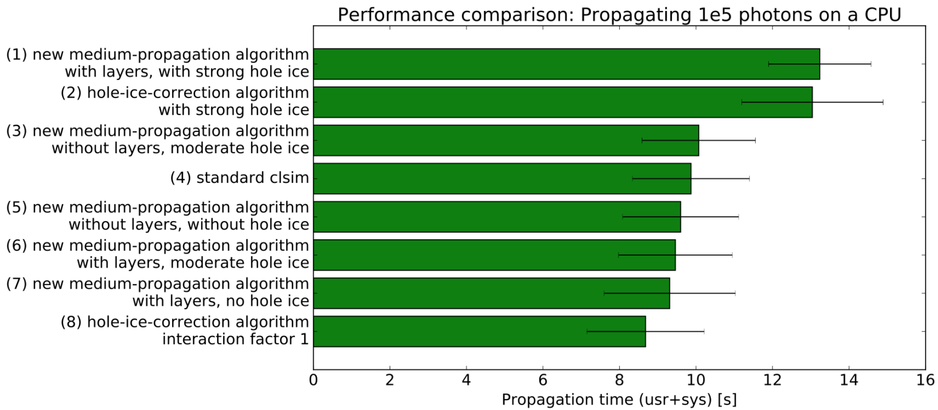
Two hole-ice algorithms

	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

Performance

Time measurement: Propagating 10^5 photons on CPU

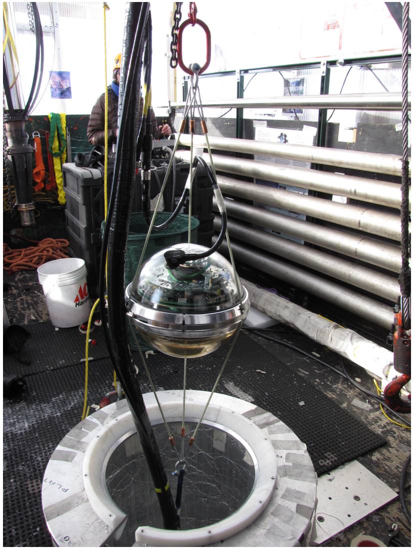


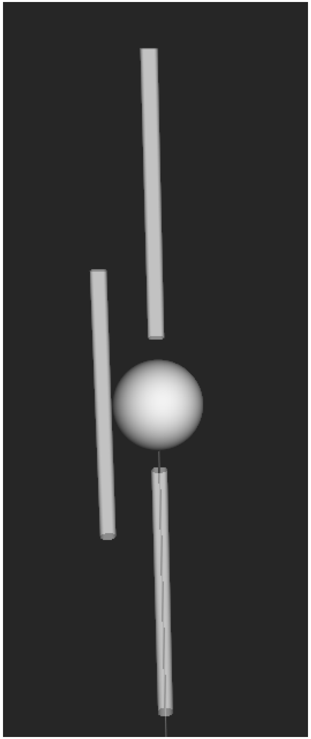

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/AngularAcceptance
time ./run.rb --distance=1.0 --number-of-runs=1 --number-of-parallel-runs=1 --cpu --angle=45 --plane-wave
↪  --number-of-photons=1e5
```

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

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

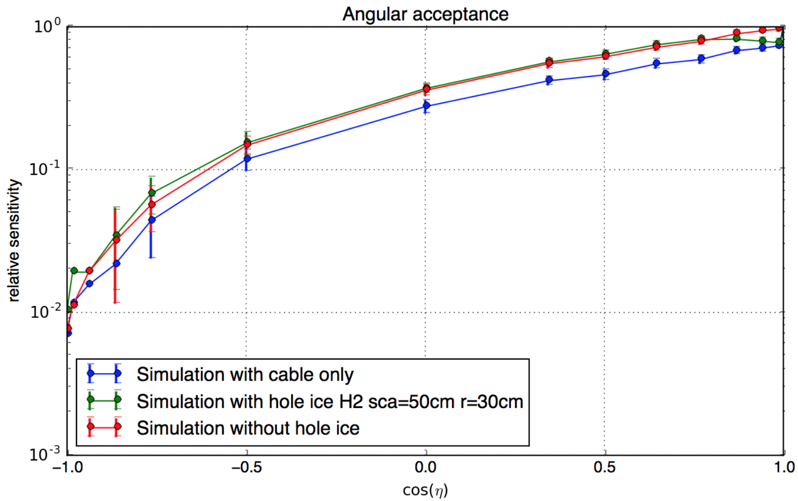
Direct cable simulation: Angular acceptance

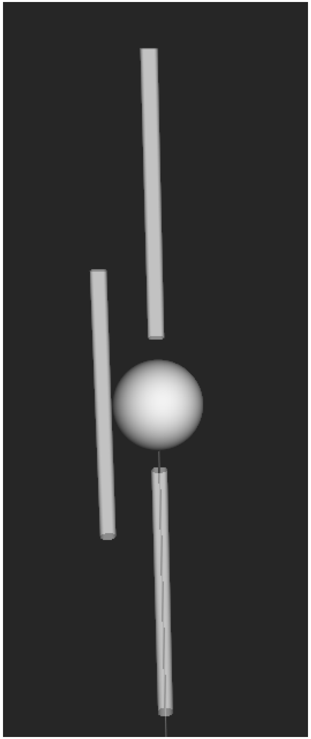




Source: https://github.com/fiedl/hole-ice-study/issues/101. **Images**: https://icecube.wisc.edu/gallery/view/153, https://gallery.icecube.wisc.edu/internal/v/GraphicRe/graphics/arraygraphics2011/sketchup/DOMCloseUp.jpg.html

Direct cable simulation: Angular acceptance

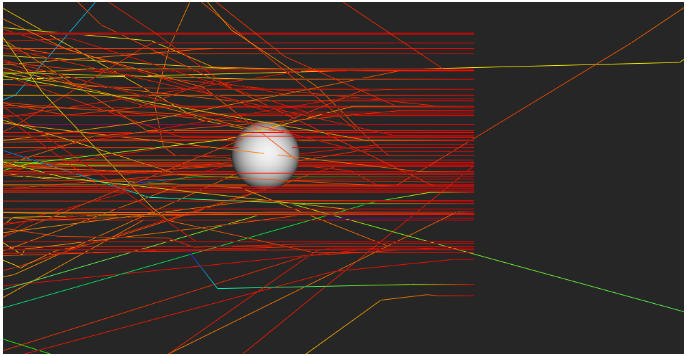




The azimuthal starting angle is such that the cable shadow is maximal.

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

Scattering example



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

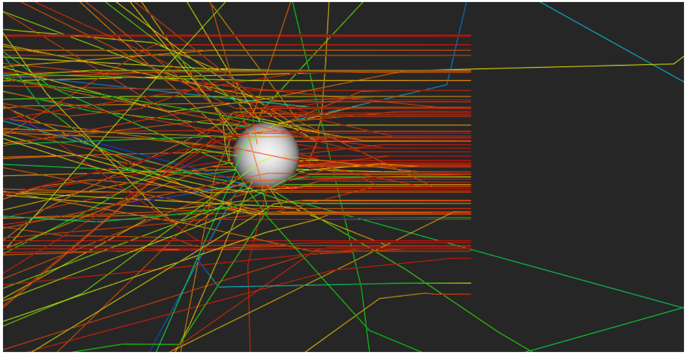
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{1} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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.

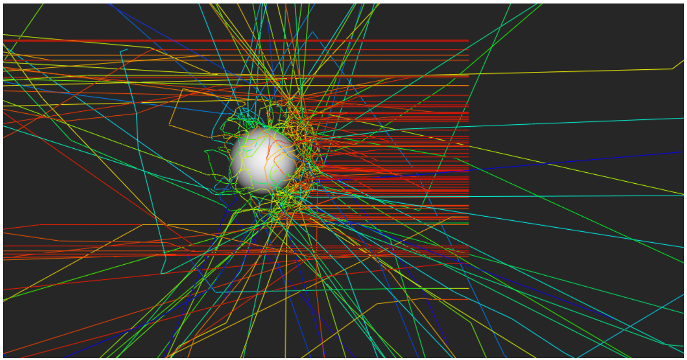
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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.

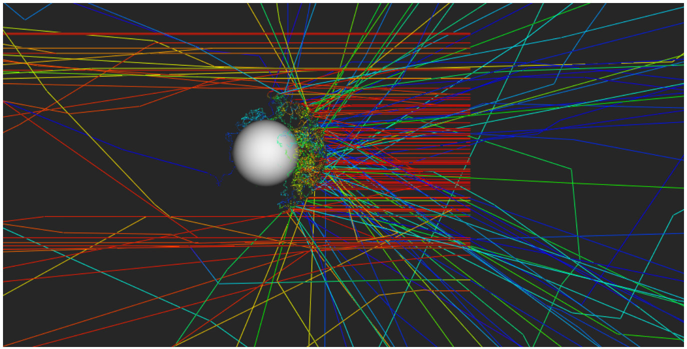
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{100} \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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.

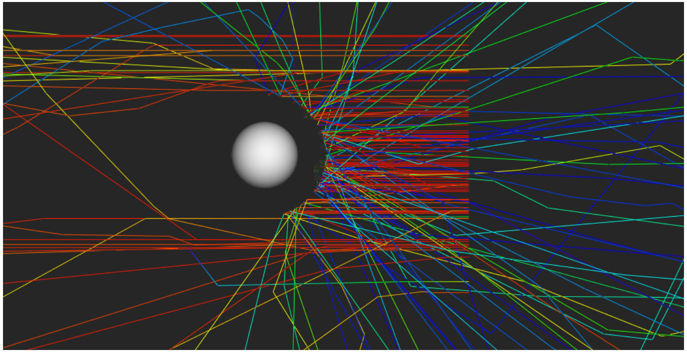
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{1\,000} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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.

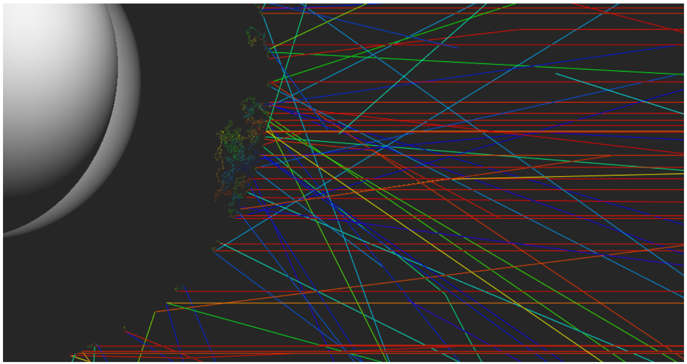
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10\,000} \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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.

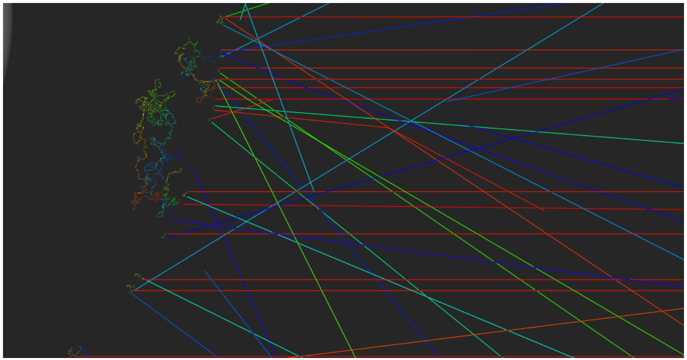
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10\,000} \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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.

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

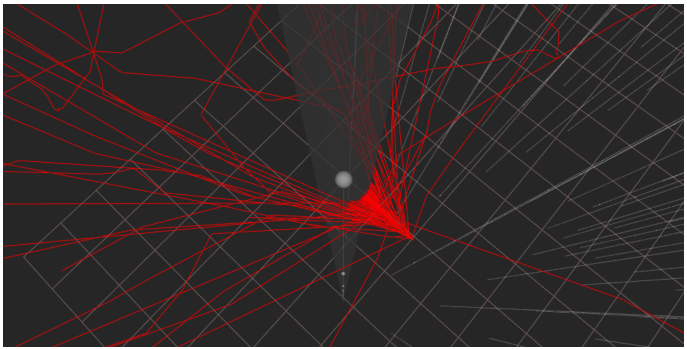
Colors indicate simulation steps, i.e. number of scatterings relative to the total number until absorption. Red: Photon just created, blue: Photon about to be absorbed.

```
$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

Instant absorption

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



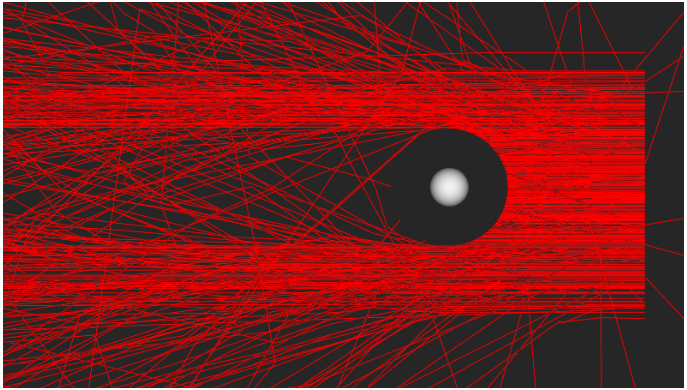
Photon point source, 3d view

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/FiringRange
./run.rb \
    --scattering-factor=1.0 --absorption-factor=0.0 \
    --distance=1.0 \
    --number-of-photons=1e3 --angle=90 \
    --number-of-runs=1 --number-of-parallel-runs=1 \
    --save-photon-paths --cpu
steamshovel tmp/propagated_photons.i3
```

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

Instant absorption

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



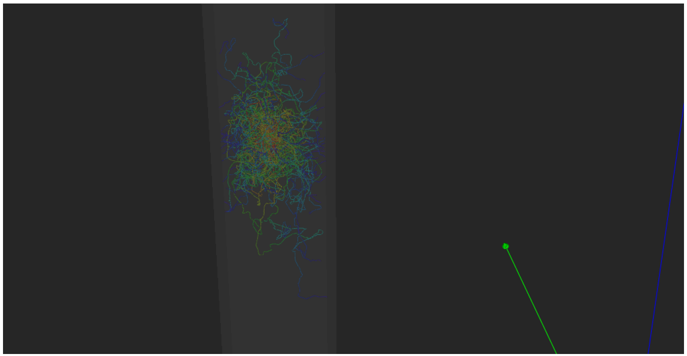
Plane wave photon source, top view

```
$ICESIM/env-shell.sh
cd $HOLE_ICE_STUDY/scripts/FiringRange
./run.rb \
    --scattering-factor=1.0 --absorption-factor=0.0 \
    --distance=1.0 --plane-wave \
    --number-of-photons=1e3 --angle=90 \
    --number-of-runs=1 --number-of-paralle-runs=1 \
    --cpu --save-photon-paths
steamshovel tmp/propagated_photons.i3
```

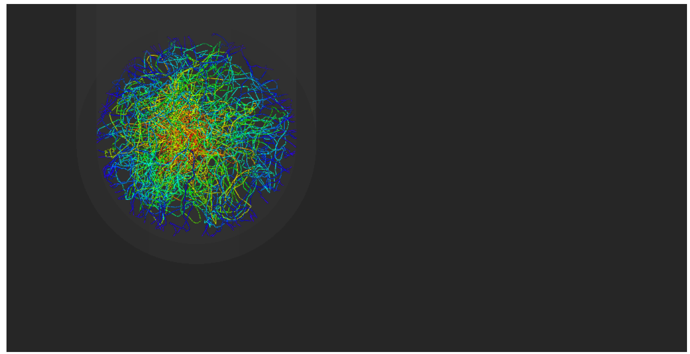
Source: https://github.com/fiedl/hole-ice-study/issues/22

Instant absorption with nested cylinders

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



With outer cylinder configured for instant absorption

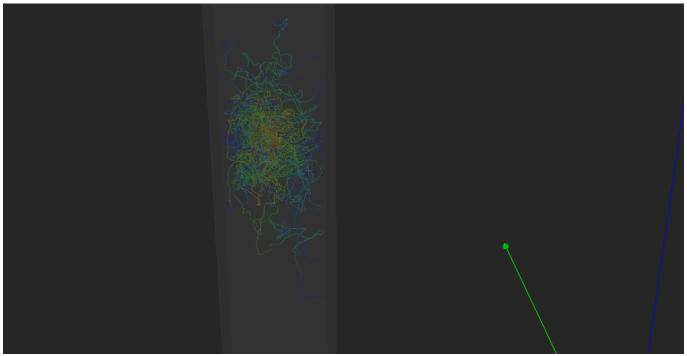


Top view

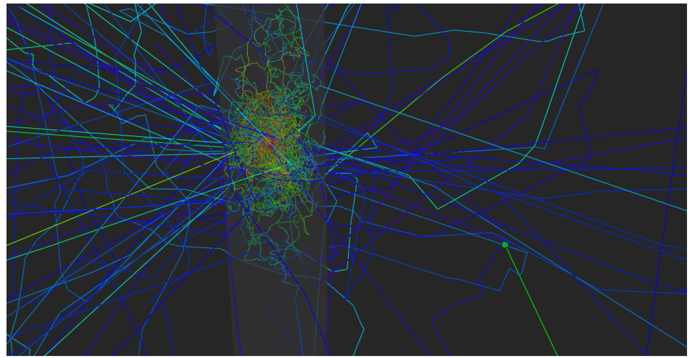
Source: `https://github.com/fiedl/hole-ice-study/issues/47`

Instant absorption with nested cylinders

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



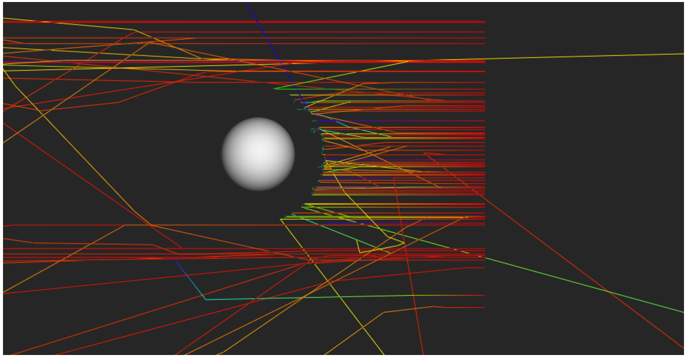
With outer cylinder configured for instant absorption



Without the outer cylinder

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

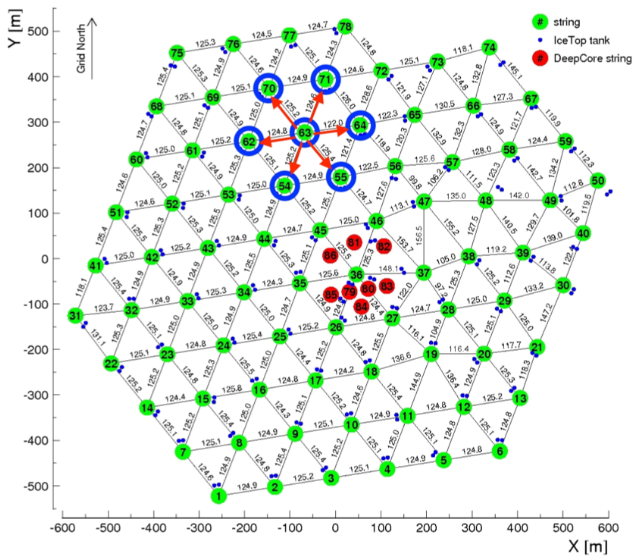
Scattering example

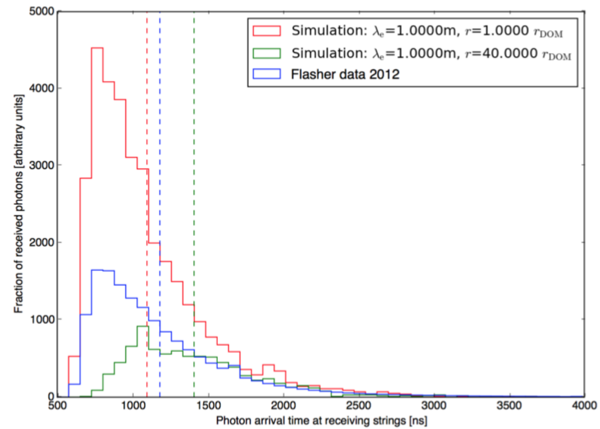


- Hole-ice absorption length: about 5 cm
- Hole-ice scattering length factor: 0.001

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

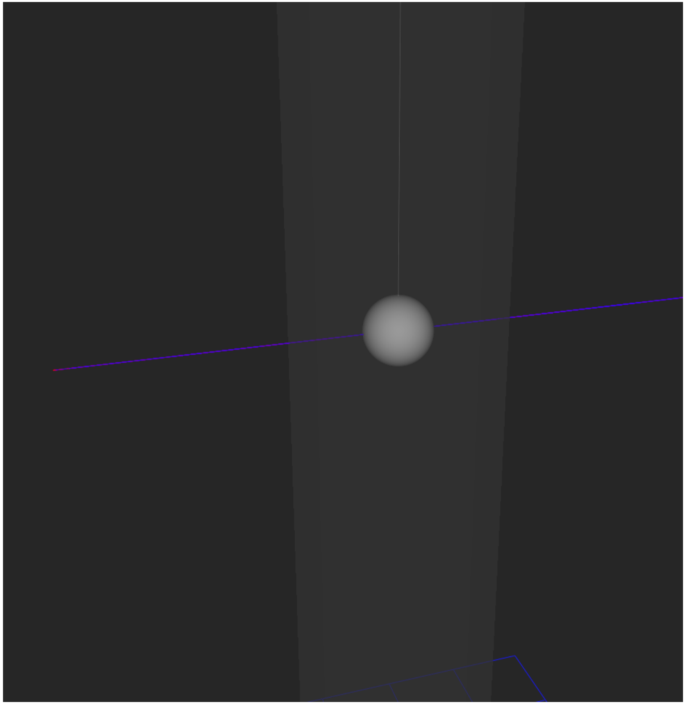
Cross checks: Arrival-time distributions

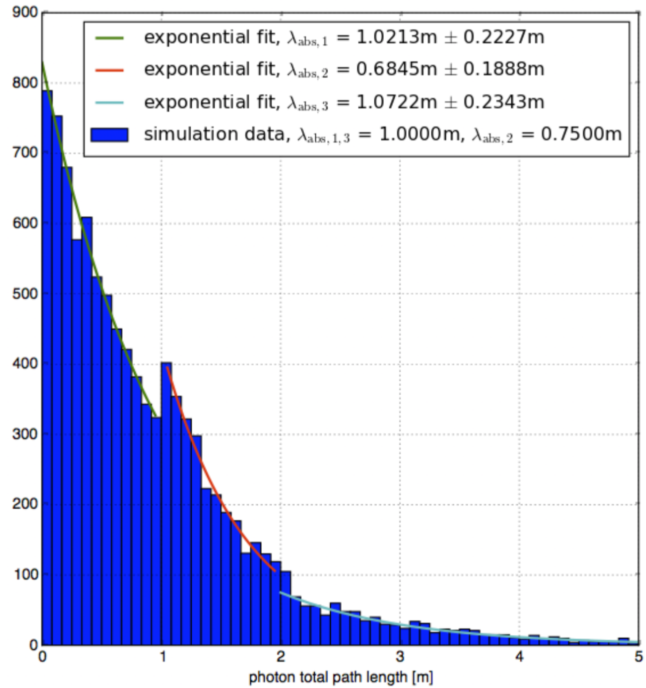




Source: `https://github.com/fiedl/hole-ice-study/issues/91`. **Image based on** `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

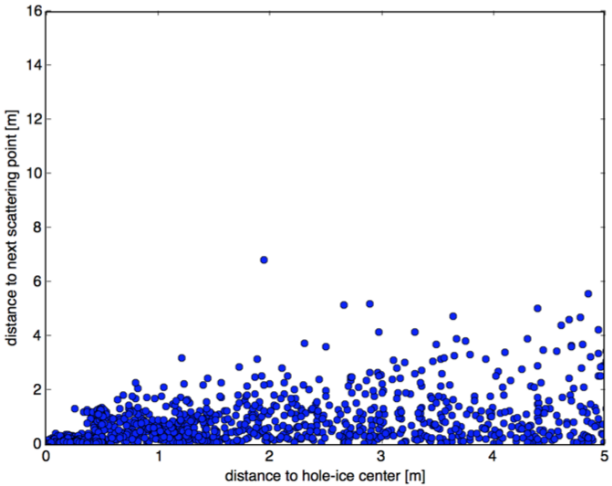
Cross checks: Path-length distributions



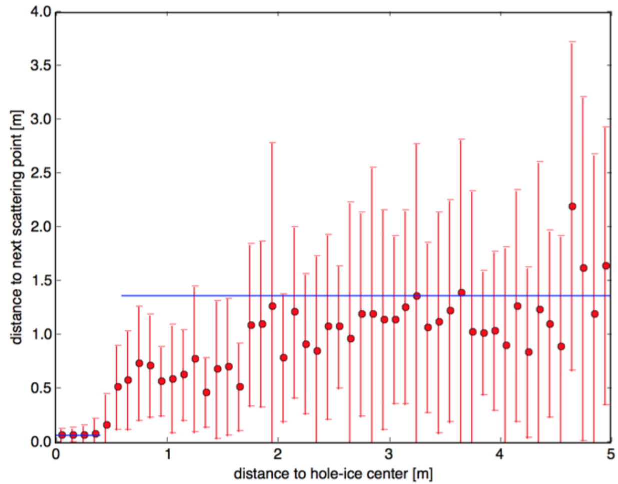


Source: `https://github.com/fiedl/hole-ice-study/issues/66`

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



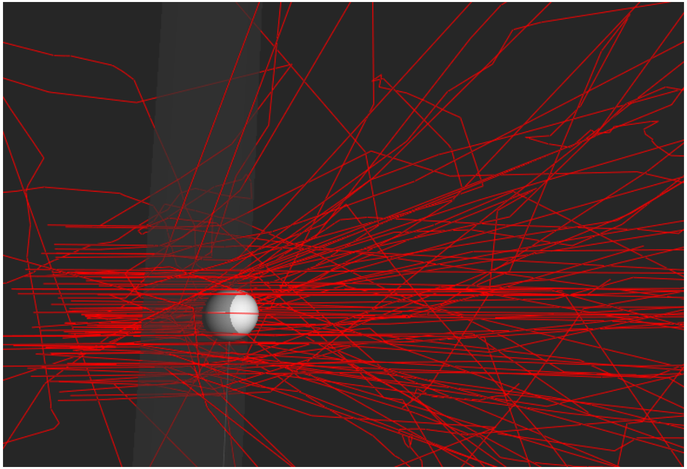
(a) All data points



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

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

Asymmetry example



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

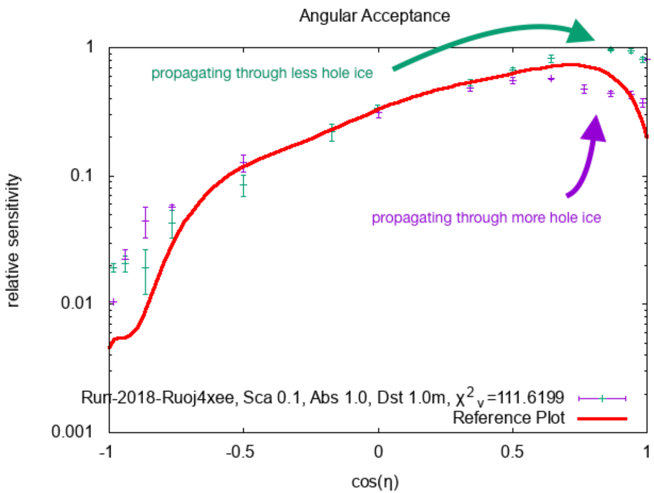
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \quad \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \quad \lambda_{\text{sca,bulk}}$$

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

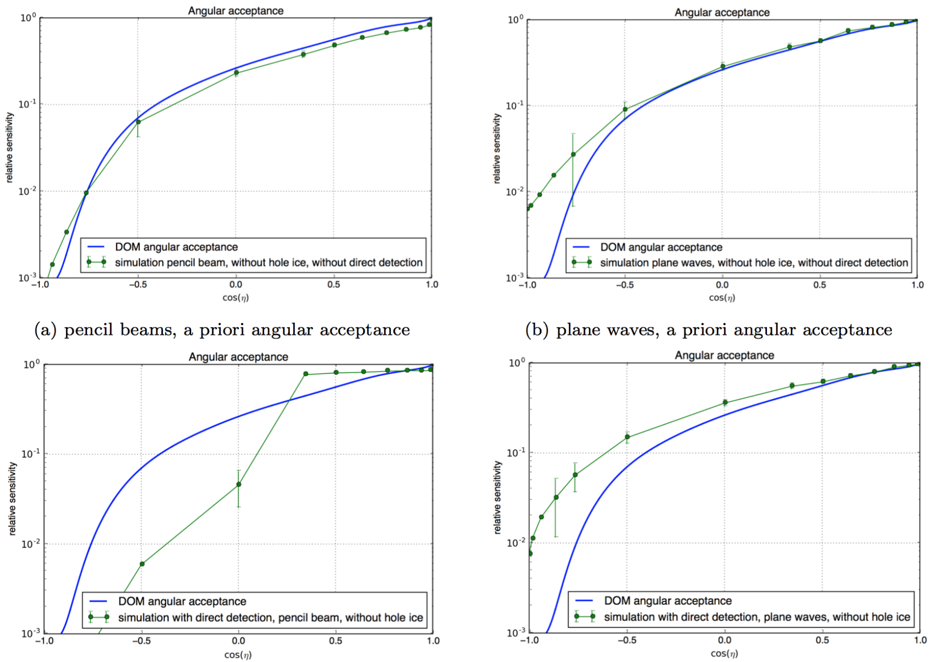
$$\lambda_{\text{sca,hole-ice}} = \frac{1}{10} \lambda_{\text{sca,bulk}}$$
$$\lambda_{\text{abs,hole-ice}} = \lambda_{\text{sca,bulk}}$$

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
```

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

Angular acceptance: Sources and acceptance criteria



(a) pencil beams, a priori angular acceptance

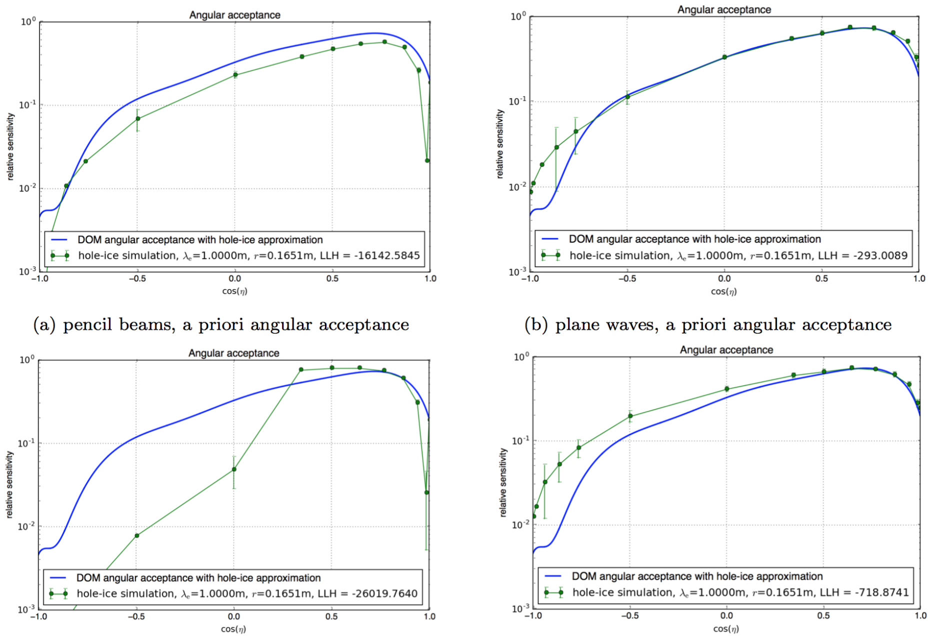
(b) plane waves, a priori angular acceptance

(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

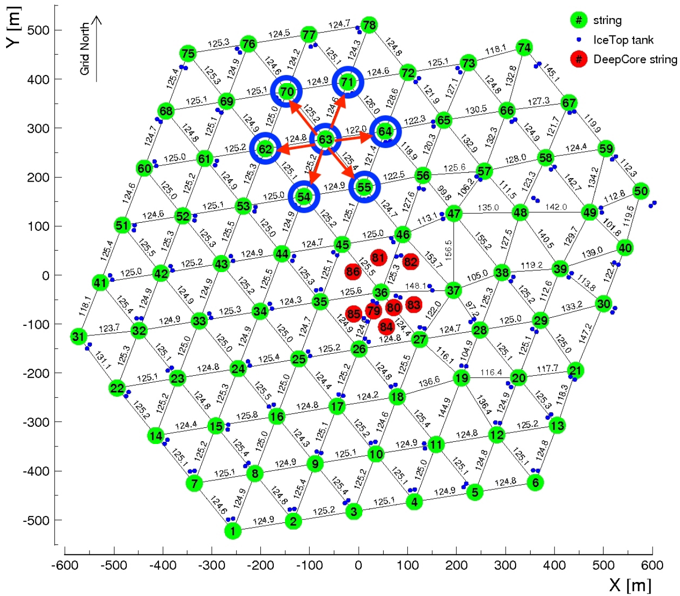
(b) plane waves, a priori angular acceptance

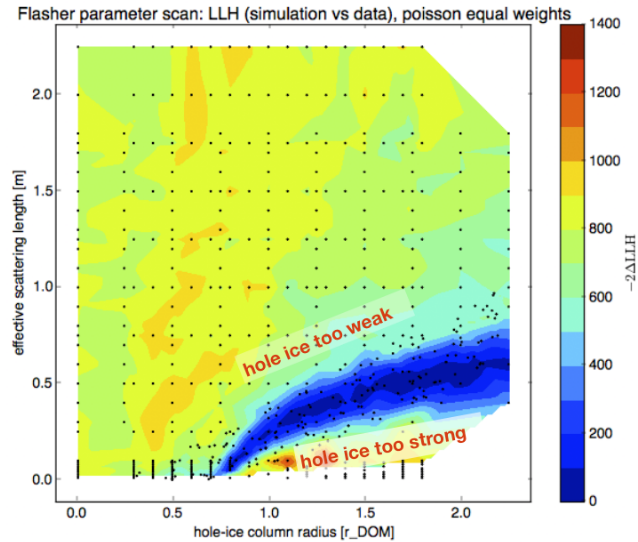
(c) pencil beams, direct detection

(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`

Flasher parameter scan

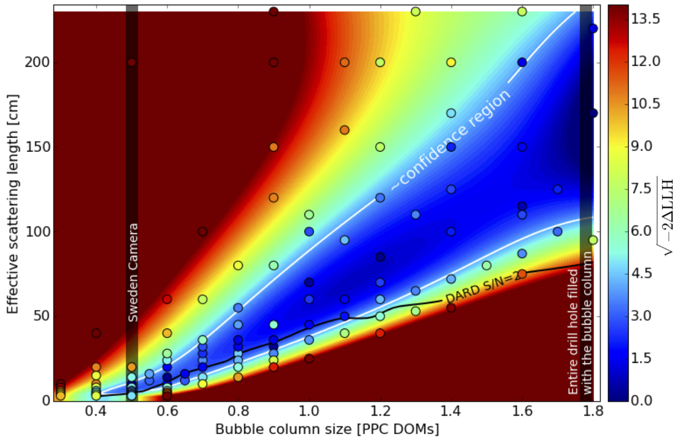




Source: `https://github.com/fiedl/hole-ice-study/issues/59`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

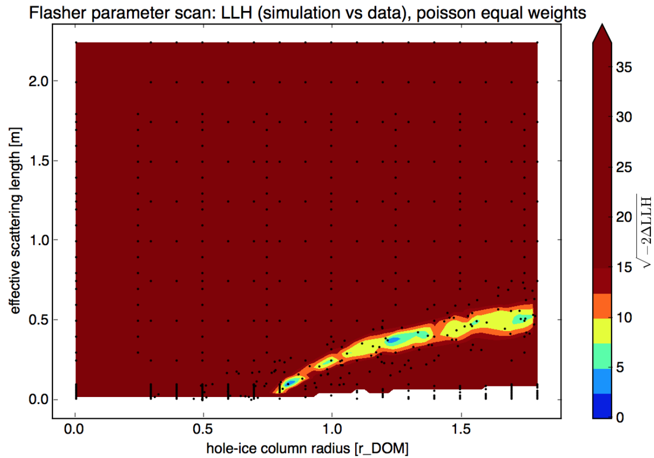
Flasher parameter scan vs. SpiceHD scan

SpiceHD with ppc:



DOM positions are fit parameters.

clsim with direct hole ice:



All DOMs perfectly centered within hole ice.

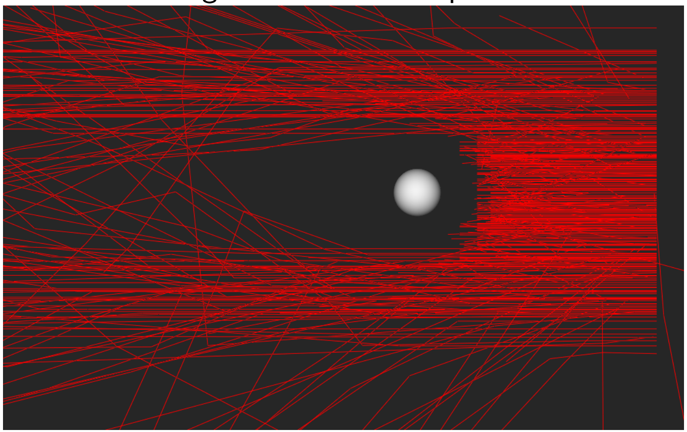
Mind systematics: DOM displacement does account for the observed scattering-length factor $\frac{1}{3}$ for the hole-ice radius of 1.8 dom radii (right-hand side of the plot).

Source: `https://github.com/fiedl/hole-ice-study/issues/106`.

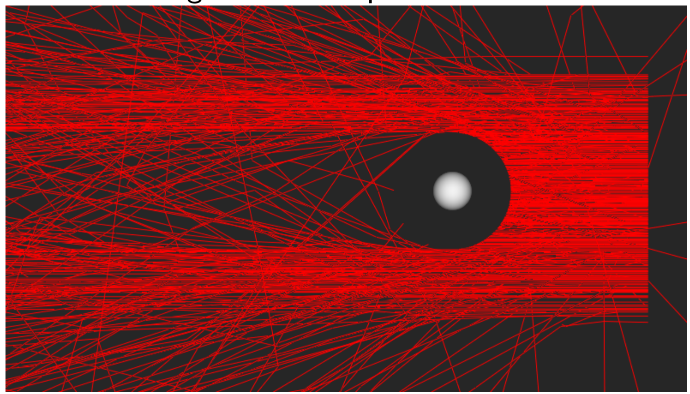
Coordinates-vs-vectors bug

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

Before: Treating coordinates as separate variables

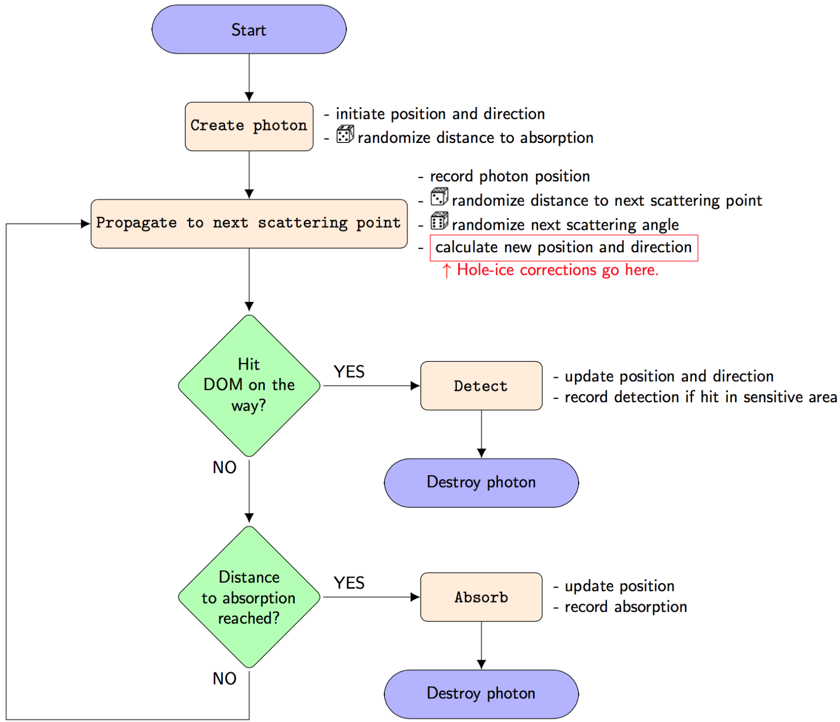


After: Treating vectors as opencl-native vectors



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

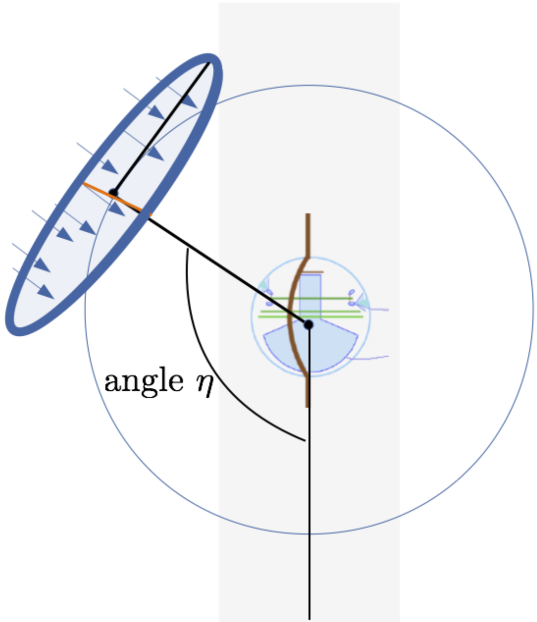
Simplified simulation-step flow chart

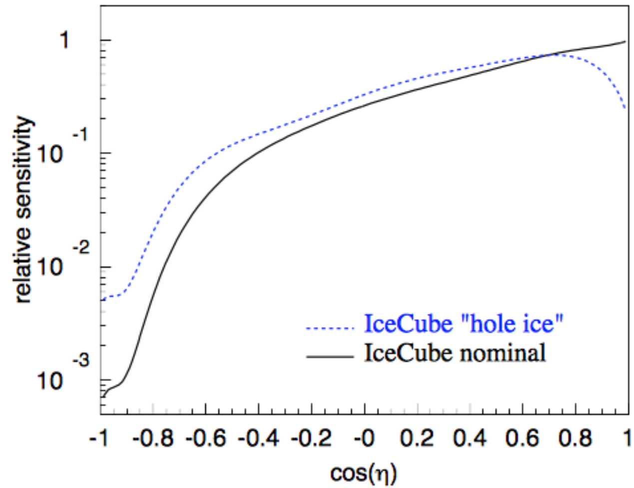


Source: `https://github.com/fiedl/hole-ice-study/issues/75`

Angular acceptance

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



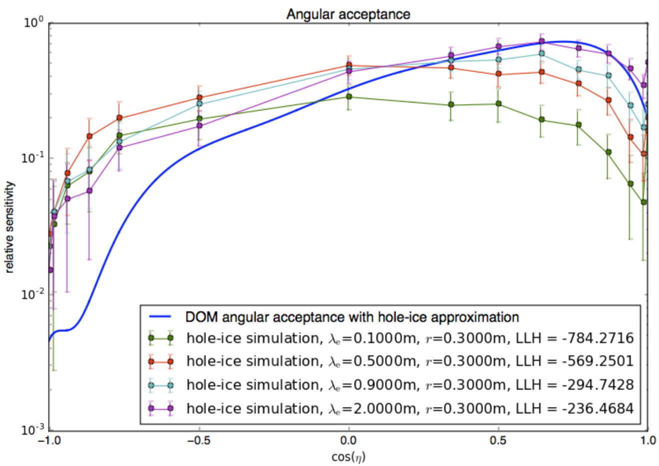


Angular acceptance *reference curves*. The nominal model is based on lab measurement, the hole ice curve on previous simulations.

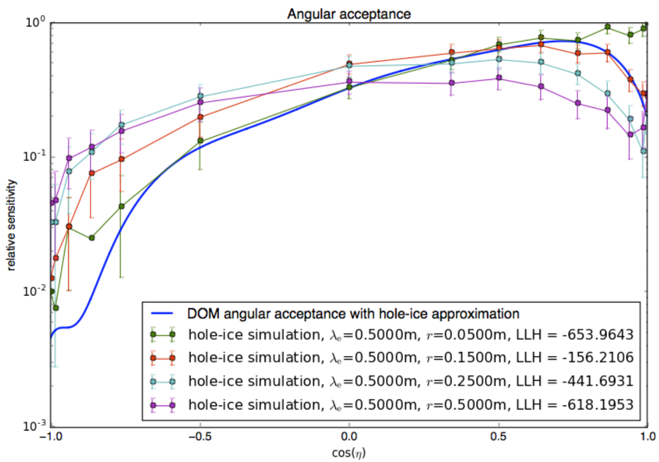
Source: Image: Martin Rongen, Calibration Call 2015-11-06, DARD Update, Slide 9
Plot: Measurement of South Pole ice transparency with the IceCube LED calibration system, 2013, figure 7. See also: `https://github.com/fiedl/hole-ice-study/issues/10`

Angular acceptance for different hole-ice parameters

Vary hole-ice scattering length:

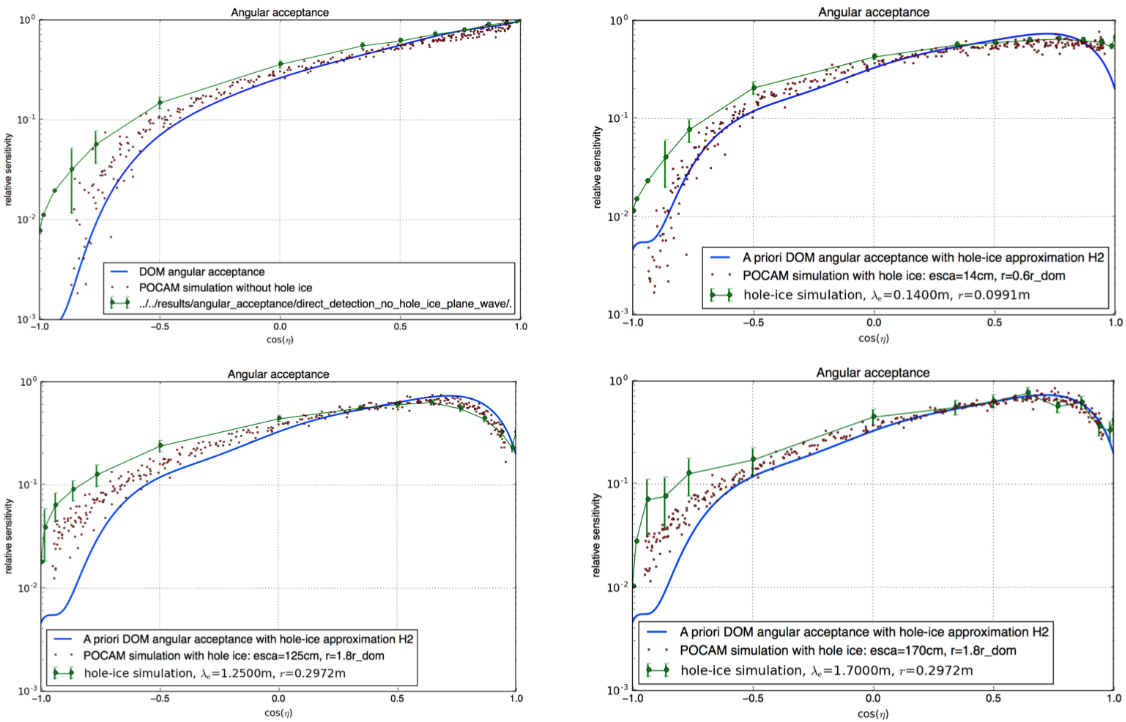


Vary hole-ice radius:



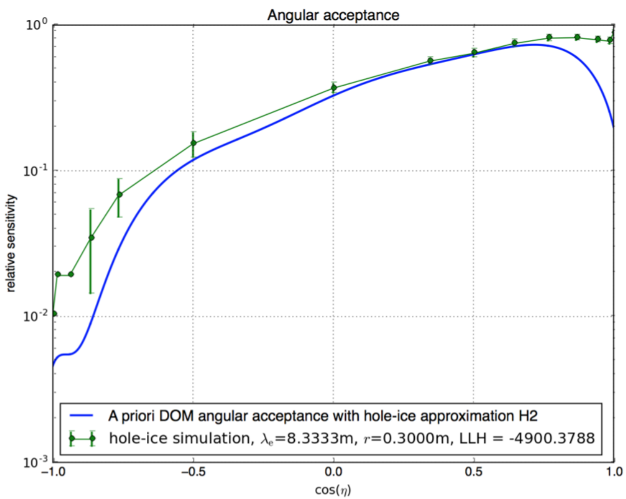
Systematics:
For direct detection + plane waves, increased number of photons for $\cos\eta < 0$.
plane extent 1 m, starting distance 1 m
non-perfect bulk-ice properties

Comparison to ppc simulation

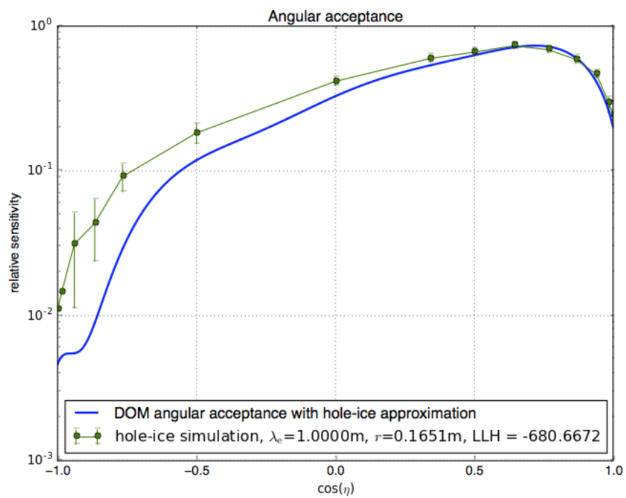


Source: `https://github.com/fiedl/hole-ice-study/issues/4`, POCAM ppc data source: Resconi, Rongen, Krings: The Precision Optical CAlibration Module for IceCube-Gen2: First Prototype, 2017.

Comparison to H2 hole-ice model



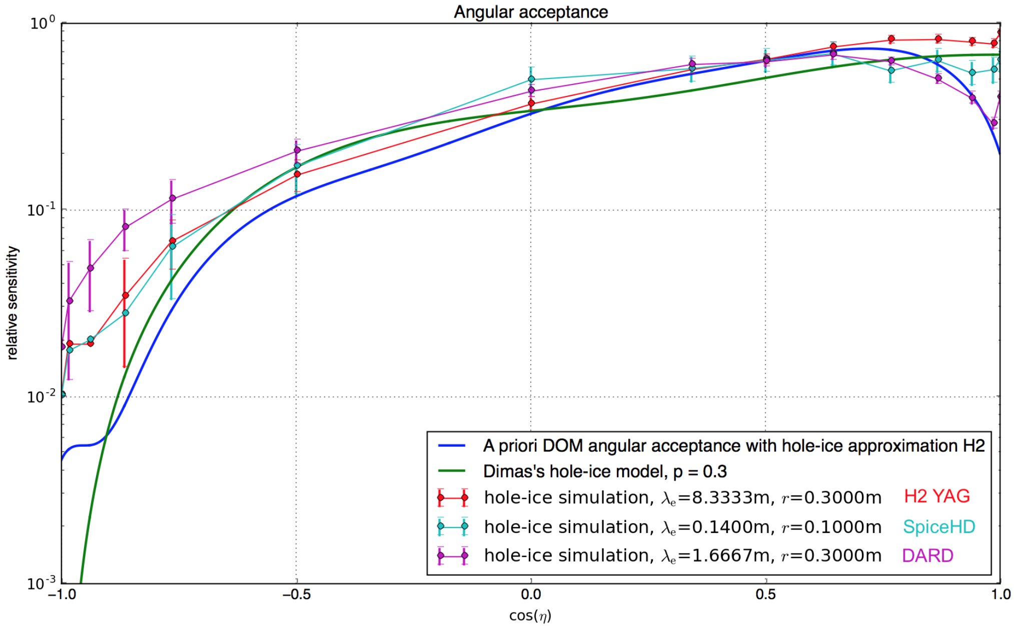
(a) CLSIM simulation with H2 hole-ice parameters: $r = 30\,\mathrm{cm}, \lambda_{\mathrm{sca}}^{\mathrm{H}} = 50\,\mathrm{cm}, \lambda_{\mathrm{sca}}^{\mathrm{H}} = 8.33\,\mathrm{m}$



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

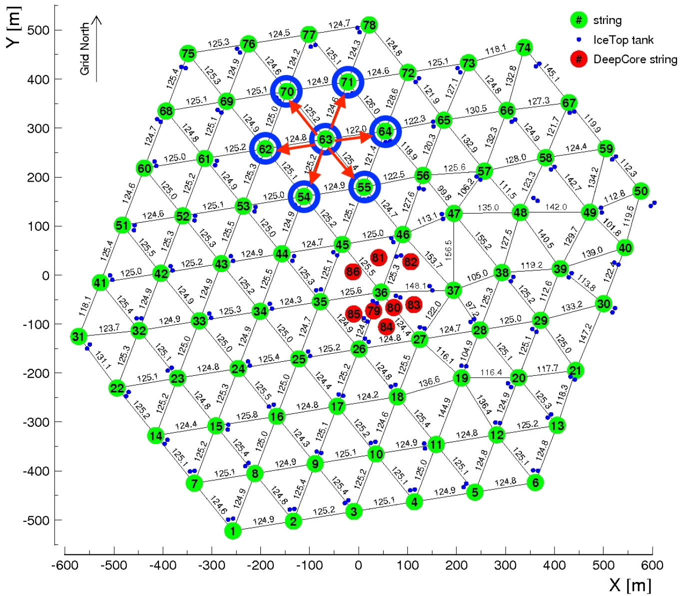
Source: `https://github.com/fiedl/hole-ice-study/issues/80`. **H2 curve source**: IceCube Collaboration et al. Measurement of South Pole ice transparency with the IceCube LED calibration system. 2013. **H2 parameter source**: Albrecht Karle. Hole Ice Studies with YAG. `http://icecube.berkeley.edu/kurt/interstring/hole-ice/yak.html`. 1998.

Comparison of parameters from calibration measurements



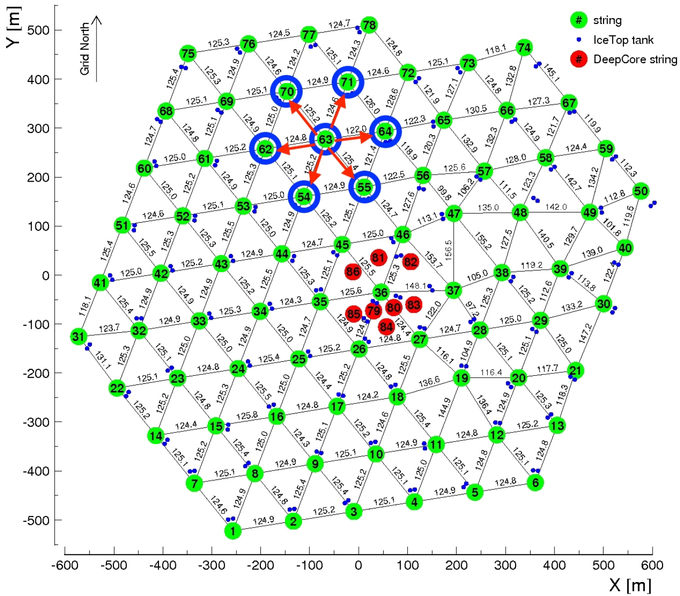
Source: `https://github.com/fiedl/hole-ice-study/issues/104` **H2 YAG**: `https://github.com/fiedl/hole-ice-study/issues/80`. Karle, Hole Ice Studies with YAG, `http://icecube.berkeley.edu/kurt/interstring/hole-ice/yak.html`, 1998. **SpiceHD**: `https://github.com/fiedl/hole-ice-study/issues/87`. Rongen, Status and future of SpiceHD and DARD, Calibration Workshop August 2017. **DARD**: `https://github.com/fiedl/hole-ice-study/issues/105`. Rongen, Measuring the optical properties of IceCube drill holes, 2016. Rongen, DARD Update, Calibration Call 2015-11-06.

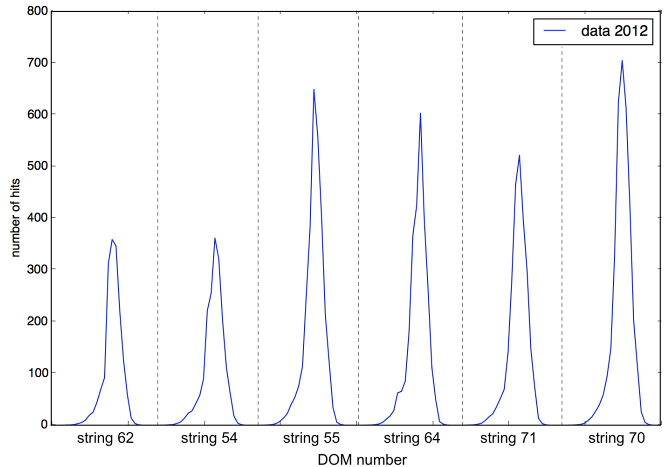
Direct cable simulation: Flasher



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

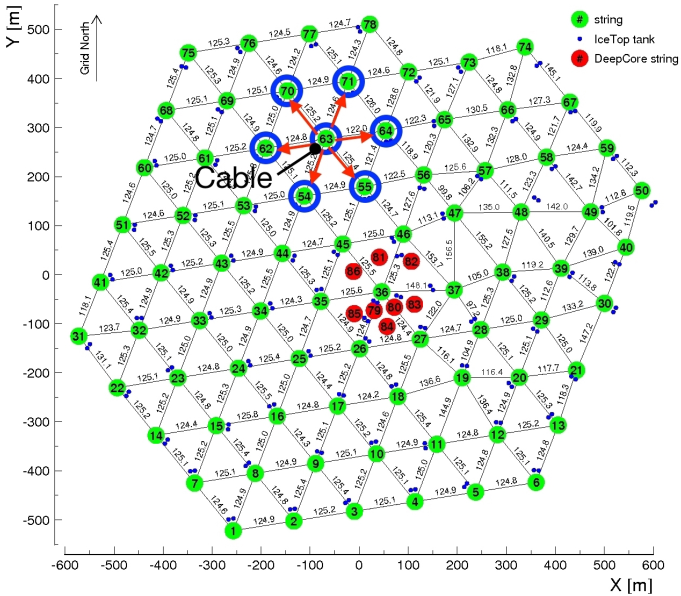
Direct cable simulation: Flasher

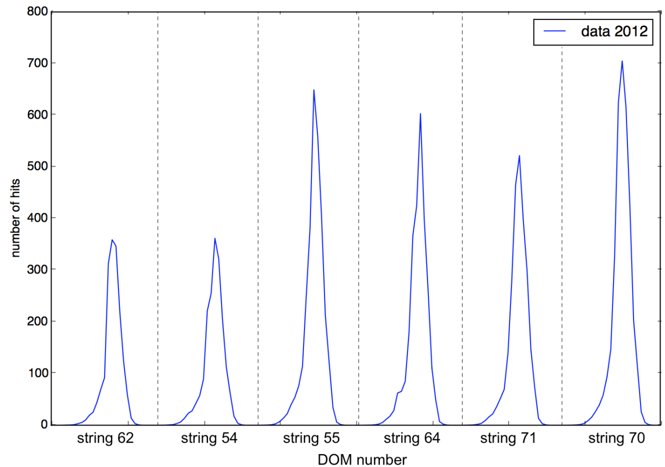




Source: `https://github.com/fiedl/hole-ice-study/issues/97`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

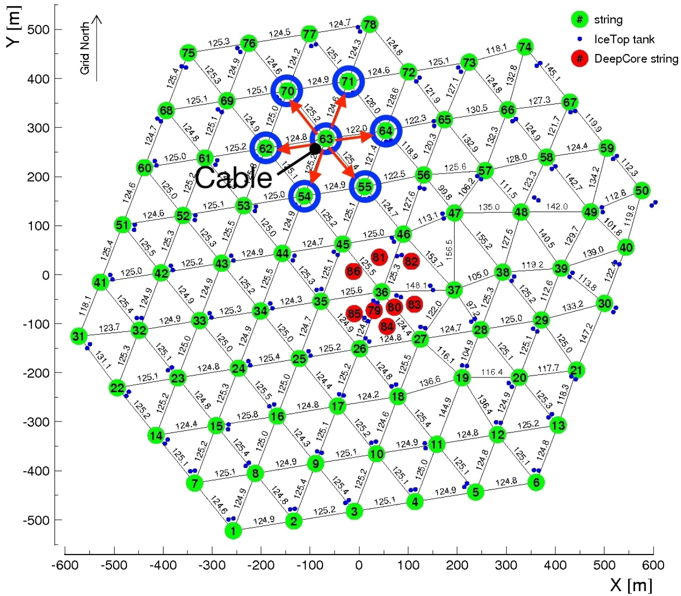
Direct cable simulation: Flasher

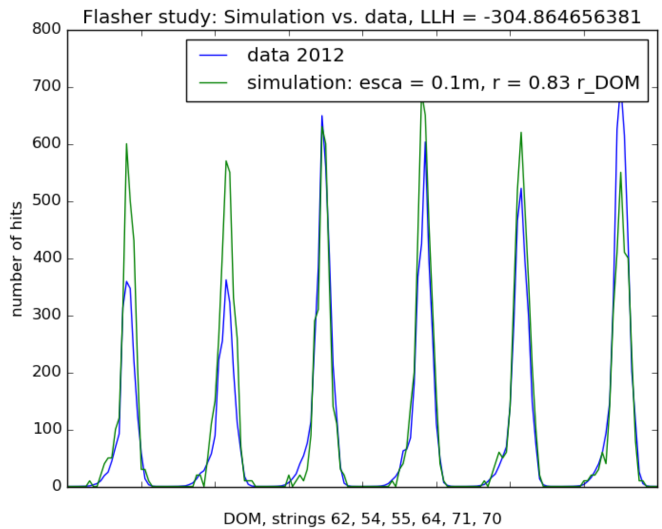




Source: `https://github.com/fiedl/hole-ice-study/issues/97`. Image based on `https://wiki.icecube.wisc.edu/index.php/File:Distances.i86.jpg`.

Direct cable simulation: Flasher





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