Improving angular resolution in IceCube cascades

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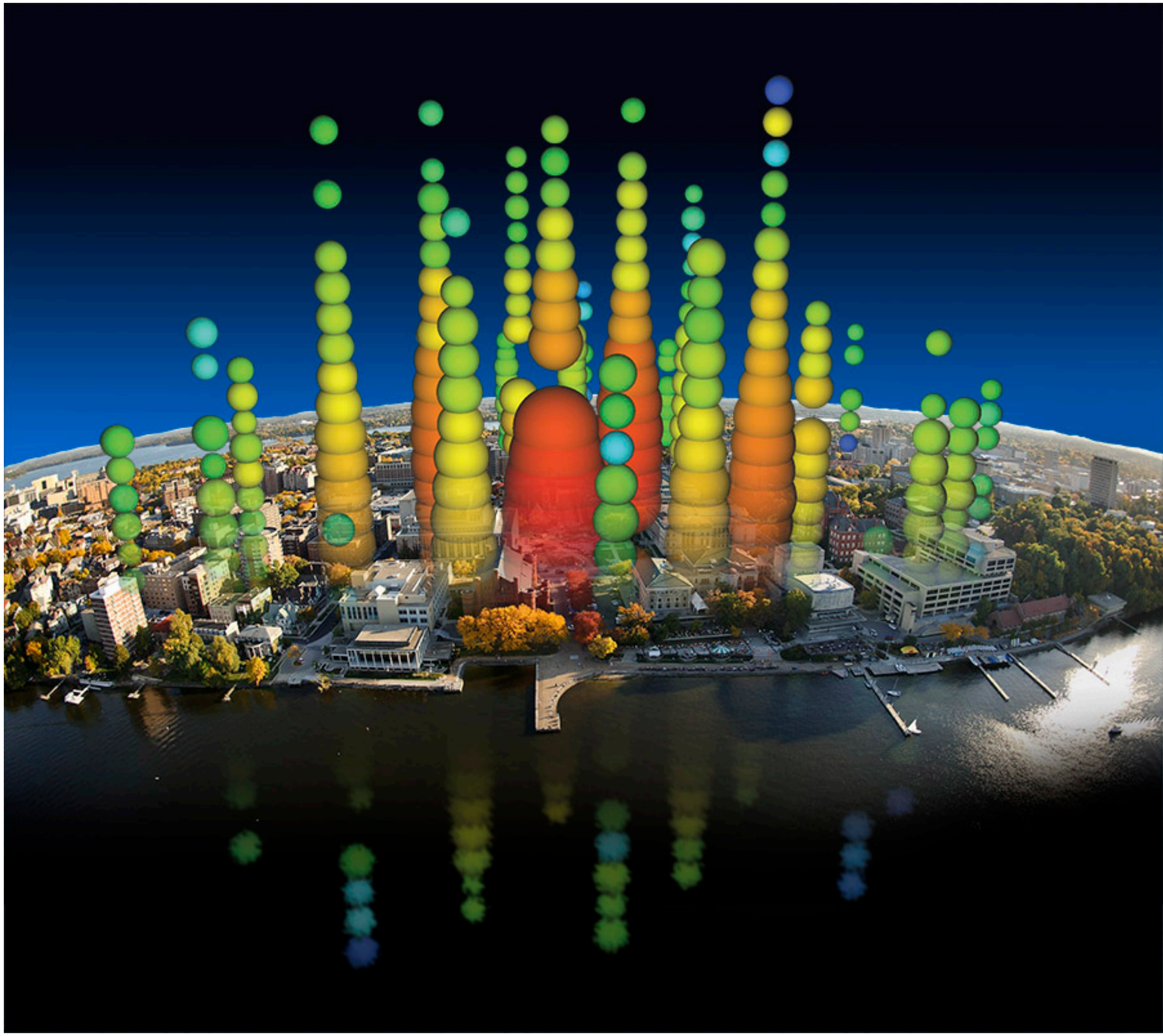
The IceCube collaboration

TeVPA, 8 Aug 2017

Columbus, OH, USA



ICECUBE

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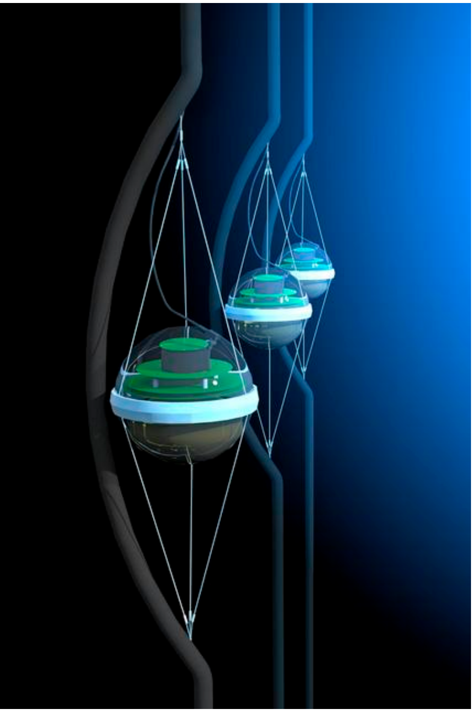
IceCube

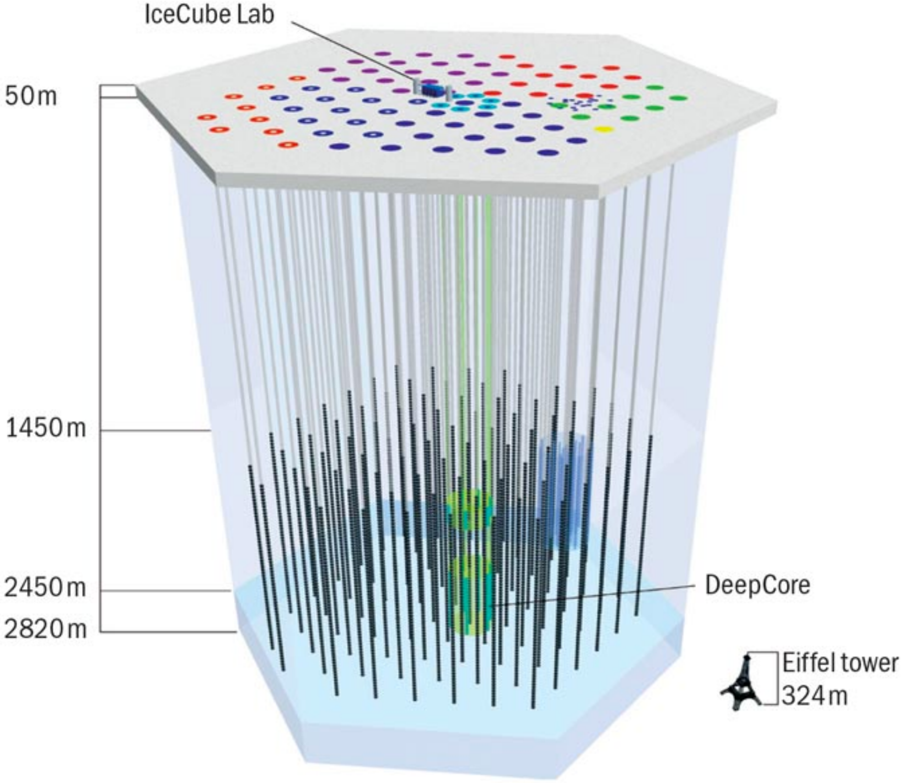
Over 5000 deployed Digital Optical Modules (DOMs) on 86 strings



Vertical PMT spacing
17m
7m in DeepCore

String spacing
125m
45-70m in DeepCore

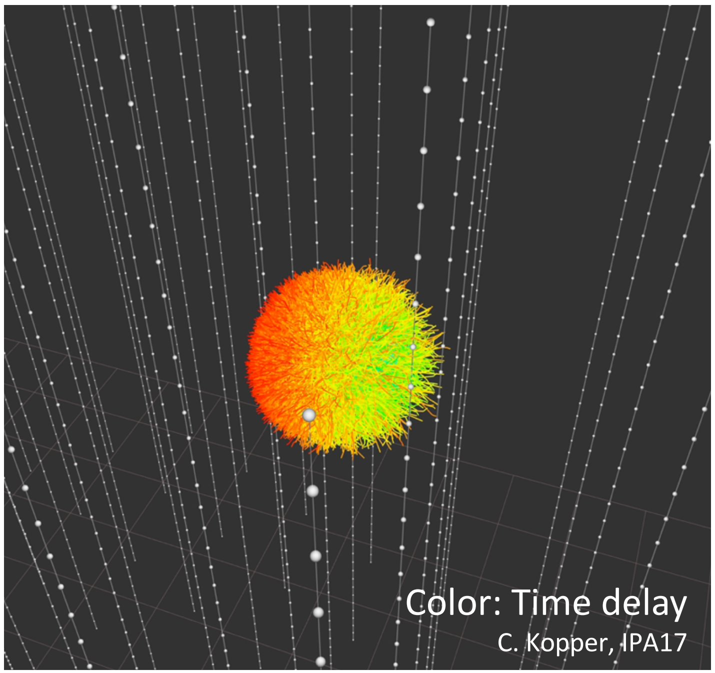
Energy range
10 GeV—10 PeV



Cascades in IceCube

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

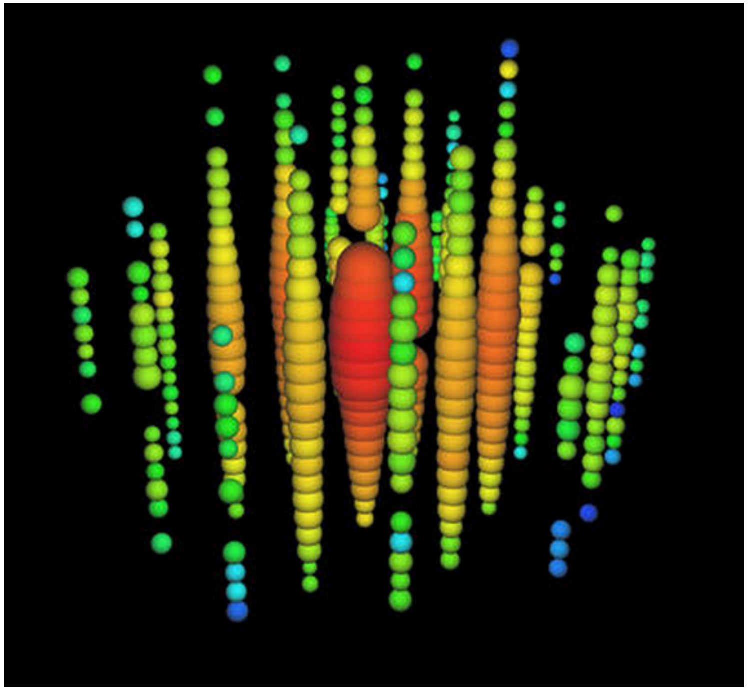
Hadronic or EM shower from neutral-current or ν_e charge-current



Simulated photons

Asymmetry in photon emission allows for directional reconstruction

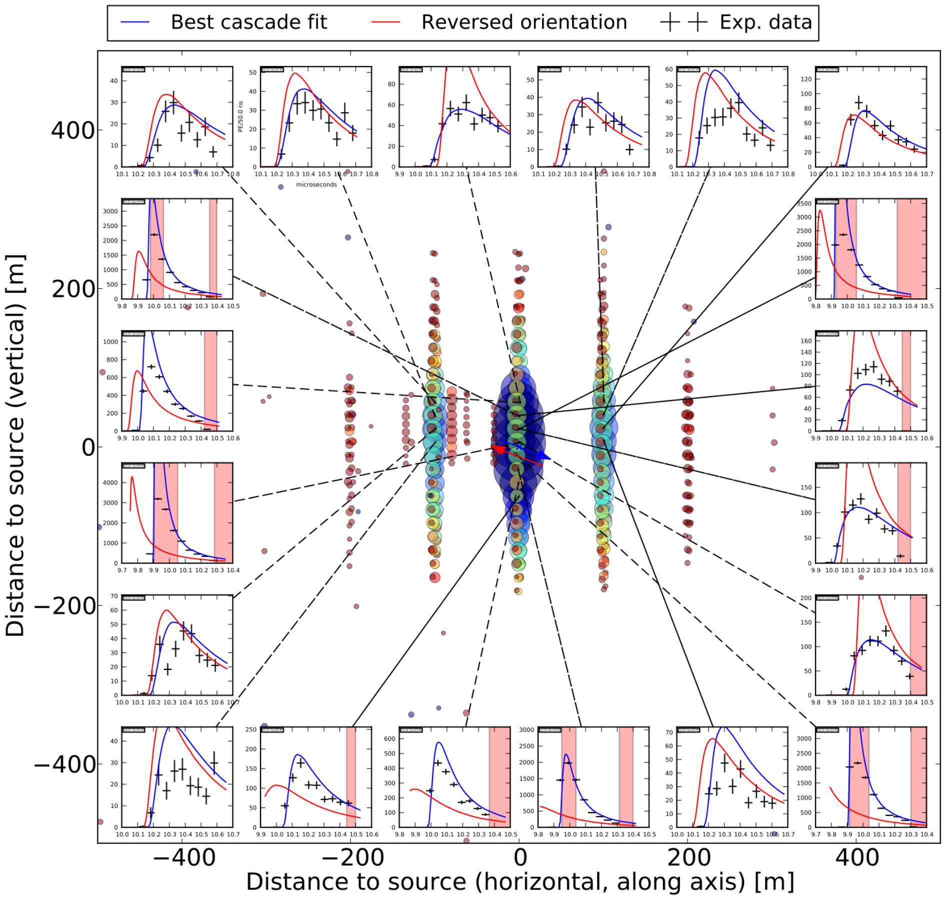
Information loss



Detected photons

Waveforms and cascade orientation

Bert "Panopticon" plot



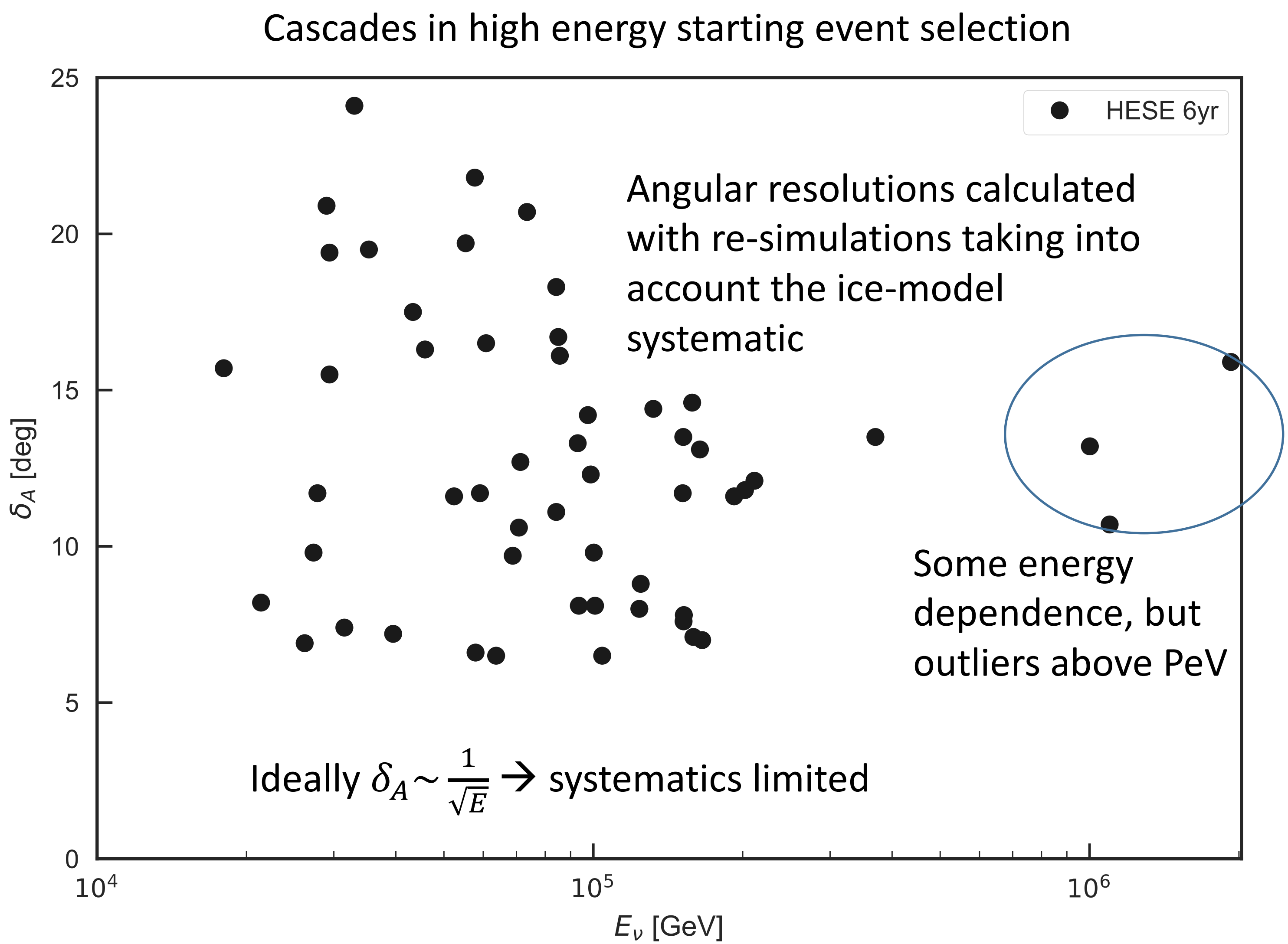
Time-windows where PMT saturates or marked as errata are shaded in red

Reconstruction relies on waveform amplitude and timing

Noticeable differences between best-fit and reversed-orientation directions

Some disagreement between best-fit and data remain and hint that there is room to improve reconstruction

Cascade resolutions for HESE

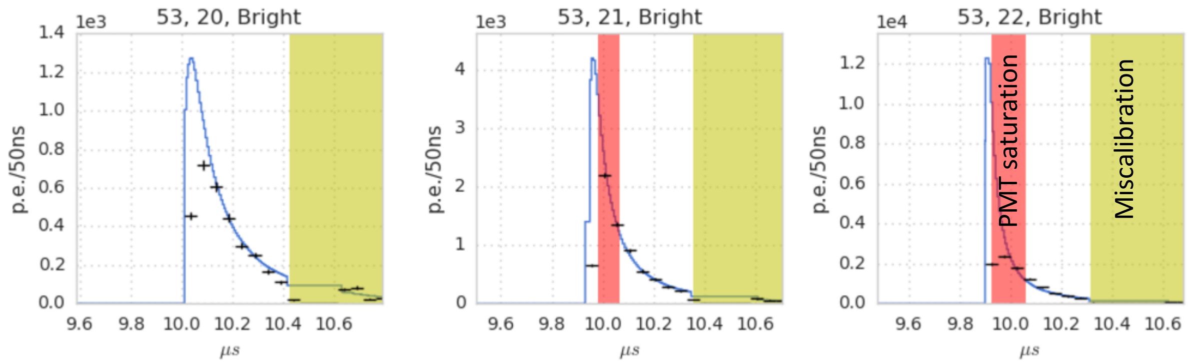


Two approaches to improved resolutions

1. Include more data

Bert waveforms on closest string

A few examples of unused waveforms

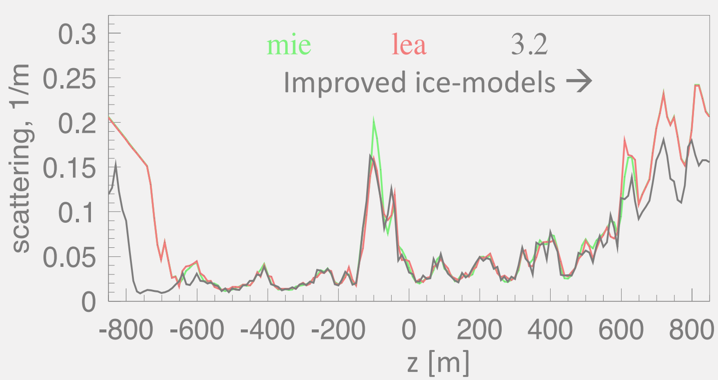


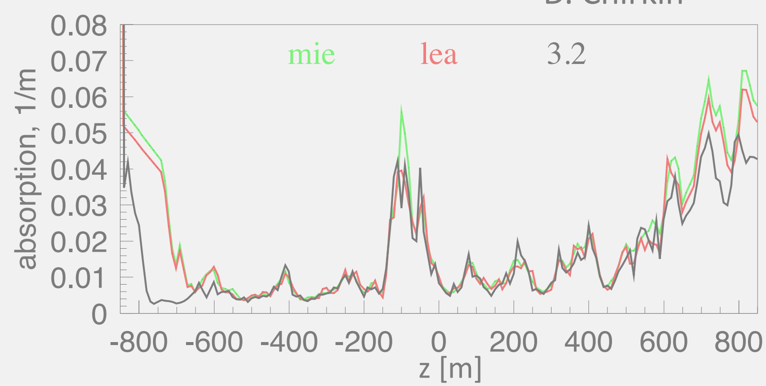
Bright DOMs are ignored in reconstruction

2. Improve ice model, reduce ice uncertainties

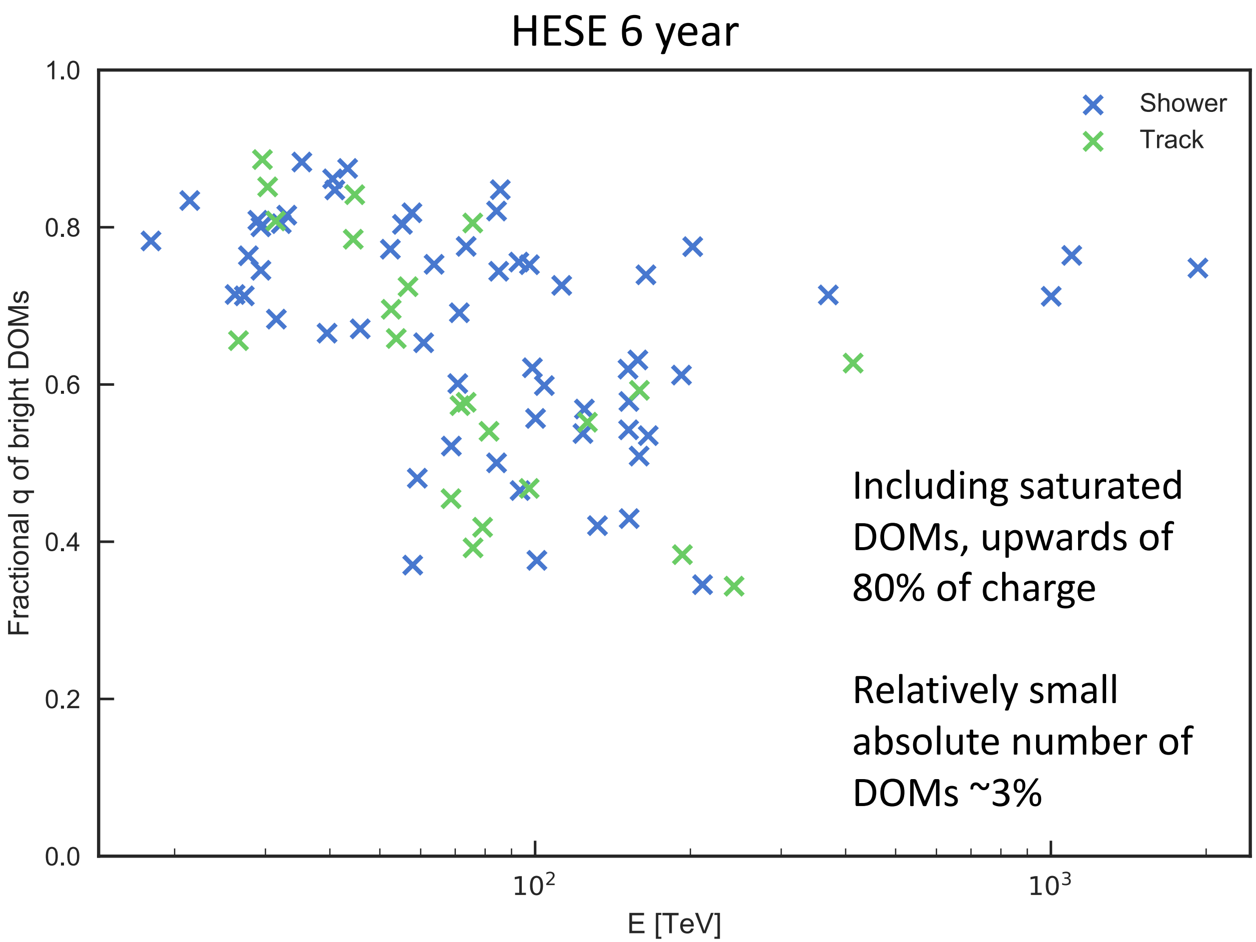
D. Chirkin

Currently an effective ice-model error of 10%





Bright DOMs in high energy events



Including saturated DOMs, upwards of 80% of charge

Relatively small absolute number of DOMs ~3%

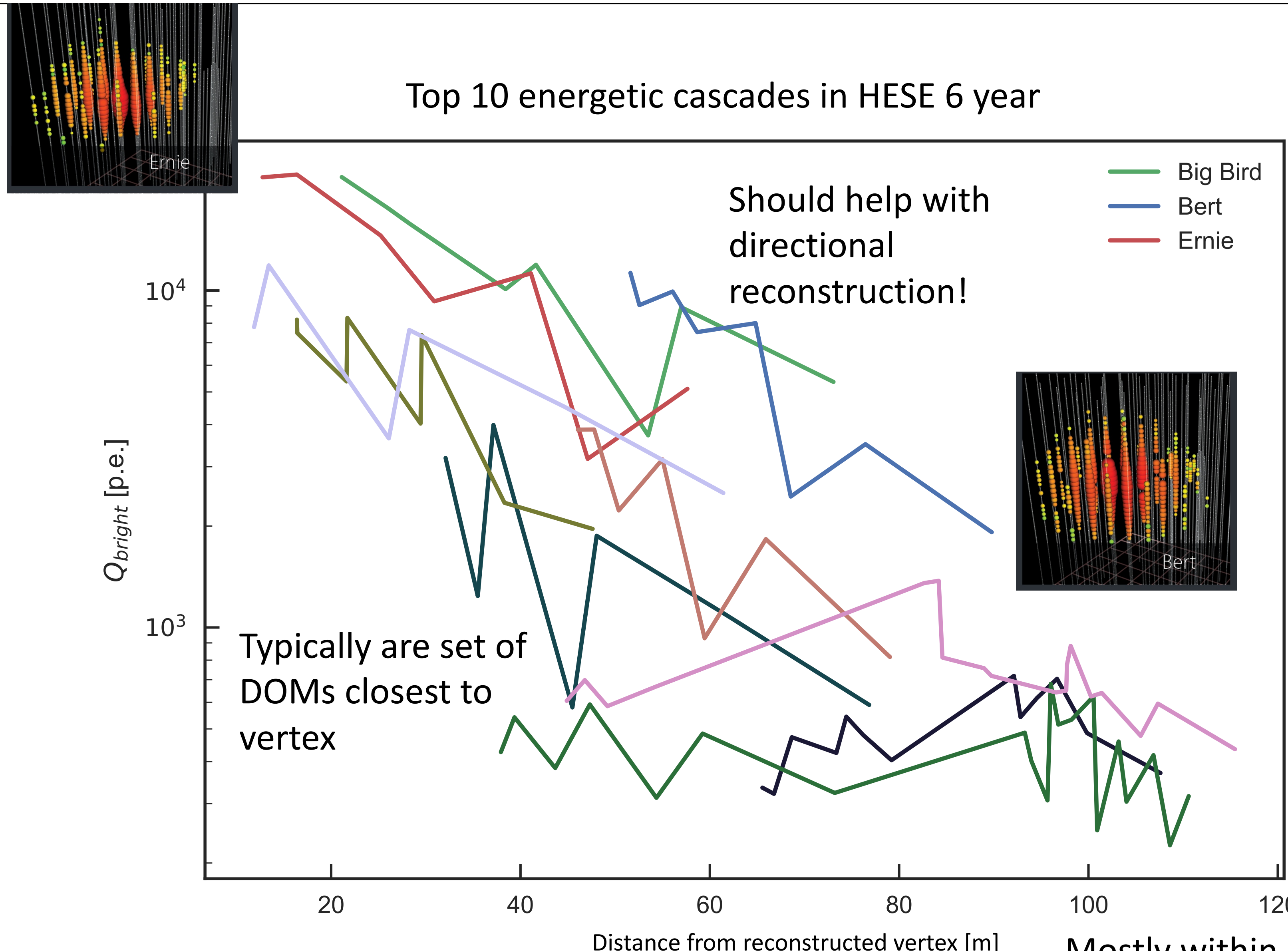
Define Q_{avg} as the mean total charge of all hit DOMs

DOMs with $Q_{bright} > 10*Q_{avg}$ are classified as “Bright”

PMT is not necessarily saturated, but excluded because systematic uncertainties start to dominate over statistical errors in fitting the waveforms

Distance to vertex of brightest DOMs

Top 10 energetic cascades in HESE 6 year



Should help with directional reconstruction!

Typically are set of DOMs closest to vertex

Mostly within single string spacing (125m)

Procedure

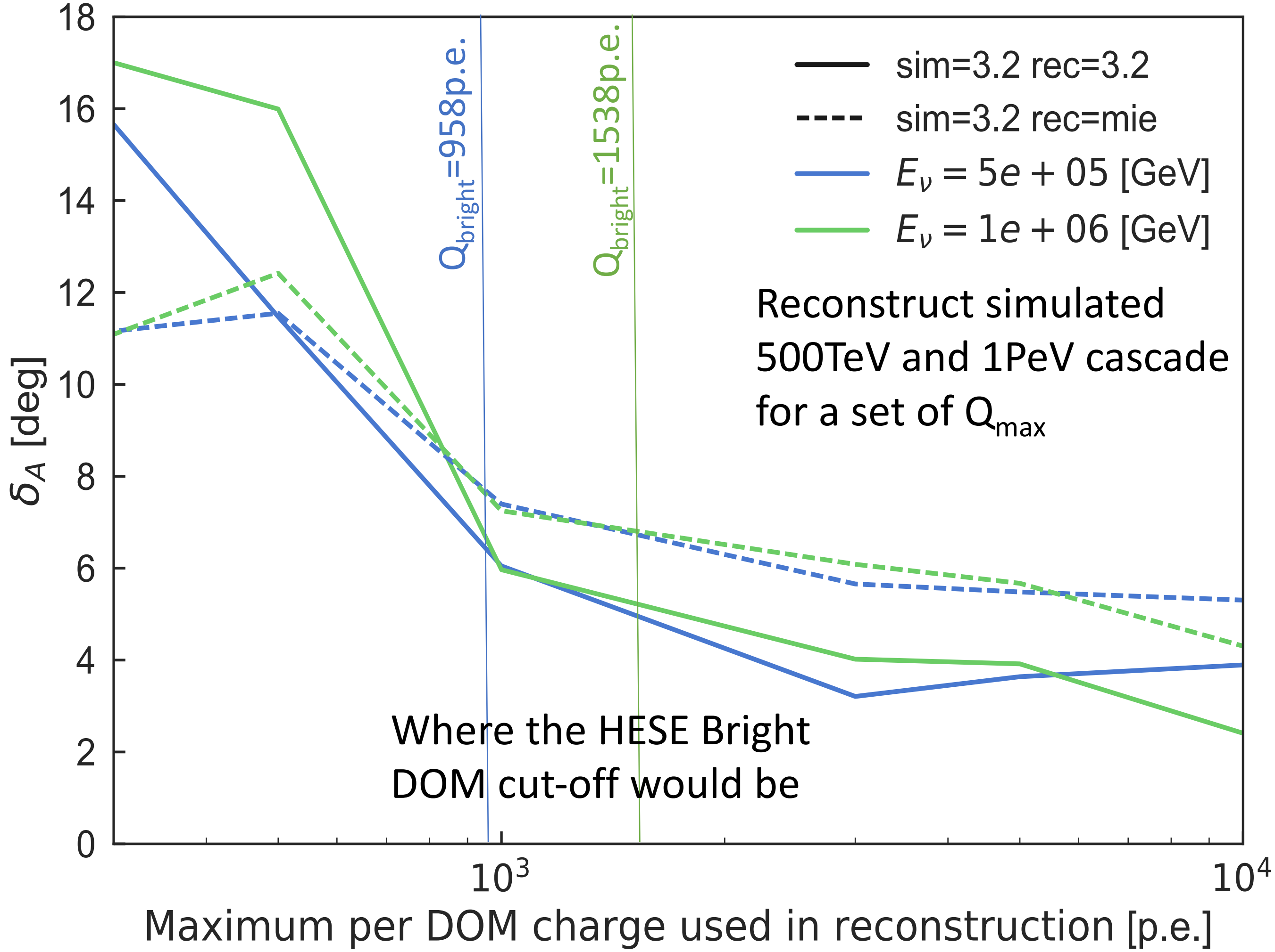
Ref. arXiv:1309.7010

1. Simulate an EM cascade at fixed location/direction and various energies with latest version of ice-model
2. For each simulated cascade, reconstruct with direct photon propagation
3. Approximate Bayesian Method (ABC) to get angular uncertainty

Reconstruction can be performed with different settings

- Identical or different ice-models: ice-rec
- Maximum per-DOM charge: Q_{max}
- Effective ice-model uncertainty parameter: σ (in a few slides)

Effect of Q_{max} on angular resolution



Tested with an identical sim-reco ice-model (3.2) and a different reco ice-model (mie)

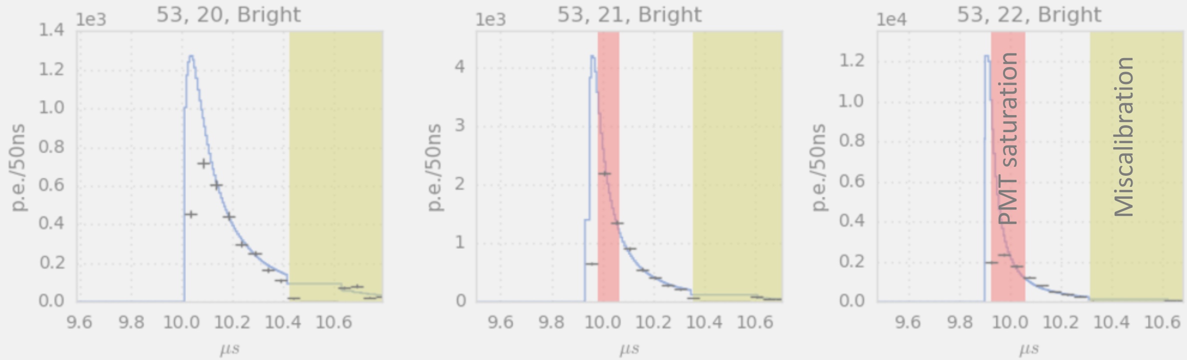
Both show a trend towards better angular resolution as more DOMs are included (increasing Q_{max})

Two approaches to improved resolutions

1. Include more data

Bert waveforms on closest string

A few examples of unused waveforms

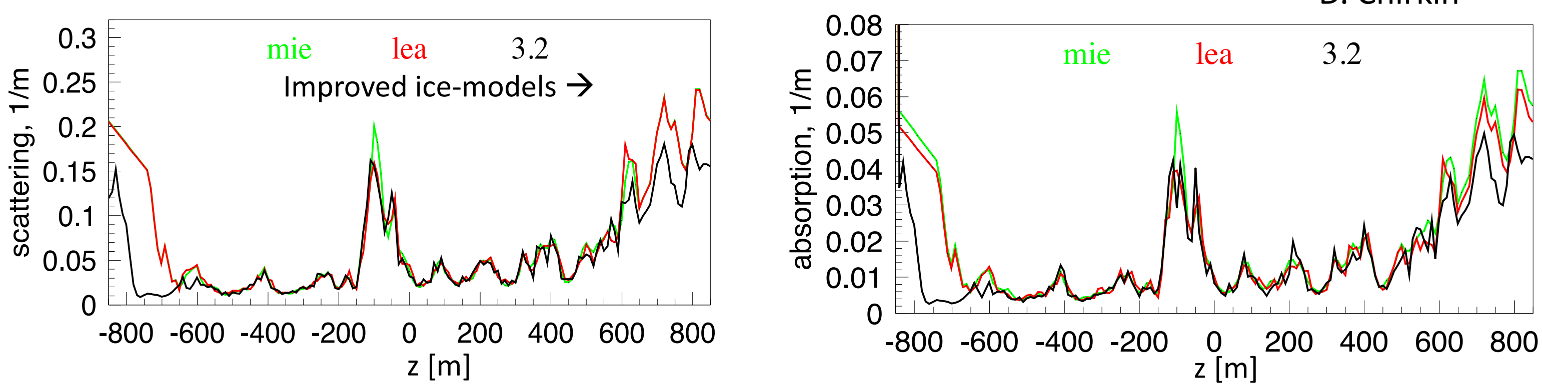


Bright DOMs are ignored in reconstruction

2. Improve ice model, reduce ice uncertainties

D. Chirkin

Currently an effective ice-model error of 10%



Effective ice-model uncertainty

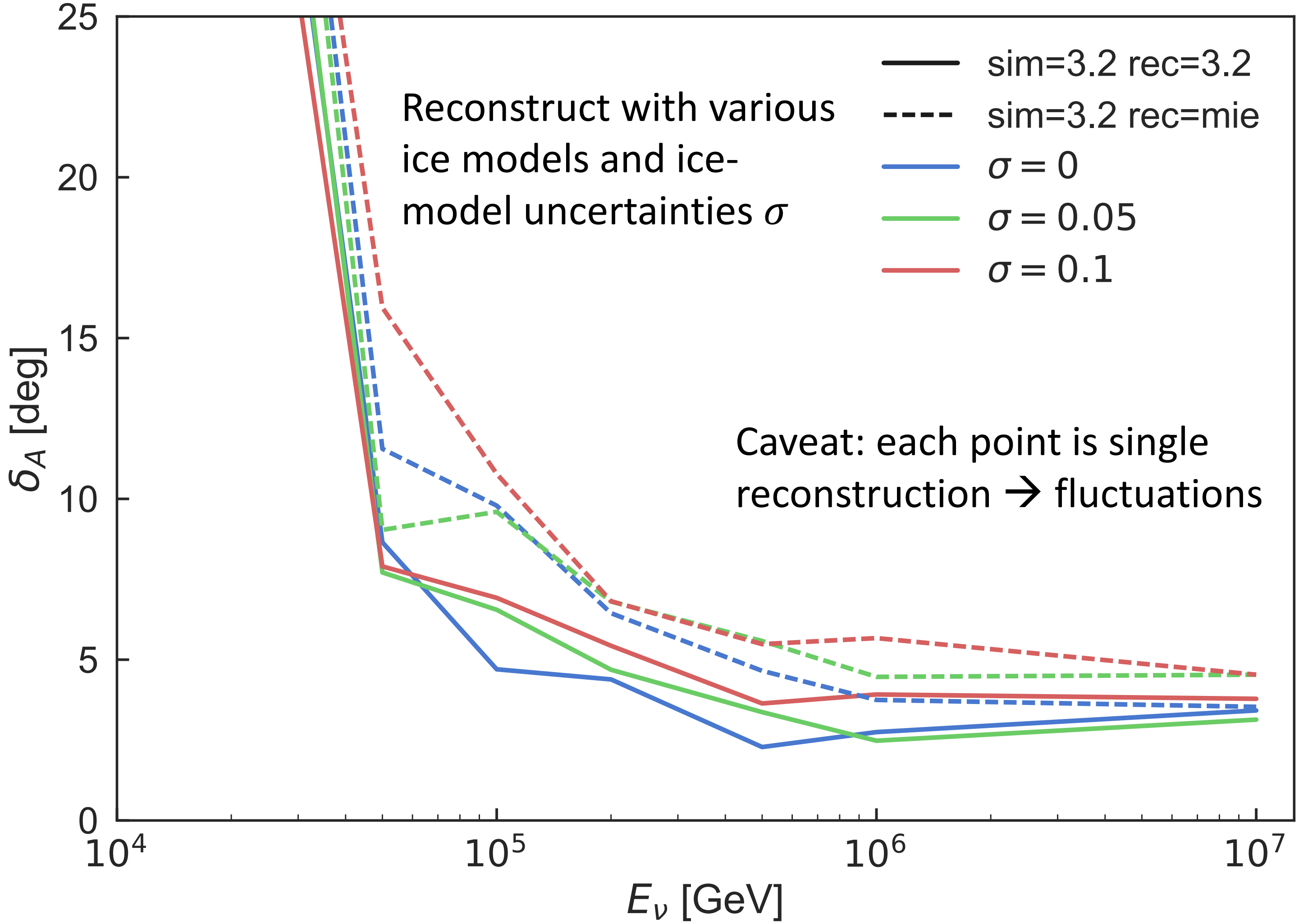
Ref. arXiv:1304.0735

Without any ice-model systematic, simulation must describe data completely within statistical errors

Add smearing to predicted charge on each DOM that penalizes the likelihood with log-normal distribution: $\exp \frac{-\ln\left(\frac{\mu_d}{\mu_s}\right)^2}{2\sigma^2}$.

Effective ice-model uncertainty parameterized with σ; based on data from in-situ LED calibration devices

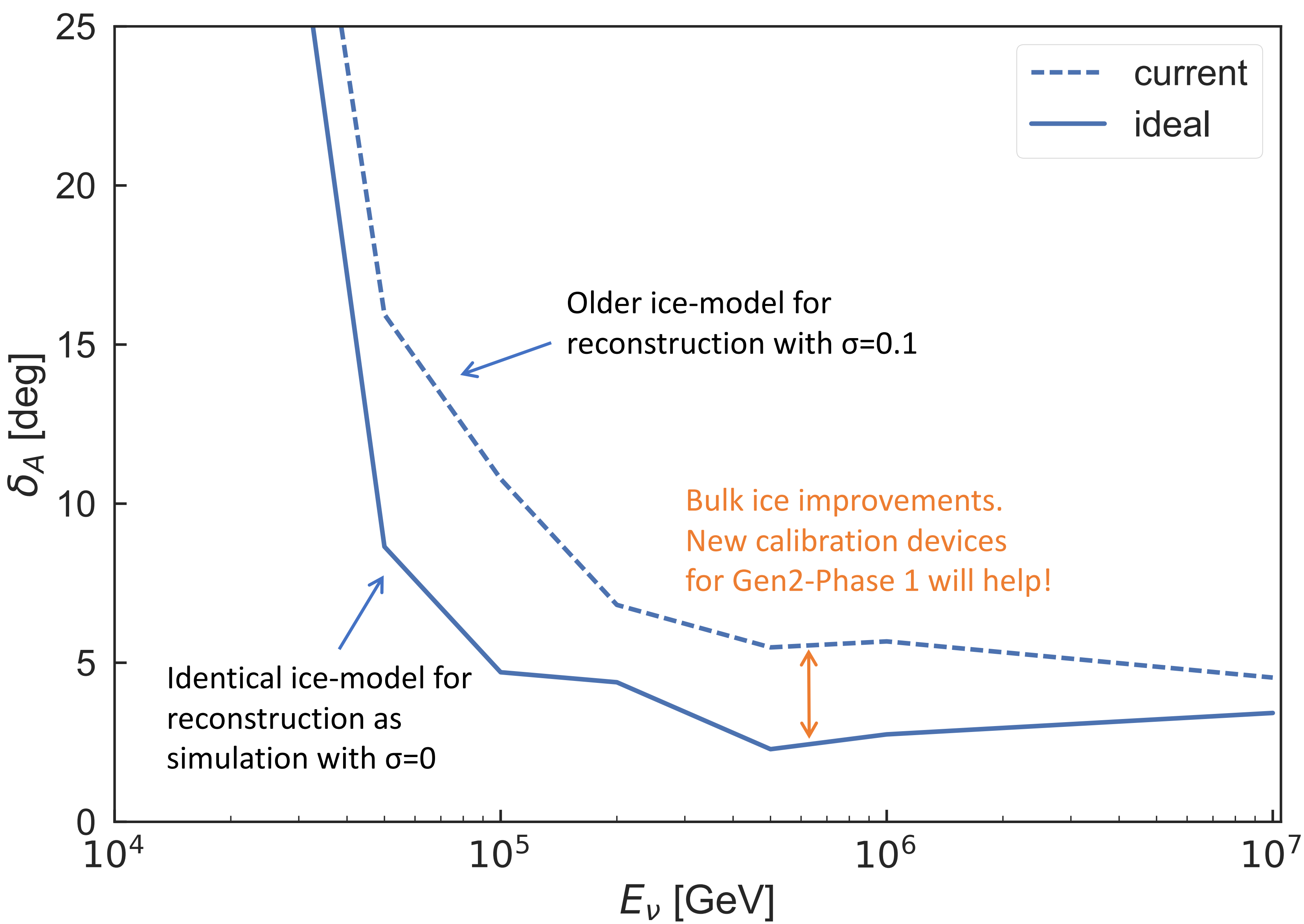
Angular resolution vs energy and σ



Reducing σ generally reduces δ_A (colors)

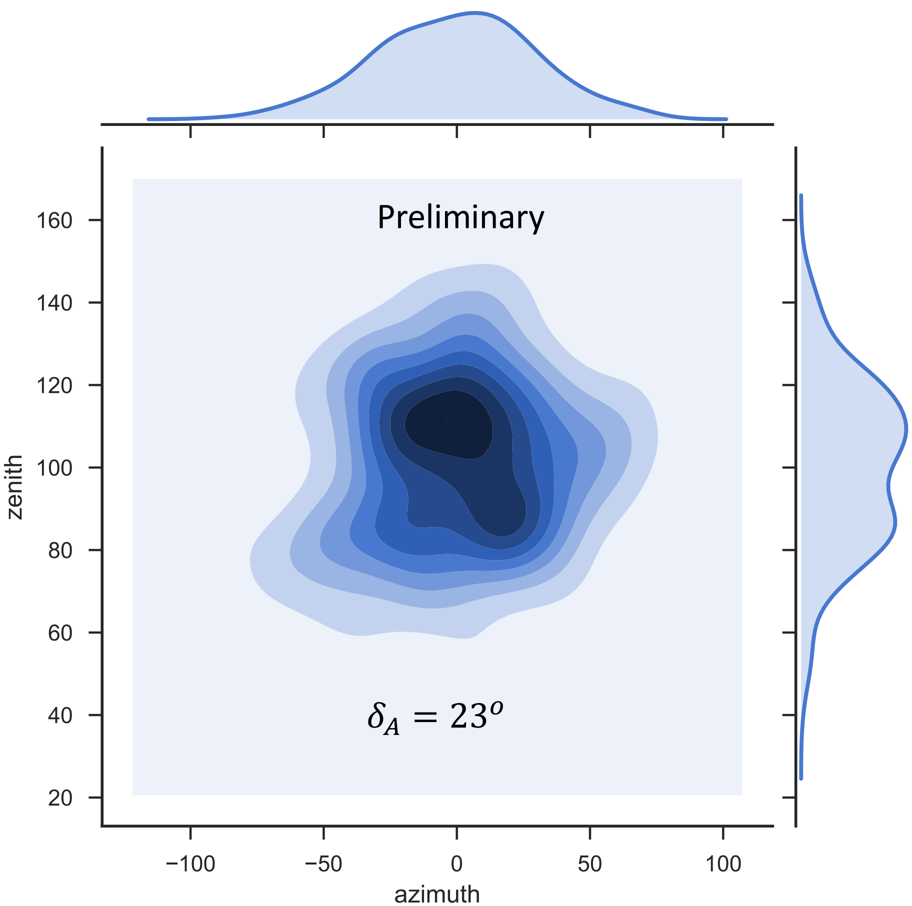
Correct knowledge of ice also reduces δ_A (dashed vs solid)

Effect of ice-model and σ on angular resolution



With more simulated photons

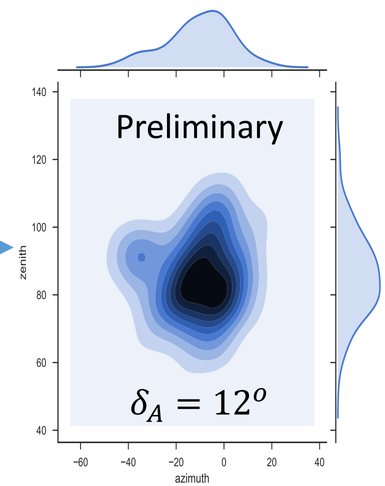
Direct photon reconstruction mean statistical uncertainties in MC



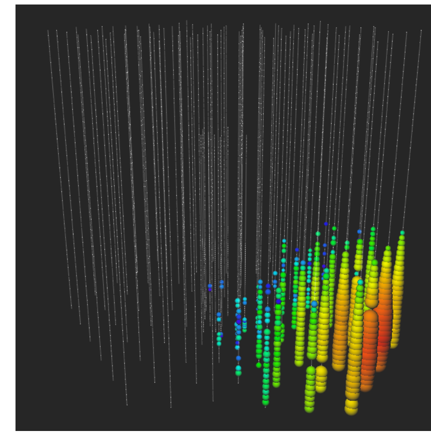
1x data statistics

Increased photon statistics improves angular resolution even more!

Limited by GPU time



10x data statistics



Performed on new non-contained PeV cascade "Hydrangea" – see Lu's talk!

$$\frac{\delta_E}{E} : 8.3\% \rightarrow 3.6\%$$

Summary

Room to improve cascade reconstruction

Currently affected by

1. Bright DOM exclusions
2. Ice-model and ice-model uncertainty

There is a concerted, ongoing effort to incorporate more waveform data and improve ice-models.

Even more improvement with increased direct photon statistics but this may prove to be impractical.

Thank you!

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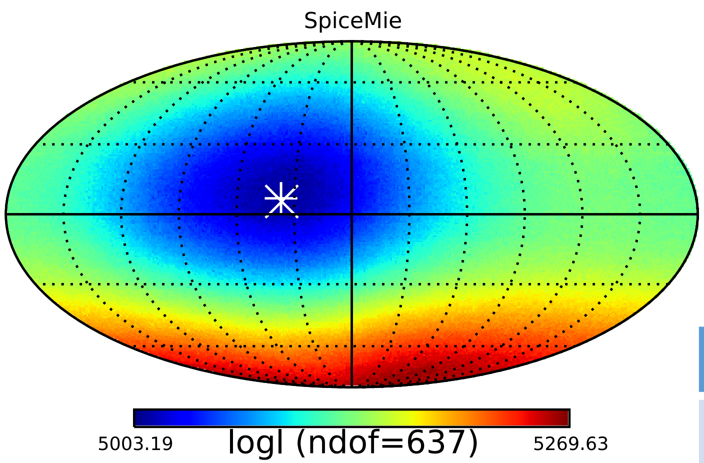
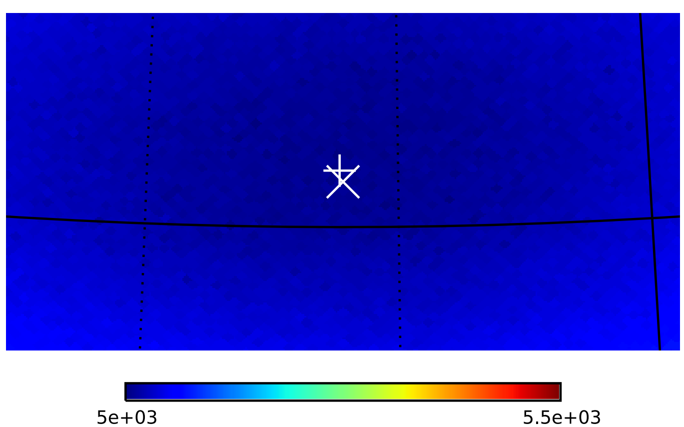
Backups

Rowlf: A particularly bad case

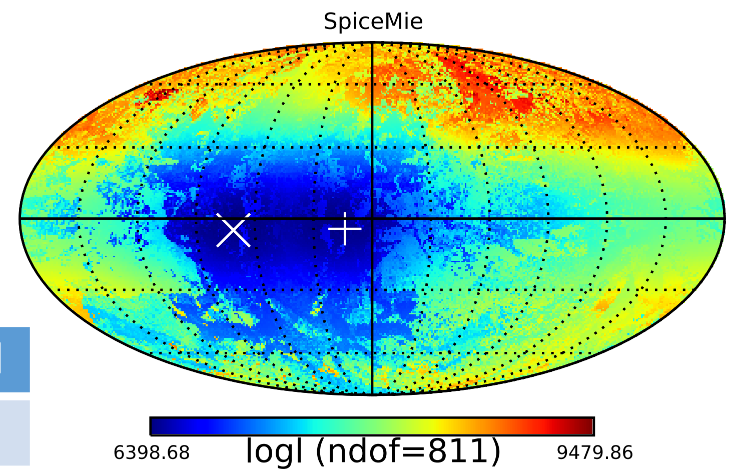
x = full sky scan
+ = iterative monopod

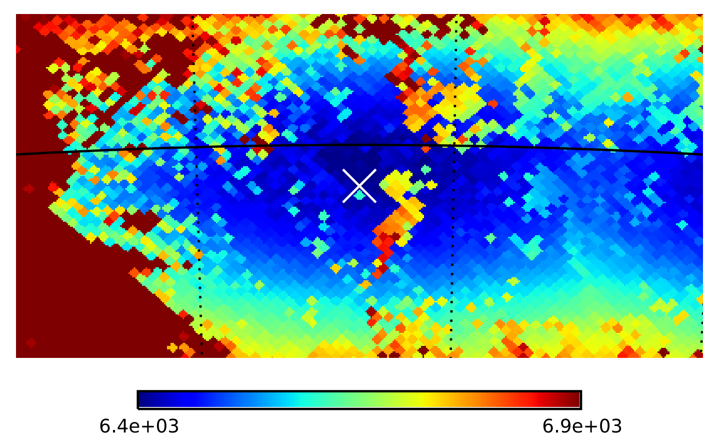
Without Brights





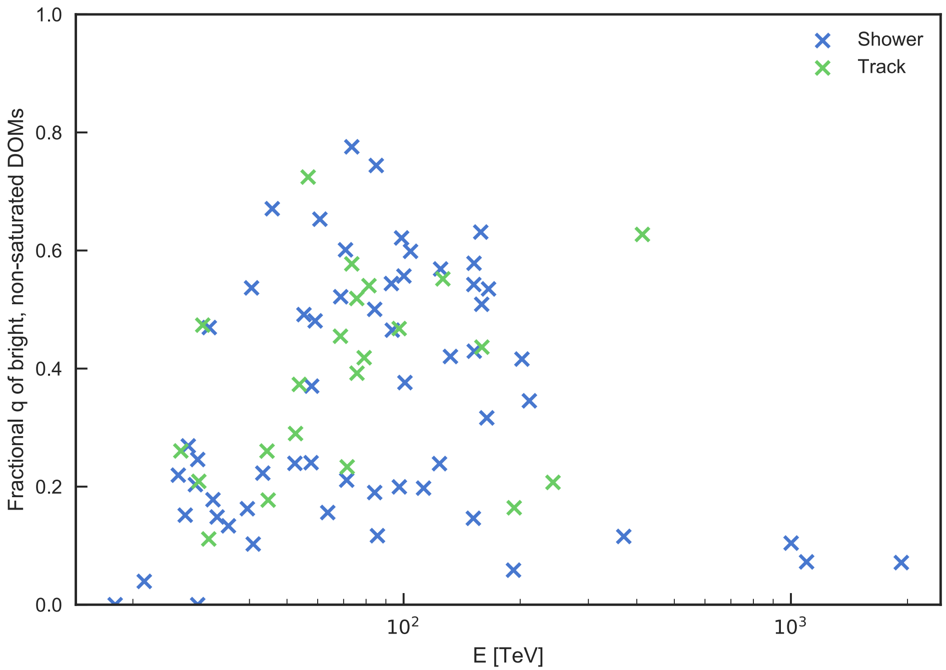
With Brights

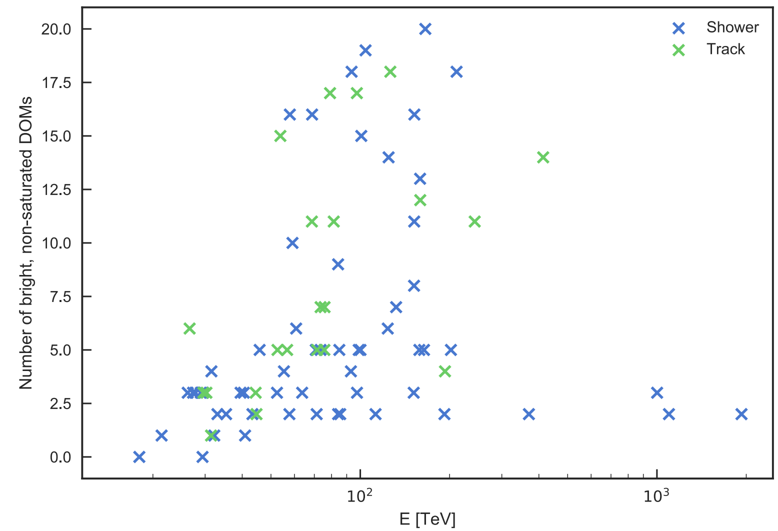


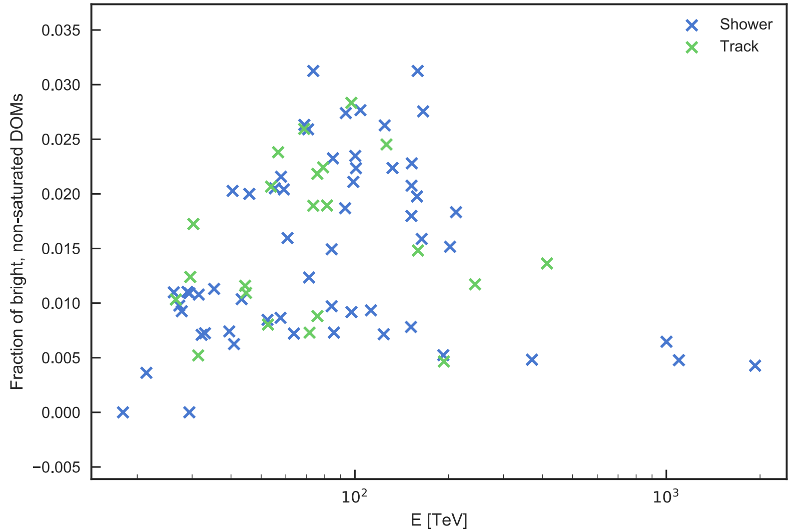


dE/E [%]	dθ [deg]
16	36

Bright but not saturated







Saturated DOMs are typically a subset of bright DOMs.

DirectFit

- DirectFit LLH includes an effective ice-model uncertainty that smears the charge on each DOM +/- 10% (default)
- This ensures that the fit isn't too biased by high statistic DOMs

$$-\ln\mathcal{L}=\sum_i\left[s_i\ln\frac{s_i/n_s}{\mu_s^i}+d_i\ln\frac{d_i/n_d}{\mu_d^i}+\frac{1}{2\sigma^2}\ln^2\frac{\mu_d^i}{\mu_s}\right].$$

"Likelihood description for comparing data with simulation of limited statistics",
D. Chirkin, arXiv:1304.0735

DirectFit

Capable of reconstructing data with direct photon simulation with ppc

Likelihood function different from the mainstream recos as the expectations from simulation is no longer analytic (e.g. Millipede)

Fit routine proceeds through several iterations of a localized random search where many position and direction are tested and the best fit energies at those steps are calculated.

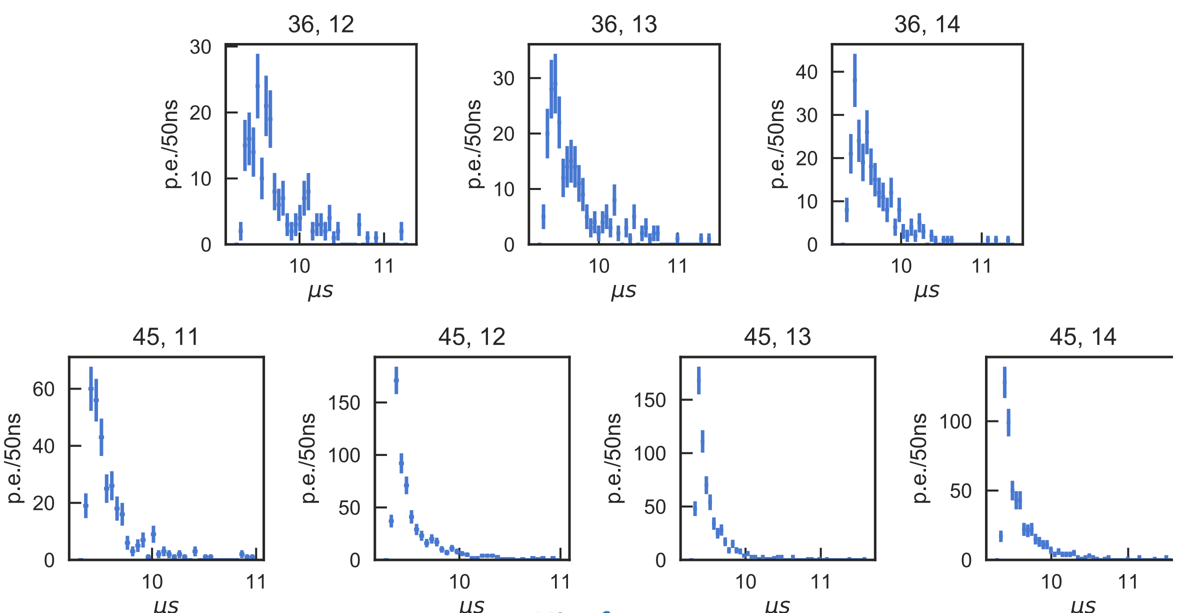
Following fit, approximate Bayesian calculation (ABC) method applied based on fit results to estimate posterior via MCMC.

Procedure

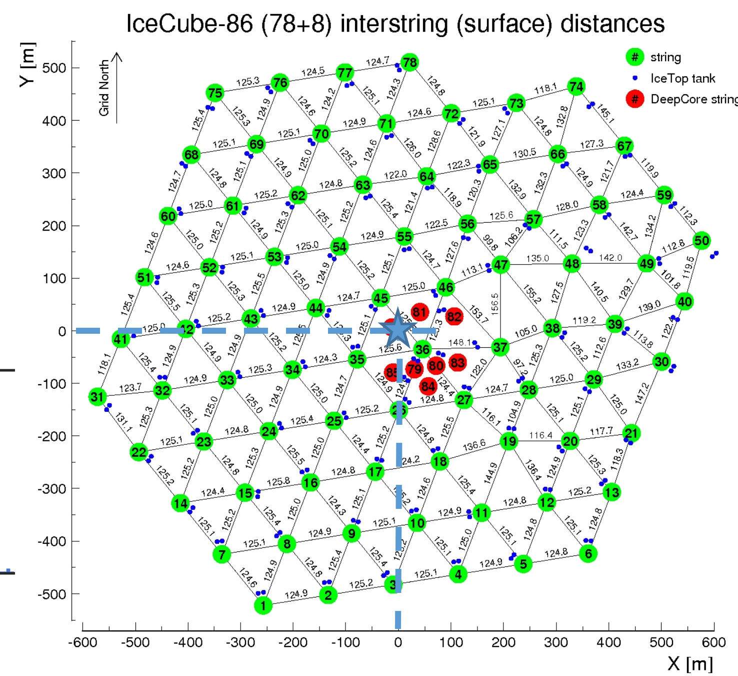
1. Simulate a EM cascade with ppc at
   - r=(0, 0, 300)m → 1648m depth
   - θ=(90 zenith, 0 azimuth)
   - Ice-sim=3.2
   - E=1E[3, 4, … 7] GeV
2. For each simulated cascade, use DirectFit to try and reconstruct the best fit point assuming
   - Ice-rec=(spice-Mie, 3.2)
   - σ=(0.0, 0.05, 0.1) ice model uncertainty
   - Q_{max}=(300, 500, 1000, 3000, 5000, 10000) p.e. cut off such that DOMs with Q_{DOM}>Q_{max} are excluded
3. Once best fit is found, sample from the approximate posterior distribution $P(r, \theta|D)$ for each combination of ice models, energies, and sigmas
   - Std deviation of this sample gives resolution: δr, δθ, δE
   - And pulls: $\frac{E-E_{true}}{\delta E}$ etc.

An example: step 1, simulation

1. E=100 TeV, ice=spice-3.2 (latest), r=(0, 0, 300), θ=(90z, 0a)

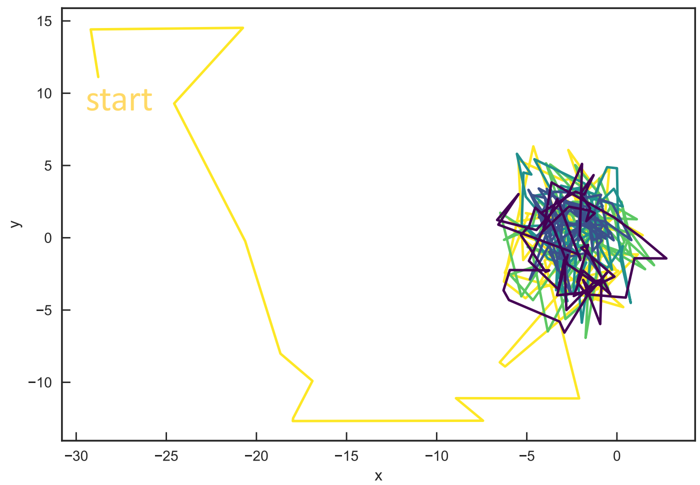


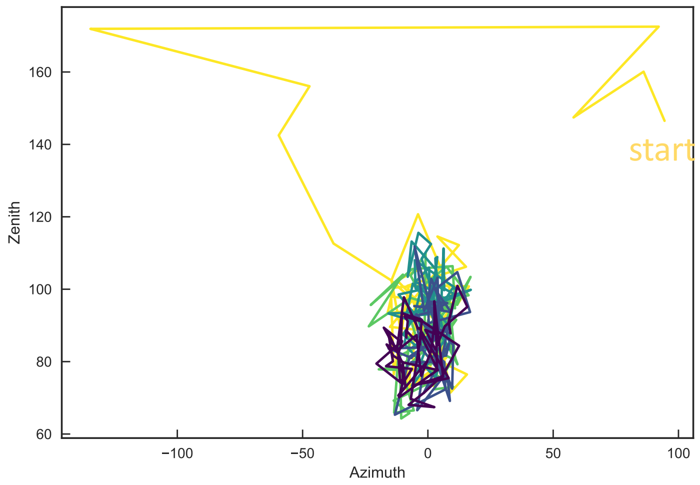
Hits from ppc



An example: step 2, reconstruction

1. E=100 TeV, ice=spice-3.2 (latest), r=(0, 0, 300), θ=(90z, 0a), σ=0.0
2. DirectFit steps to the minimum





Spread and mean of last 5% of steps
used to initialize step 3

An example: step 3, error calculation

1. E=100 TeV, ice=spice-3.2 (latest), r=(0, 0, 300), θ=(90z, 0a), σ=0.0
2. DirectFit steps to the minimum
3. Generate probabilities across the parameter space