Particle Astrophysics at 90°S

Reports from the IceCube and ARA Neutrino Observatories

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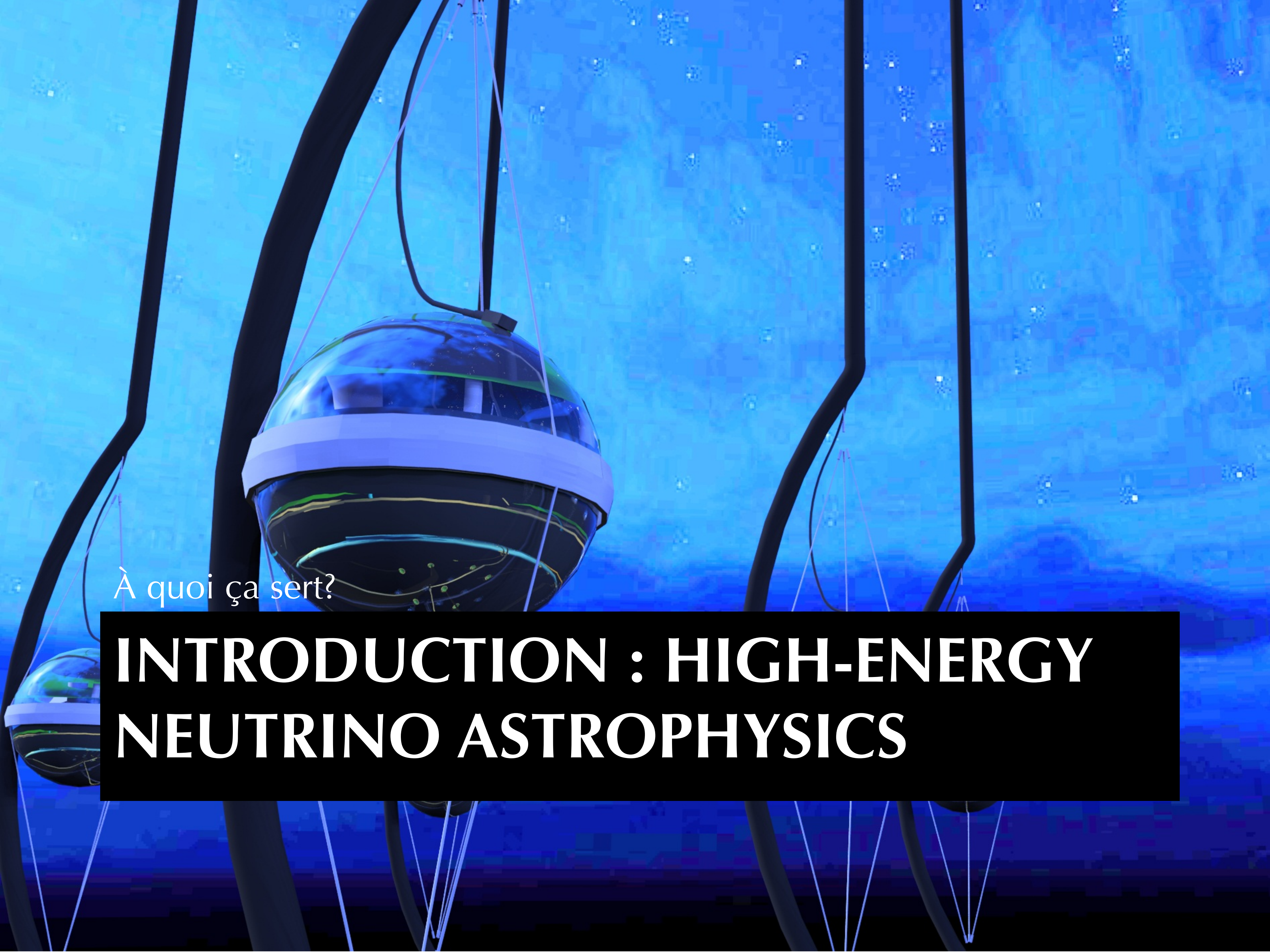
IceCube
Neutrino Observatory

ULB

Outline

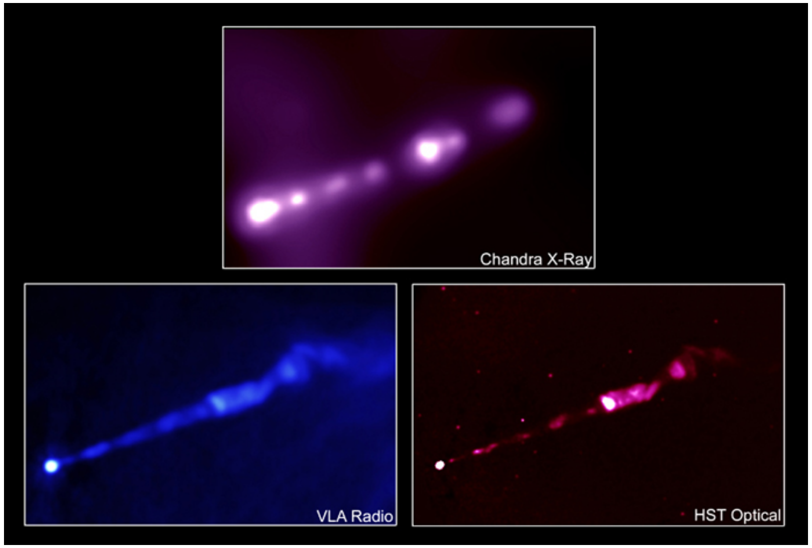
- Motivation – neutrino hunting is a big endeavor so why do it?
- The IceCube Neutrino Observatory
  - Detecting neutrinos in the ice
  - Design and performance of the detector
  - Analysis results in the IC86 era. Things are getting interesting.
- Future of optical in ice
- Radio in ice

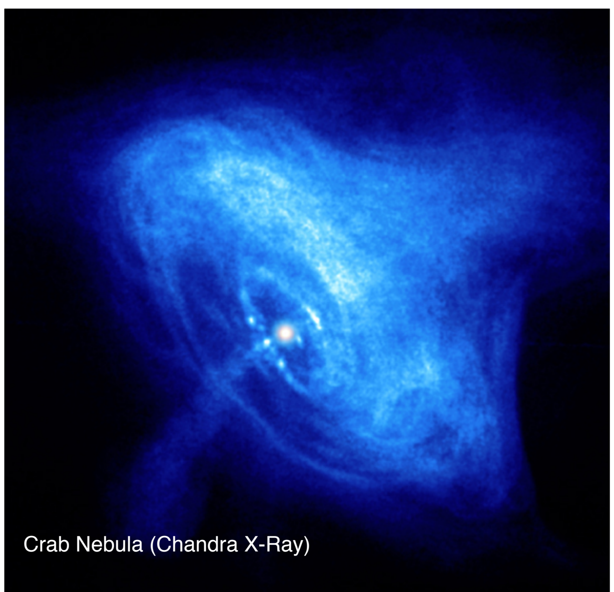


À quoi ça sert?

INTRODUCTION : HIGH-ENERGY NEUTRINO ASTROPHYSICS

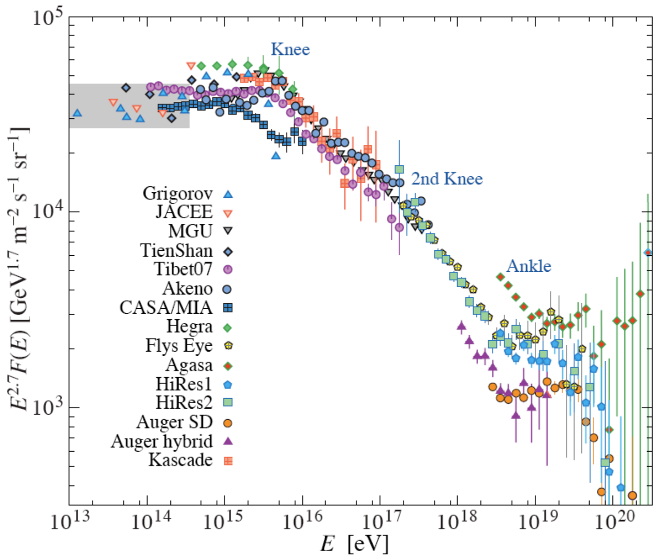
Astrophysical Sources and Messenger Particles




Crab Nebula (Chandra X-Ray)

- Long-standing problem in (particle-) astrophysics: what is origin of cosmic rays?
  - Supernova remnants are abundant even in galaxy and Fermi shock acceleration is consistent with observations up to 1 PeV, but beyond 1 PeV it is hard to justify efficient energy transfer.
  - Gamma-ray binaries, microquasars, and pulsar wind nebulae are other galactic candidate accelerators
  - Extra-galactic candidates such as AGN and GRB
- Astronomy into the 20th century used only visible light as means of observation of celestial objects. The EM spectrum has opened up and now includes everything from radio waves to TeV gamma rays (dynamic range of 10^{20}).
- Any stable, preferably neutral, particle can carry information across vastness of space, essentially this leaves protons (and heavier nuclei), electrons and gammas, neutrinos, and gravitons.

Cosmic Rays



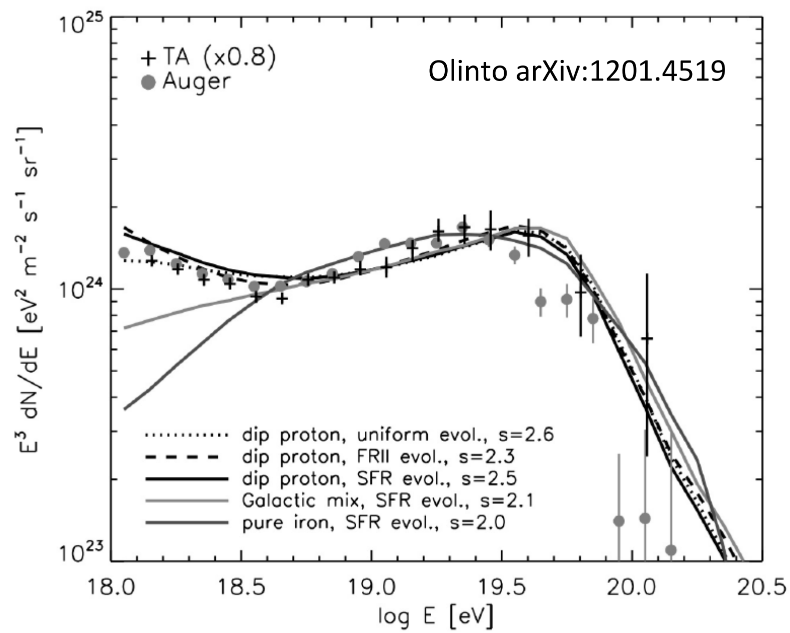
The flux of cosmic rays has been known for 100 years: it extends from roughly 1 GeV where geomagnetic cutoff and atmospheric absorption screen low energy particles to above 10^{11} GeV when even the largest detectors such as PAO (Pierre Auger Observatory, Argentina) run out of events from the diminishing flux.

Composition is principally protons below the “knee” and appears to be getting heavier above it – the composition of UHECR is an outstanding question to resolve. It is also unknown exactly what gives rise to these knees: is our galaxy leaking particles or are the galactic accelerators running out of energy and the flux is being supplied by other, higher-energy extra-galactic objects?

At the extreme end of the spectrum, above 3E19 eV, the protons can interact with the photons of the CMBR (cosmic microwave background) and form pions through Delta resonances:

$$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

This effect – conventionally known as the GZK cutoff after Greisen, Zatsepin, and Kuz’min – severely limits the range of UHECR protons to 10’s of Mpc, unfortunately just as the magnetic deflection begins to decrease to a point where particle astronomy is feasible. Notice however, that the short-lived charged pions will decay into neutrinos which we will get to in a second and then a bit later, too, so save this information.



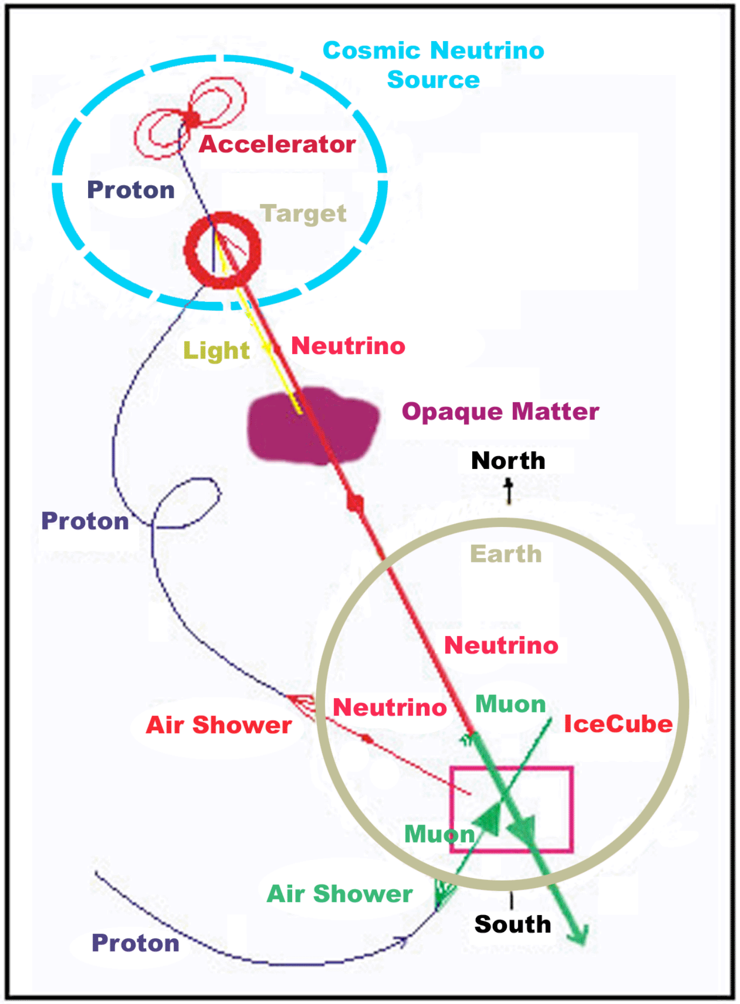
Neutrinos

Neutrinos, being chargeless and only weakly-interacting make perfect messengers to carry information from deep within the core of sources in a straight line to Earth based detectors. The neutrinos even pass through the Earth (up to 100 TeV after which the Earth becomes opaque). The Earth is then often used as a screen and detectors intentionally look below the horizon in order to discriminate neutrino-induced events from other more prevalent cosmic backgrounds. Atmospheric neutrinos are produced in the decay of charged mesons from CR-nucleus interactions in the Earth's atmosphere and constitute the main background for this genus of events.

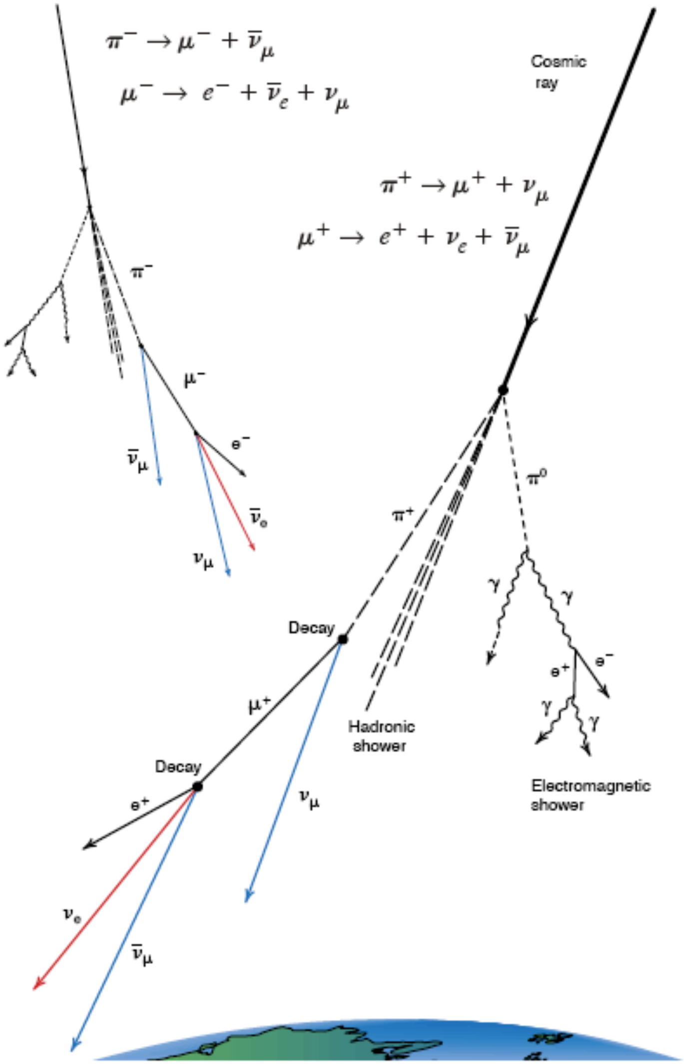
The small cross sections do demand that large target masses be instrumented. Typical theoretically predicted fluxes want cubic kilometers or square kilometers of muon effective area in order to produce viable event rates.

Observation of high-energy neutrino fluxes from an object would conclusively prove the existence of a hadronic acceleration process as neutrinos can only be produced via this mechanism. Gammas on the other hand can come from purely EM processes not linked to CR acceleration.

See also review by Anchordoqui & Montaruli [Ann. Rev. Nucl. Part. Sci 60: 129-62 (2010)]



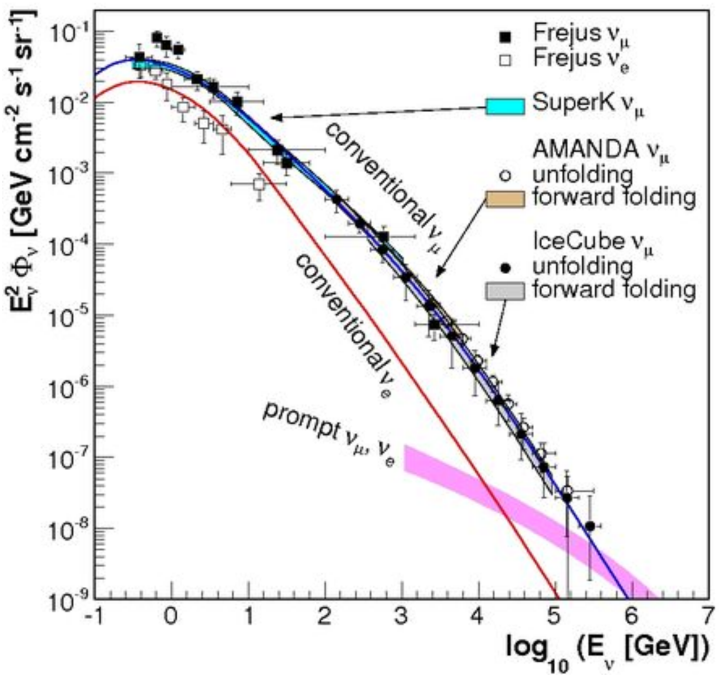
Atmospheric Neutrinos

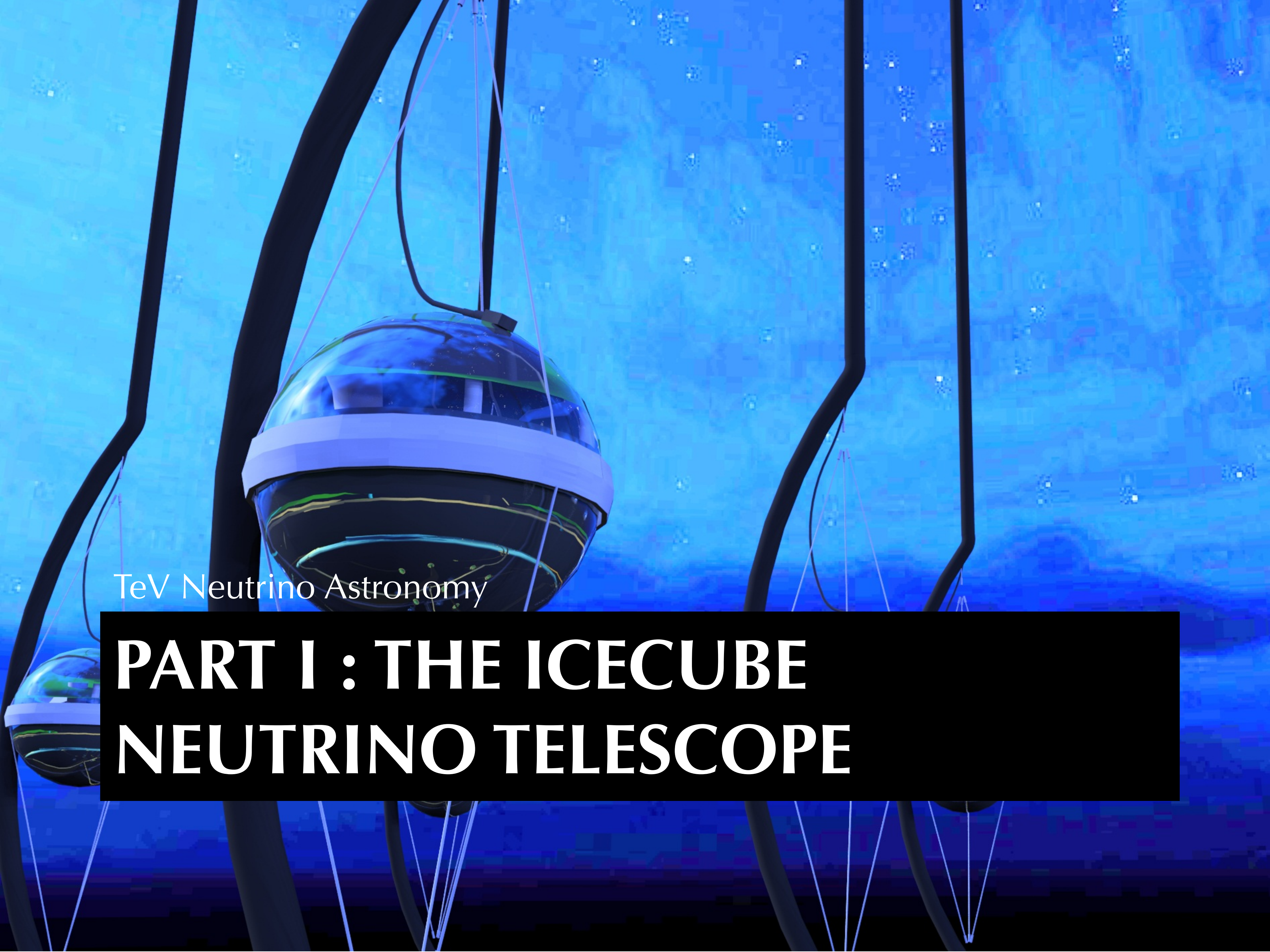


Neutrinos from meson decay in terrestrial atmosphere. Spectrum initially follows CR primary flux (-2.7) but quickly steepens due to muon energy loss. Electron neutrinos principally come from muon decay so much lower fluxes esp. at HE.

Important still unknown VHE component is prompt neutrinos from decay of heavier charmed mesons.

The atmospheric neutrino flux is background for cosmic neutrino searches but is itself interesting for study of neutrino properties.





TeV Neutrino Astronomy

PART I : THE ICECUBE NEUTRINO TELESCOPE

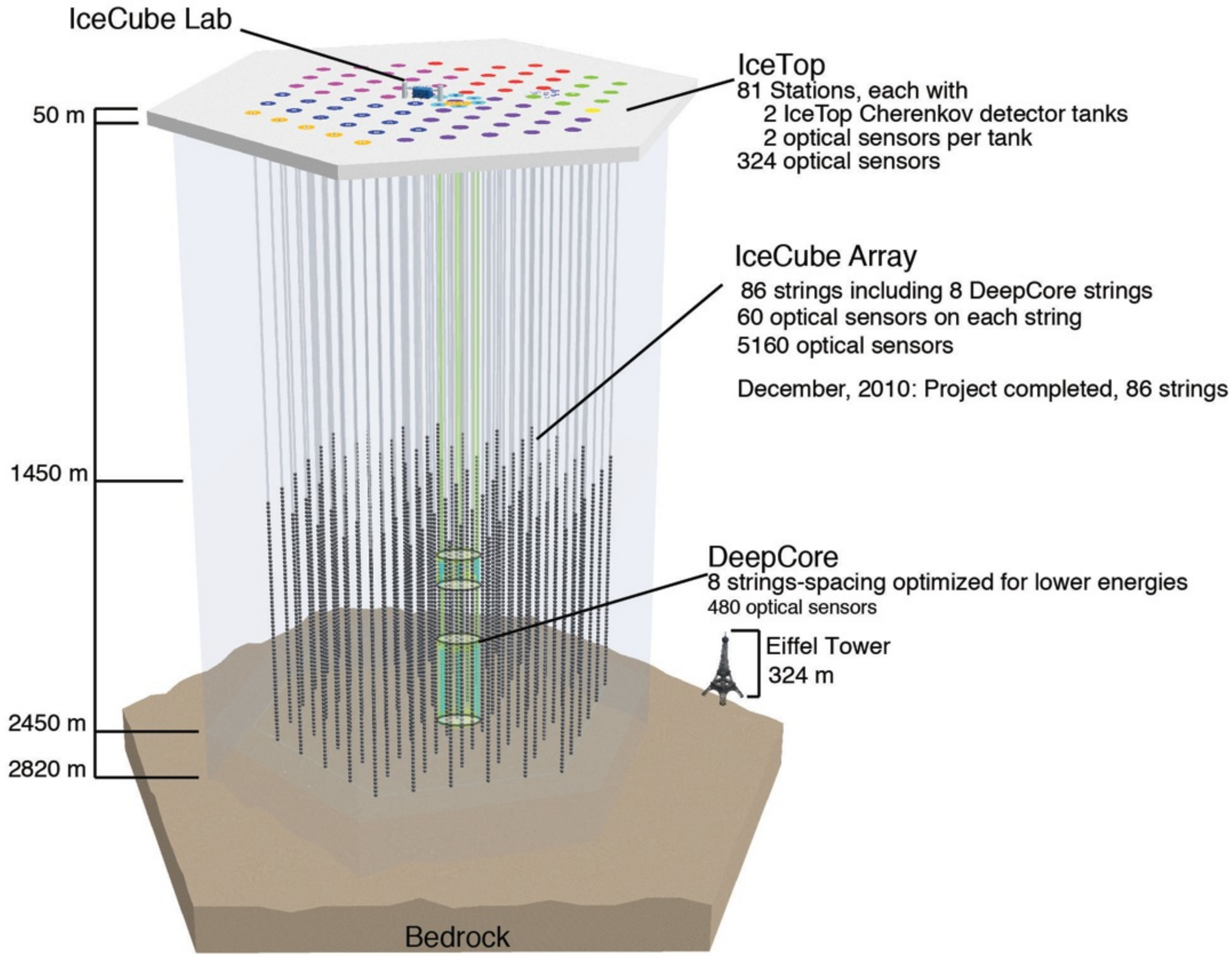
Collaborating Institutions and Financial Support

The IceCube Collaboration

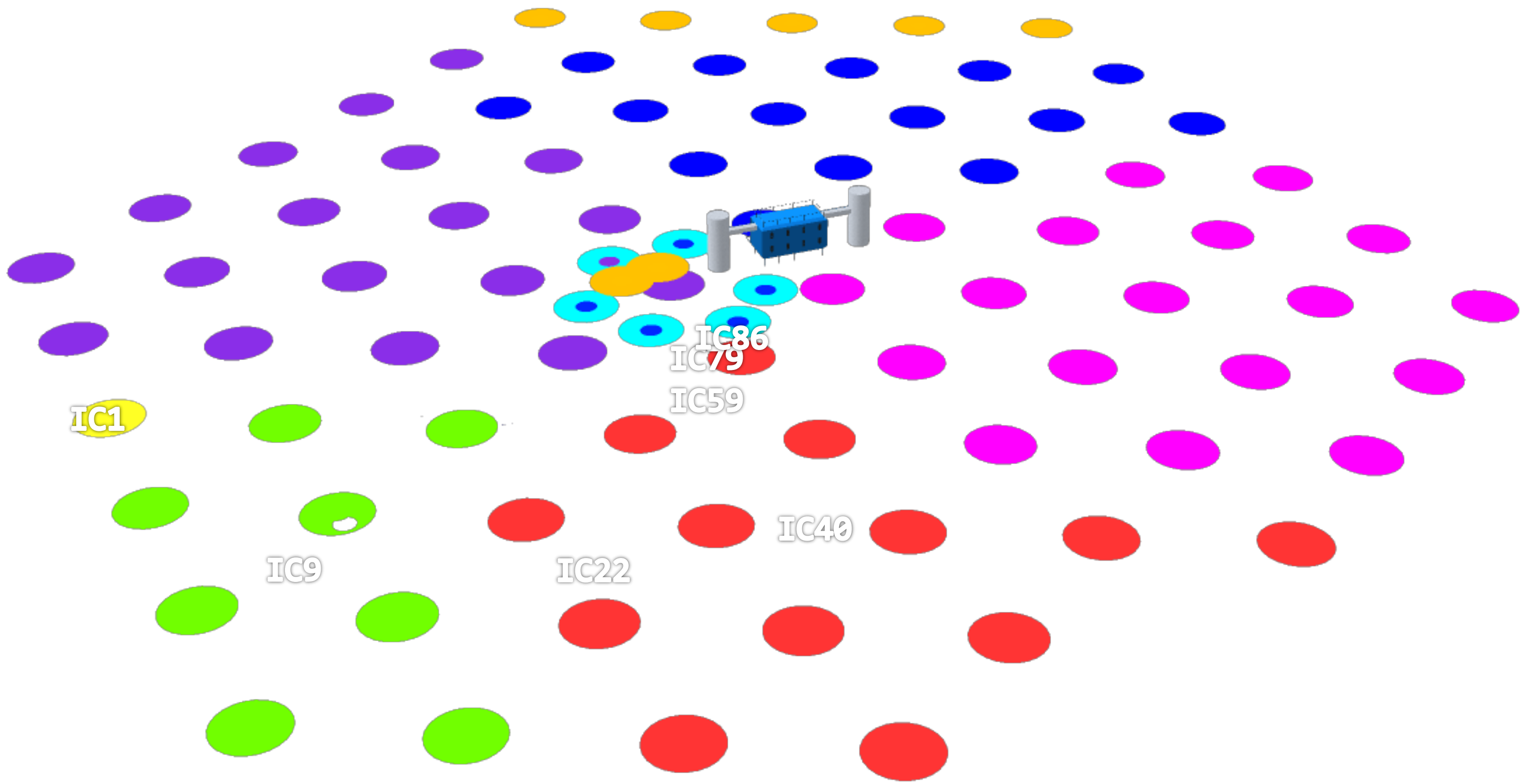
International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

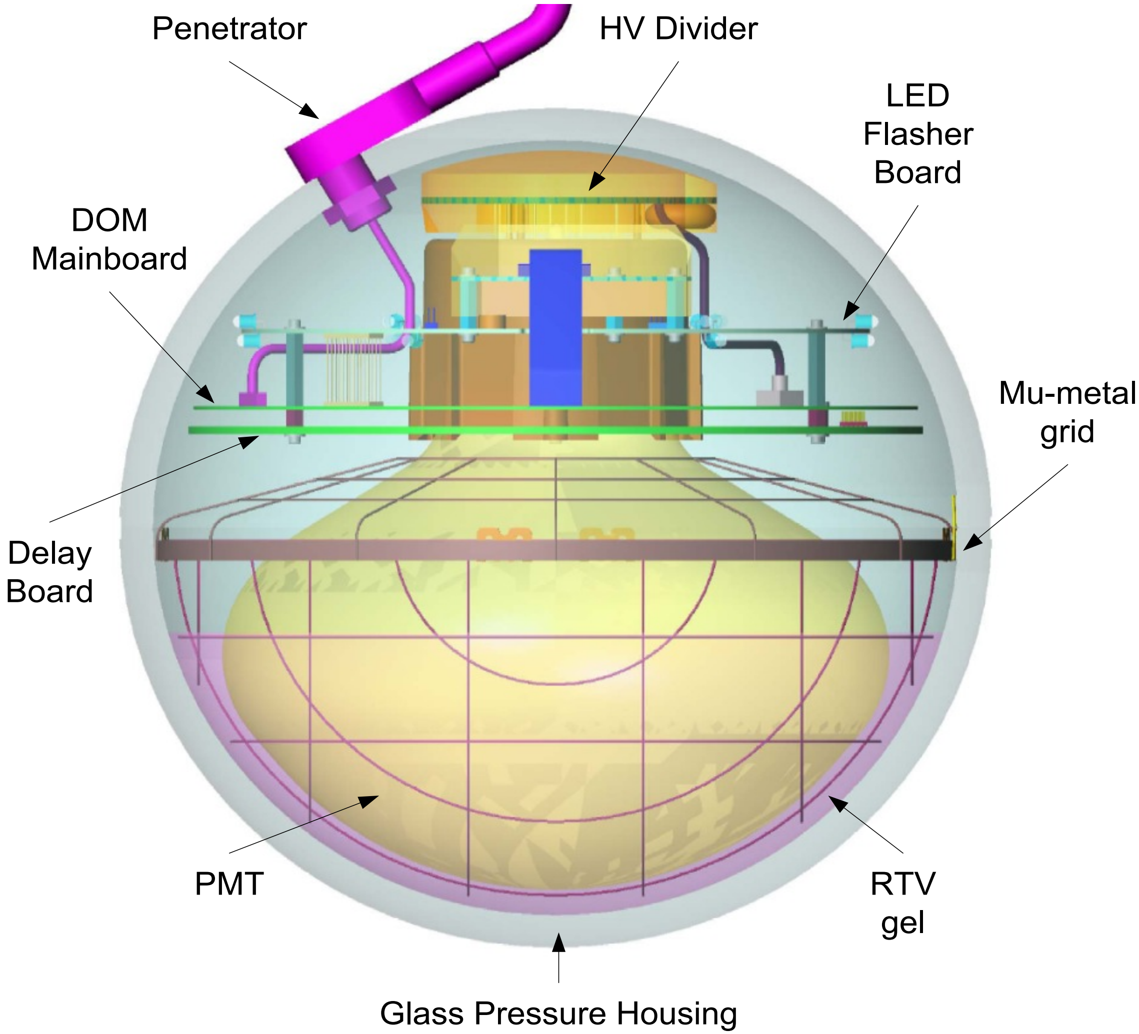
The IceCube Detector



IceCube Configuration Jargon Decoder Slide



The IceCube Digital Optical Module



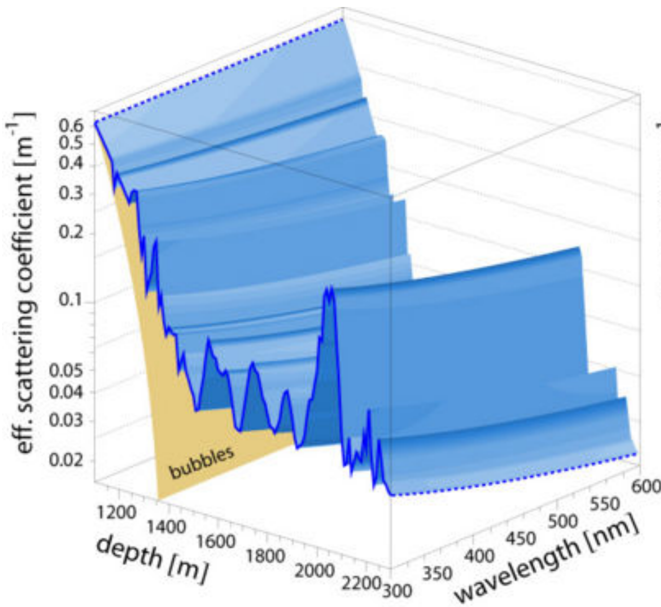
DOM Optical

- **Large Area Photocathode** 10″ 10-stage Hamamatsu R7081-02 bialkali PMT (peak *QE* 24% @ 420 nm); High QE variant (peak *QE* 35% @ 420 nm) used in DeepCore DOMs
- **Low noise** 500 Hz background counting rate in-ice @ 0.25 pe threshold
- **Glass / Gel** 0.5″ thick Benthos pressure housing rated to 10,000 psi. Better transmission in 330 - 400 nm relative to AMANDA OM. Low radioactivity glass.
- **Optical calibration** Each DOM calibrated $\varepsilon(\lambda, T)$ in the lab to about 7%; *in-situ* flashers additionally permit in-ice optical measurements

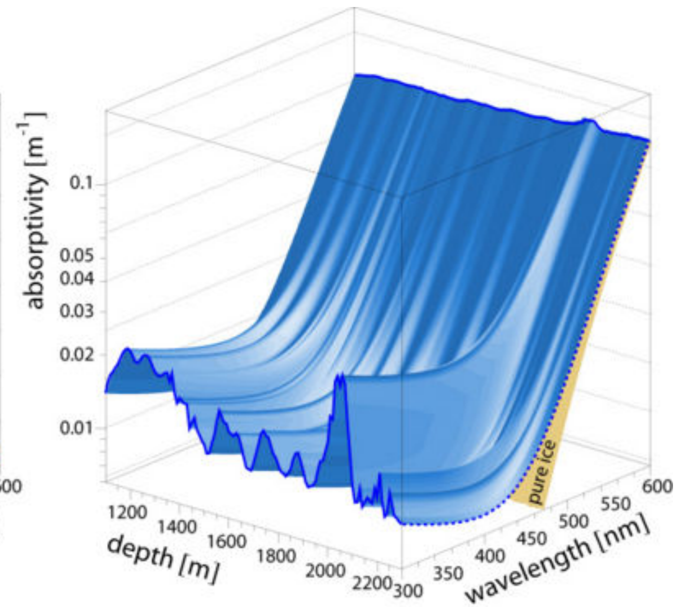
DOM Electronics

- **"Smart" autonomous digital sensor** FPGA with hardcore ARM CPU running embedded system. 4k-hit deep memory buffer stores hits until readout over 1 Mbit digital link to surface.
- **High-speed pulse digitization** Full waveform capture for hits which have coincidence trigger with neighbors. Waveform capture ASICs 14 bits effective @ 300 MSPS.
- **Array Timing** Handled in DOM comms protocol - DOM-to-DOM timing to 1-2 ns precision using *RAPCal* method.
- **Low power** - 3.75 W / DOM

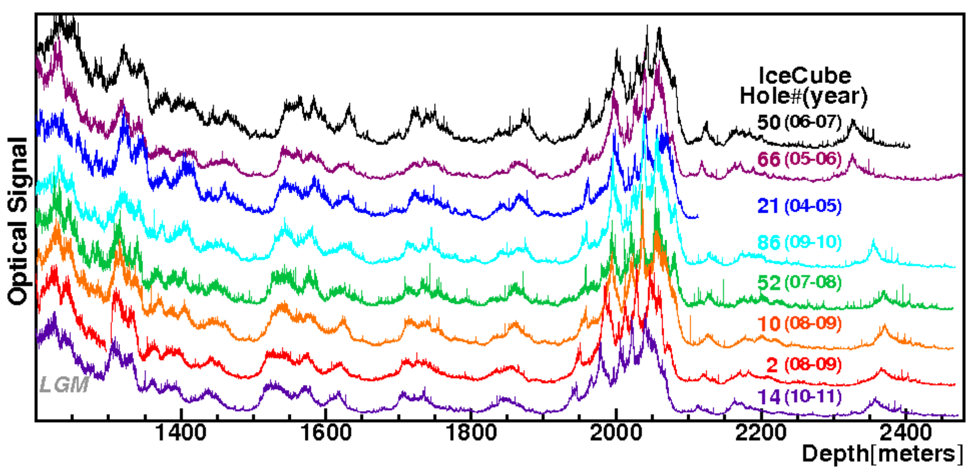
The Ice



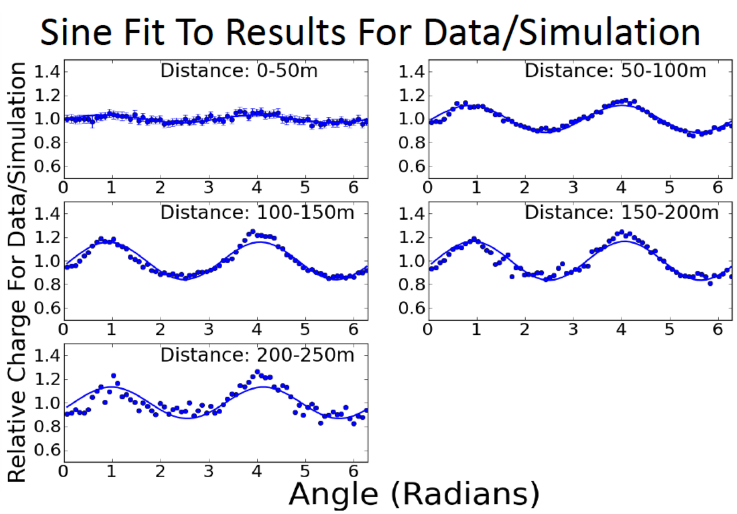
eff. scattering coefficient [m^{-1}]
0.6
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
bubbles
depth [m]
1200
1400
1600
1800
2000
2200
wavelength [nm]
300
350
400
450
500
550
600



absorptivity [m^{-1}]
0.1
0.05
0.04
0.03
0.02
0.01
pure ice
depth [m]
1200
1400
1600
1800
2000
2200
wavelength [nm]
300
350
400
450
500
550
600



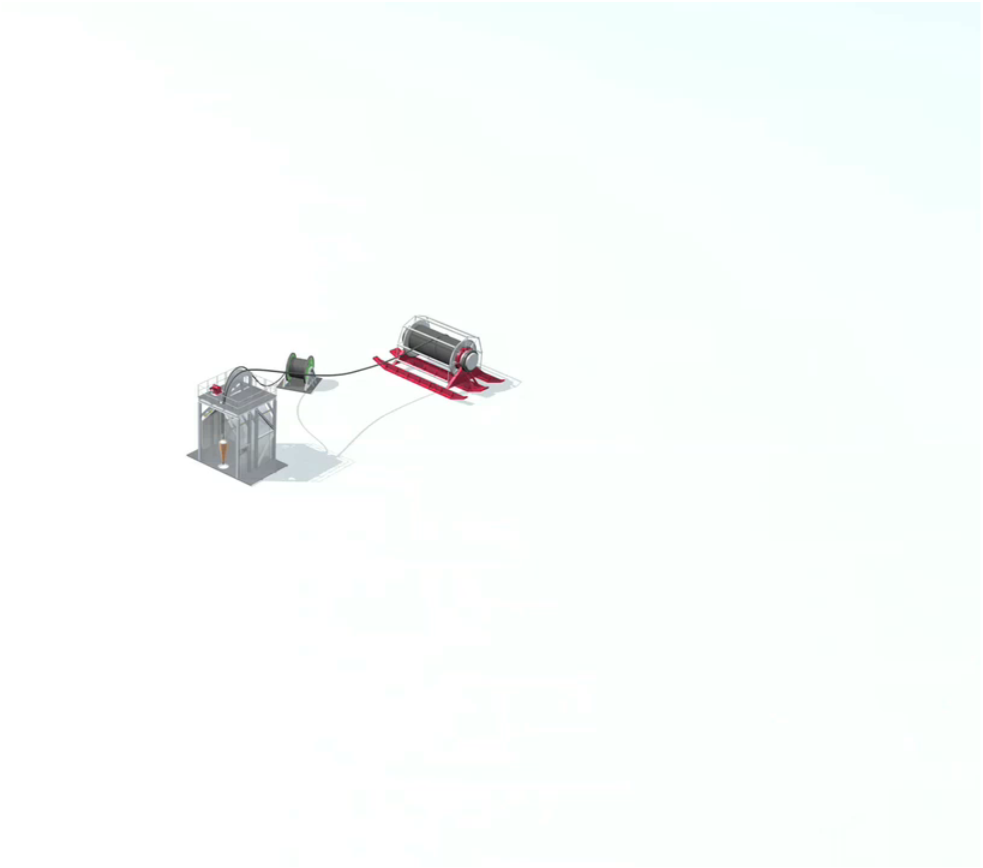
Optical Signal
IceCube Hole#(year)
50 (06-07)
66 (05-06)
21 (04-05)
86 (09-10)
52 (07-08)
10 (08-09)
2 (08-09)
14 (10-11)
LGM
1400
1600
1800
2000
2200
2400
Depth[meters]



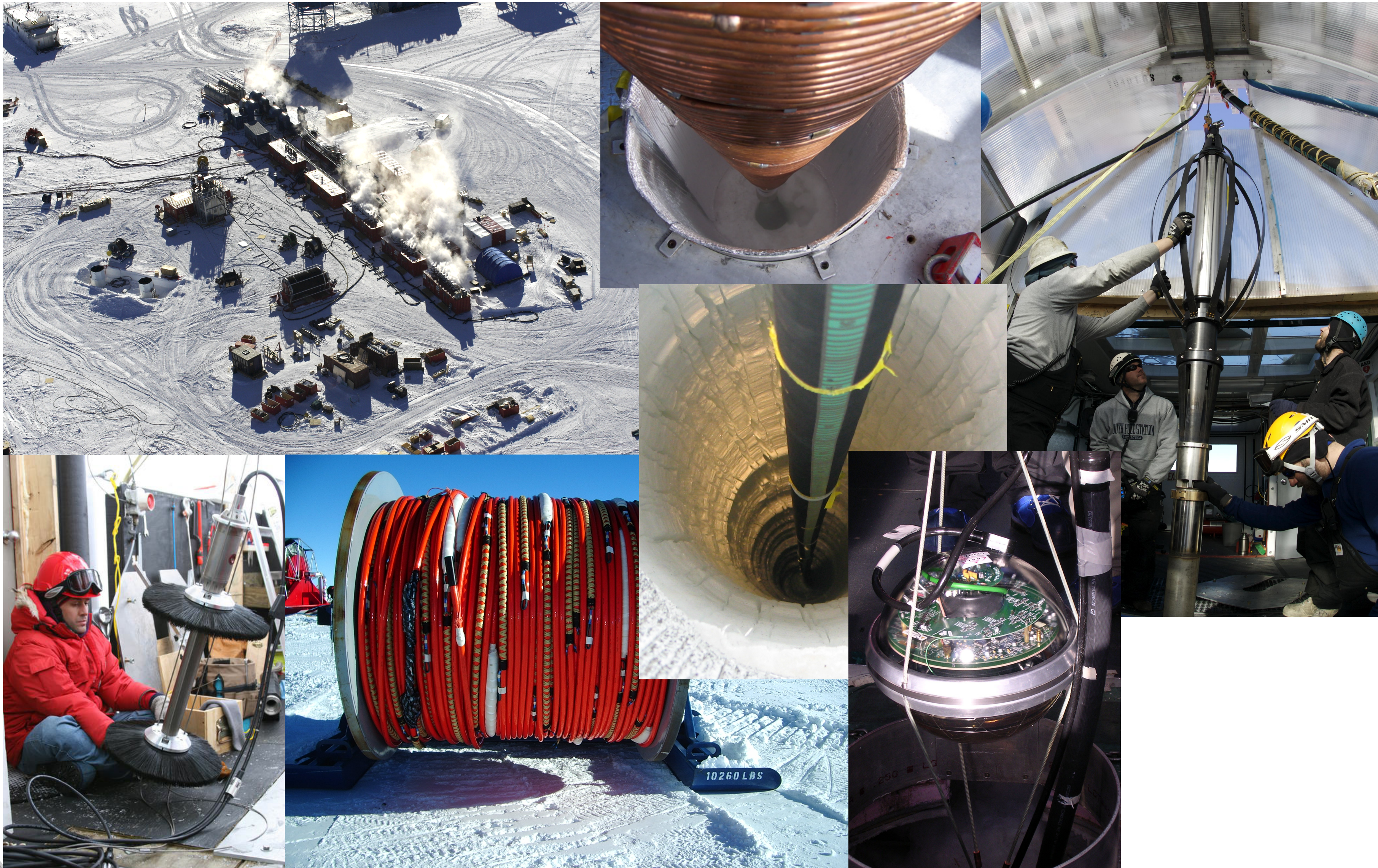
Sine Fit To Results For Data/Simulation
Distance: 0-50m
Distance: 50-100m
Distance: 100-150m
Distance: 150-200m
Distance: 200-250m
Relative Charge For Data/Simulation
Angle (Radians)

Drilling with the EHWD

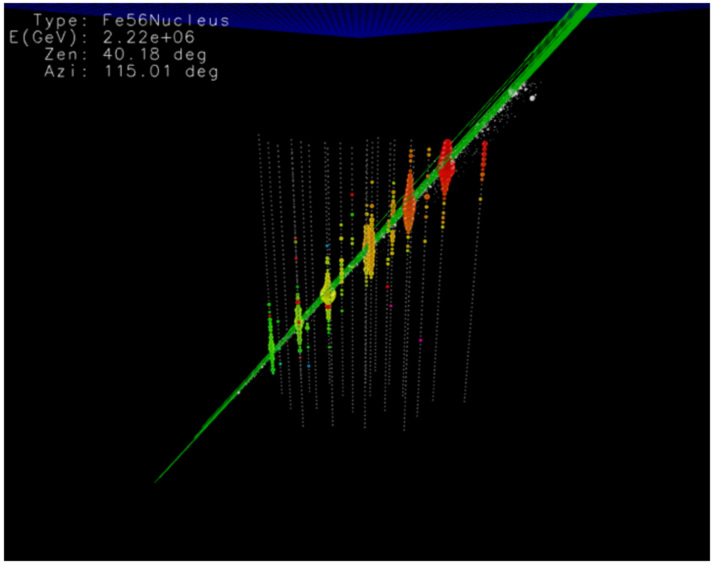
- Drill power plant 5MW
- 195°F pressurized hot water + closed loop water recovery system
- Drilling & deployment process
  - Drill 50 m with hot iron to get below hard packed snow layer called *firn*.
  - Drill 60cm hole to 2.5 km depth – takes approx 24h
  - Retrieve drill head and *ream* as you go out – takes another 6-8h
- Optical module deployment
  - DOMs attached to main cable – 5 min / DOM
  - String drop at 20 m / min after attach
  - Entire deployment is another 8h.



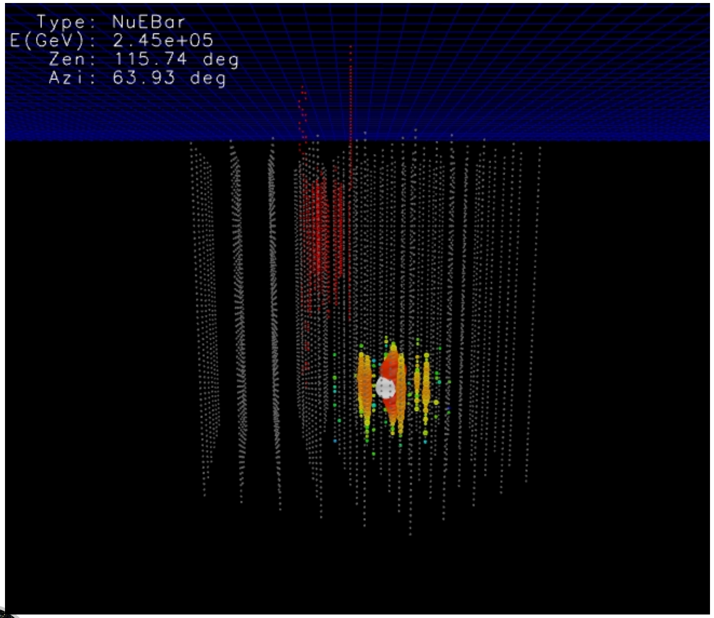
Drilling & Deployment

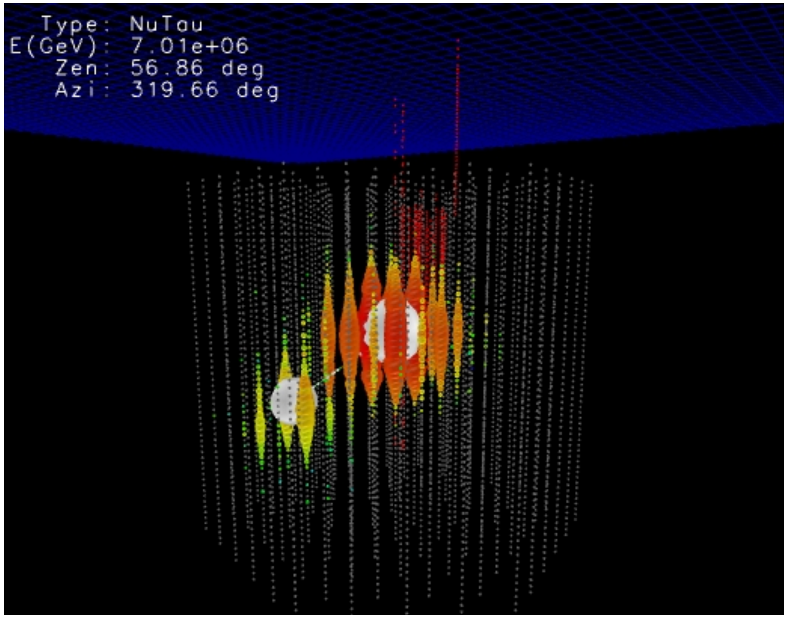


Detection of Neutrinos in the Ice

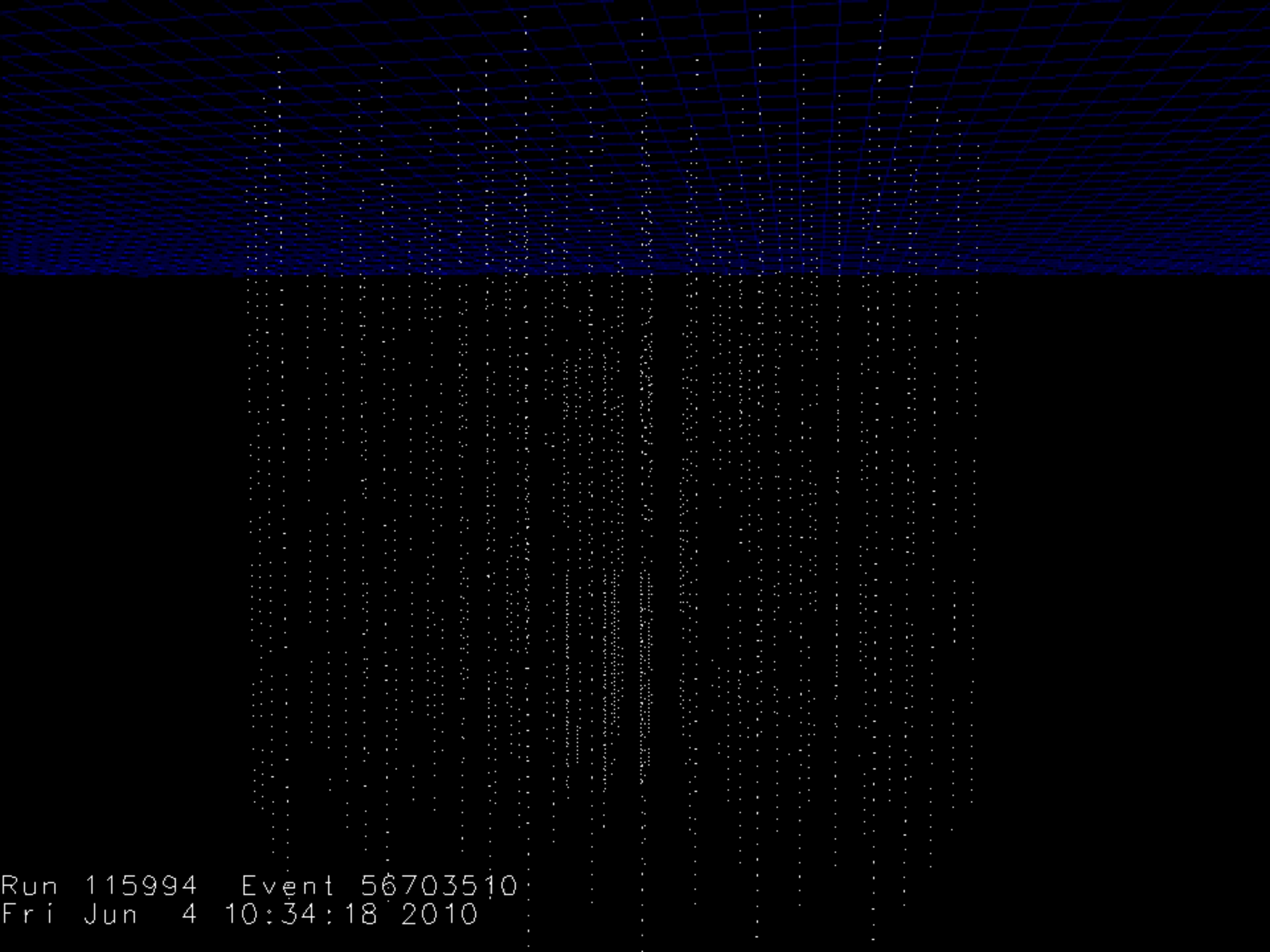


- About 25000 detectable Cherenkov photons per GeV of energy deposited within the detector – scales linear with E
- Muons leave track-like deposit.
- EM / Hadronic showers more or less ball-like but anisotropic so it is possible to achieve some angular resolution even on cascades.

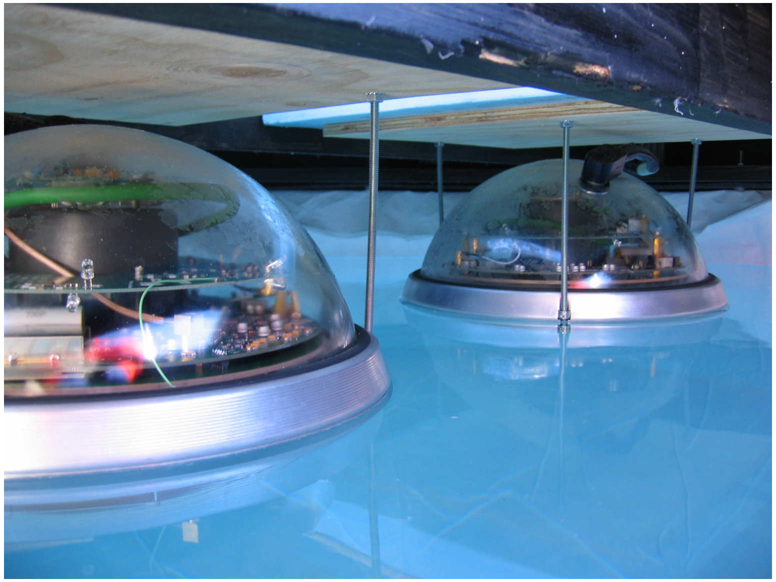




ICECUBE


Run 115994 Event 56703510
Fri Jun 4 10:34:18 2010

IceTop



The IceTop array is air shower array composed of 2 frozen ice tanks at the top of every (non-DeepCore) hole. Each tank includes 2 standard DOMs (see picture at left).

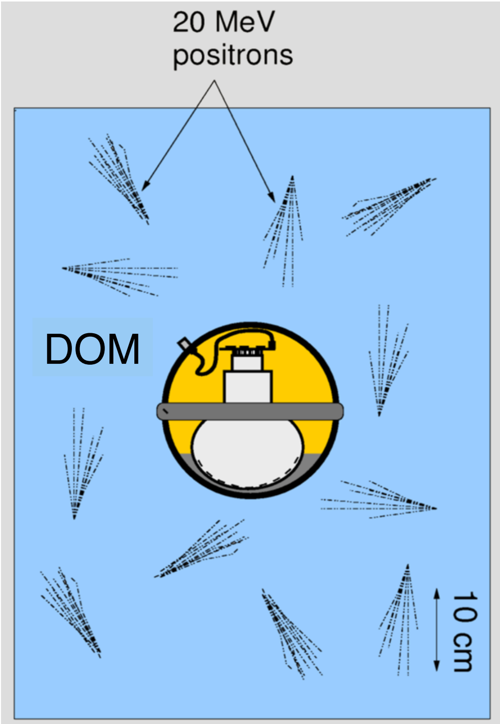
IceTop functions:

- Calibration point for deep ice array (air shower reconstruction independent and higher precision than in-ice track reconstruction).
- VETO for deep ice array with limited solid angle.
- 3D air shower detector: by analysis of surface component (mainly EM) and deep component (muons) of air shower events, it is possible to reconstruct the energy and the composition of the primary CR.

Neutrino astronomy at 1 MeV

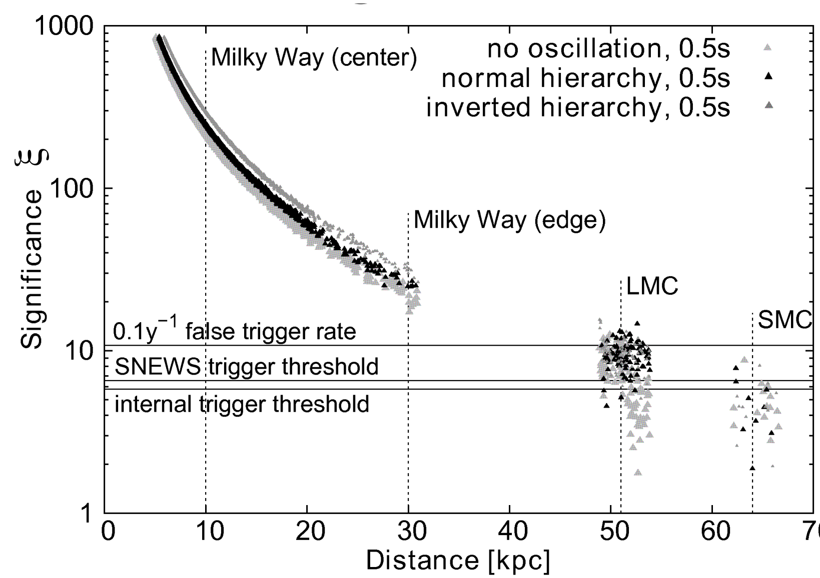
SUPERNOVA NEUTRINO DETECTION IN LARGE CHERENKOV TELESCOPES

Detection of MeV-scale positrons in IceCube



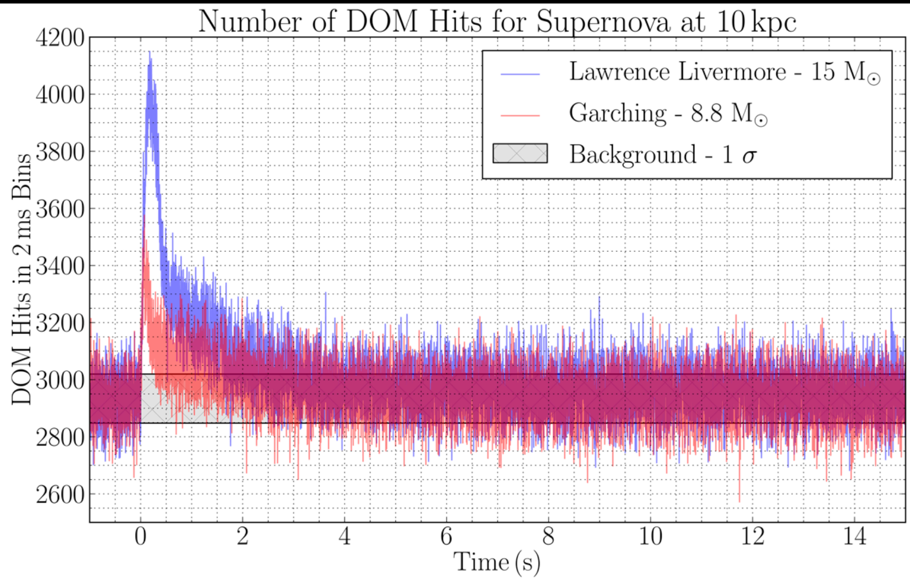
Principal detection channel inverse β decay antineutrinos → O(20) MeV e^+. Each interaction too weak to detect individually but SN burst yields 500k – 1M events in IceCube over 10s. Due to low background rate of IceCube PMTs this gives high significance detection. With artifical deadtime of 200 μs (PMT noise dominated by correlated late-light not ion afterpulsing) – background is 250 Hz / channel.

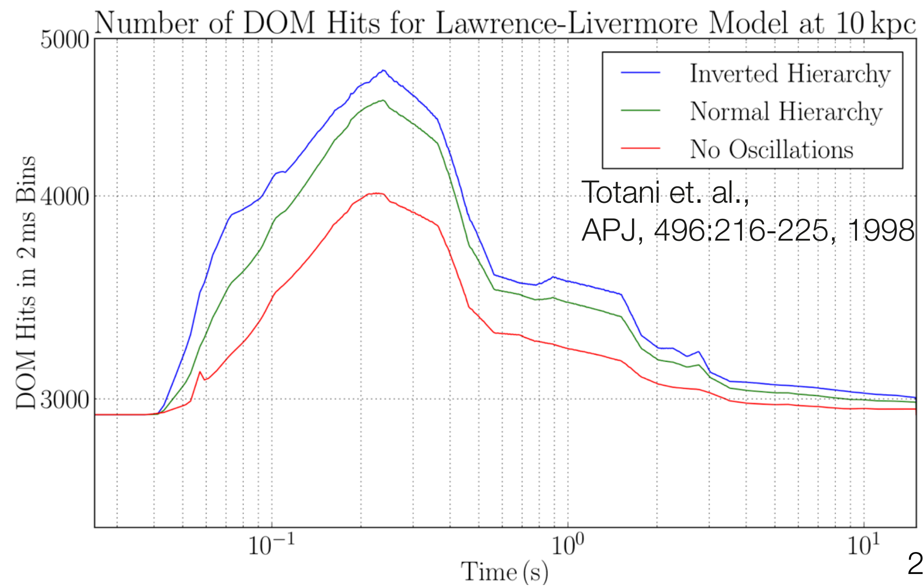
Each DOM has 1.6 ms integrating firmware counter and transmits this data separately to SN online trigger.



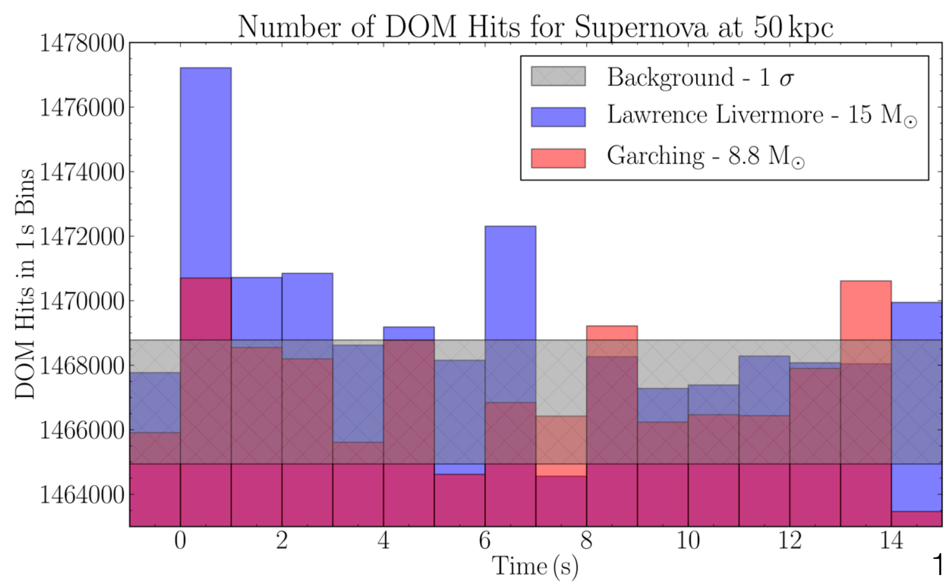
- Good time resolution but
  - No pointing
  - No energy resolution yet but feasibility studies with DeepCore DOMs indicate marginal possibility to obtain average neutrino energy.
- IceCube participating in the SNEWS global SN network since 2008.

Expected Signal from GC / LMC

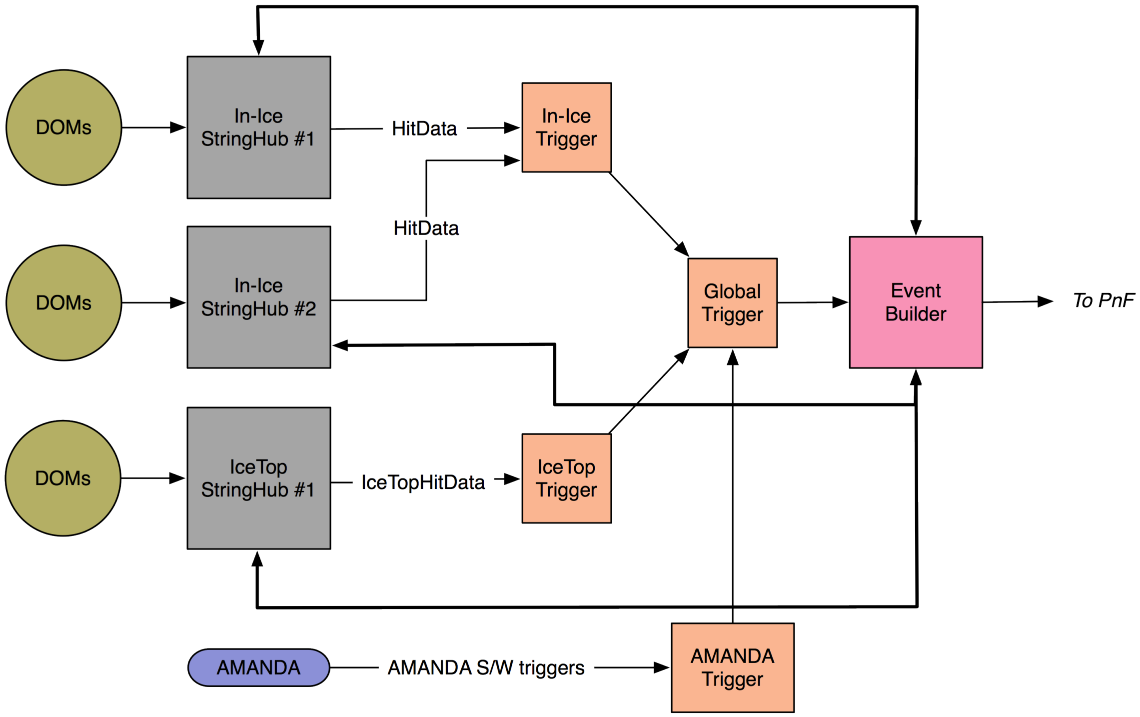


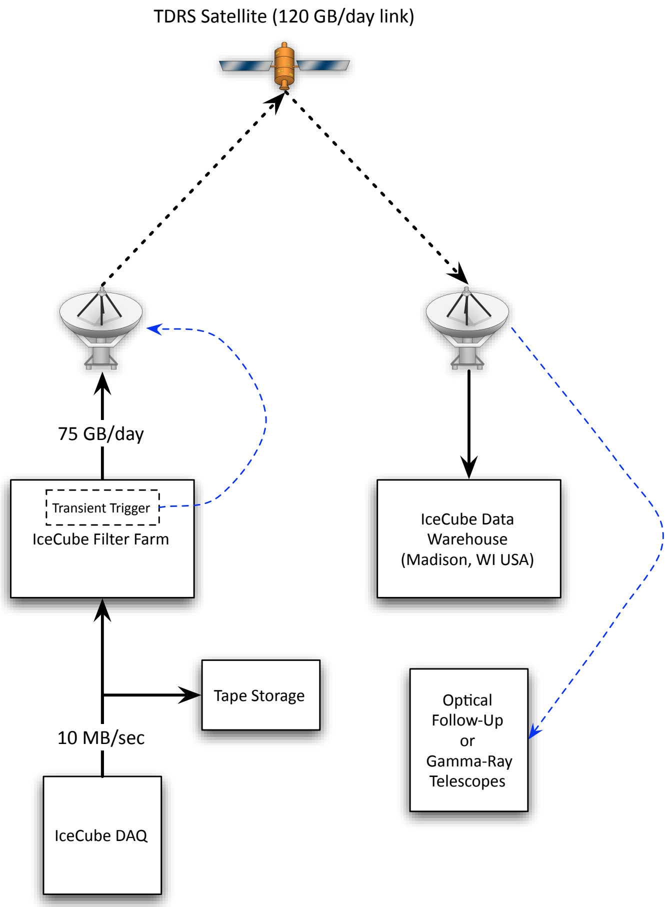


- For GC in galaxy enough statistics to in principle detect difference between NH and IH (MSW in PNS flavor changes higher-temperature flavors into electron anti-neutrinos).
- However these predictions are quite model dependent.
- Statistics marginal in LMC/satellite galaxies but completely sufficient for detection.



Triggering and Data Processing





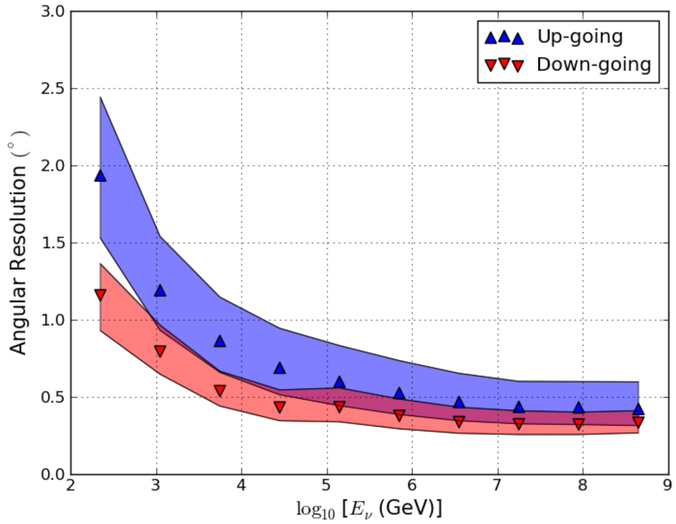
- Photon hits semi-autonomously time-stamped and digitized by DOMs (there is a local coincidence signal shared by near DOMs which determines how much information digitized).
- Readout via 3.5 km copper cable @ 1 Mbit
- Low-latency triggering (< 3s) and event assembly writes 3.5 kHz events/s (10 MB/s). Basic trigger condition is 8 hits in 5 μs but multiple triggers now running.
- Online cluster at Pole reconstructs and filters 100 GB/day and sends over TDRS link.

Fast triggers can be sent to optical follow-up instruments.

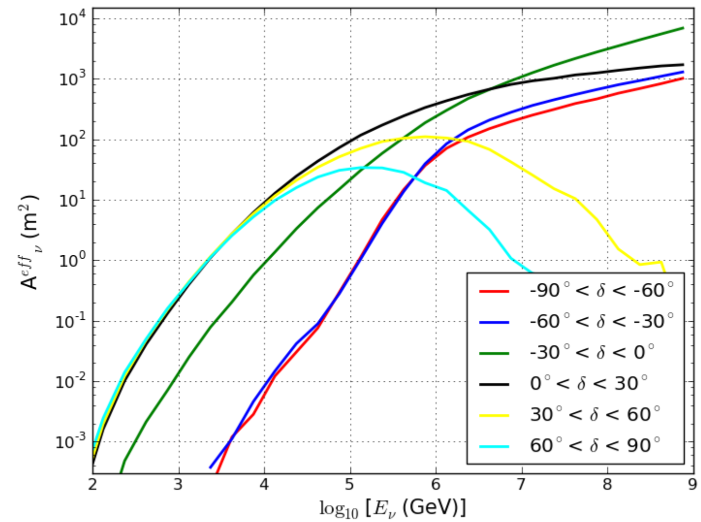
ICECUBE

IceCube Reconstruction Performance

Point sources angular resolution

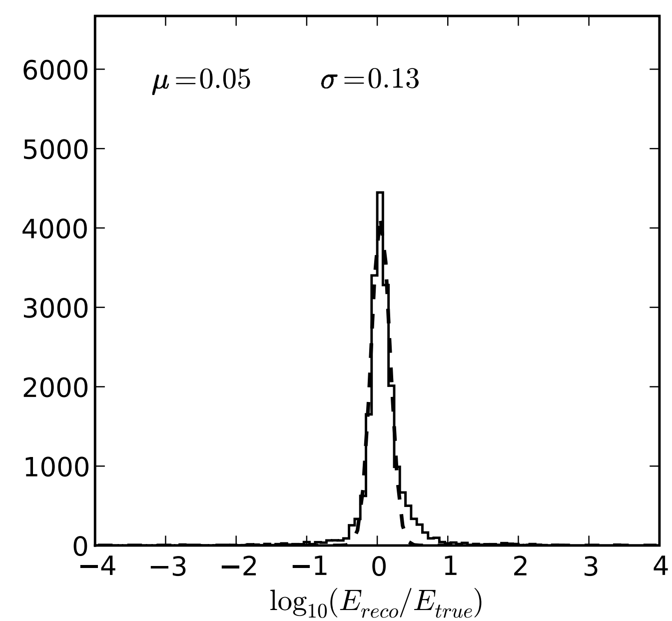


Point sources neutrino effective area

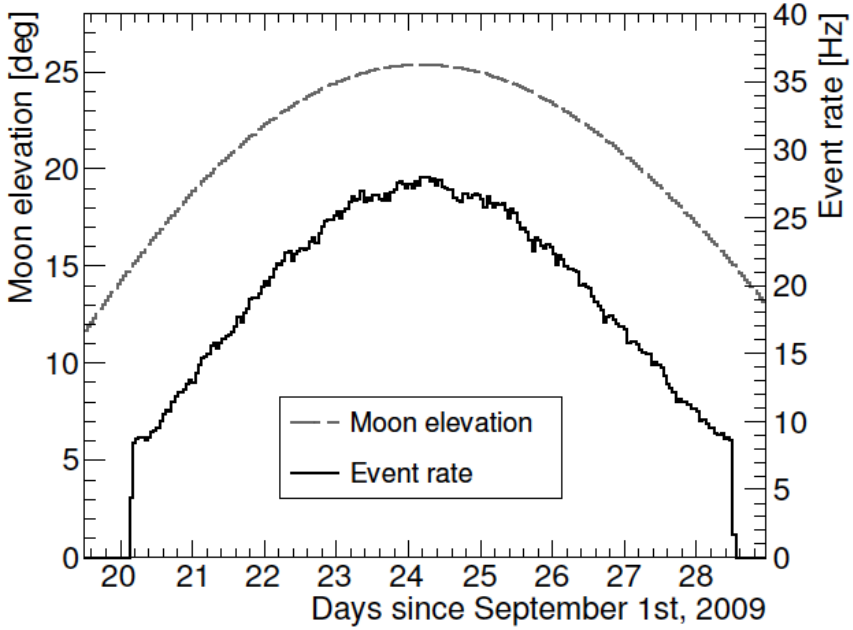


- Pointing and energy resolution *extremely* analysis dependent – these are only indicative plots
- Muon energy reco from dE/dX … but only gives the local energy of muon. Extremely hard to get good neutrino energy for through-going muons.
- Cascade angular reconstruction poor but has improved quite a bit – now O(10°).

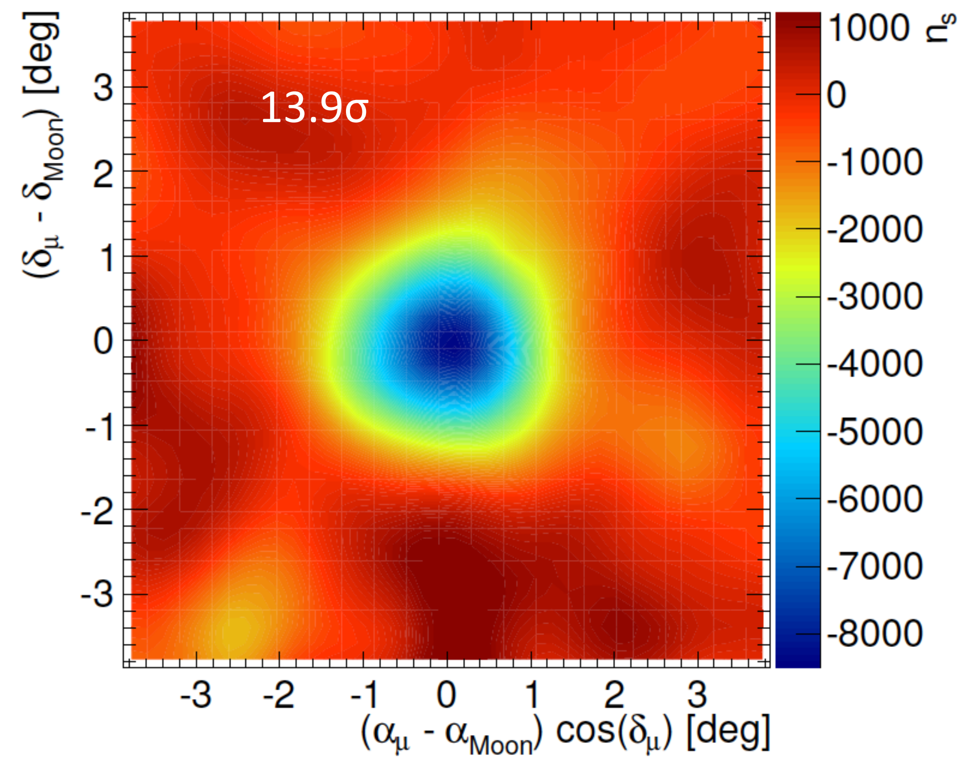
HE cascade E resolution



Shadow of the Moon IC40+IC59

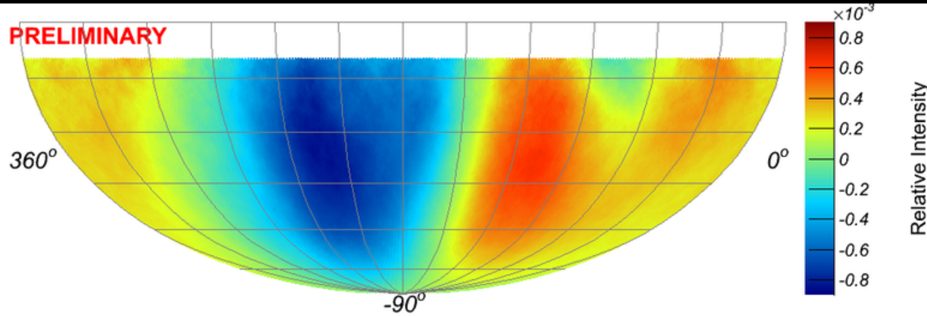


- Filter selects reco'd events with 10° in δ and 40°/cos(δ) in r.a.
- >11 DOMs on >2 strings
- 130 million events for IC40
- 180 million events for IC59
- Median E is about 40 TeV for selection in both IC40 & 59.

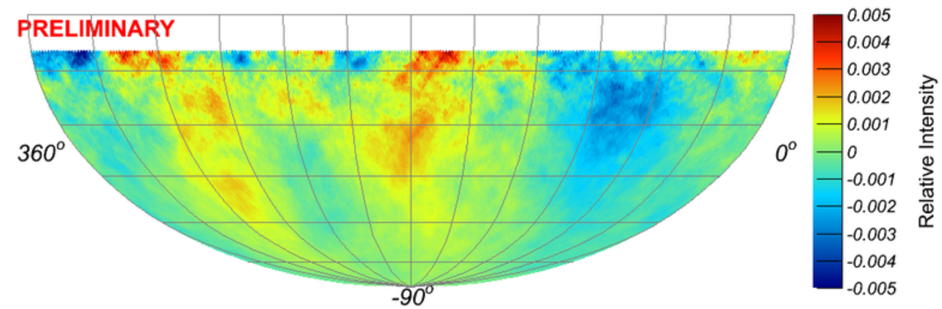


- Verifies timing accurate to minute scale (should be in fact 100 ns from GPS but nice to have X-check)
- Detector resolution
  - 1.13° IC40
  - 0.98° IC59

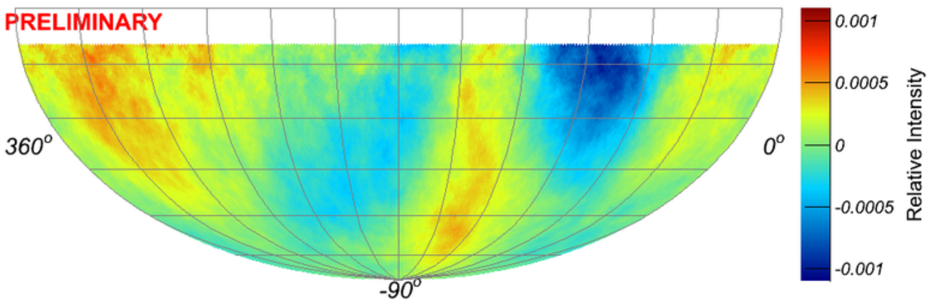
IC79 Cosmic Ray Anisotropy Measurements



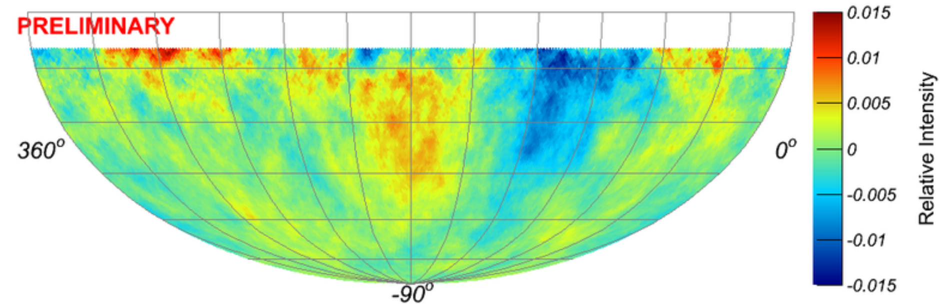
IC79 40 TeV 20° smoothing



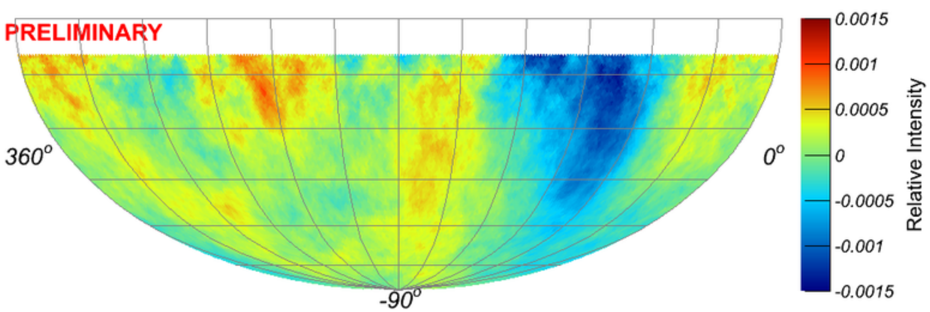
IC79 1 PeV 20° smoothing



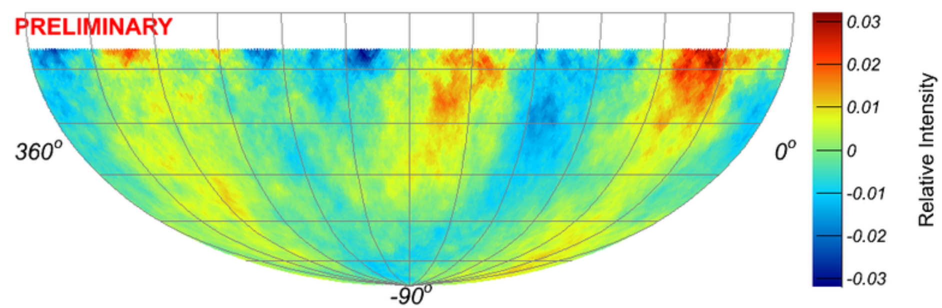
IC79 200 TeV 20° smoothing



IC79 5 PeV 20° smoothing



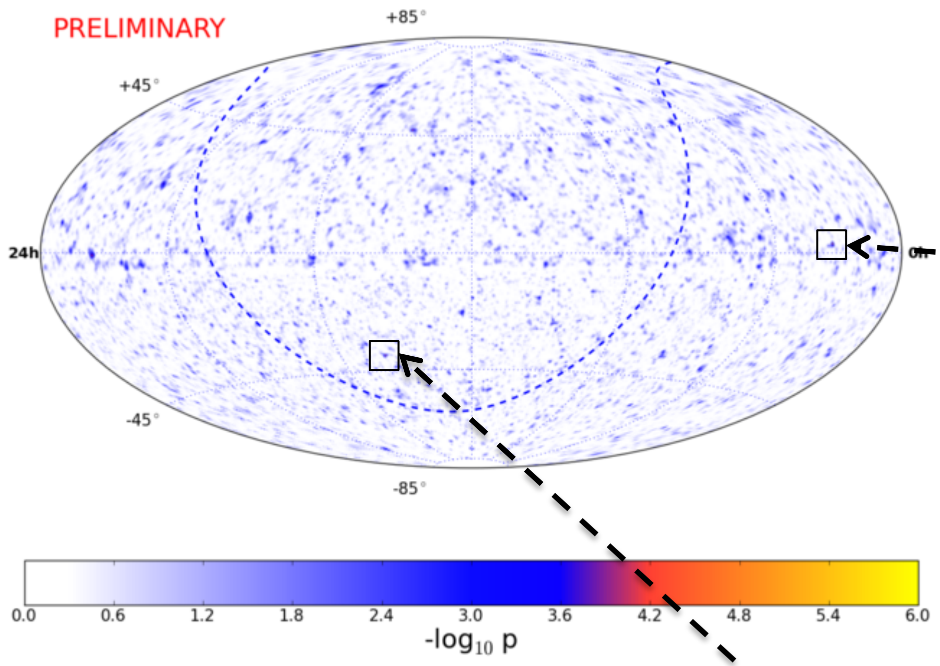
IC79 400TeV 20° smoothing

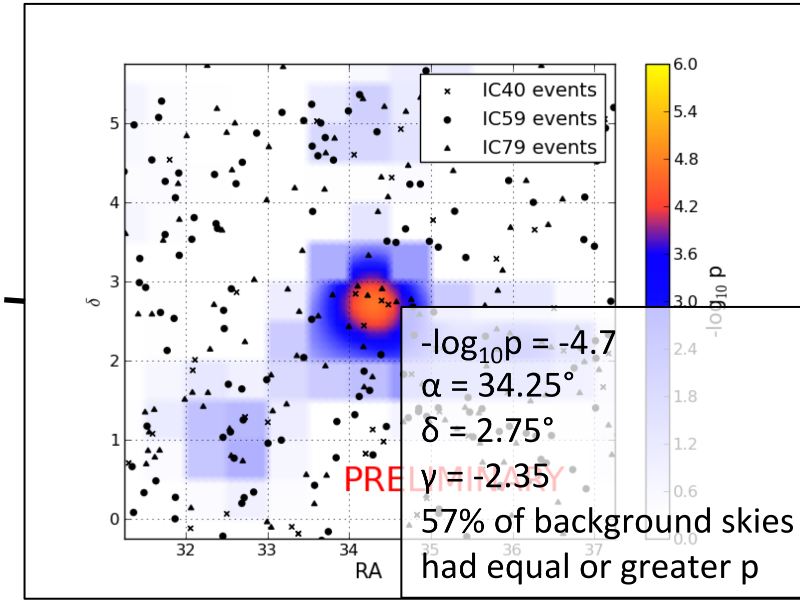


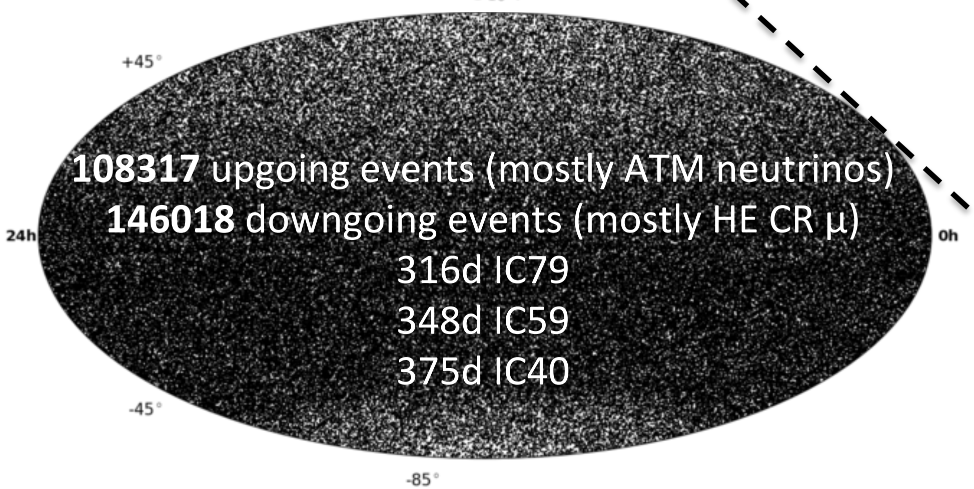
IC79 10 PeV 20° smoothing

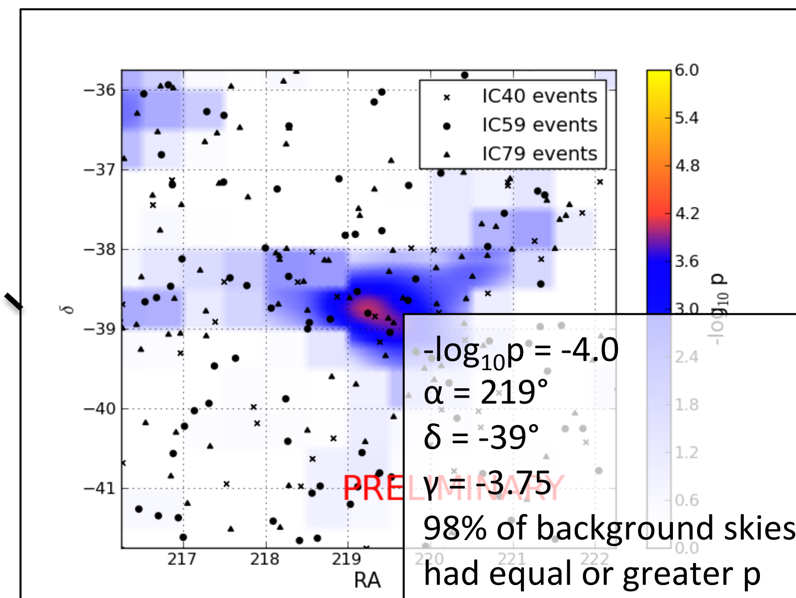
See ApJ **746** (2012) 33 or arXiv:1109.1017 for IC59 published results

IC79+59+40 Skymap

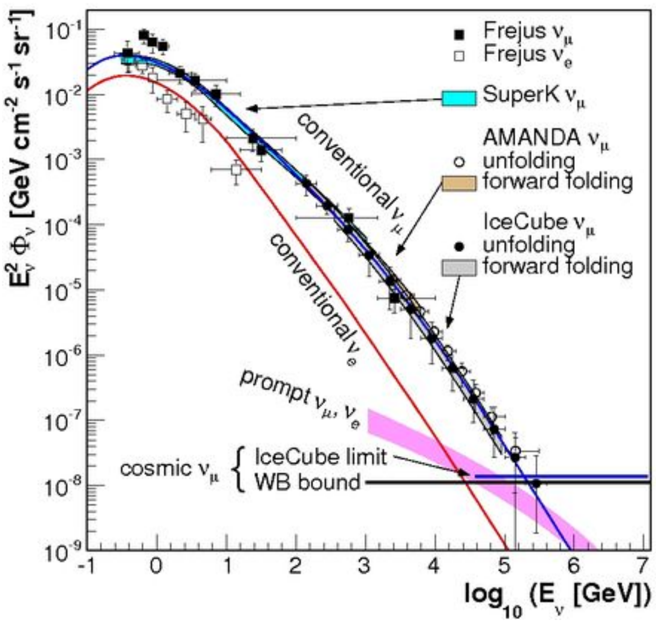


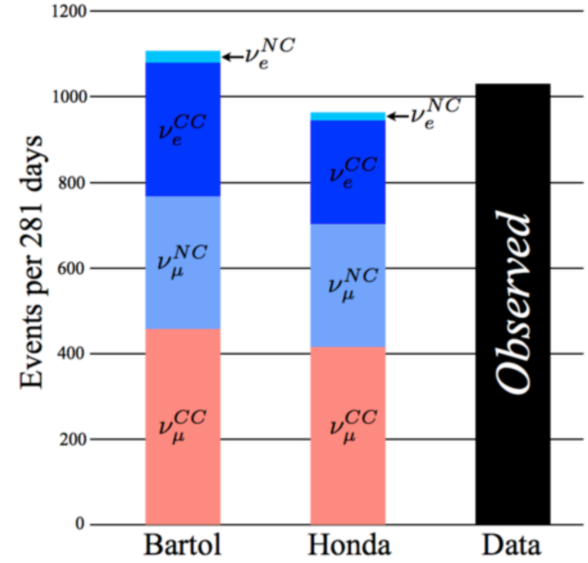






Atmospheric Neutrinos and Cascades in IceCube





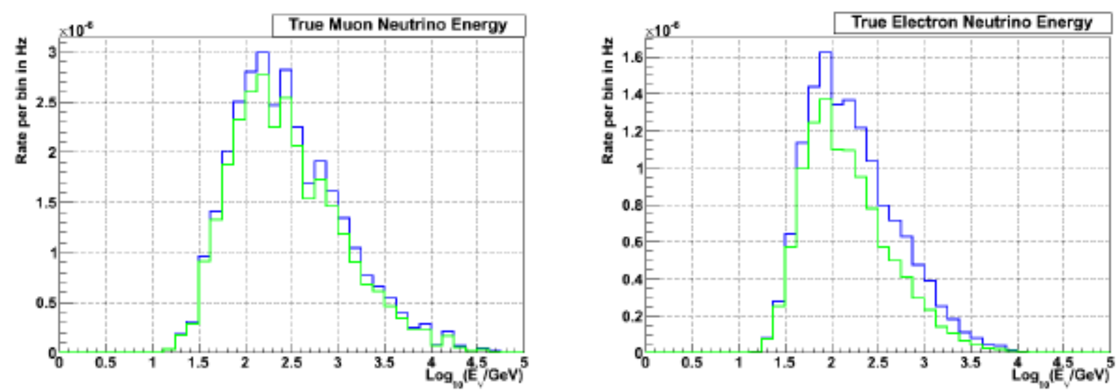
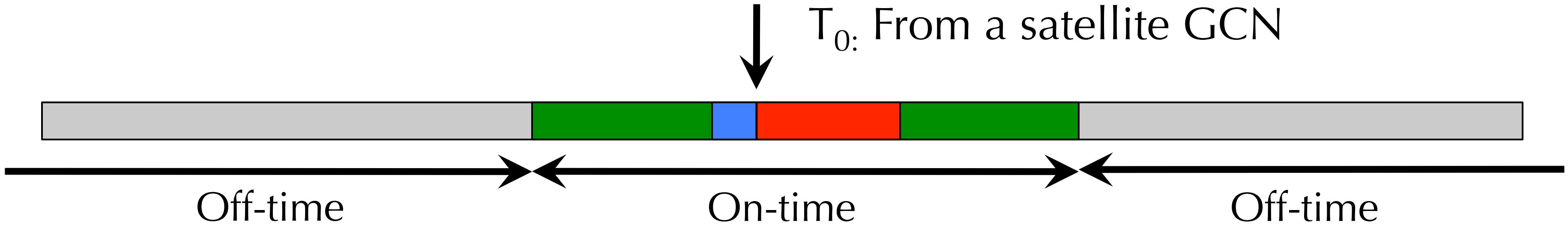


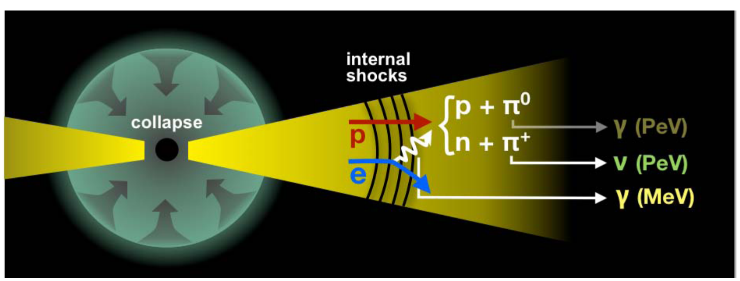
Figure 10.2. Atmospheric neutrino spectrum at final Hard Cut level (MC true energy). Left: true ν_μ energy spectrum is shown. with the Bartol model (blue) and Honda 2006 model (green). Right: true ν_e energy spectrum is shown. Large difference (40% at 1 TeV) is shown at higher energies though relatively small difference is shown at lower energies.

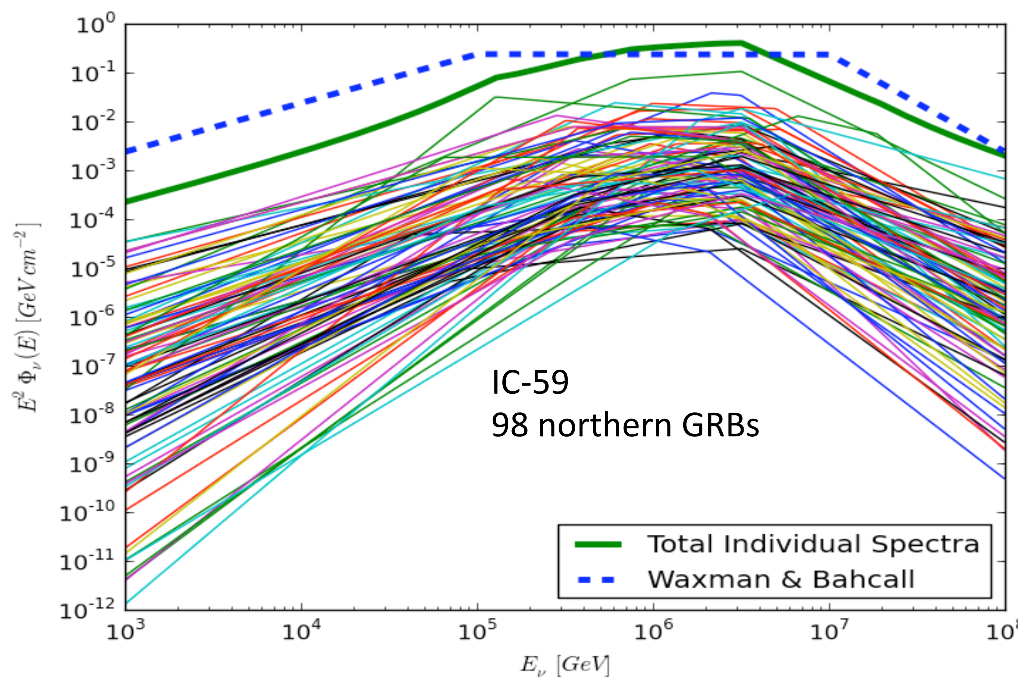
GRB Searches



- Precursor (~100 s)
- Prompt (T_{90})
- Model Independent (±24 h)
- Off-time (full year)

Very low background
One event can be significant





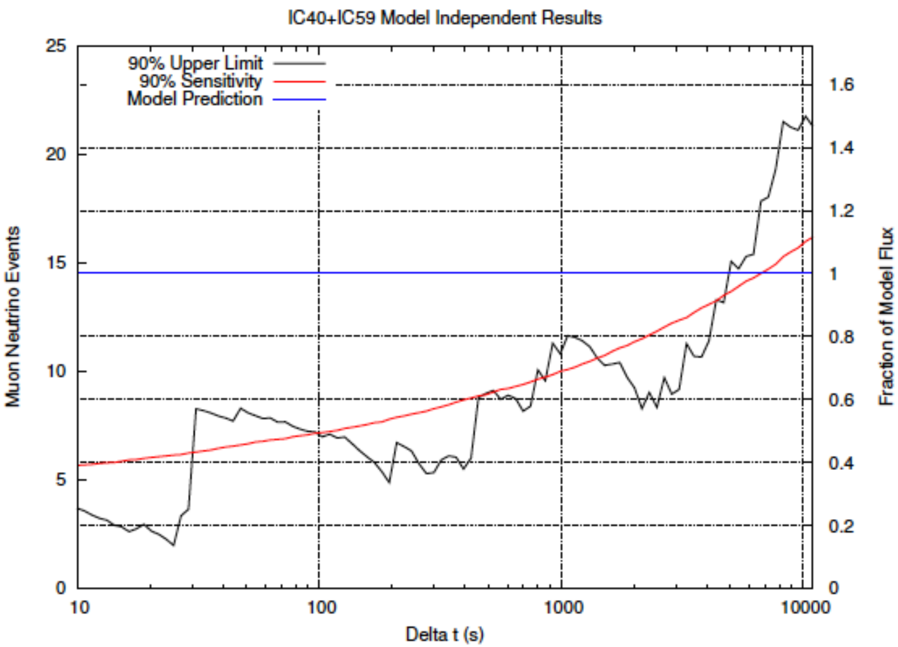
IC40 + IC59 GRB Results

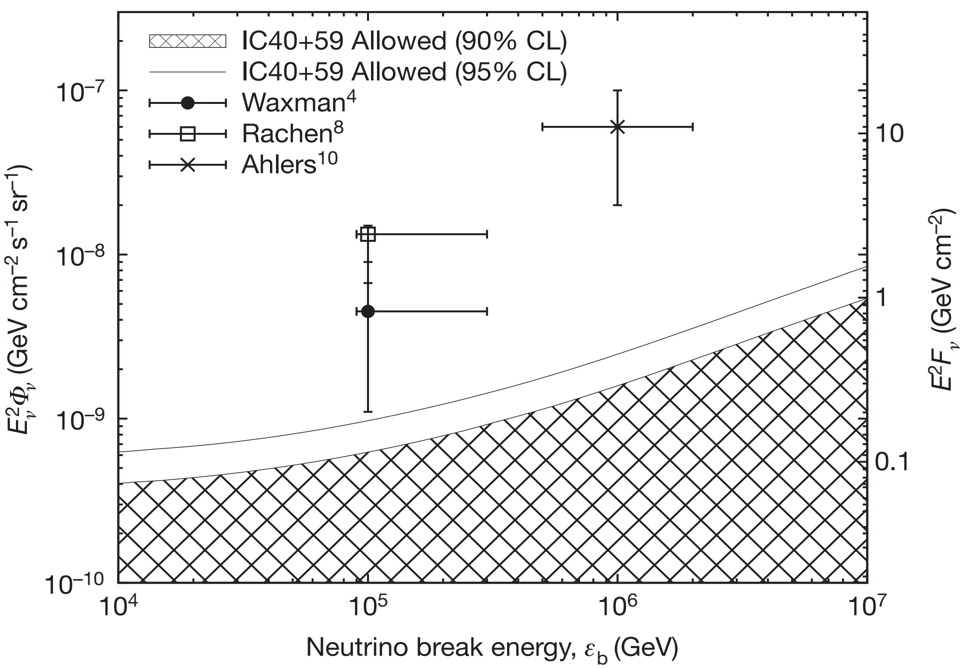
No observation of GRB neutrinos:

- "fireball" theory must be significantly revised
- hypothesis of GRBs as the only source of UHE CRs
  excluded for some models

8.4 events expected
0 events observed

Nature Vol **484**, 351 (2012)





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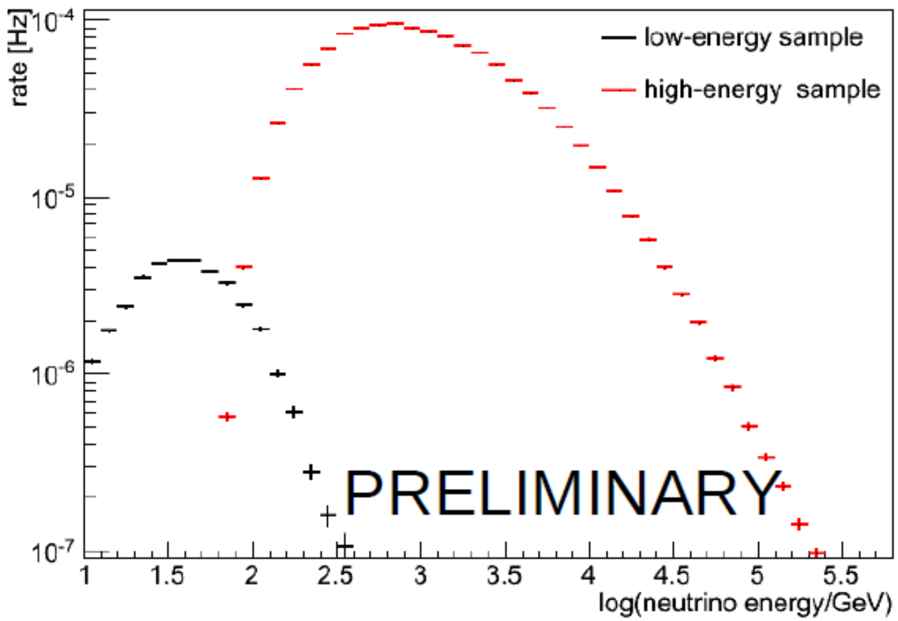
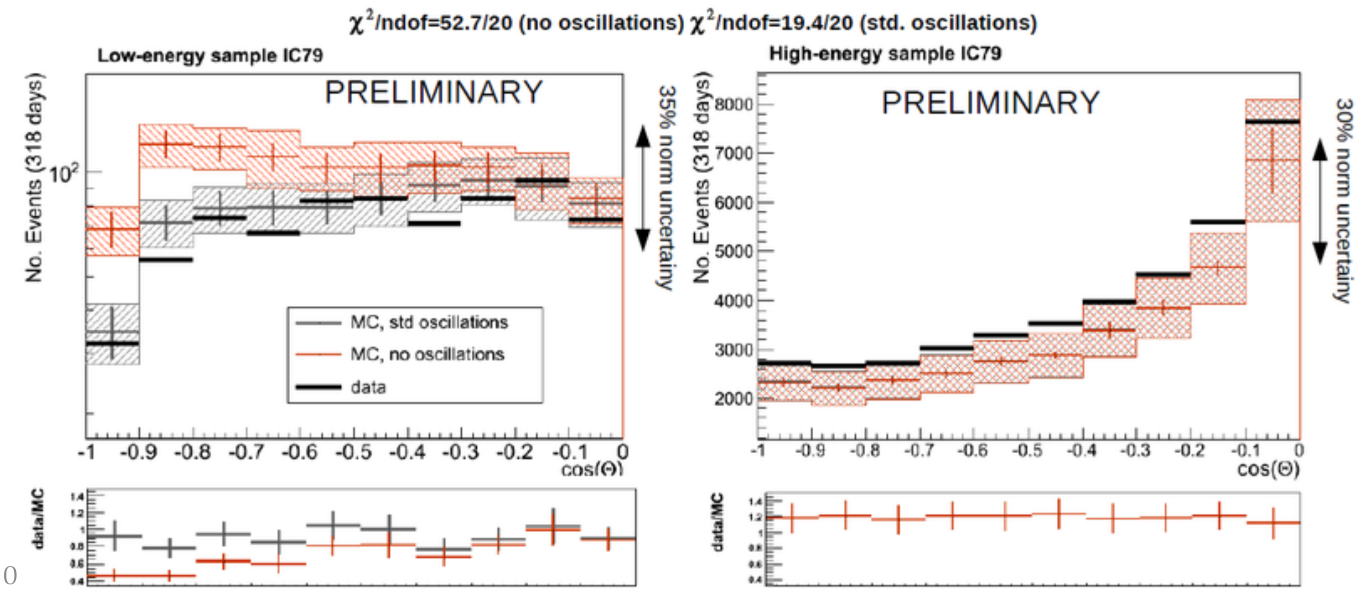
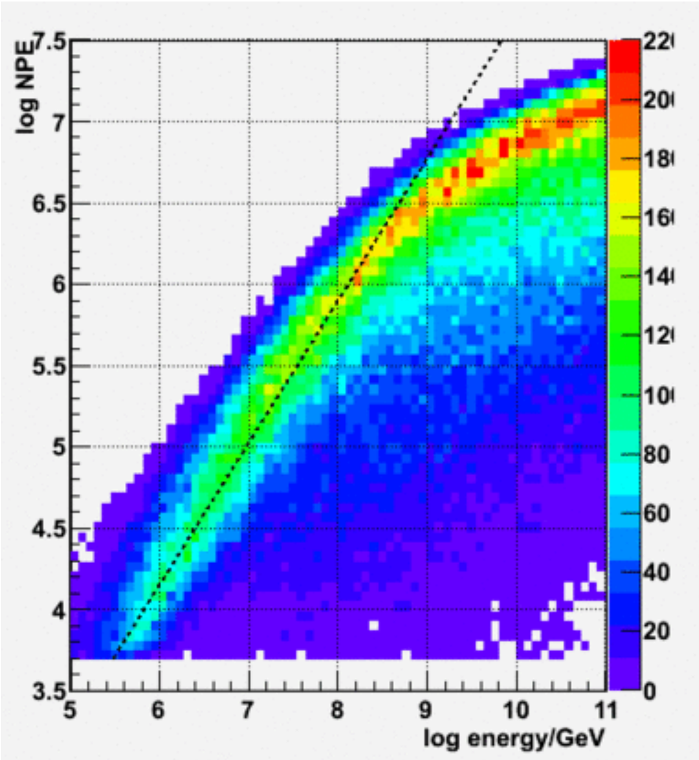
High Energy Oscillations





EHE Diffuse Analysis

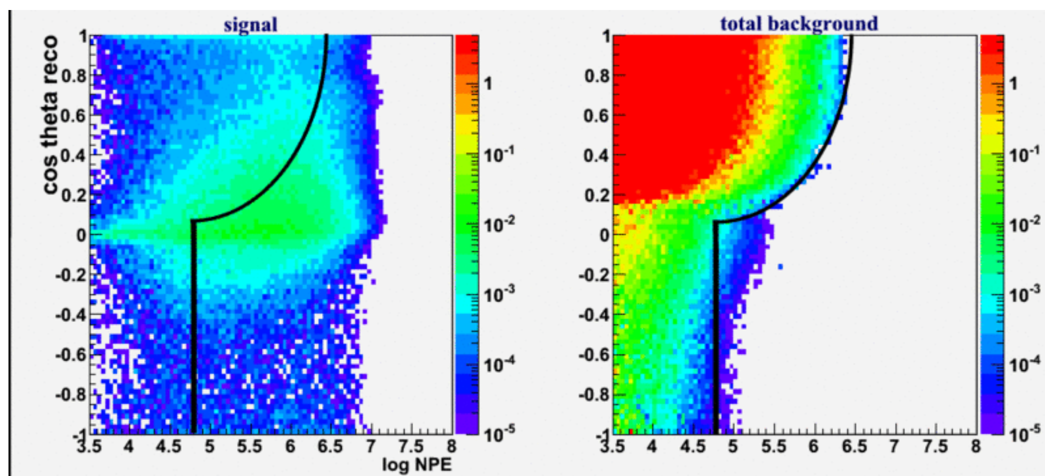


EHE event filter uses *energy proxy* NPE (# photo-electrons detected) and reconstructed zenith angle as discriminating variables. NPE is robust and fairly accurate for contained events up to almost 100 PeV. Above 100 PeV photons escape and PMT saturation becomes important.

In addition the variability of the ice clarity enlarges spread at all energies.

Combined analysis of IC79 and IC86 yields 2 cascade-like downgoing events both from IC86 run:

118545:63733662 Aug 8, 2011 1.14 PeV
119316:36556705 Jan 3, 2012 1.29 PeV



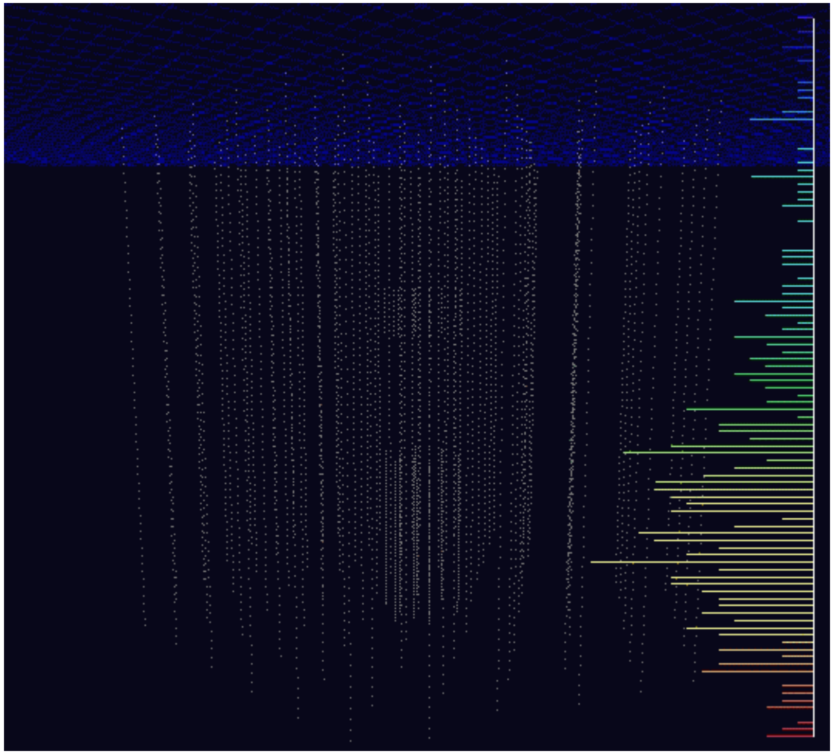
IceCube

Hints of a signal? Too early to say but certainly interesting

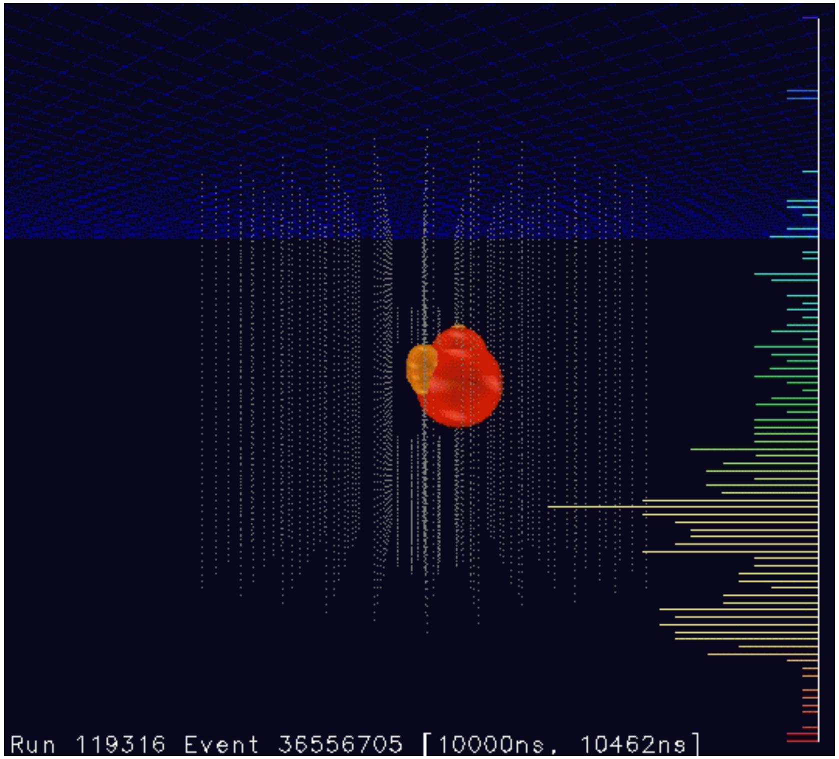
Systematics on Energy Reco ~ 35% currently but we are working to improve this.

Background estimates post-unblinding are moving target based on best available information but are all so far << 1. Follow up studies underway. Stay tuned.

EVENT 118545:63733662 1.14 PeV



EVENT 119316:36556705 1.29 PeV

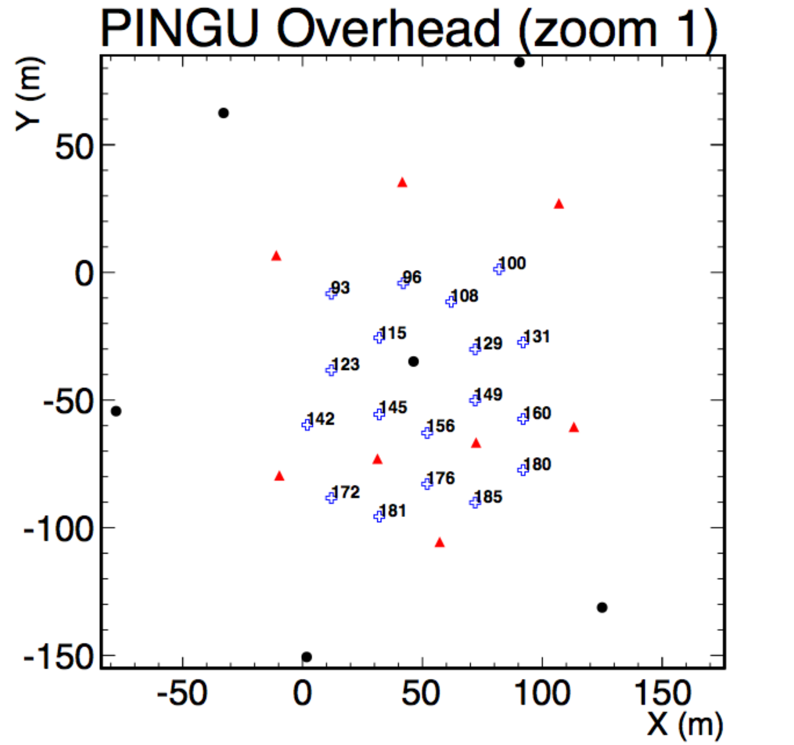


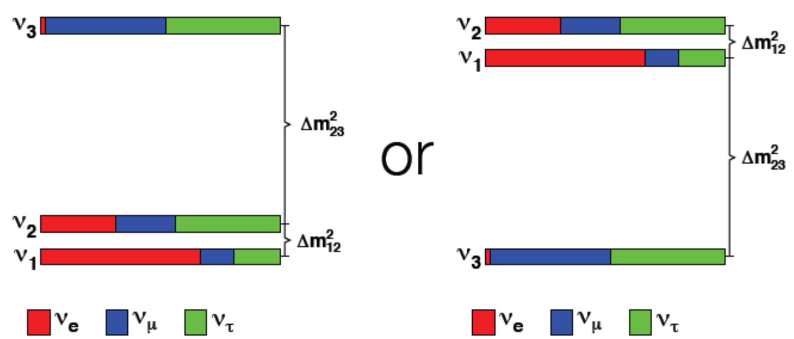
The Future of Optical Cherenkov Telescopes in the Ice

PINGU AND MICA

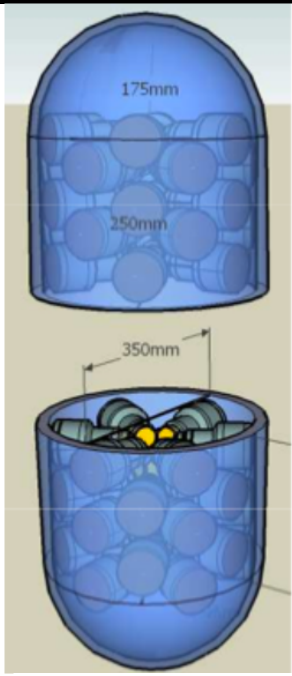
Precision **I**ceCube **N**ext-**G**eneration **U**pgrade

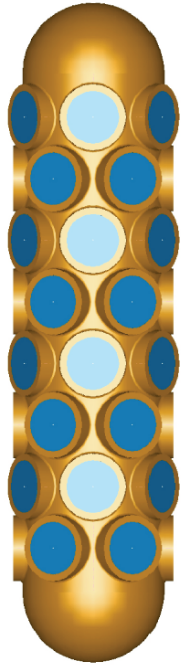
- **P**recision **I**ceCube **N**ext-**G**eneration **U**pgrade
- Motivation: Akhmedov, Razzaque, Smirnov arXiv:1205.7071 → PINGU detector has sensitivity at 3-10 σ level after 5 years to mass hierarchy due to matter effects in 5-10 GeV region.
- Detector still in concept phase but can probably predict that if it's constructed it will …
  - Be O(20) strings in-filled inside of IceCube DeepCore in deep clear ice
  - Be spaced along string in range 3-6 m
  - **Use basic DOM technology with tweaks to electronics (custom ASIC digitizers replaced by pipelined ADCs)**
  - Cost O(50 MUSD)
- Timescale is > 2016 for deployment of instrumentation
- Major logistical problem to revive IceCube EHWD which now somewhere on WAIS.

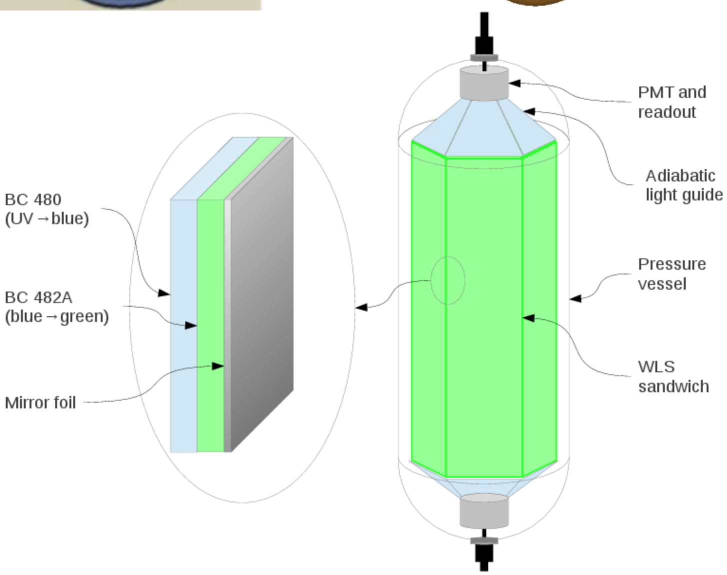




MICA







Multi-megaton Ice Cherenkov Array

- Far future project
- Main physics goal is to instrument deep quiet ice for megaton proton decay detector
- Also quite interesting for supernova physics
- 120 strings x O(100) large-area photodetectors per string
- 250 m x 40 m at bottom and center of IceCube Veto Array
- Developments to enhance effective photocathode area underway by several EU groups
  – Multi-anode PMT (30 small PMTs – no WF readout)
  – Wavelength shifters

Neutrino astronomy at 1 EeV

PART II: THE ASKARYAN RADIO ARRAY

The ARA Collaboration

KU

University of Delaware 1743

千葉大学
Chiba University

The University of Wisconsin Madison

University of Maryland 1856

University of Hawai'i

The Ohio State University

UCL

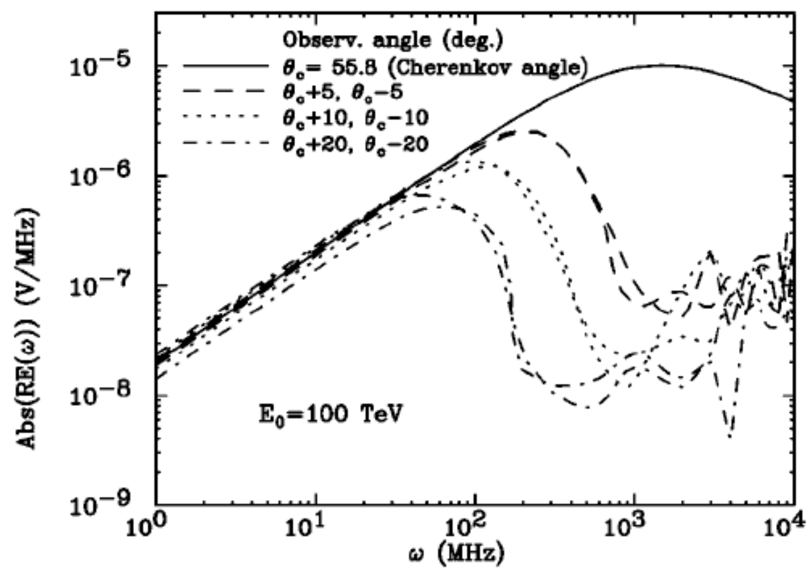
University of Adelaide

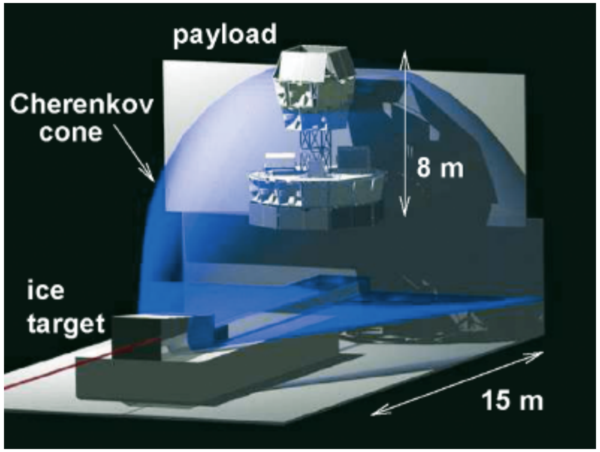
ULB Université Libre de Bruxelles

Principle of Detection

First proposed by G. Askaryan in 1960's the Askaryan effect occurs in energetic cascades due to slight excess of negative charge over positive charge; this leads to a coherent EM pulse, parameterized by ZHS (PRD 45 (1992) 362), AVZ (PRD 61 (1999), and others. General features of radiation include:

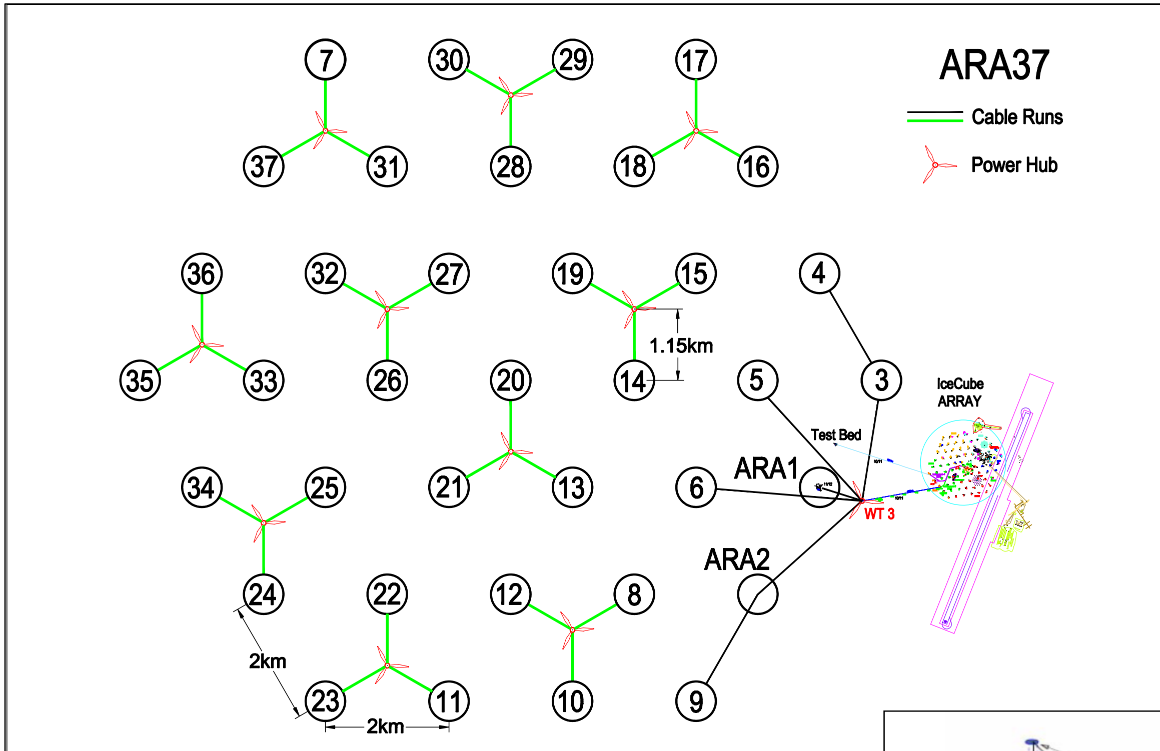
- Approx. linear scaling of impulse with cascade energy – $1/R^2$ in power ➔ $1/R$ E-field
- Peak power at GHz when detector near Cherenkov angle (55° in ice)
- At 10° off cone peak power at 200 MHz

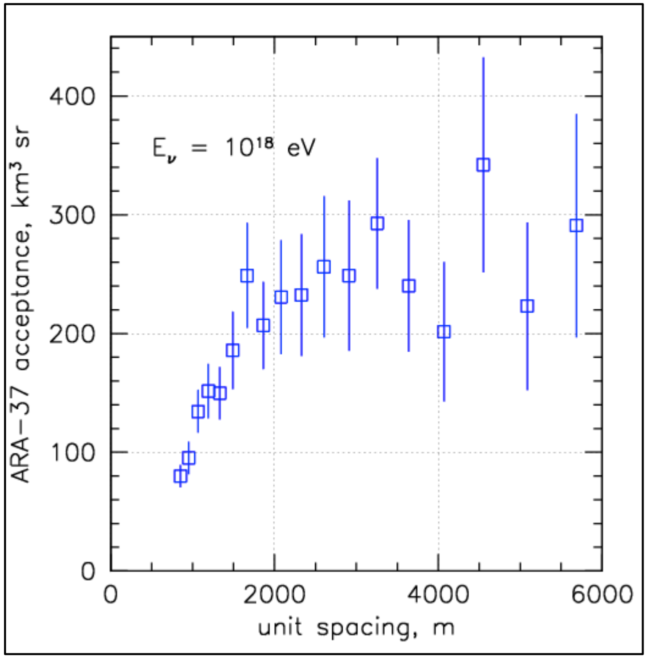


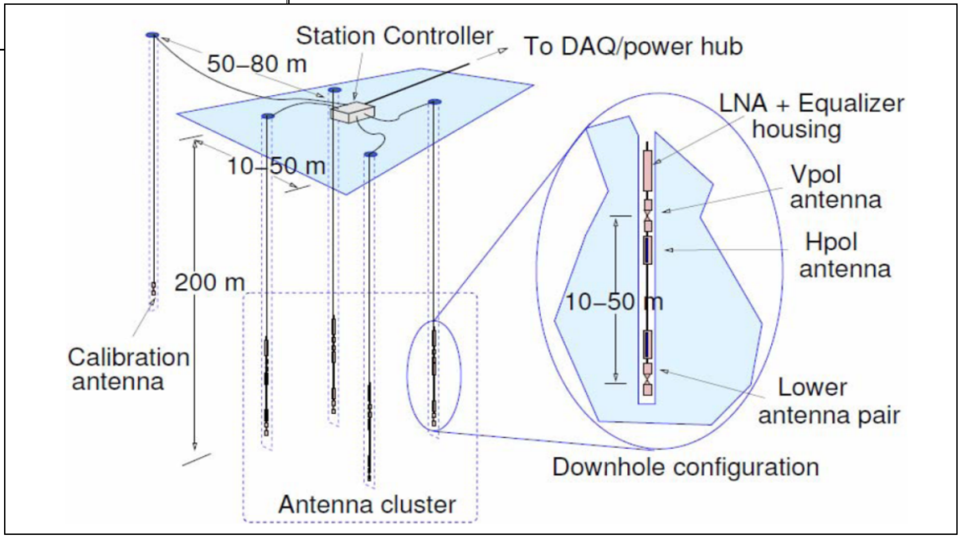


- The Askaryan effect and the parameterizations have been experimentally verified at SLAC T460 test beam (Gorham et al PRL 99 (2007) 171101)
- **Why South Pole ice?** The colder the better - top cold part of glacier at -40° C to -50° C with RF attenuation lengths of over 1 km for f = 100's of MHz and 100's of m for f ~ 1 GHz
- Antennas should be buried in bulk ice below firn layer in order to avoid ray bending in index of refraction gradient in firn.

Detector Design







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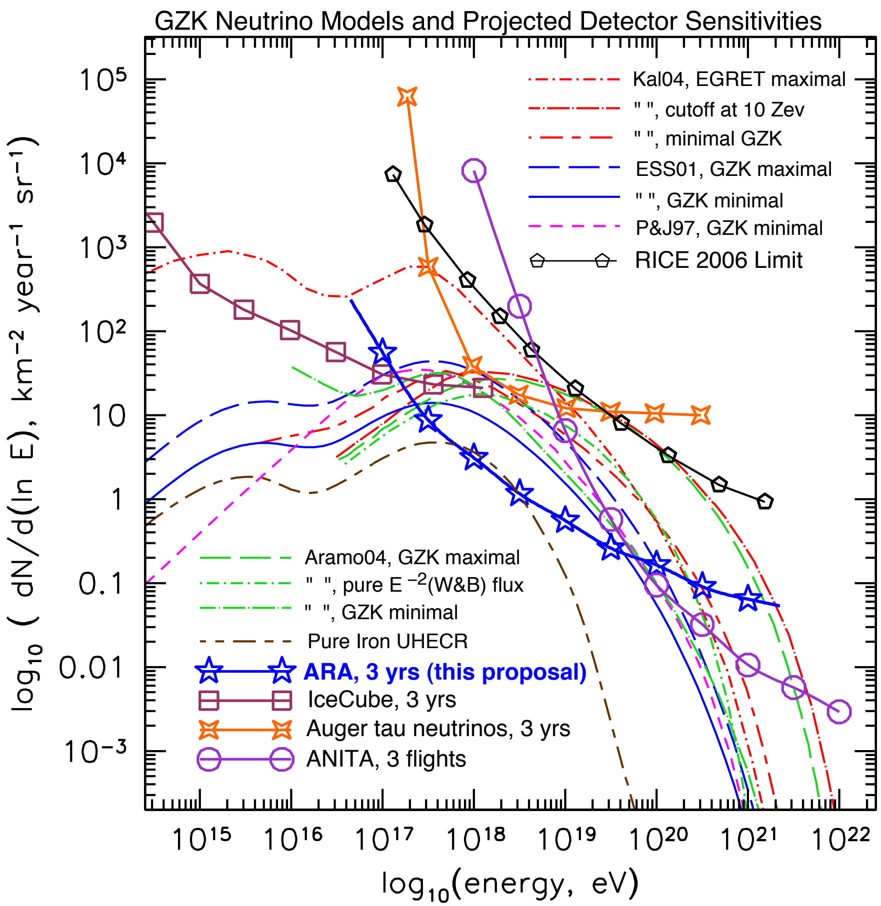
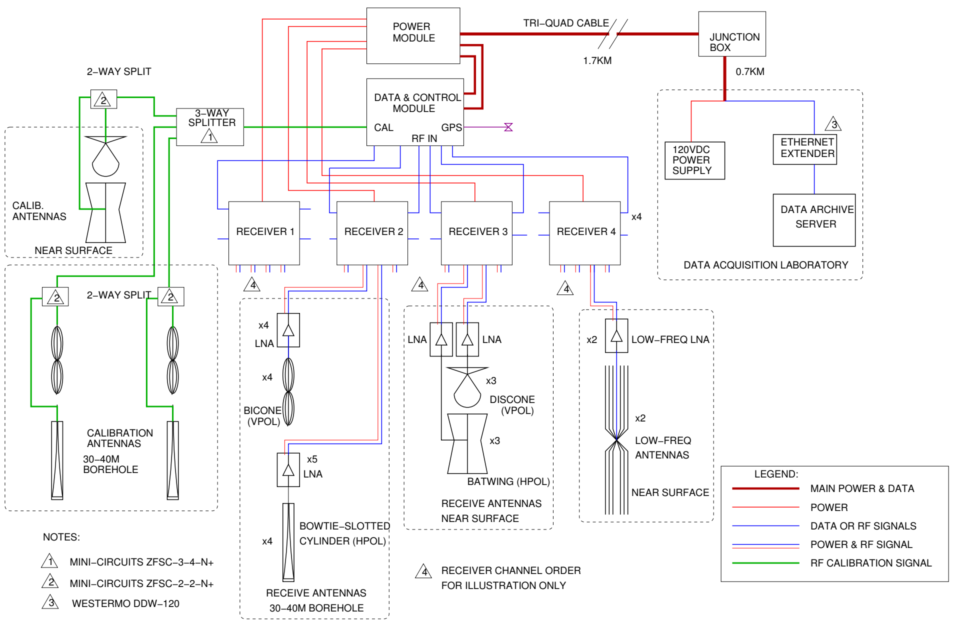
ARA Expected Performance



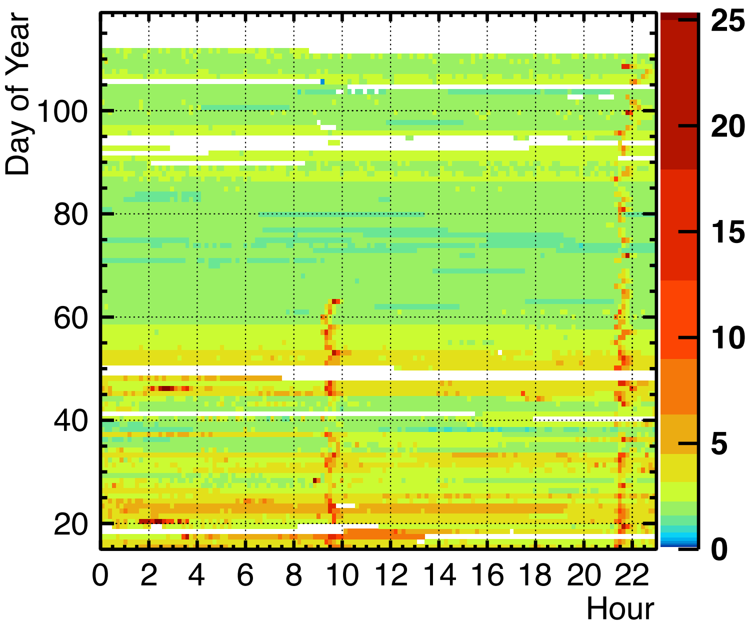
Model & references N_ν:	ANITA-II, (2008 flight)	ARA, 3 years
Baseline cosmogenic models:		
Protheroe & Johnson 1996 [36]	0.6	59
Engel, Seckel, Stanev 2001 [23]	0.33	47
Kotera,Allard, & Olinto 2010 [48]	0.5	59
Strong source evolution models:		
Engel, Seckel, Stanev 2001 [23]	1.0	148
Kalashev *et al.* 2002 [37]	5.8	146
Barger, Huber, & Marfatia 2006 [41]	3.5	154
Yuksel & Kistler 2007 [44]	1.7	221
Mixed-Iron-Composition:		
Ave *et al.* 2005 [40]	0.01	6.6
Stanev 2008 [45]	0.0002	1.5
Kotera, Allard, & Olinto 2010 [48] upper	0.08	11.3
Kotera, Allard, & Olinto 2010 [48] lower	0.005	4.1
Models constrained by Fermi cascade bound:		
Ahlers *et al.* 2010 [49]	0.09	20.7
Waxman-Bahcall (WB) fluxes:		
WB 1999, evolved sources [47]	1.5	76
WB 1999, standard [47]	0.5	27

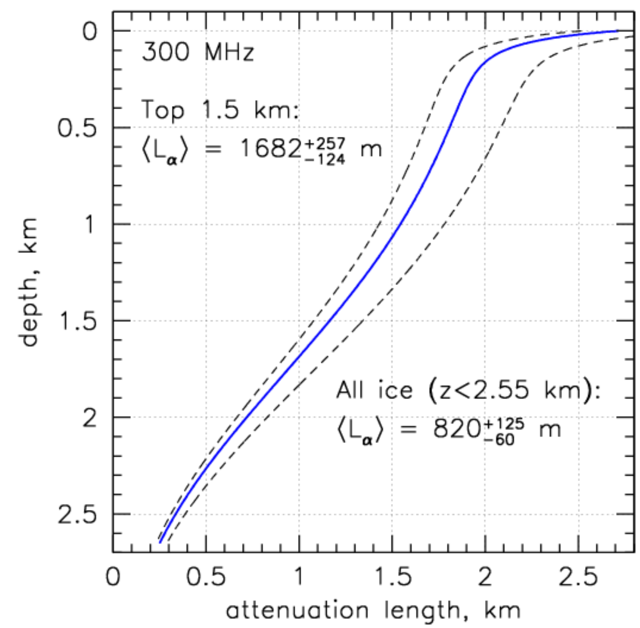
ARA Testbed

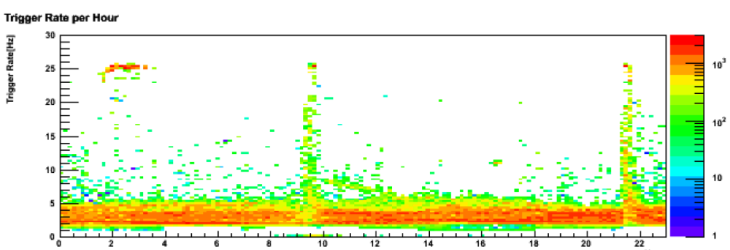
Specified parameter	ARA 2012++ planned	ARA 2011 prototype
Number of Vpol antennas	8	6 (in ice)
Vpol antenna type	bicone	bicone
Vpol antenna bandwidth (MHz)	150-850	150-850
Number of Hpol antennas	8	8 (in ice)
Hpol antenna type	quad-slotted cylinder	bowtie-slotted-cylinder
Hpol antenna bandwidth (MHz)	200-850	250-850
Number of Surface antennas	4	2
Surface antenna type	fat dipole	fat dipole
Surface antenna bandwidth (MHz)	30-300	30-300
Number of signal boreholes	4	6
Borehole depth (m)	200	30
Vertical antenna configuration	H,V above H,V	V or H above H or V
Vertical antenna spacing (m)	20	5
Approximate geometry	trapezoidal	trapezoidal
Approximate radius (m)	10	10
Number of calibration antenna boreholes	3	3
Calibration borehole distance from center (m)	40 (2), 750 (1)	30
Calibration borehole geometry	isosceles triangle	equilateral triangle
Calibration signal types	noise and impulse	impulse only
LNA noise figure (K)	< 80	< 80
LNA/amplifier dynamic range	30:1	30:1
RF amplifier total gain (dB)	> 75	> 75

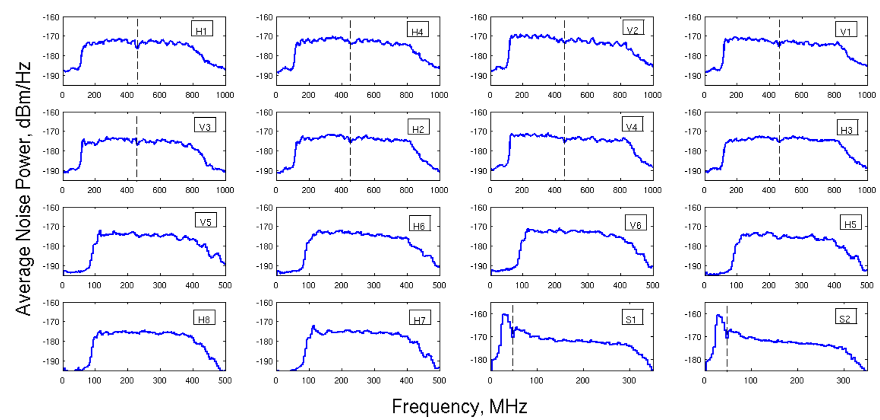


ARA Testbed Measurements









ARA Plan

- Currently installed in the ice are
  - ARA testbed (2010)
  - ARA station 1
- For this year
  - Repair malfunctioning ARA-1 surface hardware
  - Deploy up to 2 stations
- At 3 stations ARA will be within same neutrino sensitivity to GZK flux as IceCube
- Planning for the out years highly dependent on outcome of current year. Full 37 string array still 4+ years away.

Summary

- IceCube 86-string detector is completed and functioning extremely well with < 2% channels lost and operating with detector uptime in excess of 99%.
- Analyses from IC40/59 in publication. GRB fireball model excluded.
- Analyses from IC79 and IC86-1 indicate small excess of events in high-energy signal region. Exclusion of background by careful study of existing data.
- IC86-2 run underway since May 2012.
- Future of optical in ice
  - IceCube operation forseen for next 10-20 years.
  - Interest in dense detectors for oscillation study (PINGU) and proton decay. Latter requiring new developments in large area photodetectors.
  - If EHE signal optical could be extended with outer deployments, however, see below.
- Radio
  - Radio very likely *the* preferred technique for instrumentation of very large areas – O(100) km^2 and beyond.
  - ARA measurements confirm that SP is suitable environment for radio detection: long ice attenuation confirmed; low-EMI background.


END