Identifying the Sources of Cosmic Rays with AMANDA and IceCube

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University of Wisconsin - Madison

Overview

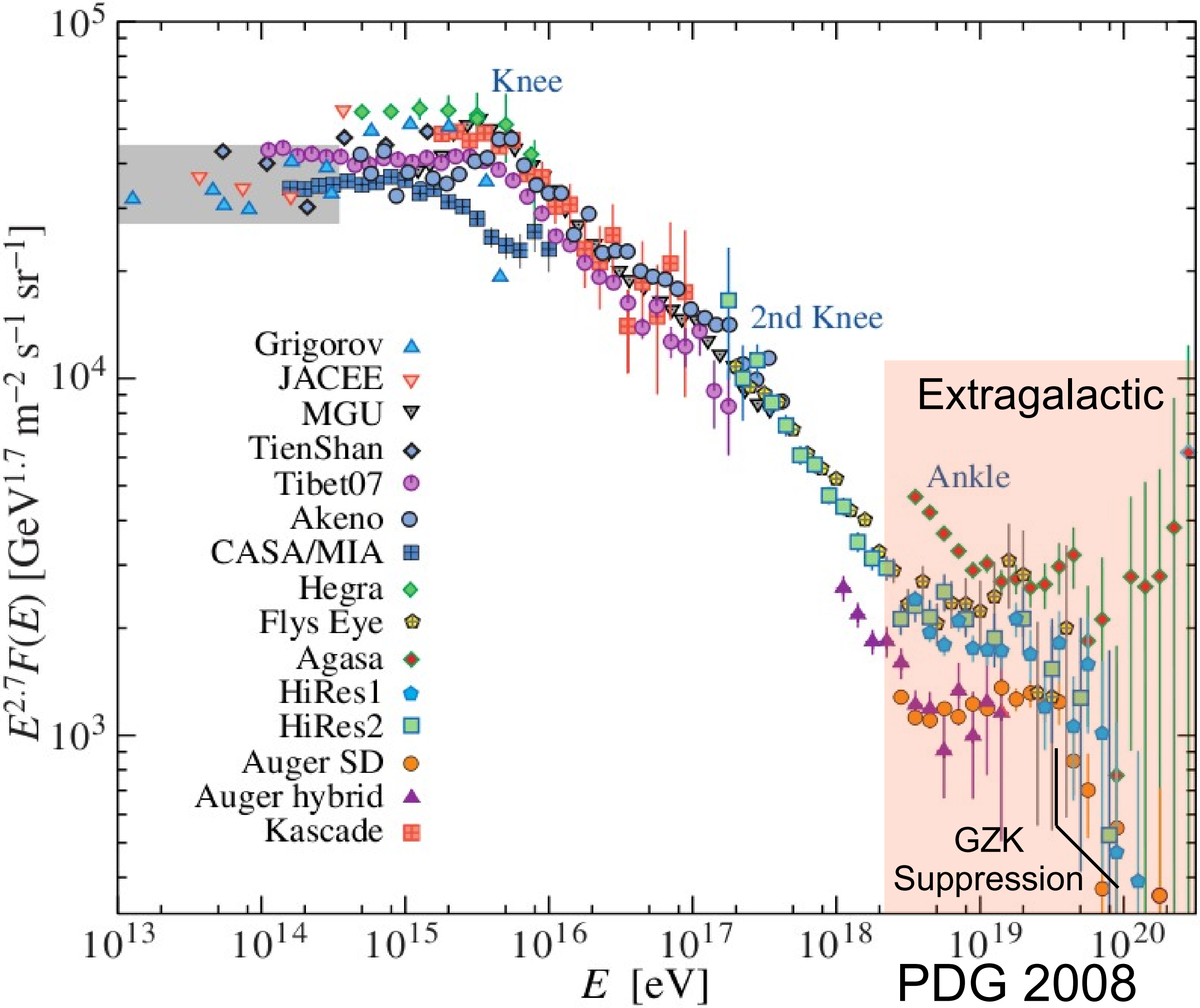
Neutrino astronomy will improve our understanding of high energy processes in the universe

The IceCube Neutrino Observatory is half complete and improves with each construction season

New search methods are improving sensitivity

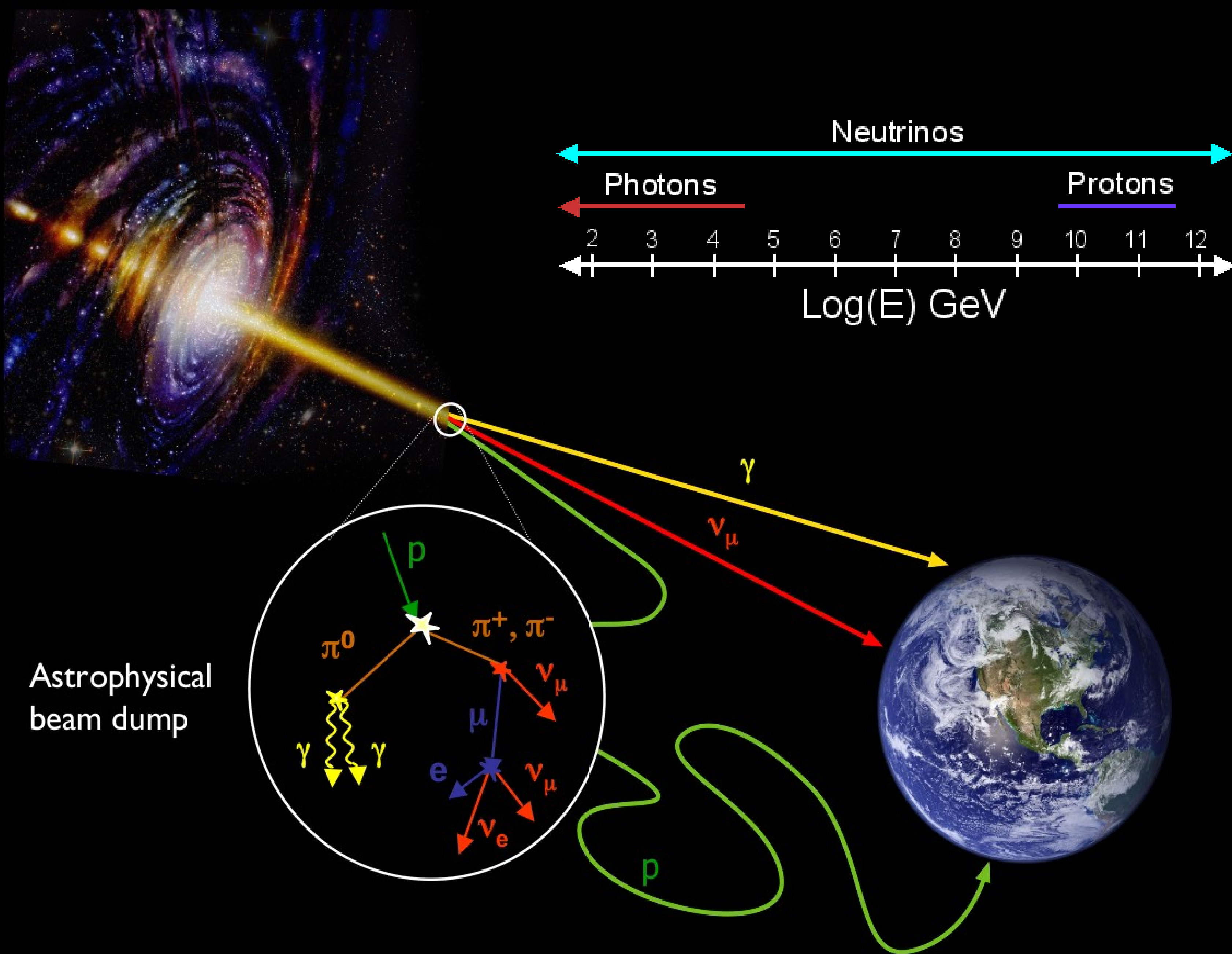
Recent results are encouraging

Cosmic Rays

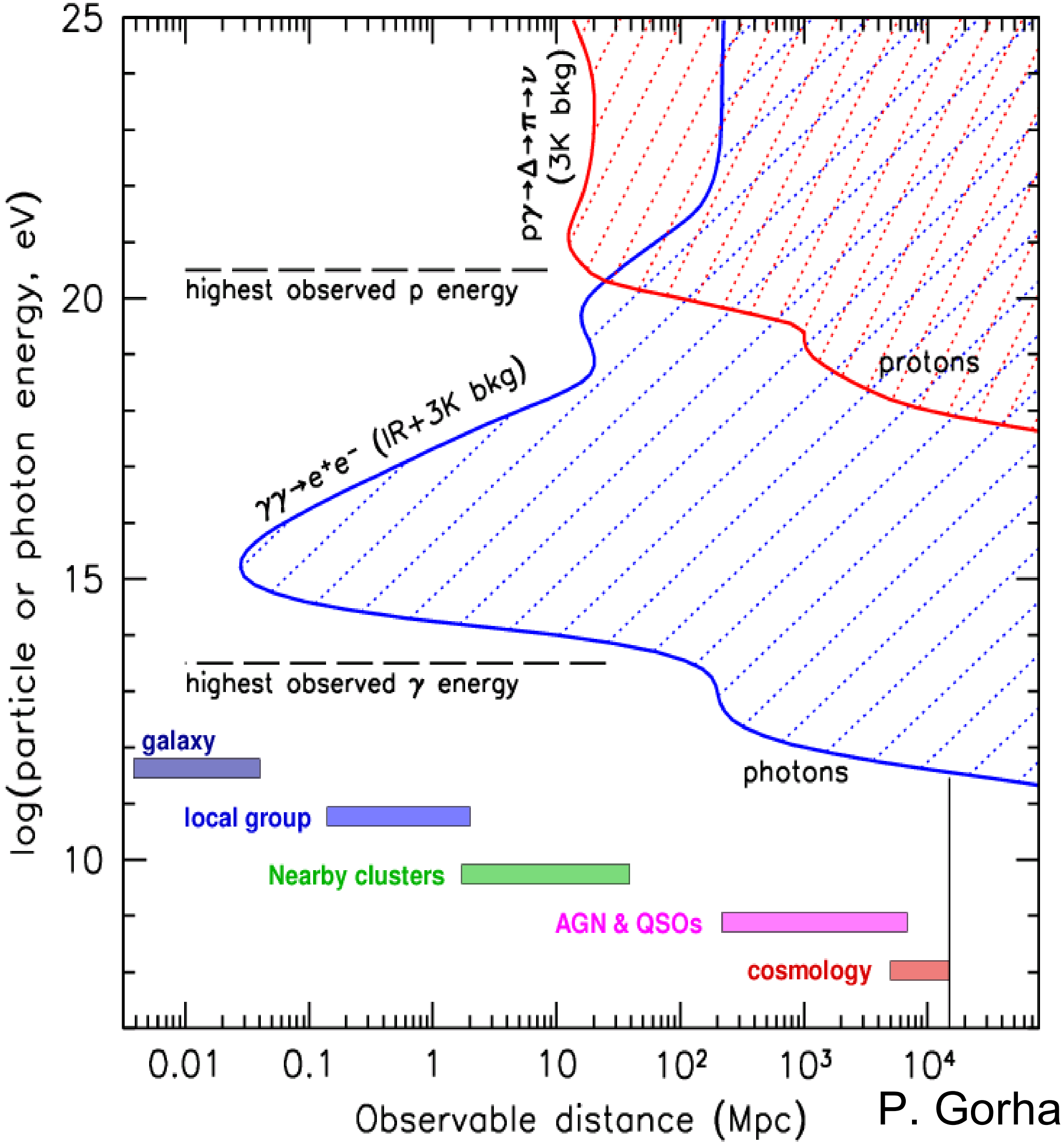


PDG 2008

Astronomical Messengers



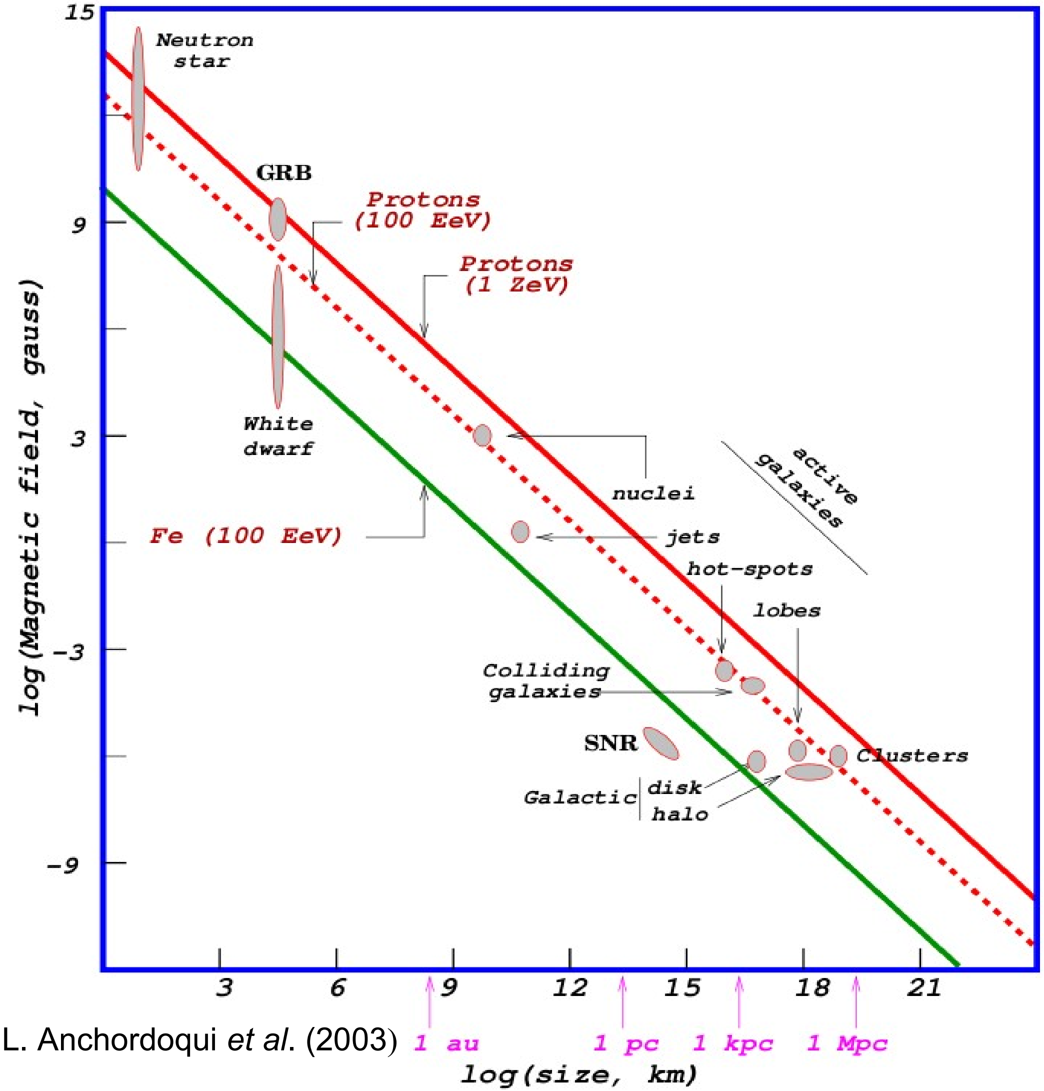
Astronomical Messengers



P. Gorham

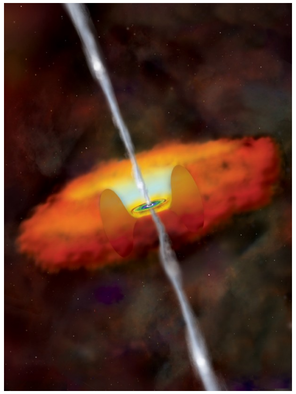
Cosmic Ray Accelerators

Fermi shock acceleration with spectral index Γ ~-2

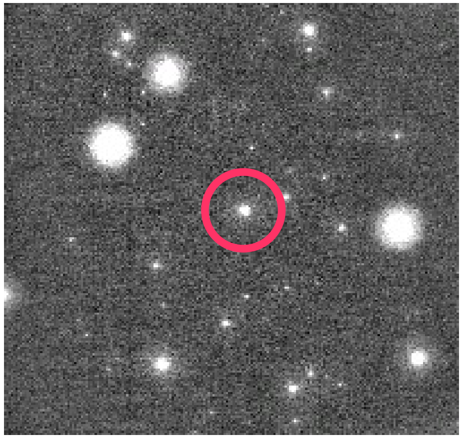


L. Anchordoqui *et al*. (2003)

SN Remnants



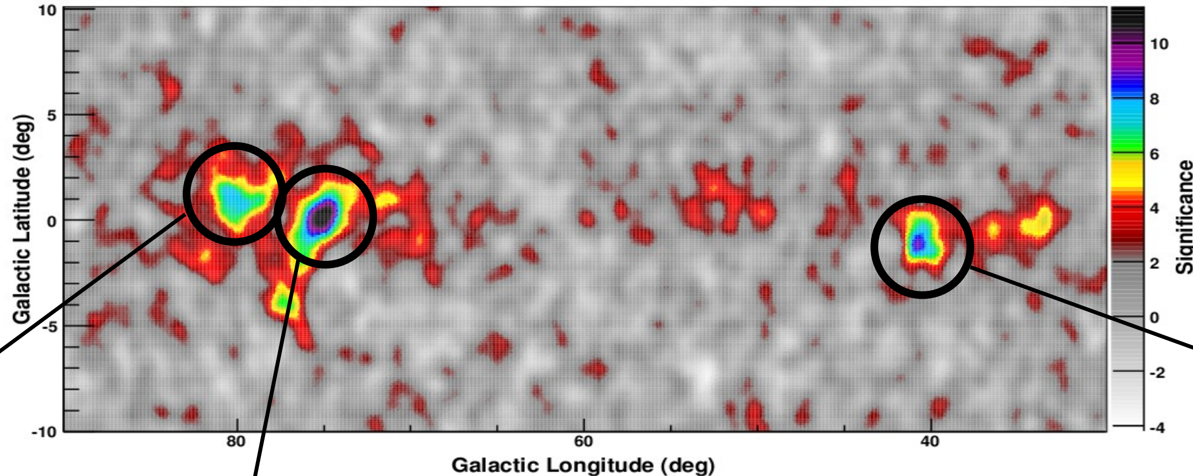
AGN



GRB 080319b

Galactic Sources

A. Abdo, Ph.D thesis, MSU (2007)

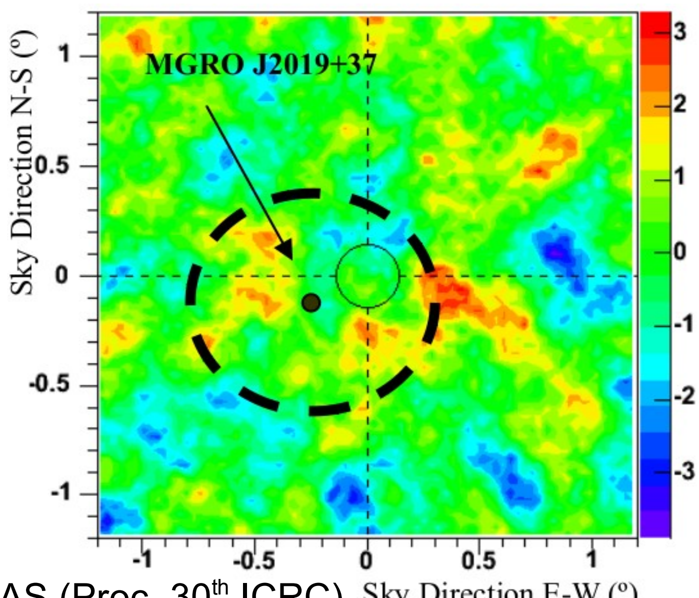


MGRO J2031+41 Γ ~-2

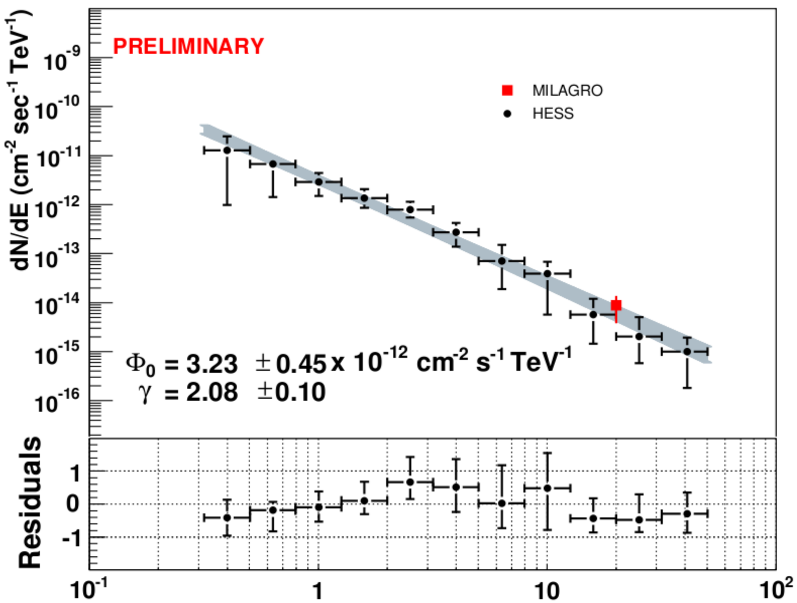
MAGIC arXiv:0801.2391v2

MGRO J1908+06 Γ ~-2

MGRO J2019+37 Γ > -2.2



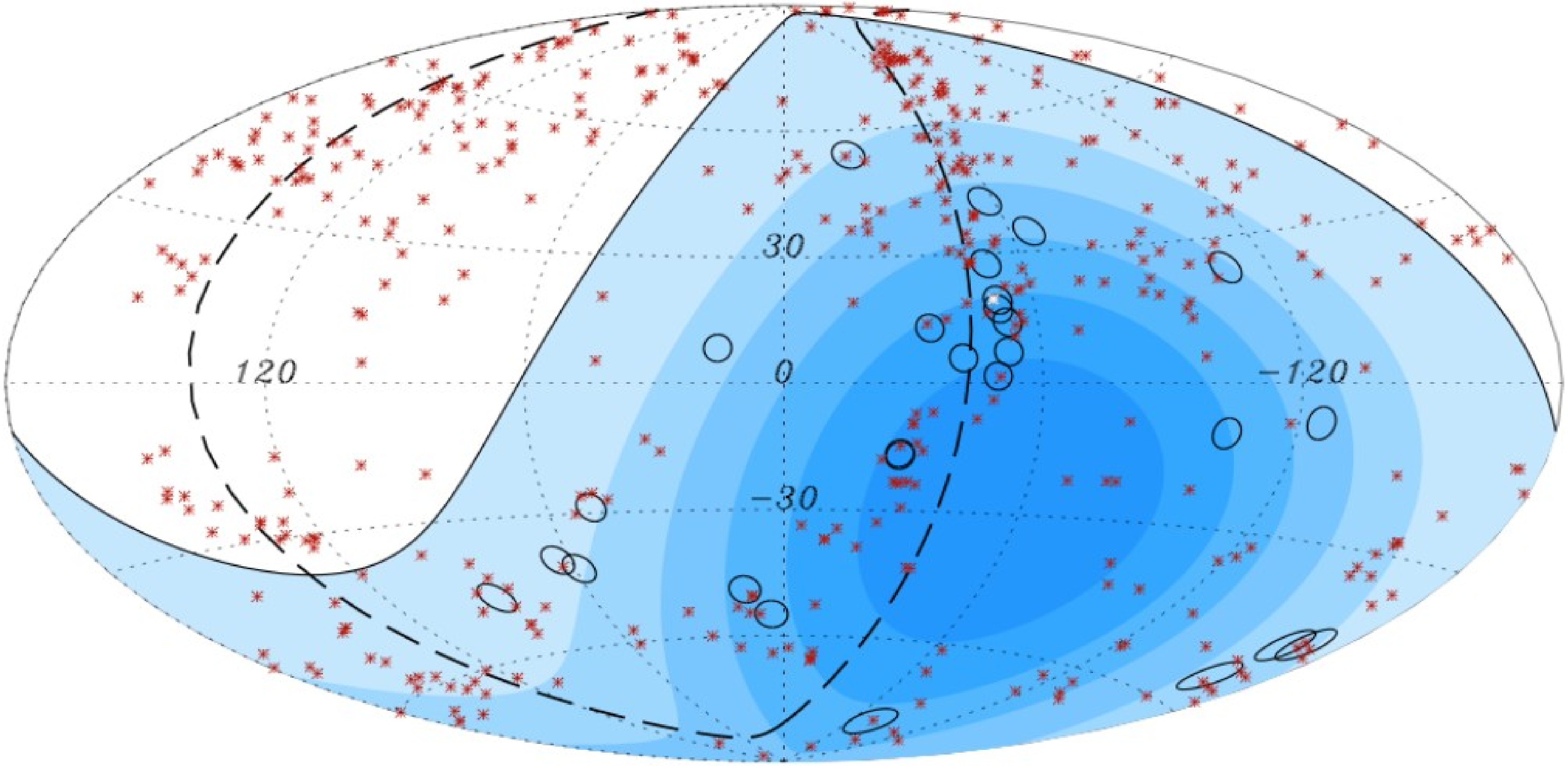
VERITAS (Proc. 30[th] ICRC)



HESS (Proc. 30[th] ICRC)

Extragalactic Sources

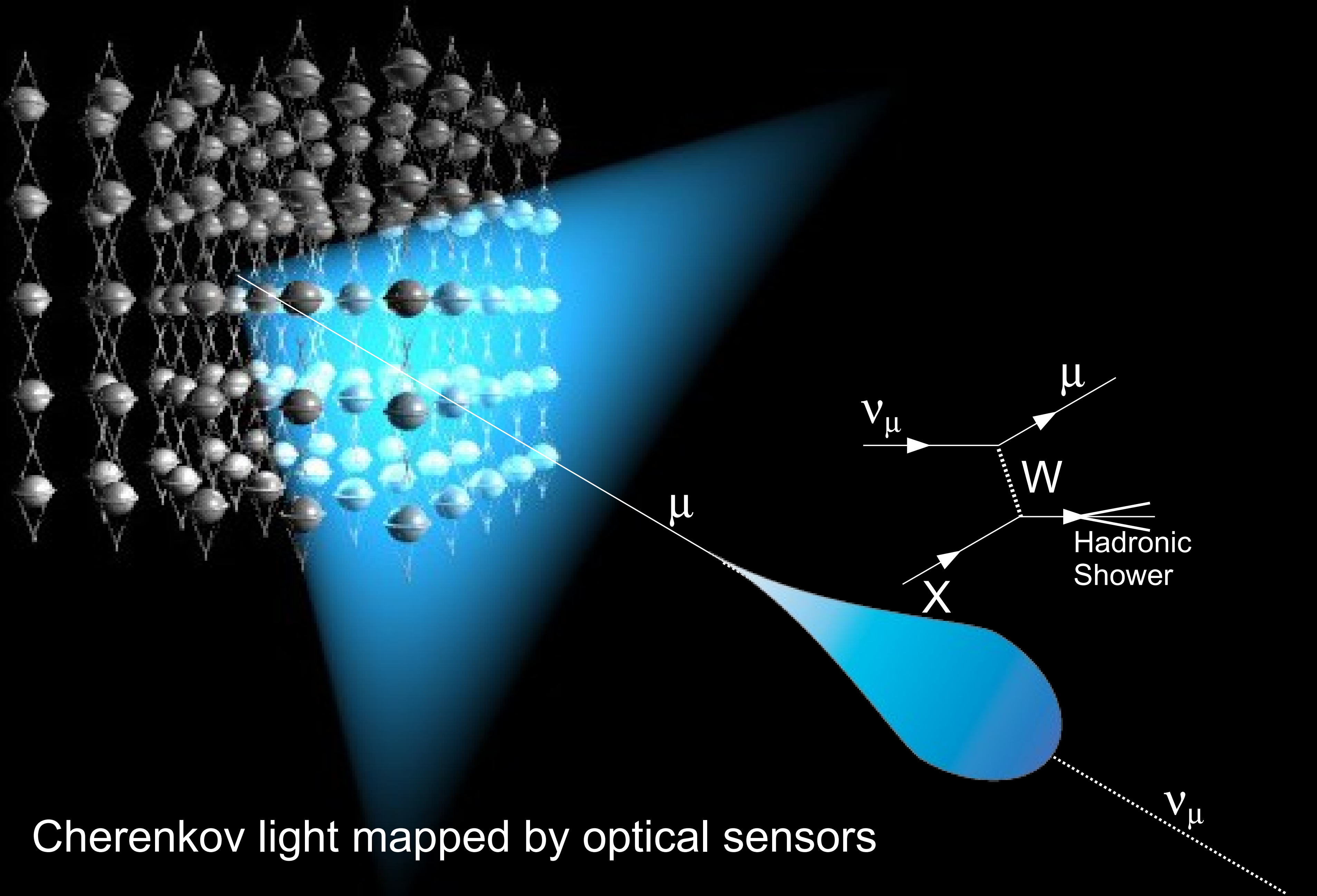
Correlations of Auger EHE events with nearby AGN and the supergalactic plane



J. Abraham *et al.*, Science 318, 938 (2007)

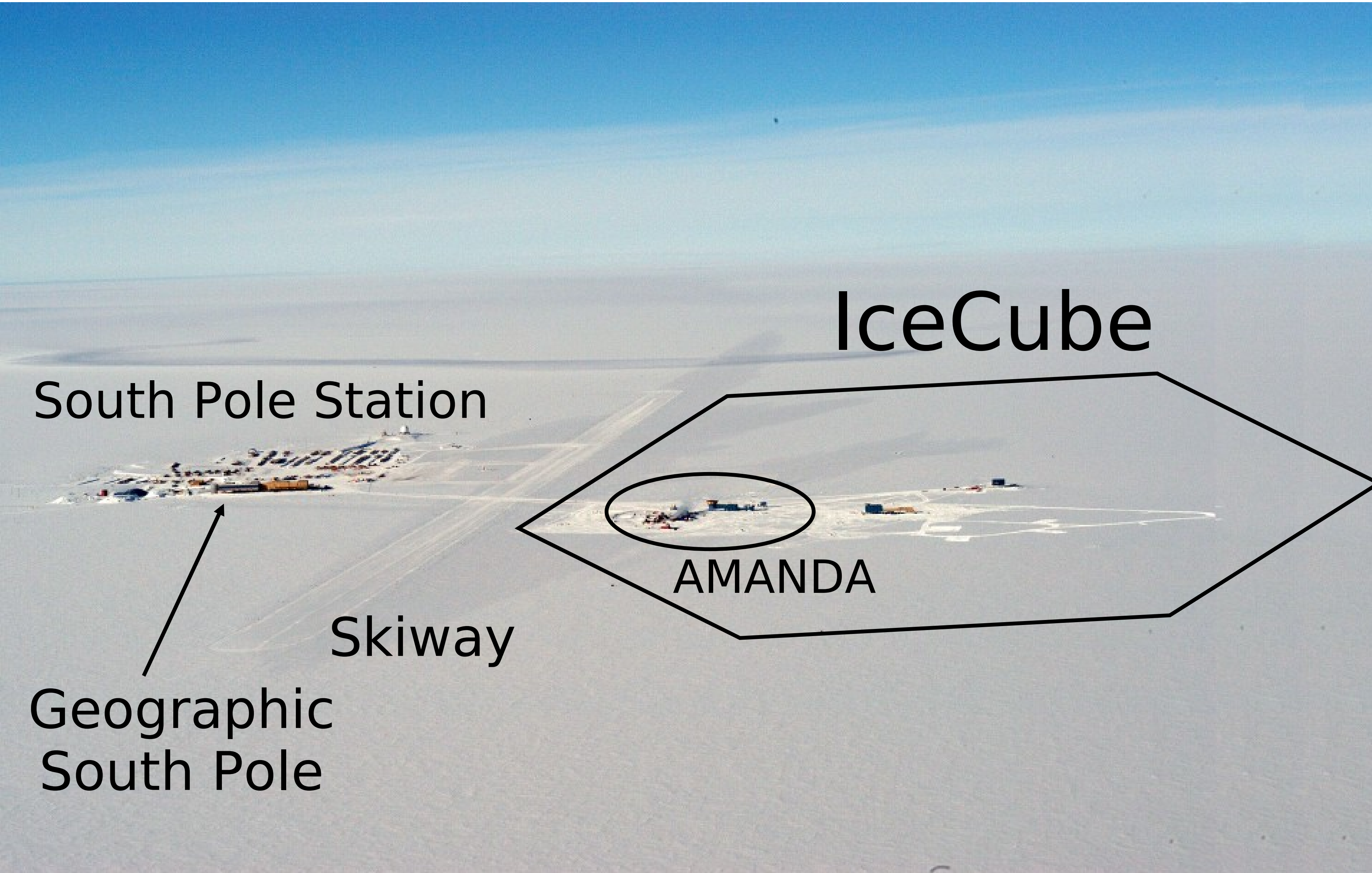
NO SMOKING GUN!

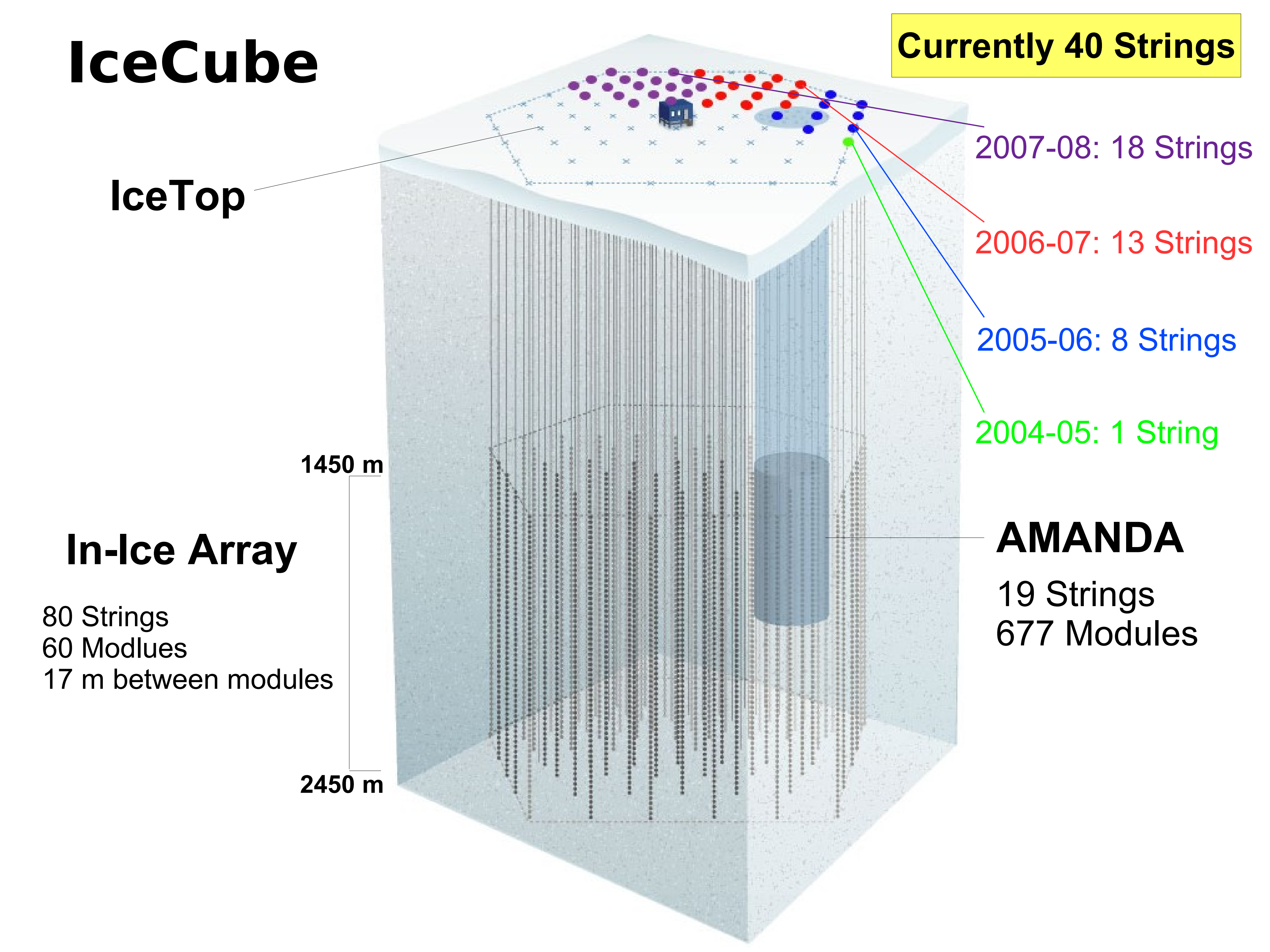
Optical Cherenkov Detection

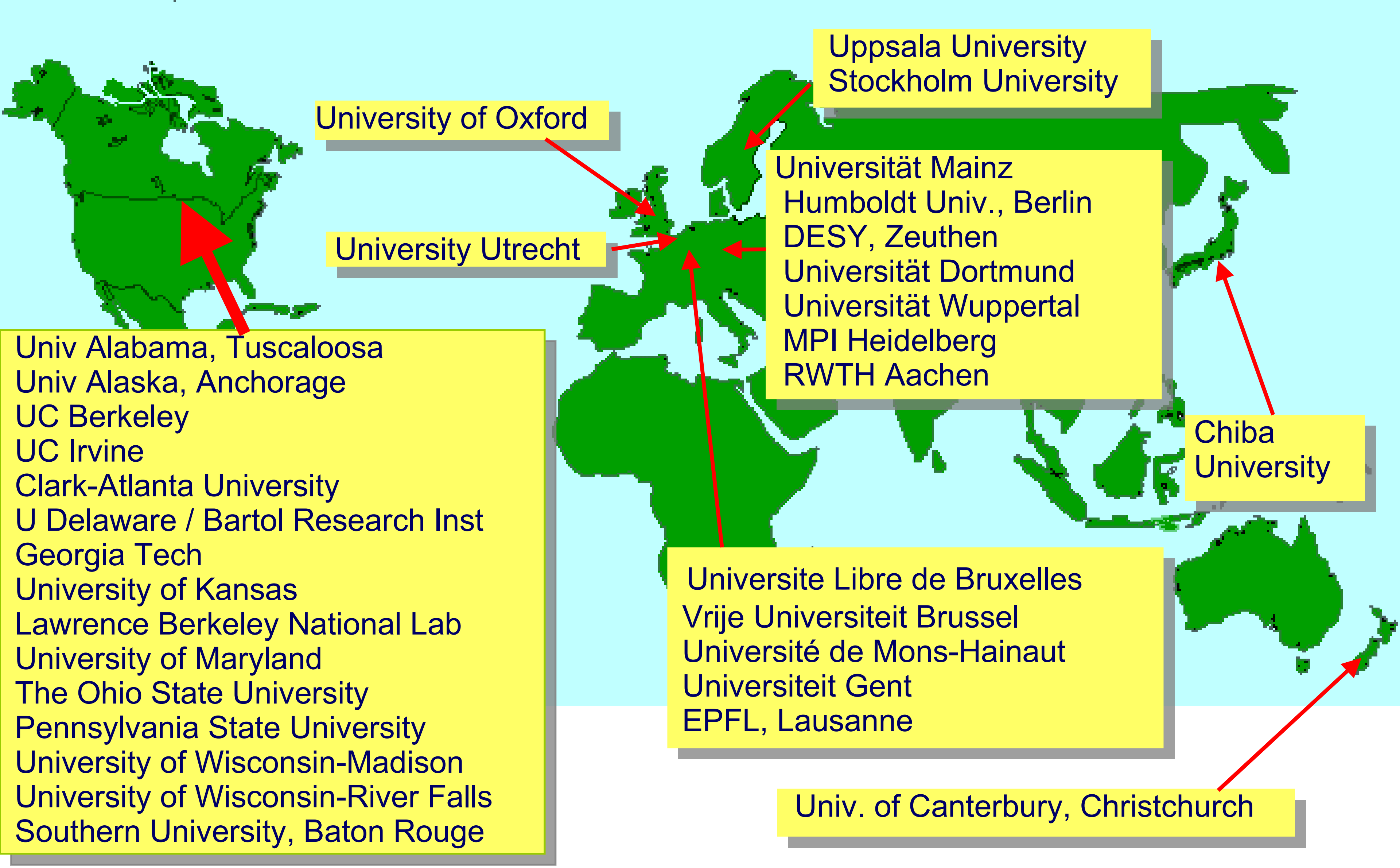


Cherenkov light mapped by optical sensors

The South Pole



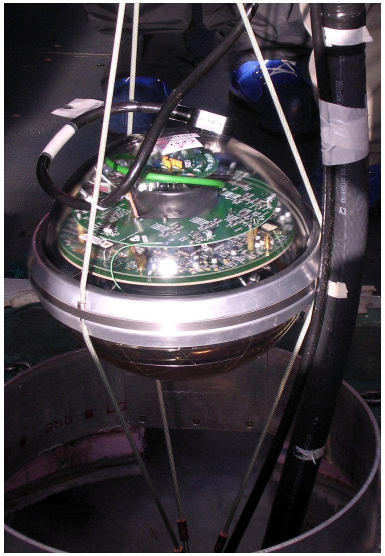

IceCube
Currently 40 Strings
IceTop
2007-08: 18 Strings
2006-07: 13 Strings
2005-06: 8 Strings
2004-05: 1 String
1450 m
In-Ice Array
80 Strings
60 Modlues
17 m between modules
AMANDA
19 Strings
677 Modules
2450 m

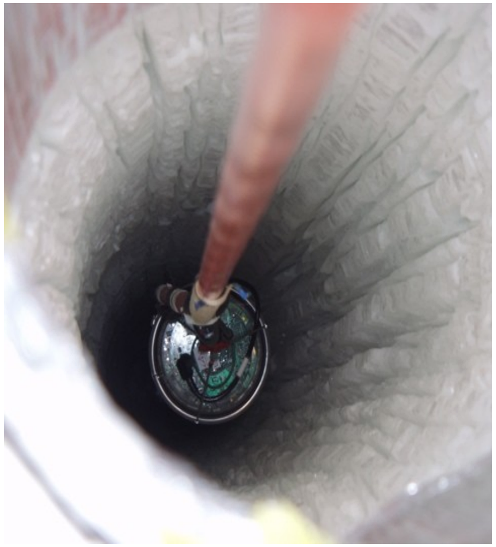


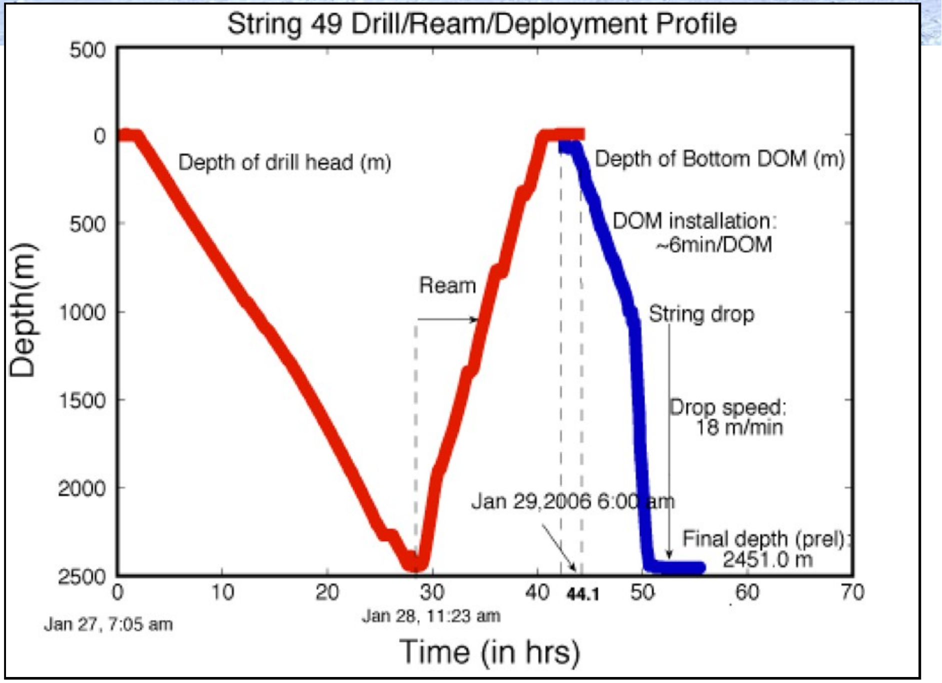
The IceCube Collaboration

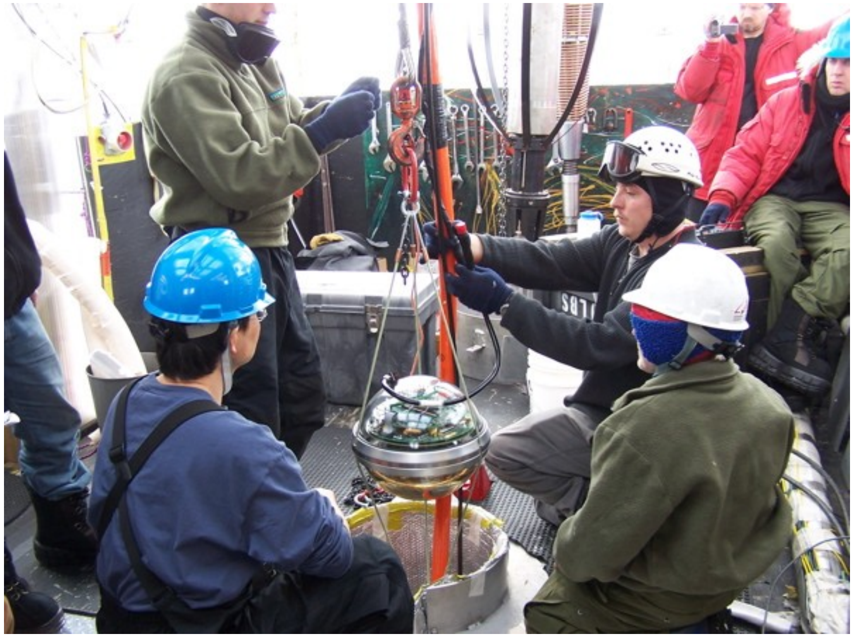
32 Institutions, ~250 members

Drilling and Deployment

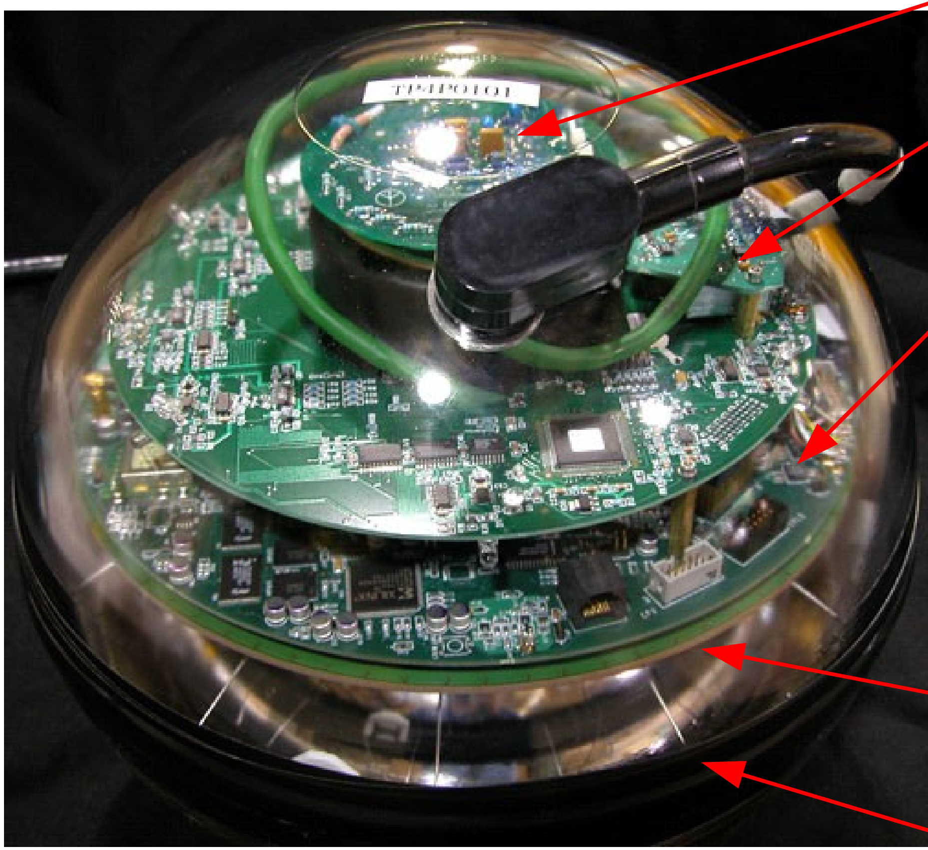








Digital Optical Module (DOM)



HV

Flasher Board with 12 LEDs

DOM Main Board

Power consumption: 3 W
Digitize at 300 MHz for 400 ns
Dynamic range 200pe/15 nsec
Excalibur FPGA/ARM CPU
Digital data transmission over copper

10 inch Hamamatsu PMT

Pressure Sphere

Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS every ≈ 10 sec

Calibration

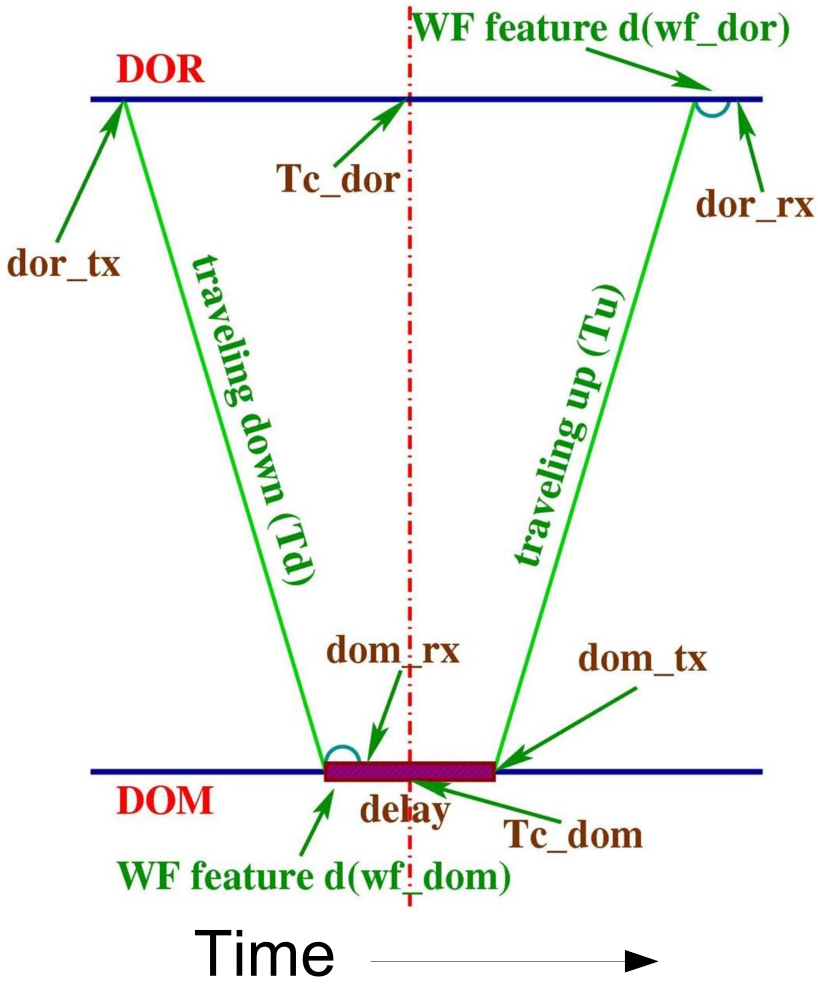
DOM local clock must be synchronized with GPS master clock

Custom PCI card (DOR) connects DOMs to surface PC and GPS clock

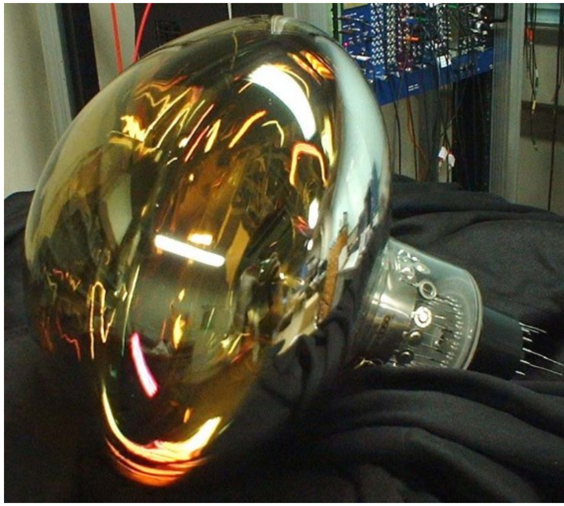
Symmetric DOR-DOM pulses are timestamped at TX and RX

Performed at ~10 sec. intervals

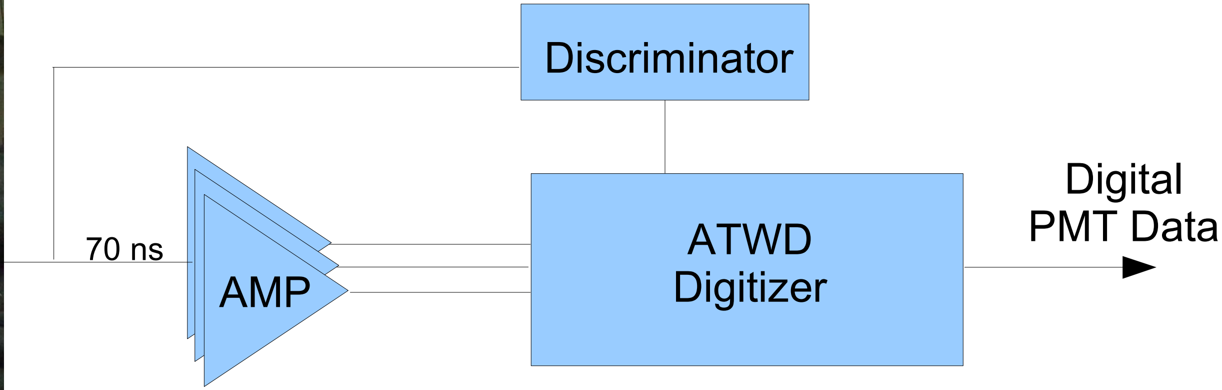
Calibration accuracy ~2 ns



DOM Front-End

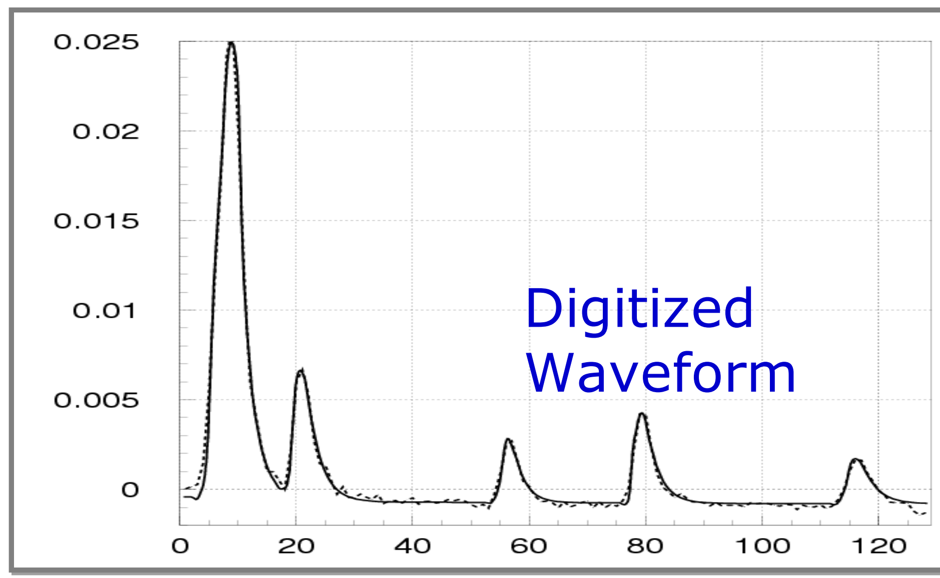


PMT

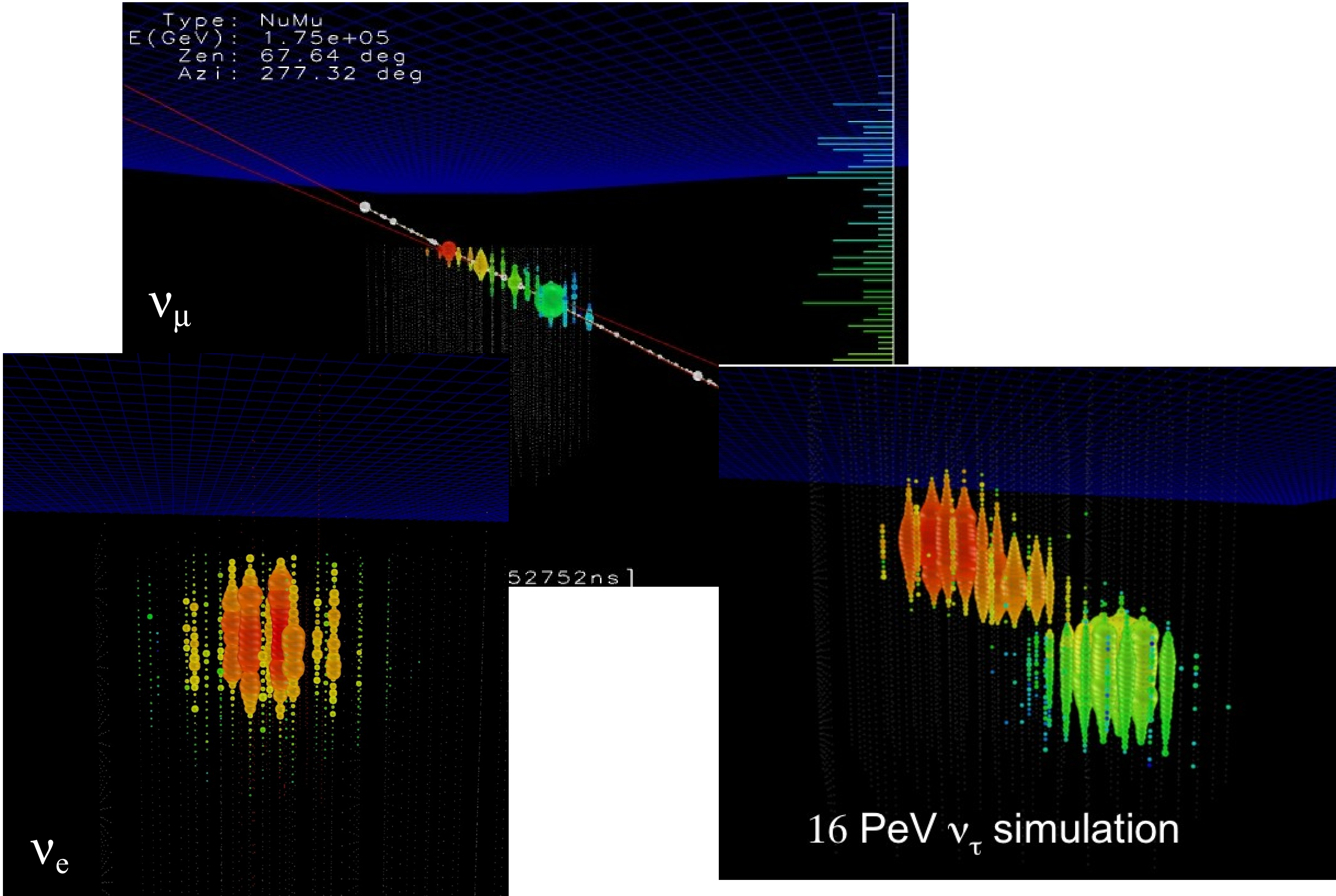


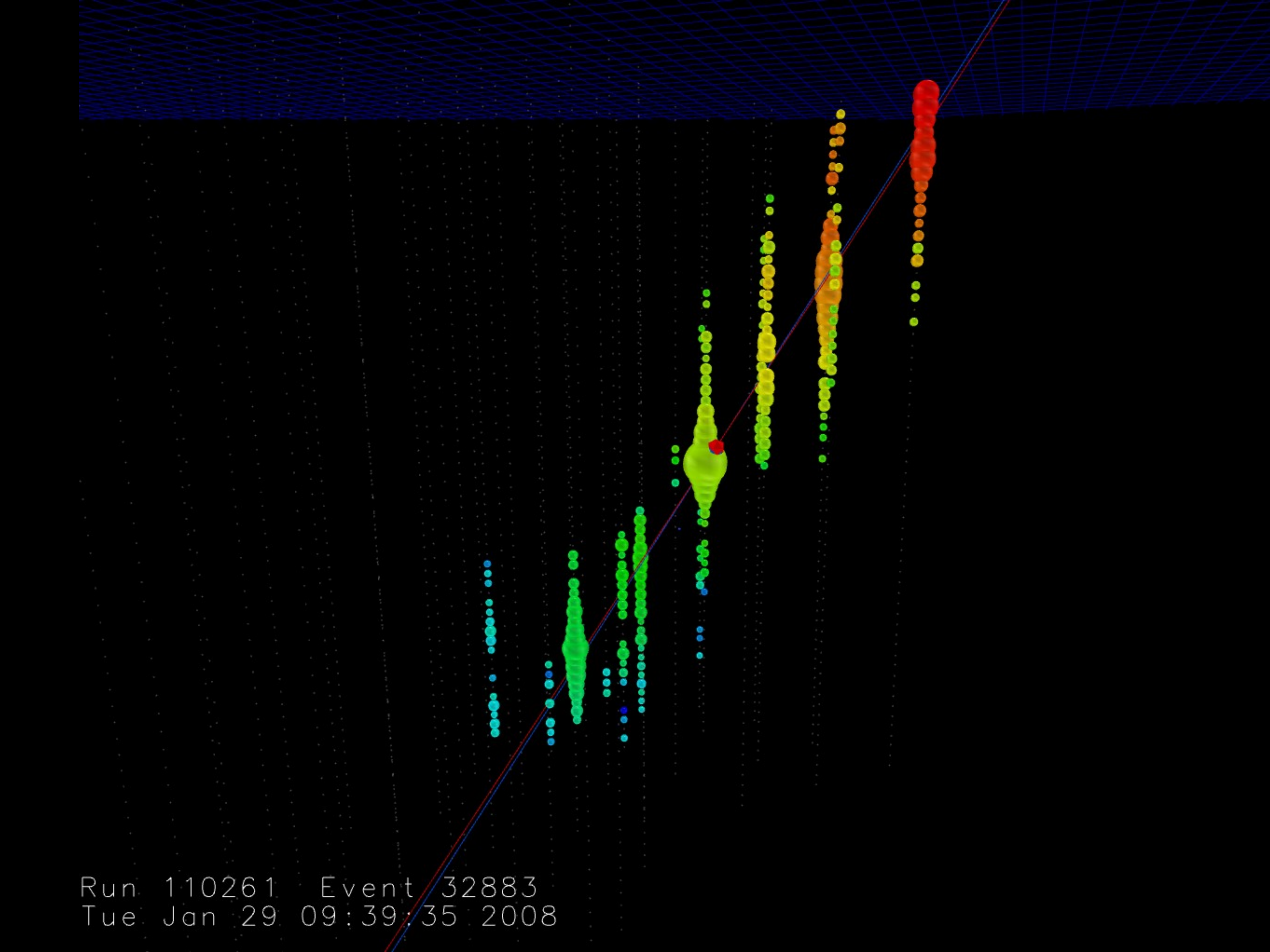
Calibrated Quantities:

- PMT Gain
- PMT Propagation Delay
- Amplifier Gains
- Discriminator Threshold
- ATWD Sampling Rate
- ATWD ADC/mV



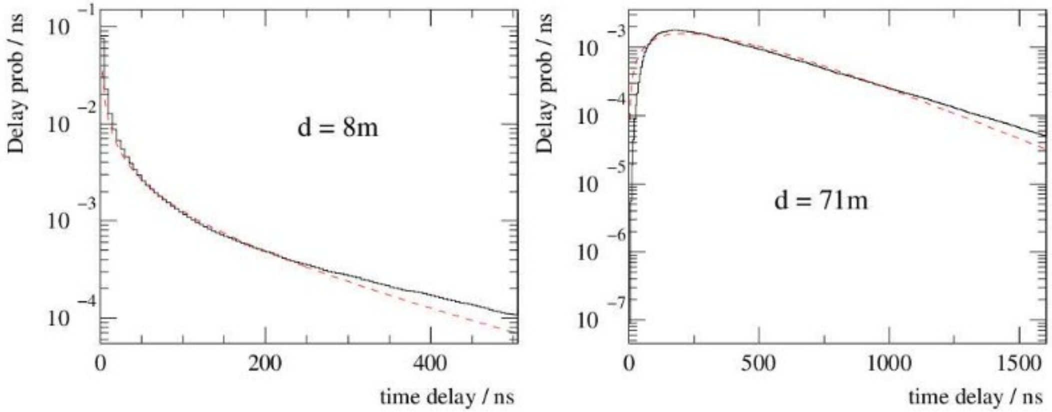
Event Topologies




Run 110261 Event 32883
Tue Jan 29 09:39:35 2008

Event Reconstruction

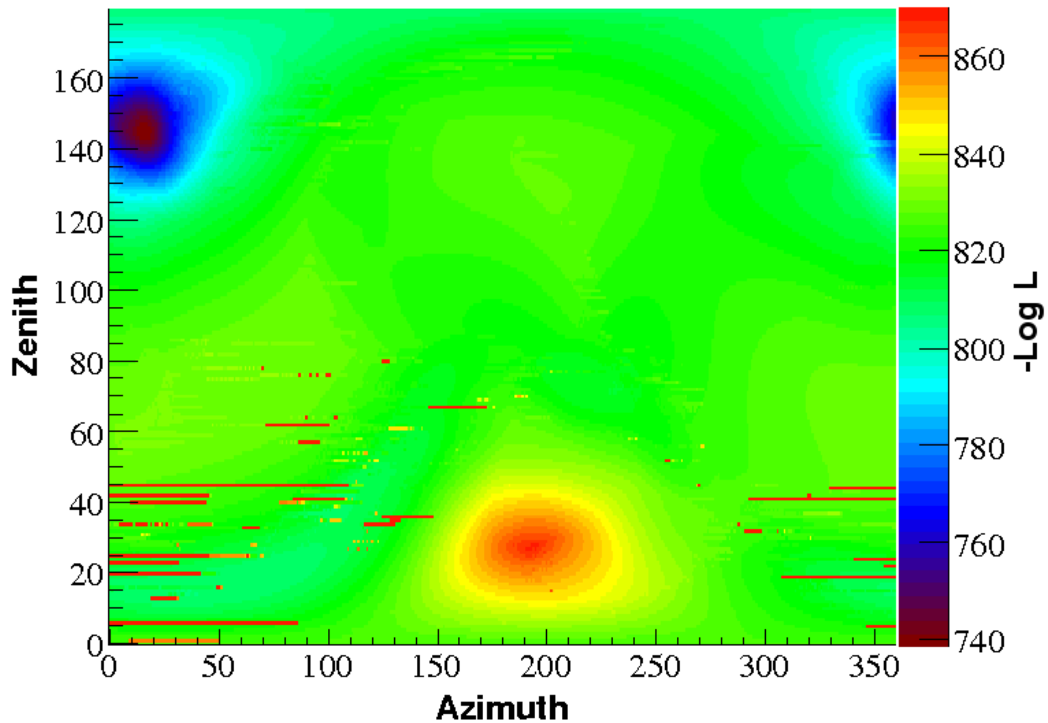
Scattering and absorption affect photon propagation in ice



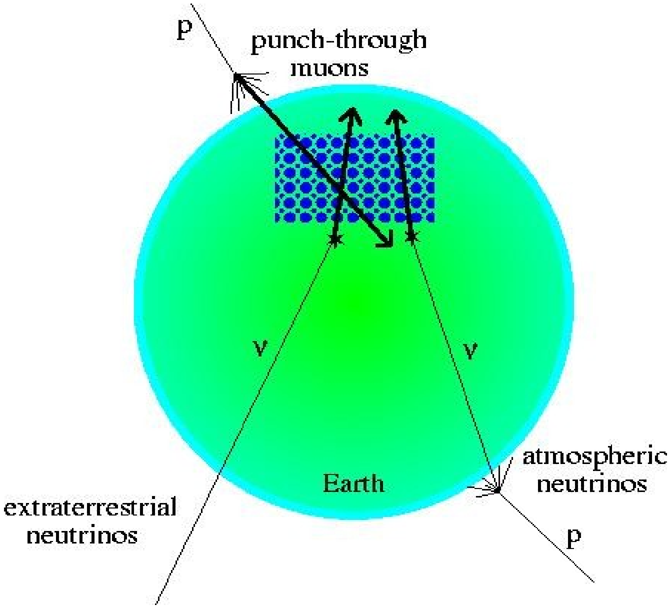
Delay probability known as a function of distance to track

$$\mathcal{L}(\theta, \phi, \mathbf{r}) = \prod_{i=1}^{N} P(t_{res}|d)$$

Minimize -Log L to find best fit hypothesis



IceCube Events

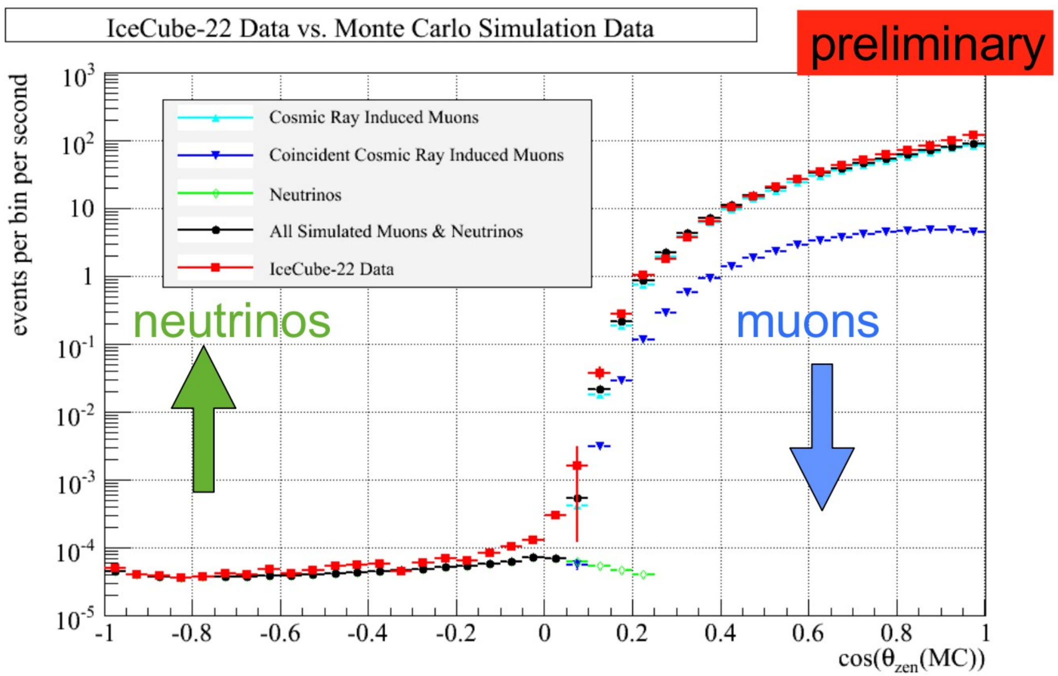


Strings	μ rate	ν rate
AMANDA	80 Hz	4.8 / day
IC22	550 Hz	28 / day
IC40*	1200 Hz	110 / day
IC80*	1650 Hz	220 / day

AMANDA: $O(10^9)$ events/yr
IceCube: $O(10^{10})$ events/yr

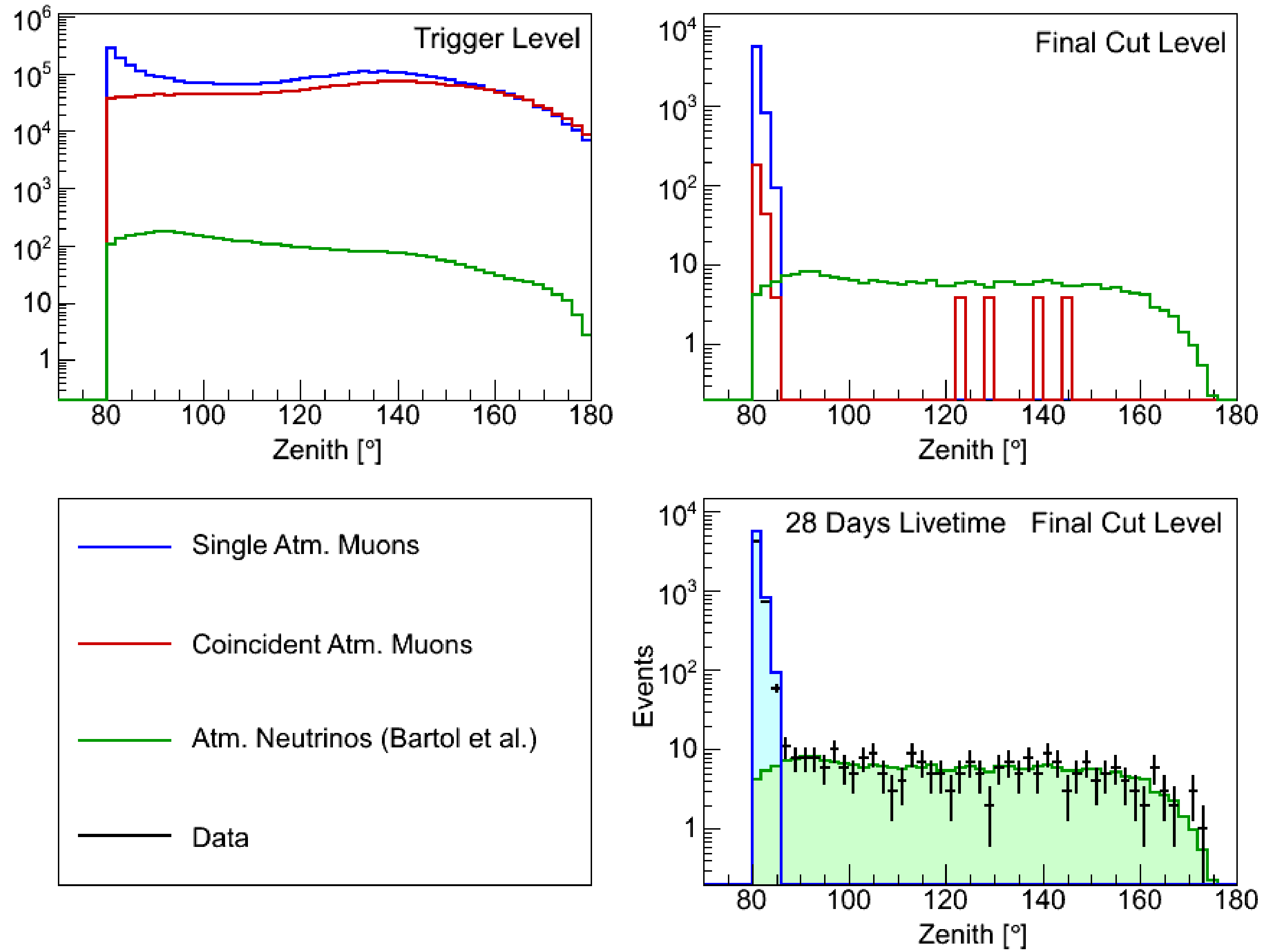
Step 1: Remove background of downgoing muons

Step 2: Isolate extraterrestrial events from "irreducible" background of atmospheric neutrinos

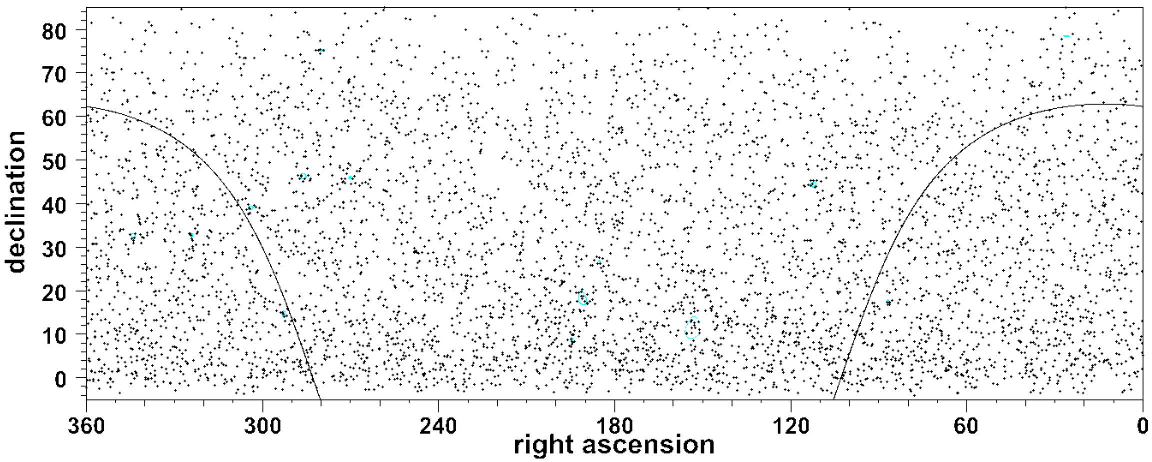


Event Selection

A combination of topological cuts reduces misreconstructed upgoing events



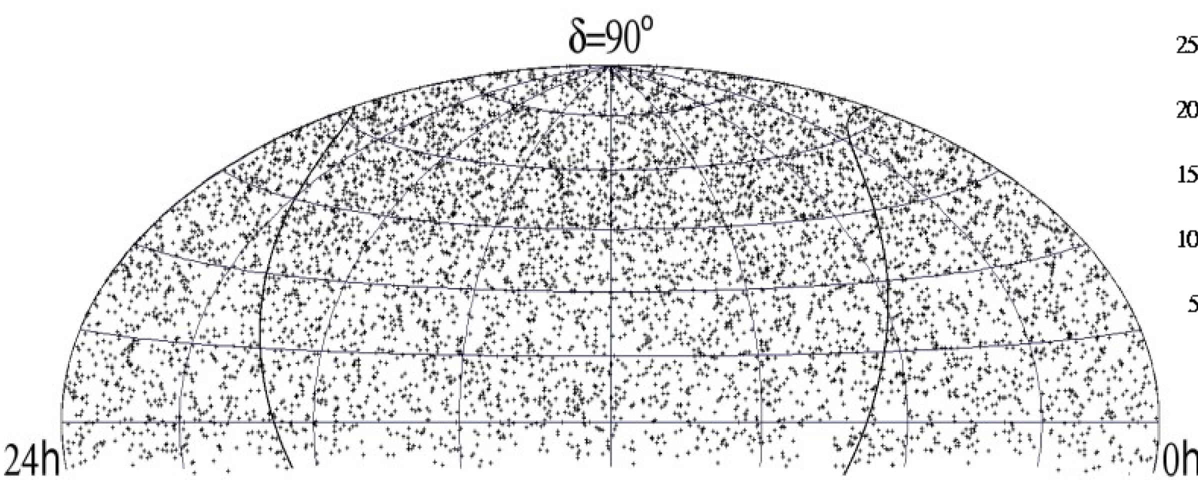
Upgoing Events

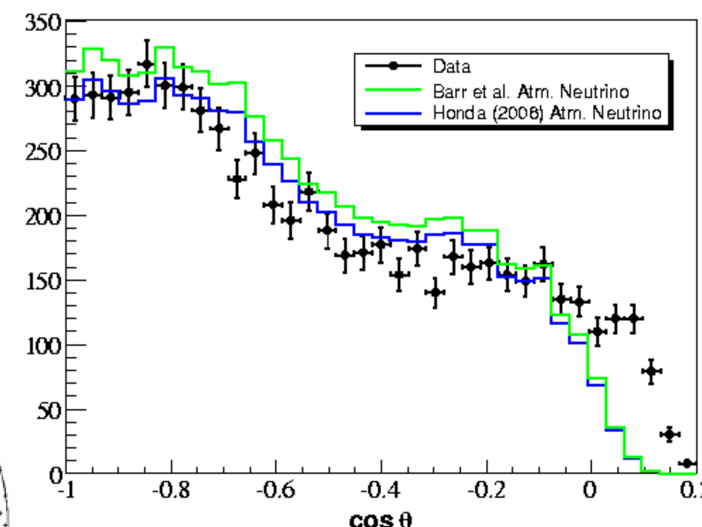


IceCube 22 String:

5114 neutrino candidates in 276 days livetime

AMANDA: 6595 ν candidates in 3.8 live-years





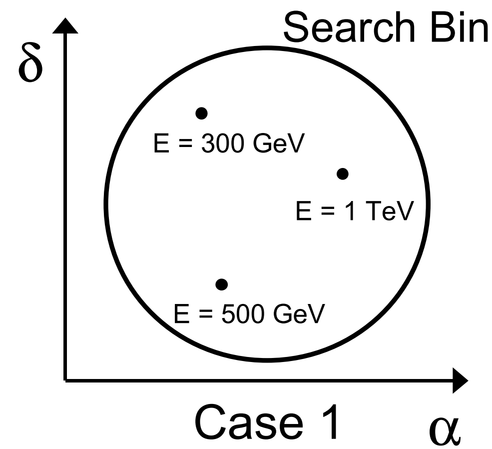
Search for Extraterrestrial Neutrinos

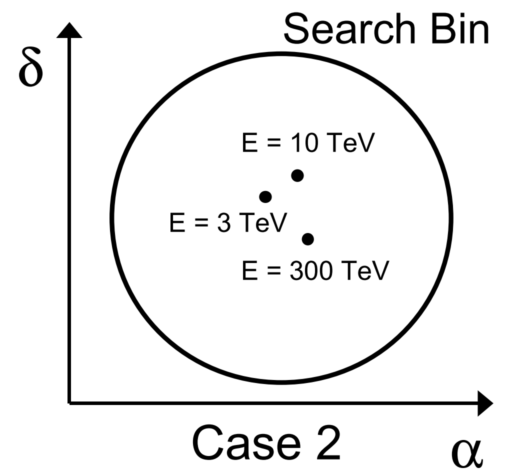
Need to separate extraterrestrial neutrinos from atmospheric neutrino background

Binned searches are suboptimal

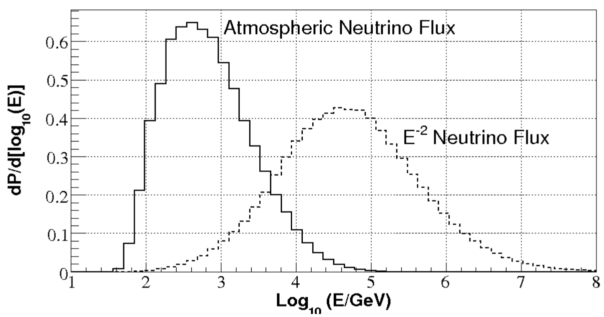
- Event loss
- Distribution of events within bin
- Track resolution
- Event energy
- Optimization

Perform search with an unbinned maximum-likelihood method





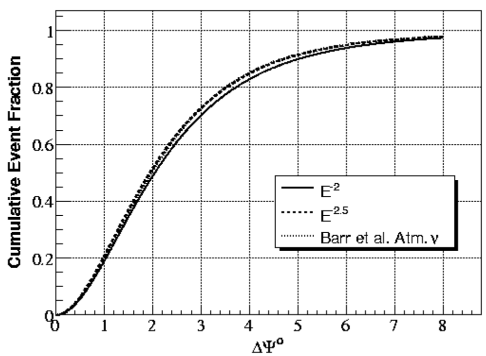
Signal PDF: $\mathcal{S}_i(\vec{x}_i, \vec{x}_s, E_i, t_i) = \underbrace{P(E_i)}_{\text{Energy}} \cdot \underbrace{P(|\vec{x}_i - \vec{x}_s|)}_{\text{Space Angle}} \cdot \underbrace{P(t_i)}_{\text{Time}}$



Energy

Extraterrestrial neutrinos should be more energetic than atmospheric neutrinos → **Diffuse Search**

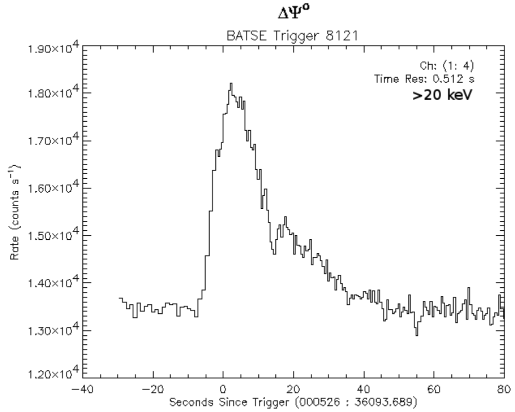
+



Space Angle

Extraterrestrial neutrinos from a point source cluster around the source location → **Point Source Search**

+



Time

Neutrinos from GRBs and flaring AGN should be clustered in time → **Time-Dependent Point Source Search**

Point Source Search

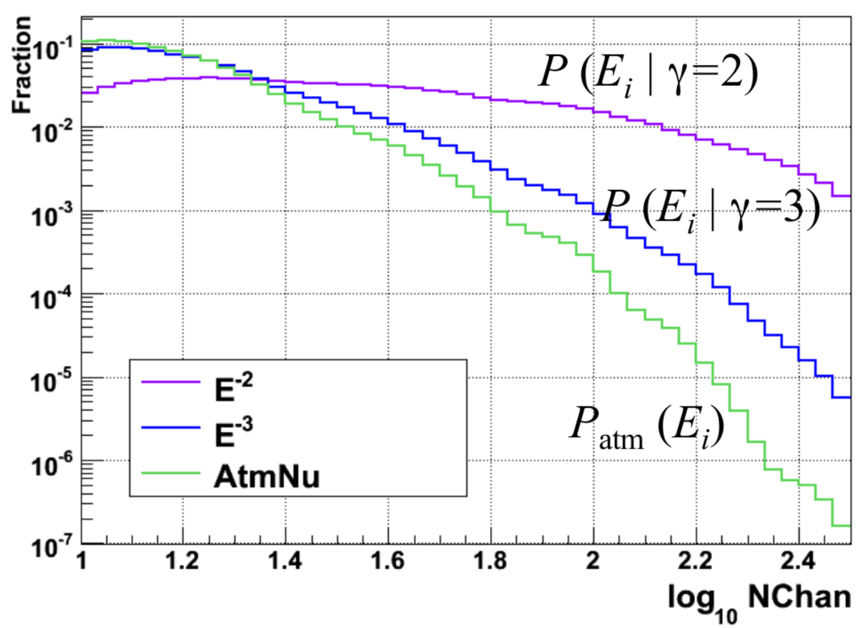
Signal PDF: $$\mathcal{S}_i(\vec{x}_i, \vec{x}_s, \sigma_i, Nch_i, \gamma) = \underbrace{\frac{1}{2\pi\sigma_i^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}}}_{\text{Space Angle}} \cdot \underbrace{P(Nch_i|\gamma)}_{\text{Energy}}$$

Space Angle Term:

– Assume $P(|x_i - x_s|)$ is a 2-D Gaussian
– Space angle uncertainty σ_i can be measured for each event during reconstruction

Energy Term:

– Use number of hit channels (Nch) as a measure of energy



Point Source Search

Background: Atmospheric neutrinos are uniform in RA

$$\mathcal{B}_i = \frac{1}{\Omega} \cdot P_{atm}(Nch_i)$$

Assume a fraction of events are signal, remainder are background

Partial probability for each event:

$$P(\vec{x}_s, n_s, \gamma, \vec{x}_i, Nch_i, \sigma_i) = \frac{n_s}{N}\mathcal{S}_i + (1 - \frac{n_s}{N})\mathcal{B}_i$$

Likelihood function:

$$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_{i=1}^{N} P(\vec{x}_s, n_s, \gamma, \vec{x}_i, Nch_i, \sigma_i)$$

Numerically minimize -Log L with respect to n_s and γ,
obtaining best fit values $\hat{n}_s, \hat{\gamma}$

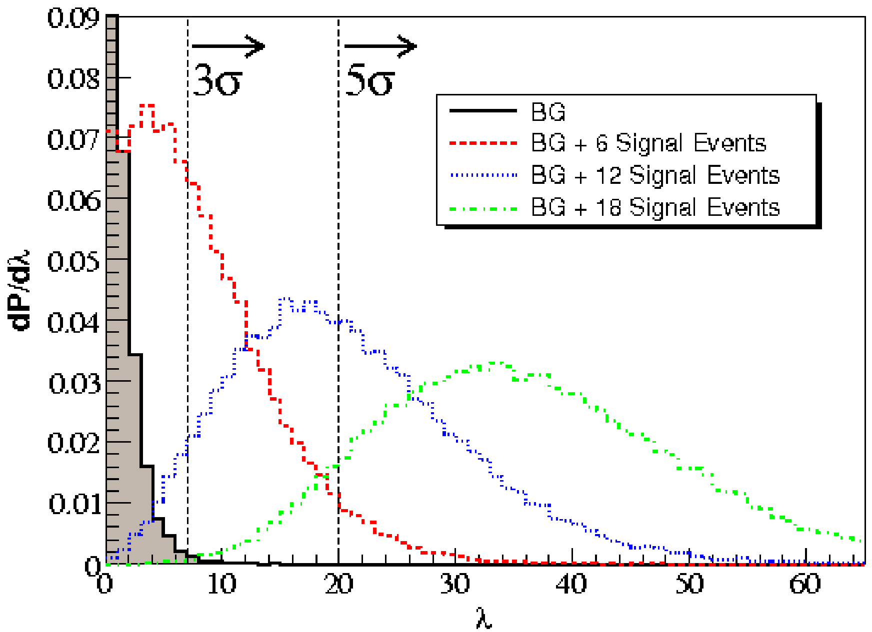
Log likelihood:

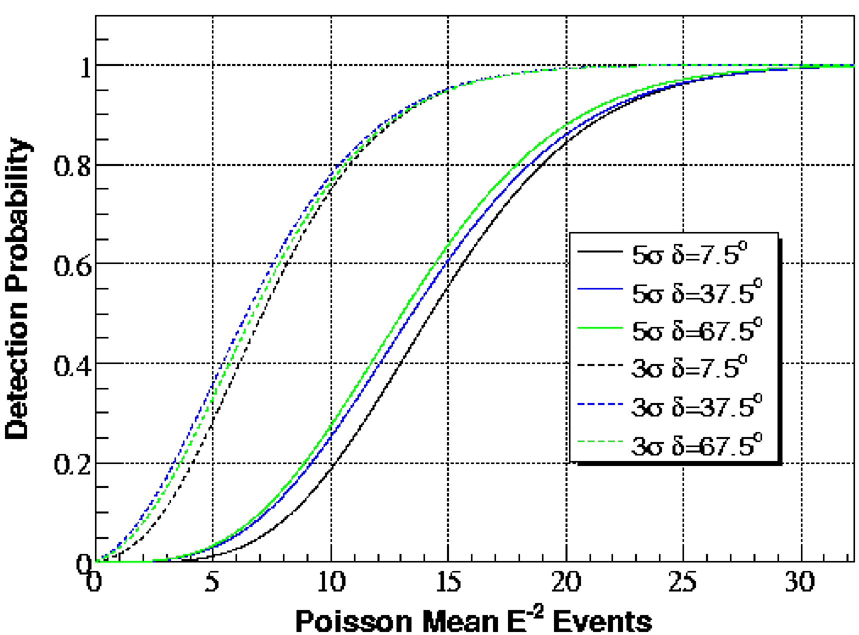
$$\lambda = -2 \cdot log\left[\frac{\mathcal{L}(\vec{x}_s, n_s = 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s, \hat{\gamma})}\right]$$

Point Source Search

Simulate sources of various strength

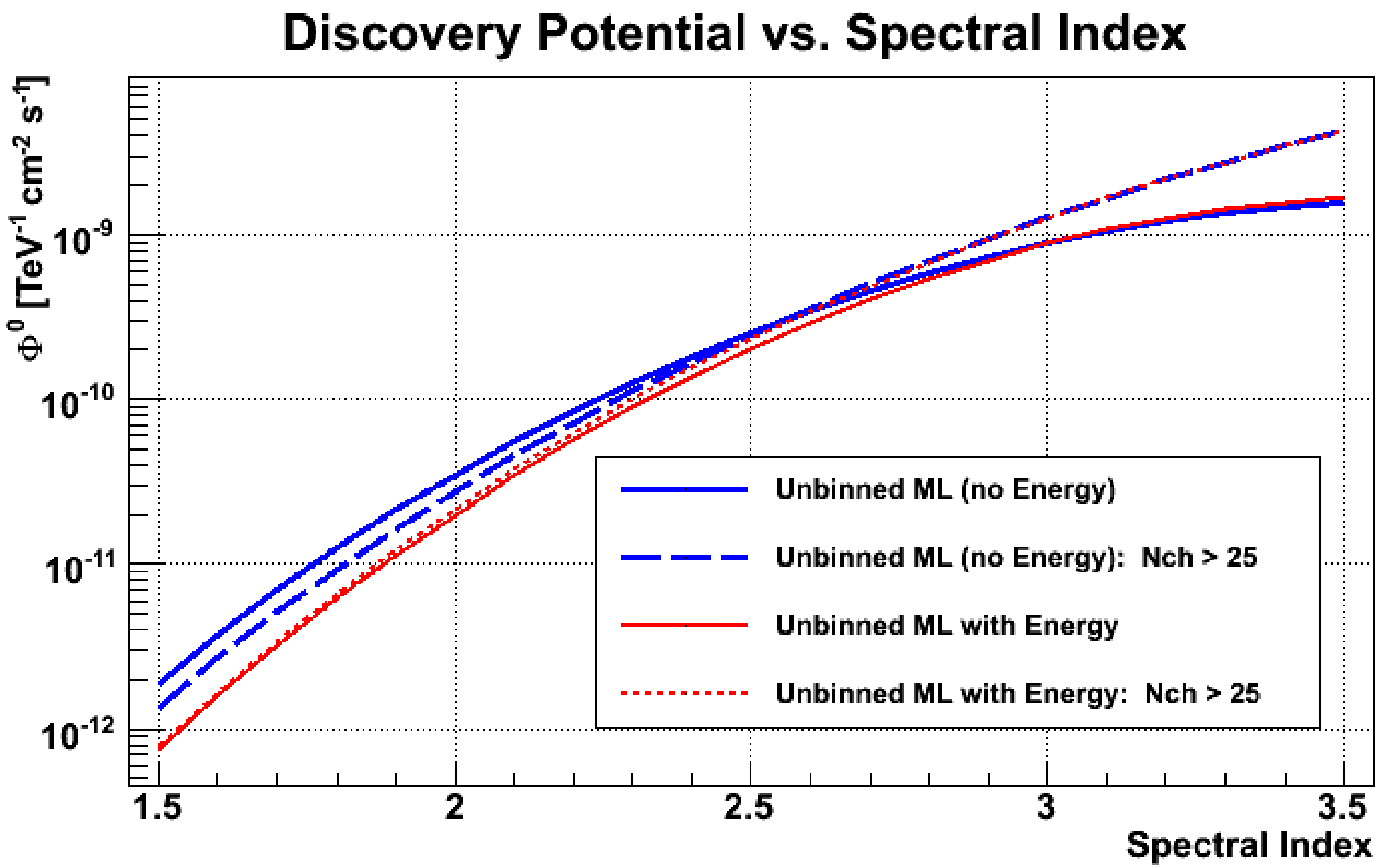
Compute significance by comparing to data randomized in RA





Method requires 30% - 50% less flux for 5σ discovery compared to binned approach

Search Optimization



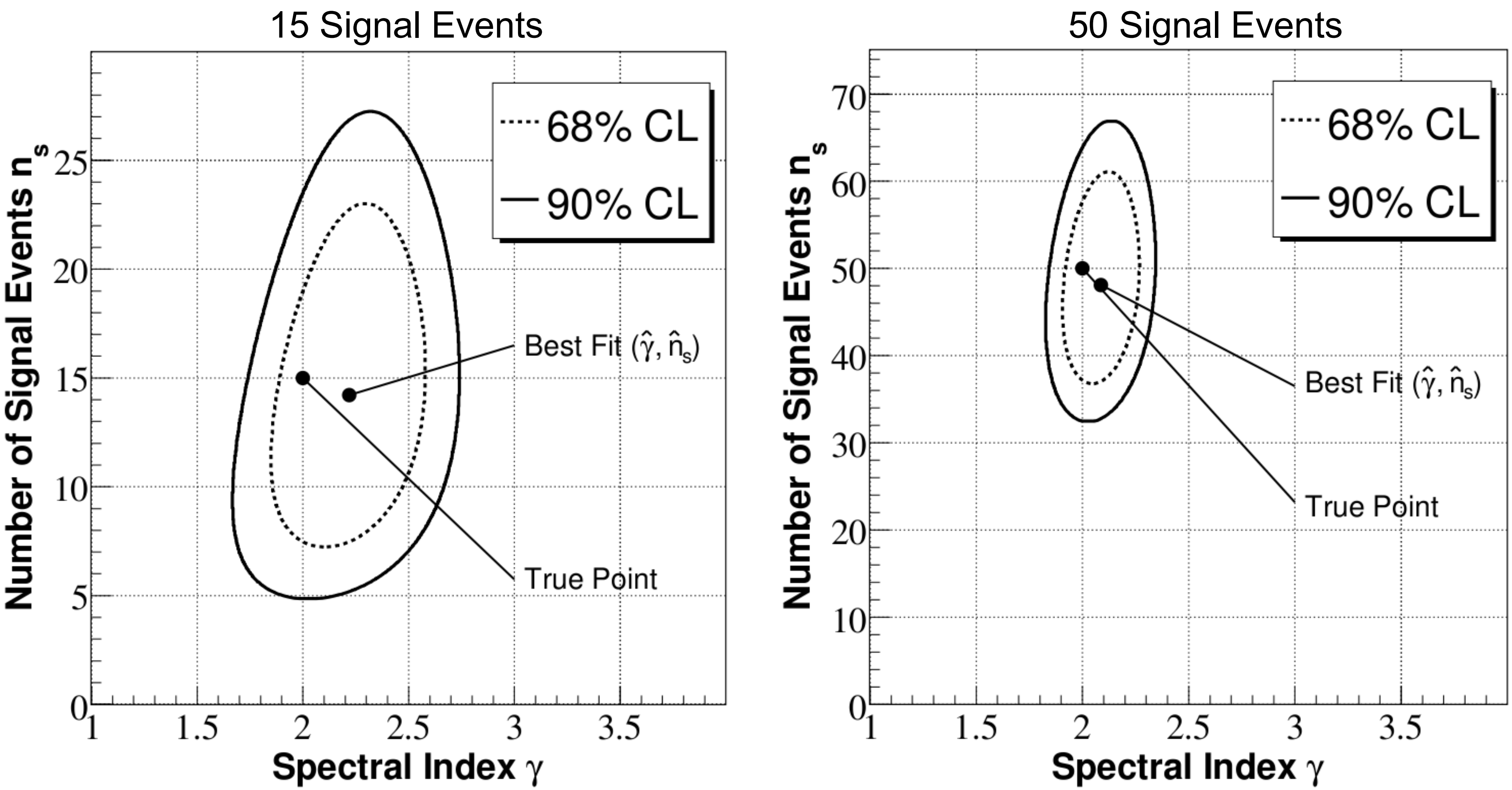
Without energy term, cuts must be optimized for either hard or soft signal spectrum.

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.

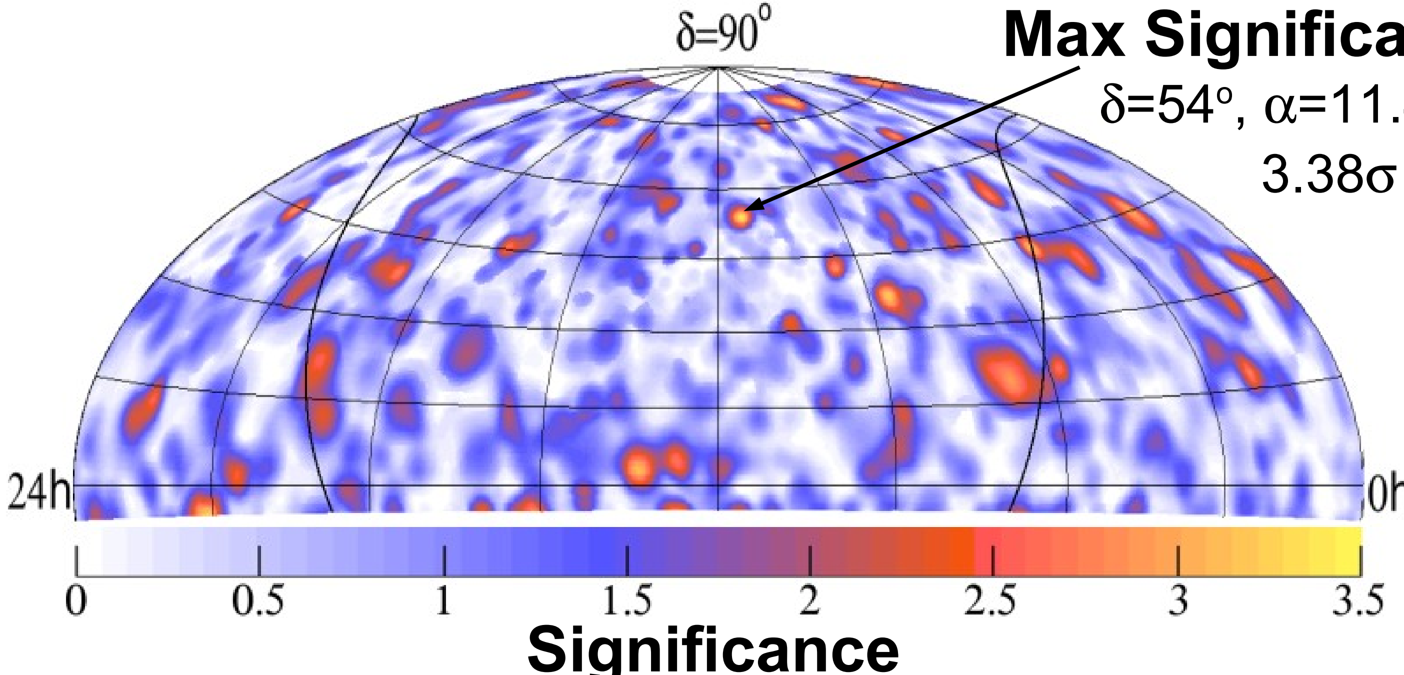
Estimating Spectral Index

Maximization of λ yields an estimate of the source strength and spectral index



Astropart. Phys. **29**, 299 (2008)

AMANDA All-Sky Search



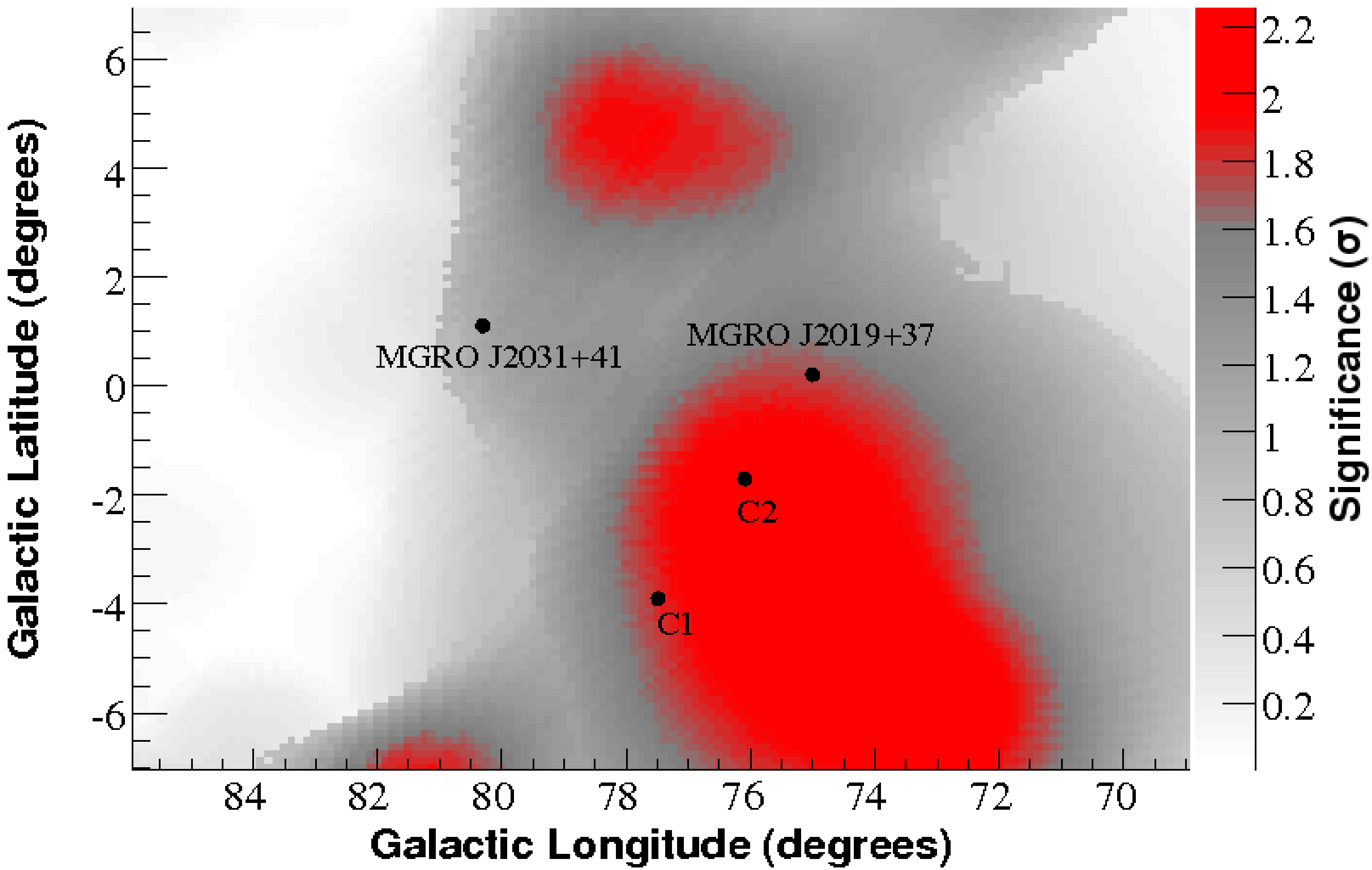
95 of 100 data sets randomized in RA have a significance ≥ 3.38σ

Source	μ_{90}	P-value
Crab	9.27	0.10
MGRO J2019+37	9.67	0.077
Mrk 421	2.54	0.82
Mrk 501	7.28	0.22
LS I +61 303	14.74	0.03
Geminga	12.77	0.0086

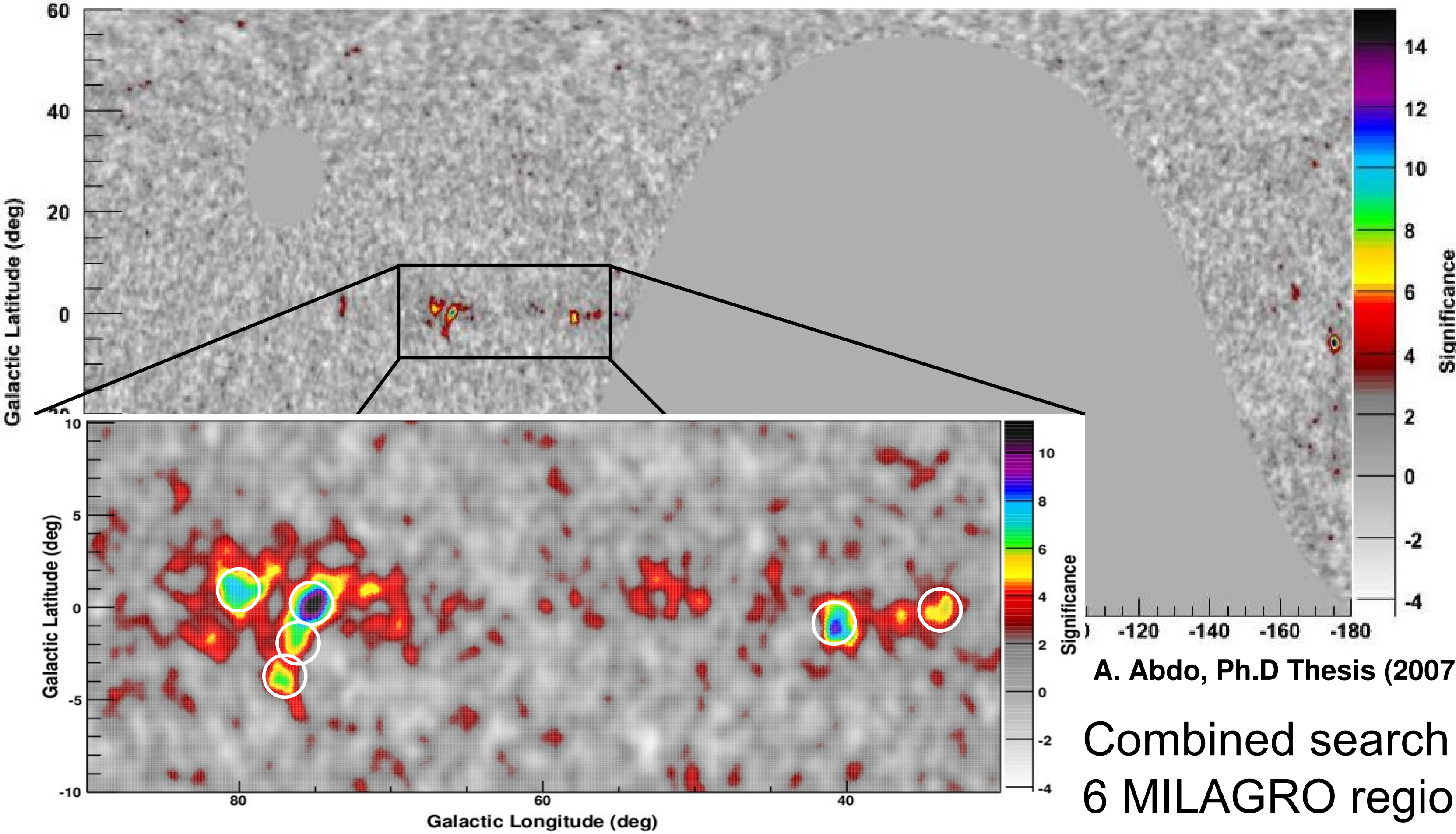
$E^2\Phi < \mu 90 * 10^{-11}$ TeV cm^{-2} s^{-1}

The probability of obtaining p ≤ 0.0086 for at least one of the 26 sources is 20%

The Cygnus Region



Milagro Stacking Search

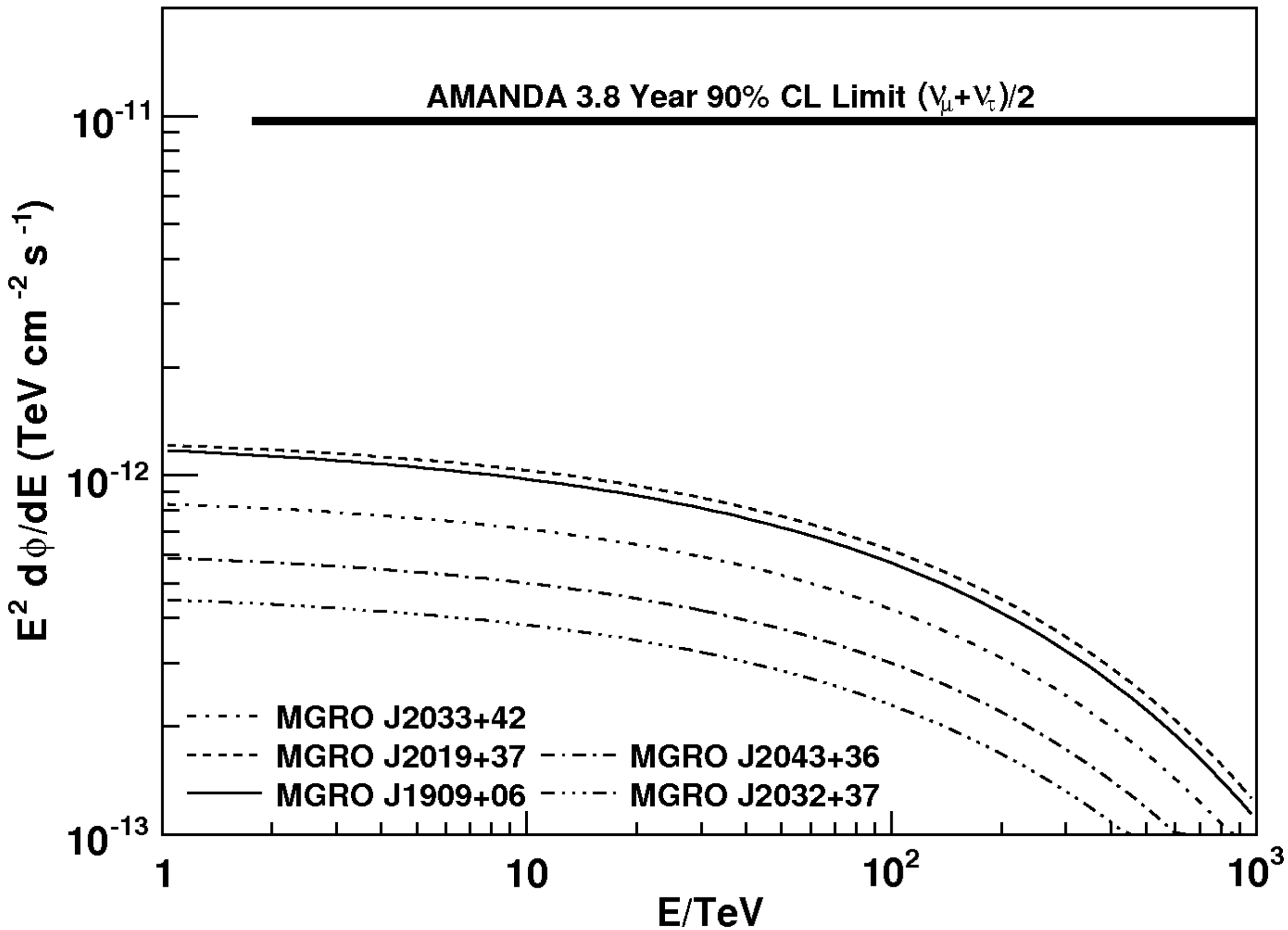


A. Abdo, Ph.D Thesis (2007)

Combined search over
6 MILAGRO regions

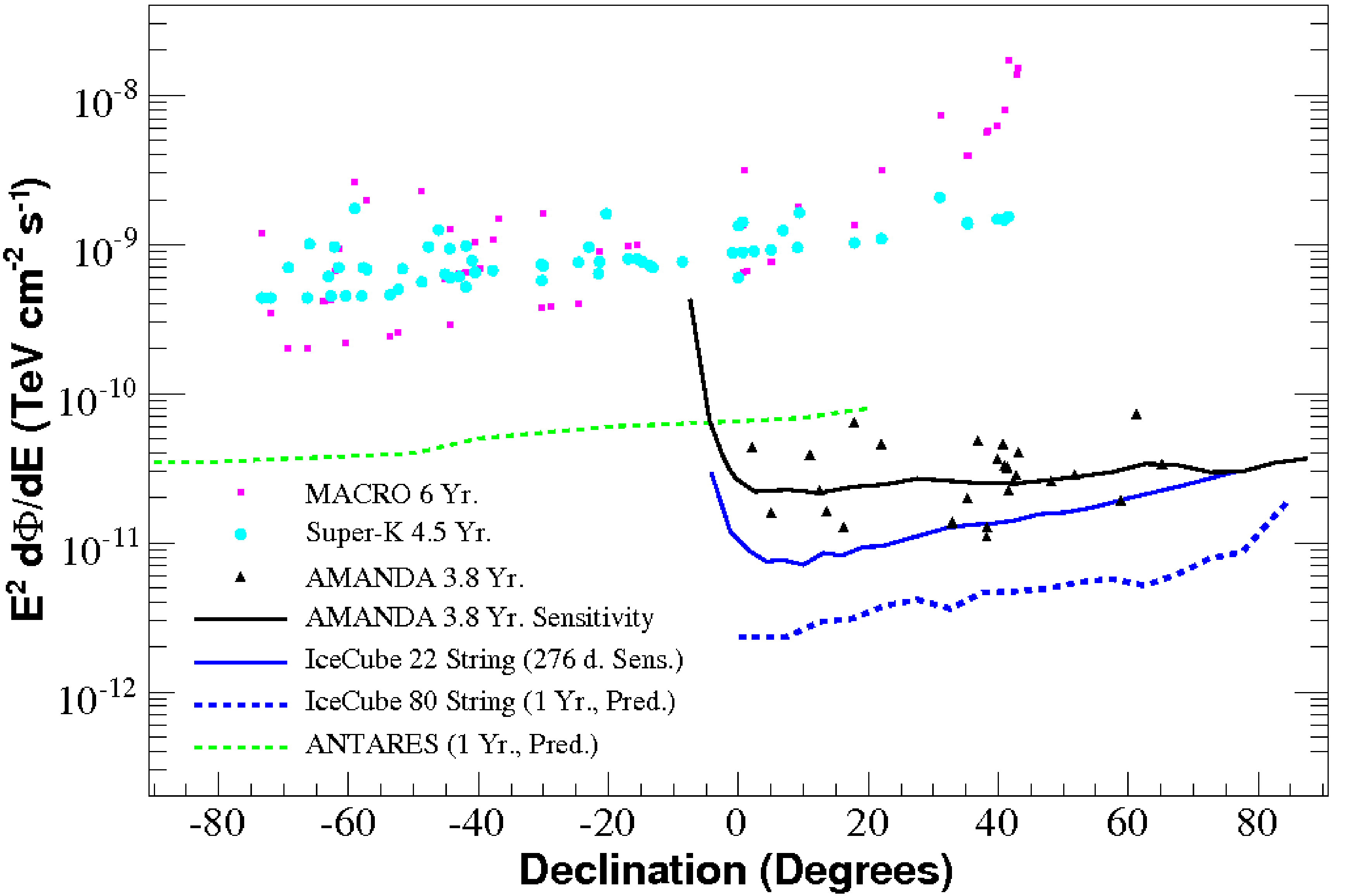
Improves per-source flux sensitivity and discovery potential by a factor of 4 compared to a fixed-point search for any of the six sources

Milagro Stacking Search

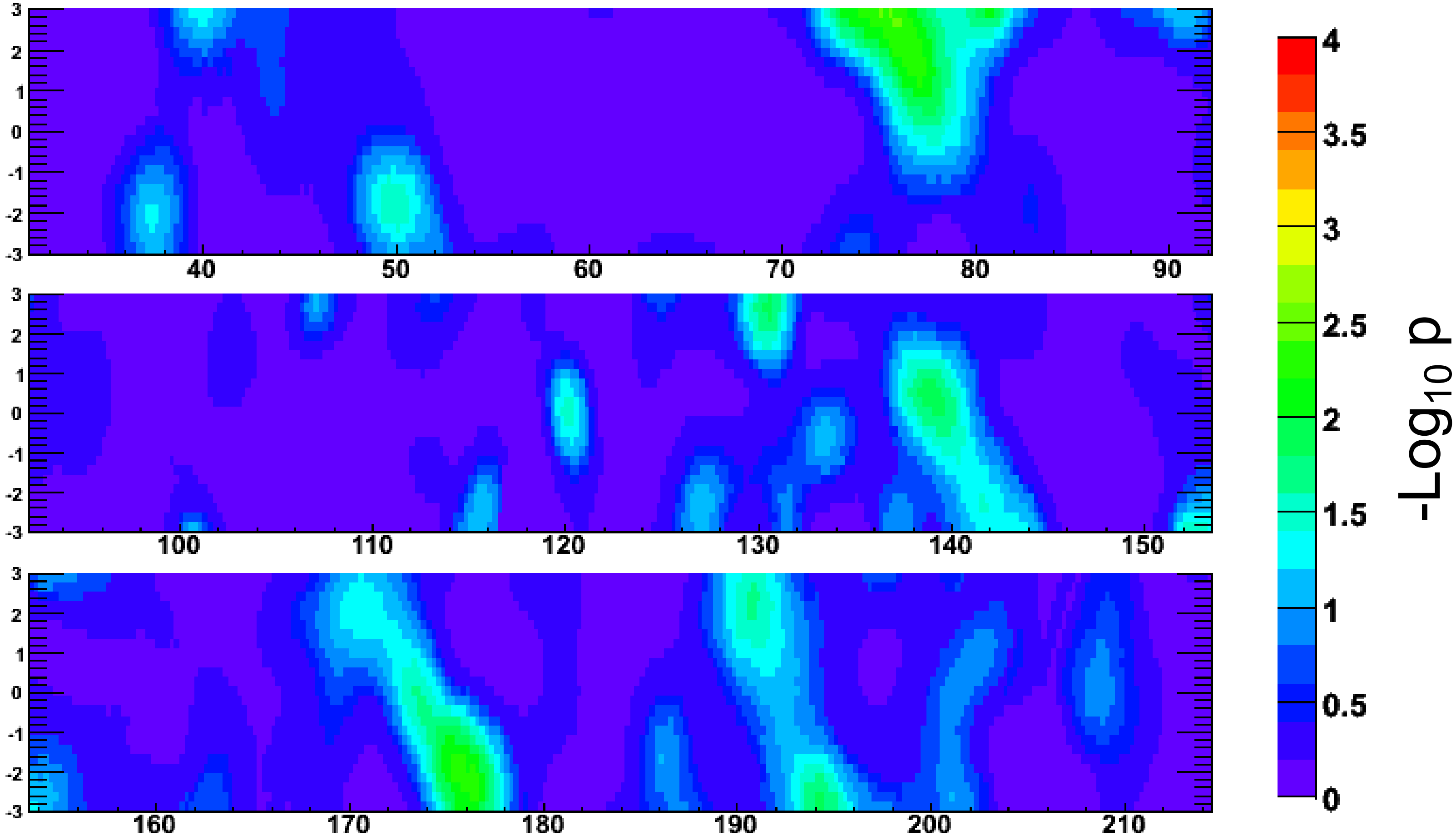


Halzen, Kappes, O'Murchada PRD **78**, 063004 (2008)

Experimental Limits



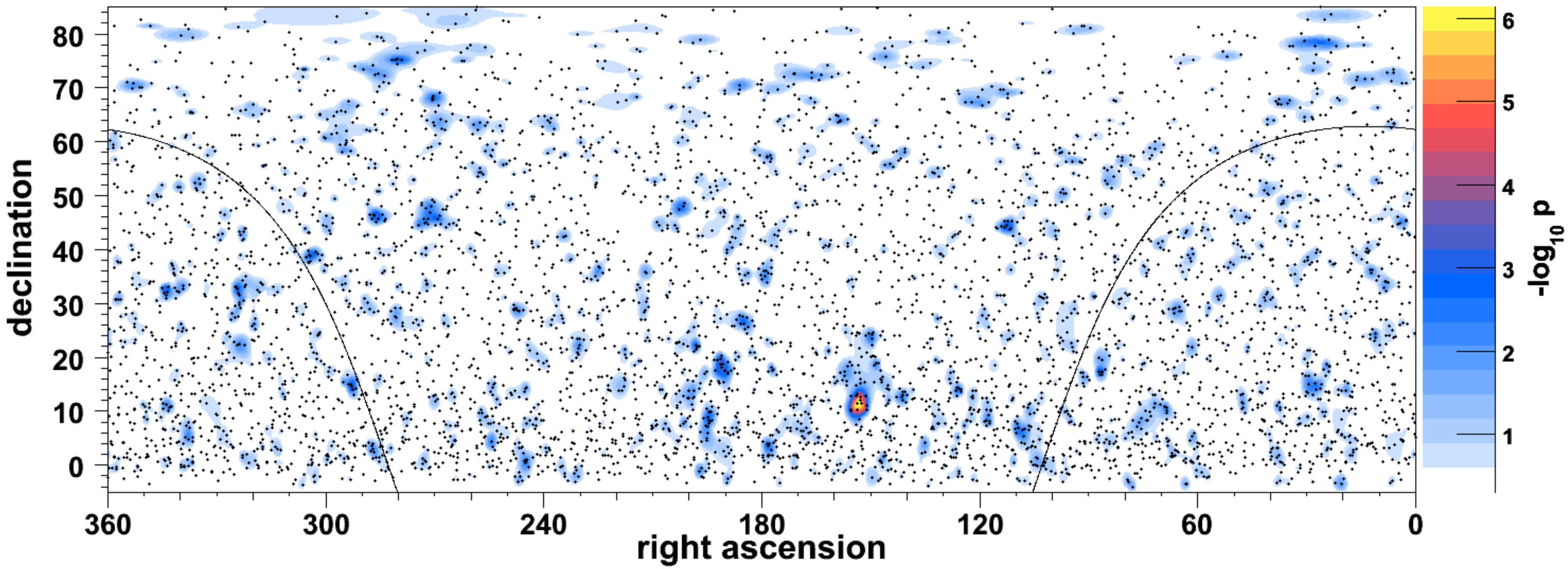
Search of the Galactic Plane with IceCube-22 + AMANDA



Optimized for low energy

No significant excess observed

IceCube 22 String



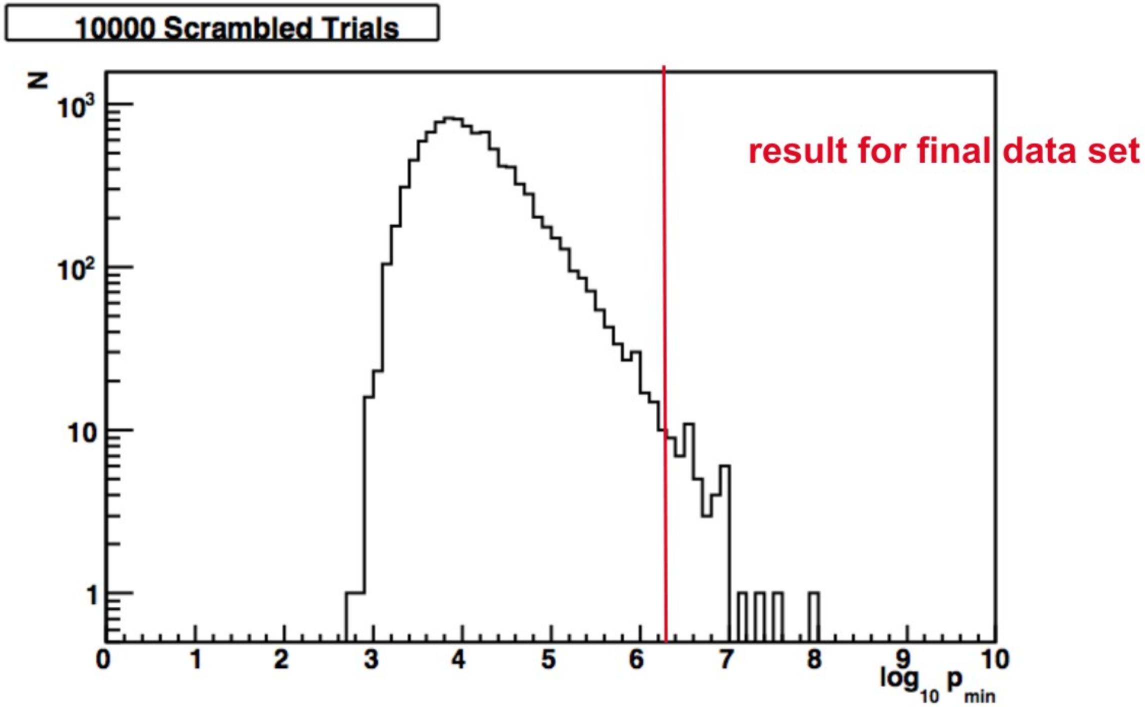
Hottest spot found at r.a. 153º , dec. 11º
pre-trial p-value: $7 \cdot 10^{-7}$ (4.8 sigma)
est. nSrcEvents = 7.7 est. gamma = 1.65

A search based on a list of sources yields no significant excess

Accounting for all trials, p-value for analysis is 1.34% (2.2 sigma).

At this significance level, consistent with fluctuation of background.

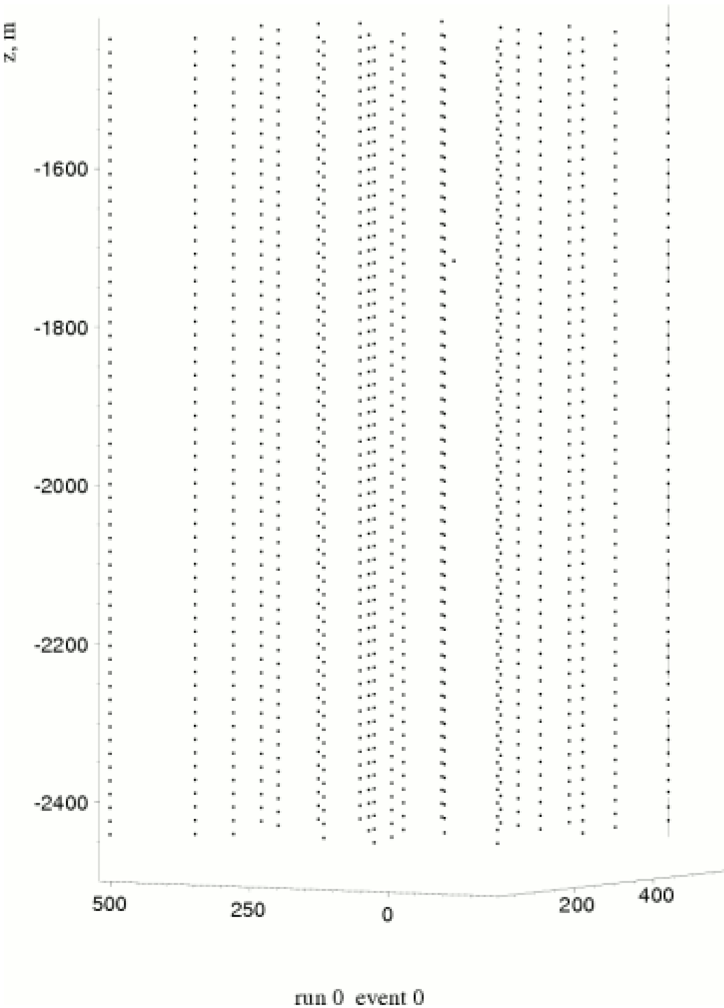
IceCube 22 String



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.

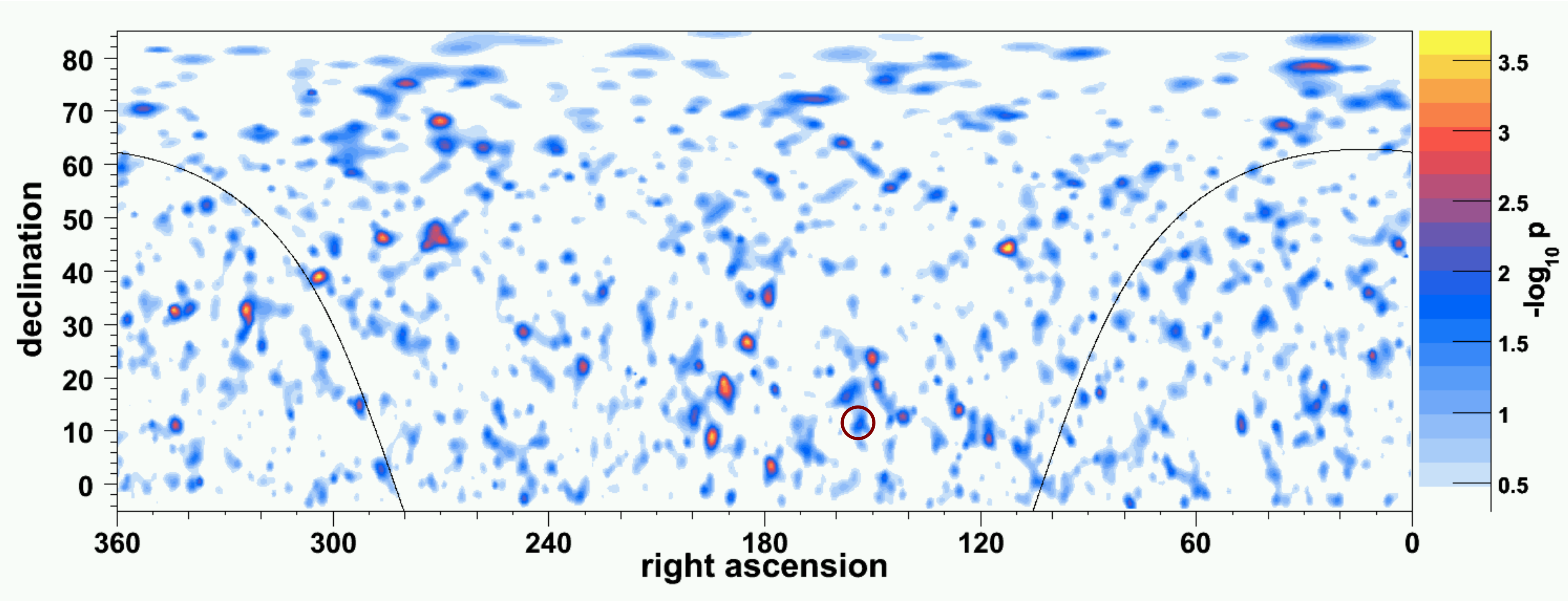
Including trial factor of two since the analysis with the a priori list was also performed, the **post-trials p-value is ~ 1.34%.**

Event from Hotspot



Number of hit modules: 148
Estimated angular error: 0.84°

IceCube 22 String



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

Time Analysis of Hotspot

Future IceCube data will test the possibility that the hottest spot is a source unless it is a **one-time occurrence**.

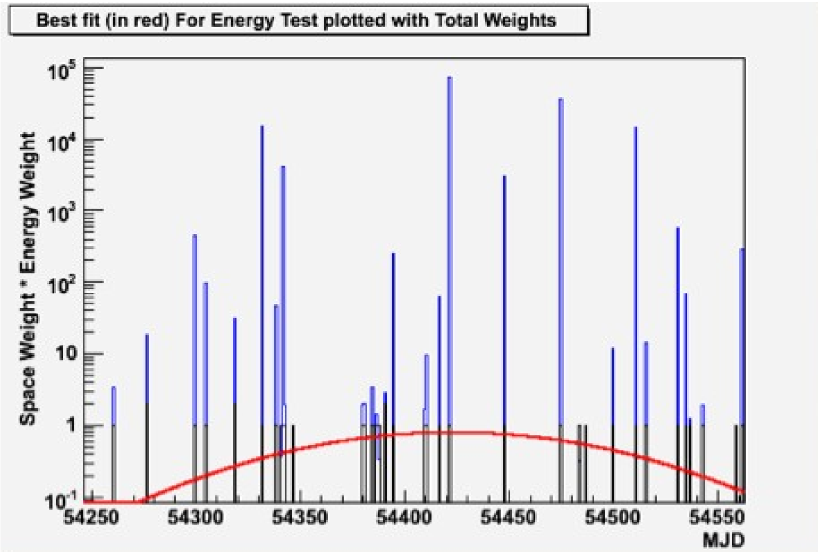
We need to perform a time-dependent analysis to take advantage of this possibility: Assume events occur in a flare or burst of unknown duration.

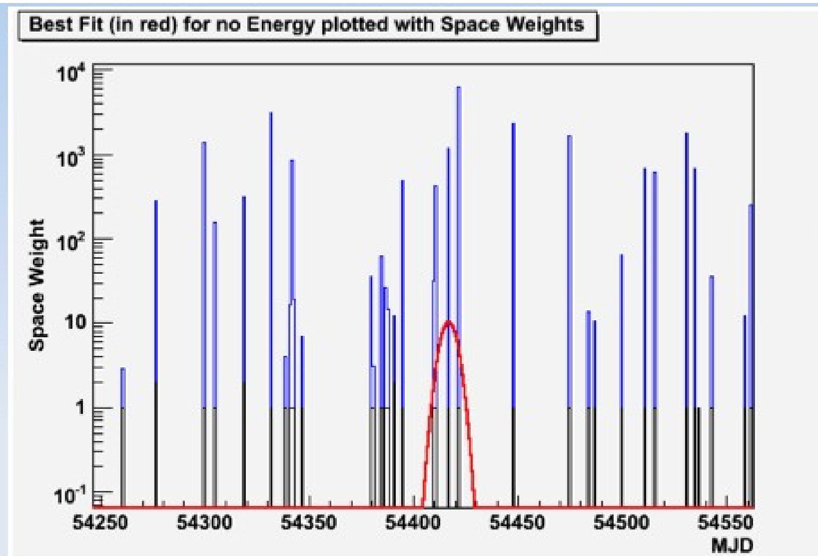
$$\mathcal{L}(\vec{x}_s, n_s, \gamma, t_o, \sigma_t) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i \cdot \frac{1}{\sqrt{2\pi}\sigma_t} e^{-\frac{(t_i - t_o)^2}{2\sigma_t^2}} + (1 - \frac{n_s}{N}) \frac{\mathcal{B}_i}{t_L} \right)$$

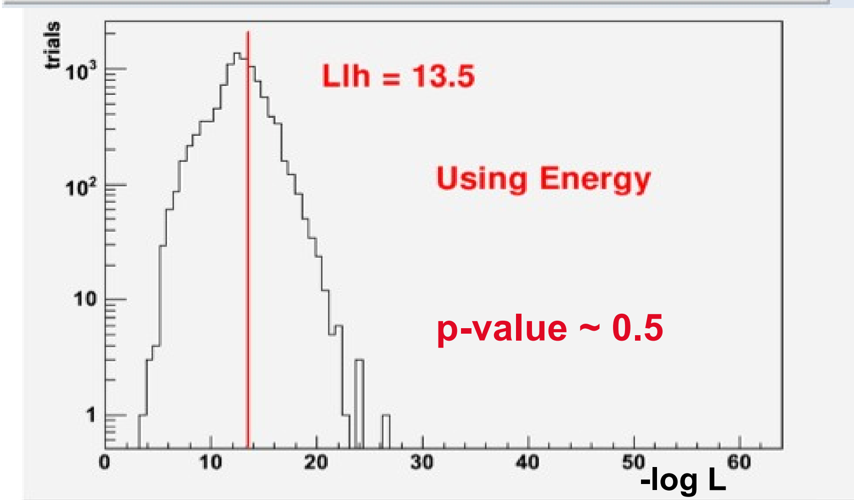
Maximize likelihood, finding the best values of σ_t and t_o

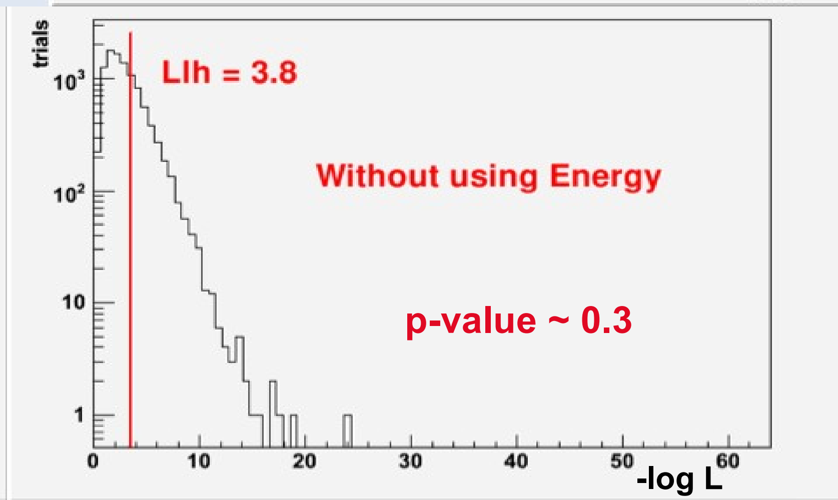
$$\lambda = -2 \cdot log \left[\frac{\mathcal{L}(\vec{x}_s, n_s = 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s, \hat{\gamma}, \hat{\sigma}_t, \hat{t}_o)} \right]$$

Time Analysis of Hotspot



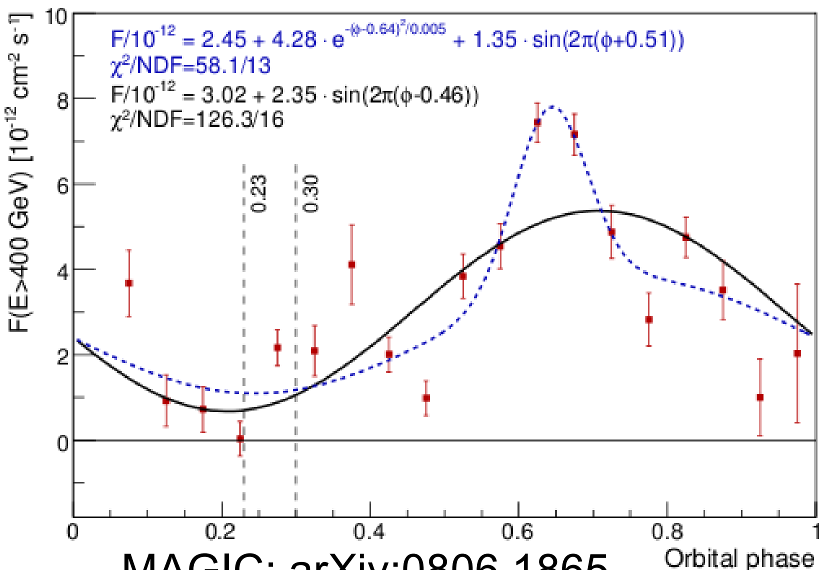






- None of the events contributing most strongly to the hotspot are closer together than 10 days. Events are distributed roughly evenly in time over the year.
- Neither analysis finds any significant single cluster of events in time.

LS I +61 303 Periodic Analysis



MAGIC: arXiv:0806.1865

- Binary system with 26.496d Radio Periodicity
- Clear TeV gamma ray periodicity observed by MAGIC
- Neutrino flux may also be periodic

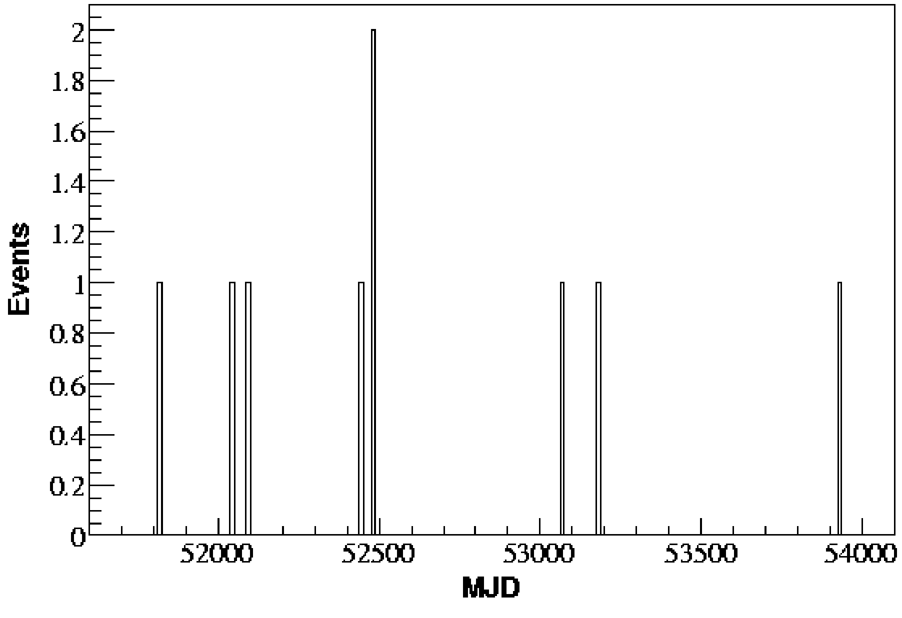
- Apply an analysis method similar to the hotspot analysis

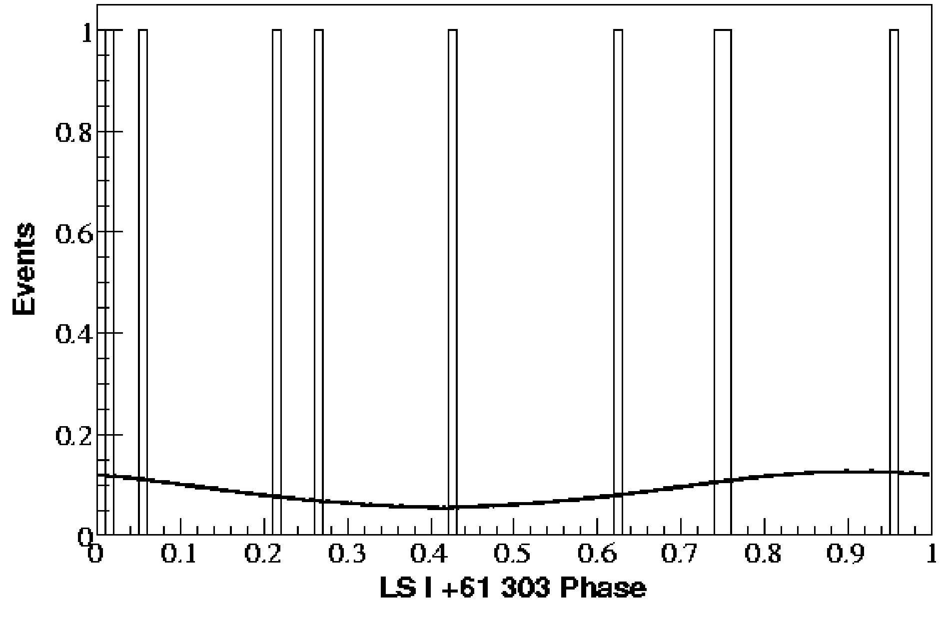
$$\mathcal{S}_i = \frac{1}{2\pi\sigma^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma^2}} \cdot P(Nch|\gamma) \cdot \frac{1}{\sqrt{2\pi}\sigma_w} e^{-\frac{(\phi_i - \phi_o)^2}{2\sigma_w^2}}$$

LS I +61 303 Periodic Analysis

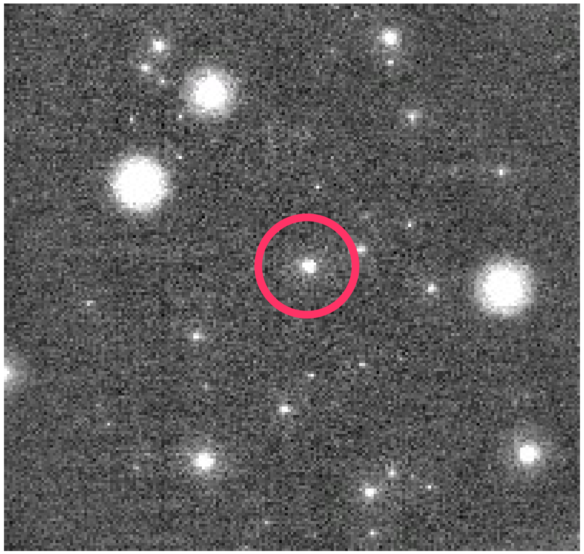
Nine events within 3 degrees, but no time correlation

ID	Nch	Phase	Year	Day	MJD	S/B
412098	42	0.211976	2000	281	51824.115521	20.611414
3219607	60	0.269850	2001	128	52037.616956	456.237216
8383068	32	0.423660	2001	185	52094.684294	15.964889
5825816	68	0.741784	2002	173	52447.561319	85.744617
6773244	57	0.951576	2002	205	52479.615961	1000.868687
3441011	20	0.050589	2002	208	52482.239398	15.908098
1718914	155	0.011549	2004	60	53064.117002	3907.663041
2314110	79	0.621906	2004	182	53186.273009	1004.641265
6875899	35	0.756908	2006	196	53931.738032	18.372001



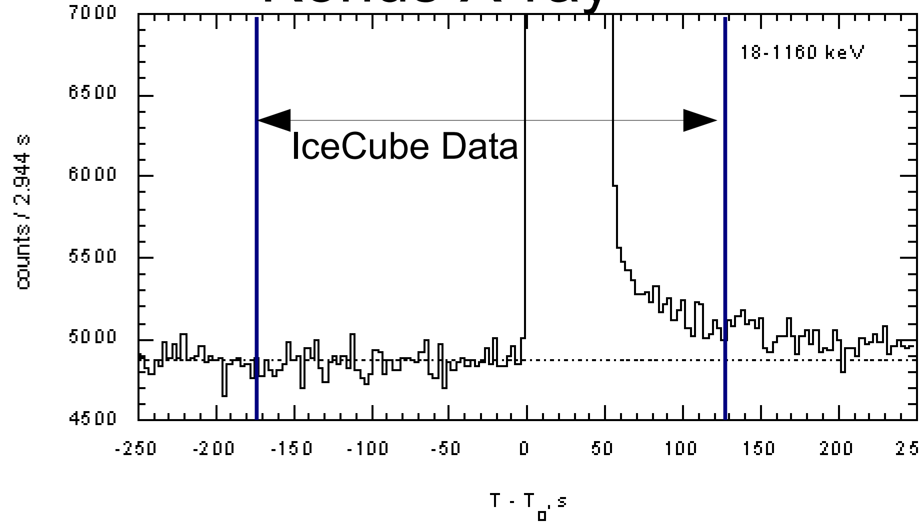


GRB 080319b



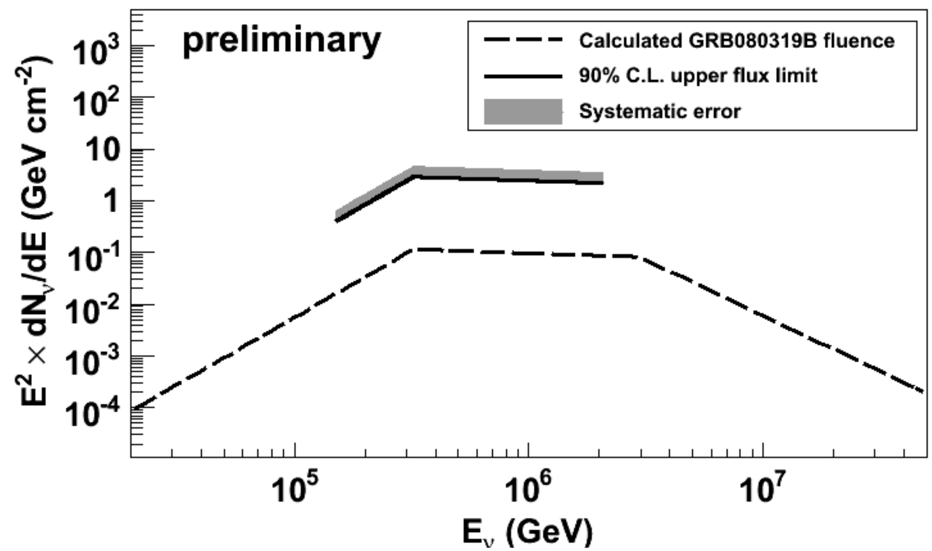
Pi of the Sky

Konus X-ray



Visual magnitude ~5.3

Data consistent with 0.0 events within window



AMANDA GRB Binned Searches

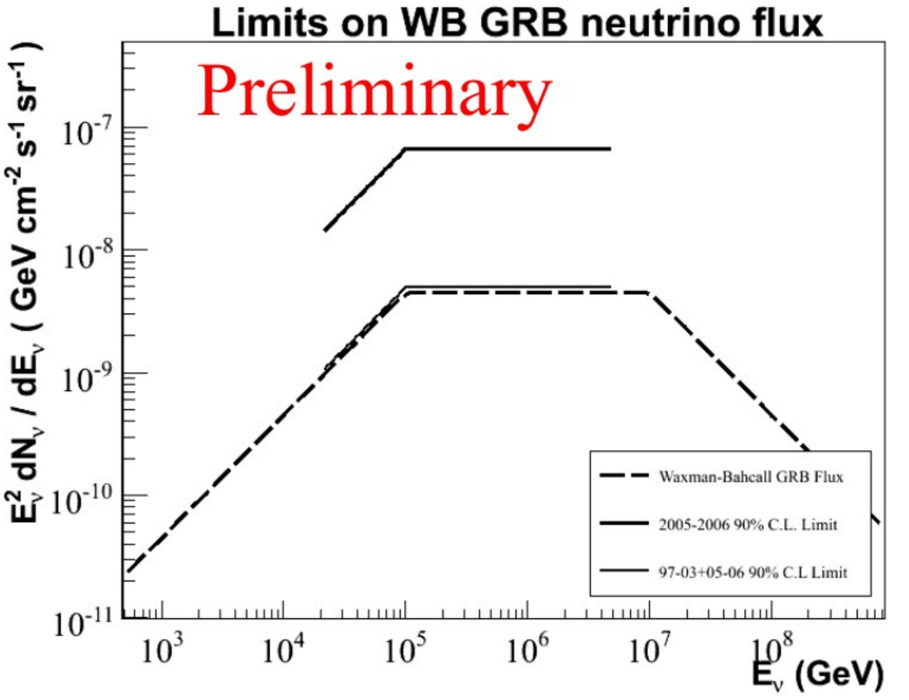
AMANDA 2005-2006 Expectation

	Upgoing	Final Cuts
Data	1703.9	0.00087
GRB Signal	0.501	0.166

86 GRBs

Observed

No events survive final cuts



2005-2006 90% CL Limit: **14.7 * WB flux**

1997-2003 + 2005-2006: **1.1 * WB flux**

The Near Future: IceCube-40

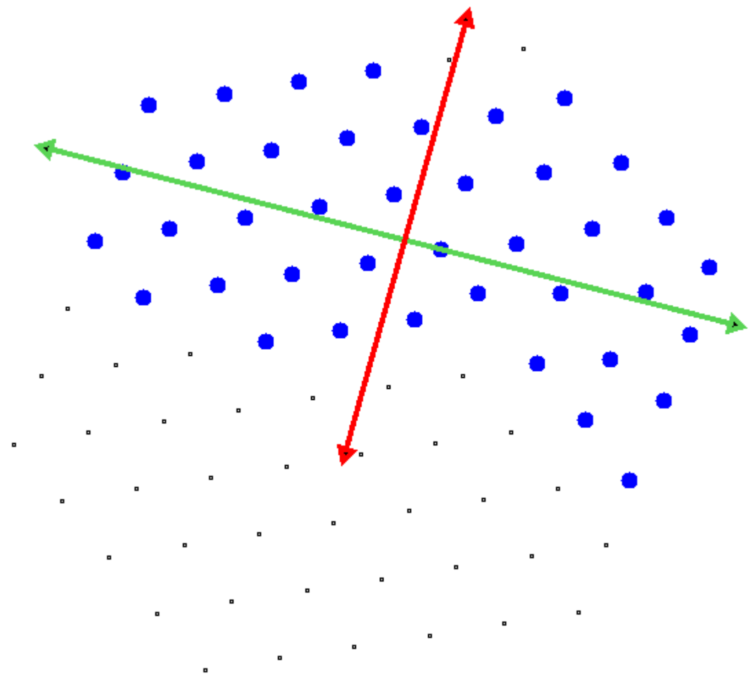
IceCube currently running with 40 strings deployed.

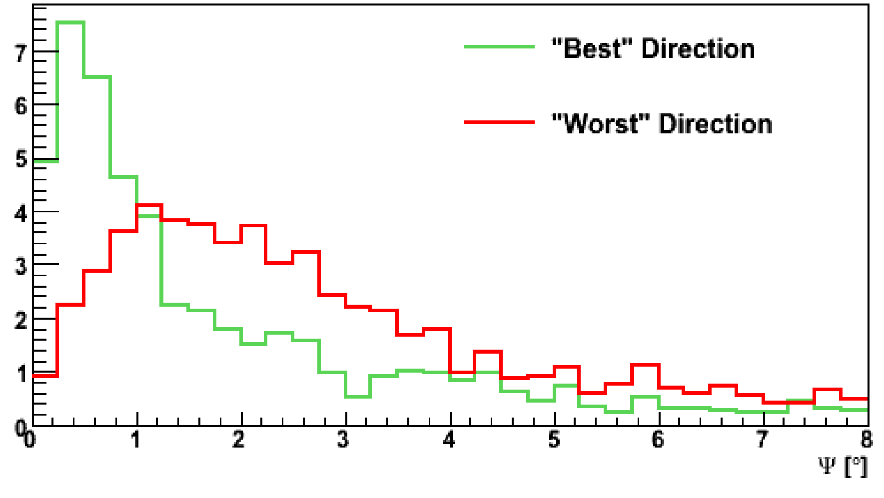
~ 2x effective area of 22 strings.

More fully contained strings.

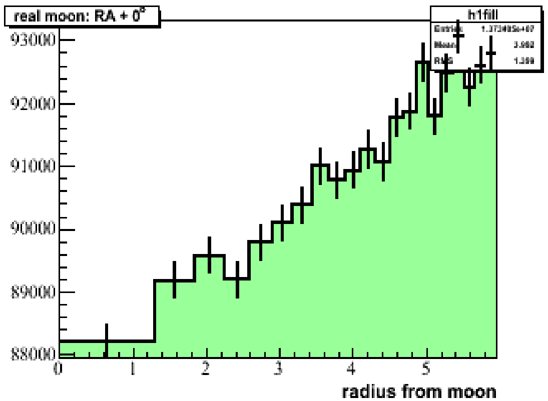
Short direction: angular resolution comparable to IceCube 22.

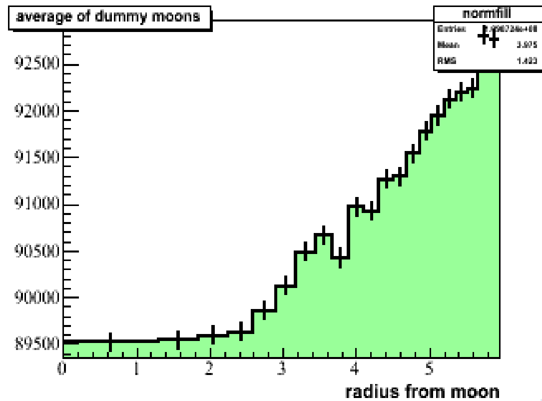
Long direction: angular resolution comparable to full IceCube 80 configuration.

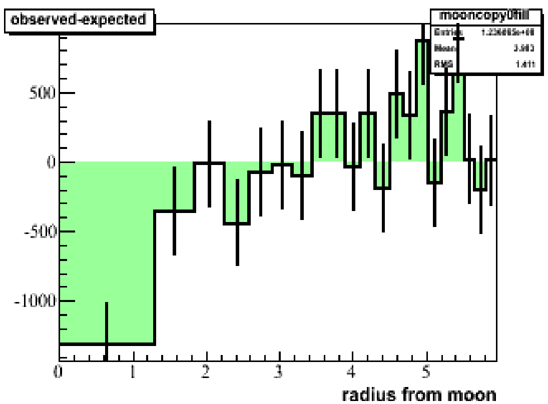


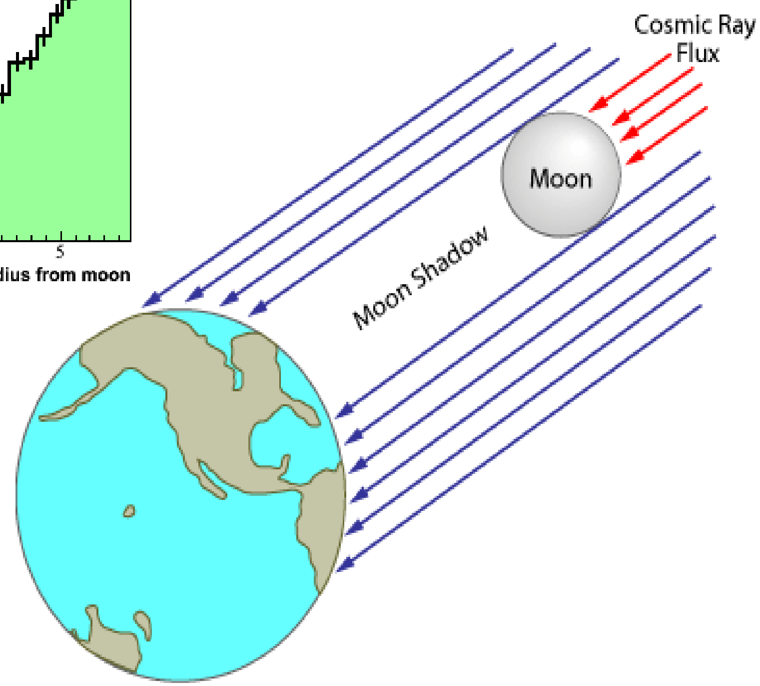


Moon Shadow









4.2σ deficit of events from direction of moon in the IceCube 40-string detector (3 months of data) confirms pointing accuracy

Calibration with moon ~monthly with completed IceCube detector

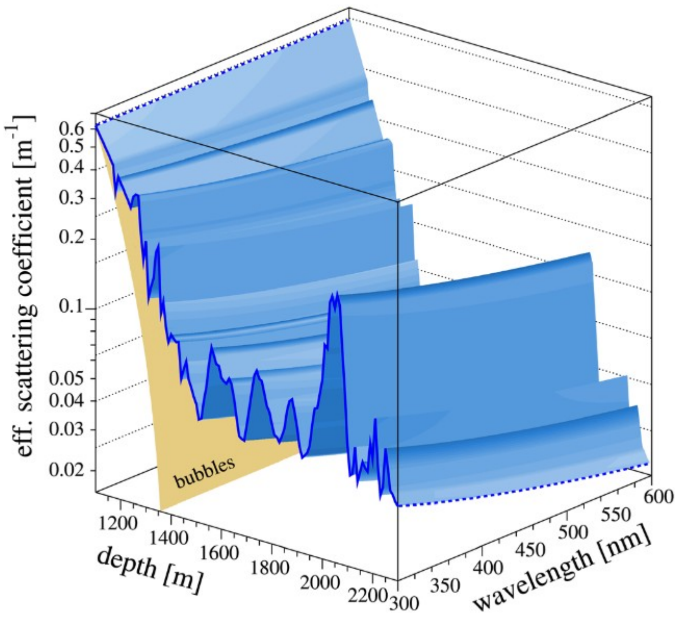
Conclusions

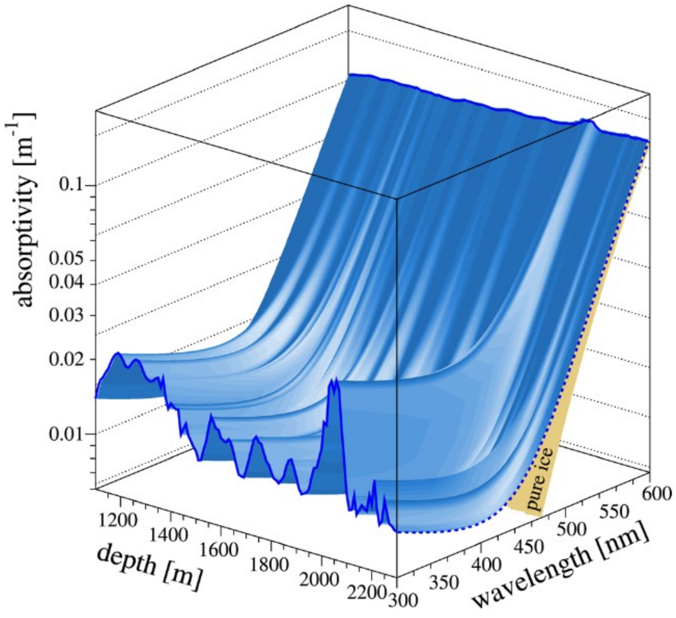
- New methodology and increasing detector size are improving the current neutrino point source sensitivity

- No evidence of neutrino point sources observed by AMANDA in 3.8 years of livetime.

- The hottest spot observed by IceCube-22 will be tested with data from IceCube-40

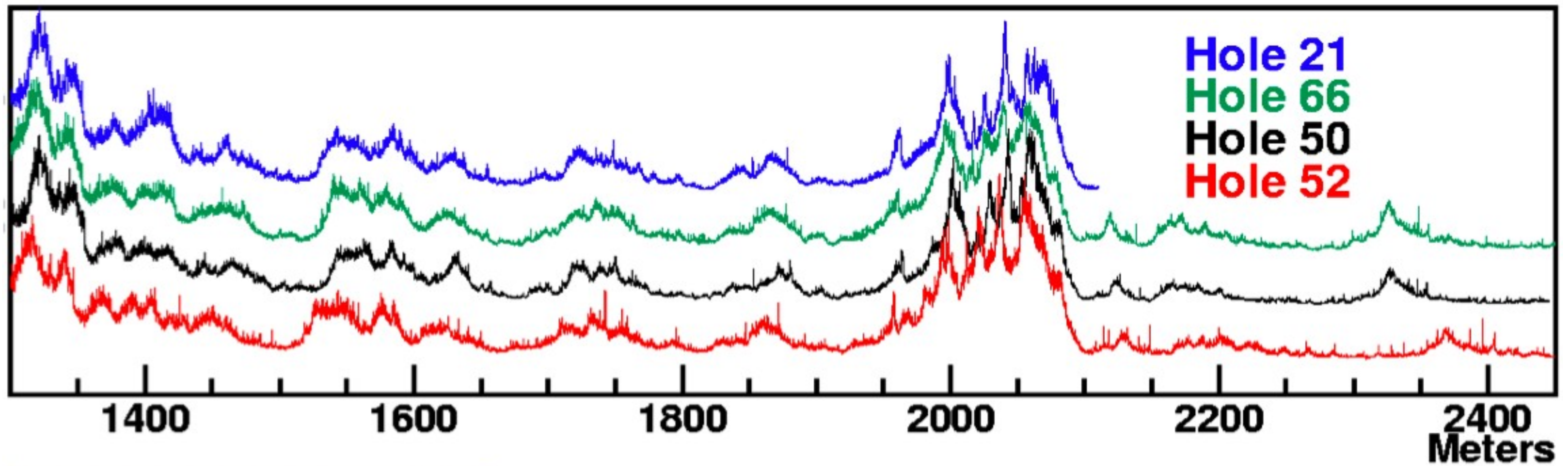
Ice: The Optical Medium





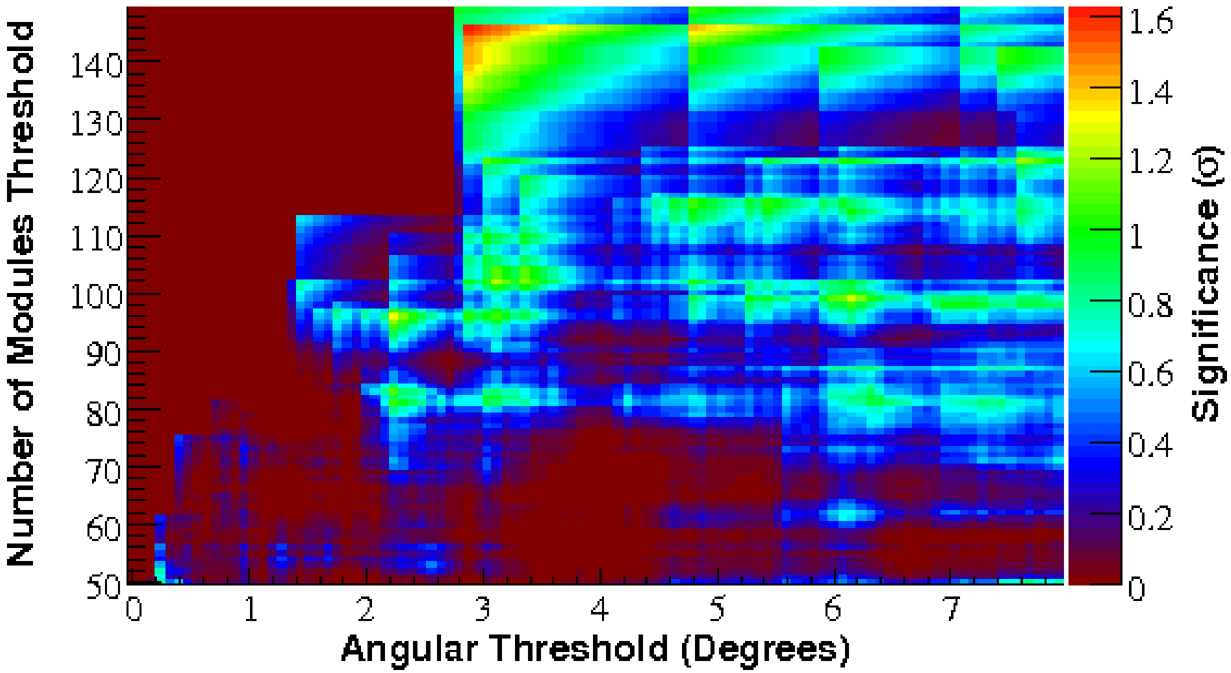
λ_{abs} ~100m

λ_{scat} ~20m



Search for Autocorrelations

- Search for event clustering at angular scales comparable to detector resolution
  - Signal scenario: A number of small event clusters
- Method: Count the number of event pairs given a maximum angular separation and minimum Nch and compare to distributions from data with randomized RA



Max significance: 1.6σ

99 out of 100 sets of randomized data have a max significance of 1.6σ or greater