# Nine-String IceCube Point Source Analysis

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# Method: Maximum Likelihood Analysis

Use unbinned maximum likelihood method: compare ratio of source likelihood (for number of signal events $n_s$) to background likelihood ($n_s = 0$).

- Partial Probability for each event

$$P_i(x, n_s) = \frac{n_s}{N} S_i(x) + \frac{N - n_s}{N} B_i(x)$$

- Likelihood function

$$L(n_s) = \prod P_i(x_i, n_s)$$

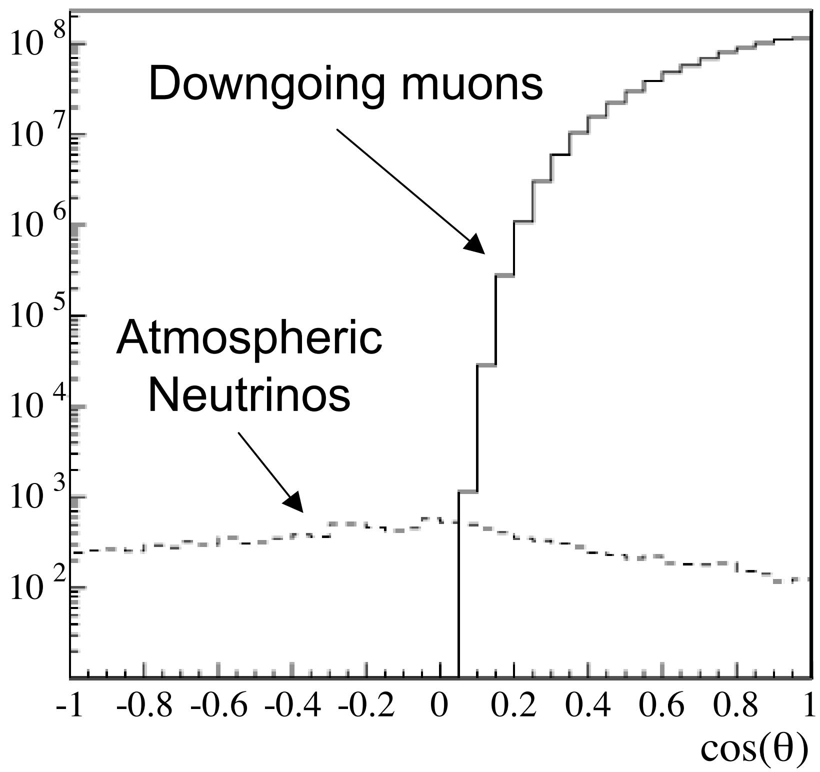
- Log Likelihood Ratio

$$\log \lambda = \log \frac{L(\hat{n}_s)}{L(n_s = 0)}$$

**Source hypothesis** uses **individual point spread functions** for each event, based on **angular uncertainty estimate** of track reconstruction

**Background hypothesis** based on **declination distribution of data events** (i.e. scrambled in right ascension) **to correctly account for all backgrounds**

# Challenge: Backgrounds




Select only up-going events.

Three principle backgrounds remain:

- **Down-going muons** (from cosmic ray showers above the detector) **mis-reconstructed as up-going**

- **Coincident muons** (two muons from different cosmic-ray showers which reconstruct as single up-going event)

=> Reject with tight quality cuts

- **Atmospheric neutrinos** (from cosmic ray showers on other side of earth)

=> Genuine up-going events; "irreducible background" in search for extra-terrestrial neutrinos

# Optimize Discovery Potential

Optimal cuts are those which can discover at 5-sigma significance the lowest source flux

**Example:**

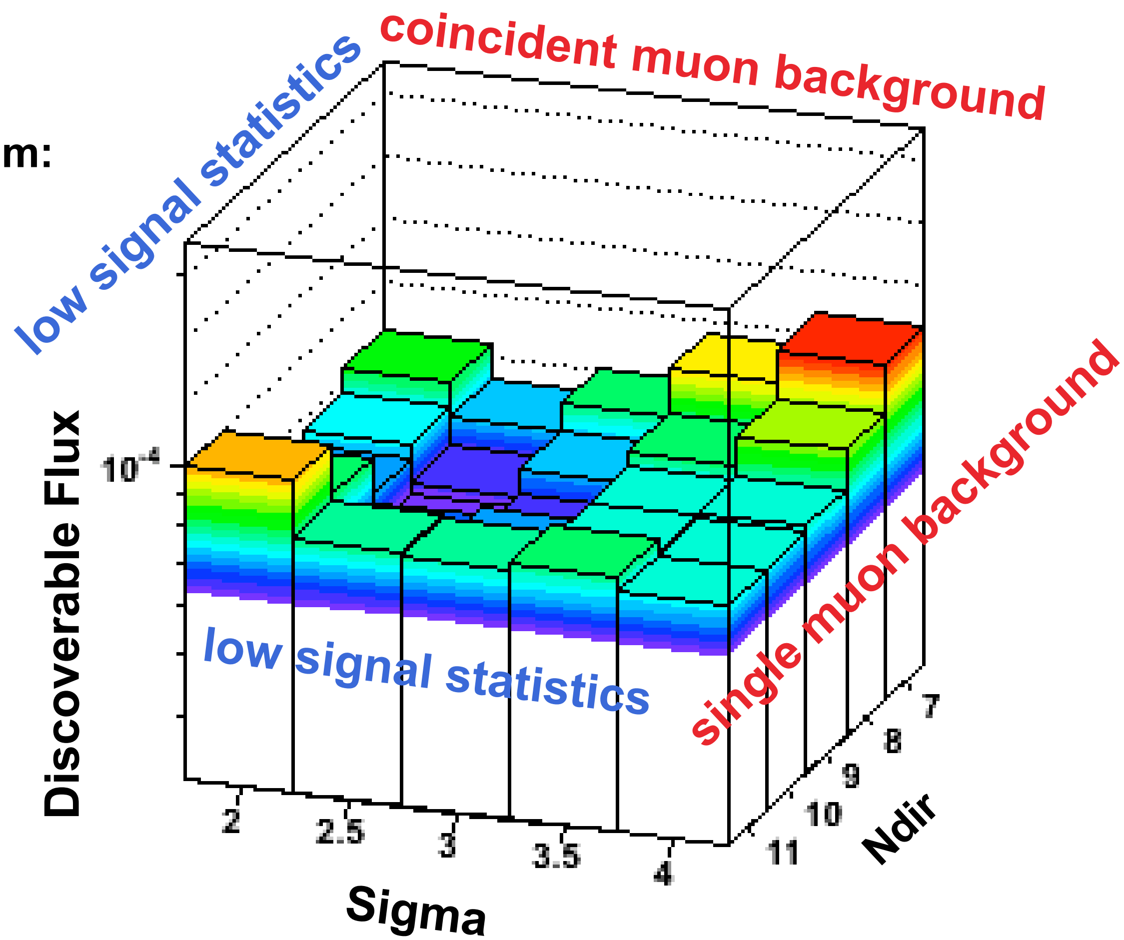
**Source at dec = 30°, $E^{-2.5}$ spectrum:**

**Sigma** (Estimated angular uncertainty of the track direction):

•cuts single mis-reconstructed muons

**Ndir** (number of direct-hit modules in -15 to +75 ns around time expected from reconstructed track)**:**

•cuts coincident down-going muons

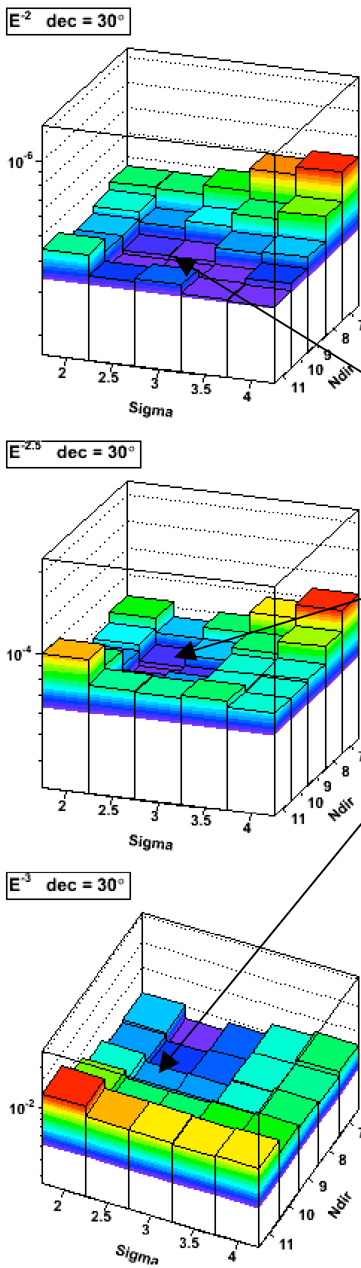


# Optimize Discovery Potential: Spectral Index Dependence

$E^{-2}$

$E^{-2.5}$

$E^{-3}$

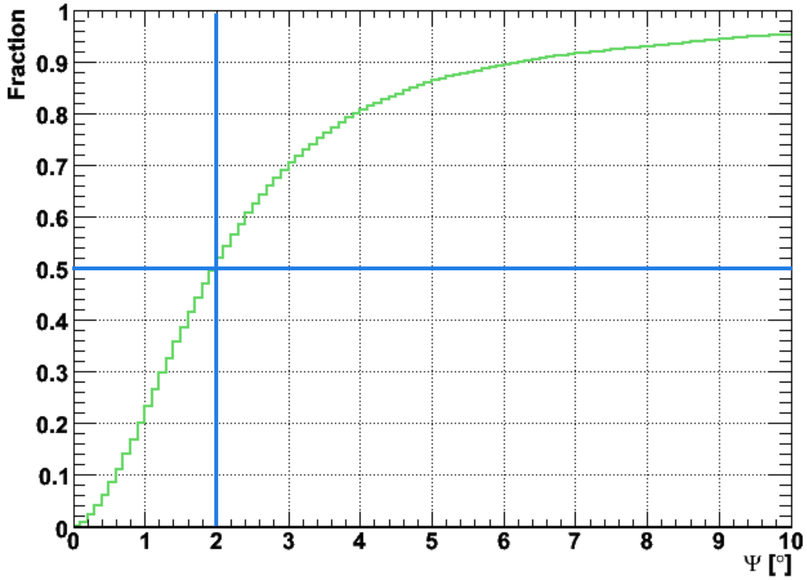



- For **hard spectrum**, source events survive higher Ndir cuts better than atmospheric neutrinos
- **high Ndir cut favored to reduce background**

**sigma < 2.5°, Ndir ≥ 9** close to optimal for all three indices

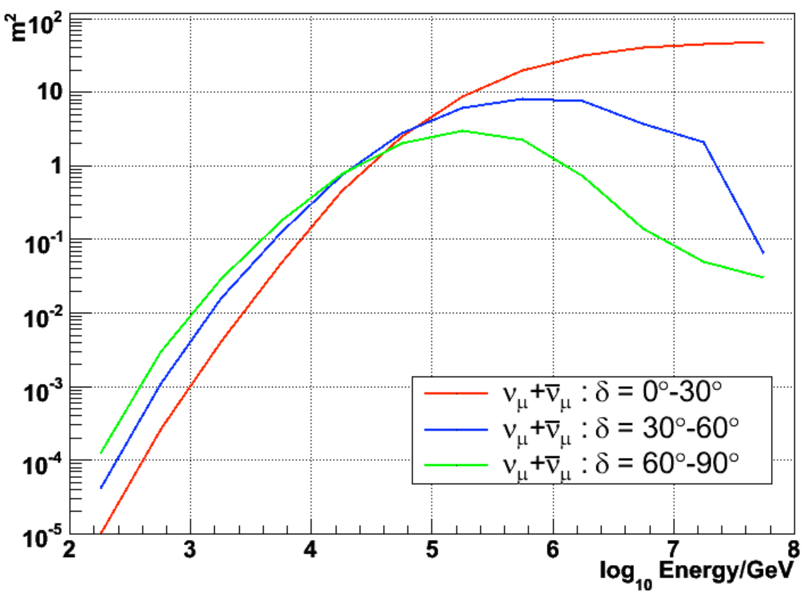
- For **soft spectrum**, source events and atmospheric neutrinos affected almost equally
- **low Ndir cut favored to keep signal**

# Detector Performance with Point Source Cuts Applied




**Median Angular Resolution:**

**50%** of simulated neutrino events ($E^{-2}$ spectrum) are reconstructed **within 2° of their true arrival direction**

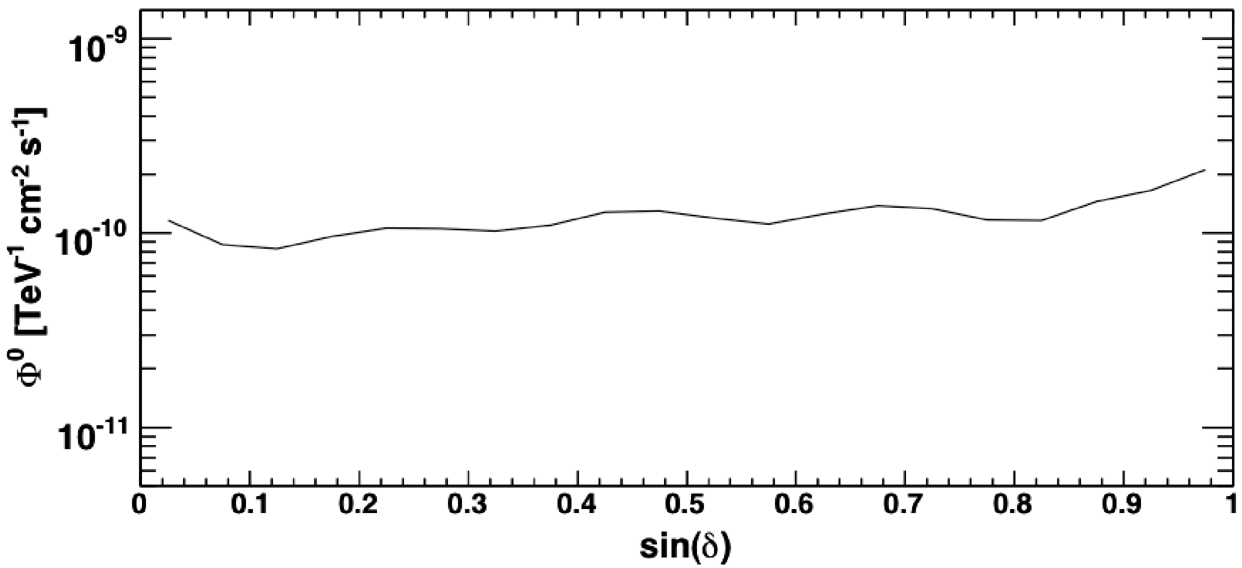



**Muon Neutrino Effective Area** for point sources in different declination ranges (assuming flux is equal mixture of neutrinos and anti-neutrinos).

Declination (zenith angle) effects:

- at high energies, earth absorption reduces rate of vertical upgoing tracks

# Point Source Sensitivity for $E^{-2}$ Spectrum




Median 90% confidence level flux upper limit $\Phi^0$ (as a function of declination) for point sources with differential flux: $d\Phi/dE = \Phi^0\ (E\ /\ \mathrm{TeV})^{-2}$.

(Specifically: in 90% of simulated trials, sources with the indicated flux or higher would result in a higher log-likelihood ratio $\lambda$ than the median log-likelihood ratio ($\log \lambda = 0$) that occurs for background-only trials.)

Sky-averaged sensitivity to point-source with $E^{-2}$ spectrum: $\mathbf{\Phi^0 = 12 \times 10^{-11}\ TeV^{-1}\ cm^{-2}\ s^{-1}}$.

Comparable to AMANDA-II 2005 sensitivity (J. Braun talk)

# Data Sample

Data taking in 2006 from beginning of June until end of November

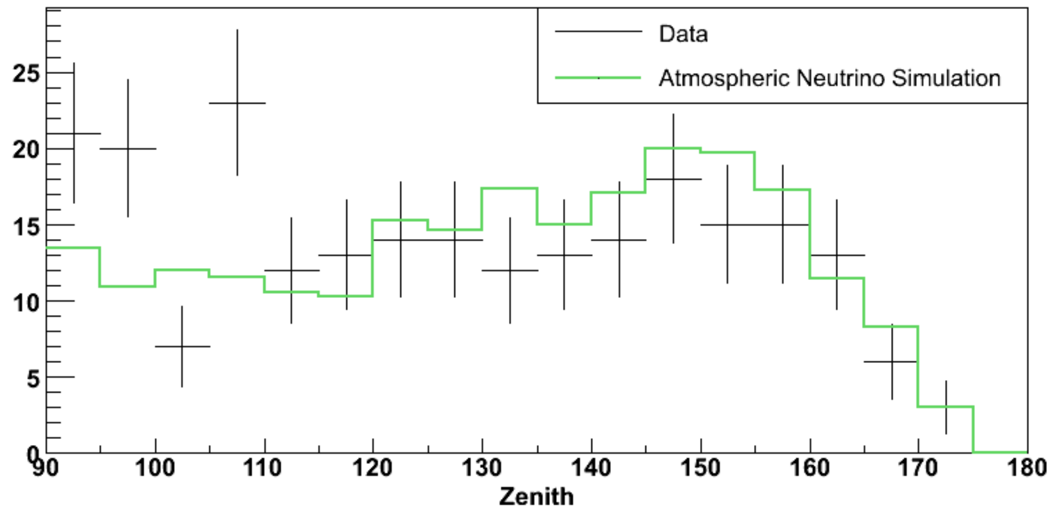
Total livetime: 137.4 days

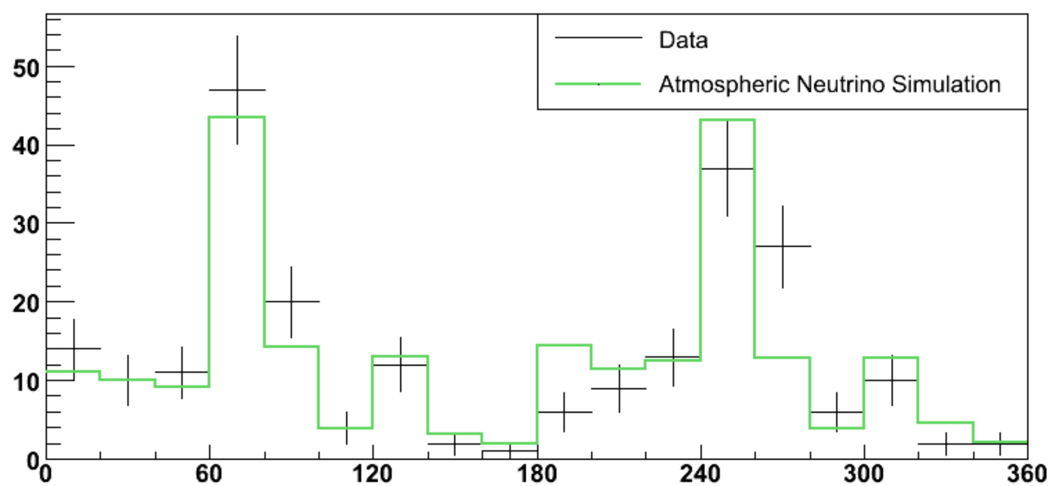
233 neutrino candidate events selected by cuts.

From simulation, expect background of:

- 227 atmospheric neutrinos (Bartol spectrum)
- < 10% mis-reconstructed down-going muons

Zenith



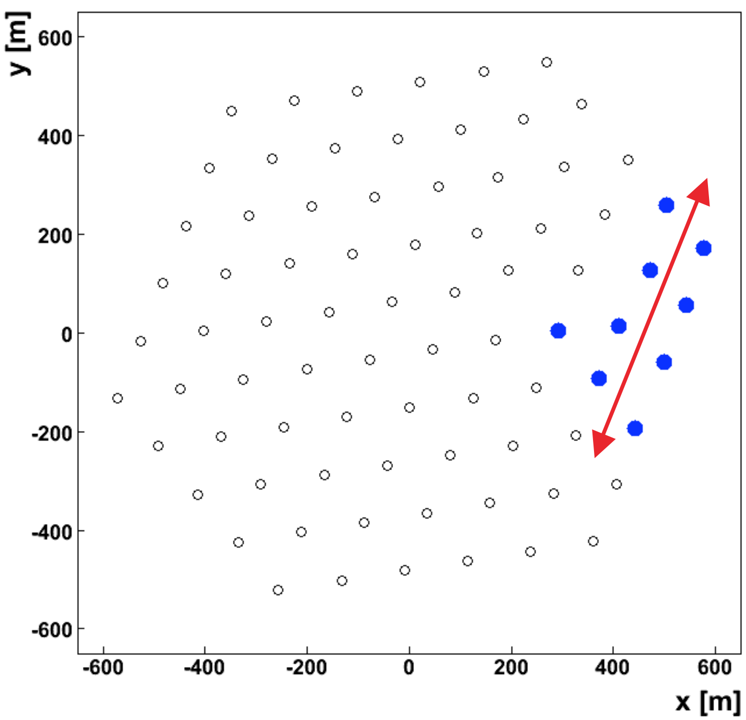



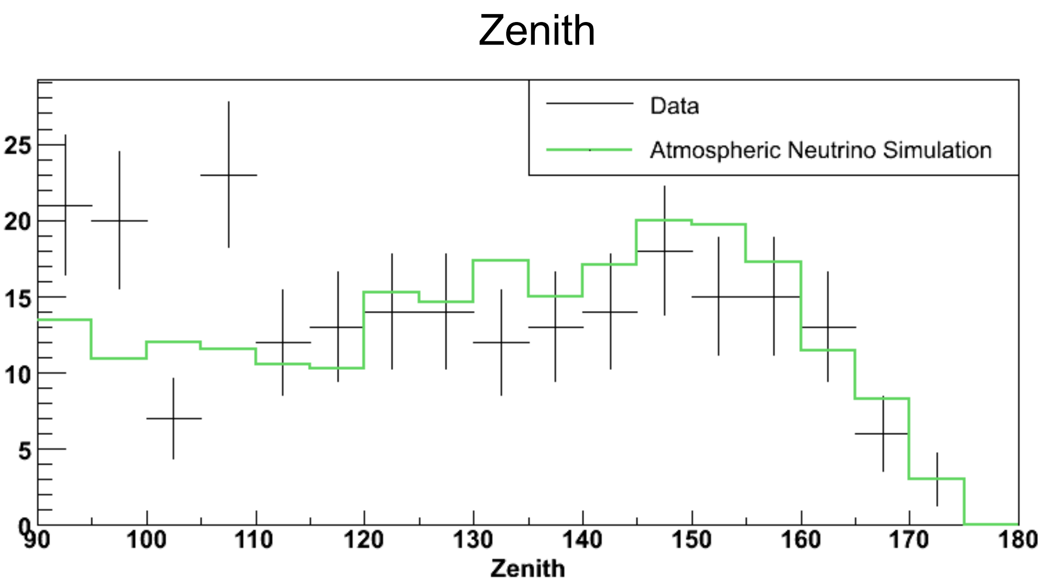

Azimuth

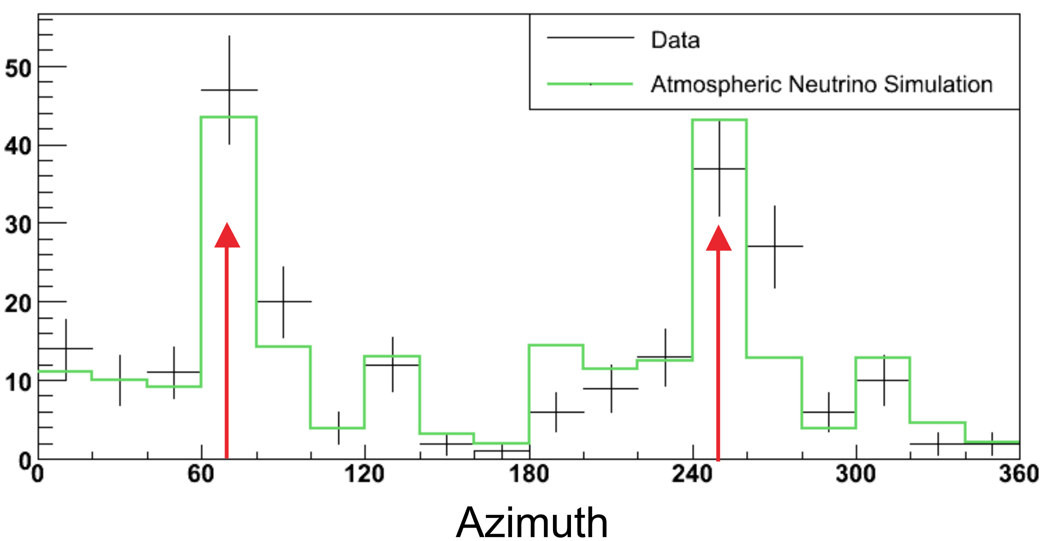
# Data Sample

Mis-reconstructed background predominantly near horizon

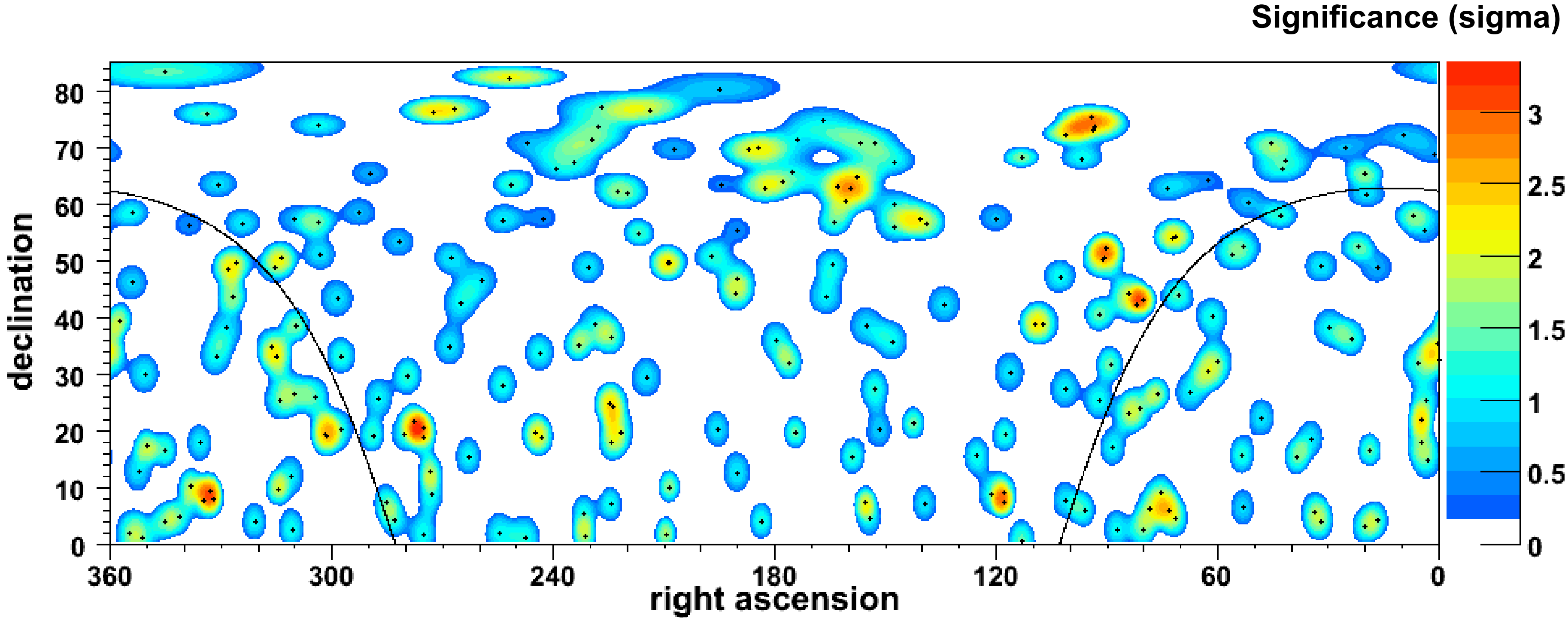
**2006: nine-string detector configuration**



# First IceCube All-Sky Map




Data Events (points); Galactic Plane (curve)

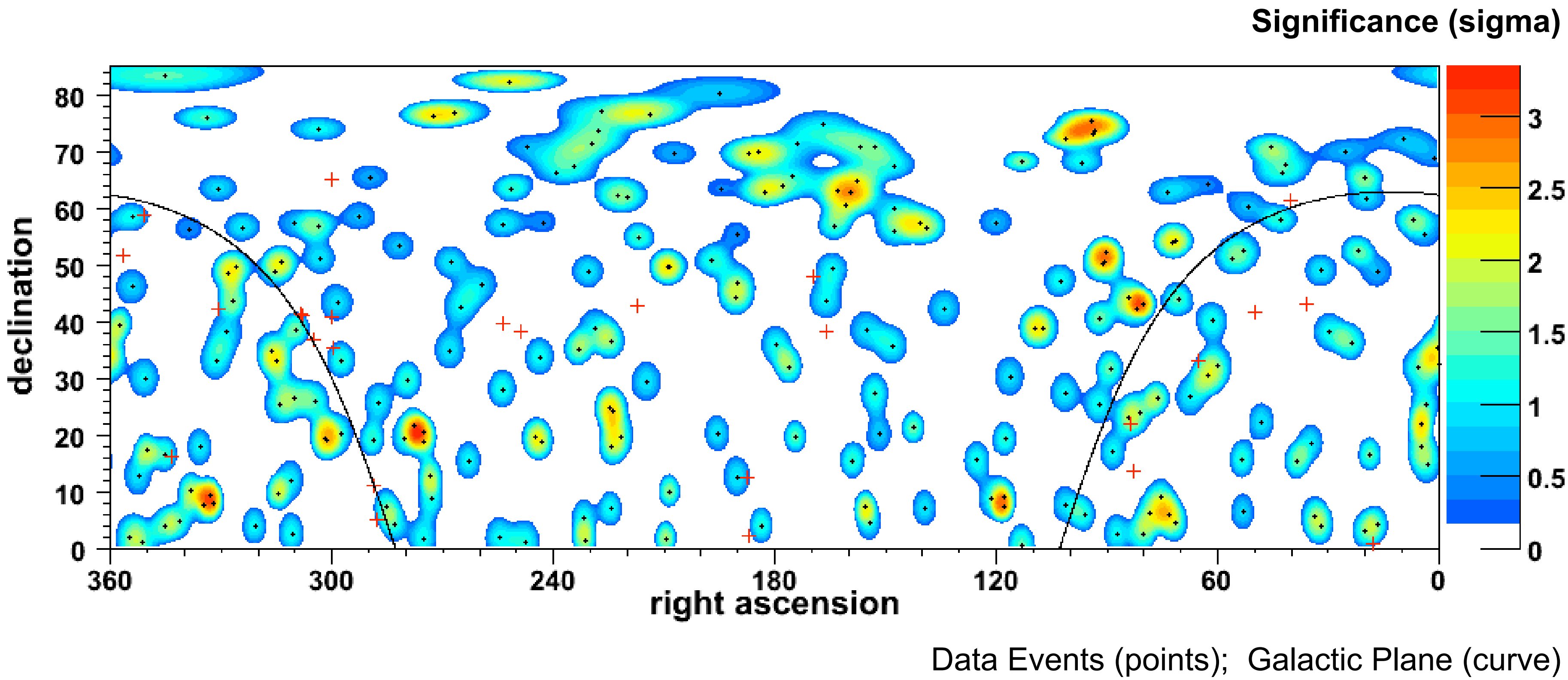
**Results:**

The maximum deviation is 3.35 sigma, at r.a. = 276.6° , dec = 20.4°.

Random clustering of background: **60%** of simulated background trials (data scrambled in right ascension), have a maximum deviation (anywhere) of **3.35 sigma** or greater.

**Chance probability of the hottest spot = 60% ... not significant.**

# Source List Search




**26 *a priori* Source Locations**

# Results: Source List Search

For source list:

Largest deviation from background: sigma = 1.77 (one-sided p-value = 0.04), in the direction of the Crab Nebula.

Chance to obtain a p-value of 0.04 or lower with 26 independent trials is **65%.**

**None of the a priori source locations shows a significant excess.**

| Object | (r.a. , dec) | : | sigma | $n_s$ est. | 90% C.L. upper limits $n_s$ | 90% C.L. upper limits $\Phi$ |
|---|---|---|---|---|---|---|
| MGRO J2019+37 | (304.8, 36.8) | : | 0.00 | 0.0 | 2.8 | 12.7 |
| Cyg OB2/TeV J2033+4130 | (308.3, 41.3) | : | 0.23 | 0.2 | 2.9 | 14.0 |
| Mrk 421 | (166.1, 38.2) | : | 0.00 | 0.0 | 2.9 | 13.1 |
| Mrk 501 | (253.5, 39.8) | : | 0.00 | 0.0 | 2.7 | 11.5 |
| 1ES 1959+650 | (300.0, 65.2) | : | 0.00 | 0.0 | 3.3 | 14.6 |
| 1ES 2344+514 | (356.8, 51.7) | : | 0.00 | 0.0 | 2.8 | 11.4 |
| H 1426+428 | (217.1, 42.7) | : | 0.00 | 0.0 | 3.0 | 14.5 |
| BL Lac (QSO B2200+420) | (330.7, 42.3) | : | 0.28 | 0.4 | 3.2 | 15.7 |
| 3C66A | ( 35.7, 43.0) | : | 0.00 | 0.0 | 3.0 | 13.3 |
| 3C 454.3 | (343.5, 16.1) | : | 1.08 | 0.7 | 3.6 | 14.4 |
| 4C 38.41 | (248.8, 38.1) | : | 0.00 | 0.0 | 2.8 | 12.6 |
| PKS 0528+134 | ( 82.7, 13.5) | : | 0.00 | 0.0 | 2.8 | 10.3 |
| 3C 273 | (187.3, 2.0) | : | 0.00 | 0.0 | 2.5 | 11.0 |
| M87 | (187.7, 12.4) | : | 0.67 | 0.5 | 3.2 | 11.4 |
| NGC 1275 (Perseus A) | ( 50.0, 41.5) | : | 0.00 | 0.0 | 2.8 | 13.4 |
| Cyg A | (299.9, 40.7) | : | 0.41 | 0.4 | 3.0 | 14.5 |
| SS 433 | (288.0, 5.0) | : | 0.12 | 0.1 | 2.4 | 8.2 |
| Cyg X-3 | (308.1, 41.0) | : | 0.51 | 0.4 | 3.0 | 14.5 |
| Cyg X-1 | (299.6, 35.2) | : | 0.52 | 0.4 | 3.0 | 12.2 |
| LS I +61 303 | ( 40.1, 61.2) | : | 0.00 | 0.0 | 3.2 | 14.2 |
| GRS 1915+105 | (288.8, 10.9) | : | 0.00 | 0.0 | 2.8 | 9.8 |
| XTE J1118+480 | (169.6, 48.0) | : | 0.00 | 0.0 | 2.8 | 12.4 |
| GRO J0422+32 | ( 65.4, 32.9) | : | 0.65 | 0.8 | 3.1 | 13.5 |
| Geminga 98.48 | ( 17.8, 0.6) | : | 0.65 | 0.8 | 3.0 | 16.4 |
| Crab Nebula | ( 83.6, 22.0) | : | 1.77 | 1.6 | 5.2 | 21.8 |
| Cas A | (350.9, 58.8) | : | 0.67 | 0.5 | 4.4 | 19.9 |

$\Phi$ Flux Units: $10^{-11}$ $(E\,/\,\mathrm{TeV})^{-2}$ $\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

# Summary

**2006:  IceCube 9 strings**

Nine strings were taking data last year.  Detector livetime was 137.4 days.

First point-source analysis with IceCube data demonstrates detector performing according to expectations and in agreement with detector simulation.

Point source sensitivity is comparable to equivalent livetime of AMANDA II detector.

**2007:  IceCube 22 strings**

Twenty-two strings deployed and currently taking data.

Much improvement in point-source sensitivity expected, due to:

- Doubling of detector volume
- Improved angular resolution, over wider range of azimuth
- Continued development of track reconstruction and background rejection algorithms

**IceCube on course to achieve unsurpassed sensitivity well before construction is completed.**