IceCube Event Reconstruction

Bunheng Ty
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ty@wisc.edu

WIPAC
Wisconsin IceCube Particle Astrophysics Center

Wisconsin
University of Wisconsin–Madison

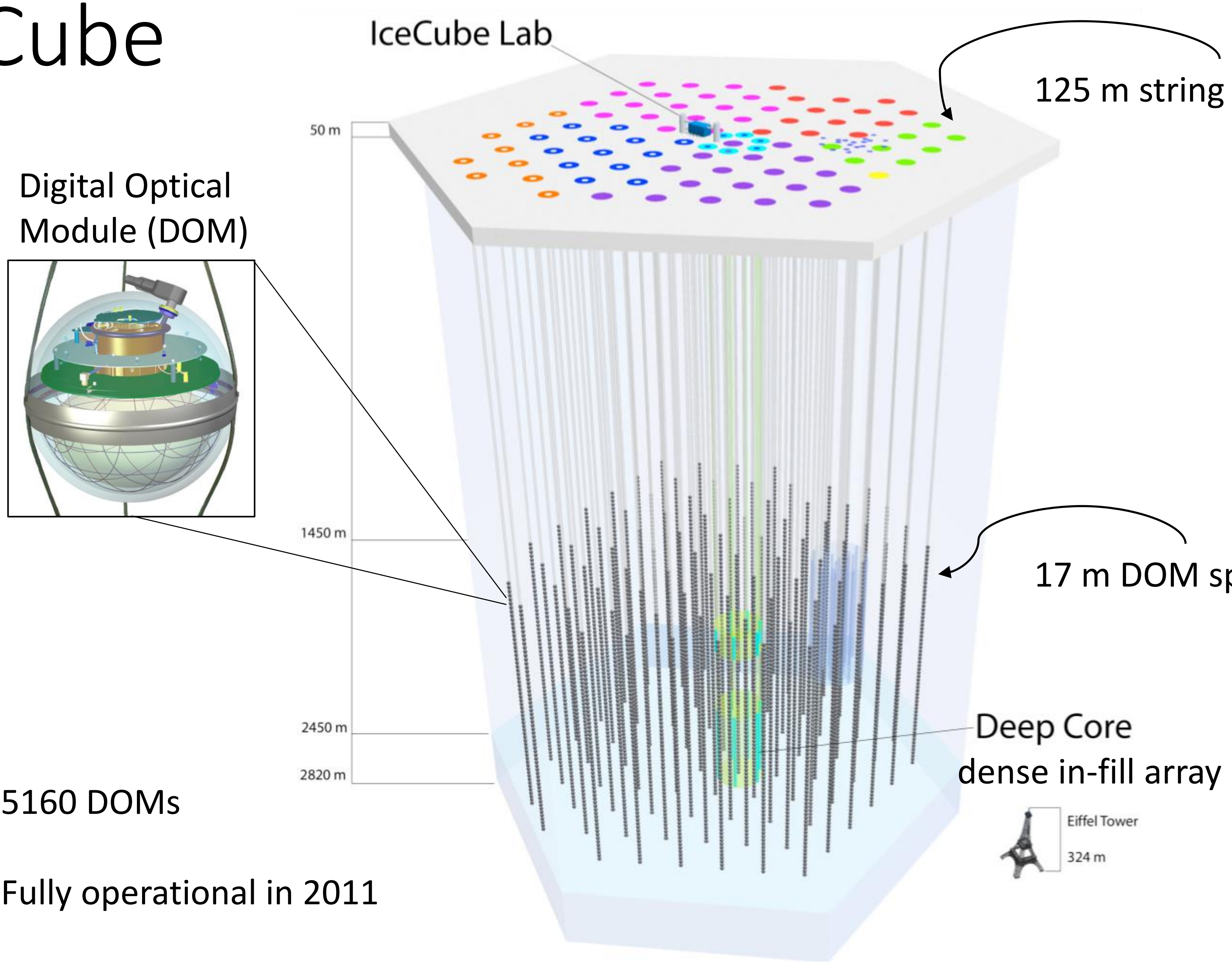
Acknowledgement

Many slides adapted from

[Event Reconstruction, Bootcamp 2019]

Thanks, Tianlu

IceCube

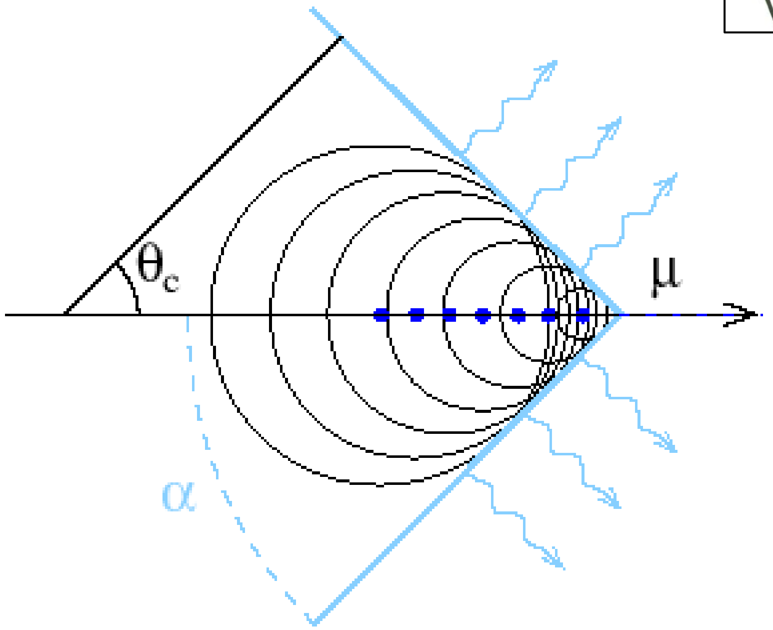


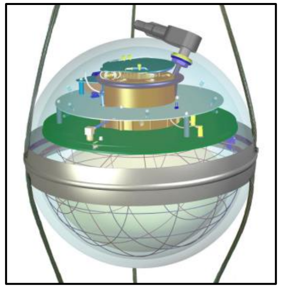
5160 DOMs

Fully operational in 2011

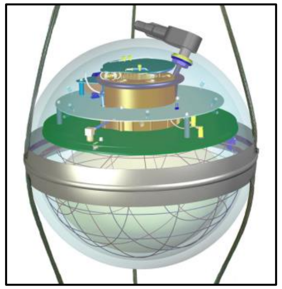
Detection Principles

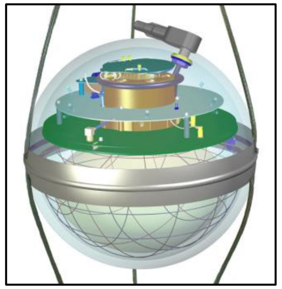
High energy particles interact with the ice, producing Cherenkov photons





DOMs detect photons





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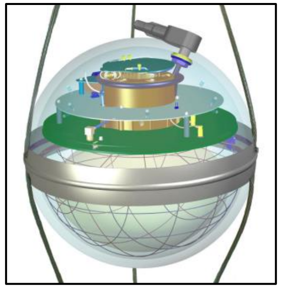

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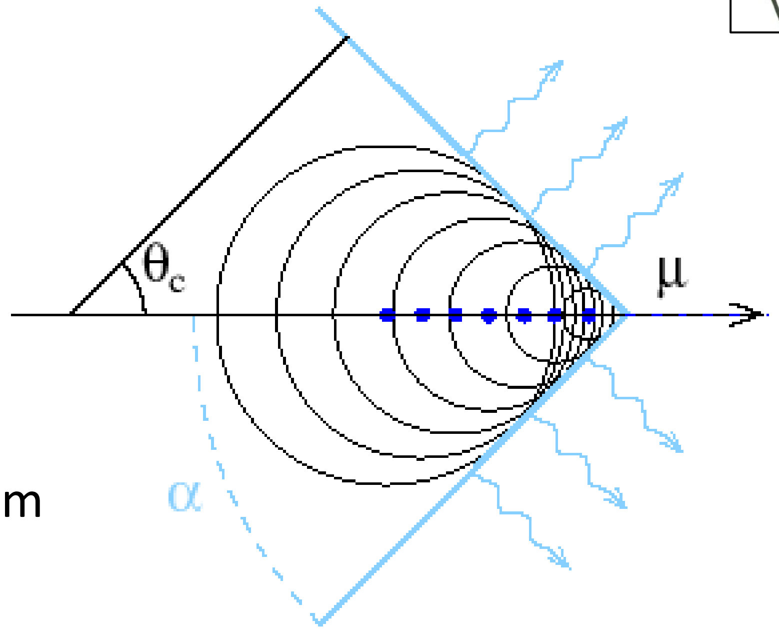
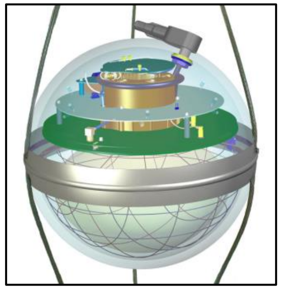
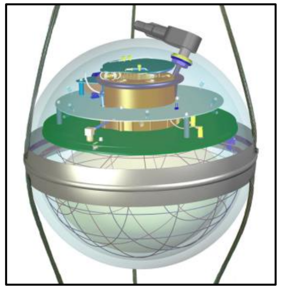




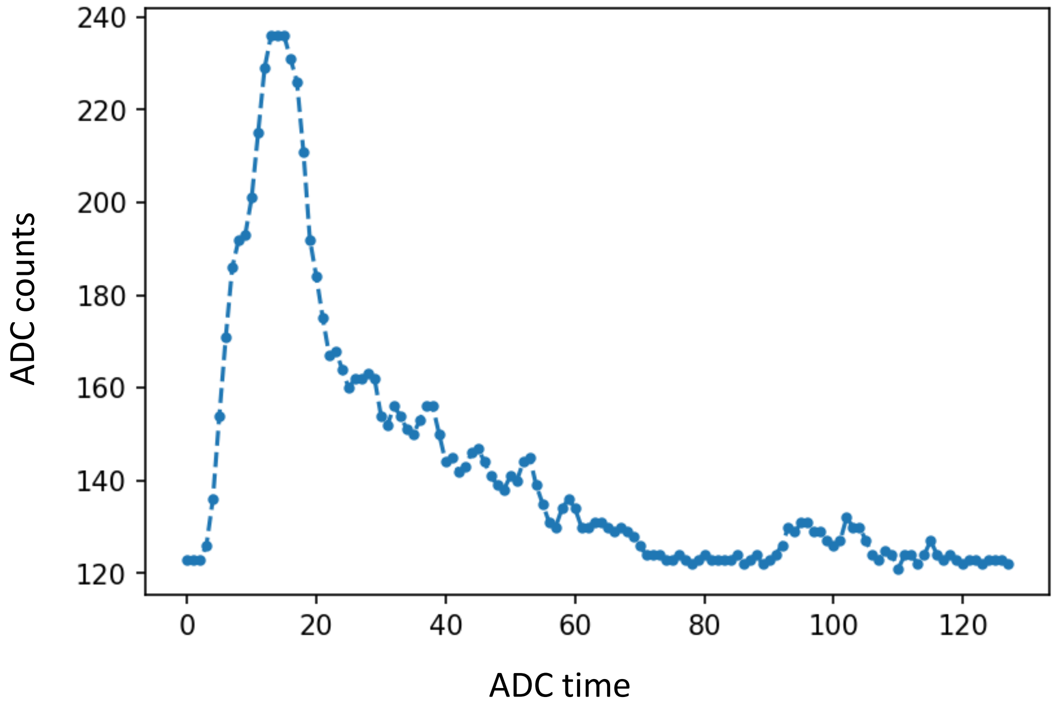
Reconstruction:
Piecing information from the DOMs for

1. energy
2. direction
3. topology



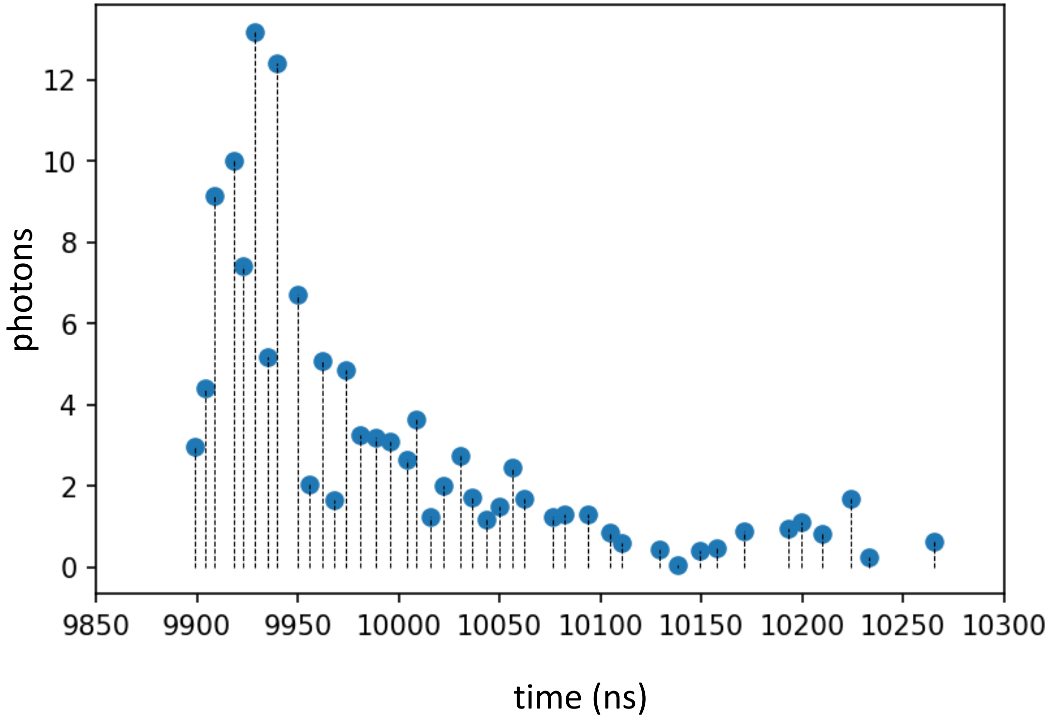
From voltage signal to photon counts

DOM raw data (PMT waveform)



Wavedeform

"pulse series"

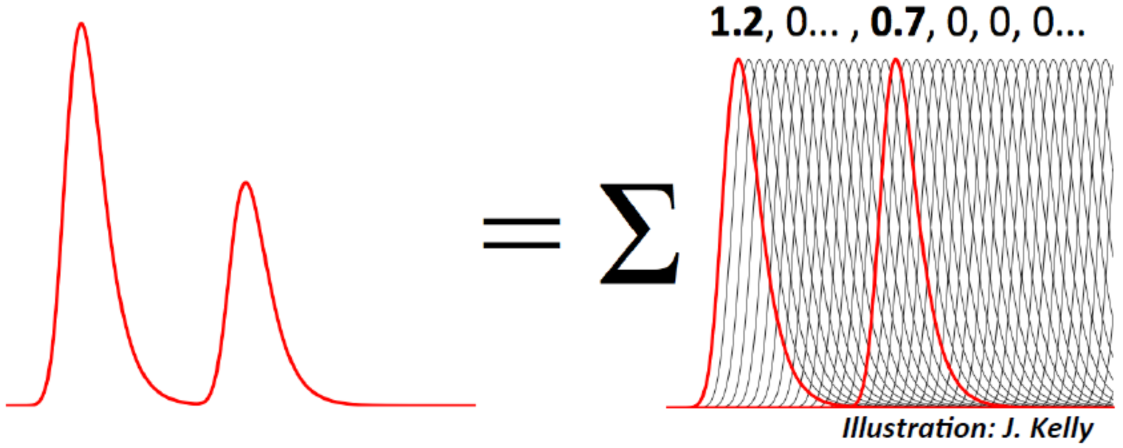


PMT + wavedeform = photon counter

Wavedeform

- **SPE template waveform represents response to SPE**
- **Waveform is a superposition of SPEs**

  → Unfold the waveform using a vector of time-shifted SPE templates as a basis

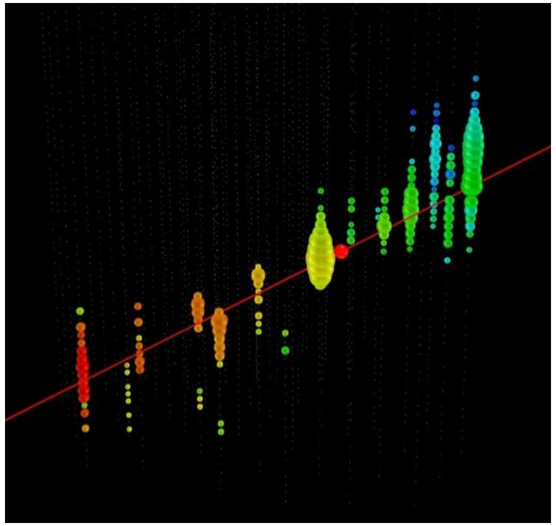


- **Formulate the unfolding as a least-squares problem**

Wavedeform Improvements, Jim Braun 2015

IceCube Event Topologies

CC muon neutrino

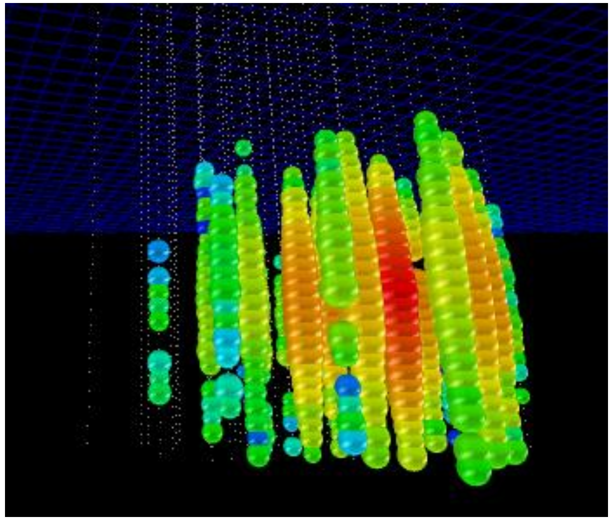


$\nu_\mu + N \rightarrow \mu + X$

track (data)

angular resolution ~ 0.5°
energy resolution ~ x2

NC or CC electron neutrino

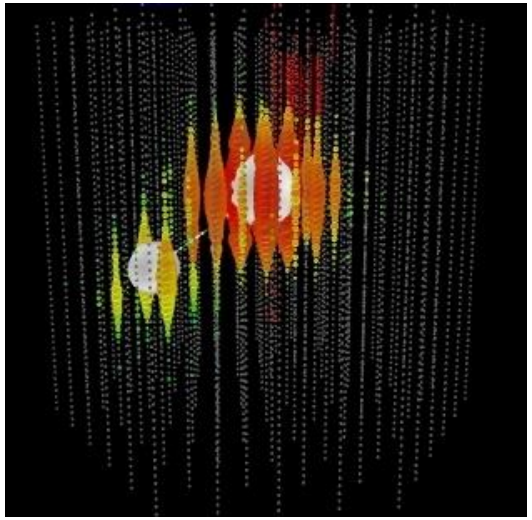


$\nu_e + N \rightarrow e + X$
$\nu_x + N \rightarrow \nu_x + X$

shower (data)

angular resolution ~ 10°
energy resolution ~ 15%

CC tau neutrino



$\nu_\tau + N \rightarrow \tau + X$

"double-bang"
(simulation)

~2 expected in 6 years

Track vs. Cascade

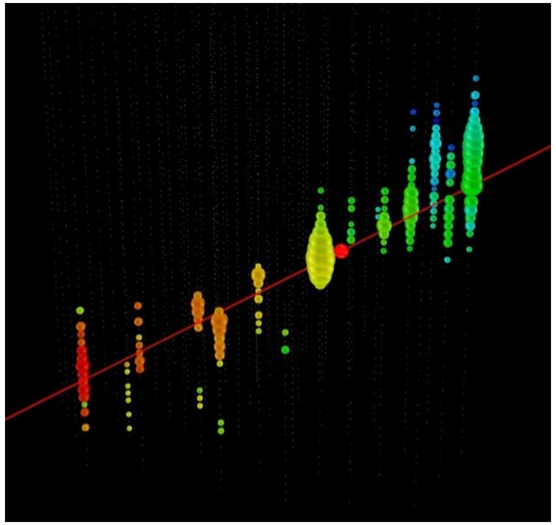
- Line-like emission vs. point-like emission

- A track is due to a muon(s).
- A cascade can be due to anything:
  - Neutrino DIS with a nucleus
  - Muon stochastic loss

- Only rarely that an IceCube event contains no track. So track reconstruction is important, even if only for the purpose of background rejection.

Linefit

- A relatively simple but robust and fast track reconstruction algorithm



  - Minimize sum of square distances, muon to DOMs

mally, assume there are N hits; denote the position and time of the ith hit as $\vec{x}_i$ and t_i, respectively. Let the reconstructed muon track have a velocity of $\vec{v}$, and let the reconstructed track pass through point $\vec{x}_0$ at time t_0. Then, linefit reconstruction solves the *least-squares* optimization problem:

$$\min_{t_0,\vec{x}_0,\vec{v}} \sum_{i=1}^{N} \rho_i(t_0,\vec{x}_0,\vec{v})^2, \tag{1}$$

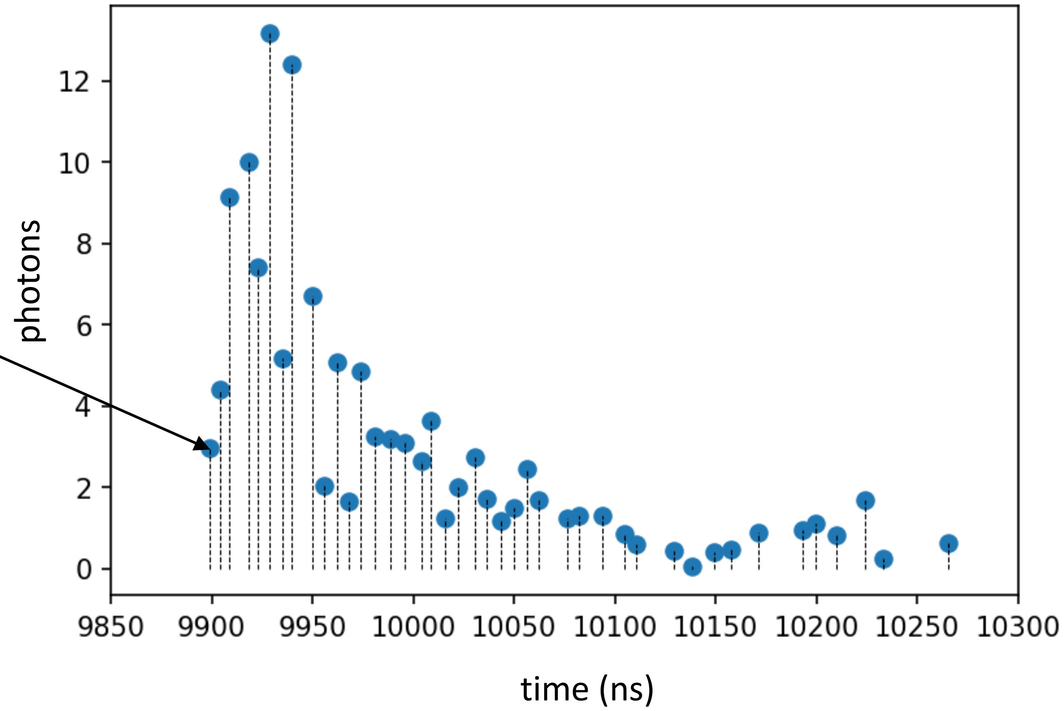
where

$$\rho_i(t_0,\vec{x}_0,\vec{v}) = \|\vec{v}(t_i - t_0) + \vec{x}_0 - \vec{x}_i\|_2 \,. \tag{2}$$

  - Technically a least square problem, but analytically solvable.
    - So just plug in numbers into the formulas

Challenge: use the whole pulse series

- Linefit (and many other algorithms) uses only the first hit time
- Ideally, want to use all of the information recorded by the DOMs.
- Possible if can solve the photon transport problem:
  - Given an arbitrary cascade/track event of $(E, t, \vec{r}, \theta, \phi)$, what is the expected $PE(t)$ on a DOM at position (x, y, z)?

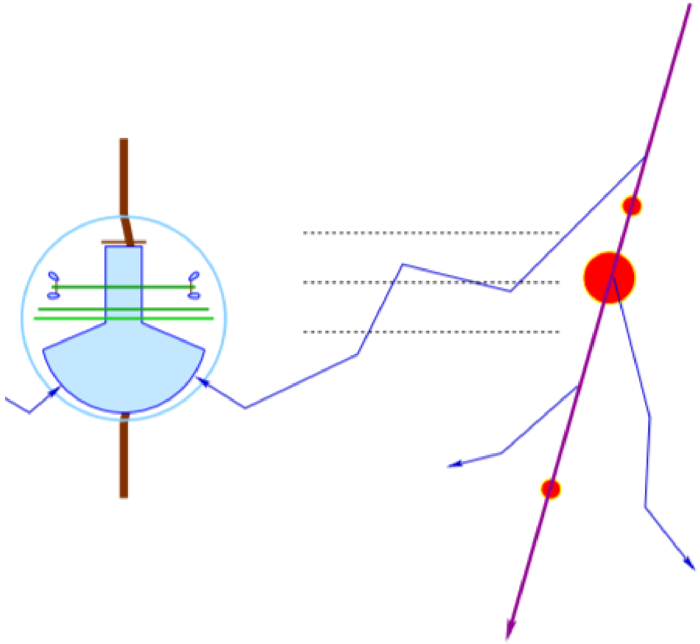


Expected photon flux at a DOM

- Analytical approximation: Pandel functions
  - Probably would work well in water
  - Unfortunately, our medium is inhomogeneous ice
  - SPEfit, CscdLlh, and some others…

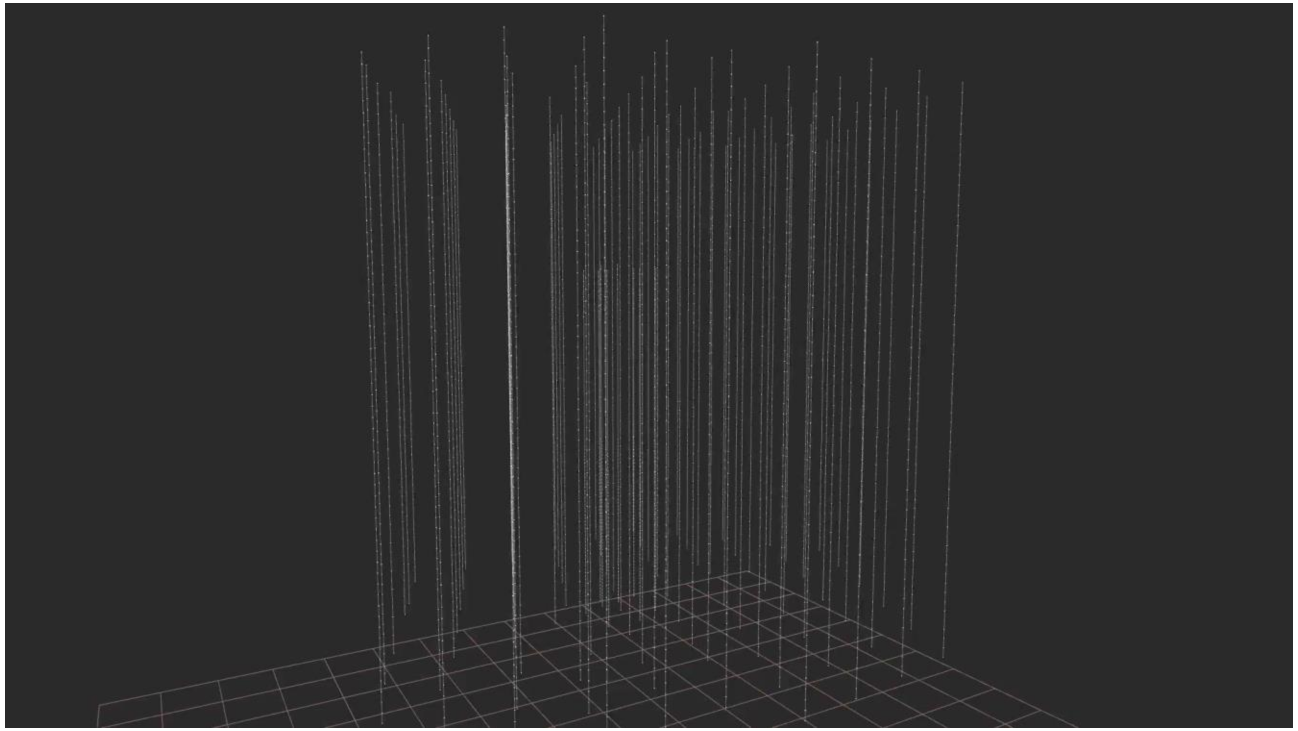
Our modern solution

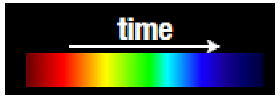
- Monte Carlo simulation: ppc



(There's a Wikipedia page on MC photon transport)

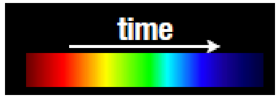
A Track simulation

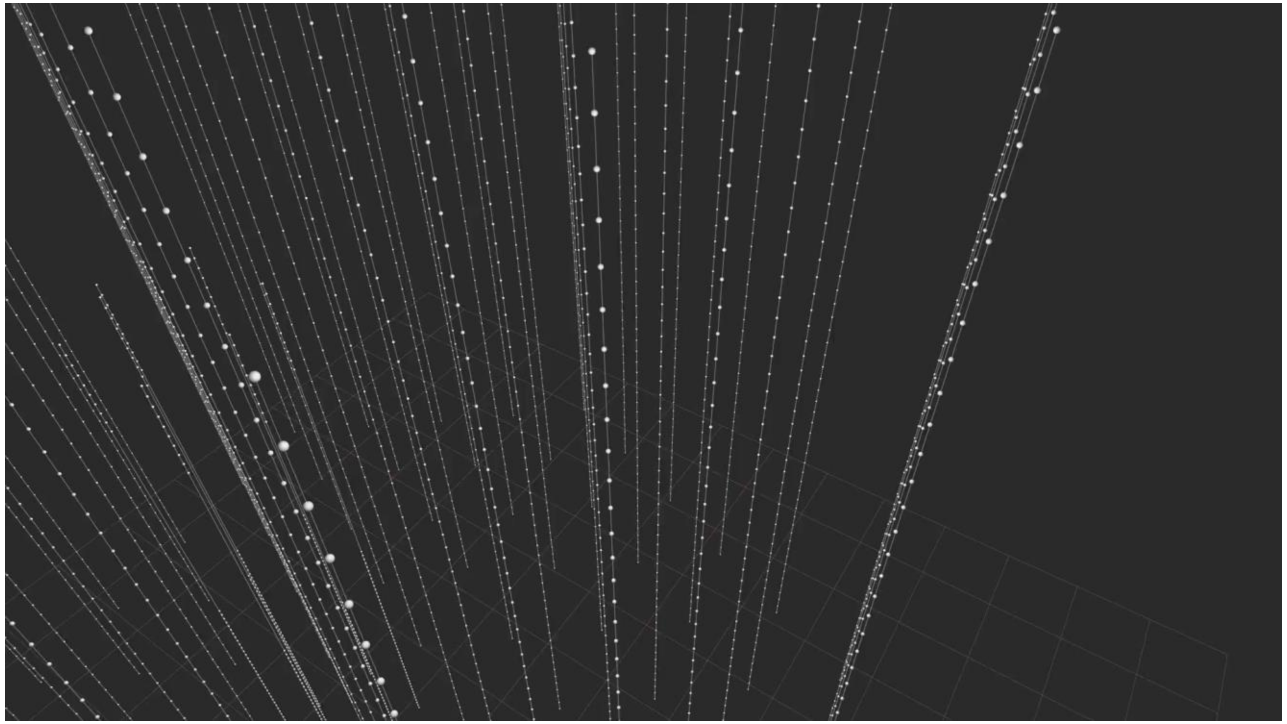




muons: long paths in the detector → **track**

A Cascade Simulation





electrons/hadrons: shower of light → **cascade**

Reconstruction

- Simulation: $(E, t, \vec{r}, \theta, \phi)$ → $PE(t, x, y, z)$
- Reconstruction: $(E, t, \vec{r}, \theta, \phi)$ ← $PE(t, x, y, z)$
  - A solution: keep simulating different $(E, t, \vec{r}, \theta, \phi)$'s until the resulting expected $PE(t, x, y, z)$ at all DOMs match well with the data.
    (ideally, to within the statistical, poissonian limit)

Reconstruction

- Direct Fit : reconstruction by running ppc a **huge** number of times
  - Resource intensive, slow, impractical for processing a large set of events

- Millipede: similar in spirit, but simulations are precomputed, stored in lookup tables.

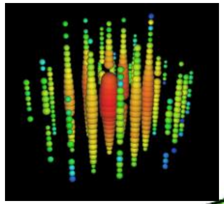
  (and others)

  These tables are known as "photon tables".

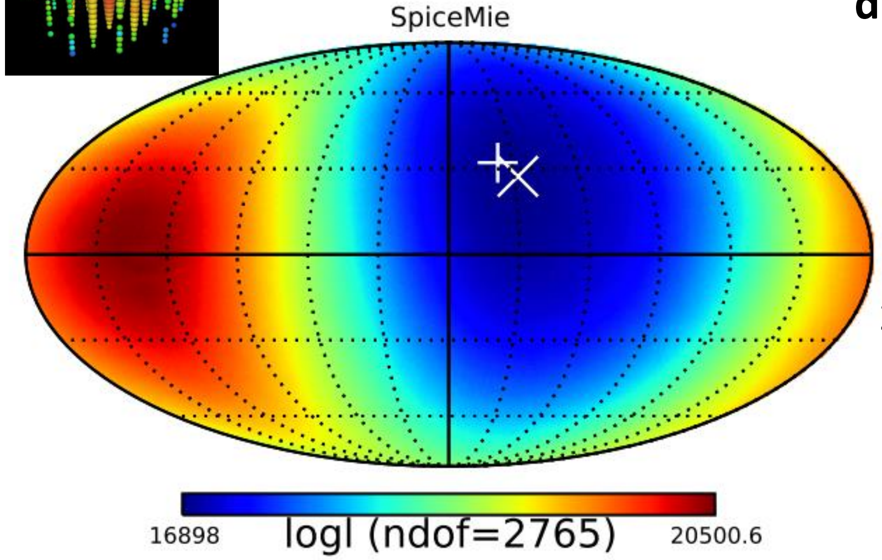
  They contain $PE(t, x, y, z)$ to all possible $(E, \vec{r}, \theta, \phi)$'s

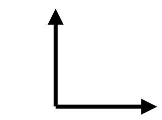
  (not really, E=1GeV only, and grid values for $(\mathrm{z}, \theta, \phi)$ with anything in between to be interpolated)

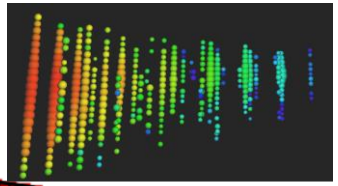
Cascade vs track skymap

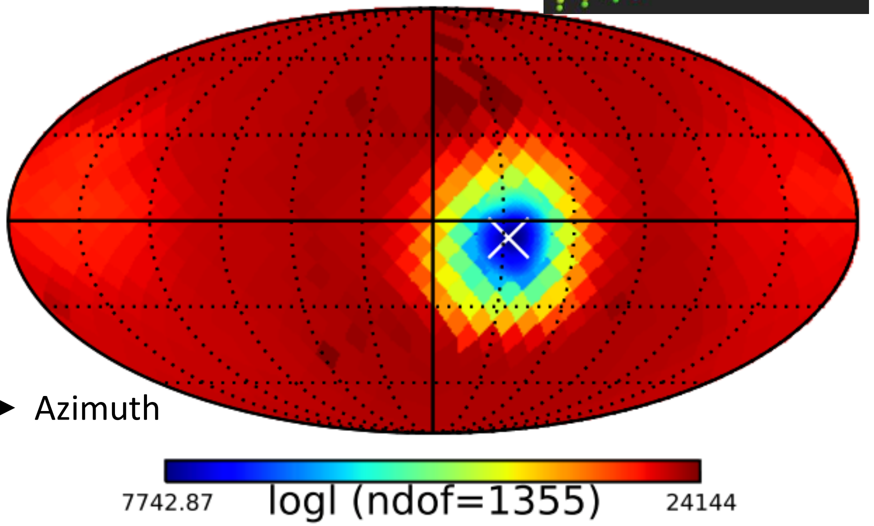


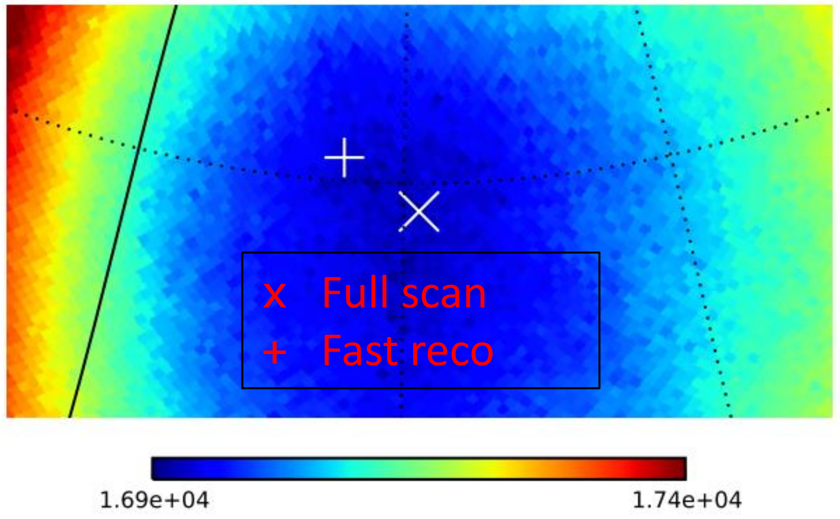
Uses splines from tabulated distributions

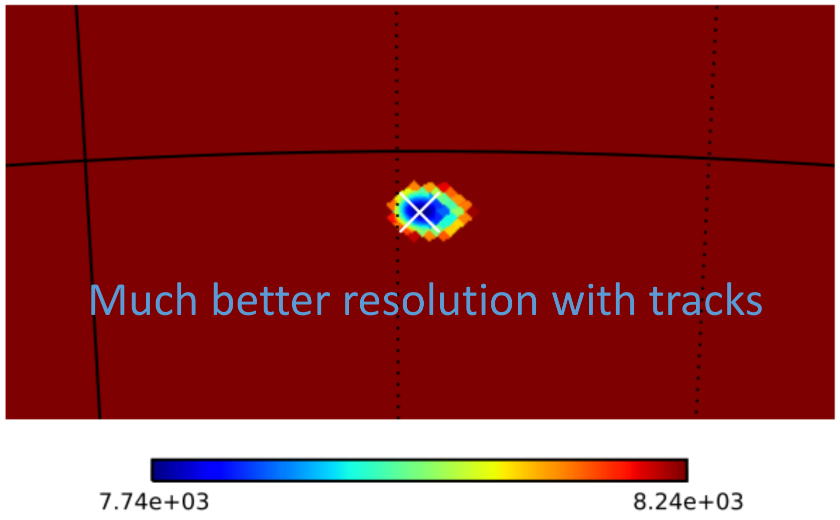






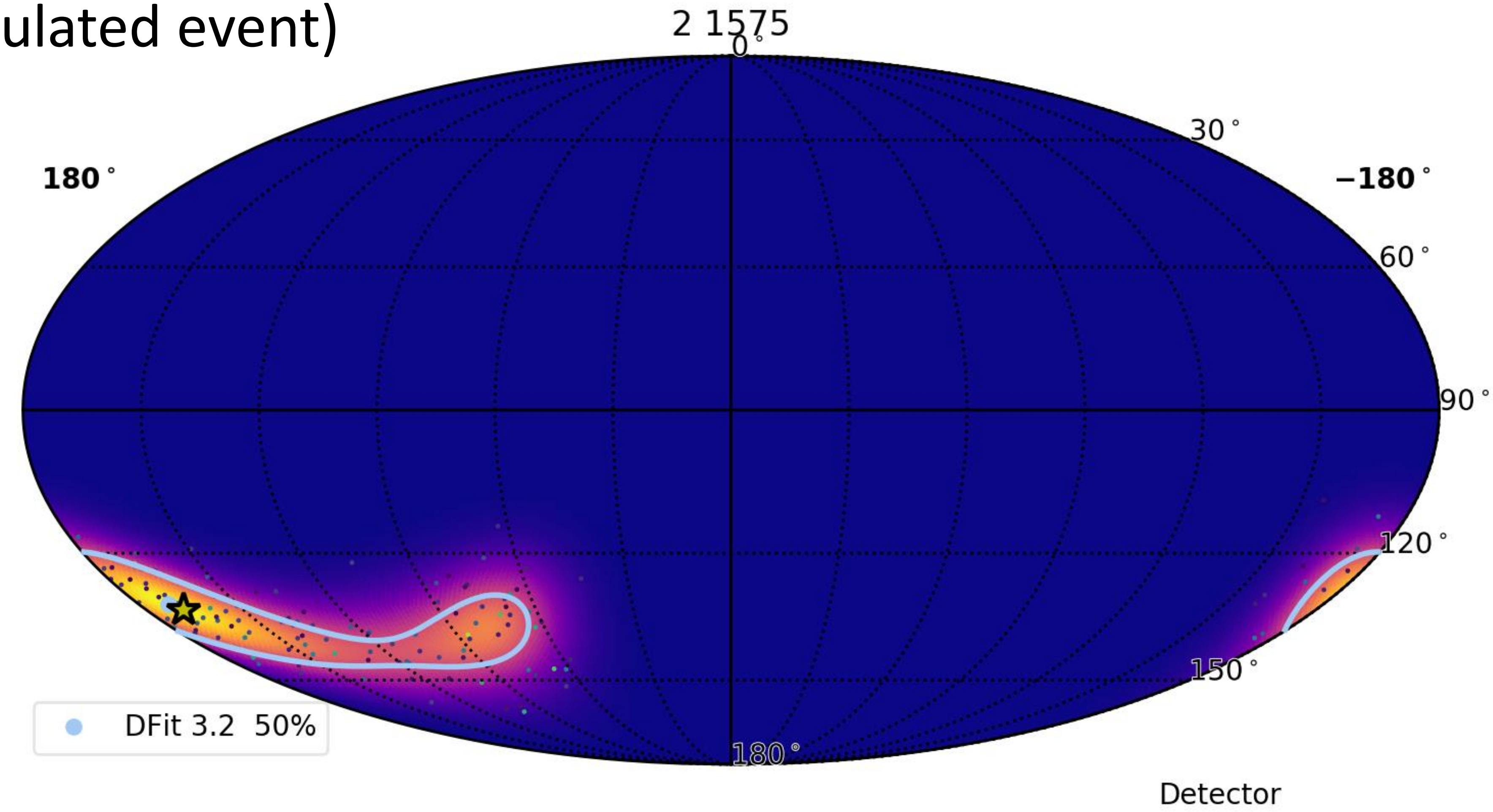




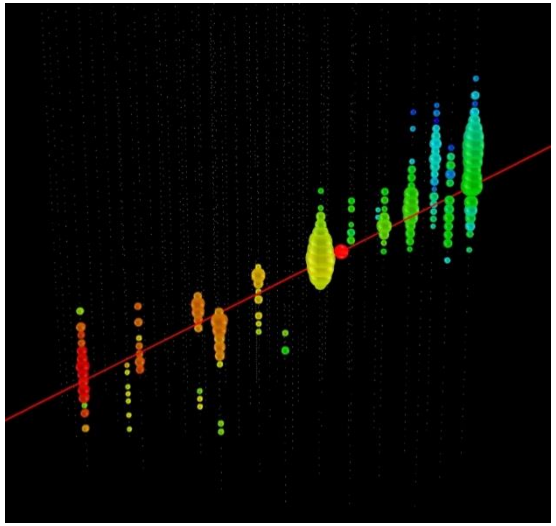
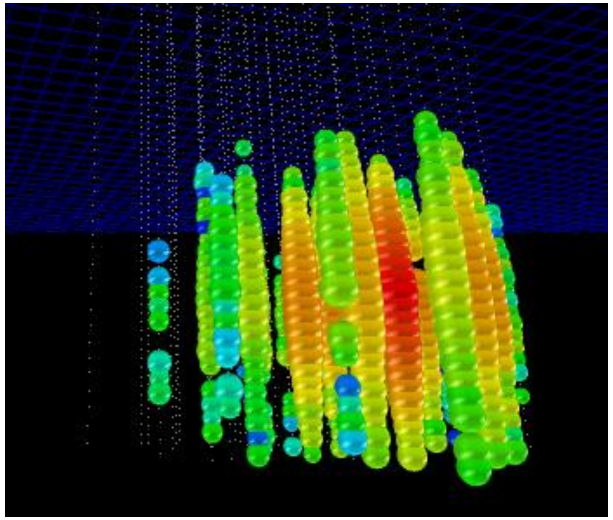
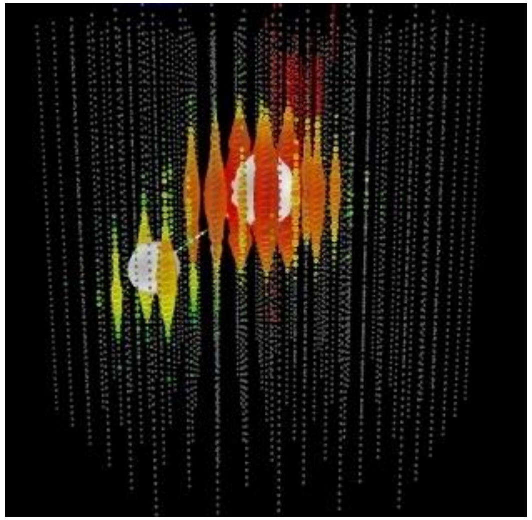


DirectFit with directional PDFs

(simulated event)



IceCube Event Topologies

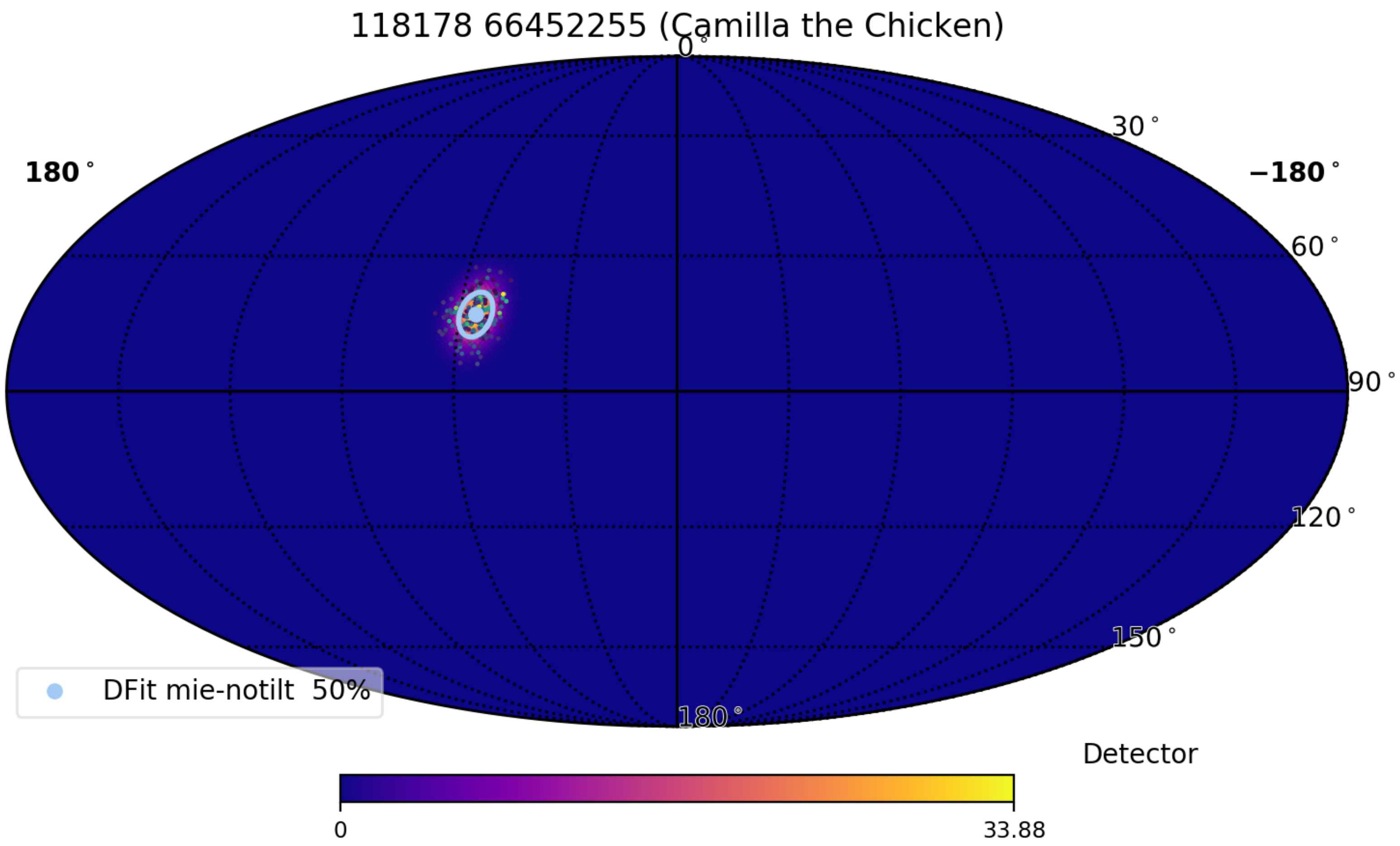
CC muon neutrino	NC or CC electron neutrino	CC tau neutrino
		
$\nu_\mu + N \rightarrow \mu + X$	$\nu_e + N \rightarrow e + X$ $\nu_x + N \rightarrow \nu_x + X$	$\nu_\tau + N \rightarrow \tau + X$
track (data)	shower (data)	"double-bang" (simulation)
angular resolution ~ 0.5° energy resolution ~ x2	angular resolution ~ 10° energy resolution ~ 15%	~2 expected in 6 years

Ice Model Uncertainties

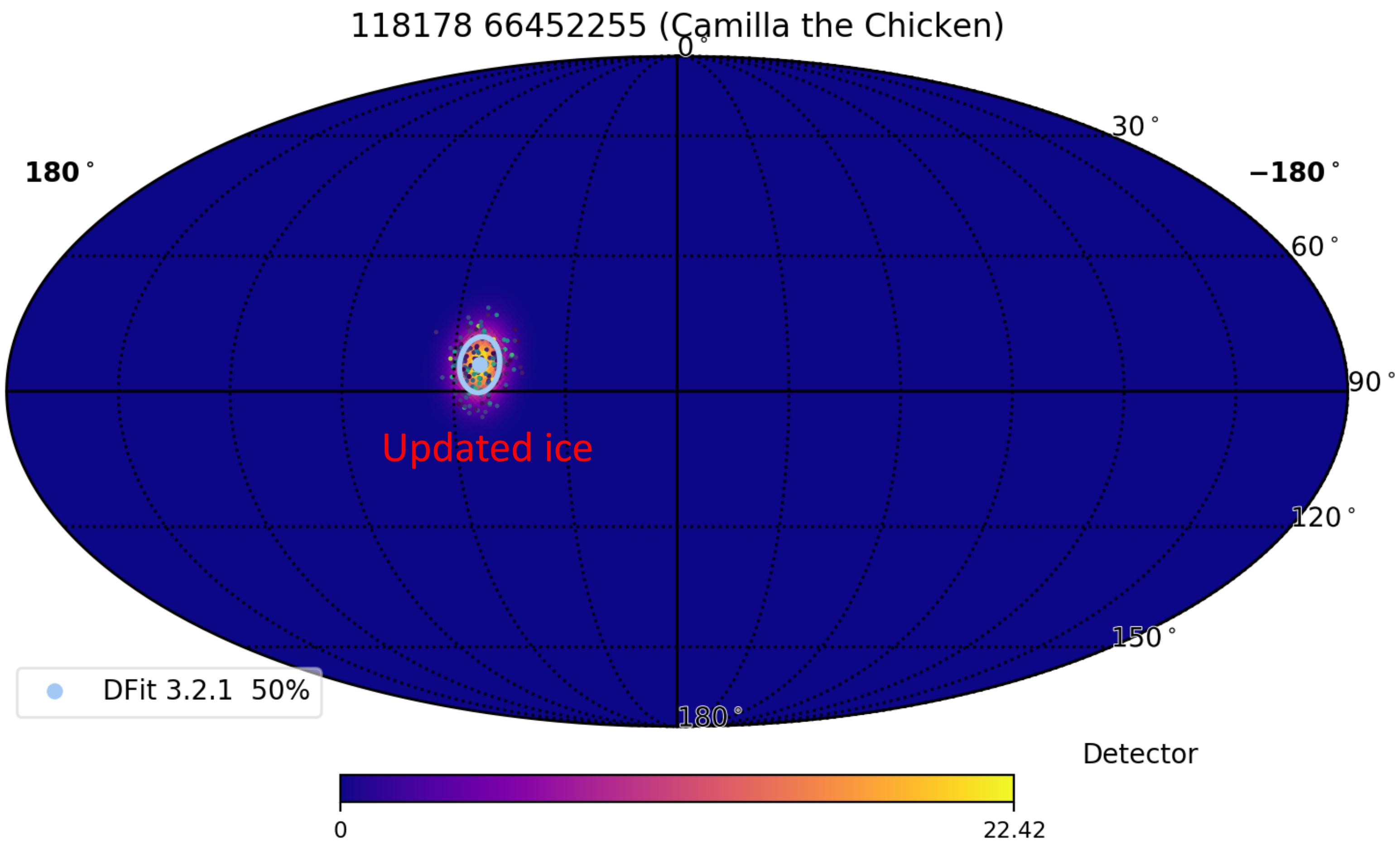
- Our most sophisticated reconstructions rely directly on our simulations, which can vary greatly with the Ice model.

- Our ice model is a work in progress, getting better with time.

→ Cascade directional reconstruction limited by our simulation model


118178 66452255 (Camilla the Chicken)
0°
30°
180°
−180°
60°
90°
120°
150°
180°
DFit mie-notilt 50%
Detector
0
33.88

Ice affects cascade reconstruction

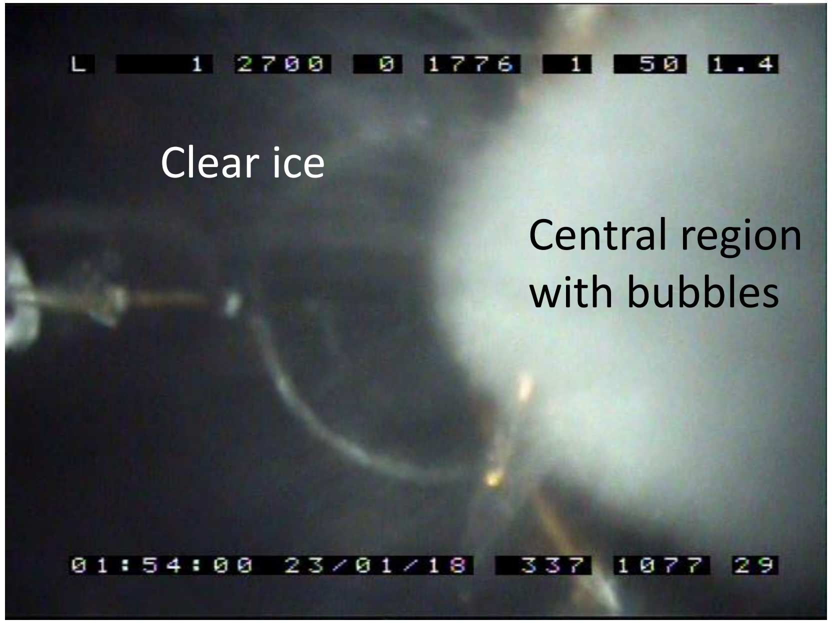


Local effects

Hole-ice

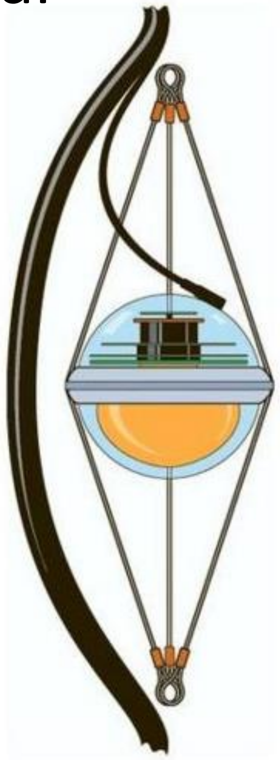
- Refrozen central column with high scattering

Looking up the string



DOM orientation

- Thick, support cable may impede direct photons if vertex is nearby
- A few DOMs may not be perfectly horizontal



Summary and Future Outlook

- IceCube reconstruction is determining event’s energy, direction, topology.
- Simple to complicated, depending on how much of the pulse series we want to used.
- Full cascade reconstruction is challenging, due to the ice medium.
  - It is a miracle that the ice is that clear in the first place.
  - Improve the ice model to improve reconstruction
- Future (cascade reconstructions): deep neural network
  - DNN offers potential direct fit performance, while fast enough to be practical for processing a large data set.