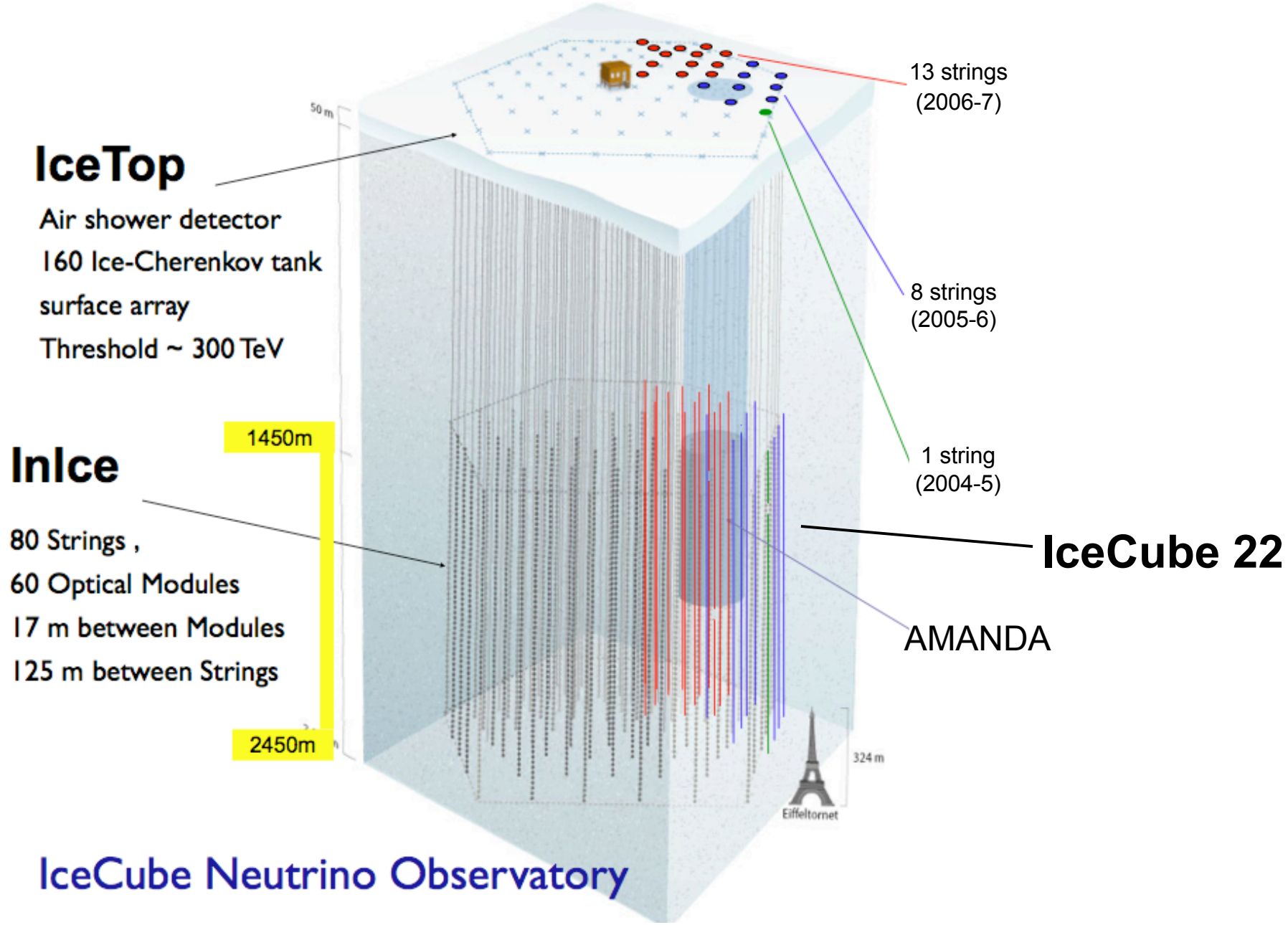
Neutrino Point Source Search with the 22-String Detector Configuration of IceCube

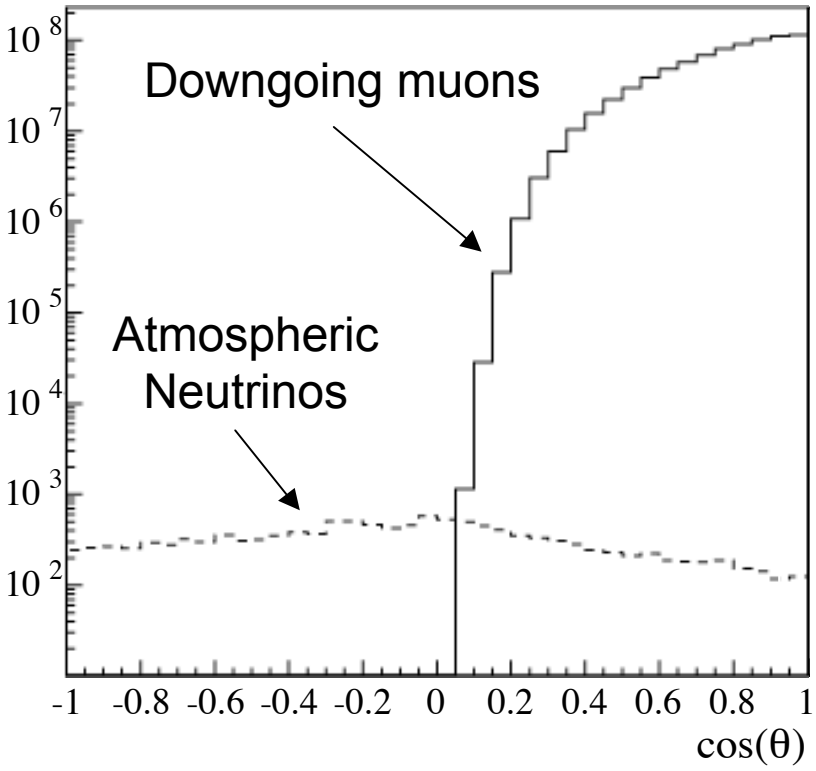
Chad Finley
University of Wisconsin, Madison
for the IceCube Collaboration

4th TeVPA Workshop Beijing, China
2008 Sept. 28

Introduction: IceCube 22-String Configuration



Challenge: Backgrounds for Point Source Search



Technique: look for upward tracks, since only neutrinos pass through through earth

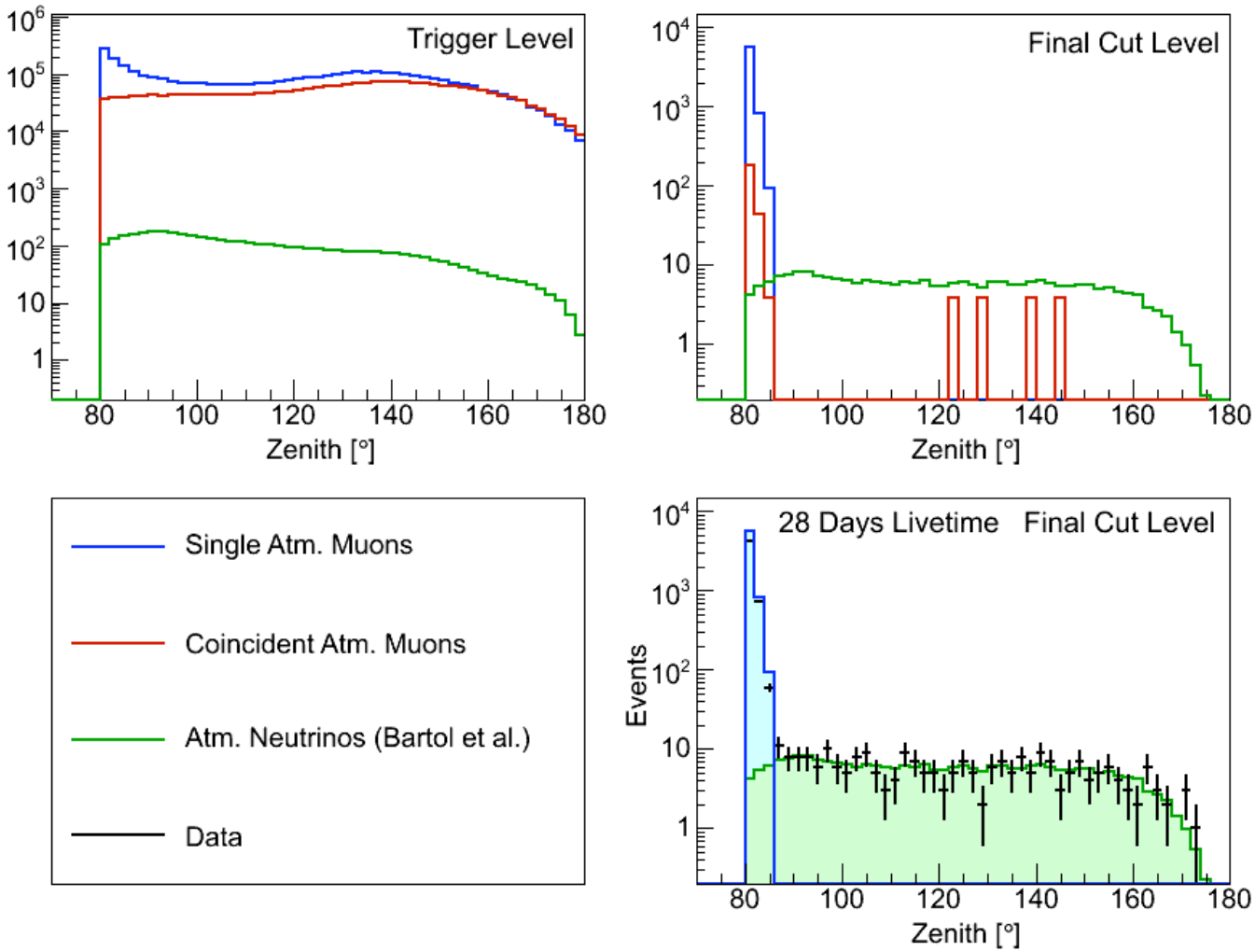
First Challenge: ignore the much higher rate of down-going muons from cosmic ray showers above the detector

Remaining up-going neutrinos are the "irreducible background" for point source searches

Second Challenge: Find a few extra-terrestrial neutrinos in background of thousands of atmospheric neutrinos (from cosmic ray showers on other side of earth)

First Challenge: Mis-reconstructed down-going events

Left: Without cuts, data sample is dominated by down-going events that are mis-reconstructed as up-going. **Right:** With hard cuts on track quality (harder than final IC-22 point source cuts), almost no mis-reconstructed down-going events remain.



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, and **energy estimators**

Background hypothesis based on **declination distribution of data events** (i.e. scrambled in right ascension) and **distribution of energy estimator for data**

Simple energy estimator in this analysis is **NChannel: the number of optical modules which are hit**

Maximum Likelihood Analysis with Energy - Overview

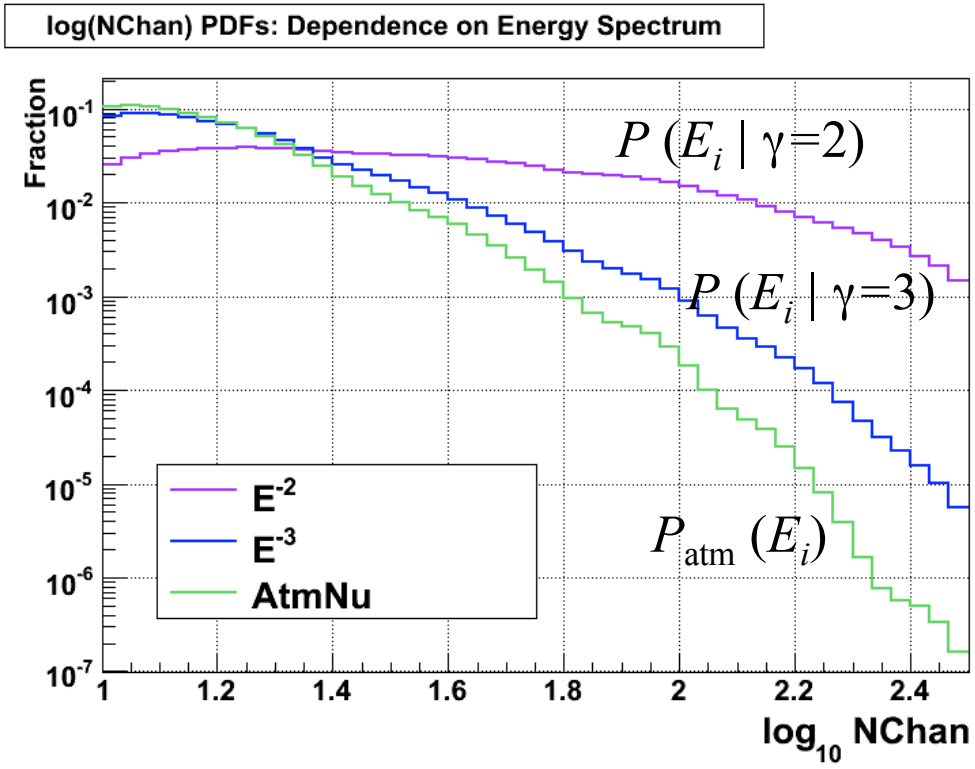
In addition to spatial information, use energy estimator (**Nchan**: number of hit optical modules) to improve separation of hard signal spectrum and softer background neutrino spectrum:

$$\mathcal{L}(n_s,\gamma) = \prod_{i=1}^{N}\left(\frac{n_s}{N}\mathcal{S}_i(\gamma) + (1-\frac{n_s}{N})\mathcal{B}_i\right)$$

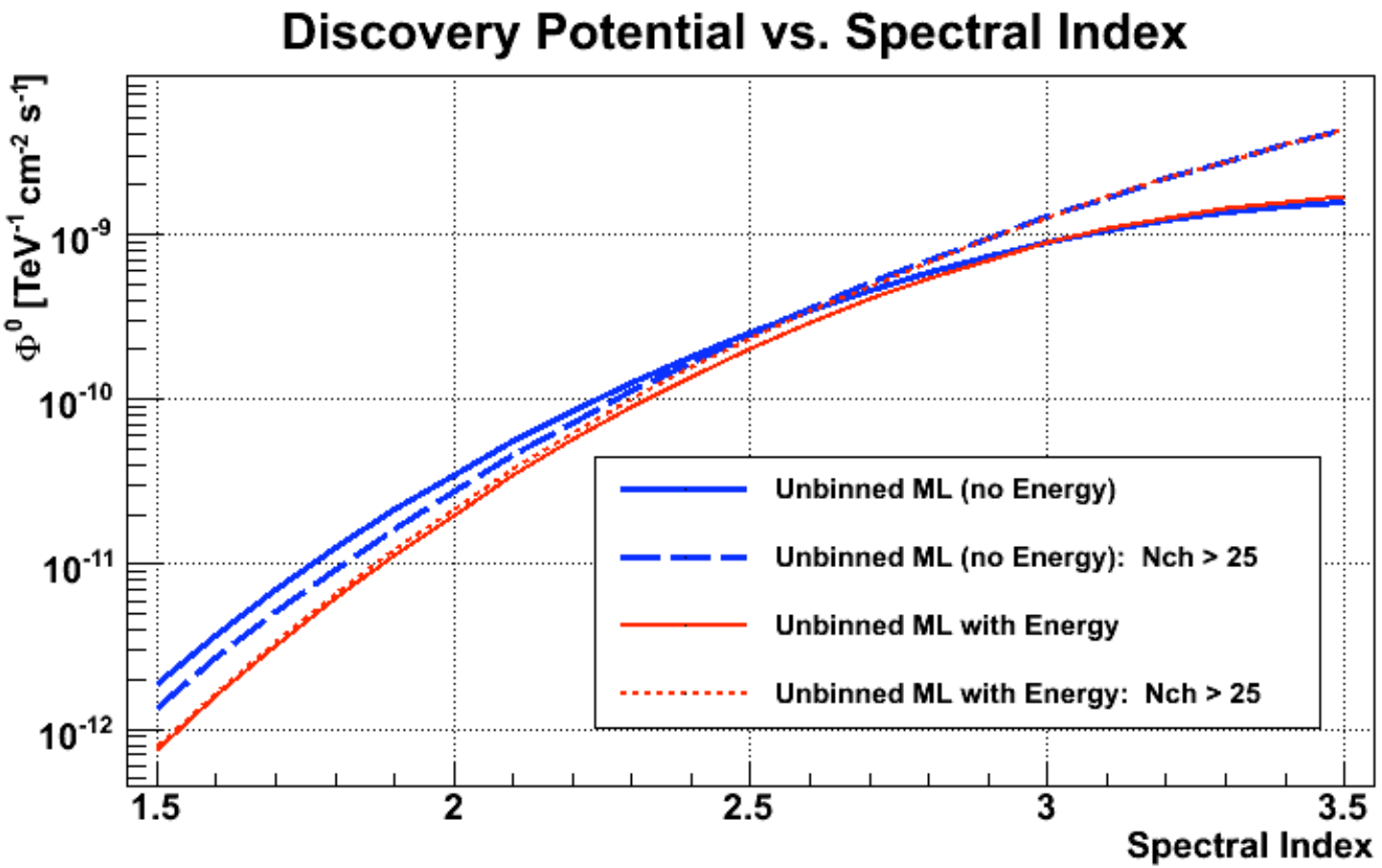
$$\mathcal{S}_i = \frac{1}{2\pi{\sigma_i}^2}e^{-{r_i}^2/2{\sigma_i}^2}\cdot P(E_i|\gamma)$$

$$\mathcal{B}_i = B_{\text{zen}}\cdot P_{\text{atm}}(E_i)$$

Actually, what is used instead of P_{atm} is $P_{Data}(E_i)$, so that bkg pdfs do not depend on simulation



Maximum Likelihood Analysis with Energy - Overview



Without energy term, cuts must be optimized for either hard or soft signal spectrum.

With the energy term, the analysis is (nearly) optimal for all signal spectra.

Background separation is done by the analysis, rather than by the cuts.

IC22 Point Source Data Set

2007 May 31 – 2008 Apr 5

275.70 days livetime after selecting good runs.

Simple set of cuts applied to data, to select good upgoing events and reject downgoing and coincident background, including:

- Estimated event directional uncertainty < 3 deg
- log likelihood ratio of best-fit upgoing track to best-fit downgoing track > 30
- if hit series is split in two, both series have best-fit zenith > 70 deg

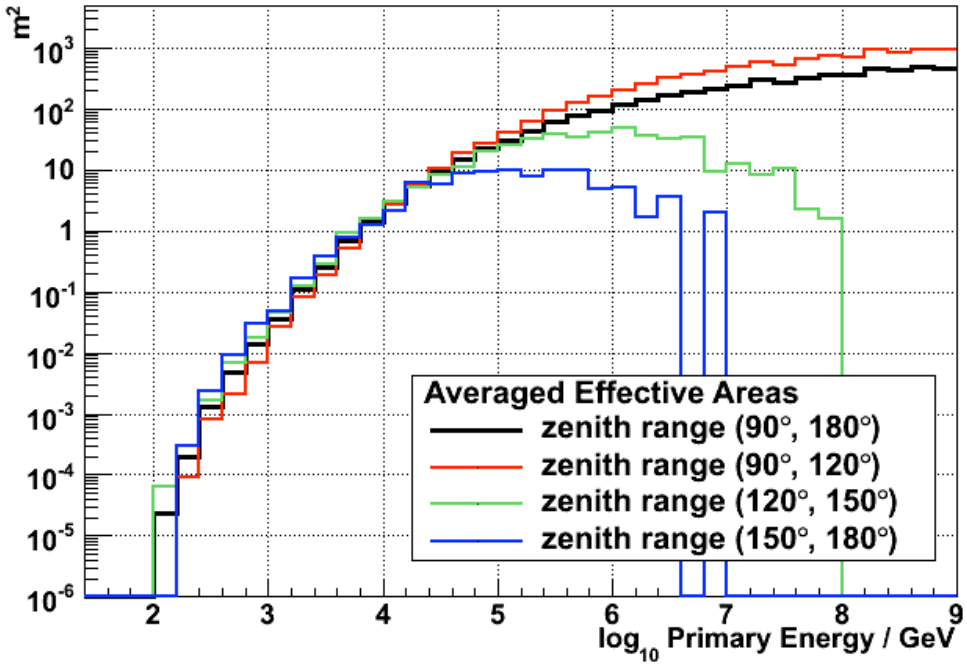
5114 Events after cuts

Perform point source search using:

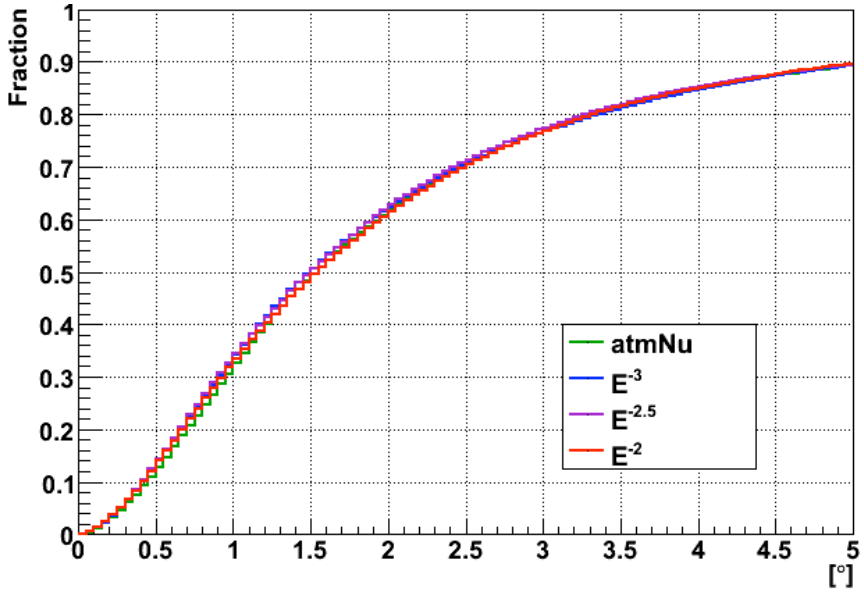
- a priori list of 28 source candidates
- all sky search from -5° to +85° declination

IC22 Point Source Analysis Characteristics

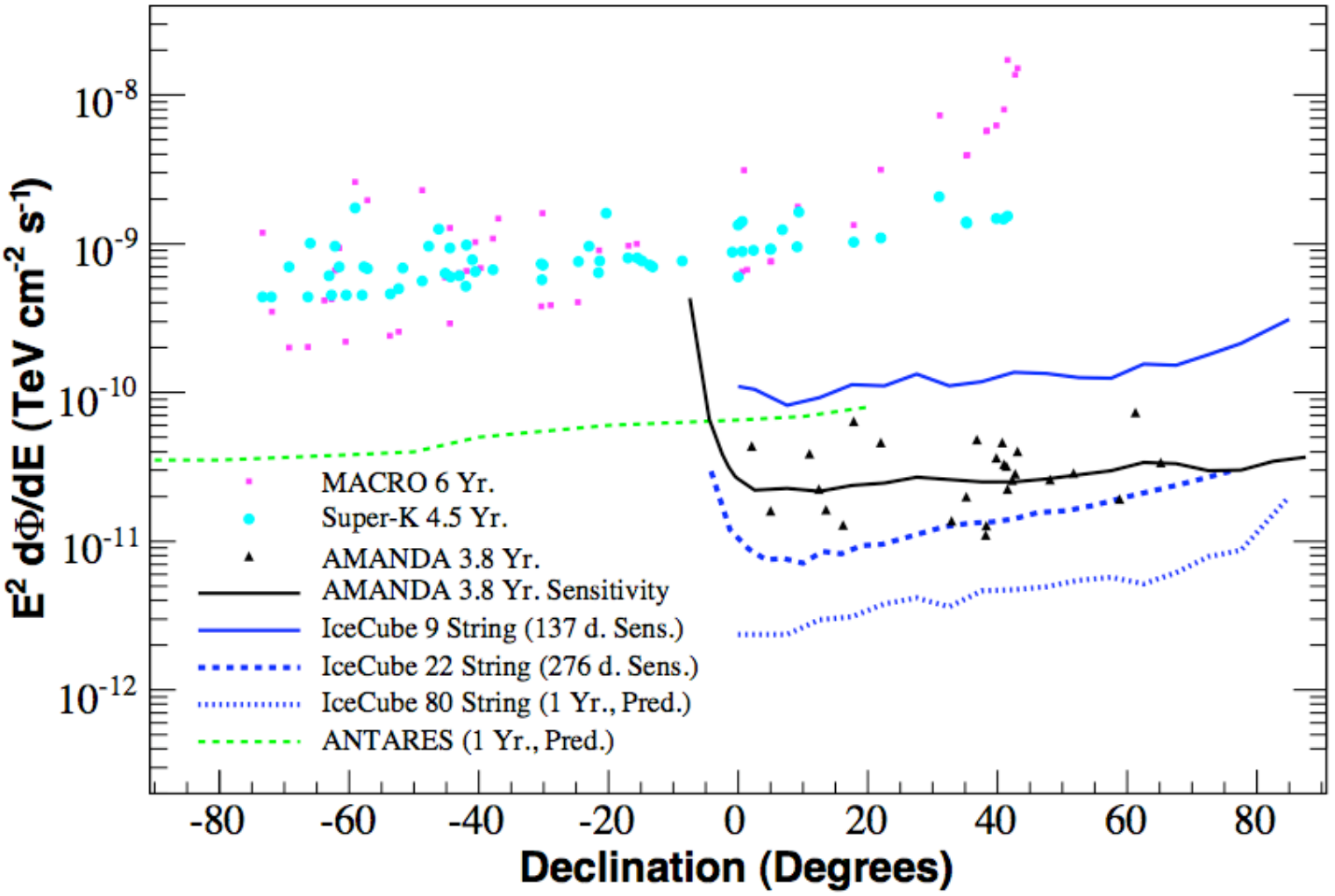
Muon Neutrino Effective Area



Point Spread Function



IC22 Sensitivity Comparison



arXiv:0809.1646

Results I: A Priori Source List

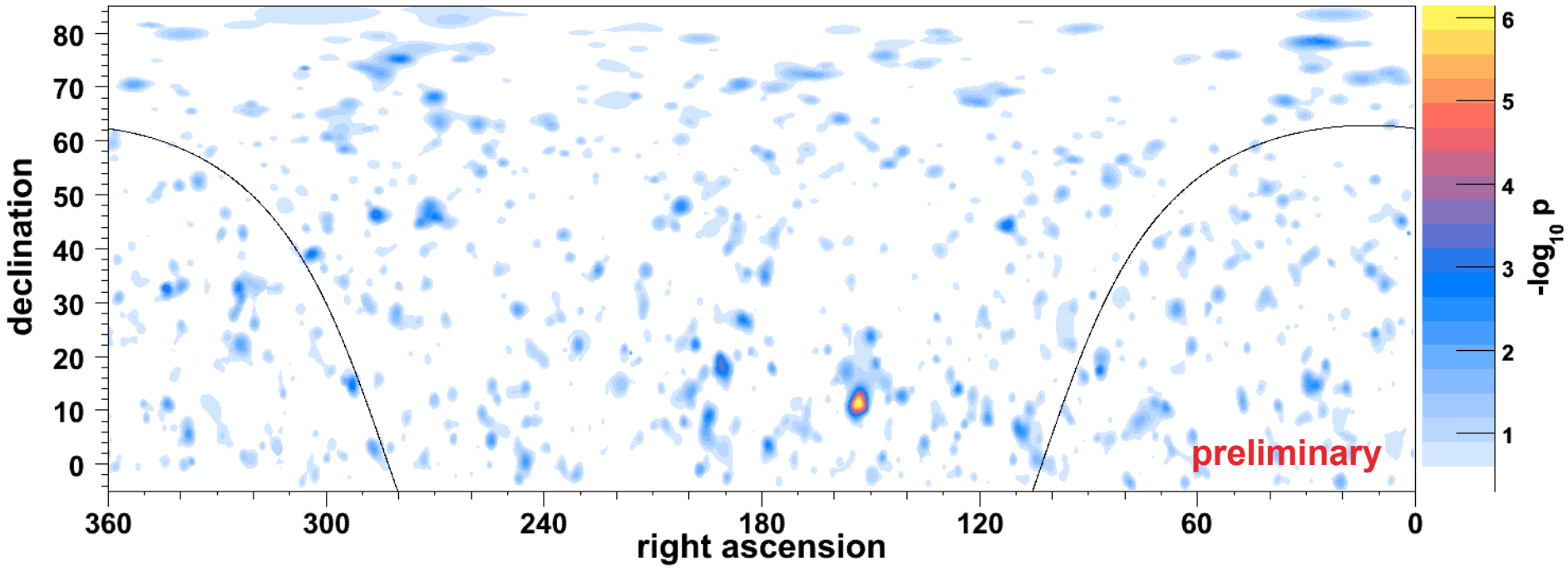
Lowest p-value (0.07) is for 1ES 1959+650.

Not significant after trial factor of 28 sources in list.

Obj. Name	ra(deg)	dec(deg)	p-value (pre-trial)
MGRO_J2019+37	(304.830 , 36.830)	:	0.251
MGRO_J1908+06	(287.270 , 6.280)	:	-----
Cyg_OB2	(308.083 , 41.510)	:	-----
SS_433	(287.957 , 4.983)	:	0.317
Cyg_X-1	(299.591 , 35.202)	:	-----
LS_I_+61_303	(40.132 , 61.229)	:	-----
GRS_1915+105	(288.798 , 10.946)	:	-----
XTE_J1118+480	(169.545 , 48.037)	:	0.082
GRO_J0422+32	(65.428 , 32.907)	:	-----
Geminga	(98.476 , 17.770)	:	-----
Crab_Nebula	(83.633 , 22.014)	:	-----
Cas_A	(350.850 , 58.815)	:	-----
Mrk_421	(166.114 , 38.209)	:	-----
Mrk_501	(253.468 , 39.760)	:	-----
1ES_1959+650	(299.999 , 65.149)	:	0.071
1ES_2344+514	(356.770 , 51.705)	:	-----
H_1426+428	(217.136 , 42.672)	:	-----
1ES_0229+200	(38.202 , 20.287)	:	-----
BL_Lac	(330.680 , 42.278)	:	0.368
S5_0716+71	(110.473 , 71.343)	:	0.309
3C66A	(35.665 , 43.035)	:	0.313
3C_454.3	(343.491 , 16.148)	:	-----
4C_38.41	(248.815 , 38.135)	:	-----
PKS_0528+134	(82.735 , 13.532)	:	-----
3C_273	(187.278 , 2.052)	:	0.369
M87	(187.706 , 12.391)	:	-----
NGC_1275	(49.951 , 41.512)	:	0.213
Cyg_A	(299.868 , 40.734)	:	-----

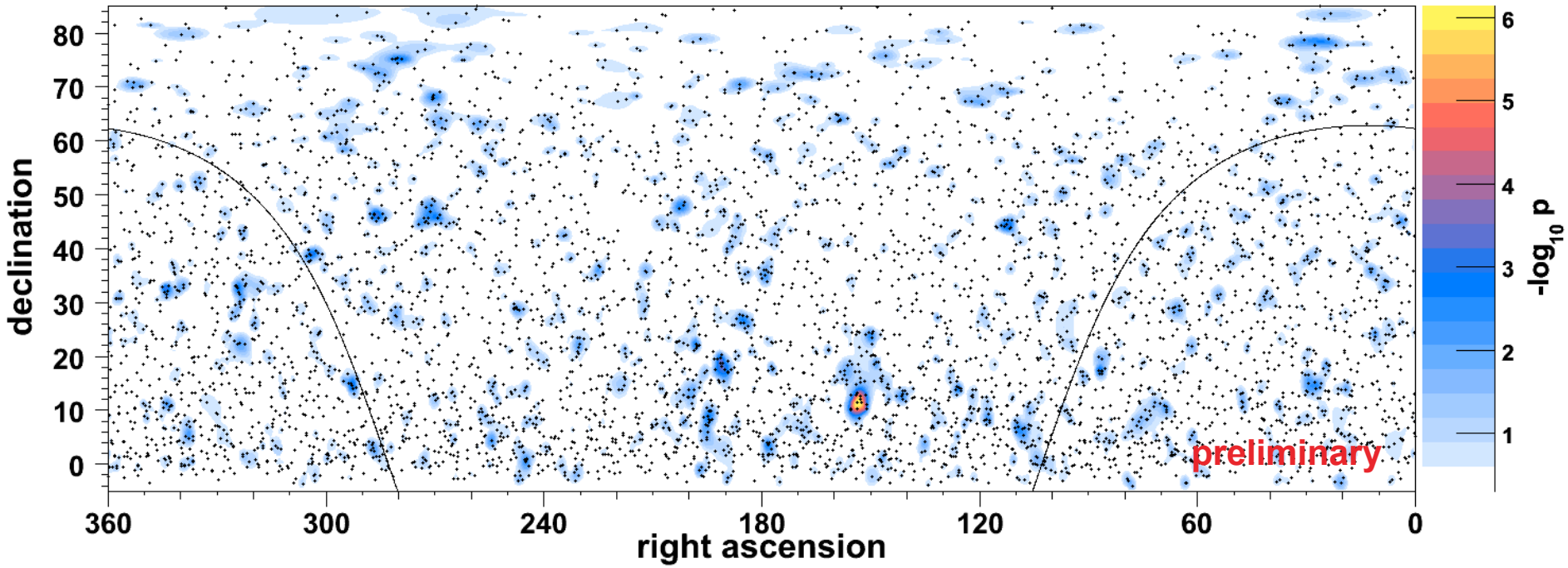
(only excesses reported, otherwise given as "---")

Results II: All Sky Search



For the all sky search, the likelihood function is sampled every 0.25° in r.a. and every 0.25° in declination.

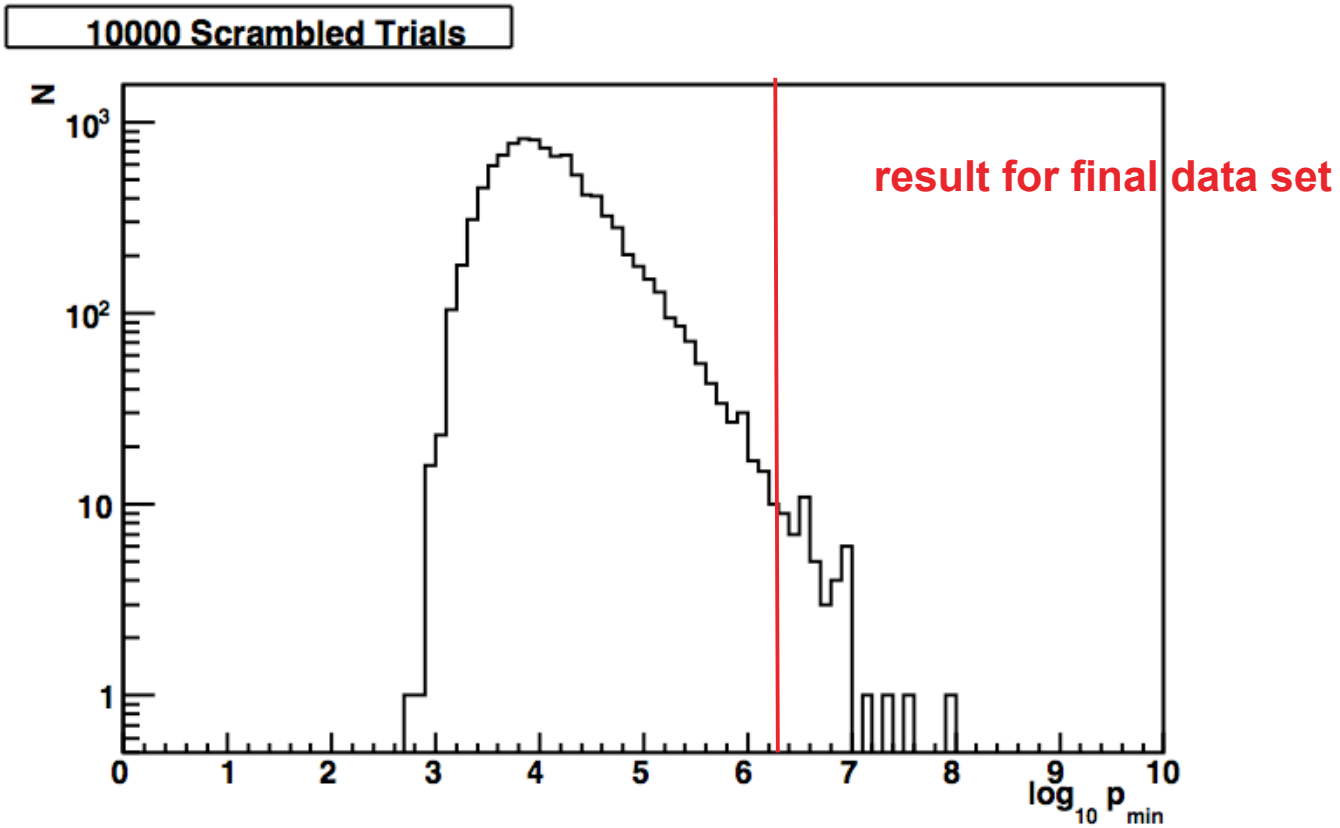
Results II: All Sky Search



Hottest spot found at r.a. 153° , dec. 11°
est. nSrcEvents = 7.7 est. gamma = 1.65
max. llhRatio = 13.4
est. pre-trial p-value: $-\log_{10}(p)$: 6.14 (4.8 sigma)

Post-trials p-value of analysis is ~ 1.34% (2.2 sigma) ...

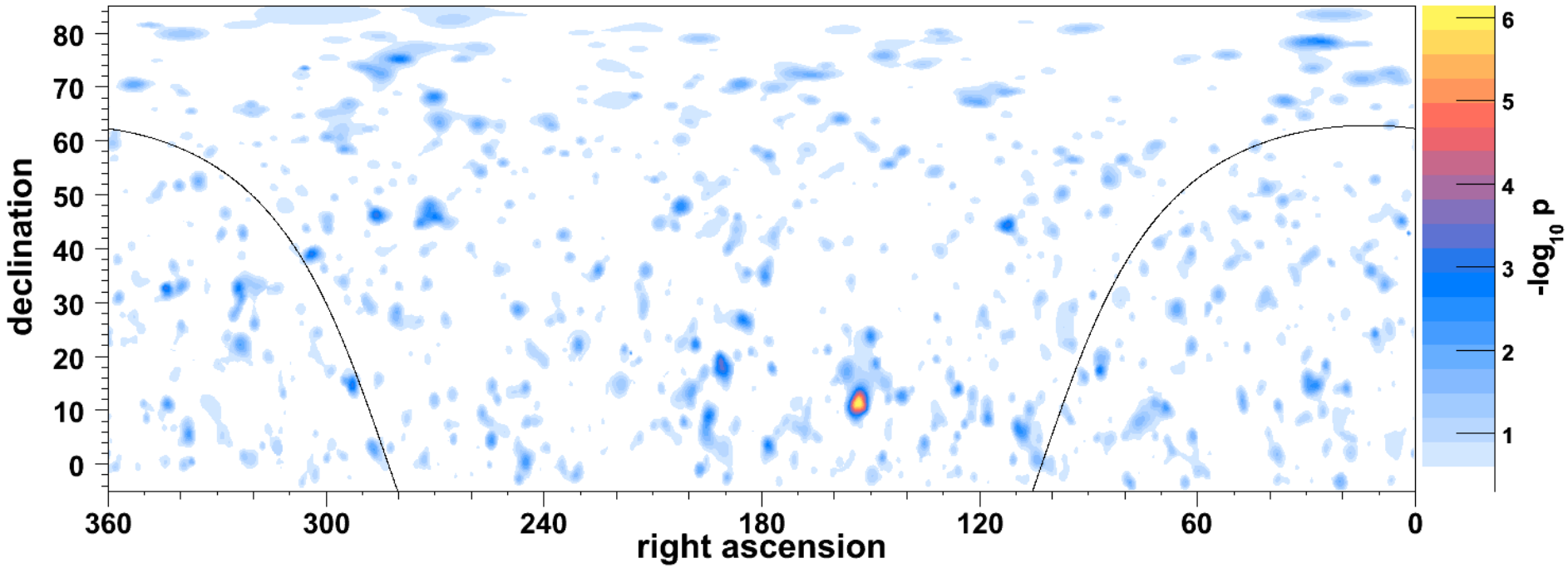
Final Result



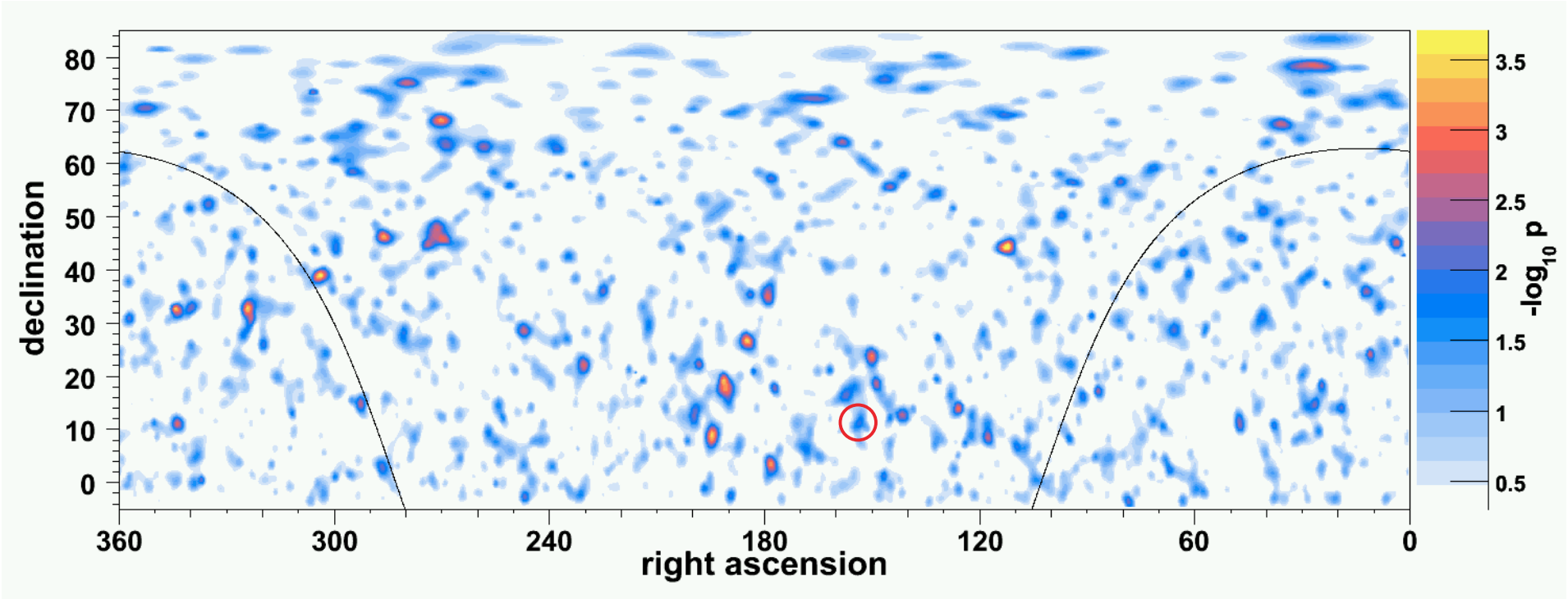
Out of 10,000 trials of scrambled data sets, 67 (0.67%) have a test-statistic (max llhRatio or p-value of hottest spot) more significant than that found in the data.

Including trial factor of two since the analysis with the a priori list was also performed, the **post-trials p-value is ~ 1.34%.**

All Sky Search (with energy term)



All Sky Search (without energy term)

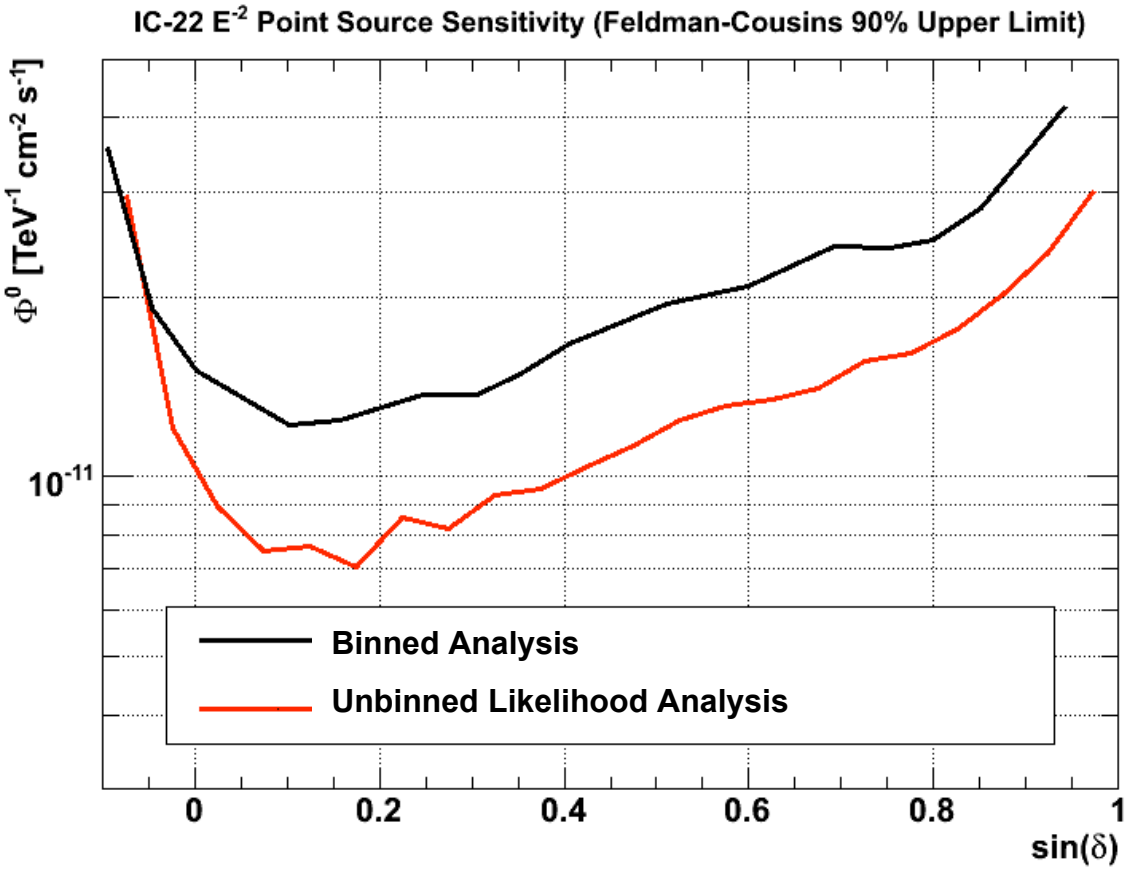


If the unbinned analysis is performed without the energy / NChan term, the original hottest spot is still an excess, but no longer significant at all.

(Note that the scale has changed and no spot is significant after trials).

=> The significance at this spot depends on contribution of high energy (high NChan) events

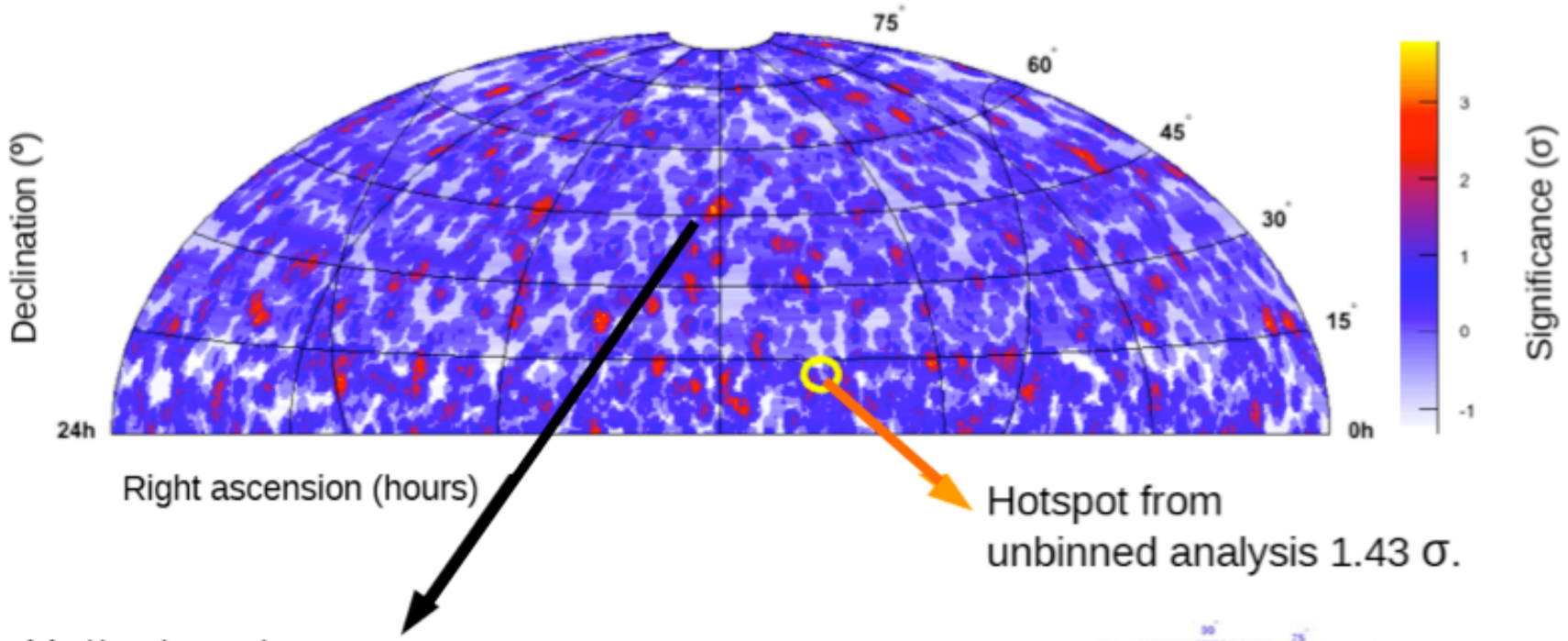
IceCube-22 Binned Analysis



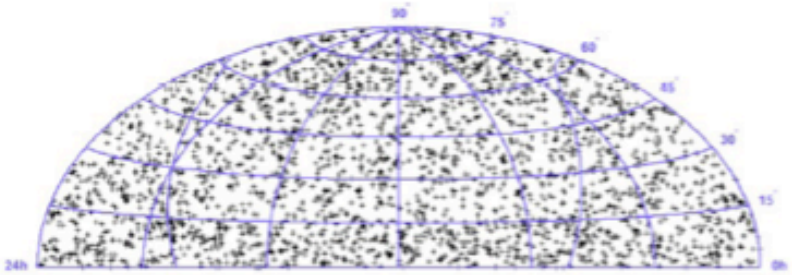
• A binned analysis has also been performed on the IceCube-22 data, with independent set of cuts and different track reconstruction. Optimized for E^{-2} spectrum.

• Binned analysis is not as sensitive as unbinned likelihood analysis, but is a **straight-forward and important general cross-check.**

IceCube-22 Binned Analysis: Results



- Hottest spot:
- Dec=47°, RA=12.2h.
- Pre-trials significance 3.79 σ.
- 67.7% of greater significance in (1000) randomized skymaps.



- If the binned analysis were performed using the same track reconstruction as the unbinned analysis, the significance of this spot would be 3.7 sigma (pre-trial).
- Therefore both analyses performing consistently. Main difference in hottest spots because of different track reconstructions.

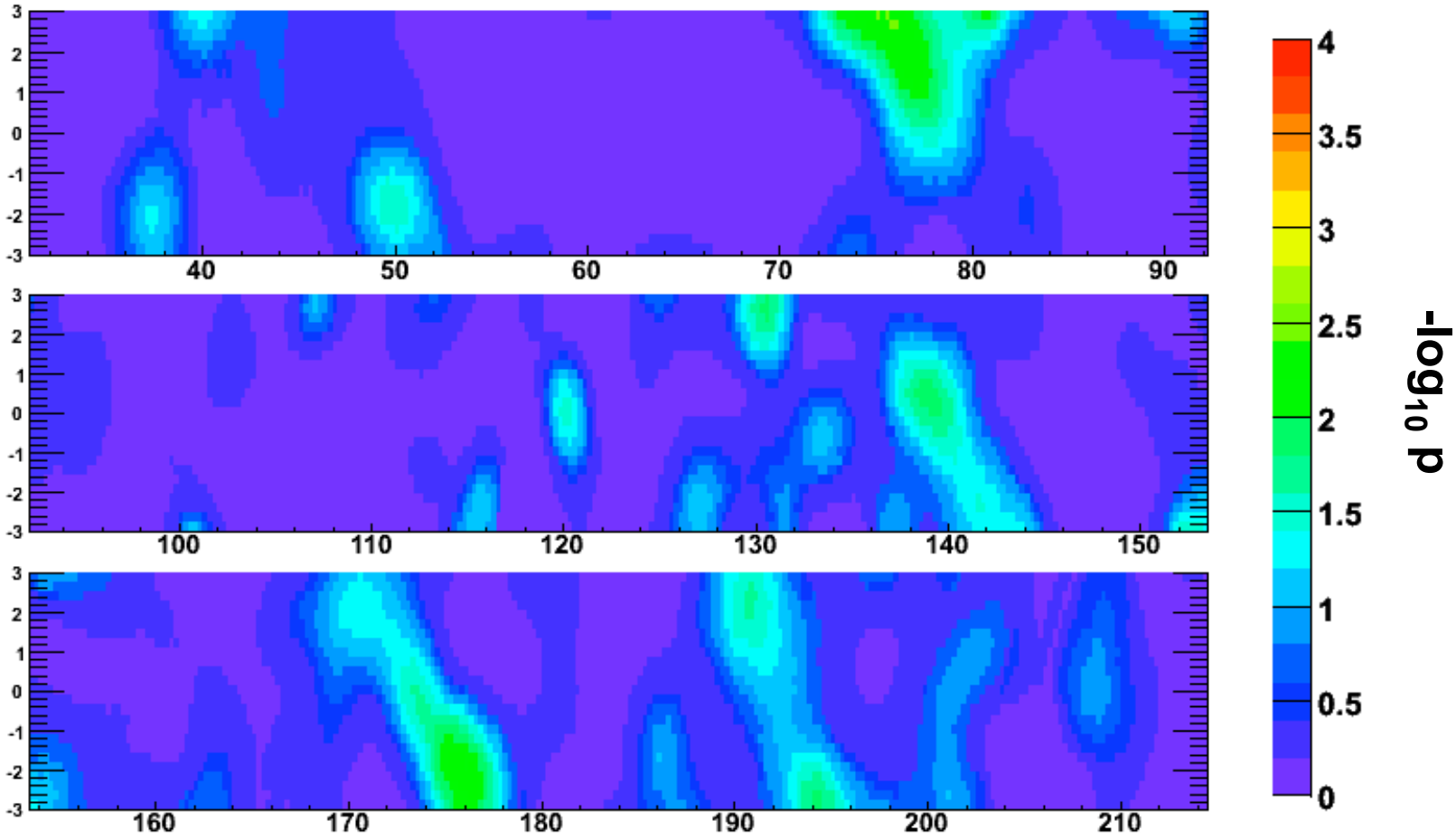
IceCube / AMANDA Low-Energy-Optimized Point Source Analysis

IceCube operating jointly with the smaller, denser AMANDA detector enhances the sensitivity to lower energy neutrinos.

This data set has served as the basis for a likelihood point source search optimized for spectra that are soft or have exponential cutoff.

Analysis has been performed on the galactic plane and selected galactic sources

IceCube / AMANDA Low-Energy-Optimized Point Source Analysis



Galactic Plane Scan:
hottest spot: l=75.875, b=2.675 (gal. coord.)
smallest pre-trial p-value: 0.0037 (2.7 sigma)
expected in 95% of randomized samples

A priori Source Candidate List:

- **Crab Nebula: p=0.14, Ns = 3.3**
- **Cas A: p=0.65, Ns=-1.9**
- **SS433: p=0.67, Ns=-0.9**
- **LS I +61 303: p=0.47, Ns= -0.4**

p<0.14 expected in 37% of randomized samples

Study of Events Contributing to the Hottest Spot in Unbinned Search

rank	Analysis S/B ratio	Nch	Ang. Unc.	dAngle to Spot	CogZ
1:	67449.380	145	0.84	0.717	-349.2
2:	33656.799	148	1.75	1.086	-167.8
3:	15483.897	77	0.88	1.203	-456.1
4:	13593.747	168	2.68	1.924	-289.5
5:	4169.923	65	1.52	2.337	-285.8
6:	3199.724	51	1.62	0.444	25.6
7:	639.997	29	1.51	1.385	-198.6
8:	490.646	28	1.68	1.634	158.0
9:	308.372	44	2.79	4.595	-324.8
10:	271.344	34	1.23	2.538	139.6

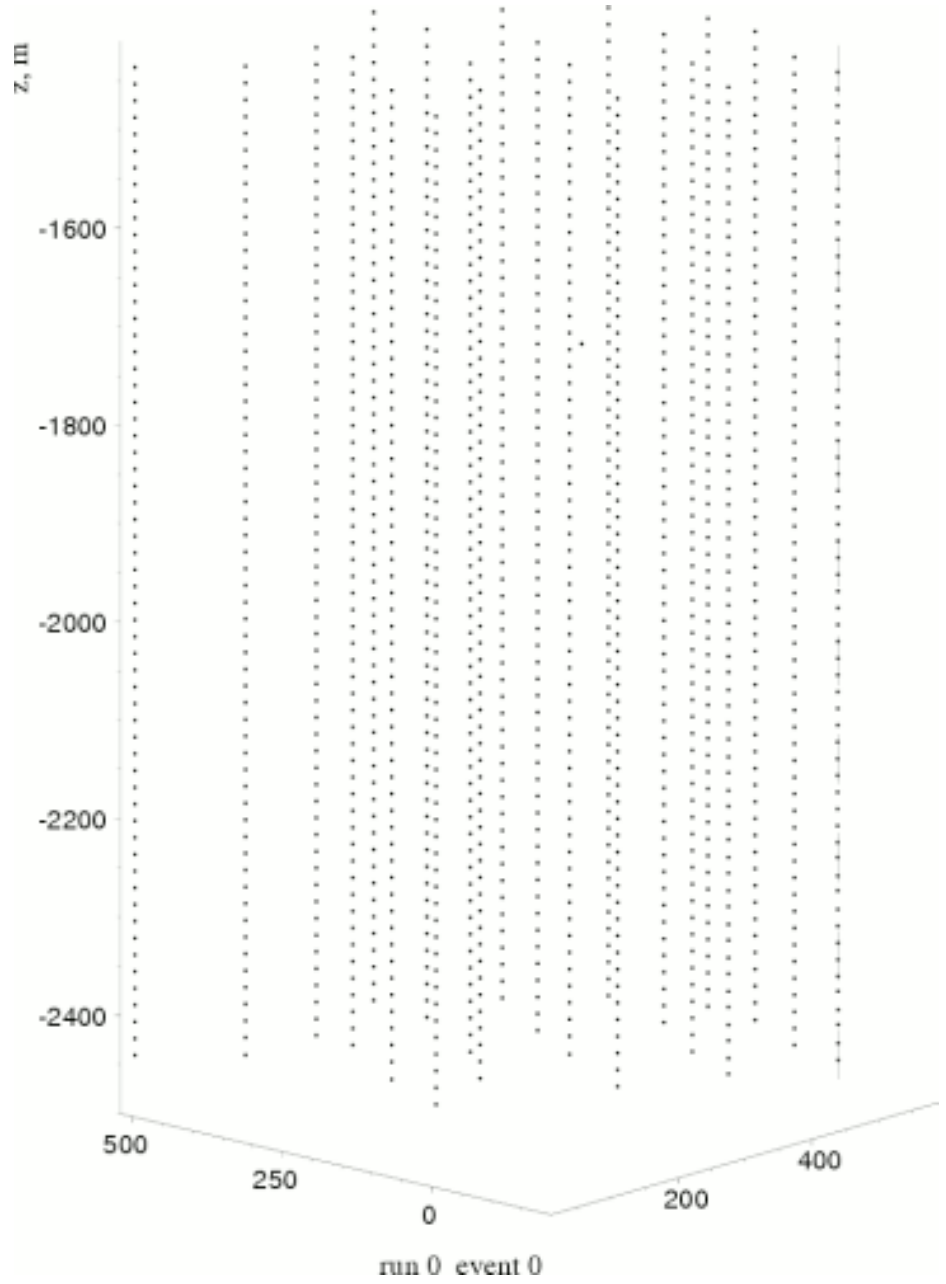
To Note:

- Combination of high Nchan and good reconstruction count the most
- CogZ: Center of gravity of hits, with respect to center of detector
  - majority in the lower half of the detector, clearer ice

Event Display

Number of hit modules: 148

est. angular error: 0.84°



Time Analysis

- IceCube 40 should be able to test possibility that the hottest spot was due to a source, **unless the events are due to a one-time occurrence.**

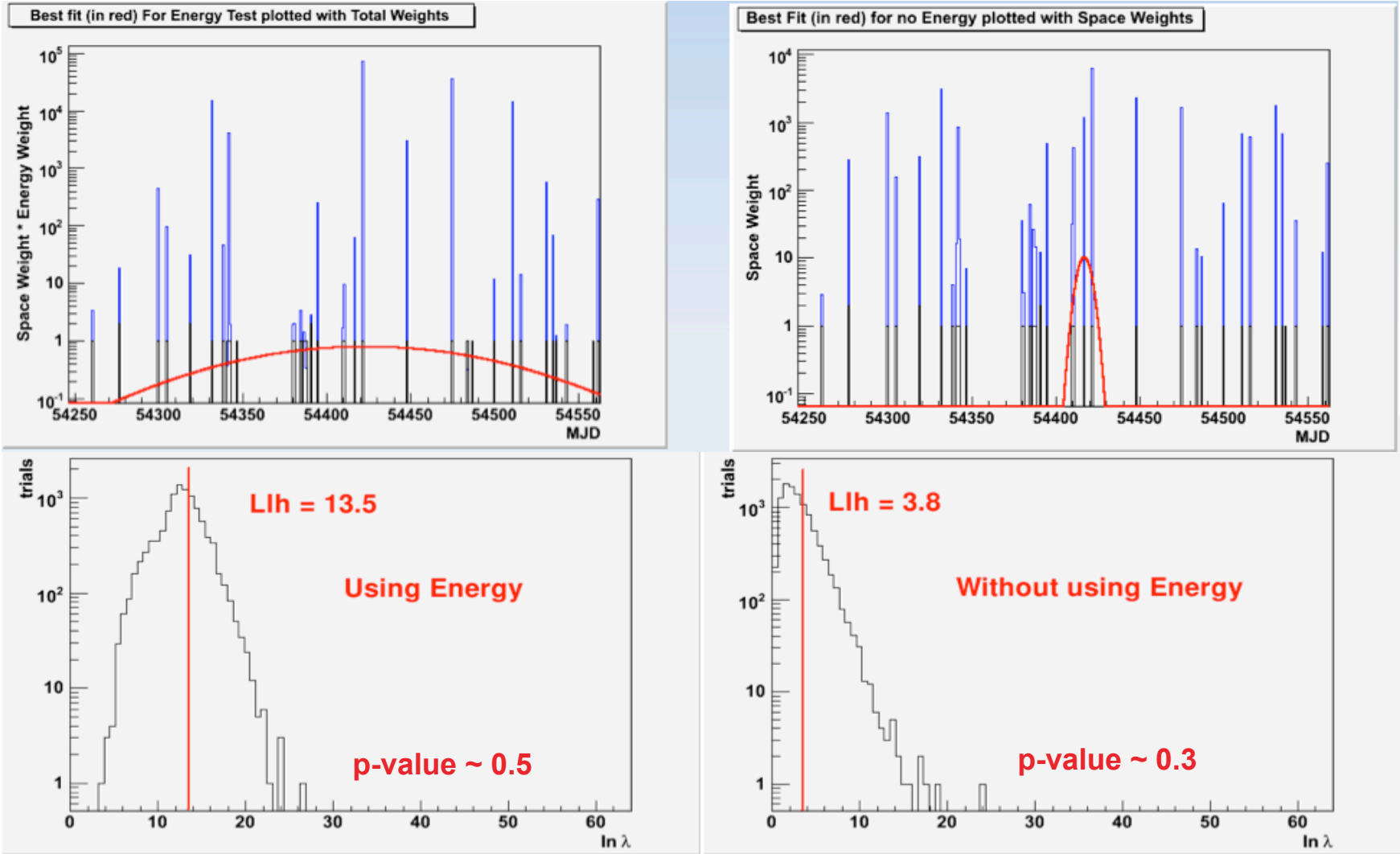
- Event times were kept blinded until time-dependent analysis could be performed, so that statistical significance would be unbiased.

- A previous **time-dependent likelihood analysis** applied to AMANDA-II point source data was adapted to search for the **best fit of a single Gaussian (of any time duration)** plus background to the event time distribution of the events in the hottest spot.

- The definition of “an event in the hottest spot” is taken as those events with S/B > 1 in the point-source analysis, and the event times are weighted with the same S/B ratios. Two trials:

  - weights according to analysis with energy information
  - weights according to analysis without energy information

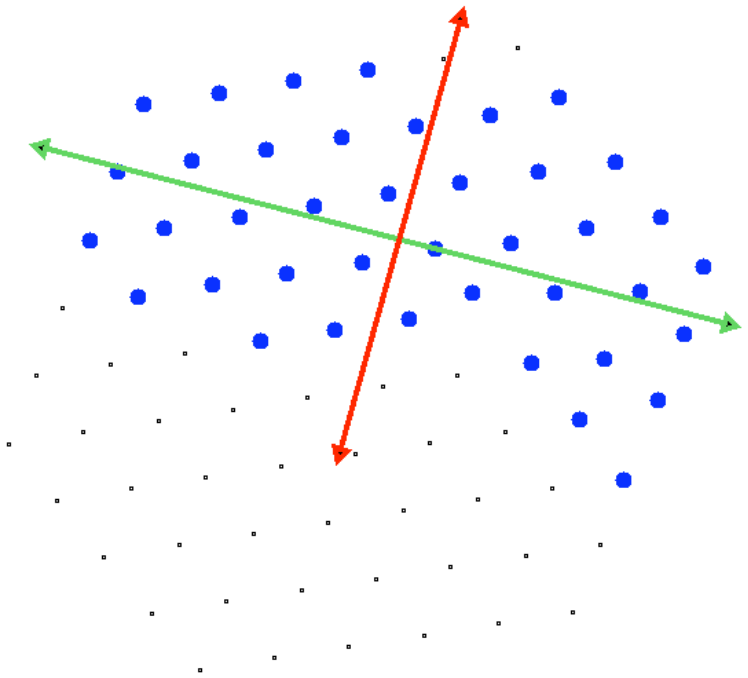
Time Analysis



- None of the events contributing most strongly to the hotspot are closer together than 10 days. Events are distributed roughly evenly in time over the year.
- Neither analysis finds any significant single cluster of events in time.

Prospects for IceCube 40

IceCube currently running with 40 strings deployed.

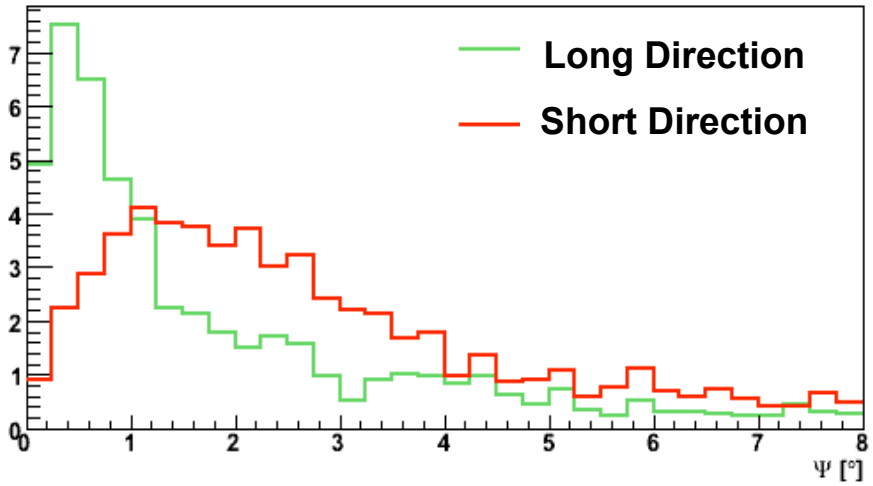


~ 2x effective area of 22 strings.

More fully contained strings.

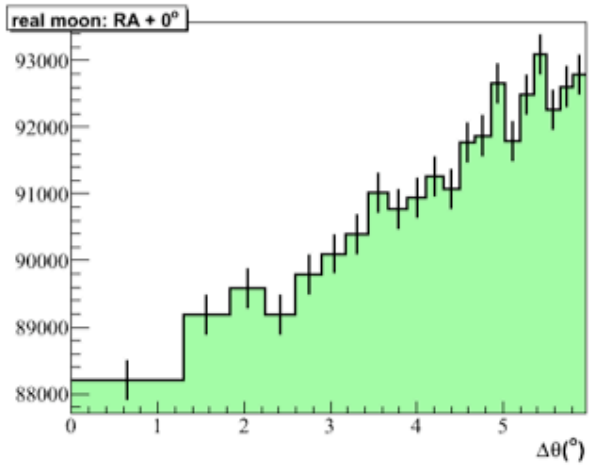
Short direction: angular resolution comparable to IceCube 22.

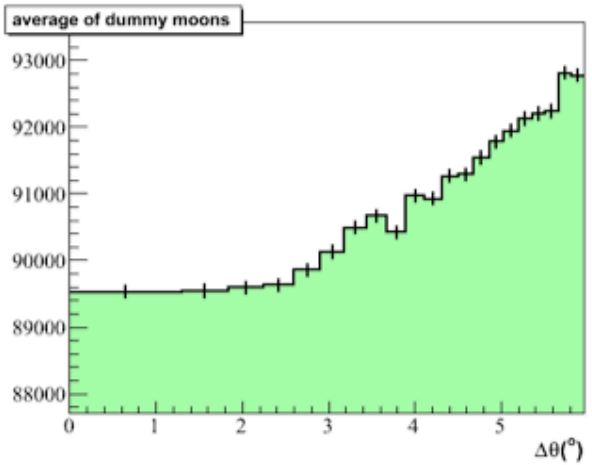
Long direction: angular resolution comparable to full IceCube 80 configuration.



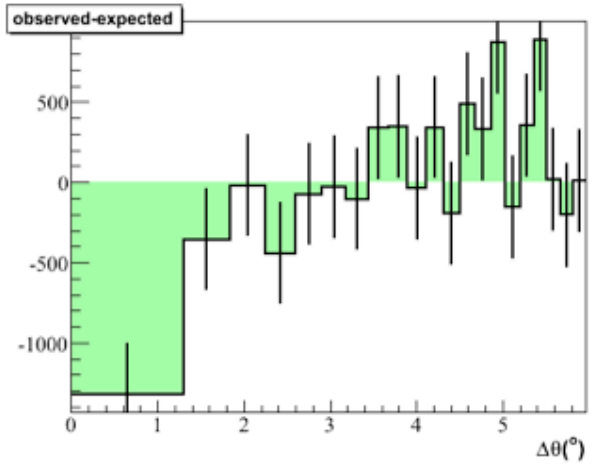
Preliminary Point Spread Function for IceCube-40

IceCube-40: First Results of Moon Shadow Analysis





preliminary



observed: 88202 events

expected: 89522 events

deficit: -1320 events

error: 315 events

significance: -4.2 σ

- Cosmic rays blocked by the moon lead to a point-like deficit in the distribution of down-going muons in the detector.
- Need high statistics and good angular resolution! IceCube 22 could not yet see the shadow, but first few months of IceCube 40 data already do.

Summary

• IC22 provides the best sensitivity to date for high energy neutrino point sources in the northern hemisphere.

• No evidence for astrophysical neutrinos in the direction of any a priori source candidates.

• The hottest spot in the all-sky search has a post-trials p-value of ~ 1.34% (2.2 sigma).

• No additional information (time-dependent analysis, source catalog searches, cross-checks with other analyses) gives indication that the result is related to a signal. Therefore the result is currently consistent with a fluctuation: a chance alignment of reconstructed event directions. More systematic checks are ongoing using different energy and direction reconstructions.

• The enlarged 40-string IceCube detector configuration running this year will provide substantially larger data set, and will start to achieve the sharp angular resolution of the final 80-string IceCube.