IceCube event reconstruction

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IceCube Bootcamp

June 19, 2018

ICECUBE

WISCONSIN
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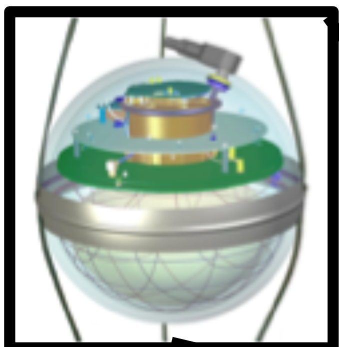
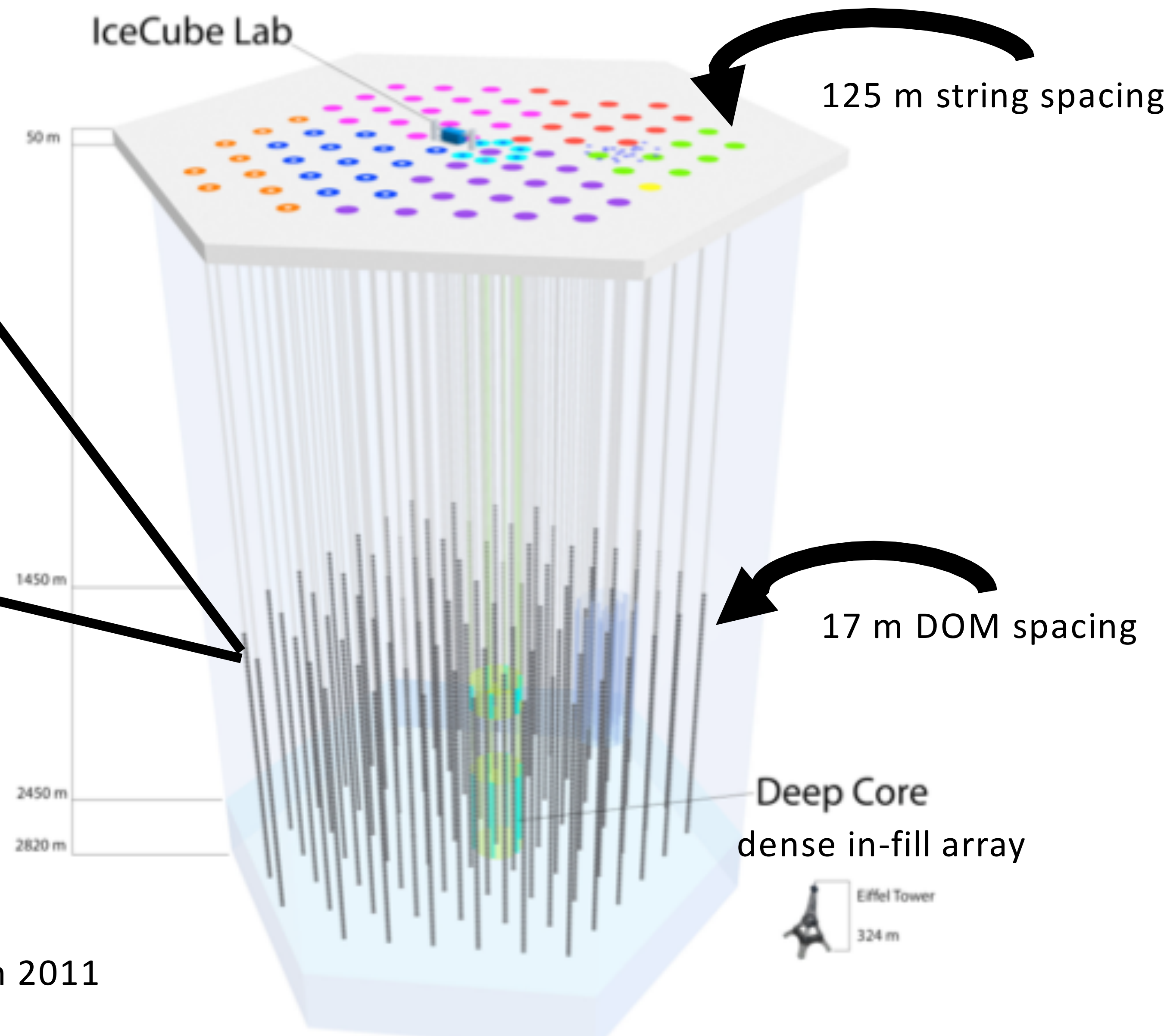
IceCube

Digital Optical Module (DOM)





5160 DOMs

Fully operational in 2011

Detection principals

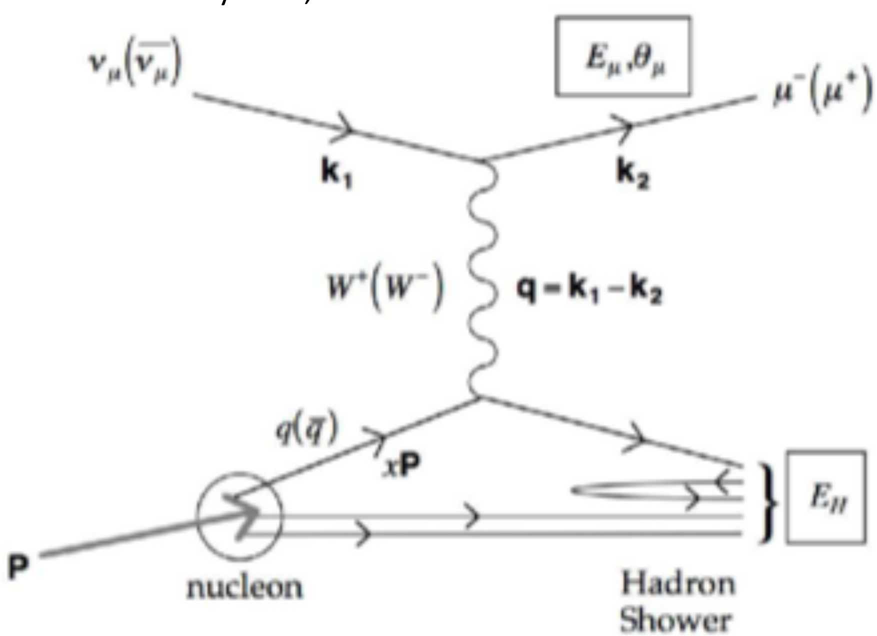
Neutrino interacts via weak force with targets in ice

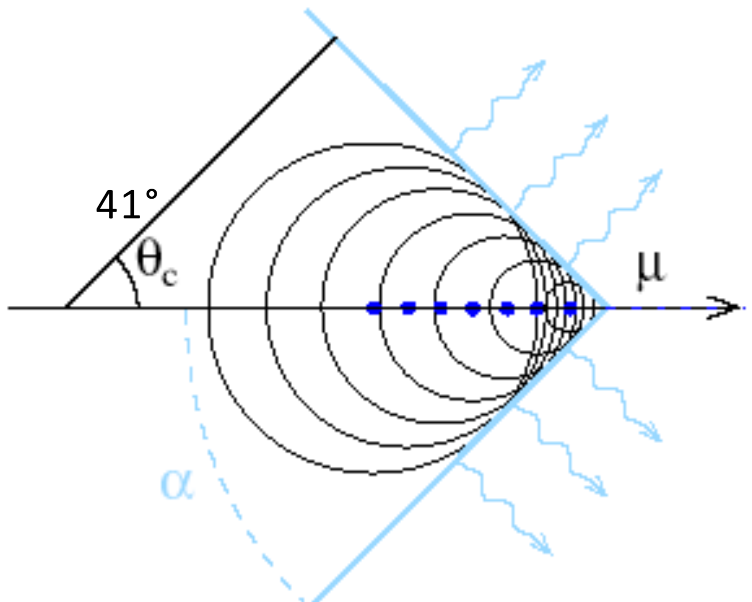
- At IceCube energies, primarily deep-inelastic scattering (DIS) off nucleons

Nucleon breaks apart; outgoing particles may be charged

Charged particles emit **Cherenkov radiation** detectable by PMTs

Rev. Mod. Phys. 84, 1307





Cherenkov radiation

Occurs when a charged particle travels faster than light-in-medium

Constructive interference of EM-field to form a plane wave

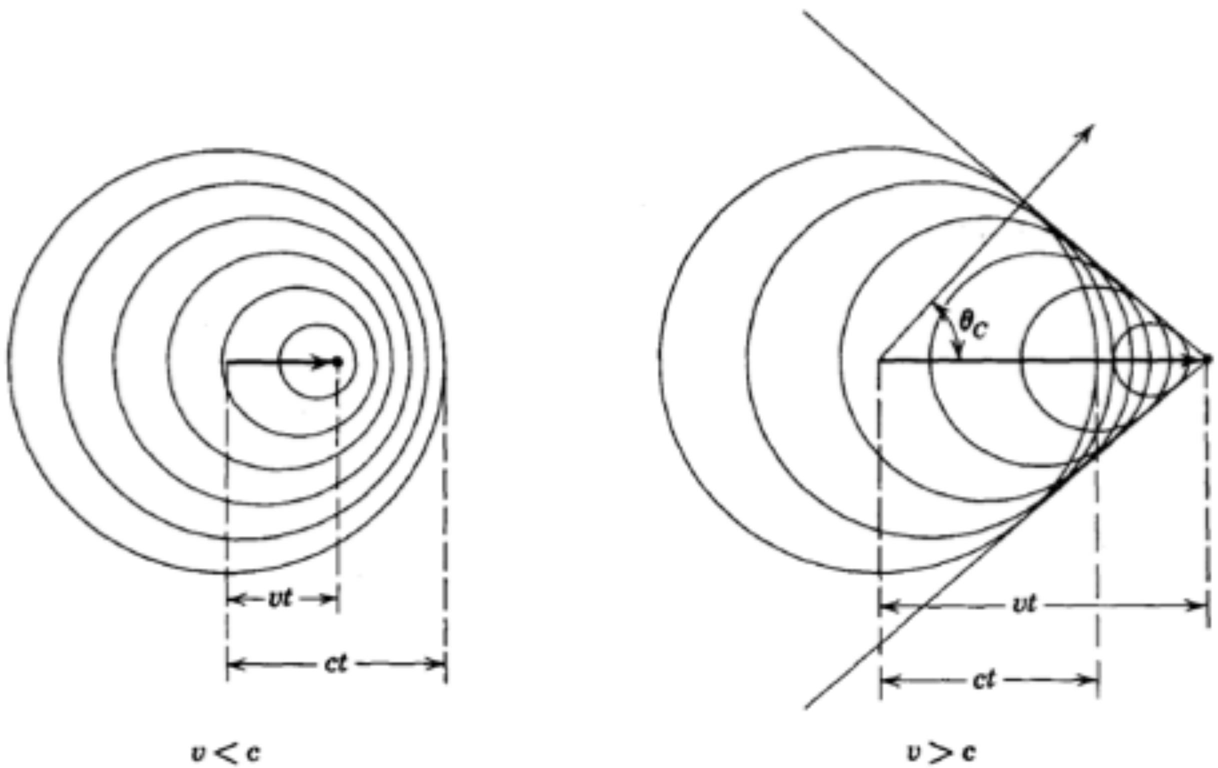
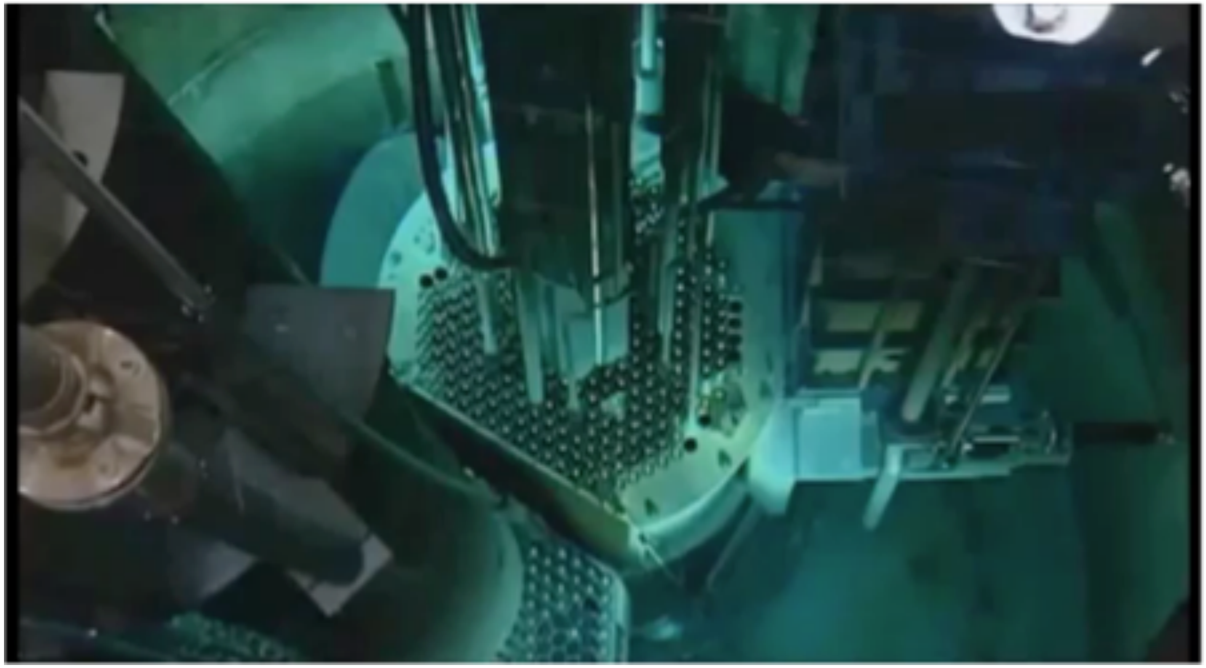
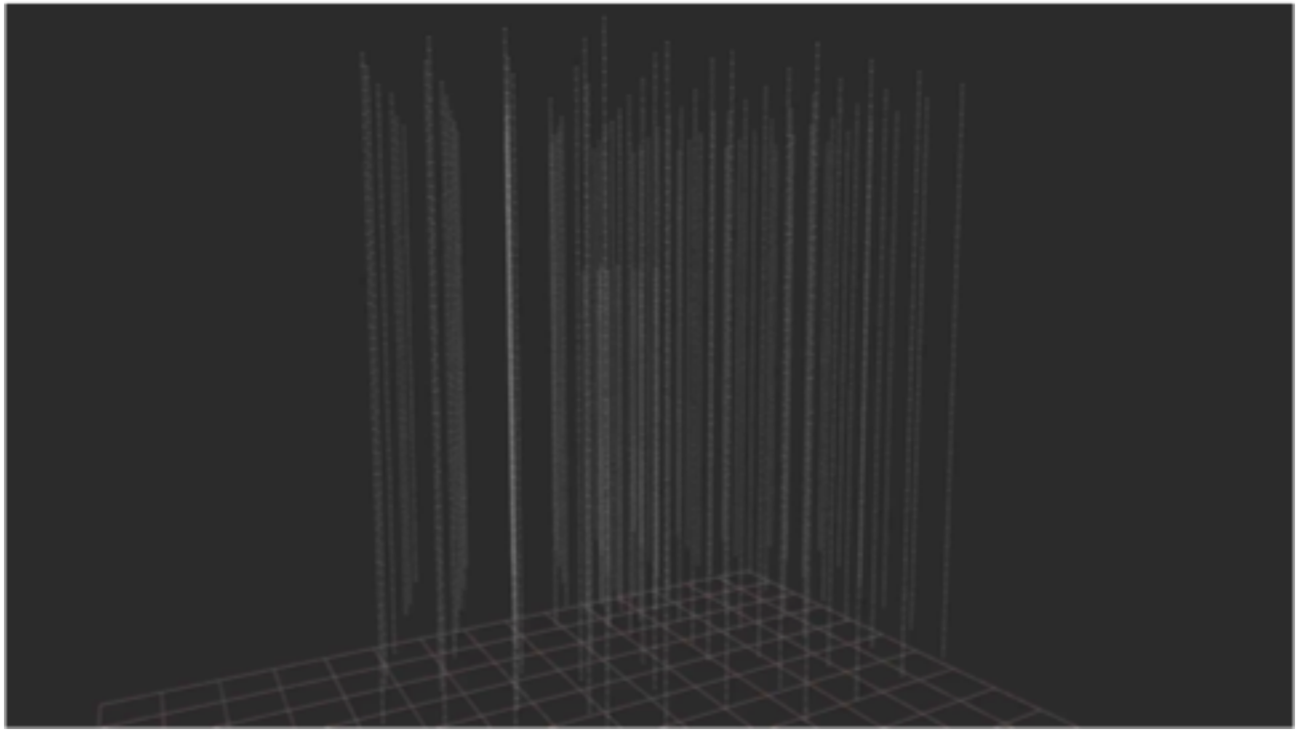


Fig. 14.14 Cherenkov radiation. Spherical wavelets of fields of a particle traveling less than, and greater than, the velocity of light in the medium. For $v > c$, an electromagnetic "shock" wave appears, moving in the direction given by the Cherenkov angle θ_c.

Cherenkov radiation in water



What do neutrinos look like in IceCube?



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

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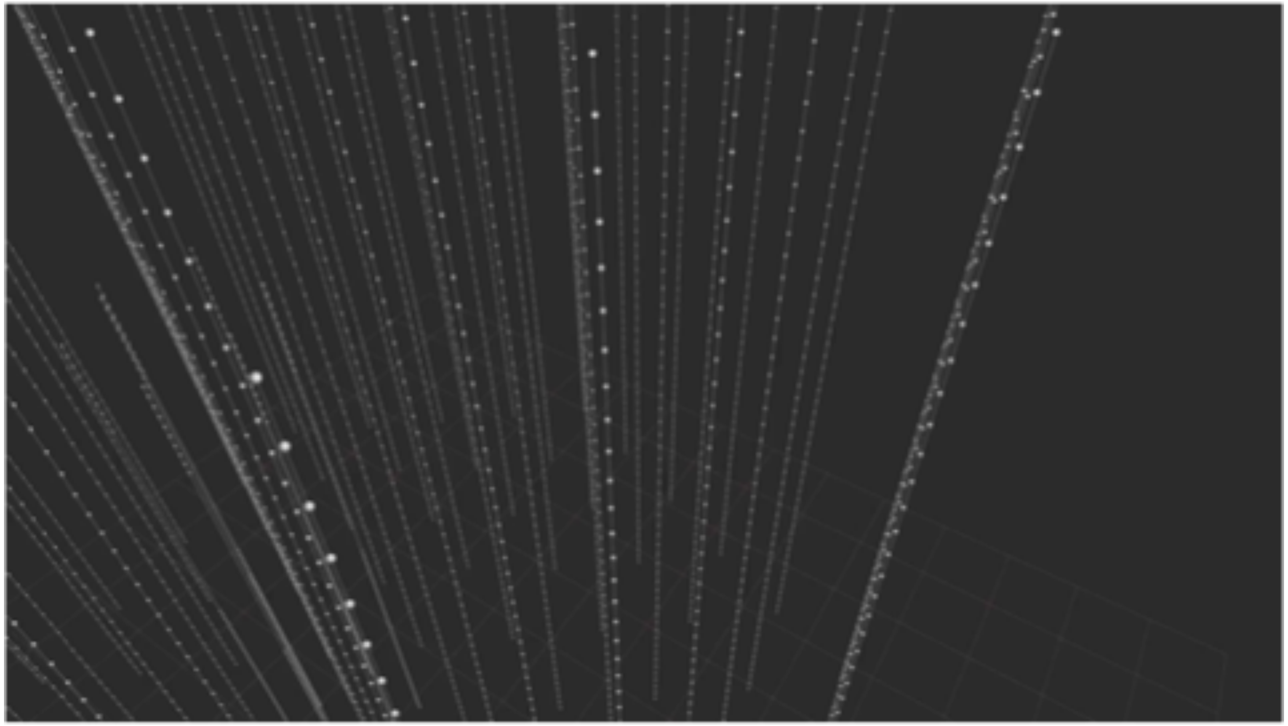
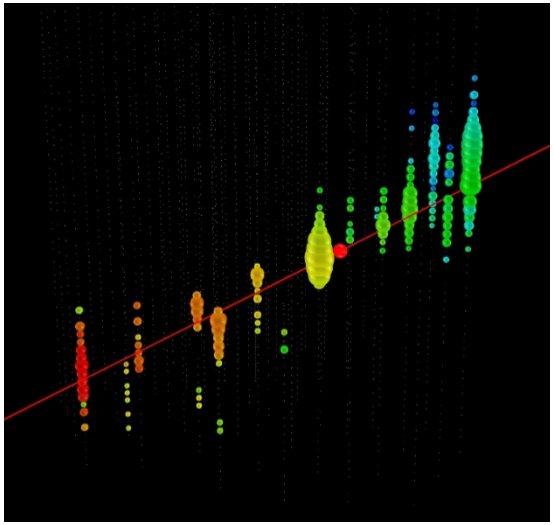


electrons/hadrons: shower of light → **cascade**

What IceCube actually sees

CC muon neutrino

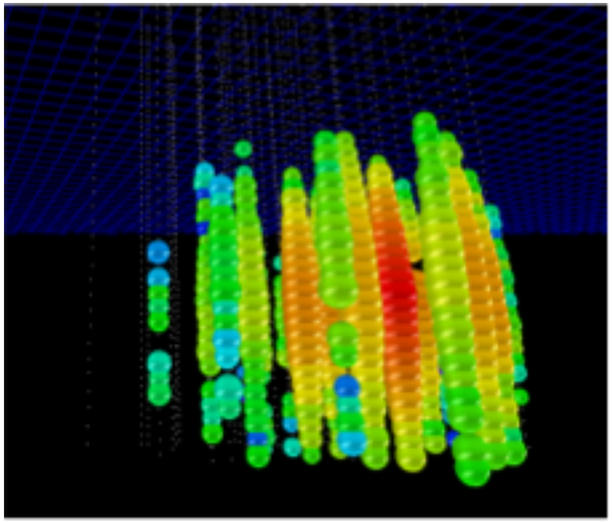


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

angular resolution ~ 0.5°
energy resolution ~ x2

NC or CC electron neutrino

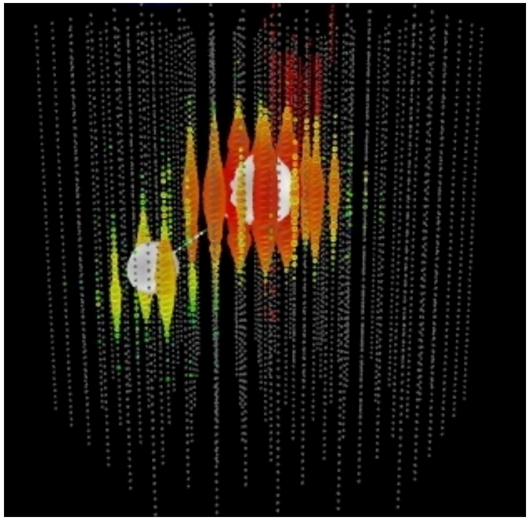


$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

shower (data)

angular resolution ~ 10°
energy resolution ~ 15%

CC tau neutrino



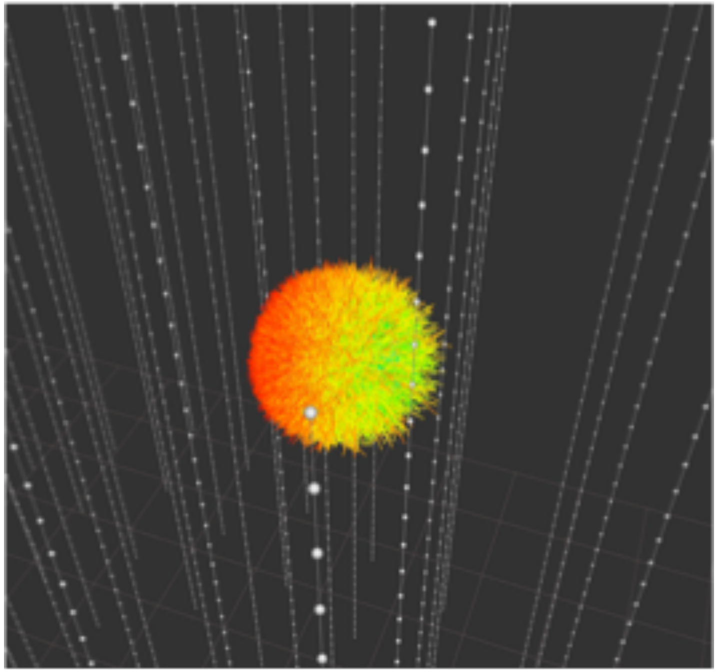
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang"
(simulation)

~2 expected in 6 years

Event reconstruction

Emitted

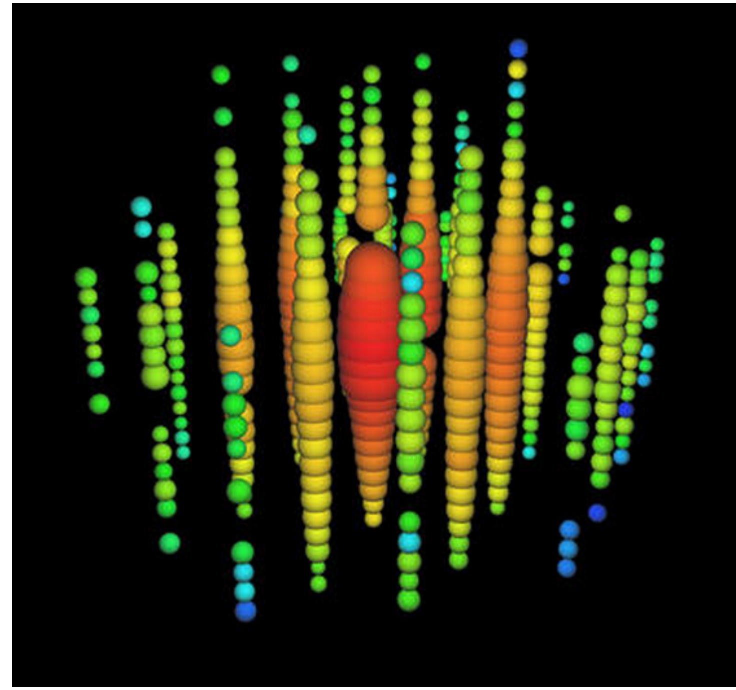


Asymmetry in photon emission helps with directional reconstruction

Information loss

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

Detected



Physics model (emission, absorption, scattering)

$\boldsymbol{\Theta} = (x, y, z, \theta, \phi, E, t)$

$X = q_{DOM}\,(t)$

Maximize $\mathcal{L}(\boldsymbol{\Theta}|\mathrm{X}_{\mathrm{Data}})$

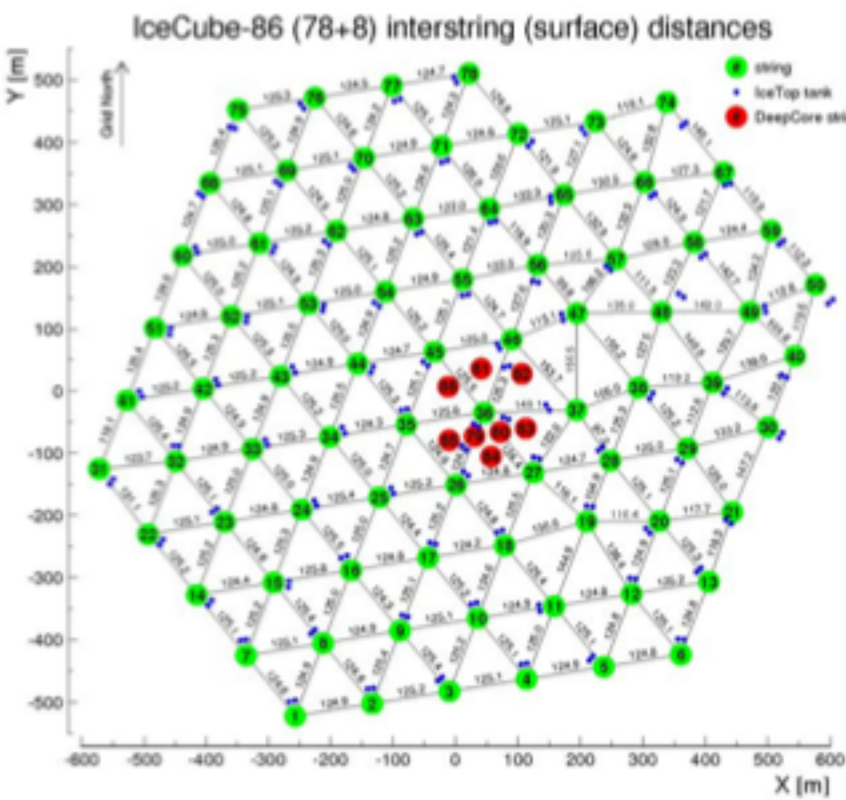
Physics parameters and IceCube coordinates

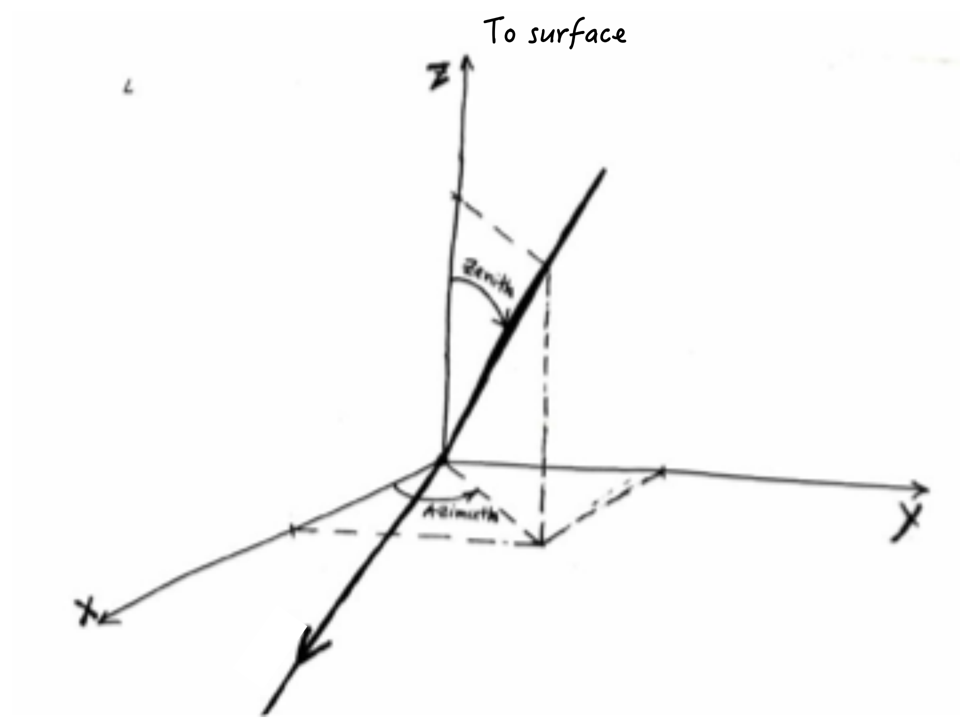
$$\mathbf{\Theta} = (x, y, z, \theta, \phi, E, t)$$

Detector coordinate system centered in middle of detector

(θ, ϕ) = (zenith, azimuth) corresponds to *arrival* direction

Usually, (θ, ϕ, E) are the physics parameters we're most interested in

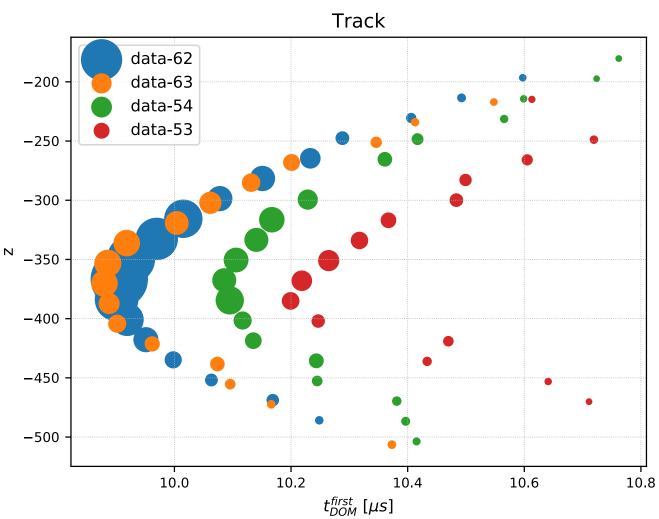


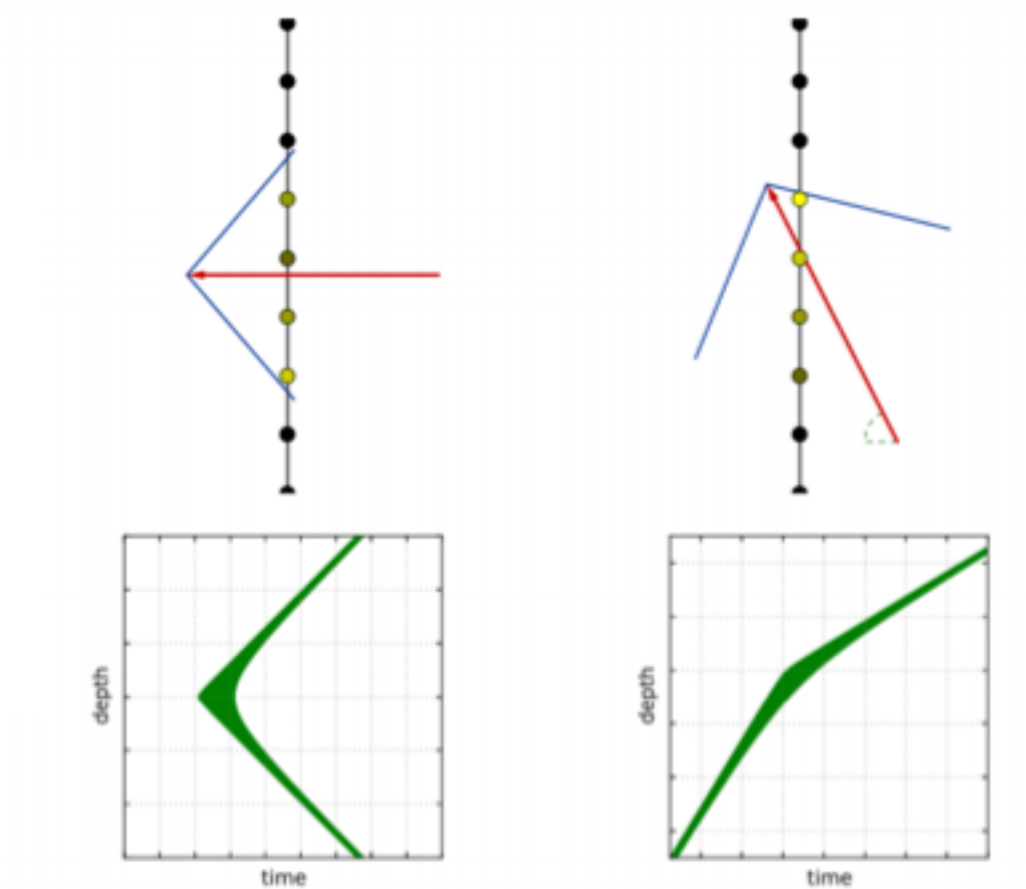


Approaches for reconstruction

Tracks

- Use **first-hit times** for *directional* reconstruction (SplineSPE, SANTA)



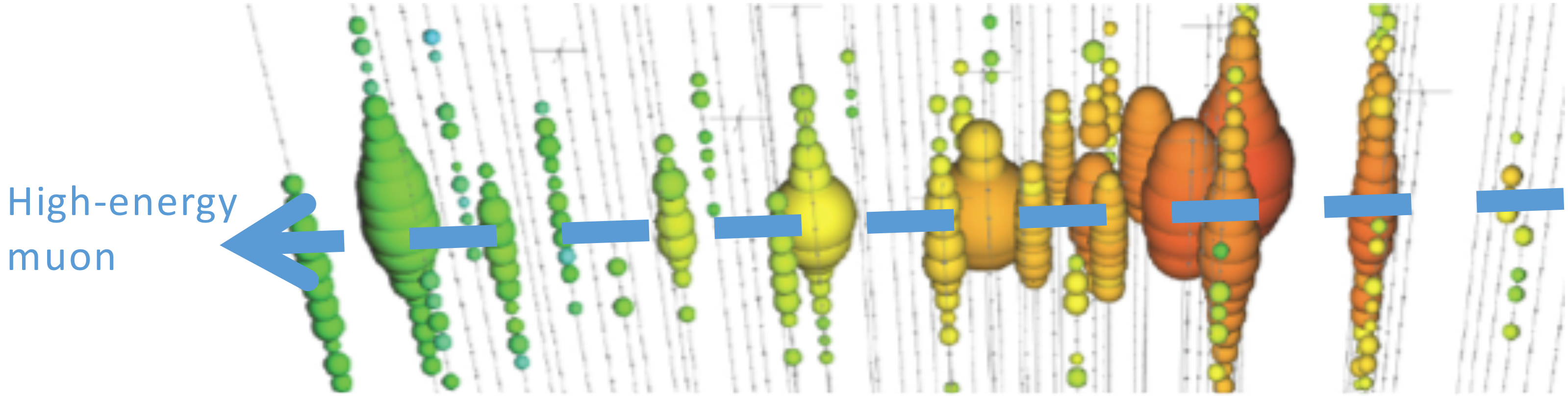


Juan Pablo Yanez

Approaches for reconstruction

Tracks

- Use **first-hit times** for *directional* reconstruction (SplineSPE, SANTA)
- Use **full-waveform** information by fitting predicted light yields to what is actually seen (MuEx, Millipede, DirectFit, DirectReco)
- Millipede works for **high-energy tracks** by breaking it up into multiple cascades along the track due to muon stochastic energy losses



Approaches for reconstruction

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Cascades

- Use **full-waveform** information by fitting predicted light yields to what is actually seen (Monopod, DirectFit, DirectReco)
- Train a Deep Neural Net on simulation (DNN)

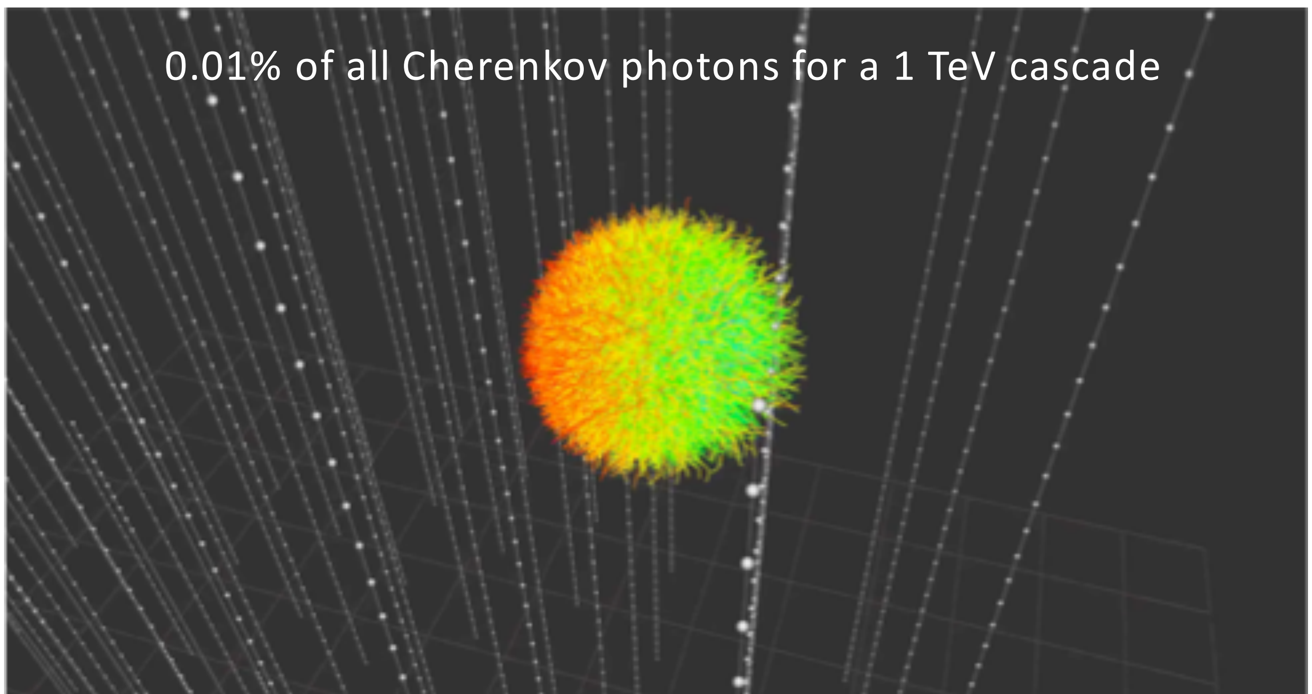
Challenges in cascade reconstruction

Large distances between DOMs means not many detected photons

Small asymmetry means high dependence on ice modeling

Sheer number of photons difficult to simulate

1. Tabulate photon yields for a single ice model (Millipede/Monopod)
    - Fast, less flexible, table generation time-consuming
2. Directly propagate all photons for any ice model (DirectFit)
    - Slow, more flexible



Two approaches to **full-waveform** reconstruction

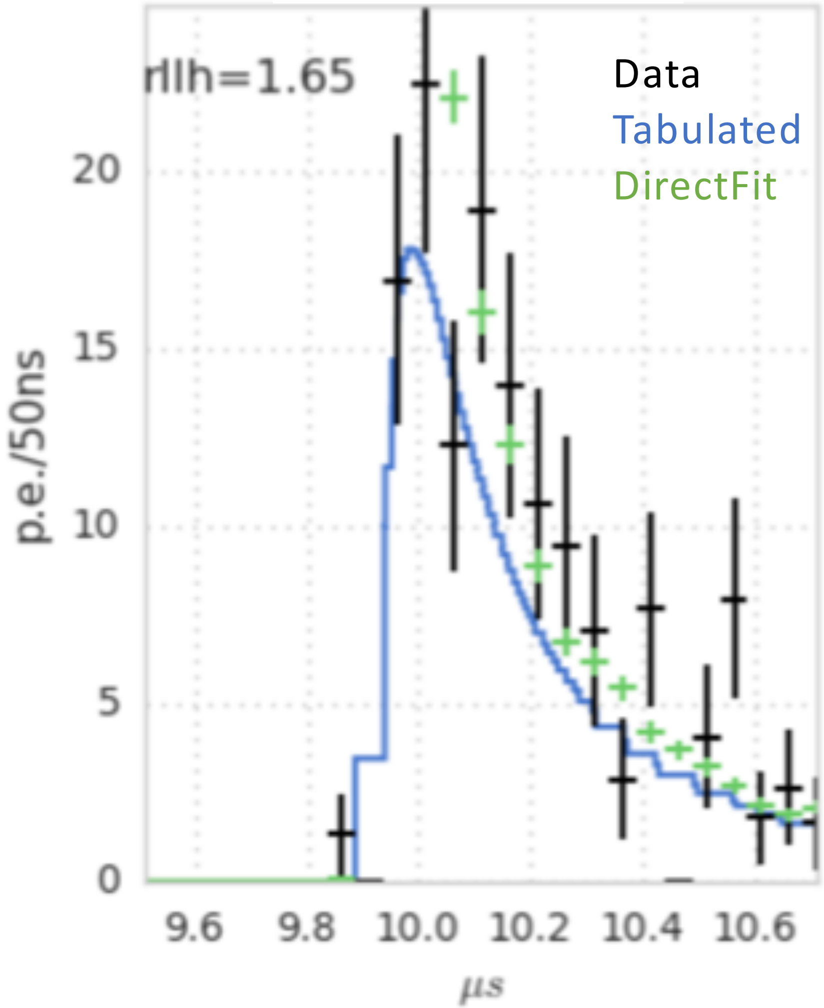
Tabulated photon yields

- Pros: Fast runtime; gradients
- Cons: Limited ice-models

Direct photon propagation

- Pros: Any ice-model can be used
- Cons: Statistical errors from both data and MC; slow

Example waveform



IC collaboration, 1311.4767
D. Chirkin, arXiv:1304.0735

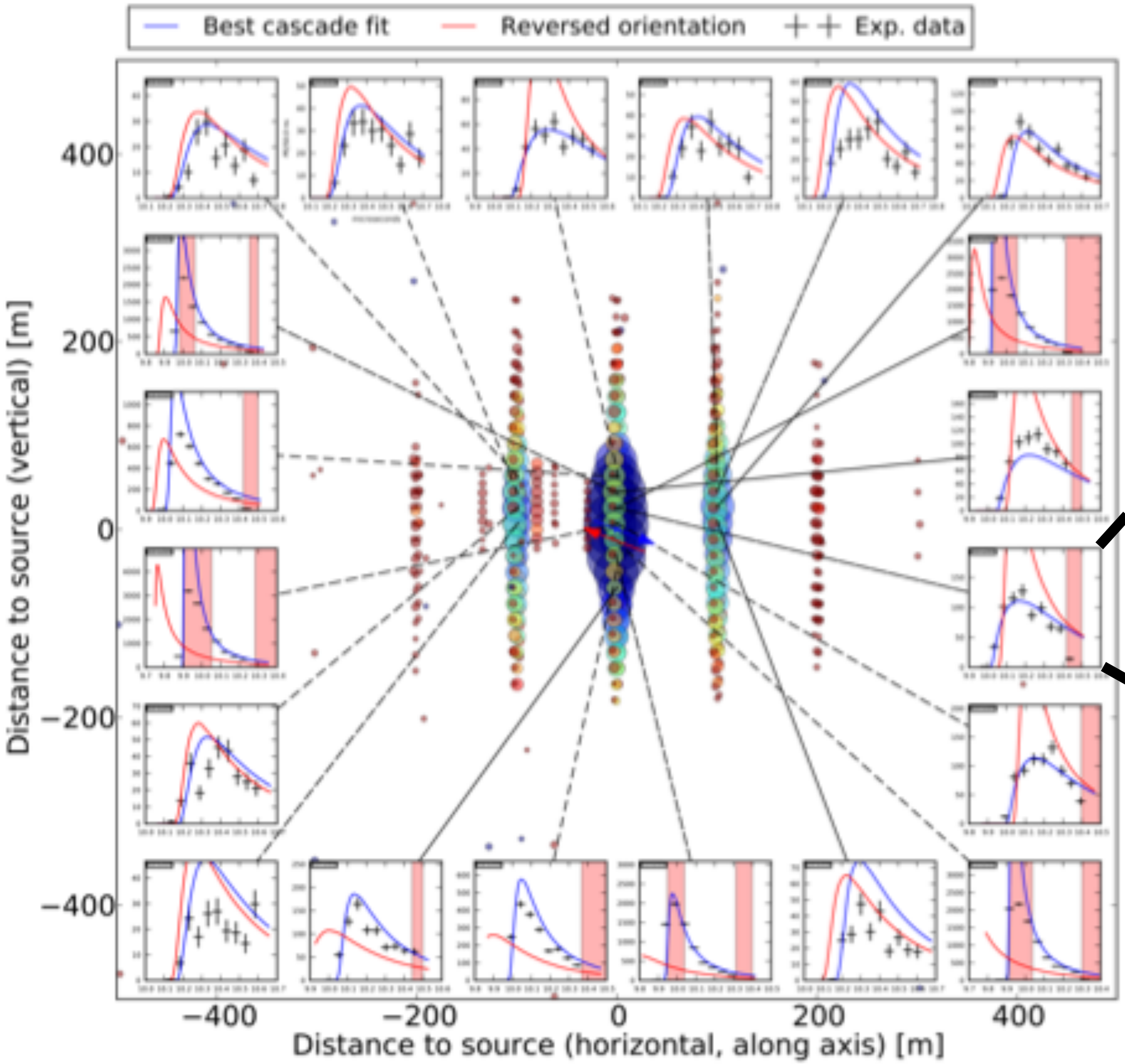
Minimization approaches

Given a likelihood $\mathcal{L}(\boldsymbol{\Theta}|\mathrm{X}_{\mathrm{Data}})$ as a function of $\boldsymbol{\Theta} = (x, y, z, \theta, \phi, E, t)$, want to find $\boldsymbol{\Theta_0}$ that minimizes the negative likelihood

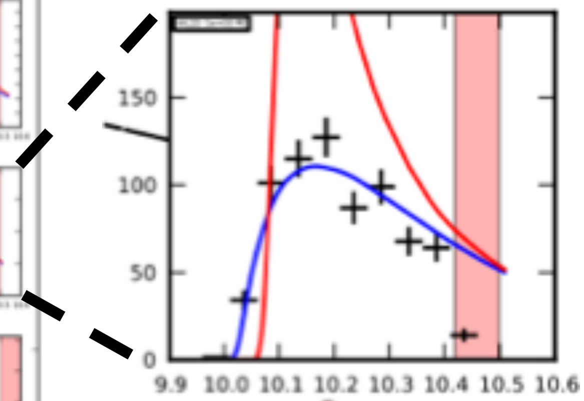
Need to explore 7D space which is challenging

- Millipede/Monopod uses **photon tables** which allows for iterative gradient descent

Cascade orientation from full-waveform



Differences between best-fit and reversed-orientation from Monopod



Time-windows where PMT saturates or calibration failed are shaded

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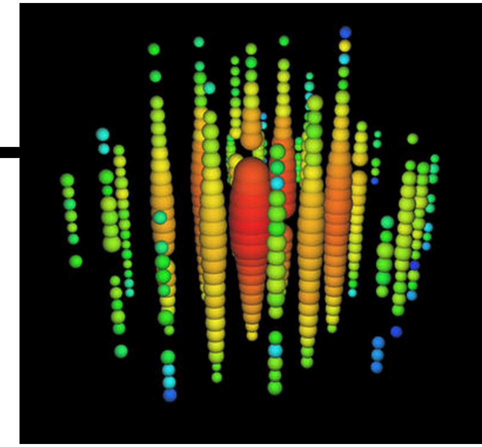
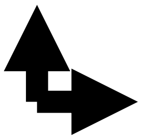
- Millipede/Monopod uses **photon tables** which allows for iterative gradient descent
  - Doesn't always find the global minimum

- Can also **brute force** all possible directions (θ, ϕ) to reduce the minimization to only 5 dimensions

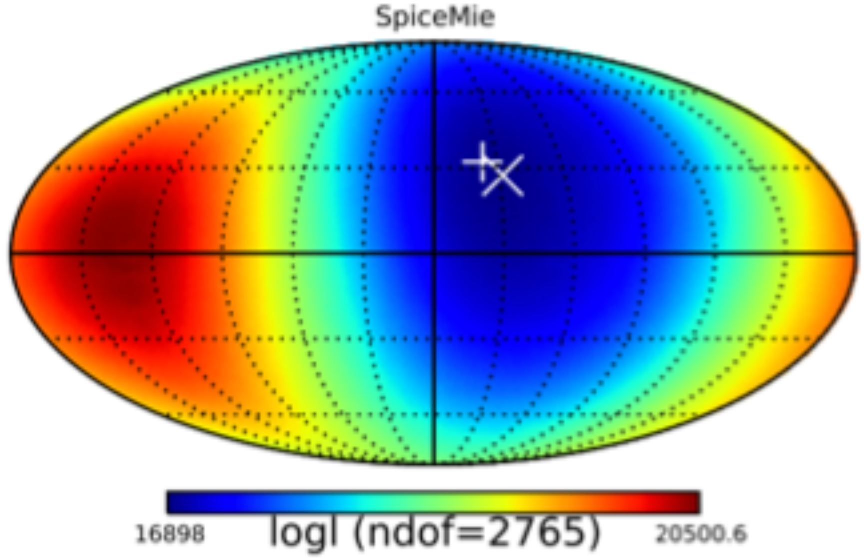
Monopod LLH skymap for cascade

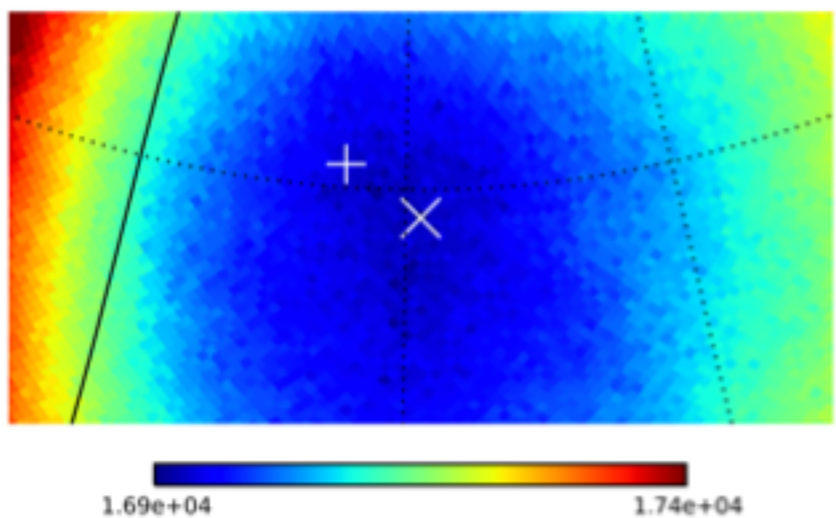


Zenith



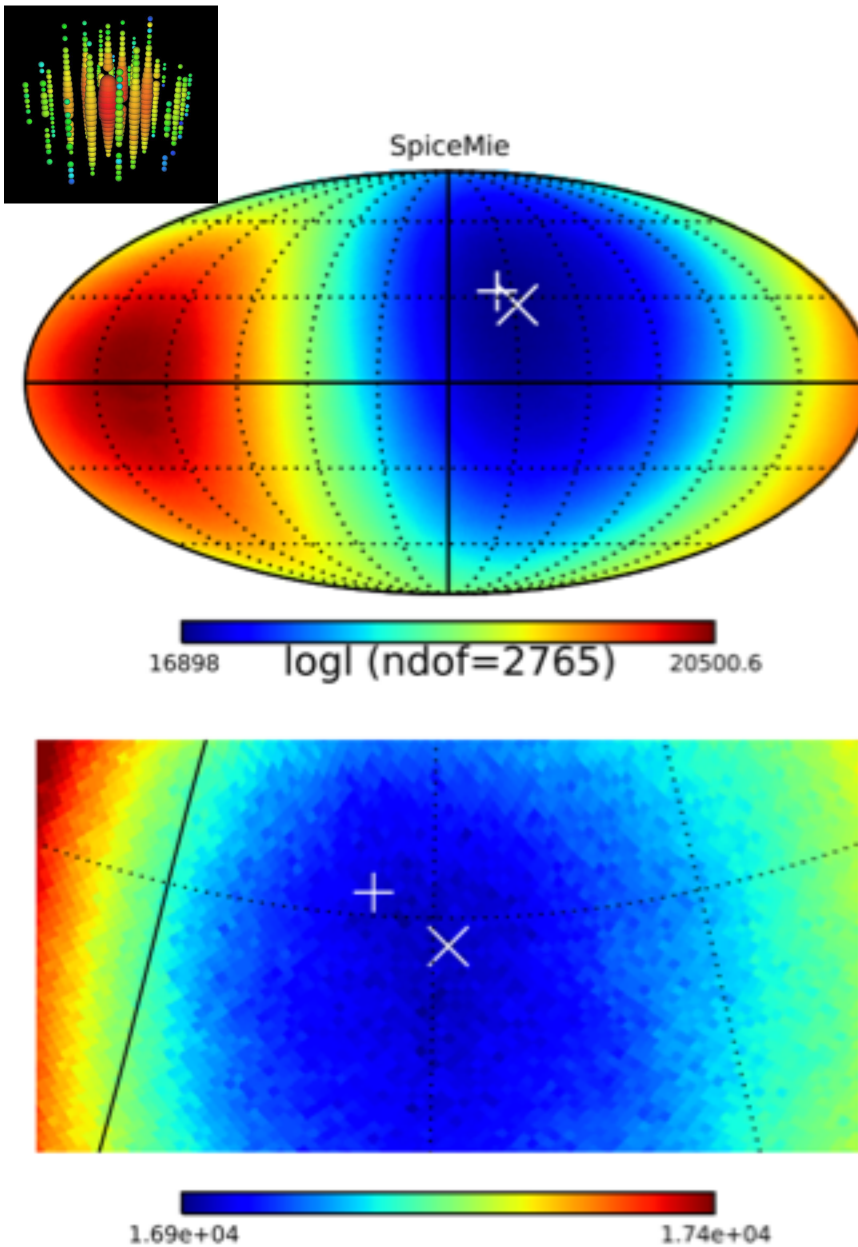
Azimuth

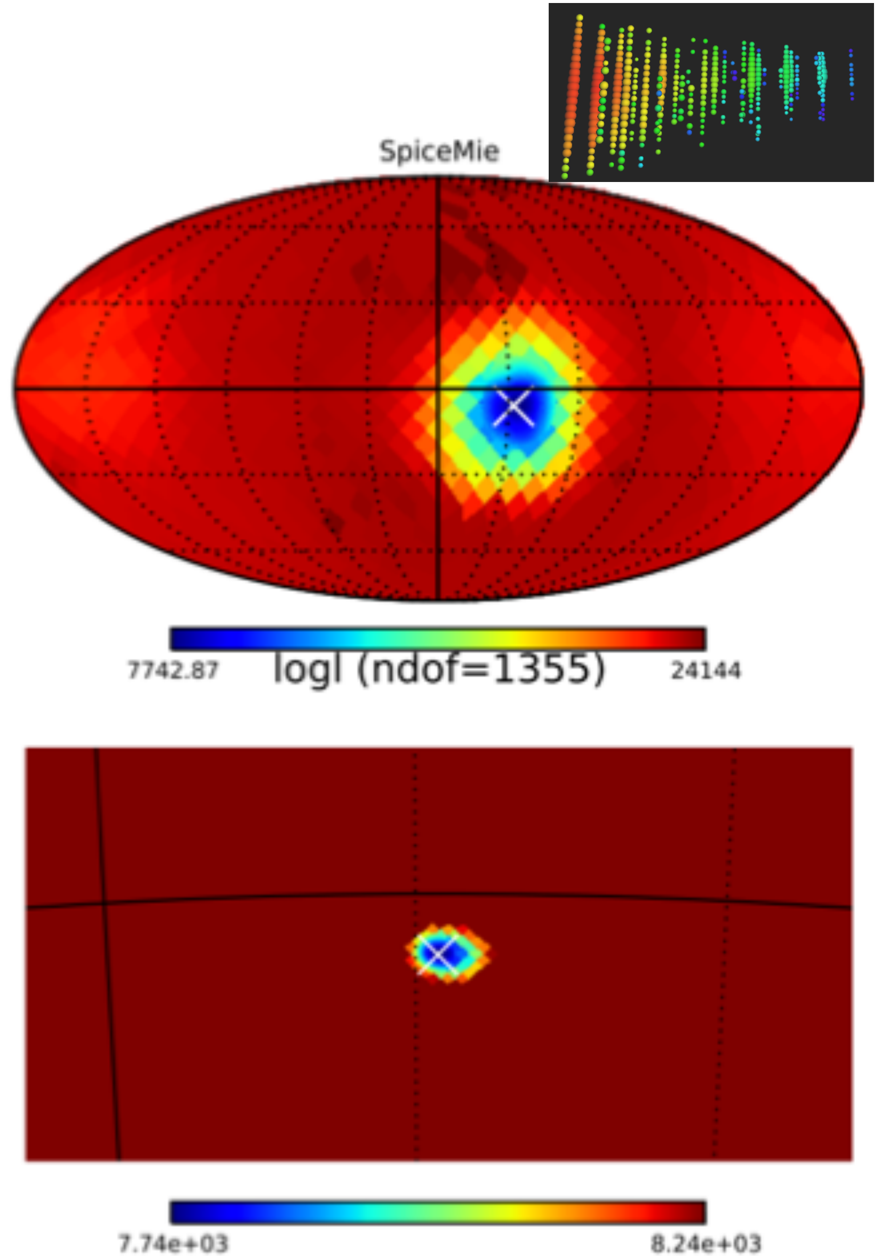




x Brute force
+ Iterative fit

Cascade vs track skymap





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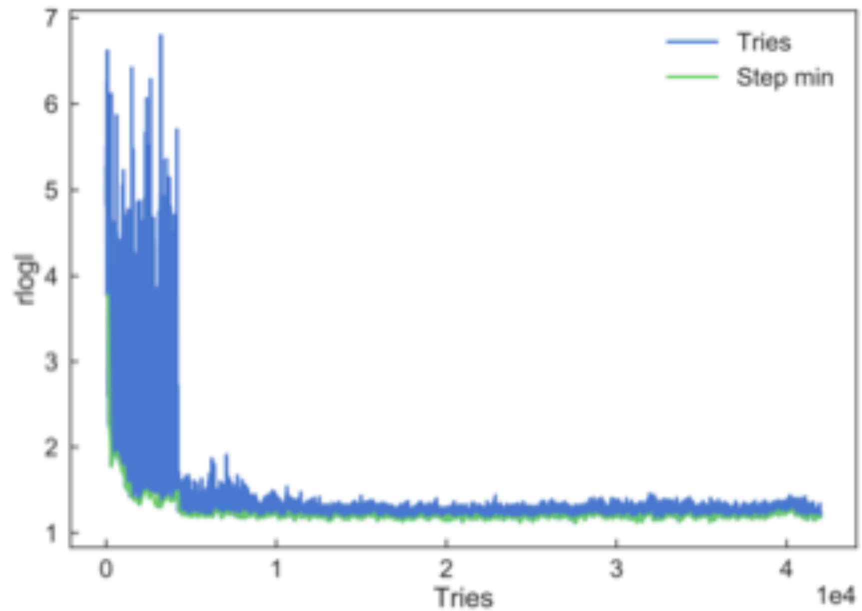
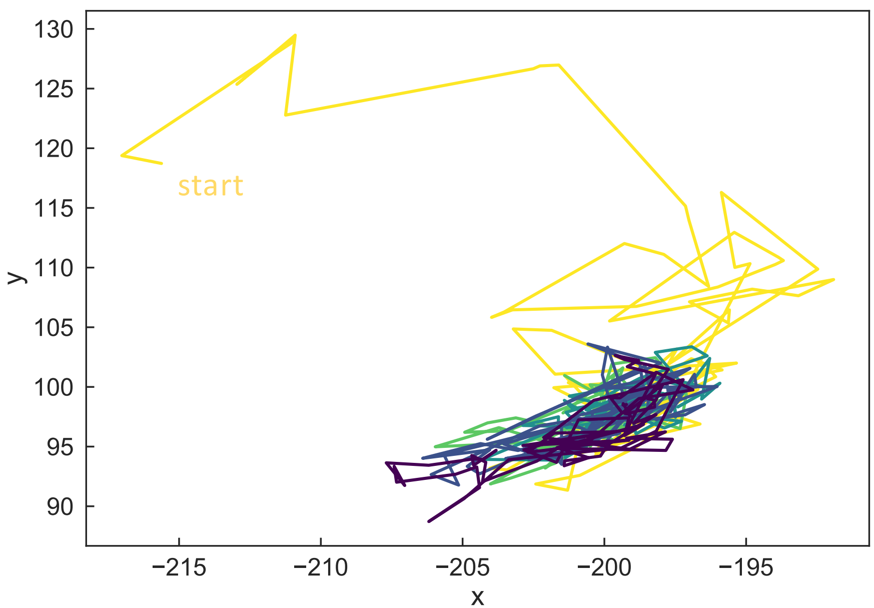
- DirectFit attempts to find minimum using **localized random search**, randomly sampling points in (x, y, z, θ, ϕ) within a "search radius" that is refined iteratively

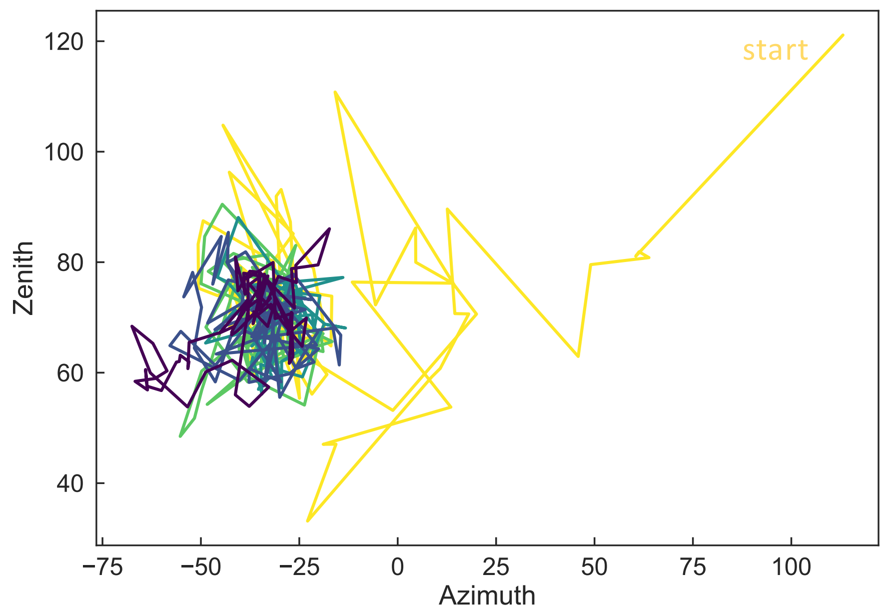
DirectFit minimization

Likelihood gradually improves from start to finish

Following this, MCMC approach to sample from posterior pdf

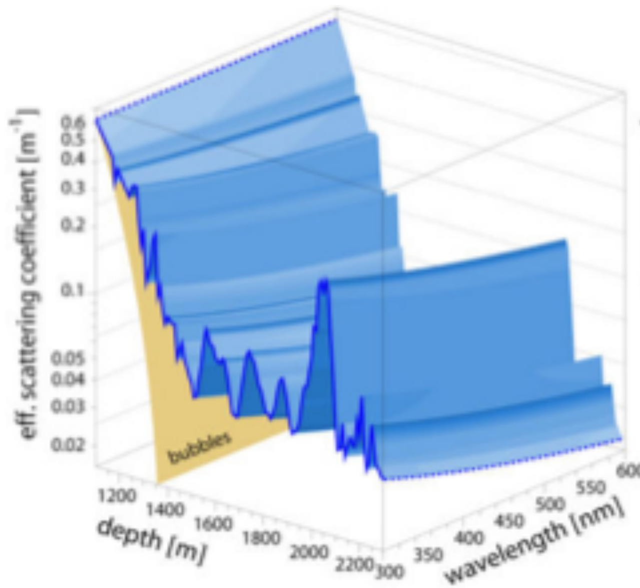


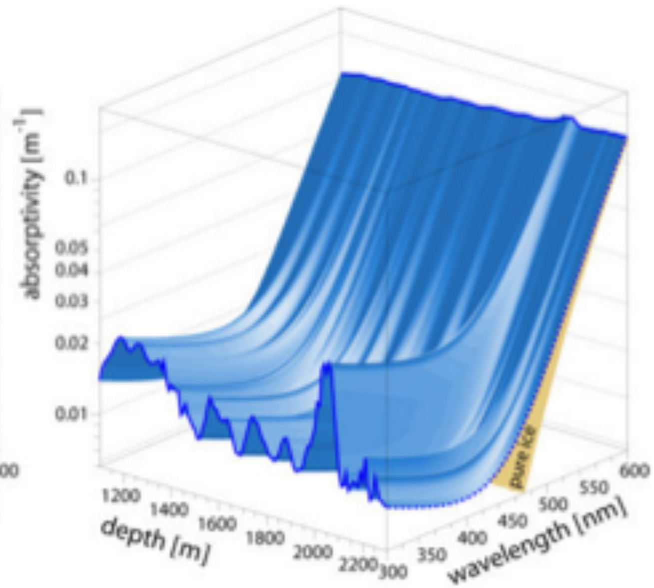




Ice modeling is important!

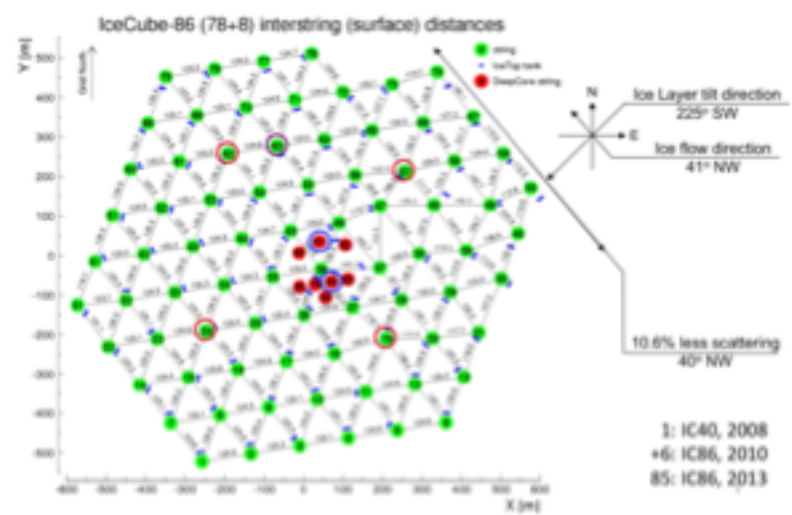
Bulk ice described by scattering and absorption coefficients as a function of depth → these have been refined over time





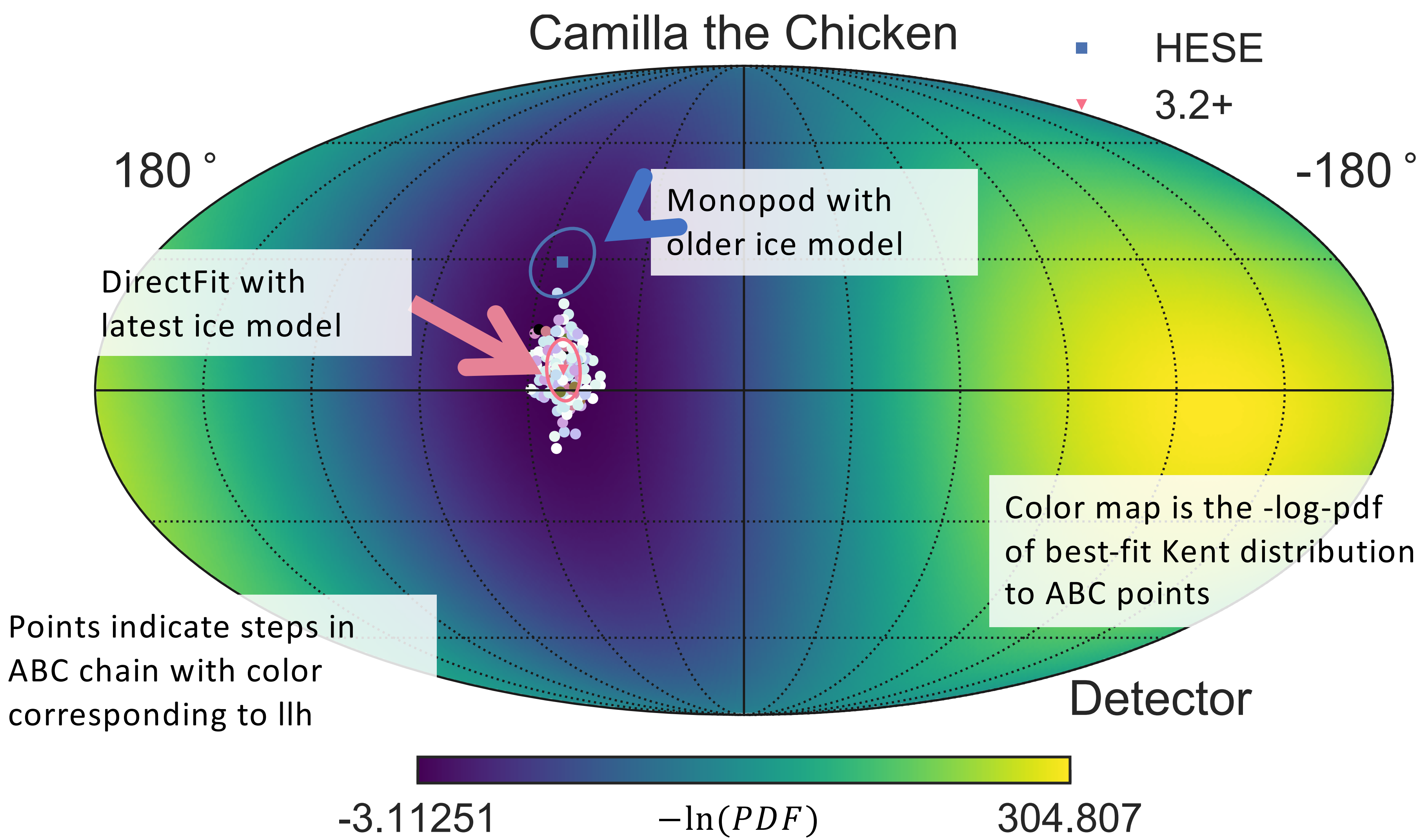
Ice layers were found to be tilted [arXiv:1301.5361]

Ice was also discovered to be anisotropic [ICRC 2013, 0580]



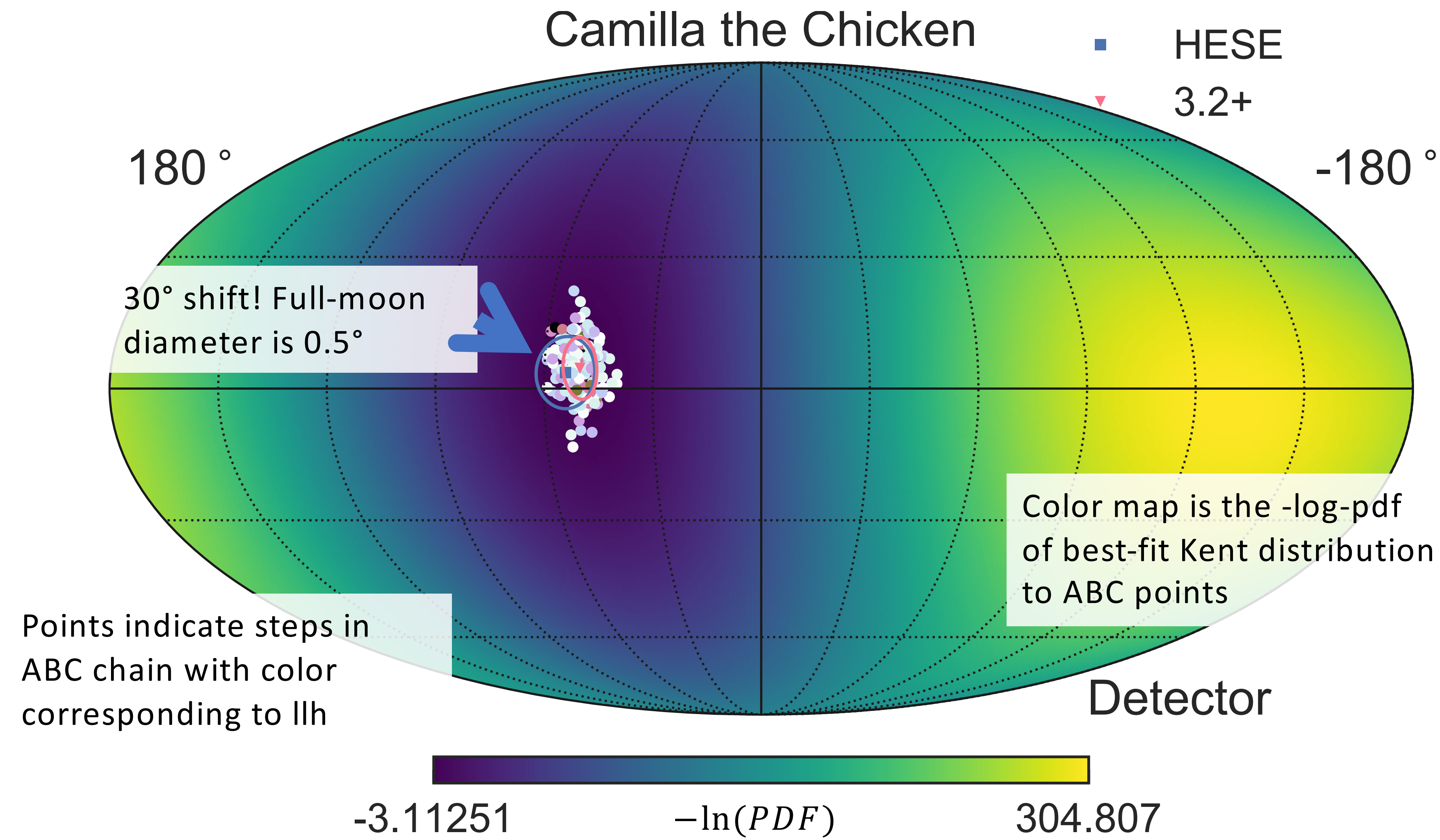
Directional bias due to different ice models

Previous HESE reconstruction uses photon tables for older ice model



Reduction in bias with updated ice model

Better agreement with updated tables that includes anisotropy [PoS(ICRC2017), 974]



Local effects

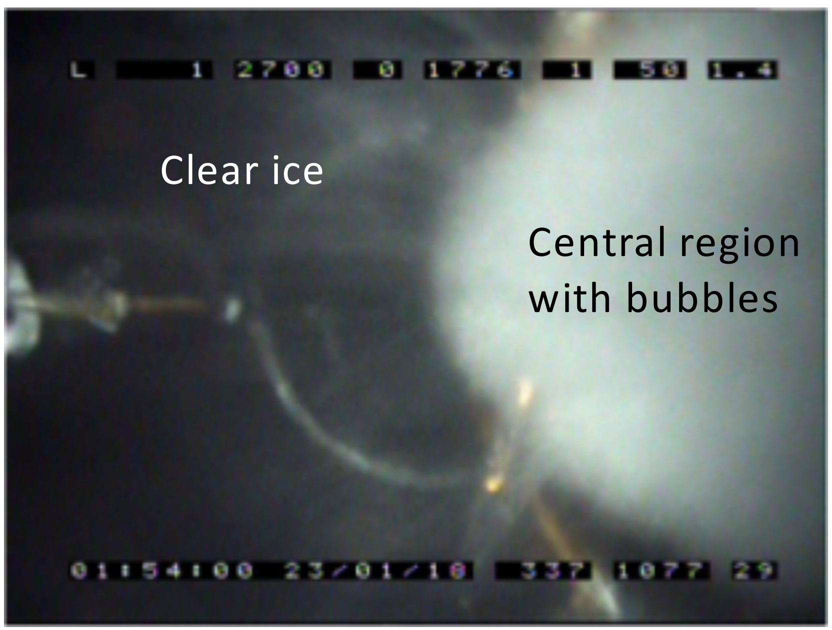
Hole-ice

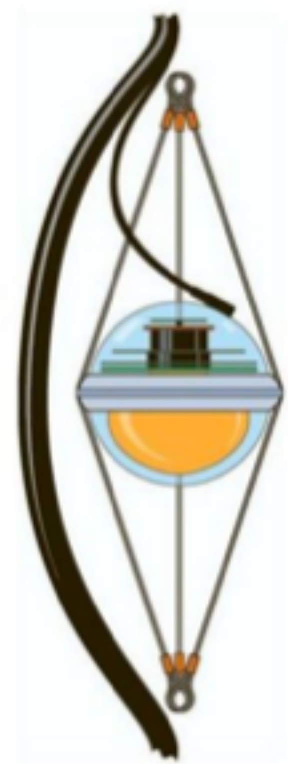
- Refrozen central column with high scattering

DOM orientation

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

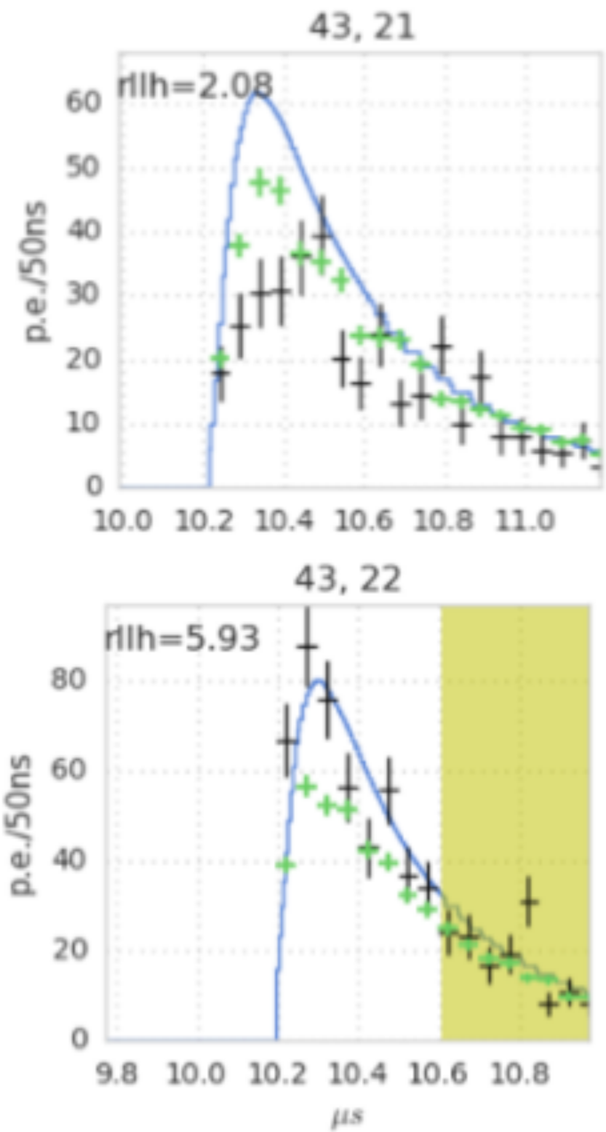
Looking up the string





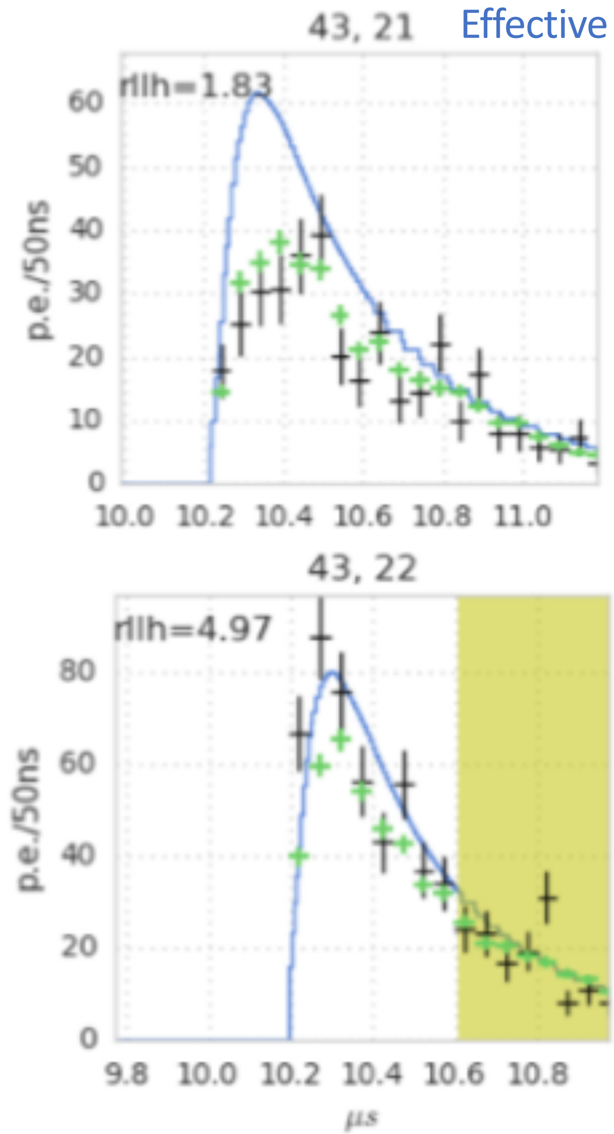
Local effects: DOM orientation and cable position

Without local effects



With local effects

Bert data
Direct photon MC
Effective photon MC

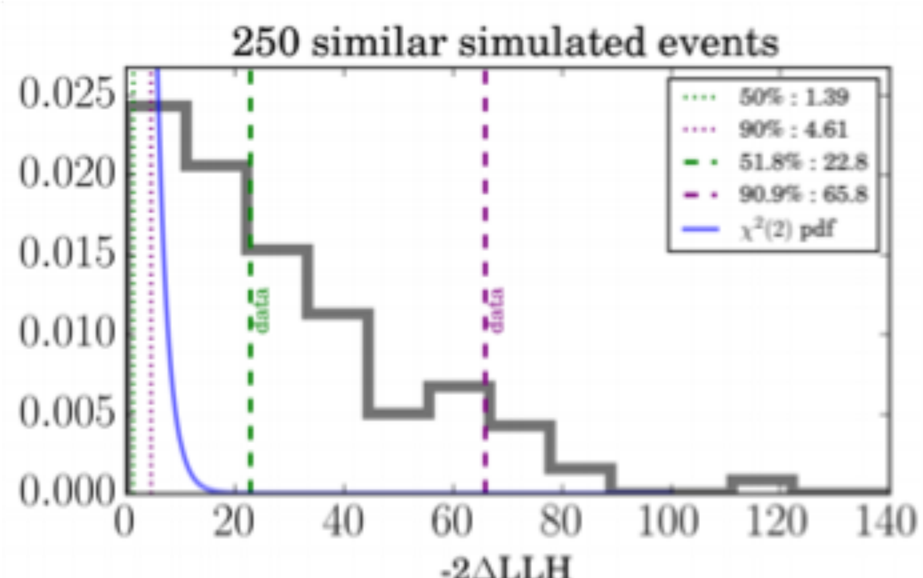


Uncertainty estimation

Ice uncertainties affect reconstructed directions

Directional uncertainties important for point-source searches

With Millipede/Monopod full-sky scan, can draw a contour at some value of Δllh derived from resimulations with different ice models



With DirectFit, can reconstruct with different ice-models and combine into larger contour

Summary

Reconstruction in IceCube is often a challenge

Many algorithms exist, separable into high-energy/low-energy and track/shower

Each has pros and cons

Ice models are important; try to use the latest version available

Didn't talk about multinest, Spline-reco, DNN

Backups