The Shadow of the Moon in IceCube

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Young Scientists Forum
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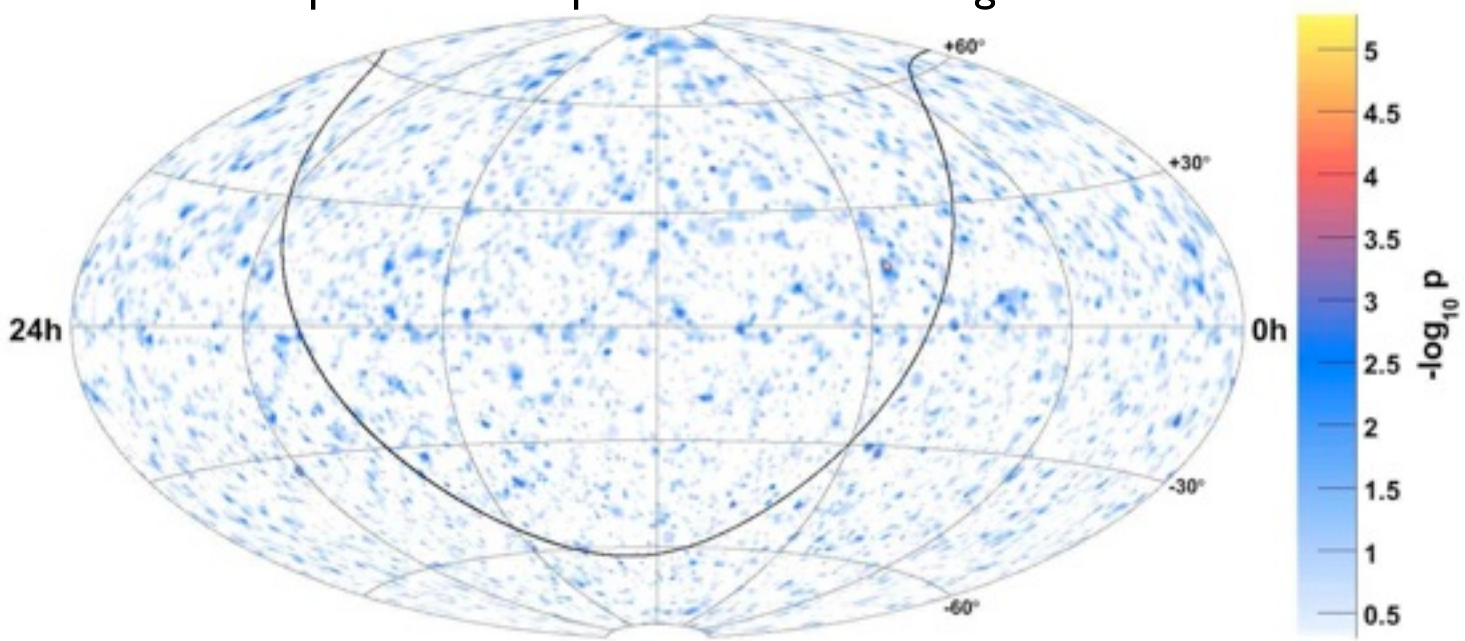
Motivation: we know where it is

Northern hemisphere: atmospheric neutrino background



Southern hemisphere: cosmic ray muon background
Accepted ApJ, arXiv: 1012.2137 [astro-ph]

IceCube is an observatory, but instead of light we use neutrinos to look into space.

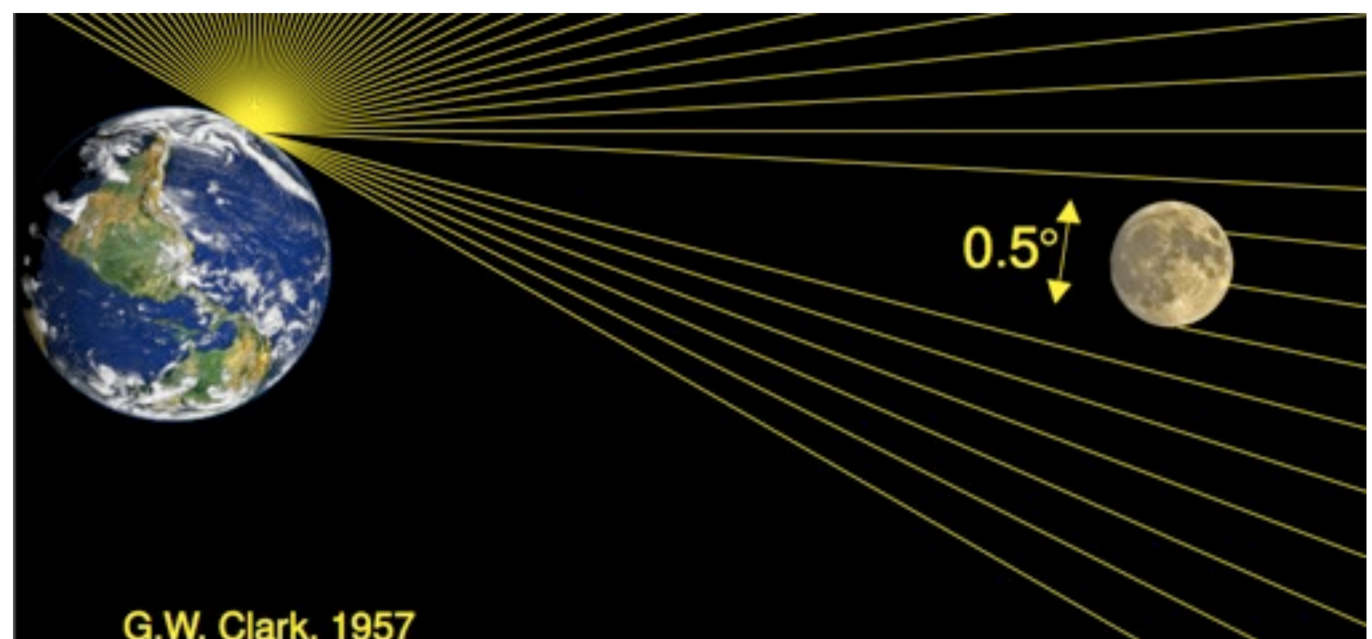
To resolve stars, we must first be able to resolve the Moon.

This End-to-end check of detector systematics and pointing.

Caveat: we look for astrophysical point sources in neutrinos, but we look for the moon in downgoing muons.

If IceCube wants skymaps to look like this...

Hubble Space Telescope Star Cluster NGC 290

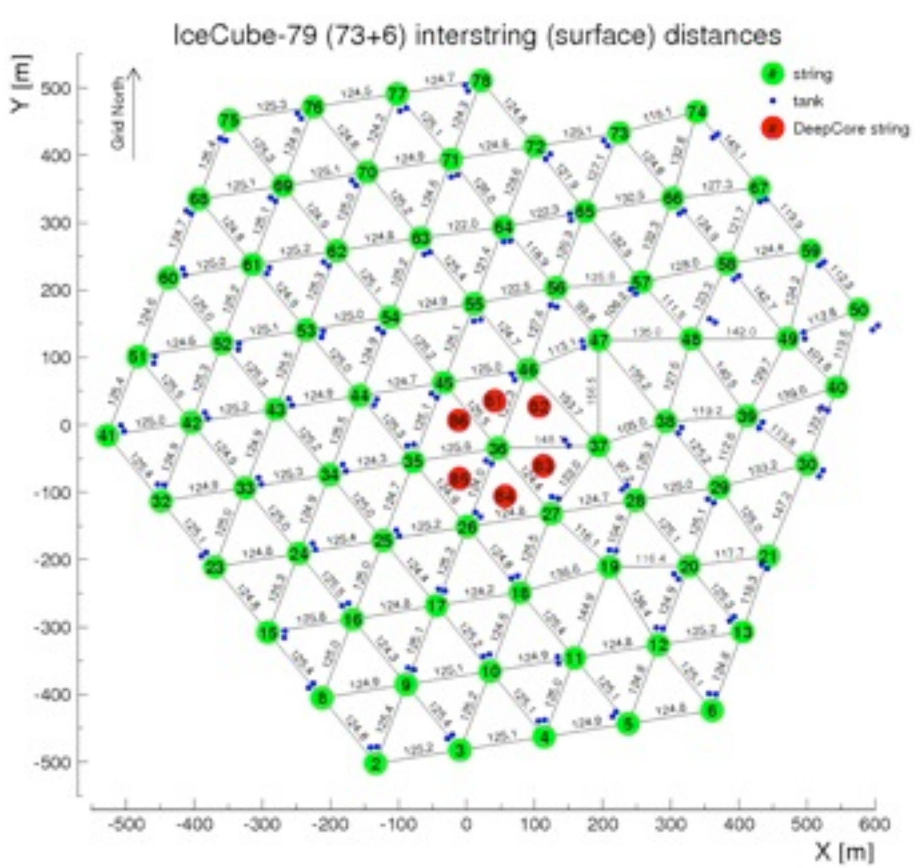


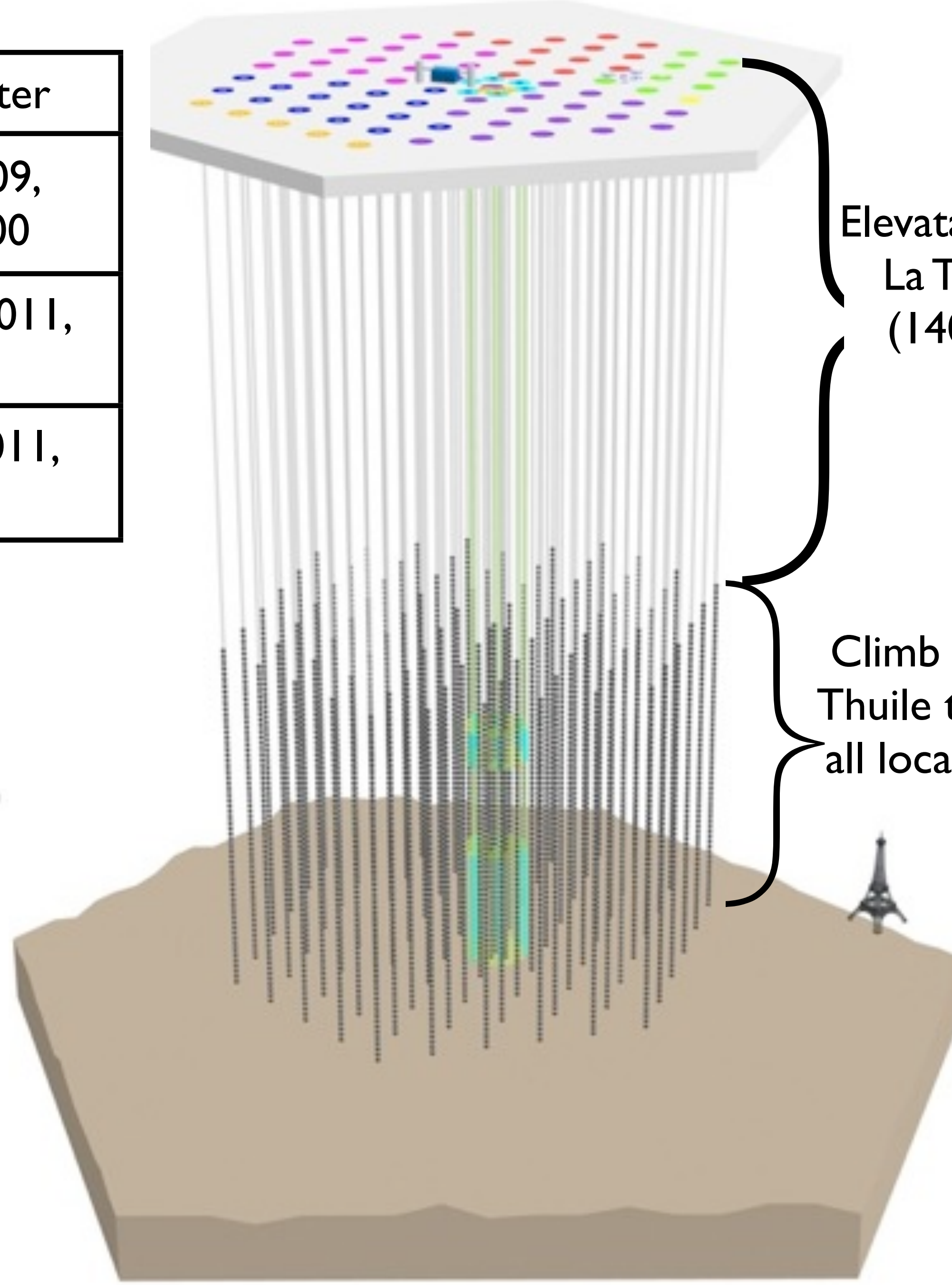
Analysis History

IceCube Moon Shadow Analyses shown here

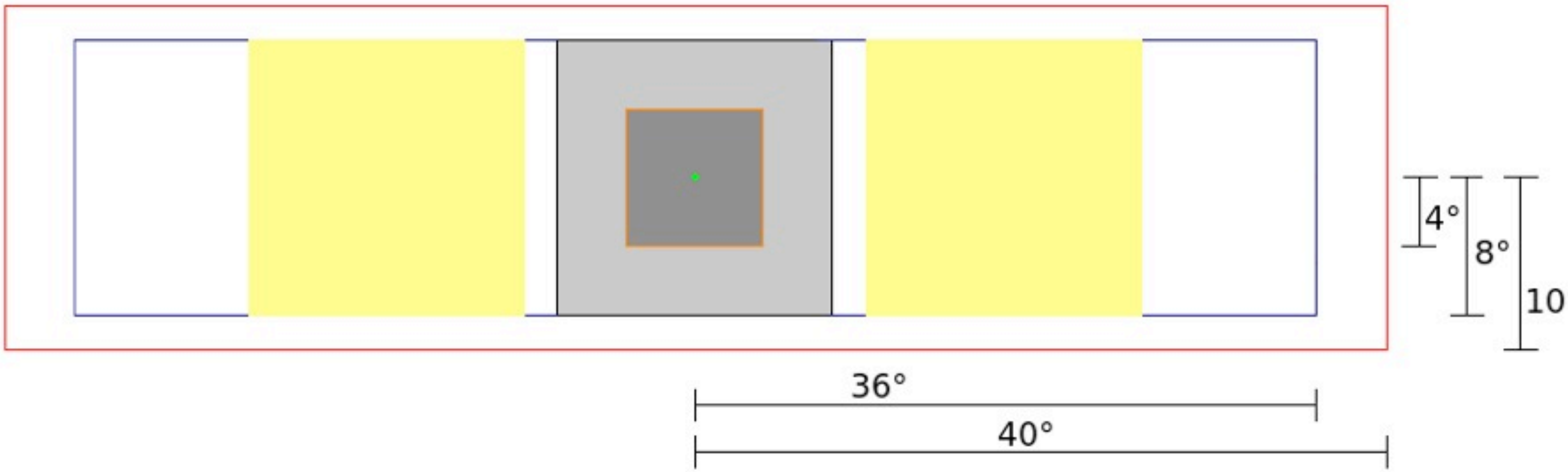
22	2.7σ	Binned	L. Gladstone	COSMO08 poster
40	7.5σ	binned: ask about backup slides	L. Gladstone	ICRC proc. 2009, arXiv:1002.4900
59	12σ	Unbinned	H. Stiebel	Masters Thesis 2011, Stockholm
40, 59	8σ, 12σ	Likelihood	J. Blumenthal	Diplomarbeit 2011, Aachen

Number of strings in IceCube during this data set, out of 86

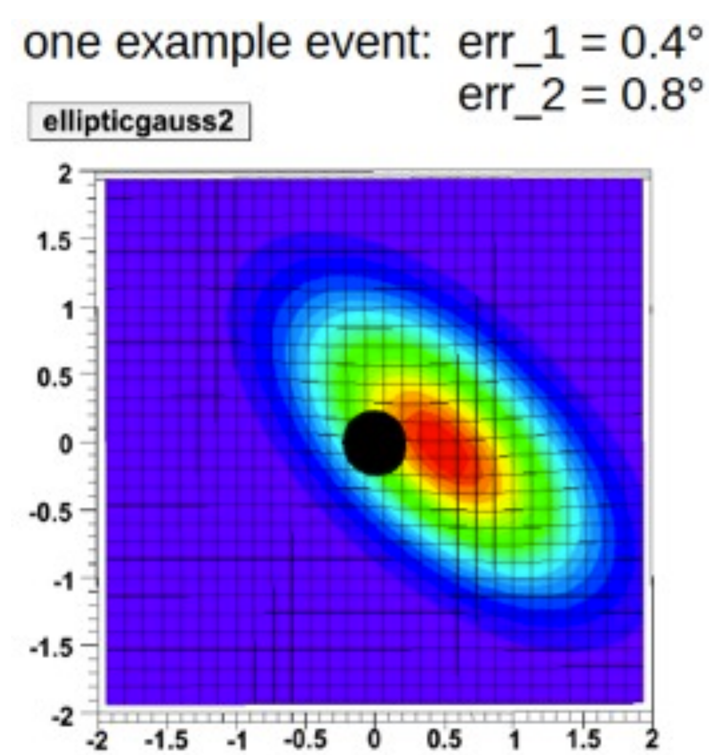




Data Sample



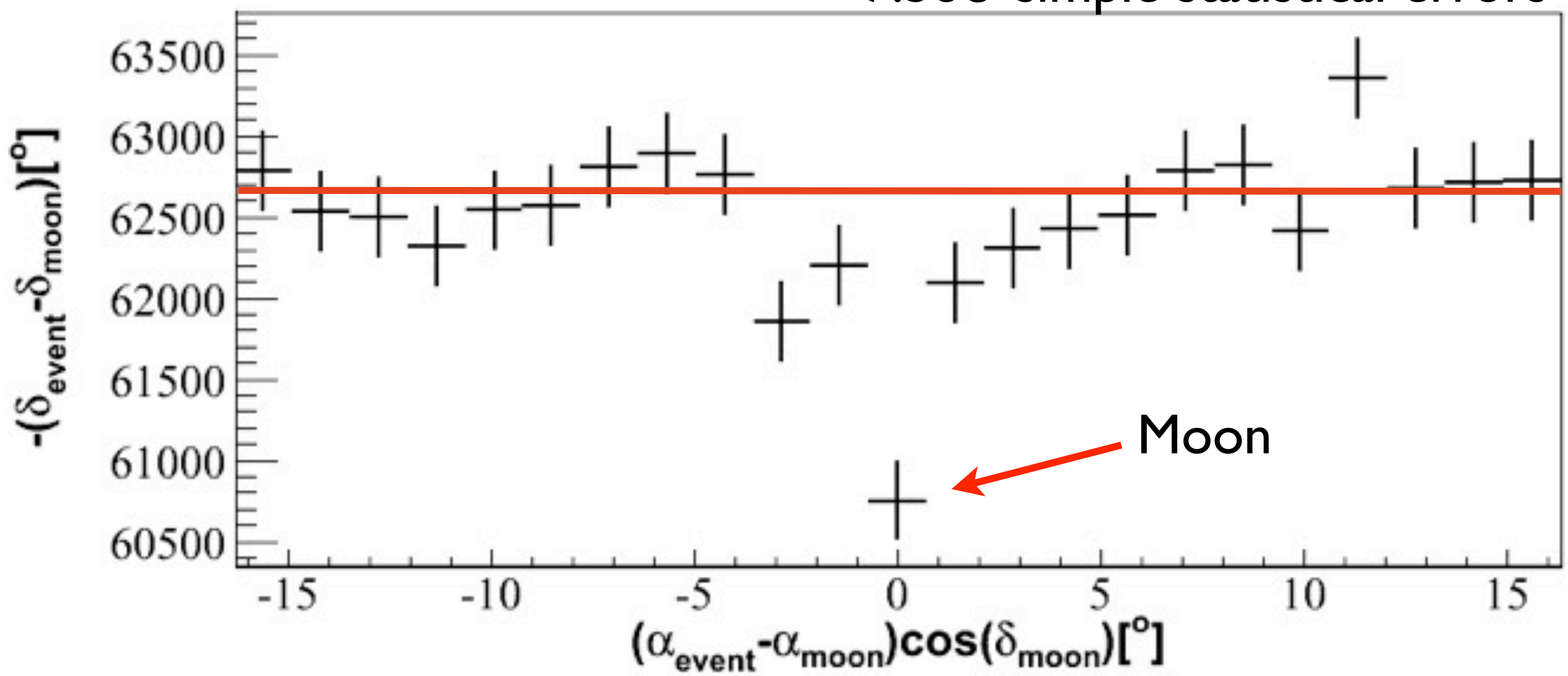
- Use events from a window around the Moon for both signal and background measurement
- Angular resolution of IceCube is comparable to the size of the Moon
- Minimum energy of primary cosmic ray: 2 TeV



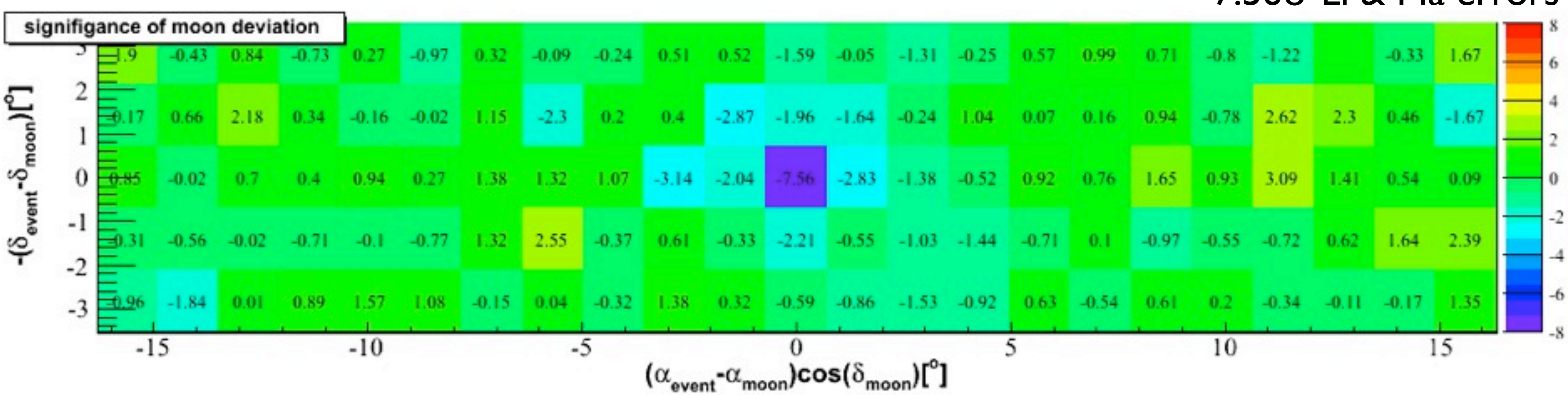
Binned Approach

- Data from detector setup with 40 of 86 strings installed
- 10 lunar months

7.58σ simple statistical errors



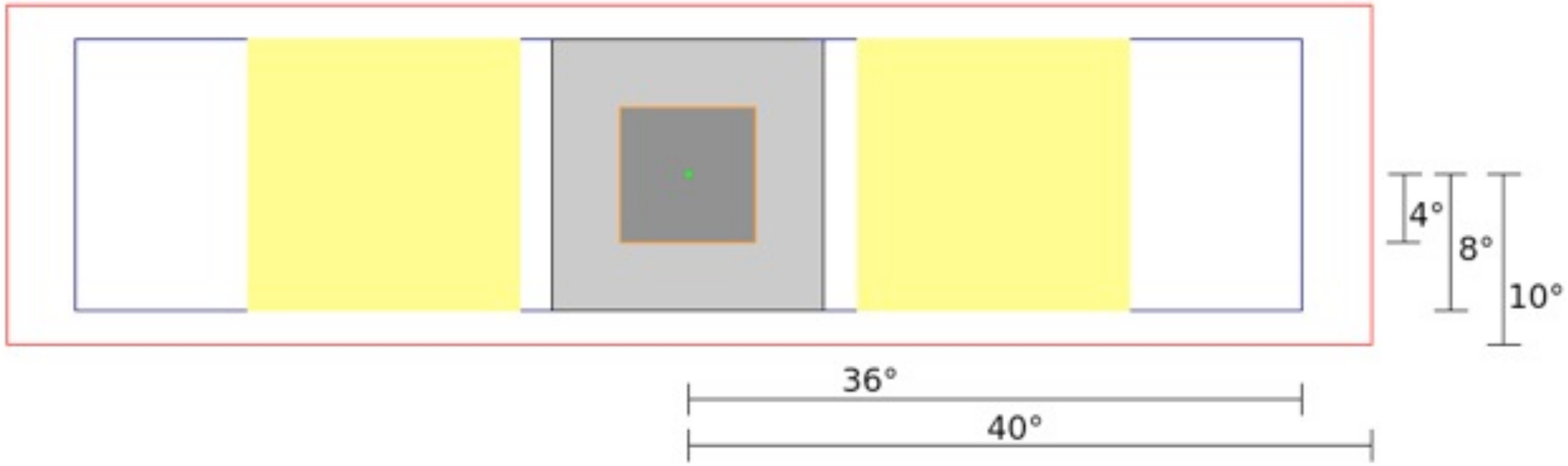
7.56σ Li & Ma errors

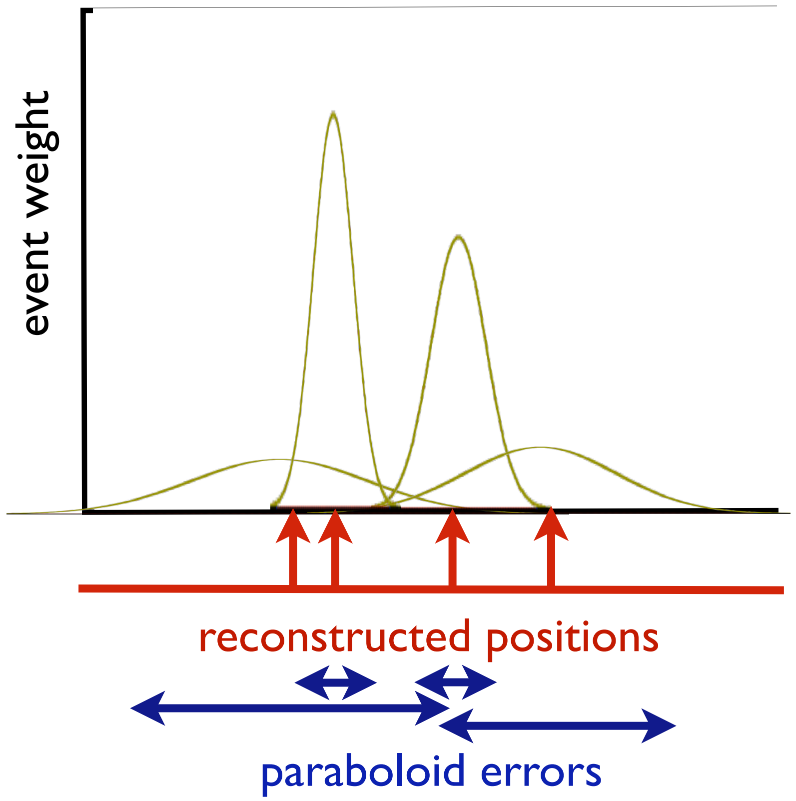


Likelihood Approach

$$L(\vec{x}_s, \boxed{n_s}) = \sum_i^N \log\left(\frac{\boxed{n_s}}{N} S_i + (1 - \frac{\boxed{n_s}}{N} B_i)\right)$$

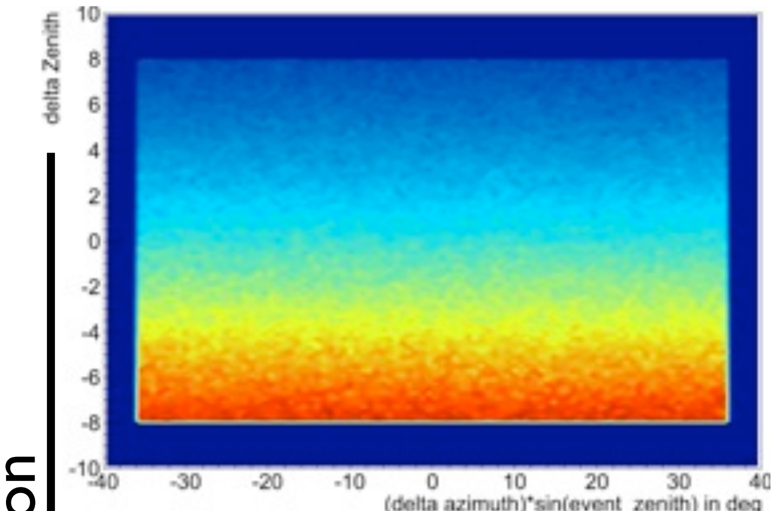
- Use central signal region and off-source background region
- At each point, vary the number of events blocked by the Moon, n_s
- Maximize likelihood



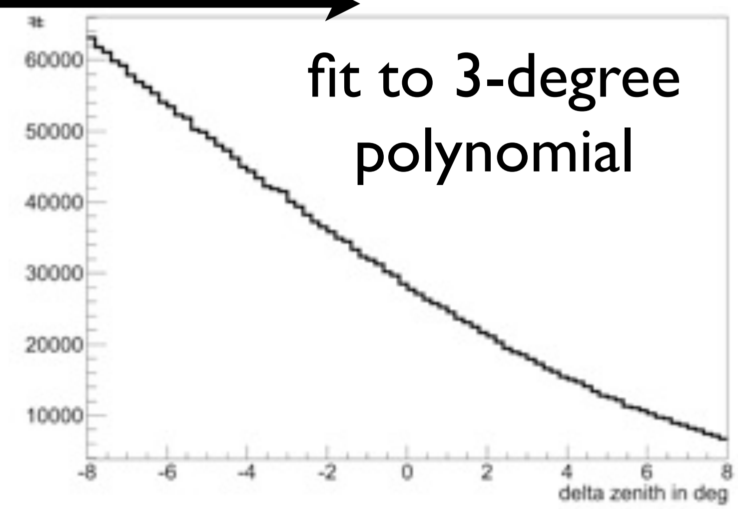


Background for likelihood

Background measured in off-source region:



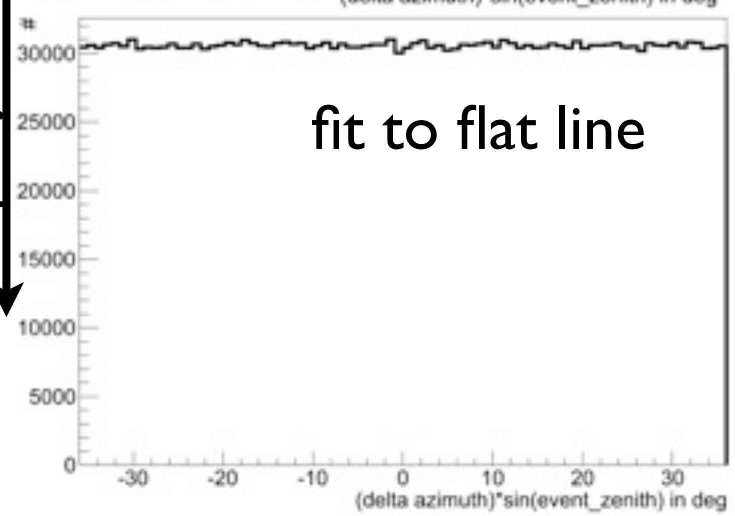
projection



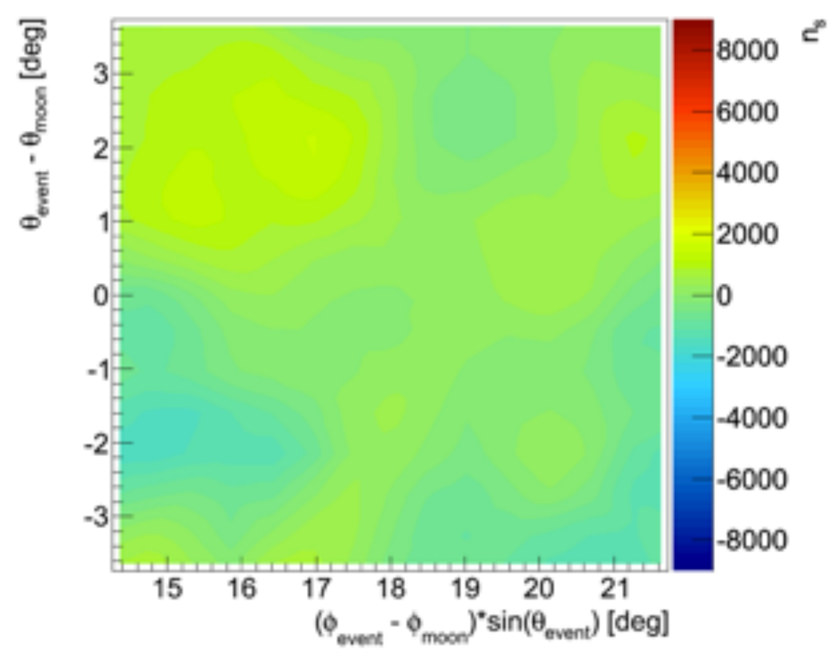
fit to 3-degree polynomial

Polynomial background model in zenith and azimuth

projection

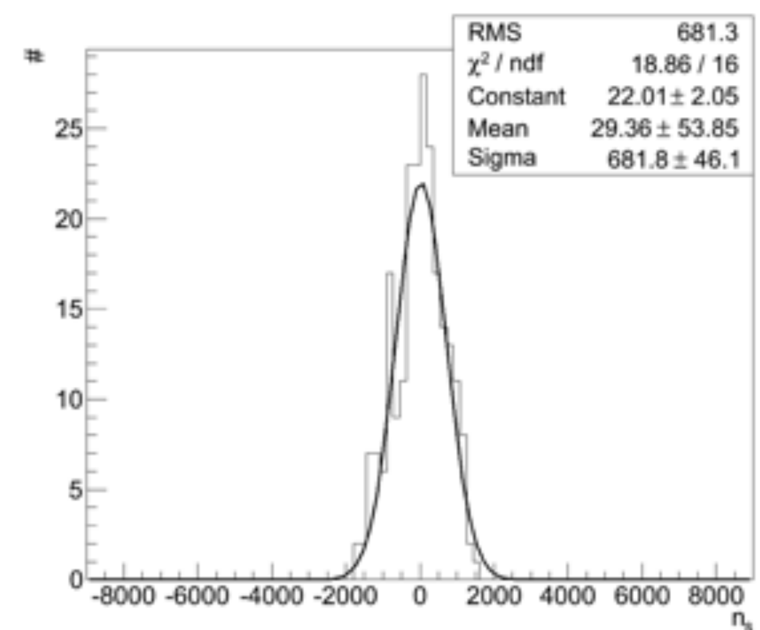


fit to flat line

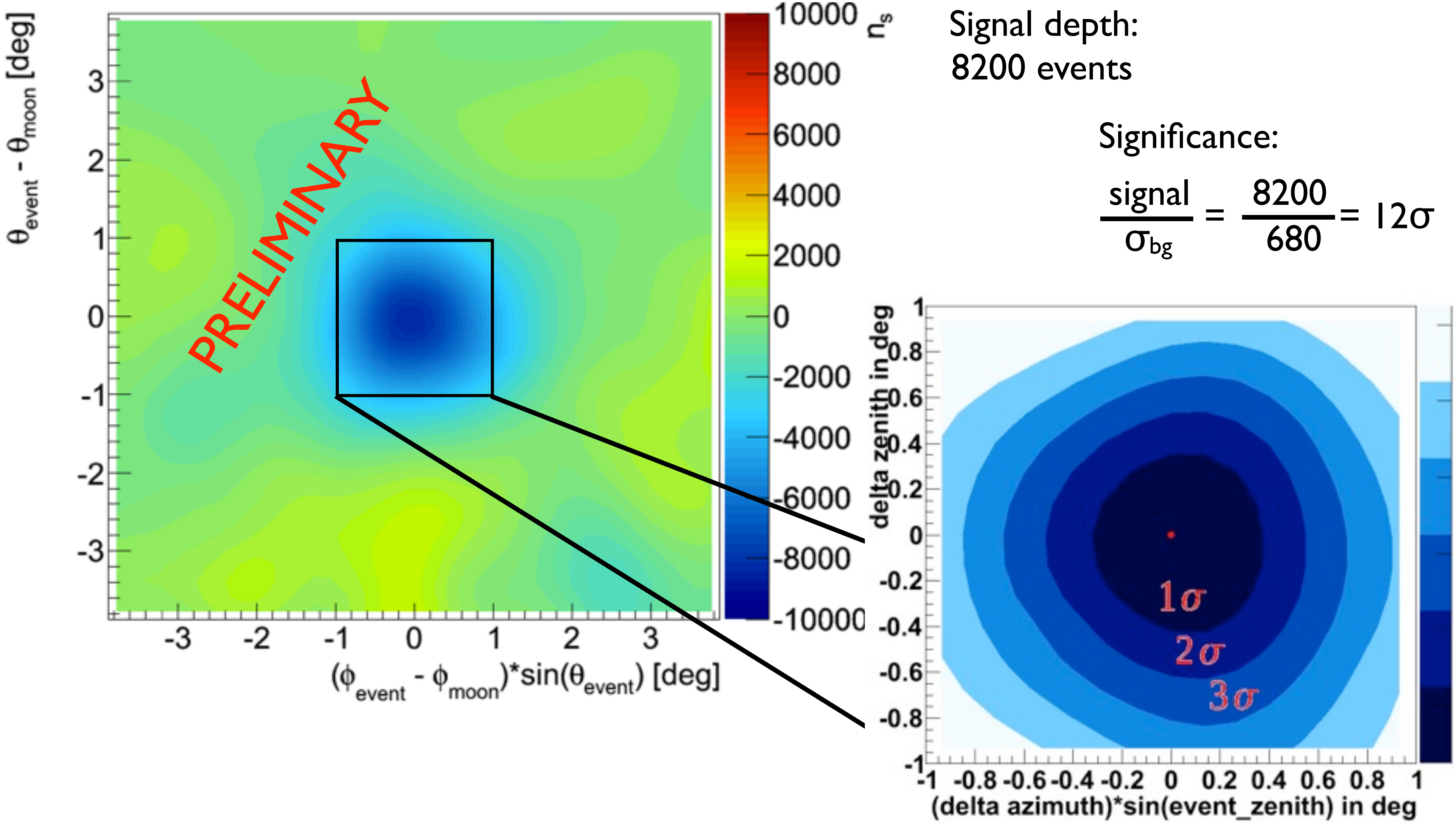


Random fluctuations around background model:

σ_{bg} = 680 events



Likelihood result PRELIMINARY

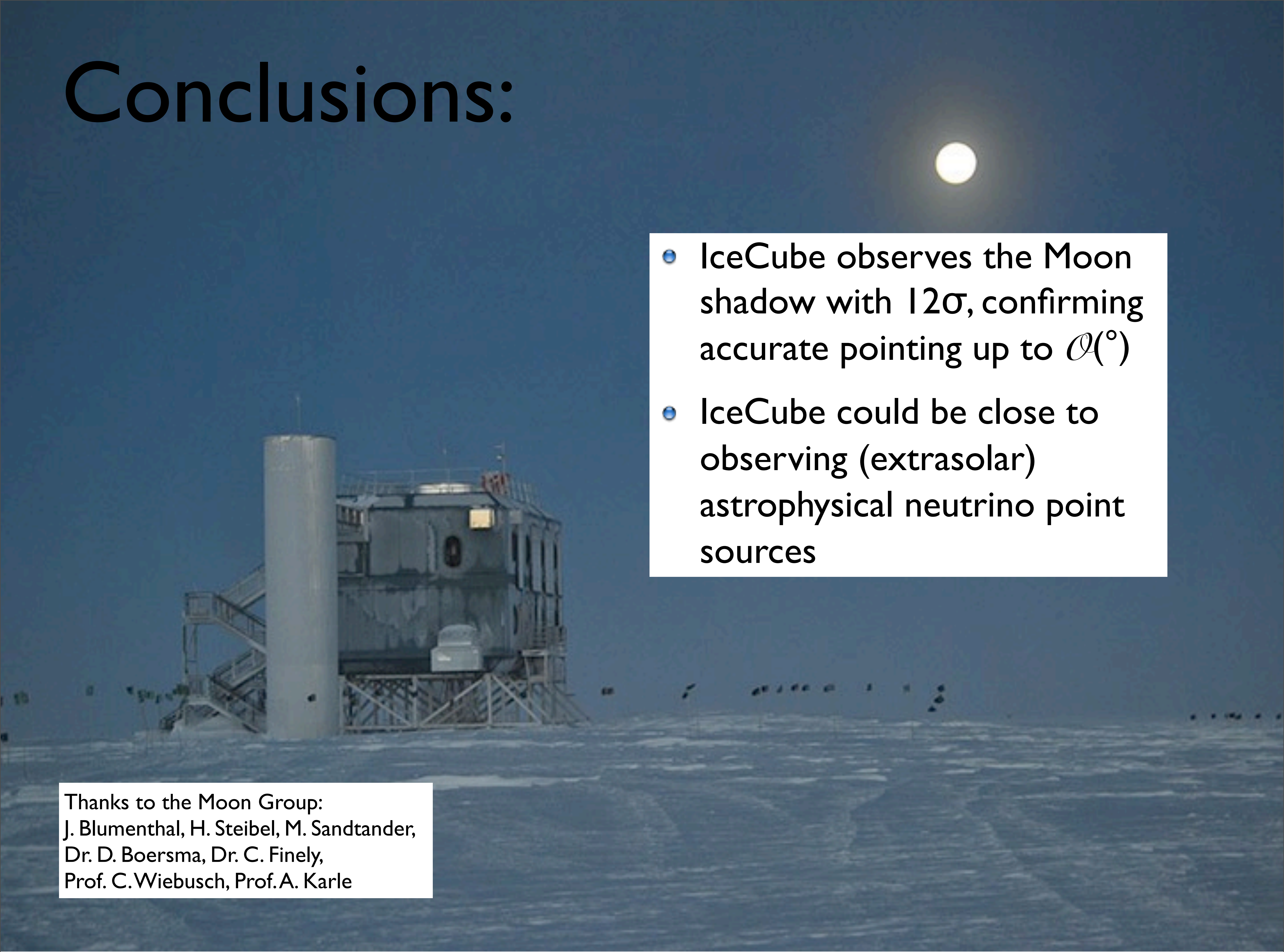


Signal depth:
8200 events

Significance:

$$\frac{\text{signal}}{\sigma_{bg}} = \frac{8200}{680} = 12\sigma$$

Conclusions:



- IceCube observes the Moon shadow with 12σ, confirming accurate pointing up to $\mathcal{O}(^\circ)$
- IceCube could be close to observing (extrasolar) astrophysical neutrino point sources

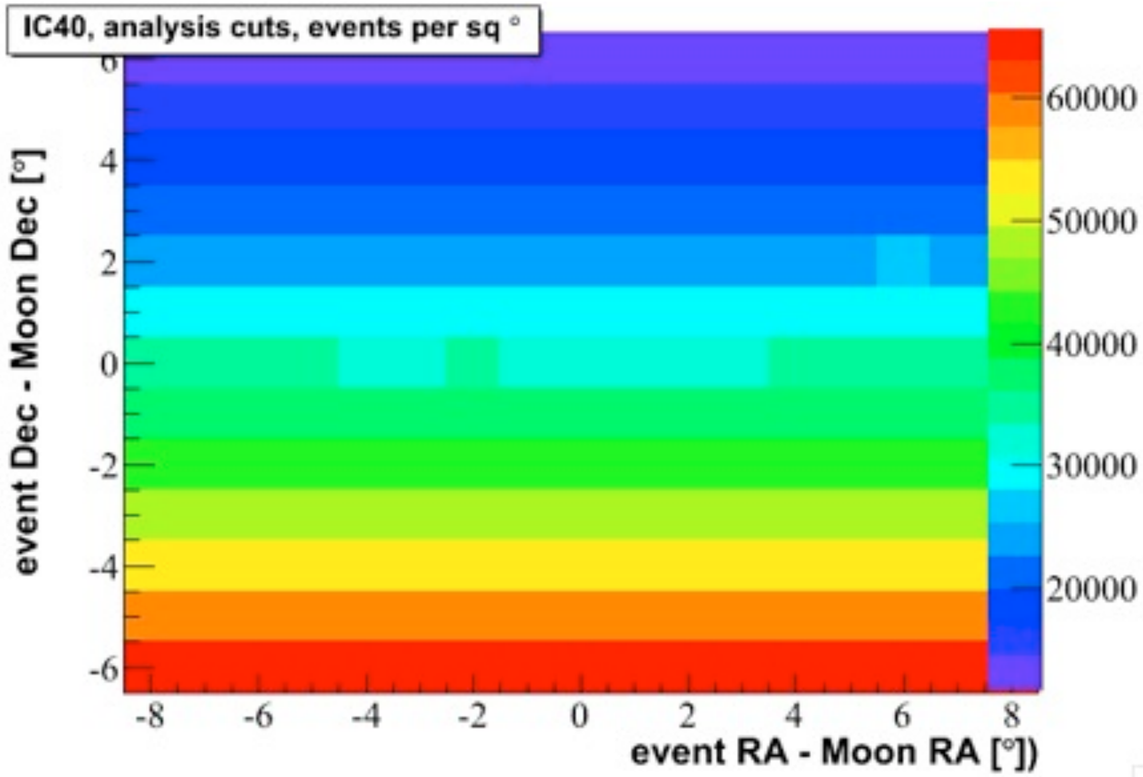
Thanks to the Moon Group:
J. Blumenthal, H. Steibel, M. Sandtander,
Dr. D. Boersma, Dr. C. Finely,
Prof. C. Wiebusch, Prof. A. Karle

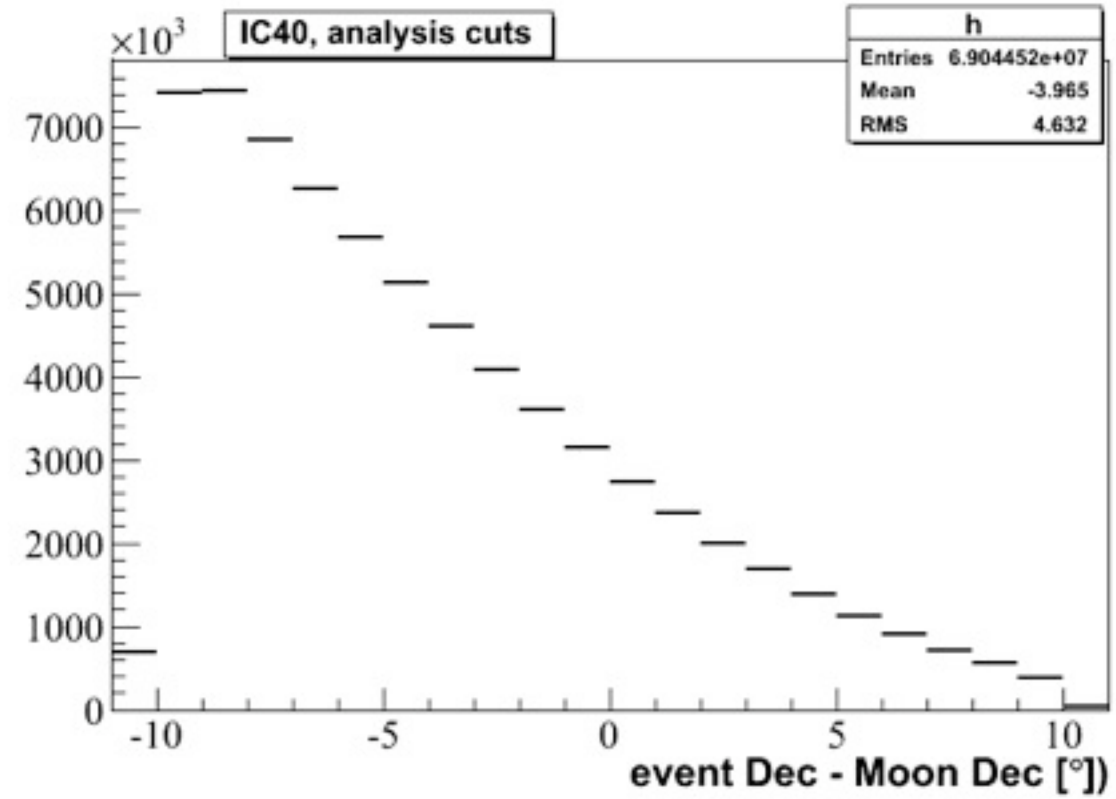
Backup:

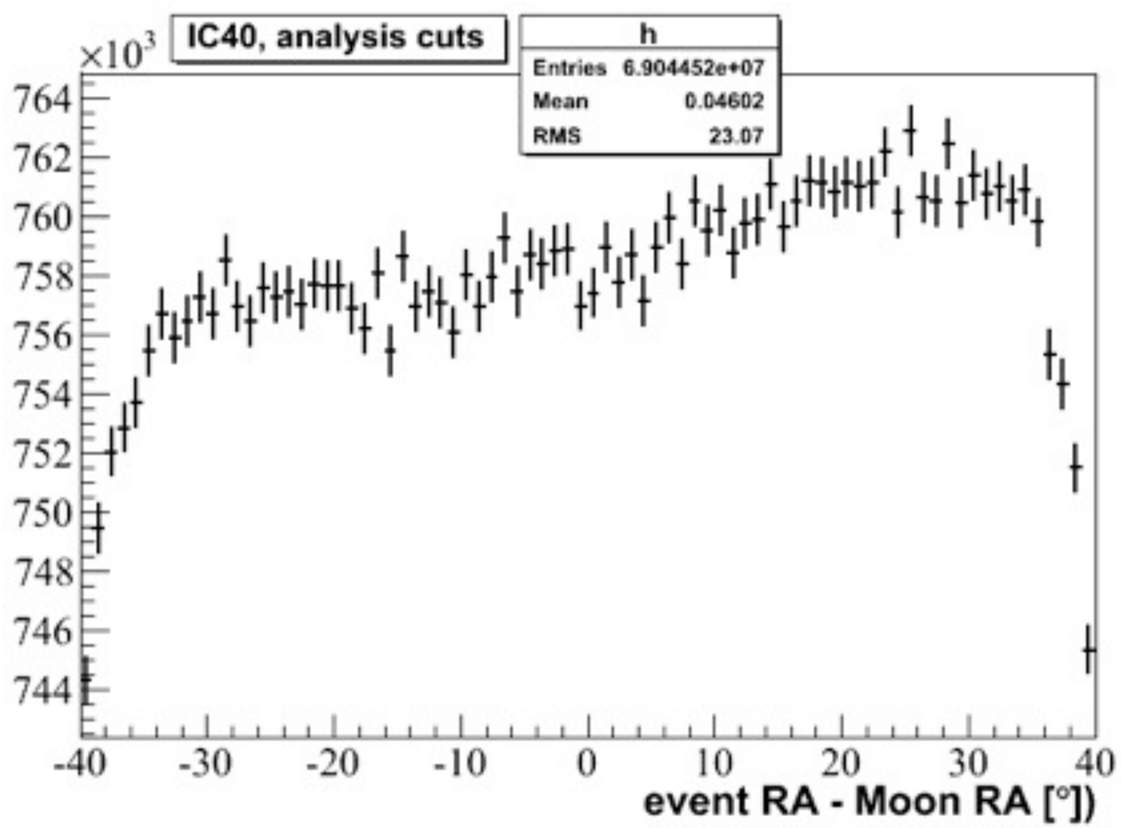
- Binned Search, as applied to IC40
- Unbinned Search as applied to IC40

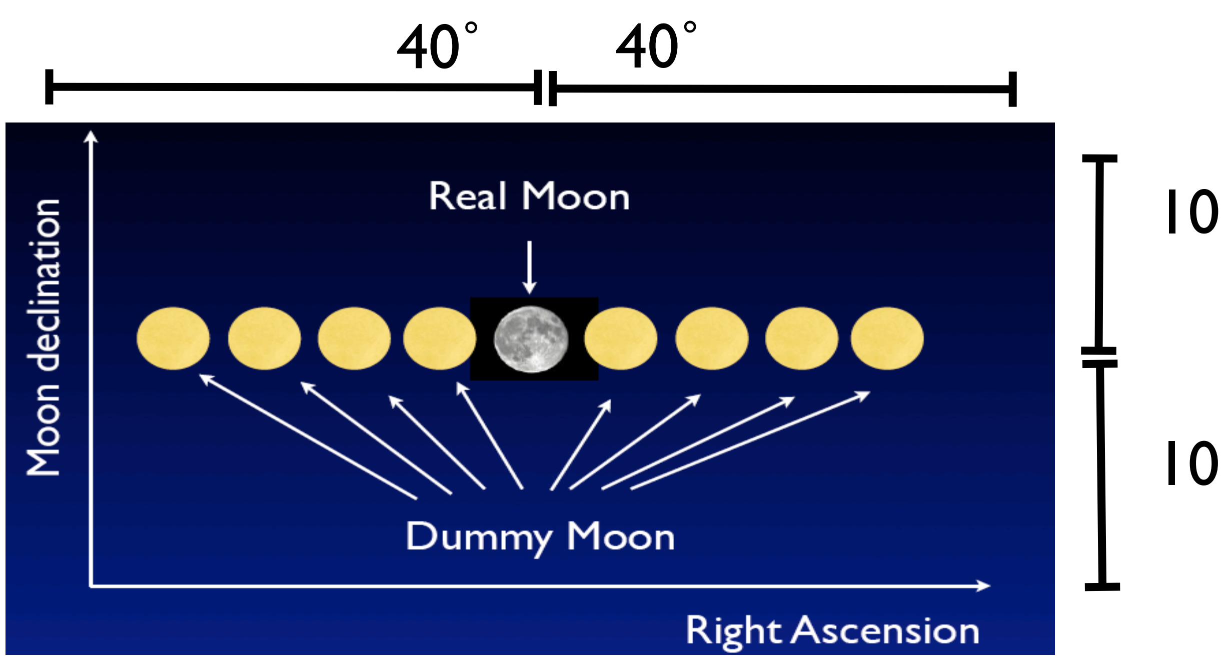
yes, I have been to the South Pole.

IC40 Data set







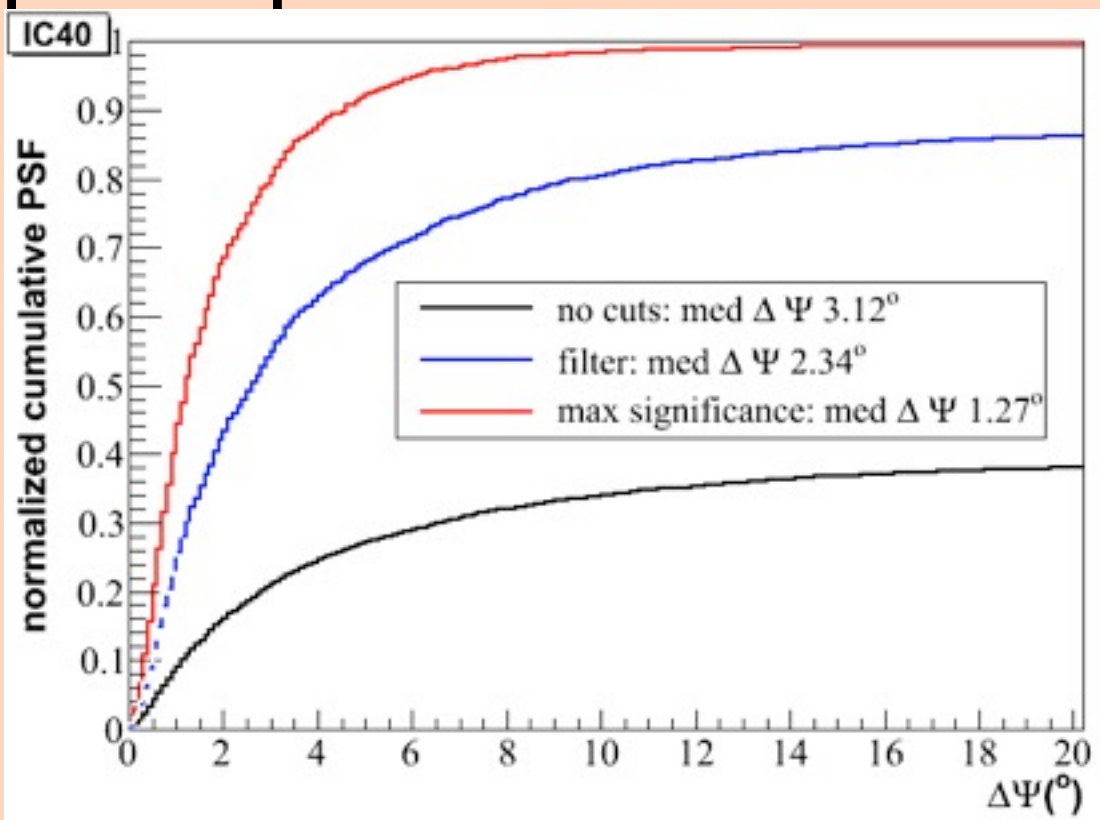


IC40 Binned Search Cuts

- Filter-level cuts:
  - (number of hit DOMs) $\equiv$ NCh $\geq$ 12
  - (number of hit strings) $\geq$ 3
- Analysis-level cuts:
  - estimated angular $\boxed{\text{error of reconstruction} \leq 1.6^{\circ}}$
- Resulting sample:
  - 69M events, 53% efficiency from filter
  - median angular resolution: 1.27°
- $\boxed{\text{Search Bin Size: } 0.8^{\circ}}$

Search bin size optimization

Signal: use simulated point spread function

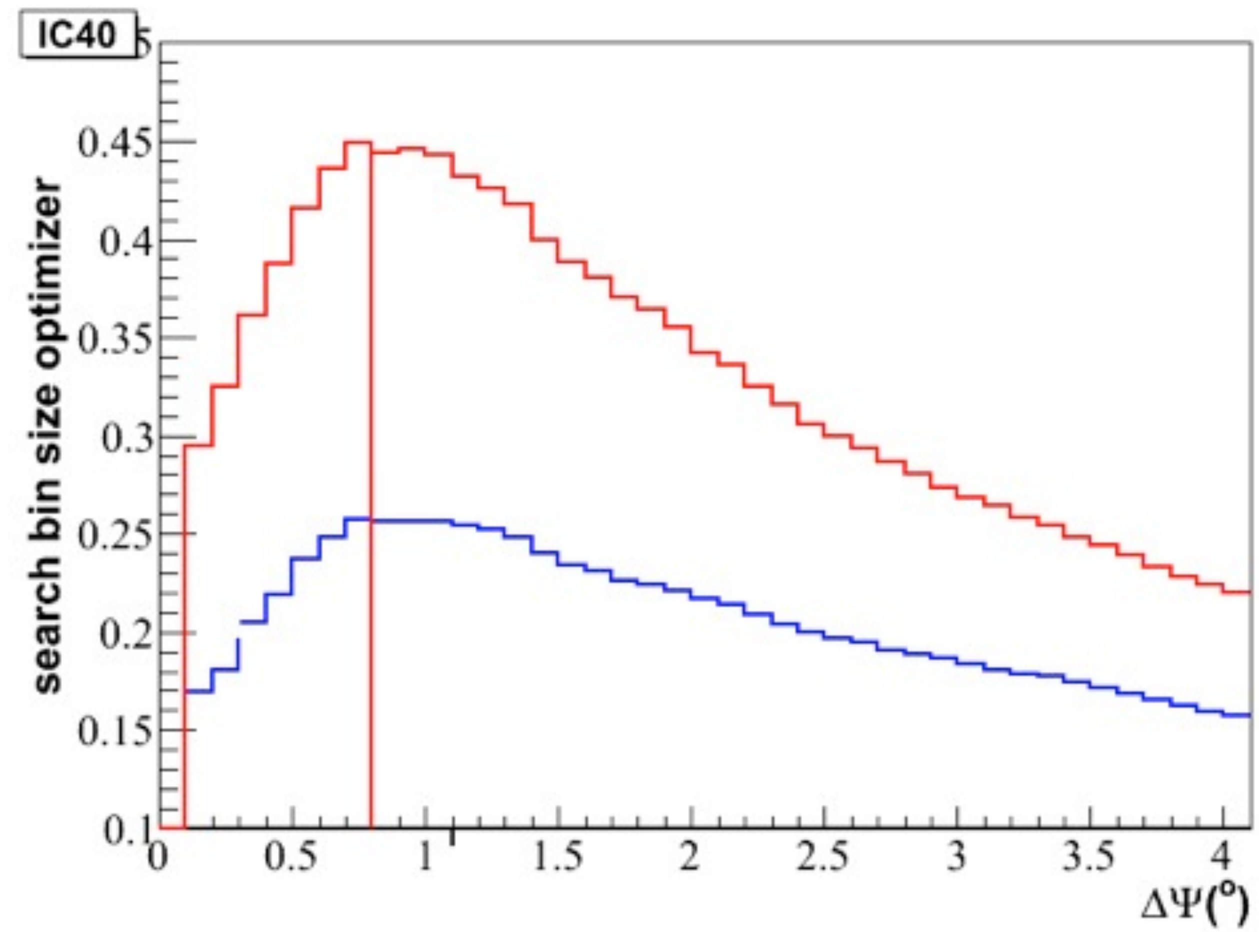


Background: scales with area

$N_{bkgd} \propto \mathrm{Area} \propto \pi r^2$

$\sqrt{N_{bkgd}} \propto r$

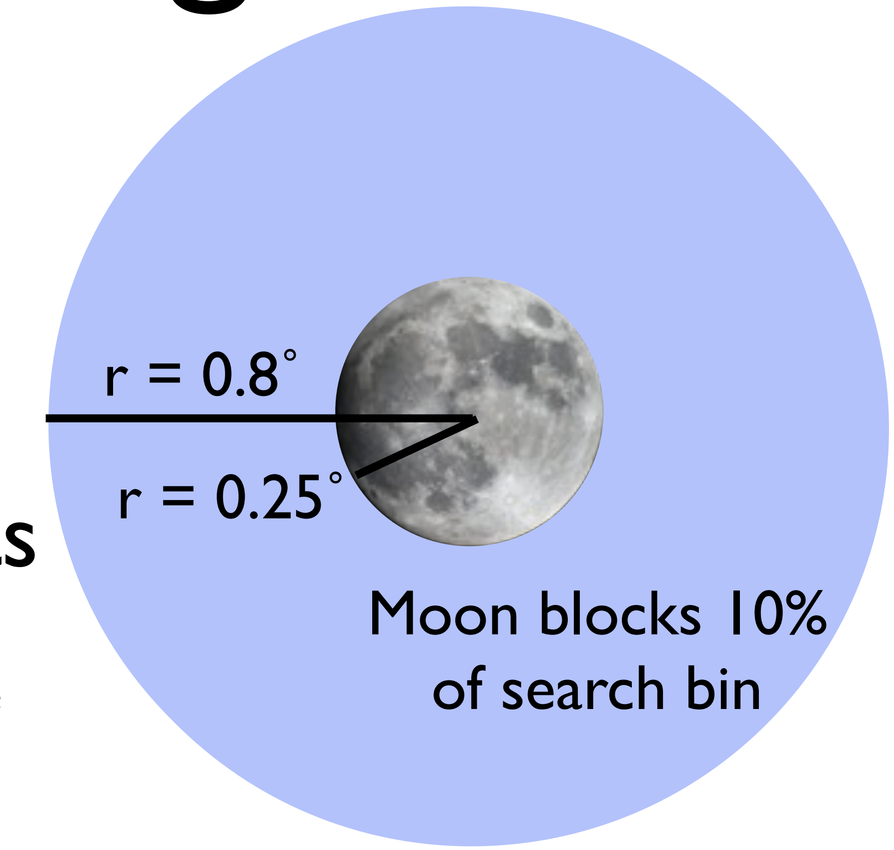
significance ~ $\frac{N_{sig}}{\sqrt{N_{bkgd}}}$



Expect best result with search bin of 0.8°

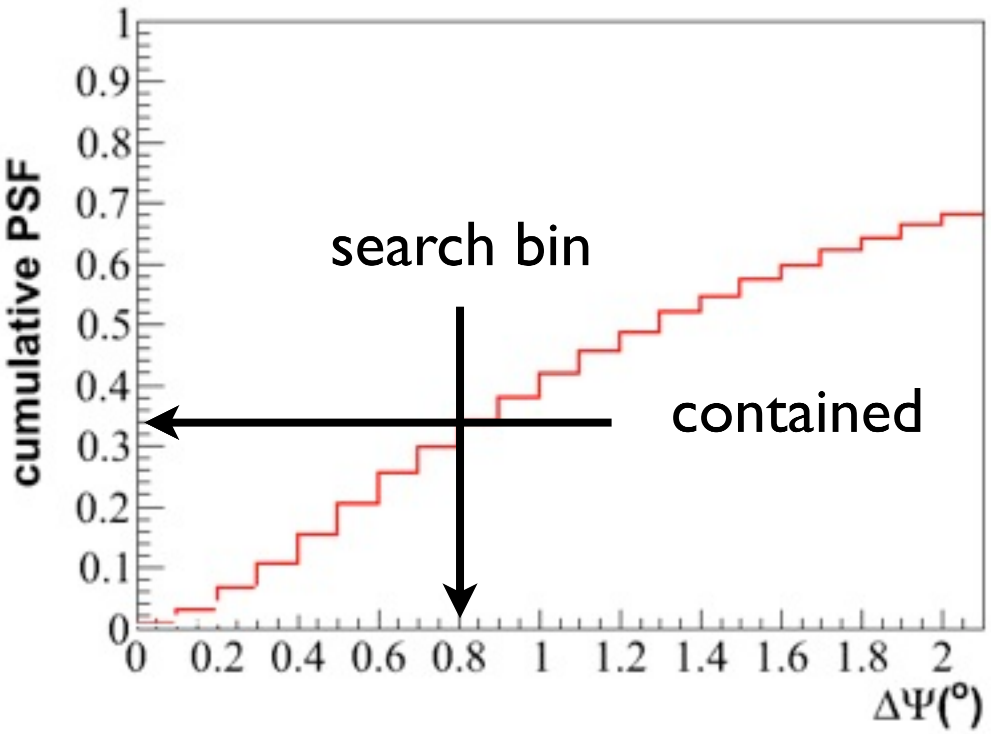
Back-of-the-Envelope Significance

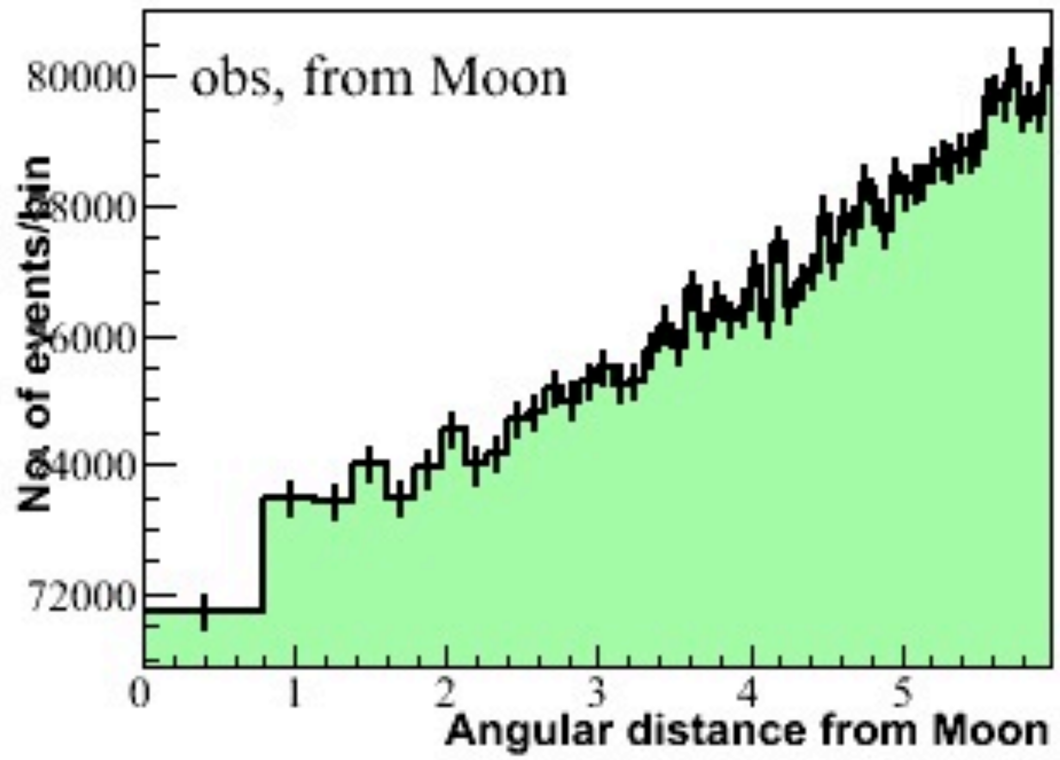
- Observe rate: 35k events/ sq°
  - 70.4k in each background bin
  - 7k events blocked by Moon
- Search bin contains 35% blocked events

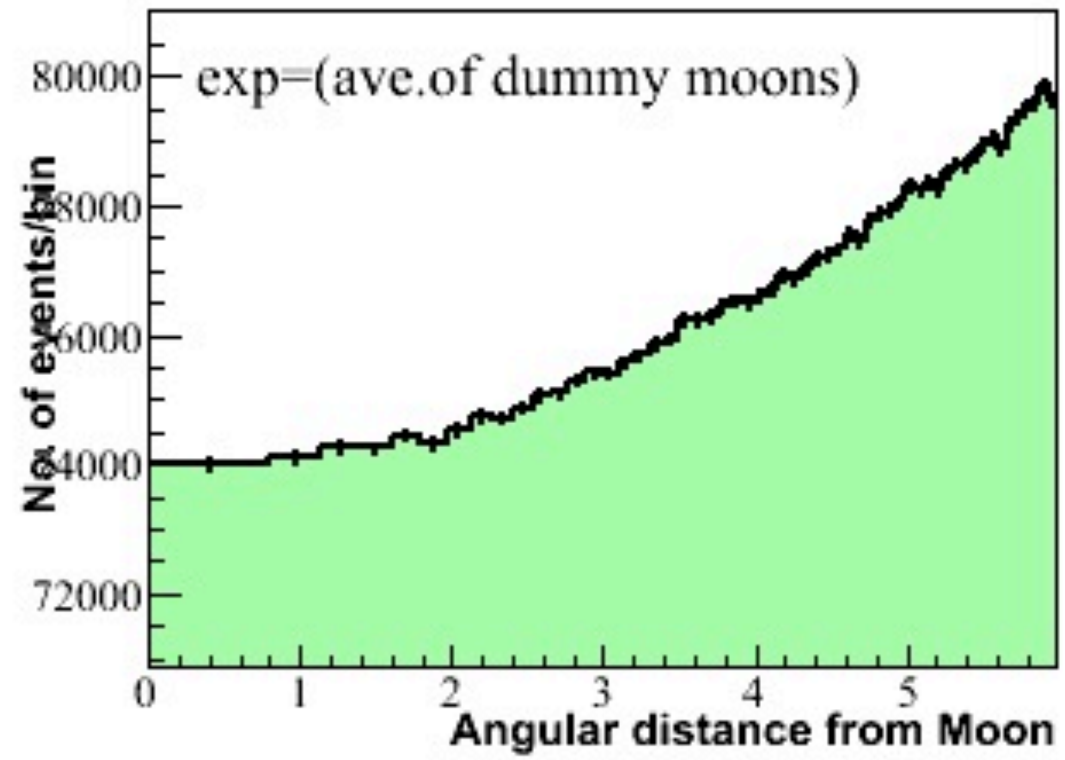


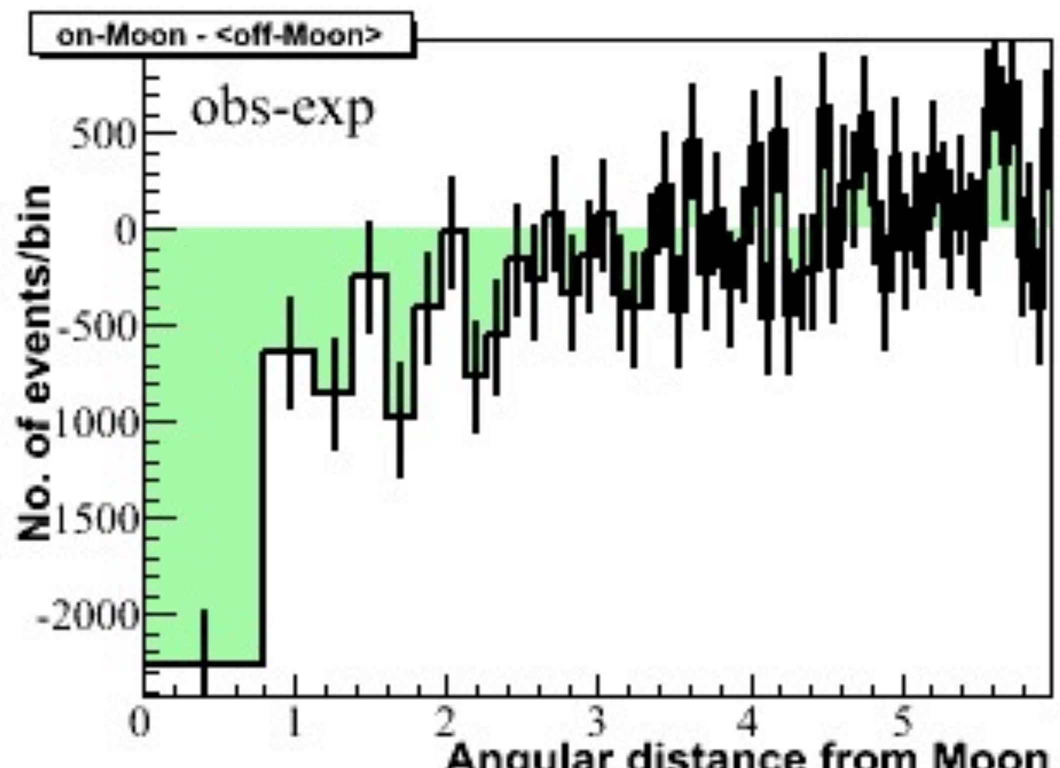
$$S = \sqrt{2}\left\{N_{\mathrm{on}}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\mathrm{on}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right] + N_{\mathrm{off}}\ln\left[(1+\alpha)\left(\frac{N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]\right\}^{1/2}$$

Expect 2500 event deficit:
8.9σ









observed: 7.173e+04 events

expected: 7.4e+04 events

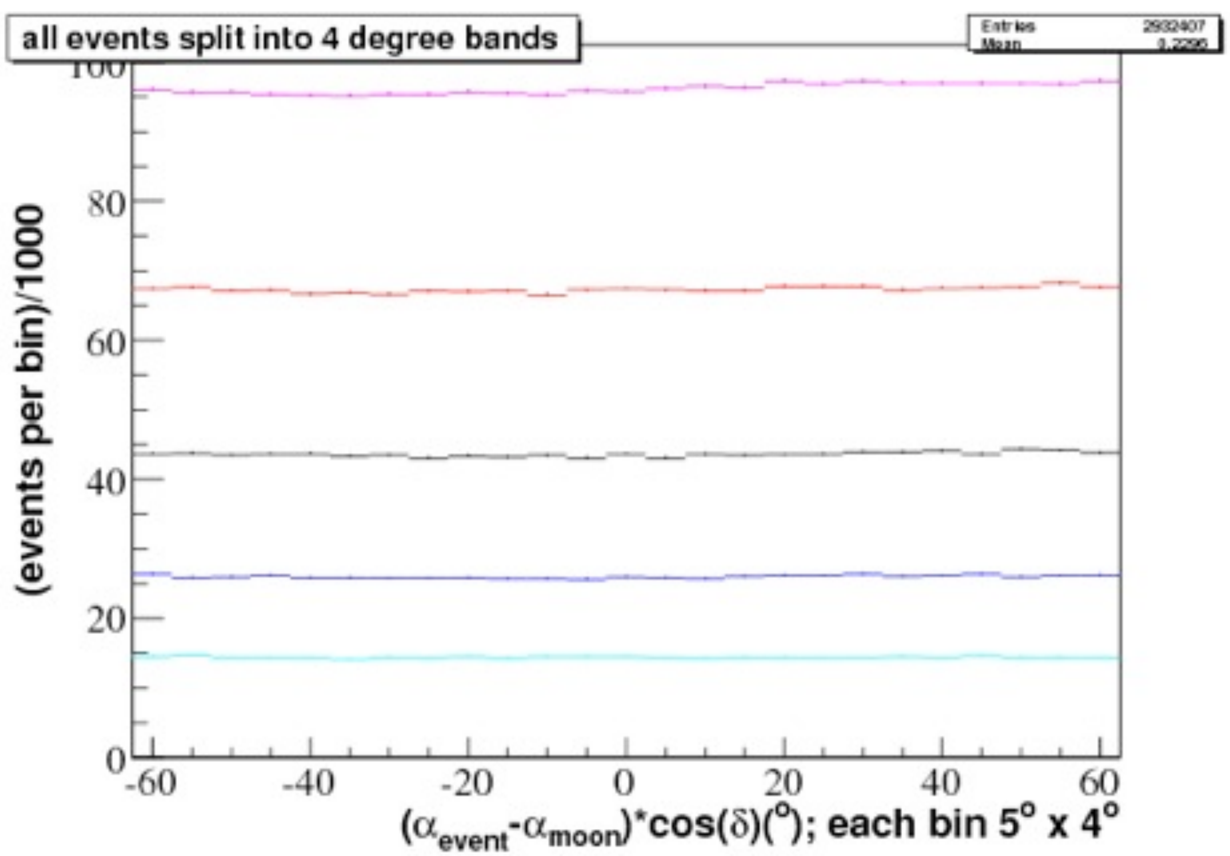
deficit: -2262 events

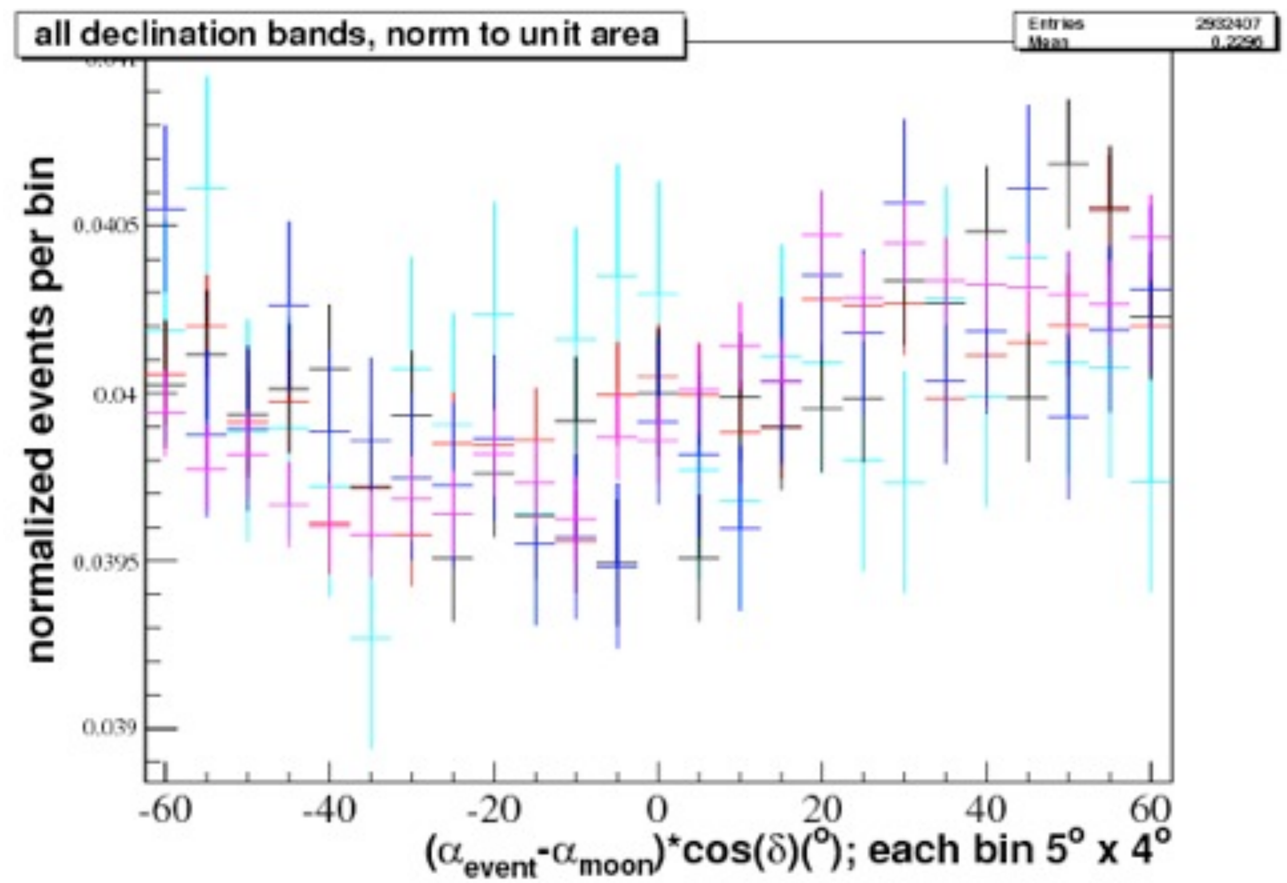
error: 285 events

significance: -7.9σ

Alternate Binned Method

- Consider several declination bands:
- Use off-Moon bands to correct Moon band RA structure
- This was tried on IC22

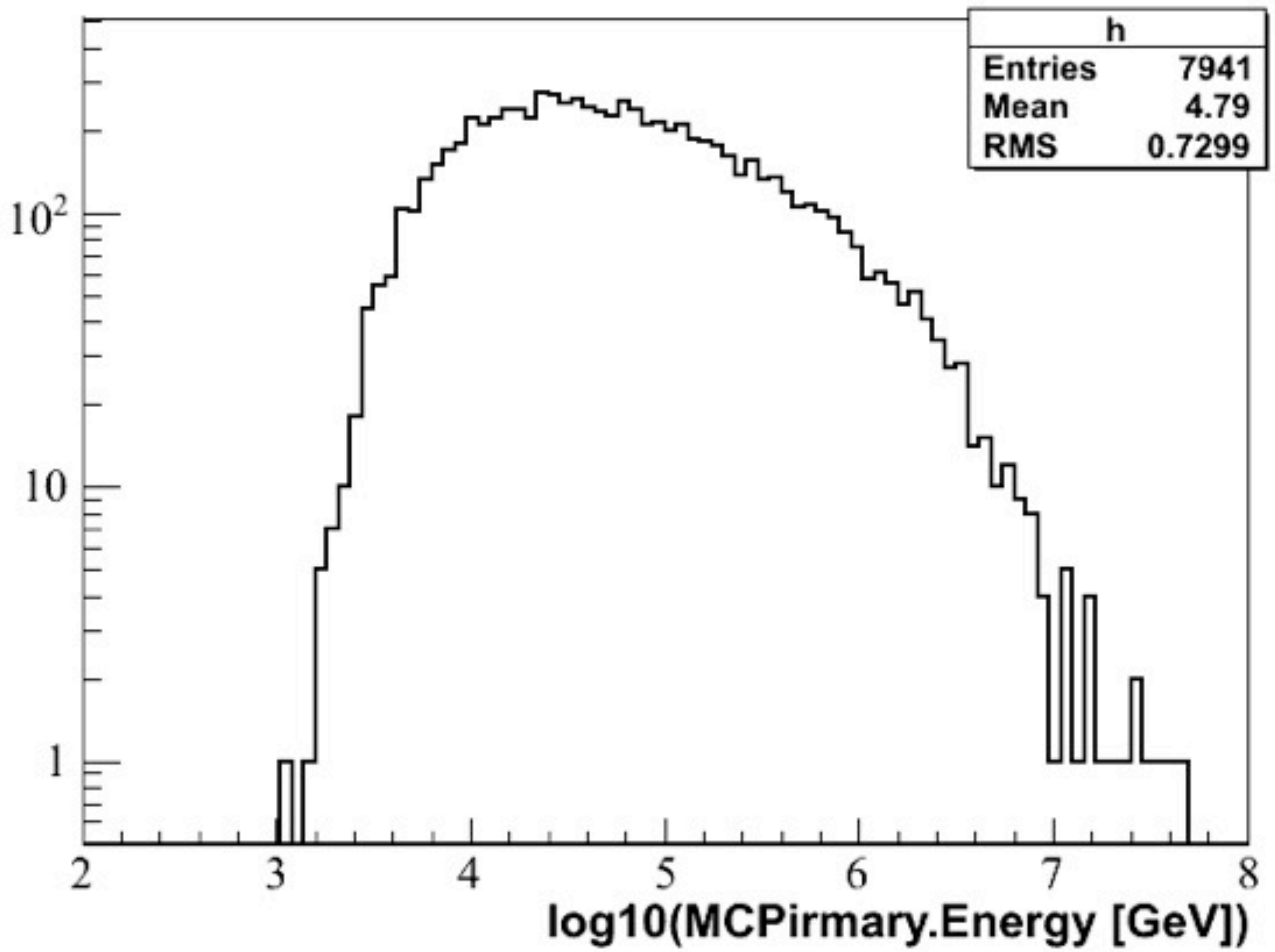


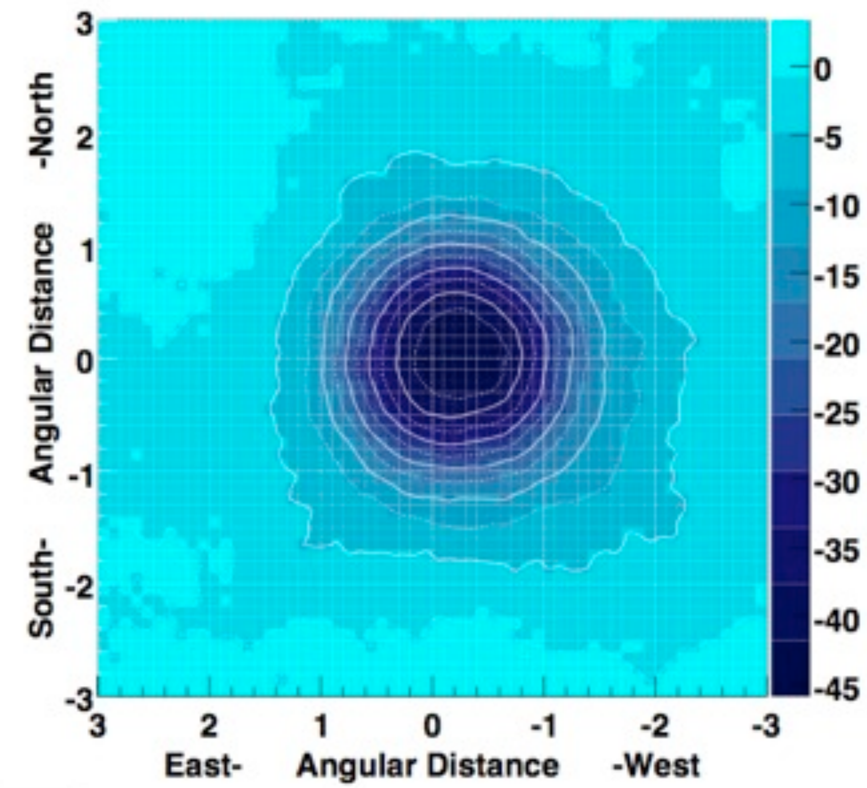


It didn't work well enough with IC22,
and with IC40 a simpler binned analysis was good enough

Does Geomagnetic field matter?

- filter level cuts, zenith > 50°





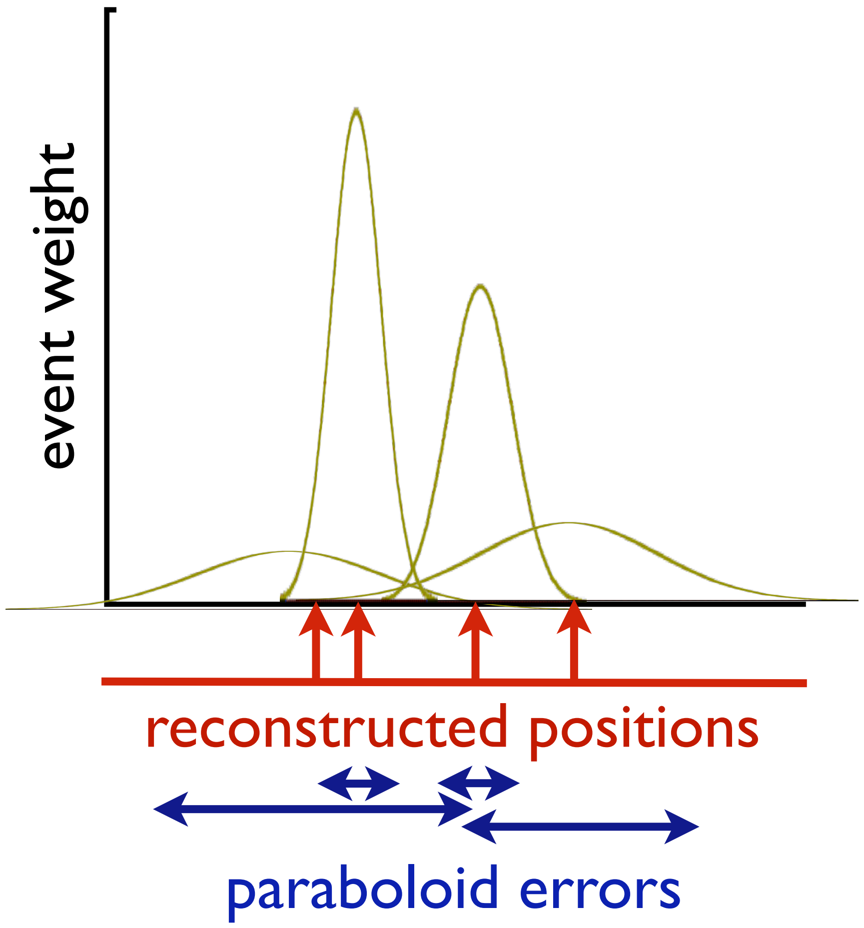
Shift from magnetic fields is negligible
Tibet Air Shower Array
arXiv:0810.3757v1 [astro-ph]
1-40 TeV

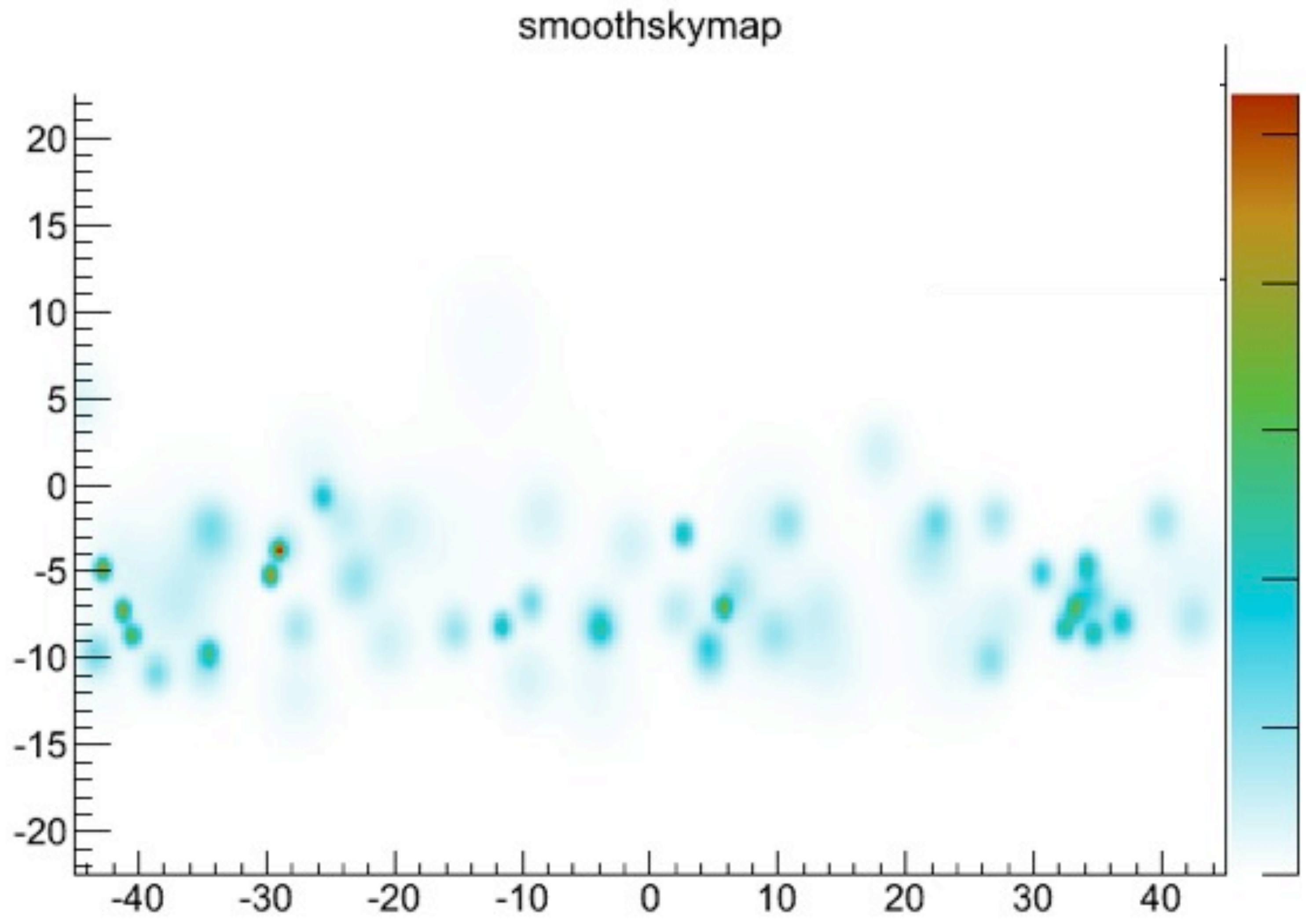
→shift is also negligible in this analysis

Approach II: Unbinned skymap

Smear each event by its paraboloid error

Map the total weighted event sum





Unbinned Skymap

- Healpix: program for skymaps-- uses equal-area bins
  - Box-shape is from filter window
  - Gradient from zenith dependence of CR flux
- Draw Moon centered at its average position