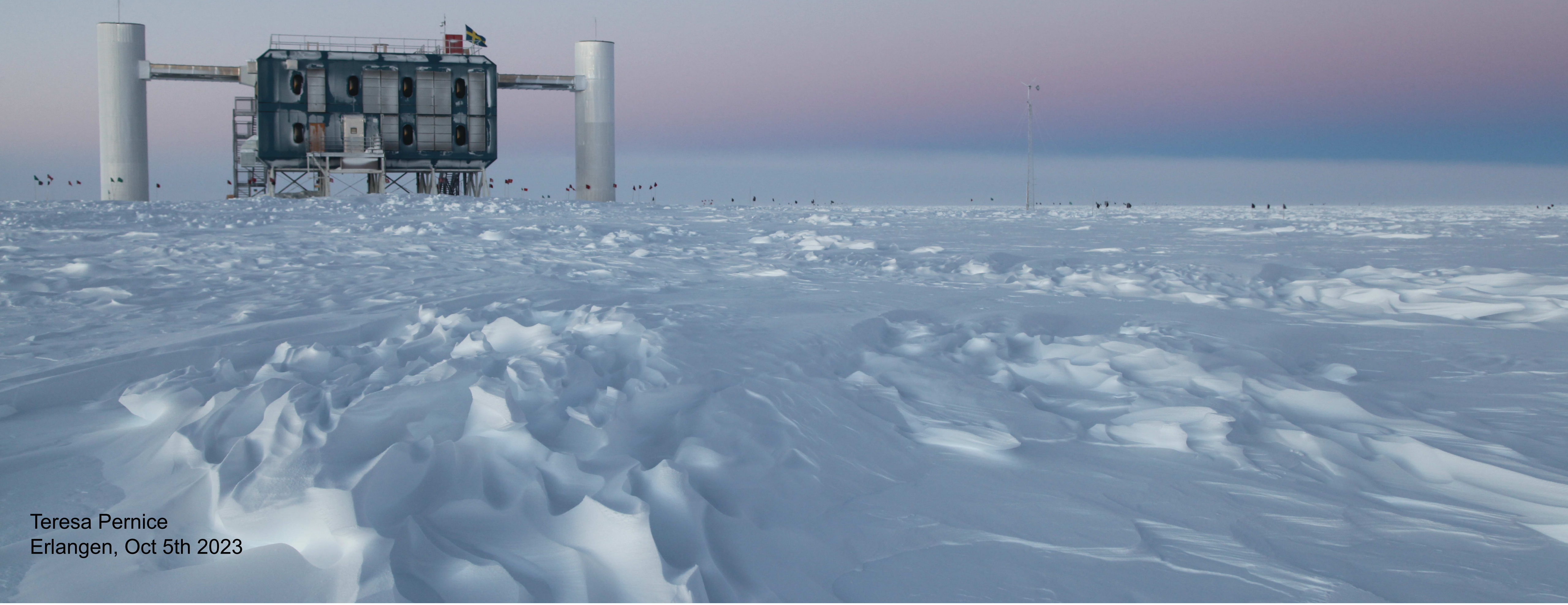
Photon propagation in the ice of the South Pole

A toy simulation to study photon diffusion in dust layers of the Antarctic ice



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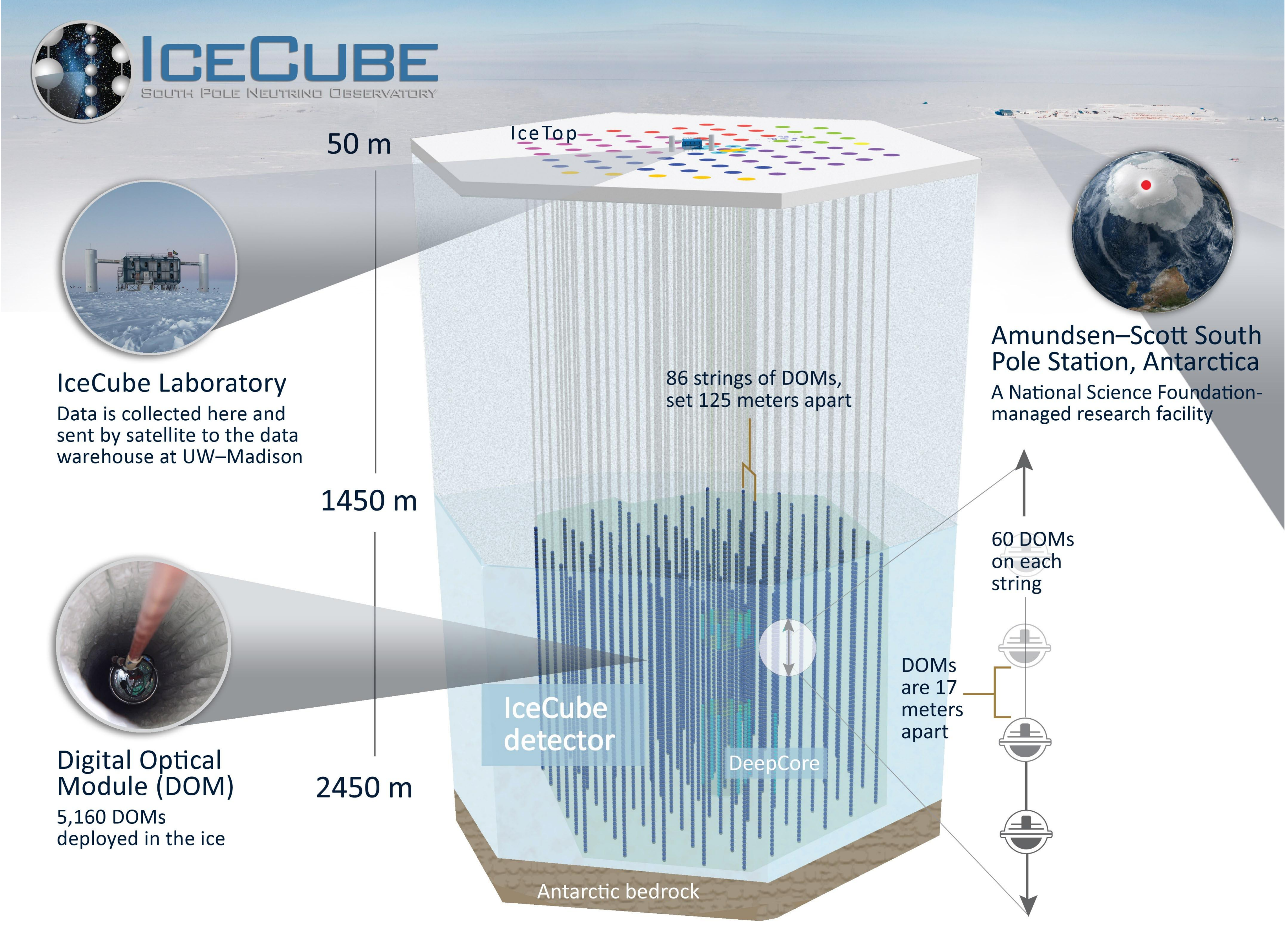
Erlangen, Oct 5th 2023

HELMHOLTZ
Young Investigators

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

DESY.



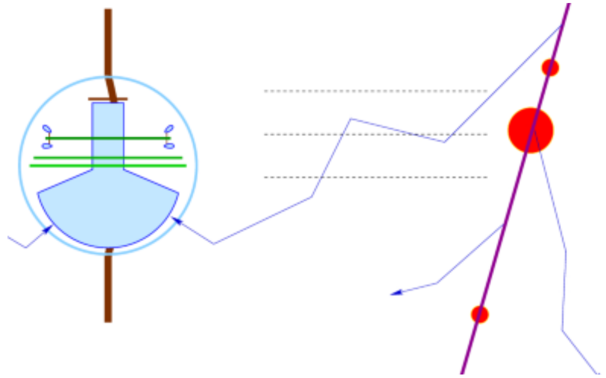
IceCube

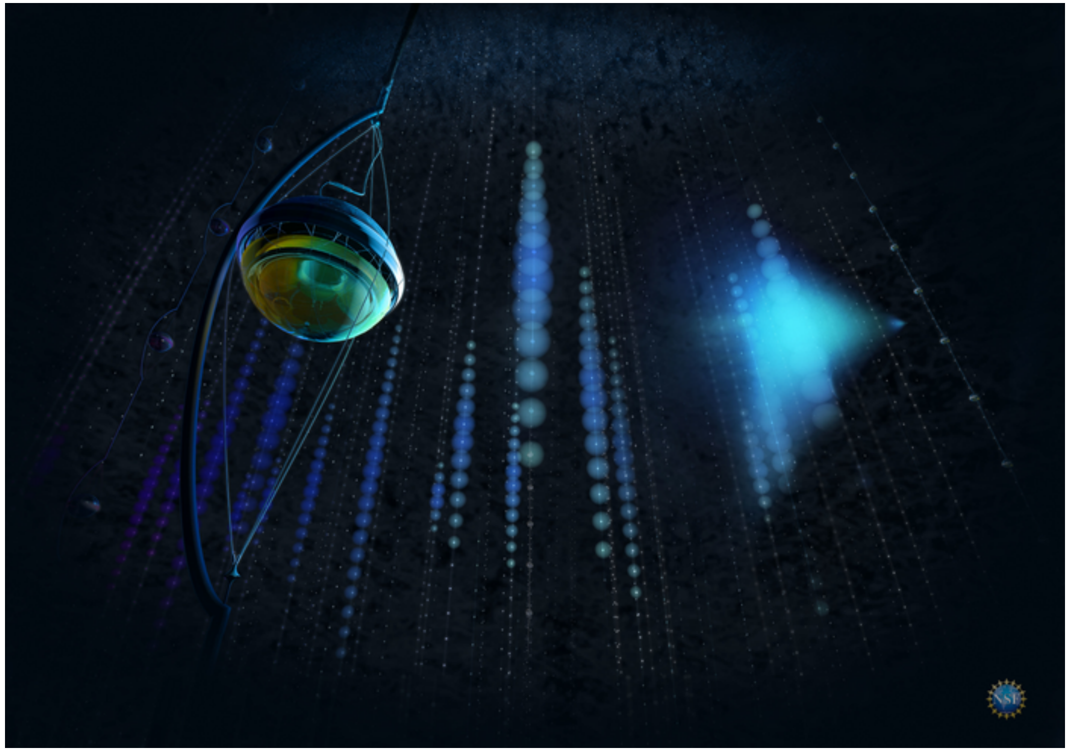
- **Cubic-kilometer** neutrino detector made of Antarctic ice buried below the surface.
- **86 strings** with a total of 5160 **digital optical modules (DOMs)** used to sense and record neutrino events.
- **Ice-top** consist of 81 stations, built as a **veto** and **calibration** detector and to detect cosmic ray **showers**.
- **DeepCore** is located at the centre of the array, in a denser configuration to study neutrino oscillations.

Figure: IceCube collaboration

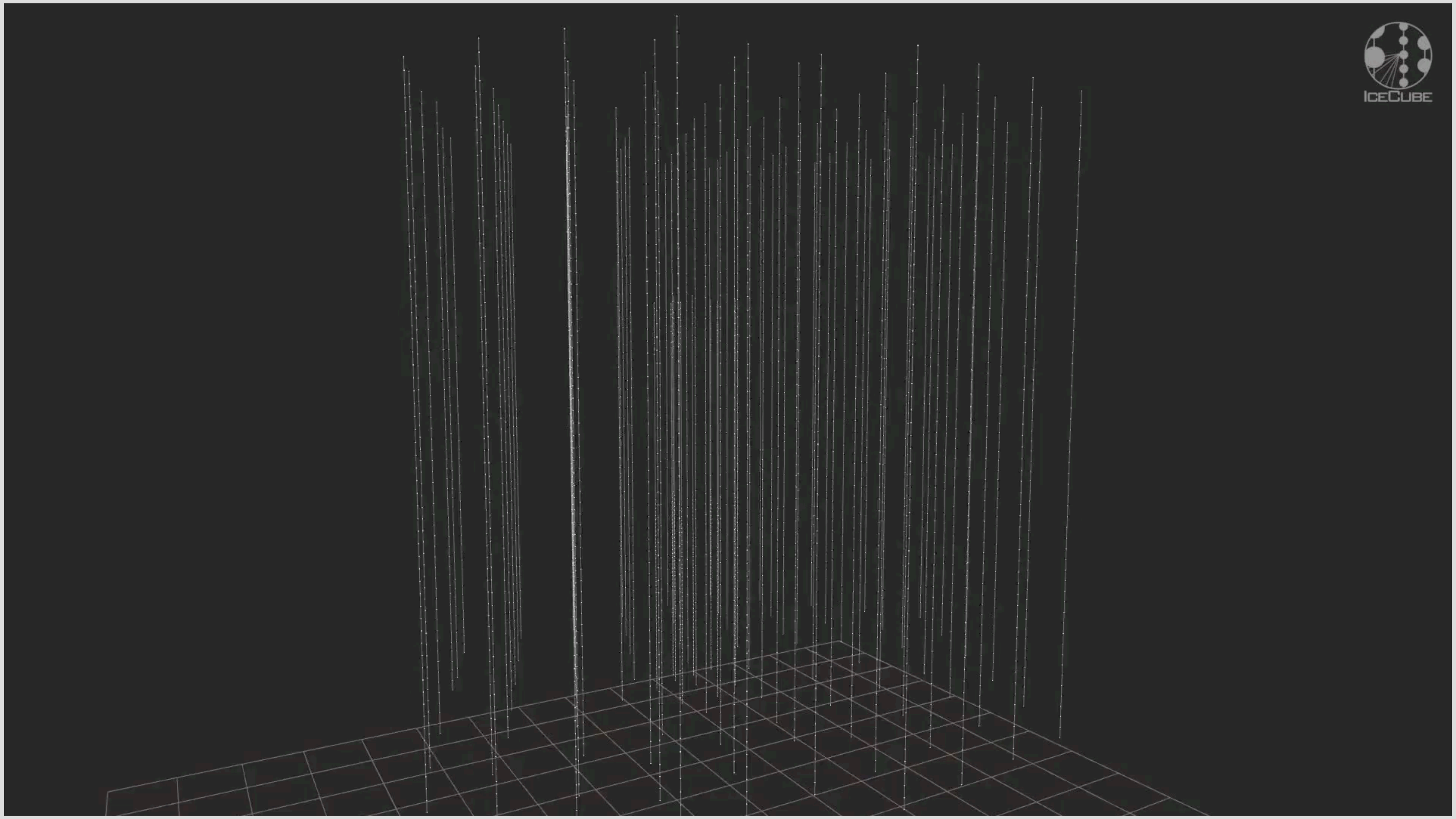
Neutrino Detection

- Neutrino are electrically neutral leptons that rarely interact with matter.
- When they do react with molecules of ice, they can produce electrically charged secondary particles that emit **Cherenkov radiation**.
- This light can be detected by **photomultiplier** tubes within the DOMS in IceCube.
- The light pattern and photon arrival time are used to reconstruct direction and energy of the incoming neutrino.
- Understanding the optical properties of the Antarctic ice is crucial to the performance of IceCube.





Photons propagating in IceCube

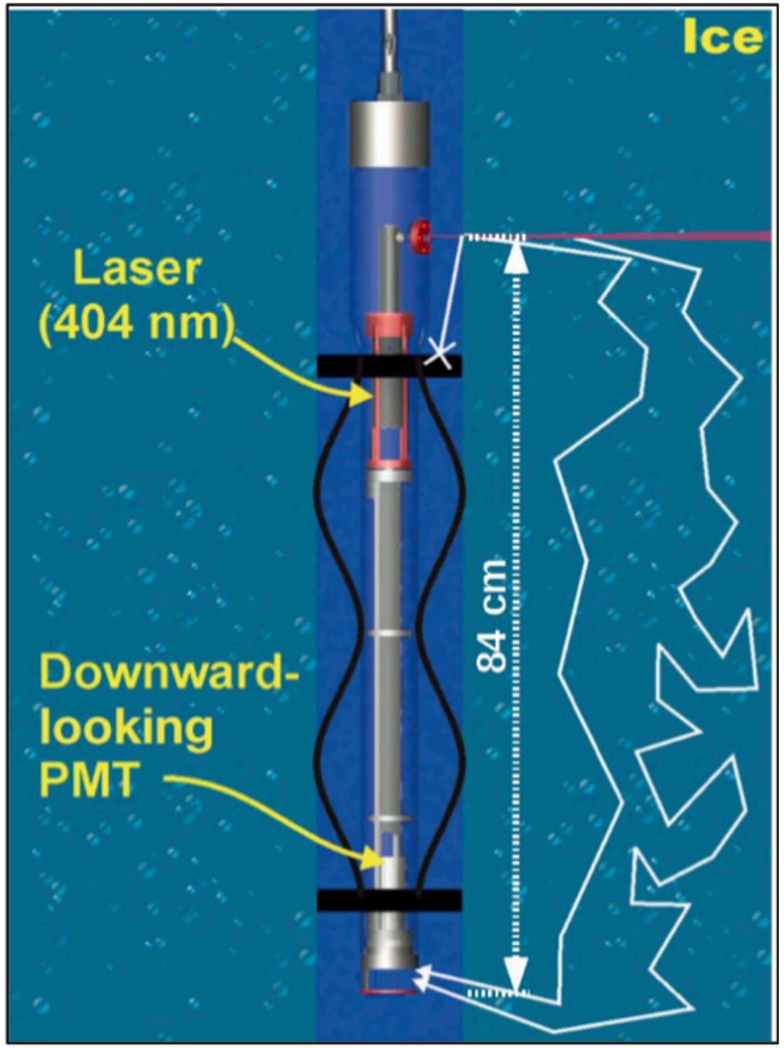


0.01% of Cherenkov photons generated by a 100 TeV muon in ice

Ice Anisotropies and Calibration

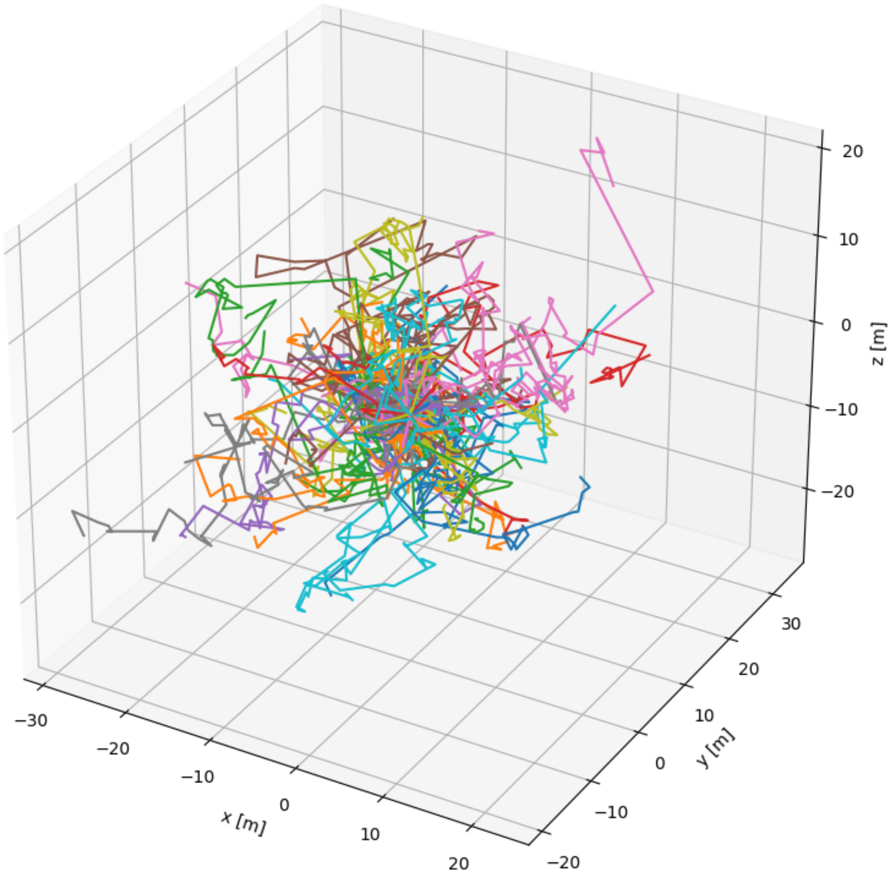
Dust layers and dust loggers

- Characterisation of physics quantities possible by calibrating the ice and instruments.
- **Dust loggers** shone a fan-shaped horizontal beam of laser light which is recorded by a downward- pointing Photo-Multiplier Tube (PMT) after scattering in the ice
- The loggers produced a record of **dust layers** in ice with very high resolution that have identical optical scattering and absorption
- These layers have so far been described in 10 m wide ice bins
- **Optical anisotropy** was observed : photon propagation is affected depending on their direction
- From dust loggers data we know that after 2000 m in depth, the South Pole ice presents a dust layer with higher scattering and absorption coefficients



MC Simulation: trace photons through homogeneous ice

- **Homogeneous** ice
- **Isotropic** scattering
- Number of photons: 10000
- Step size: 0.5 m
- Number of steps: 2000
- Scattering length λ_s: 2.5 m
- Absorption length λ_a: 60 m
- Probability of scattering at each step: $P_s \simeq dx/\lambda_s$
- Probability of absorption at each step: $P_a \simeq dx/\lambda_a$

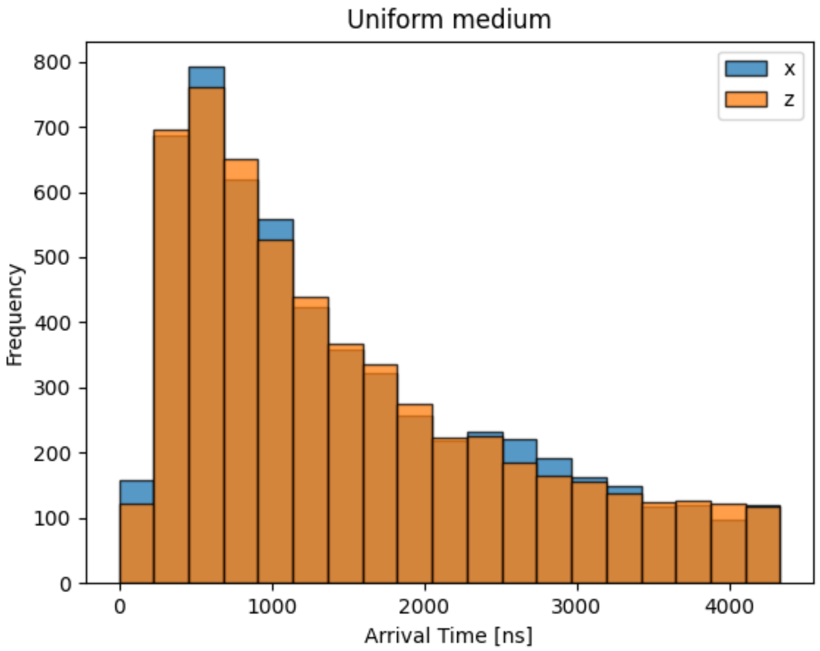


100 steps trajectories of first 200 photons starting from the origin

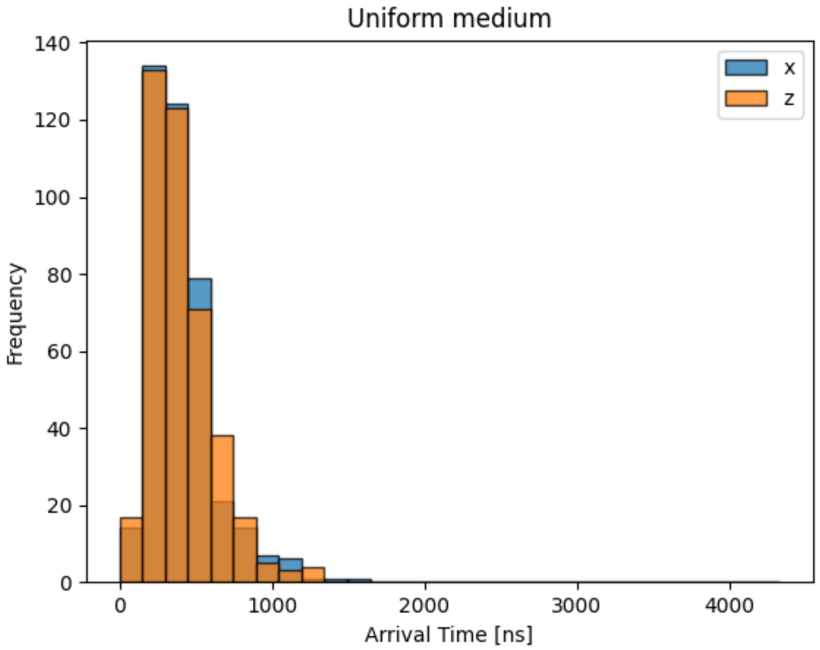
Photon propagation

Homogeneous ice

- Photon arrival time distribution along **horizontal** and **vertical** direction, at a distance of d = 20 m
- Only scattering



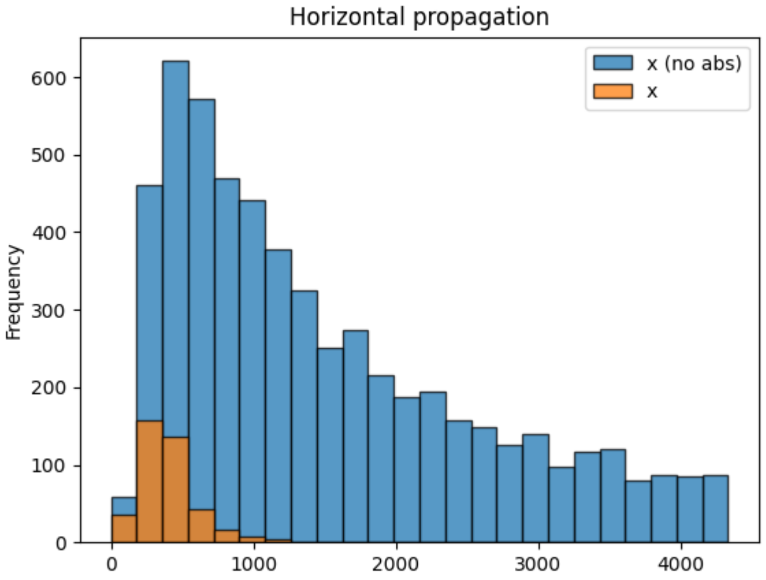
- Photon arrival time distribution along the horizontal and vertical direction, at a distance of d = 20 m
- Scattering and Absorption

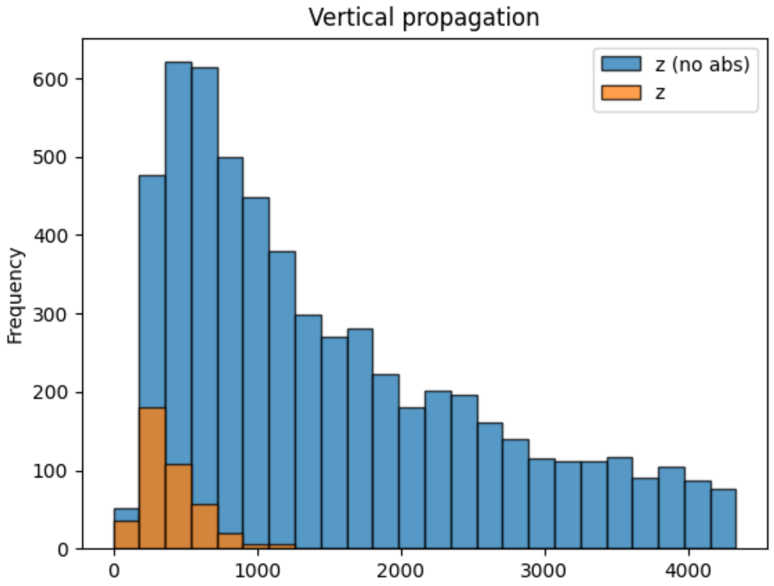


Horizontal and Vertical propagation

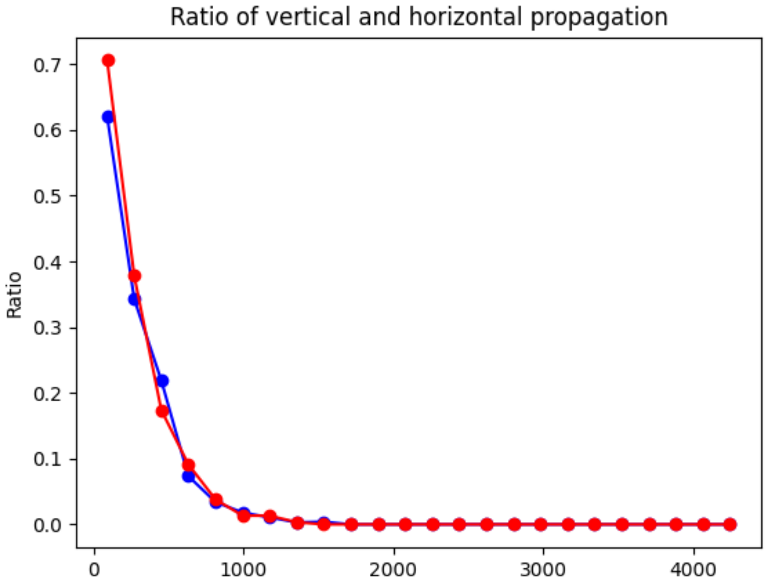
Homogeneous Ice

- Arrival time distribution of photons reaching 20 m along the **x-axis** and the **z-axis**





- Ratio of with and without absorption distributions, for both vertical and horizontal propagation



Photon propagation as diffusive process

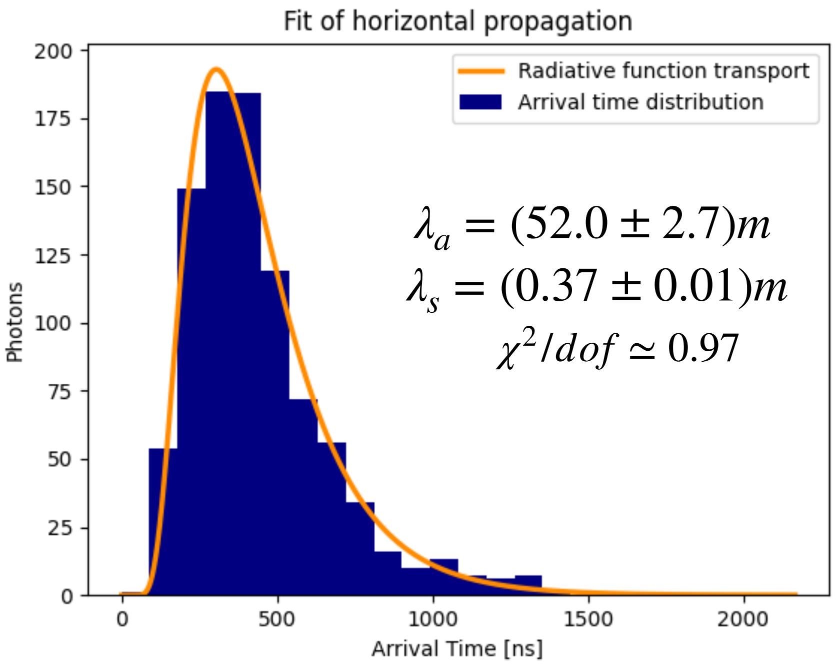
- After a large number of scatterings the process can be considered **diffusive** (Random Walk)
- Fit of the distribution using Green's function for radiative transport

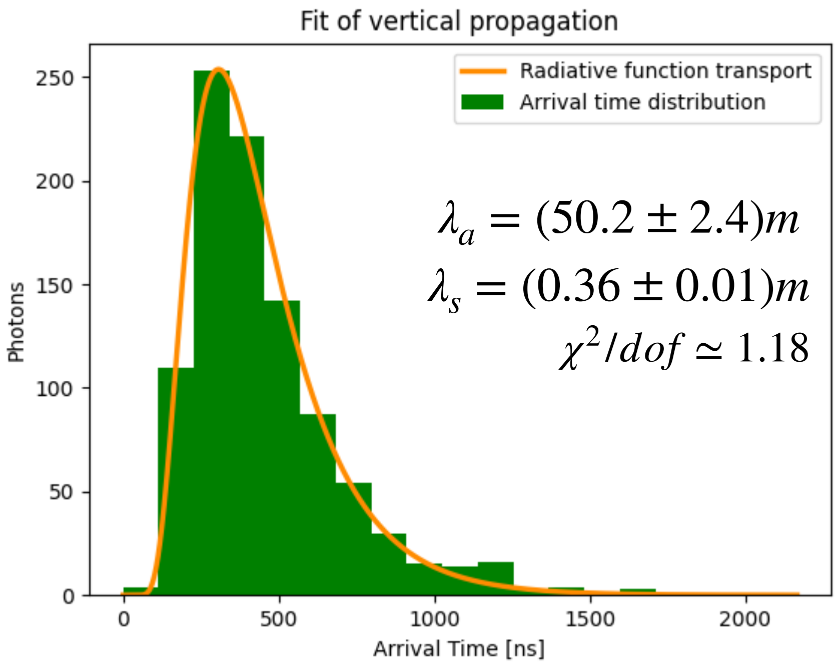
$$u(d,t) = \frac{1}{(4\pi D t)^{3/2}} e^{\frac{-d^2}{4Dt}} e^{\frac{-c_i t}{\lambda_a}}$$

- *u(d,t)* : density of photons (normalised to unity at t=0)
- *d* distance from the source at time *t*
- $D = \frac{c_i \lambda_s}{3}$ constant of diffusion
- c_i velocity of light in ice

Simulation parameters:

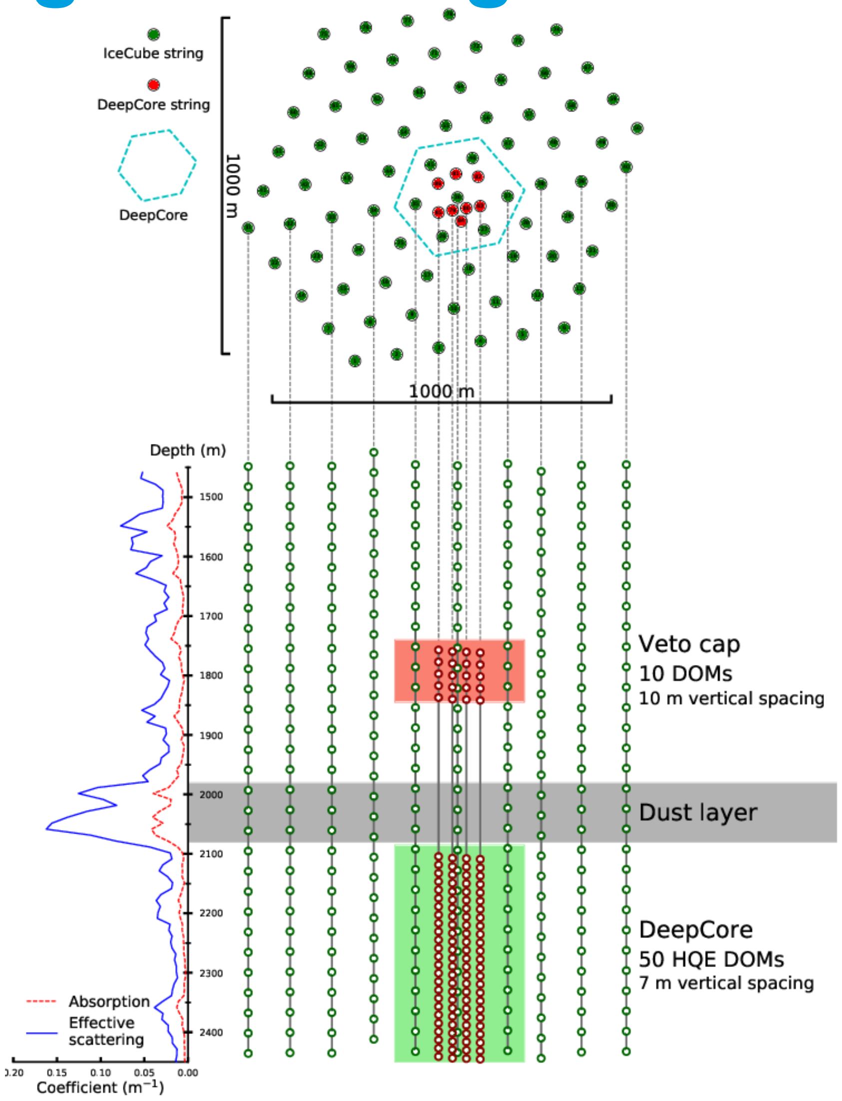
- d = 10 m, 30000 photons, dx = 0.1, 5000 steps
- $\lambda_s = 0.5m, \lambda_a = 60m$
- 10 repetitions





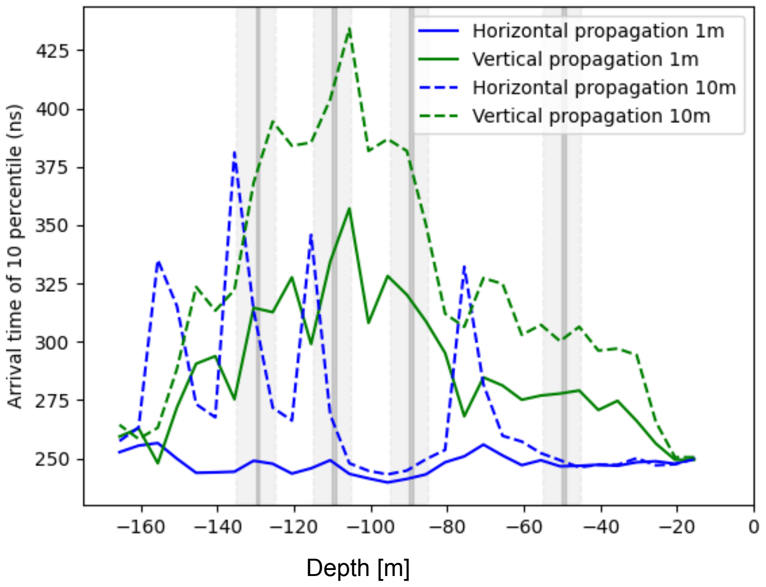
MC Simulation: trace photons through inhomogeneous ice

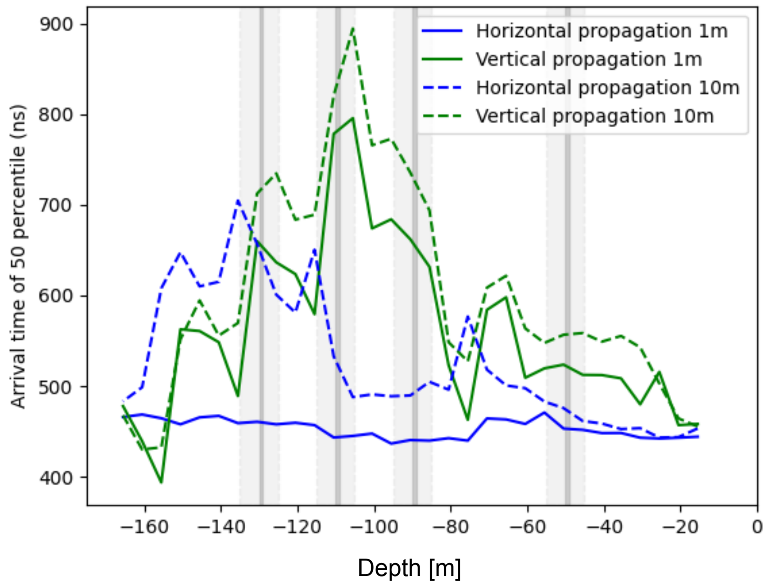
- **Layered** ice
- **Isotropic** scattering
- Number of photons: 10000
- Step size: 0.05 m
- Number of steps: 10000
- **Dust layer** modelled with **4 thin layers** with higher scattering and absorption coefficients separated by thicker layers with lower interaction probability

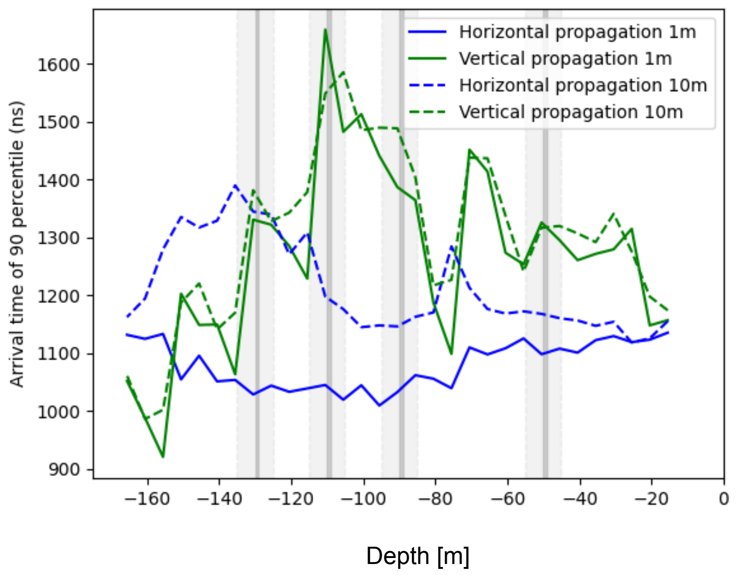


Top and side view of IceCube detector. Figure: IceCube collaboration

Arrival time of photons as a function of depth







- Study of the arrival time of the first **10%**, **50%** and last **10%** photons to an observer placed **60 m** from the emitter
- **Depth** is the z-coordinate of the half-distance between observer and receiver
- Two layer configurations: **1 m** and **10 m** wide bins

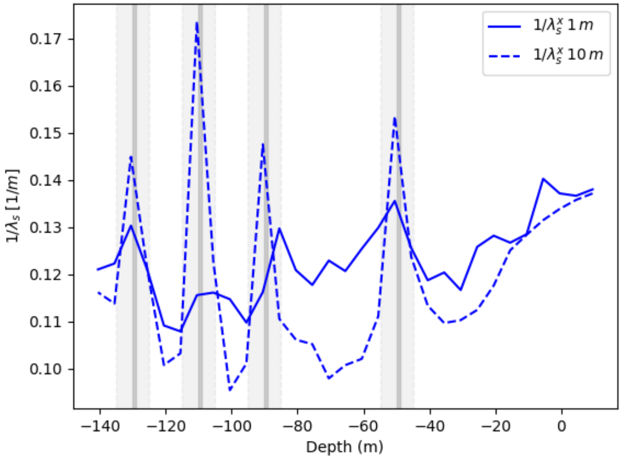
- Scattering and absorption lengths change of a factor ten in the two configurations
- Photons arrival time for vertical propagation becomes similar for the late photons
- Horizontally, photons take more time to reach the observer in wider bins

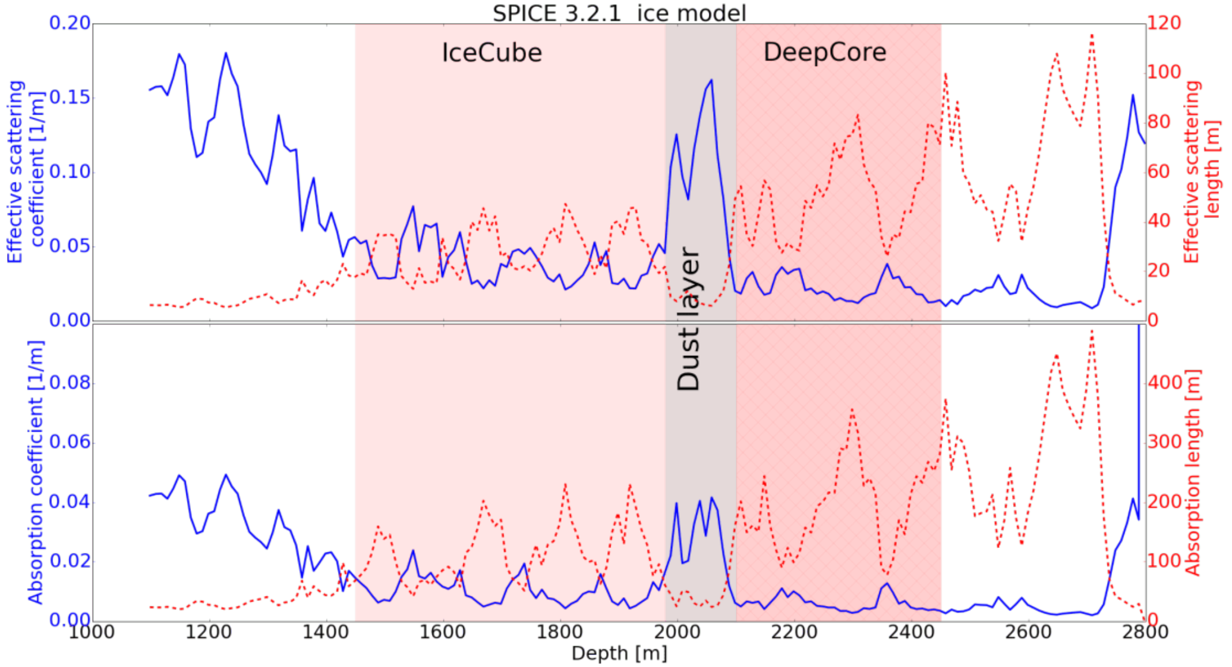
Summary

- The code works well for isotropic scattering and absorption in homogeneous ice
- Green’s function for radiative transport reconstructs scattering and absorption length from the arrival time PDFs
- There is a difference in arrival time for vertical propagation of early photons between 1m and 10 m wide bins
- Horizontal propagation has a clear different behaviour in the two bins configuration

Next steps:

- Use another diffusive model to fit arrival time distribution in inhomogeneous ice
- Recreate the dust layer depth profile for both configuration by tuning the simulation parameters





Thank you!

Contact

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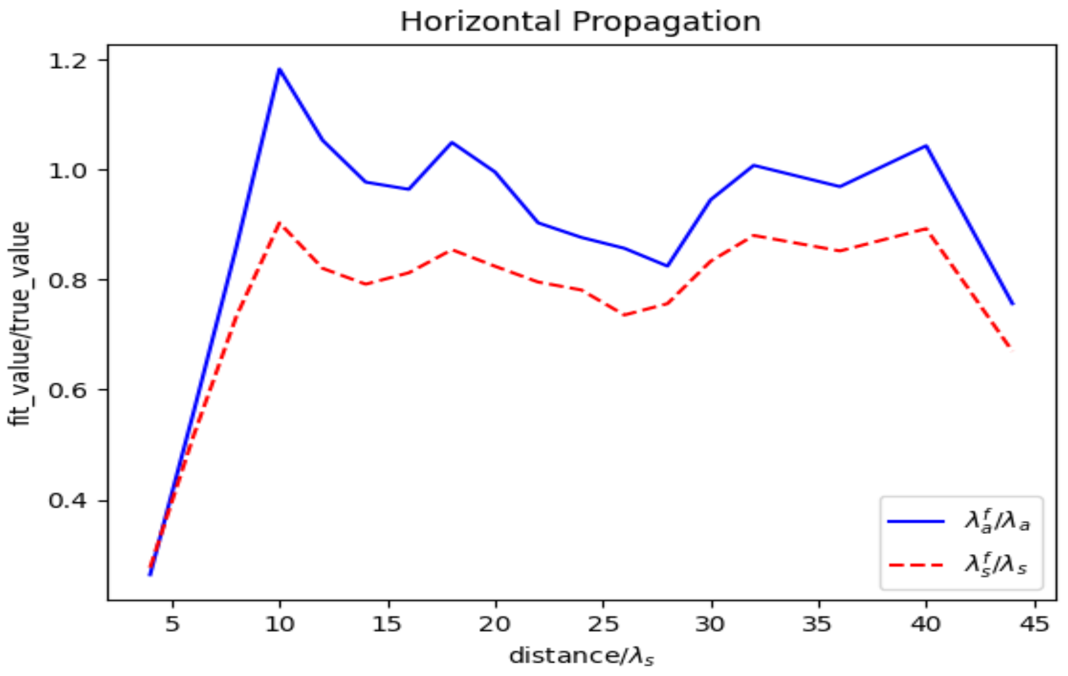
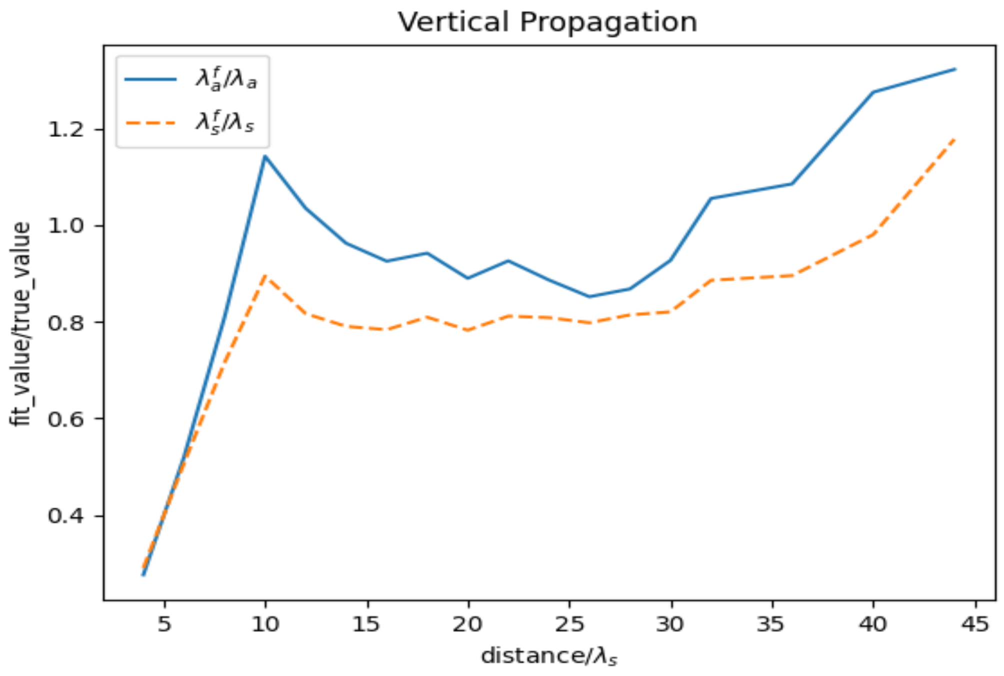
Backup slides

Scattering and Absorption length

As a function of distance between source and observer

- Ratio between the value obtained from the fit of scattering (absorption) length over the true value (of the MC simulation)
- For shorter distances both scattering and absorption lengths are underestimated.





Scattering coefficient as a function of depth