

Neutrino Astrophysics with IceCube

Jim Braun for the IceCube Collaboration
INFO Workshop, Santa Fe, 2009

The IceCube Collaboration

USA:

Bartol Research Institute, Delaware
University of California, Berkeley
University of California, Irvine
Pennsylvania State University
Clark-Atlanta University
Ohio State University
Georgia Tech
University of Maryland
University of Alabama, Tuscaloosa
University of Wisconsin-Madison
University of Wisconsin-River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University and A&M
College, Baton Rouge
University of Alaska, Anchorage

Sweden:

Uppsala Universitet
Stockholm Universitet

UK:

Oxford University

Netherlands:

Utrecht University

Switzerland:

EPFL

Belgium:

Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

Germany:

DESY-Zeuthen
Universität Mainz
Universität Dortmund
Universität Wuppertal
Humboldt Universität
MPI Heidelberg
RWTH Aachen

Japan:

Chiba University

New Zealand:

University of
Canterbury

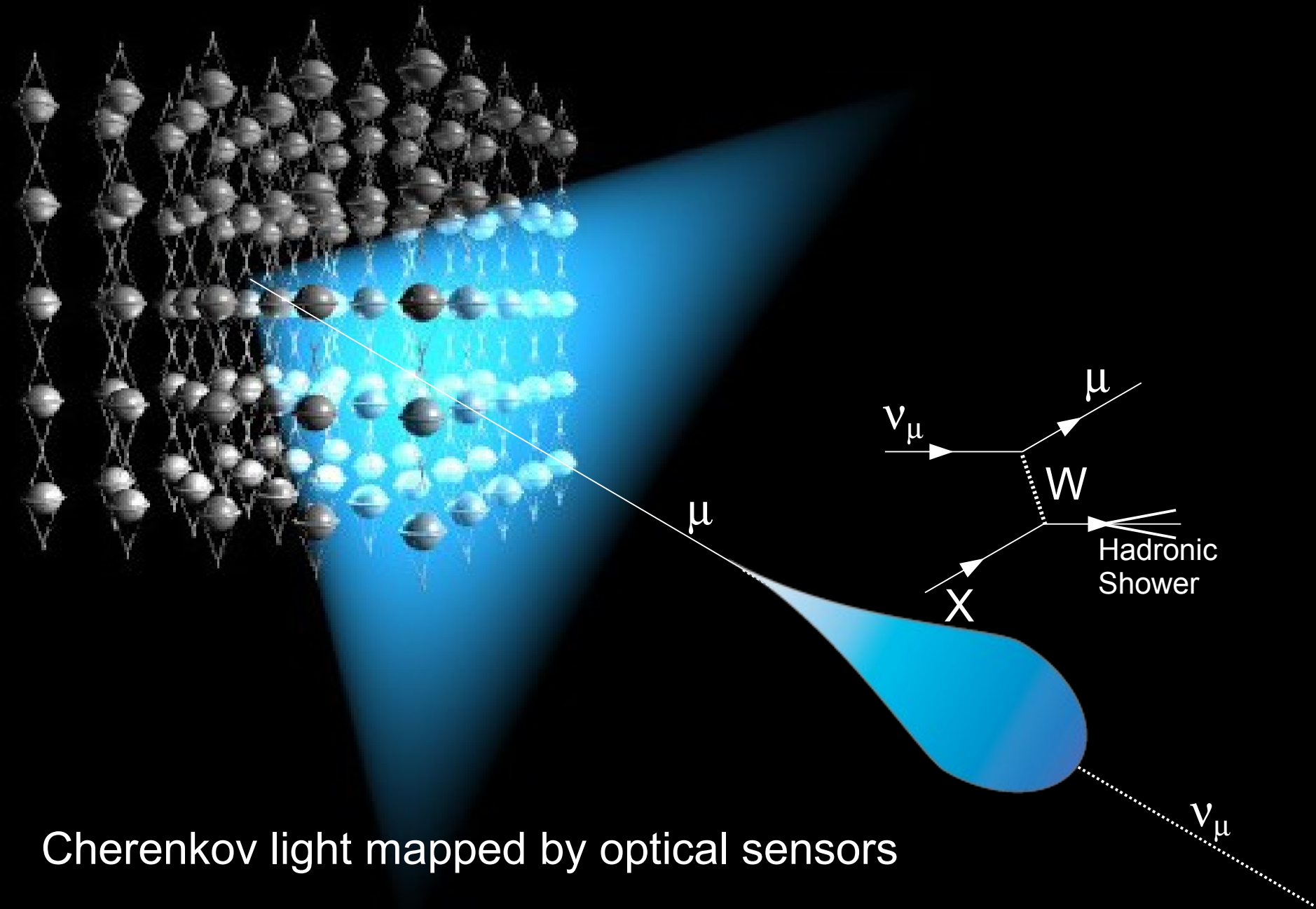
33 institutions, ~250 members
<http://icecube.wisc.edu>

IceCube: Design and Construction Status

Neutrino Astrophysics with IceCube:

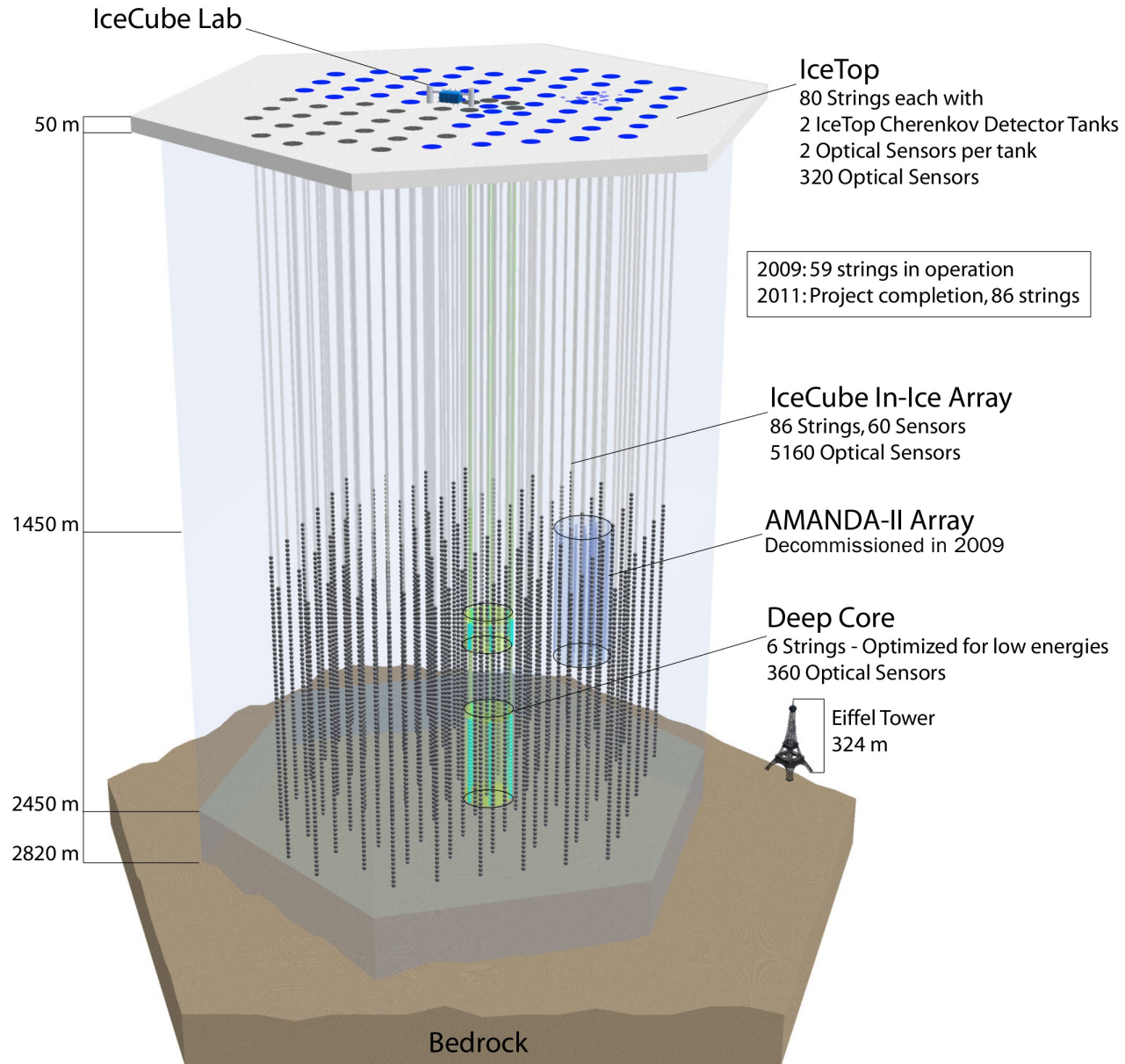
- Astrophysical Neutrino Searches
- Supernovae
- Atmospheric Neutrinos
- IceCube DeepCore Extension
- Indirect Dark Matter Searches

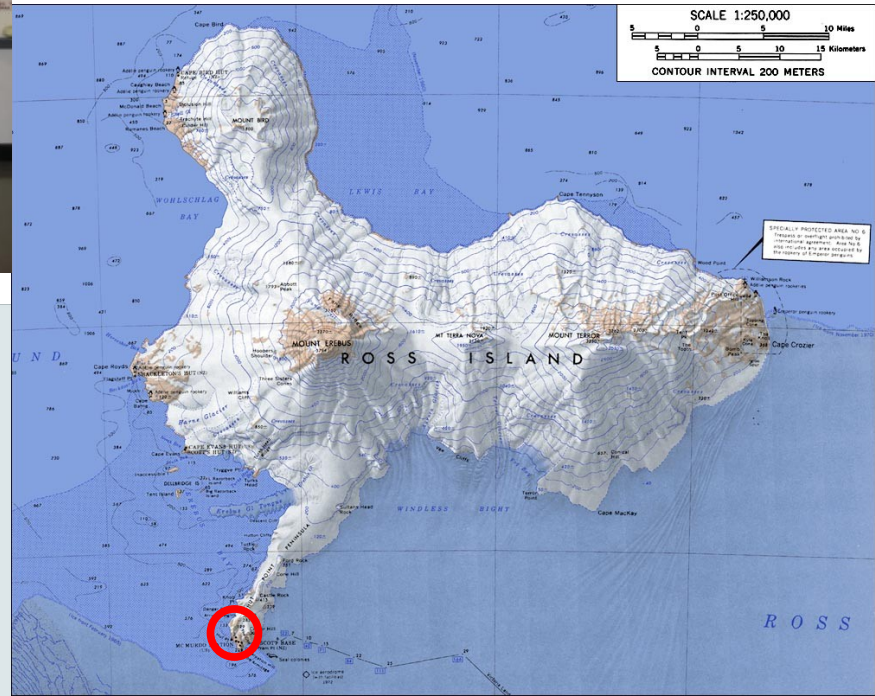
Optical Cherenkov Detection

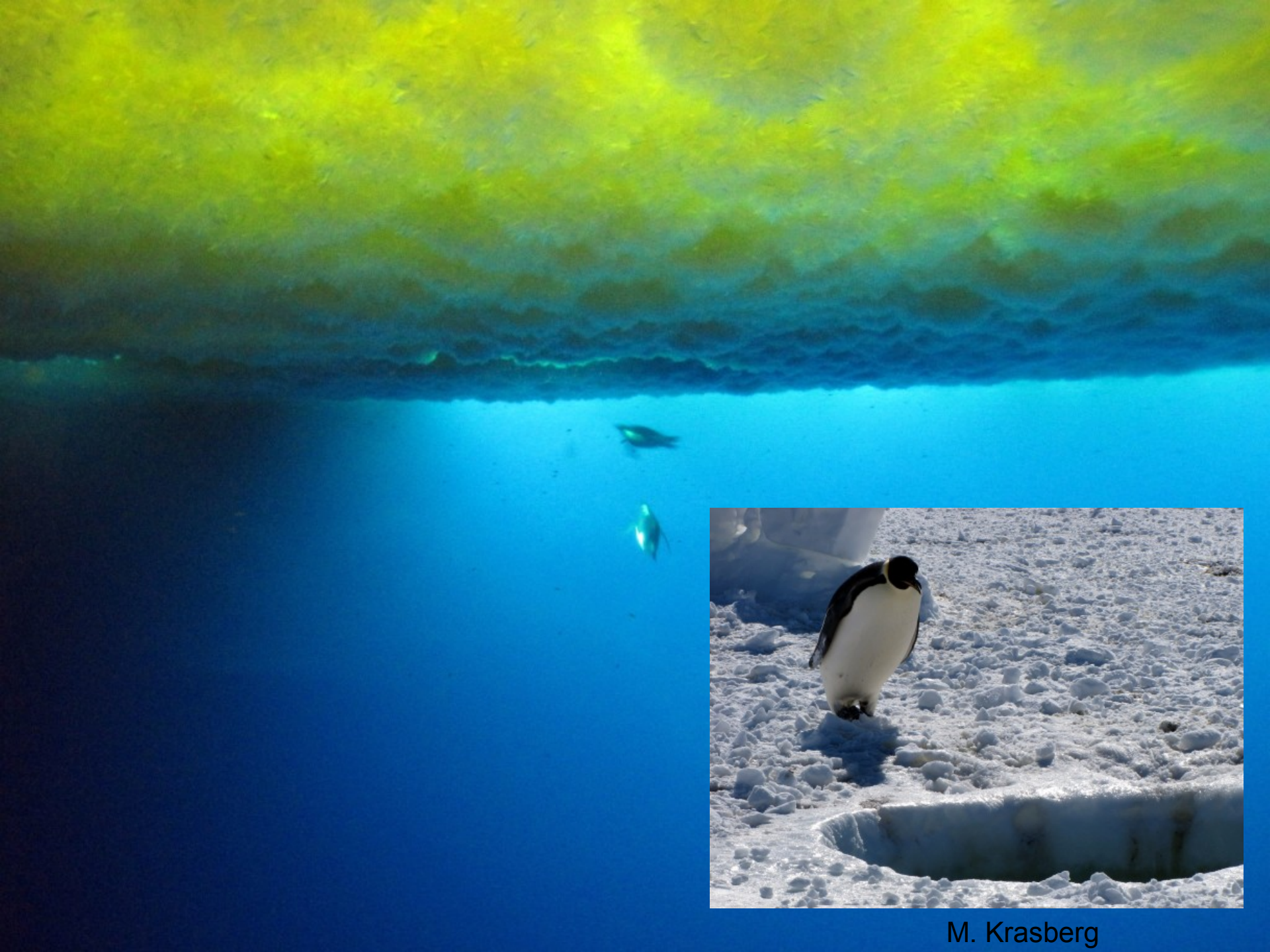


Cherenkov light mapped by optical sensors

IceCube





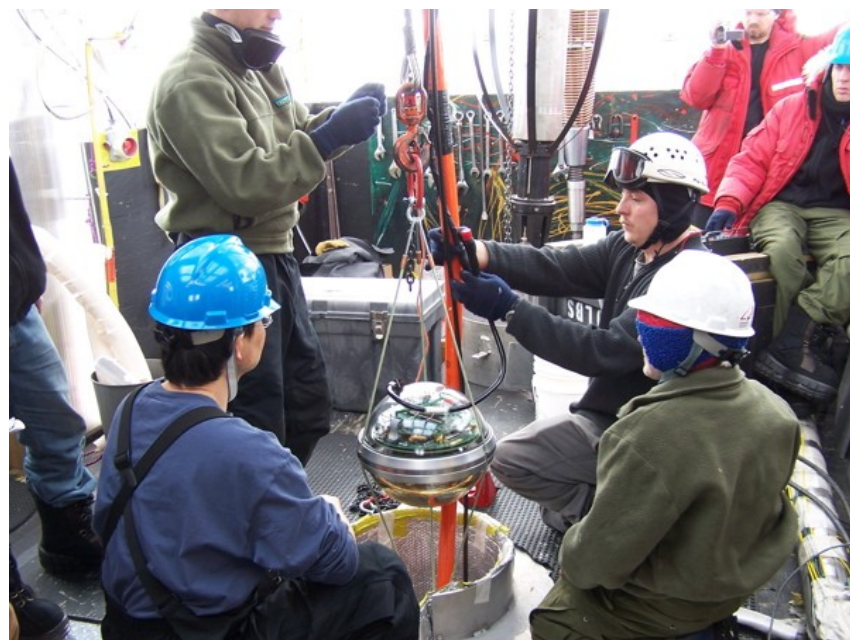
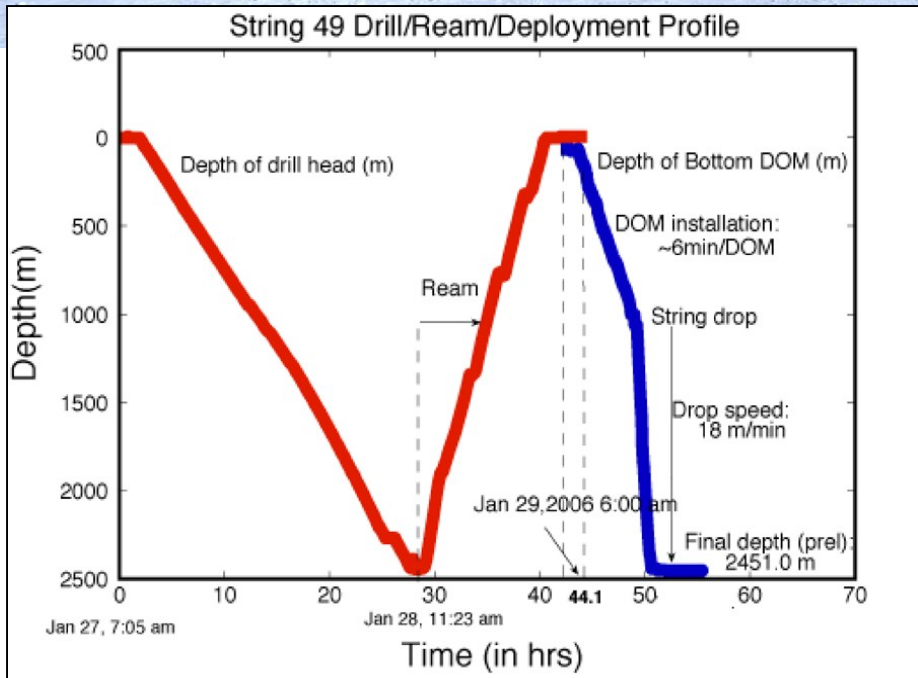


M. Krasberg

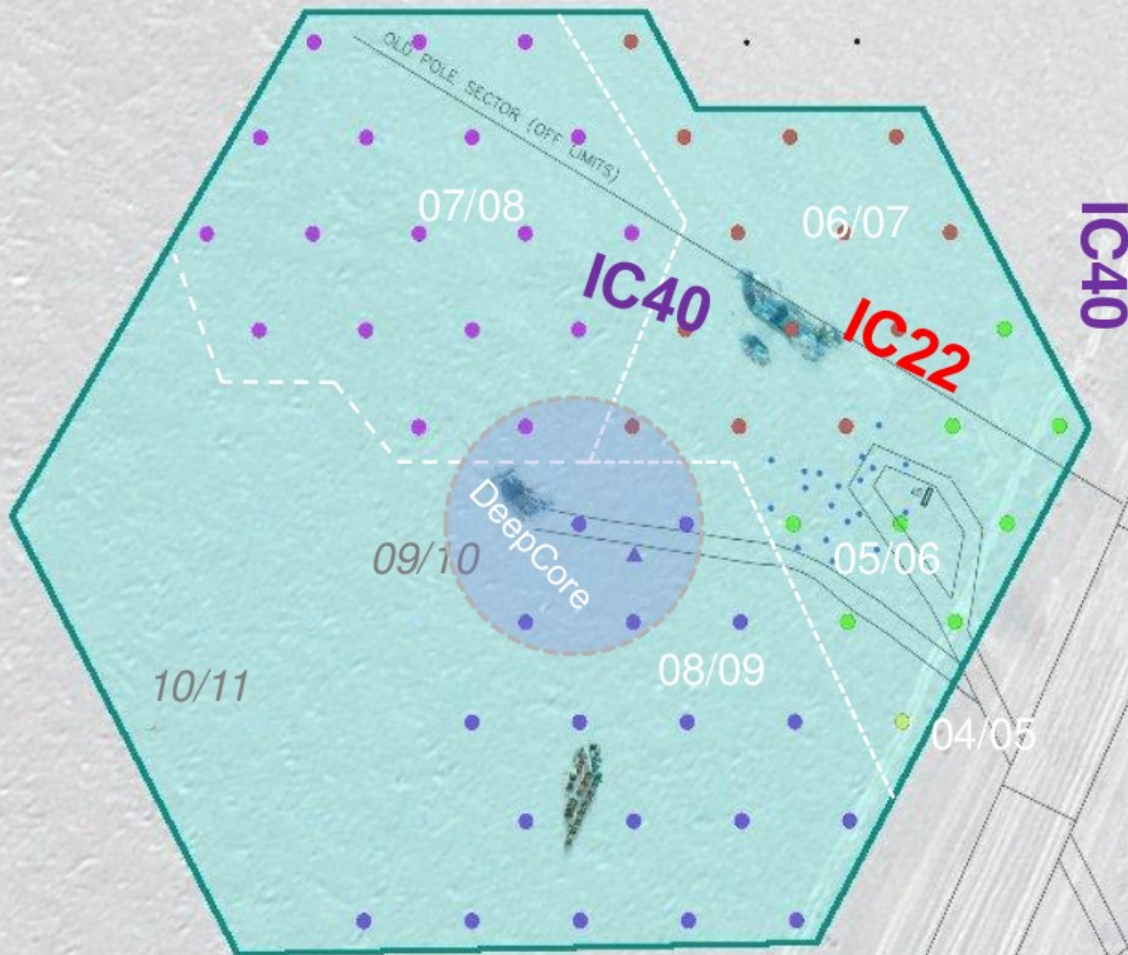




Drilling and Deployment



IceCube Detector Status



Season	Deployed
2004-2005	1 string
2005-2006	8 strings
2006-2007	13 strings
2007-2008	18 strings
2008-2009	18+1 strings

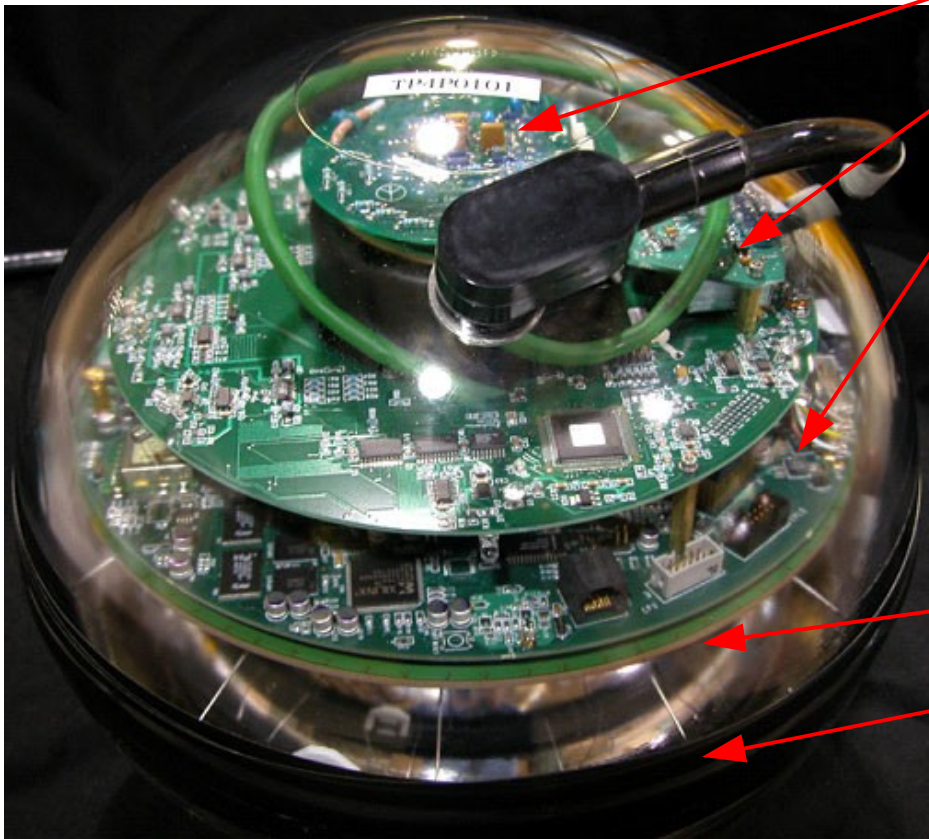
IC22

IC40

SECTOR



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

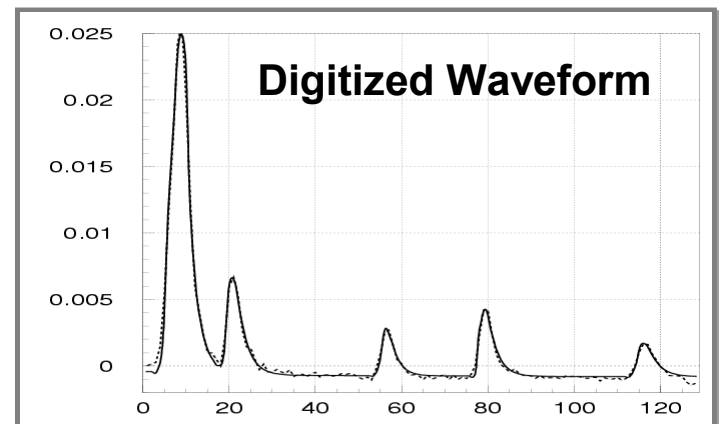
NIM A 601, 294 (2009).

10 inch Hamamatsu R7081 PMT

Pressure Sphere

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

Optical noise rate ~ 300 Hz in ice



Time Calibration

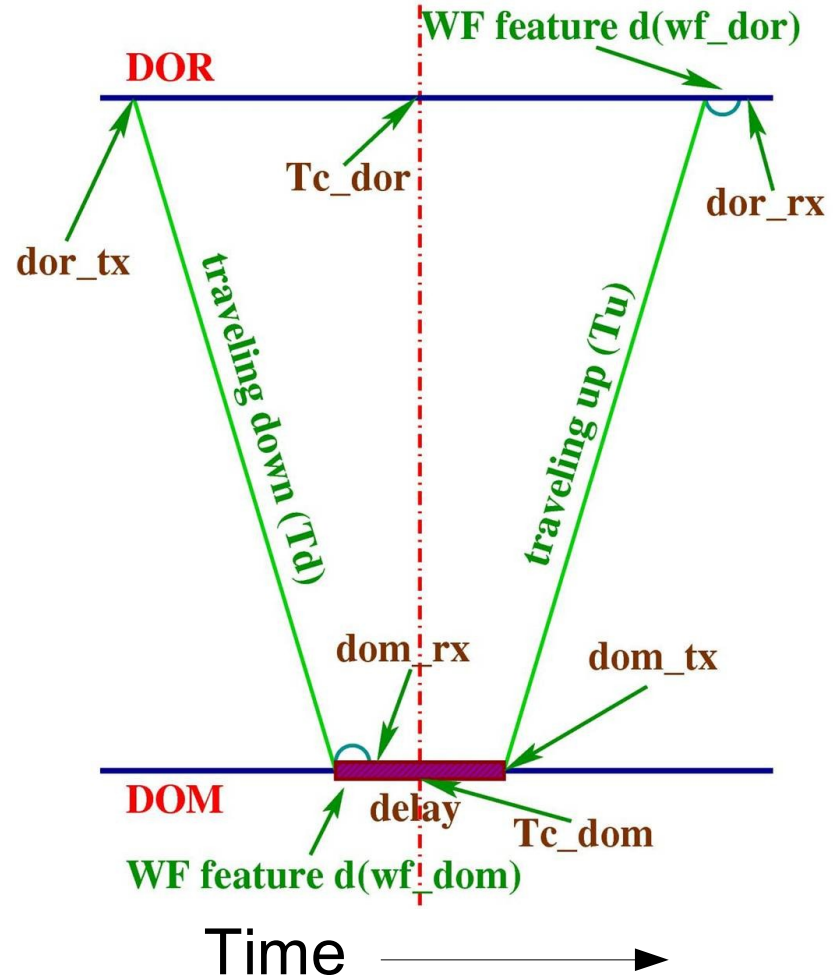
Synchronize DOM clock with GPS master clock

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

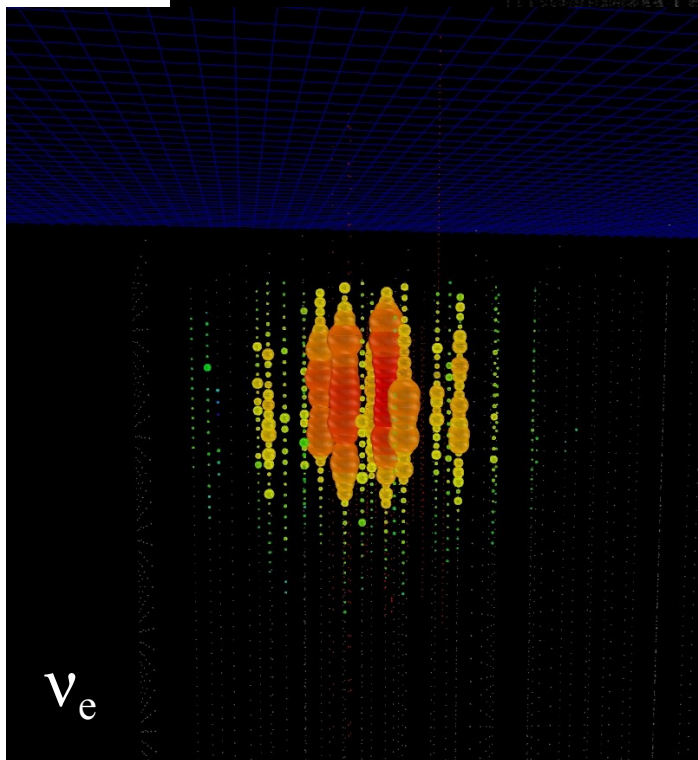
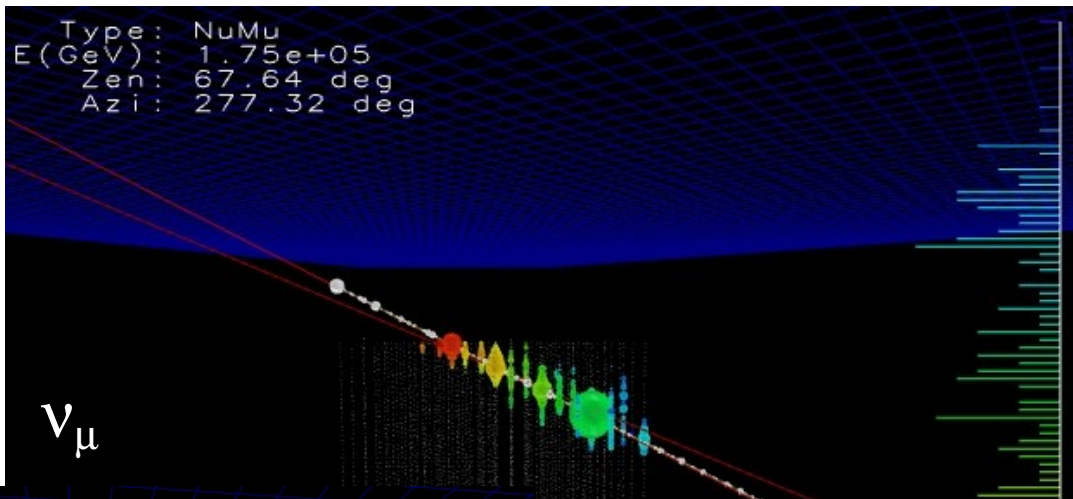
Symmetric DOR-DOM pulses are timestamped at TX and RX

Average of DOM and DOR TX and RX times provides a calibration point

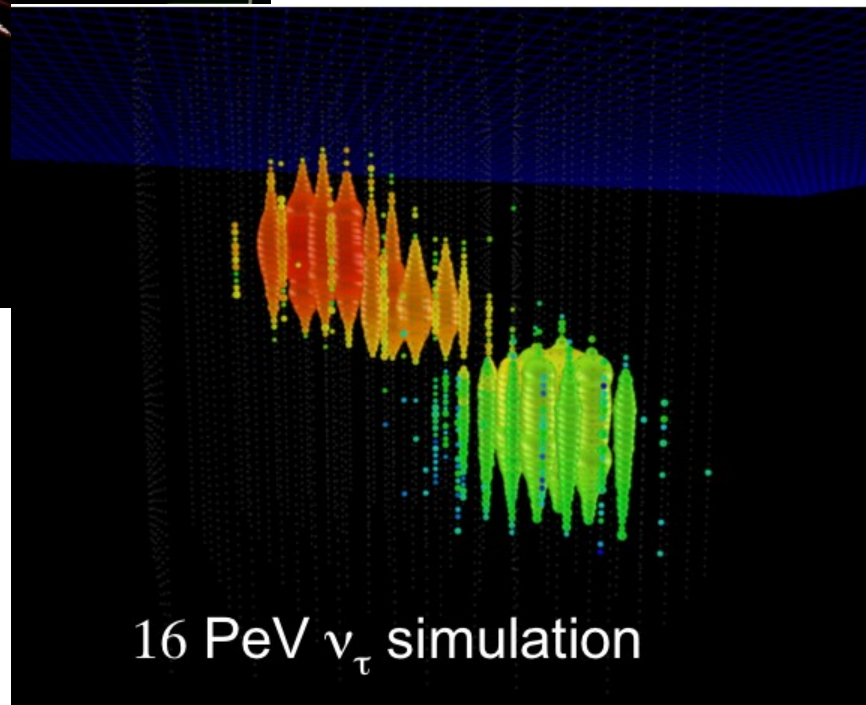
Time calibration is automatic and accurate to ~ 2 ns



Event Topologies



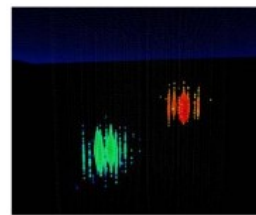
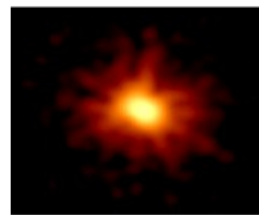
52752ns]





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

Neutrino Astrophysics with IceCube

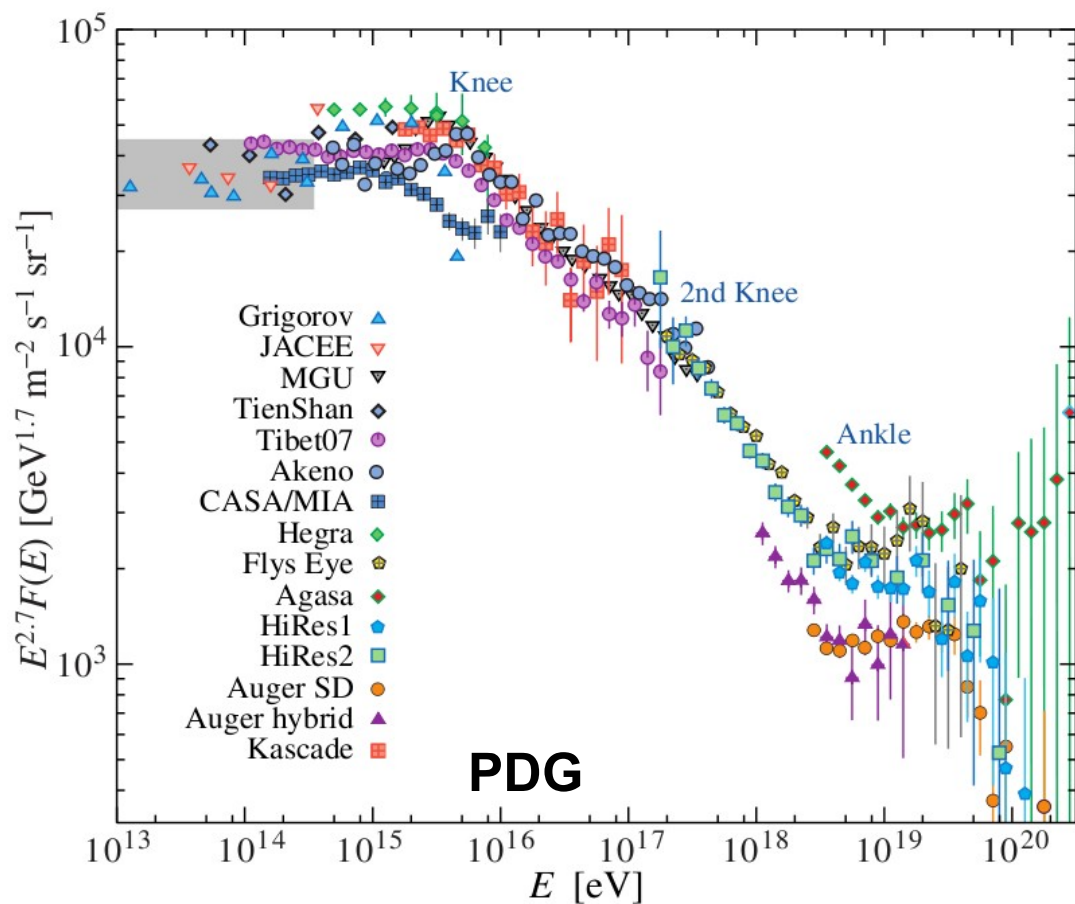


Energy range	~MeV	GeV-TeV	TeV-PeV	PeV-EeV	>EeV
Physics	Supernovae	Dark Matter, Oscillations, Atmospheric ν ,	Point sources, GRB, Diffuse	GZK Neutrinos, Cosmic Rays	?
Signature	Average increase in the PMT counting rate	Tracks, Contained Events	Tracks, Cascades	Tracks, Cascades, Double Bang, Lollipops	Christmas Tree

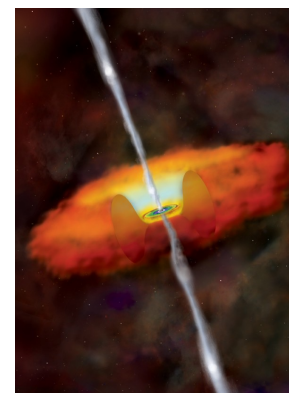
Many new results at ICRC 2009

Cosmic Ray Accelerators

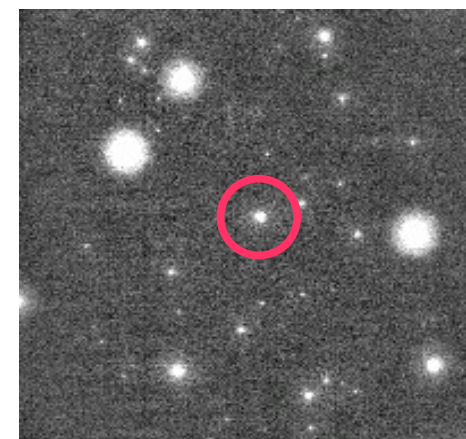
Fermi shock acceleration with spectral index $\Gamma \sim -2$



SN Remnants



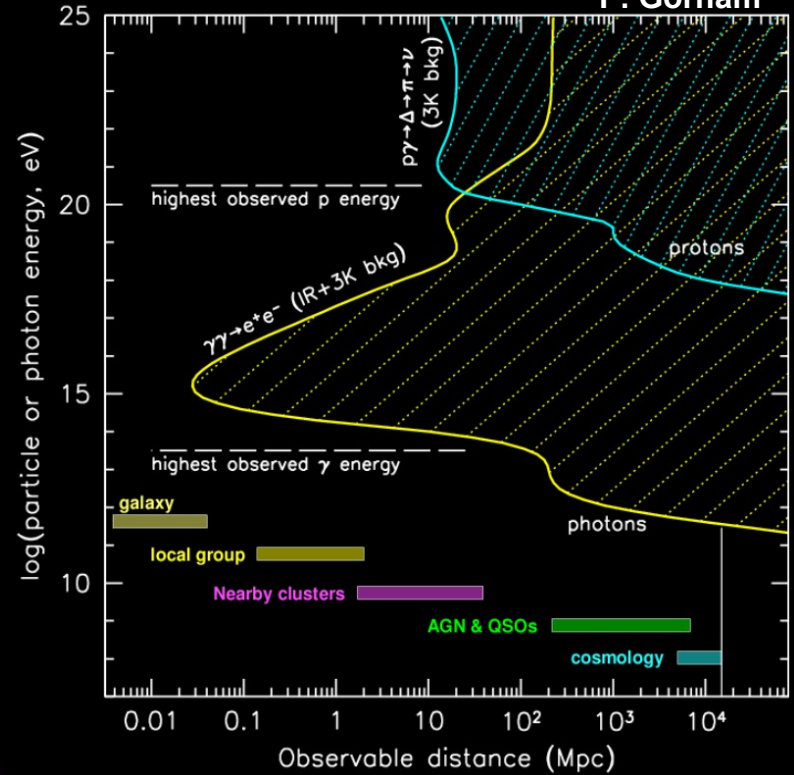
AGN



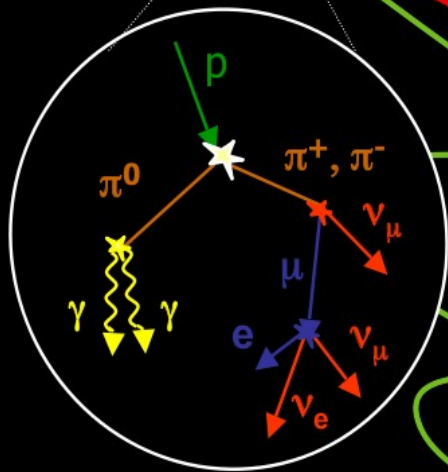
GRB 080319b

Astronomical Messengers

P. Gorham

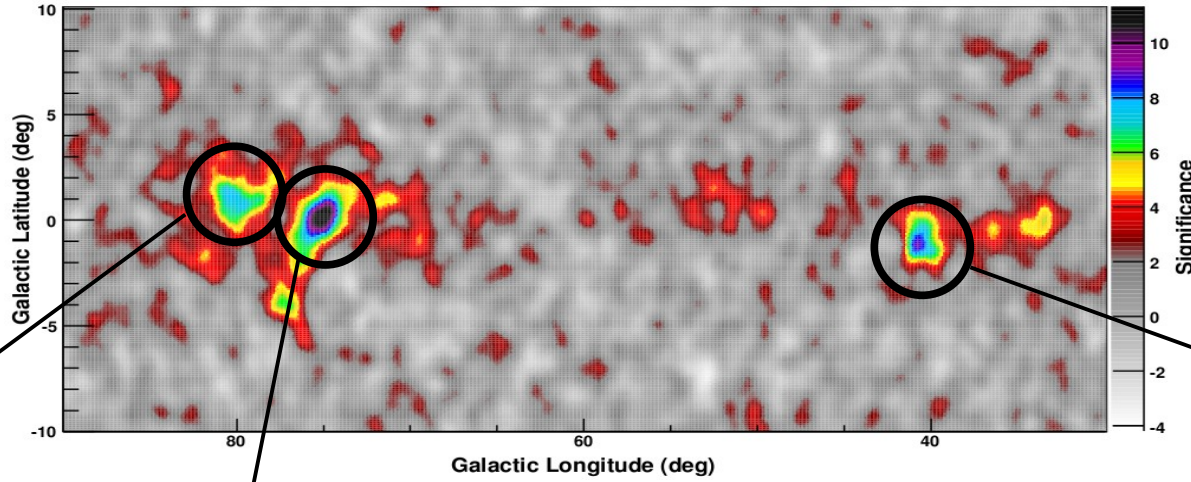


Astrophysical beam dump



Milagro Sources

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



MGRO
J2031+41

$\Gamma \sim -2$

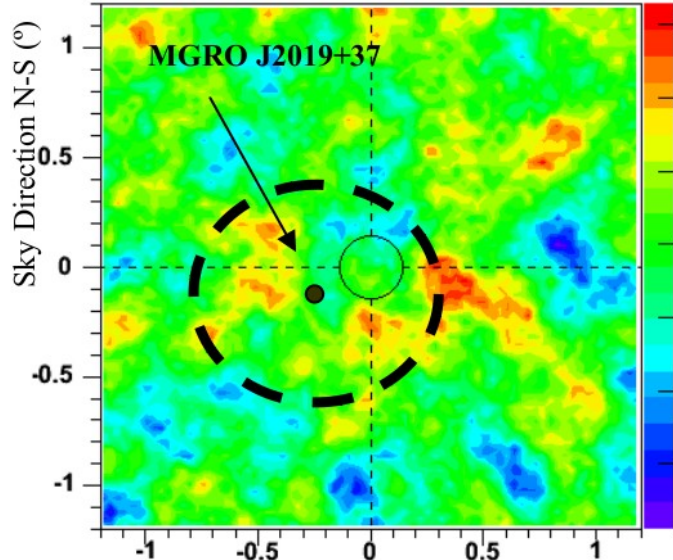
MAGIC

arXiv:0801.2391v2

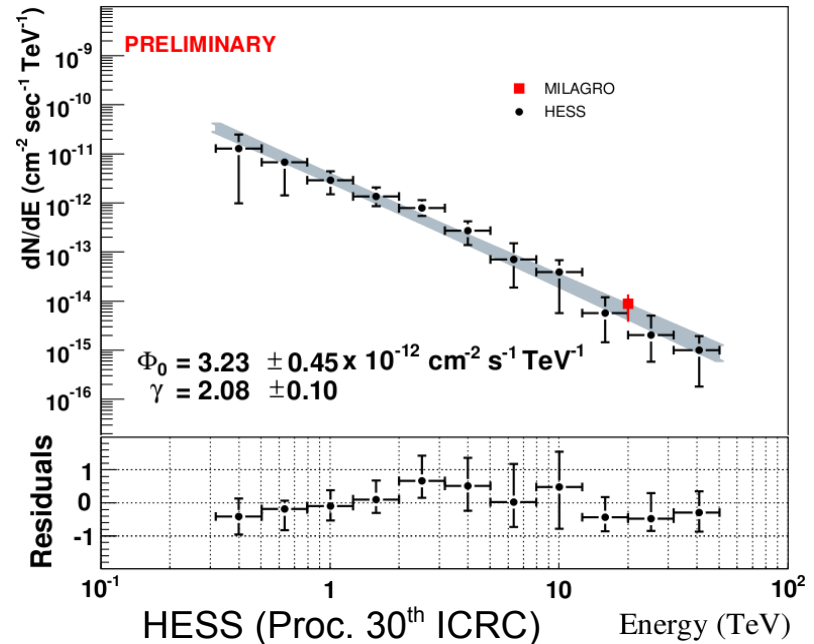
MGRO
J1906+08

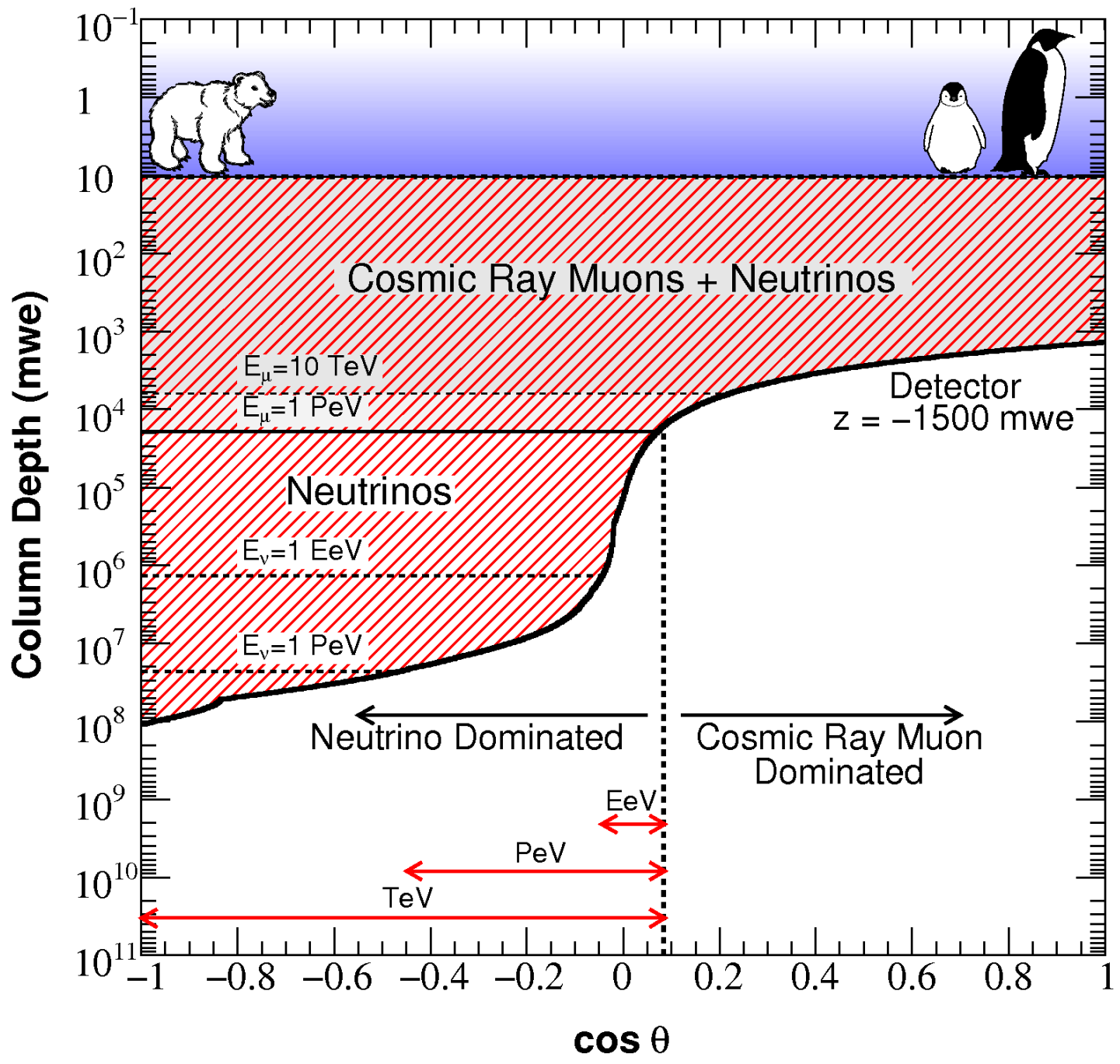
$\Gamma \sim -2$

MGRO J2019+37 $\Gamma > -2.2$

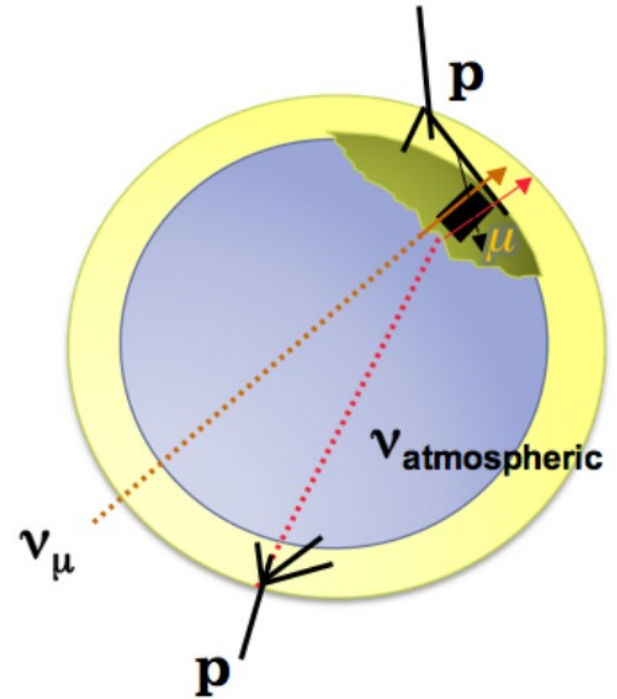
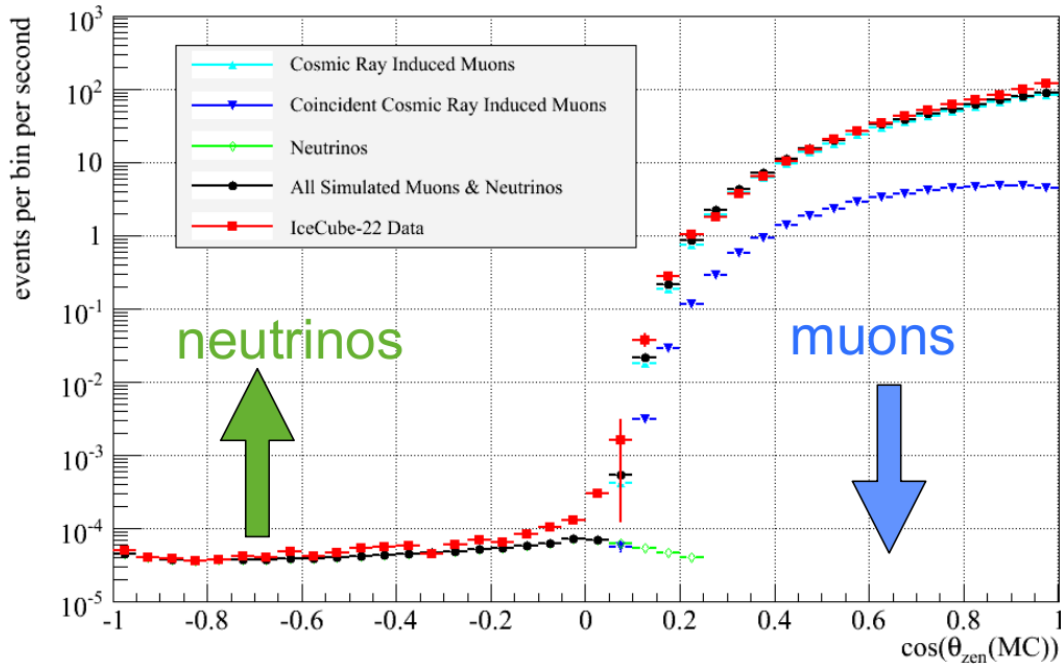


VERITAS (Proc. 30th ICRC) Sky Direction E-W (°)



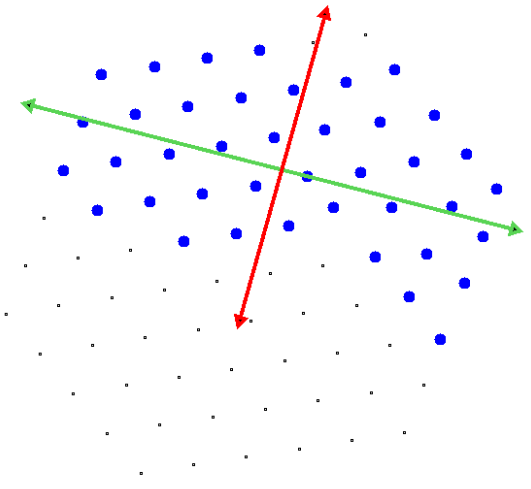
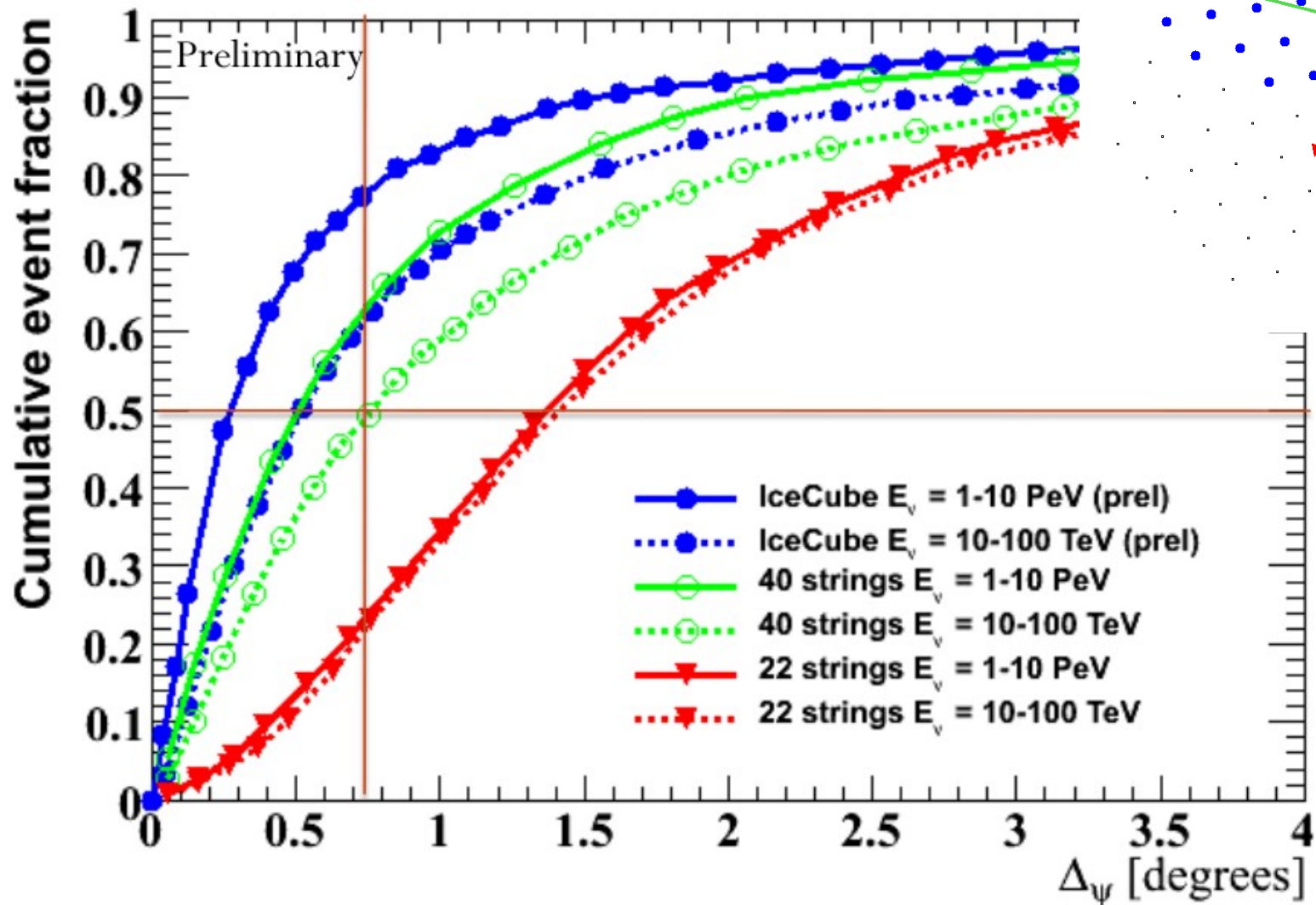


IceCube Muon Events

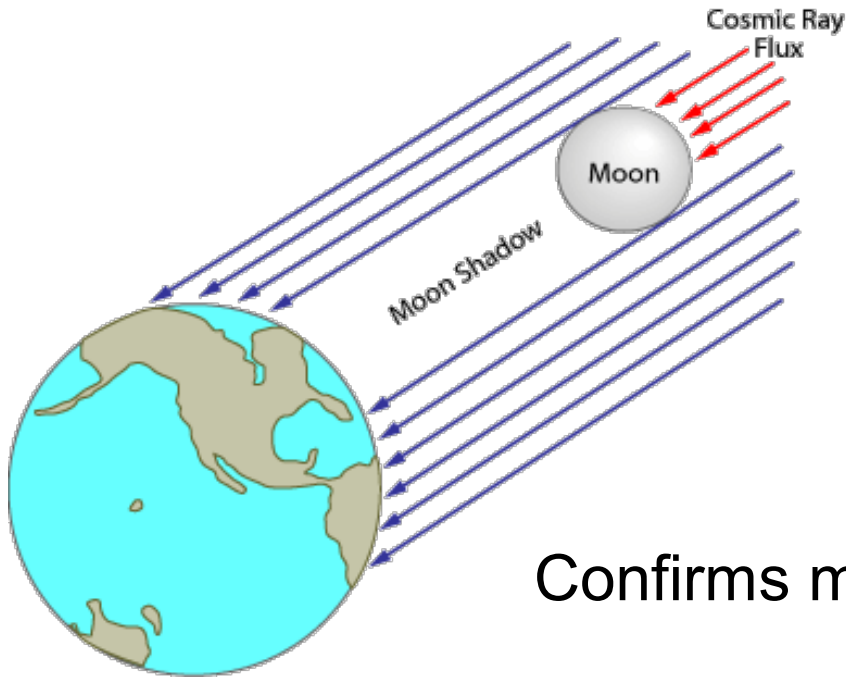


Strings	μ rate	ν rate
AMANDA	80 Hz	4.8 / day
IC22	550 Hz	28 / day
IC40	1200 Hz	110 / day*
IC80	1650 Hz*	220 / day*

Muon Angular Resolution

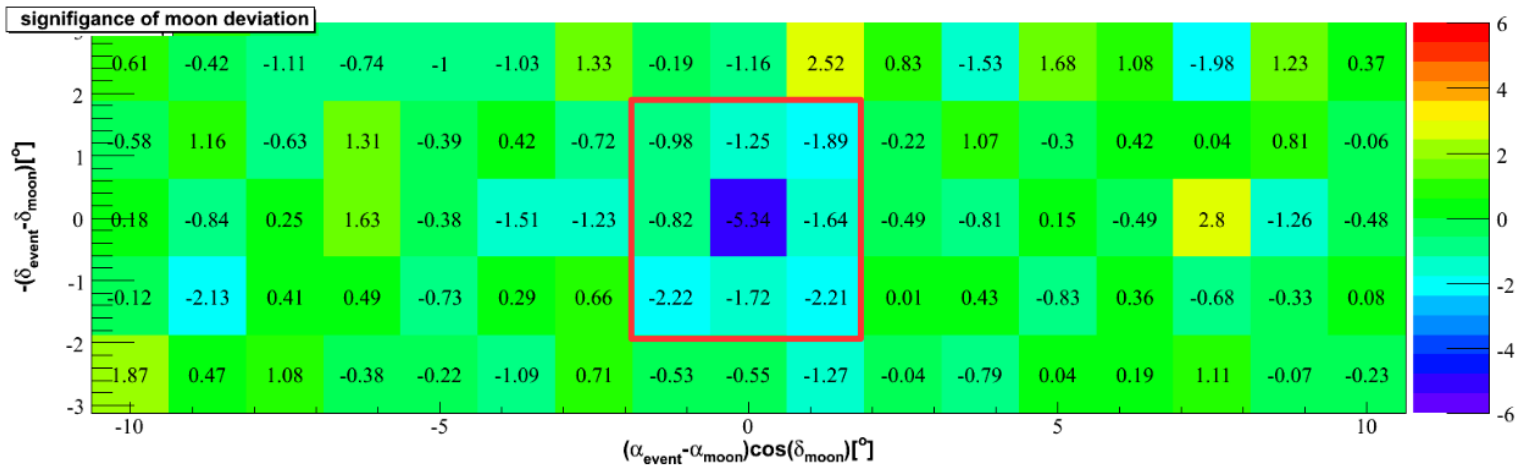


The Moon Shadow

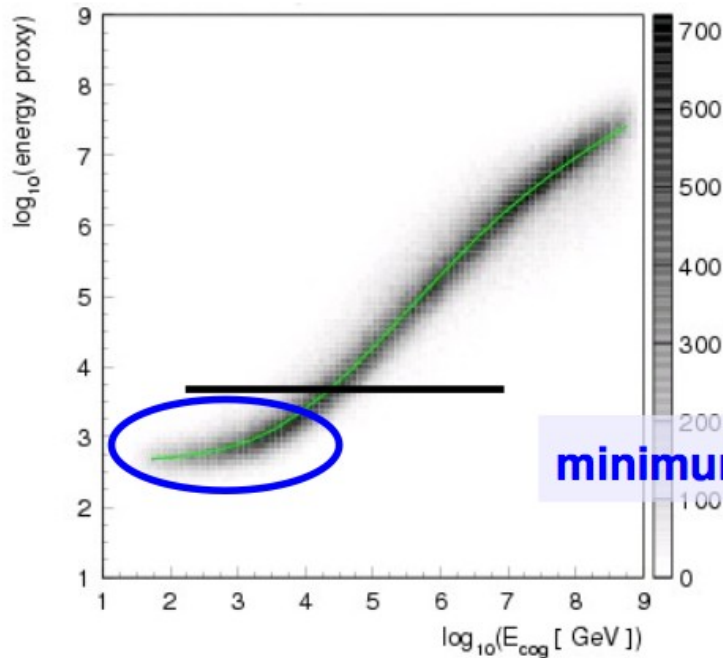
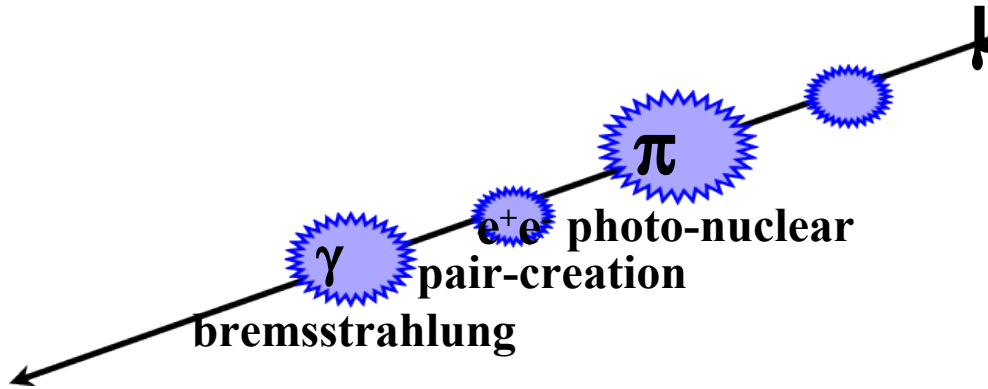


5.34 σ deficit found
6.1 σ expected

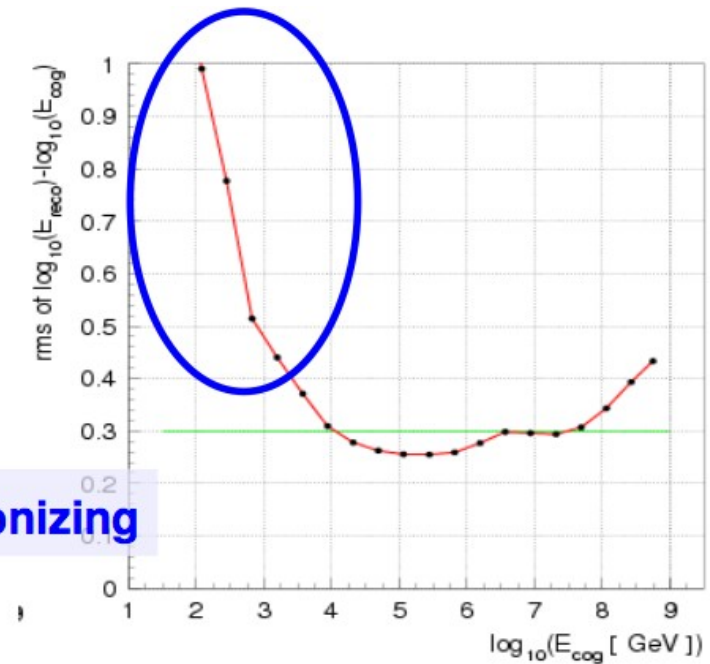
Confirms muon pointing resolution in IC-40



Muon Energy Resolution



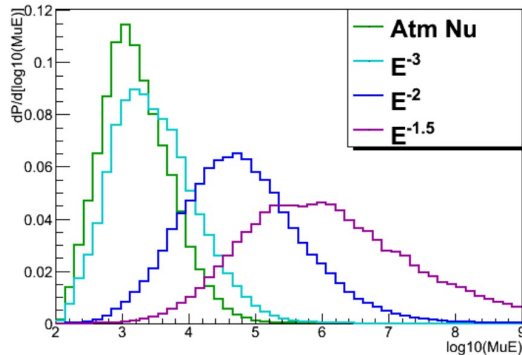
Source: D. Chirkin, UW



Energy Resolution
 $\sigma(\log_{10} E) \sim 0.3$

Astrophysical Neutrino Searches

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



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

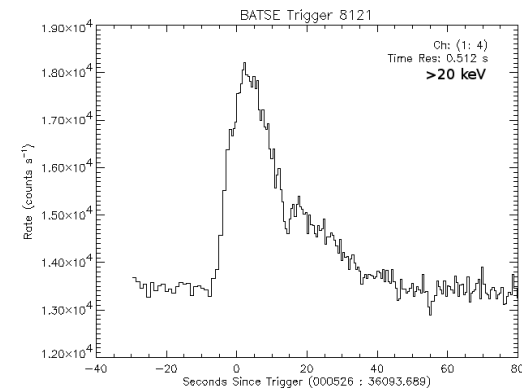
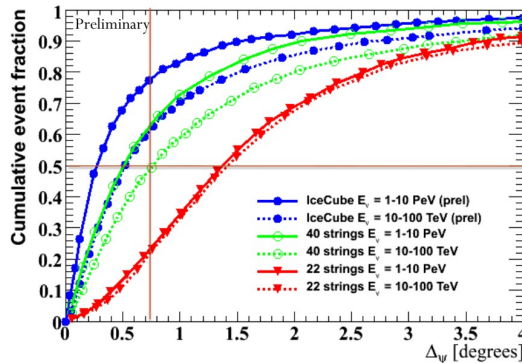
→ Point Source Search

+

Time

Neutrinos from GRBs and flaring AGN should be clustered in time

→ Time-Dependent Point Source Search



Each term provides additional power to reject background

Neutrino Point Source Search

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

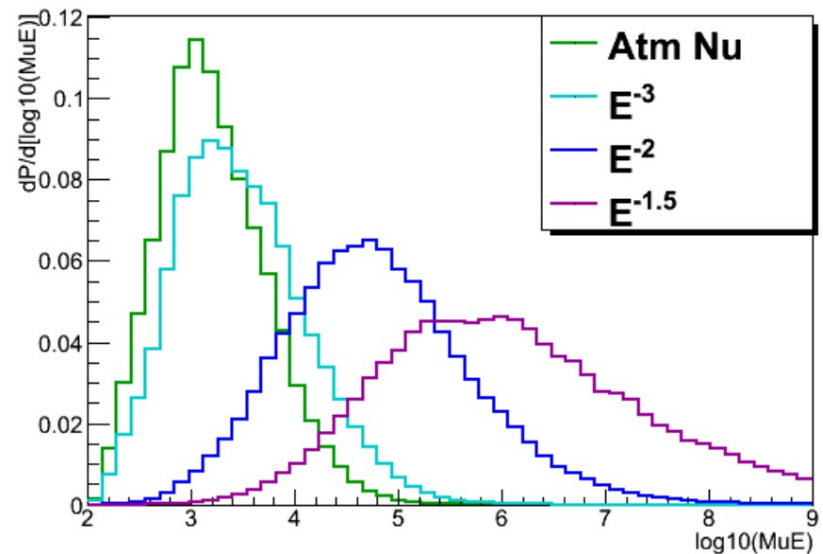
Space Angle Term:

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:

Assume emission follows a power law energy spectrum



Neutrino Point Source Search

Background: Events are uniform in RA

$$\mathcal{B}_i = \frac{1}{\Omega} \cdot P_{bkgd}(E_i)$$

Assume a fraction of events are signal, remainder are background

Partial probability for each event:

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

Likelihood function:

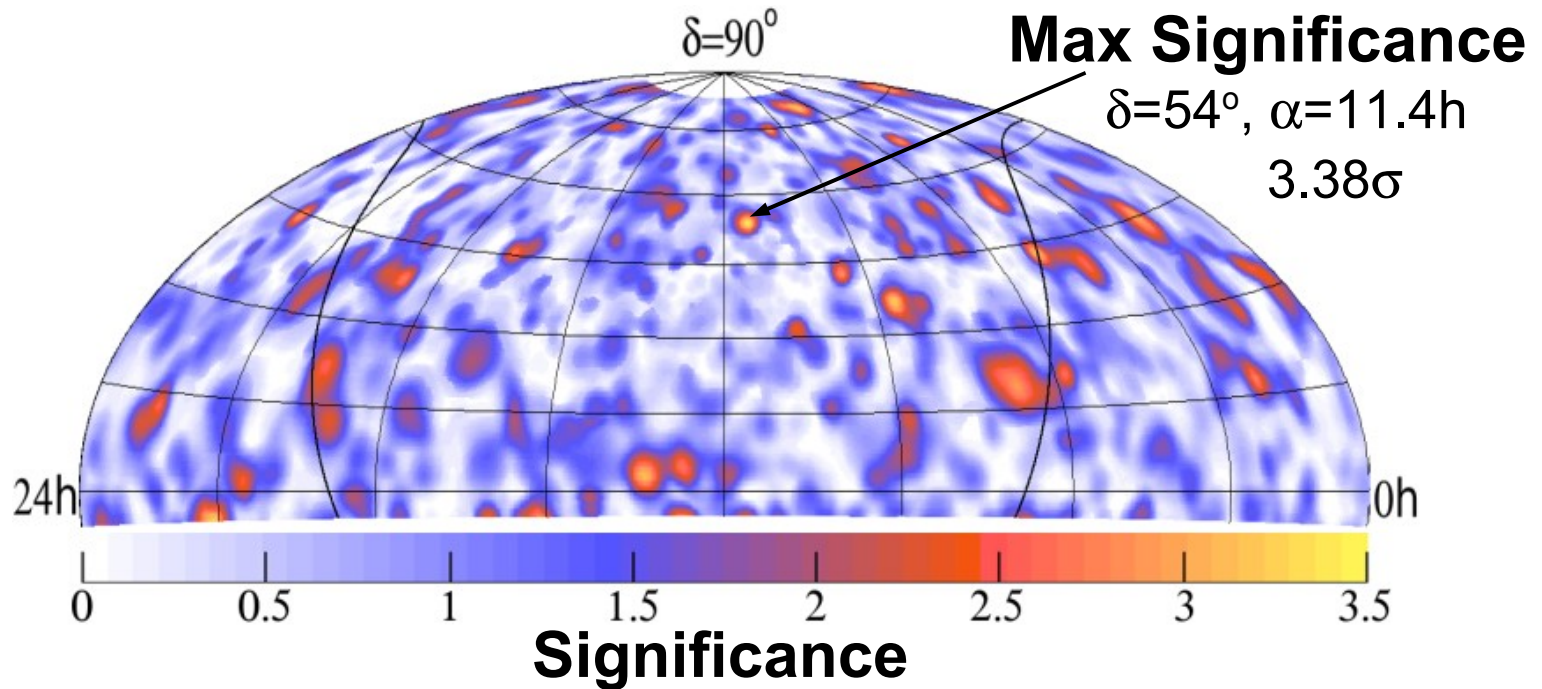
$$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_{i=1}^N P(\vec{x}_s, n_s, \gamma, \vec{x}_i, E_i, \sigma_i)$$

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

Log likelihood:

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

AMANDA

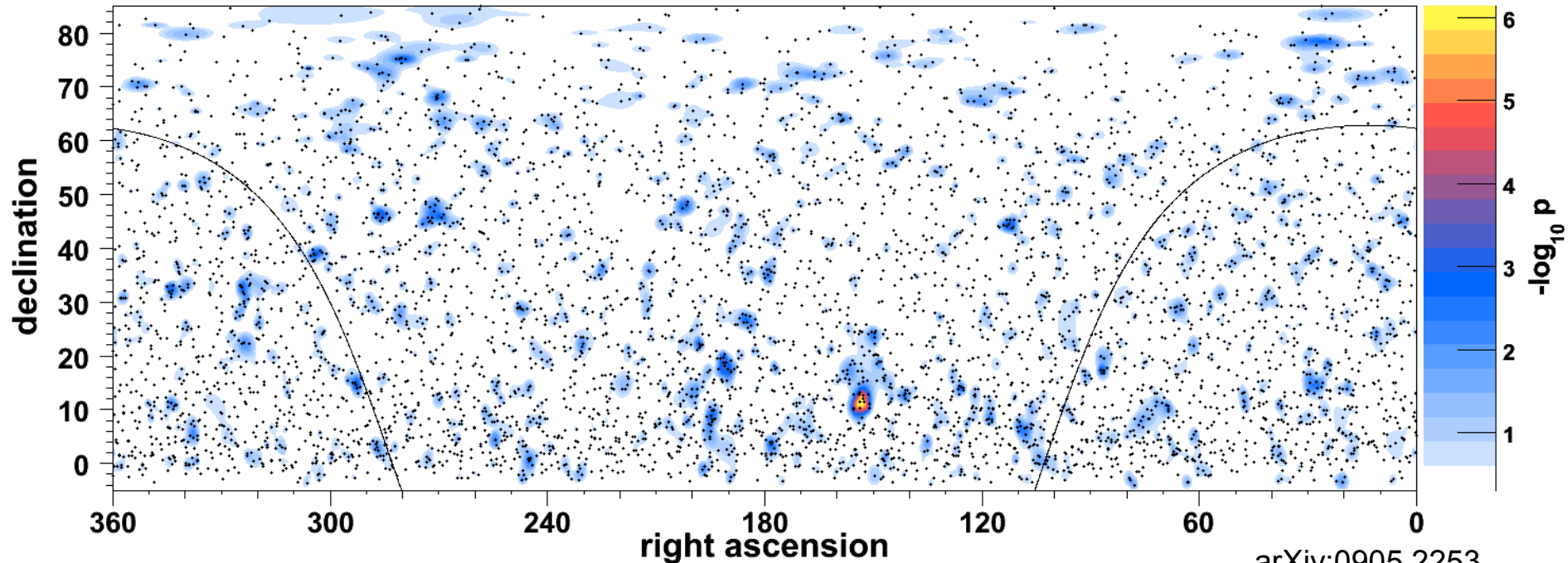


95 of 100 data sets randomized in RA have a significance $\geq 3.38\sigma$

AMANDA Analyses: Milagro stacking, AGN stacking, multipole search
→ Negative results

Phys. Rev. D **79**, 062001 (2009)
arXiv:0906.3942

IceCube 22 String



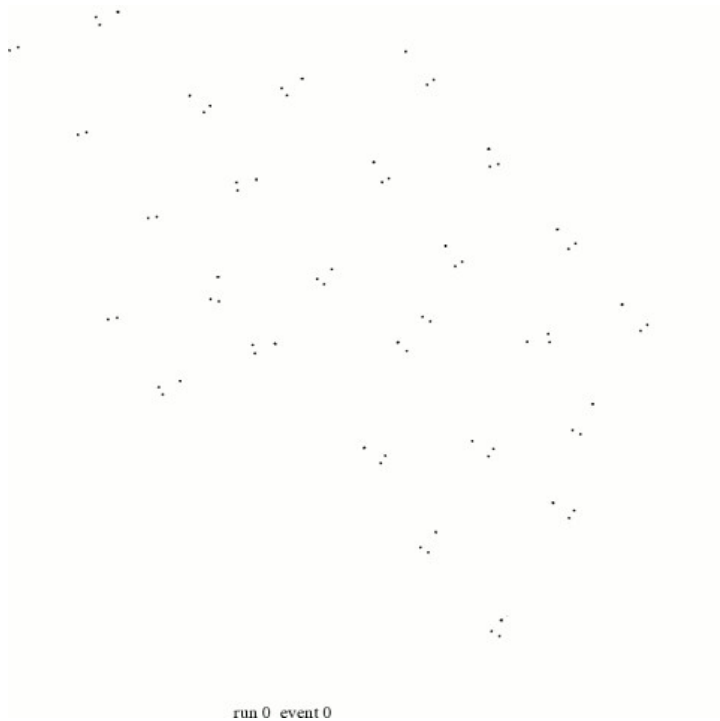
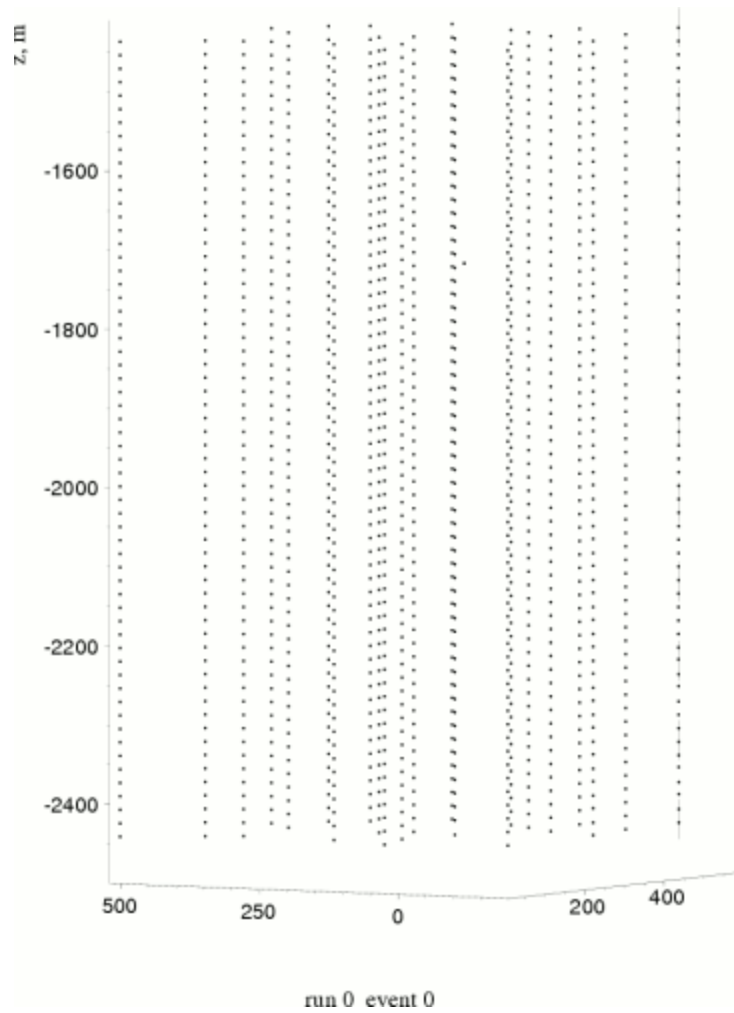
arXiv:0905.2253
to appear in ApJL

**Hottest spot found at r.a. 153° , dec. 11°
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.



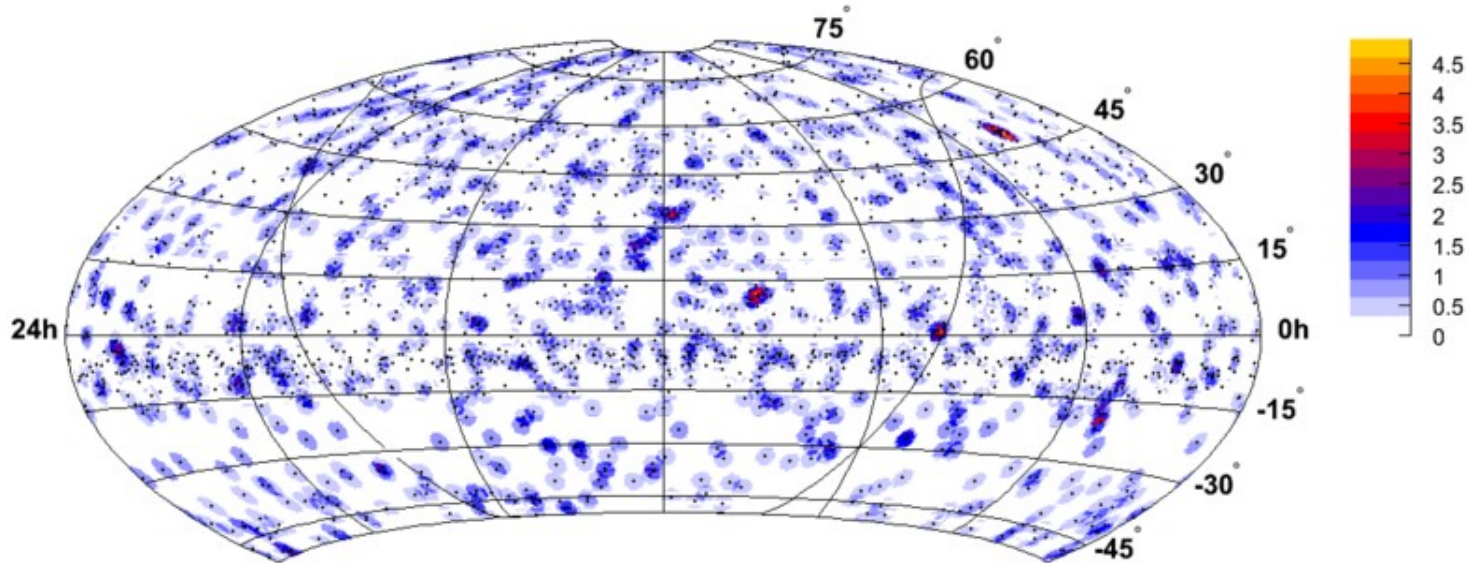
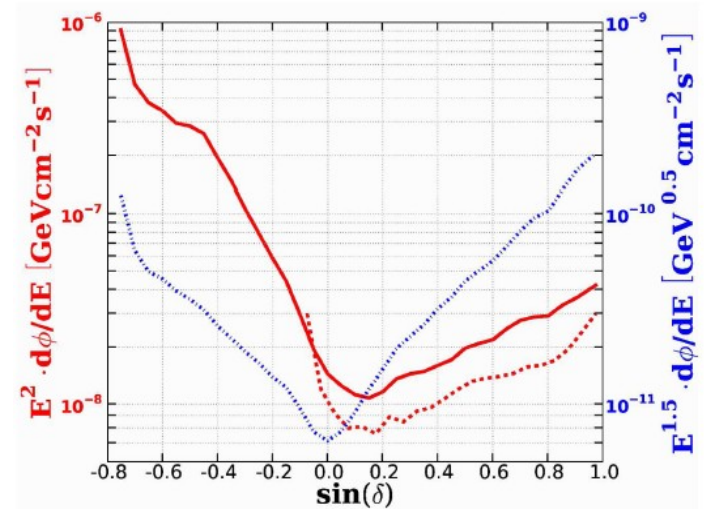
Number of hit modules: 148
Estimated angular error: 0.84°

IceCube 22 String

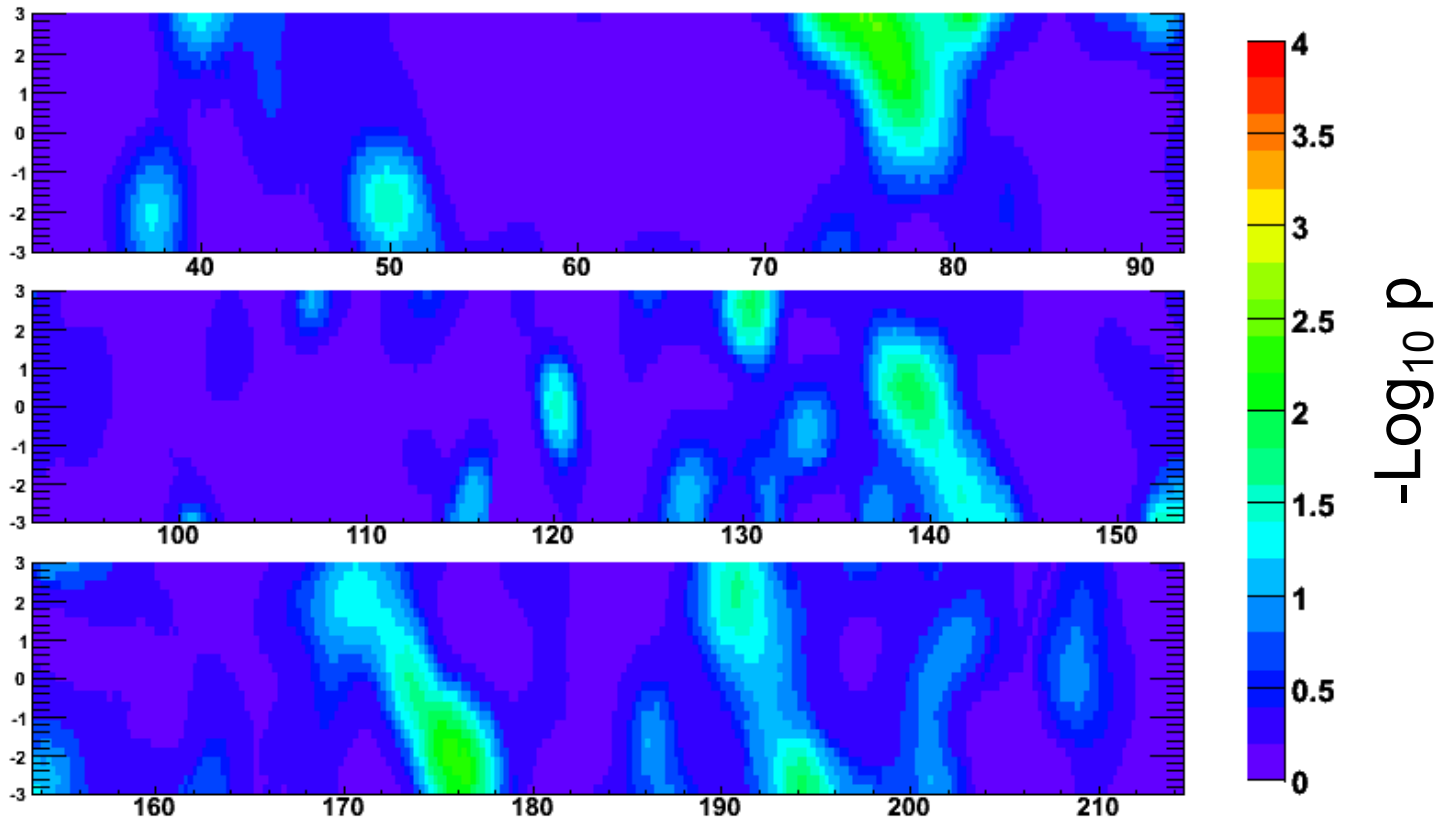
PeV – EeV neutrino-induced muons are more energetic than the vast majority of cosmic ray muons

Selecting such high energy muons provides sensitivity in the downgoing direction

No excesses observed in binned search ($p=0.37$)

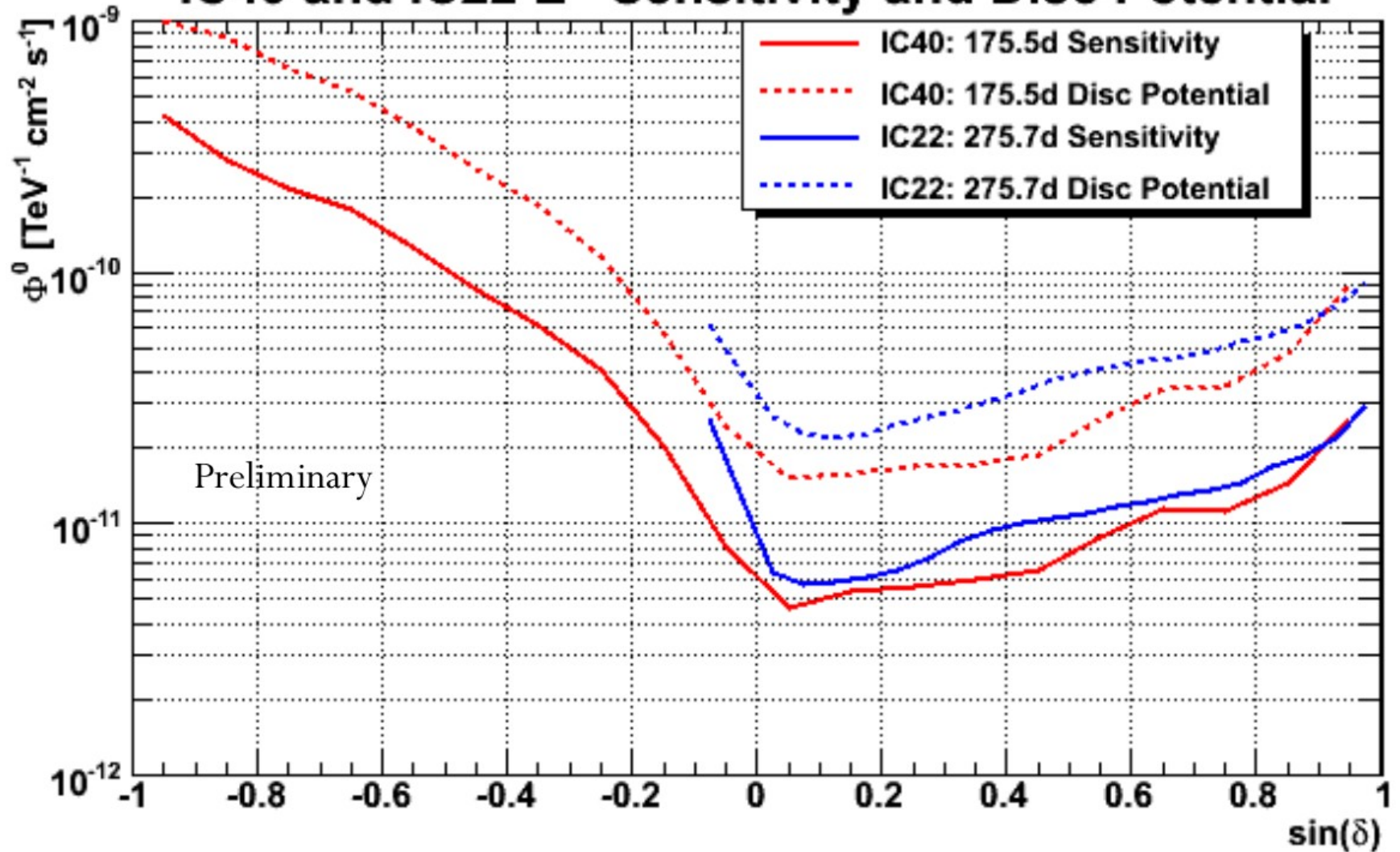


Search of the Galactic Plane with IceCube-22 + AMANDA



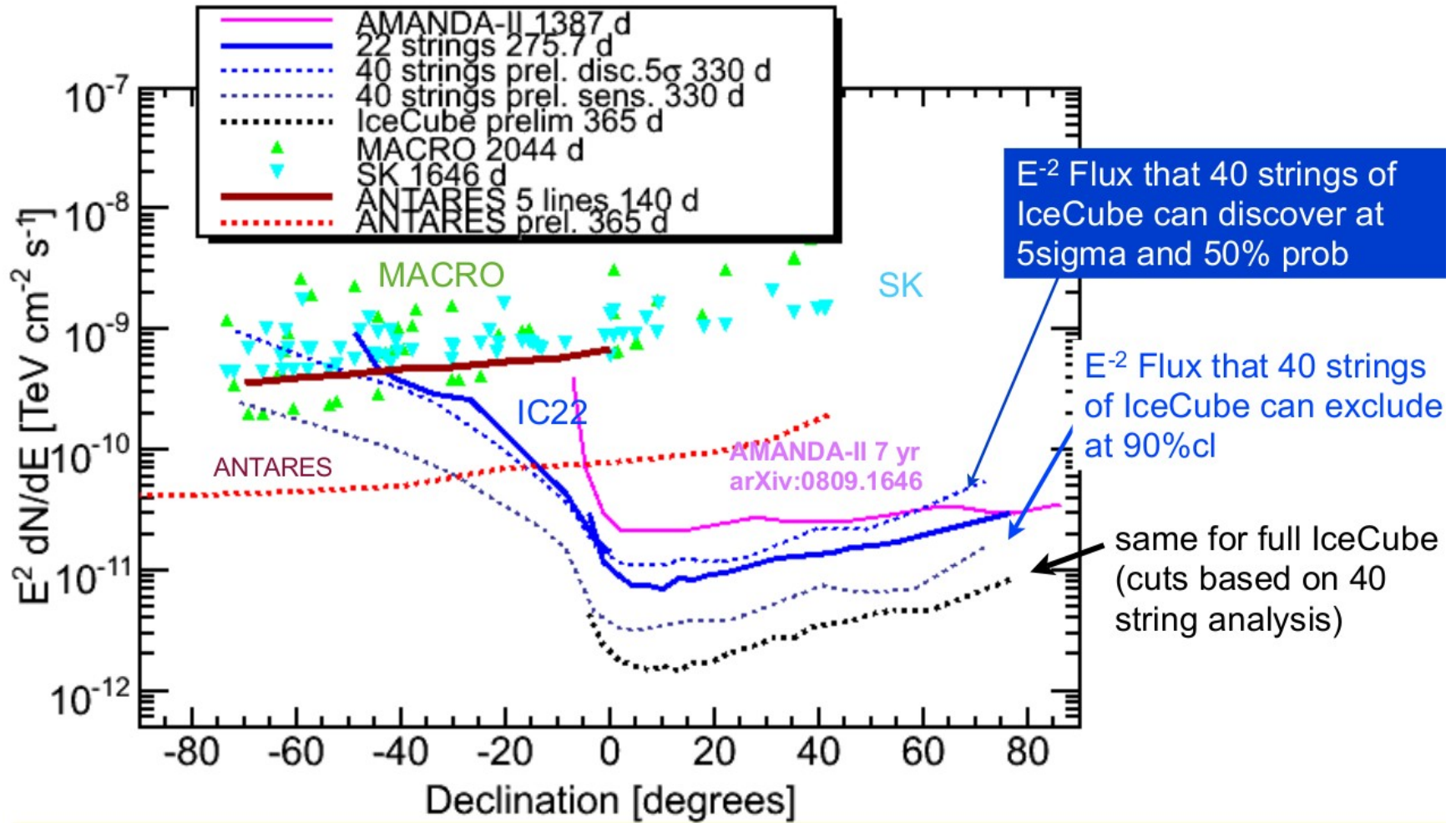
Optimized for low energy; no significant excess observed

IC40 and IC22 E^{-2} Sensitivity and Disc Potential



IC40 6-month Results to be presented at ICRC

40 String Detector and Beyond



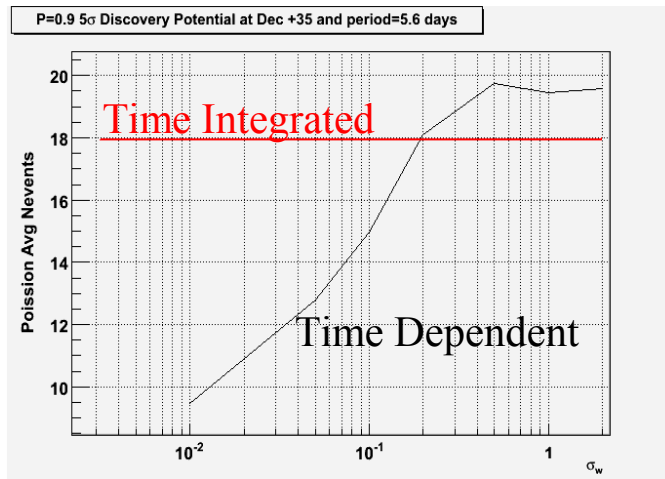
Time-Dependent Point Sources

Multiwavelength Flare Search

IC22: No neutrino correlations to photon

high states of several objects (e.g. 1ES 1959, Cygnus X-1)

Microquasars

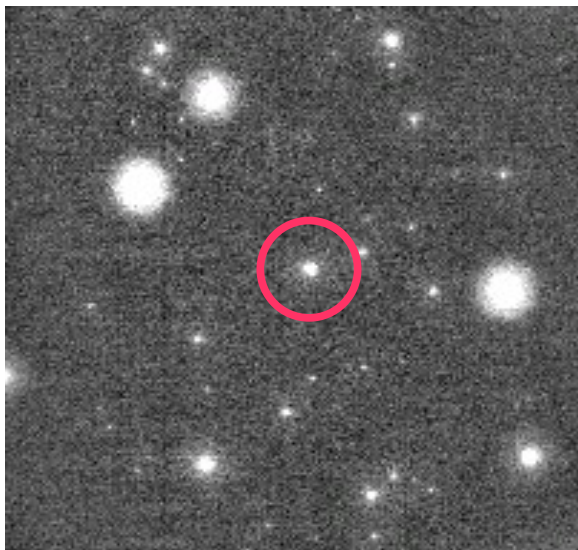


IC22: No periodic emission for 7 microquasars in the Northern Sky

Unbiased Flare Search

To be presented at ICRC

GRB 080319b

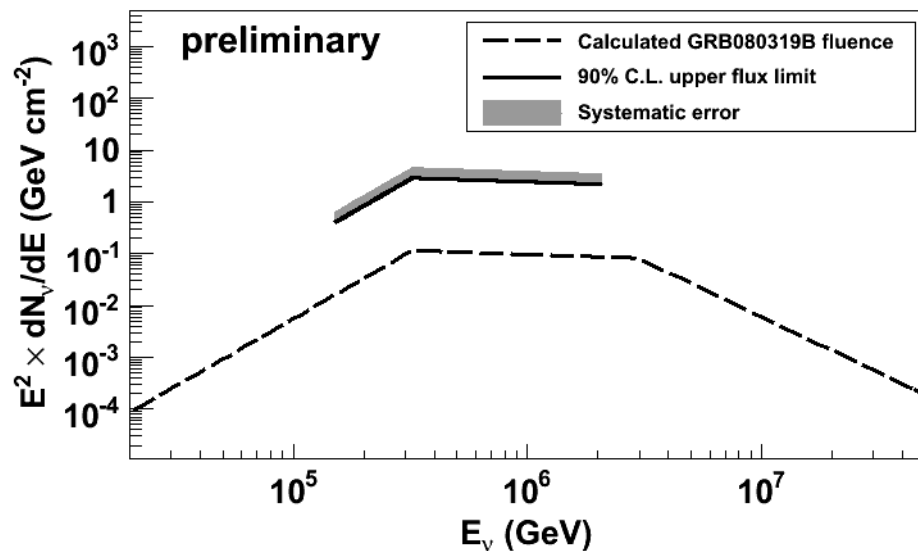
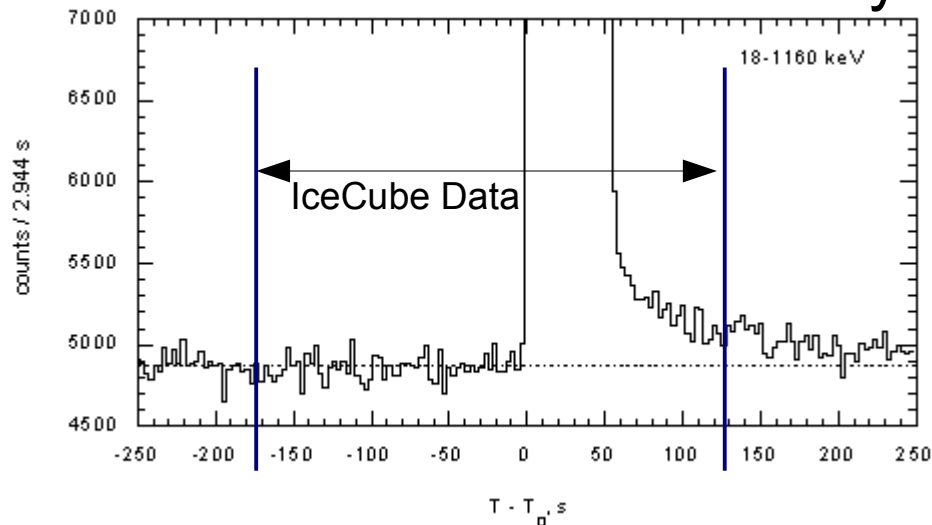


Pi of the Sky

March 19, 06:12 UT (duration ~ 70 s)
Brightest (optical) GRB (mag. ~ 5.3)
 $z = 0.94$ (DA = 1.6 Gpc)

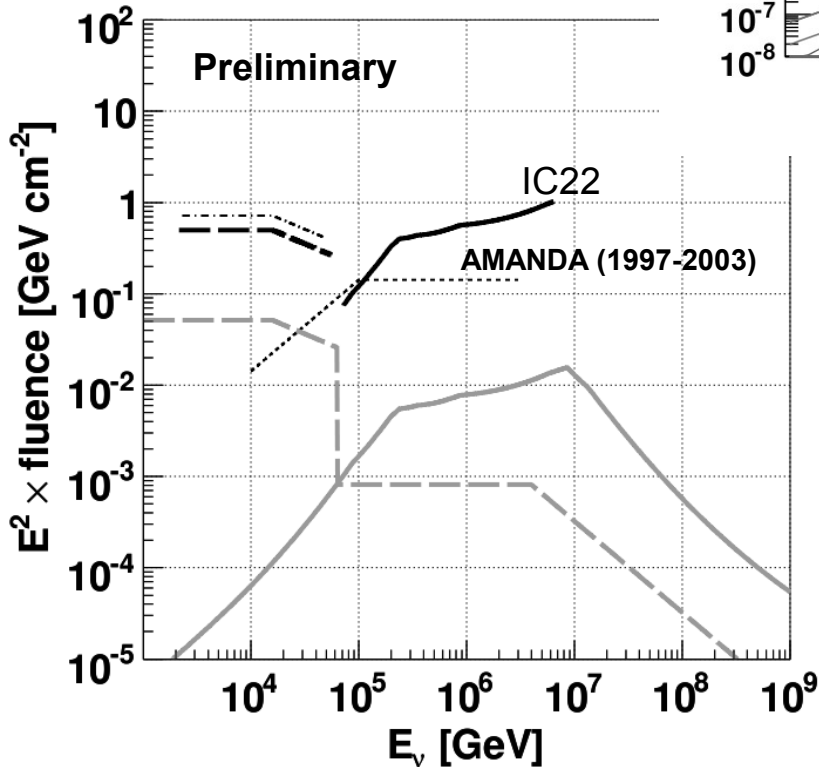
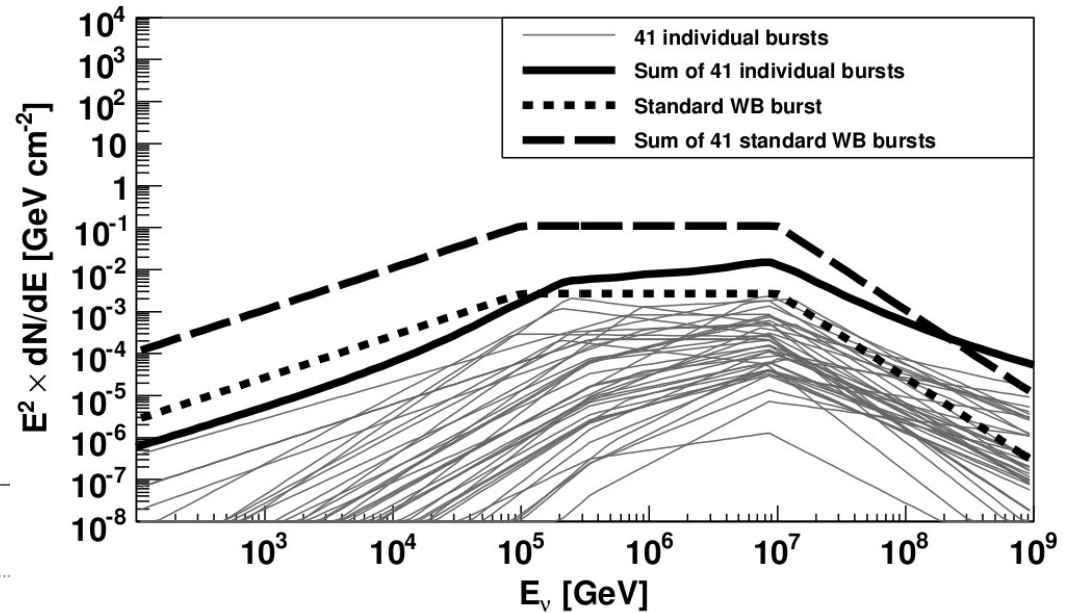
Data consistent with 0.0
events within window

Konus X-ray



Northern Hemisphere GRBs

41 satellite triggered bursts during IC22



Expect:

~0.03 prompt events

~0.3 precursor events

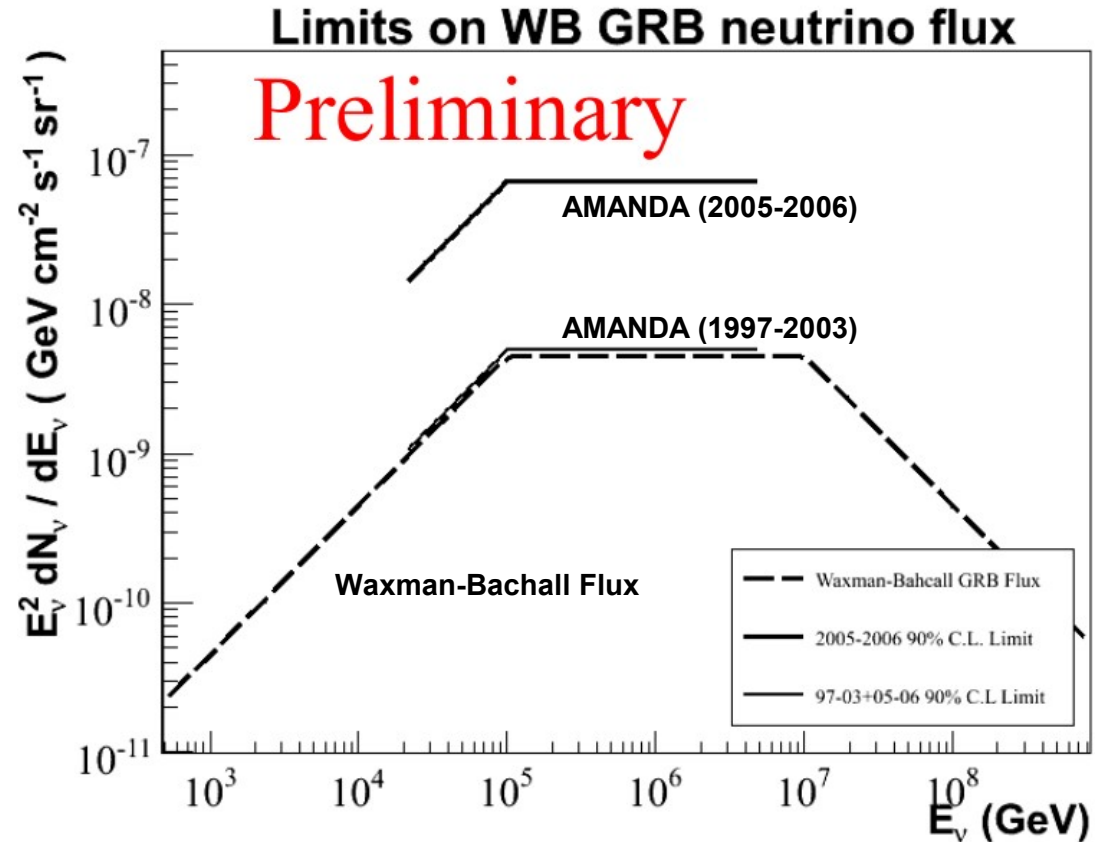
Data consistent with zero signal

Northern Hemisphere GRBs

Most sensitive limits
still from AMANDA
1997 – 2003
(419 bursts)

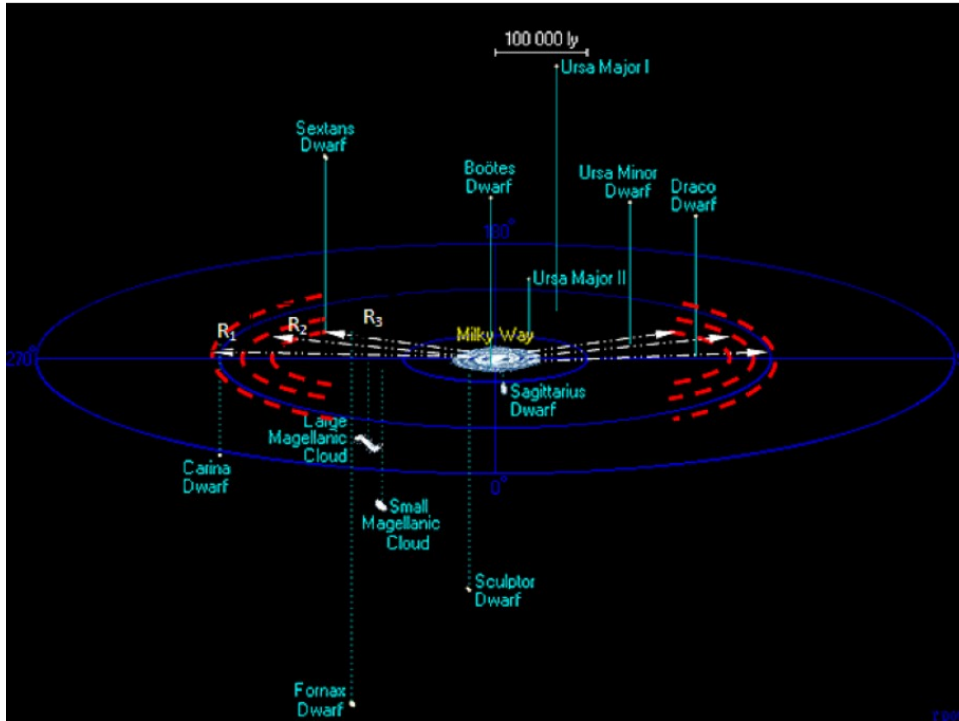
ApJ **674**, 357 (2008)

Binned Searches



Full IceCube detector would detect this flux at 5σ in less than one year (100 Swift + Fermi bursts)

Supernovae

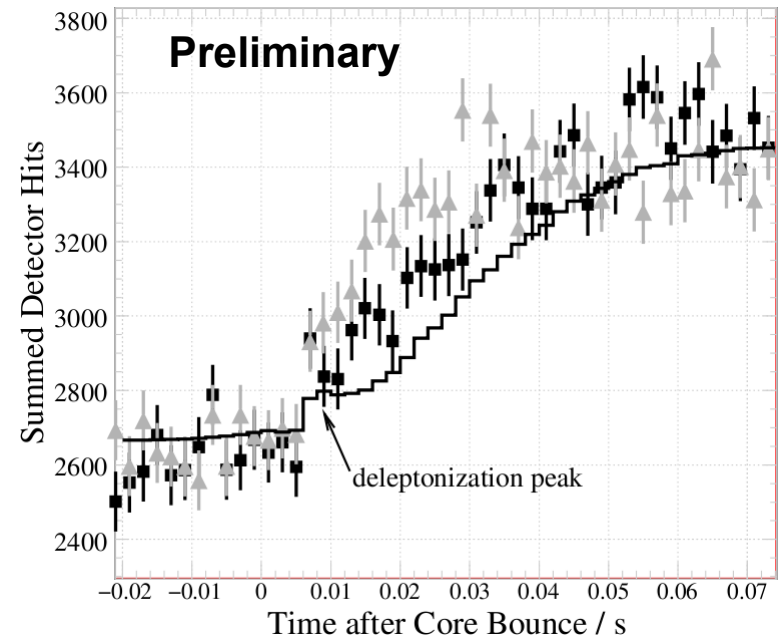


5σ detection to ~ 50 kpc in full IceCube

Measurement of neutrino light curves:
 $\sim 10^6$ neutrinos at 7.5 kpc

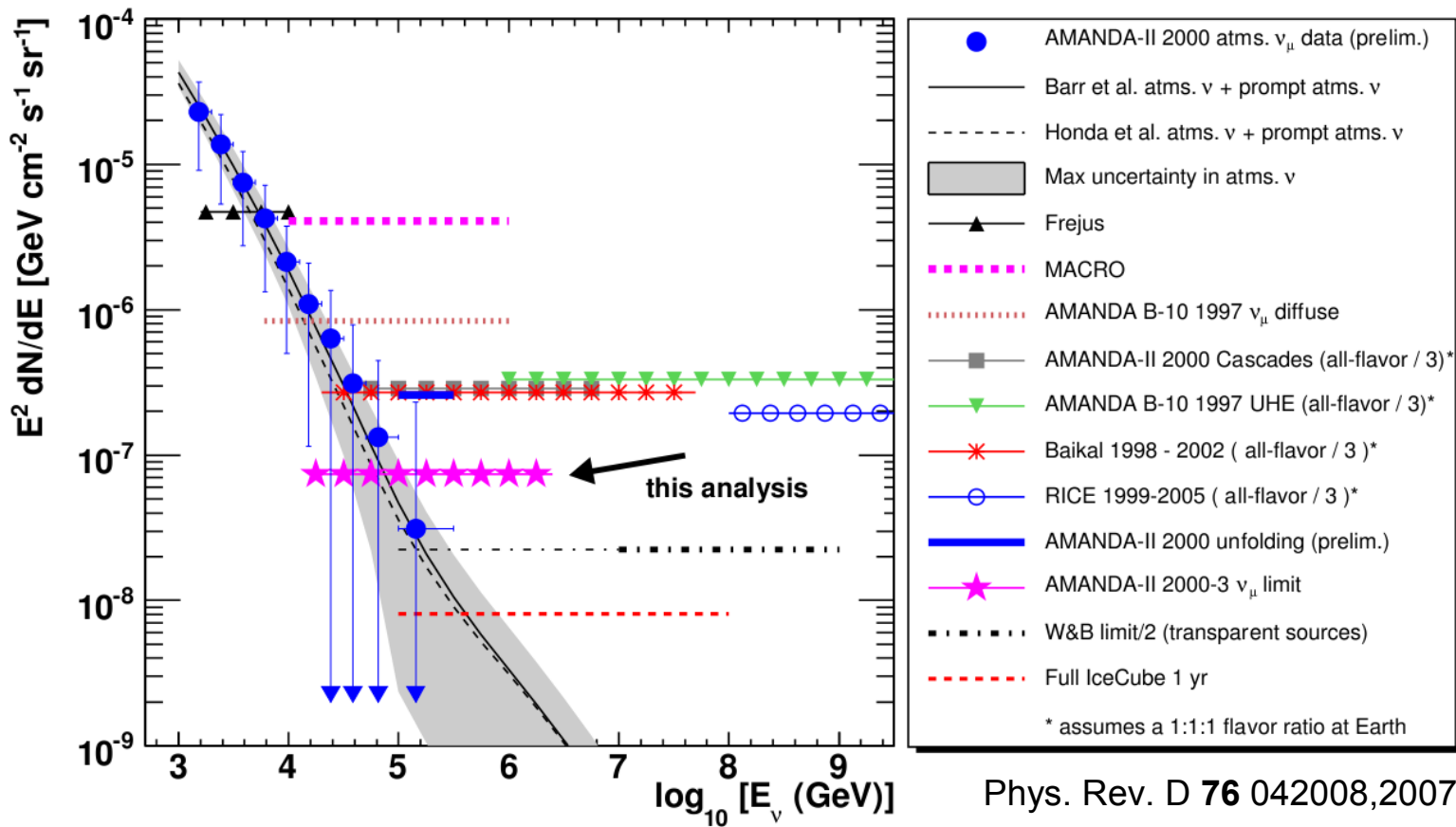
\sim MeV SN neutrinos produce an increase in photon rates

No pointing resolution



Presented at ICRC 2009

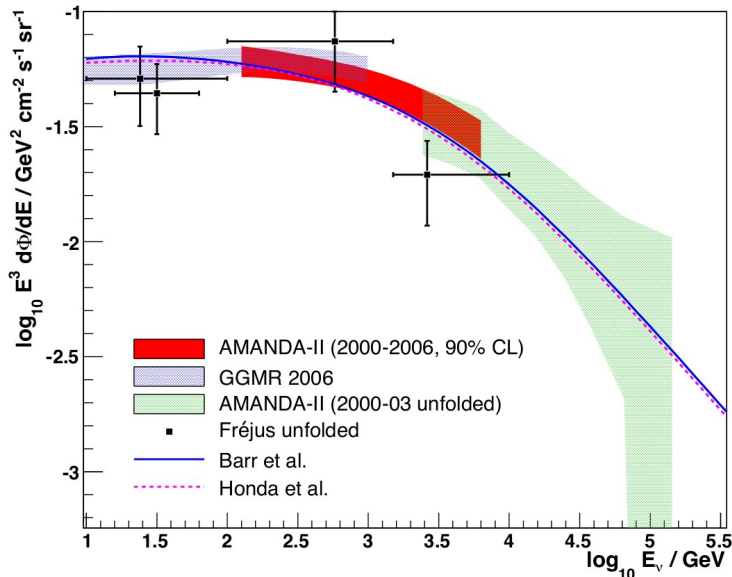
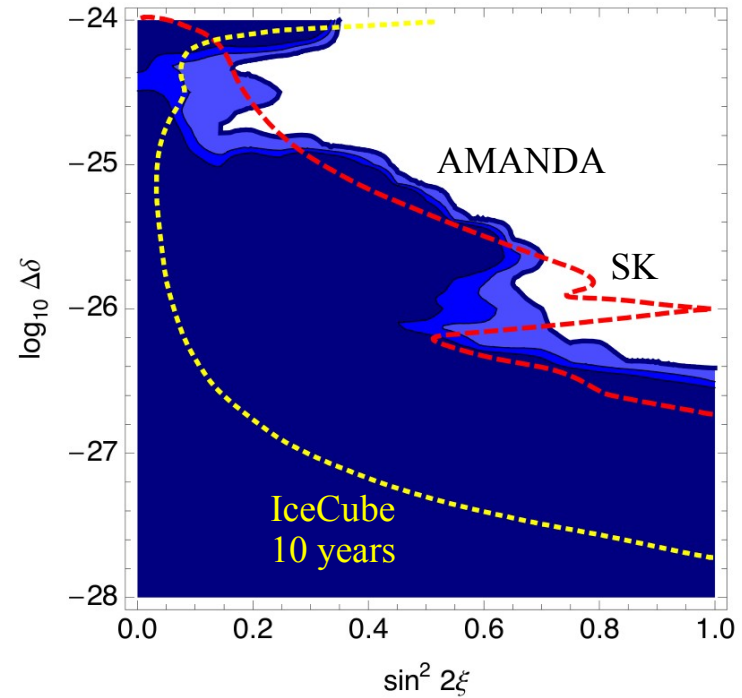
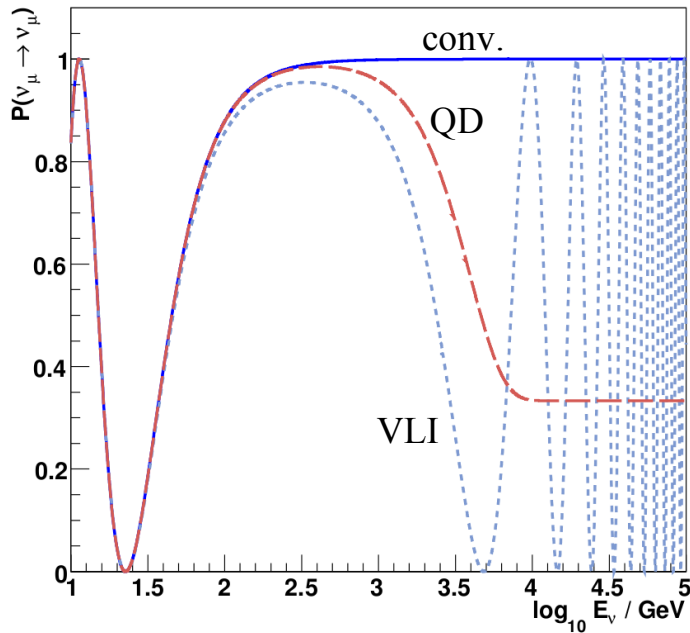
Diffuse Neutrino Fluxes



Preliminary IC40 diffuse sensitivity >5x better than AMANDA

New AMANDA UHE diffuse limit near W&B Bound (ICRC 2009)

Atmospheric Neutrinos



No evidence of QD or VLI effects
 $(\delta c/c < 2.8 \times 10^{-27}$ 90% CL)

New measurement of the
 atmospheric neutrino flux
 with AMANDA

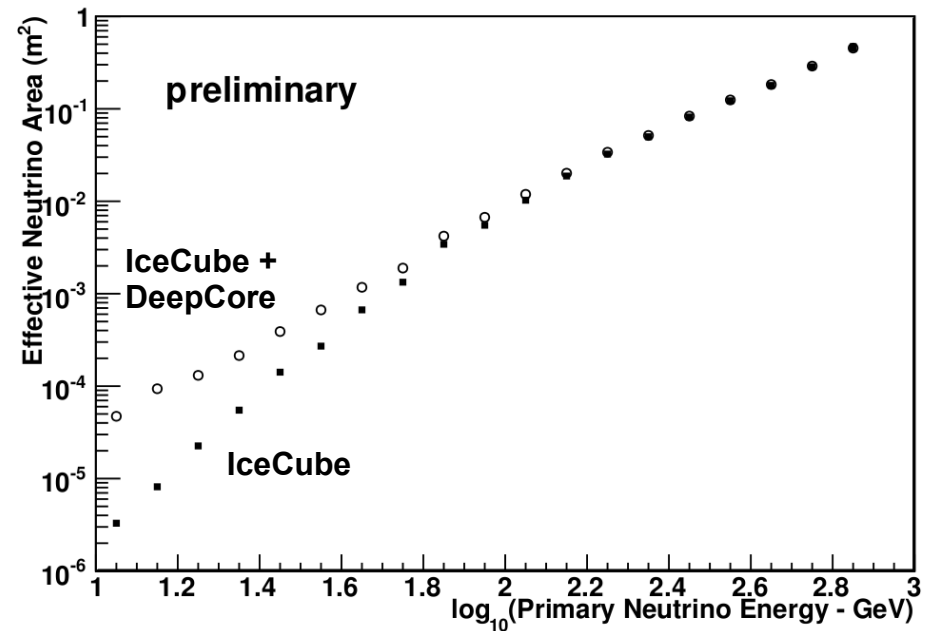
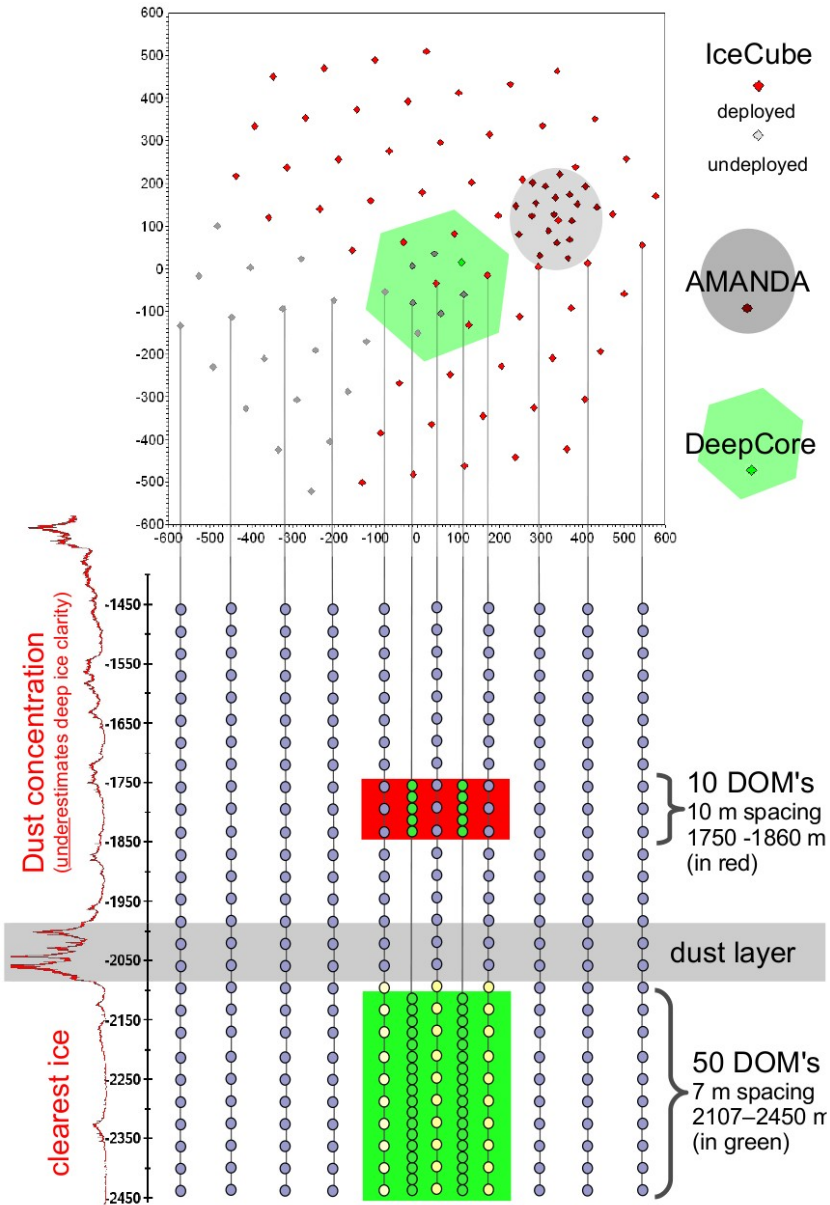
Phys. Rev. D **79**, 102005 (2009)

IceCube DeepCore

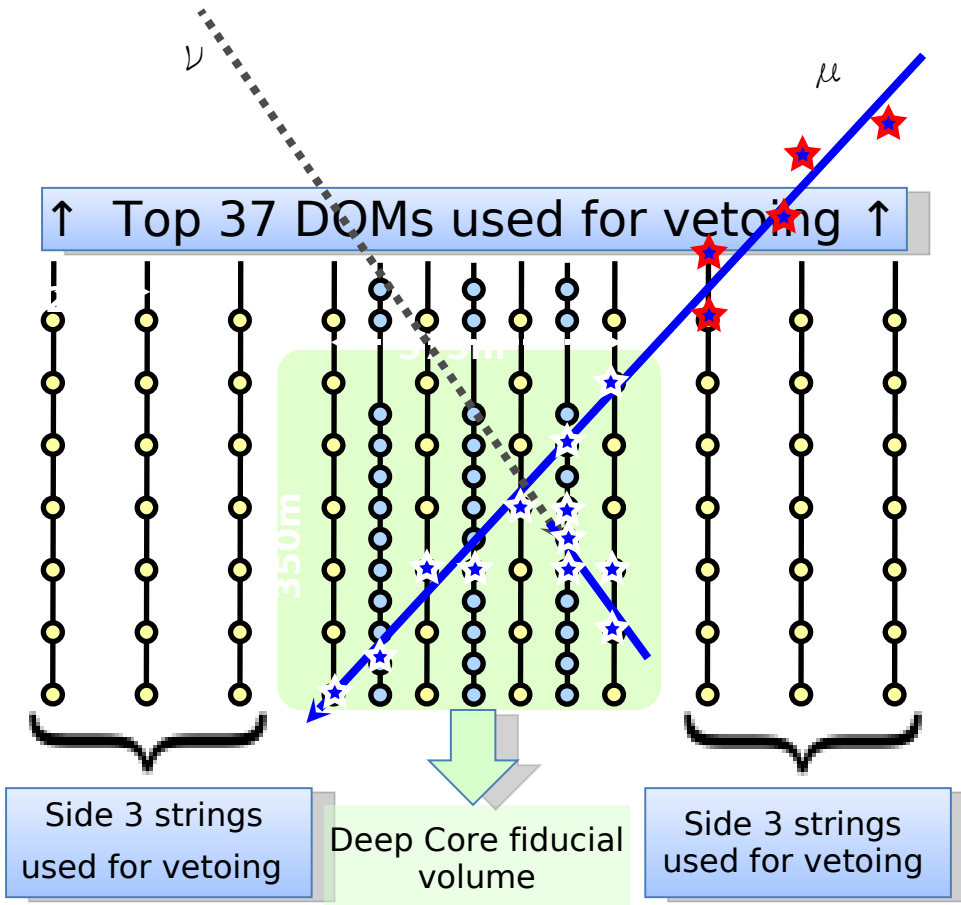
6 strings with dense DOM spacing and high QE PMTs

Located in deep, clear ice

Will improve IceCube physics reach at 10 – 100 GeV



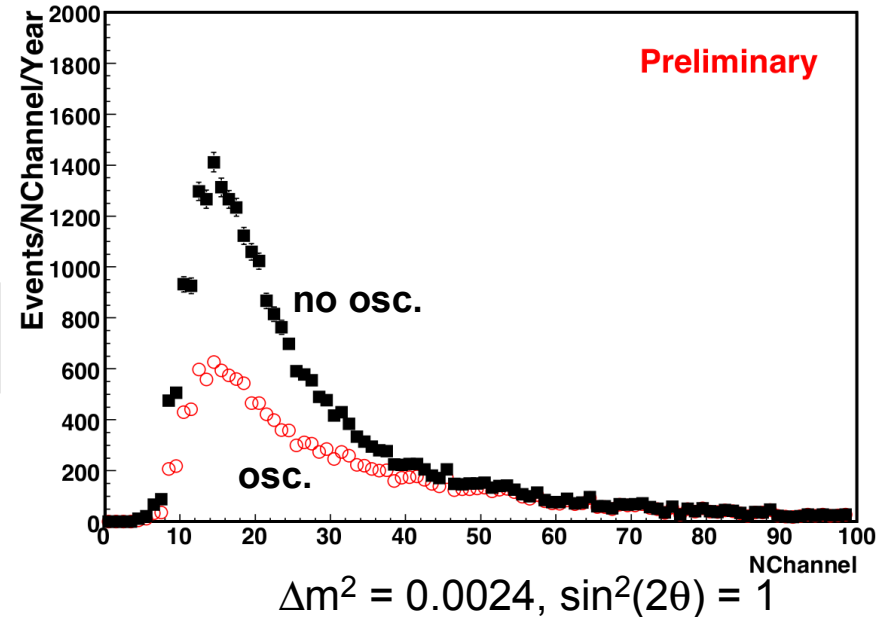
Neutrino Physics with Deep Core



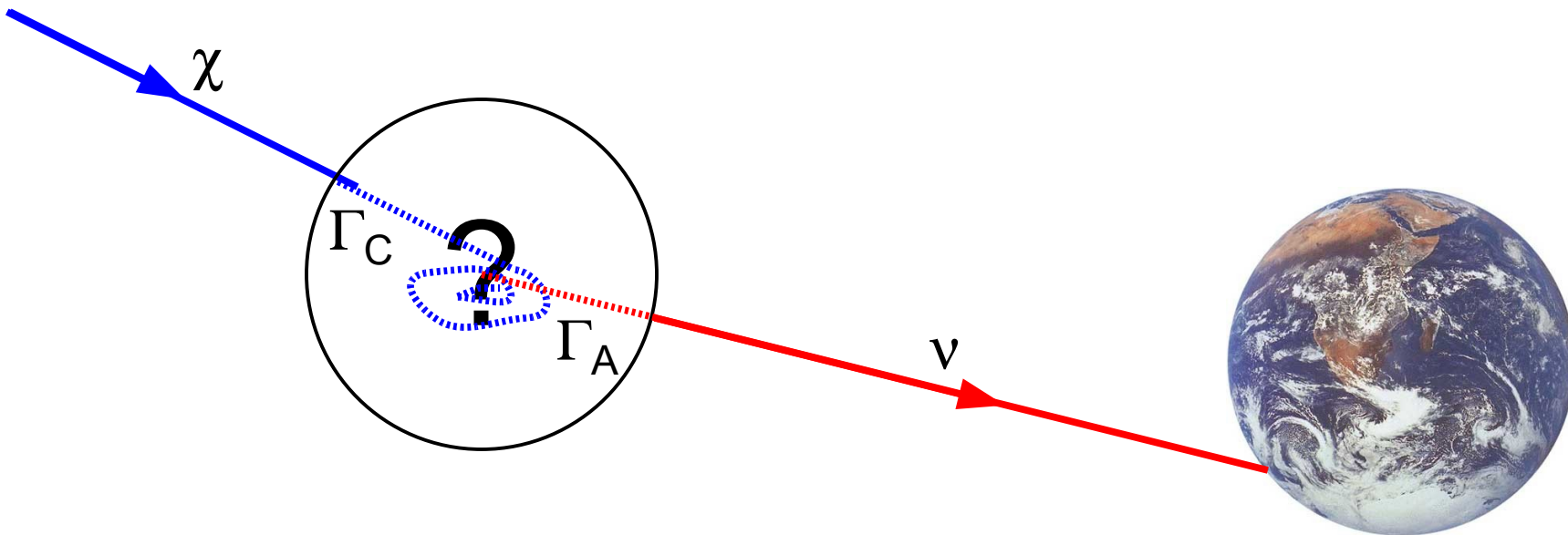
Good sensitivity to atmospheric oscillations with DeepCore

Selection of starting muons allows 4π acceptance

Upper half of IceCube is an active muon veto



WIMP Capture and Annihilation



WIMPs accumulate at center of massive objects and annihilate

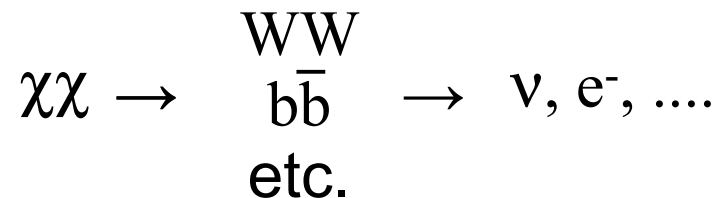
Capture rate dependent on WIMP-nucleon cross section

Annihilation rate should approach equilibrium with capture rate

Annihilation produces a neutrino flux at Earth

Neutrino spectra dependent on annihilation mode

$$\Gamma_A \sim \frac{1}{2} \Gamma_C$$

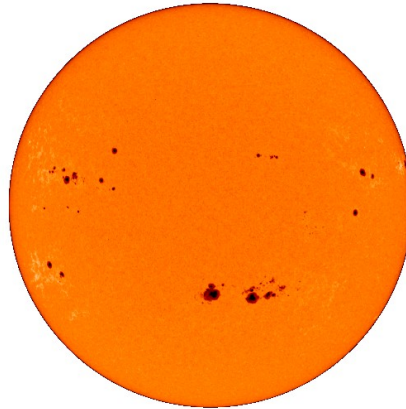


WIMP Capture



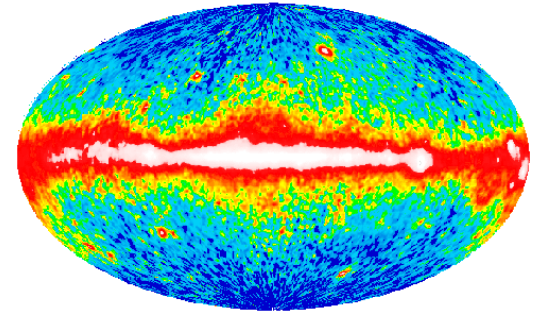
Always fully visible
(vertical upgoing
events)

Small mass



Sun below horizon
half of the year

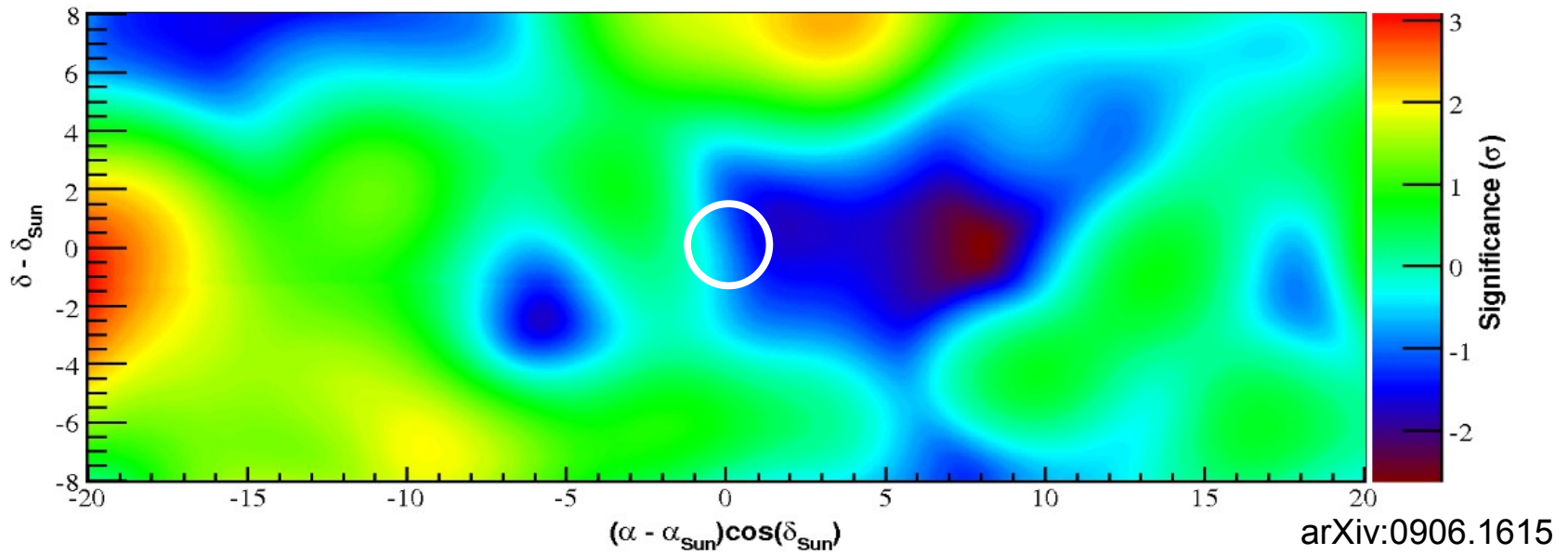
Large mass



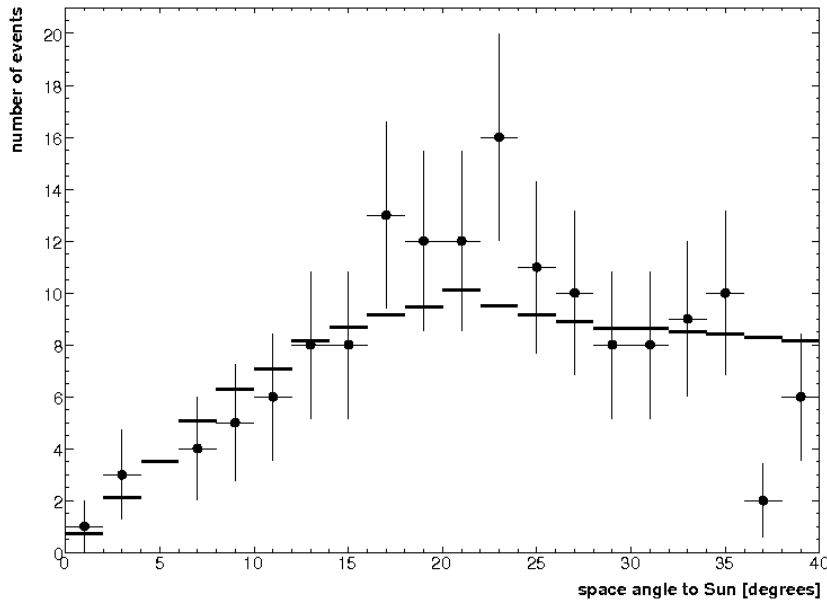
GC always above the
horizon, with large
CR background

Extreme mass

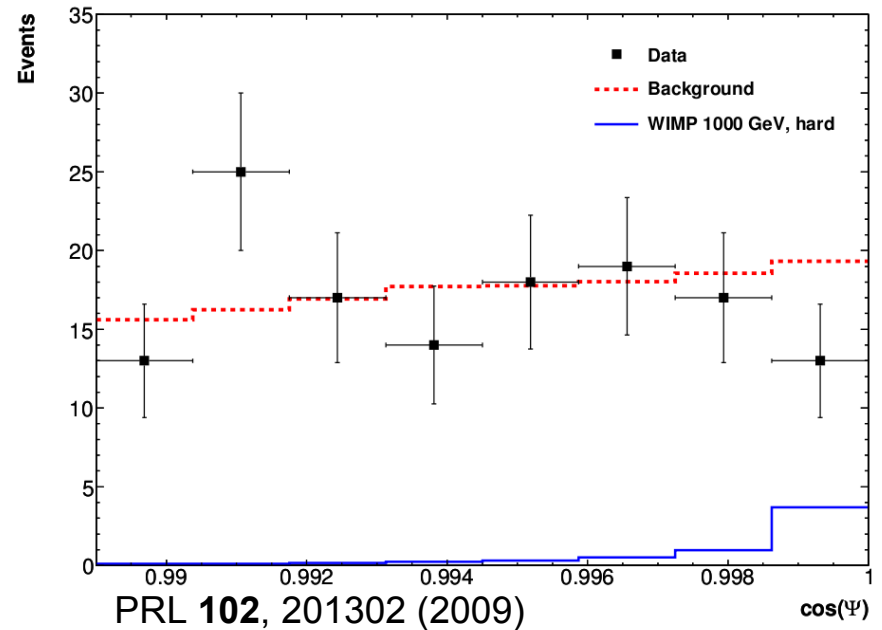
AMANDA 2000-2006

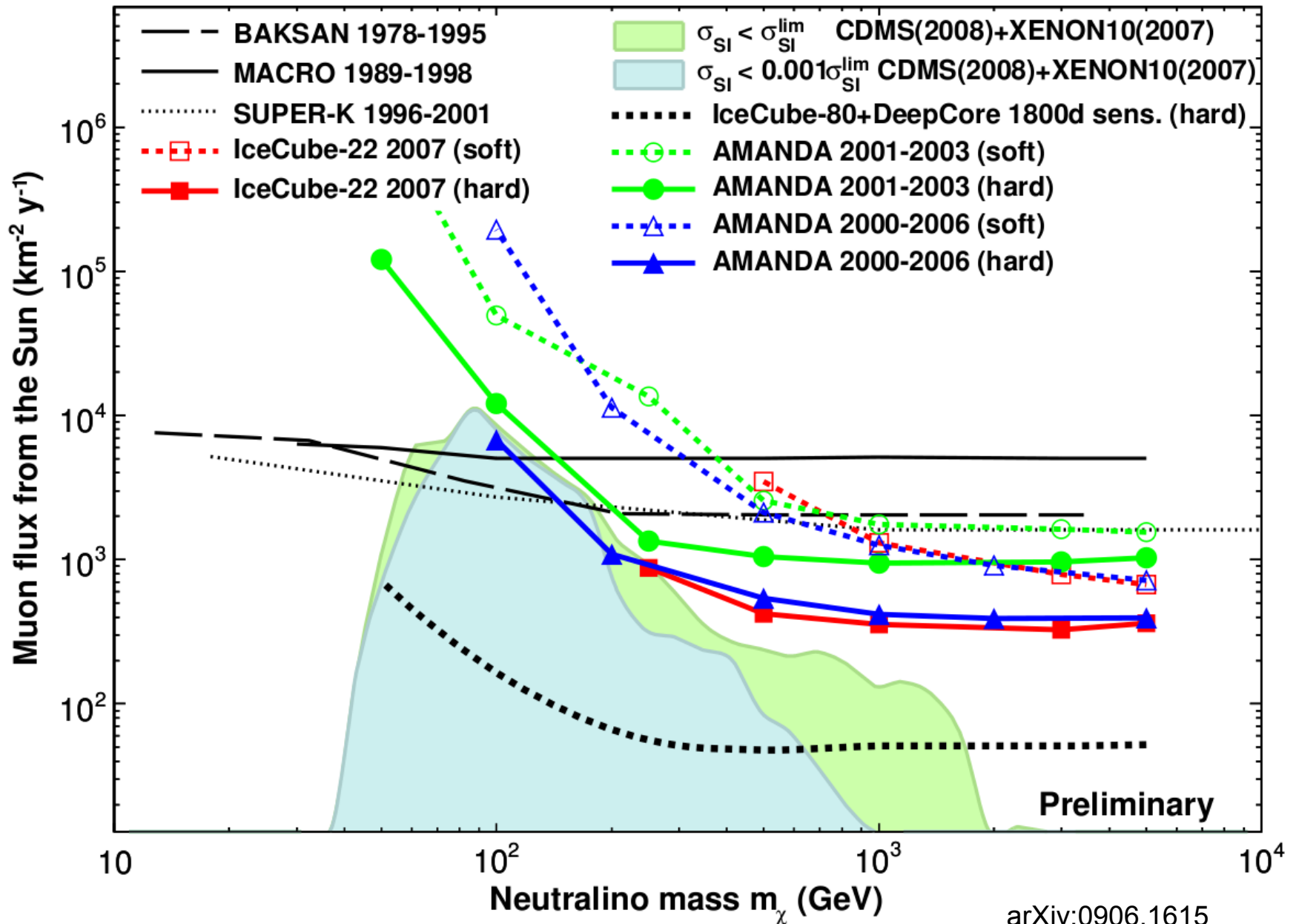


AMANDA 2001-2003

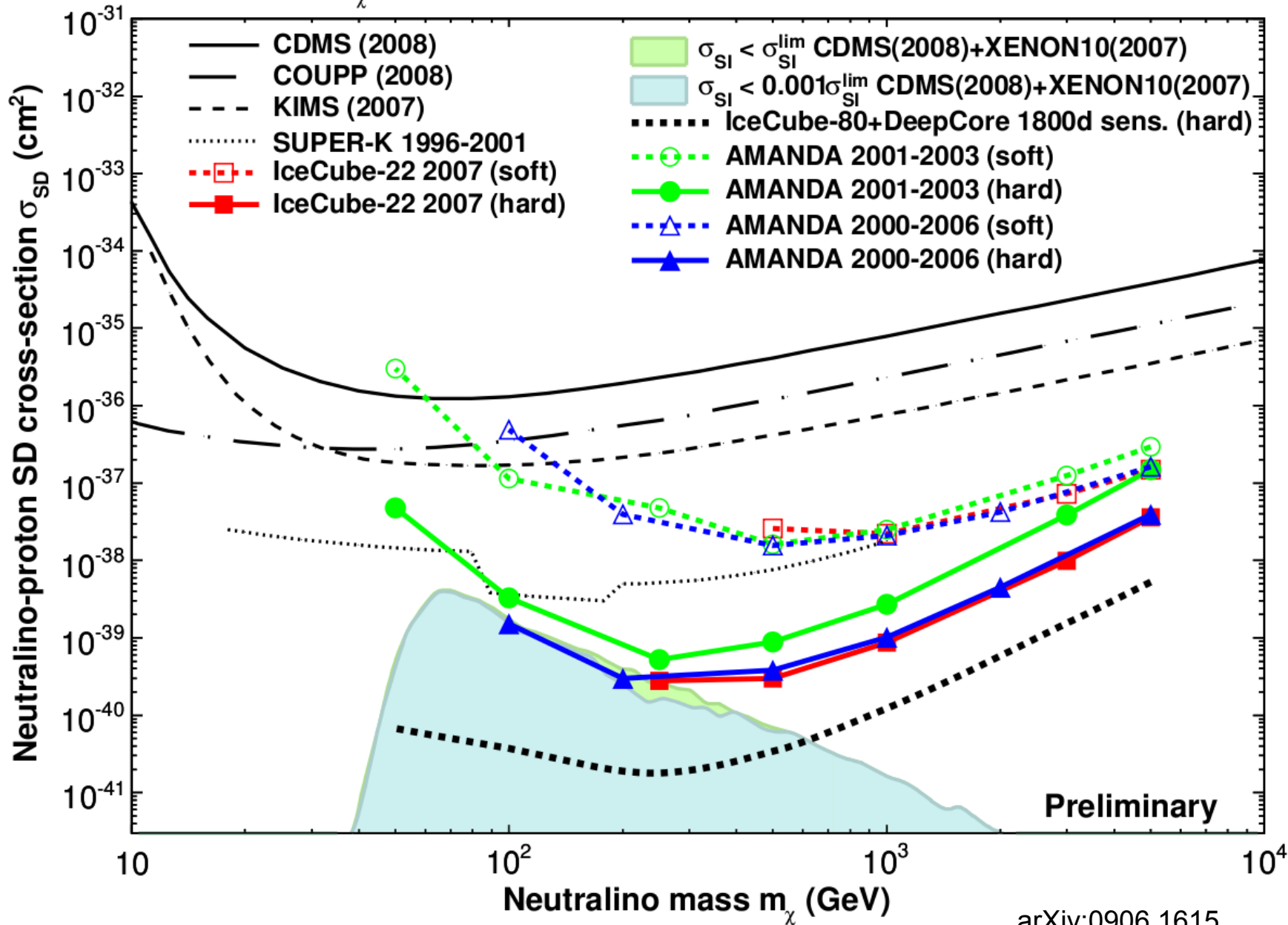


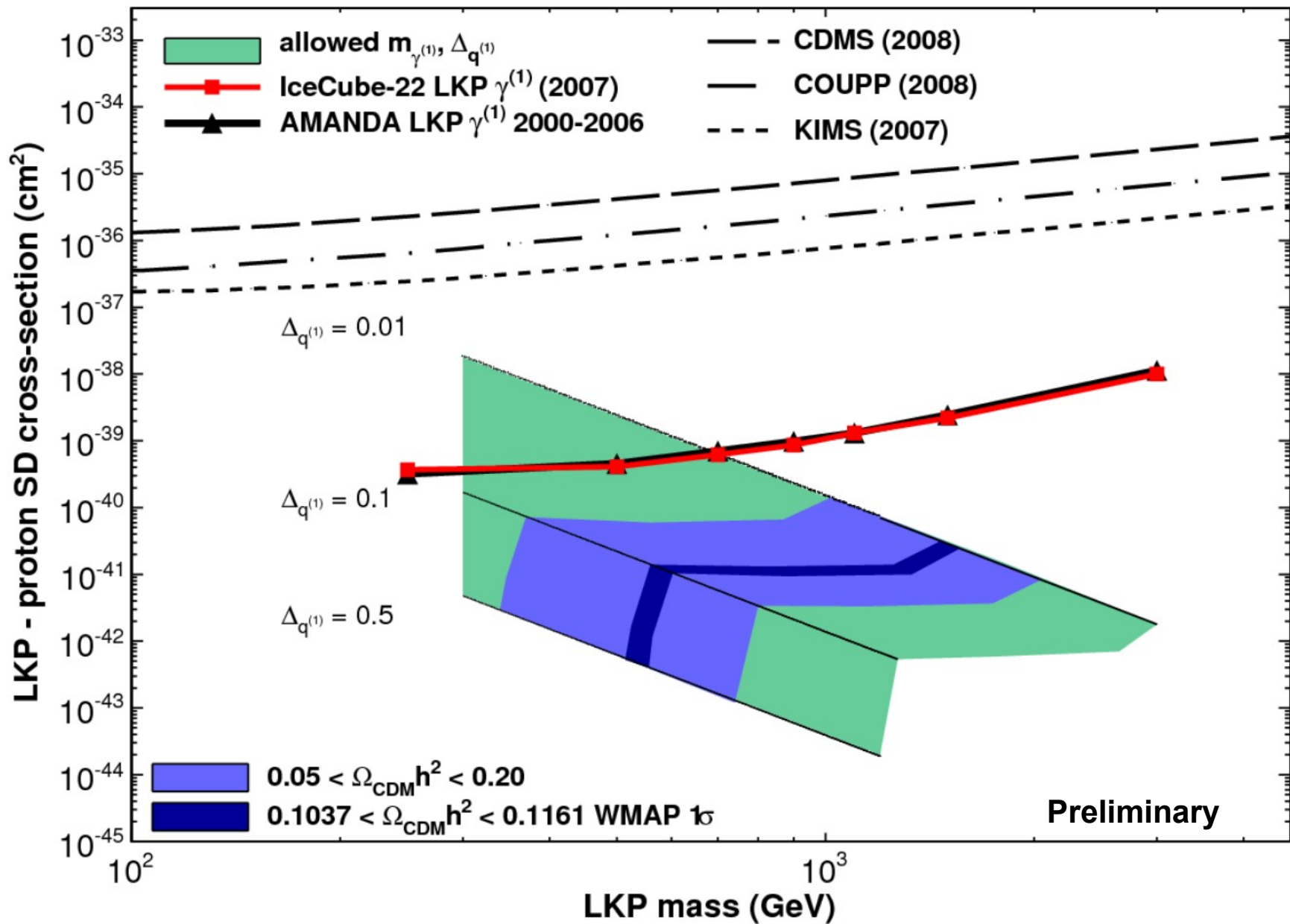
IC22



$0.05 < \Omega_\chi h^2 < 0.20$ Indirect searches - $E_\mu^{\text{thr}} = 1 \text{ GeV}$ 

$0.05 < \Omega_\chi h^2 < 0.20$





Summary

IceCube is now ~70% complete with 19 new strings installed this past season

We observe no evidence of an astrophysical neutrino flux

IceCube sensitivity is rapidly improving and 40-string analyses are underway

New WIMP-proton spin-dependent cross section limits complement those from direct detection experiments

The DeepCore extension will improve physics reach at low energies