The Ohio State University's Center for Cosmology and AstroParticle Physics

Latest results from the IceCube Neutrino Observatory

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http://www.icecube.wisc.edu

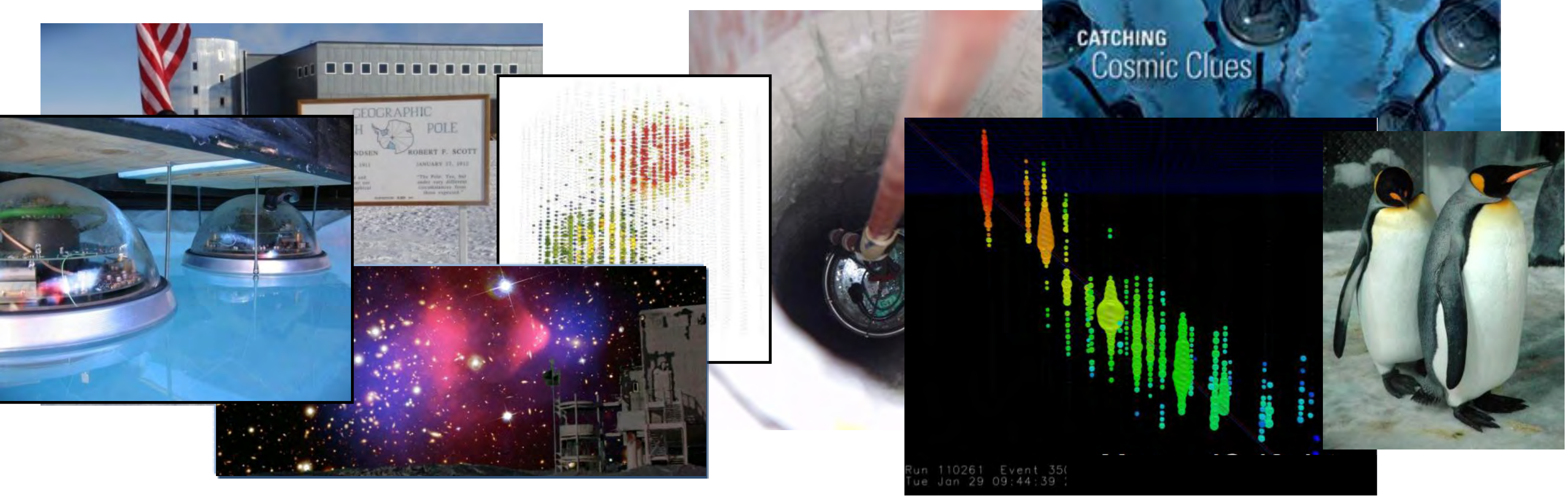
XLIVth Rencontres de Moriond

ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES....

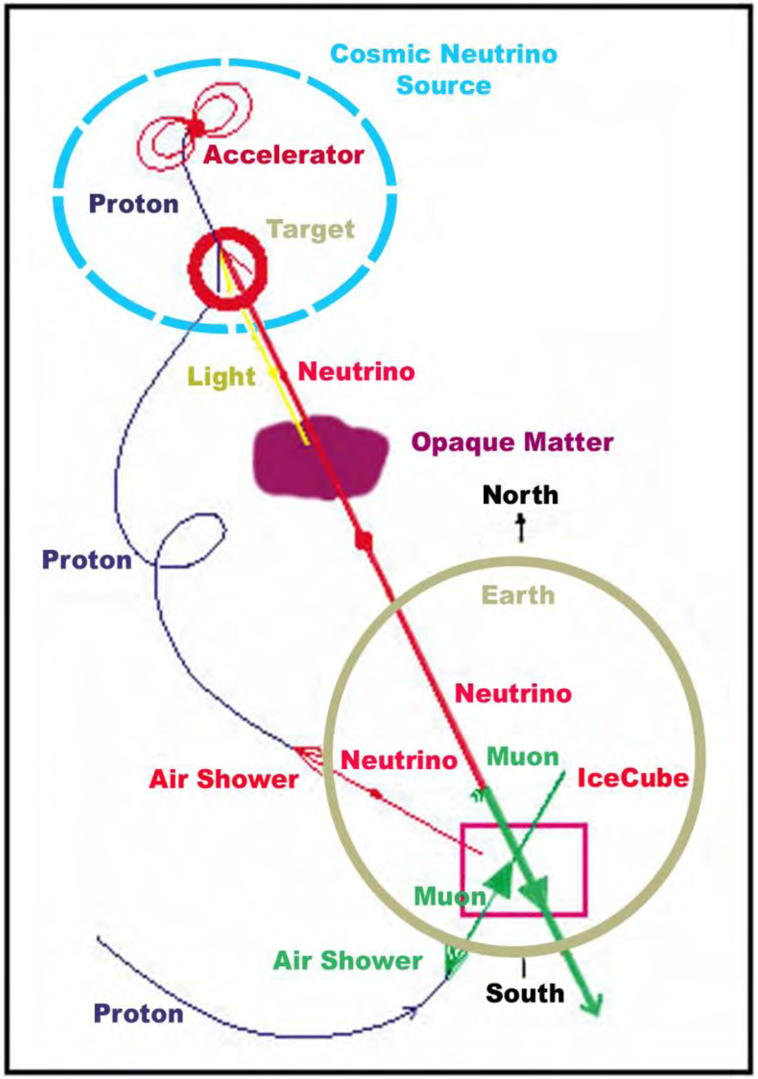
March 7 – 14, 2009

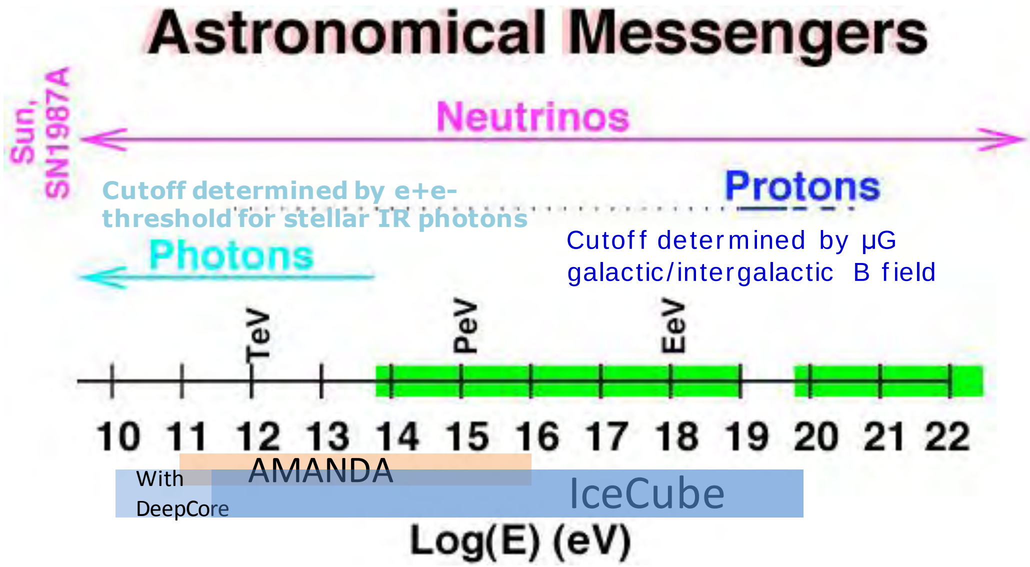
Outline

- Motivation
- The IceCube Neutrino Observatory
- Pole/Detector Status
- Summary of Recent Results
- Conclusions



Astro Messengers





Neutrinos

- Unobscured view into depth of space
- Point back to their sources
- Cover entire energy spectrum

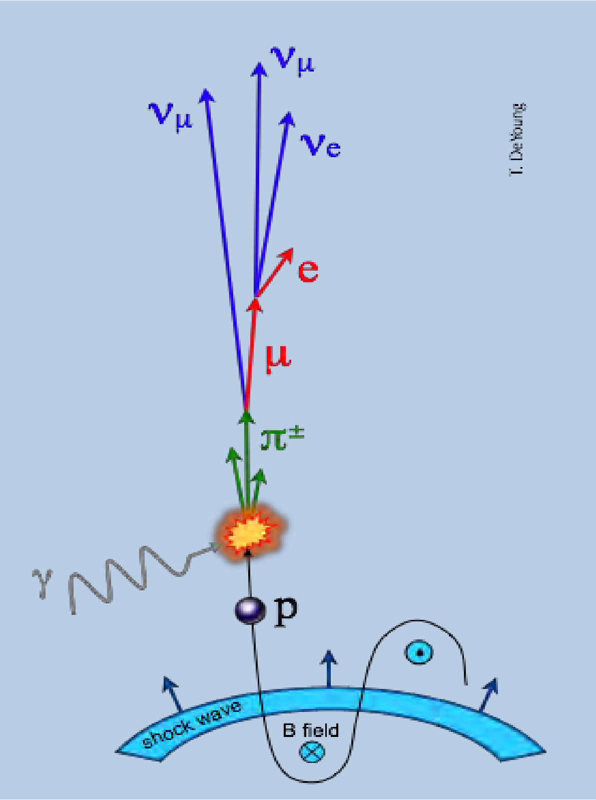
Protons

- bent below about 10 EeV
- above ~55EeV attenuated (GZK cut-off)

Photons

- scattered/absorbed above 50 TeV

Neutrino Sources



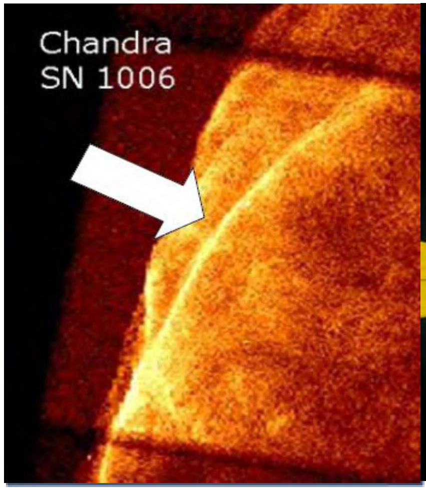
Protons interact in "target area" to produce pions:

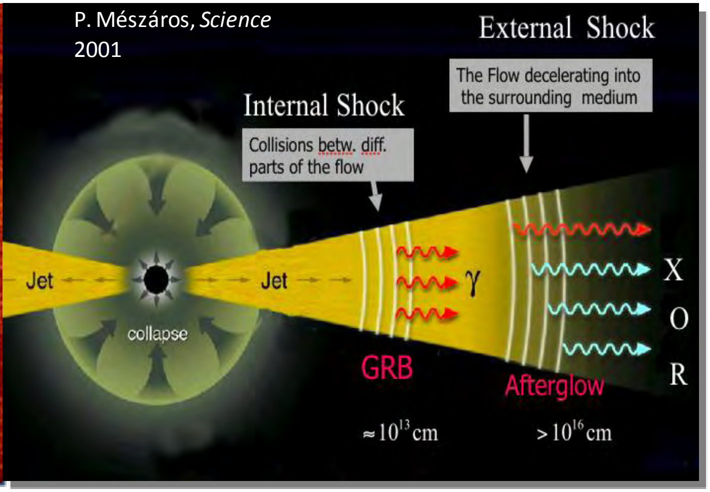
$$p + (p \text{ or } \gamma) \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$
$$\rightarrow \pi^\pm \rightarrow \nu_e \nu_\mu \rightarrow \nu_e \nu_\mu \nu_\tau$$
$$(1:2:0)\ \ (1:1:1)$$

Neutral pions $\rightarrow$ Photons
Charged pions $\rightarrow$ Neutrinos
Oscillations result in equal flavor ratio at detector

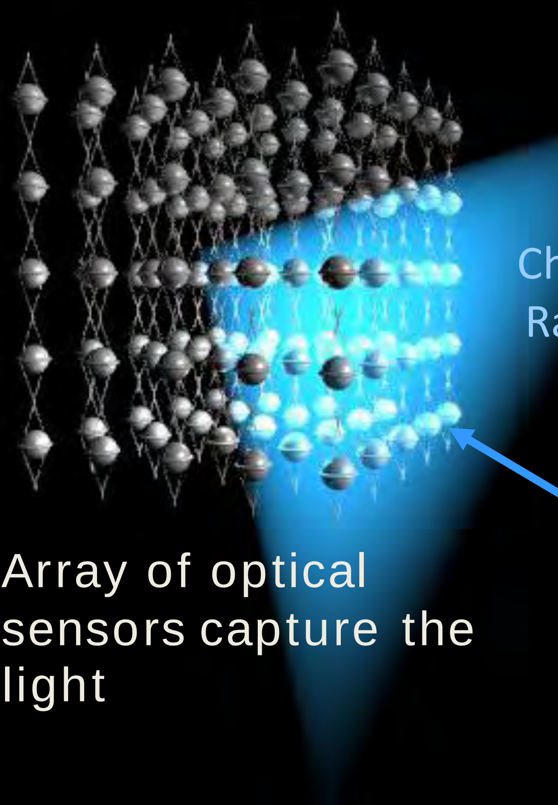
Source Candidates:

- Supernova Remnants
- Gamma Ray Bursts
- Active Galactic Nuclei
- …



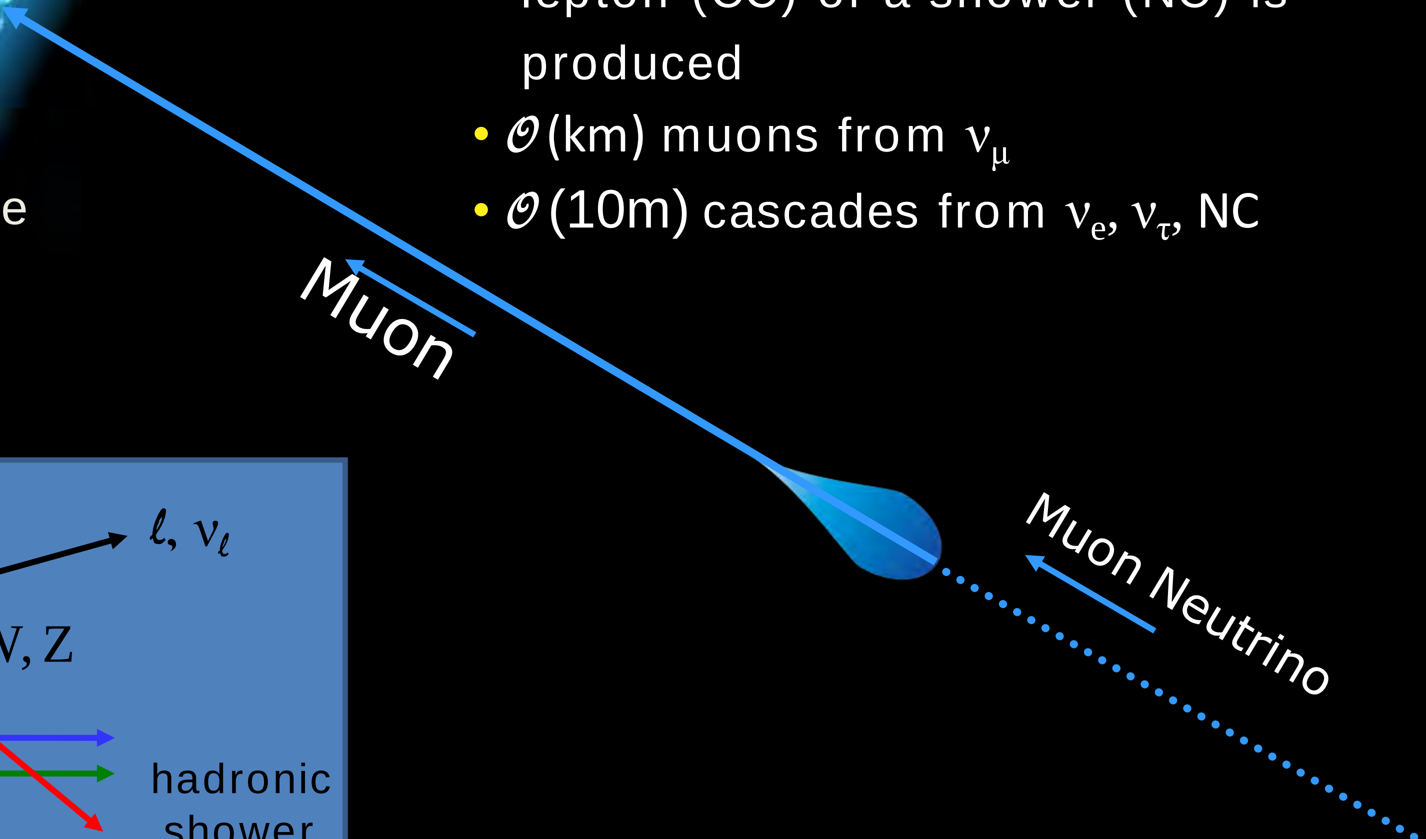


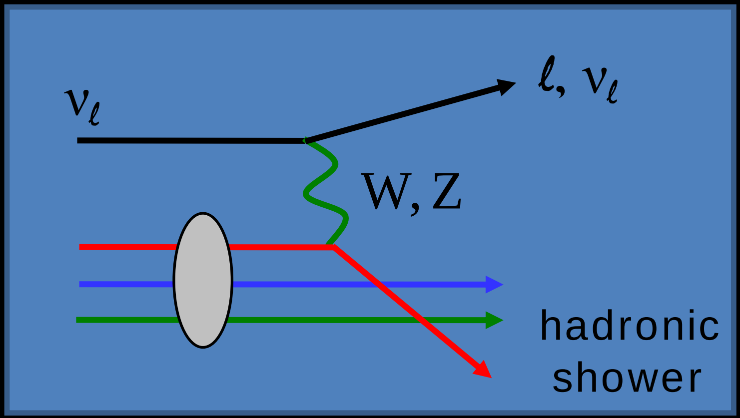
An Optical Neutrino Telescope



Array of optical sensors capture the light

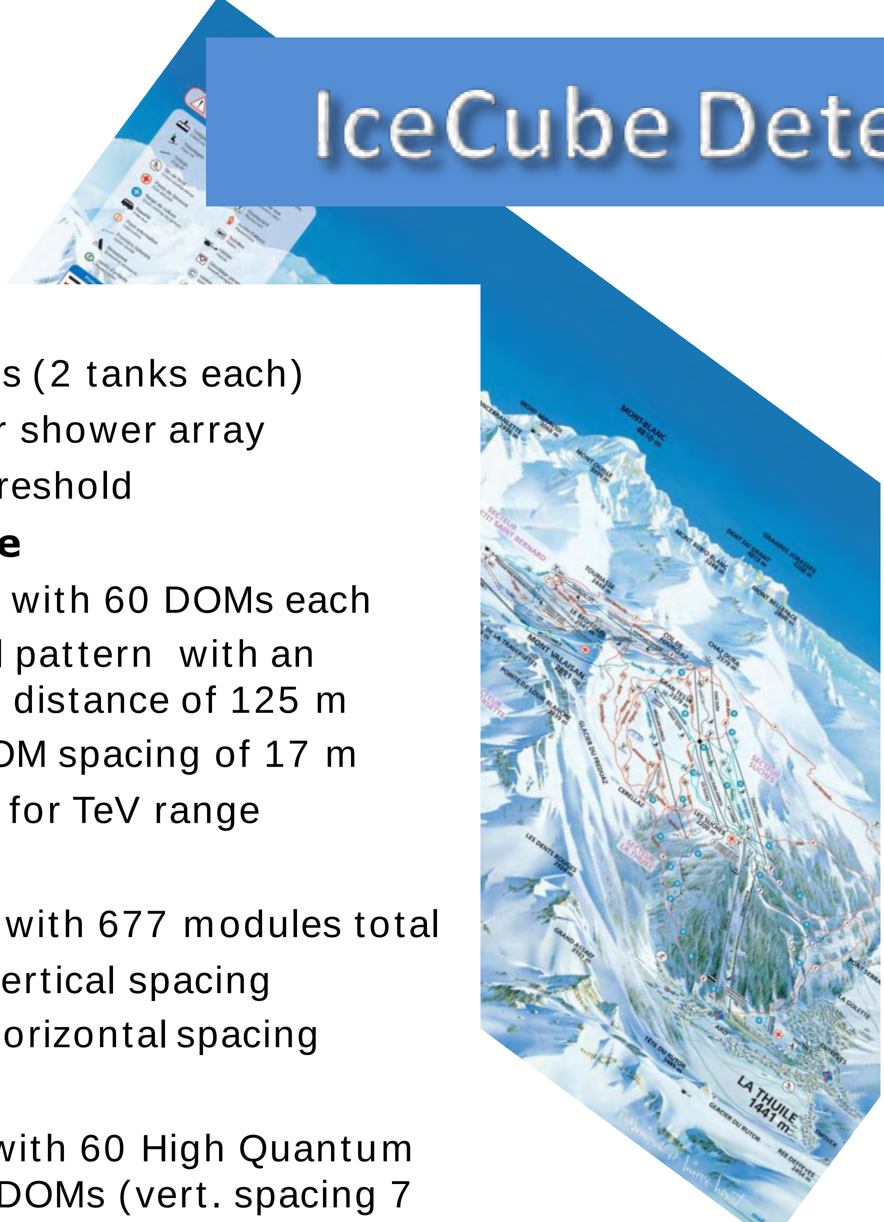
- Neutrinos interact in or near the detector
- Depending on the interaction a lepton (CC) or a shower (NC) is produced
- $\mathcal{O}$(km) muons from ν_μ
- $\mathcal{O}$(10m) cascades from ν_e, ν_τ, NC

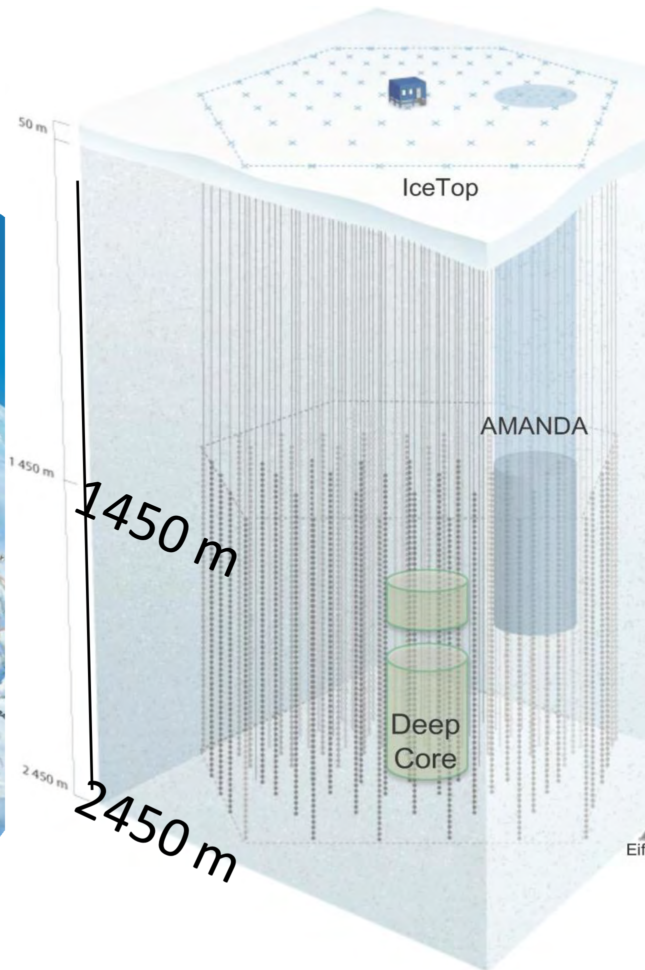




IceCube Detector Layout

- **IceTop**
  - 80 Stations (2 tanks each)
  - Surface air shower array
  - 300TeV threshold
- **IceCube InIce**
  - 80 Strings with 60 DOMs each
  - Hexagonal pattern with an interstring distance of 125 m
  - Vertical DOM spacing of 17 m
  - Optimized for TeV range
- **AMANDA**
  - 19 strings with 677 modules total
  - 10-20 m vertical spacing
  - 40-50 m horizontal spacing
- **Deep Core**
  - 6 Strings with 60 High Quantum Efficiency DOMs (vert. spacing 7 m)
  - Low Energy extension (20-100GeV)

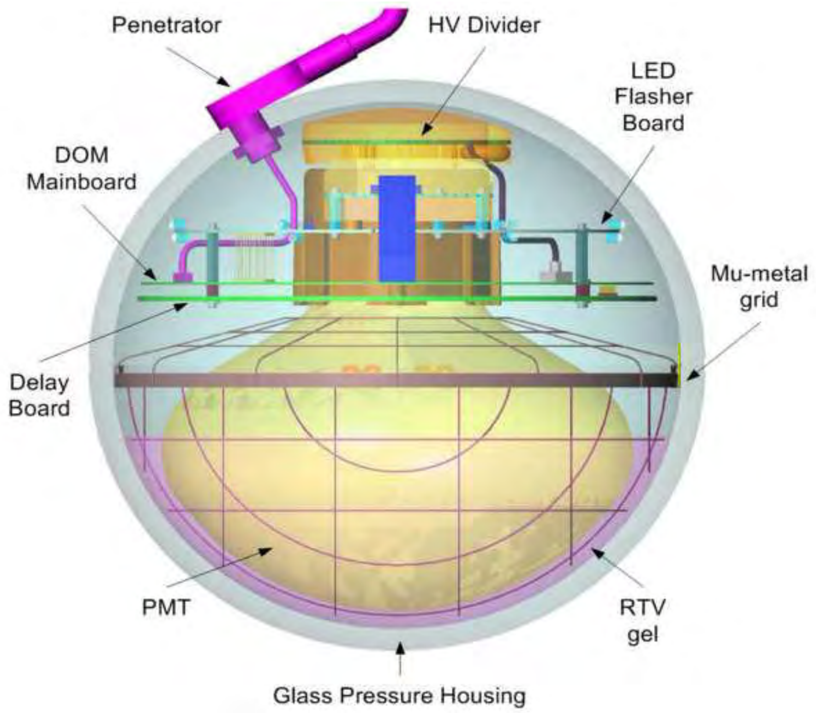




IceCube will instrument a volume of one cubic kilometer of Antarctic ice by 2011

DOM (Digital Optical Module)

10 inch Hamamatsu PMT (R-7081-02)

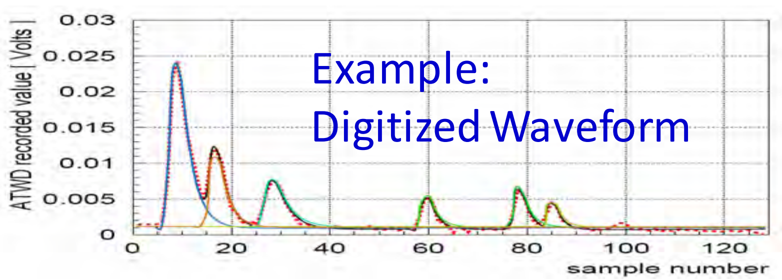


- Dark Noise rate ~ 700 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Signal digitized in the ice

arXiv:0810.4930 (accepted NIM)

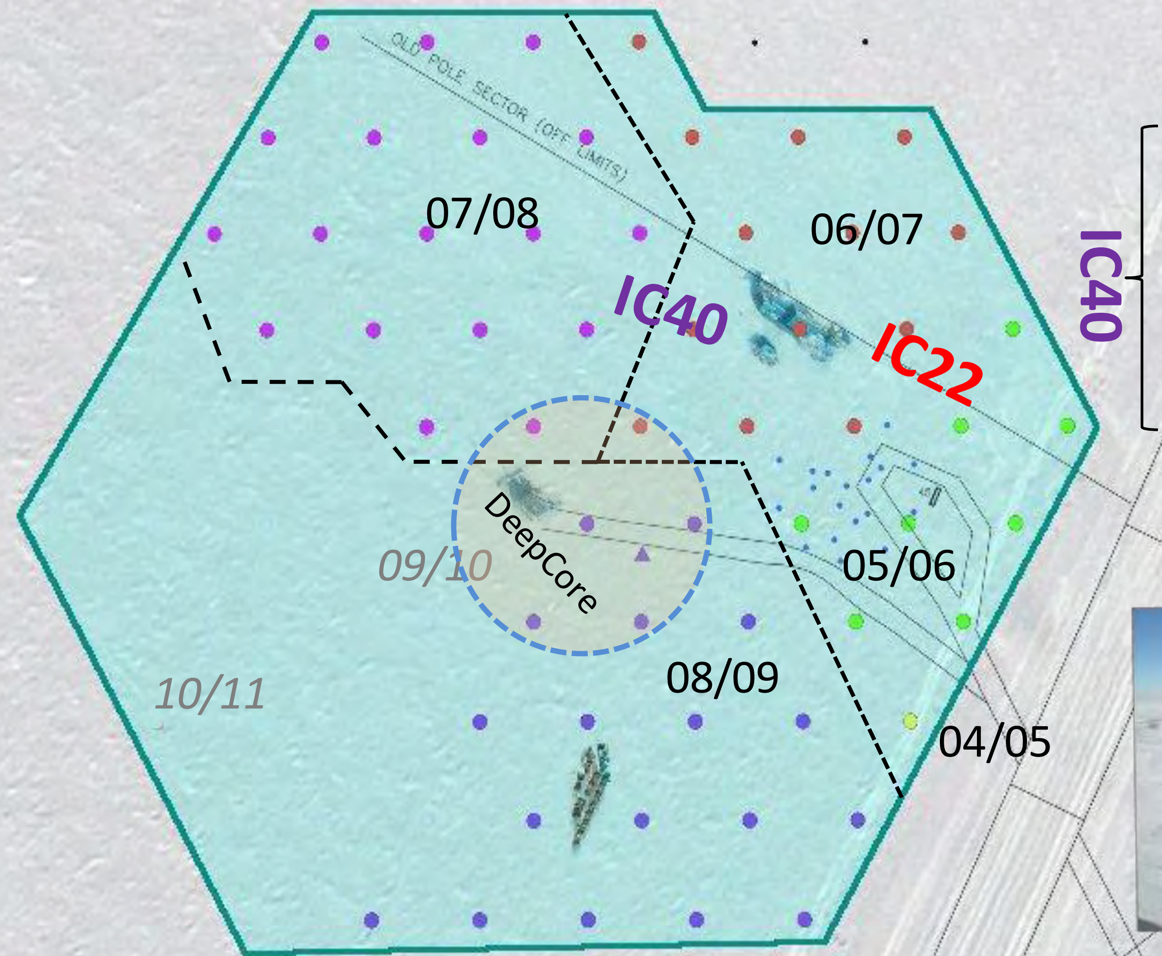
Measure individual photon arrival time:

- 2 ping-ponged four-channel Analog Transient Waveform Digitizers:
    - 128 samples (400 ns max range)
    - ~3.3 ns bin
    - 400 pe / 15 ns
- fast Analog-to-Digital Converter:
    - 40 MHz
    - 6.4 μs range



Hardware extremely reliable

IceCube Detector Status

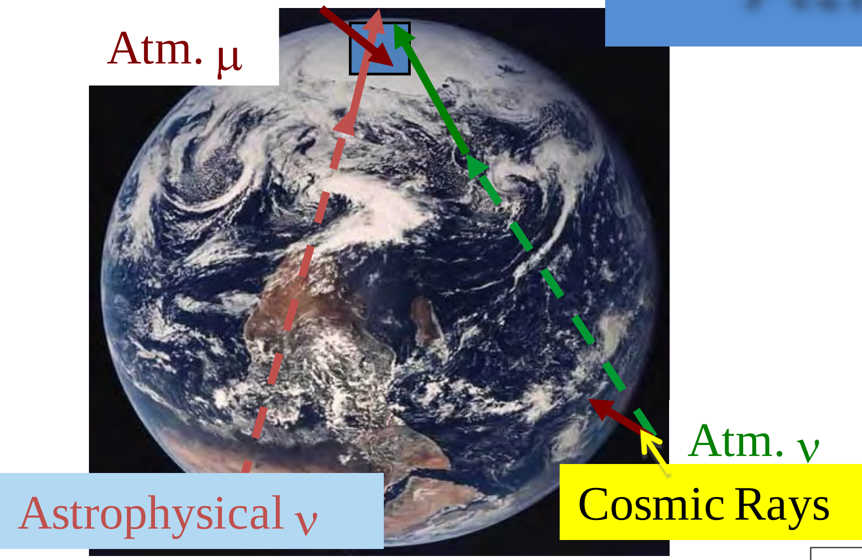


Season	Deployed
2004-2005	1 string
2005-2006	8 strings
2006-2007	13 strings
2007-2008	18 strings
2008-2009	18+1 strings

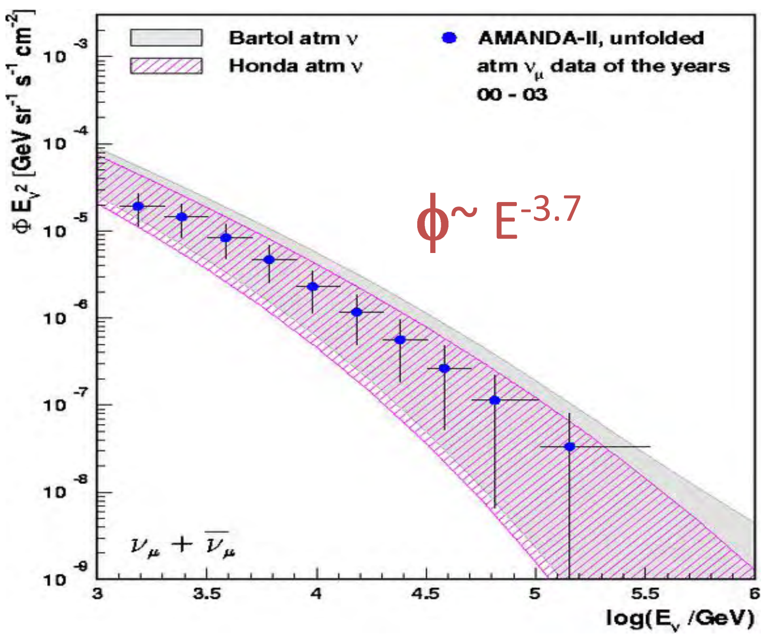
IC40

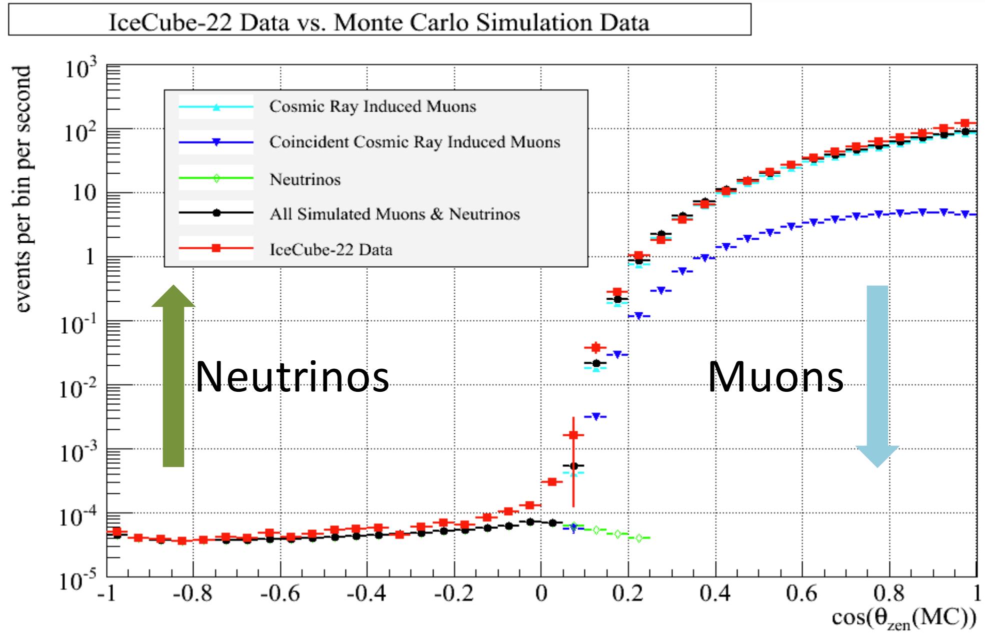
IC22

Atmospheric Neutrinos



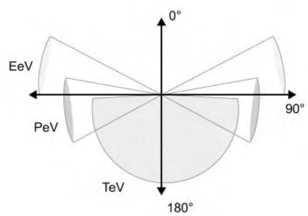
Strings	μ rate	ν rate
AMANDA	~80 Hz	~4.8 / day
IC22	~550 Hz	~28 / day
IC40	~1000 Hz	~110 / day
IC80*	~1650 Hz	~220 / day



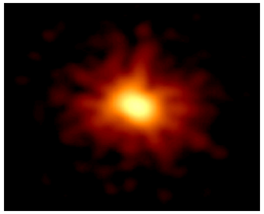
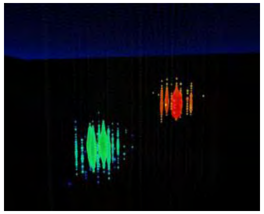


Scientific Program

IceCube is a multipurpose detector sensitive to **neutrinos of all flavors** at energies from **~10^{11} to 10^{20} eV + (MeV bursts)**

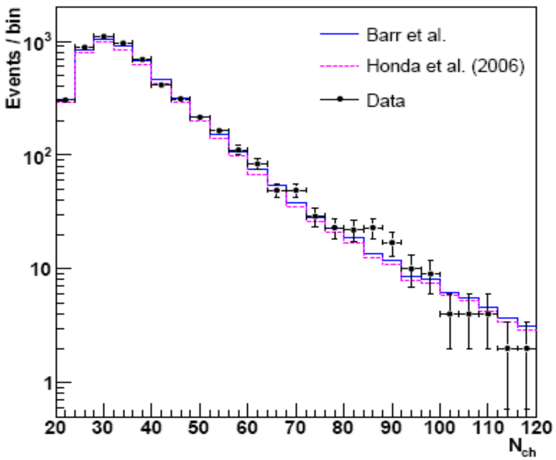


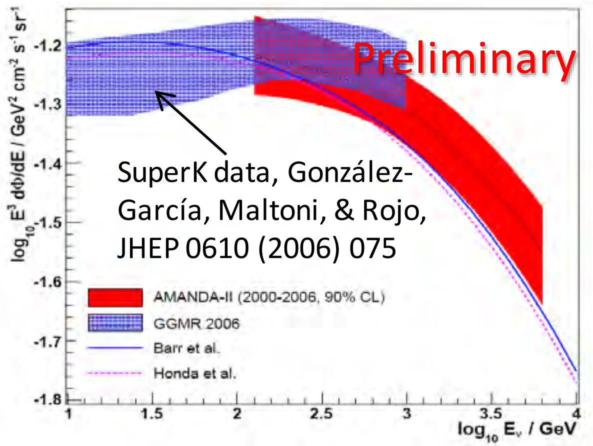



Energy range	**~MeV**	**GeV-TeV**	**TeV-PeV**	**PeV-EeV**	**>EeV**
Physics	Supernovae	Dark Matter, Oscillations, Atmospheric ν,	Point sources, GRB, Diffuse	GZK Neutrinos, Cosmic Rays	?
Signature	Average increase in the PMT counting rate	Tracks, Contained Events	Tracks, Cascades	Tracks, Cascades, Double Bang, Lollipops	Christmas Tree
Coverage/ Directionality	All sky, but no directionality	Up-going	Up-going	Horizontal, down-going IceTop/InIce	Down-going

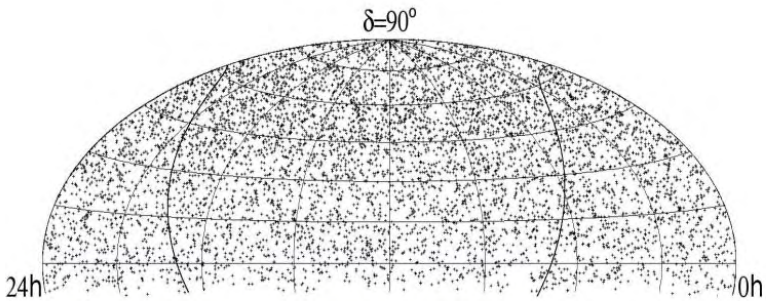
AMANDA 2000-2006 Analyses



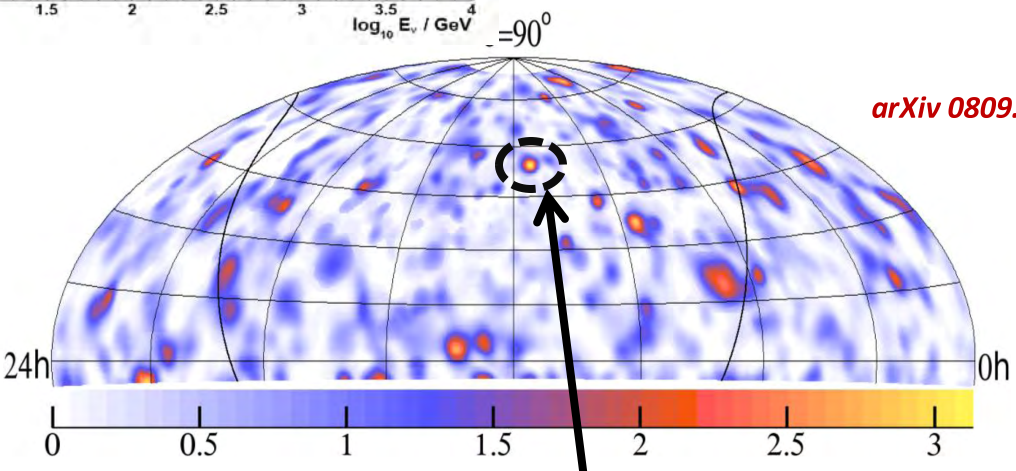


arXiv 0902.0675 (submitted to PRD)

1387 days of livetime
6595 Neutrino candidates



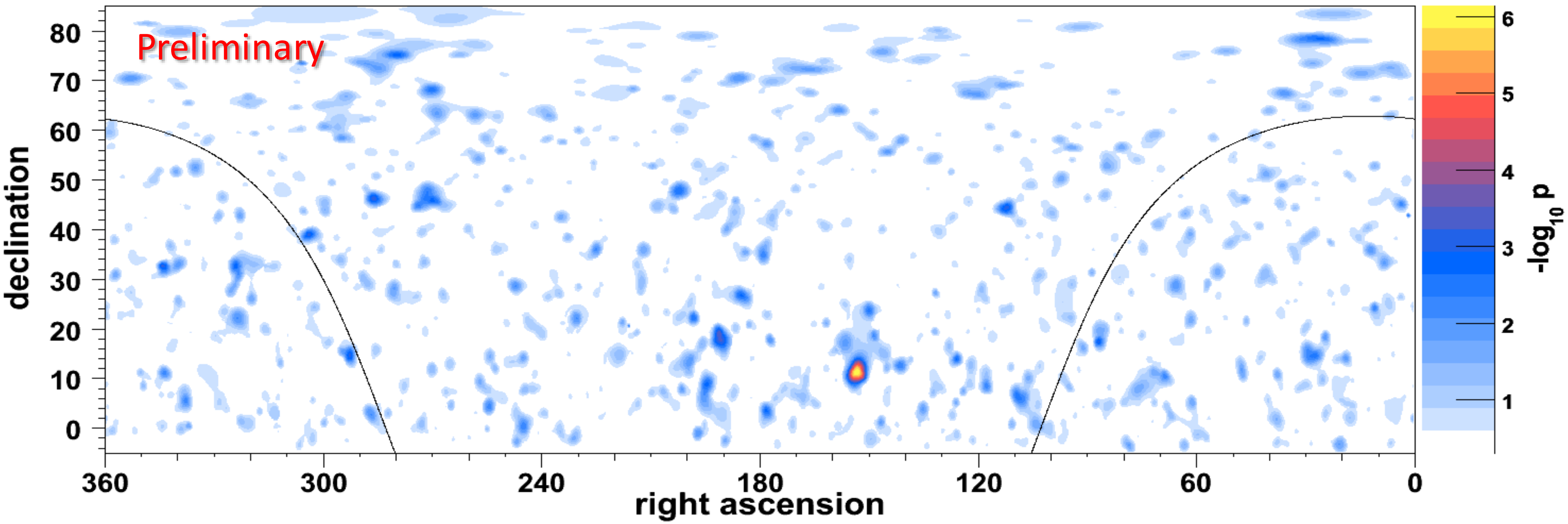
http://www.icecube.wisc.edu/science/data



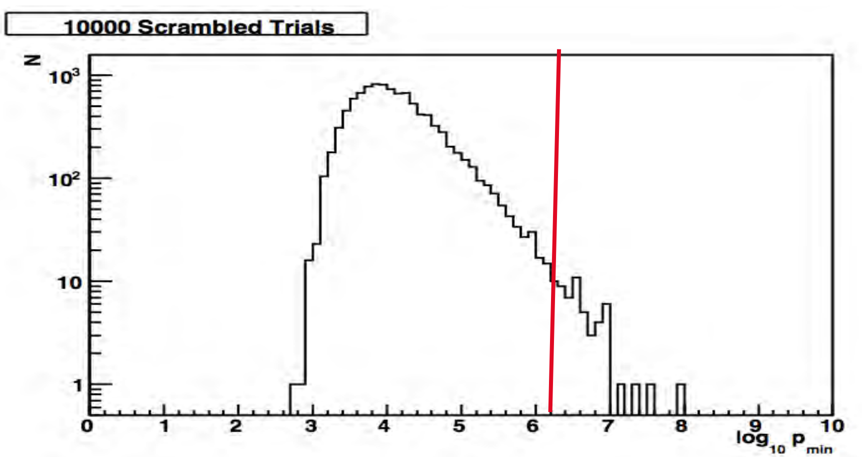
arXiv 0809.1646

- Maximum significance is 3.38σ at δ = 54°, α = 11.4 hr
- 95% of randomized sets have same or greater significance

IceCube-22 Point Source Search (energy weighted)



5114 neutrino candidates in 276 days livetime



Hottest spot found at r.a. 153º , dec. 11º
est. pre-trial p-value: $-\log_{10}(p)$: 6.14
(4.8 sigma)

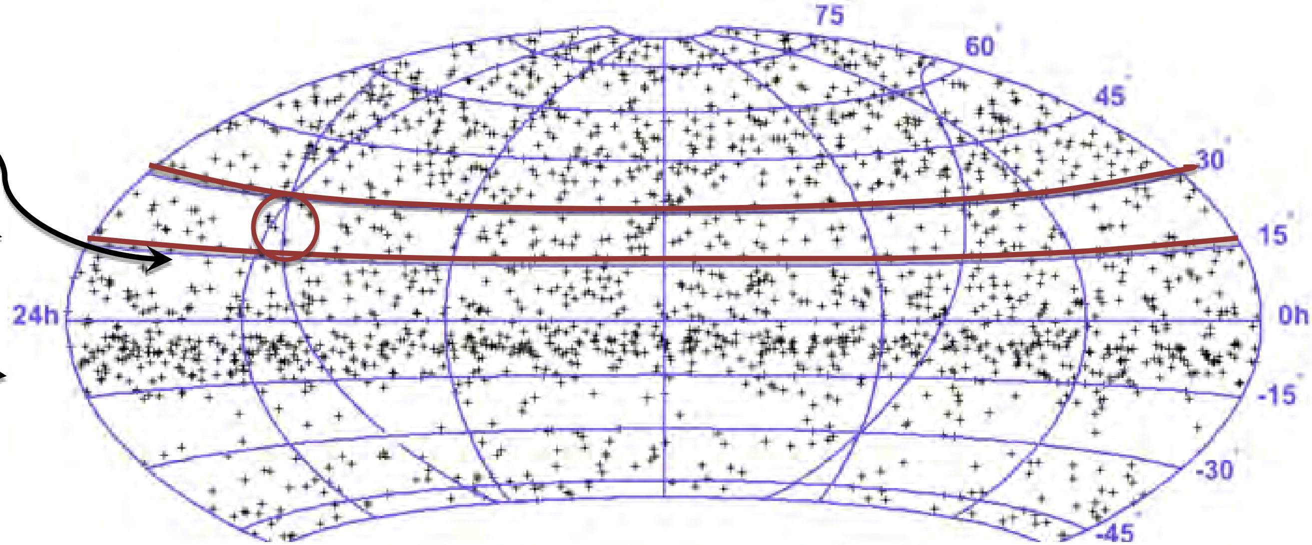
Post-trials p-value of analysis is ~ 1.34% (2.2 sigma) …

IceCube-22 ... moves above the horizon

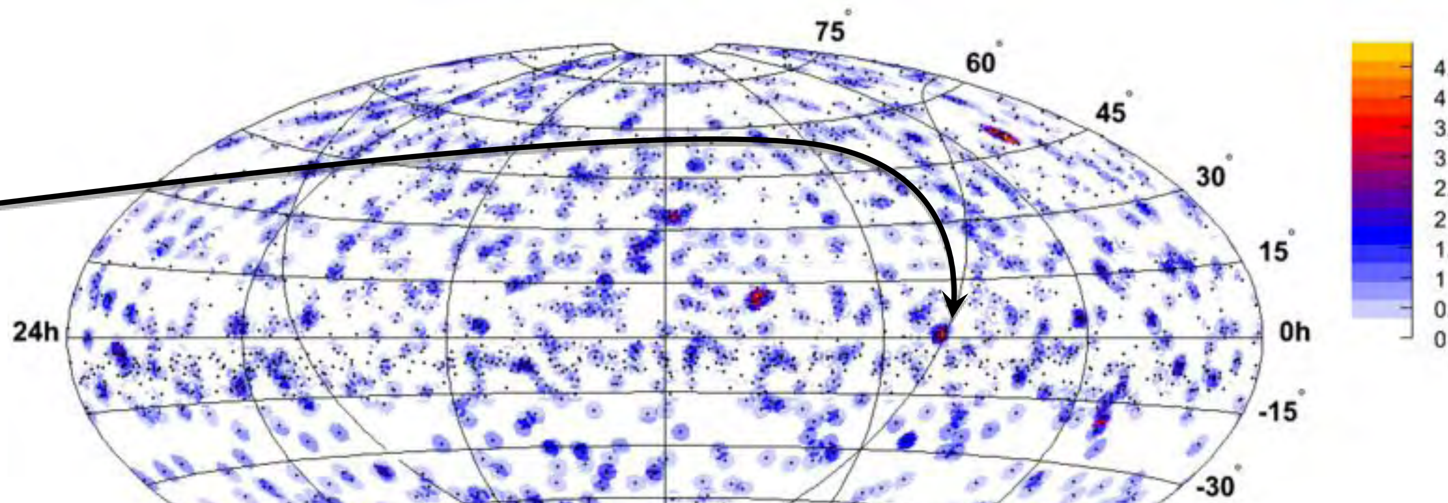
search in 2.5 degree bins

background calculation from same declination band

large irreducable background just below the horizon



Coordinates:
Dec. 1.00°, RA 103.5° (6.9 h)
P-value:
2.9×10^{-5} (pre-trial prob.)
Bin content:
8 events with 1.2 expected
(109 in dec. band)



*The **trial-corrected probability for a random excess of the same or larger value i**n 37.4% of scrambled maps, **i.e. not significant.***

Diffuse Neutrino Flux Limits

- Atmospheric neutrinos behave like $E^{-3.7}$
- Typical extraterrestrial fluxes are expected to behave like E^{-2}
- Do we see any extraterrestrial flux compornent ?

Look for excess of events at high energy, or high number of channels
IC9: Nch ≥ 60

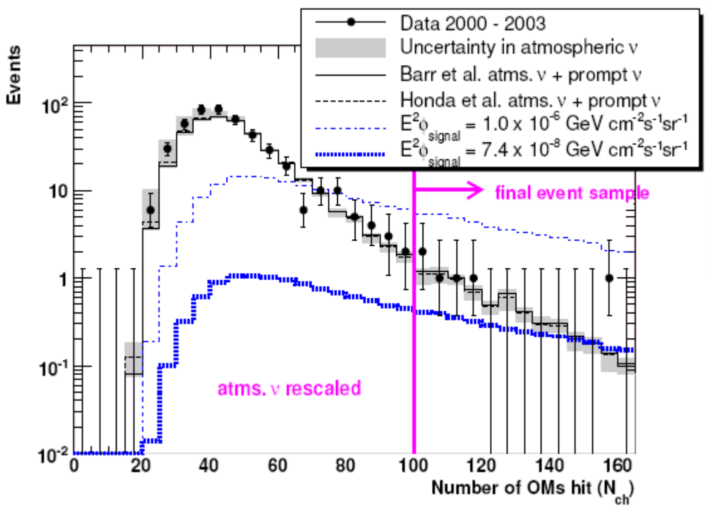
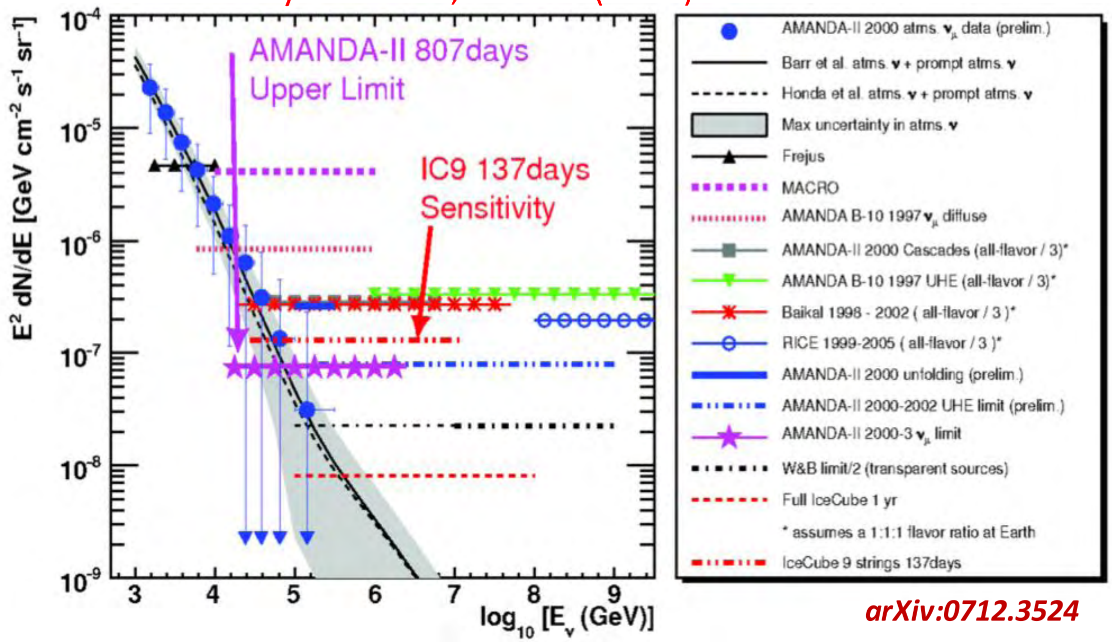


Figure 1. N_{ch} for the AMANDA-II 2000–2003 diffuse muon neutrino analysis compared to atmospheric neutrino expectations [6, 8].

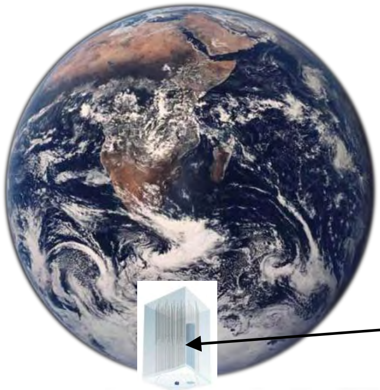
Phys Rev. D76, 042008 (2006)

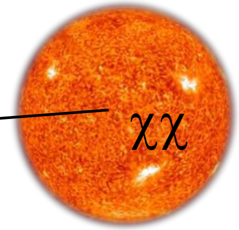


arXiv:0712.3524

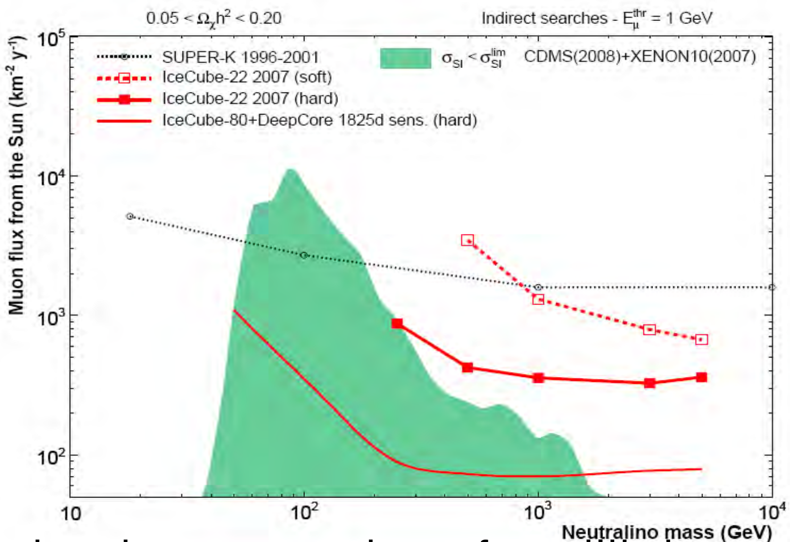
IC9 sensitivity:
$E^2\Phi < 1.4\ 10^{-7}$ GeV/cm^2 s sr (for E ≲ 10 PeV)
AMANDA II Limit: $E^{-2} < 7.4 \times 10^{-8}$GeVcm^{2}s^{-1}sr^{-1}

IceCube-22 Solar WIMPs



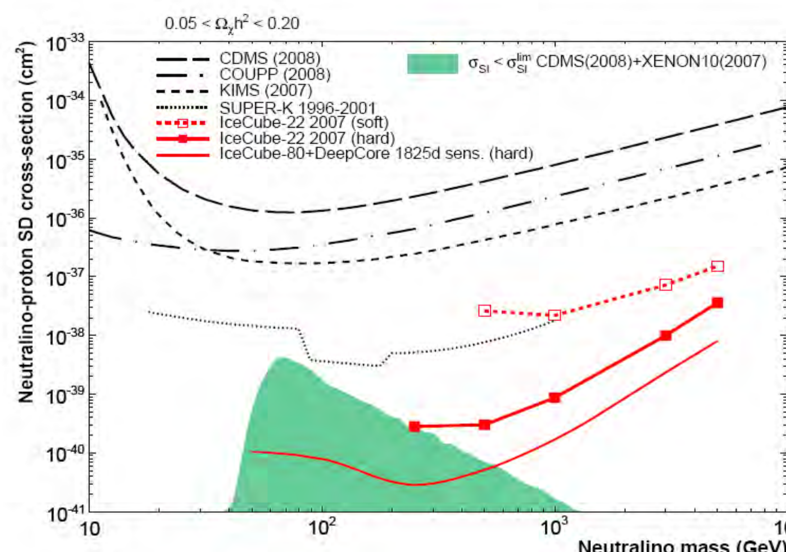


Solar WIMPs



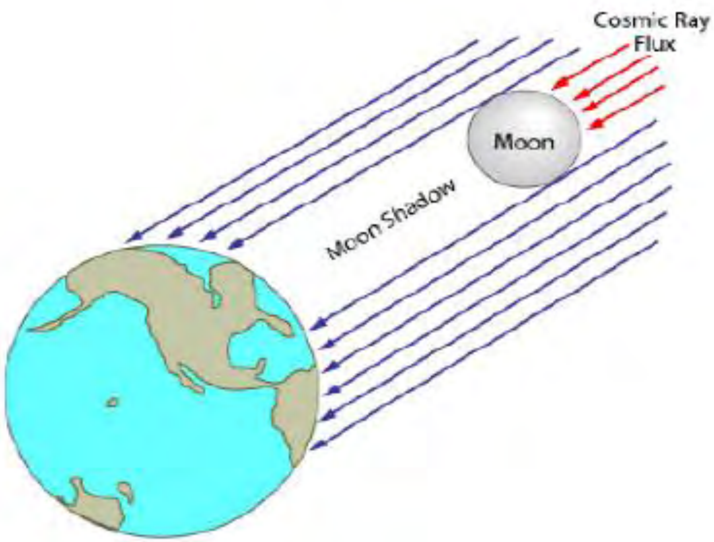
- Look for an excess of neutrinos in the direction of the sun
- No evidence for a signal observed
- Upper limits on muon flux from neutralino annihilations in the Sun

- Under the assumption of equilibrium condition in the Sun, a limit on the WIMP-Nucleon cross-section can be obtained
- For spin-dependent couplings, IceCube's sensitivity is about 2-orders of magnitude better than direct searches

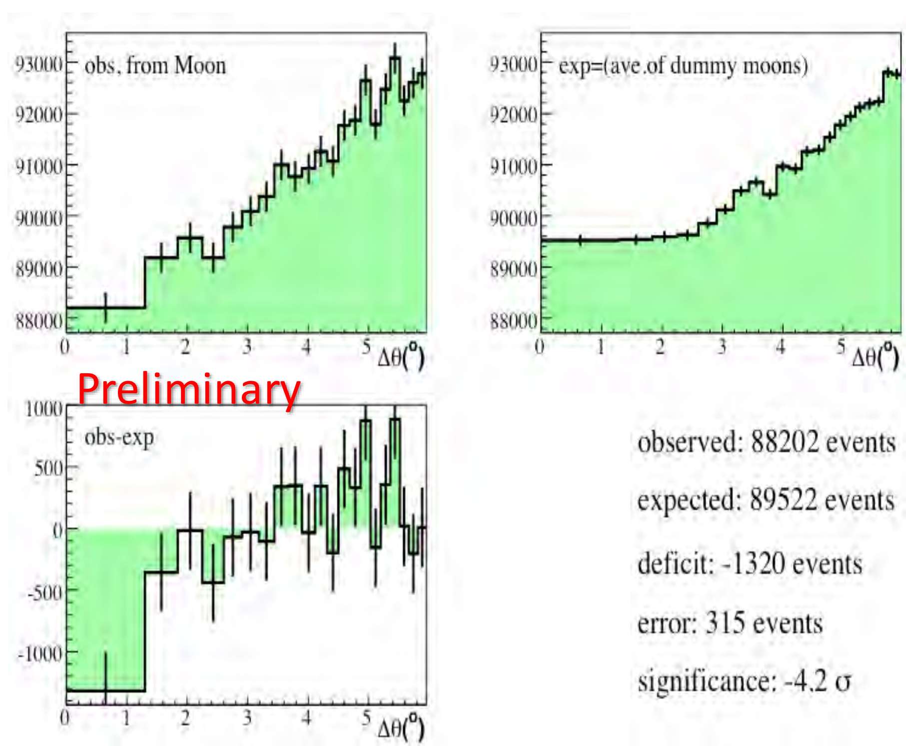


arXiv: 0902.2460 (submitted to PRL)

IceCube-40 - Moon Shadow



Cosmic rays blocked by the moon lead to a point-like deficit in the distribution of down-going muons in the detector



Moon shadow observed in first 3 months of IC40 data

- Validates pointing capabilities:

Angular resolution:

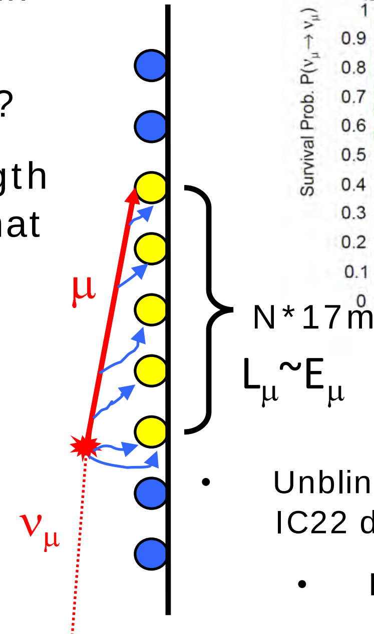
– IceCube 22 < 1.5°

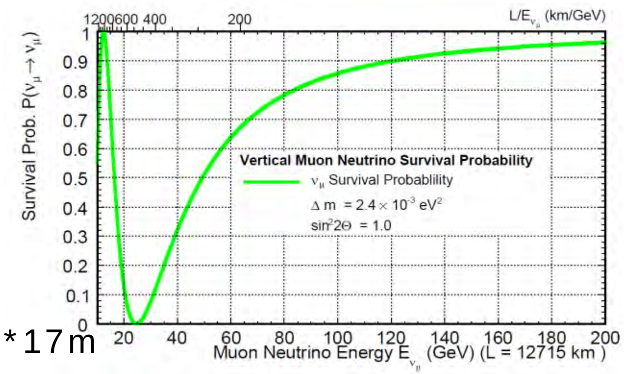
– IceCube 80 < 1°

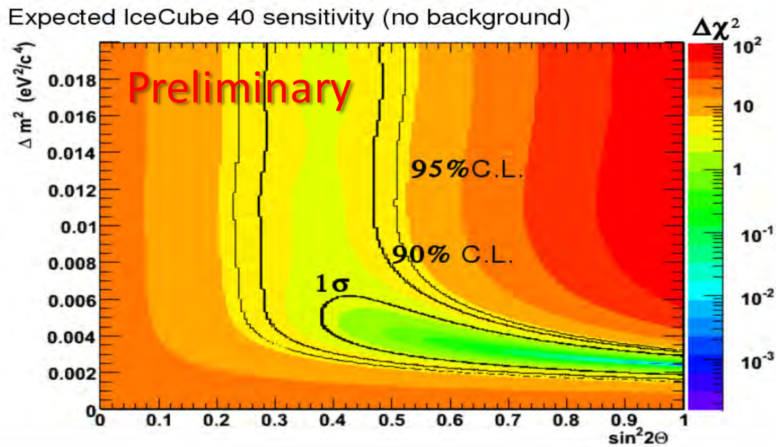
- Used to determine detector angular resolution

IceCube-40 - Oscillation Sensitivity

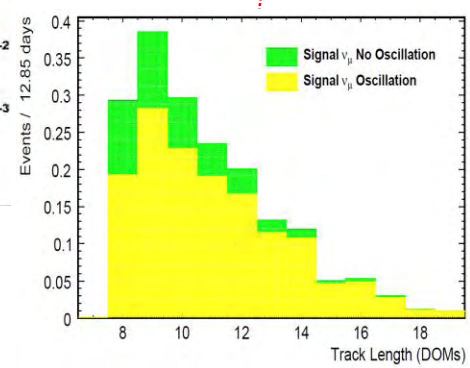
- IceCube's lowest energy threshold is realized in vertical events (due to its geometry)
- Can we see atmospheric neutrino oscillations?
- Expected results of χ^2 test using the track length as energy estimator (under the assumption that remaining background can be rejected)







arXiv:0810.3698



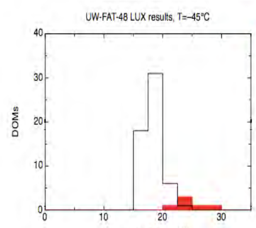
- Unblineded a small subset of the IC22 data for validation purposes:
  - Expected:
    - Signal (Muon Neutrinos): 1.81 (no-osc) / 1.42 (osc)
    - Background: 0.0 +/- 20.3
  - Observed three events

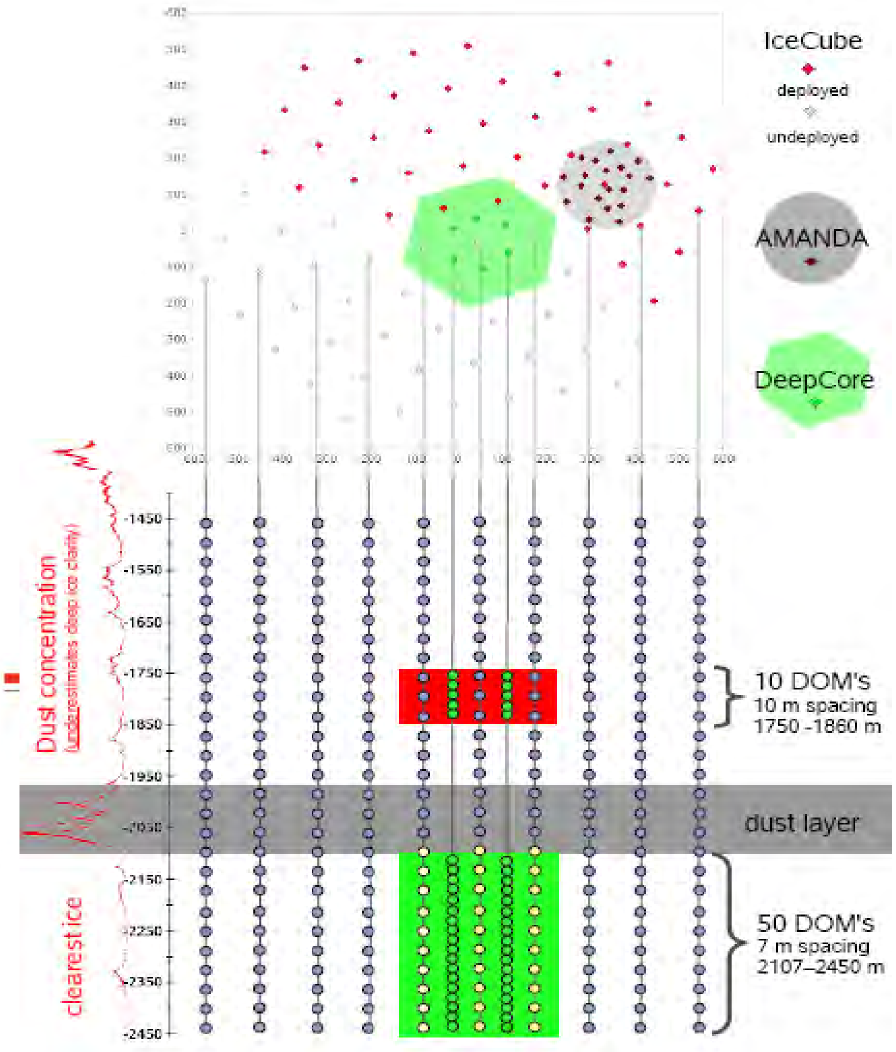
Larger MC background dataset is currently studied

- Oscillation effects might be observable in IceCube 40 data

Deep Core Extension

- Deep Core Strings
  - 6 strings with high quantum efficiency PMTs, densely spaced
  - 7 "standard" IceCube strings
- located in best ice (below 2100 m exceptionally clear)
- Interstring spacing 72m
- Uses high Quantum Efficiency PMTs, that have about 40% higher efficiency
- Located in the deep ice
  - Lower atmospheric muon background
  - Larger scattering length ~40m

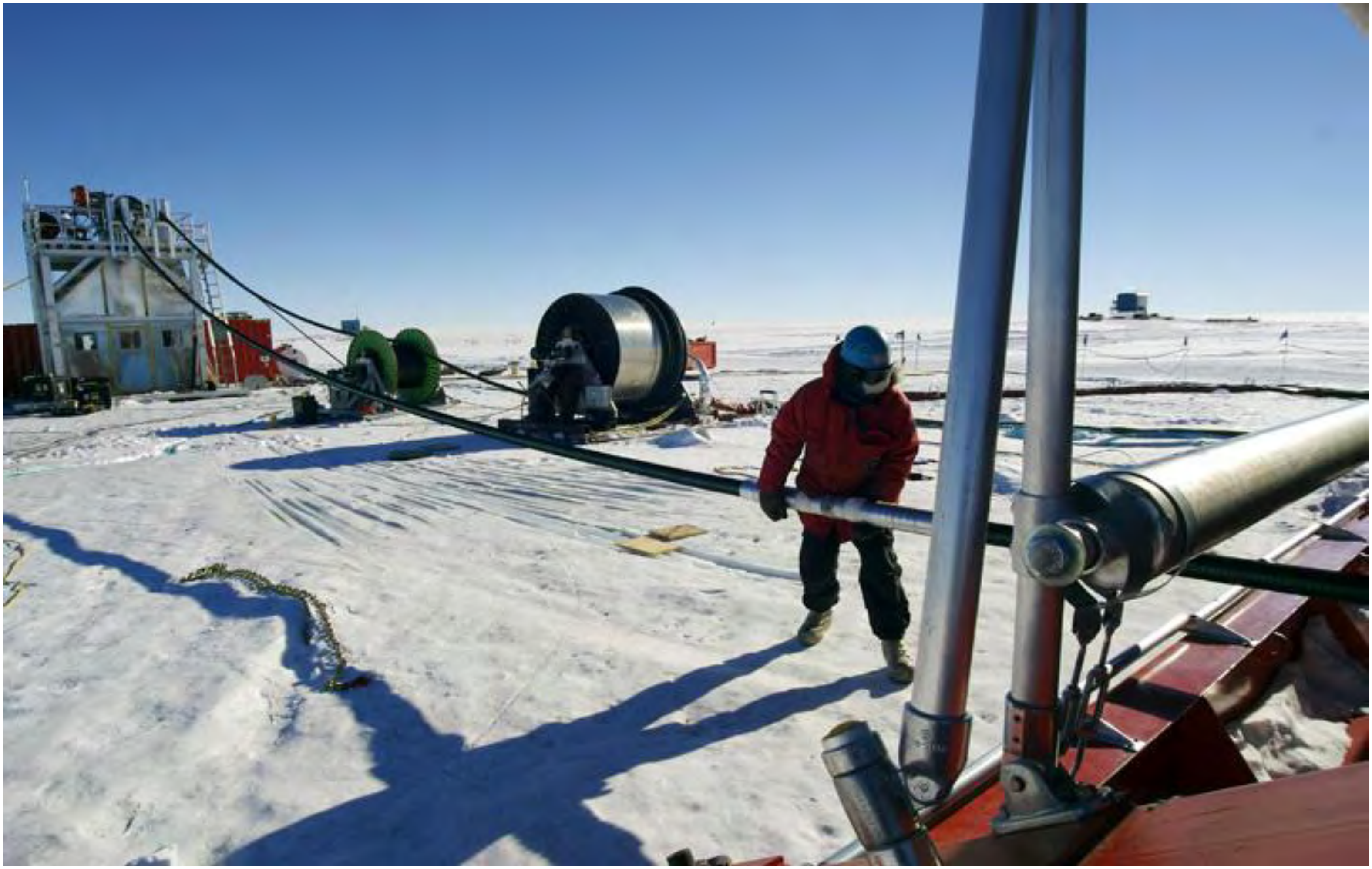




Conclusions

- Phenomenal austral summer season 08/09:
  - 19 new strings deployed (incl. first Deep Core String)
- IceCube deployment is more than two thirds complete!
- IceCube is actively taking data and shows a good long-term hardware reliability
- New most stringent limit on spin-dependent WIMP-nucleon cross-section
- Many analyses with the 40-string detector underway … stay tuned

Bonus Slides



The IceCube Collaboration

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

Universität Dortmund
MPIfK Heidelberg
Humboldt Universität, Berlin
Universität Mainz
DESY, Zeuten
BUGH Wuppertal
RWTH Aachen

Stockholms Universitet
Uppsala Universitet

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

Chiba University

University of Canterbury, Christchurch

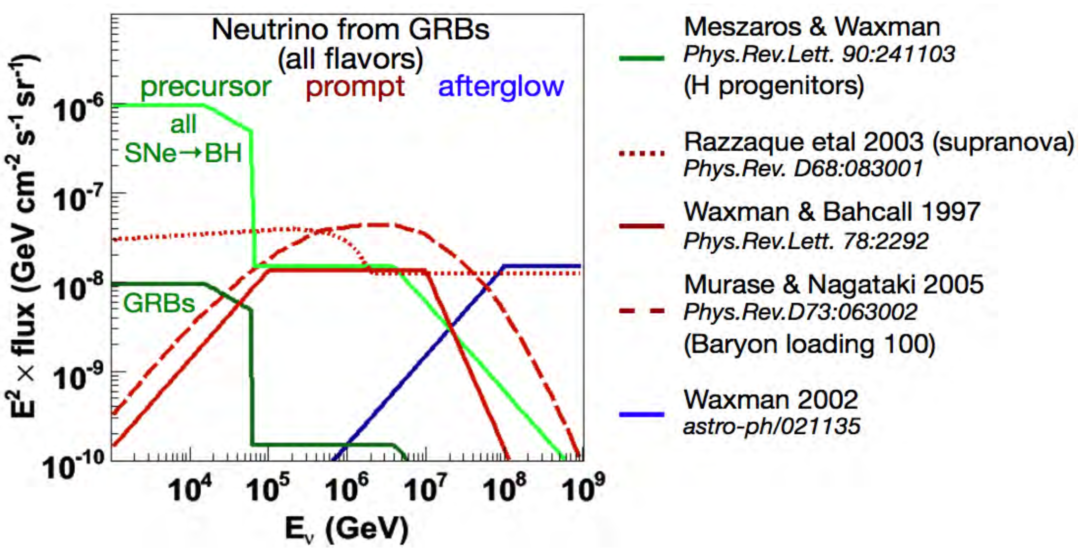
Universiteit Utrecht

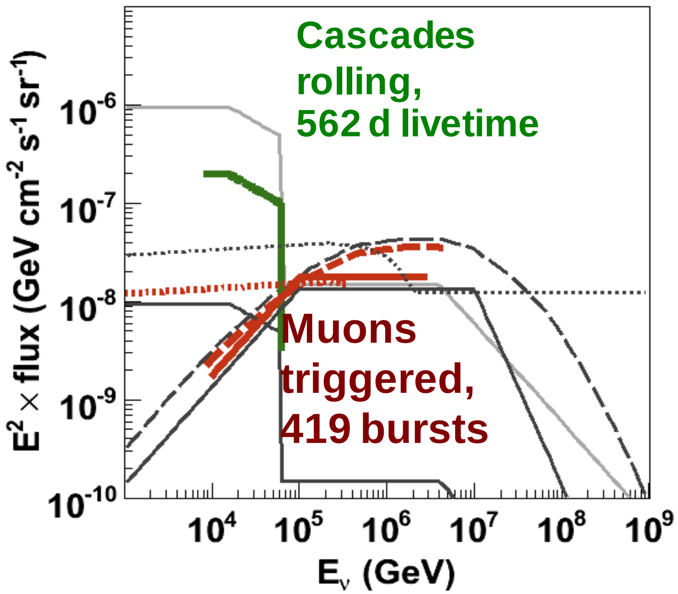
Oxford University

EPF Lausanne

Neutrinos from GRBs

- Search for events correlated in time and direction with observed GRBs
- Small time and space window reduces background rate
- 93 SWIFT bursts during IC22 runs
- IceCube will be able to detect Waxman-Bahcall or similar GRB fluxes within the next few years

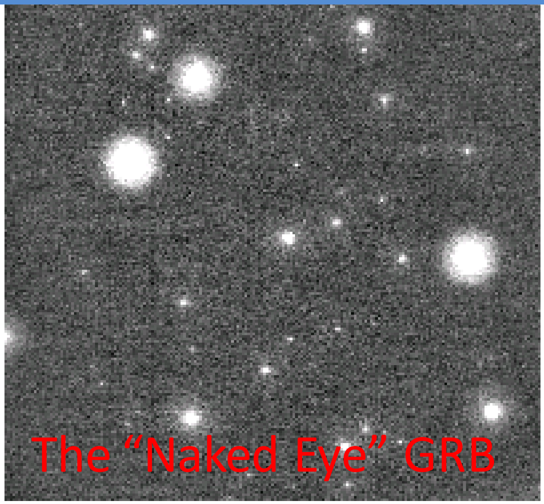




A. Achterberg et al, ApJ 674:357, 2008 (Muon)
A. Achterberg et al, ApJ 664:397, 2007 (Cascades)
arXiv:0902. 0131(GRB080319B)

GRB080319B

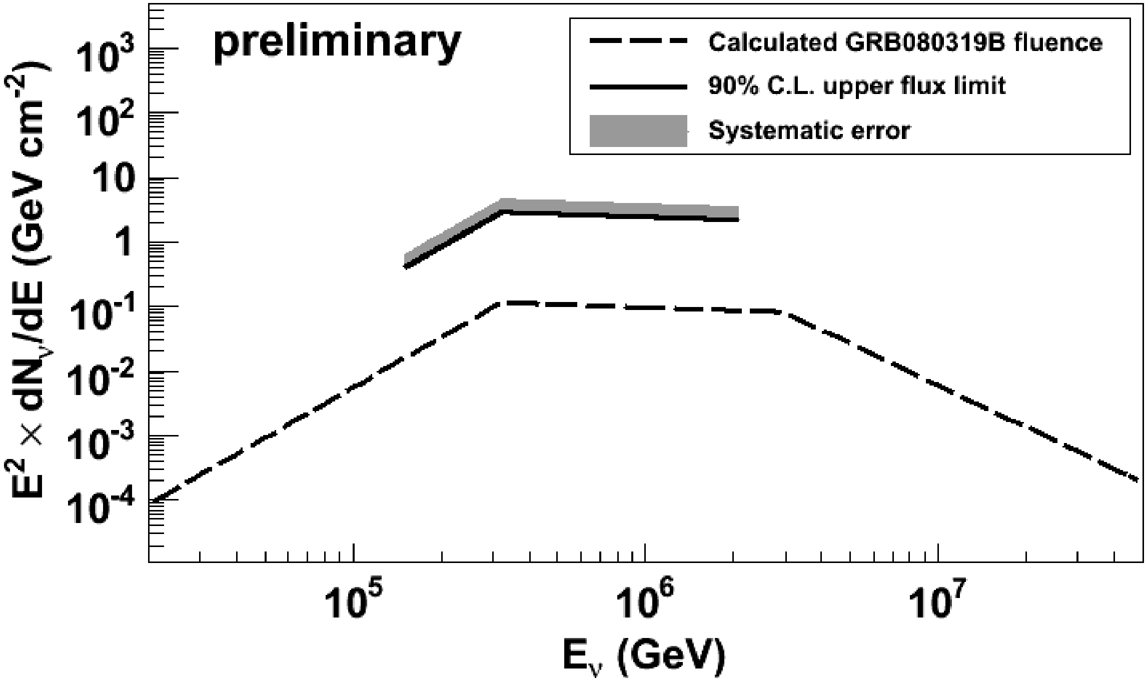
March 19, 06:12:49 UT (duration ~70 s)
- *Position: RA = 217.9°, Dec = +36.3°*
- *Brightest (optical) GRB ever observed*
- *z = 0.94 (DA = 1.6 Gpc)*



- Detector was running in test mode
- (9 out of 22 strings taking data)
- Expect 0.1 events
- No neutrino candidate near GRB coordinates

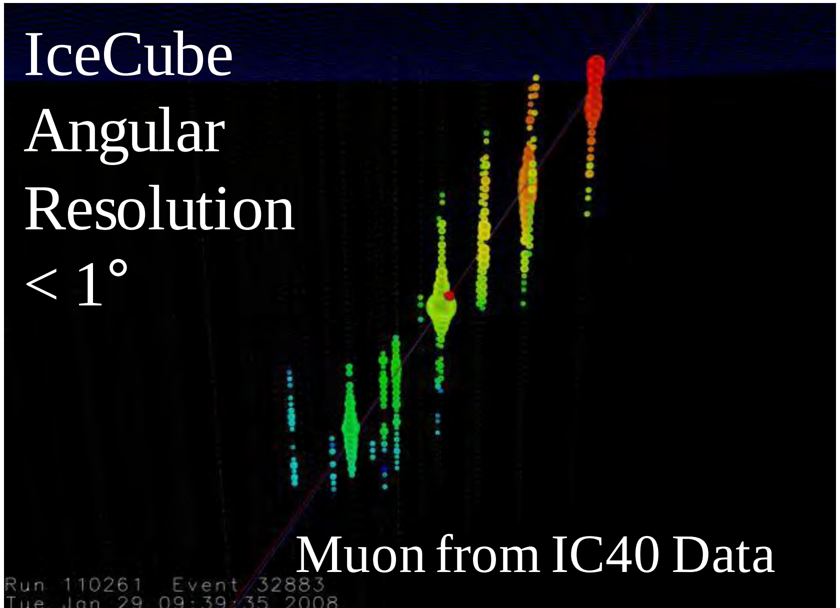
→ 90% upper flux limit

- Would expect ~*1* event from similar burst in IceCube 80-strings

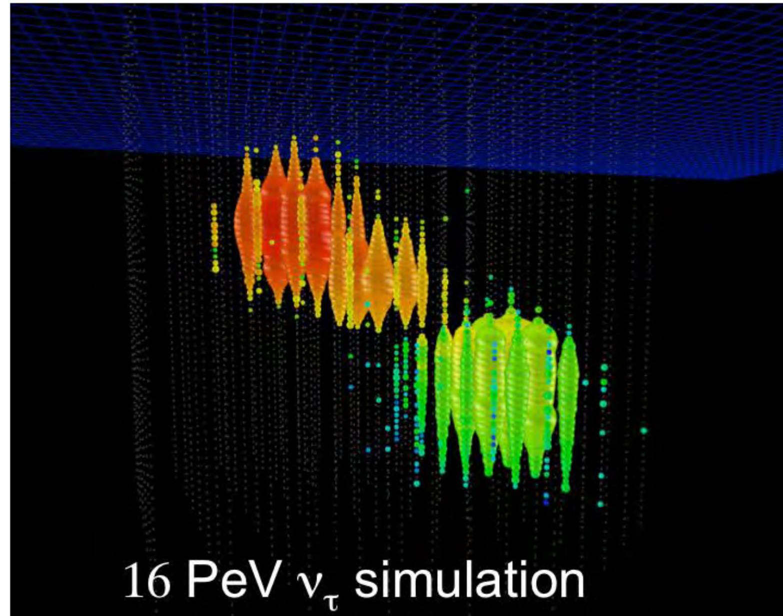


Neutrino Event Identification

Tracks



Cascades



Track-Like	IceCube	AMANDA
Time Resolution	2 ns	5-7 ns
Energy Resolution ($\log_{10}E$)	0.3 – 0.4	0.3 – 0.4
Field of View	2π	2π
Noise Rate	low	
Angular resolution	<1°	~1.5-2.5°

Cascade-Like	IceCube	AMANDA
Time Resolution	2 ns	5-7 ns
Energy Resolution ($\log_{10}E$)	0.18	0.18
Field of View	4π	4π
Noise Rate	low	
Angular resolution	30°	~30-40°

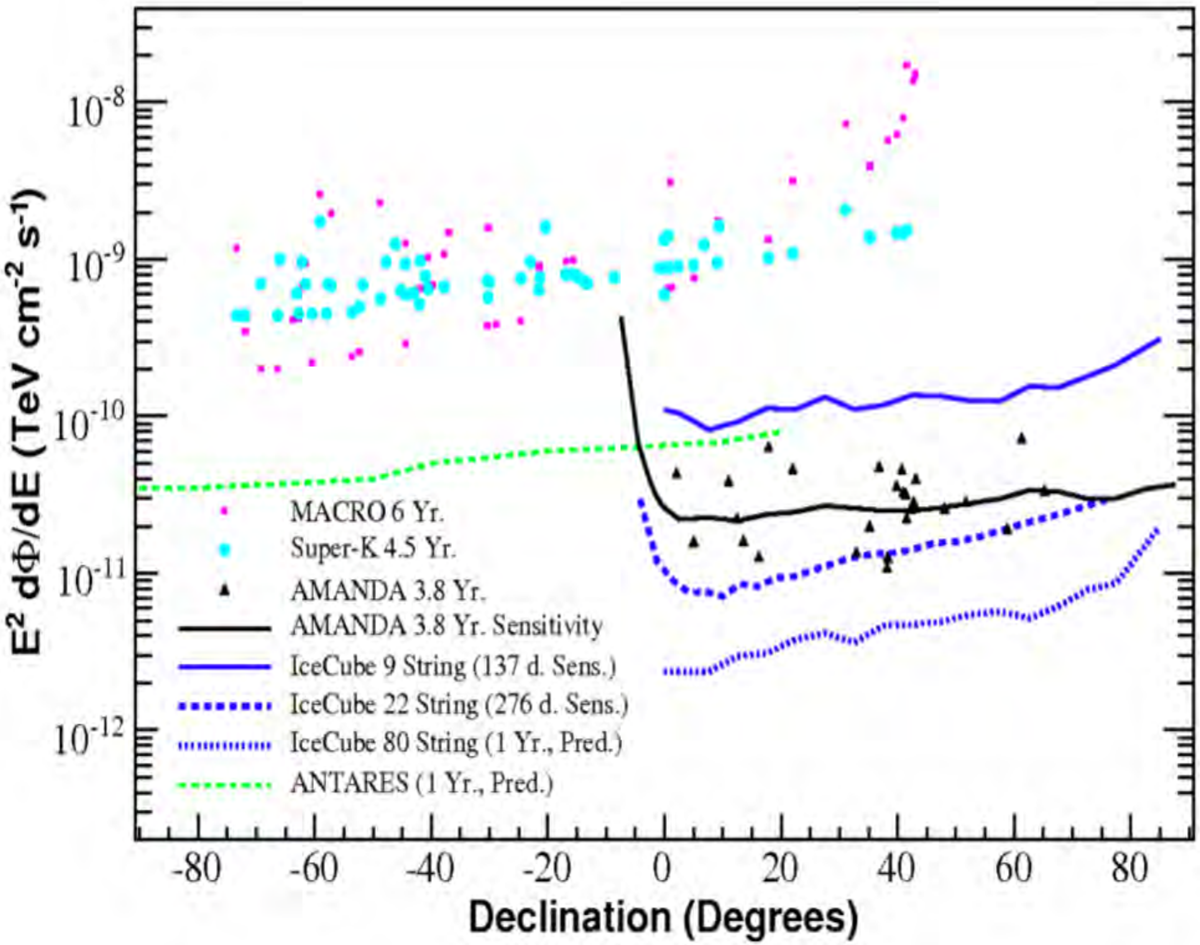
IceCube-22 Source List

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)	-----

<u>28 sources chosen in advance</u>

- Most significant excess is 1ES 1959+650 with a pre-trial p-value of 0.07
- Not significant after trial factor

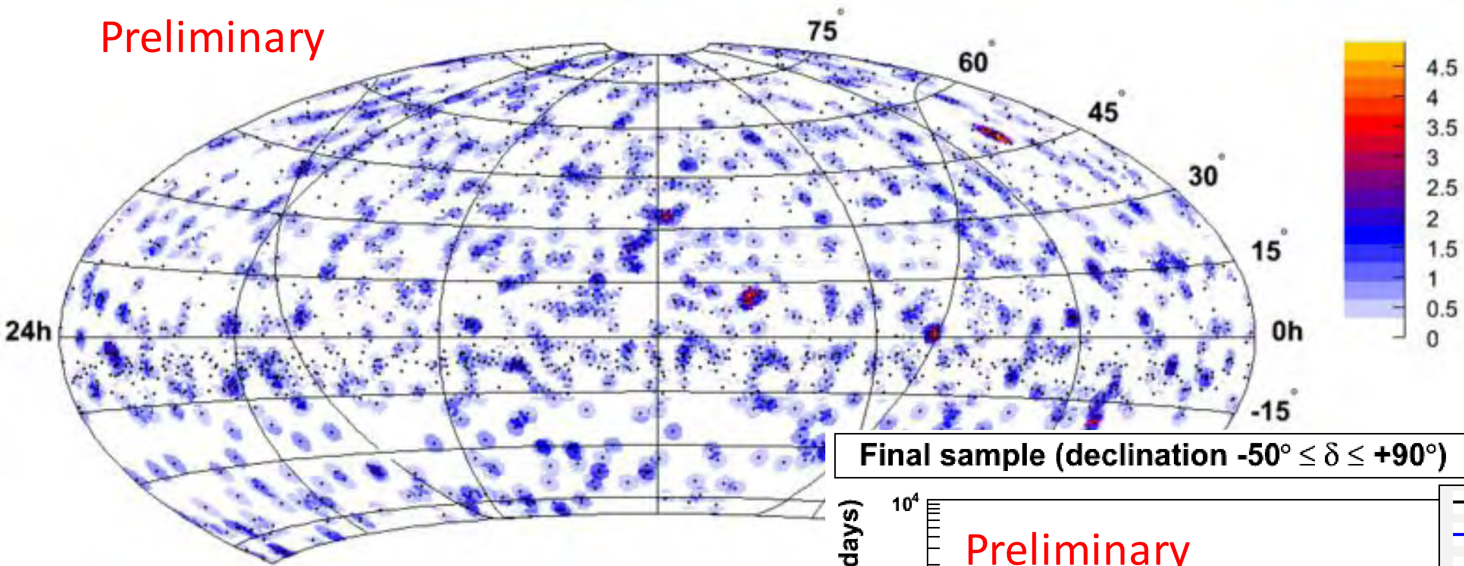
Diffuse Flux Limits

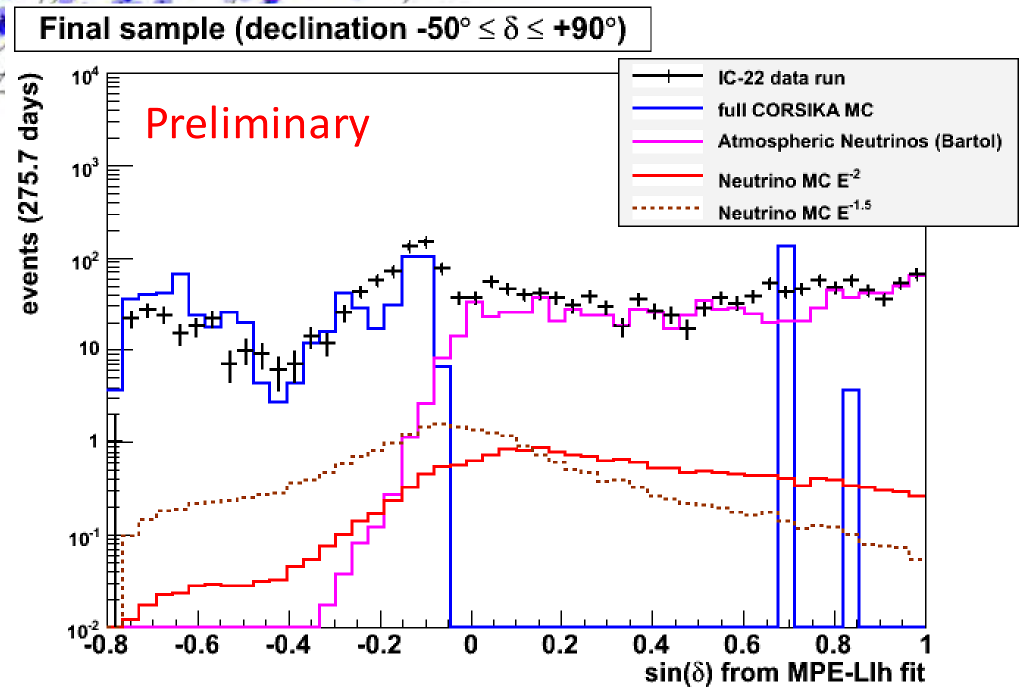


Astrophysical E^{-2} neutrino diffuse flux limits

- Amanda ~ 2-3 10^{-11} TeV/cm^2 s
- IC22 ~ 8-30 10^{-12} TeV/cm2 s
- IC80 ~ 2-20 10^{-12} TeV/cm2 s

IceCube-22 ... moves above the horizon





- **Data (275.7 days) 1885**

Background simulation:

- **CORSIKA muons 769 ± 25**
- **Atm. neutrinos 853 ± 3**

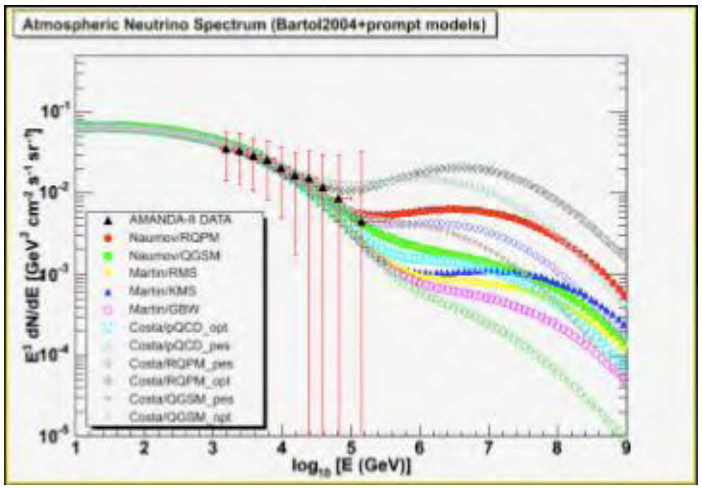
Signal simulation:

- **$E^{-1.5}$ neutrino-signal**
- **E^{-2} neutrino-signal**

Diffuse Neutrino Flux Limits

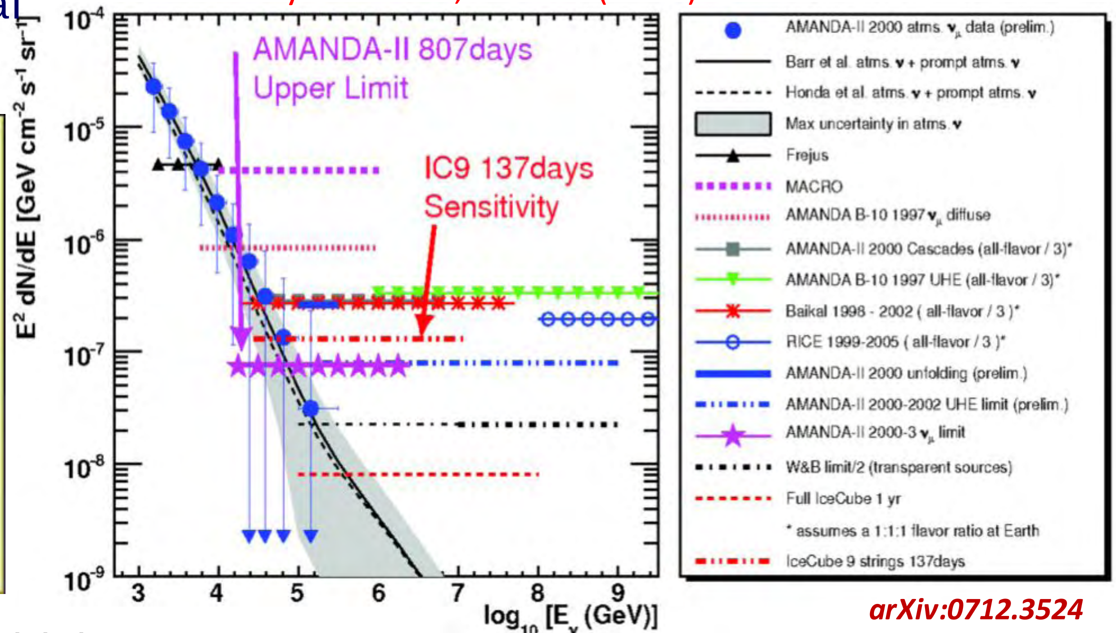
- Atmospheric neutrinos behave like *E-3.7*
- Typical extraterrestrial fluxes are expected to behave like E-*2*
- Do we see any extraterrestrial flux compornent ?

Look for excess of events at high energy, or high number of channels
IC9: Nch ≥ 60



Prompt Neutrino Flux
(charmed Mesons)

Phys Rev. D76, 042008 (2006)

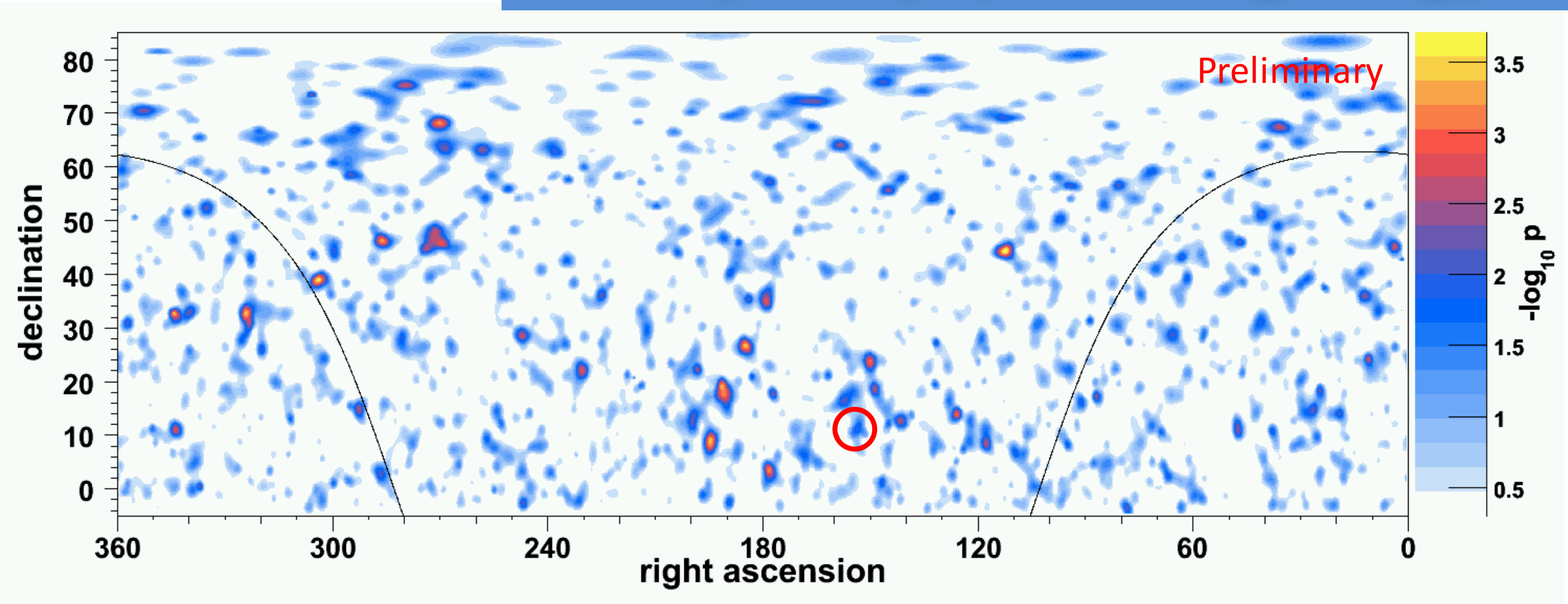


arXiv:0712.3524

IC9 sensitivity:
$E^2\Phi < 1.4\ 10^{-7}$ GeV/cm² s sr (for E ≲ 10 PeV)

AMANDA II Limit: $E^{-2} < 7.4\times10^{-8}\,\mathrm{GeV cm^{2} s^{-1} sr^{-1}}$

Sky Map (no weighing)

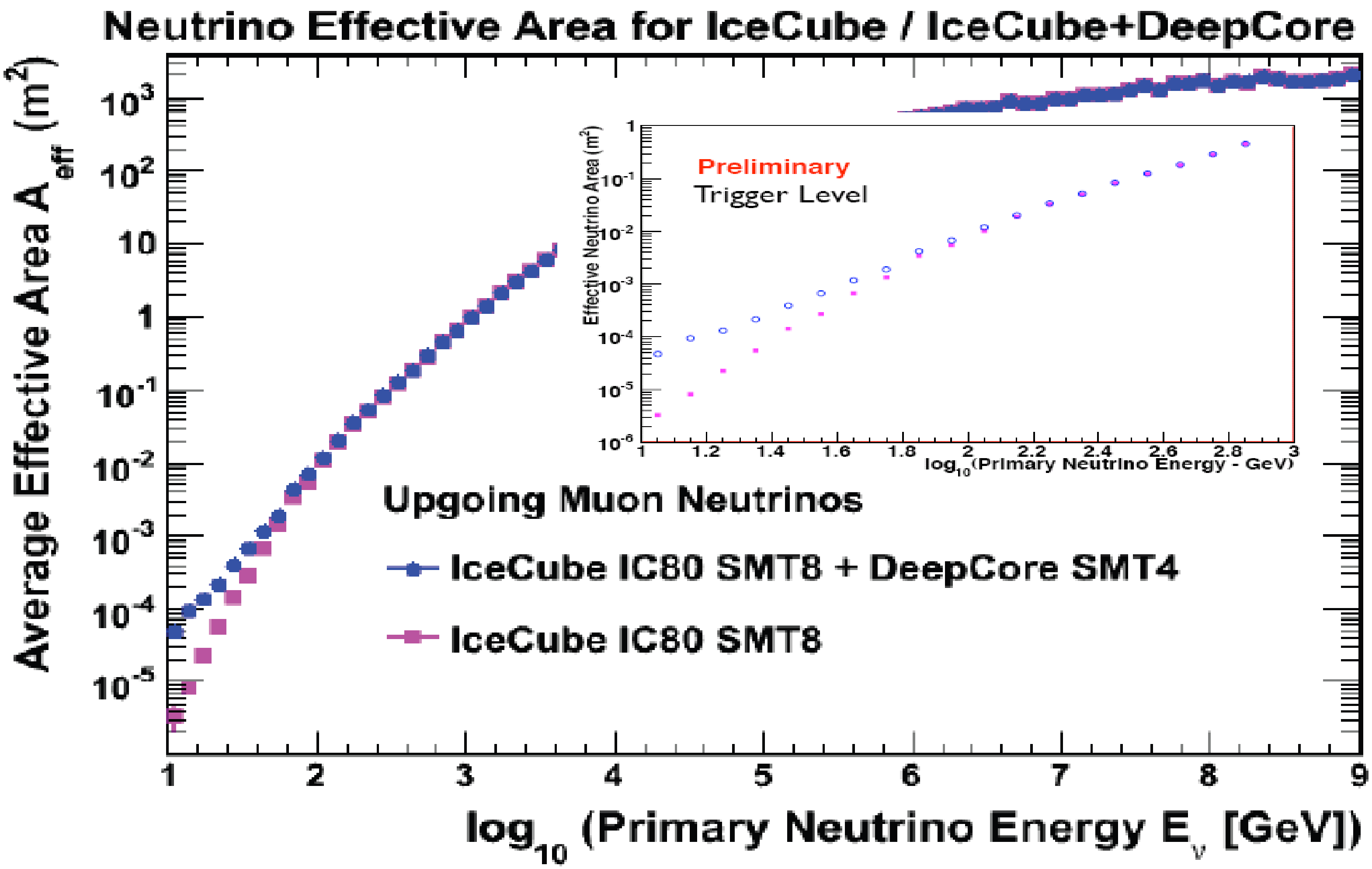


If the unbinned analysis is performed without the energy / NChan term, the original hottest spot is still an excess, but no longer significant at all.

(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

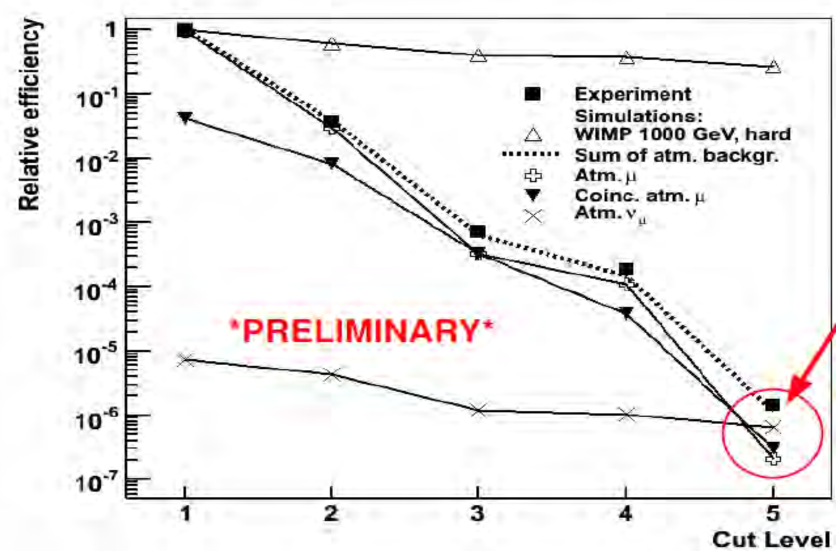
Deep Core - Effective Area

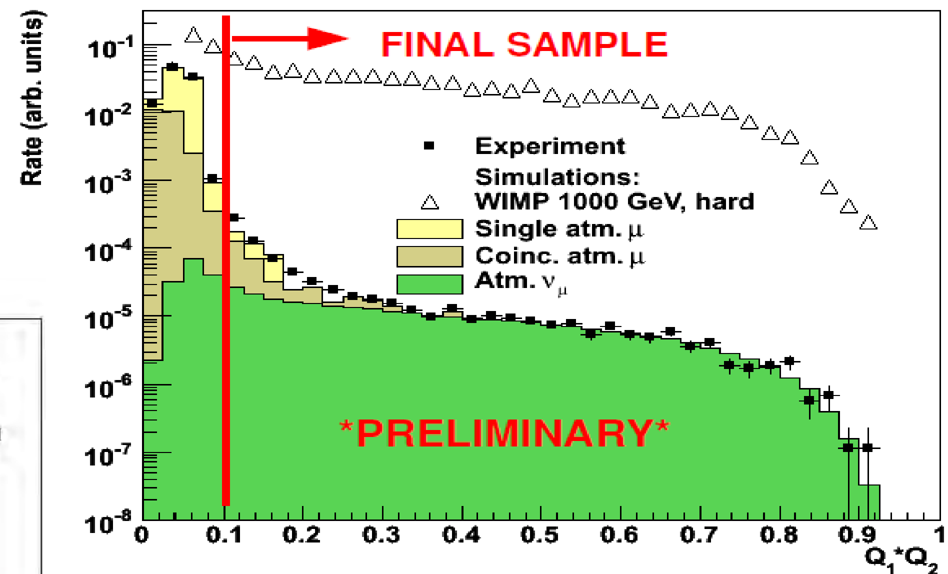


Solar WIMPs

Product of two SVMs Q1*Q2 was used to remove background at final cut level

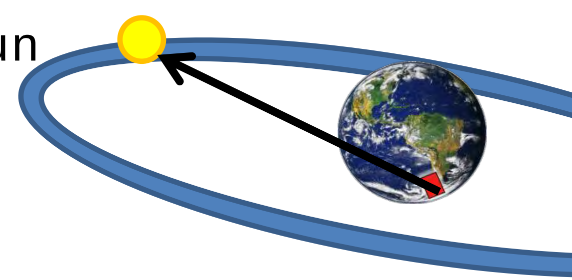
Data and simulation agree well



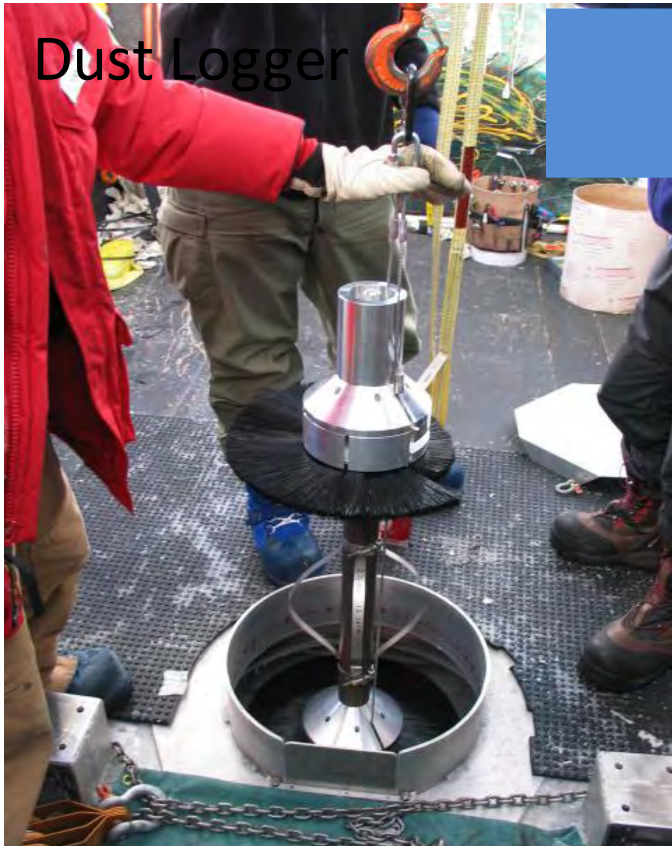


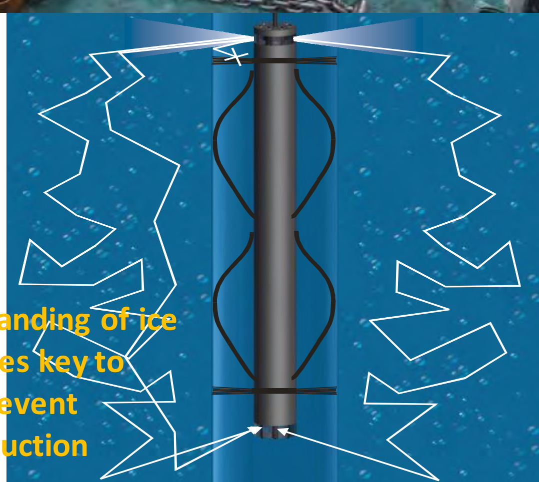
At the final cut level, atm. neutrinos form biggest background

Direction of the sun still remained scrambled to this point

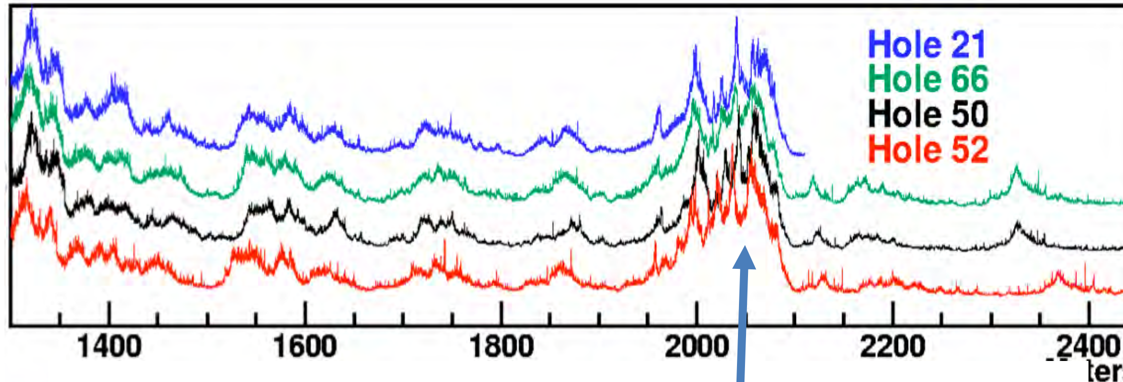


Ice Effects

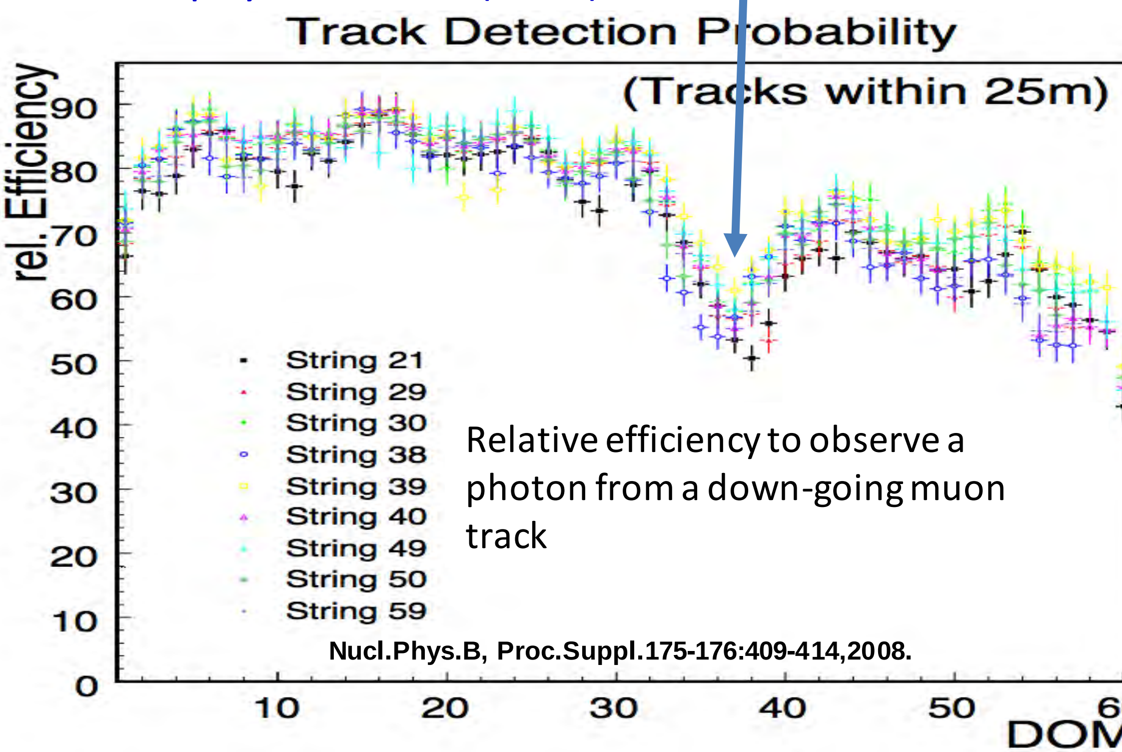




Understanding of ice properties key to reliable event reconstruction



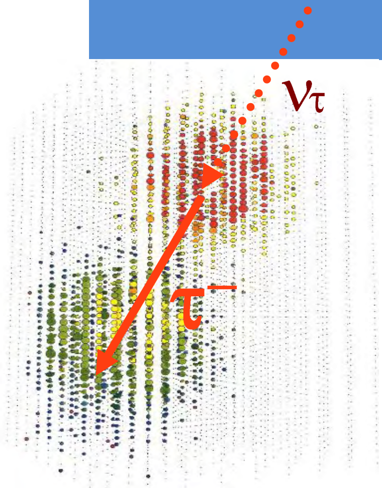
J. Geophys. Res. 111 (2006) D13203



Relative efficiency to observe a photon from a down-going muon track

Nucl.Phys.B, Proc.Suppl.175-176:409-414,2008.

Other exciting signatures … Tau Search



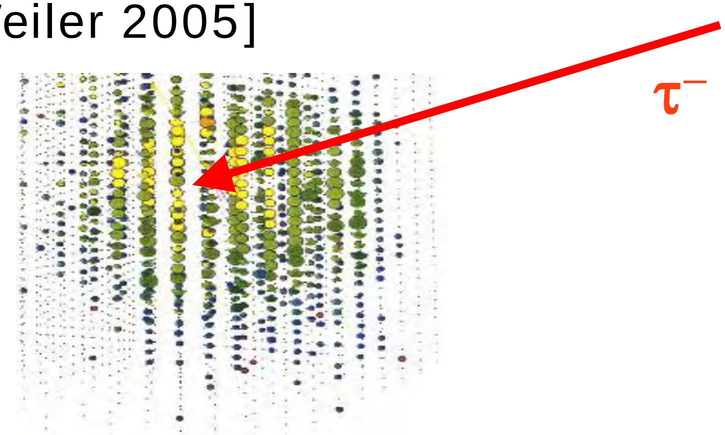
Double Bang

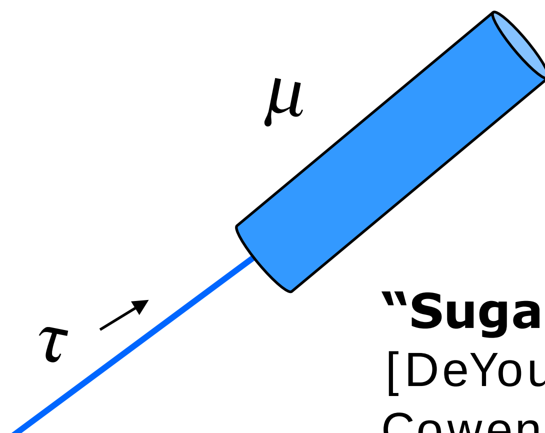
< ~20PeV

[Learned & Pakvasa 1995]

Decay mode	Branching fraction	
$\cdot\ \tau \rightarrow \nu_\tau + e + \nu_e$	17.8%	double bang / lollipop
$\cdot\ \tau \rightarrow \nu_\tau + X$ (hadronic)	~65%	
$\cdot\ \tau \rightarrow \nu_\tau + \mu + \nu_\mu$	17.4%	

"Lollipop" – half double bang
[Beacom, Bell, Hooper, Pakvasa & Weiler 2005]





$$\langle E_\mu \rangle = 0.35\, E_\tau$$

"Sugar daddy"
[DeYoung, Razzaque, & Cowen, 2007]

Searches for tau-neutrinos are underway …