Geometry Calibration of IceCube

using Photon Timing from Downgoing Muons

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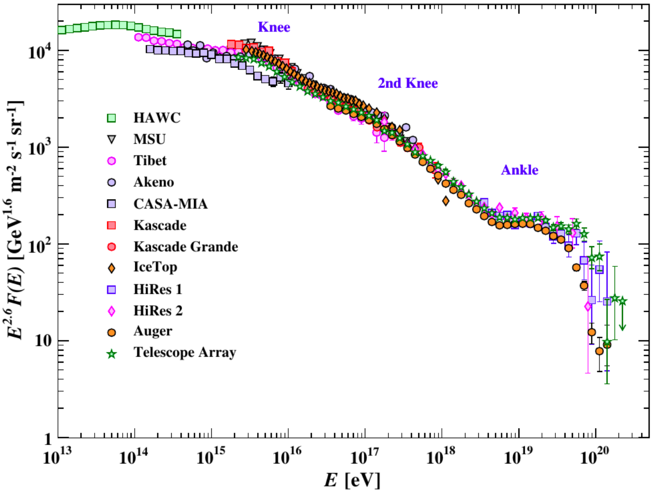
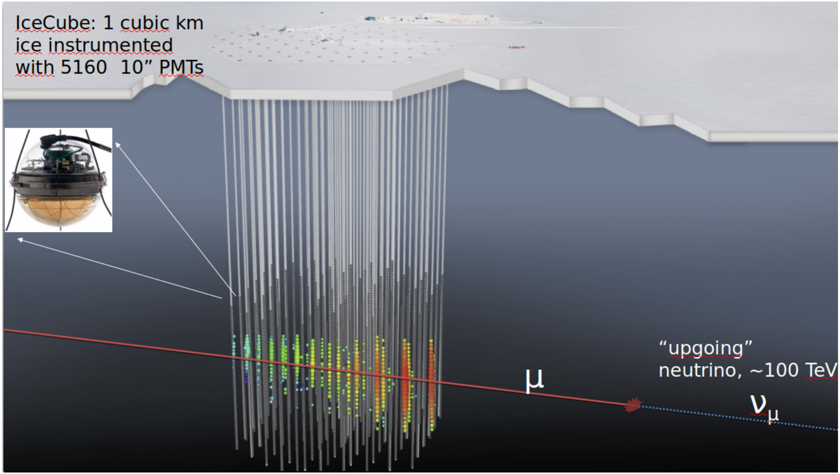
Cosmic Rays



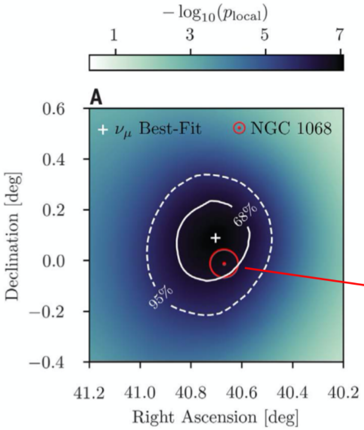
Knee
2nd Knee
Ankle
HAWC
MSU
Tibet
Akeno
CASA-MIA
Kascade
Kascade Grande
IceTop
HiRes 1
HiRes 2
Auger
Telescope Array
$E^{2.6} F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]

Neutrino Astronomy



Neutrino Emission from NGC 1068

Stockholm University



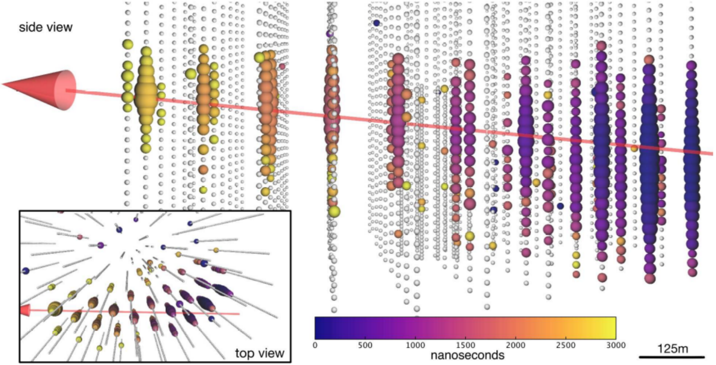
Science 378, 6619 (2022) 538

4.2 σ evidence of neutrino emission from the nearby (47 Mly) active galaxy NCG 1068

Reconstructed source location is 0.11° away from the galaxy's center

IceCube Alert Event IC170922A

Stockholm University



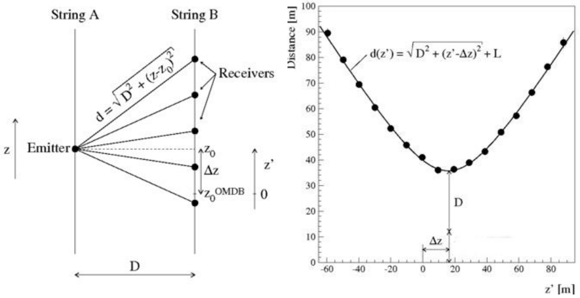
Science 361, 6398, (2018) eaat1378

Geometry Calibration

How do you measure the position of something 2 kilometers under the ice?

Flasher data for *z* calibration

Stockholm University



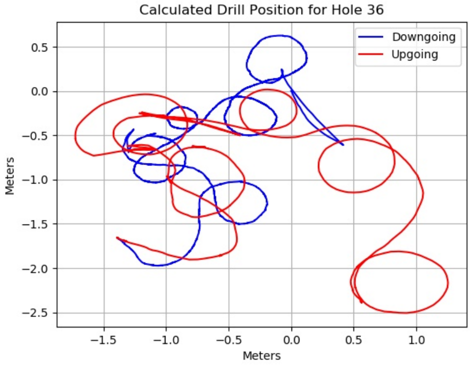
The method for extracting relative depth from flasher data. On the left is an overview of a single DOM flashing and for DOMs on nearby strings the time delay will give a measured distance *d*. By doing this to all DOMs on a pair of strings we get the plot on the right where each dot is the average of all distances with the nominal vertical distance of z' and the bars shows the spread. The parameters D, Δz and L are fitted for and Δz is the calibrated vertical offset between the two strings.

What about x and y?

Installation

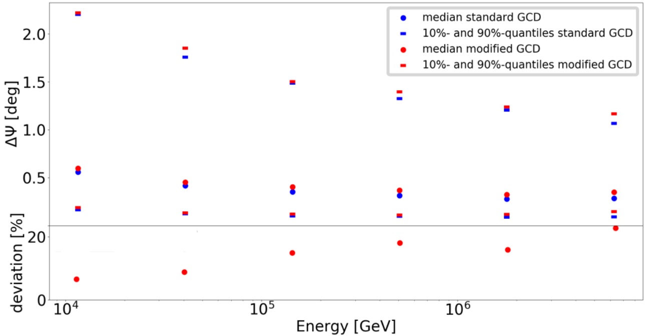
The drill works by flushing 90℃ water, melting ice in front. During drilling the depth is measured by a pressure gauge and the orientation is measured by two pendulums and a fluxgate magnetometer. This data can be used to reconstruct the drill hole by integrating along the path of the drill.

Drill Data



But as we were drilling with hot water it did not have to melt the ice in a straight line and the drill data has not been trusted for details, but it does tell us that the DOMs are less than ∼2m from nominal.

Impact of *x* and *y* Misalignment



ΔΨ: opening angle between true and reconstructed direction

If the drill data is representative for *x* and *y* we have 15% larger opening angle.

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- Our reconstruction gives us the origin of that light.
- Given the PMT timings and tracks we can estimate the location of our DOMs.

Method

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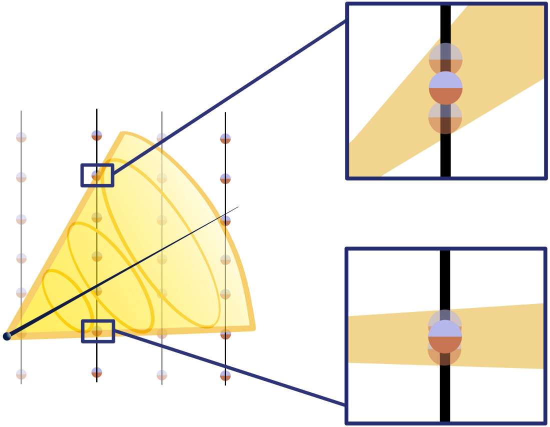
- For a large number of tracks:
  - Remove hits on the string being calibrated.
  - Require at least 30 hits left.
  - Reconstruct the track.
- For track i, corresponding photon times $t_{i0}...t_{in_i}$ and noise level b find DOM position $(\hat{x}, \hat{y}, \hat{z})$ that maximizes

$$L(x, y, z) = Log\Big(\prod_{i}\prod_{t=t_{i0}}^{t_{in_i}}(p(t|i, x, y, z) + b)\Big)$$

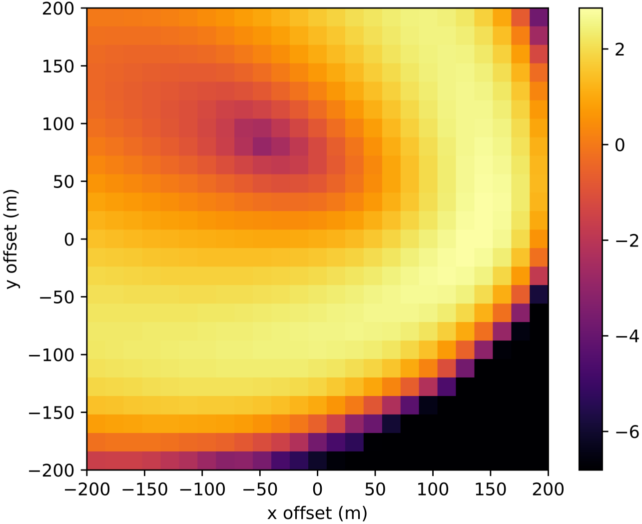
, where p is the photon time pdf.

Cherenkov cone

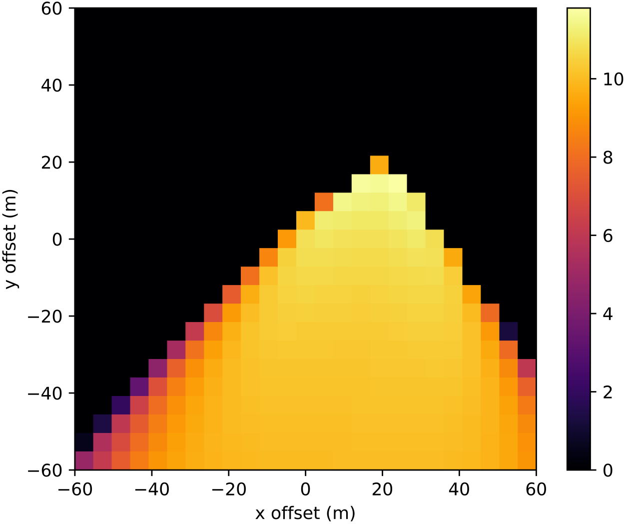


[0]Illustration by K. Deoskar.

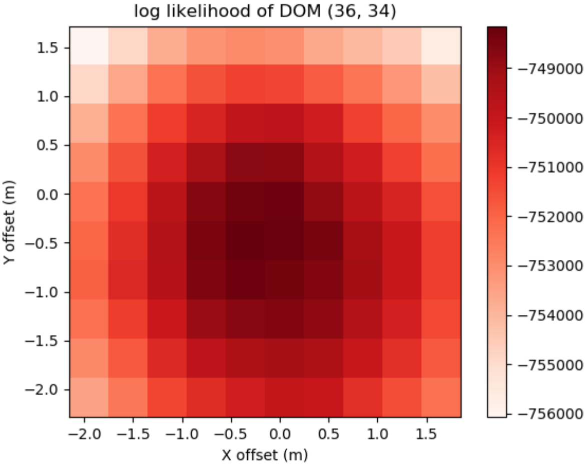
Delta LLH of Single Event (late hit)



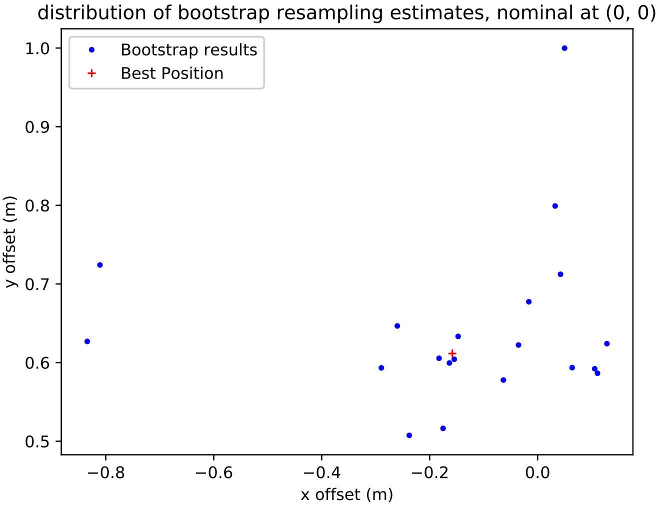
Delta LLH of Single Event (early hit)



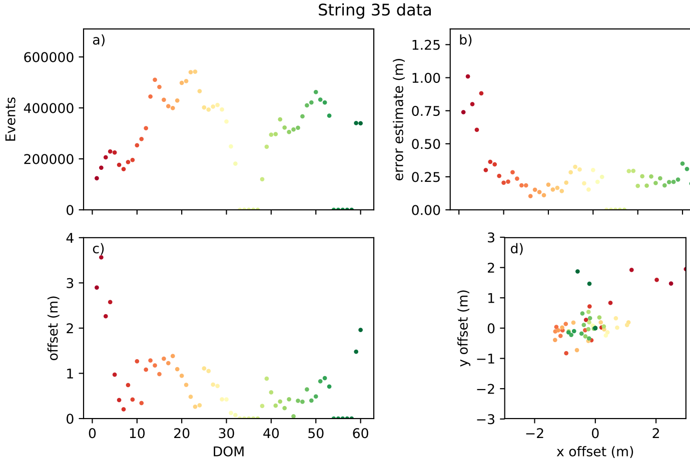
Likelihood of many events



Estimating Error with bootstrap

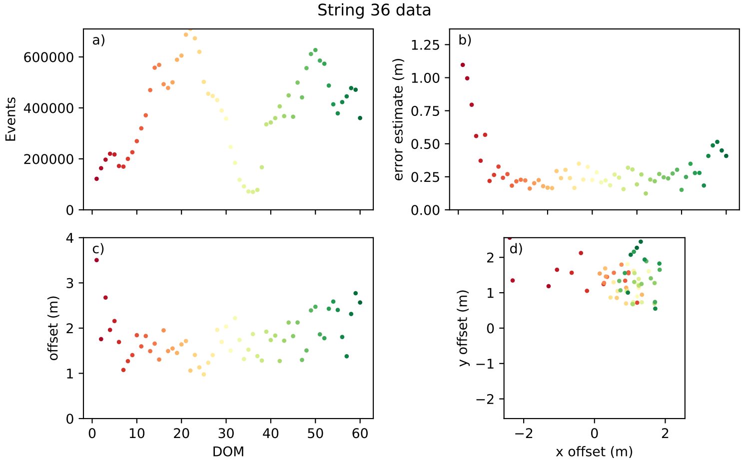


String 35 results



a) number of events per DOM. b) error estimate given by bootstrap. c) offset from nominal positions. d) best fit positions for each DOM.

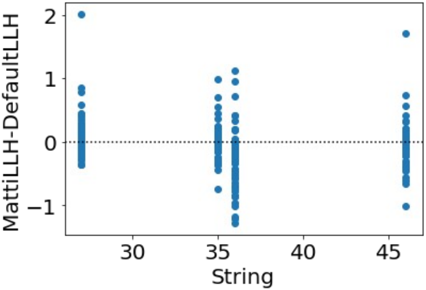
String 36 results



a) number of events per DOM. b) error estimate given by bootstrap. c) offset from nominal positions. d) best fit positions for each DOM.

Confirmation with flashers

Recent improvements in modeling of light propagation in the ice (in particular birefringence) has shown flasher data to be consistent with my results.



Using the new geometry for the central strings we find that for strings where the DOM positions are clustered around nominal there is no change in likelihood but for string 36 which has moved over a meter the new position is a significantly better fit to the flasher data.

Summary

- Angular precision improves sensitivity to cosmic neutrino sources.
- The horizontal geometry is a systematic error that may impact angular resolution up to 15% .
- A muon based calibration is the first method in IceCube with precision to measure meaningful offsets from nominal.
- Using 4 days of data, three strings were consistent with nominal positions and one string is found with a statistically significant shift from nominal.
- The change in position of string 36 has been shown to also improve the description of flasher data.
- Next: Plan to apply both the muon and improved flasher calibration method to other strings, crosschecking each other, in order to provide an *xy* geometry for IceCube.

Thank you for your attention!