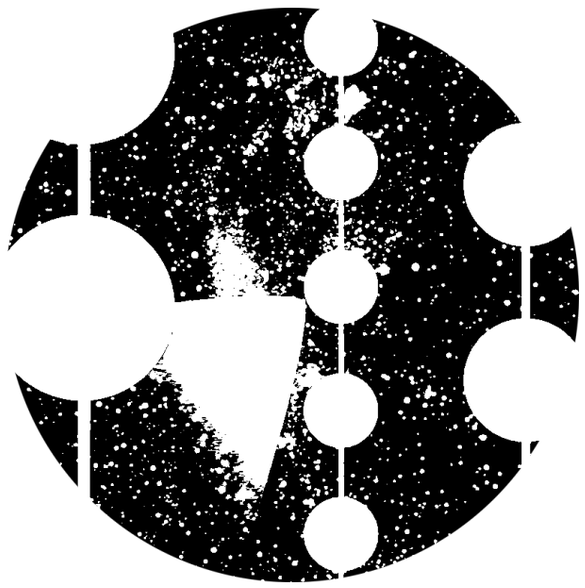
IceCube Primer

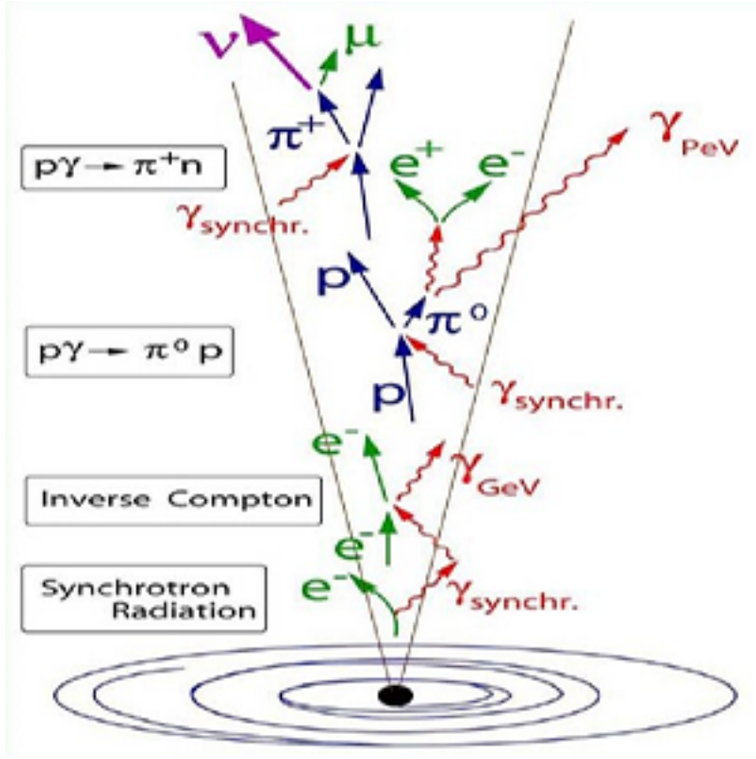
Gearing up for High Energy Neutrino Astrophysics at the Bottom of the World

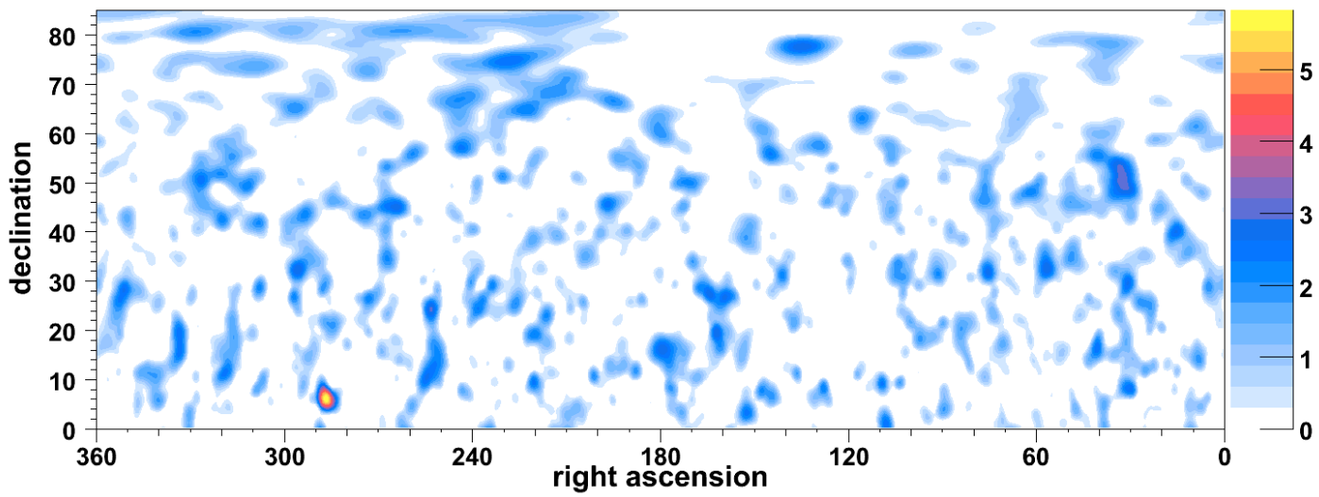
Dr. Kael D. Hanson
UW Madison IceCube Center
Presentation at Université Libre de Bruxelles
June 12th 2008



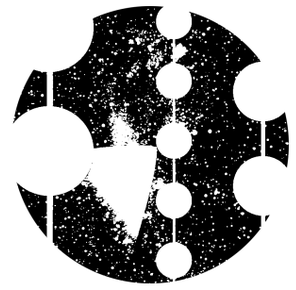
The Big Picture – Motivation

- We are finally seeing how much we are not seeing - baryons are only 4% of the mass of the universe. Dark matter is 22%. The rest is the ultra-mysterious dark energy.
- The sources of the highest energy cosmic rays remain anonymous.
- Multi-wavelength astronomy is all the rage: optical, radio, IR, UV, X-ray, gamma-rays all the way up to TeV. The sky is abundant with new sources as new telescopes scan the Universe. The HE gamma sky should indeed get very interesting soon (yesterday?) when NASA launches the GLAST mission.
- The yet-to-be-discovered neutrino sky awaits ...





Findings of the Particle Physics Project Prioritization Panel

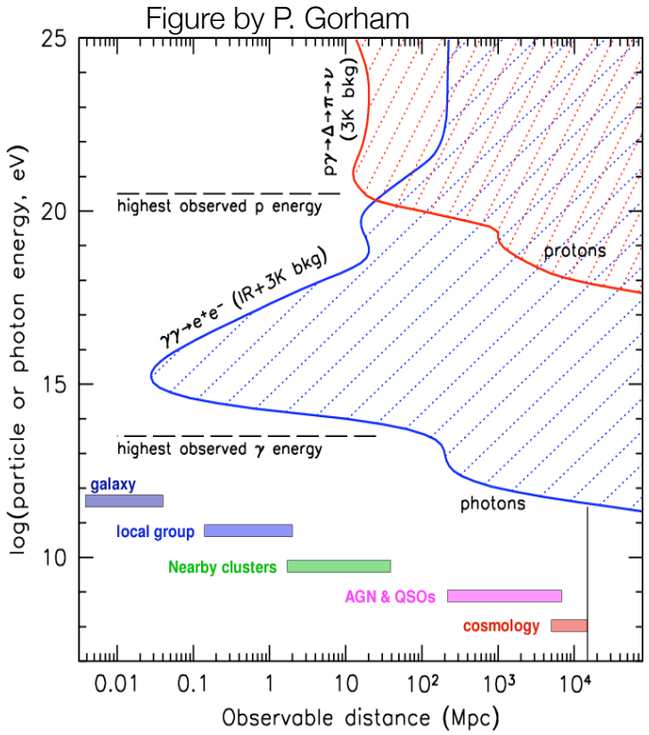


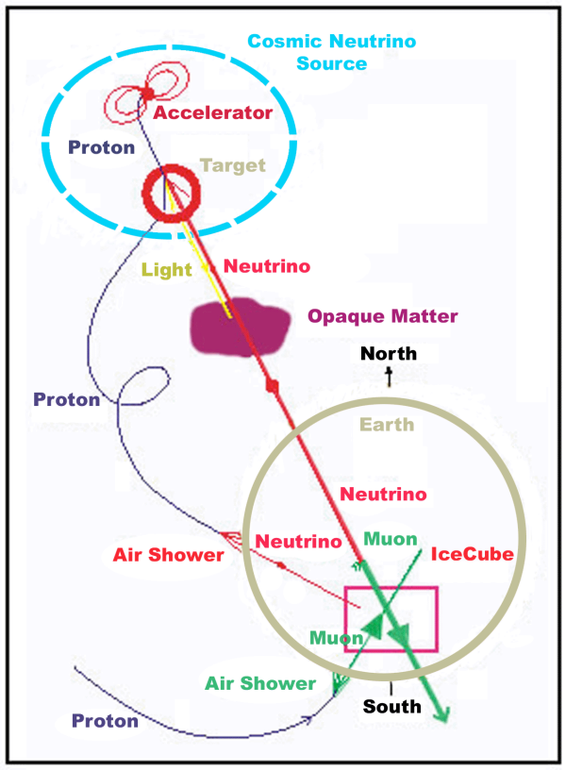
- The study of high-energy particles from space—ultrahigh energy cosmic rays, gamma rays, and neutrinos—is a vibrant, rapidly developing area of science at the boundary between particle physics and astrophysics. These projects bring important diversity to particle physics, so relatively small investments are a high priority, even in the leanest budget scenarios. Due to extreme budget pressures, very large investments at this time are only possible in the higher budget scenarios. Multiagency, international cooperation is particularly important for the support of this exciting science.
- The panel recommends limited R&D funding for these other particle astrophysics projects under all budget scenarios considered by the panel, but support for any possible large construction projects should be considered only under funding scenarios C and D.
- The panel recommends that the funding agencies establish a Particle Astrophysics Science Advisory Group to advise DOE and NSF on the relative merits of the various proposals anticipated in this area.

The Case for Neutrino Astronomy

- Cosmic ray protons bent in B fields until GZK energy when interaction length limits travel to 10s of Mpc.
- TeV **γ** rays have 'horizon' of 200 Mpc from pair production on EBL with rapid decrease for increasing E.
- Neutrinos are not bent by magnetic fields - particles point back to source.

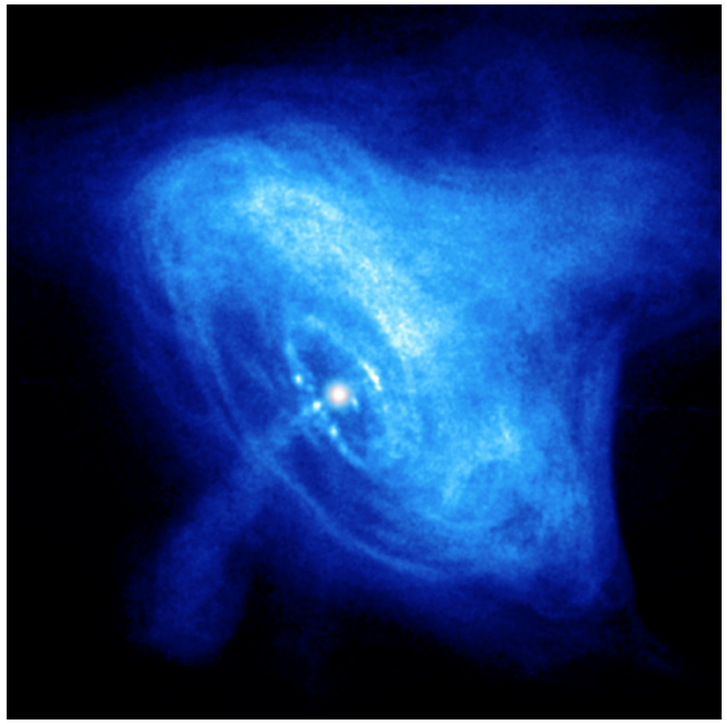
Figure by P. Gorham

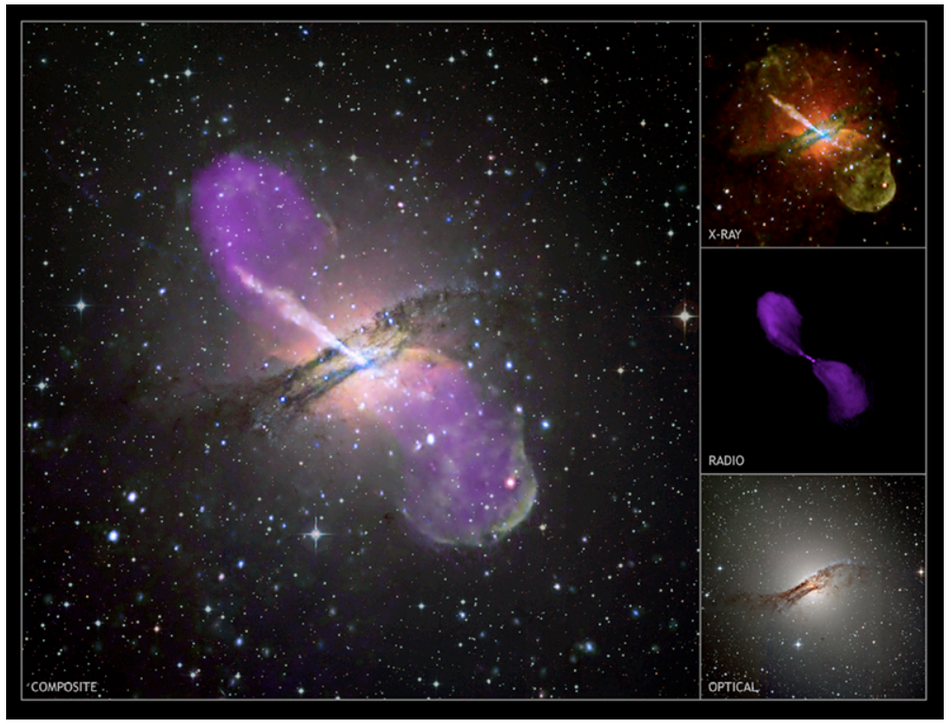




- Neutrino cross-section extremely small - 1 PeV **ν** has interaction length of 10,000 km.w.e - impervious to ISM. Note that this is approximately the thickness of the Earth - the Earth *is* opaque to UHE neutrinos!
- By same token one needs a large active target mass for detecting the **ν**s; benchmark volume is 1 km^3

Sources of HE Neutrinos - Many More Too

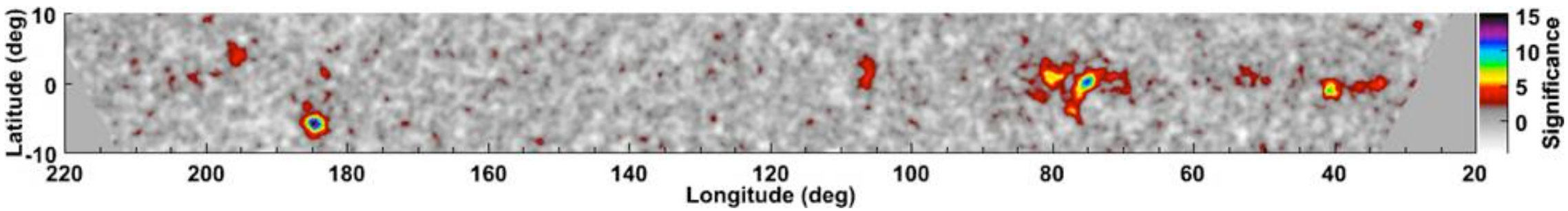




Left: Crab in the X-ray.

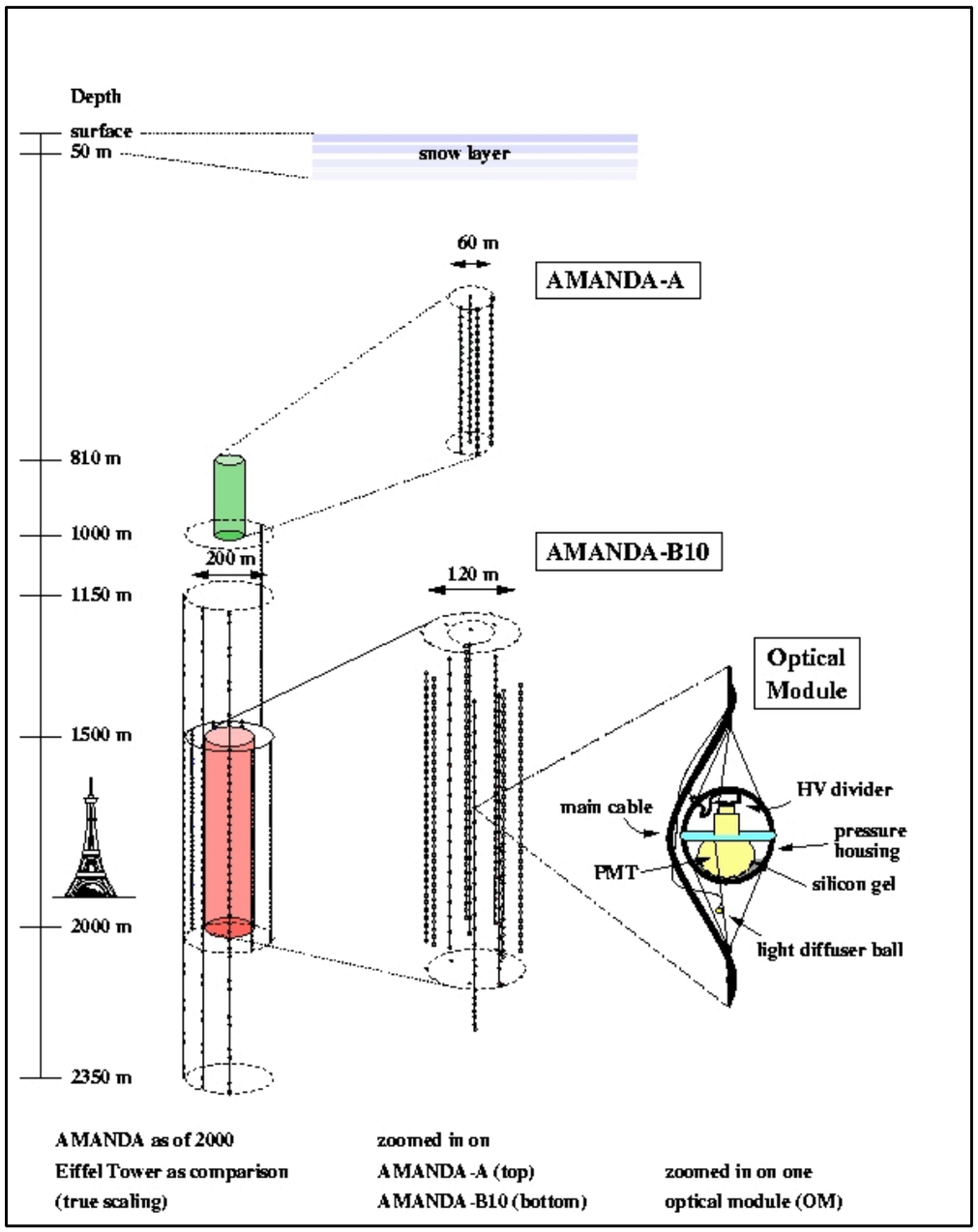
Right: CenA - nearby 12 Mpc AGN with potential UHECR production observed by Auger.

Credits: Chandra



Galactic sources such as these Milagro hotspots may be nearby factories with hard spectrum well-suited for IceCube detector response (100 TeV region).

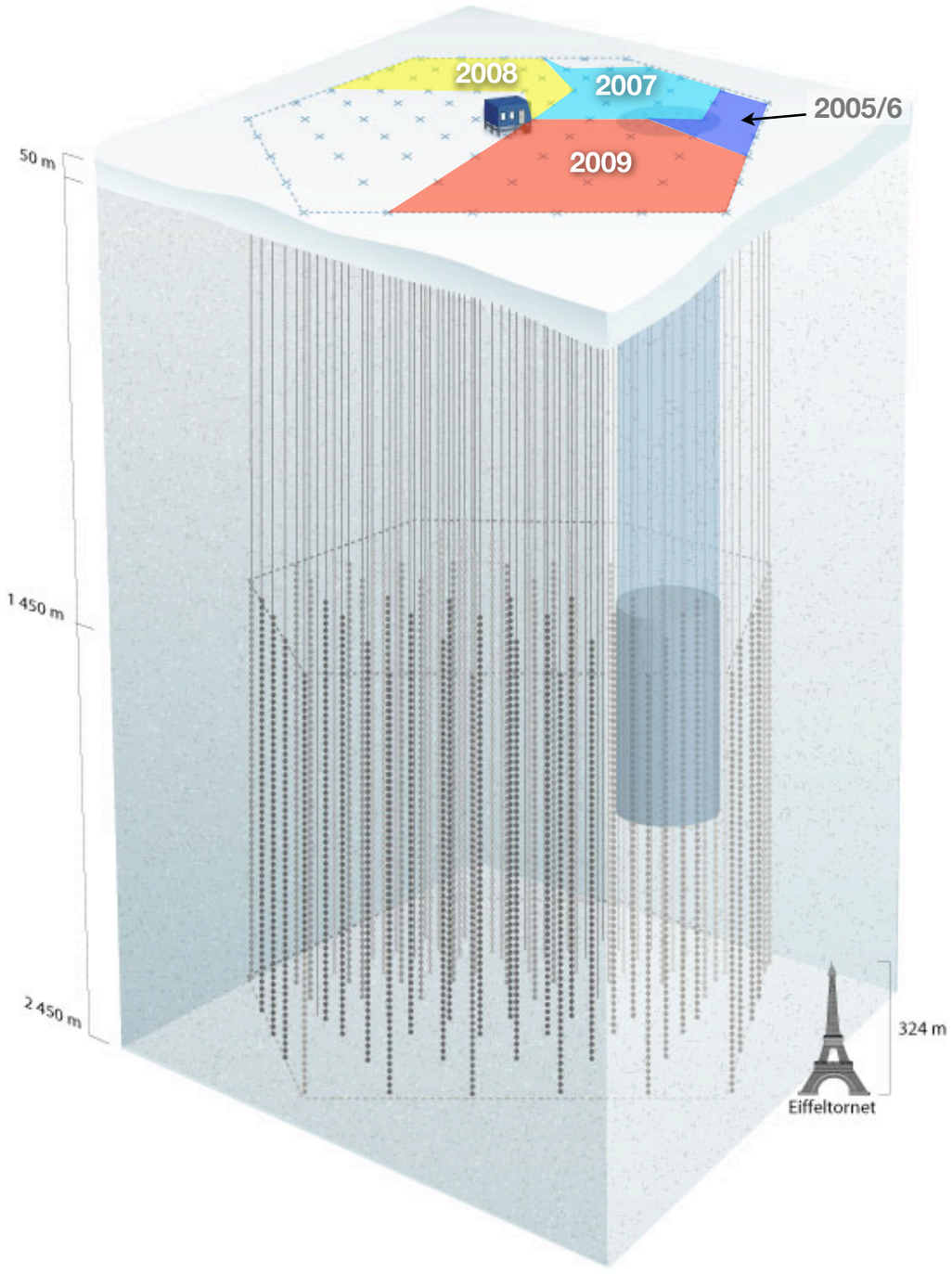
Antarctic Muon and Neutrino Detector Array (AMANDA)



- 677 analog OMs deployed along 19 strings
  - 10 strings 1997 (AMANDA B10)
  - 3 strings 1998 (AMANDA B13)
  - 6 strings 2000 (AMANDA II)
- Analog PMT signals using electrical and optical transmission lines.
- 200 m diameter, 500 meters height; AMANDA II encompasses 20 Mton instrumented ice volume.
- AMANDA will remain operational and form IceCube Inner Core Detector for low E physics (~ 100 GeV) to be replaced by additional IceCube strings 2010
- Conventional TDC / ADC technology for AMANDA has been entirely replaced by TWR system.
- Beginning 2007 season, AMANDA / IceCube data streams are combined; detector subsystems will share trigger information.

IceCube: the age of km-scale instruments begins





The IceCube Collaboration



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



- University of Canterbury, Christchurch



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



- Oxford University



- 千葉大学 (Chiba University)



- Ecole Polytechnique Fédéral de Lausanne



- Universitiet Utrecht

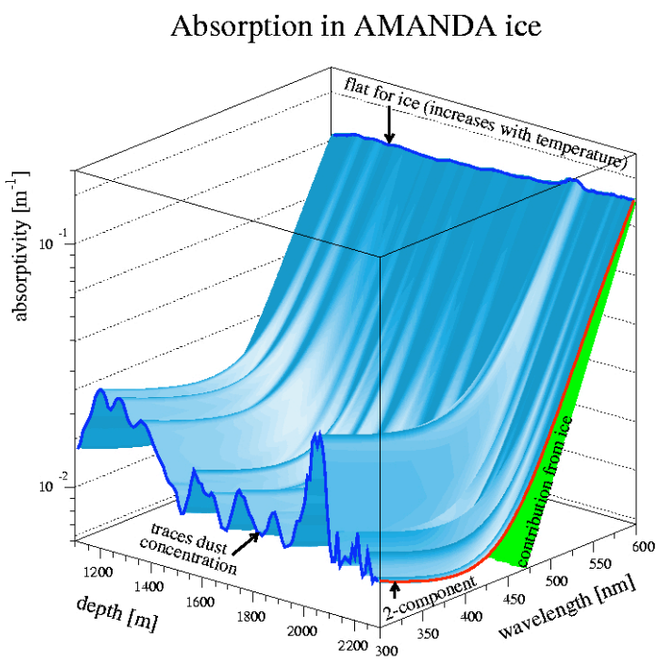


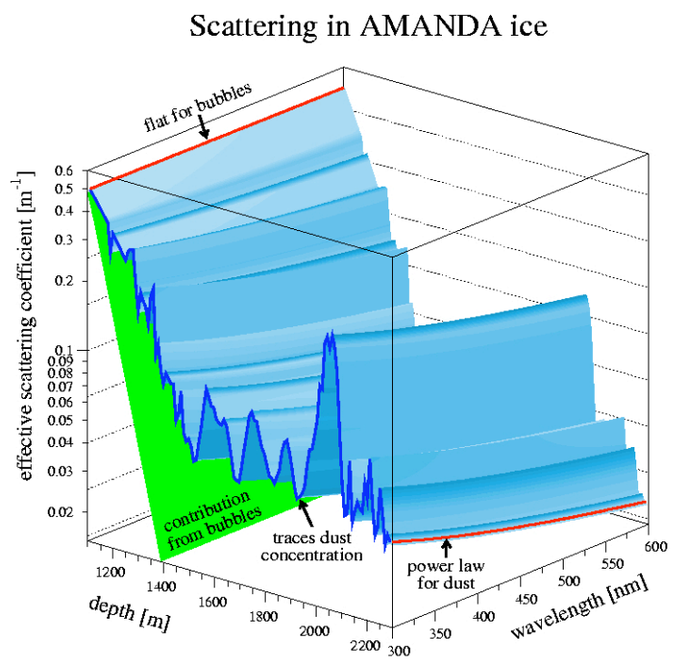
- University of Alaska, Anchorage
- University of California, Berkeley
- University of California, Irvine
- Clark-Atlanta University
- University of Delaware, Bartol Research Inst
- University of Kansas
- Lawrence Berkeley National Lab
- University of Maryland
- Pennsylvania State University
- Southern University, Baton Rouge
- University of Wisconsin - Madison
- University of Wisconsin - River Falls



- Uppsala Universitet
- Stockholms Universitet

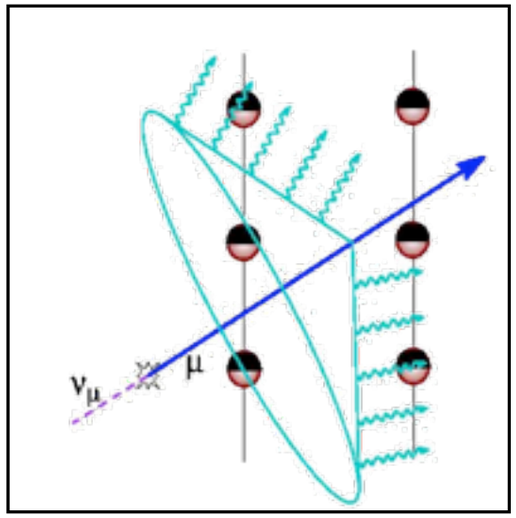
Why South Pole Ice?



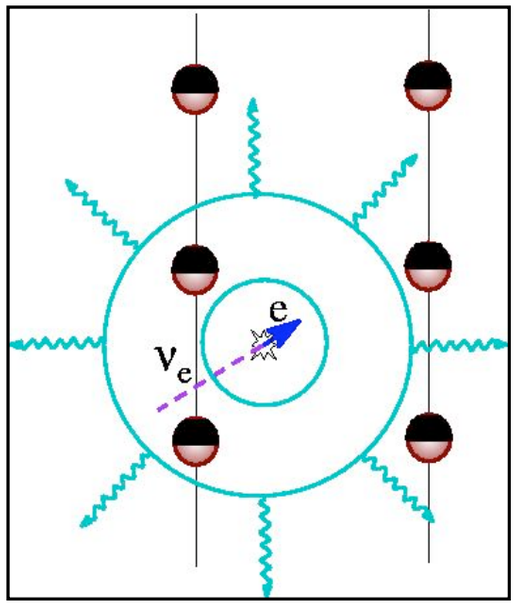


- Why deploy in ice? Deep glacial ice is optically transparent. Two mechanisms: scattering length ~ 20 m, absorption ~ O(100) m. Ice has several layers of dust from prehistoric events. Monte Carlo detector simulation must account for this. Reconstruction methods involving maximum likelihood tests against hypotheses have been developed to overcome difficulties posed by photon scattering.
- Plots above from in situ measurements using artificial light sources in AMANDA. “Hole ice” around deployed modules must also be taken into account and is to date one of the major contributors to systematic error.

Observing Neutrinos in Ice : Cherenkov Radiation

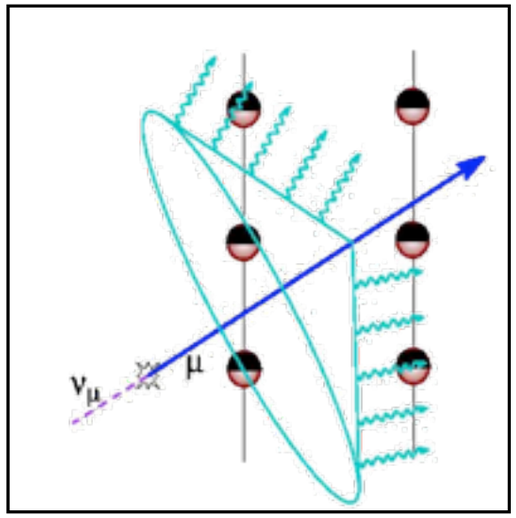


Muon tracks radiate Cherenkov cone. Good pointing - poor energy reconstruction.

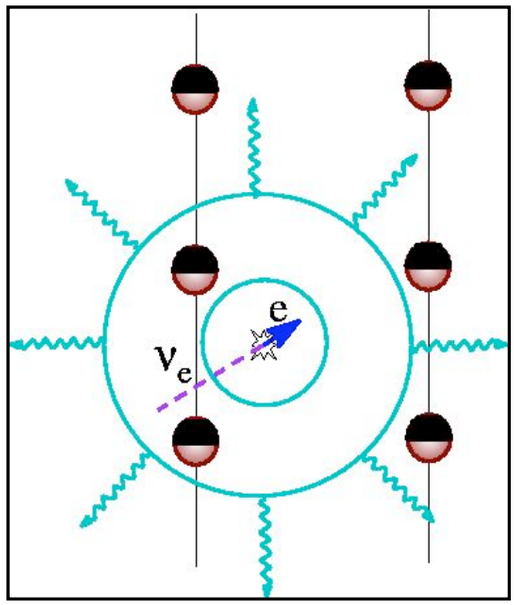


EM / hadronic cascades manifest as pseudo-spherical distribution. Good E resolution - poor pointing.

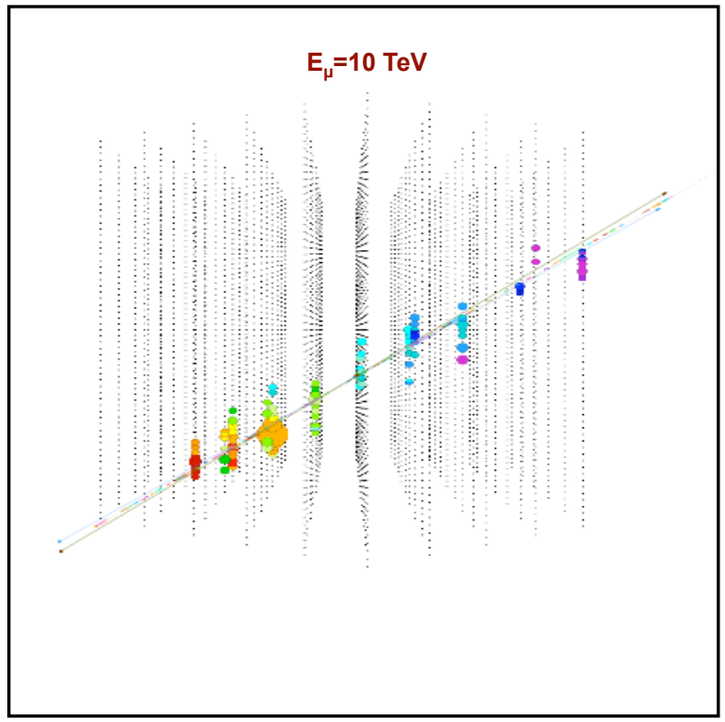
Observing Neutrinos in Ice : Cherenkov Radiation



Muon tracks radiate Cherenkov cone. Good pointing - poor energy reconstruction.



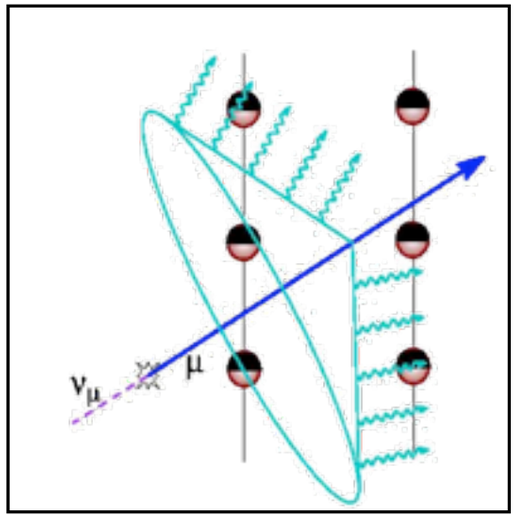
EM / hadronic cascades manifest as pseudo-spherical distribution. Good E resolution - poor pointing.



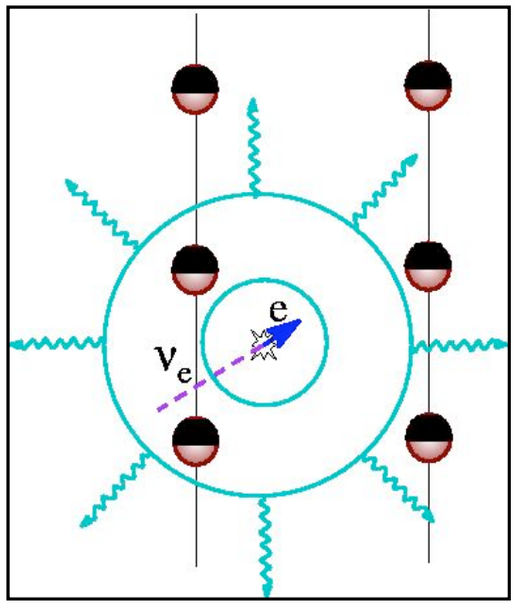
Track-like muons

ν_μ (or UHE ν_τ) produces μ or τ via CC scatter. which can travel for many kilometers along linear track radiating Cherenkov photons in conical wavefront about track. The extended range of taus and muons means vertex can lie far outside detector volume – detector effective area is key performance parameter.

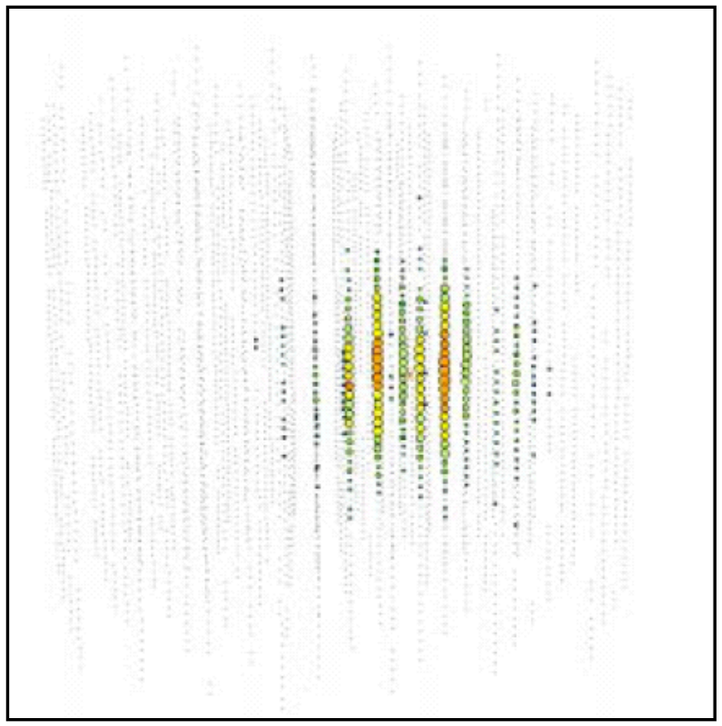
Observing Neutrinos in Ice : Cherenkov Radiation



Muon tracks radiate Cherenkov cone. Good pointing - poor energy reconstruction.



EM / hadronic cascades manifest as pseudo-spherical distribution. Good E resolution - poor pointing.



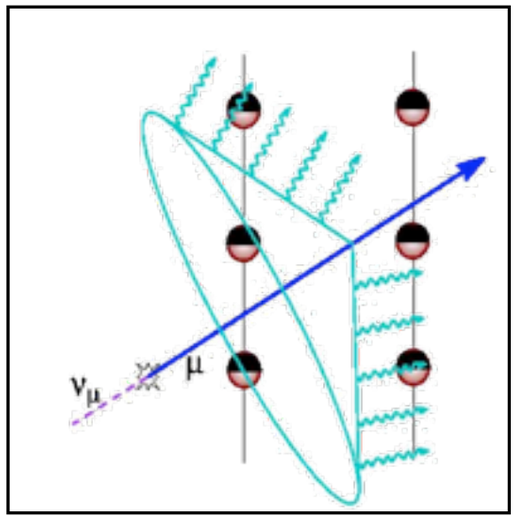
Track-like muons

ν_μ (or UHE ν_τ) produces μ or τ via CC scatter. which can travel for many kilometers along linear track radiating Cherenkov photons in conical wavefront about track. The extended range of taus and muons means vertex can lie far outside detector volume – detector effective area is key performance parameter.

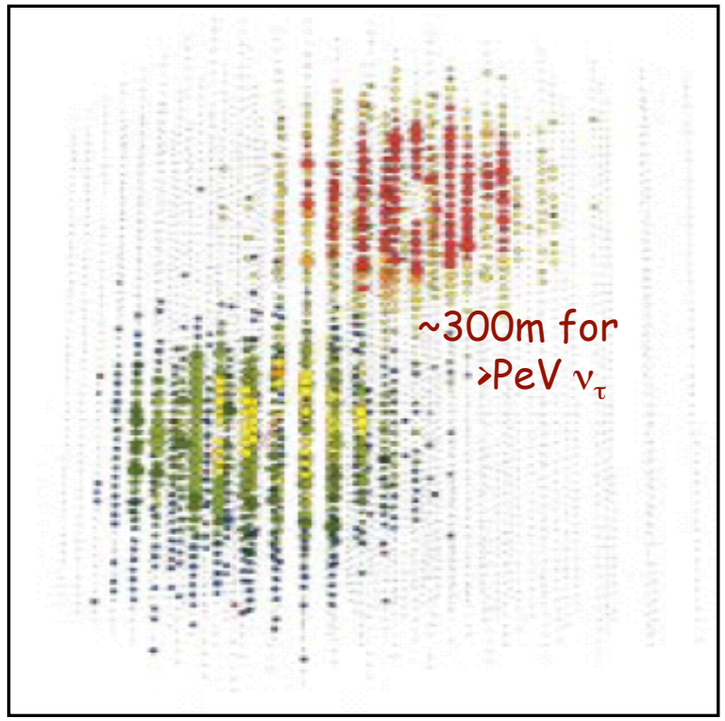
Cascades

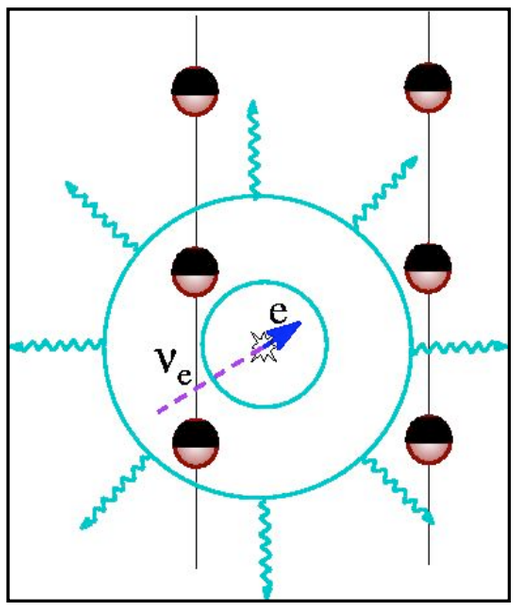
ν_e CC or ν_X NC nuclear interactions produce either EM or hadronic cascades. These cascades can produce enormous amounts of Cherenkov photons (10^8 photons per TeV) which are radiated over 4π. The extent of the particle cascade is small; the expanding, roughly spherical wavefront approximated as coming from a point although shower does have longitudinal extent - especially due to LPM. Detector effective volume is operational parameter for cascades.

Observing Neutrinos in Ice : Cherenkov Radiation



Muon tracks radiate Cherenkov cone. Good pointing - poor energy reconstruction.





EM / hadronic cascades manifest as pseudo-spherical distribution. Good E resolution - poor pointing.

Track-like muons

ν_μ (or UHE ν_τ) produces μ or τ via CC scatter. which can travel for many kilometers along linear track radiating Cherenkov photons in conical wavefront about track. The extended range of taus and muons means vertex can lie far outside detector volume – detector effective area is key performance parameter.

Cascades

ν_e CC or ν_X NC nuclear interactions produce either EM or hadronic cascades. These cascades can produce enormous amounts of Cherenkov photons (10^8 photons per TeV) which are radiated over 4π. The extent of the particle cascade is small; the expanding, roughly spherical wavefront approximated as coming from a point although shower does have longitudinal extent - especially due to LPM. Detector effective volume is operational parameter for cascades.

"Double-Bang" Taus

VHE ν_τ interacting inside the detector produces the primary recoil cascade and a τ which radiates as muon track until it decays and produces a secondary cascade – leaving a very distinct event.

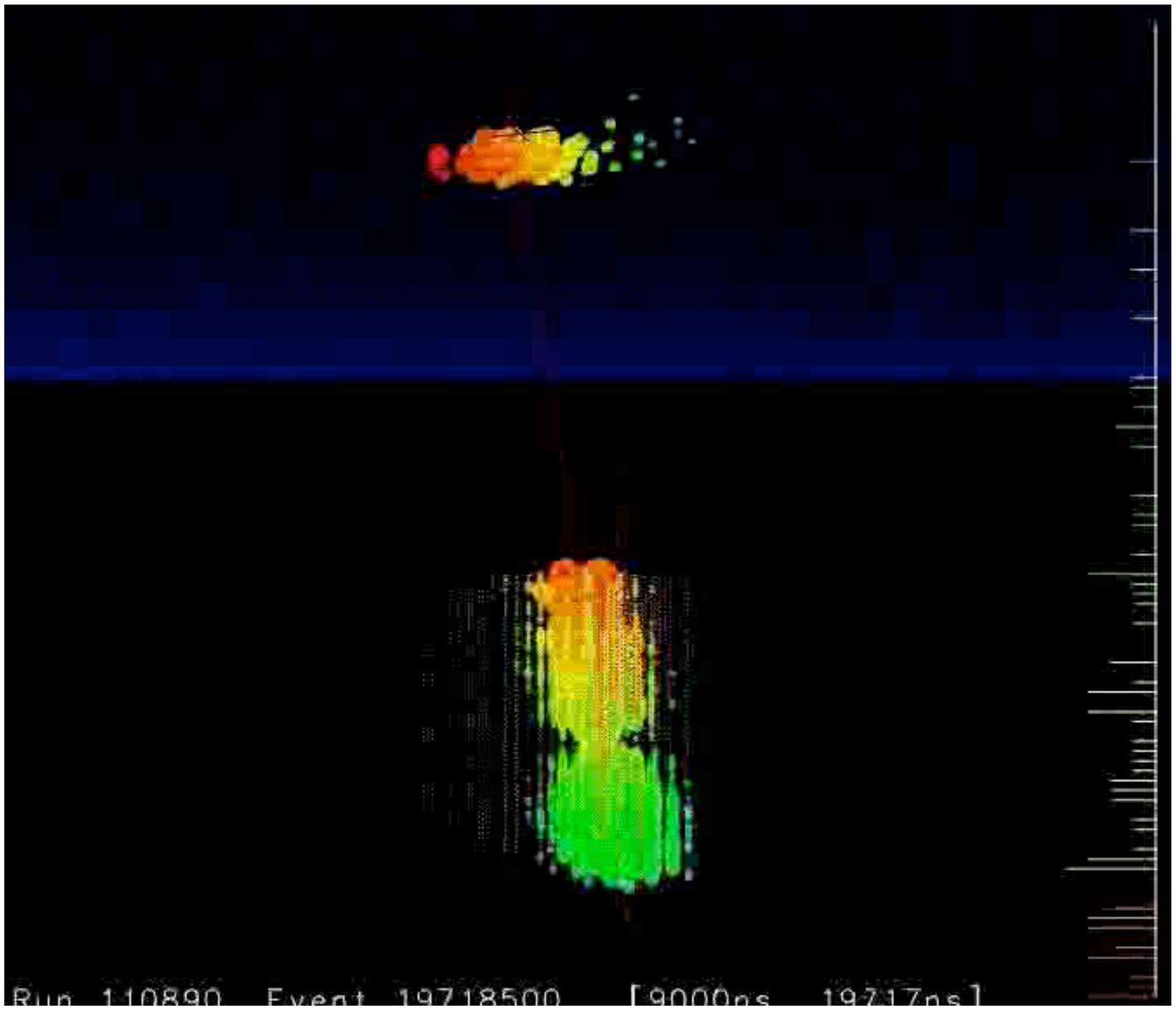
IceCube Event

- Example of IceTop / In-Ice event. Data from surface array tanks and in-ice strings is handled by same data acquisition system - events from either detector subsystem can trigger readout of entire array.

- This event reconstructed to 900 PeV from surface airshower.

- Note extended lobe in lower half of IceCube - the ice below 2000 m is much clearer than estimated. This has aroused interest in deploying deep *inner core* detector.

IceCube Event

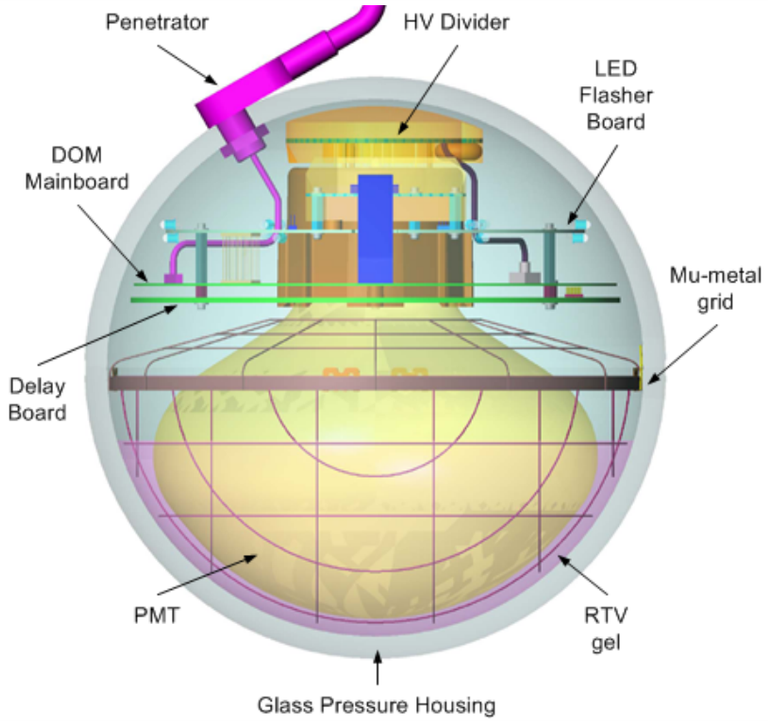


- Example of IceTop / In-Ice event. Data from surface array tanks and in-ice strings is handled by same data acquisition system - events from either detector subsystem can trigger readout of entire array.

- This event reconstructed to 900 PeV from surface airshower.

- Note extended lobe in lower half of IceCube - the ice below 2000 m is much clearer than estimated. This has aroused interest in deploying deep *inner core* detector.

The IceCube Digital Optical Module (DOM) and the Data Acquisition System



DOM Highlights - Optical

- Large Area Photocathode
  10” Hamamatsu R7081-02 bi-alkali PMT
- Low background noise
  < 300 Hz spe rate in-ice with 200 μs deadtime
- Glass / Gel improvements vs AMANDA
- Optical Calibration
  Each DOM calibrated in the lab to about 10%. On-board flashers allow in-ice calibrations

Triggering in the IceCube DAQ

- DOM
  - Trigger discriminator set to 0.25 pe - 500 Hz
  - Also require real-time trigger coincidence with neighbor DOMs up to two distant – LC – 5-20 Hz.
- Java application code readouts out buffered data into CPU cluster on surface and performs triggering:
  - Simple majority trigger (SMT)
    8 hits anywhere in array in 5 μs
  - “String” trigger
    5 hits in run of 8 on string in 1.5 μs

DOM Highlights - Electronics

- High-speed waveform digitization
- “Smart” sensor digital technology
  Versatile Altera FPGA is field programmable. All realtime core of data acquisition system is in DOM itself.
- Array Timing
  Automatic clock synchronization and cable transit calibration every 1 sec allows 1 ns time-stamping across entire array.
- Low power - 3.75 W per channel

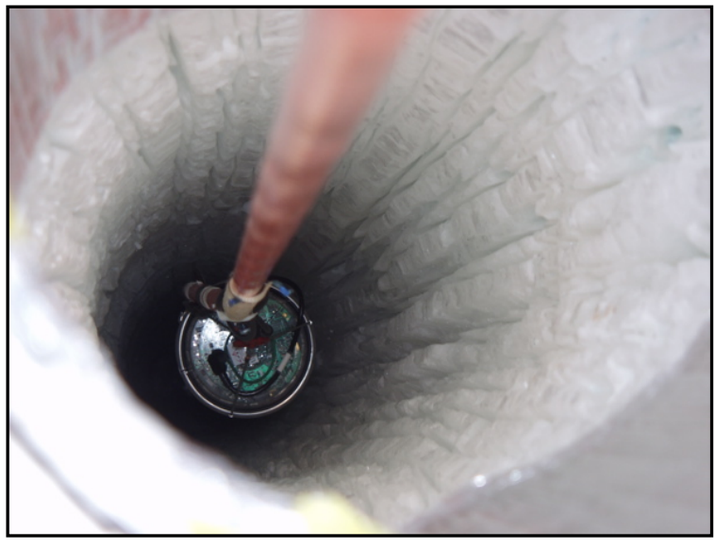
Deep Ice Drilling

Deep Ice Drilling

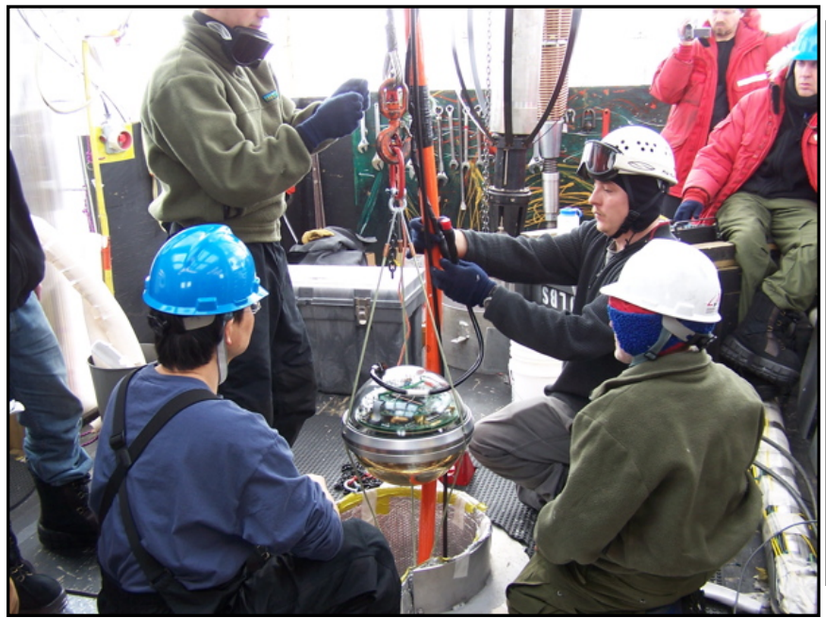


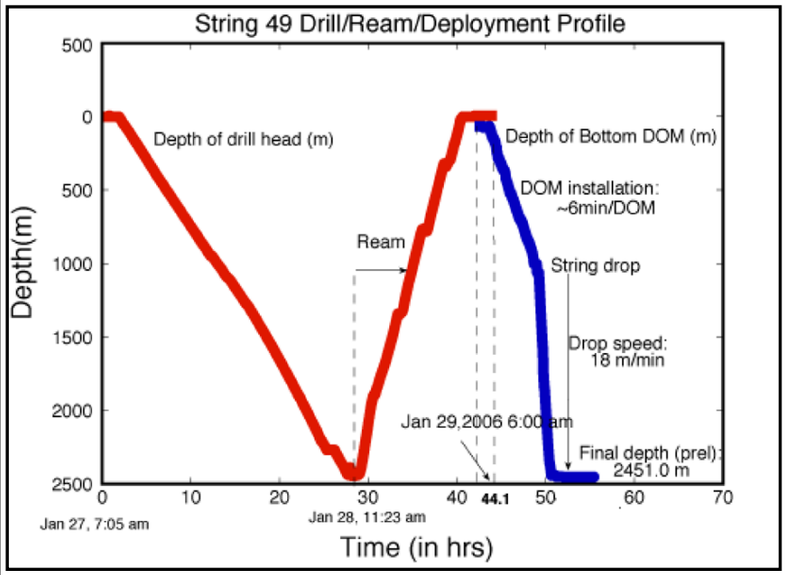
Module Deployment



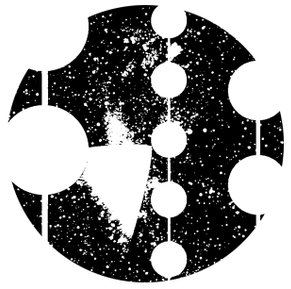






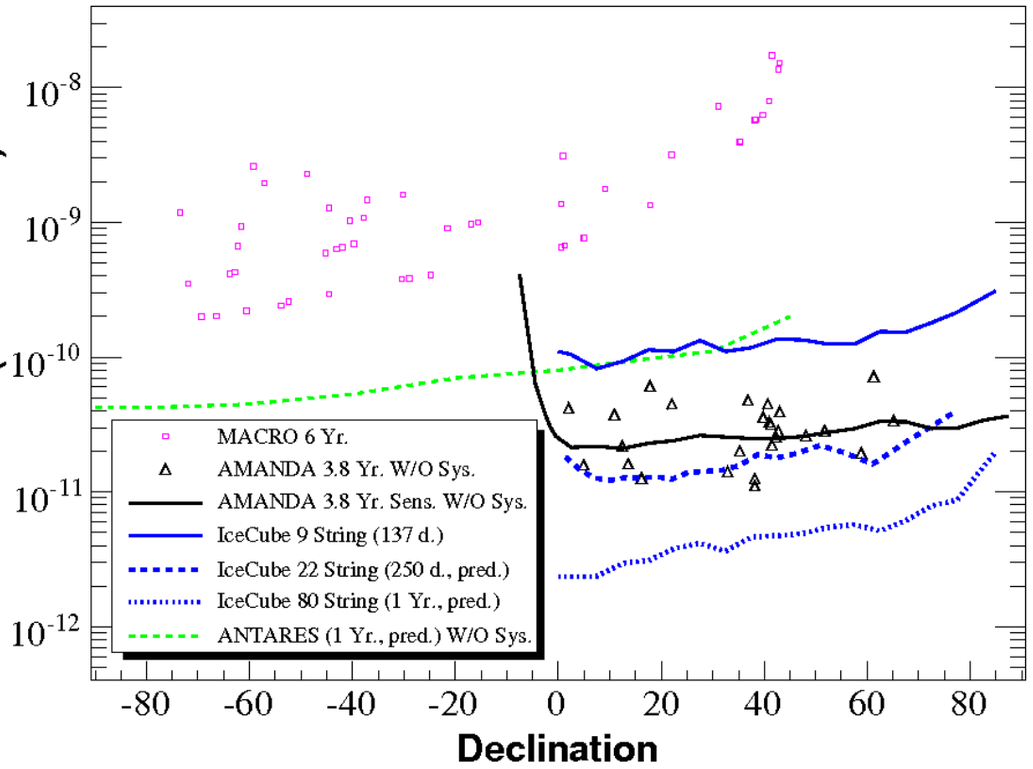


IceCube Status – 2008

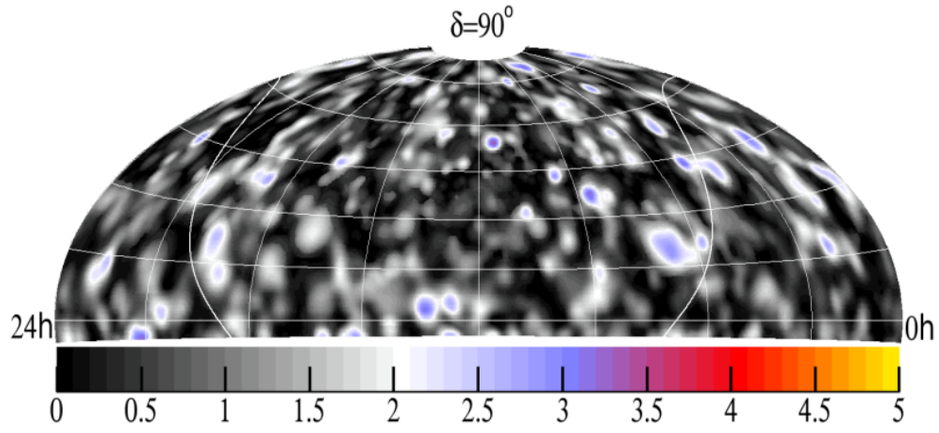


- The MRE construction project hit its peak year in 2006
  - 50% of IceCube is deployed - ½ km^3 is in the ice!
  - “The Project” is 80% complete.
- Original IceCube design for 80 strings - internal successes and additional external funding make probable 86 or even more strings at completion!
- January 25, 2008: deployment of 40th IceCube deep-ice string
- April 5, 2008: completed 304 day 22-string run; begin 40-string run
- Plan to deploy strings for 3 more seasons, including deep core which will be fully deployed by beginning 2011.
- Many science results to come from IC22 run by Fall 2008!

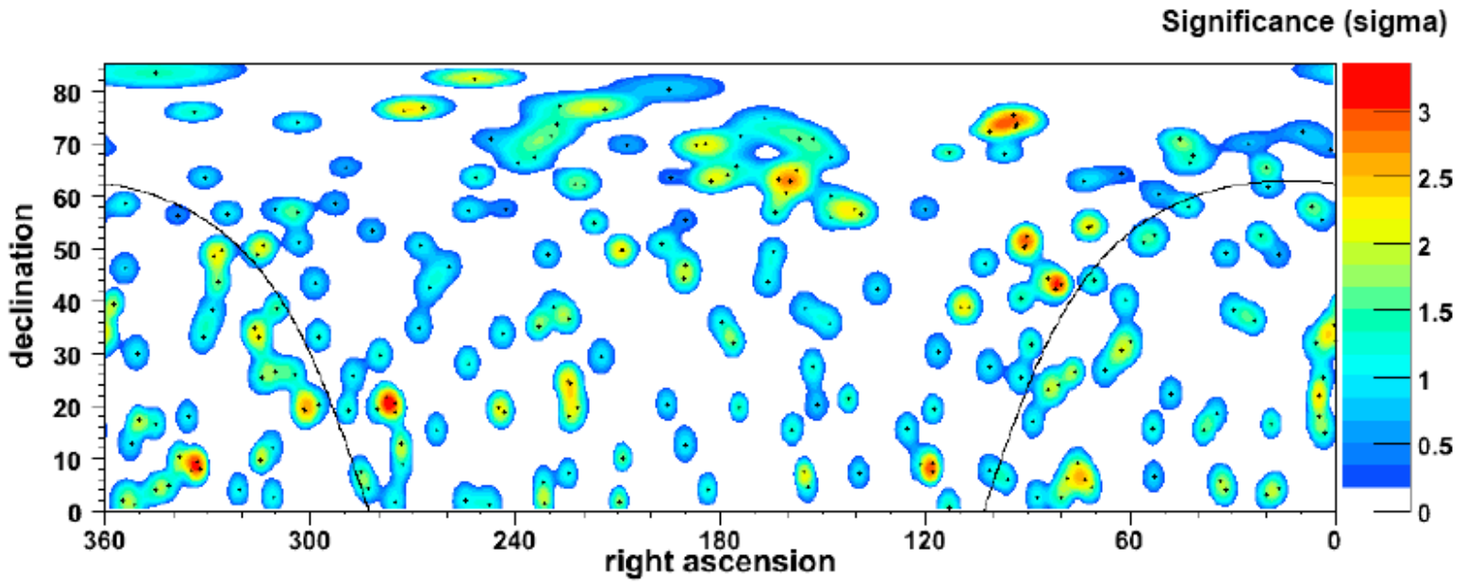
Point Sources



From IC9 analysis of Finley, Montaruli, Dumm
Sky-averaged sensitivity is
1.2×10^{-7} / GeV·cm^2·s

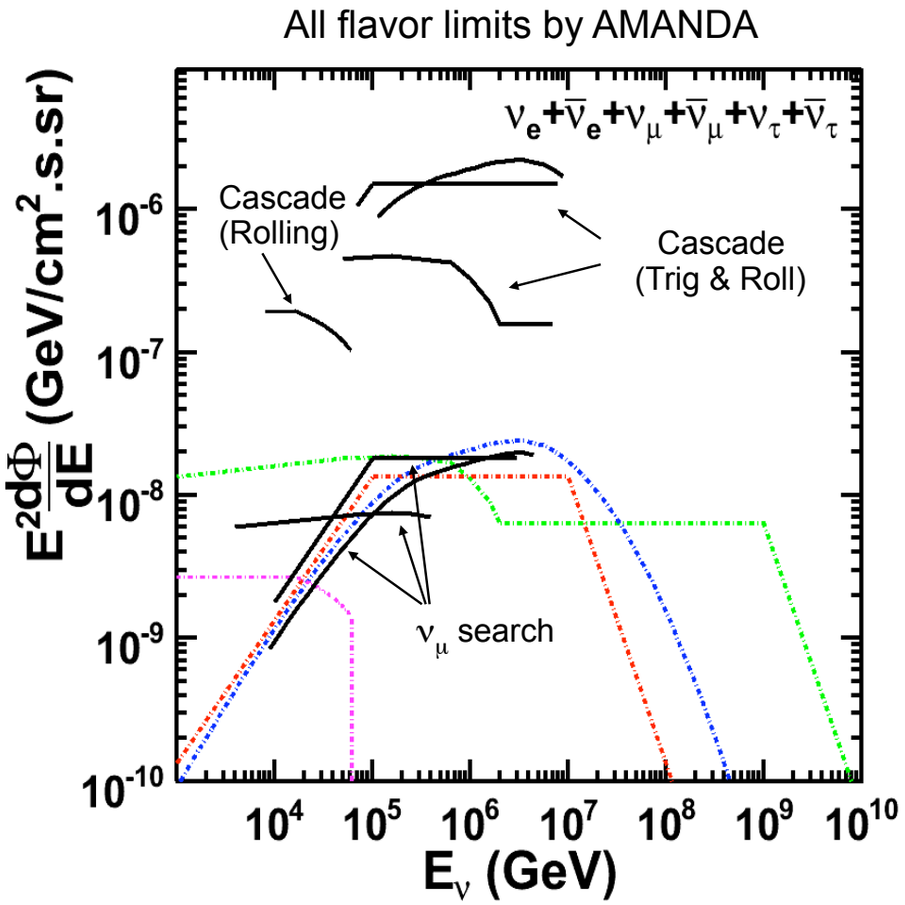


J. Braun Ph.D. thesis - AMANDA 7 year



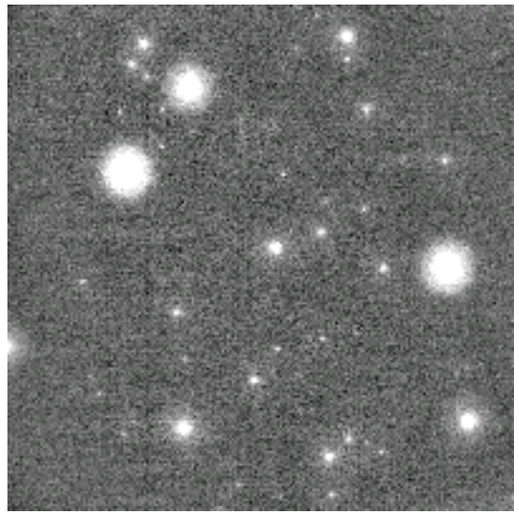
Data Events (points); Galactic Plane (curve)

Gamma Ray Bursts



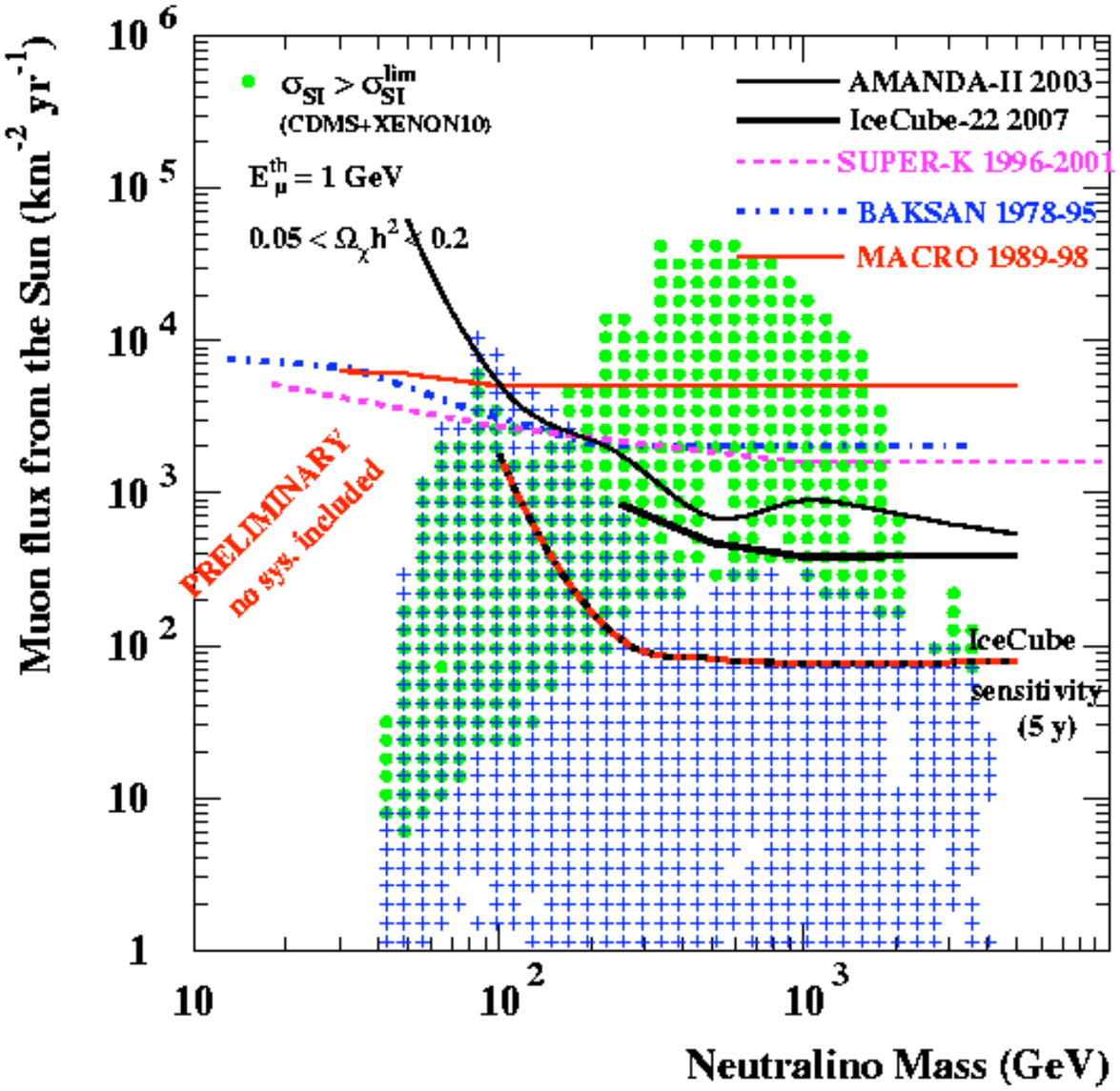
- Triggered searches - look in coincidence with satellite triggered burst
- Burst-specific: “If you’ve seen one GRB, then you’ve seen one GRB.”
- Rolling burst, unbinned burst searches

GRB080319b
“Naked Eye” GRB



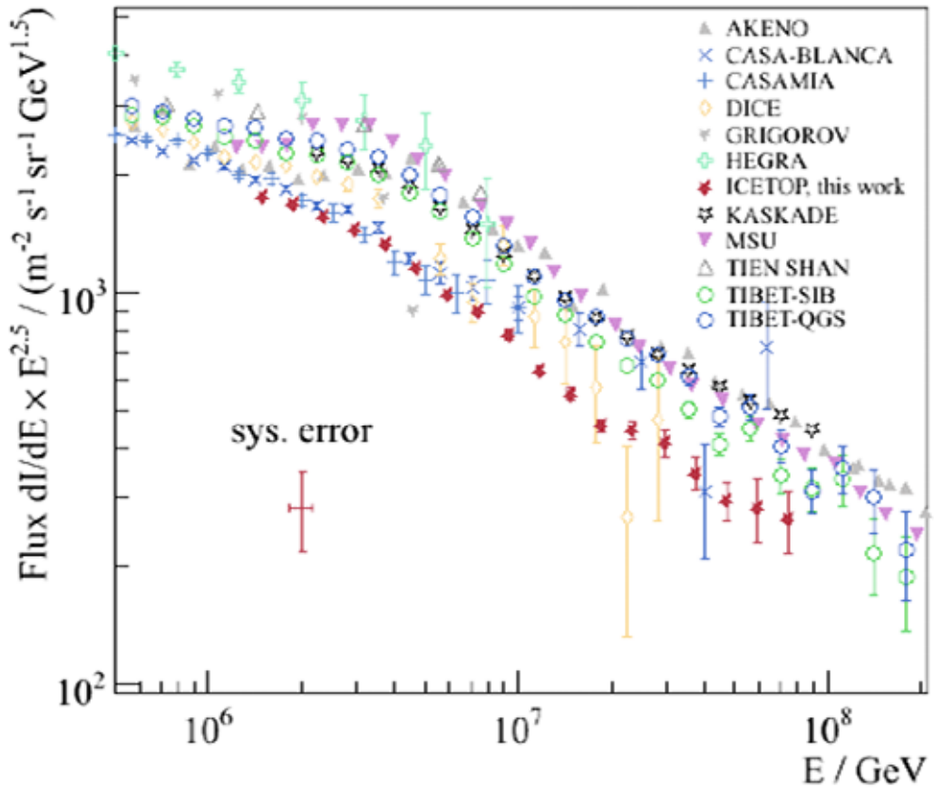
Dark Matter Detection

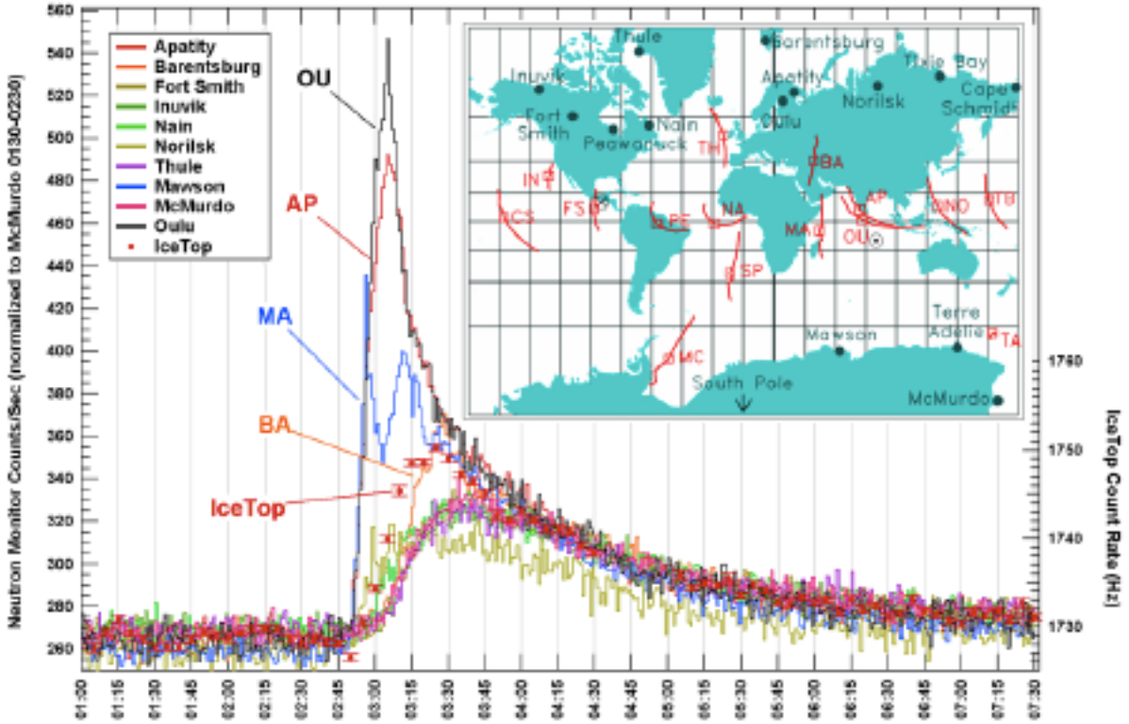
- Indirect DM searches competetive with AMANDA/IceCube
- Relic neutralinos become gravitationally bound in Solar System eventually becoming trapped in Sun.
- Annihilations produce neutrino flux observable at South Pole detector
- Sensitivity to low WIMP masses aided by AMANDA / deep core extension.

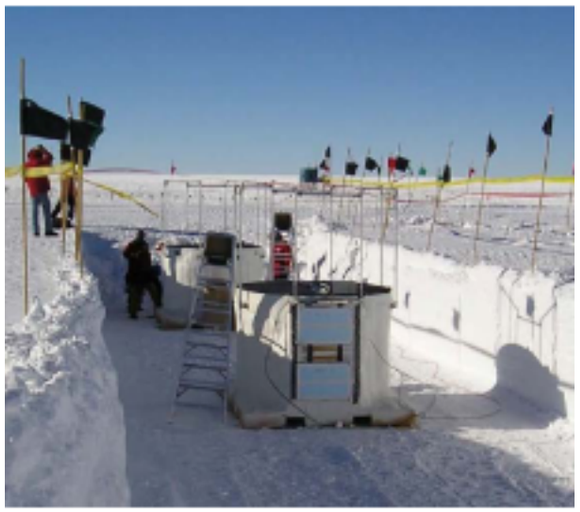


Cosmic Rays with IceCube & IceTop

- IceTop surface array is EAS detector with PeV threshold
- Join with deep ice strings and you have a 3D airshower detector capable of measuring CR energy *and* composition!
- IceTop tanks also good thick detectors for SEP - proposal submitted to NSF to instrument Greenland Summit Station with IceTop-style tanks and join to worldwide array of moniitors.

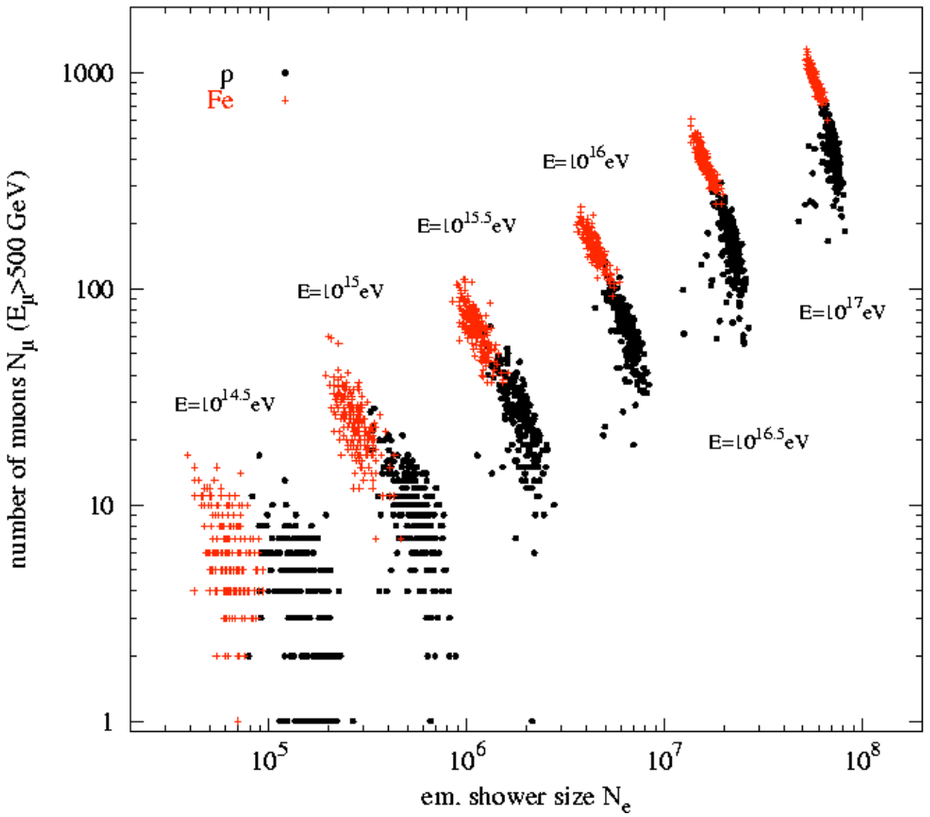


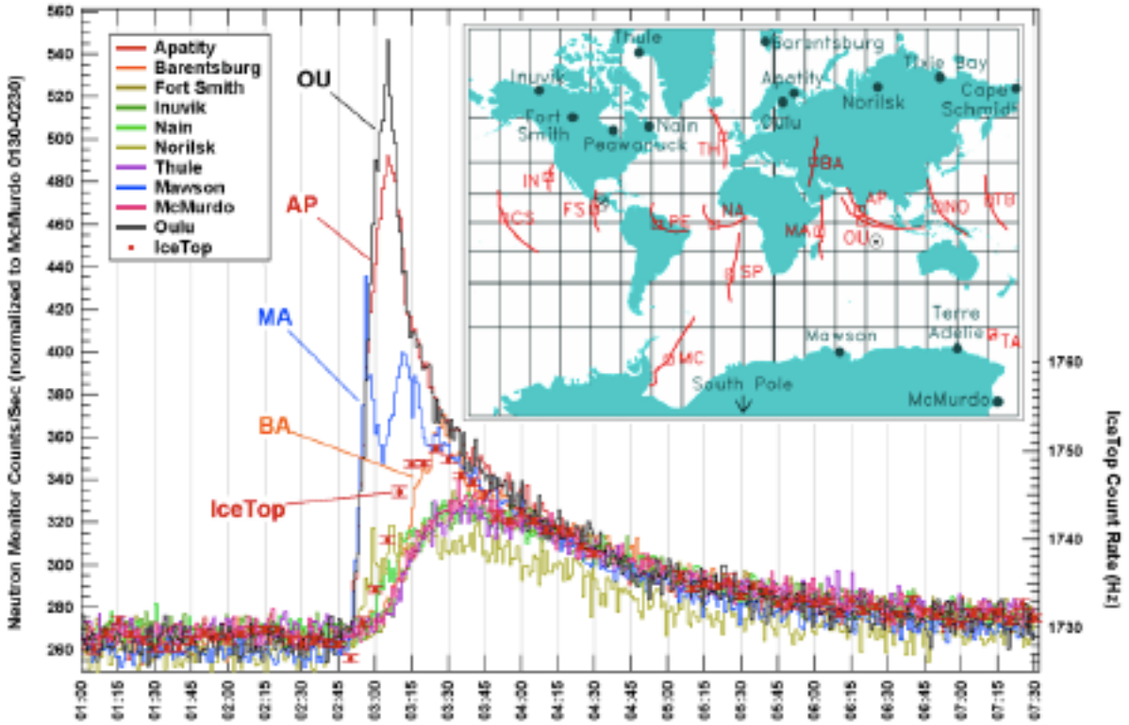


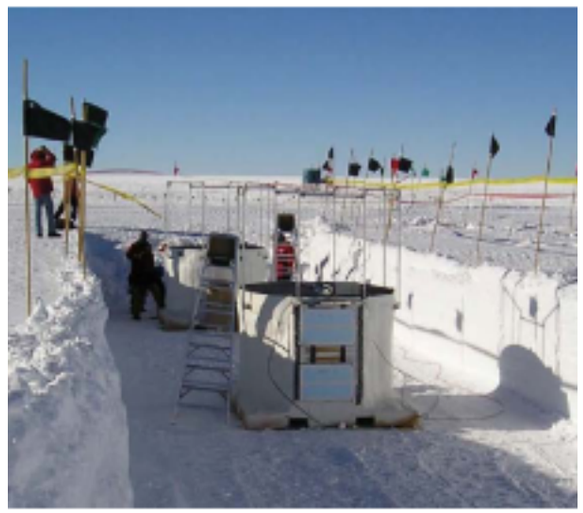


Cosmic Rays with IceCube & IceTop

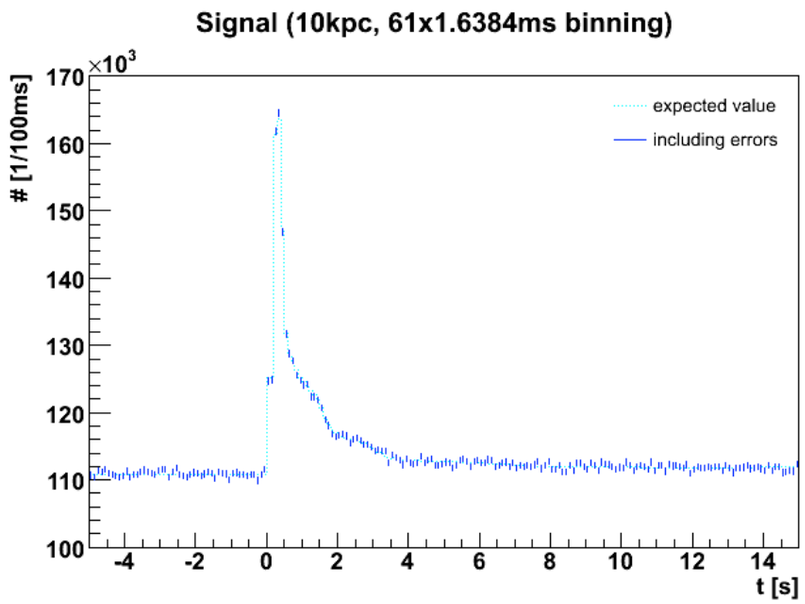
- IceTop surface array is EAS detector with PeV threshold
- Join with deep ice strings and you have a 3D airshower detector capable of measuring CR energy *and* composition!
- IceTop tanks also good thick detectors for SEP - proposal submitted to NSF to instrument Greenland Summit Station with IceTop-style tanks and join to worldwide array of moniitors.

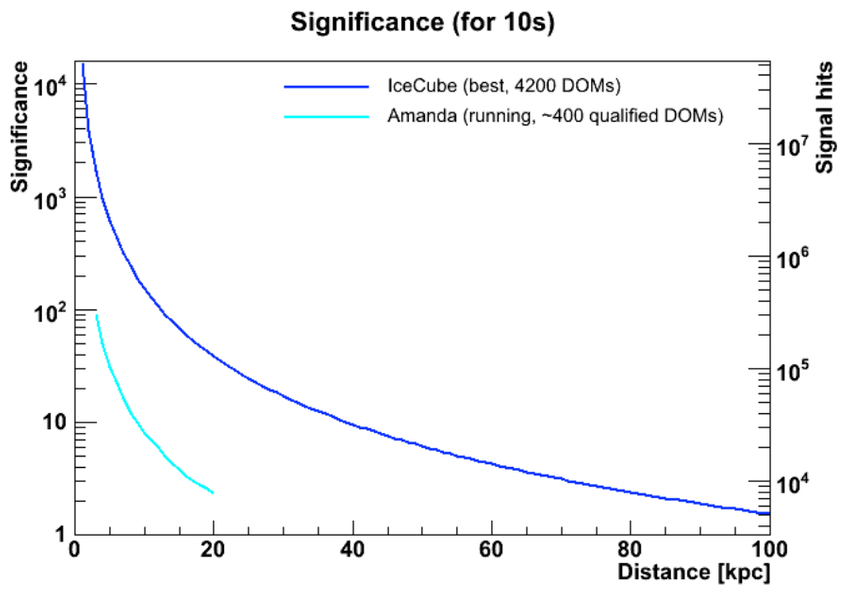


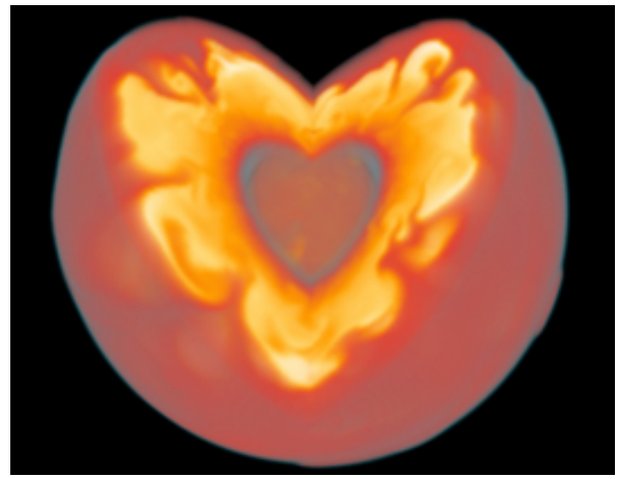




Supernova Detection in IceCube

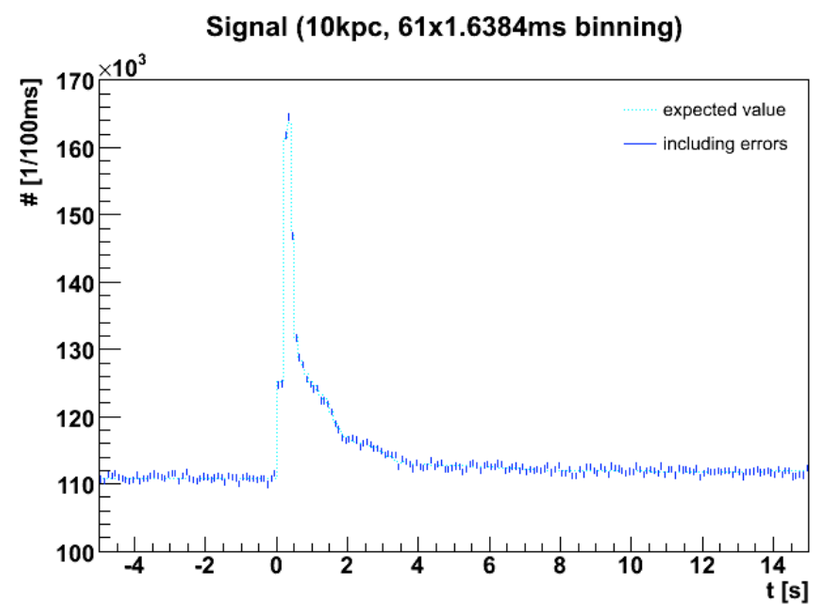


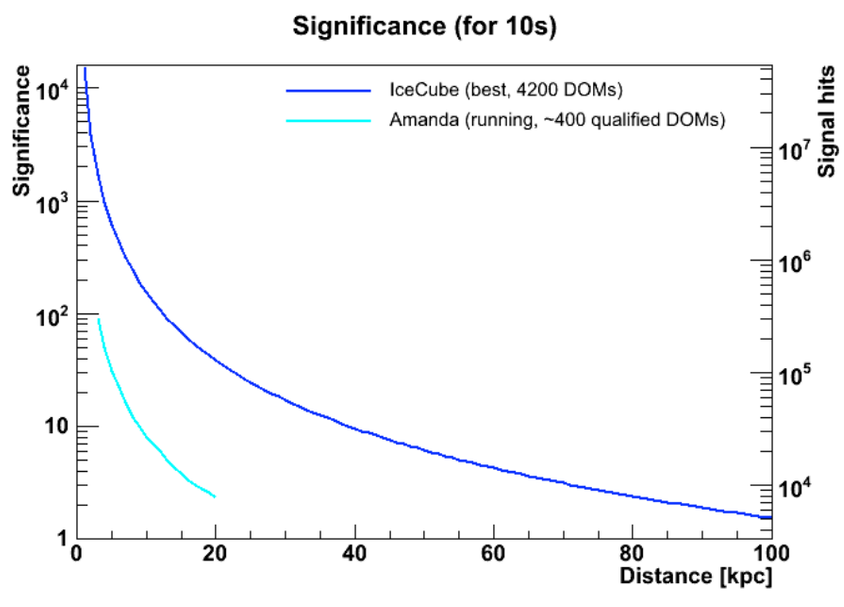


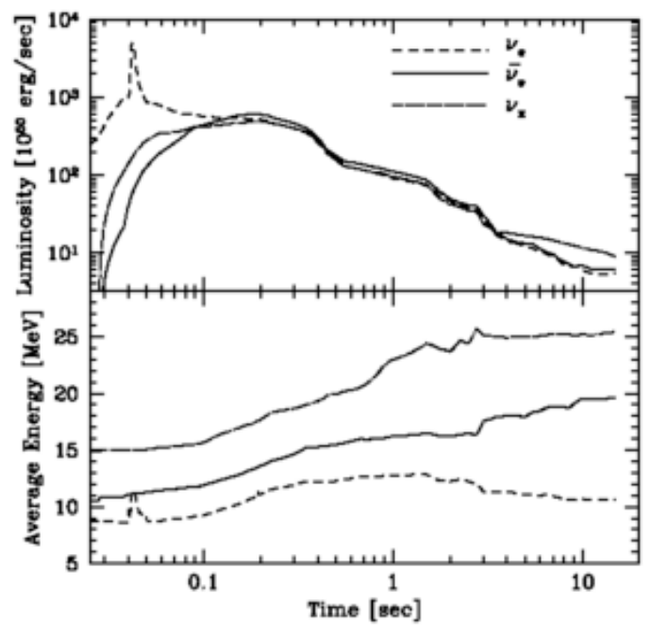


- Physics of core-collapse supernovae (Type Ib/c and II) still not understood well - cannot reliably ‘provoke’ explosions from the complex simulations
- Suggestion to use massive H_2O Cherenkov detectors for supernova detection first proposed by Jacobsen, Halzen, Zas **PRD** 49 (1994) - simple counting expt!!!
- AMANDA instrumented with VME scaler DAQ for supernova search 2000-2007.
- IceCube S/N ratio (optical efficiency/√BKG) far superior to AMANDA OM - DOM FPGA resources dedicated to scaler counting.
- Sensitive to galactic SN only (1-3 per century) but SN1987A SNe at gal. center; 10^6 signal counts - S/N > 100 : 1!
- Some surprising particle physics topics reachable through study of neutrino luminosity curve - see Dinghe, Keil, and Raffelt **JCAP** 0306 (2003) 005

Supernova Detection in IceCube



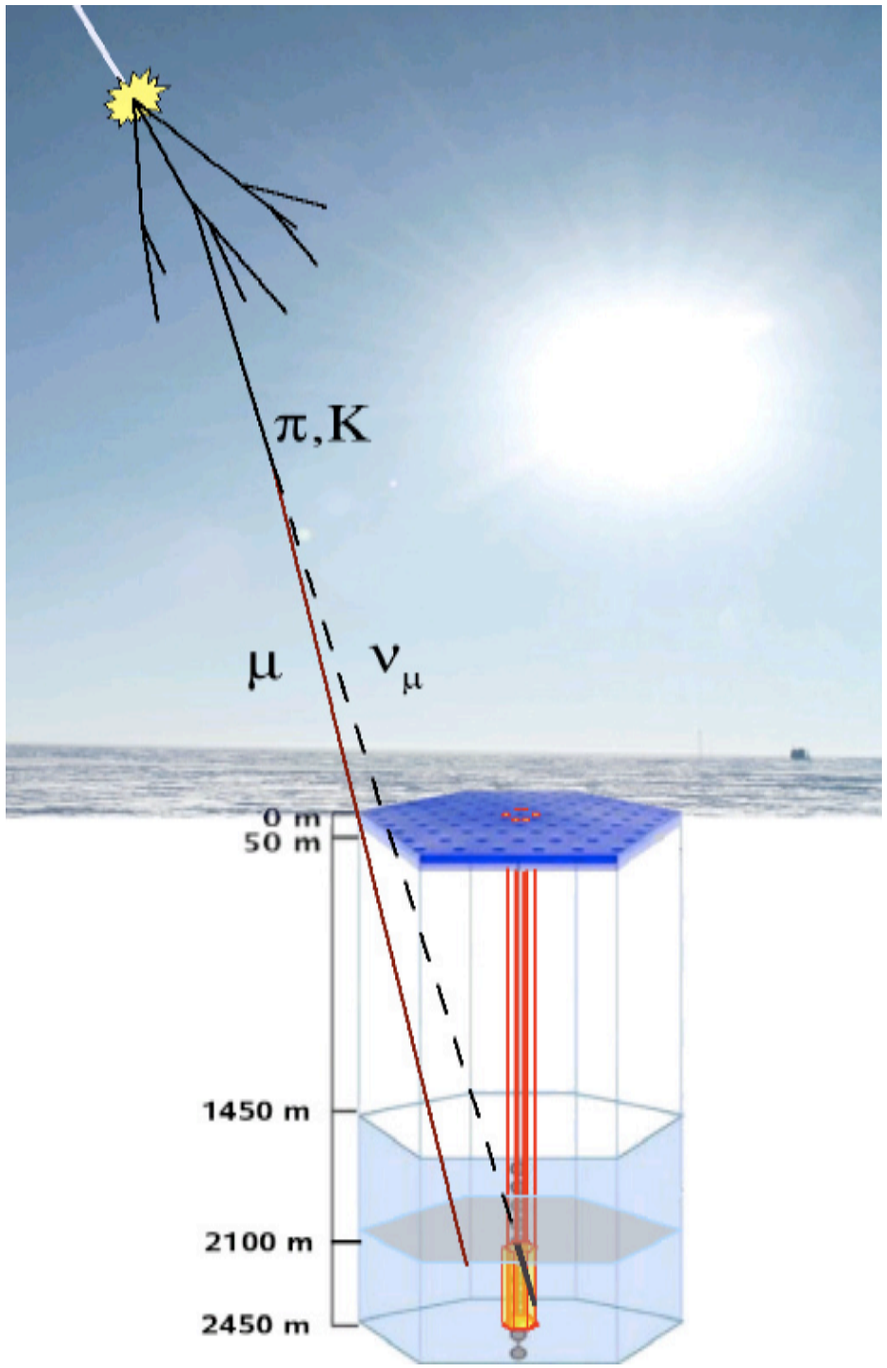




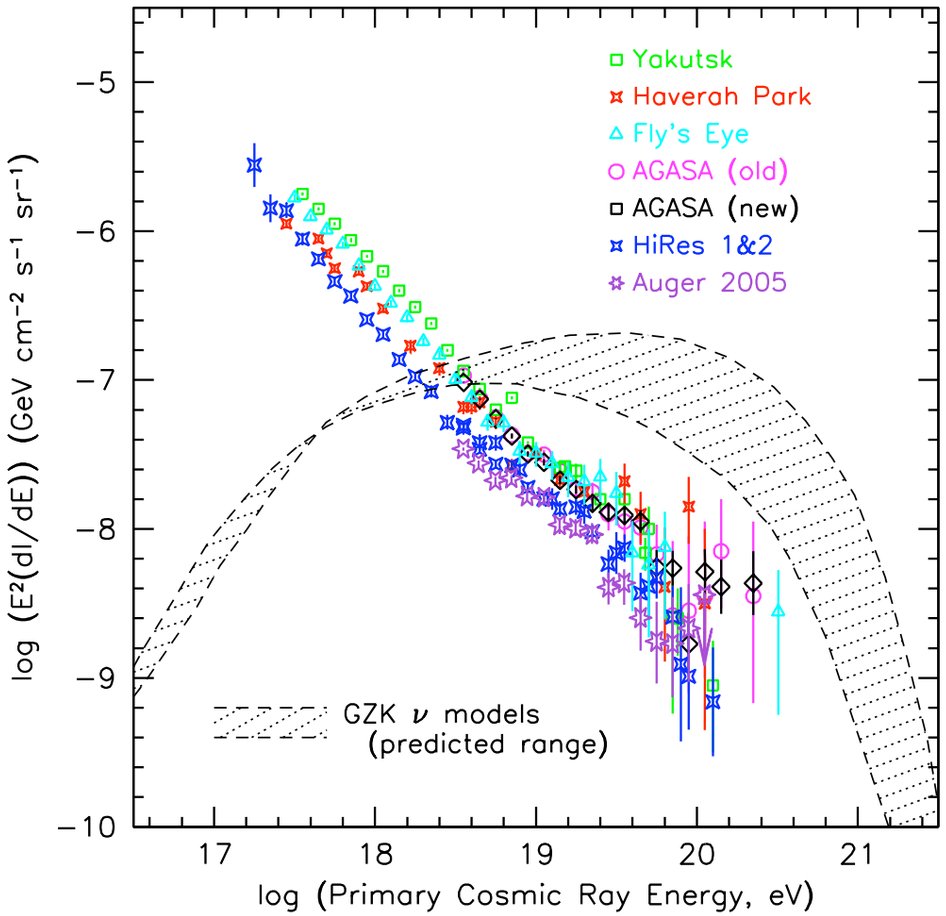
- Physics of core-collapse supernovae (Type Ib/c and II) still not understood well - cannot reliably ‘provoke’ explosions from the complex simulations
- Suggestion to use massive H_2O Cherenkov detectors for supernova detection first proposed by Jacobsen, Halzen, Zas **PRD** 49 (1994) - simple counting expt!!!
- AMANDA instrumented with VME scaler DAQ for supernova search 2000-2007.
- IceCube S/N ratio (optical efficiency/√BKG) far superior to AMANDA OM - DOM FPGA resources dedicated to scaler counting.
- Sensitive to galactic SN only (1-3 per century) but SN1987A SNe at gal. center; 10^6 signal counts - S/N > 100 : 1!
- Some surprising particle physics topics reachable through study of neutrino luminosity curve - see Dinghe, Keil, and Raffelt **JCAP** 0306 (2003) 005

Extension to Low Energy : Deep Core

- Swedish, German, Belgian funding obtained for 6 extra strings
- These strings to be placed deep where ice is clear and in center of existing IceCube array which will serve as veto
- Denser spacing - 7 m - using new high QE PMTs from Hamamatsu
- New ideas associated with low energy topics - need more people to fill these in.
- First string next year, 5 strings in 2009-2010.

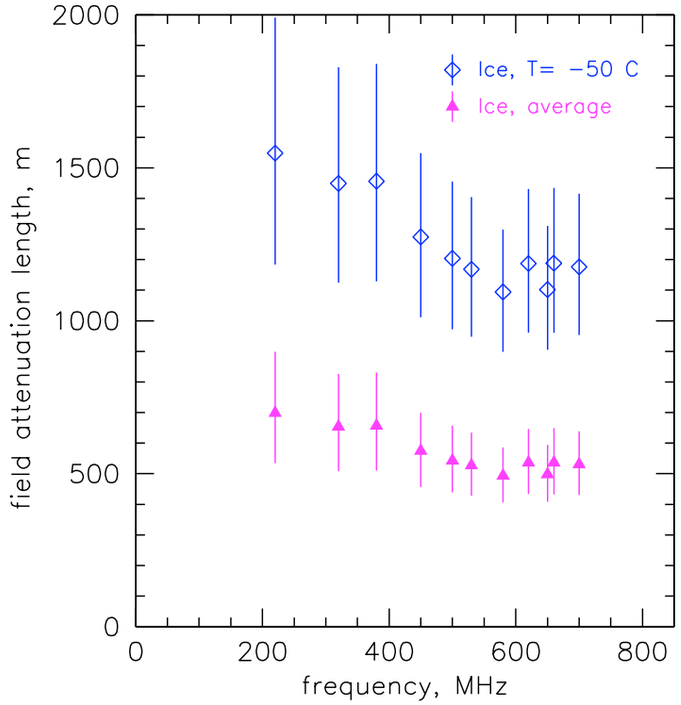


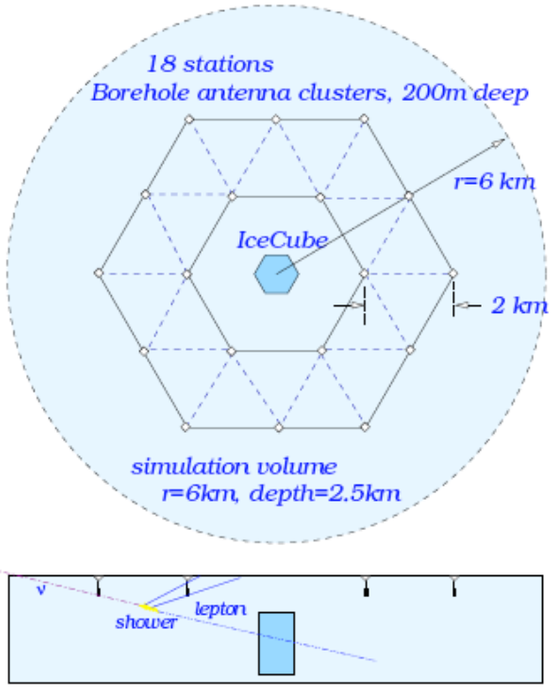
Extension to GZK Energies - Radio R&D



- Cosmogenic neutrinos produced from interaction of UHE CR on CMBR.
- Newer models are less optimistic -IceCube detector potential to observe statistically significant sample is diminished.
- Extensions of IceCube array (optical outriggers) discussed but logistics for deep-ice drilling over extended baseline is complex and expensive.
- In 1960's G. Askaryan predicts radio wave emission from UHE neutrino interactions
- 1997 ZHS paper models Askaryan radio.
- 2004 ZHS verified in test beam at SLAC.

Radio Detection in Ice

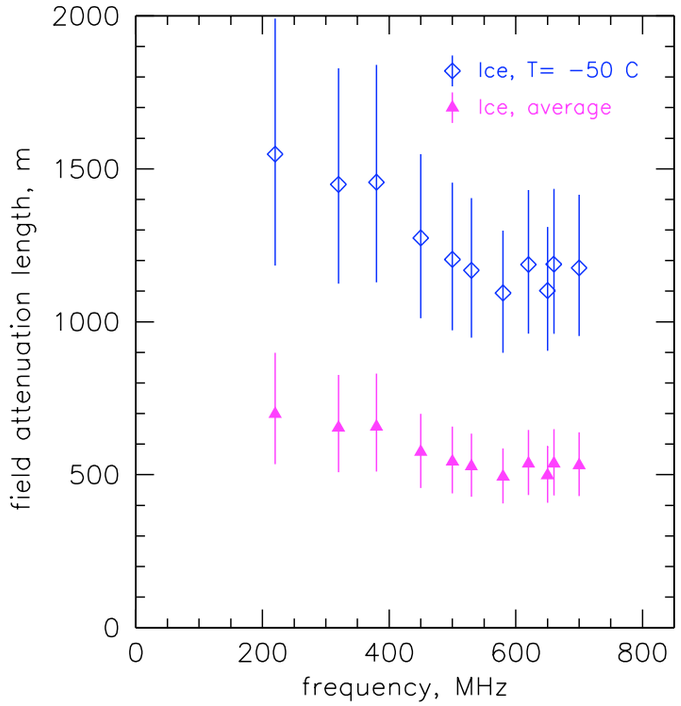


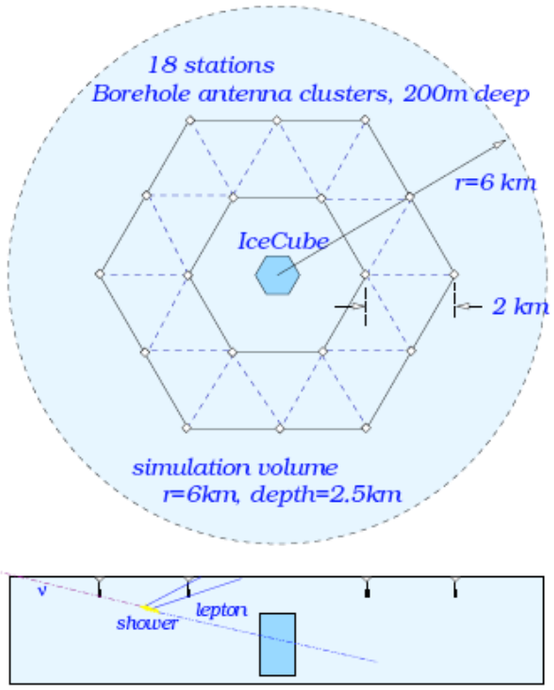


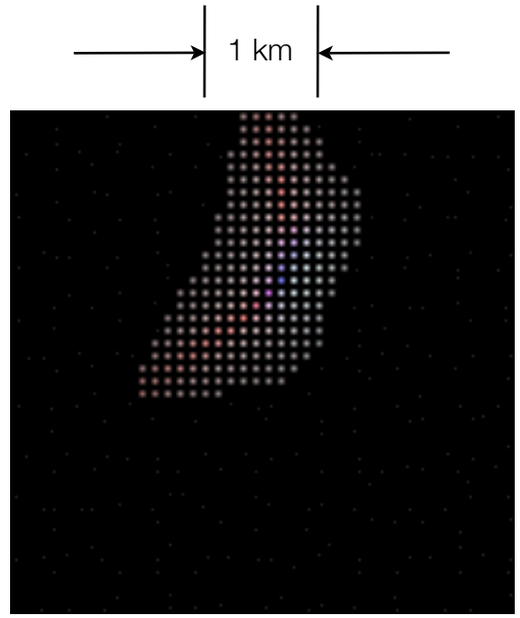


- Attenuation length in ice is 10x longer than optical photons - can place antennas at great distance.
- Mirage effects from graded n at firn layer suggest drilling, however depth is 200 - 400 m not 2 km.
- AURA R&D effort has placed 2 antenna clusters in IceCube holes - plans for 3 more this season.
- Group of scientists from IceCube and ANITA collaborations seeking to submit proposal to deploy 35 sq-km intermediate array around IceCube with eventual hopes for larger array.
- Possible cooperation with acoustic R&D groups (Ghent U and others) on drilling / science.

Radio Detection in Ice







- Attenuation length in ice is 10x longer than optical photons - can place antennas at great distance.
- Mirage effects from graded n at firn layer suggest drilling, however depth is 200 - 400 m not 2 km.
- AURA R&D effort has placed 2 antenna clusters in IceCube holes - plans for 3 more this season.
- Group of scientists from IceCube and ANITA collaborations seeking to submit proposal to deploy 35 sq-km intermediate array around IceCube with eventual hopes for larger array.
- Possible cooperation with acoustic R&D groups (Ghent U and others) on drilling / science.

Summary and Outlook



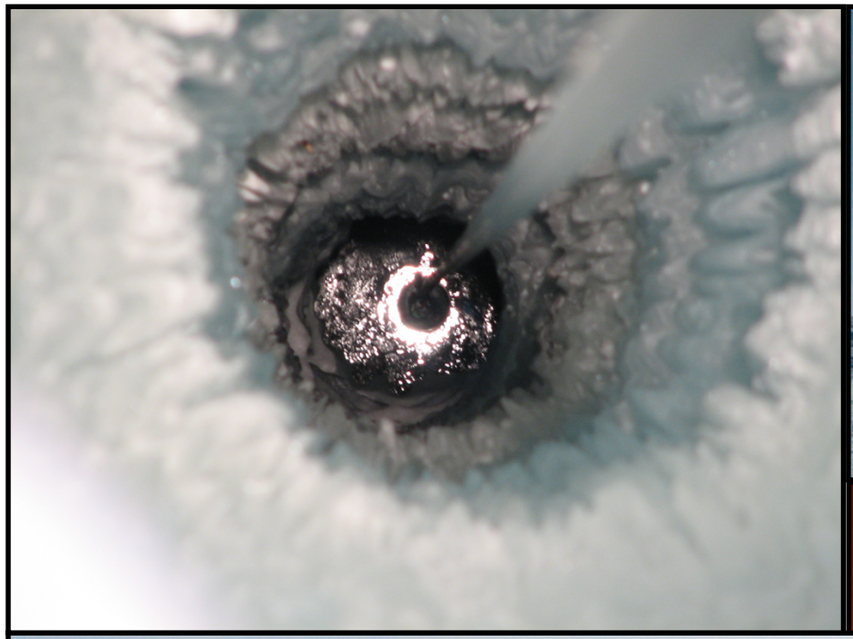
- We are at threshold of new age of kilometer-scale neutrino detectors with IceCube leading the world in neutrino astrophysics from GeV to PeV energies.

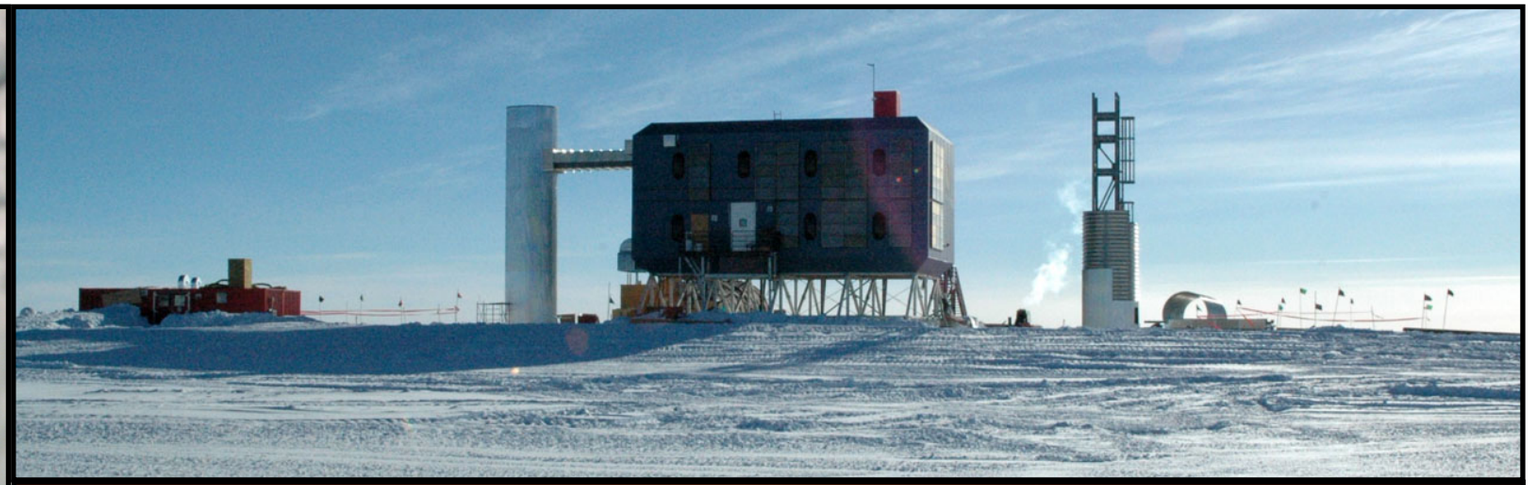
- IceCube at beginning of operational phase. The versatile detector is producing extremely high quality data useful for a broad range of science topics. Abundant room for growth of collaboration to join in data analysis effort; field is *wide open*. We continue to find new ways to use the detector.

- Looking to the future it will be necessary to pursue aggressive R&D on detection technologies that will enable effective volumes 10 to 100 times to be equipped. Radio / acoustic technologies and perhaps even hybrid radio, acoustic, and optical arrays under development.

- South Pole ice is the optimal environment for such future detectors.

Final Message : Enjoy whatever it is you do!



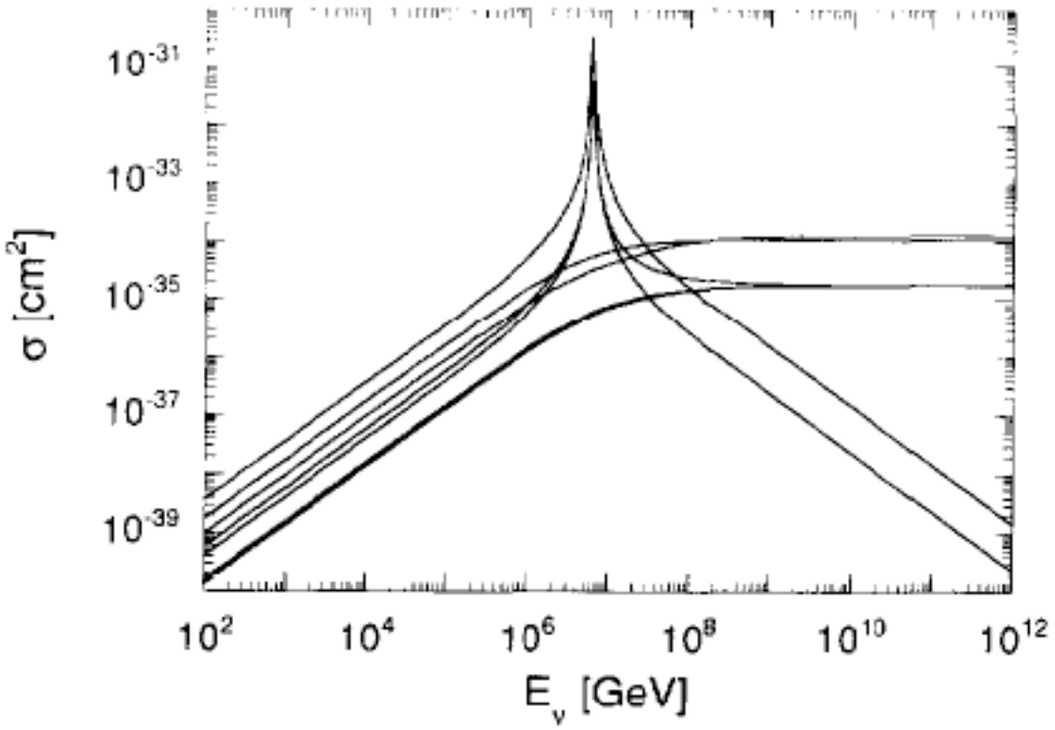




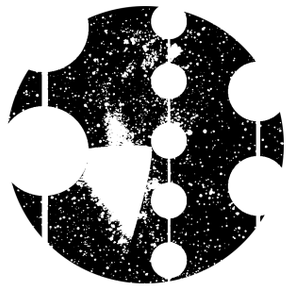


Overflow Slides

More on UHE Neutrino Cross Sections



SNe



- Categorization of SNe historically based on presence of hydrogen in spectroscopic lines:
  - Type I SNe don’t have it
  - Type Ia probably from dwarf stars accreting mass to Chandrasekhar limit, then exploding.
- Type Ib/c core collapse SNe but have lost hydrogen envelope because of stellar winds (Wolf-Rayet stars) or perhaps mass transfer to companion star. Incidentally, recent investigations associate these types with GRBs (e.g. Woosley and Bloom astro-ph/0609142); variations with slower jets may further be γ dark but still produce TeV ν detectable in IceCube and may be much more common.
- Type II SNe have the hydrogen lines - these are likely massive stars with hydrogen envelopes intact that undergo core collapse
- Intense neutrino luminosities only with core collapse SNe Type Ib/c and Type II.
- Galactic rate of core collapse SNe given by INTEGRAL measurements - 1-3 per century (Nature 439 (2006) 45). Optimistically, given IceCube lifetime of 15 years - 40% chance of observing galactic event.

Artificial Deadtime

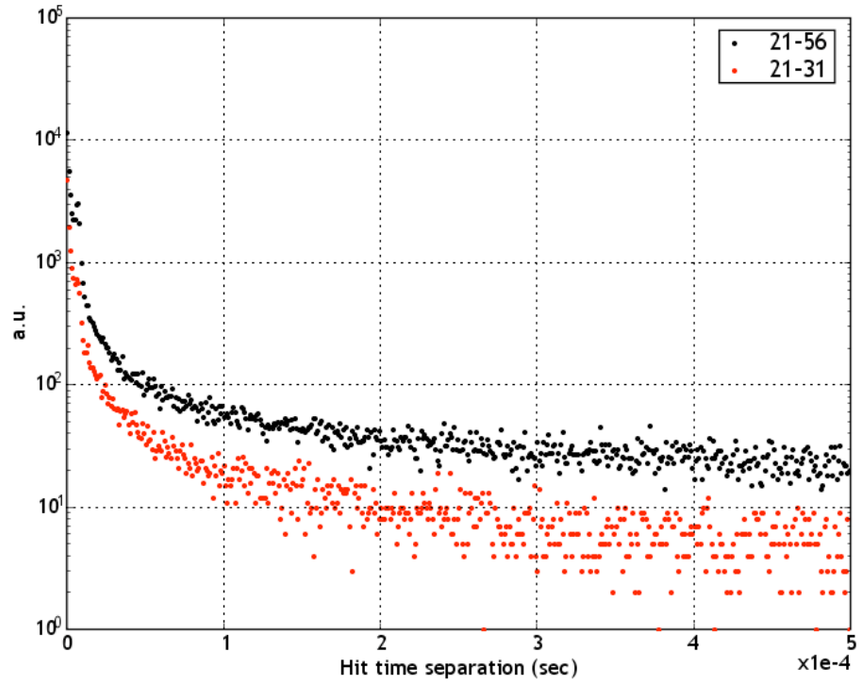
Correlated noise in PMTs

Measurements counting all PMT pulses in deployed DOMs yield average rate of approx. 700 Hz / module. Study of the time structure of this noise clearly indicates correlated noise patterns:

PMT Afterpulses
Well-known that ionized residual gases in PMTs cause afterpulses on timescale (for large PMTs) of 6-10 μs.

Glass Scintillation
Small contamination of rare-earth oxides produces further tail out to 100's of μs due to scintillation processes.

To reduce noise rate and restore Poissonian behavior to fluctuations ,it is necessary to apply afterpulse inhibit (deadtime) when pulse counting. Analysis of real data demonstrates that 200 μs afterpulse suppression window reduces background by factor of 4 while sacrificing only few percent of signal.



Real-time Supernova Detection

Real-time detection of SNe

Don't stop there: real-time detection and reporting of burst candidates gives "heads-up" to optical observers.

In addition, combining many, distributed observatories makes more sensitive, robust alert.

SuperNova Early Warning System [NJP **6** (2004)114] … Strict requirement that individual detector produce no more than 1 false alarm / week.

SNEWS and IceCube

Mainz supernova group adapting AMANDA online trigger to handle data feed from IceCube DAQ.

Necessary to thoroughly evaluate system to demonstrate that we meet the strict requirement of < 1 false alarm / week.

22-string IceCube will join end of year 2007.

SNEWS and AMANDA

AMANDA official participant since 6/2005.

Near real-time delivery of alerts possible through Iridium link to pole (24/7; low-bandwidth)

Noise rates in AMANDA can be highly variable. Real-time detection of noisy channels necessary; additionally, detector chi-square reports uniformity of signal in detector (good SN totally uniform).

Statistics based on Gaussian approx.; OK for large bins.

$$r_i = n_i/\Delta t \quad ; \qquad \langle r_i \rangle = \mu_i \,, \quad \sigma_{r_i} = \sigma_i$$

$$p(r) = \frac{1}{\sqrt{2\pi}\,\sigma_i}\, \exp - \frac{(r-\mu_i)^2}{2\sigma_i^2}$$

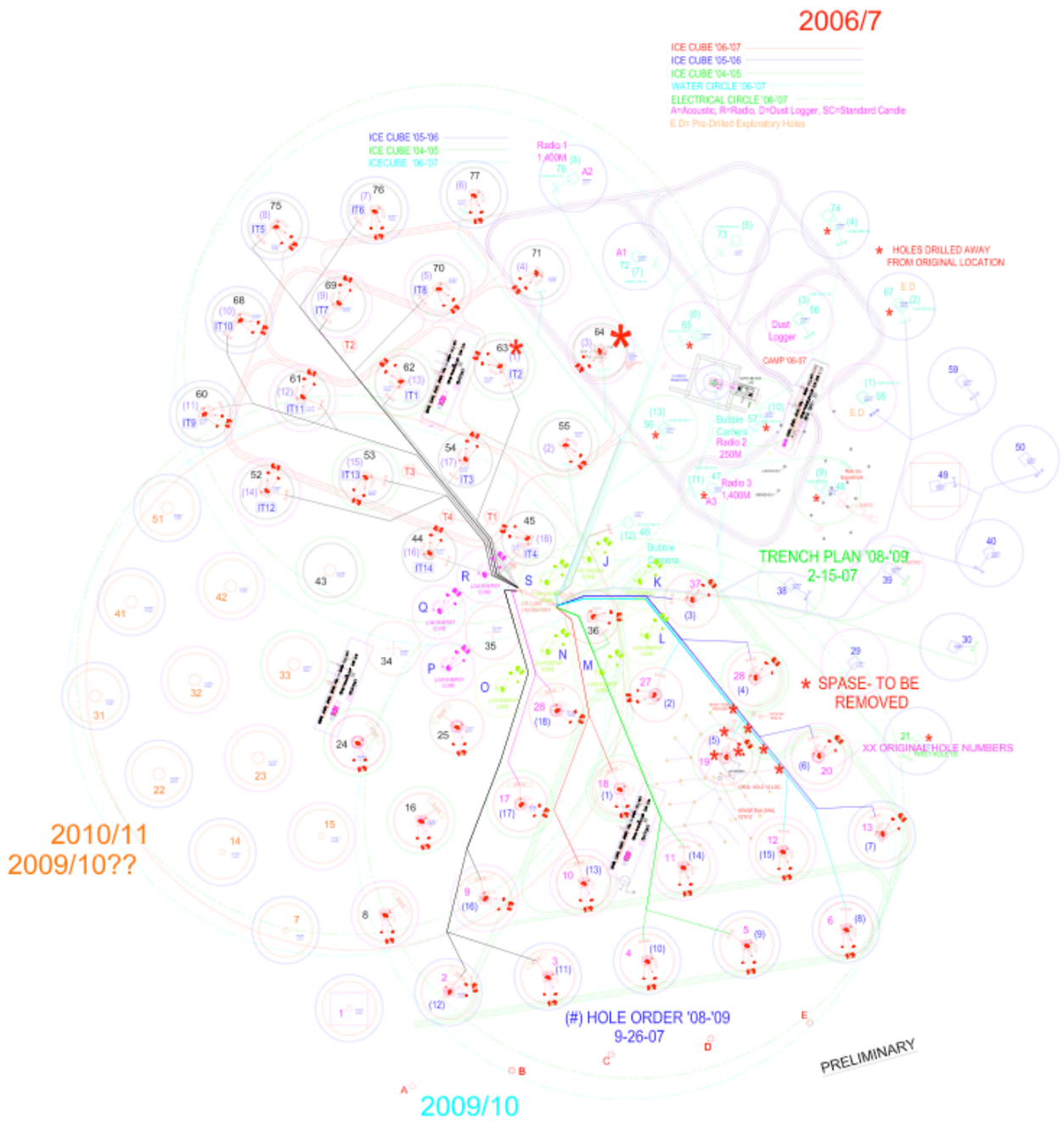
$$\mathcal{L}(\Delta\mu) = \frac{1}{\sqrt{2\pi}\,\sigma_i}\, \exp - \frac{(r_i - (\mu_i + \Delta\mu'))^2}{2\sigma_i^2}$$

$$\mathcal{L}(\Delta\mu)\big|_{\max} = \prod_{i=1}^{N_{OM}} \frac{1}{\sqrt{2\pi}\,\sigma_i}\, \exp - \frac{(r_i - (\mu_i + \epsilon_i\,\Delta\mu))^2}{2\sigma_i^2}$$

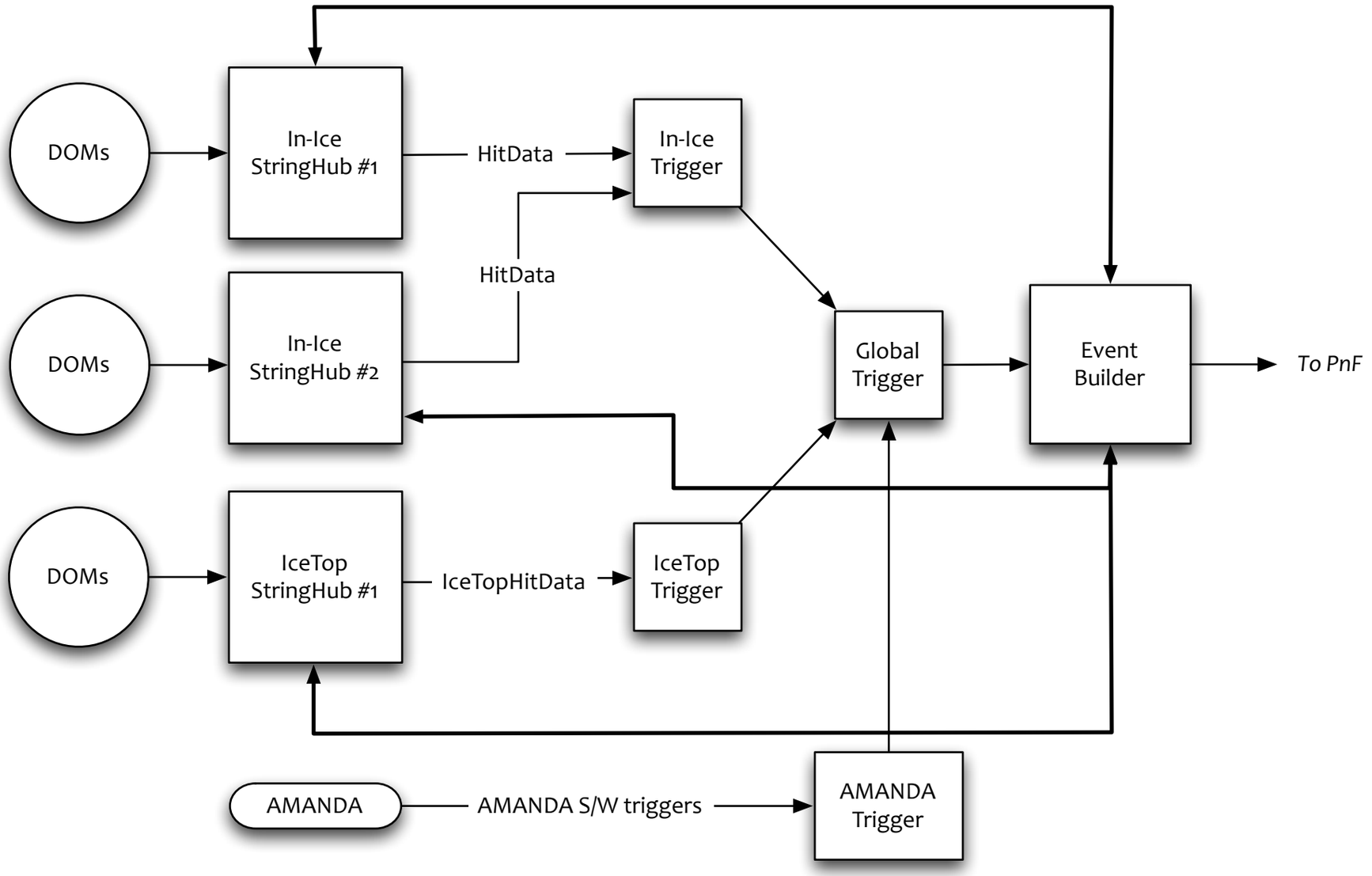
$$\chi^2(\Delta\mu) = \sum_{i=1}^{N_{\rm OM}} \left(\frac{r_i - (\mu_i + \epsilon_i\,\Delta\mu)}{\sigma_i} \right)^2$$

$$\Delta\mu = \sigma^2_{\Delta\mu} \cdot \sum_{i=1}^{N_{\rm OM}} \frac{\epsilon_i\,(r_i - \mu_i)}{\sigma_i^2} \quad , \quad \text{with} \quad \sigma^2_{\Delta\mu} = \left(\sum_{i=1}^{N_{OM}} \frac{\epsilon_i^2}{\sigma_i^2} \right)^{-1}$$

IceCube Drilling Map



DAQ Diagram


DOMs
In-Ice StringHub #1
HitData
In-Ice Trigger
HitData
DOMs
In-Ice StringHub #2
Global Trigger
Event Builder
To PnF
DOMs
IceTop StringHub #1
IceTopHitData
IceTop Trigger
AMANDA
AMANDA S/W triggers
AMANDA Trigger