Recent Results and Current Status of IceCube

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April 3, 2009, Fermilab

- Neutrino Physics and Astronomy
- Neutrino Detection
- IceCube Design and Construction
- IceCube Current Results and Prospects

Neutrino Physics and Astronomy

Universe is not transparent for HE photons or nuclei

Photons above 100 TeV:

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$

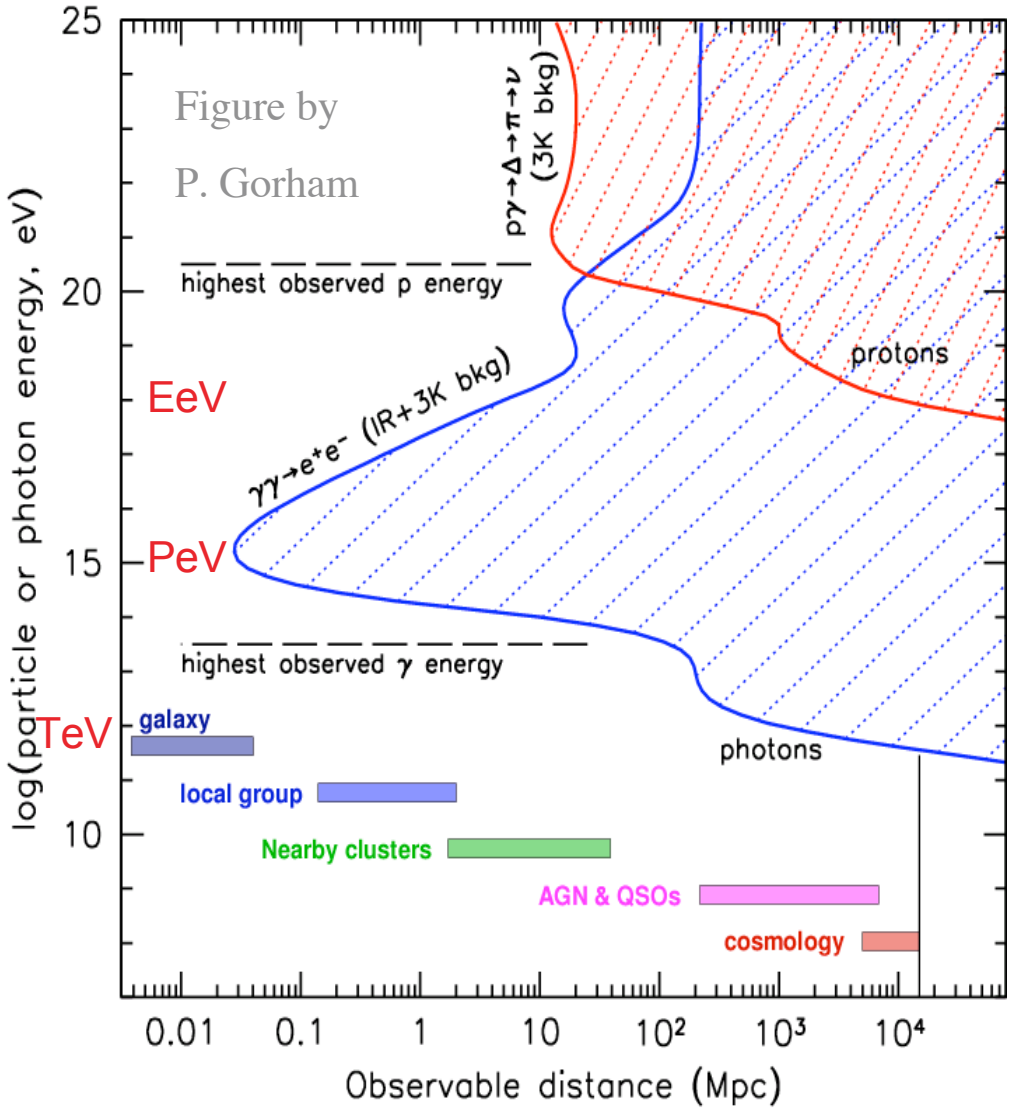
Protons above 50 EeV:

$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$

Protons below 50 EeV:

deflected by mag. fields

Neutrinos unique high energy particle messenger: unabsorbed, undeflected



High Energy Neutrino Sources

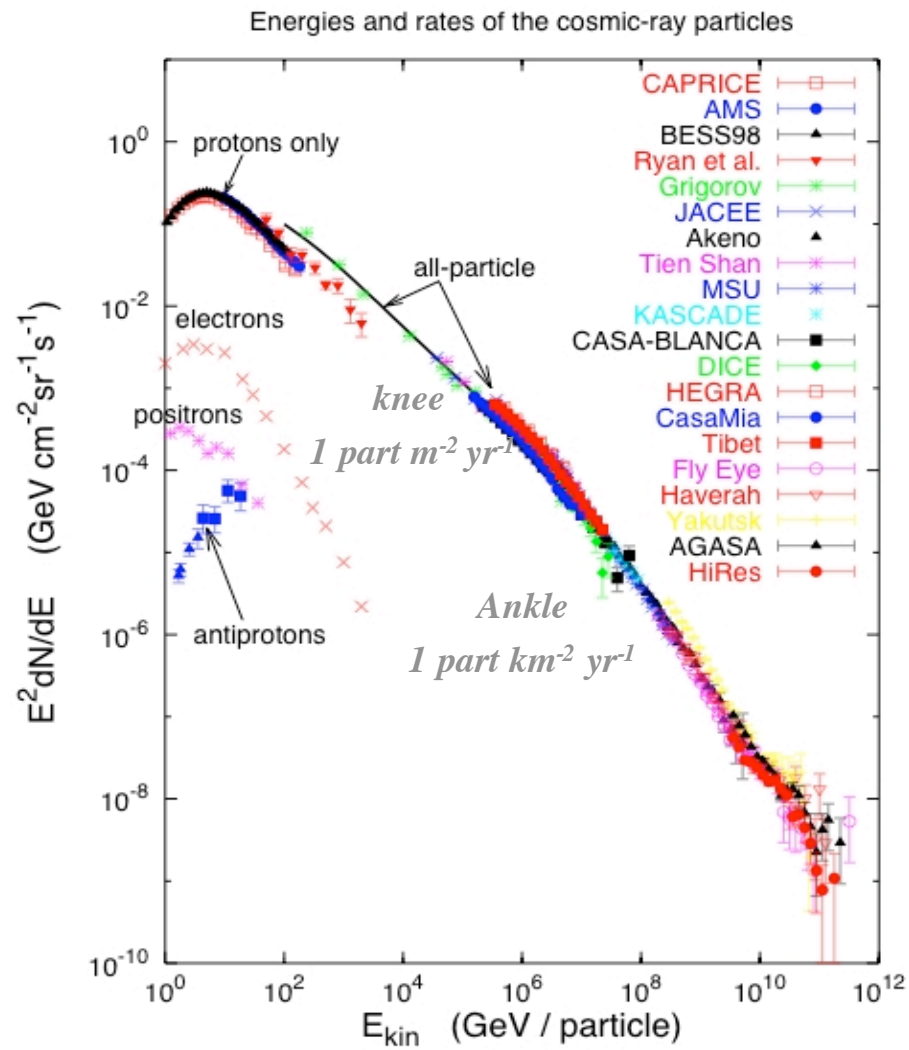
Do sources of high energy neutrinos exist?

We know: cosmic rays exist up to ultrahigh energies (10^{20} eV)

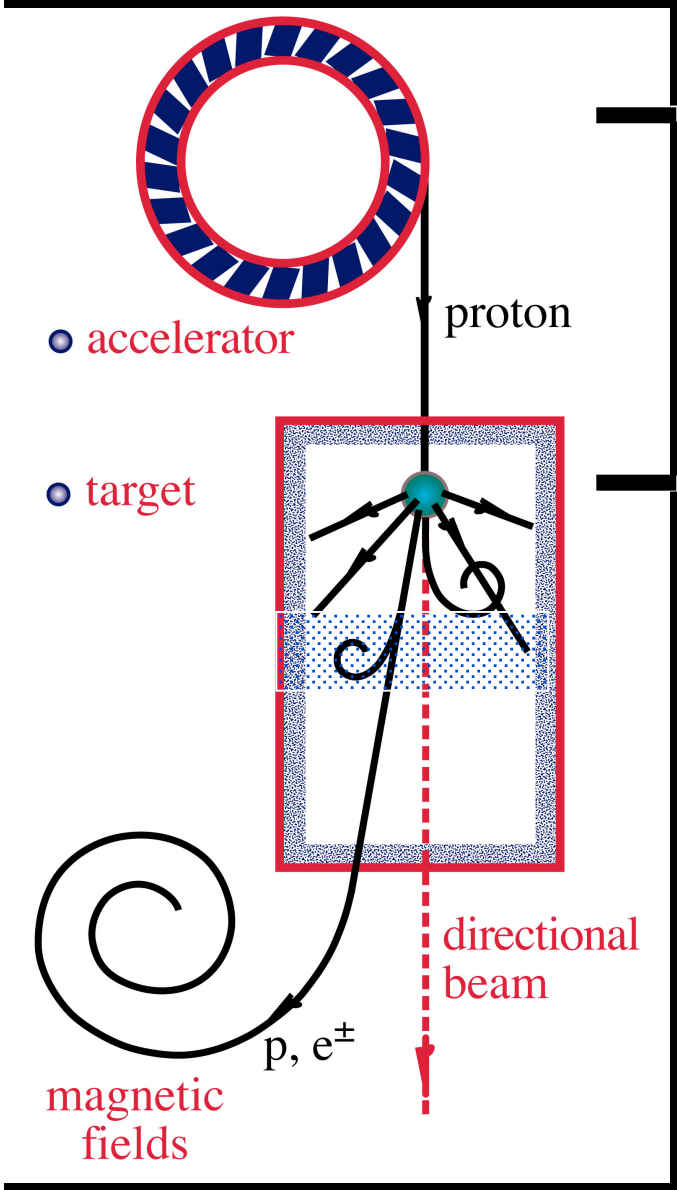
We know: black holes accelerate electrons -- seen as synchrotron photons by x-ray and gamma-ray telescopes

Cosmic rays

T. Gaisser 2005

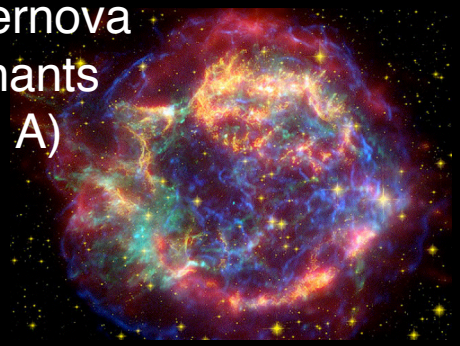


Cosmic Sources of High Energy Neutrinos



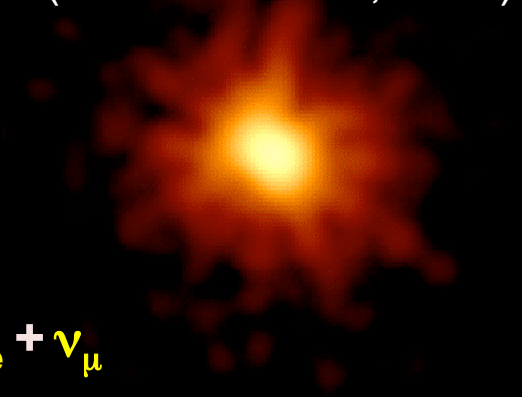
Cosmic ray accelerator

Supernova remnants (Cas A)



Target:
- photon field
- molecular cloud
- interstellar medium

Gamma-ray bursts (GRB 080319B, Swift)



$$p + p(\gamma) \rightarrow \pi^{\pm} + X$$
$$\rightarrow \mu + \nu_{\mu}$$
$$\rightarrow e + \nu_{e} + \nu_{\mu}$$

cosmic ray + neutrinos

$$p + p(\gamma) \rightarrow \pi^{0} + X$$

cosmic ray + photons

?

Physics Motivations for TeV Neutrino Observatory

- Neutrinos are ideal messenger to study the high-energy universe
  - Travel unimpeded
  - Point back toward source
  - Carry information from potentially deep within source
- Search for cosmic-ray accelerators
- Supersymmetry / WIMPs, exotic particles
- Supernova neutrinos (MeV-scale)
- Neutrino / particle-physics (**10^5 atmnu/year**!):
  - UHE cross-section measurements
  - Charm physics
  - Neutrino oscillations
  - Tests Lorentz Invariance – gamma of TeV-scale neutrinos way beyond reach of other techniques.

Candidate sources:

- Shock fronts in supernova remnants
- microQuasars
- Active Galactic Nuclei
- Gamma Ray Bursts
- Dark Matter
- Exotics

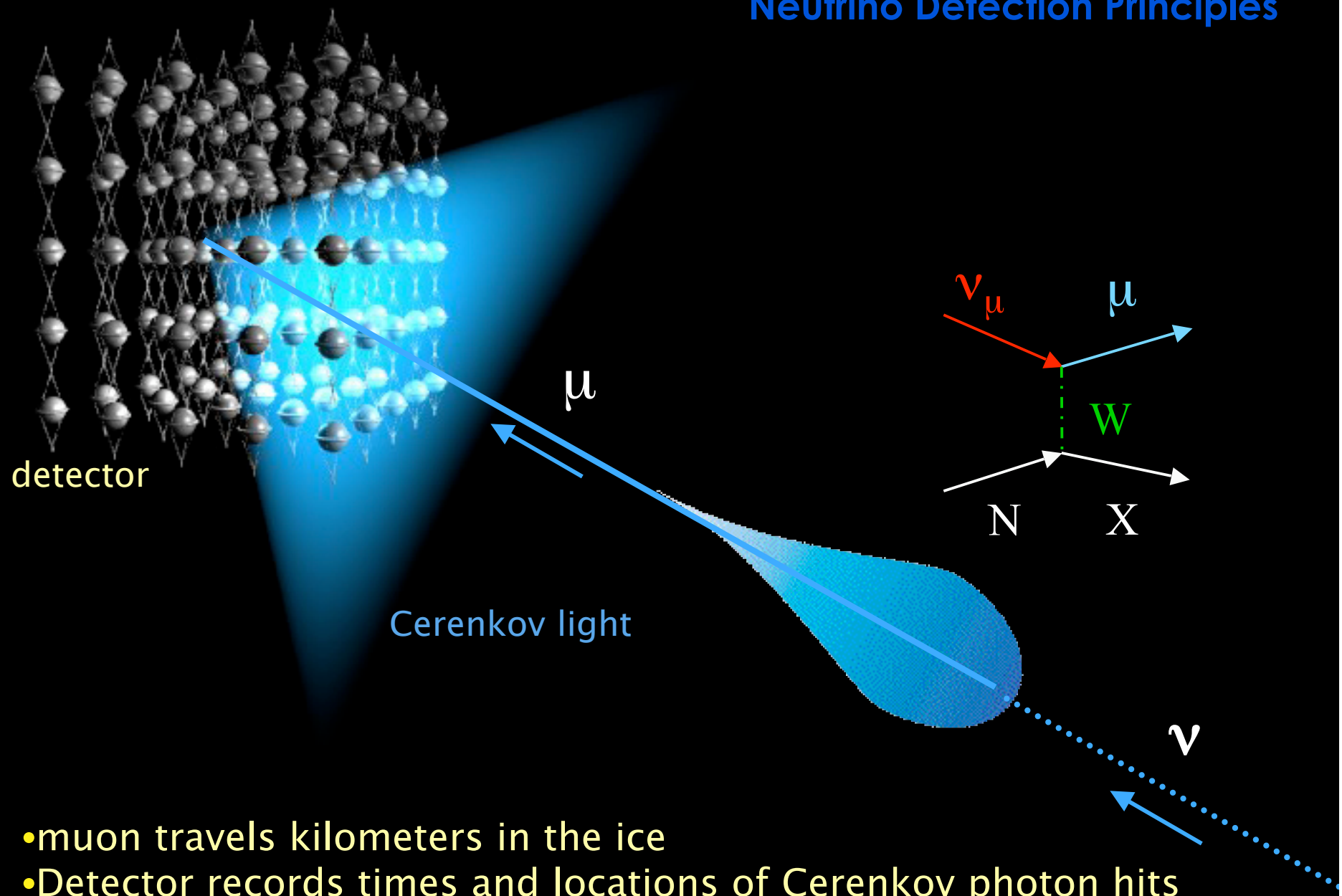
Guaranteed sources:

- Galactic plane: CR interacting with ISM, concentrated on the disk
- Starburst galaxies
- GZK

  $$p\,\gamma \rightarrow \Delta^+ \rightarrow n\,\pi^+ \; (p\,\pi^0)$$
- Atmospheric neutrinos

Neutrino Detection

Neutrino Detection Principles



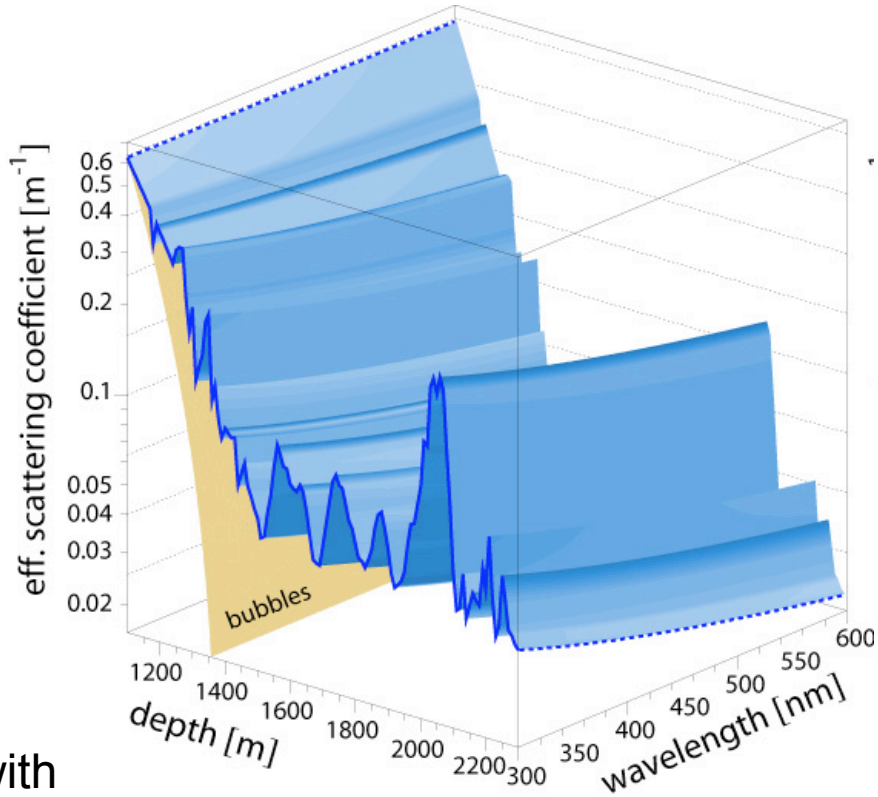
- muon travels kilometers in the ice
- Detector records times and locations of Cerenkov photon hits
- => Effective area greater than size of detector

Ice Properties

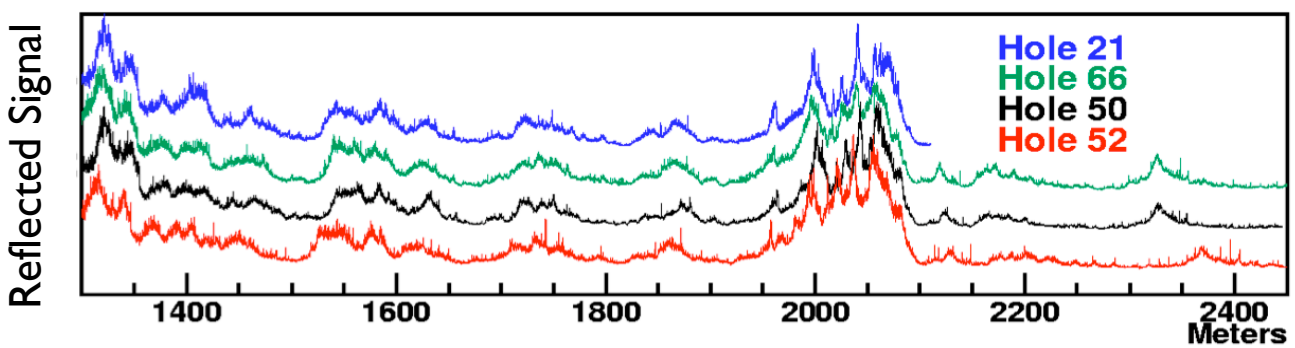
Deep glacial ice is **optically transparent**: **absorption length ~ 100 m**, much longer than water, but

scattering length ~ 20 m is much shorter than water.

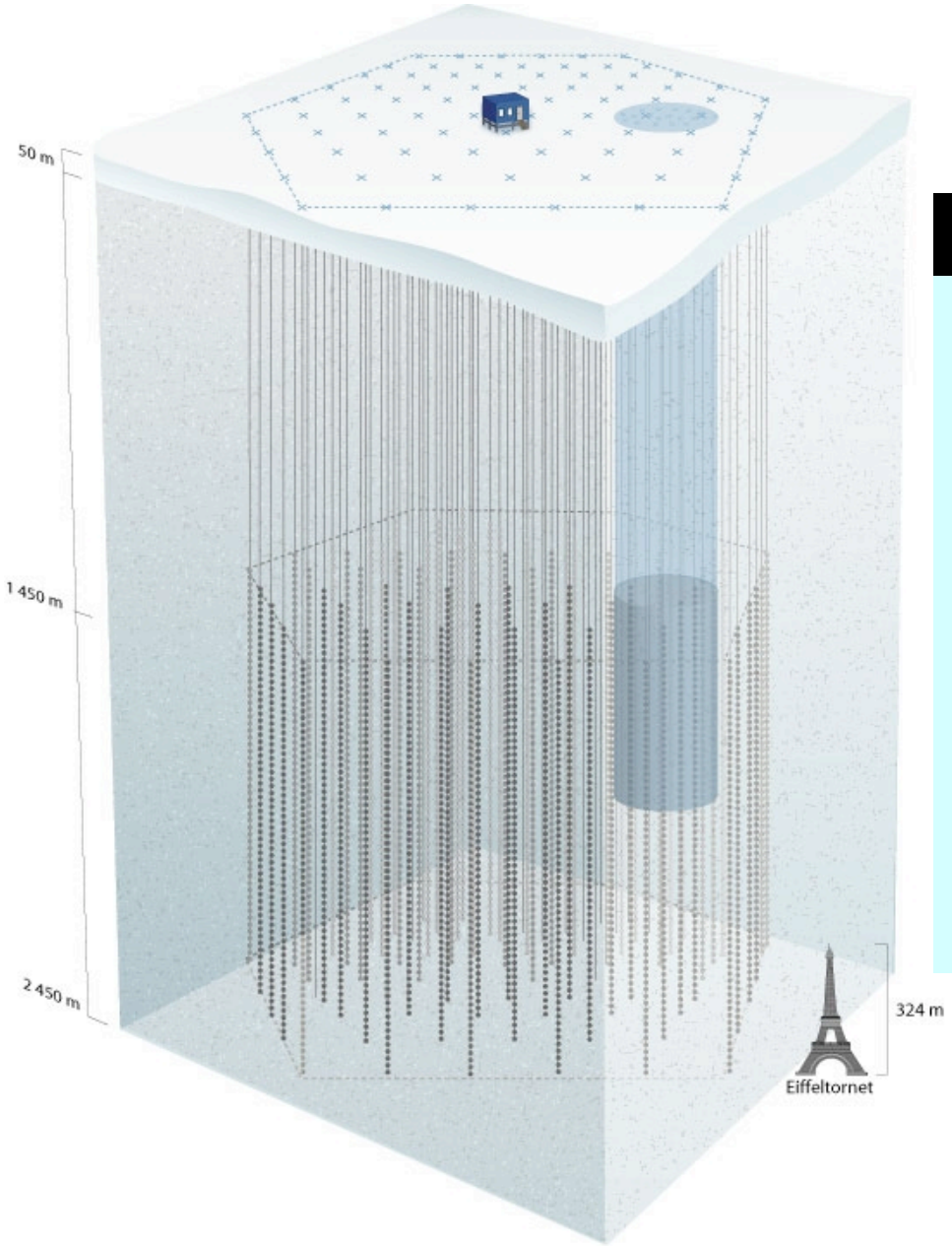
Deep ice is **quiet**: noise rates < 1 kHz (~50 kHz in seawater).



Ice Properties measured with specialized device



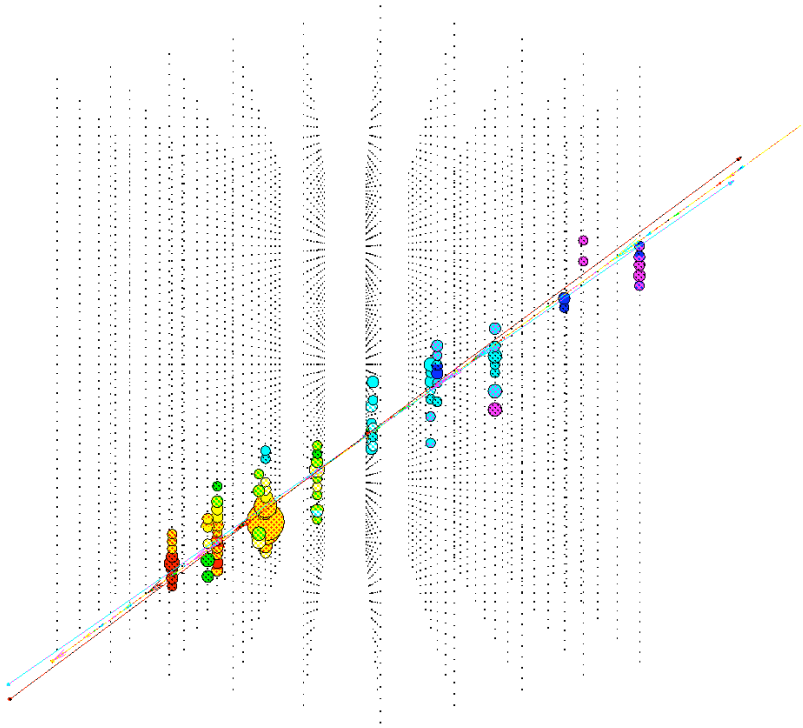
The IceCube Detector Array



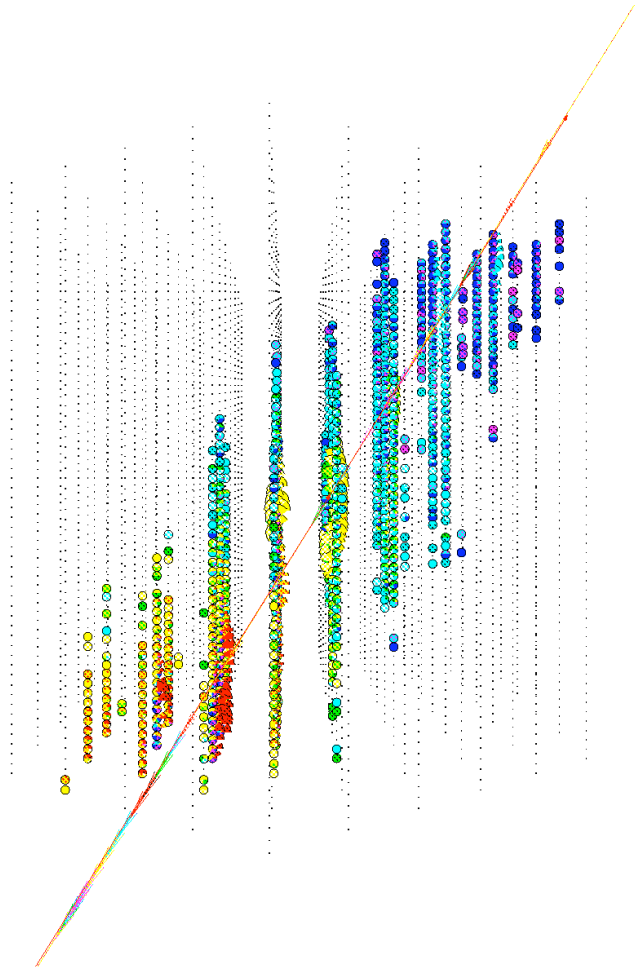
Design Overview

- 1 km^3 -- 1 Gton instrumented volume
- 80 strings
  - 1.5 km - 2.5 km deep
  - 125 m spacing between strings
- 60 Optical Modules per string
  - 17 m vertical spacing between modules

ν_μ Detection in IceCube



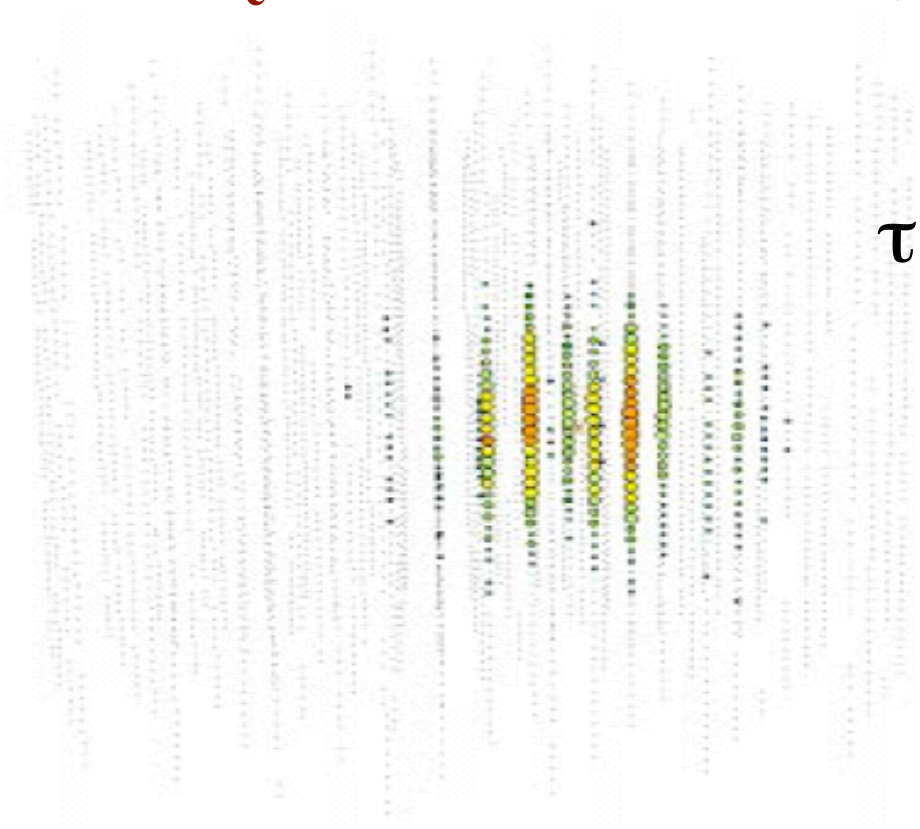
E = 6 TeV



E = 6400 TeV

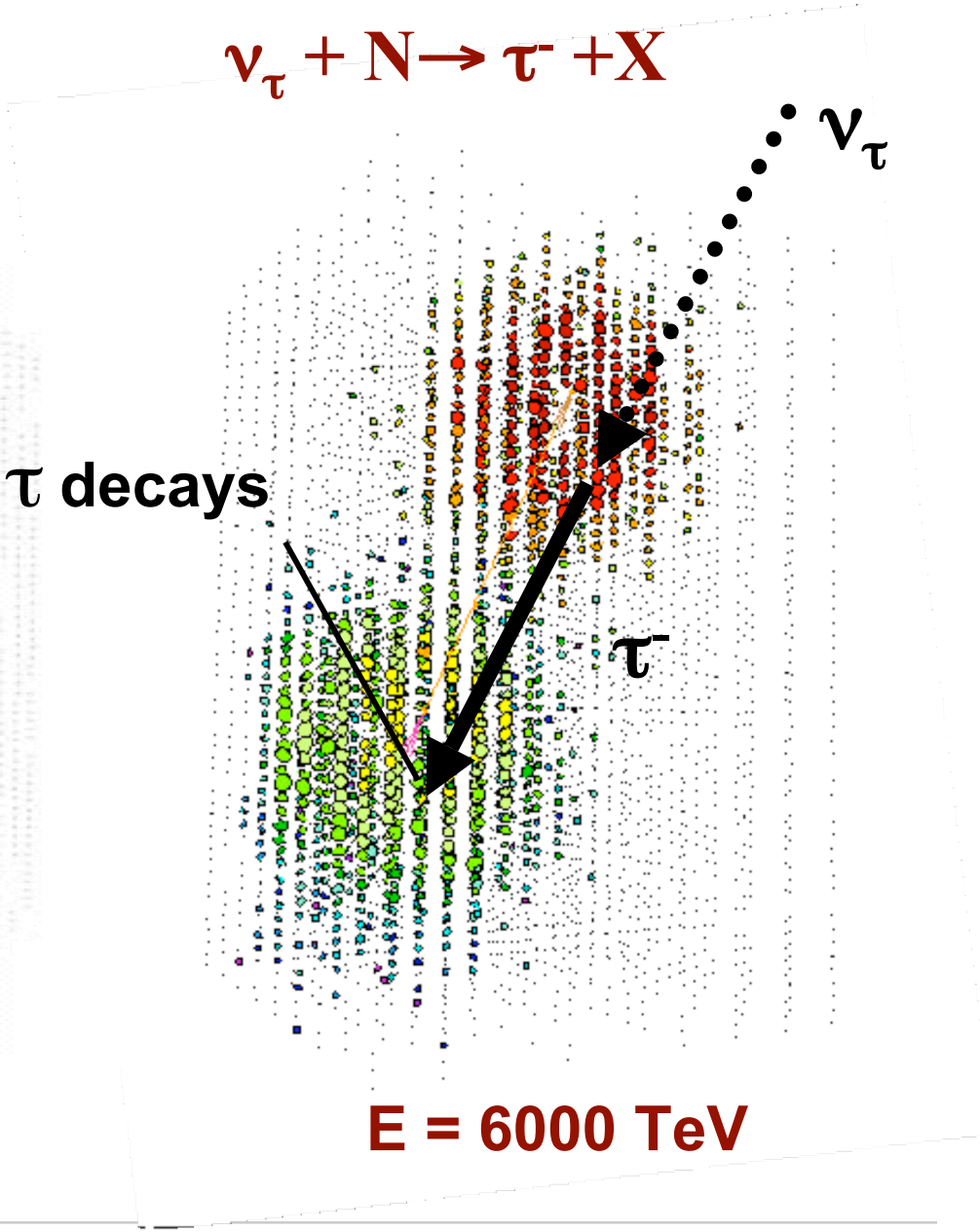
ν_e and ν_τ cascade detection in IceCube

$\nu_e + N \rightarrow e^- + X$



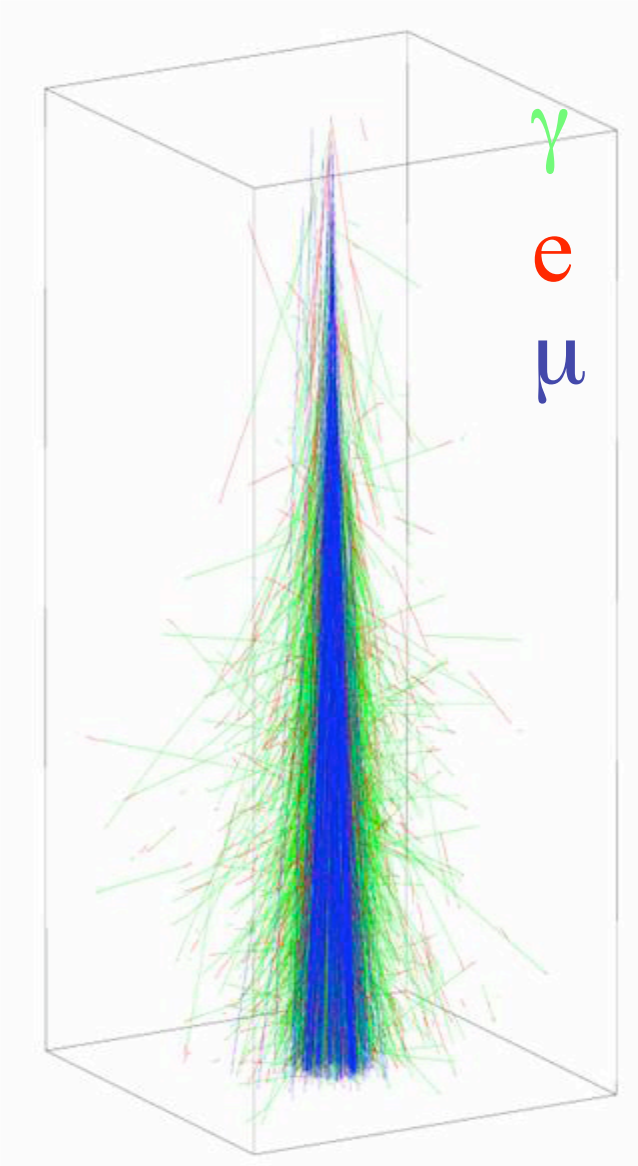
E = 375 TeV

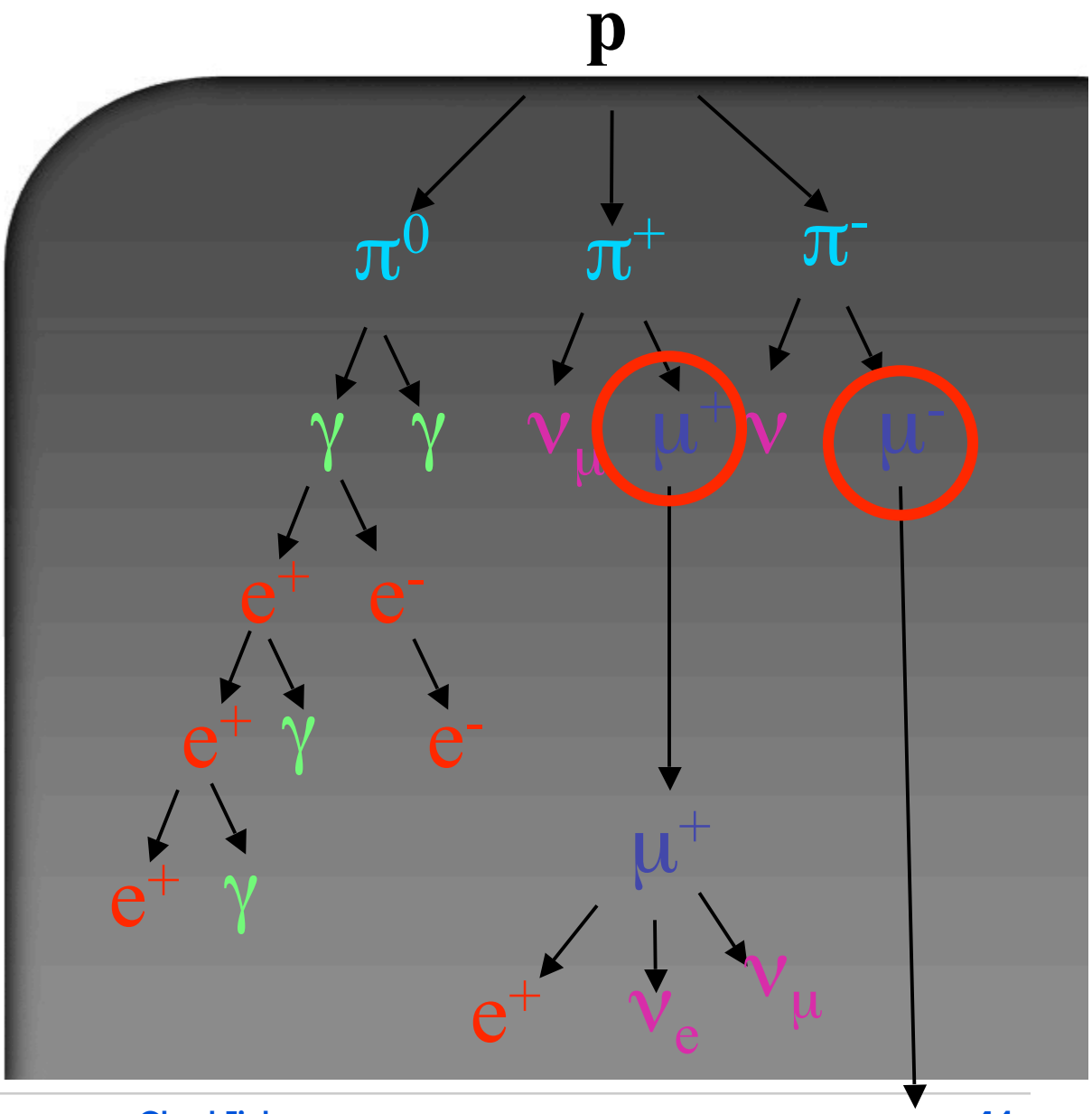
$\nu_\tau + N \rightarrow \tau^- + X$



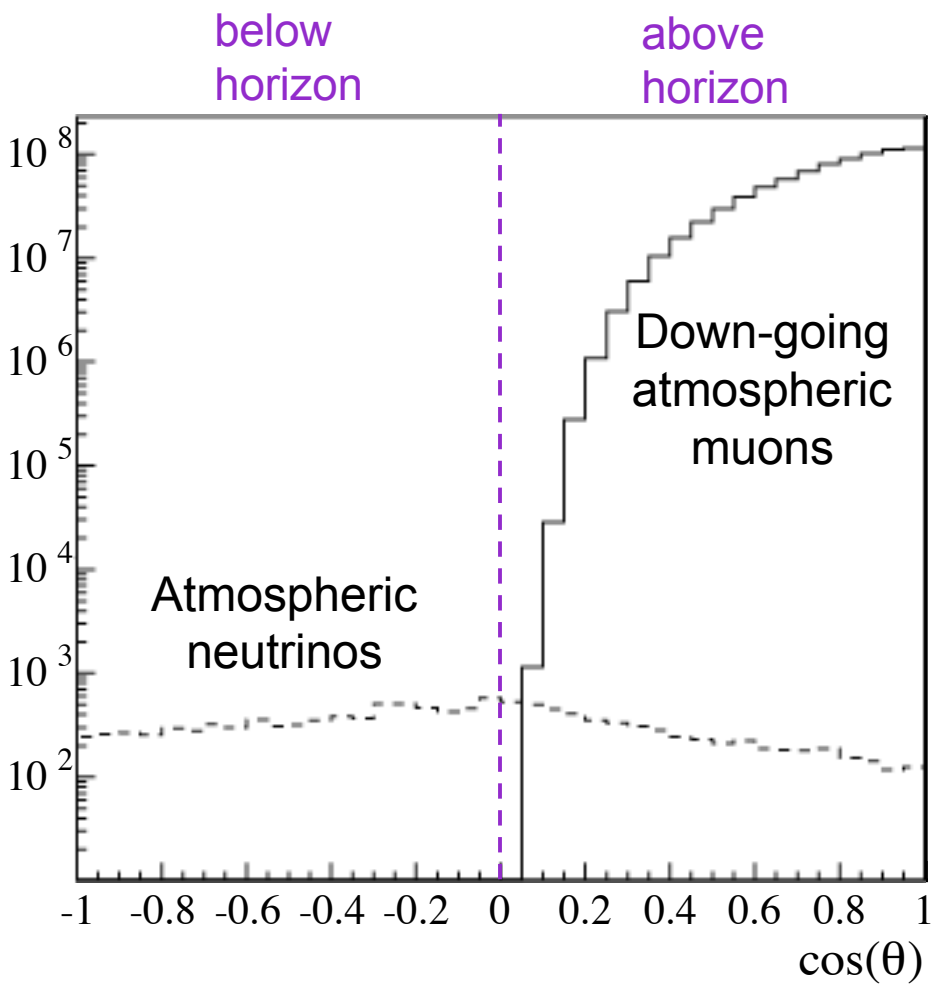
E = 6000 TeV

Background: Muons from Cosmic Ray Showers





Background



Cosmic rays (nuclei) entering Earth's atmosphere create particle showers.

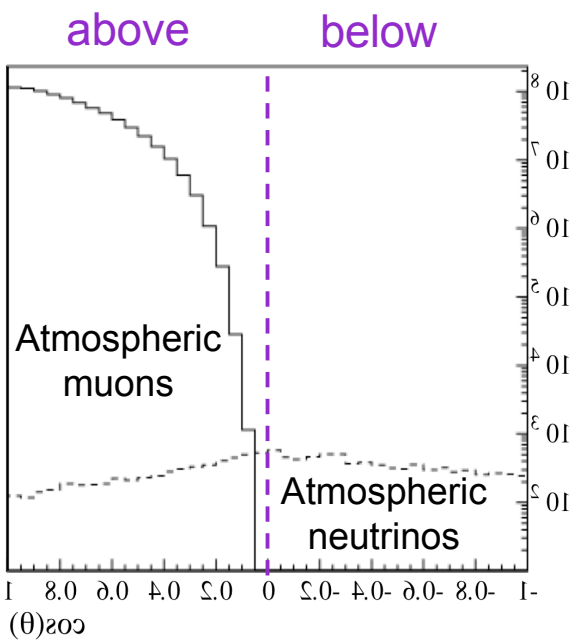
So-called **atmospheric muons and neutrinos** created by the showers are the background for astrophysical neutrino searches.

Atmospheric muons dominate downgoing trigger rate

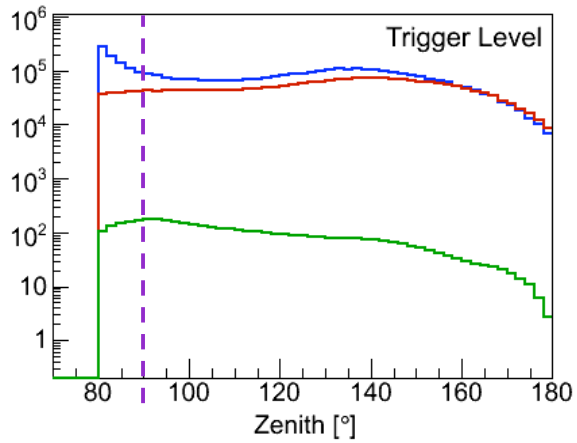
Atmospheric neutrinos (detected via induced muon) can arrive from any direction

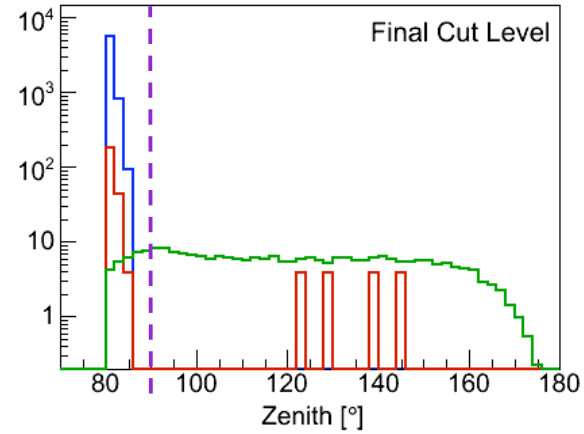
Background

True Zenith Angle

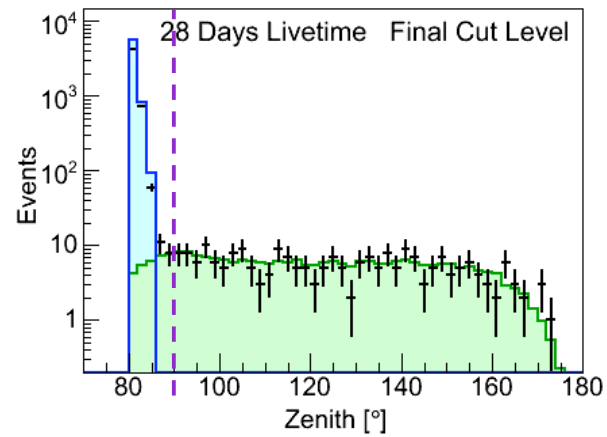


Reconstructed Zenith Angle





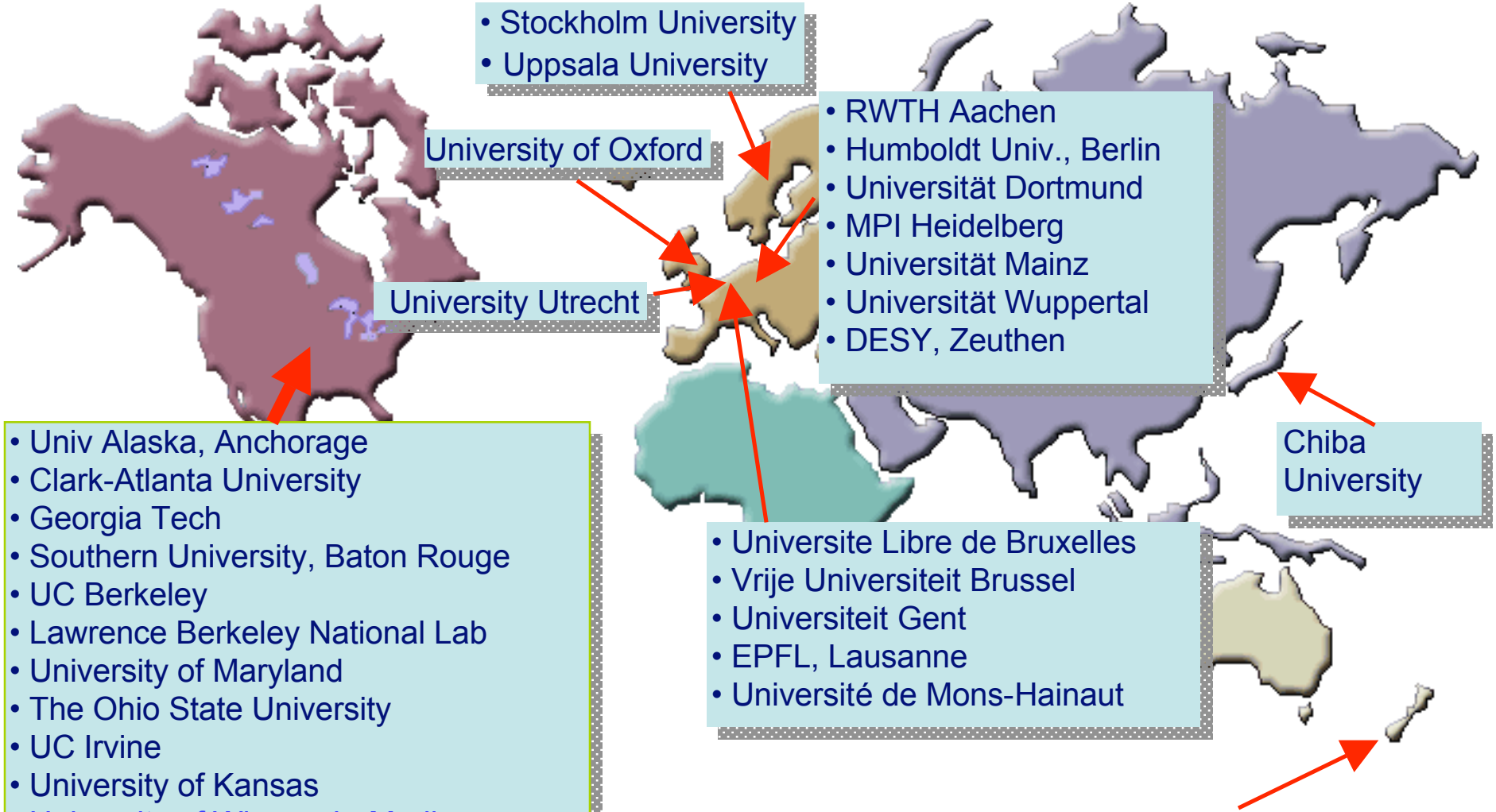
- Downgoing muons
- Coincident muons
- Atmospheric nu's
- Data (22-string IceCube)



High quality cuts remove mis-reconstructed events. In up-going direction, only atmospheric neutrinos remain.

Atmos. neutrinos are "irreducible" background to astrophysical neutrino searches. But they are good calibration**: verify event reconstruction and neutrino detection**.

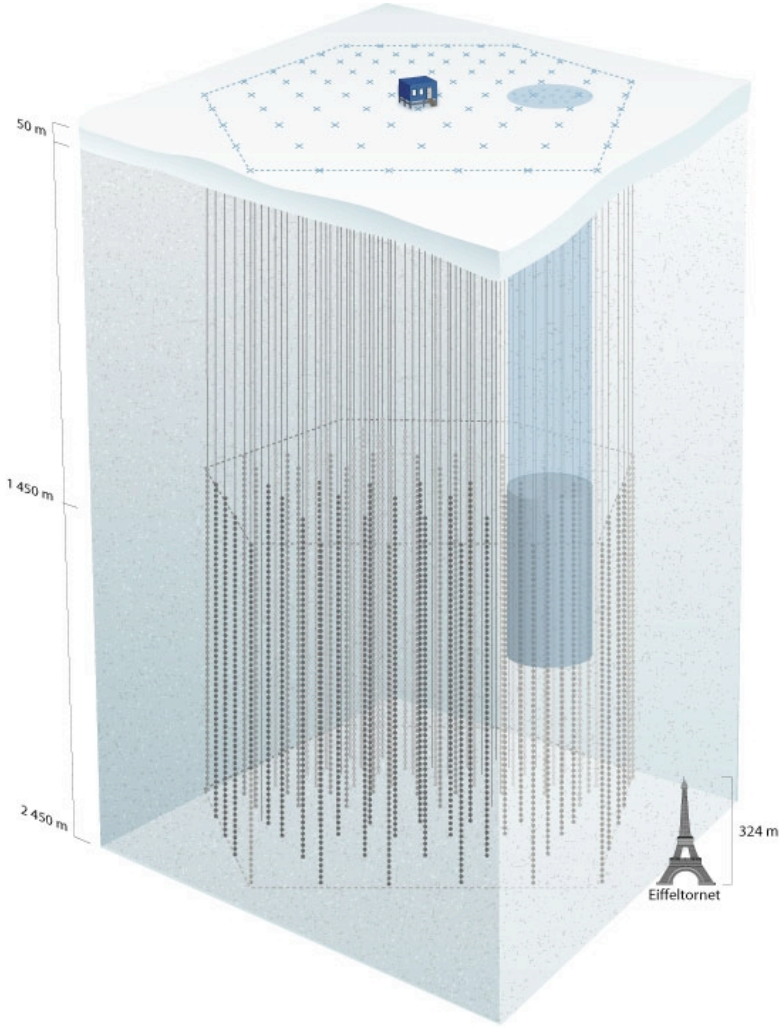
IceCube Design



The IceCube Collaboration

33 Institutions, ~250 members

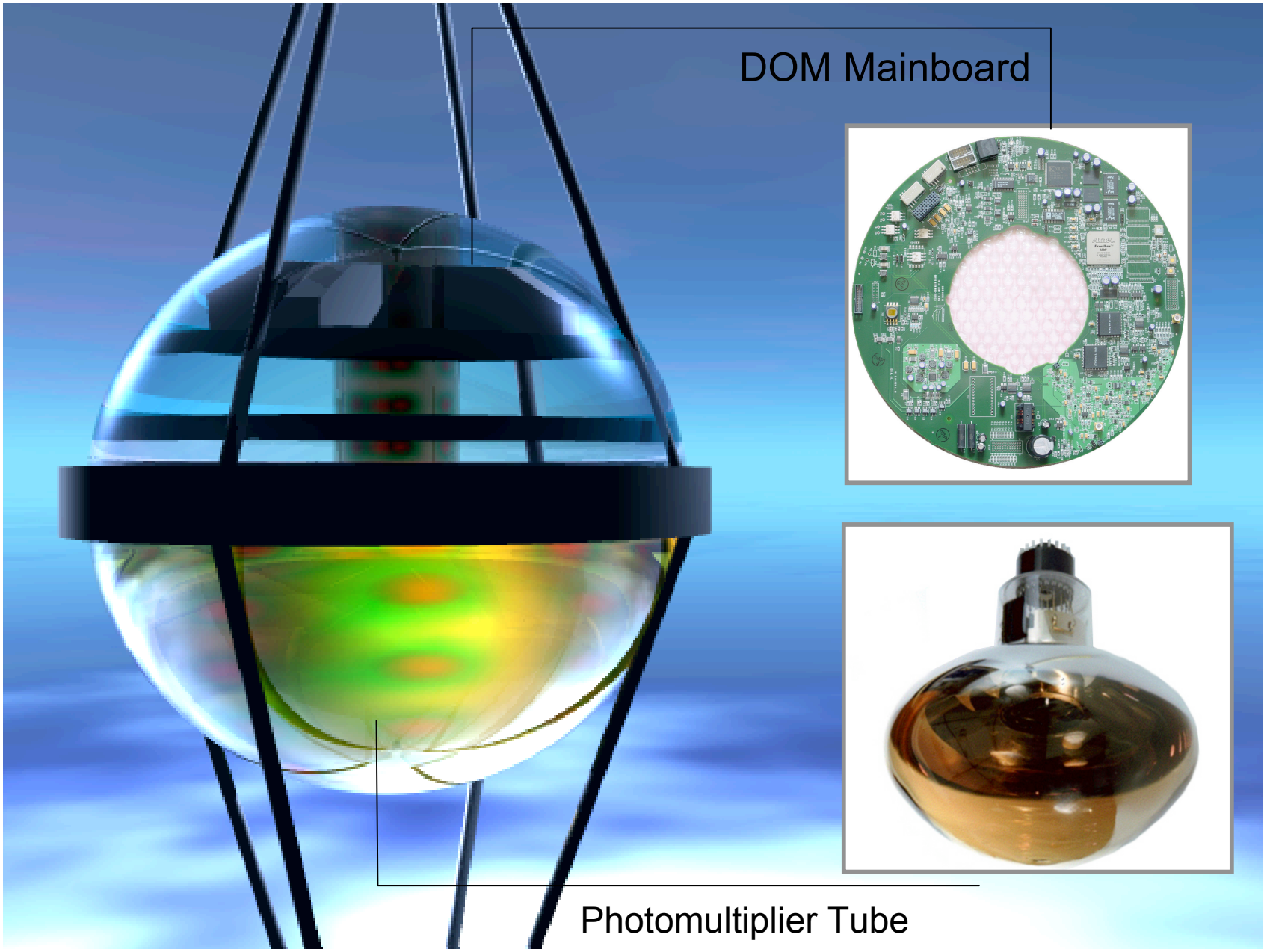
The IceCube Detector Array



Design Specifications

- 1 km^3 -- 1 Gton instrumented volume
- 80 strings with 60 Digital Optical Modules (DOMs) on each string
  - between 1500 - 2500 m deep
  - 17 m vertical spacing between DOMs
  - 125 m lateral spacing between strings
- IceTop air shower array:
- 80 pairs of surface frozen water tanks (2m diameter)
- Each tank contains two DOMs
- AMANDA will be decommissioned in 2009. A new Deep Core detector sub-array will be deployed for low E physics (~ 100 GeV)

Digital Optical Module: PMT + Electronics + Housing



Digital Optical Module

Resistant to ~700 bars and transparent to blue light

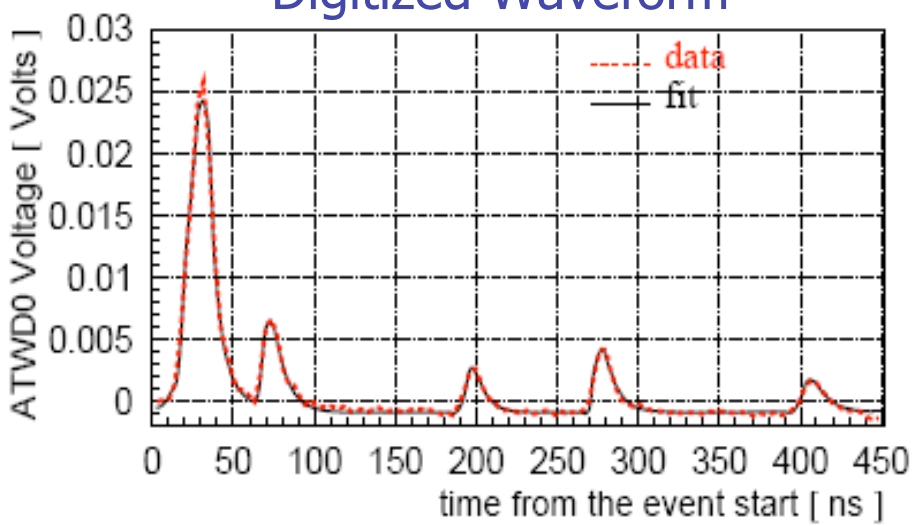
10 inch Hamamatsu R-7081

Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS time every ≈10 sec
at a precision of rms = 2 nsec

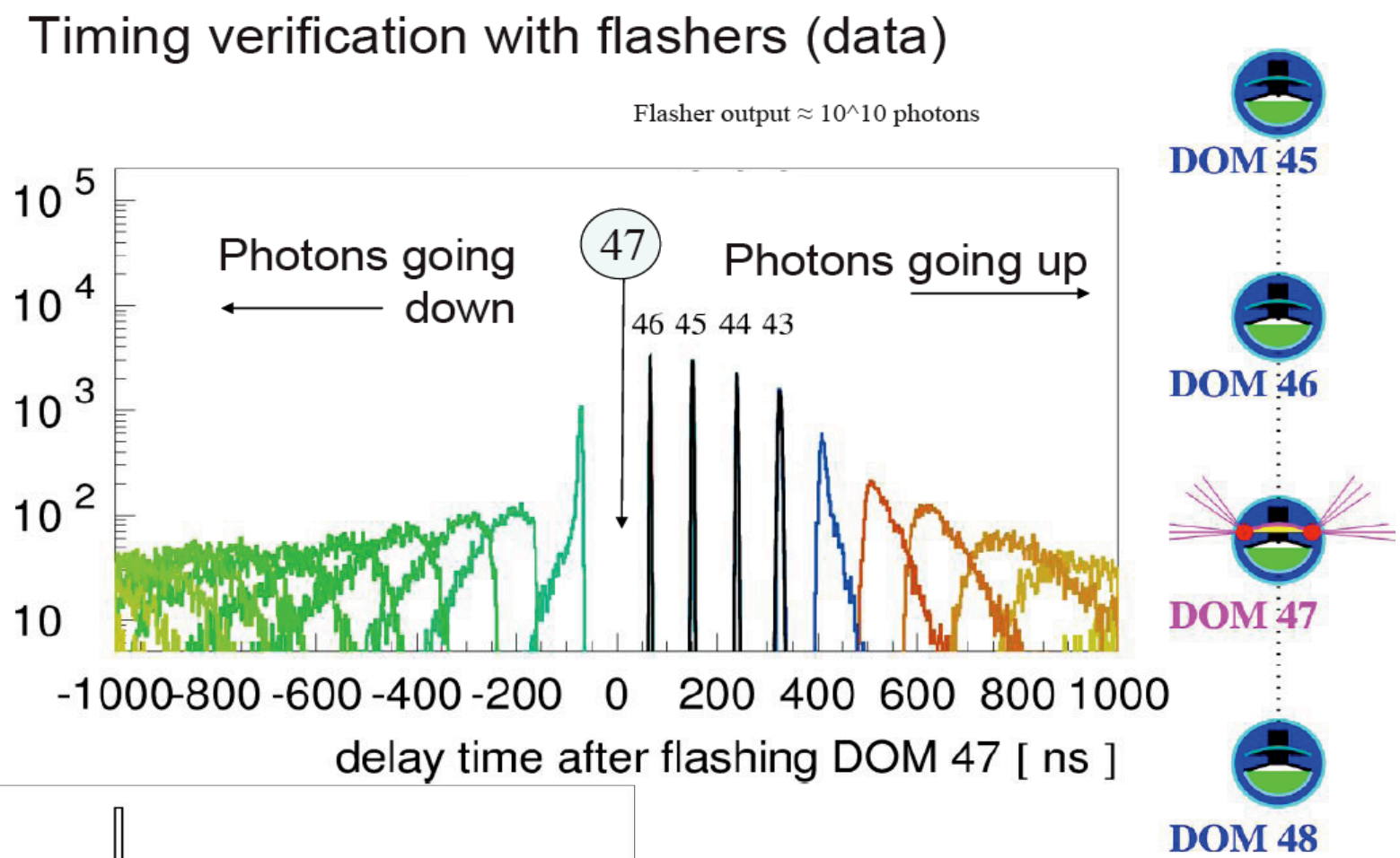
Each DOM is an autonomous data collection unit

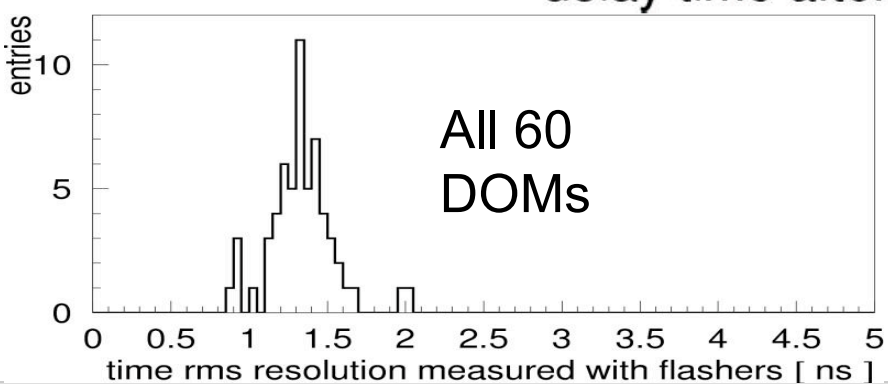
Measure arrival time of every photon
Digitize at
300 MHz, 400 ns (Fast ADC)
400 MHz, 6.4 μs
Power consumption 3.5 W

Digitized Waveform

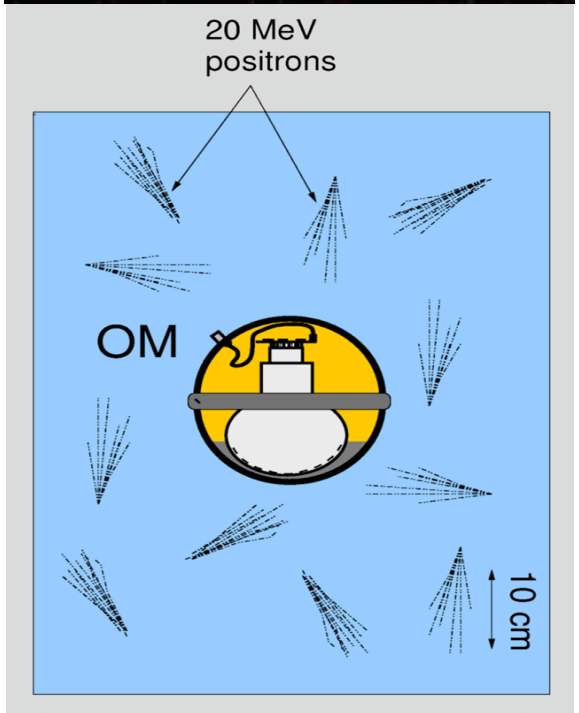


Timing verification: LED flashers





Supernova MeV Neutrino Detection in IceCube



Bursts of low-energy (MeV) neutrinos from core collapse supernovae

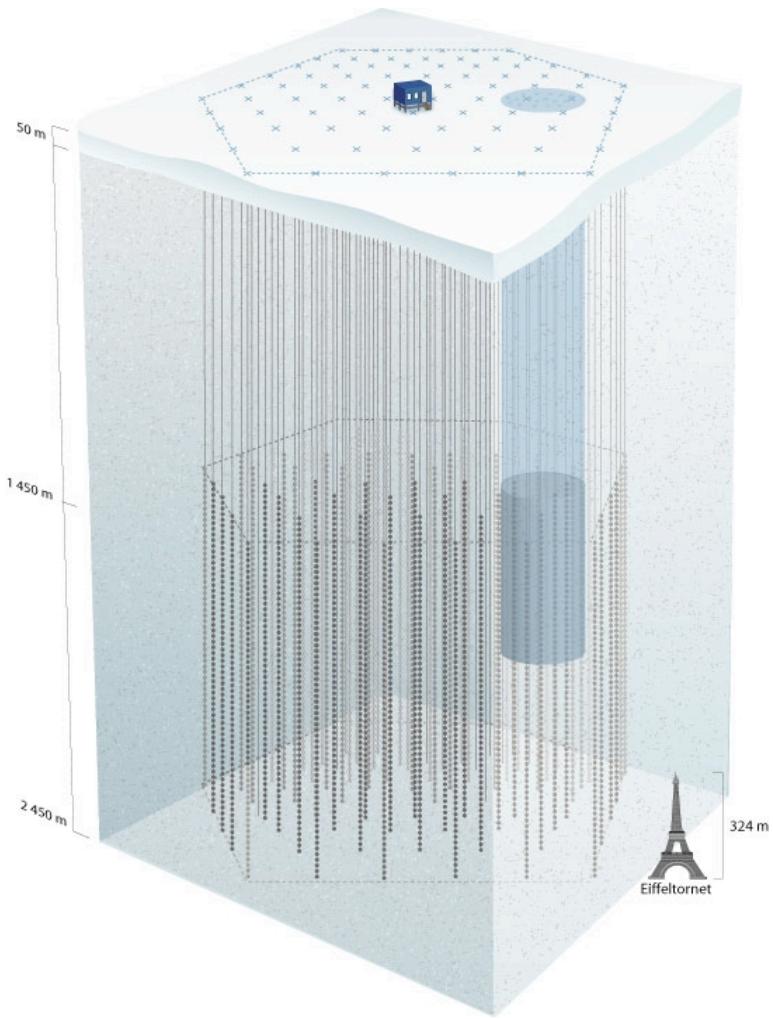
Neutrinos interact in the ice:

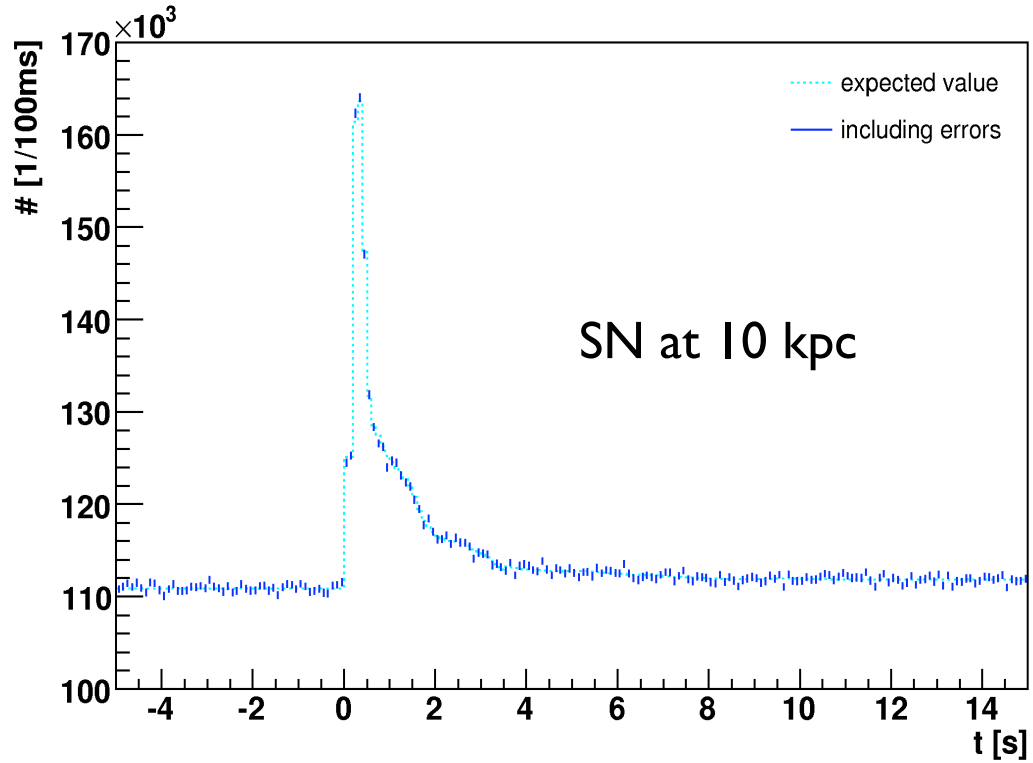
$$\bar{\nu}_e + p \rightarrow n + e^+$$

The produced positron is emitted almost isotropically

Short paths of MeV positrons do not create detectable "tracks." But they increase the **noise rate**.

IceCube as MeV SN ν detector

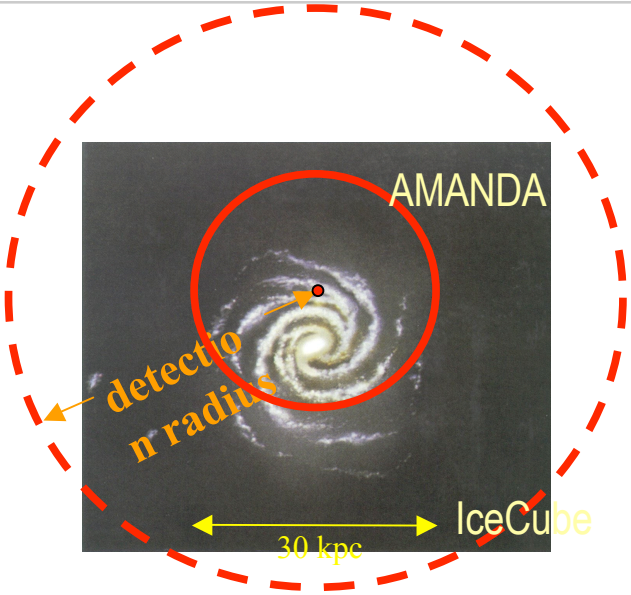




Detection via increase of the dark noise rate globally throughout detector

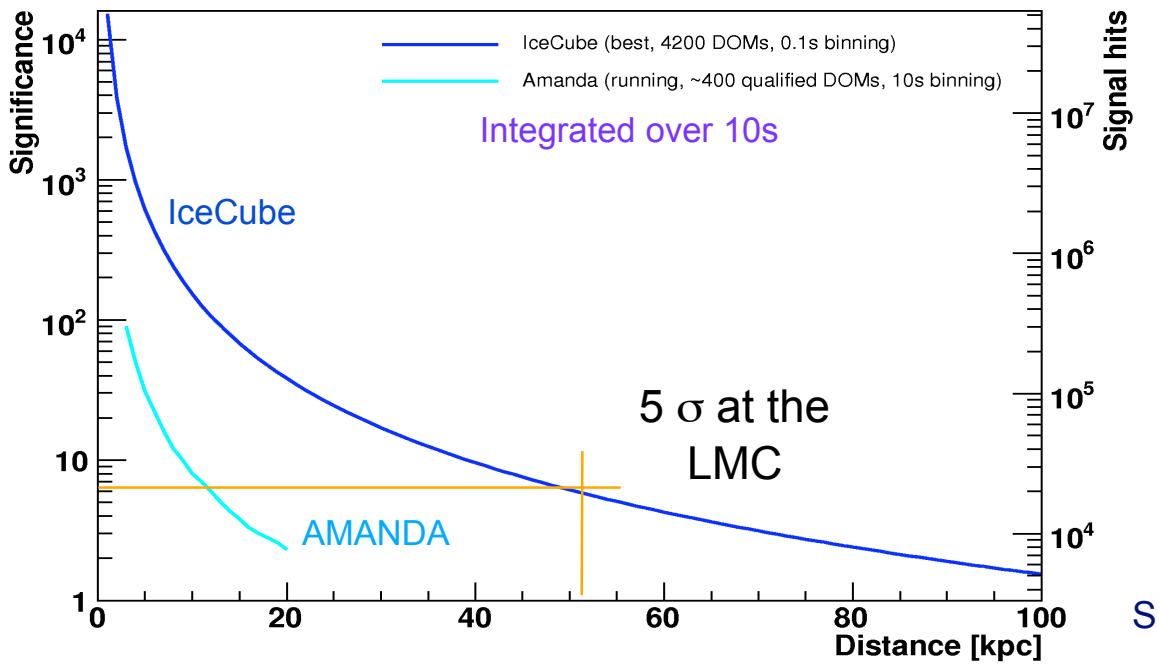
No directionality, but excellent time resolution and high significance signal

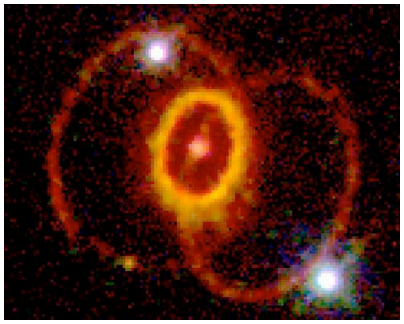
Supernova Neutrino Search



Participate in SNEWS (SuperNova Early Warning System): a collaborative effort among Super-K, SNO, LVD, KamLAND, IceCube, BooNE and gravitational wave experiments

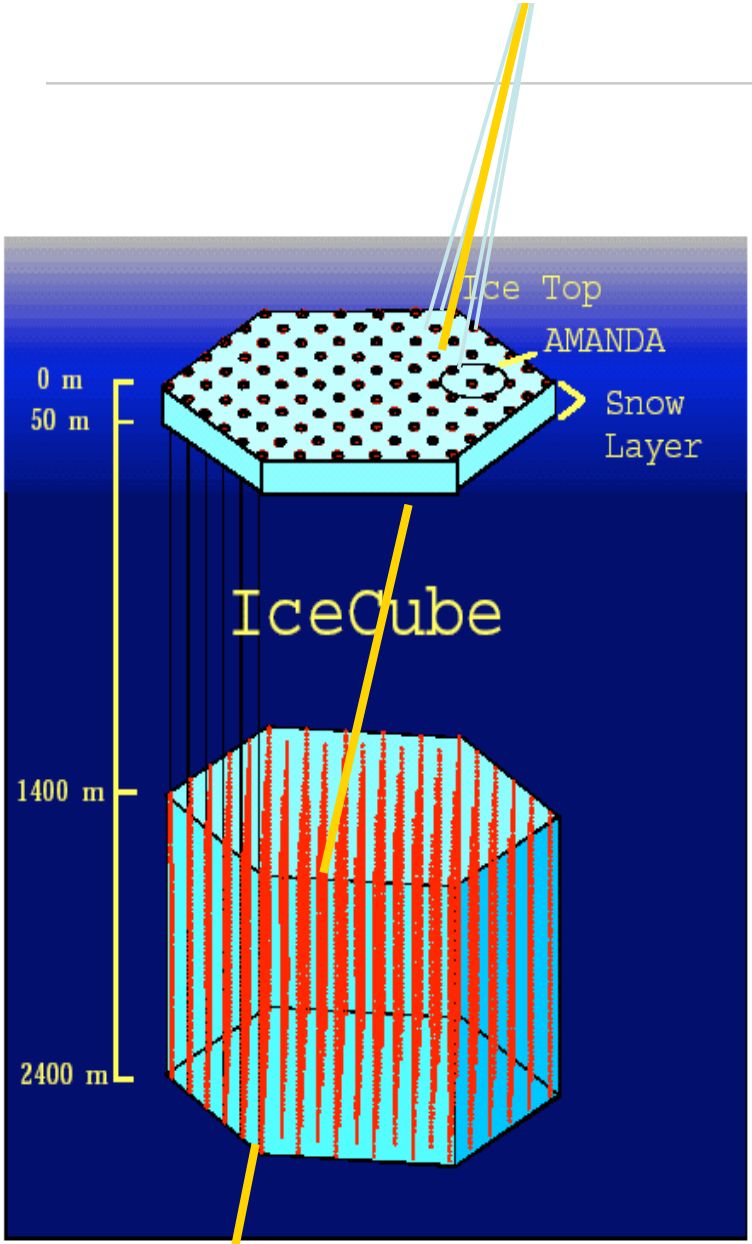
- **AMANDA saw 90% of the galaxy**
- **IceCube will see out to the LMC (~50 kpc)**





SN 1987A in Large Magellanic Cloud

IceCube with IceTop surface array



Area--solid-angle ~ 1/3 km^{2}sr
(*including angular dependence of EAS trigger*)

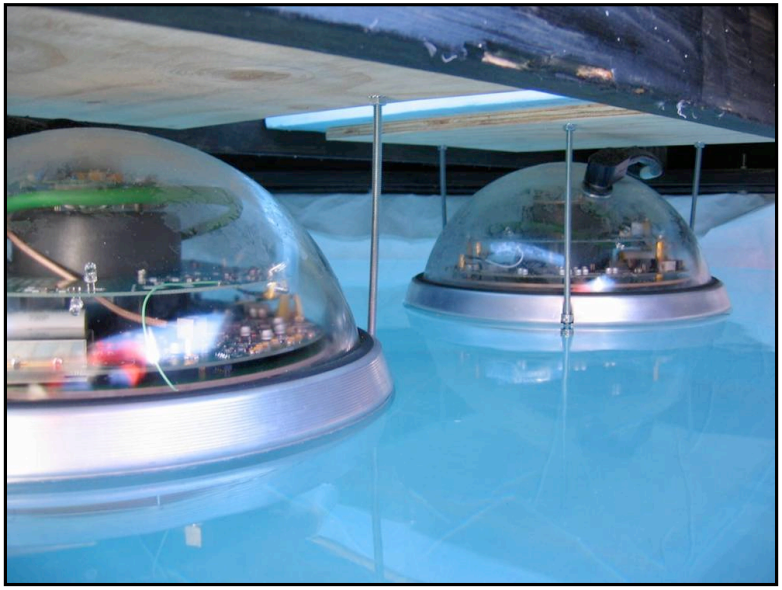
IceTop:

- Pair of tanks (2m diameter) above each string
- Two DOMs in each tank

Valuable for:

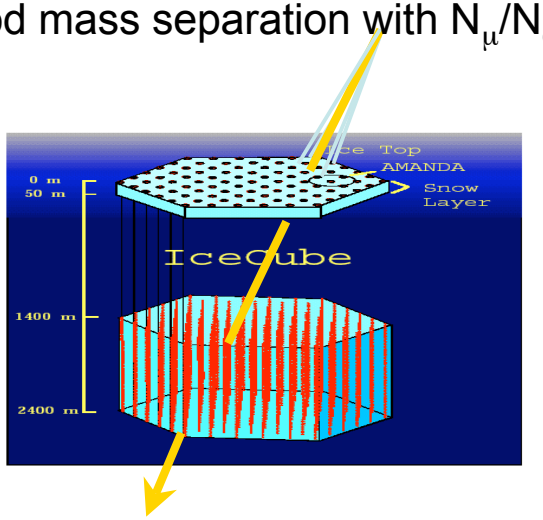
- Calibration
- Veto of HE shower background
- Cosmic Ray/air shower physics up to 10^{18} eV

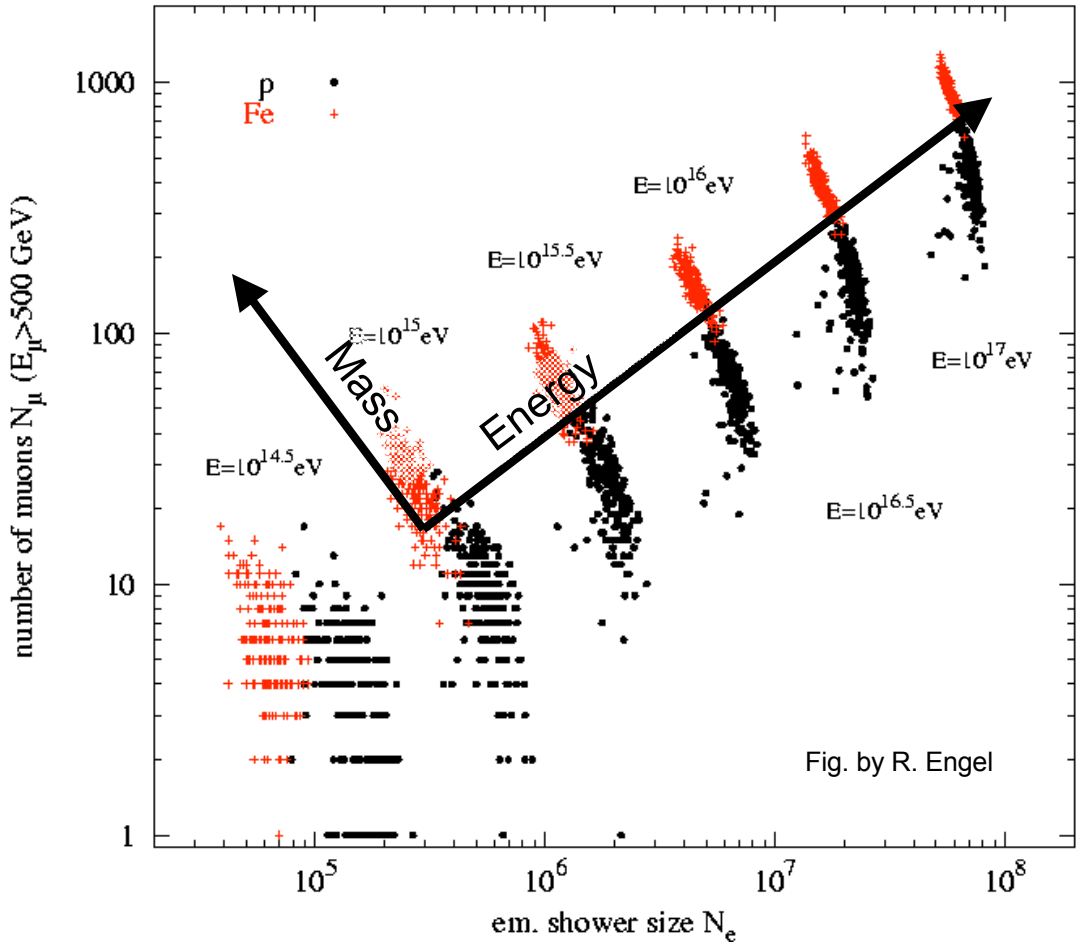
DOMs in ice (not water)



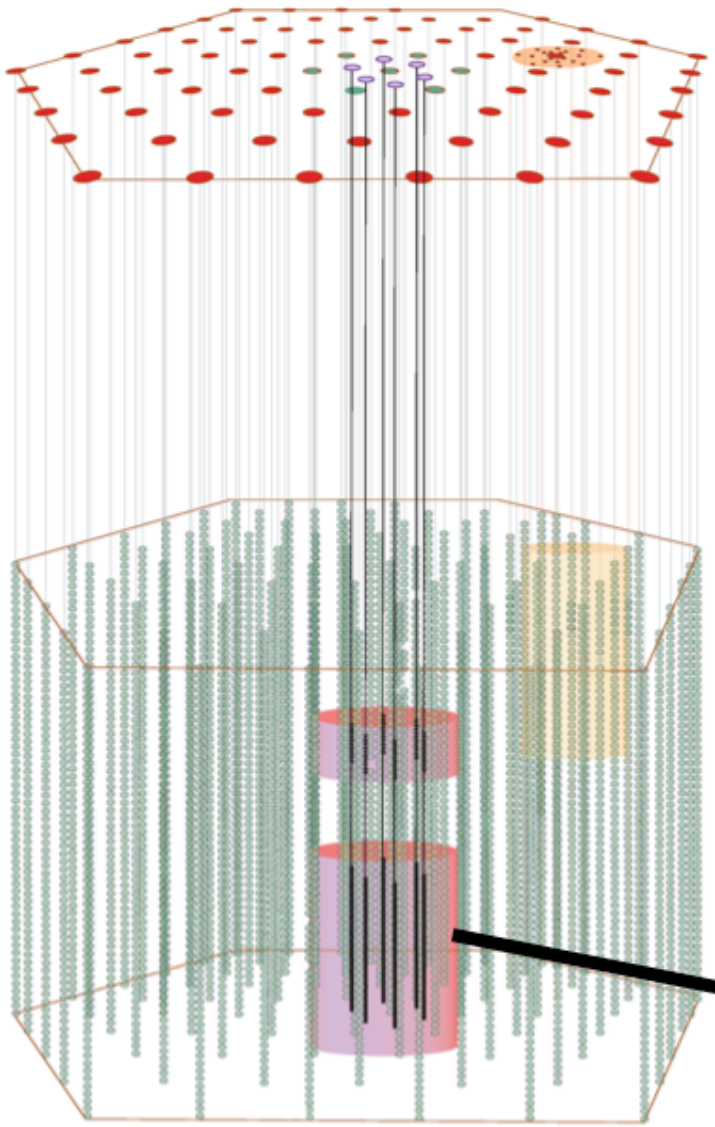
Cosmic Ray Physics : IceCube Deep Ice + IceTop Surface Arrays

- 1/3 km^2 sr (2000 x SPASE-AMANDA)
- sub-PeV to EeV energies
- Cosmic Ray Composition Studies
- Measure:
  - N_μ from deep IceCube
  - N_e from IceTop
- High altitude allows good energy resolution
- Good mass separation with N_μ/N_e

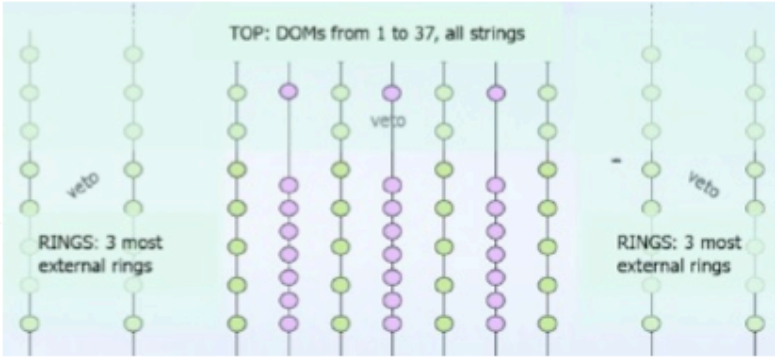




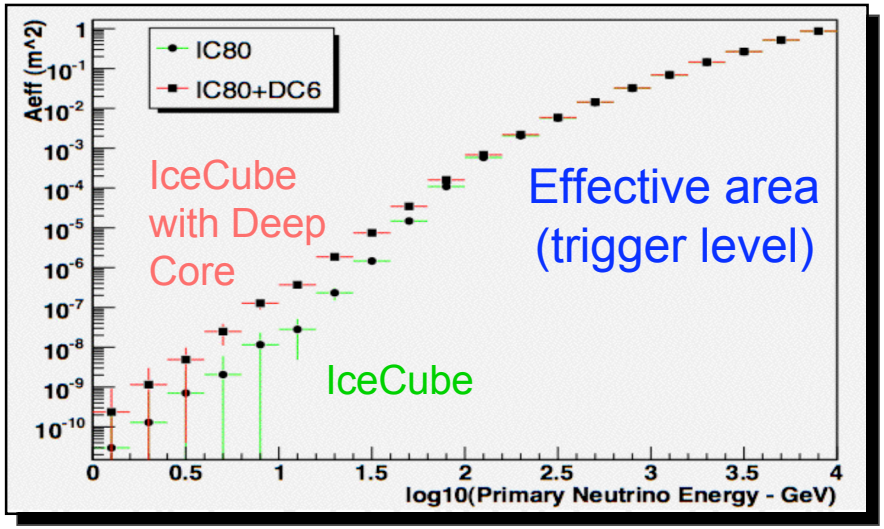
Low Energy Extension: Deep Core



- 6 additional strings with densely spaced DOMs (7m vertical, 72m string-to-string)
- Placed in the deepest ice in the center of IceCube
- IceCube is active veto for DeepCore
- DeepCore strings to be deployed in 2009 and 2010



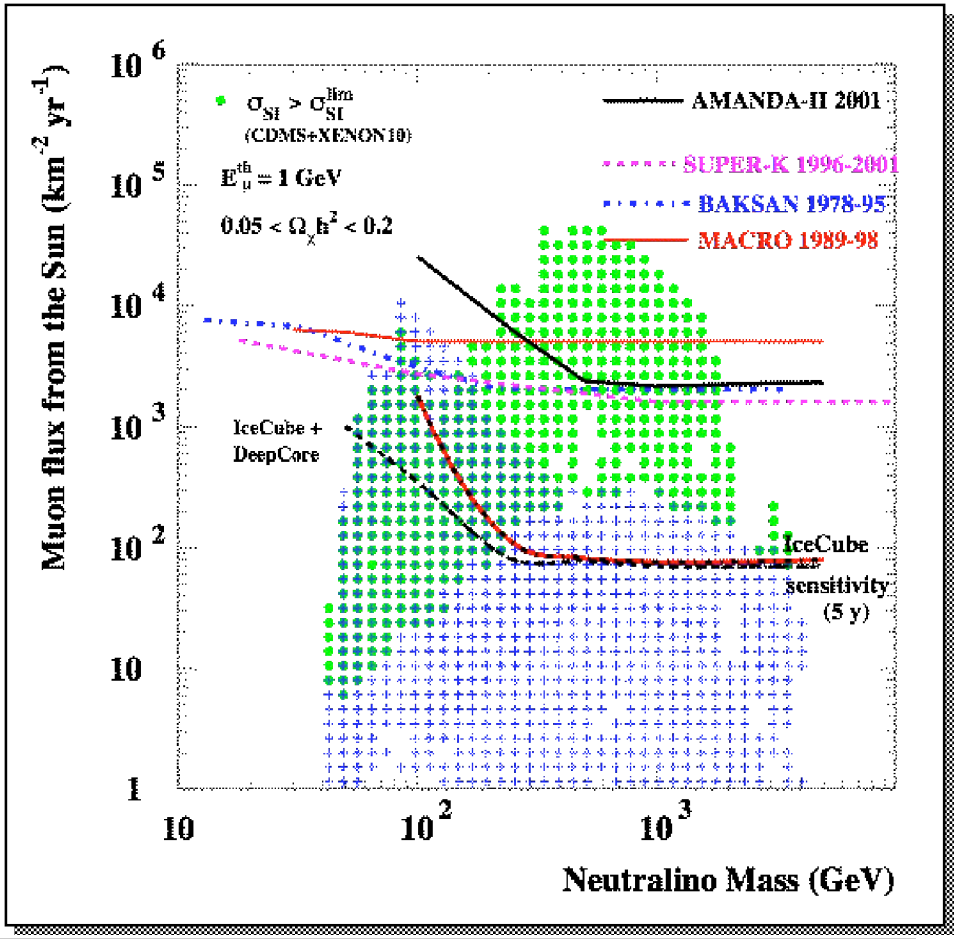
Low Energy Extension: Deep Core



Replacement for AMANDA strings

DOMs built using high QE PMTS

Extends IceCube sensitivity to neutrino energies below ~100 GeV



IceCube Construction and Status

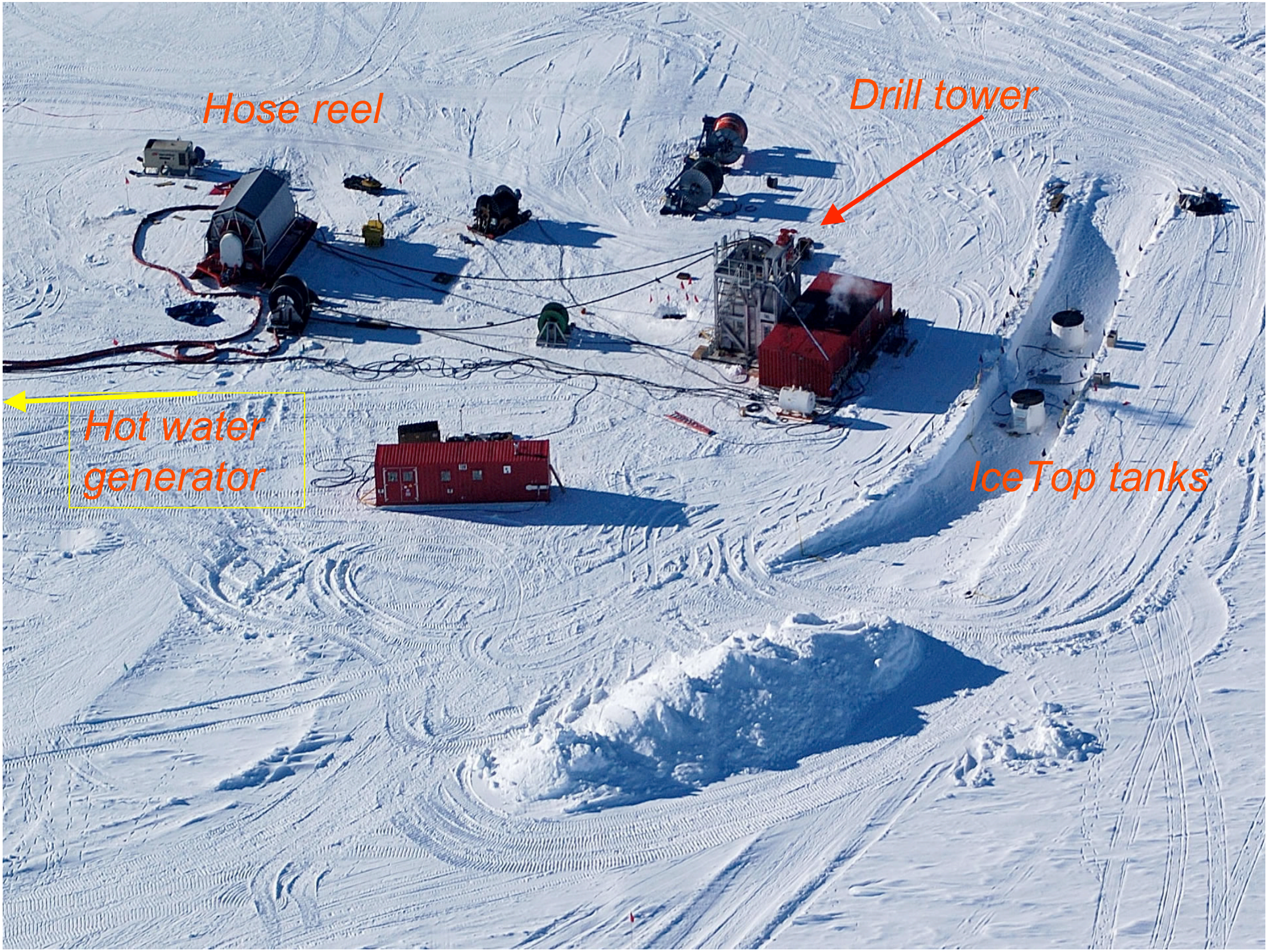
Amundsen-Scott South Pole Station

Schedule & Logistics

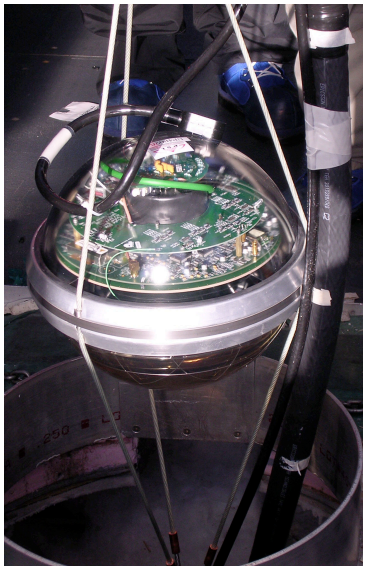
- Can work during summer: November to mid-February
- Logistics
  - Icebreakers, planes on skies,…
  - Only planes from McMurdo to Pole. Possible land traverse in the future

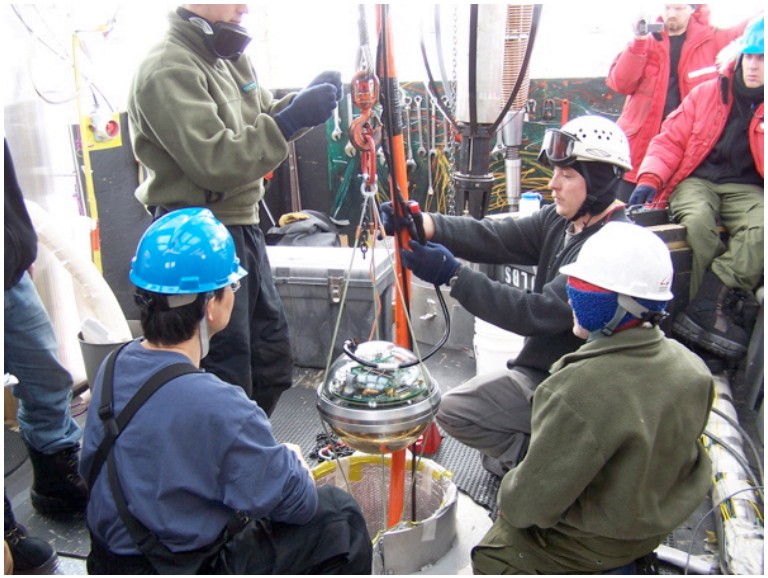
•1 million pounds of cargo

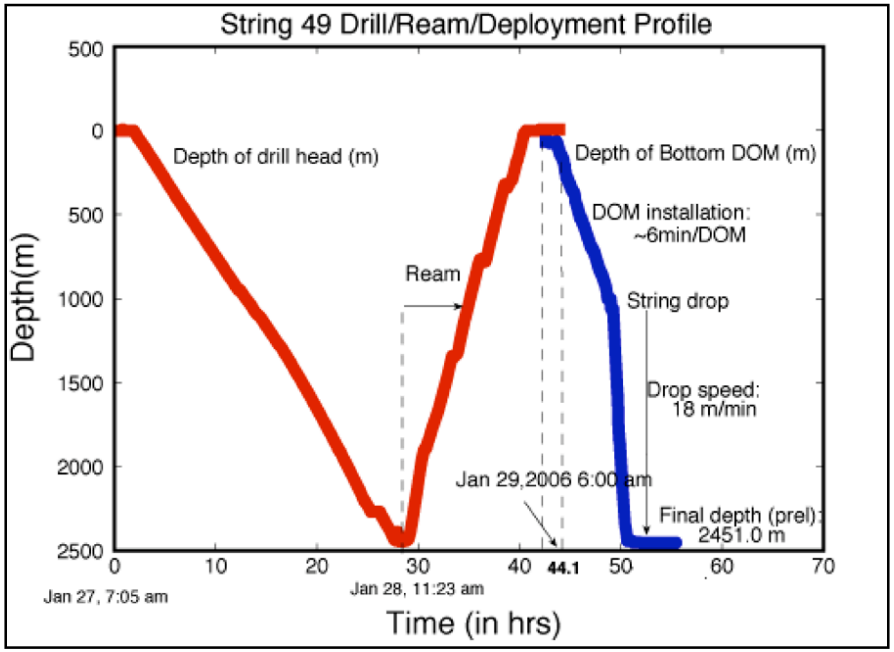
•C-130 planes: > 50 flights


Hose reel
Drill tower
Hot water generator
IceTop tanks

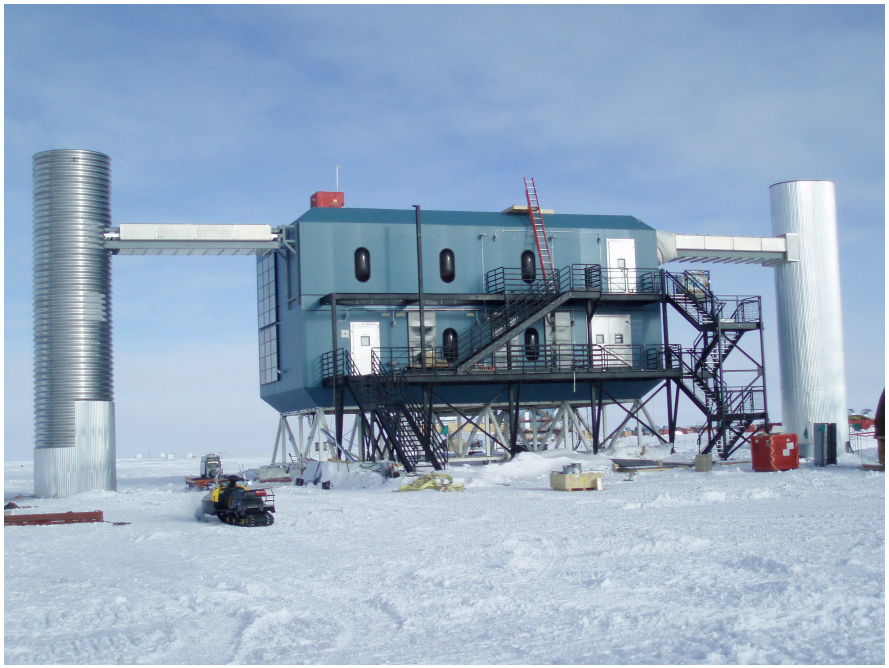
Drilling and Deployment





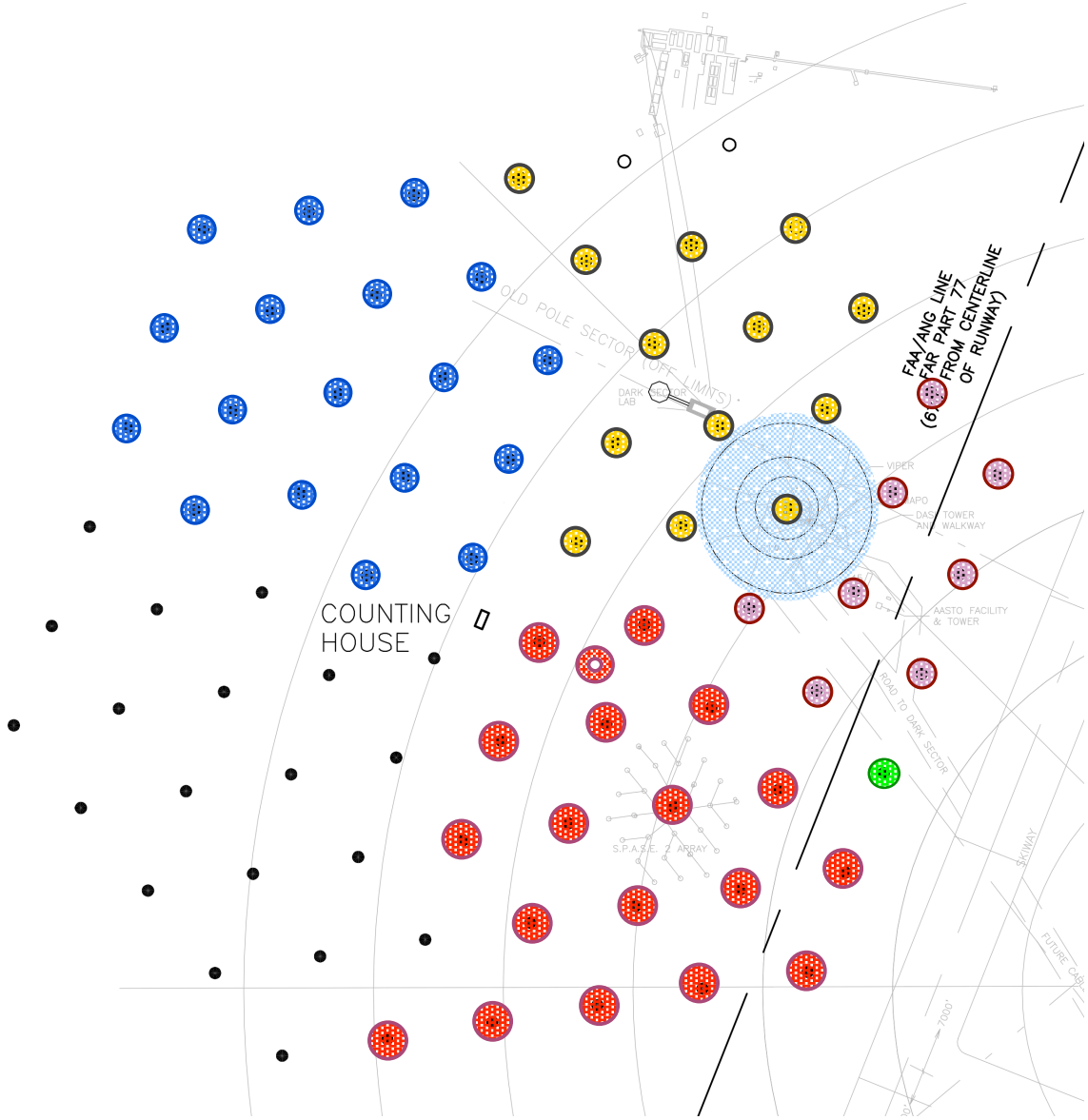


IceCube Laboratory



- ICL is central data center for IceCube at South Pole
  - Opened in January 2007
  - 17 racks of computers
- All cables and servers for IceCube DOMs, DAQ and online filtering
- All Level 1 filtering done at South Pole in real time and data sent north via satellite

IceCube Today: 58 Strings + 1 Deep Core String



AMANDA

2004 – 2005

2005 – 2006

2006 – 2007

2007 – 2008

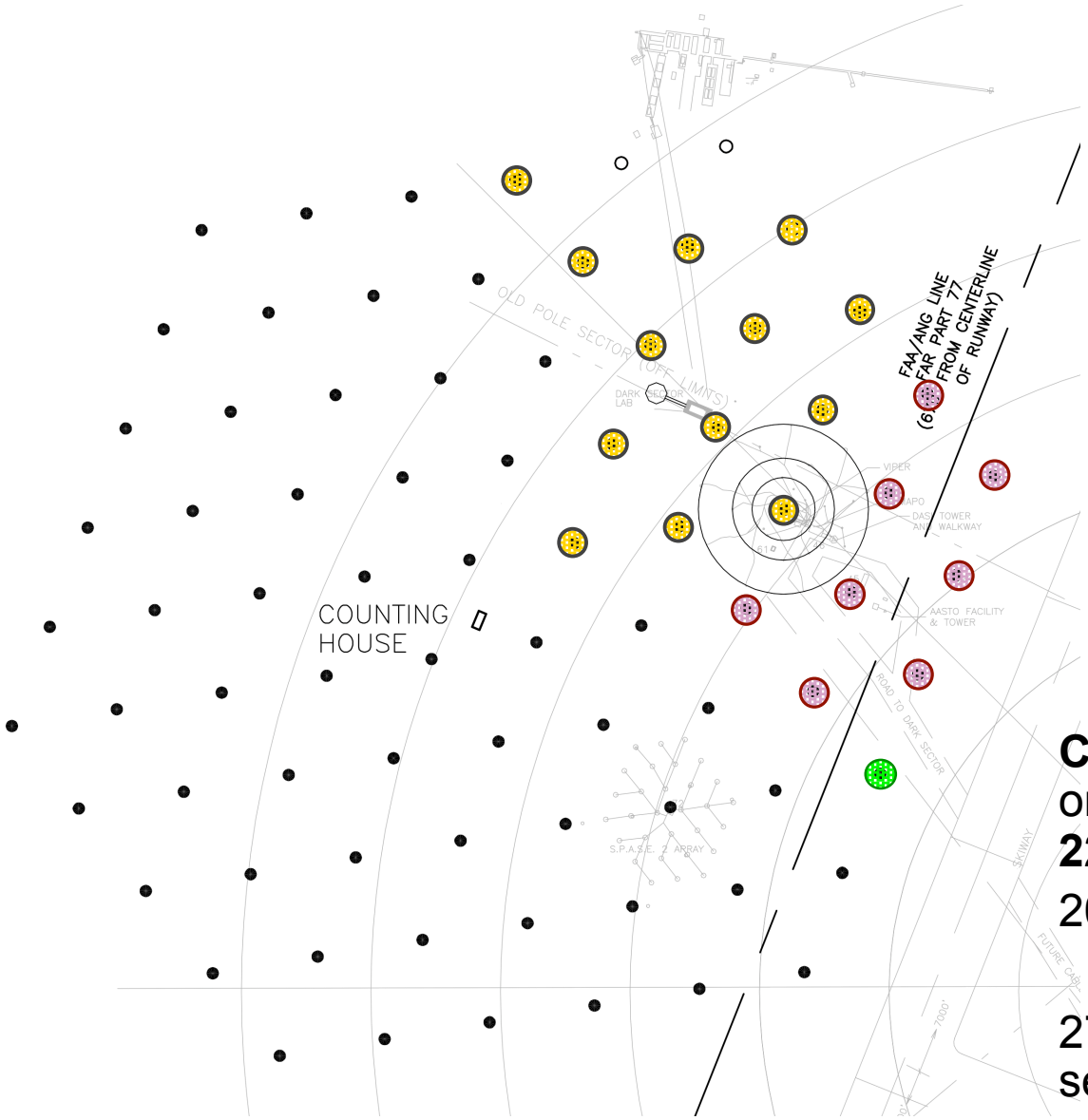
2008 – 2009

40 Strings previously +

18 + 1 (Deep Core) New Strings deployed this season

IceCube Results

22-String Configuration (2007 - April 2008)



Deployment Seasons

- 2004 – 2005
- 2005 – 2006
- 2006 – 2007

Current Analyses based on science data taken with **22-strings** during 2007 May 31 - 2008 Apr 5

275.70 days livetime after selecting good runs.

IC22 Point Source Data Set

2007 May 31 - 2008 Apr 5
275.70 days livetime after selecting good runs.

Simple set of cuts applied to data, to select good upgoing events and reject downgoing and coincident background, including:

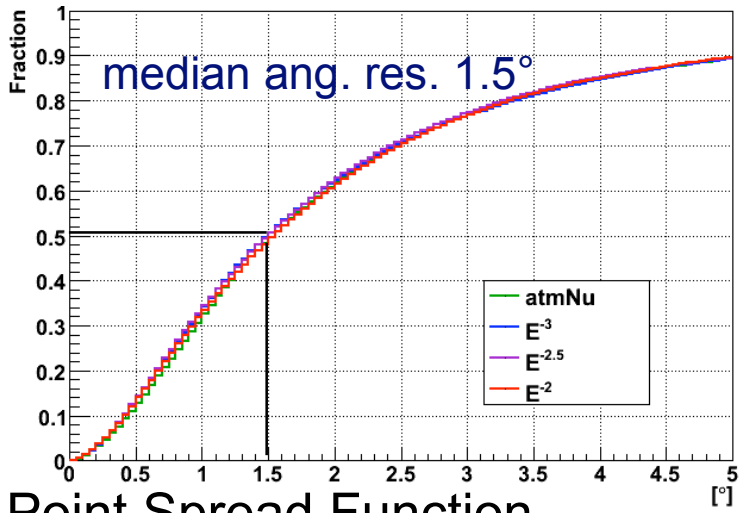
- Estimated event directional uncertainty < 3 deg
- log likelihood ratio of best-fit upgoing track to best-fit downgoing track > 30
- if hit series is split in two, both series have best-fit zenith > 70 deg

5114 Events after cuts

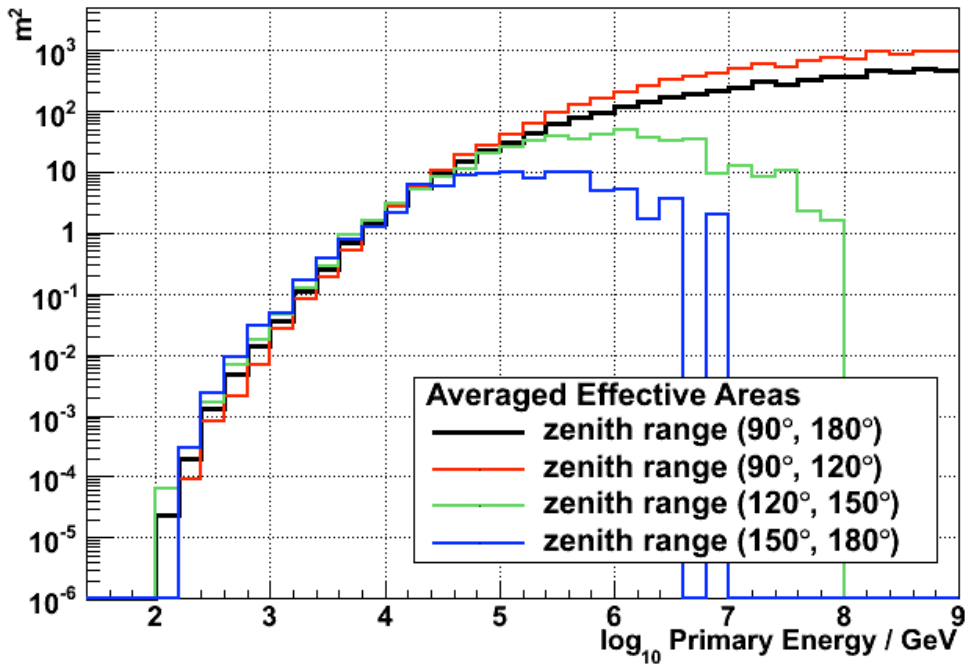
Perform point source search using:

- **a priori list of 28 source candidates**
- **all sky search from -5° to +85° declination**

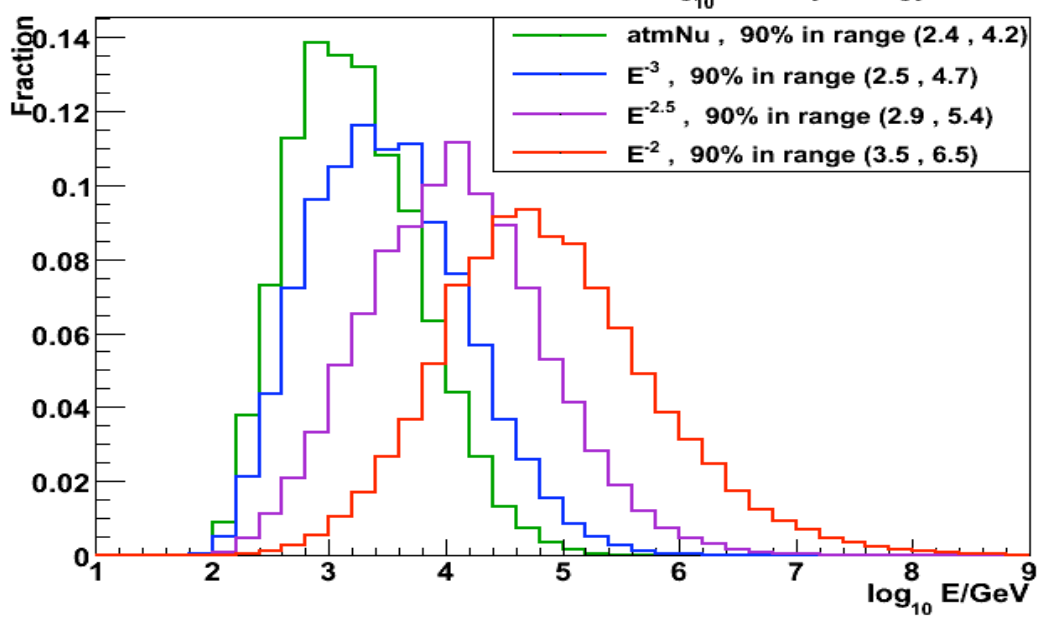
IC22 Point Source Analysis Characteristics



Point Spread Function



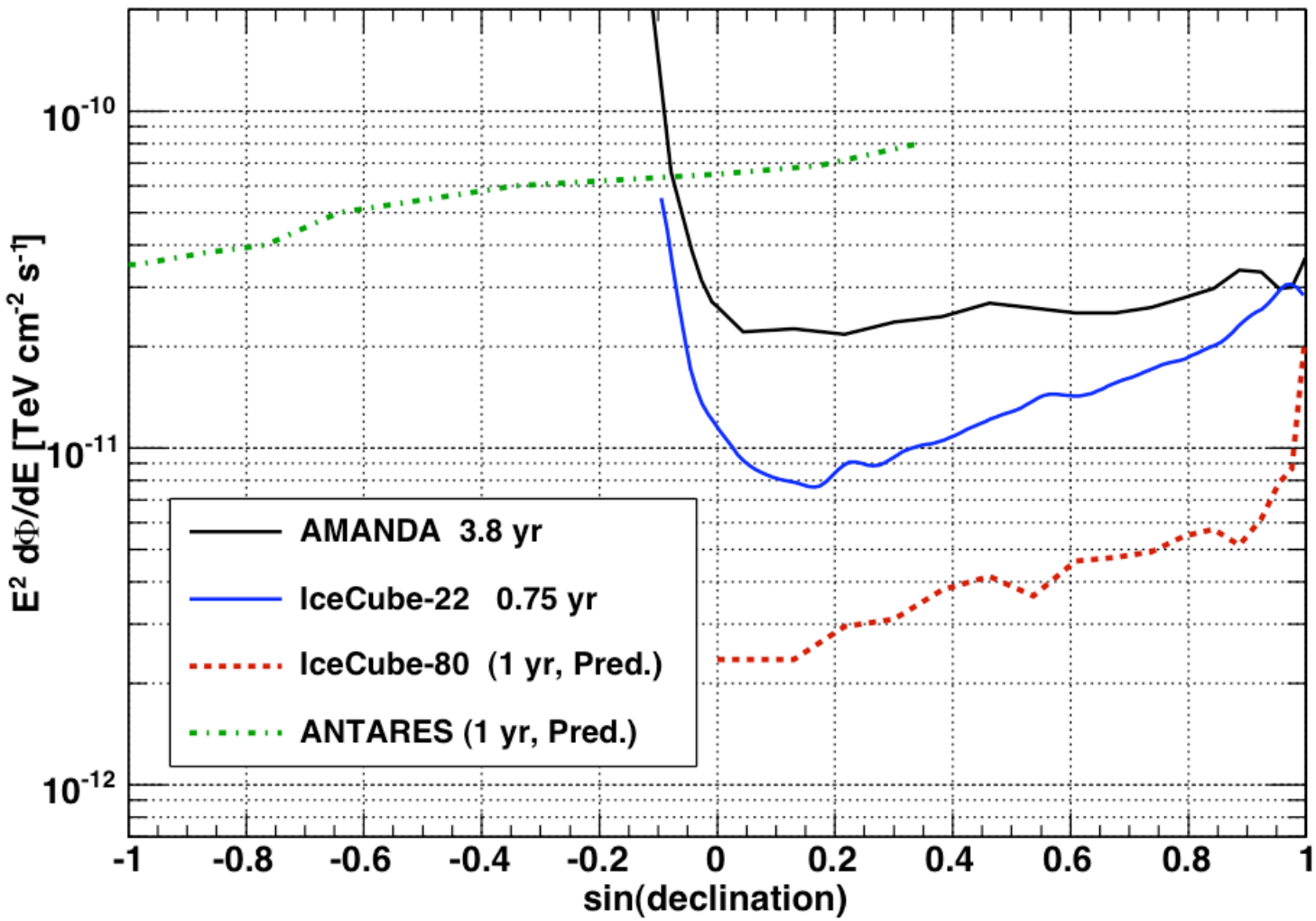
Muon Neutrino Effective Area



Neutrino Energy Distribution

(Energy is used in Likelihood analysis to separate atm. Nu background from harder spectra signal)

IC22 Sensitivity Comparison: E^{-2} spectrum



One season of IceCube 22-strings already ~ **2x** more sensitive than seven seasons of AMANDA-II

Results I: A Priori Source List

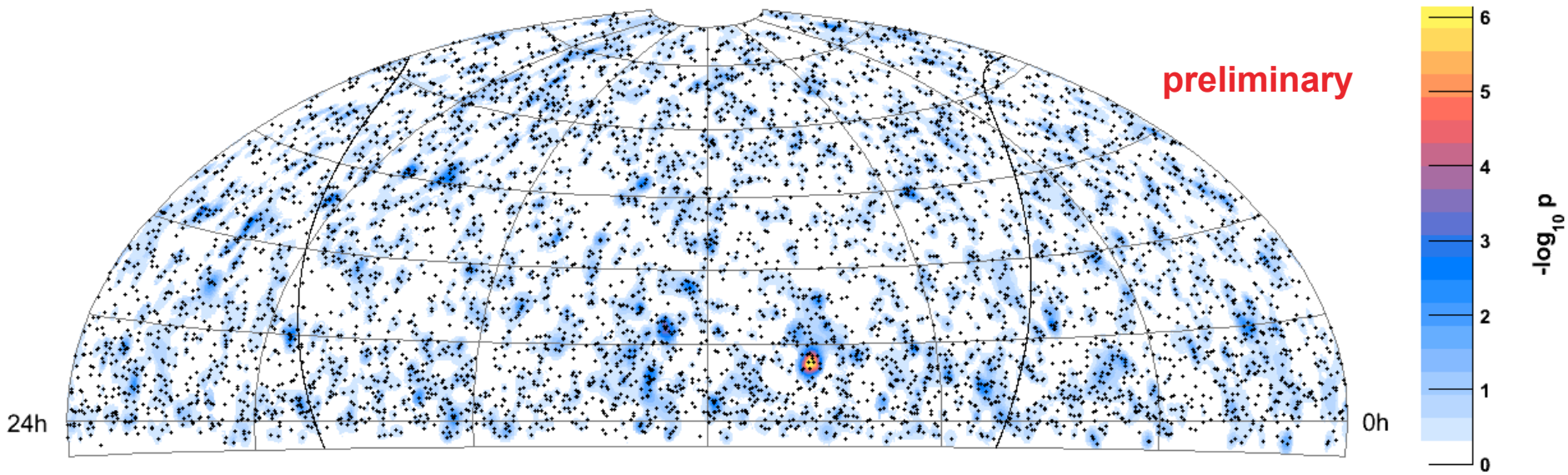
Lowest p-value (0.07) is for 1ES 1959+650.

Not significant after trials: 66% of scrambled data sets have at least one source with the same or smaller p-value.

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)	: -----

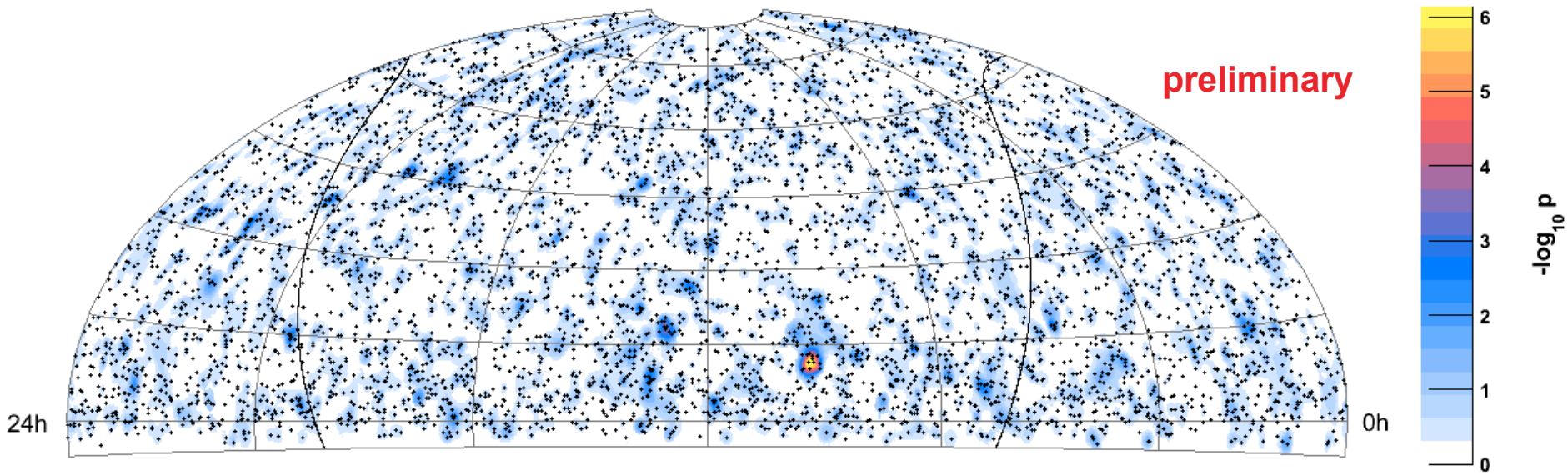
(only excesses reported, otherwise given as "---")

Results II: All Sky Search



For the all sky search, the likelihood function is sampled every 0.25° in r.a. and every 0.25° in declination.

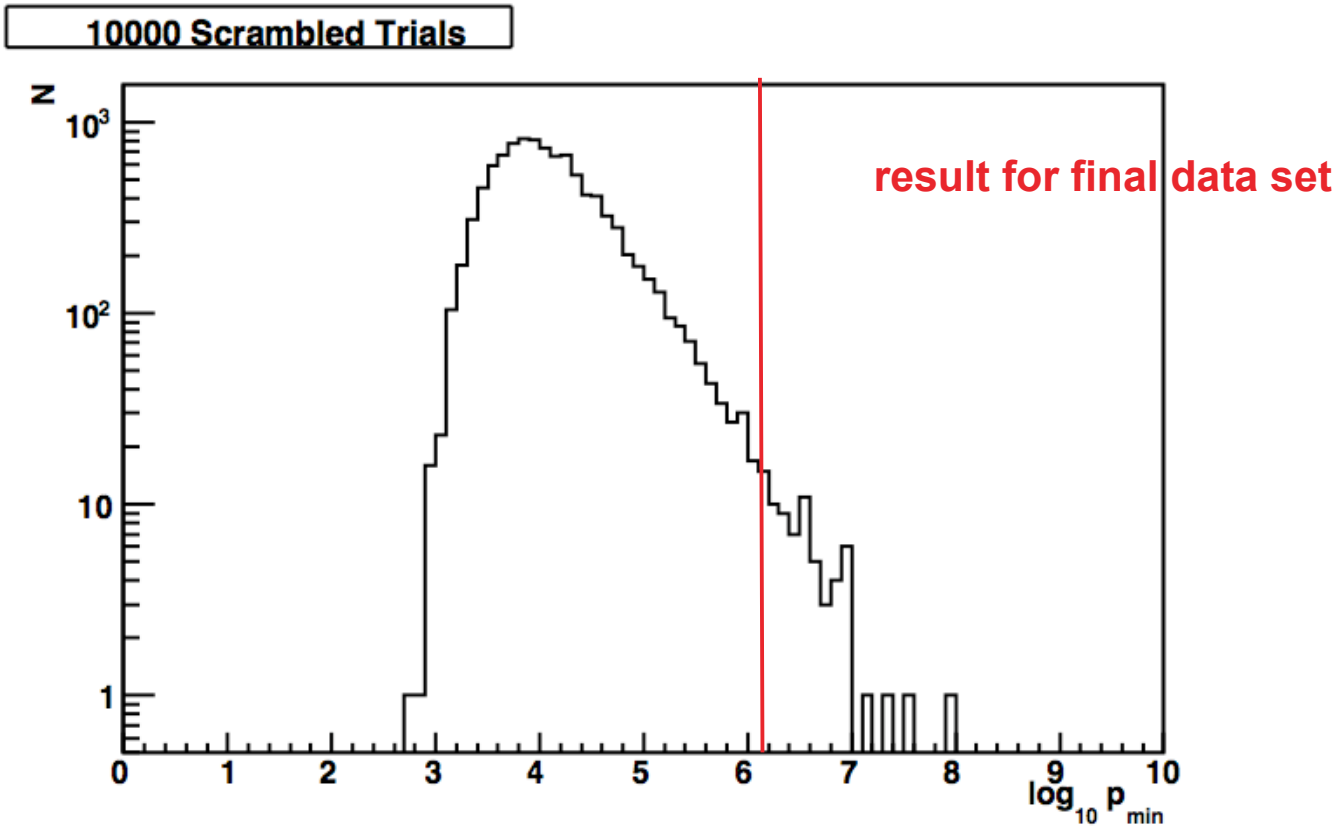
Results II: All Sky Search



Hottest spot found at r.a. 153º , dec. 11º
est. nSrcEvents = 7.7 est. gamma = 1.65
max. llhRatio = 13.4
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) ...

Final Result



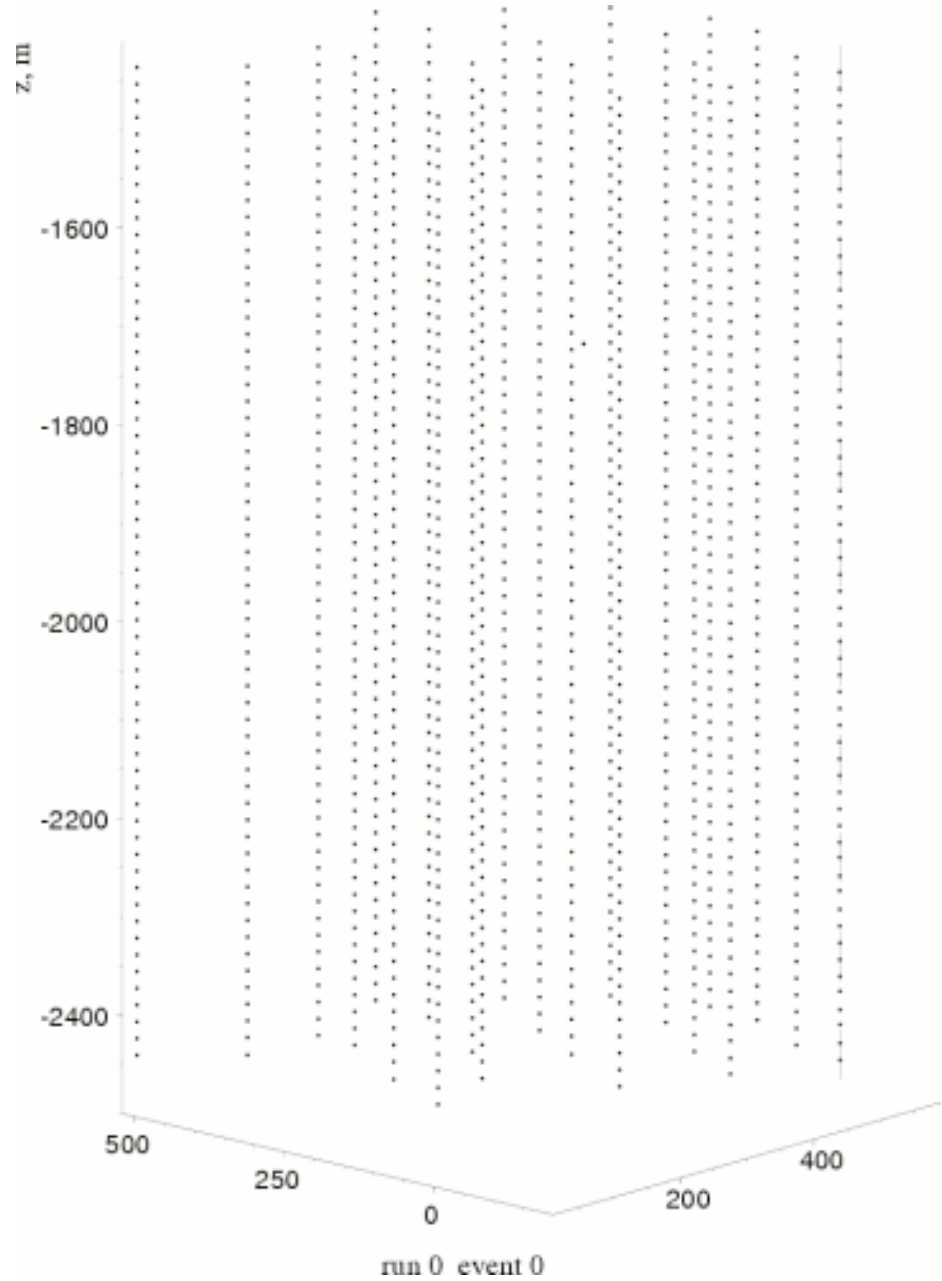
Out of 10,000 trials of scrambled data sets, 67 (0.67%) have a test-statistic (max llhRatio or p-value of hottest spot) more significant than that found in the data.

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 Display

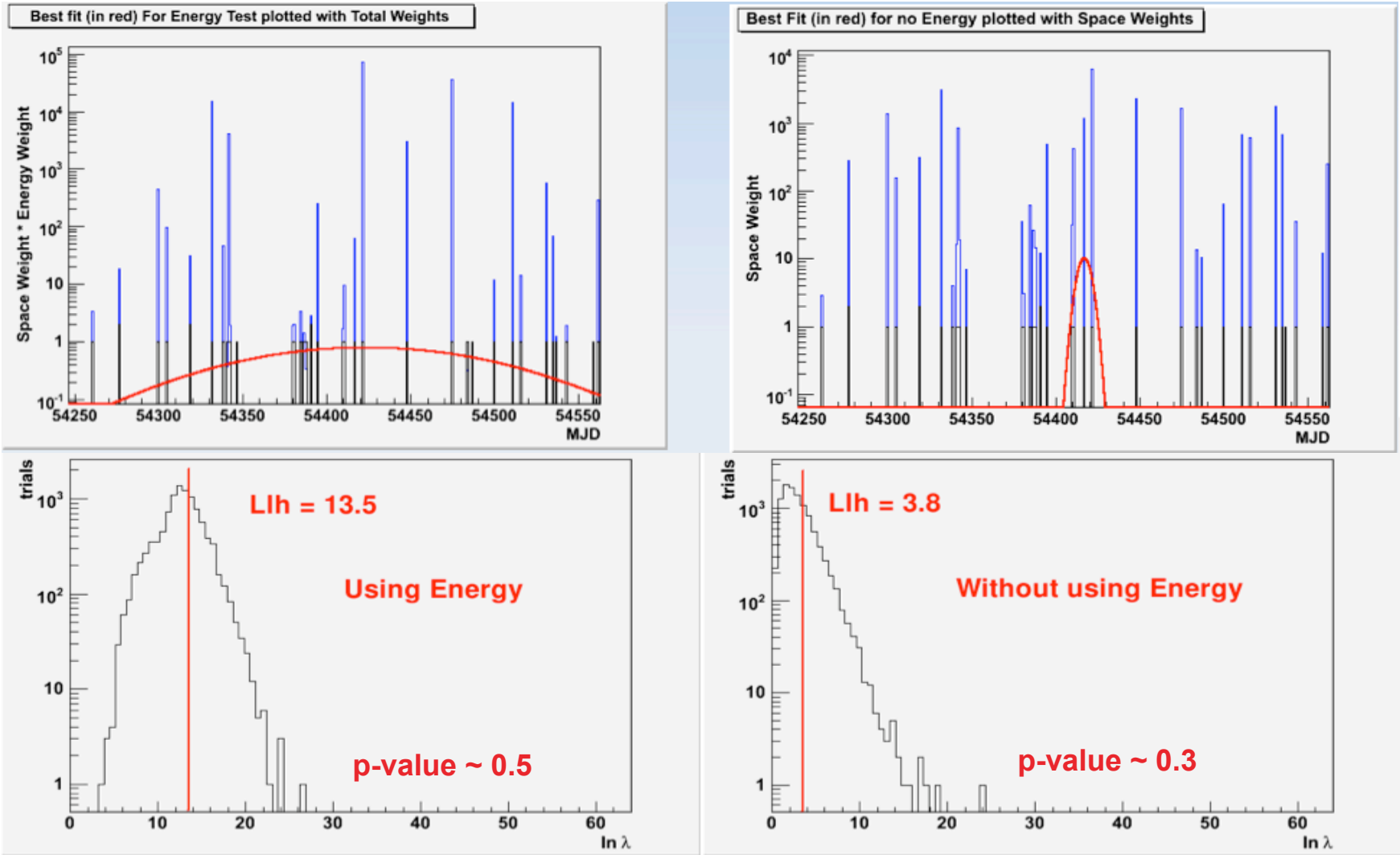
Number of hit modules: 148

est. angular error: 0.84°



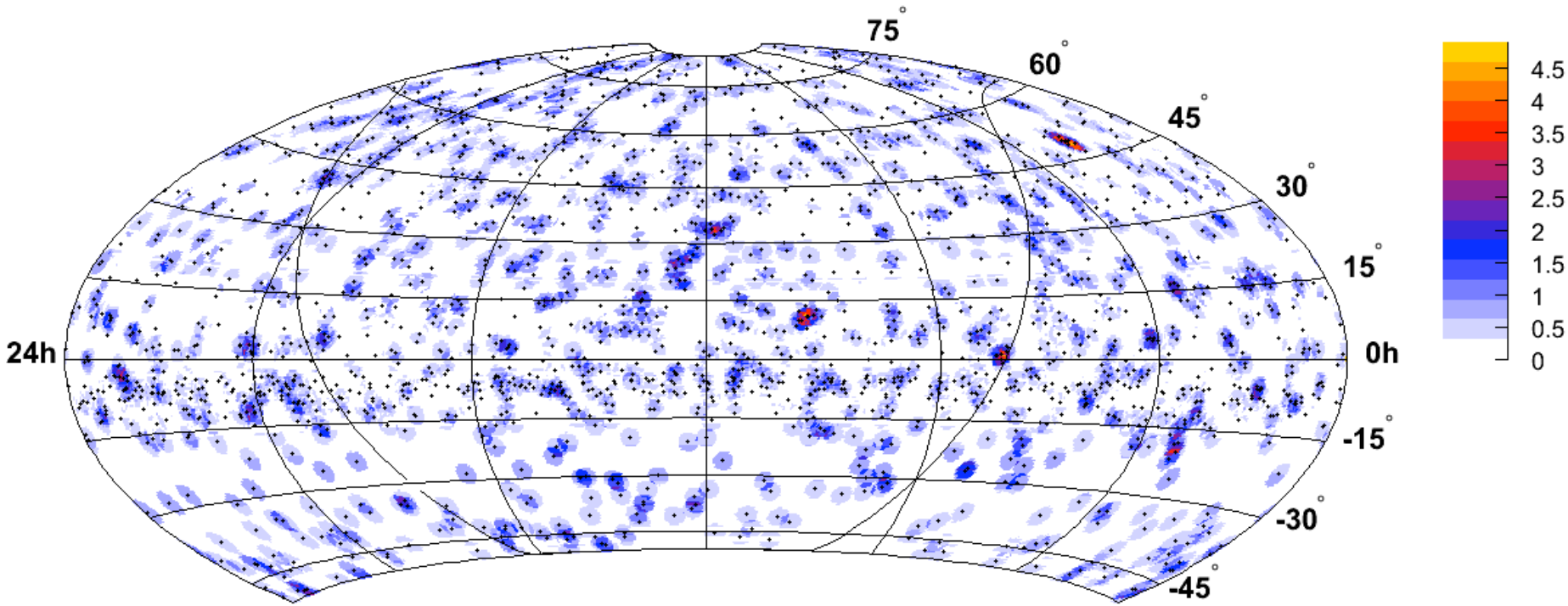
Time Analysis

preliminary



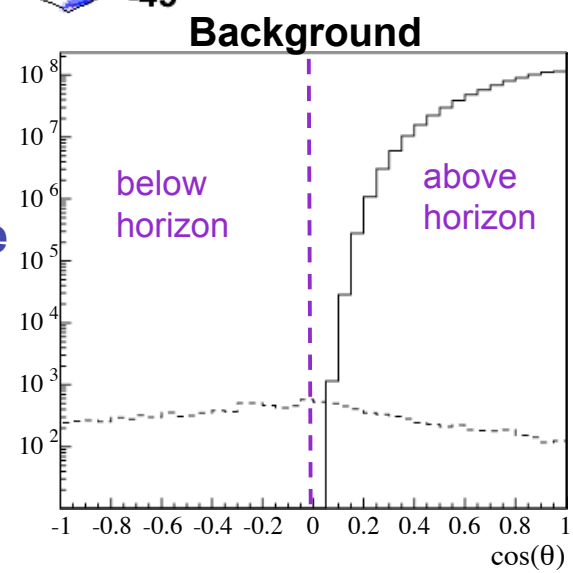
None of the events contributing most strongly to the hotspot are closer together than 10 days. Events are distributed roughly evenly in time over the year.

UHE Analysis: Extension to Southern Sky



Recall: extreme background of cosmic ray muons when looking "up". But for energies above PeV, muon background also becomes manageable.

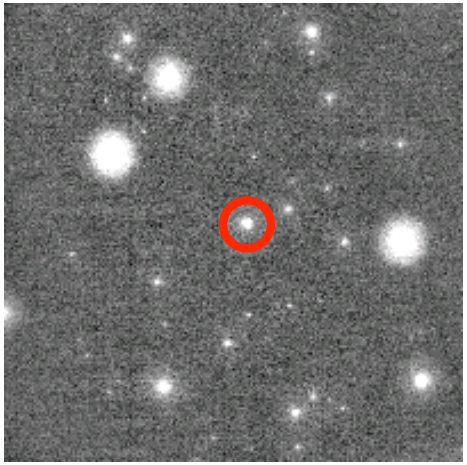
Sensitivity to hard $E^{-1.5}$ spectrum is comparable above and below horizon.



Hottest spot in sky found at r.a. 104° , dec. 1°
8 events on expected bkg of 1.2
35% of scrambled skymaps have similar or hotter spot

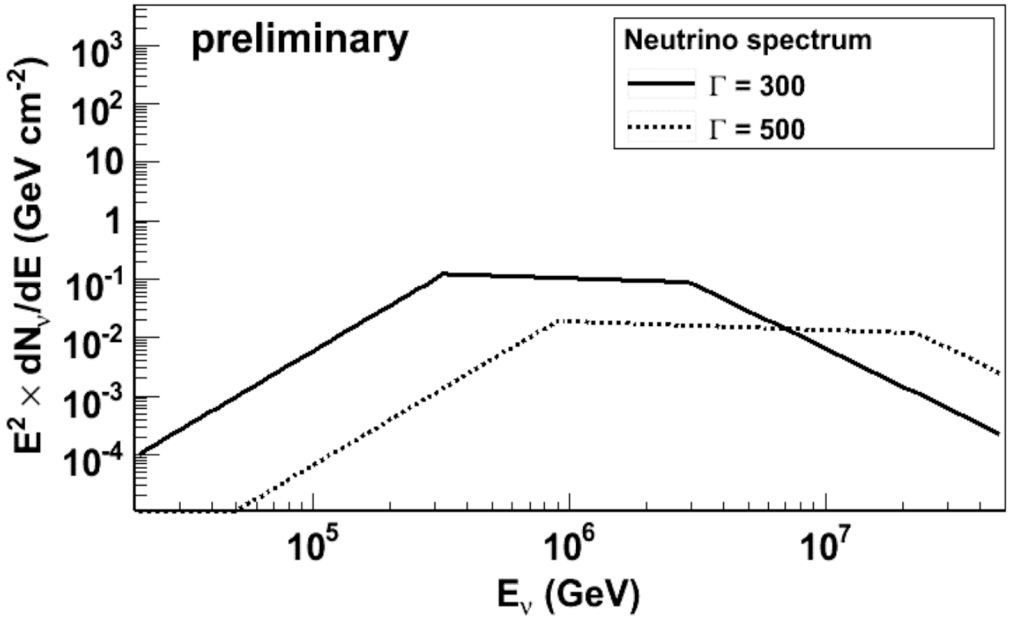
Analysis of "naked eye" GRB 080319B

- March 19, 06:12:49 UTC (duration ~70 s)
- Position: RA = 217.9°, Dec = +36.3°
- Brightest (optical) GRB ever observed:
  z = 0.94 (D_A = 1.6 Gpc, light travel time 7.5 Gyr)



Pi-of-the-Sky (optical)

- Expect ~0.1 events in IceCube 9-strings
  (Fireball model, Γ = 300)



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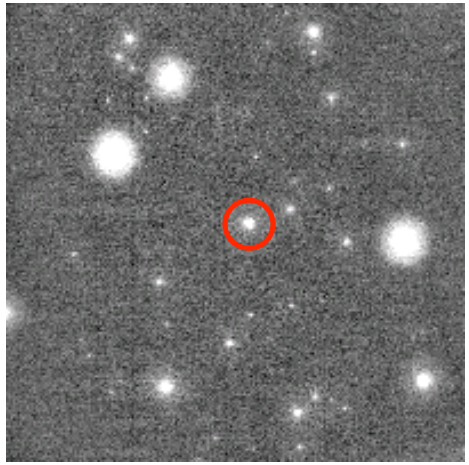
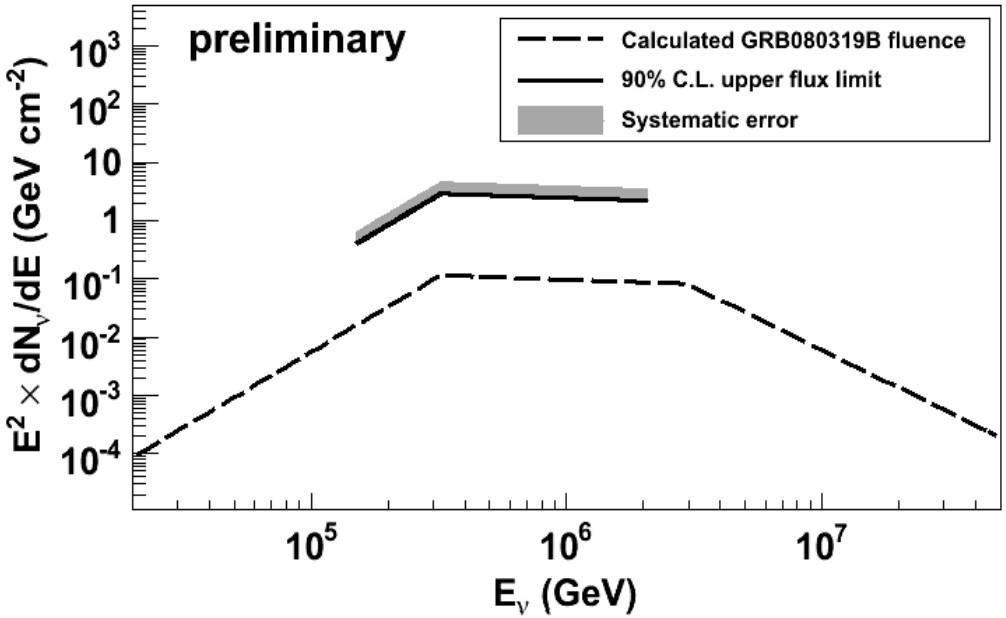


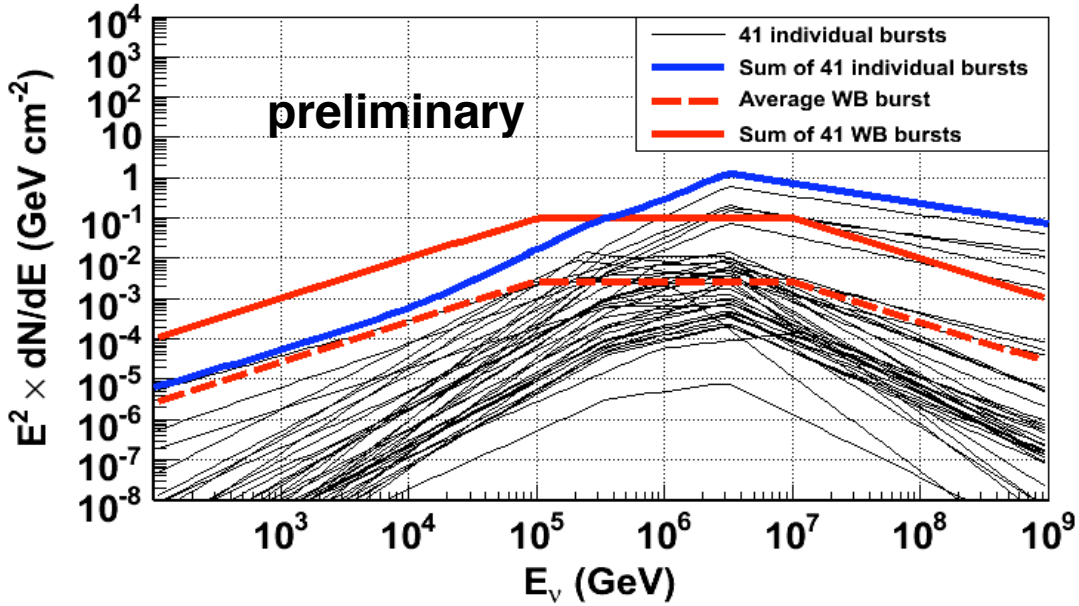
Pi-of-the-Sky (optical)

- Expect ~0.1 events in IceCube 9-strings
  (Fireball model, Γ = 300)
- Unbinned likelihood method yields 0 signal events
- Expect $\mathcal{O}(1)$ event in IceCube 80 from similar burst!

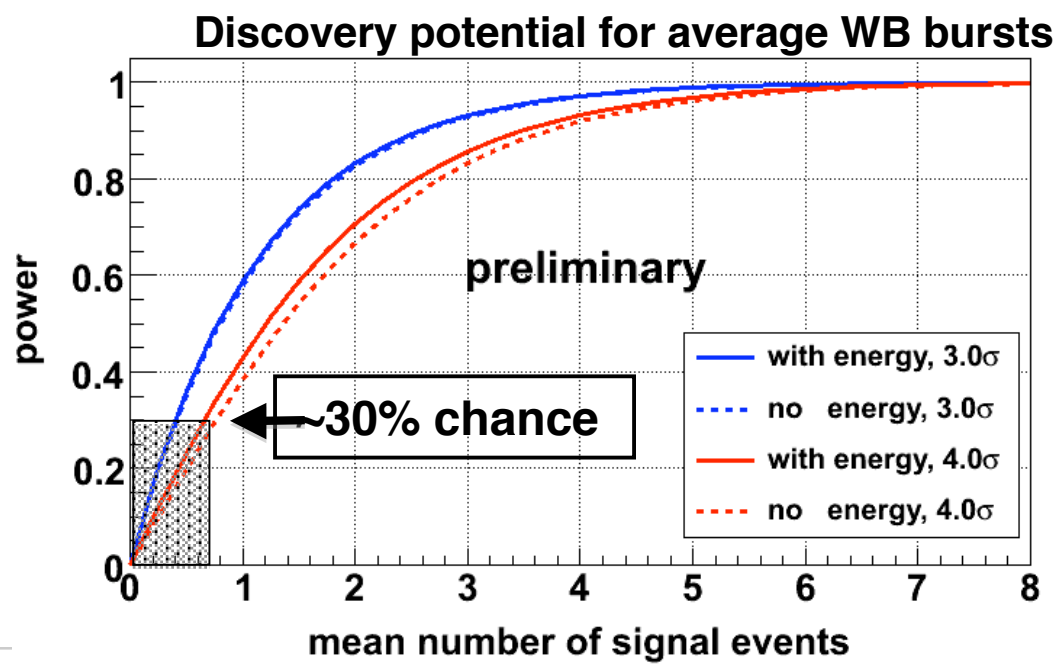


Gamma-ray bursts with IceCube 22-strings

- Analysis of data from 41 bursts (Swift, AGILE + others)
- **Individual** modeling of bursts according to GRB fireball model



- **Expected events in IC-22 Analysis:**
  - average Waxman-Bahcall ~0.7
  - individual GRB spectra ~0.5



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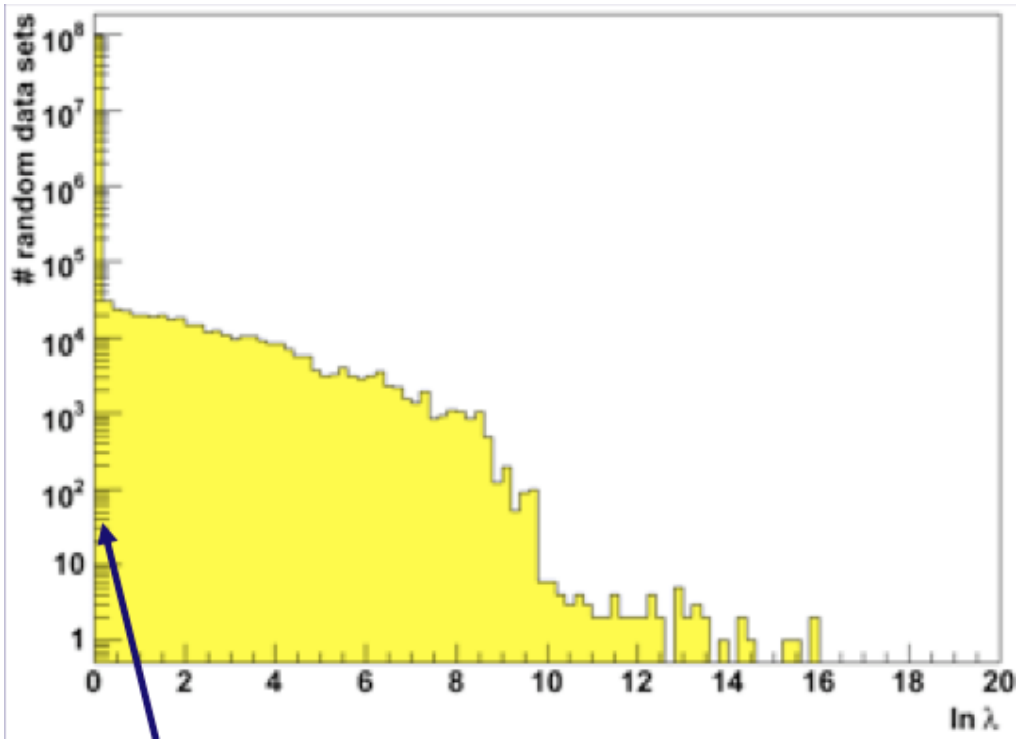


Value of likelihood result is consistent with null hypothesis

Measured

Preliminary Limit = 4.6 × Predicted Flux

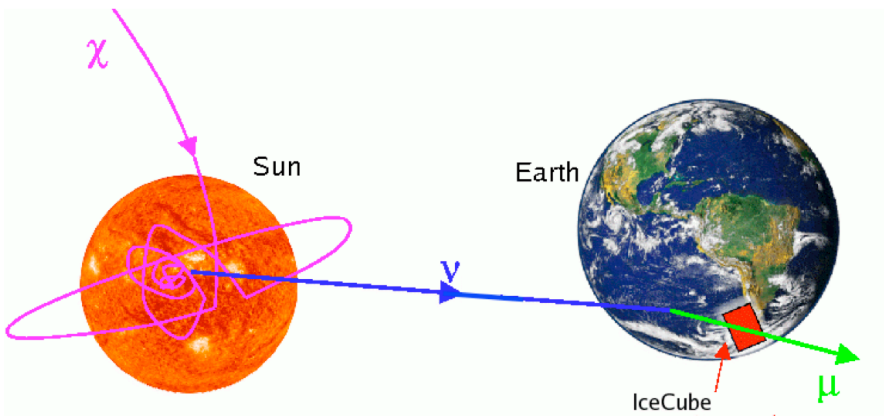
•**Outlook for full detector:** IceCube 80 will be able to see WB GRB flux within few years

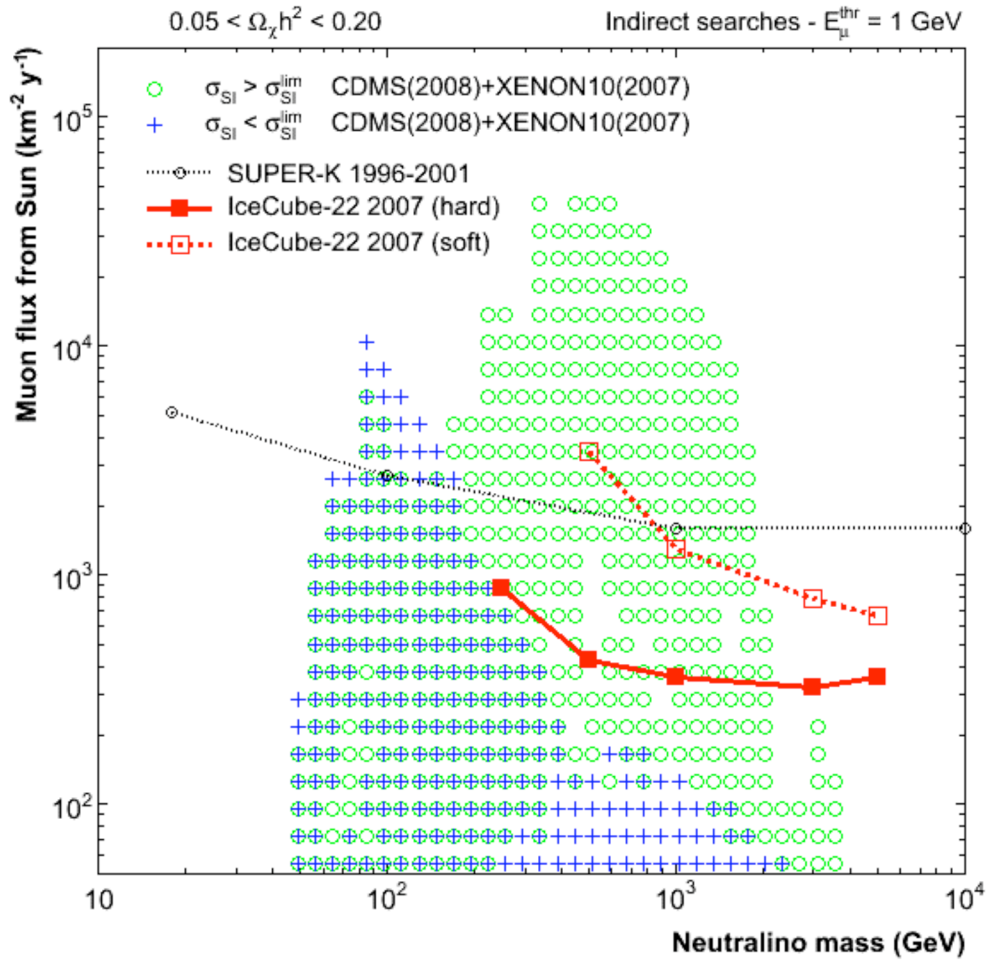
Indirect solar WIMP searches

Search for neutrino signal from neutralino annihilation

$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$

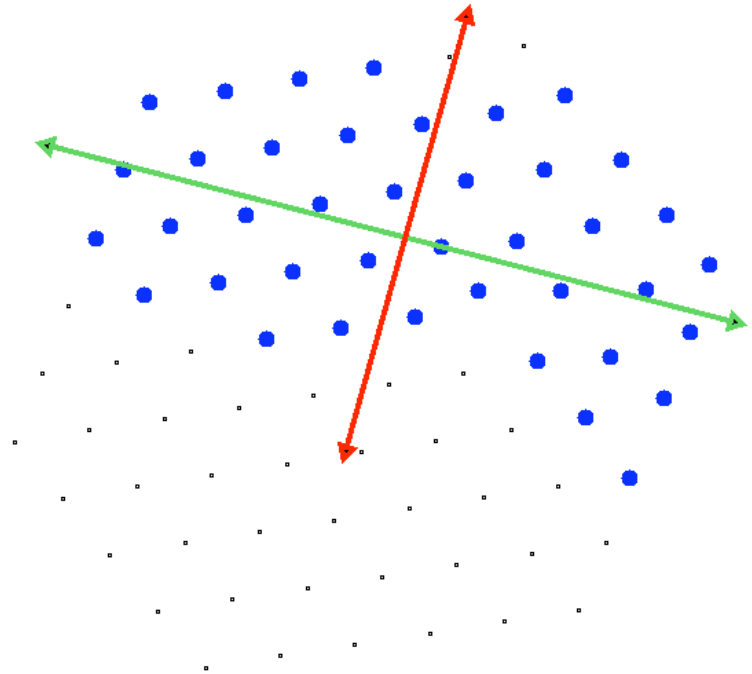
No excess observed. Constrains allowed MSSM models





Early Look at IceCube 40

IceCube currently running with 40 strings deployed.

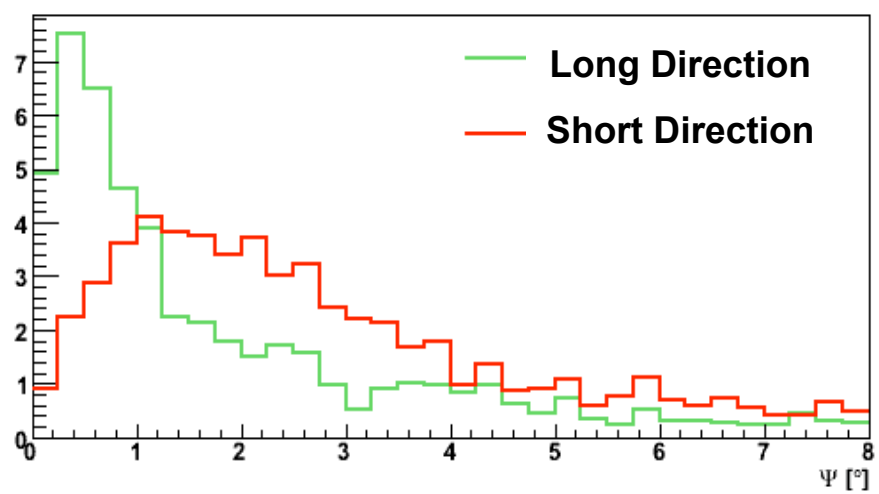


~ 2x effective area of 22 strings.

More fully contained strings.

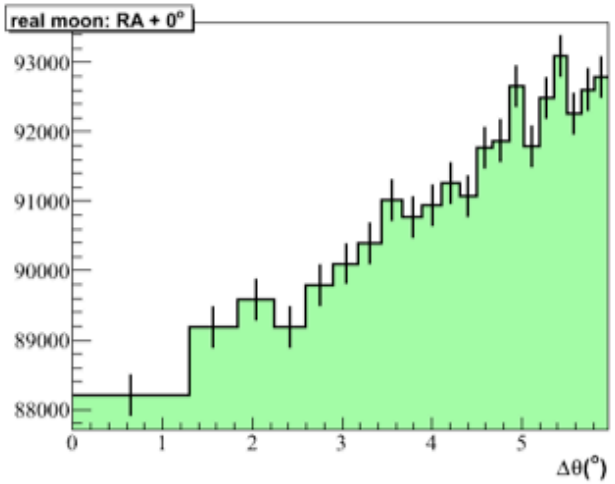
Short direction: angular resolution comparable to IceCube 22.

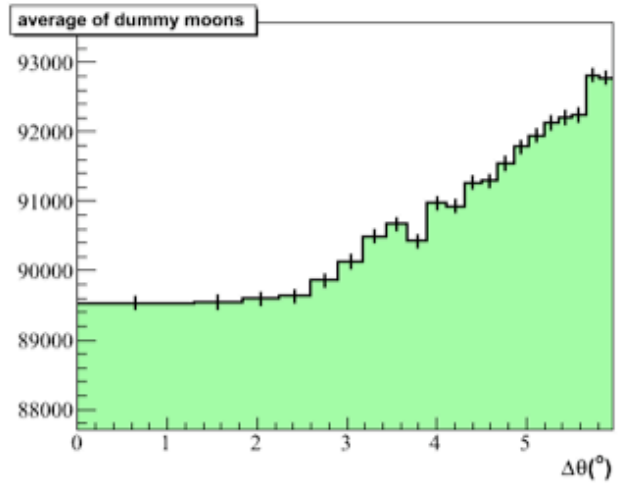
Long direction: angular resolution comparable to full IceCube 80 configuration ~ 0.5 degrees



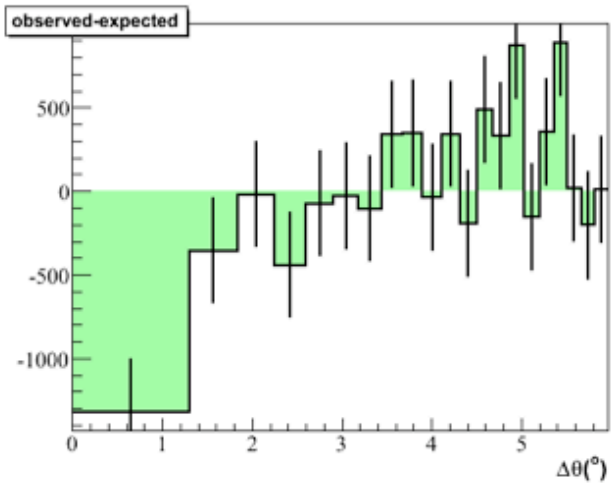
Preliminary Point Spread Function for IceCube-40

IceCube-40: First Results of Moon Shadow Analysis





preliminary



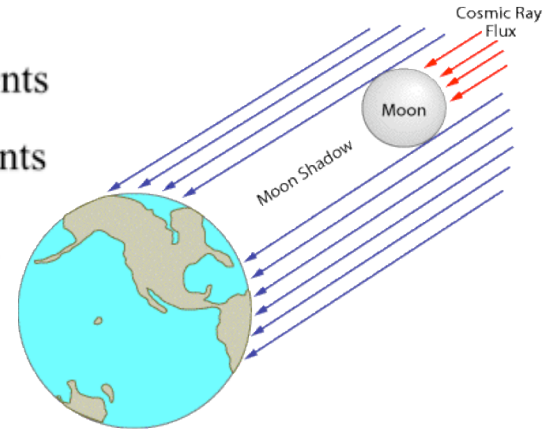
observed: 88202 events

expected: 89522 events

deficit: -1320 events

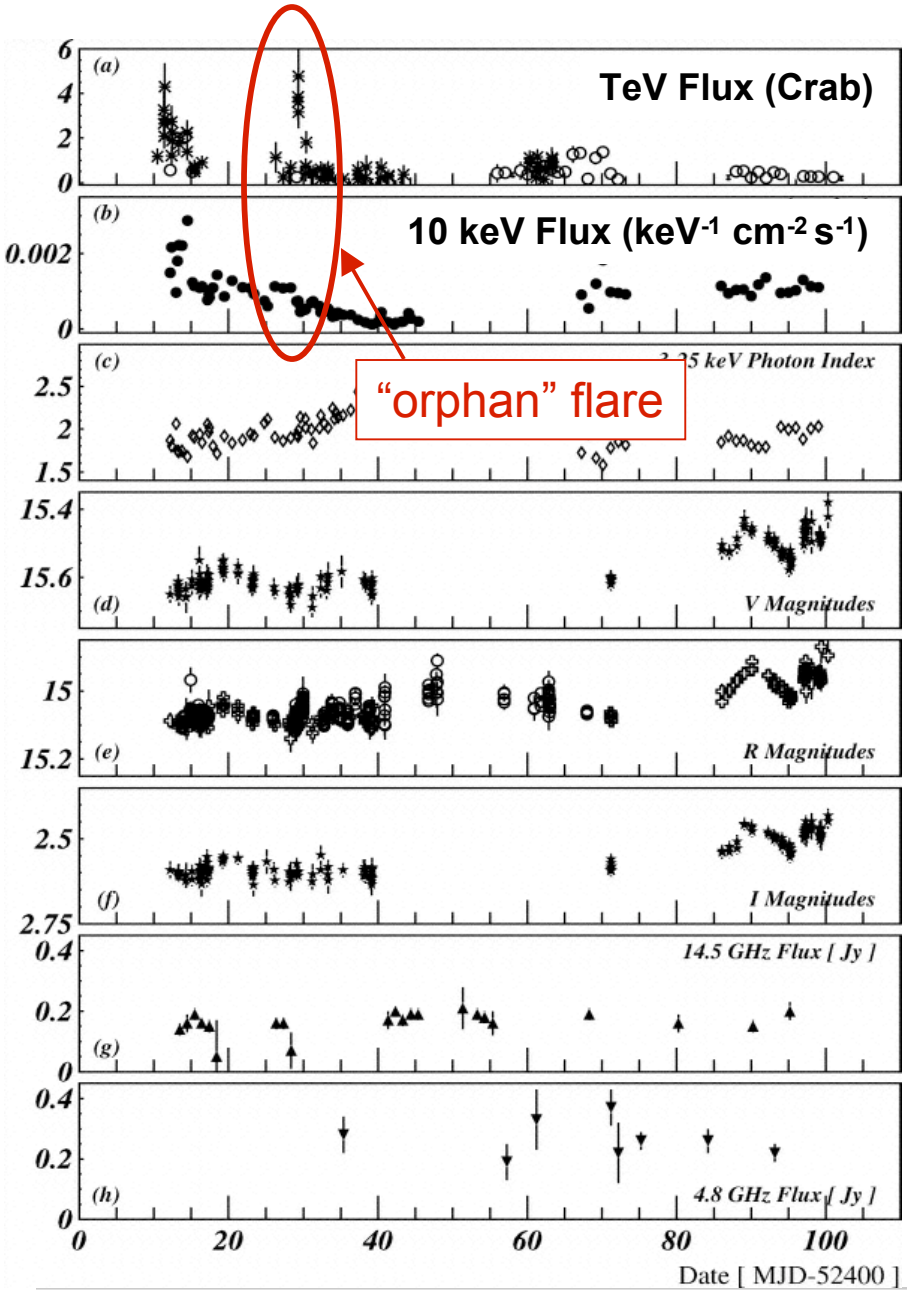
error: 315 events

significance: -4.2 σ

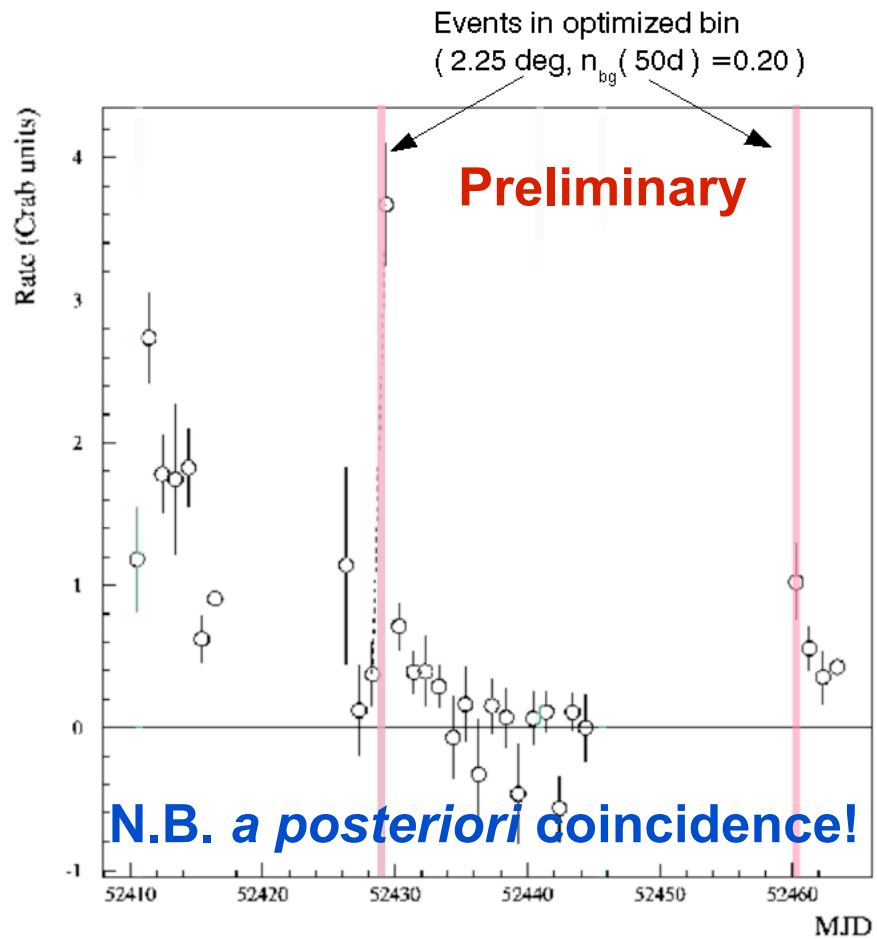


- Moon blocks cosmic rays ⇒ creates point-like deficit in the distribution of down-going muons in the detector
- Need high statistics and good angular resolution! IceCube 22 could not yet see the shadow, **but first few months of IceCube 40 data already do**

AMANDA-II Coincidence with TeV Orphan Flare in 1ES 1959+650



H. Krawczynski et al, 2004ApJ,601 151K
'Multiwavelength Observations of Strong Flares from the TeV Blazar 1ES 1959+650'



Timing Is Everything

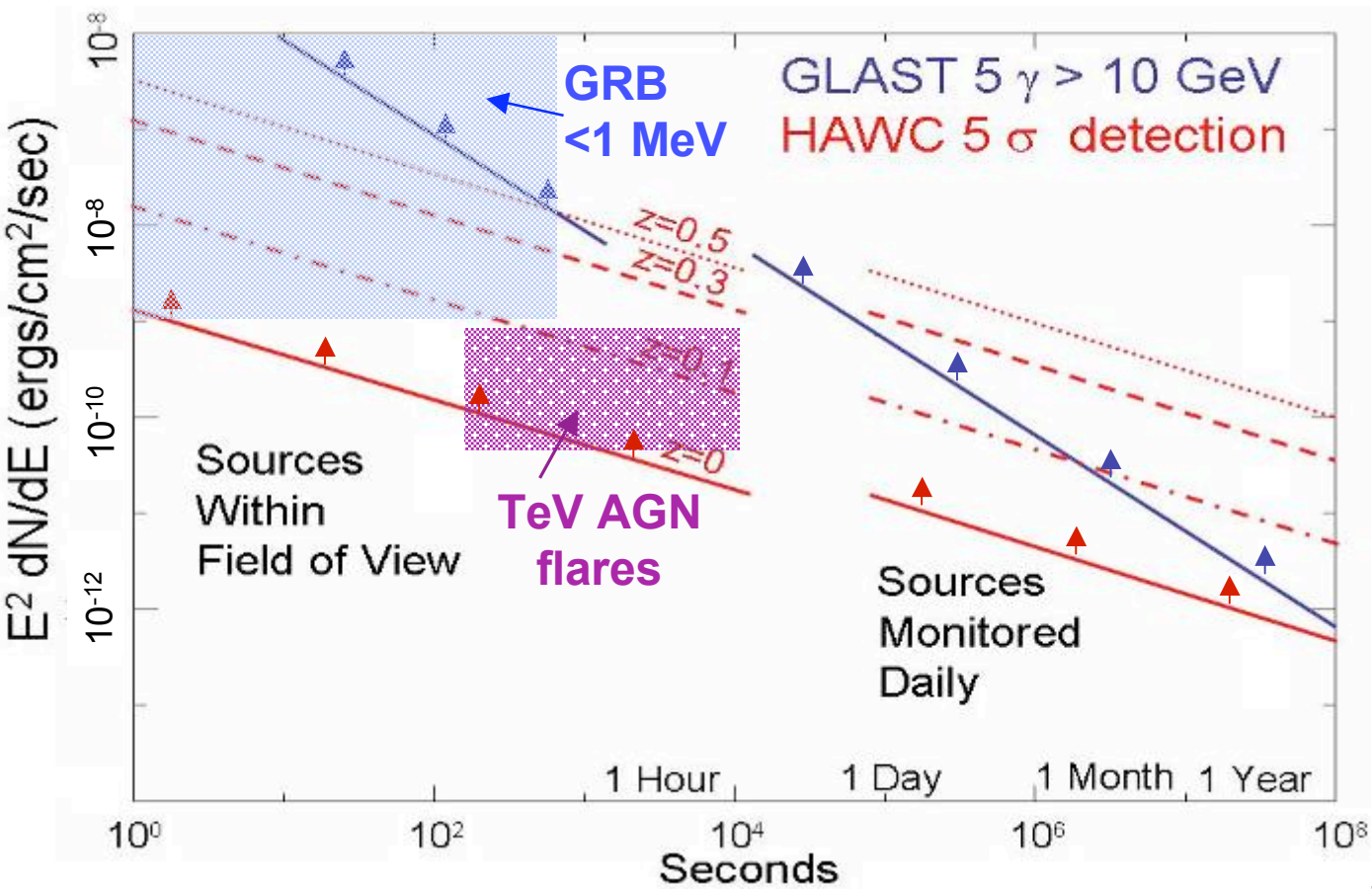
Importance of Correlating with Observations of Transient Sky:

- Reduces (practically eliminates) atmospheric neutrino background, even downgoing muon background. In principle, a single neutrino event can be significant.
- Timing of neutrinos relative to multiwavelength observations (optical, X-ray, TeV, gravitational) provides unique information about physics of supernovae, GRBs, AGN and other flaring sources
- For small signals, requires well-defined a priori analysis methods

Gamma-Ray Detector Sensitivity to Transients: AGN and GRB

"All-Sky" Gamma-Ray Monitors:

- Recently launched Fermi (formerly GLAST) satellite
- Proposed HAWC (High Altitude Water Cherenkov) Detector



GLAST and HAWC sensitivity for a source of spectrum $dN/dE=KE^{-2}$

z=0 no E cutoff
z=0.1 E_{exp}~700GeV
z=0.3 E_{exp}~260GeV
z=0.5 E_{exp}~170GeV

Burst Transients: IceCube + LIGO

LIGO

Gravitational Wave detectors sensitive to extreme astrophysical events: core collapse supernovae / hypernovae ; mergers of neutron stars / black holes ; Soft Gamma-ray Repeaters (SGR) ... **All are potential sources of TeV neutrinos.**

GW and ν propagate unimpeded from source to earth

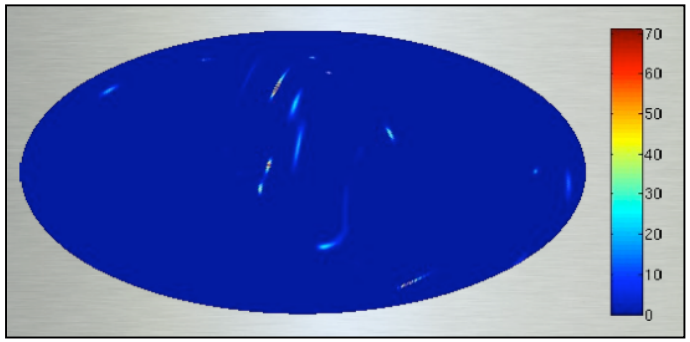
GW and ν detectors are continuous "all-sky" monitors, with sensitivity to short time scales.

Well suited for discovering unexpected bursts and novel phenomena (e.g. choked GRBs -- supernova with jet that stalls below the surface, thus γ-ray dark)

Joint search can leverage the individual sensitivities of independent experiments

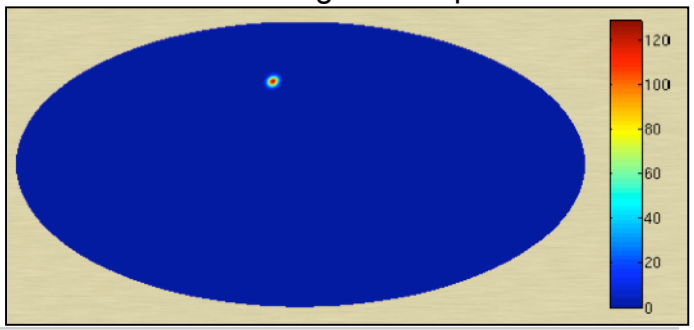
"Search method for coincident events from LIGO and IceCube detectors," Y. Aso, Z. Marka, C. Finley, J. Dwyer, K. Kotake, S. Marka, *Classical and Quantum Gravity* 25, 114039 (2008)

Simulated Coincident GW + ν Event



LIGO+Virgo Point Spread Function

IceCube 22-String Point Spread Function



Outlook

- IceCube construction well on the path to completion
  - Beginning to take data with 58 + 1 DeepCore strings this month
  - Up to 80+6 strings by 2011

- Analyses have begun on previous year of data with 22-string detector
  - ~5000 atmospheric neutrinos detected
  - Already sets best limits to date for high energy neutrino point sources and competitive limits on dark matter annihilation in the sun

- Full detector may still yield 10x improvement for many analyses

- Anticipate more multi-wavelength observations of the transient sky
  - Correlated observations enhance signal to background ratio for neutrinos
  - Relative timing of neutrinos, photons, gravitational waves offers rich insights

IceCube is a discovery instrument with potential in wide range of astro- and particle physics. Prospects are good for opening a new window in astronomy using neutrinos as unique messengers.