Cascade Simulation for Neutrino Telescope

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Part I

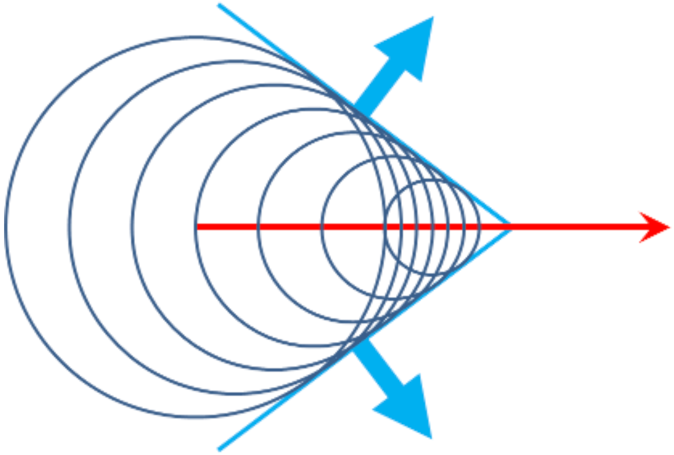
Cascade Event in Neutrino Telescope

1.1 The Neutrino Telescope

Detection Principle

Neutrino Telescope observe the Cherenkov photons from charged particles produced by neutrino-nucleon interaction.

Observation by arrays of Digital Optical Module (DOM) housing in the medium.



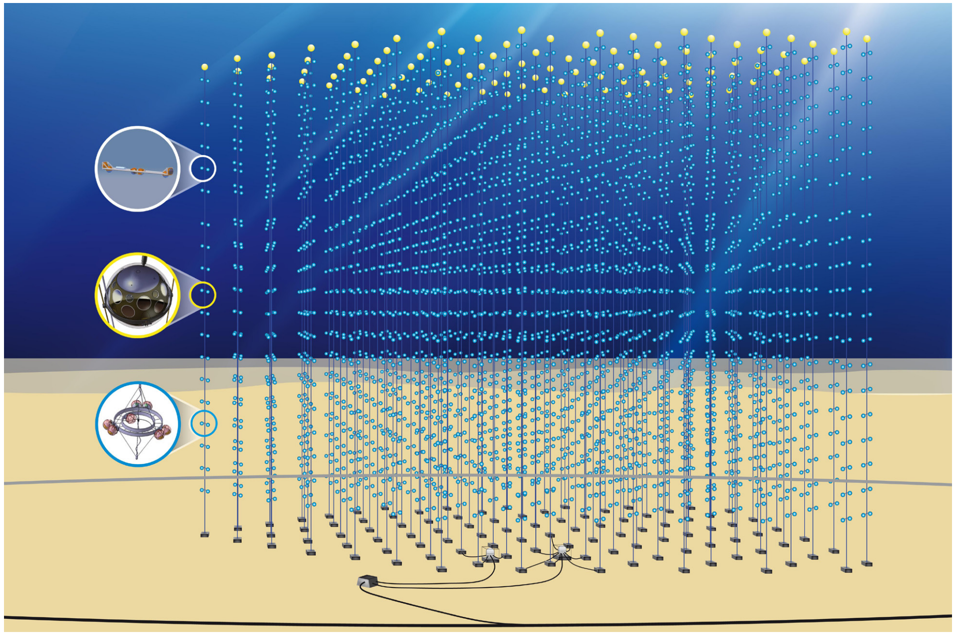


Image from KM3NeT website

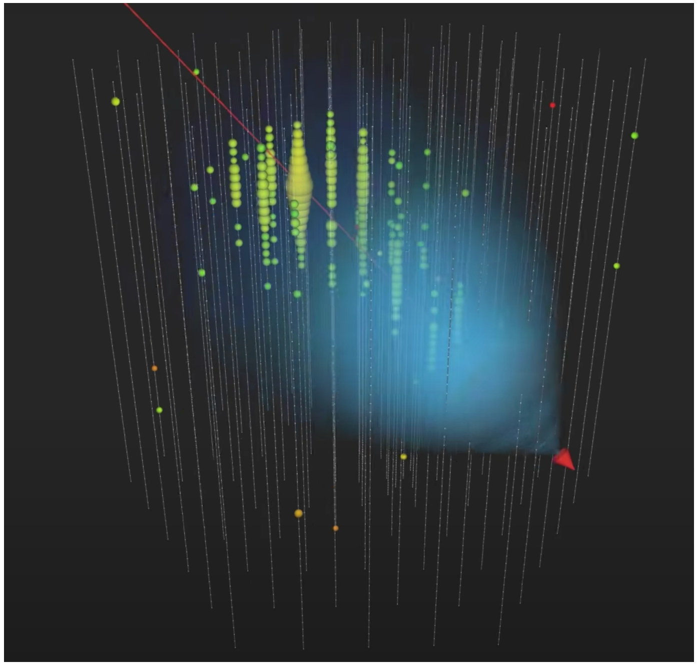
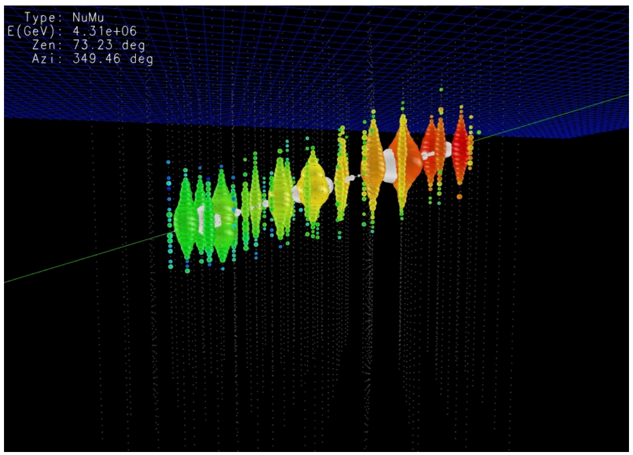


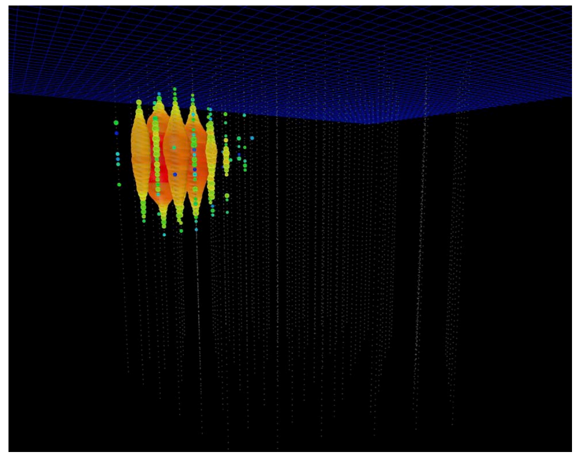
Image from IceCube website

1.2 Event in Neutrino telescope

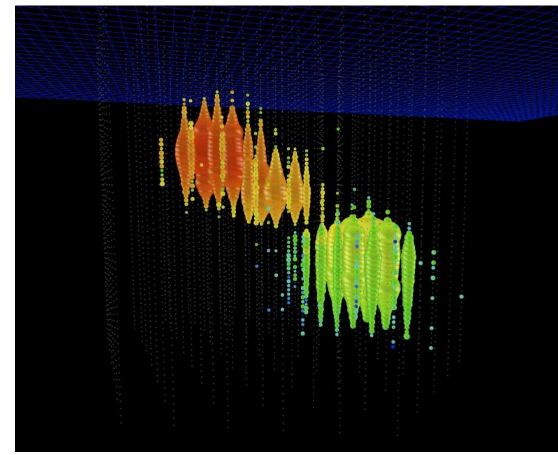
Track event by ν_μ CC



Cascade event by ν NC or ν_e, ν_τ CC



Double cascade event by ν_τ CC and τ decay



From F. Halzen and S. R. Klein, Review of Scientific Instruments, 2010

1.3 Reconstruction of Cascade Event

Direction uncertainty:
- IceCube: $> 10°$
- KM3NeT: $\gtrsim 1°$ *A. Trovato, PhD Thesis, 2014*

Mainly due to the difference of photon scattering length in water and ice.

Effective scattering length:
- IceCube: $\lesssim 20\ m$
- KM3NeT: $\lesssim 500\ m$

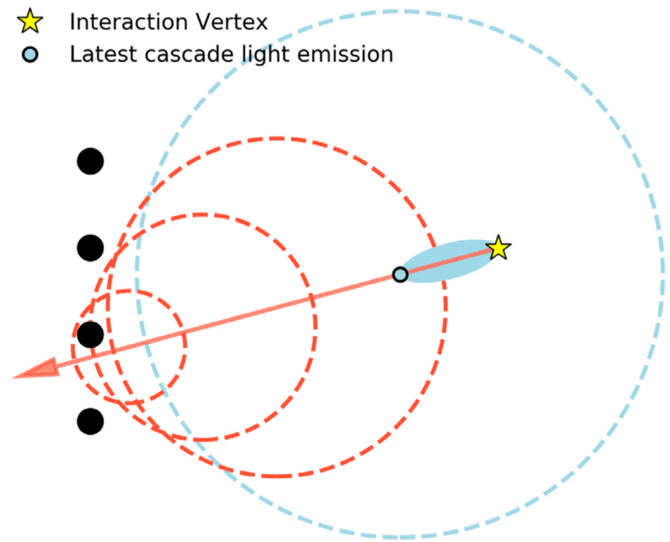
The string spacing length is ~100m.
For water medium, the scattering length is much longer than string spacing length.
We can see the cascade more clearly.

1.4 More Physics to Gain with Cascade

Using high energy muons generated in hadronic cascade to improve the angular resolution of cascade event.

$\gtrsim$ 10 muons above 10 GeV for a hadronic cascade of 1 PeV

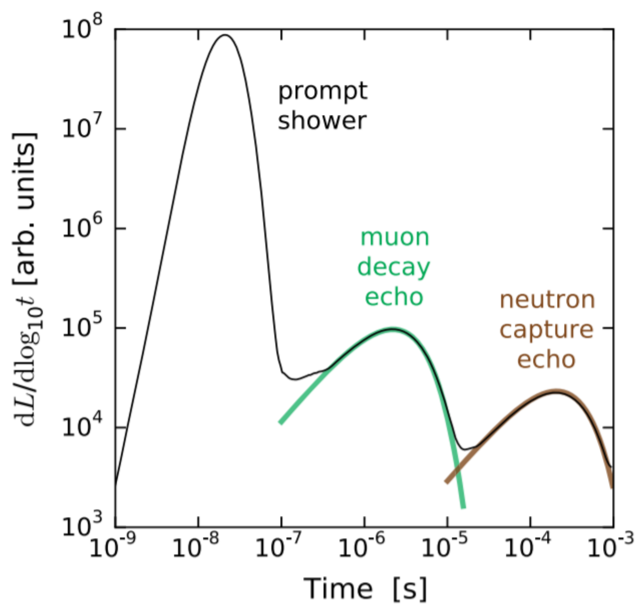
C. Haack et. al. in ICRC 2019



Distinguish hadronic cascade and EM cascade by low energy physics.

- Muon echo: π^- capture and π^+ decay followed by μ^+ decay.
- Neutron echo: neutron capture emit gamma rays and Compton scatter electrons.

S. Li et. al. PRL, 2019



Part II

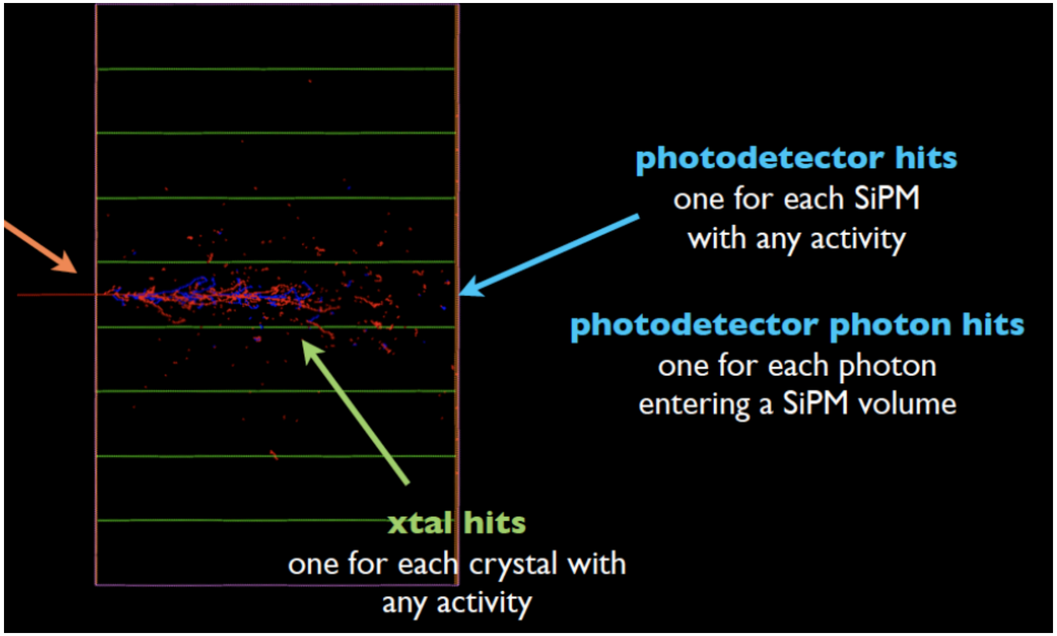
Simulation of Cascade Event with Geant4

2.1 Geant4 Simulation

Geant4 is a powerful toolkit used in HEP.
One can simulate 'any' physical process in Geant4 as long as the right physics models are used.

The framework of Geant4 is more suitable for detector response simulation.

- Handle complex geometry
- Sensitive detector settings



EM cascade in lead calorimeter

2.2 Geant4 Simulation - Limitation

1. Energy limit:

The hadronic inelastic interaction model provided by Geant4 (FTFP_BERT / QGSP_BERT) are only valid at energy below 100 TeV/n
'Standard' EM interaction has energy threshold of 1 PeV.

One have to build his/her own Physics Processes at higher energy.

2. Speed limit:

It takes too much time to track all secondaries down to Cherenkov energy threshold ($v = 0.5c$) of a high energy cascade event.

There are $>$ 1 billion of Cherenkov photons generated in a ~100 TeV cascade event. It is almost impossible to track those photons in Geant4.

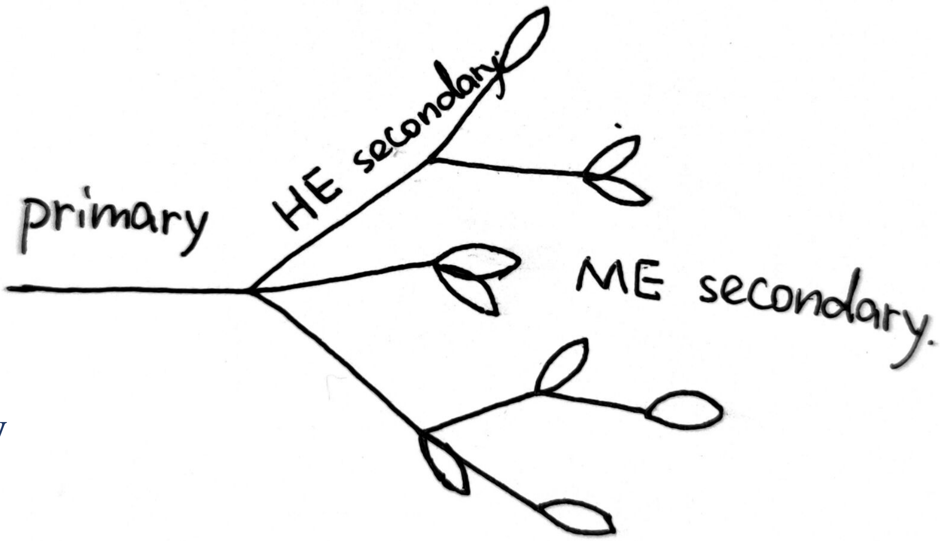
2.3 Simulation Strategy – Set Cut

Set energy cut:

If a secondary particle has energy in between 1GeV and 100GeV, we pop it out and record it for the next step simulation.
Those middle energy secondaries are the main sources of Cherenkov photons (> 99% of total energy).

Schematic diagram:

- Root: primary particle
- Stem: high energy secondary
- Leaf: middle energy secondary



2.4 Simulation Strategy – Use GPU

Propagate photons in GPU:

Use an external CUDA program to generate photons, track photon scattering and absorption, test photon intersection with detector (ray-tracing).

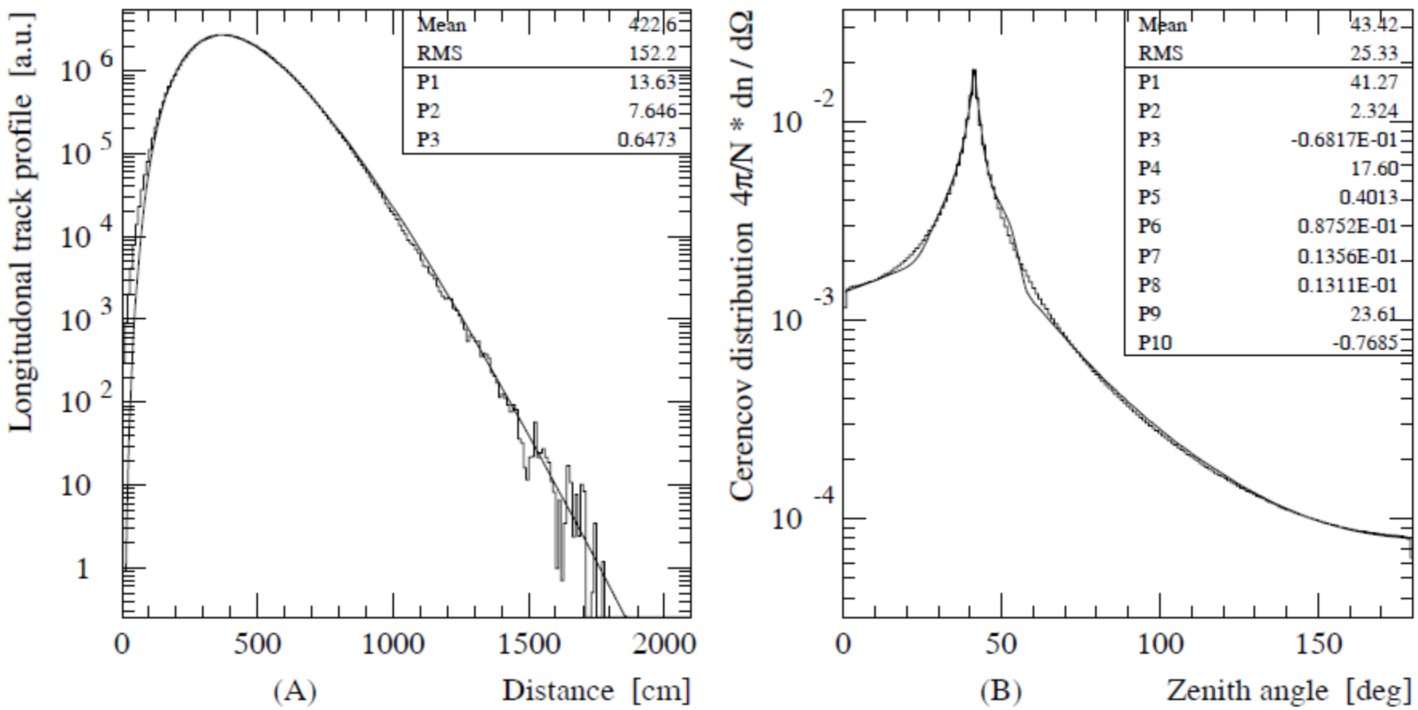
- Read the middle energy secondaries to GPU.
- Use a parameterization method to generate Cherenkov photons from those secondaries.
- Do photon propagation, scattering, absorption and intersection test.
- Output hits of photons.

2.4.1 Parameterization of Photon Production

EM cascade:

$$\frac{dl}{dt} = 10\ \mathrm{cm} \cdot E_0 \cdot K \cdot b \cdot \frac{(bt)^{a-1}\exp(-bt)}{\Gamma(a)}$$

$$\frac{\mathrm{d}n}{\mathrm{d}\Omega}(\theta) = \frac{1}{2\pi}\cdot\Bigg[N_1\cdot\exp\left(-\left|\frac{\theta-\Theta_c}{\sigma_1+\epsilon_1\cdot(\theta-\Theta_c)}\right|\right) + N_2\cdot\exp\left(-\left|\frac{\theta-\Theta_c}{\sigma_2+\epsilon_2\cdot(\theta-\Theta_c)}\right|^2\right) + N_3\cdot\exp\left(-\left|\frac{\theta-\Theta_c}{\sigma_3+\epsilon_3\cdot(\theta-\Theta_c)}\right|^3\right)\Bigg]$$

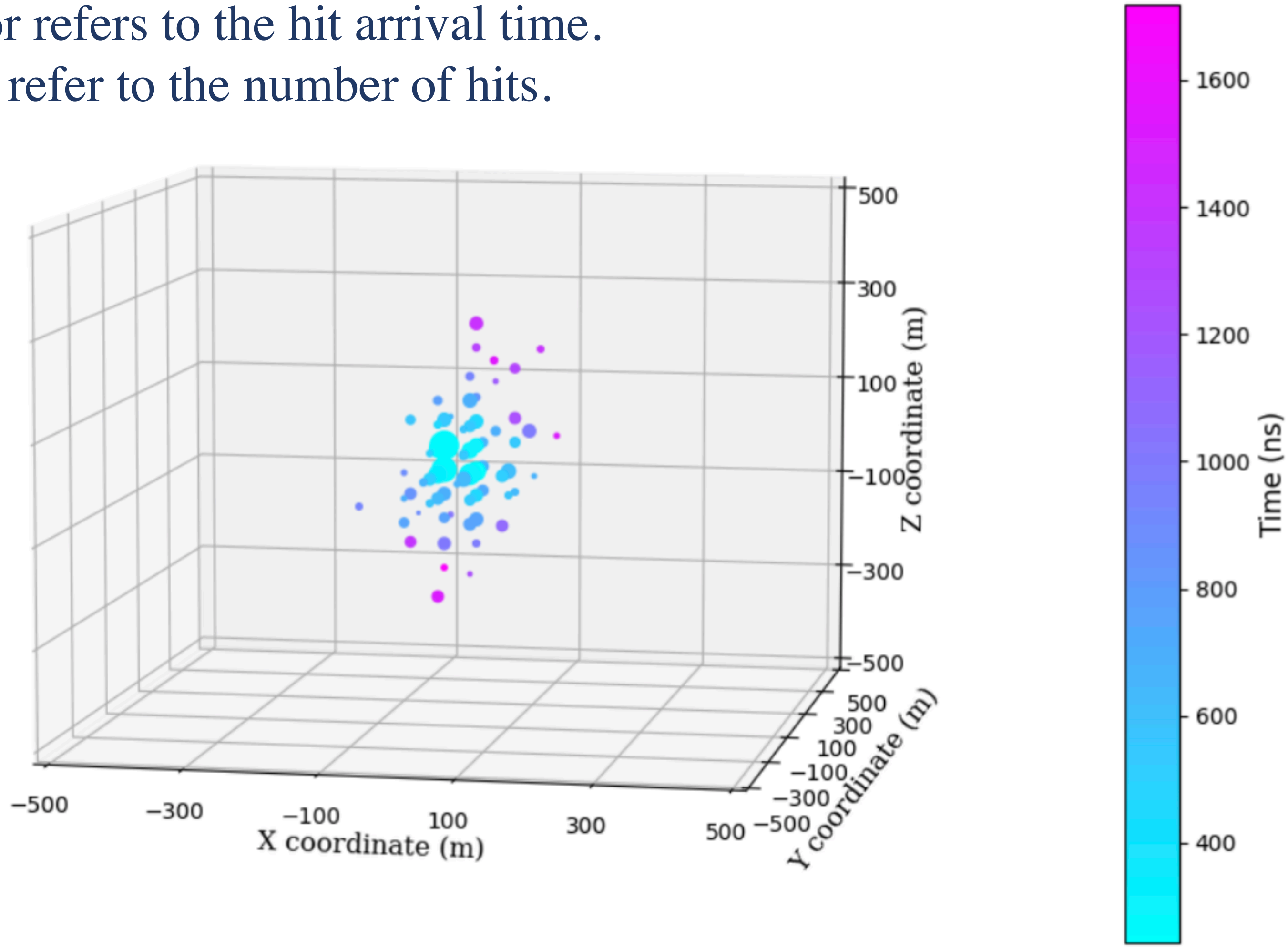


Refer to Wiebusch's PhD Thesis

2.4.2 Hit Output

Primary particle: 100 TeV electron from $(0, 0, 0)$ moving towards $(1, 0, 0)$

The color refers to the hit arrival time.
The size refer to the number of hits.



Part III

Expectation for CORSIKA 8

3. Expectation for CORSIKA 8

CORSIKA is more dedicated for the cascade simulation. In the future, we want to use it to do cascade simulation in water/ice.

Primary concerns:

1. Accurate and fast shower development simulation in water.

- The water is much more denser than air. The shape of shower in water is different from air shower. For example, most of pions loss their energy before decay.
- There are some low energy physics that might help cascade reconstruction.

3. Expectation for CORSIKA 8

CORSIKA is more dedicated for the cascade simulation. In the future, we want to use it to do cascade simulation in water/ice.

Primary concerns:

2. How to generate and propagate Cherenkov photons.

- GPUs are needed for ray-tracing the billions of photons.
- We must generate Cherenkov photons in GPU instead of CPU due to the cost of data transmission between memories.
- Maybe we should use an intermedium data between CPU part and GPU part. For example, generate ‘charged particle steps’ in CORSIKA; read those steps to GPU and generated Cherenkov photons from steps.

- Simon Blyth built up a state-of-art program (*Opticks*) to use NVIDIA OptiX to deal of ray-tracing associated with Geant4 simulation. It is used to simulate the ~100 GeV muon background in JUNO detector.

3. My working interests in CORSIKA Development

- The code organization of CORSIKA 8 is modern
- The cooperation in GitLab is high-efficient
- The physics in cascade is charming

Focus point:

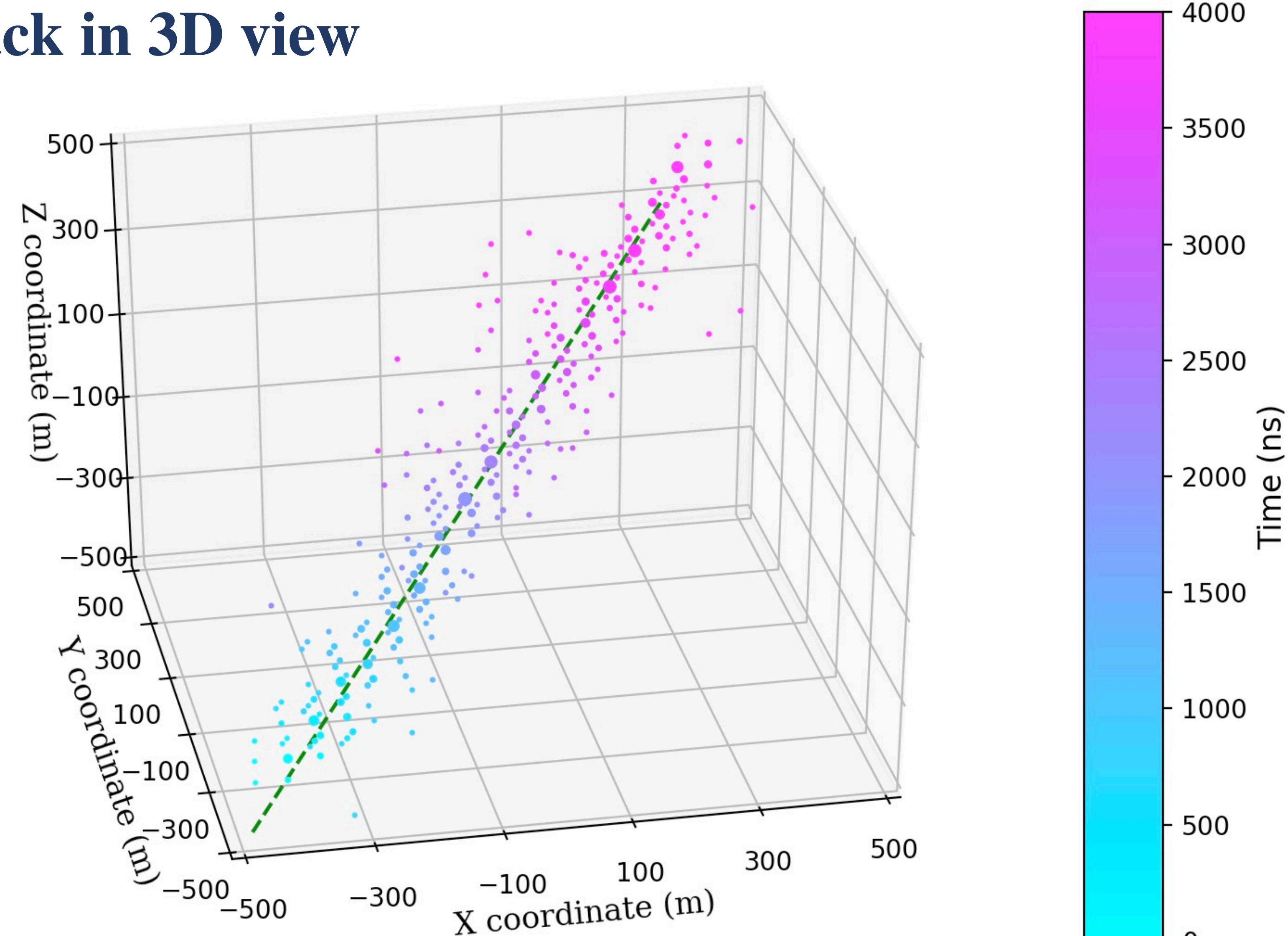
- Help do simulation and validation of cascade in water/ice medium
- The Cherenkov photon generation and propagation process

Glad to join CORSIKA 8 development.
Thanks for listening!

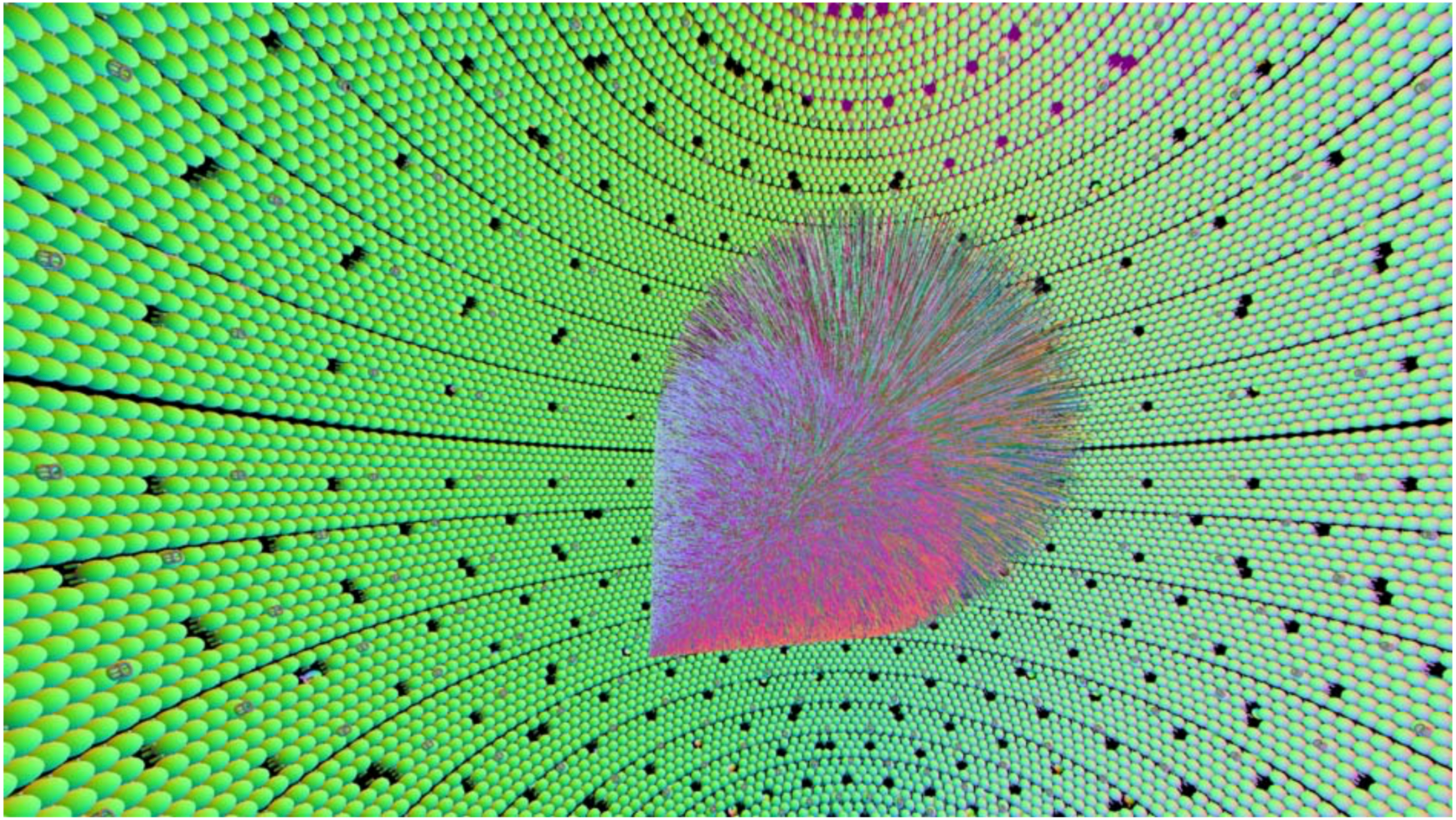
Backups

Hits from bare muon

Track in 3D view



Opticks Ray-Tracing



Opticks Ray-Tracing Principles

Optical Simulation : Computer Graphics vs Physics

CG Rendering "Simulation"	Particle Physics Simulation
simulates: image formation, vision	simulates photons: generation, propagation, detection
(red, green, blue)	wavelength range eg 400-700 nm
ignore polarization	polarization vector propagated throughout
participating media: clouds,fog,fire [1]	bulk scattering: Rayleigh, MIE
human exposure times	nanosecond time scales
equilibrium assumption	transient phenomena
ignores light speed, time	arrival time crucial, speed of light : 30 cm/ns

- **handling of time is the crucial difference**

Despite differences many techniques+hardware+software directly applicable to physics eg:

- GPU accelerated ray tracing (NVIDIA OptiX)
- GPU accelerated property interpolation via textures (NVIDIA CUDA)
- GPU acceleration structures (NVIDIA BVH)