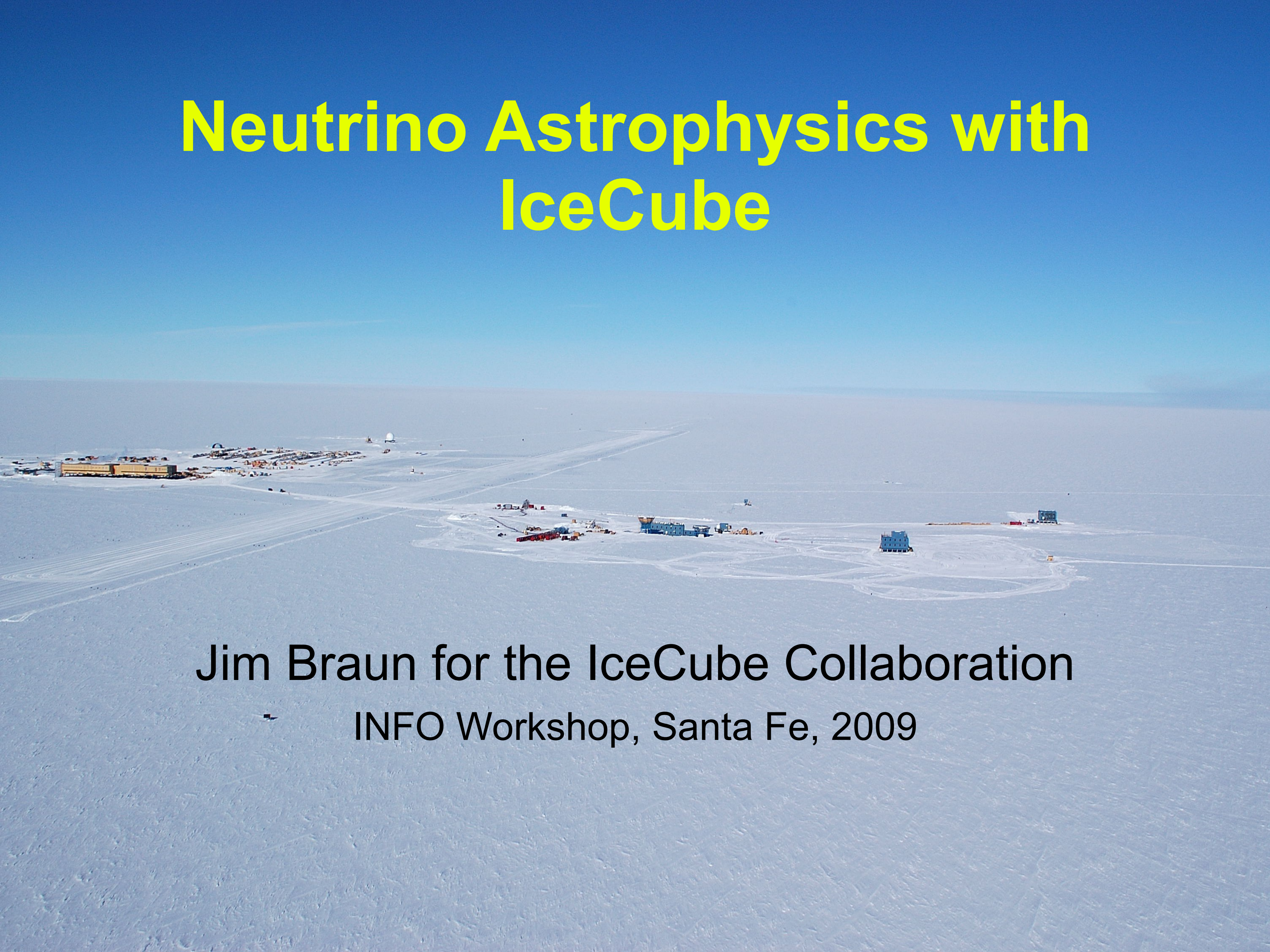
Neutrino Astrophysics with IceCube



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

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

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

Japan:
- Chiba University

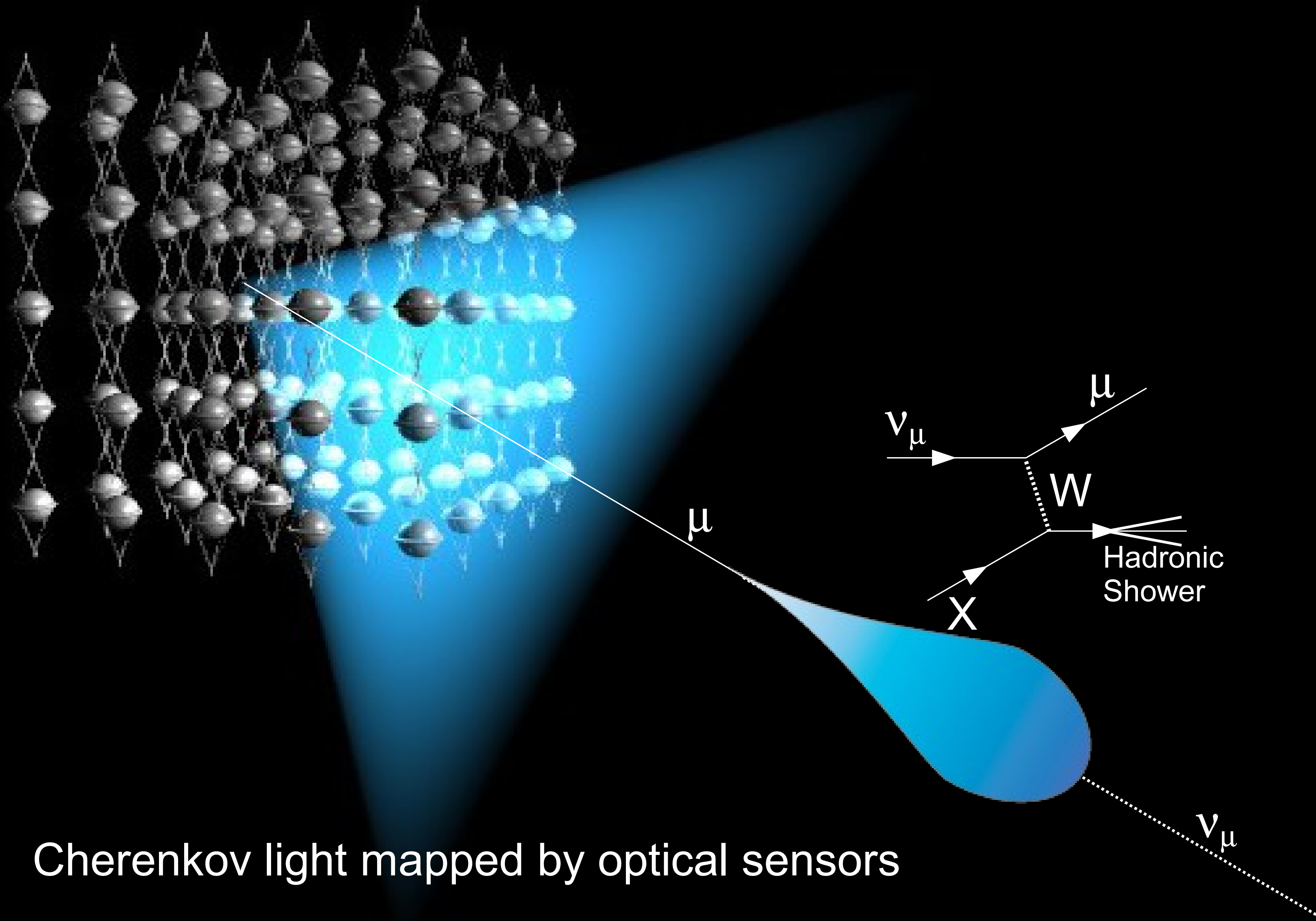
New Zealand:
- University of Canterbury

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

Neutrino Astrophysics with IceCube:

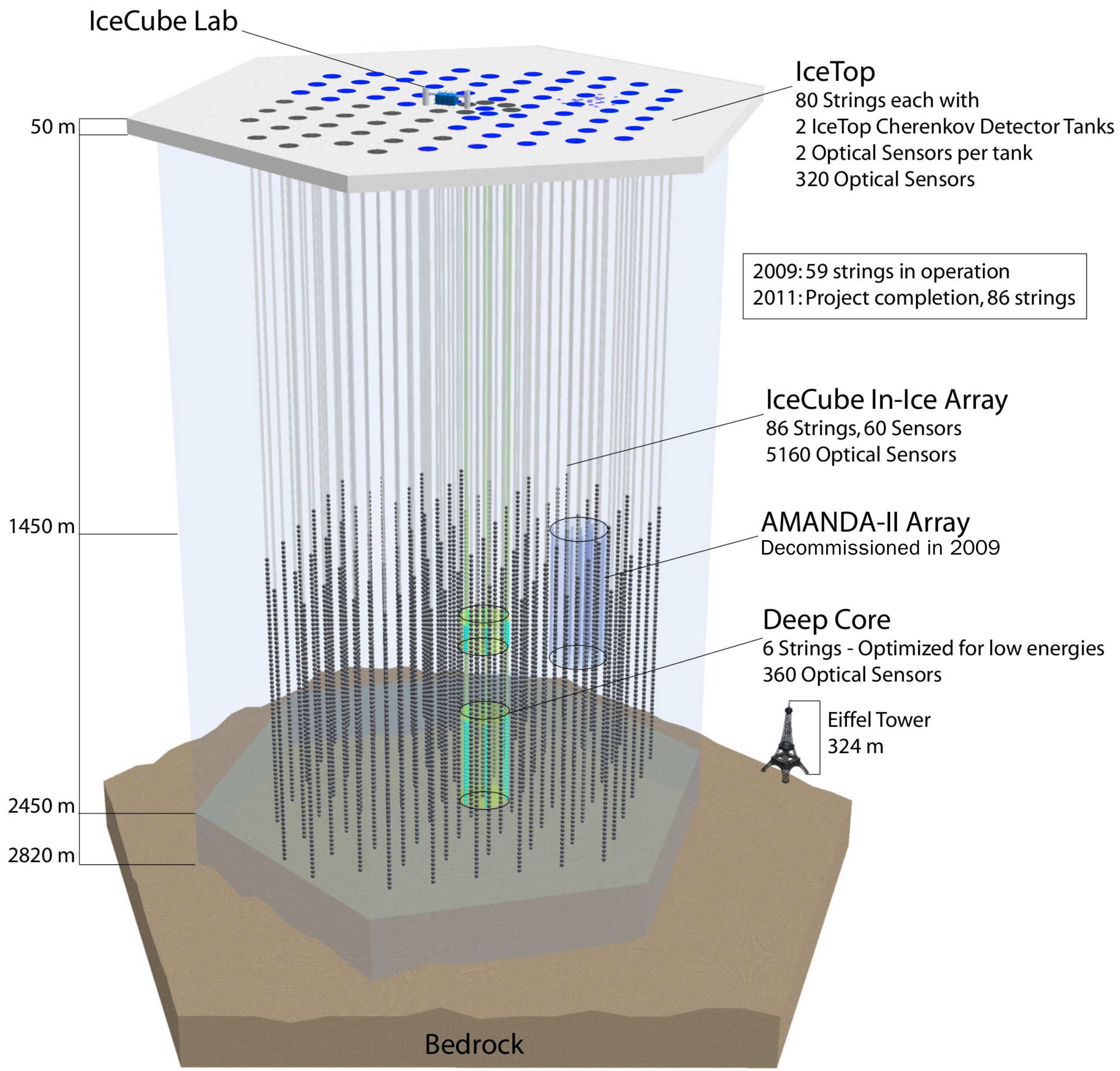
- Astrophysical Neutrino Searches
- Supernovae
- Atmospheric Neutrinos
- IceCube DeepCore Extension
- Indirect Dark Matter Searches

Optical Cherenkov Detection

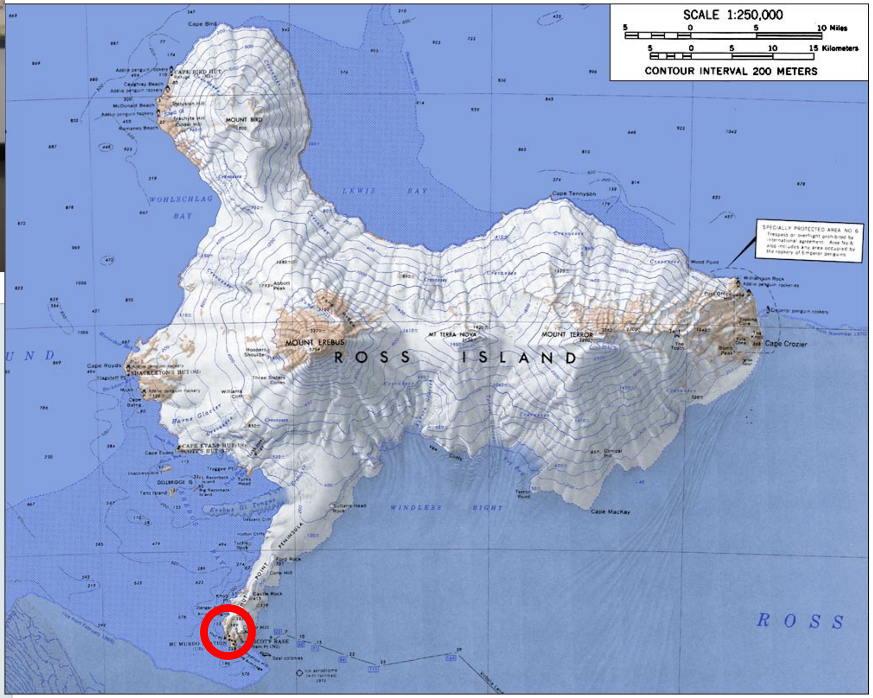


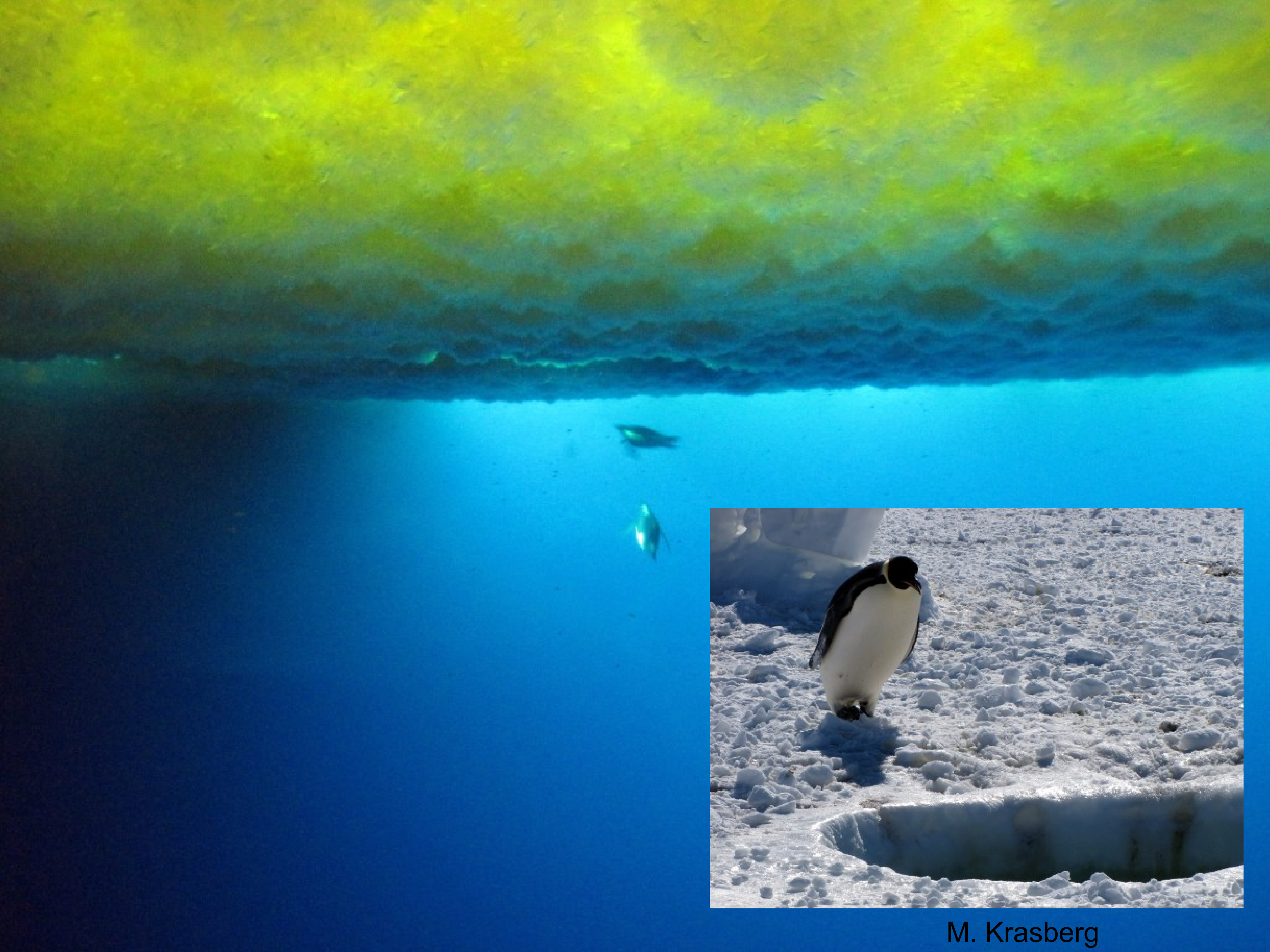
Cherenkov light mapped by optical sensors

IceCube



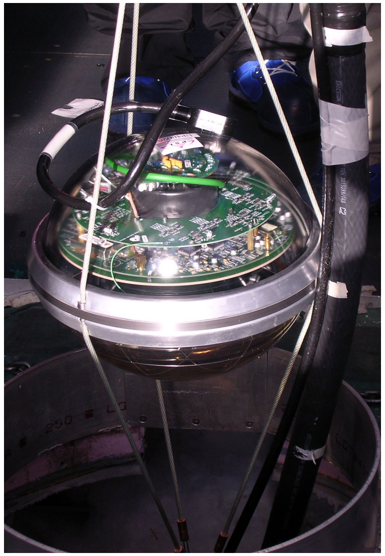
IceCube Lab
IceTop
80 Strings each with
2 IceTop Cherenkov Detector Tanks
2 Optical Sensors per tank
320 Optical Sensors
50 m
2009: 59 strings in operation
2011: Project completion, 86 strings
IceCube In-Ice Array
86 Strings, 60 Sensors
5160 Optical Sensors
1450 m
AMANDA-II Array
Decommissioned in 2009
Deep Core
6 Strings - Optimized for low energies
360 Optical Sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock

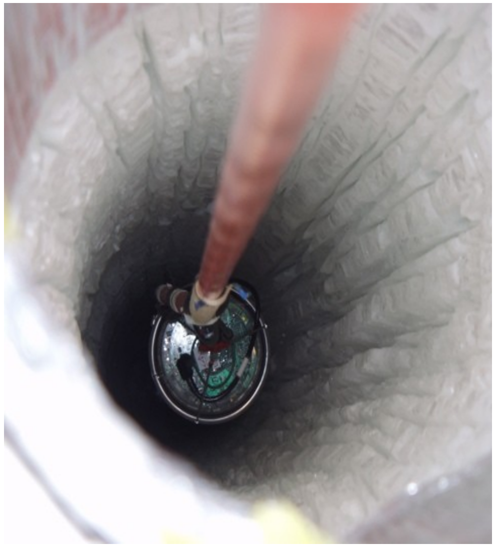

SCALE 1:250,000
10 Miles
15 Kilometers
CONTOUR INTERVAL 200 METERS
Cape Bird
MOUNT BIRD
LEWIS BAY
WOHLSCHLAG BAY
Cape Tennyson
MOUNT EREBUS
MT TERRA NOVA
MOUNT TERROR
ROSS ISLAND
Cape Crozier
Cape Royds
Cape Evans
WINDLESS BIGHT
Cape MacKay
ROSS

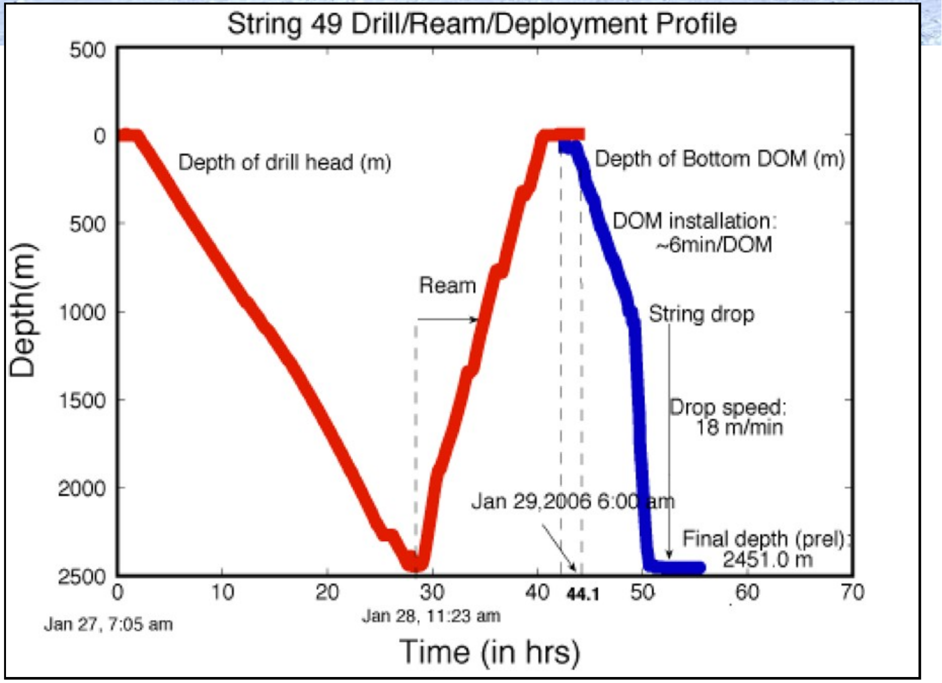


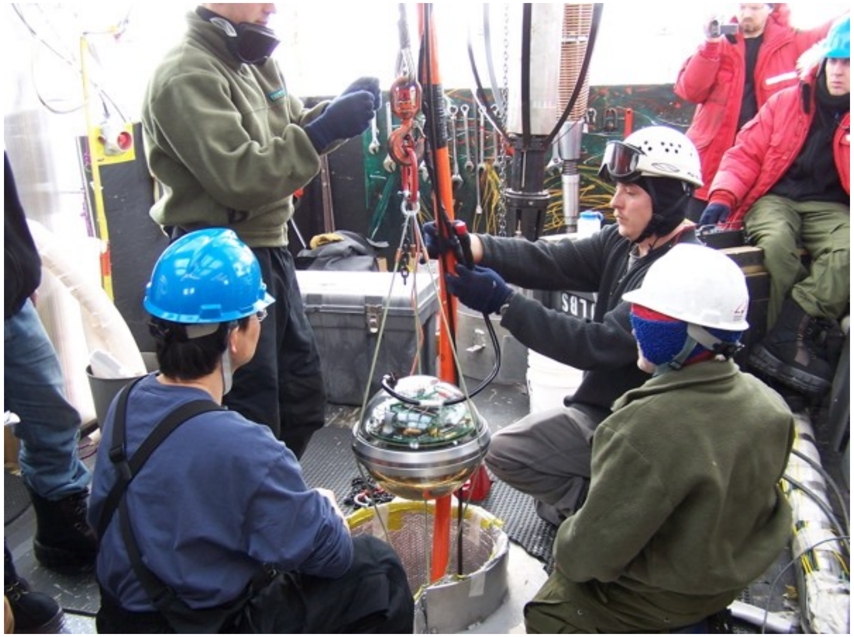
M. Krasberg

Drilling and Deployment

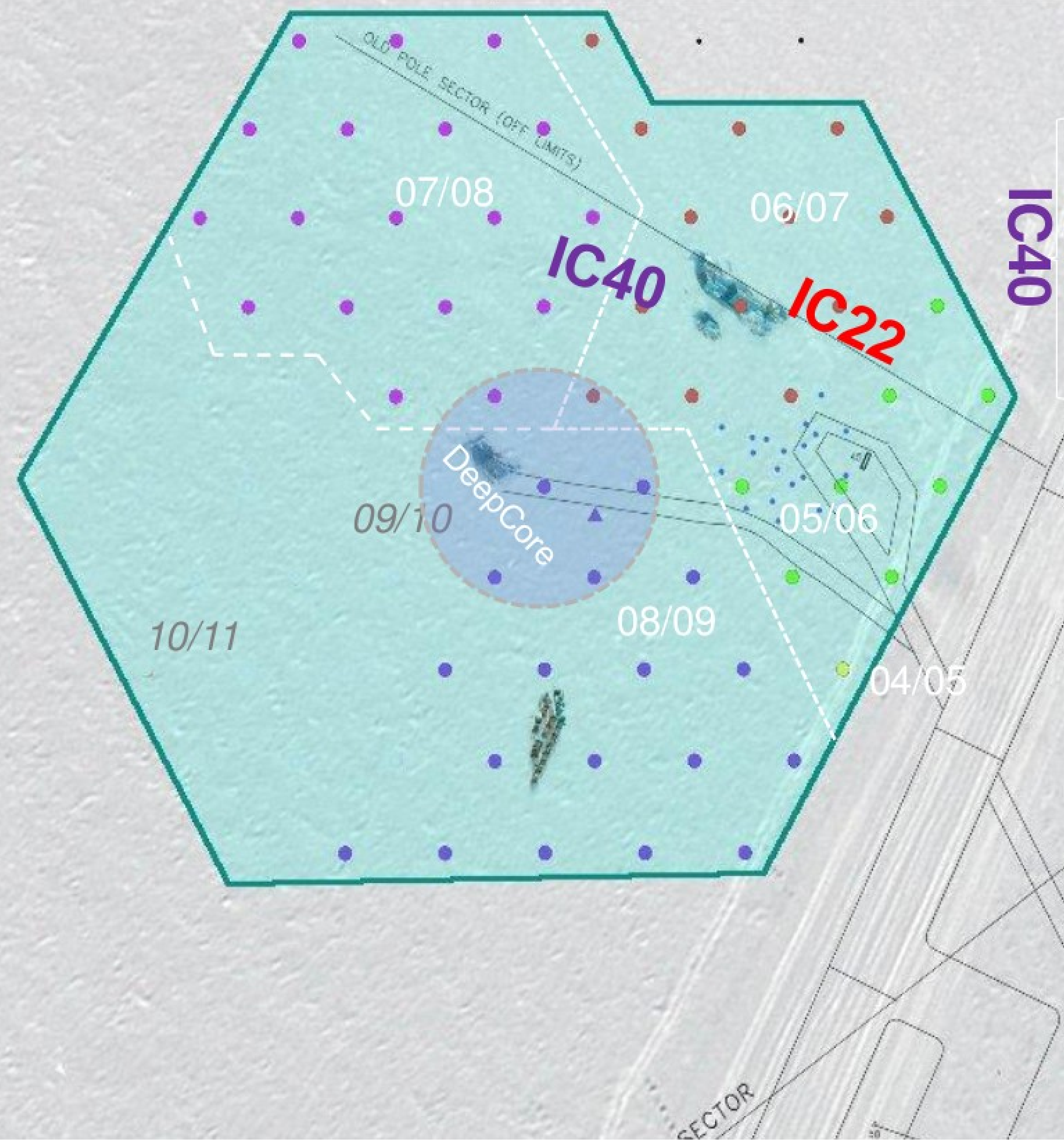








IceCube Detector Status

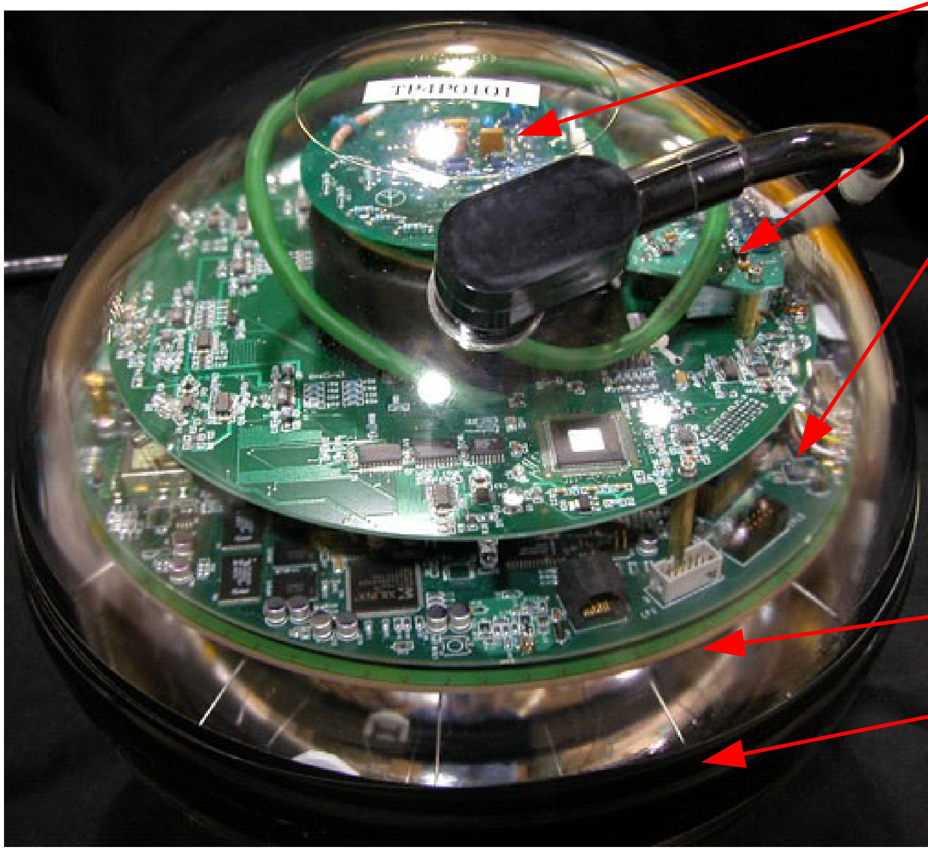


Season	Deployed
2004-2005	1 string
2005-2006	8 strings
2006-2007	13 strings
2007-2008	18 strings
2008-2009	18+1 strings

IC40

IC22

Digital Optical Module (DOM)



HV

Flasher Board with 12 LEDs

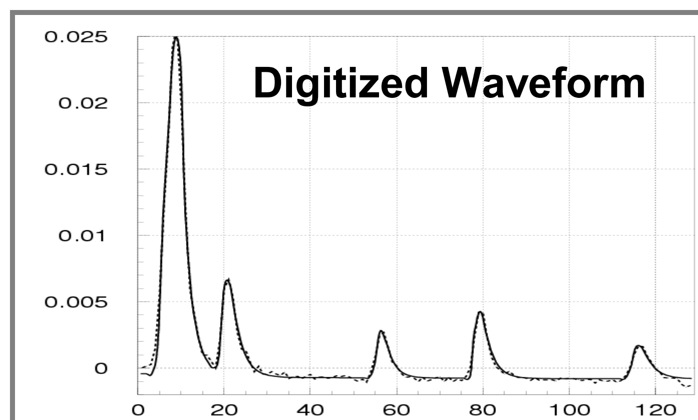
DOM Main Board

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

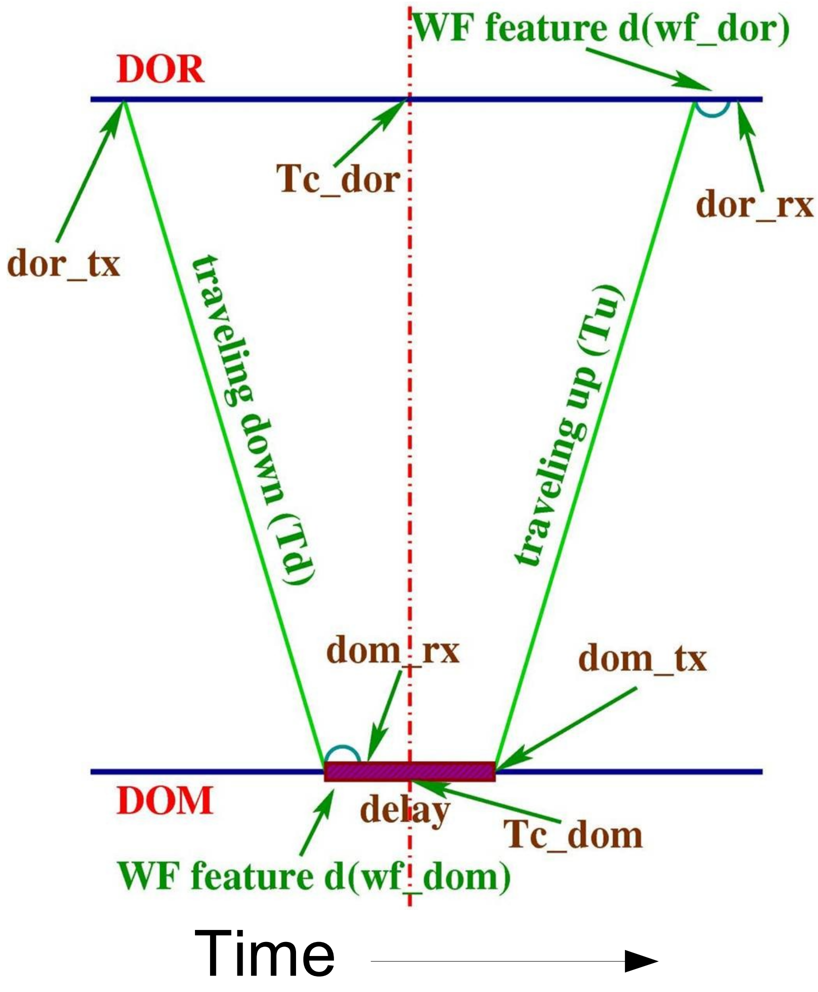
Synchronize DOM clock with GPS master clock

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

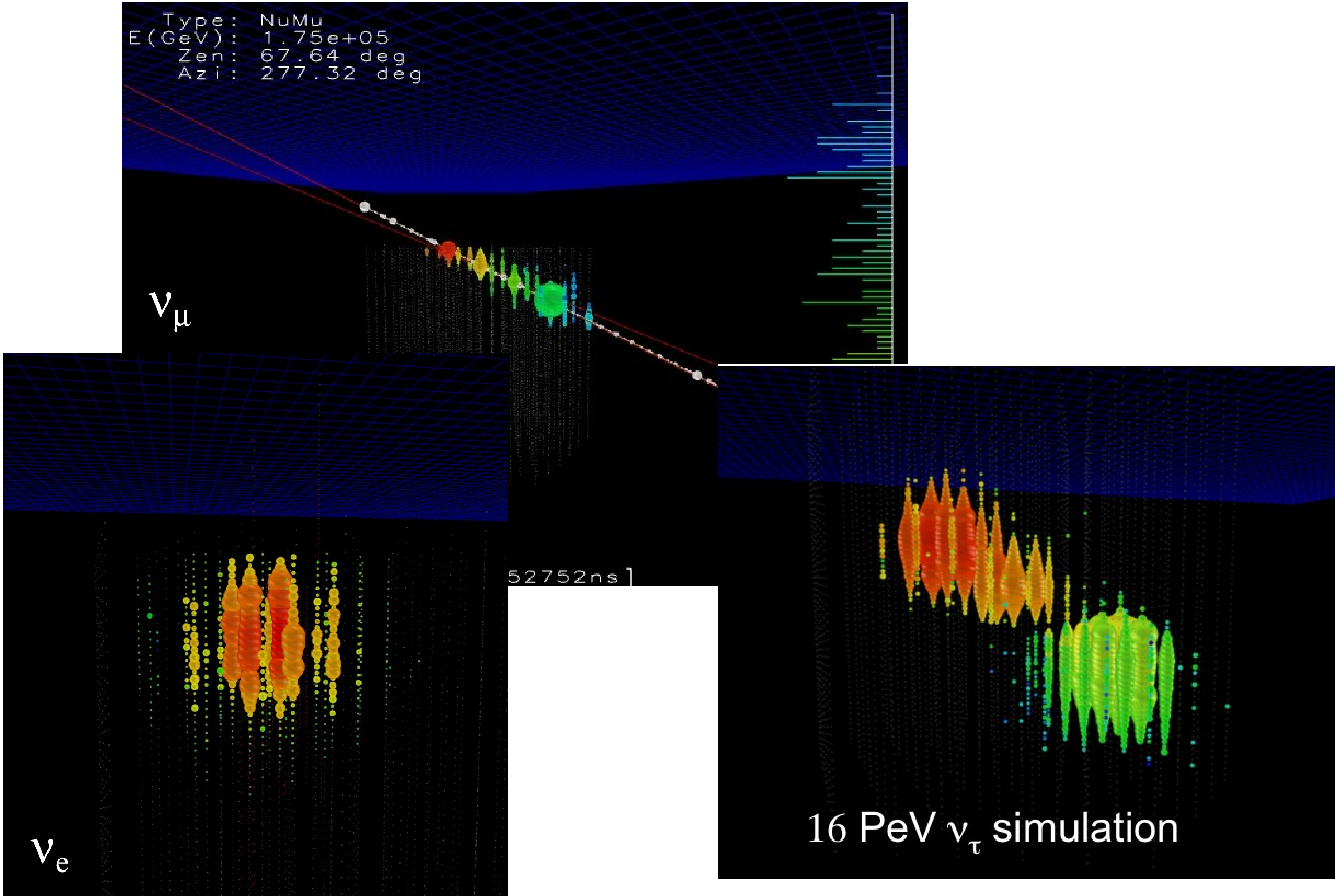
Symmetric DOR-DOM pulses are timestamped at TX and RX

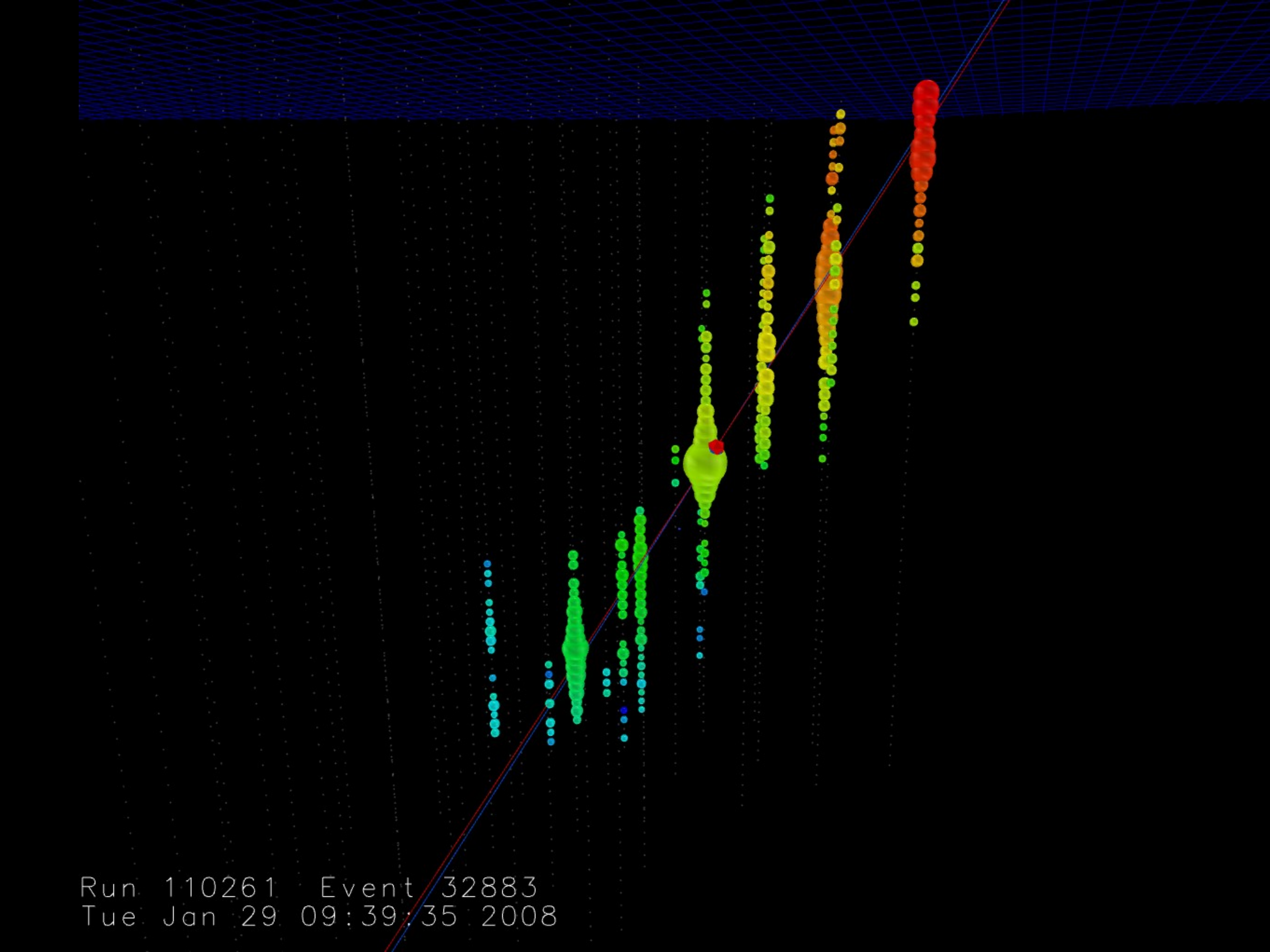
Average of DOM and DOR TX and RX times provides a calibration point

Time calibration is automatic and accurate to ~2 ns



Event Topologies

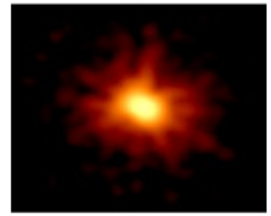
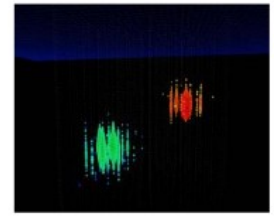




Run 110261 Event 32883
Tue Jan 29 09:39:35 2008

Neutrino Astrophysics with IceCube



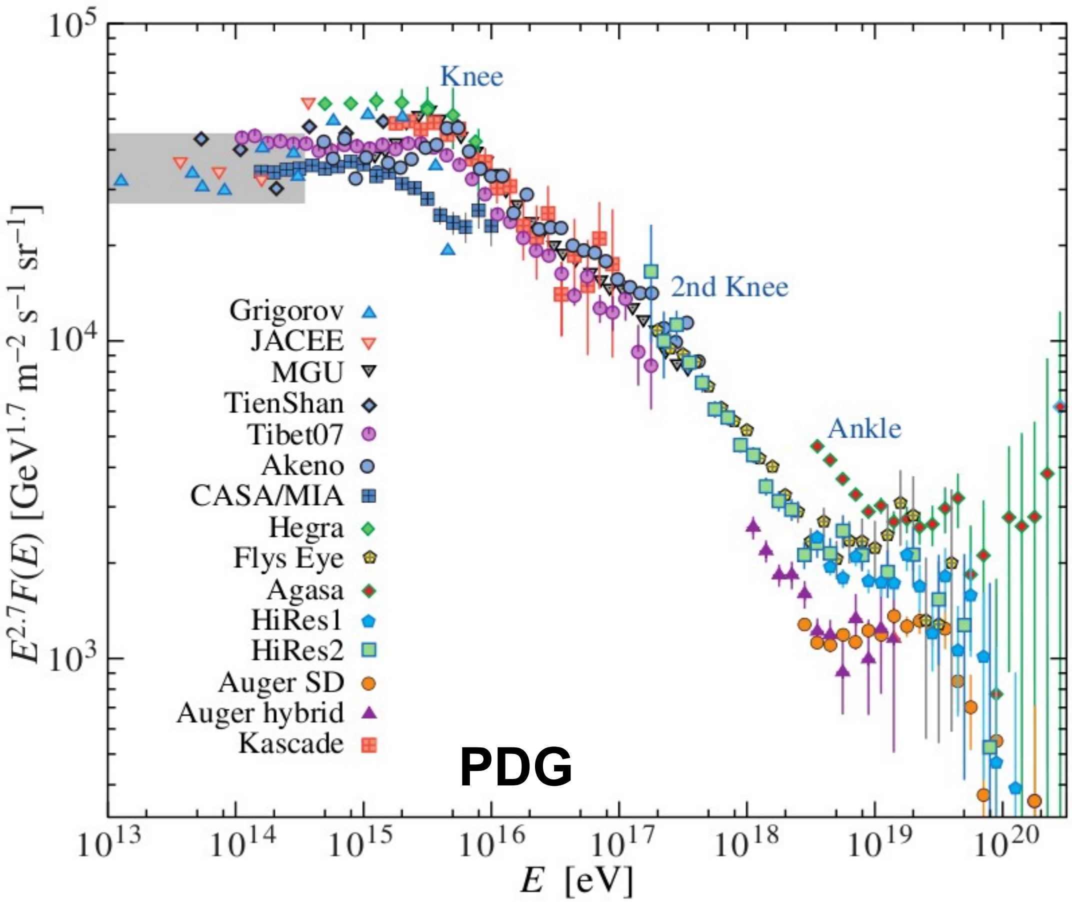




Energy range	~MeV	GeV-TeV	TeV-PeV	PeV-EeV	>EeV
Physics	Supernovae	Dark Matter, Oscillations, Atmospheric ν,	Point sources, GRB, Diffuse	GZK Neutrinos, Cosmic Rays	?
Signature	Average increase in the PMT counting rate	Tracks, Contained Events	Tracks, Cascades	Tracks, Cascades, Double Bang, Lollipops	Christmas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

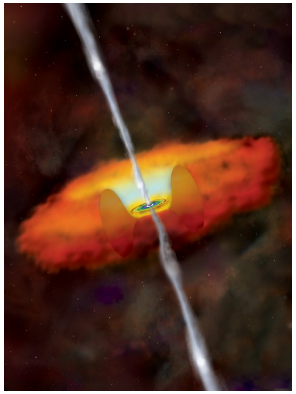
Many new results at ICRC 2009

Cosmic Ray Accelerators

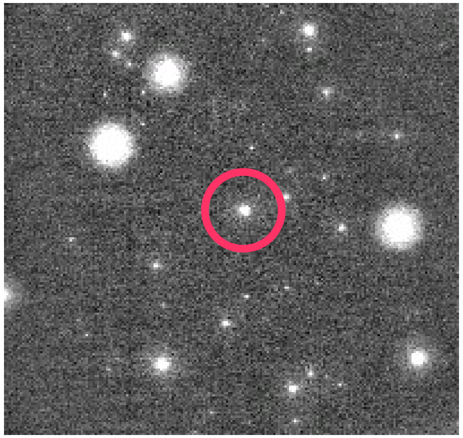
Fermi shock acceleration with spectral index Γ ~-2



SN Remnants



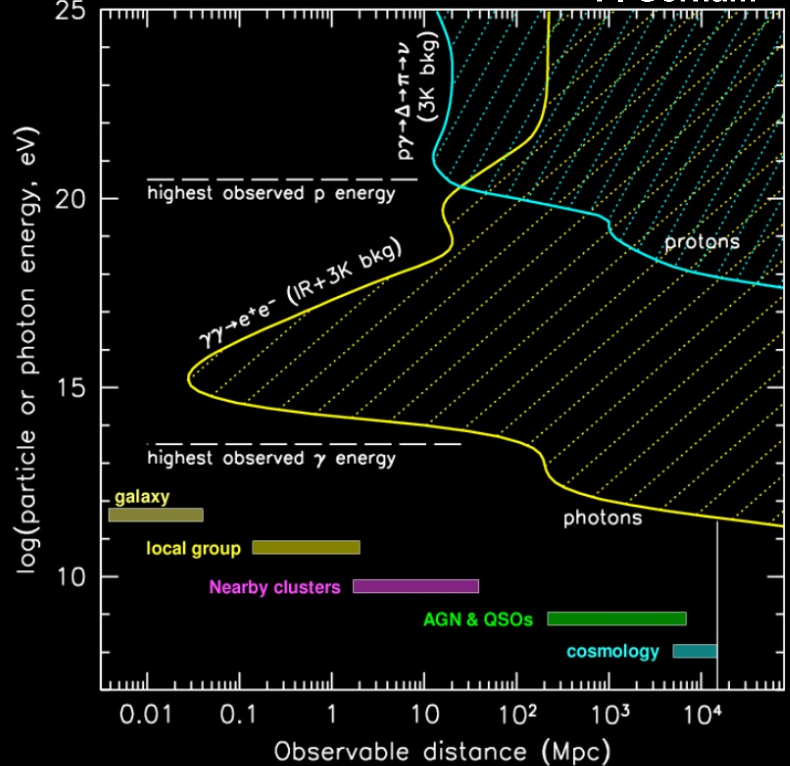
AGN

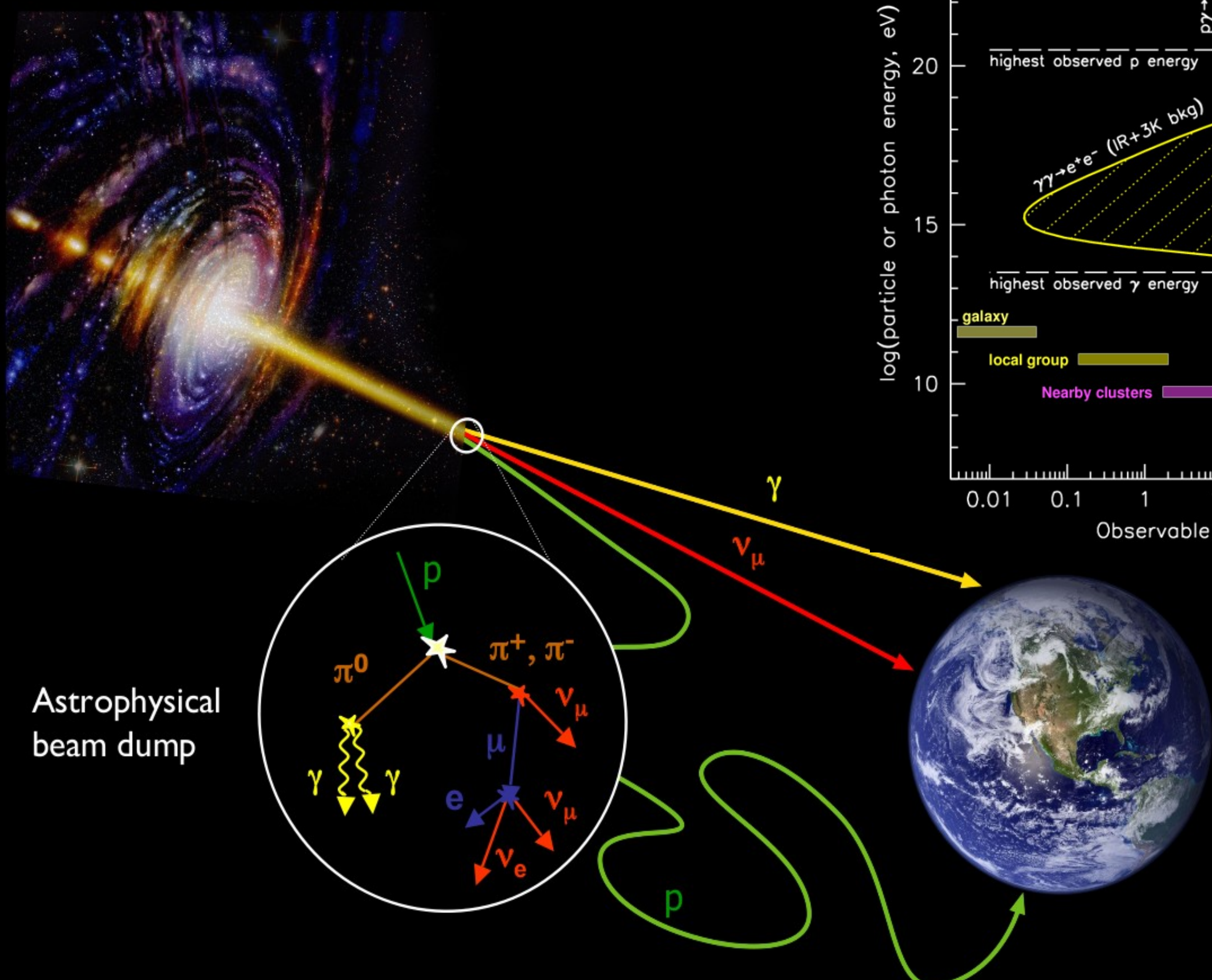


GRB 080319b

Astronomical Messengers

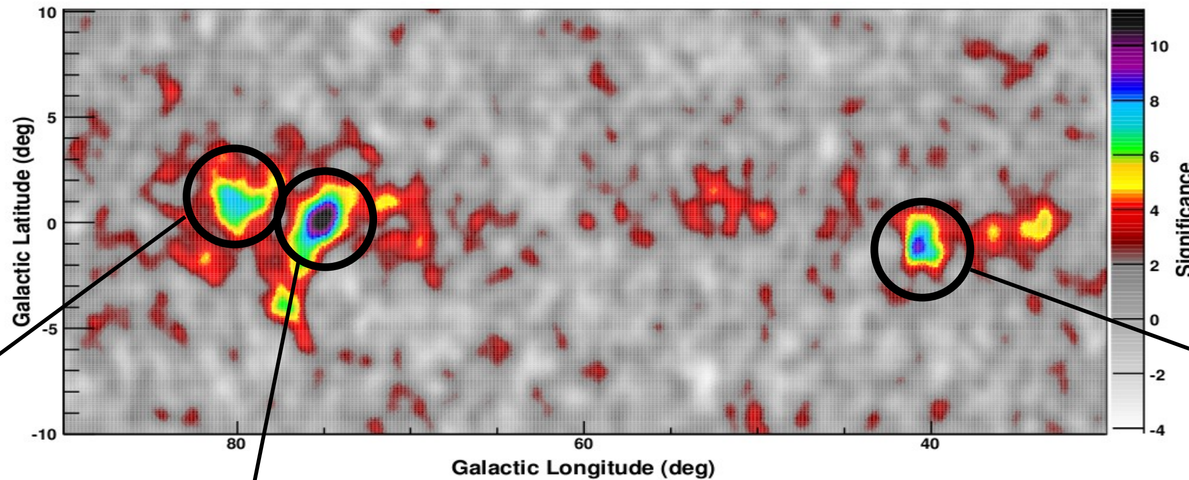
P. Gorham





Milagro Sources

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

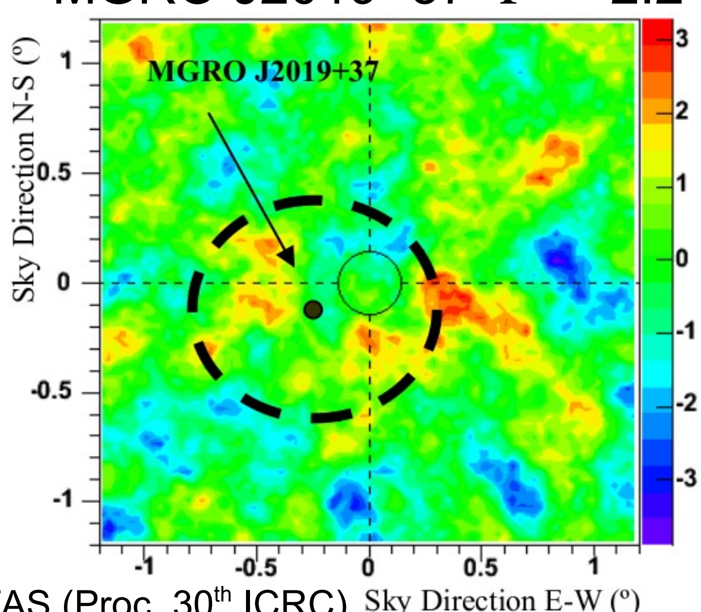


MGRO J2031+41 Γ ~-2

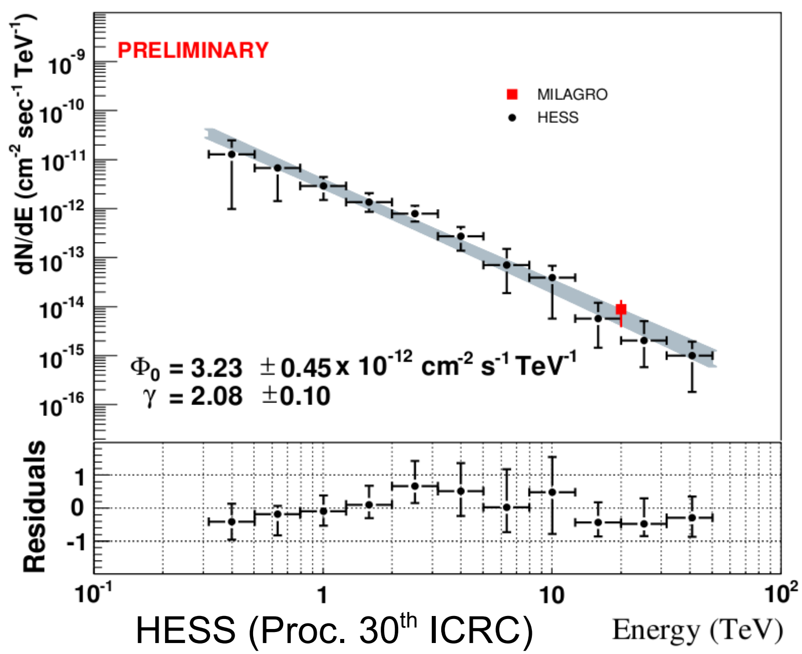
MAGIC arXiv:0801.2391v2

MGRO J1906+08 Γ ~-2

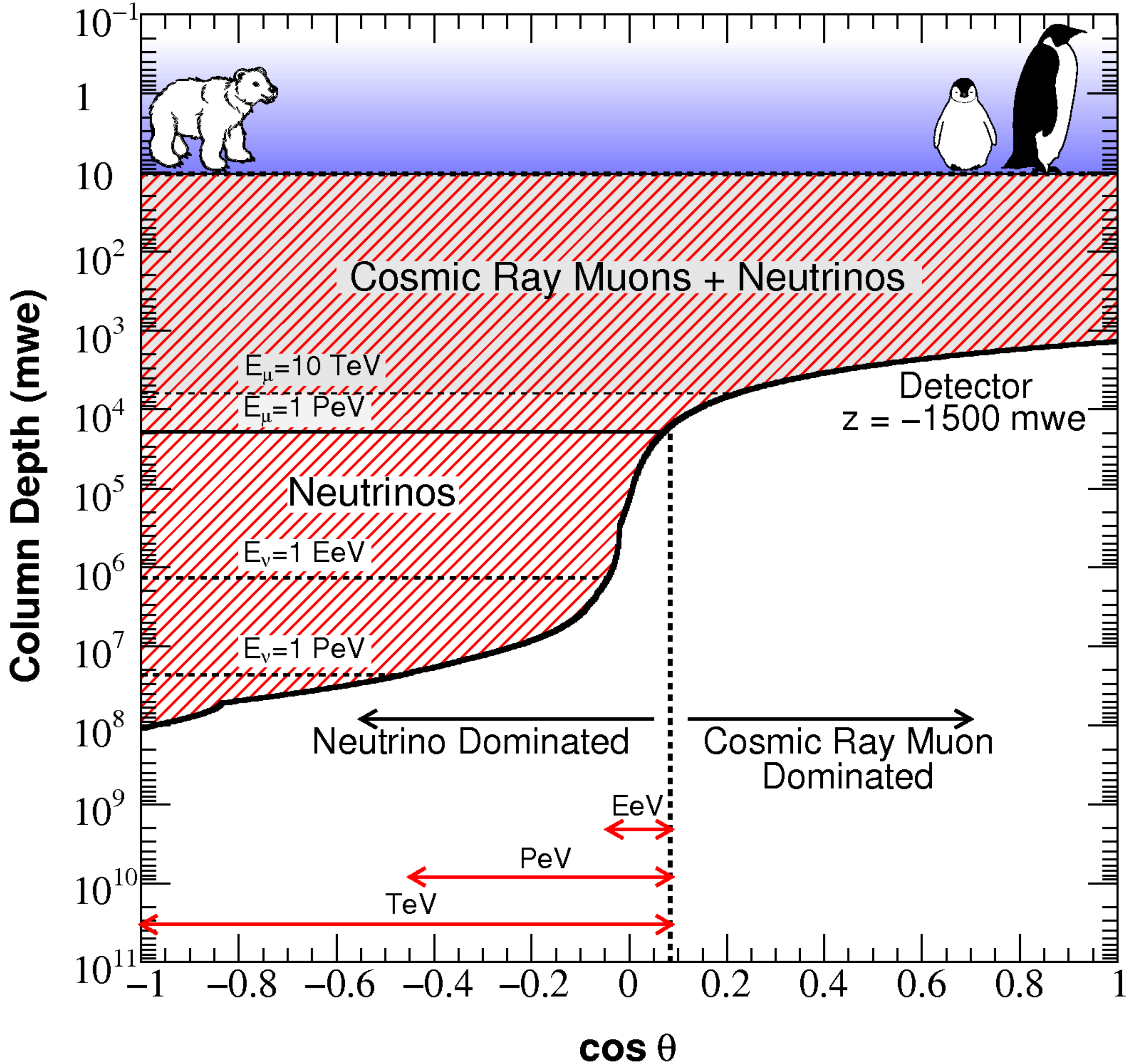
MGRO J2019+37 Γ > -2.2



VERITAS (Proc. 30th ICRC)

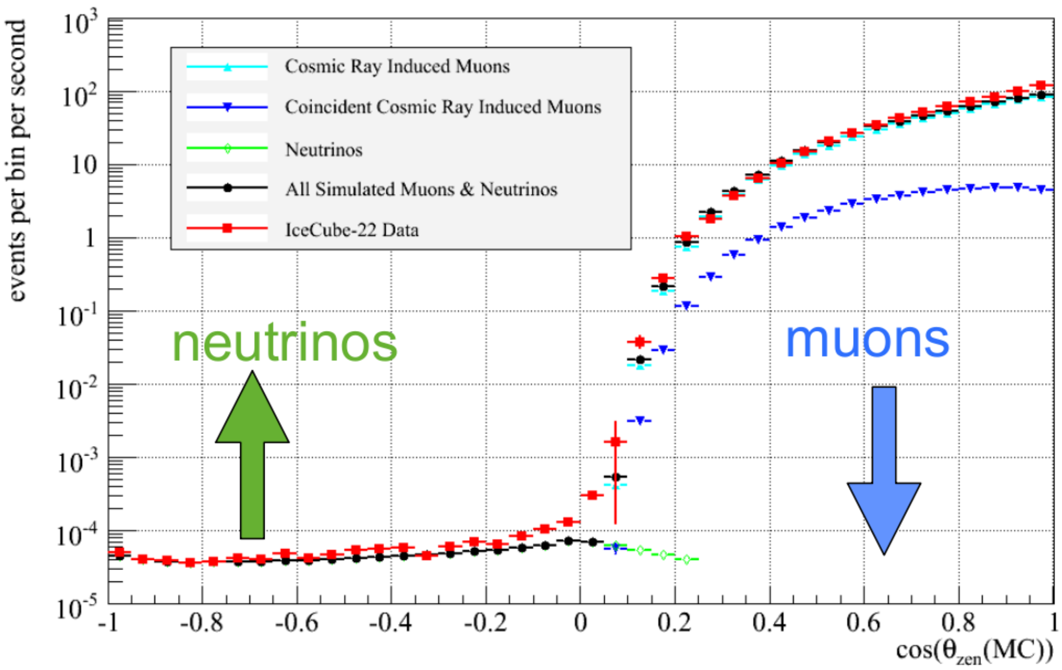


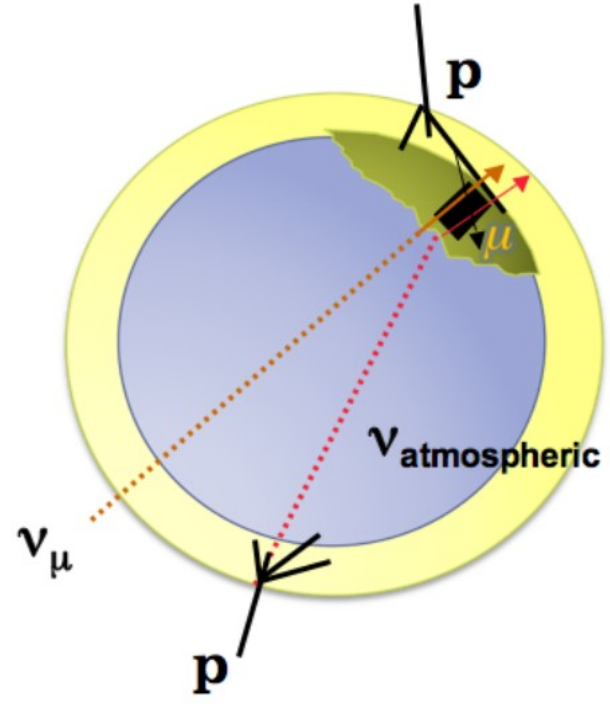
HESS (Proc. 30th ICRC)



Cosmic Ray Muons + Neutrinos
Eμ=10 TeV
Eμ=1 PeV
Detector
z = −1500 mwe
Neutrinos
Eν=1 EeV
Eν=1 PeV
Neutrino Dominated
Cosmic Ray Muon Dominated
EeV
PeV
TeV
Column Depth (mwe)
cos θ

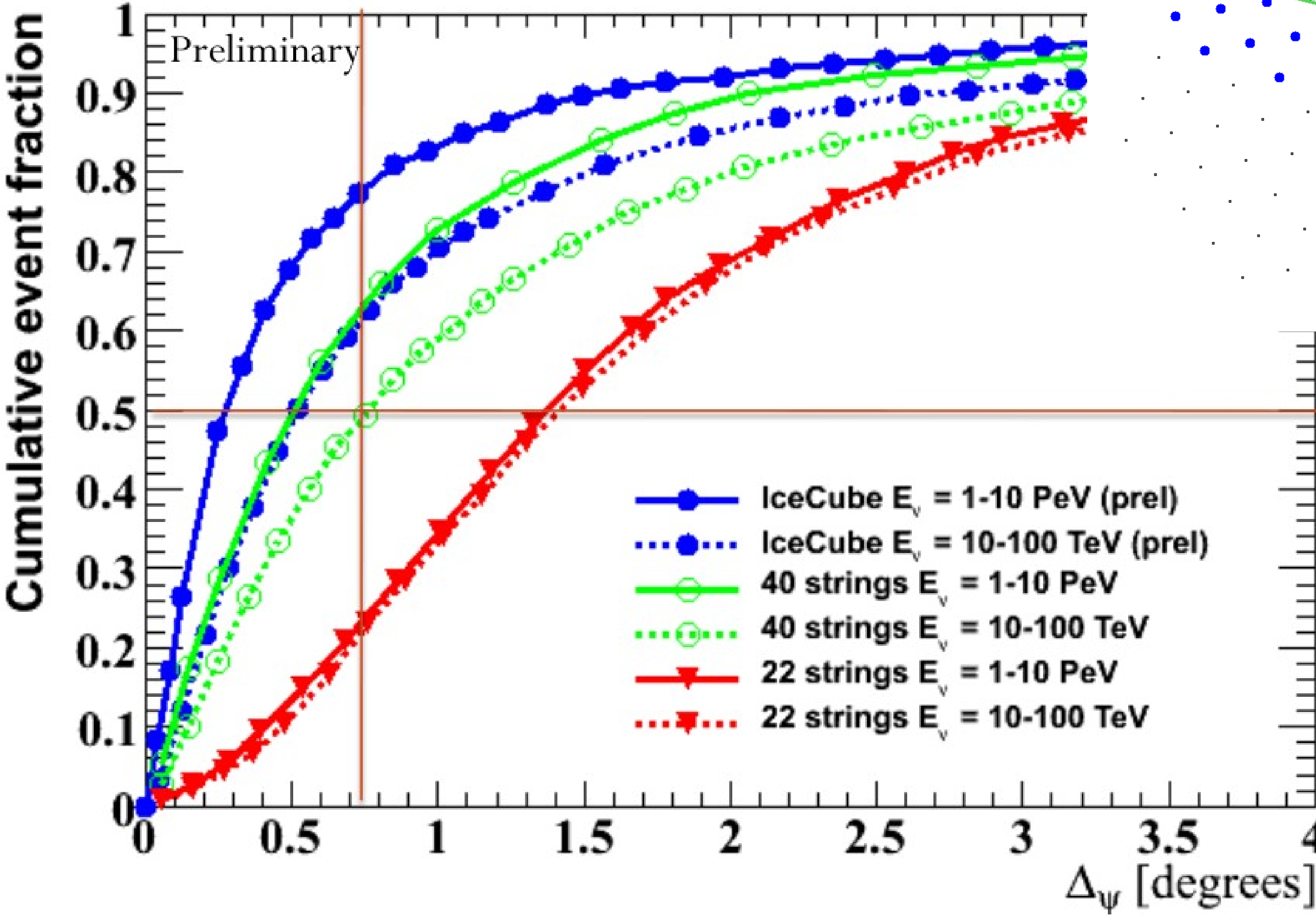
IceCube Muon Events

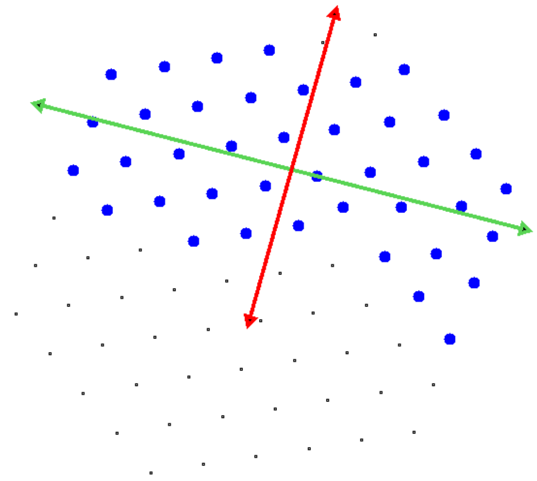




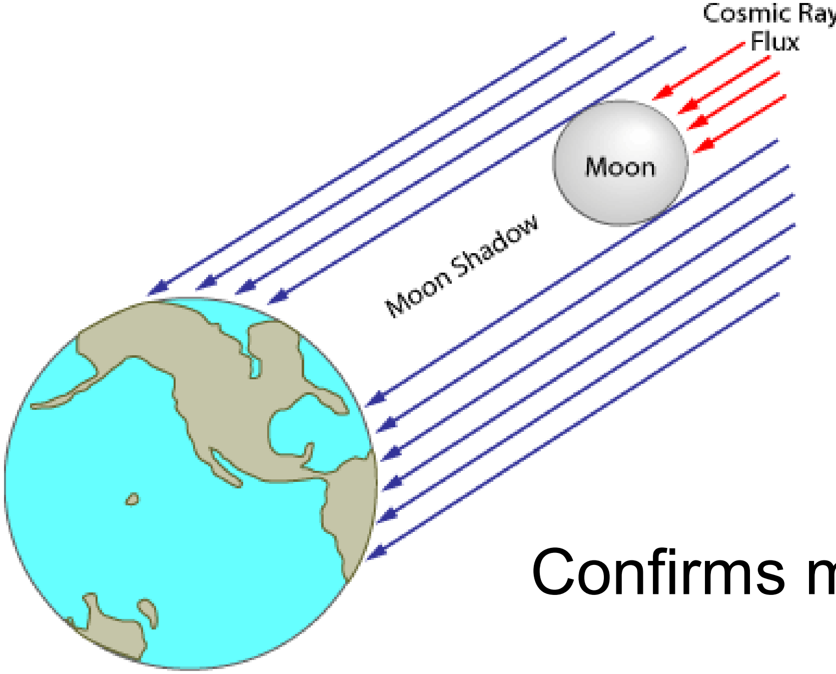
Strings	μ rate	ν rate
AMANDA	80 Hz	4.8 / day
IC22	550 Hz	28 / day
IC40	1200 Hz	110 / day*
IC80	1650 Hz*	220 / day*

Muon Angular Resolution





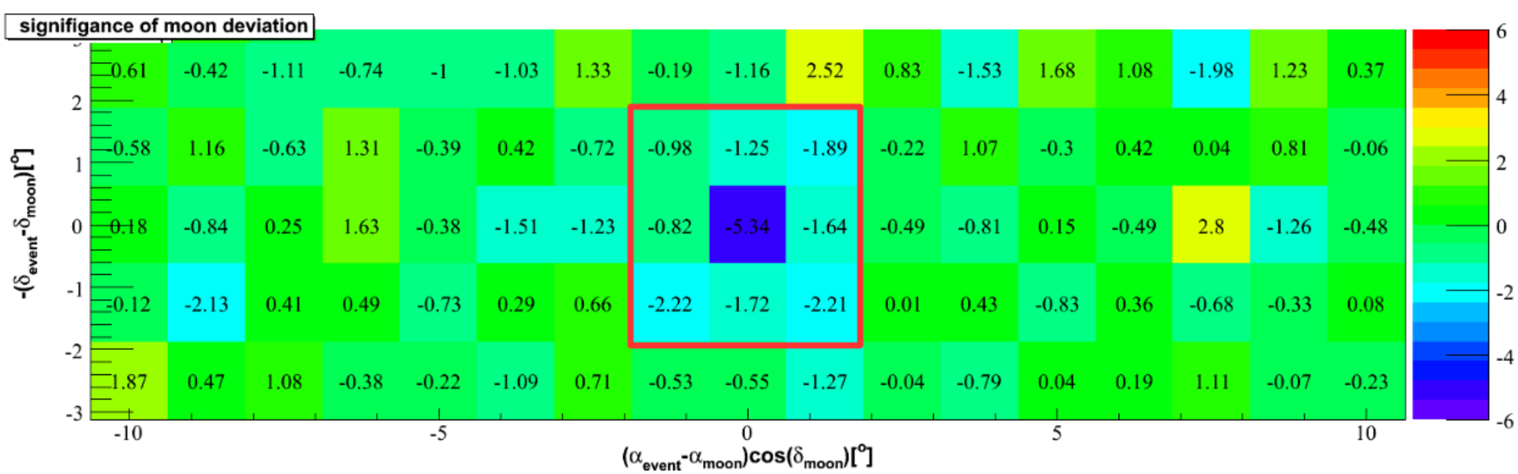
The Moon Shadow



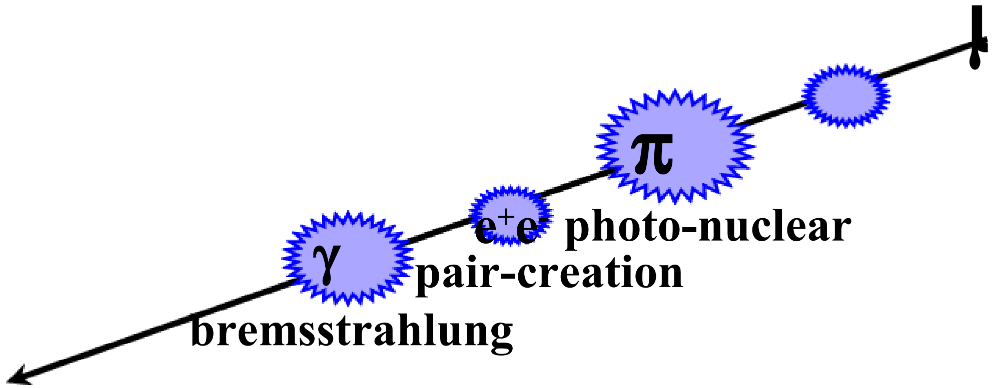
5.34σ deficit found

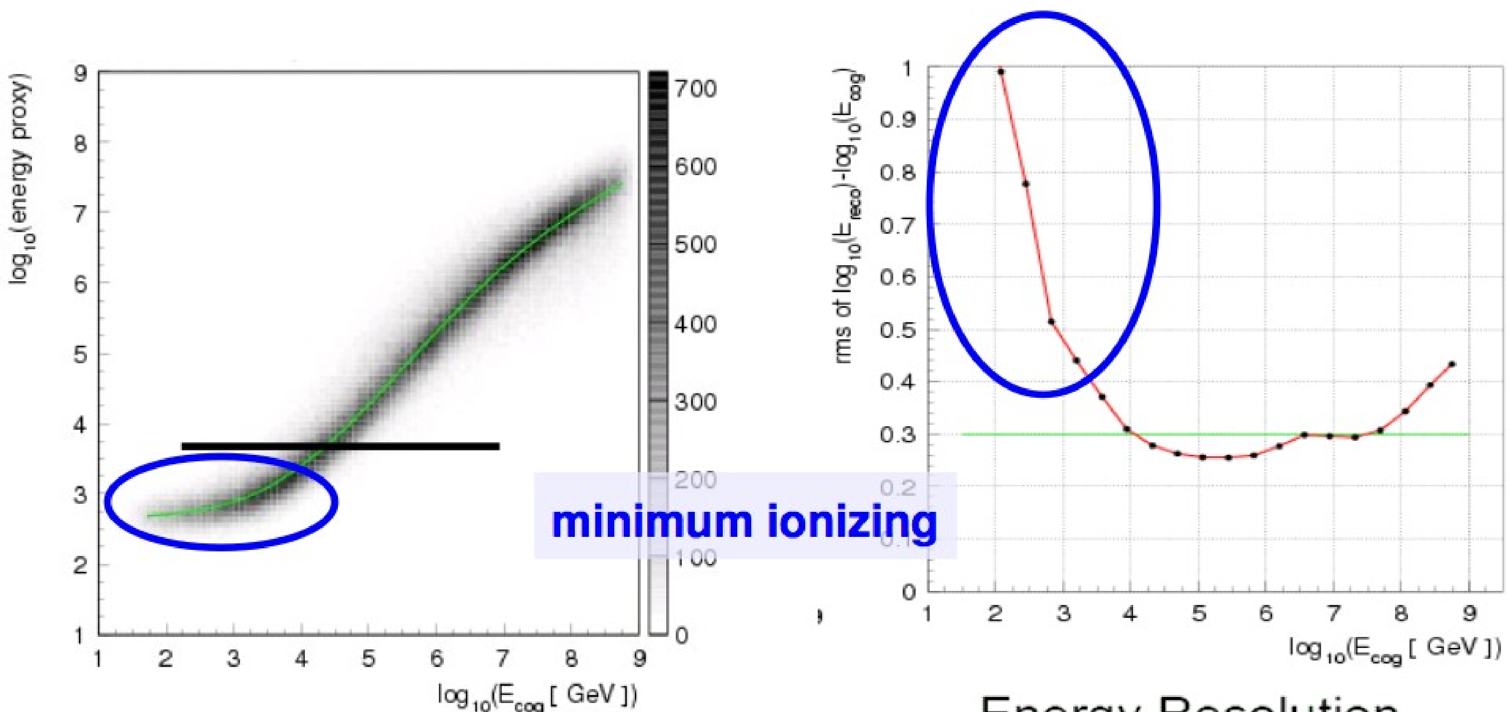
6.1σ expected

Confirms muon pointing resolution in IC-40



Muon Energy Resolution



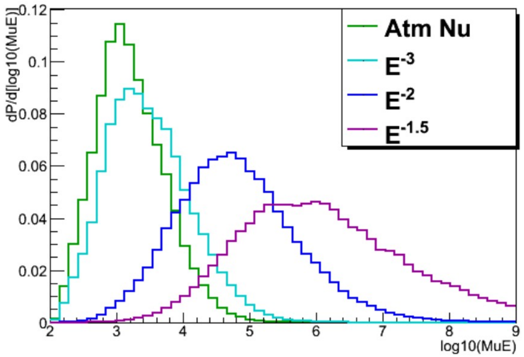


Source: D. Chirkin, UW

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

Astrophysical Neutrino Searches

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

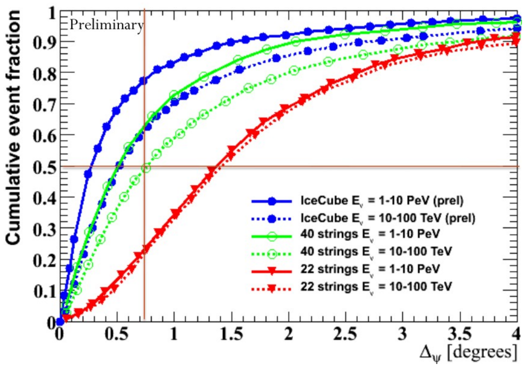


Energy

Extraterrestrial neutrinos should be more energetic than atmospheric neutrinos

→ **Diffuse Search**

+

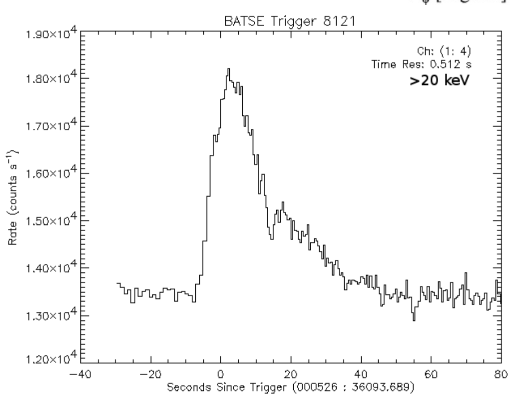


Space Angle

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**

Each term provides additional power to reject background

Neutrino Point Source Search

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

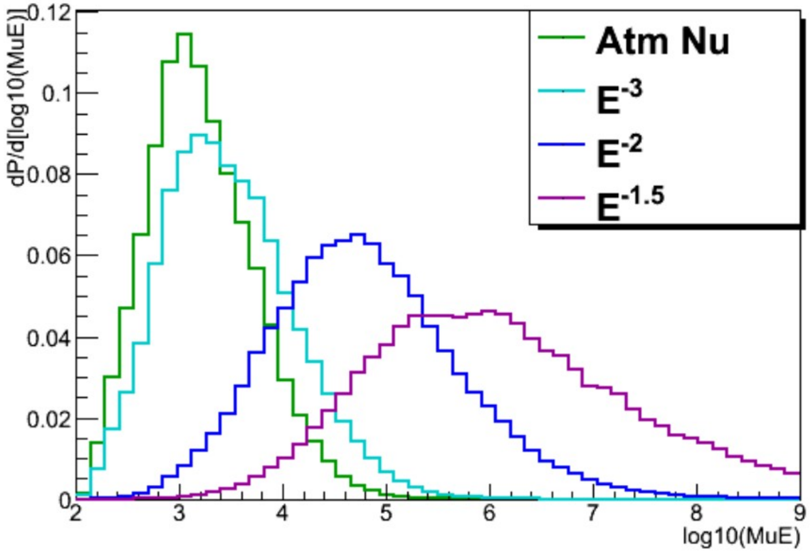
Space Angle Term:

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

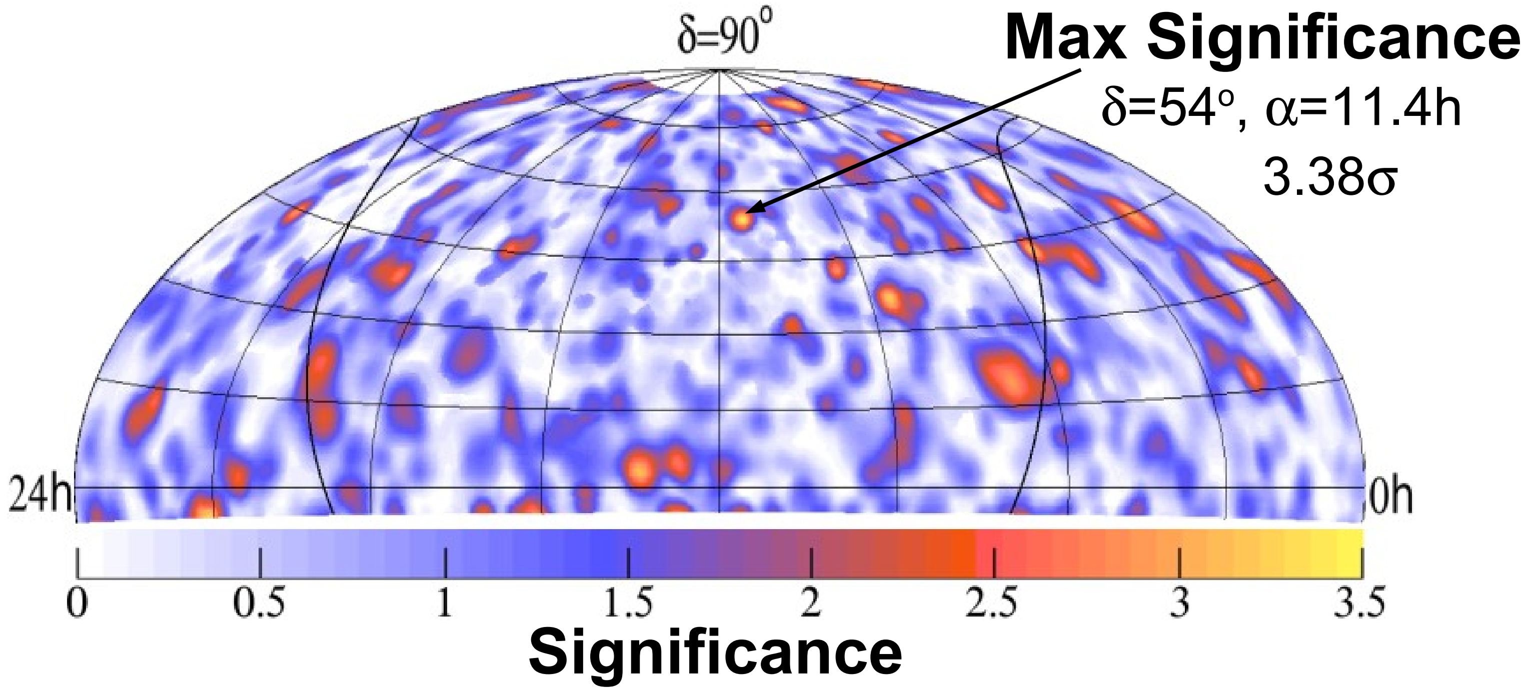
Likelihood function: $$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_{i=1}^{N} P(\vec{x}_s, n_s, \gamma, \vec{x}_i, E_i, \sigma_i)$$

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

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

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

AMANDA

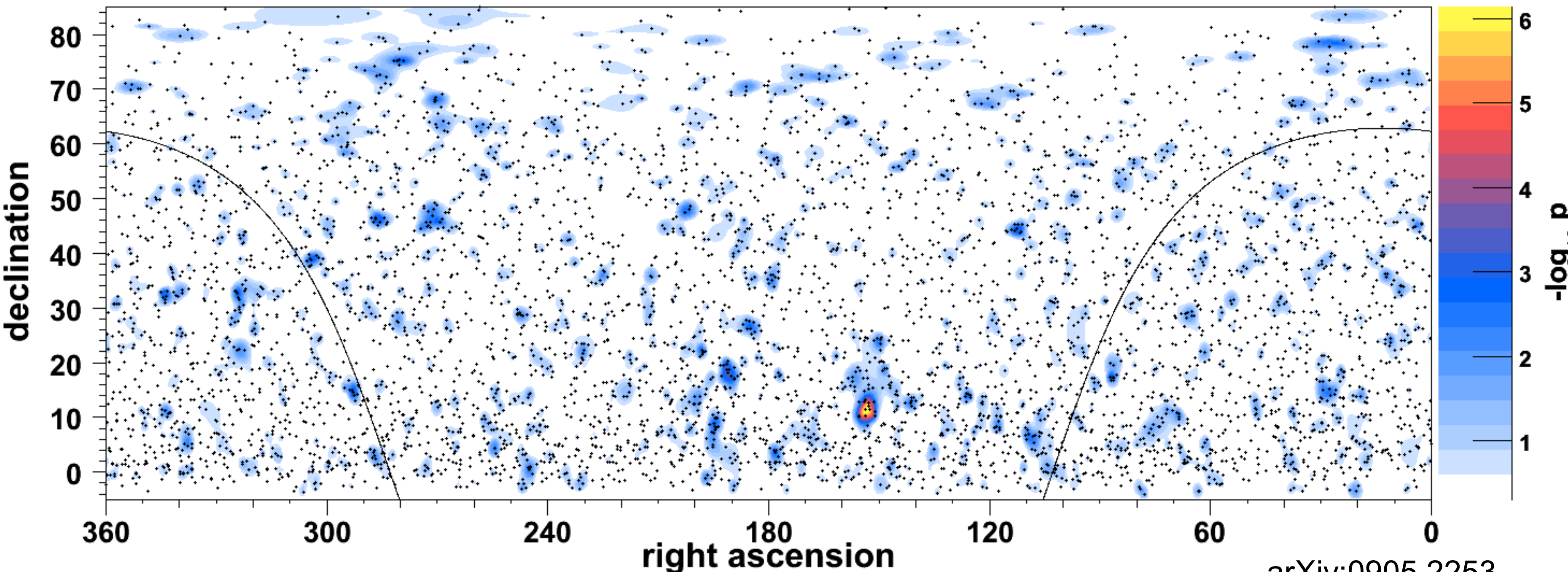


95 of 100 data sets randomized in RA have a significance ≥ 3.38σ

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

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

IceCube 22 String



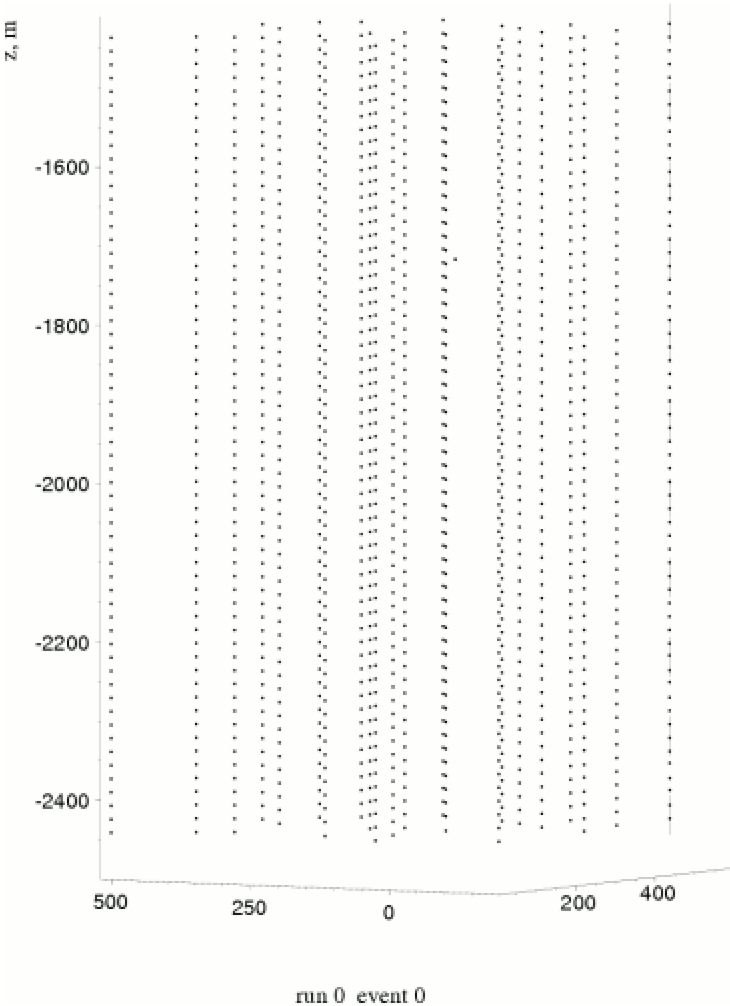
arXiv:0905.2253
to appear in ApJL

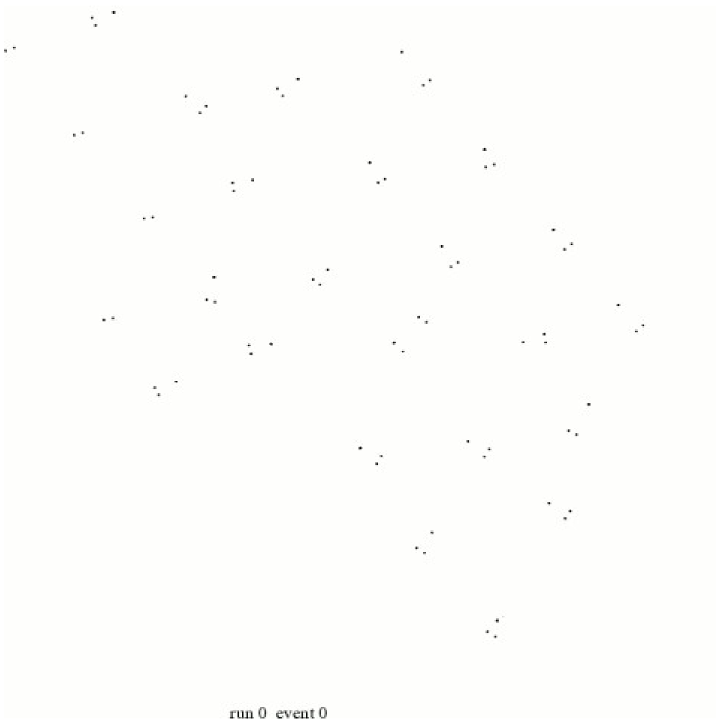
Hottest spot found at r.a. 153º , dec. 11º
pre-trial p-value: $7 \cdot 10^{-7}$ (4.8 sigma)
est. nSrcEvents = 7.7 est. gamma = 1.65

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.





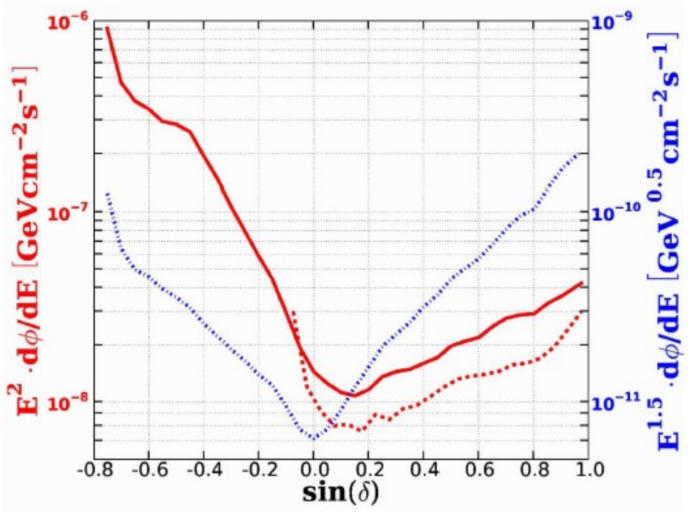
Number of hit modules: 148
Estimated angular error: 0.84°

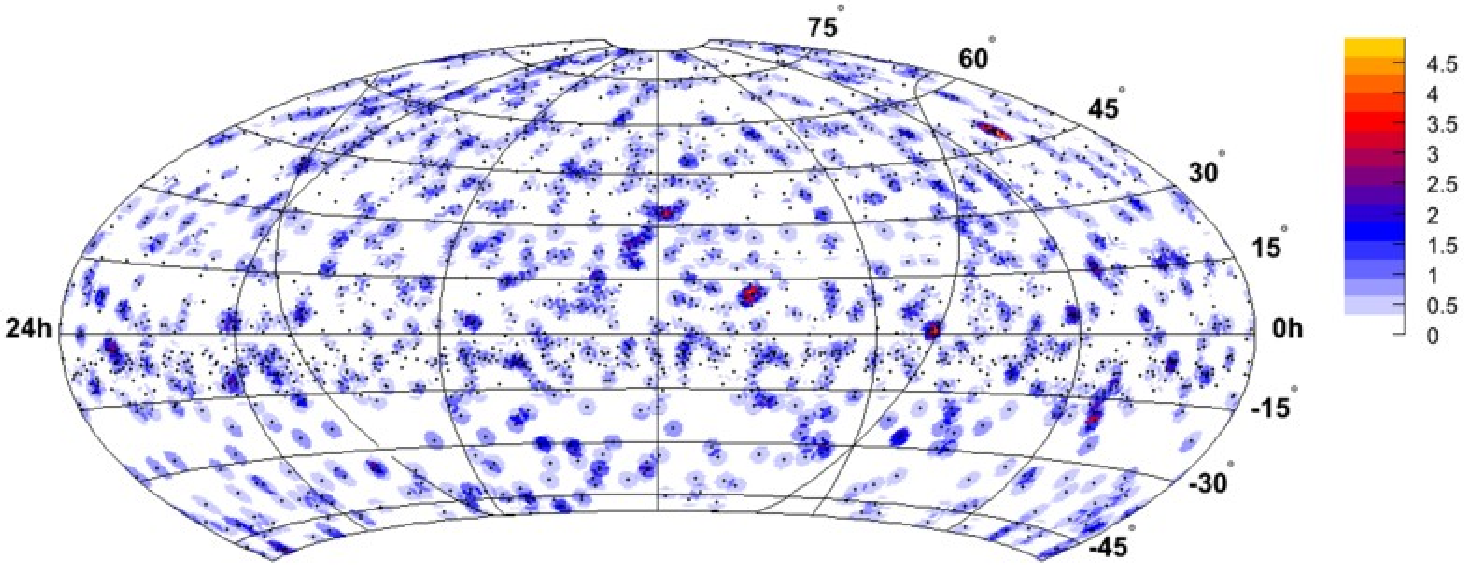
IceCube 22 String

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

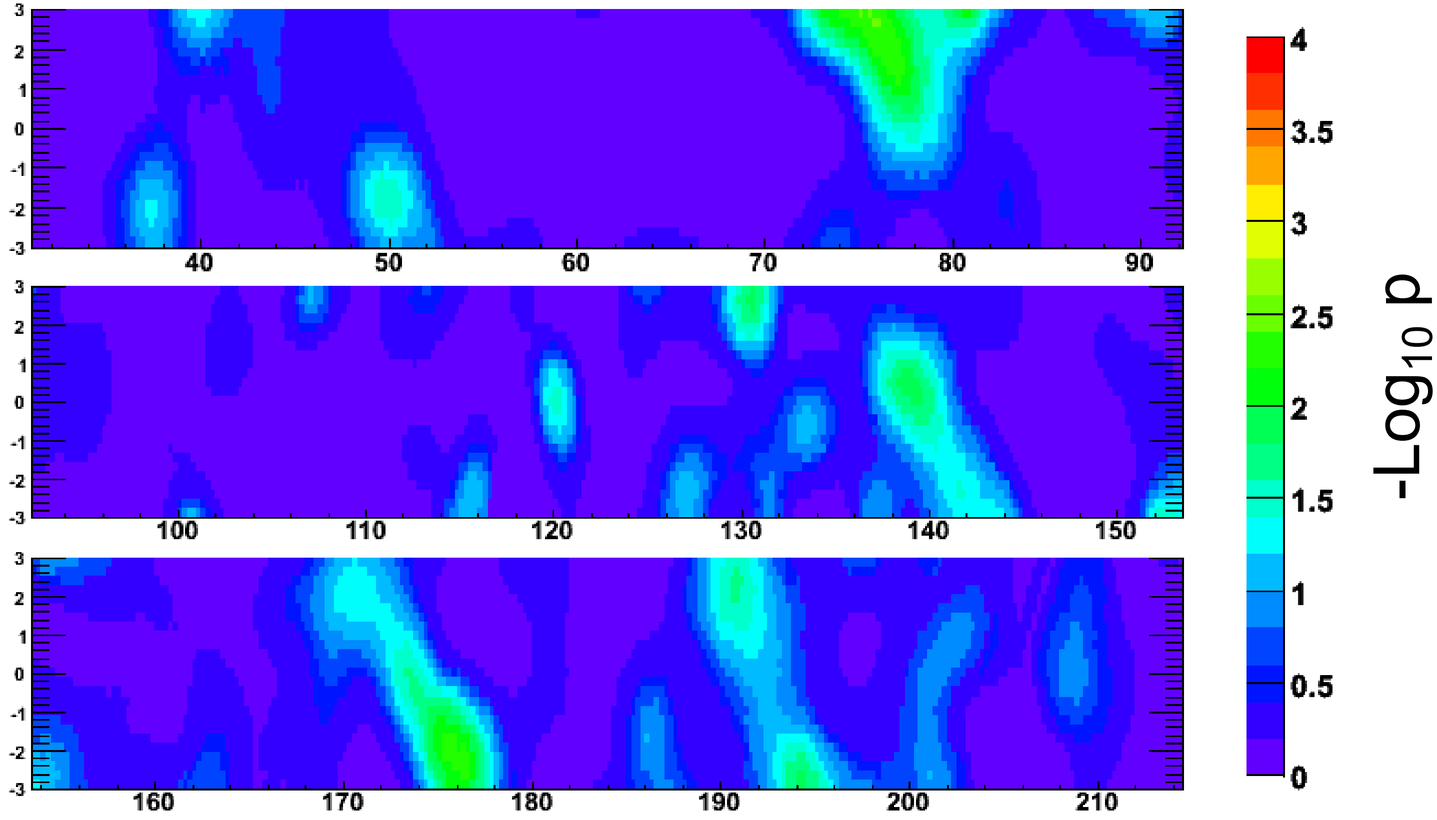
Selecting such high energy muons provides sensitivity in the downgoing direction

No excesses observed in binned search (p=0.37)

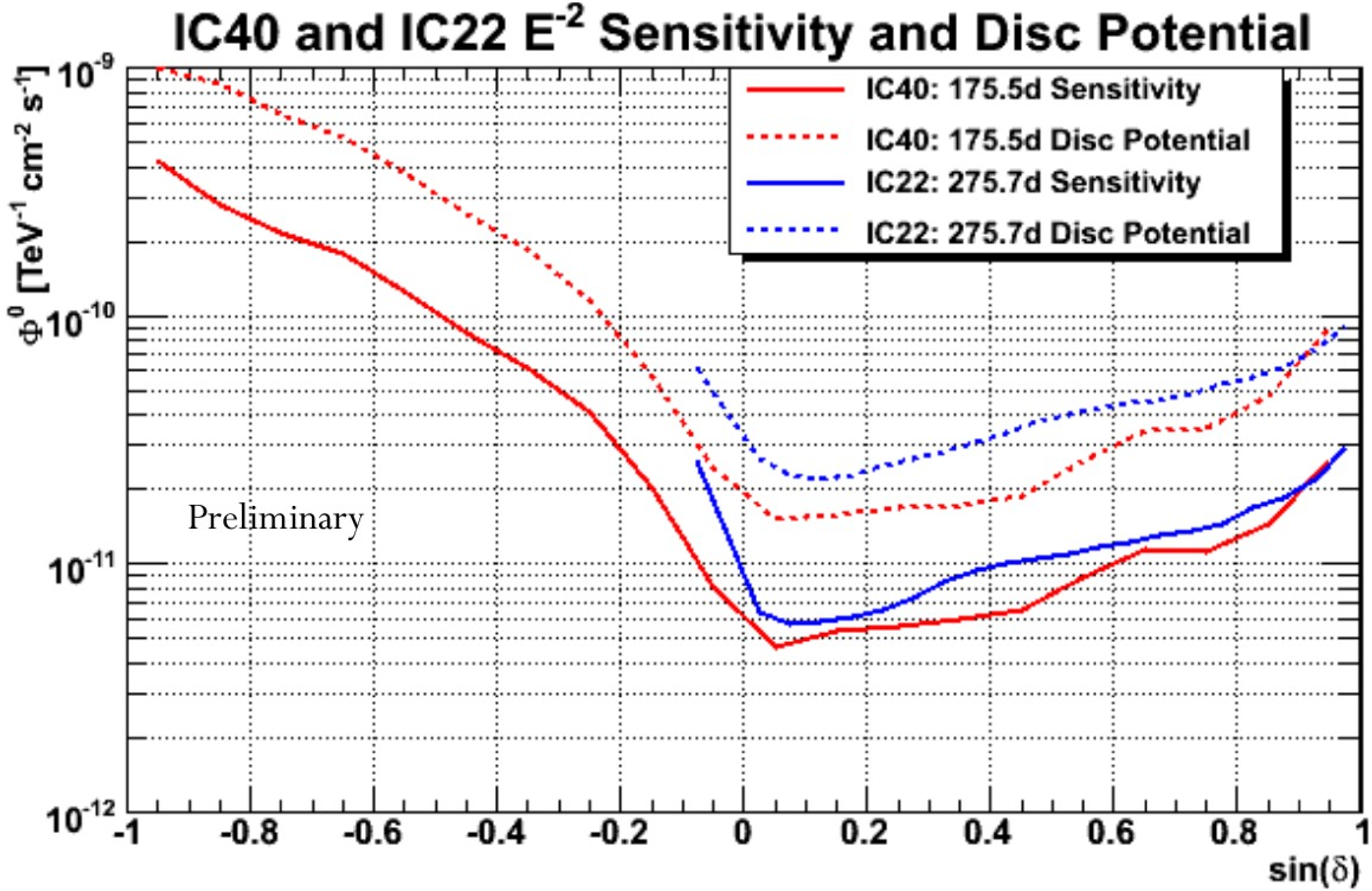




Search of the Galactic Plane with IceCube-22 + AMANDA

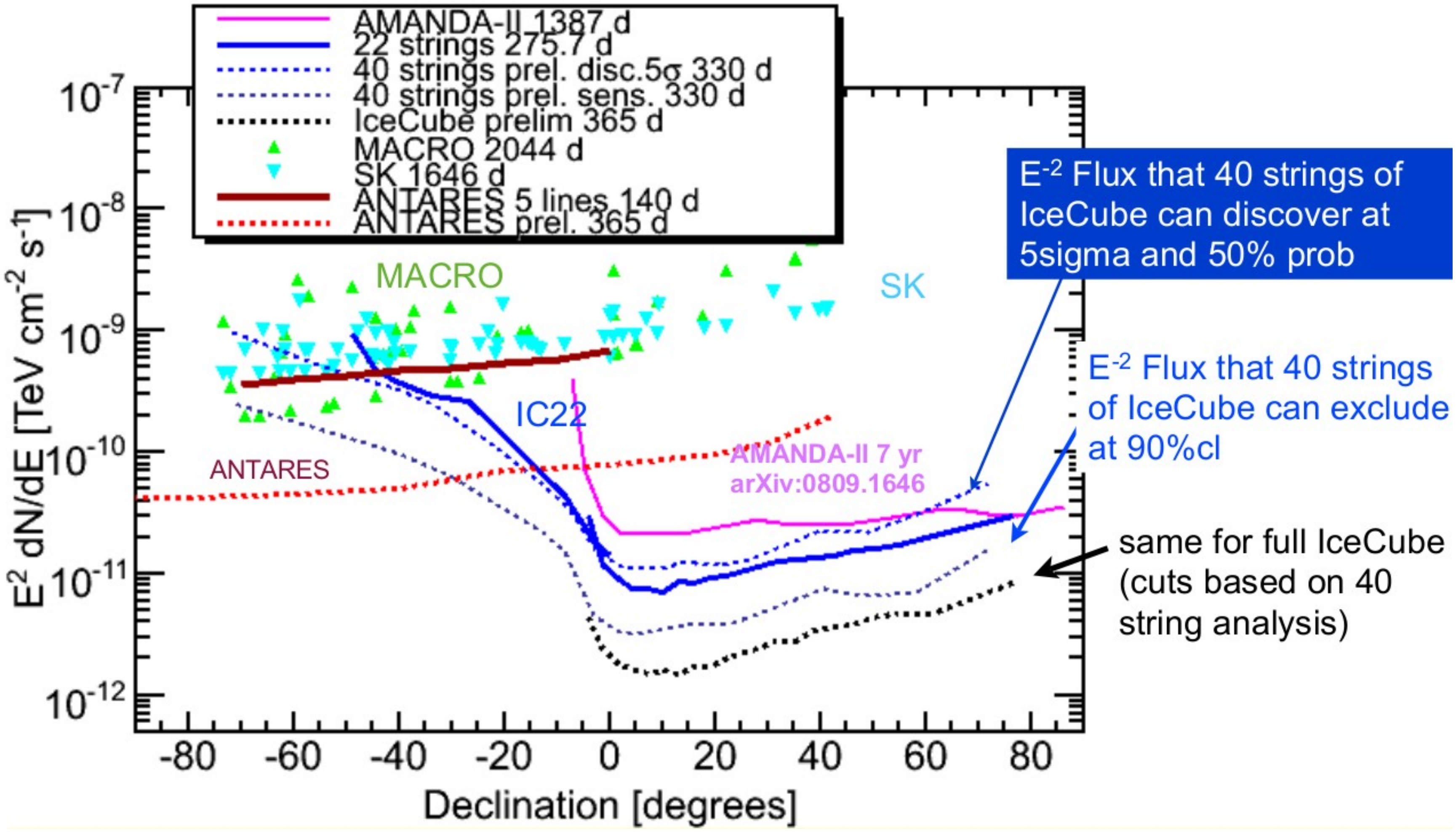


Optimized for low energy; no significant excess observed



IC40 6-month Results to be presented at ICRC

40 String Detector and Beyond

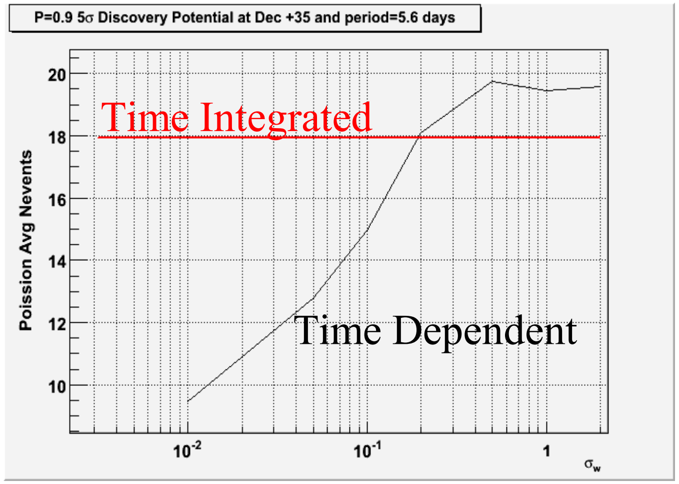


Time-Dependent Point Sources

Multiwavelength Flare Search

IC22: No neutrino correlations to photon
high states of several objects (e.g. 1ES 1959, Cygnus X-1)

Microquasars

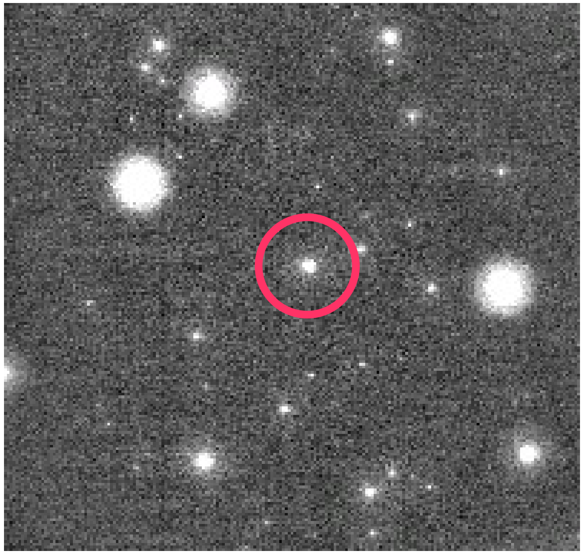


IC22: No periodic emission for 7 microquasars in the Northern Sky

Unbiased Flare Search

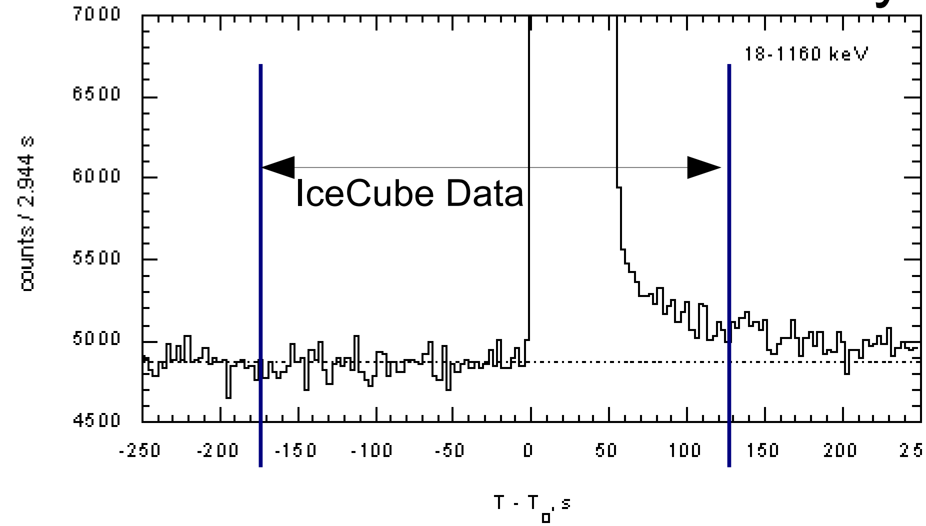
To be presented at ICRC

GRB 080319b



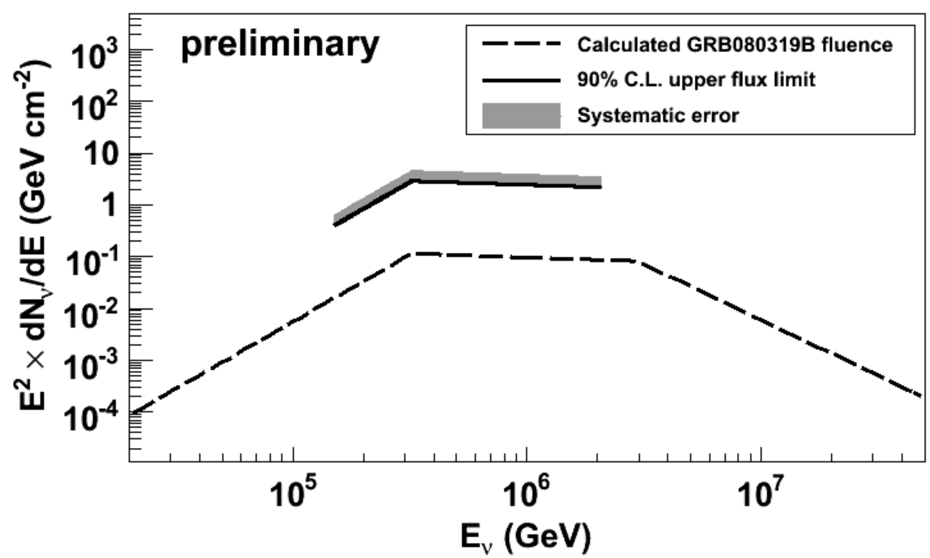
Pi of the Sky

Konus X-ray



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

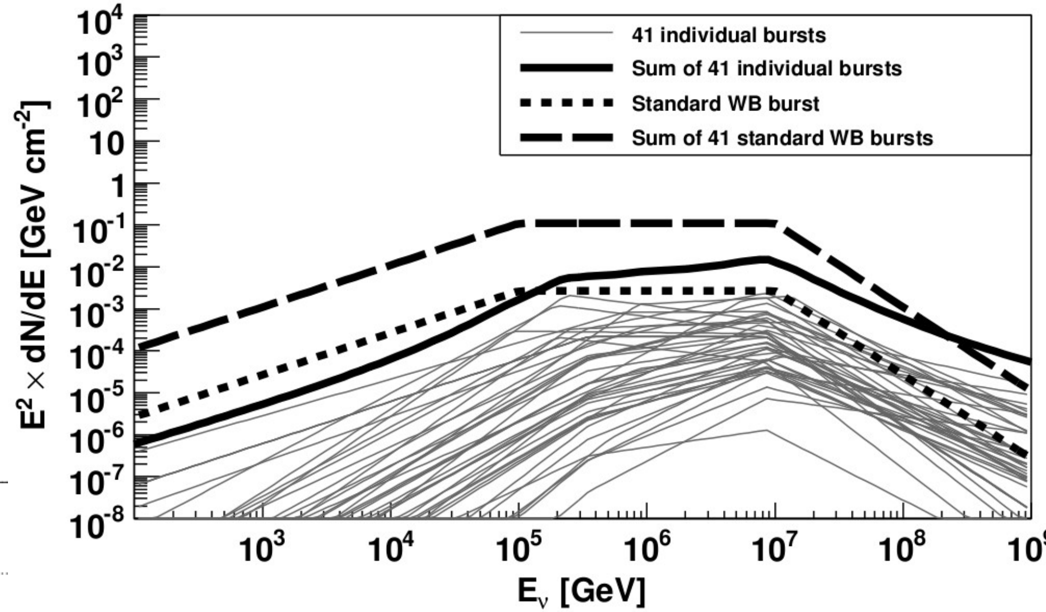
Data consistent with 0.0 events within window

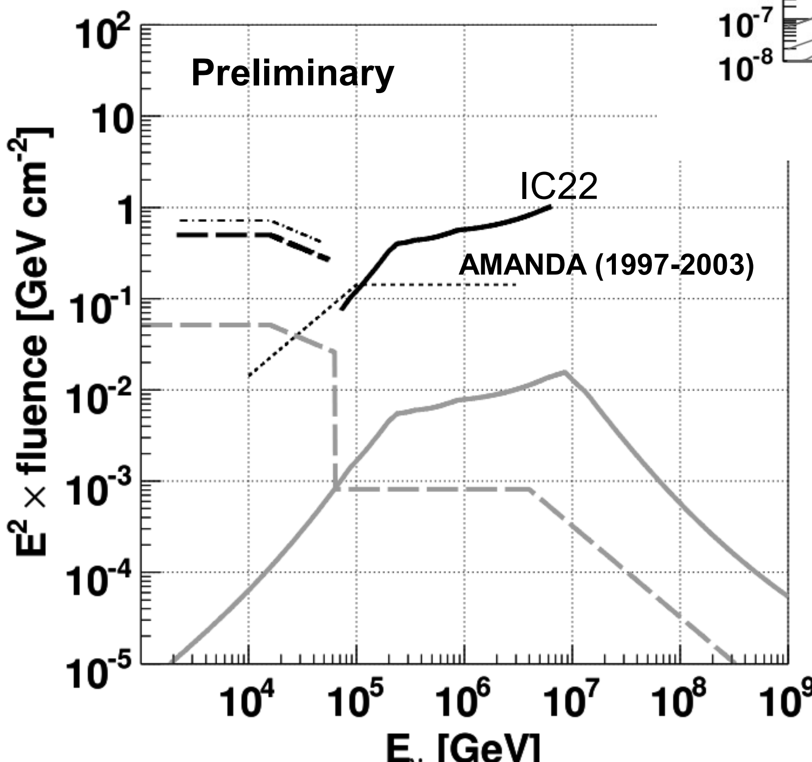


arXiv:0902.0131

Northern Hemisphere GRBs

41 satellite triggered bursts during IC22





Expect:
- ~0.03 prompt events
- ~0.3 precursor events

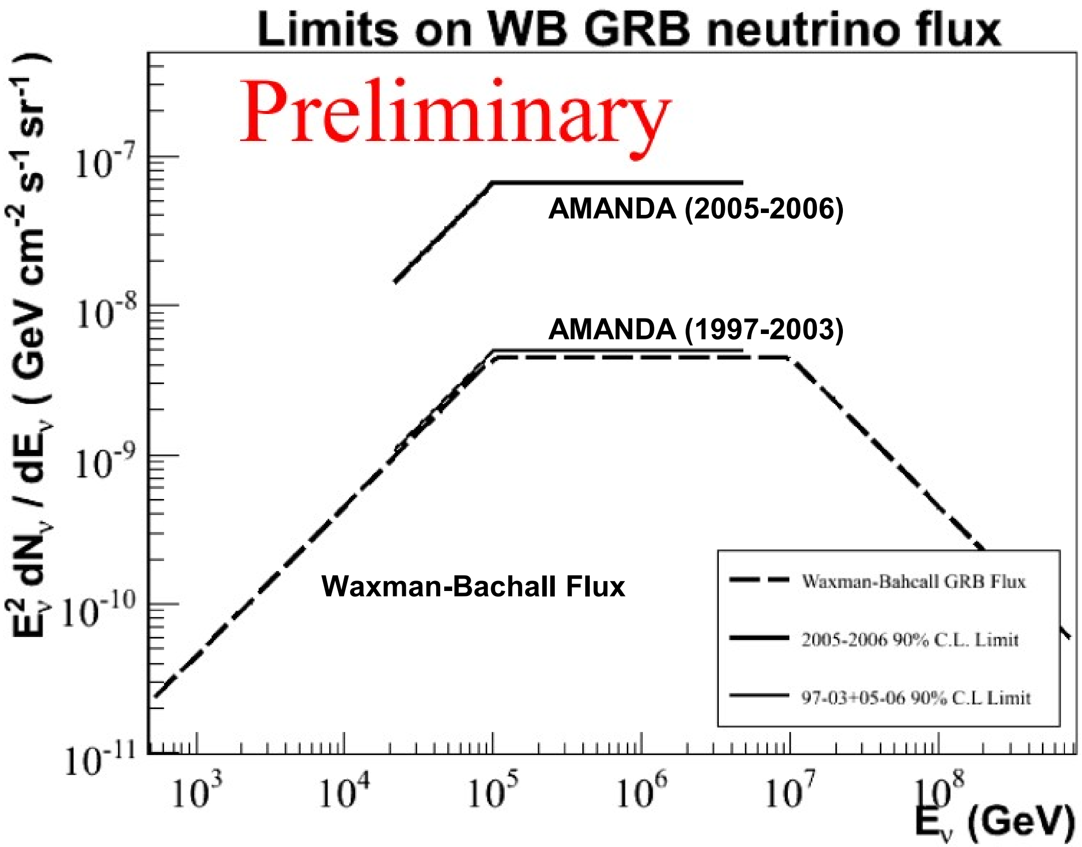
Data consistent with zero signal

Northern Hemisphere GRBs

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

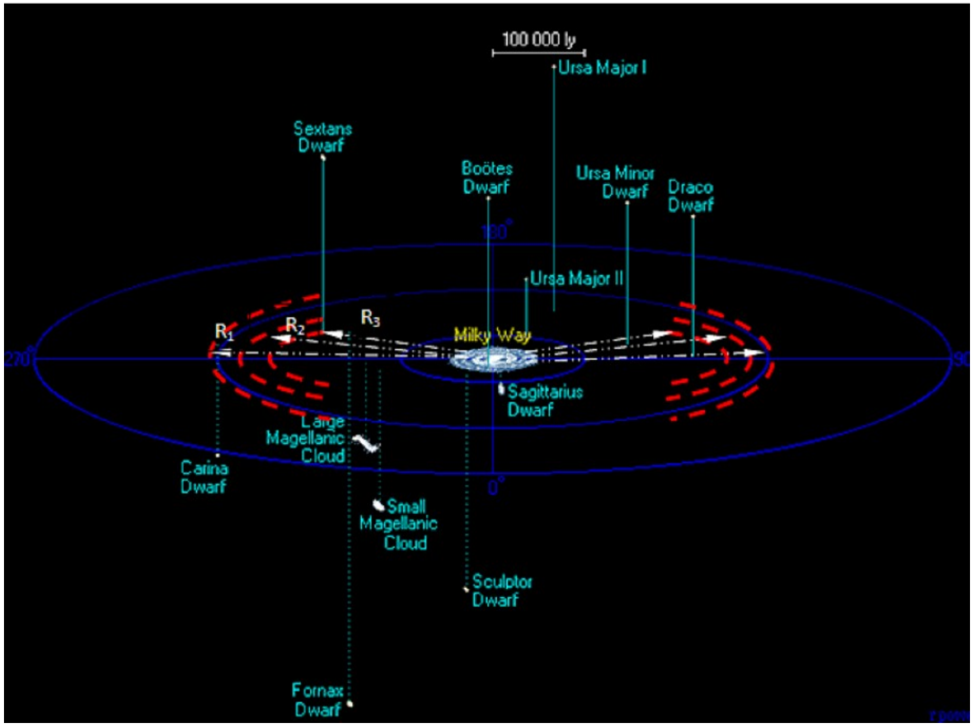
ApJ **674**, 357 (2008)

Binned Searches



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

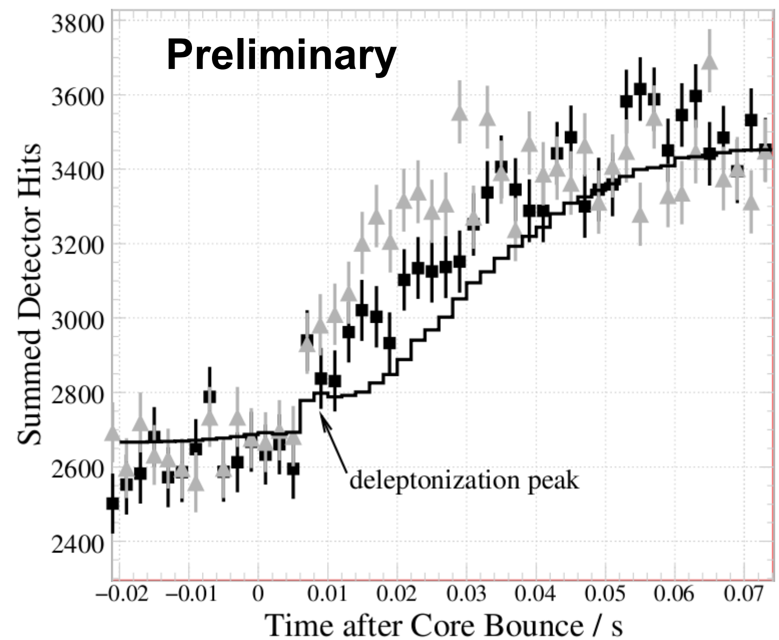
Supernovae



~MeV SN neutrinos produce an increase in photon rates

No pointing resolution

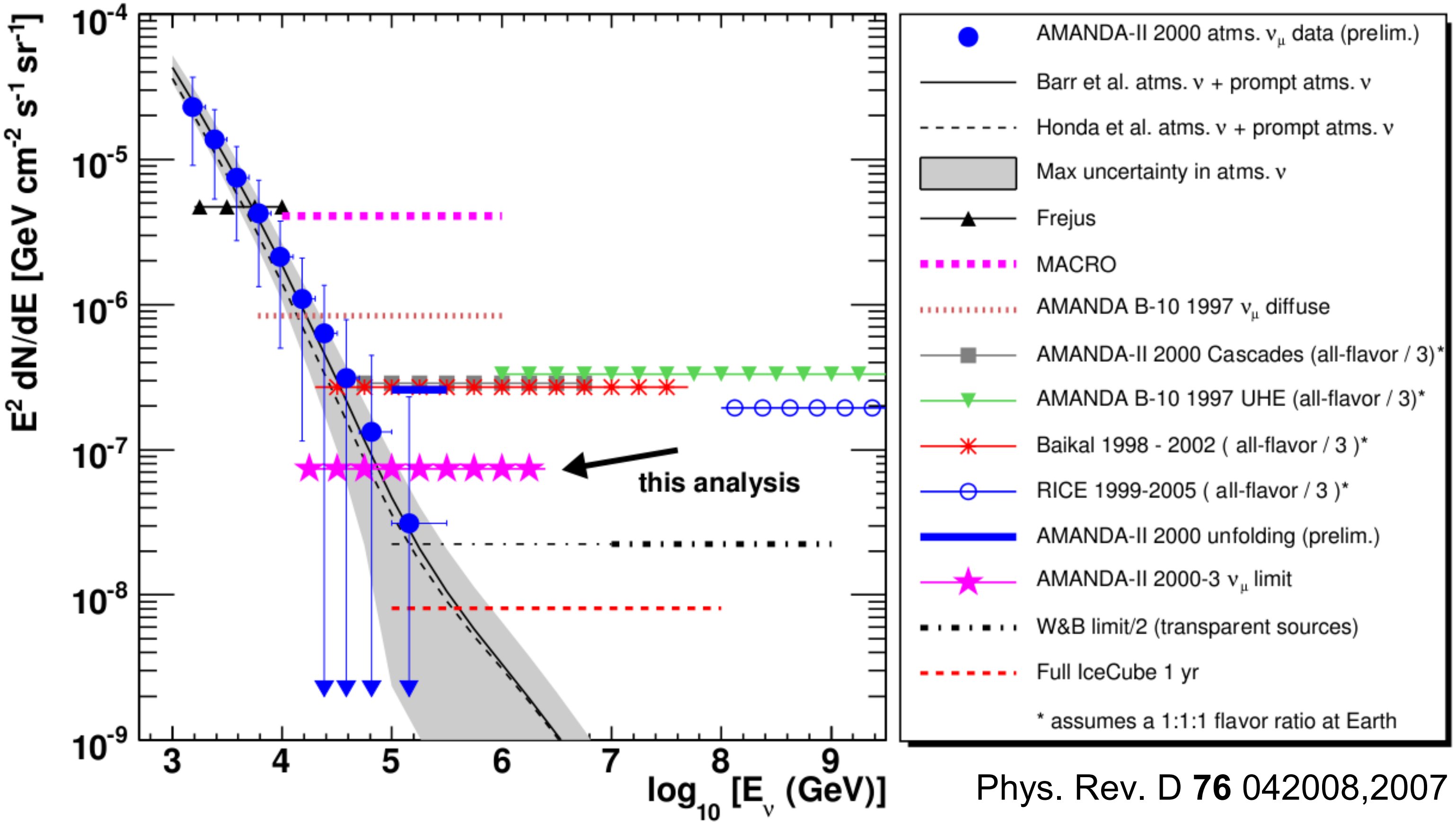
5σ detection to ~50 kpc in full IceCube



Measurement of neutrino light curves:
~10^6 neutrinos at 7.5 kpc

Presented at ICRC 2009

Diffuse Neutrino Fluxes

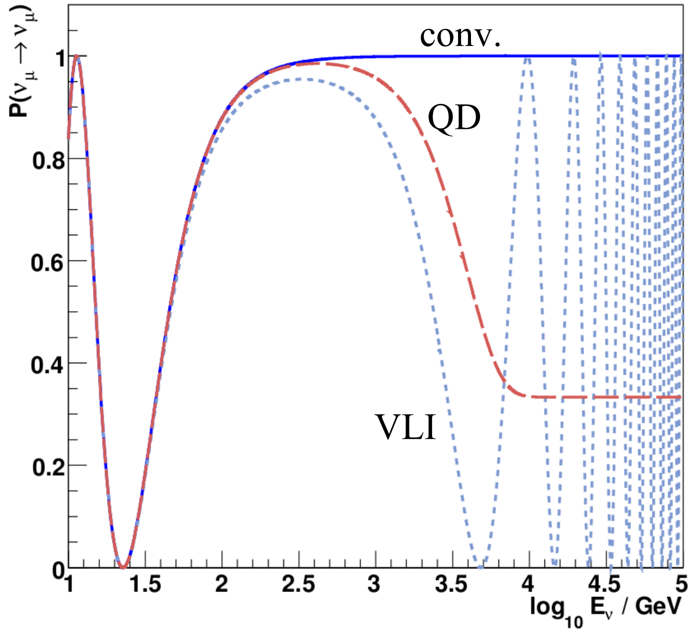


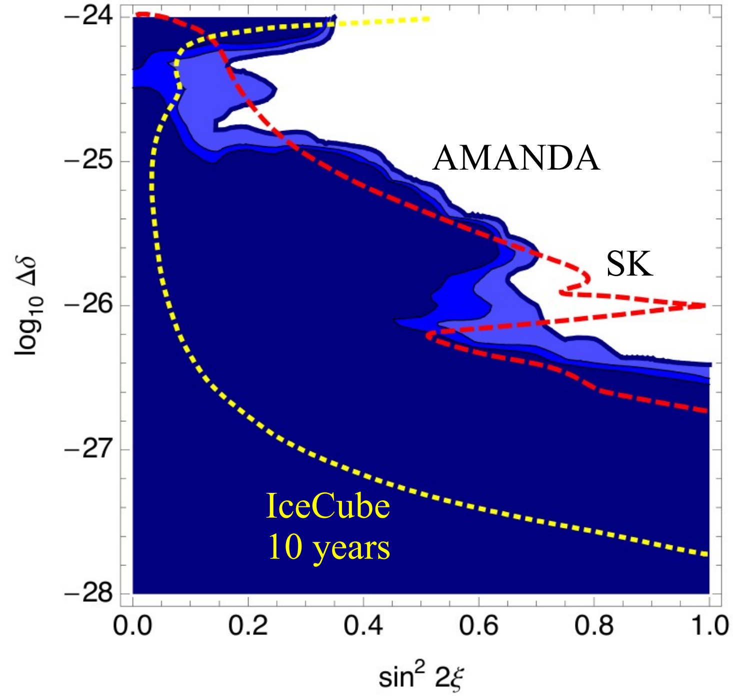
Phys. Rev. D **76** 042008,2007

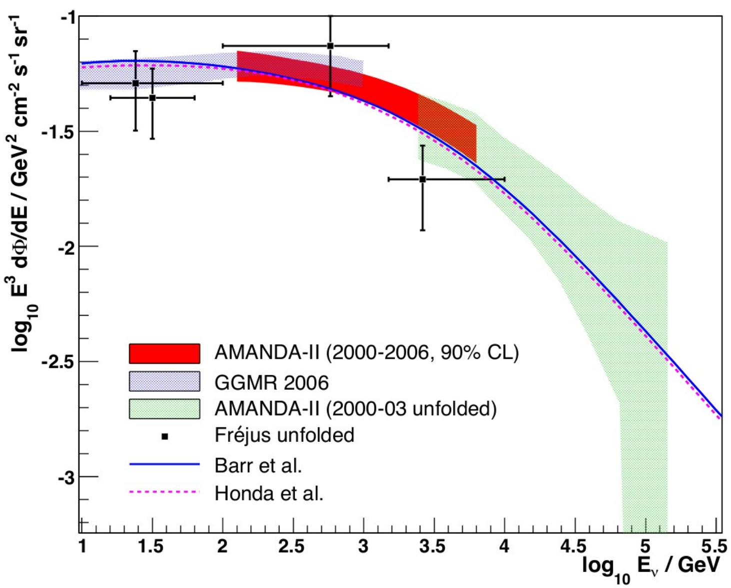
Preliminary IC40 diffuse sensitivity >5x better than AMANDA

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

Atmospheric Neutrinos





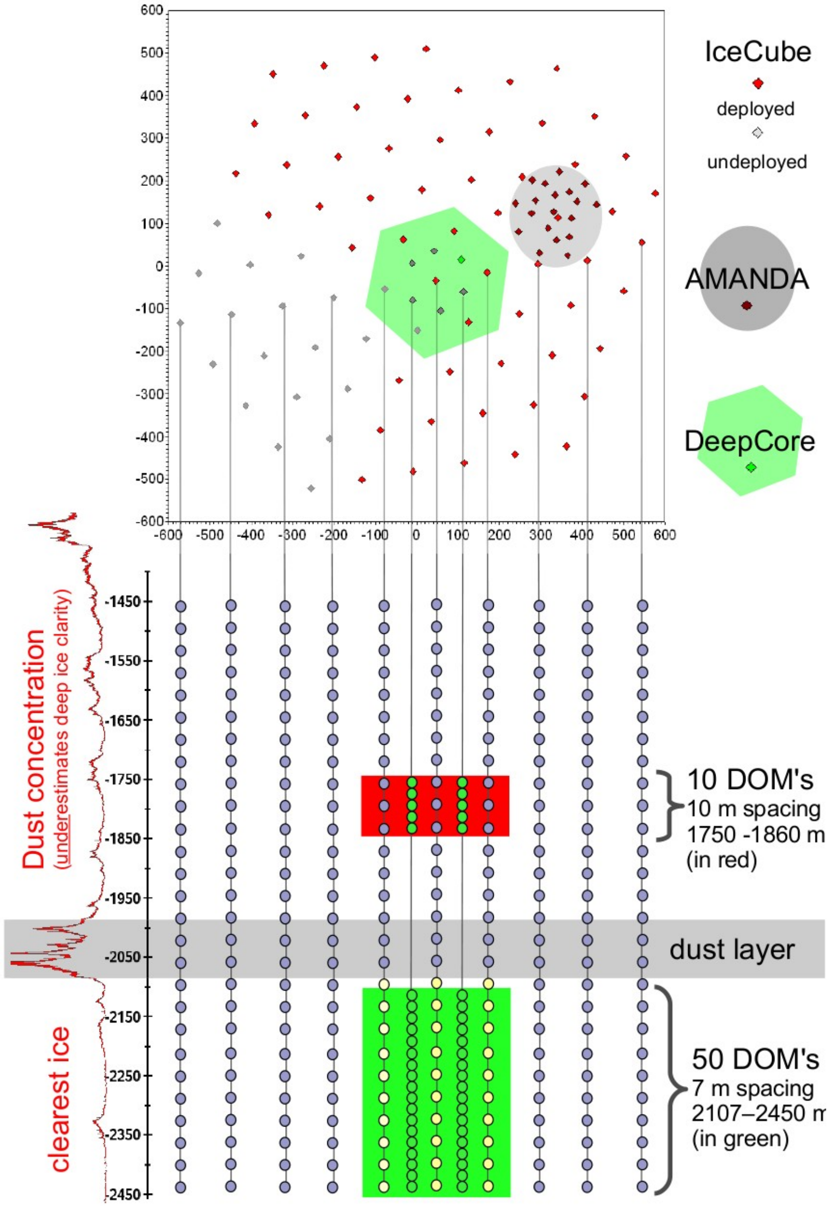


No evidence of QD or VLI effects ($\delta c/c < 2.8 \times 10^{-27}$ 90% CL)

New measurement of the atmospheric neutrino flux with AMANDA

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

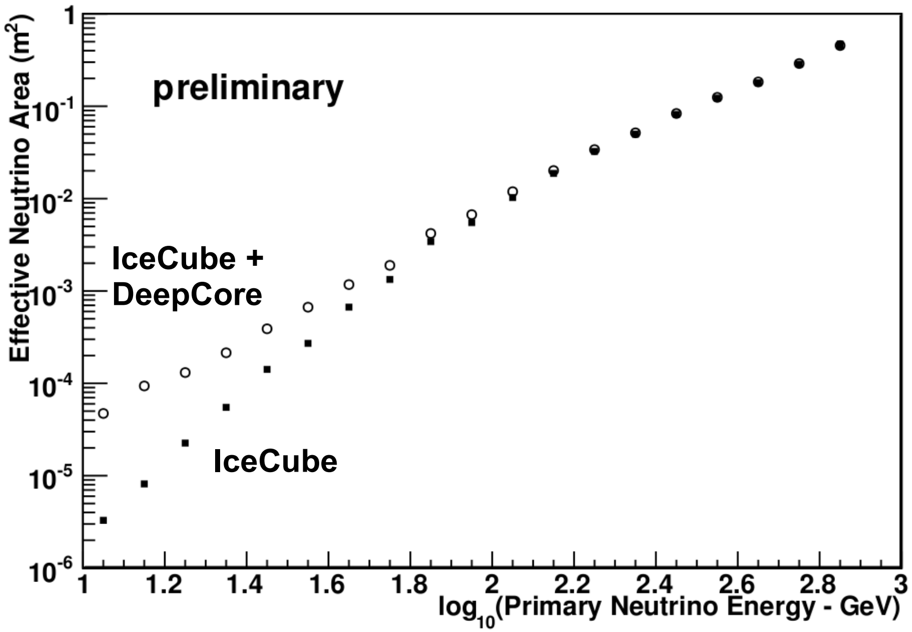
IceCube DeepCore



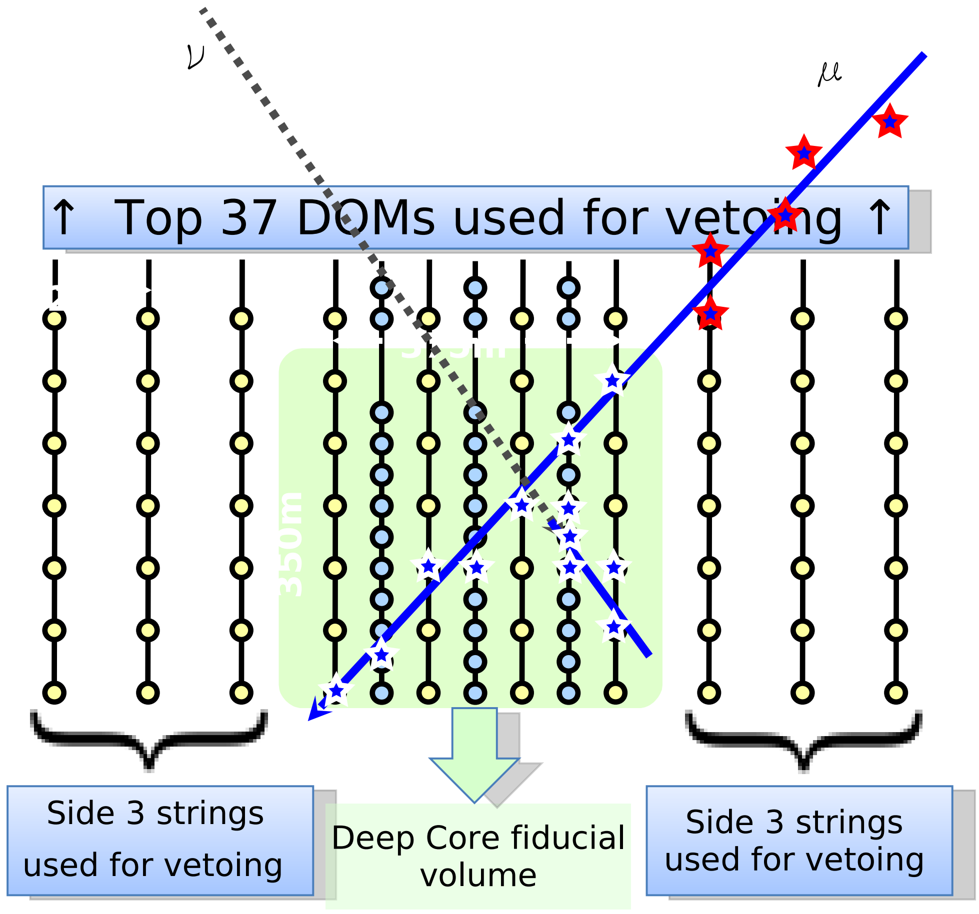
6 strings with dense DOM spacing and high QE PMTs

Located in deep, clear ice

Will improve IceCube physics reach at 10 – 100 GeV

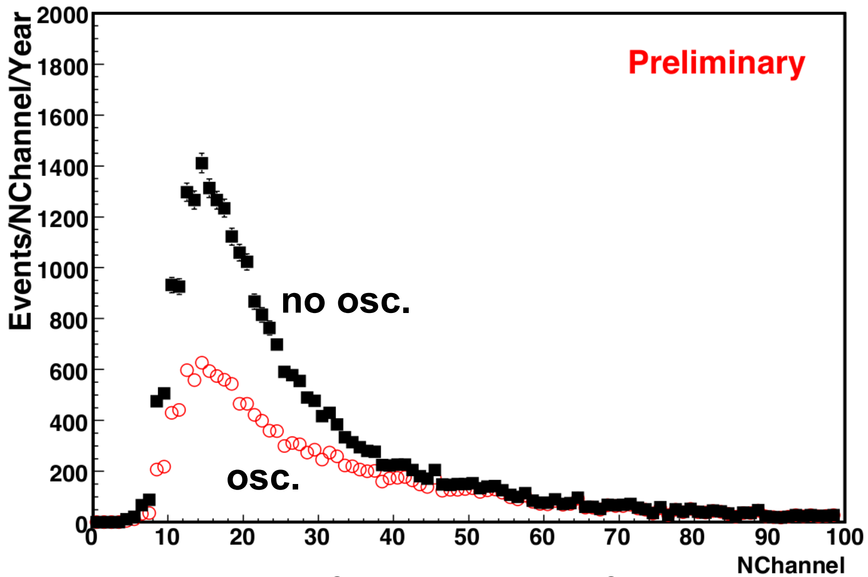


Neutrino Physics with Deep Core



Selection of starting muons allows 4π acceptance

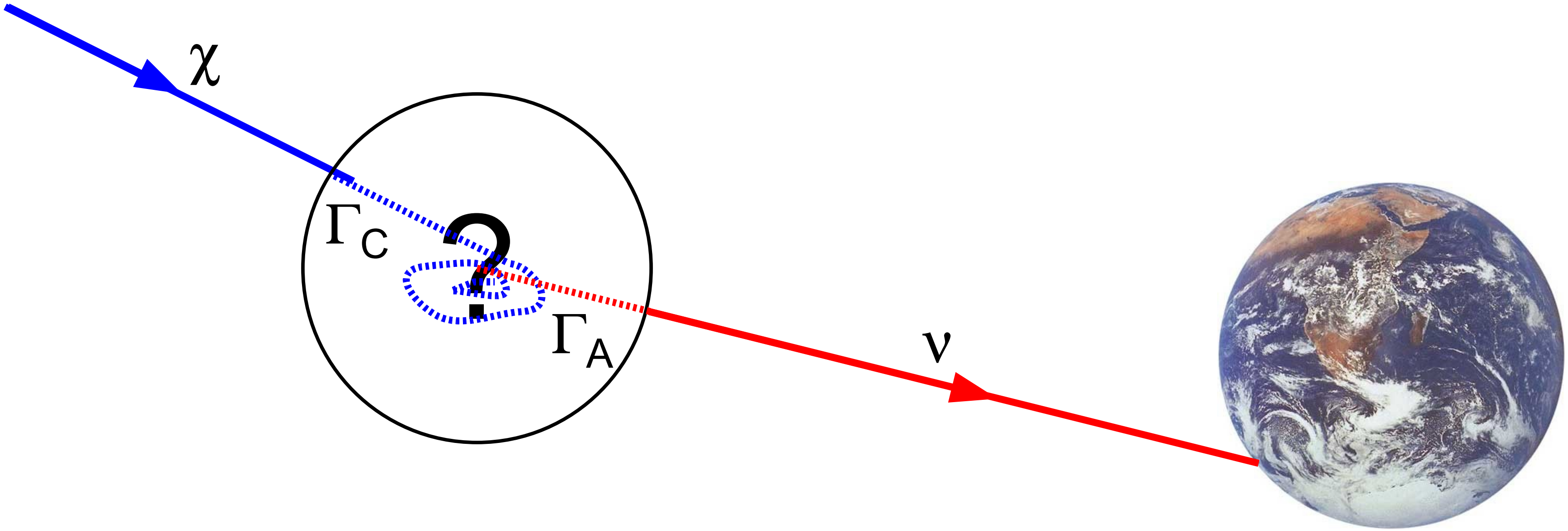
Upper half of IceCube is an active muon veto



$\Delta m^2 = 0.0024$, $\sin^2(2\theta) = 1$

Good sensitivity to atmospheric oscillations with DeepCore

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

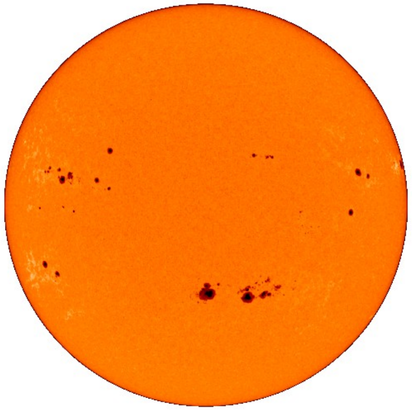
$$\Gamma_A \sim \frac{1}{2}\Gamma_C$$

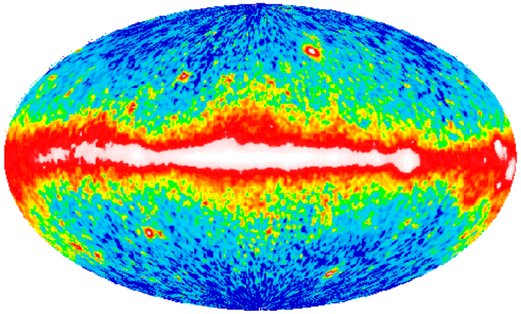
Annihilation produces a neutrino flux at Earth

- Neutrino spectra dependent on annihilation mode

$$\chi\chi \rightarrow \begin{matrix} WW \\ b\bar{b} \\ \text{etc.} \end{matrix} \rightarrow \nu, e^-, ...$$

WIMP Capture





Always fully visible (vertical upgoing events)

Small mass

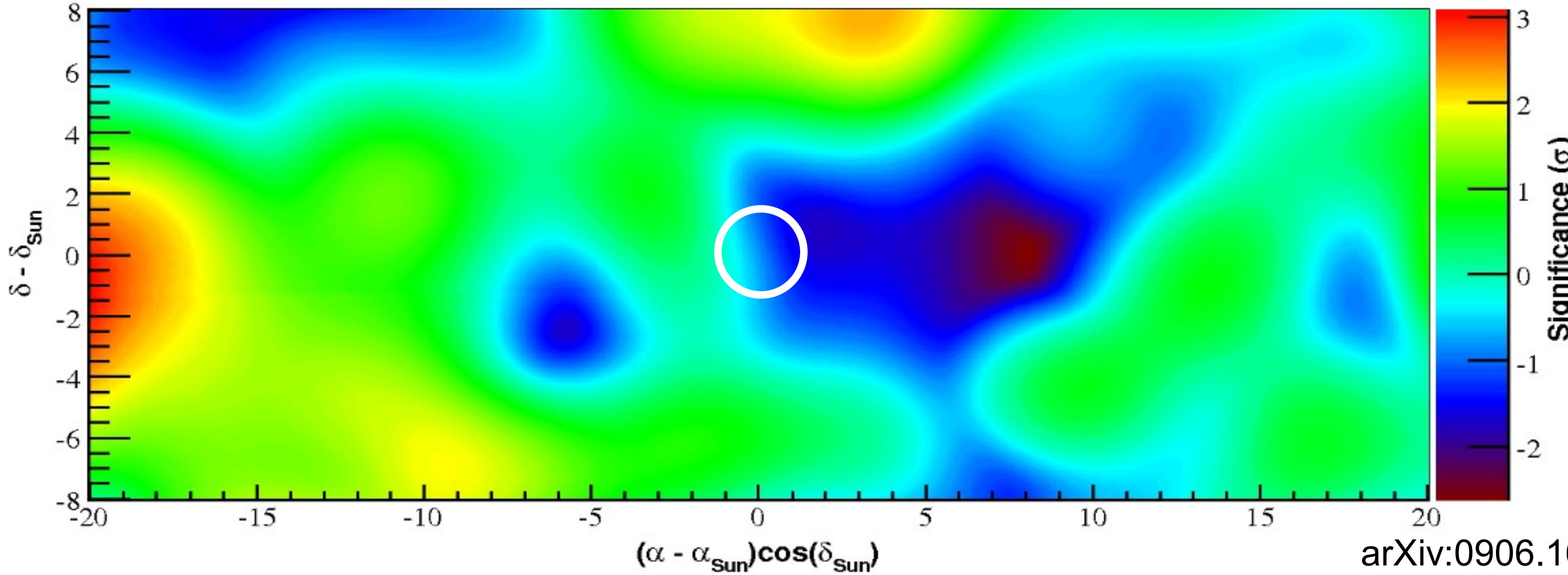
Sun below horizon half of the year

Large mass

GC always above the horizon, with large CR background

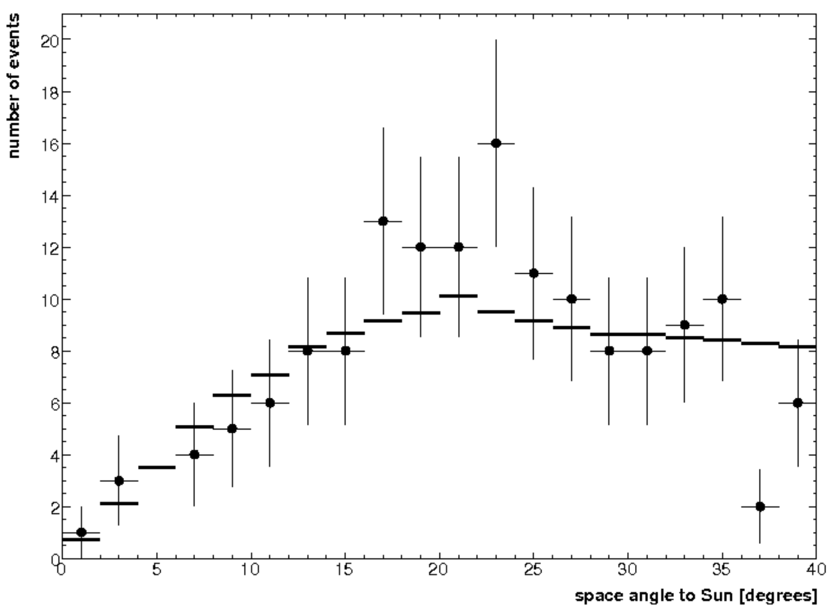
Extreme mass

AMANDA 2000-2006

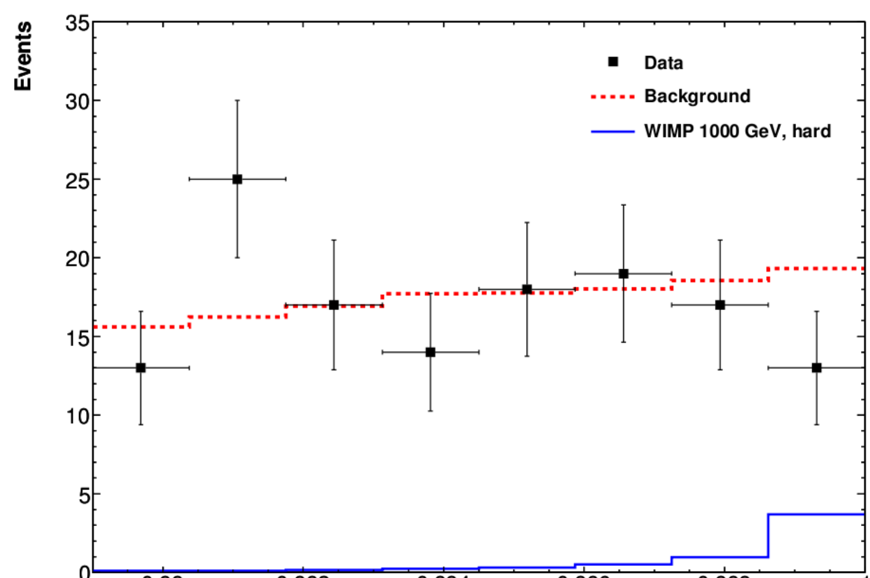


arXiv:0906.1615

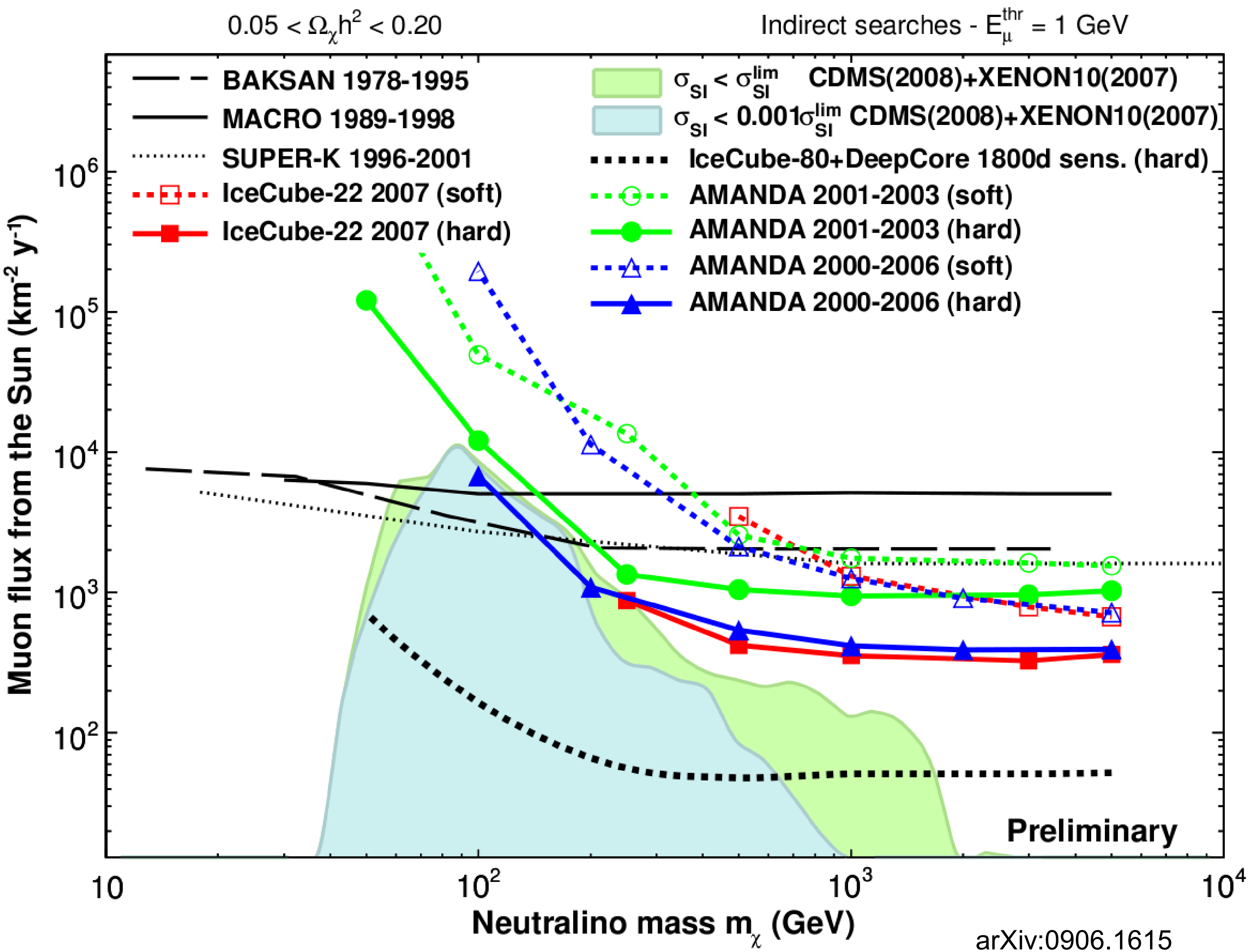
AMANDA 2001-2003

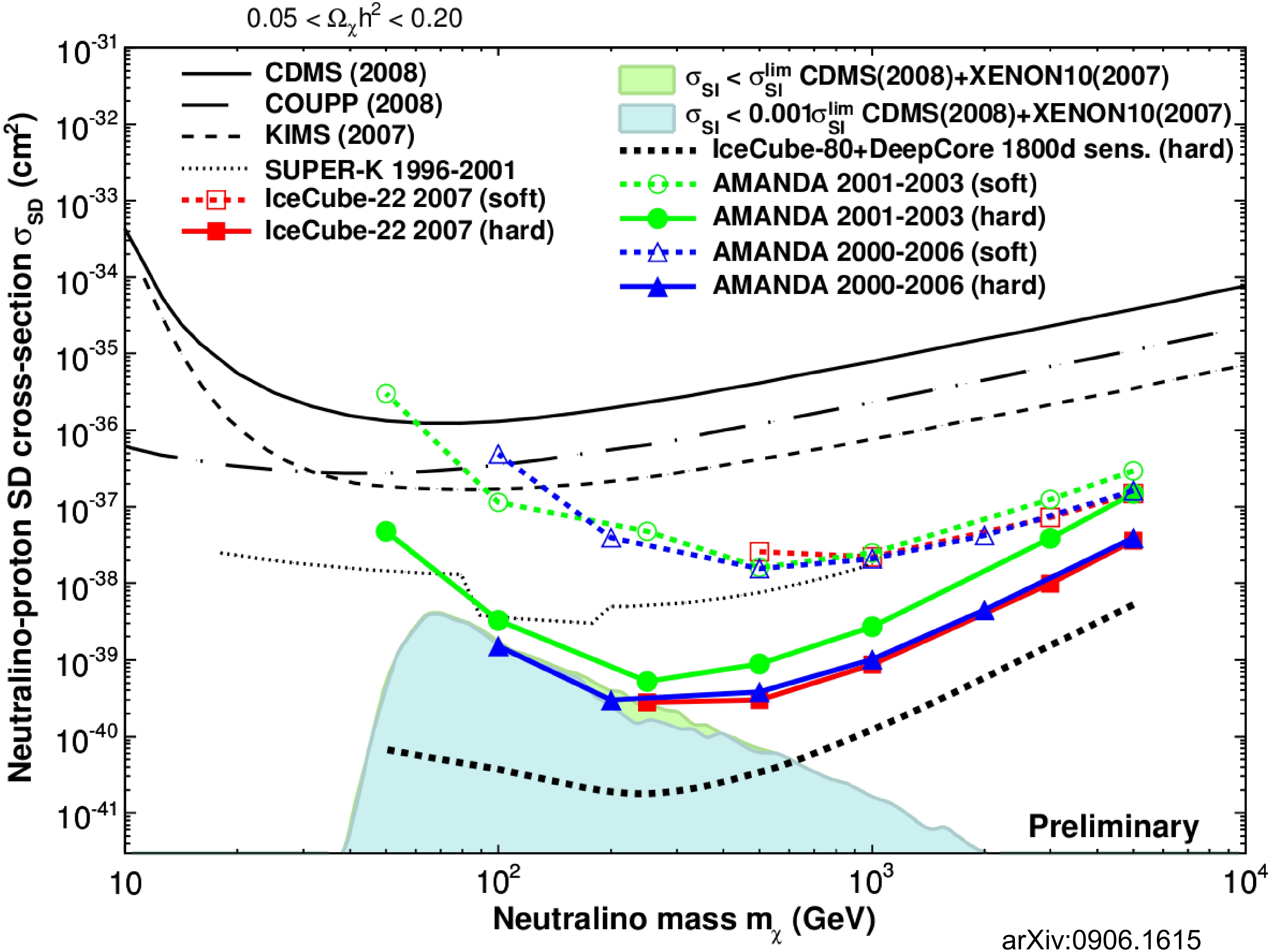


IC22

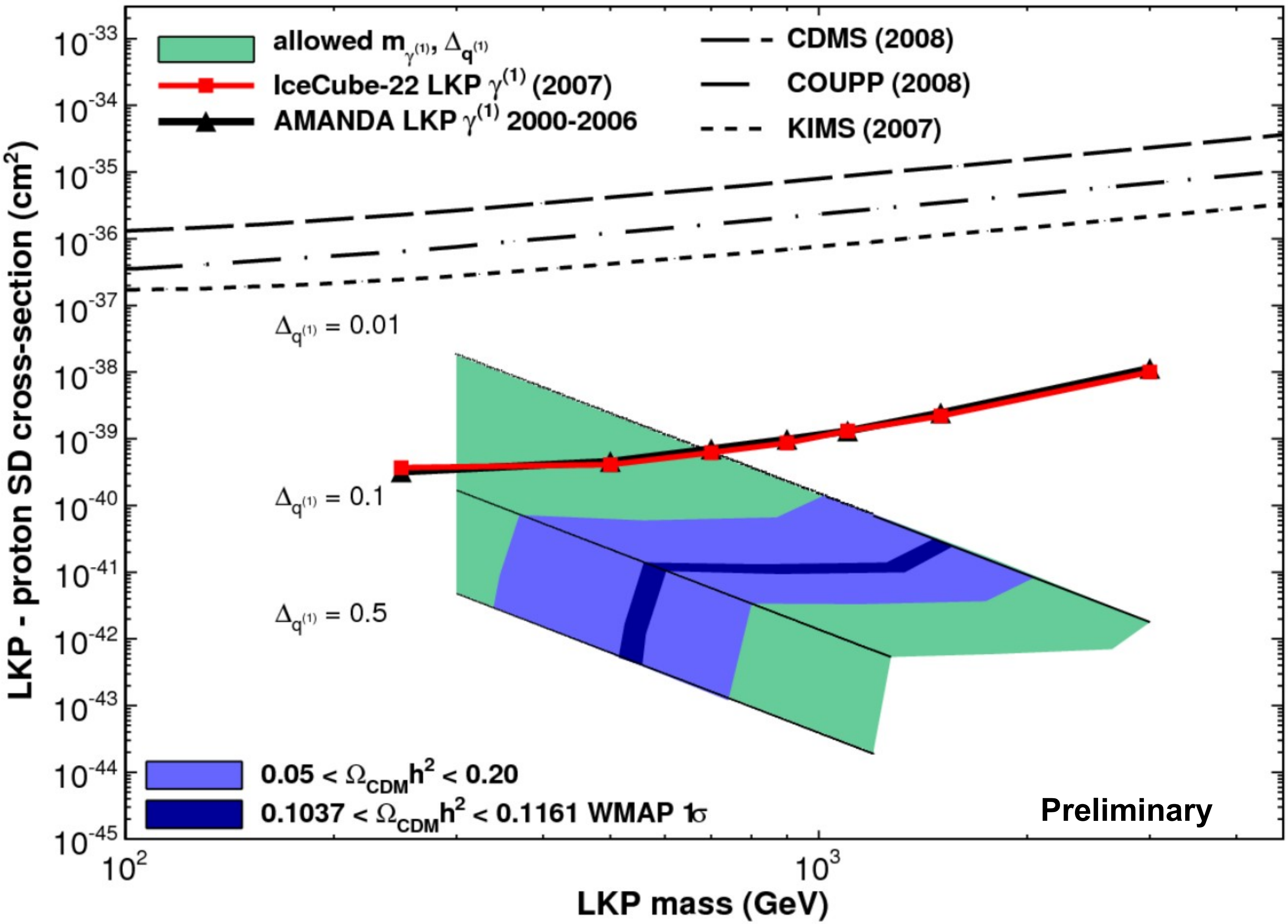


PRL **102**, 201302 (2009)


0.05 < Ωχh² < 0.20
Indirect searches - E_μ^thr = 1 GeV
BAKSAN 1978-1995
MACRO 1989-1998
SUPER-K 1996-2001
IceCube-22 2007 (soft)
IceCube-22 2007 (hard)
σSI < σSI^lim CDMS(2008)+XENON10(2007)
σSI < 0.001σSI^lim CDMS(2008)+XENON10(2007)
IceCube-80+DeepCore 1800d sens. (hard)
AMANDA 2001-2003 (soft)
AMANDA 2001-2003 (hard)
AMANDA 2000-2006 (soft)
AMANDA 2000-2006 (hard)
Preliminary
Muon flux from the Sun (km⁻² y⁻¹)
Neutralino mass mχ (GeV)
10
10²
10³
10⁴
10⁵
10⁶
arXiv:0906.1615



arXiv:0906.1615



allowed $m_{\gamma^{(1)}}$, $\Delta_{q^{(1)}}$
IceCube-22 LKP $\gamma^{(1)}$ (2007)
AMANDA LKP $\gamma^{(1)}$ 2000-2006
CDMS (2008)
COUPP (2008)
KIMS (2007)
$\Delta_{q^{(1)}} = 0.01$
$\Delta_{q^{(1)}} = 0.1$
$\Delta_{q^{(1)}} = 0.5$
$0.05 < \Omega_{CDM}h^2 < 0.20$
$0.1037 < \Omega_{CDM}h^2 < 0.1161$ WMAP 1σ
Preliminary
LKP - proton SD cross-section (cm^2)
LKP mass (GeV)

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