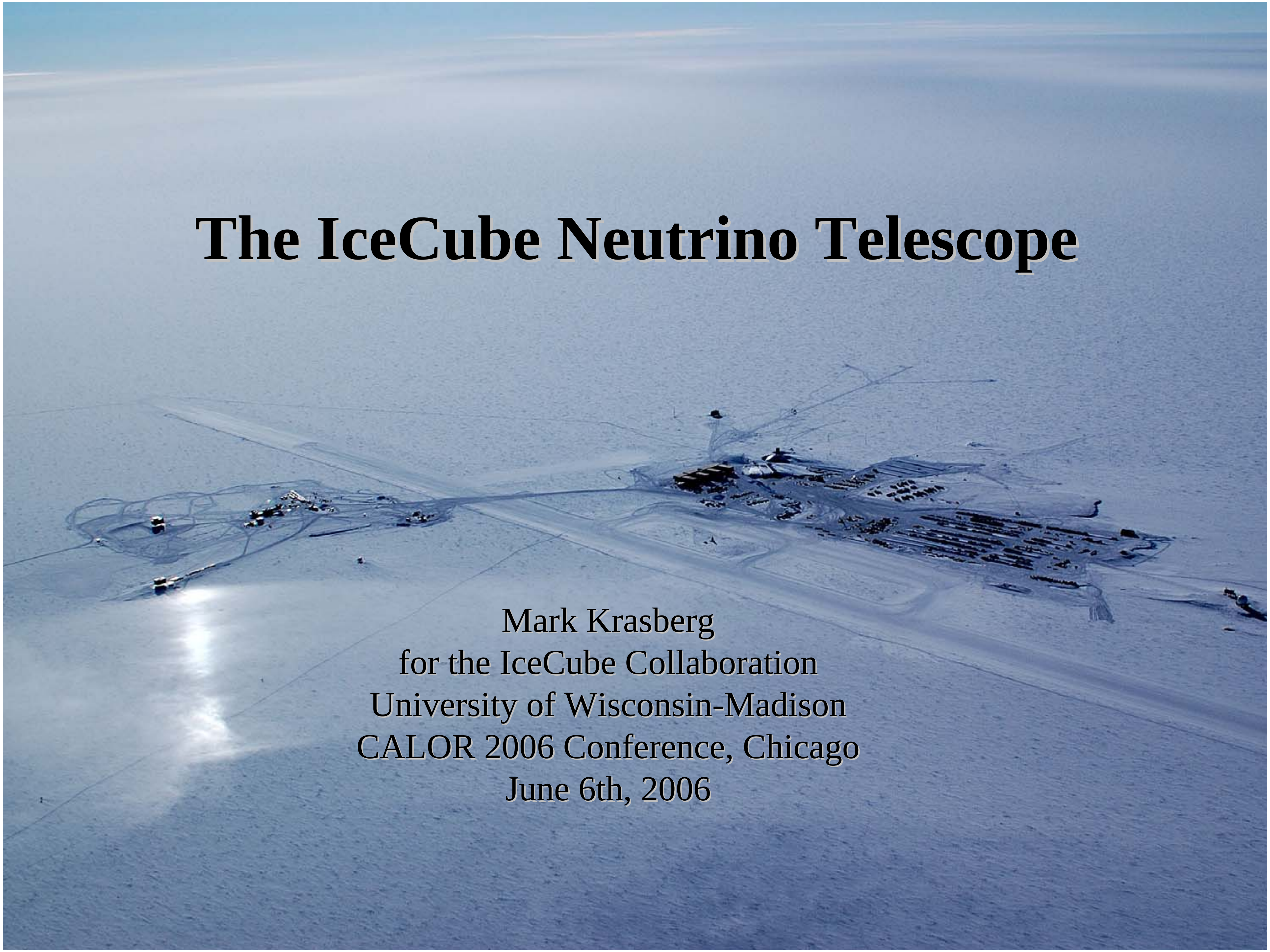
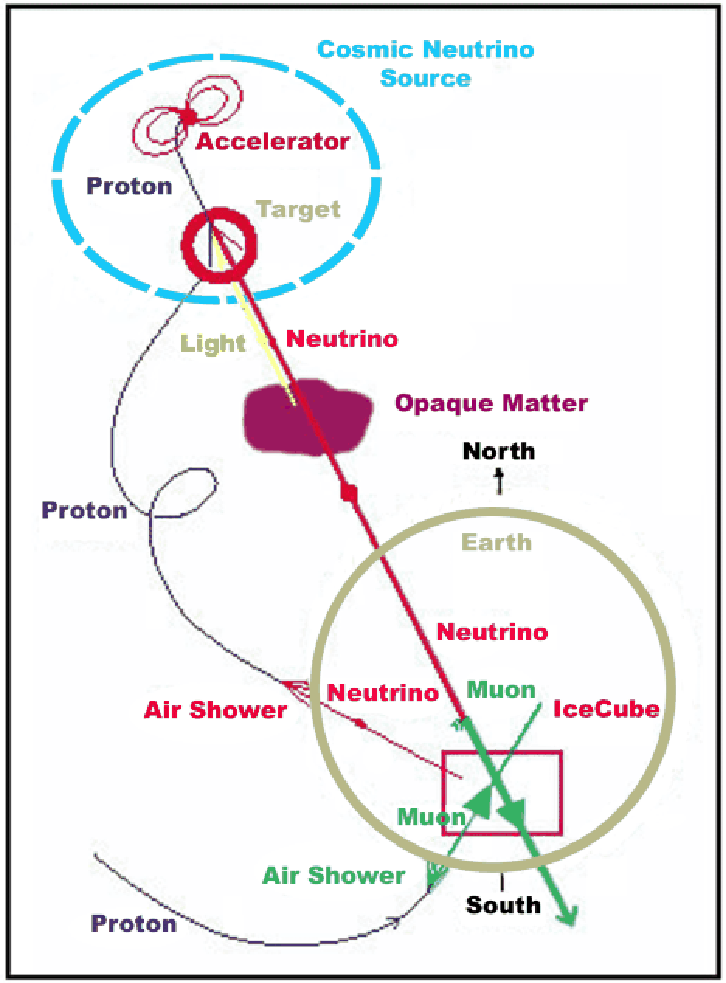


The IceCube Neutrino Telescope

Mark Krasberg
for the IceCube Collaboration
University of Wisconsin-Madison

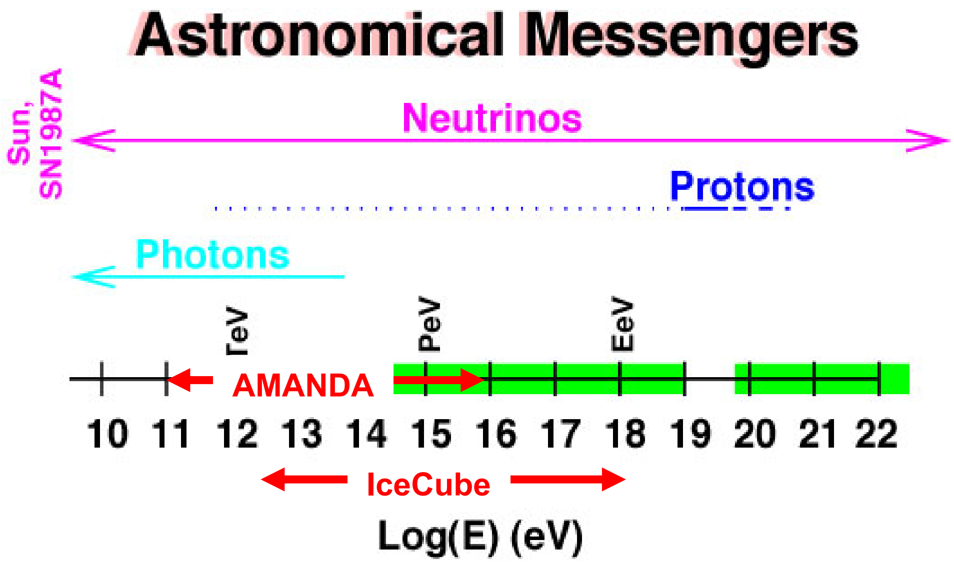
CALOR 2006 Conference, Chicago
June 6th, 2006

UHE Neutrino Astronomy



Still unresolved questions regarding production of UHECR – no resolved sources to date. Neutrinos are ideal particles to trace back deep inside astrophysical sources:

- Not deflected by magnetic fields
- Not absorbed at source, nor in transit
- Neutrinos produced in "beam dumps"



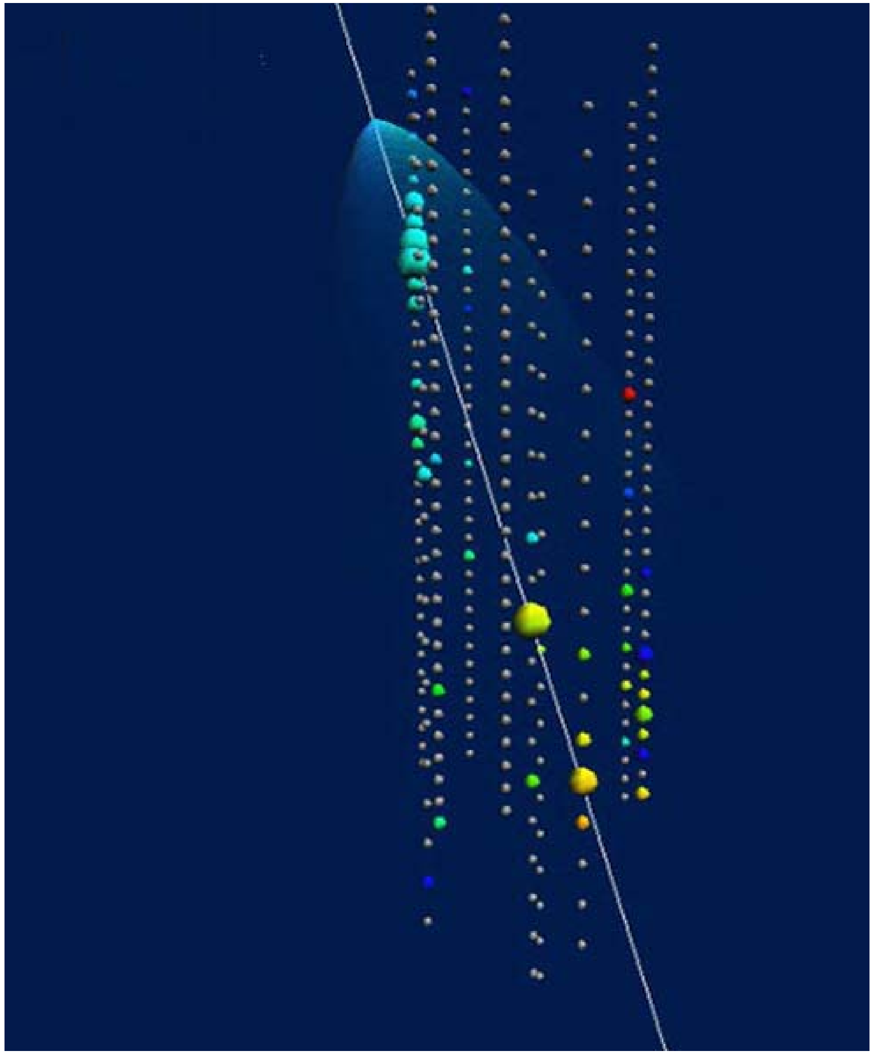
IceCube – a next generation ν observatory

a cubic kilometer successor to AMANDA
(Antarctic Muon and Neutrino Detector Array)

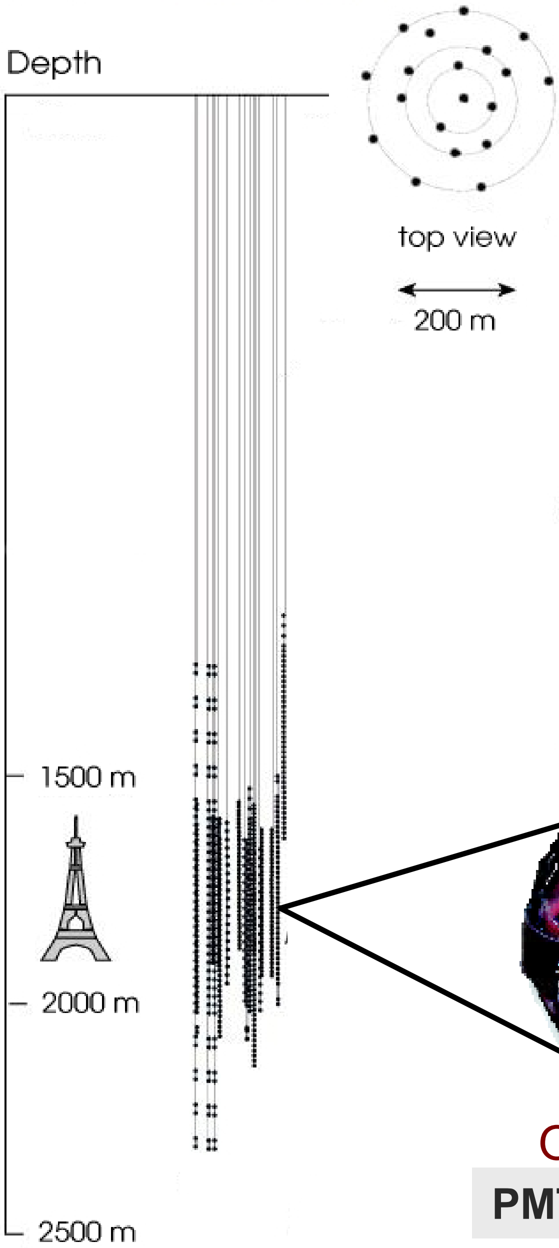
Detection of Cherenkov light from
the charged particles produced when
a ν interacts with rock or ice

Direction reconstructed from
the time sequence of signals

Energy measured from counting
the number of photoelectrons

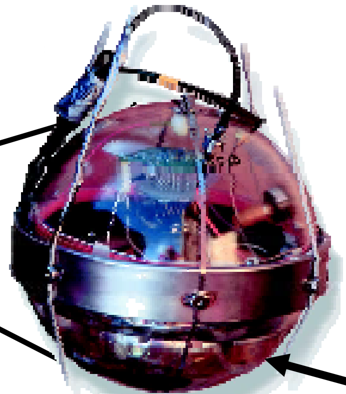


Expected performance wrt AMANDA
- improved angular resolution
- improved energy resolution
  - increased effective area/volume
  - entire waveform read out



AMANDA-II

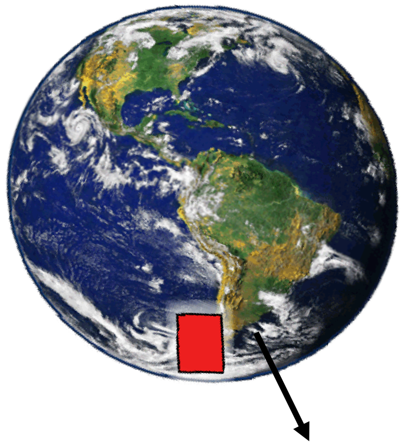
19 strings
677 OMs
Trigger rate: 80 Hz
Data years: >=2000



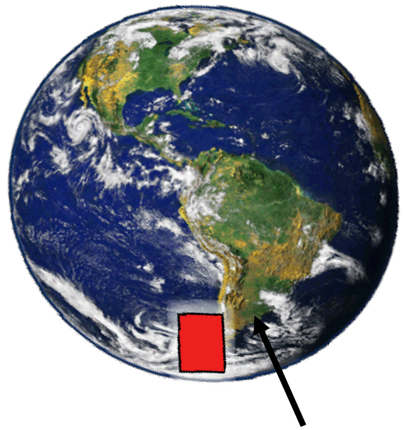
Optical Module

PMT noise: ~1 kHz

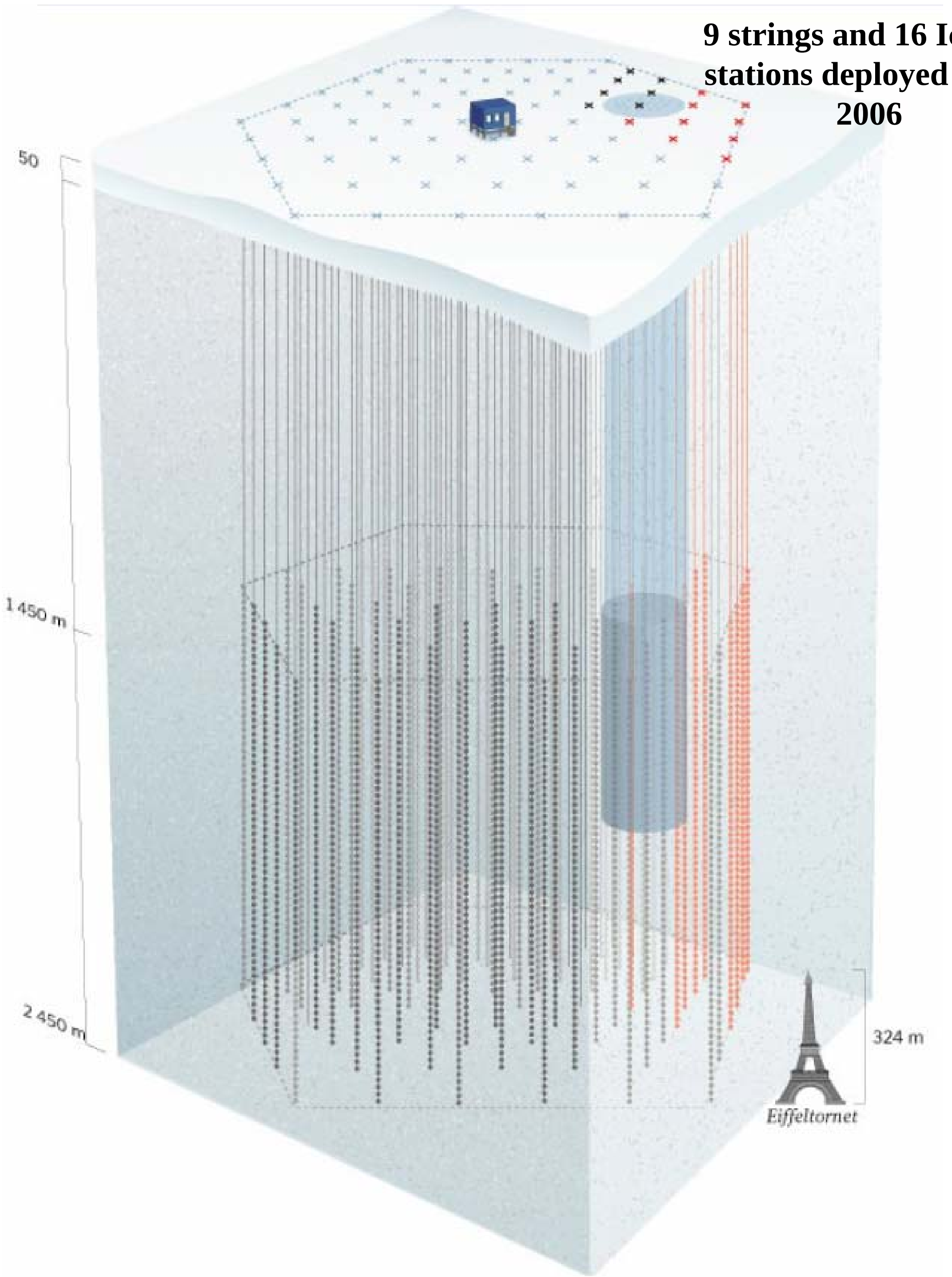
“Up-going”
(from Northern sky)



“Down-going”
(from Southern sky)



PMT looking downward



The Design

- 1 Gton instrumented volume
- >70 strings of 60 Digital Optical Modules (DOMs)
  - 1450-2450 m deep
  - 17 m spacing
  - 125 m hexagonal grid
  - geometry optimized for detection of TeV – PeV ν's
  - DOMs look downward
- No single point failure: 1 cable/2DOMs
- IceTop air shower array
  - 2 surface tanks for each string/station (2m diameter)
  - each tank contains 2 DOMs

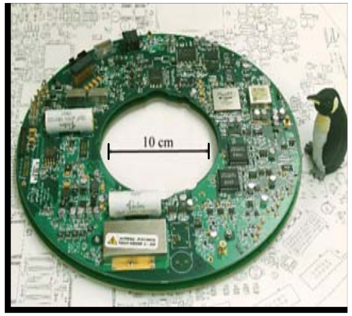
IceCube Science Goals

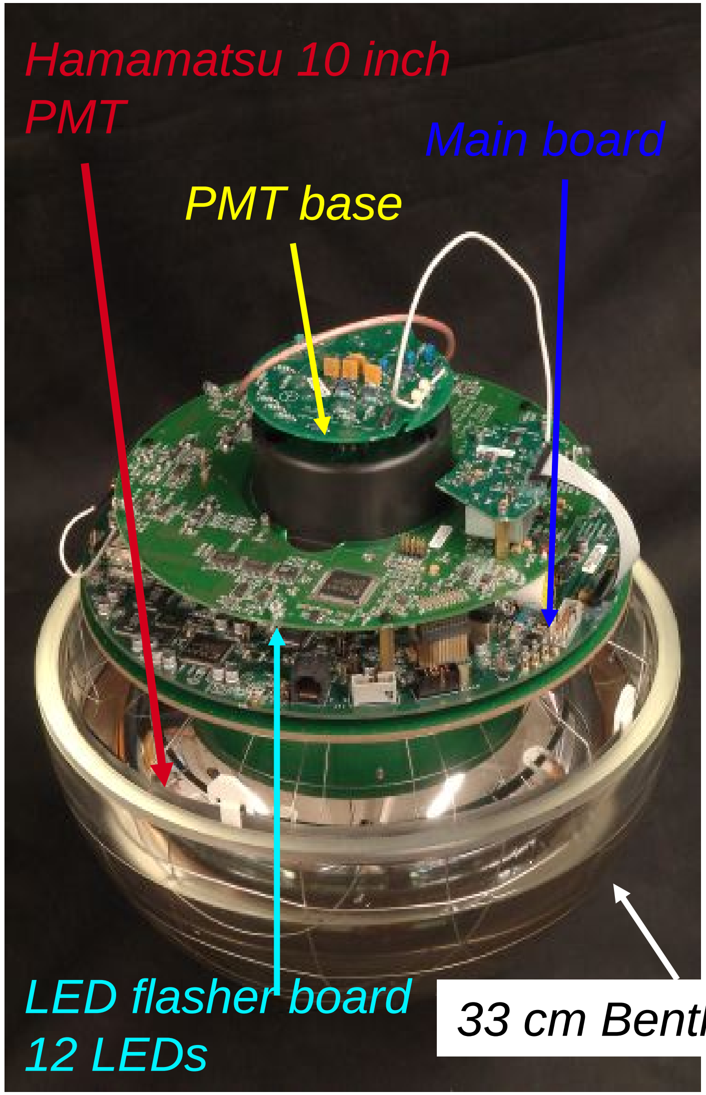
- Steady galactic and extra-galactic neutrino sources (SNRs, AGNs, binary stars)
- Variable neutrino sources (micro-quasars, magnetars)
- Transient neutrino sources (GRBs)
- Exotic neutrino sources (monopoles, nuclearities)
- Cosmic Ray composition (IceCube/IceTop)

The DOMs

Each DOM is an autonomous data collection unit

Power consumption: 3W

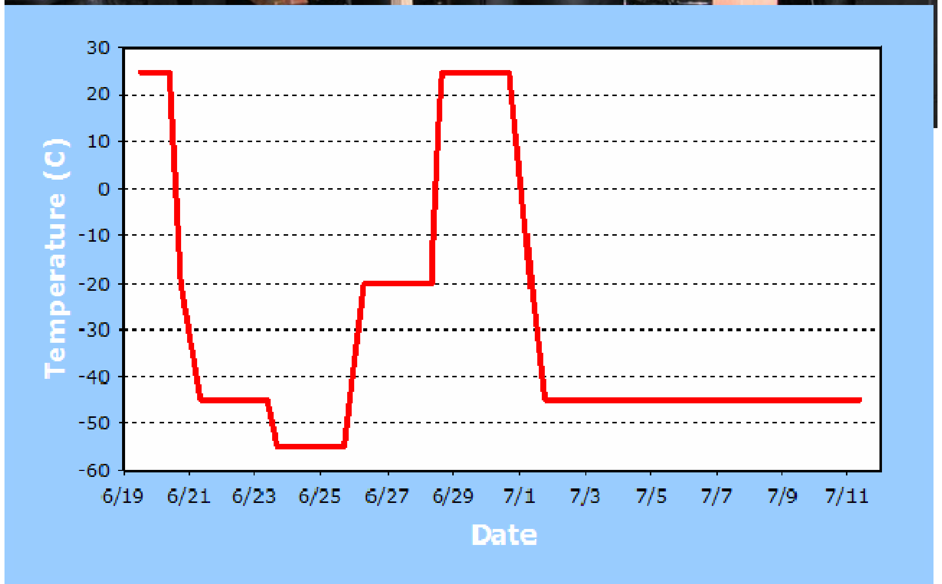




- Measure arrival time of every photon
- 2 Analog Transient Waveform Digitizers at 300 MHz for 400 ns (signal complexity) and an FADC recording at 40 MHz FADC 6.6 μs (event duration in ice)
  - ATWDs have low, medium and high gain channels
- Dynamic range 500pe/15 nsec 25000 pe/6.4 μs
- Can do local coincidence triggering
- transmits to surface at request via digital communications
- Data sent over 3.3 km twisted pair copper cable: power, data and time stamping

Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS time every ≈5 sec at a precision rms = 2 nsec (Rapcal calibrations)

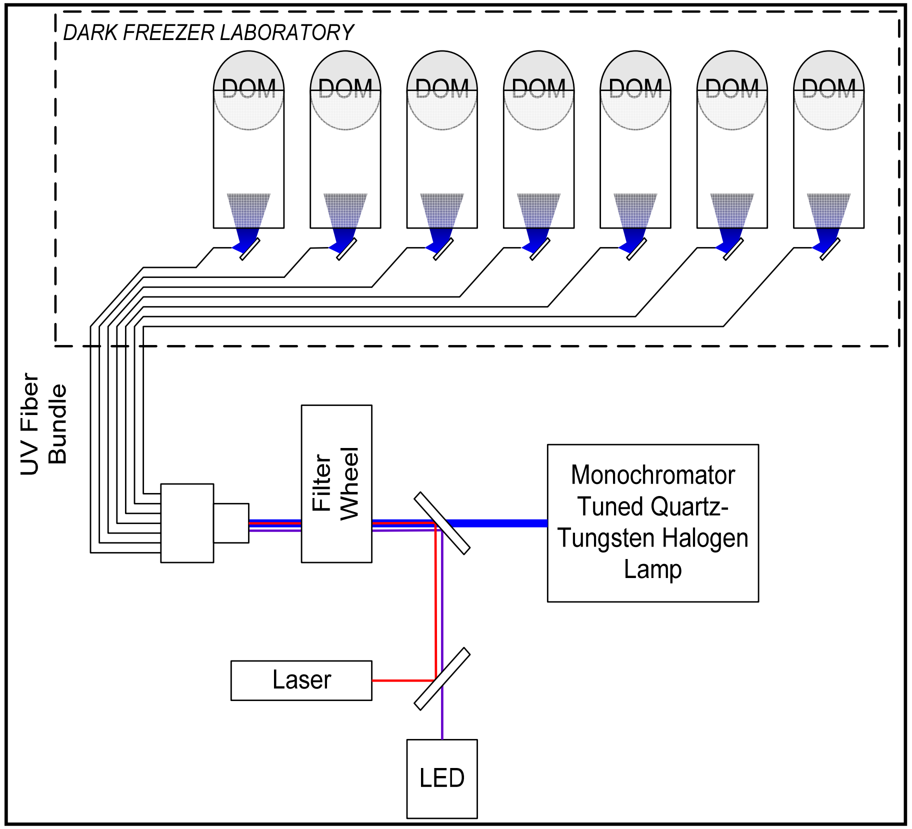
DOM Testing



Temperature vs time profile of FAT.

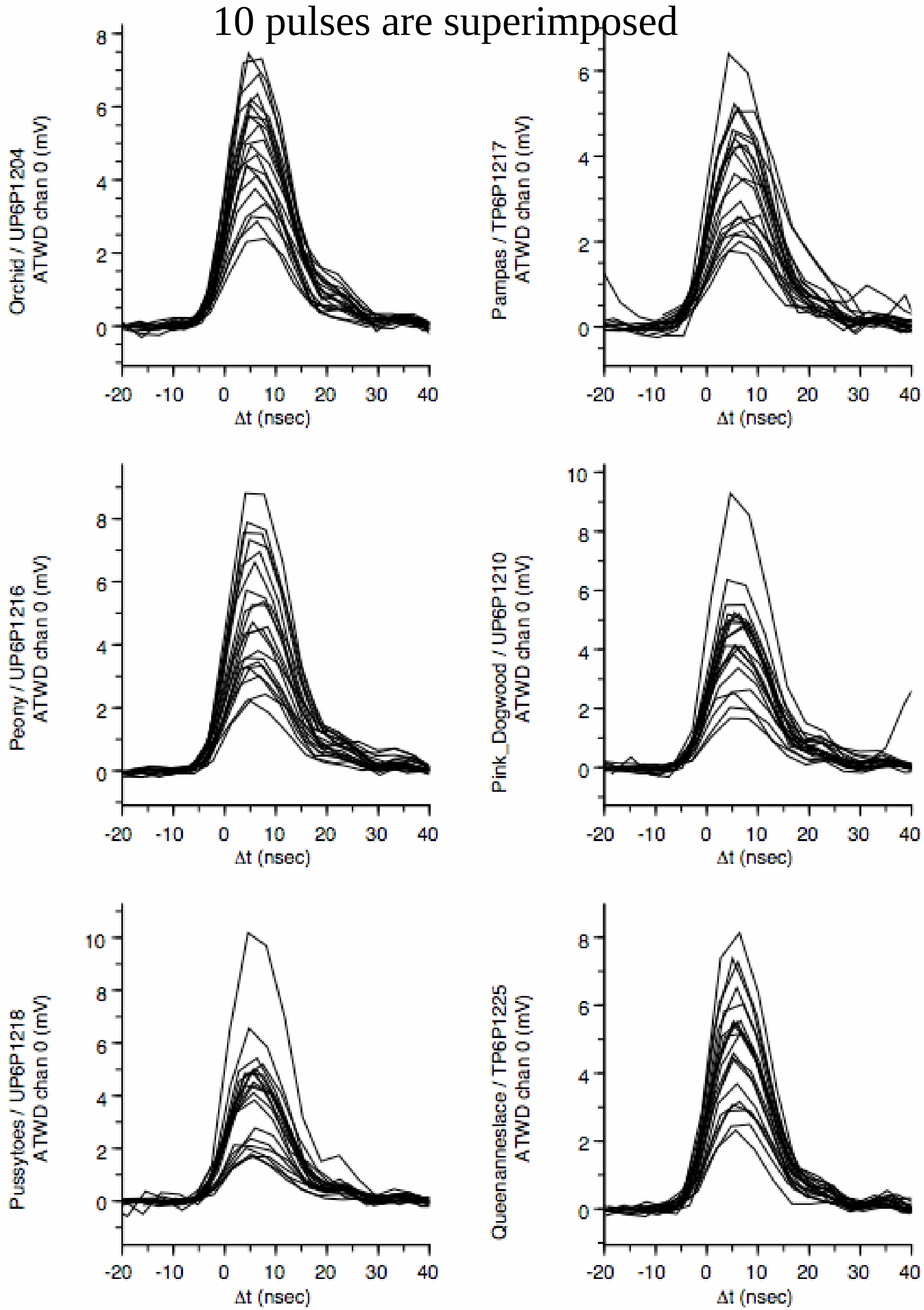
Final Acceptance Test

- Check basic DOM optoelectronic function
- Perform extended life and stability tests of DOMs in temperature cycled environment over ~ weeks
- Calibrate DOM optical sensitivity



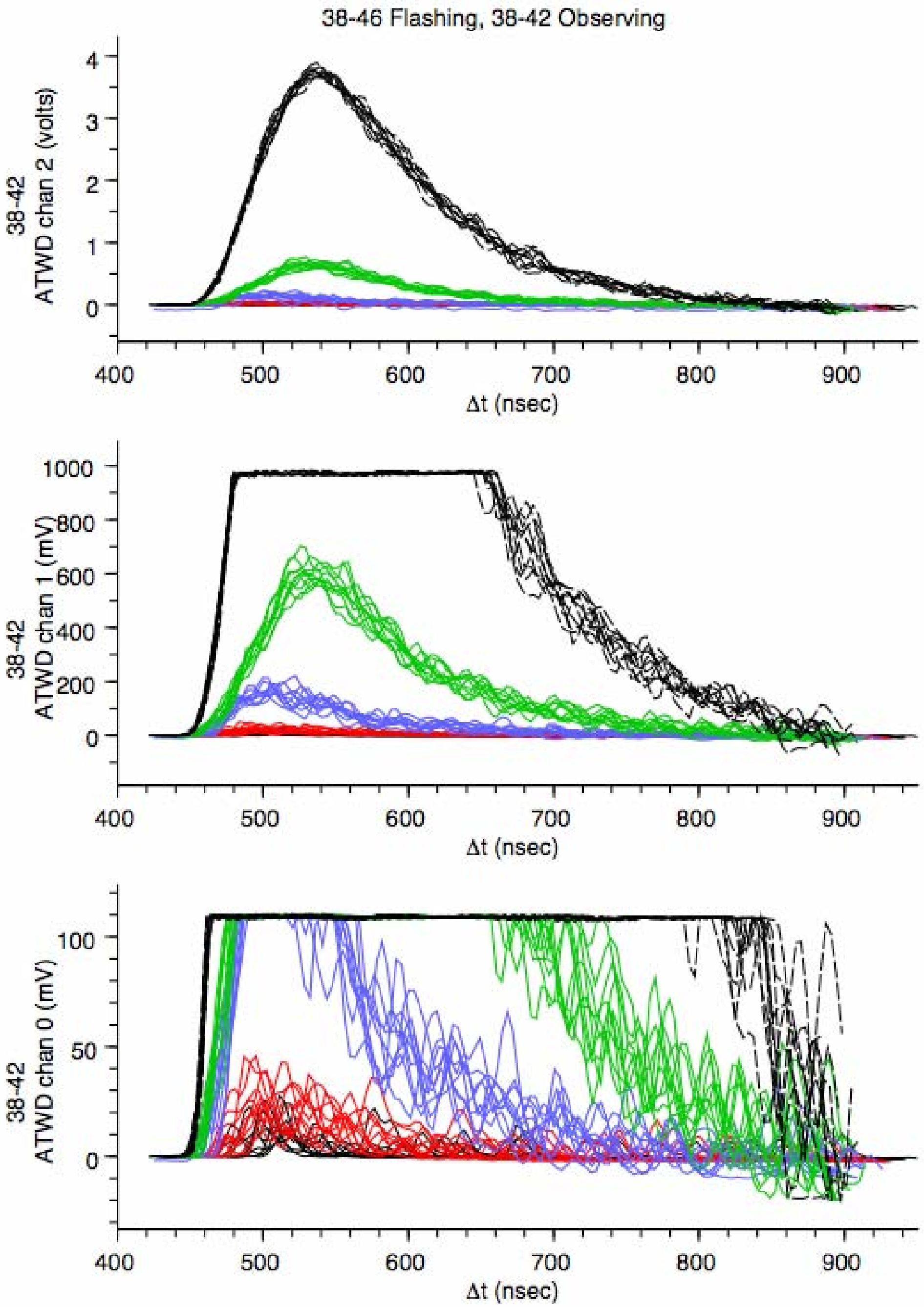
Single photoelectron pulses recorded with ATWD

- Single photoelectron pulses (SPE) recorded in 6 DOMs during the final acceptance test.
- All PMT gains are set to 1E7.
- Threshold at 0.3 SPE
- FWHM=13.6 ns



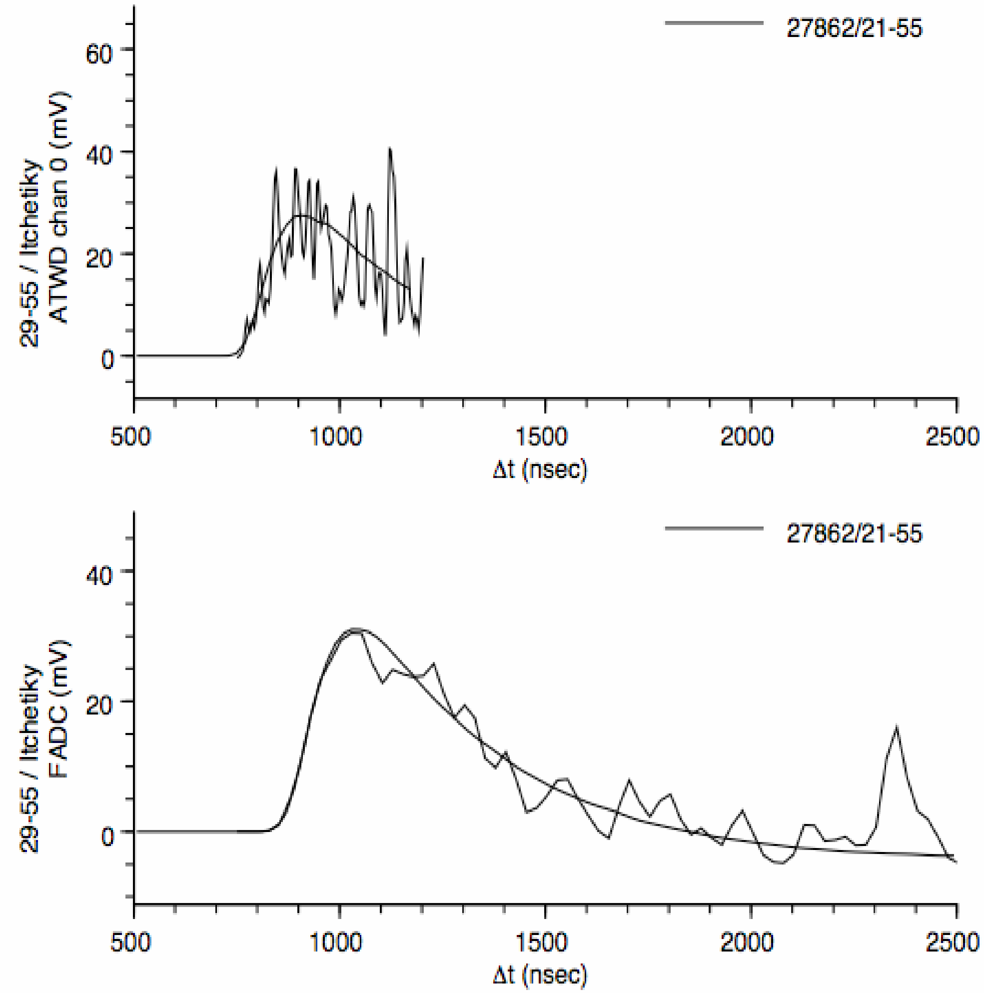
Pulse shapes taken in situ

- Pulse shapes are recorded with three ATWD channels for high dynamic range coverage.
- Runs of 10 flasherboard pulses at 5 different brightness settings are shown.
- High saturation in channel 0 (high gain), but good coverage of the brightest pulses in channel 2 (low gain).



ATWD and FADC

- Pulse shapes are recorded with ATWD and with FADC.
- Shown is an average flasher pulse and a single shot superimposed at 125 m distance.
- The ATWD captures 400 ns of this pulse (top). The full waveform is recorded in the FADC (bottom).



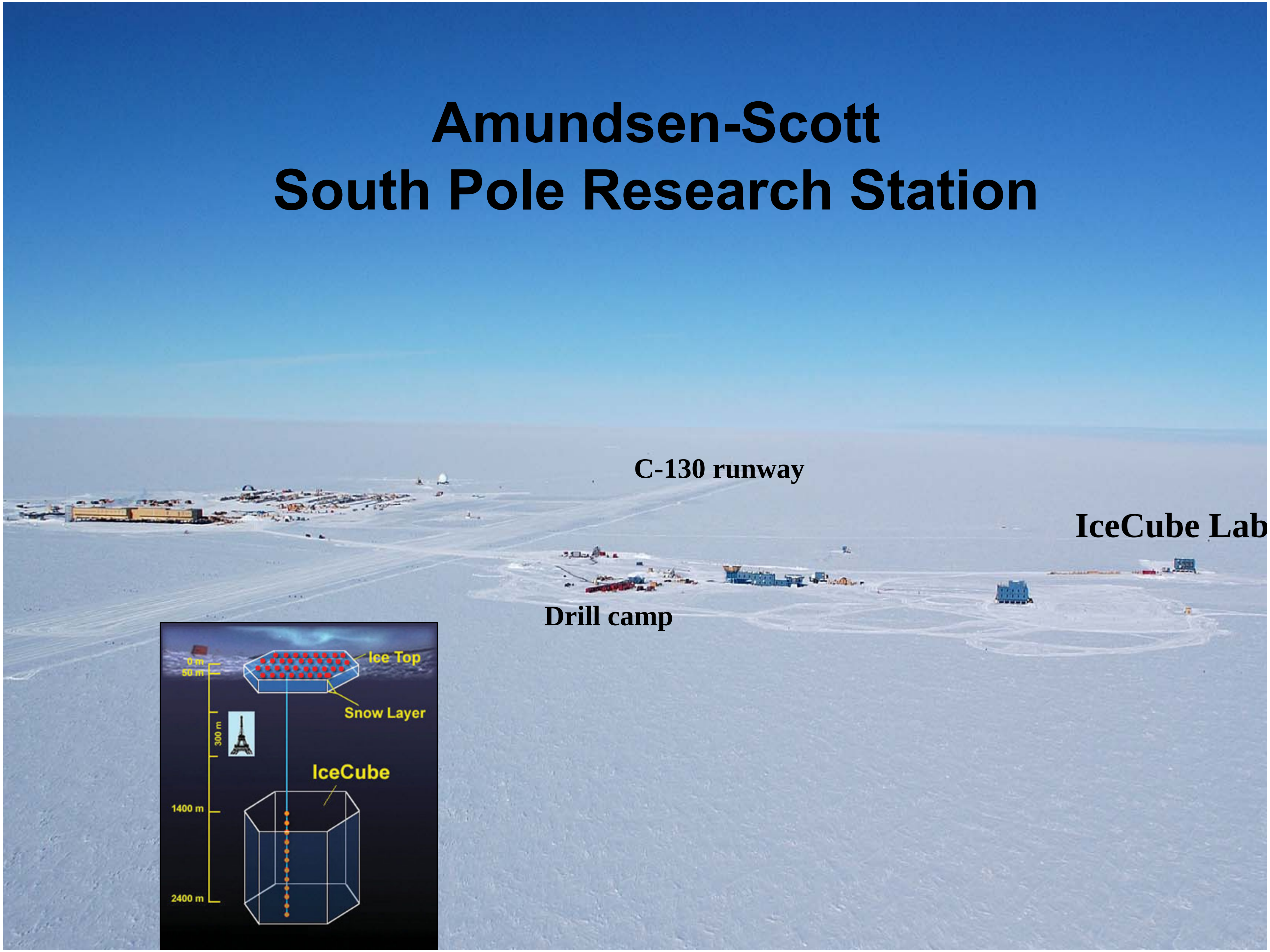
Here the flasher is 21-55 and the receiver is 29-55 (neighboring string, 125m away).
This is a 50 nsec pulse, maximum brightness, six horizontal LEDs flashing.The smooth curve shows the average of several thousand events.
One example waveform is superimposed.

Getting to the South Pole

A six hour flight from New Zealand to McMurdo Station, via C-141 “Starlifter”
(now C-17 “Globemaster” is used)


MCMURDO STATION
ANTARCTICA
UNITED STATES OF AMERICA
ANTARCTIC PROGRAM

A three hour flight from McMurdo to South Pole Station, via C-130 “Hercules”


Amundsen-Scott
South Pole Research Station
C-130 runway
IceCube Lab
Drill camp
Ice Top
0 m
50 m
Snow Layer
300 m
IceCube
1400 m
2400 m

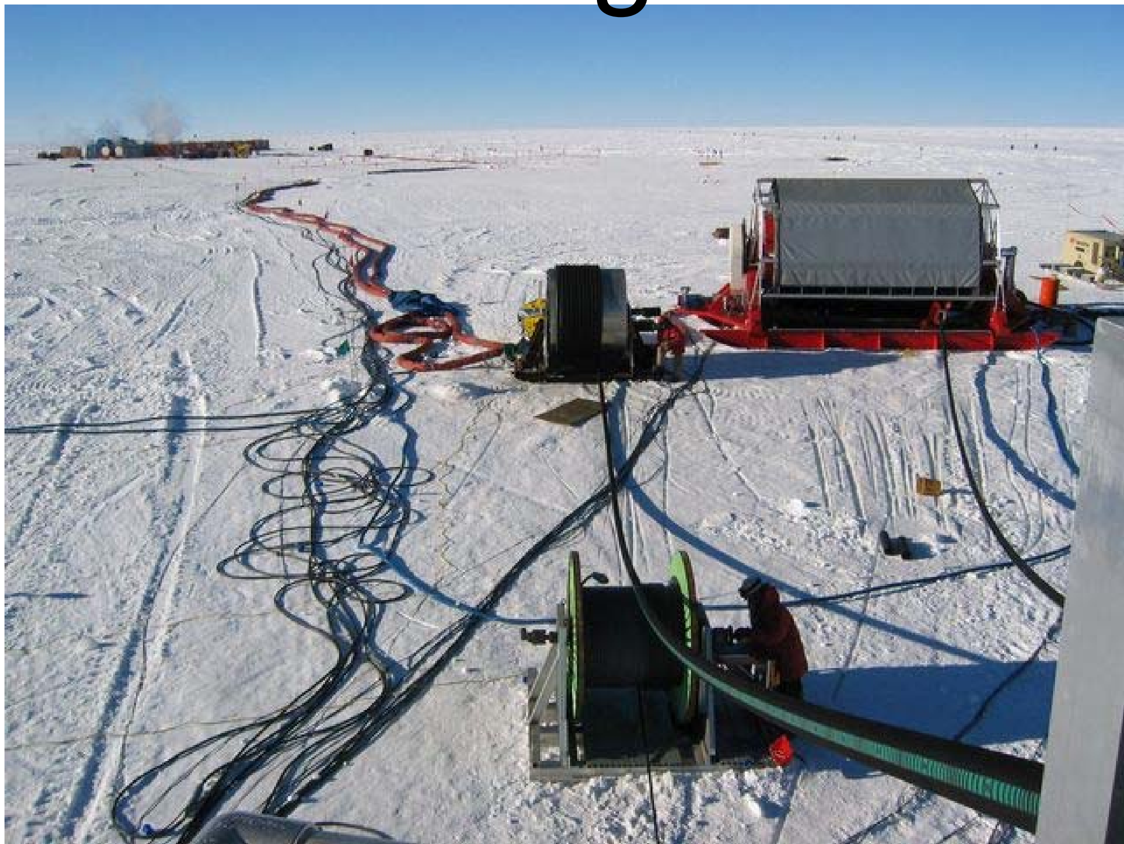
A view from last season

Working time: Nov. - mid-Feb

Plan: deploy 14 strings/season

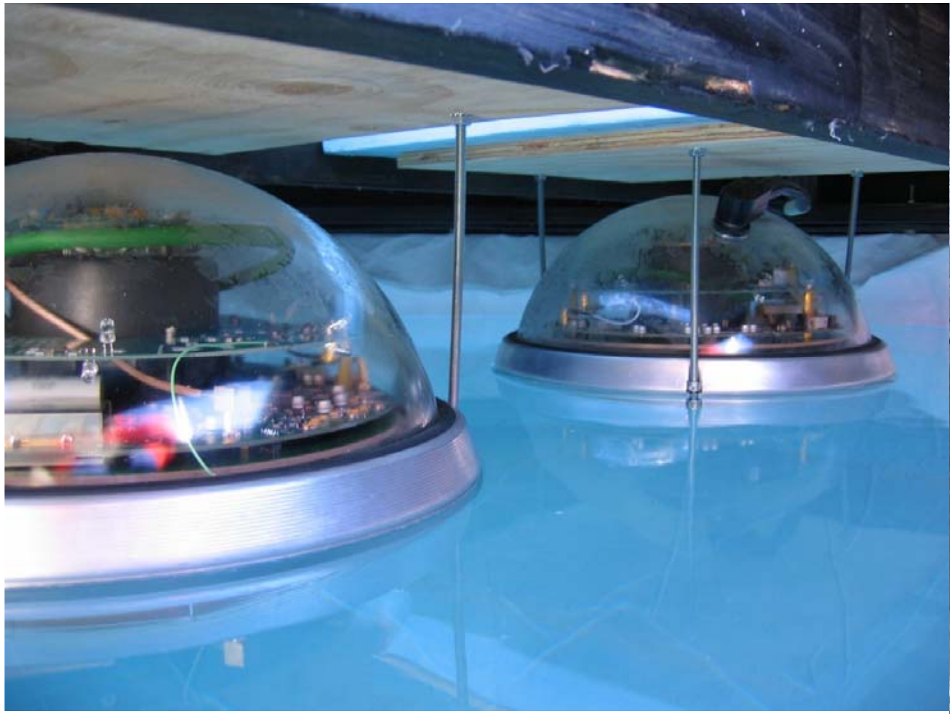
Completion: 2011

Hot Water Drilling



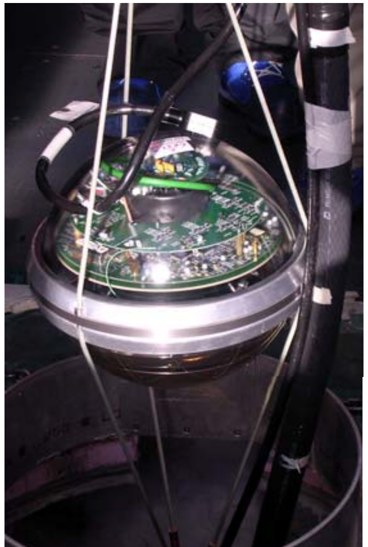
IceCube Enhanced Hot Water Drill significant operation – entire drill camp setup, including generators, heater plants, fuel systems, and support workshops. This camp doesn't move during the season.

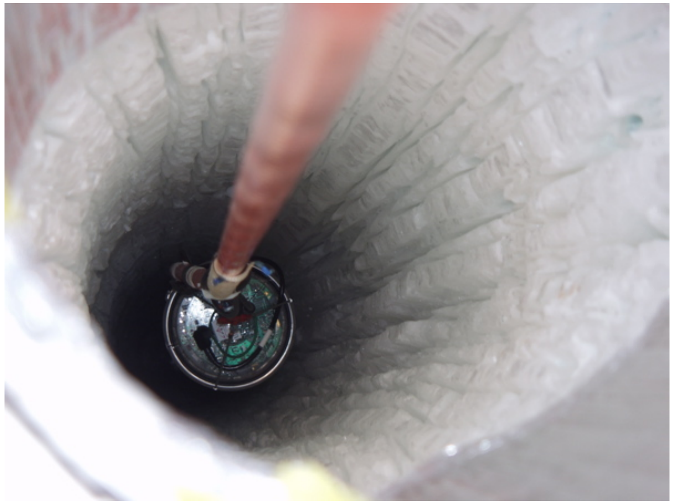
2 drill towers connect to central plants and leapfrog over holes.

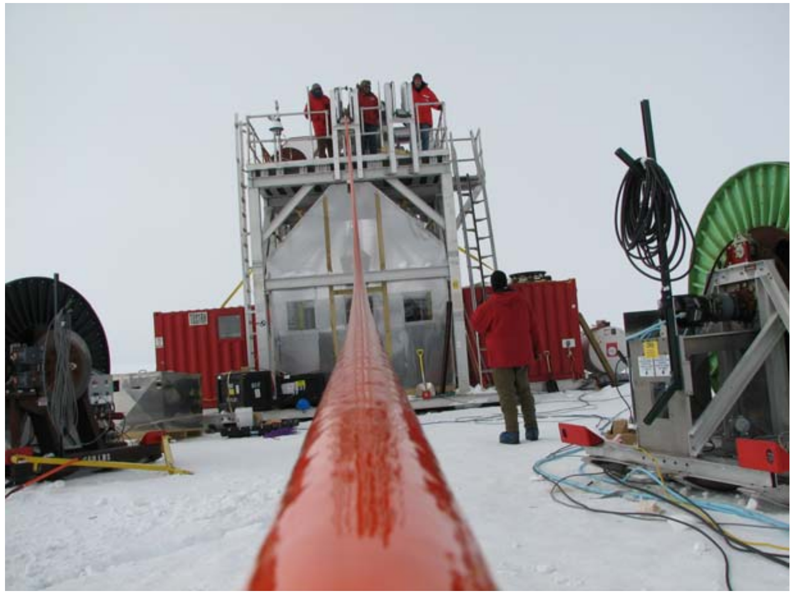


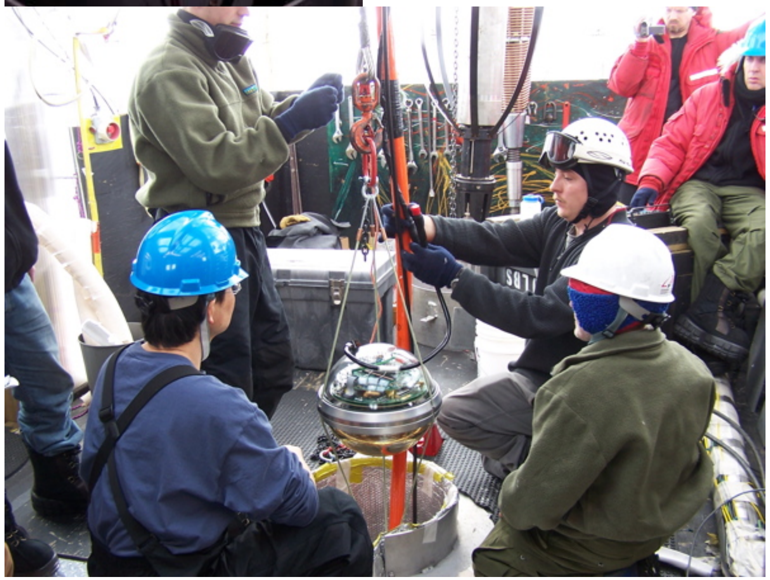
Ice Top

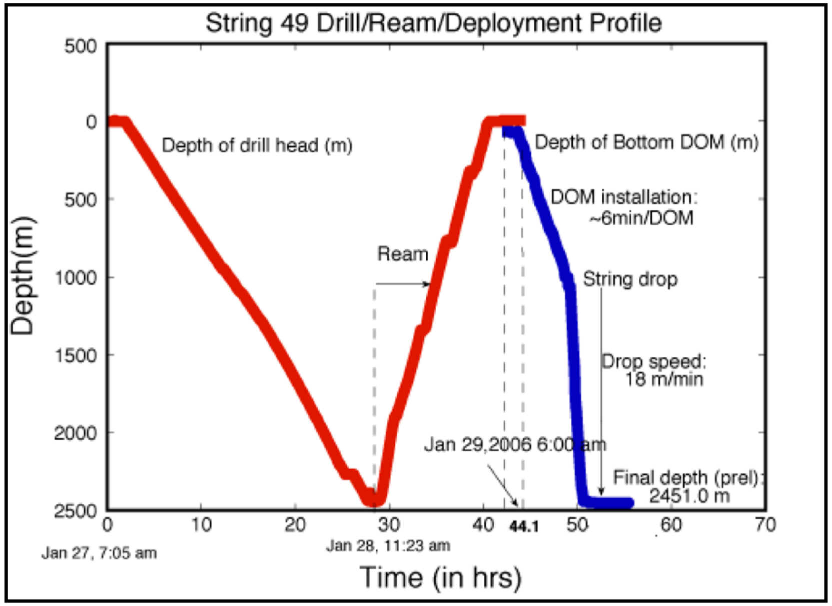
Deployment





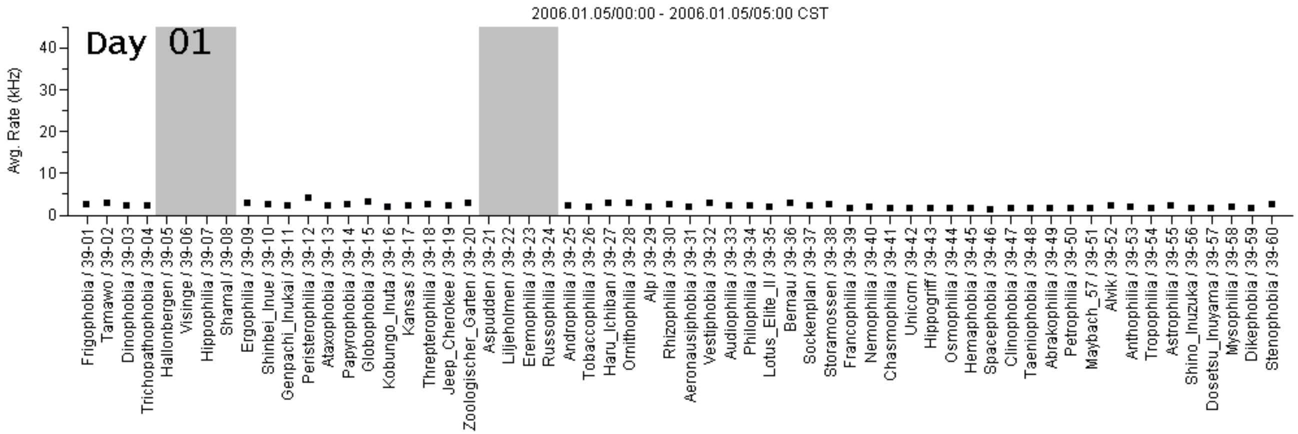


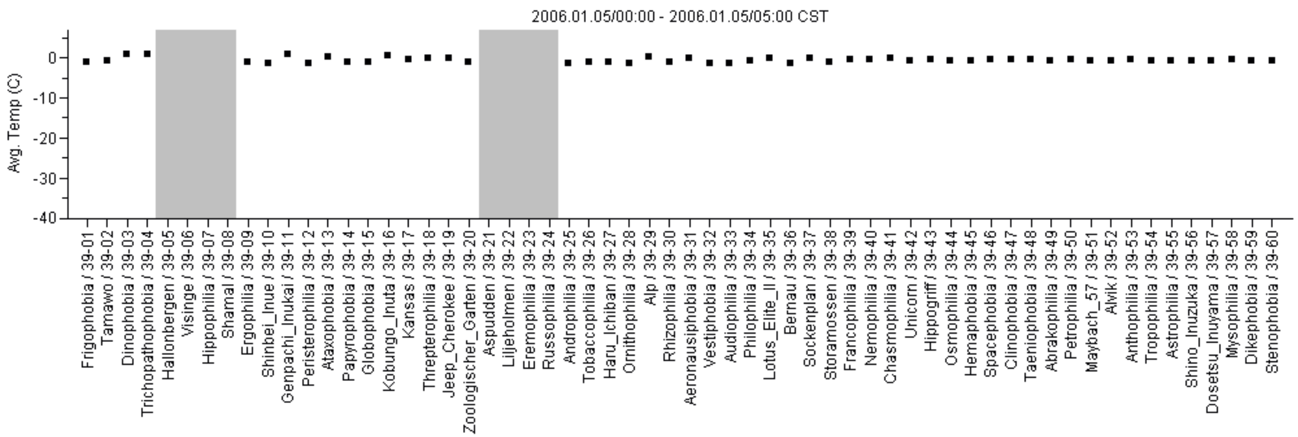




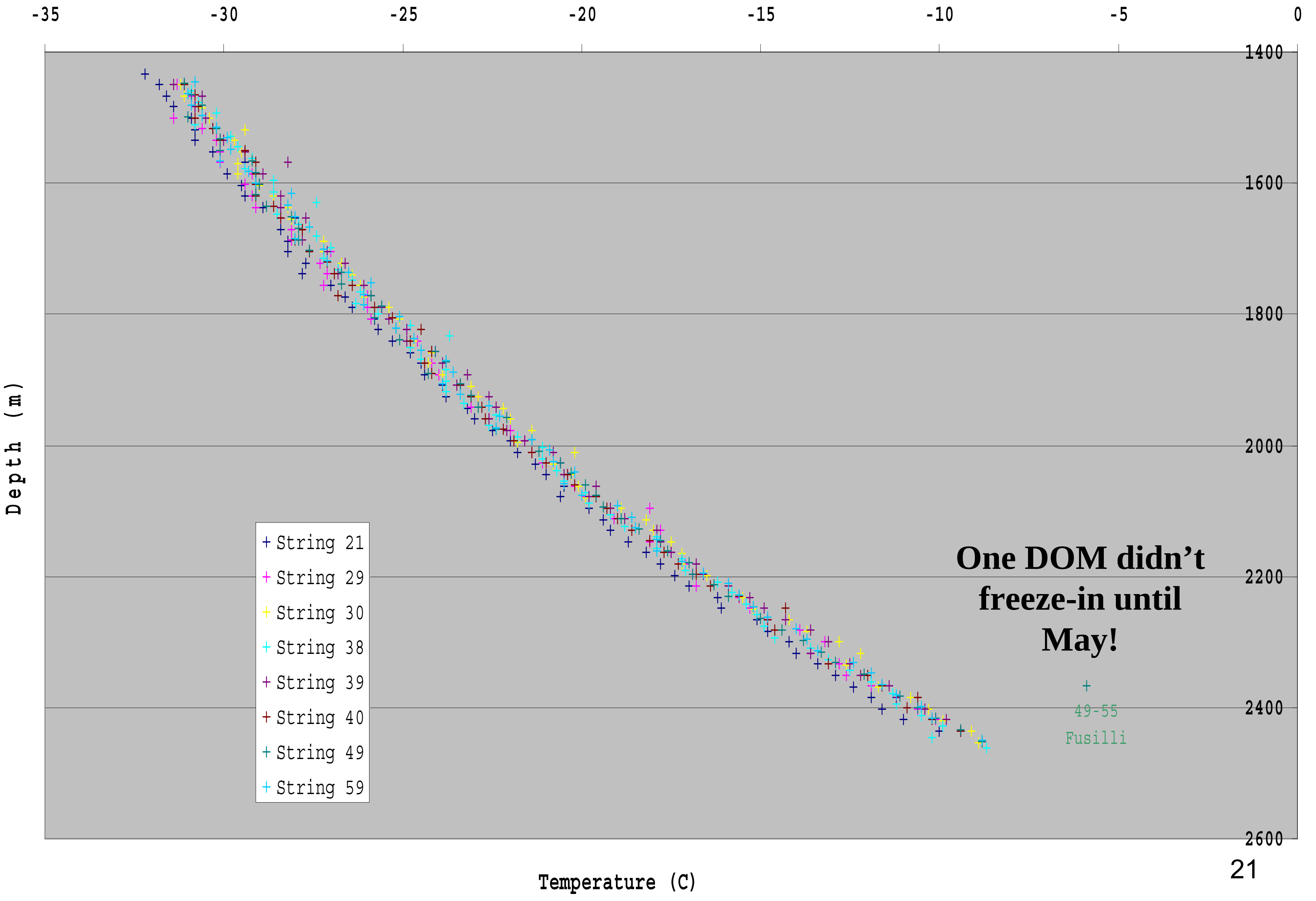
99% of 604 DOMs survive deployment and freeze-in

String 39 two-week freeze-in movie





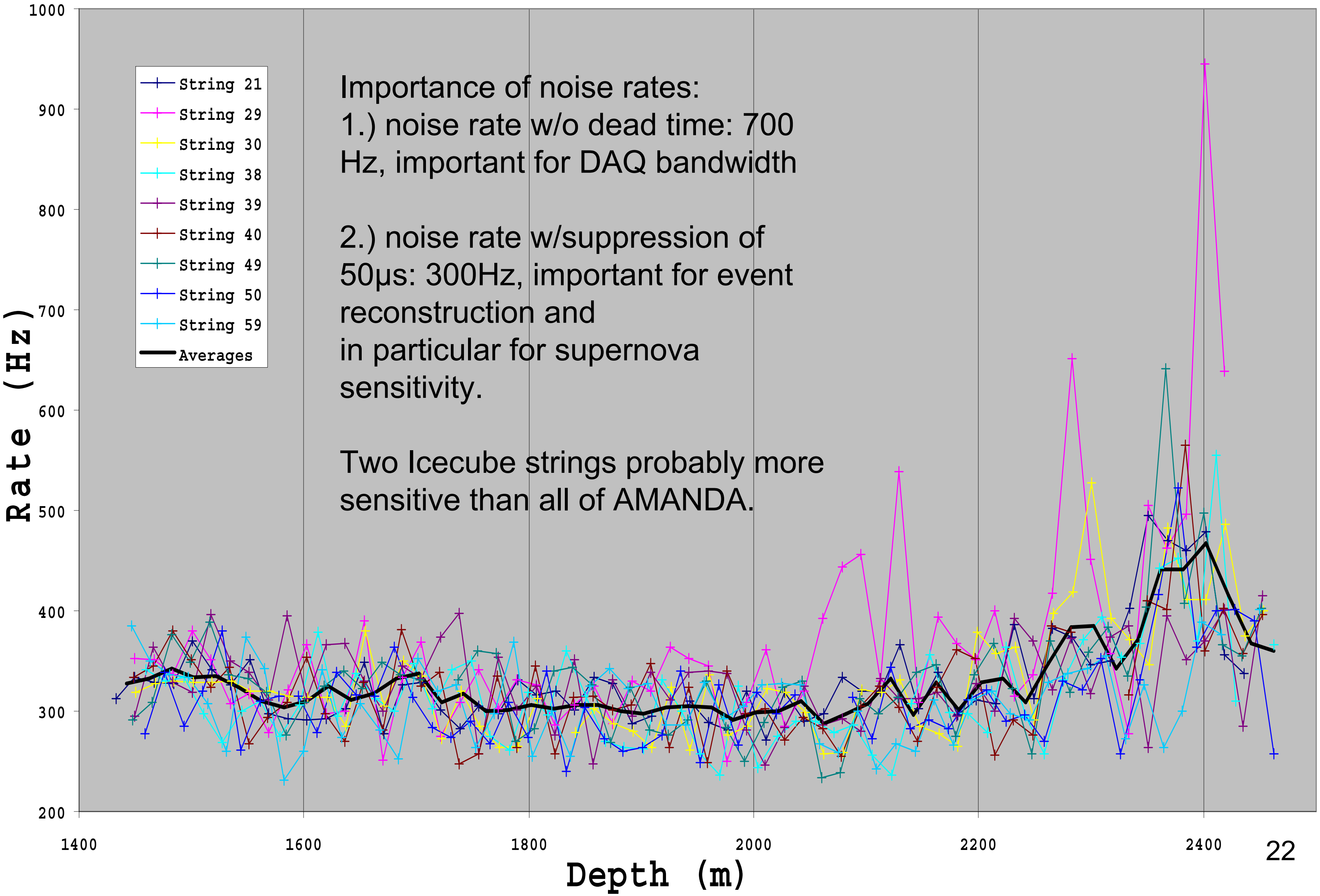
Dom Temperature vs Depth



One DOM didn't freeze-in until May!

Dom Rate vs Dom Depth 5.14.06

(calibrated)



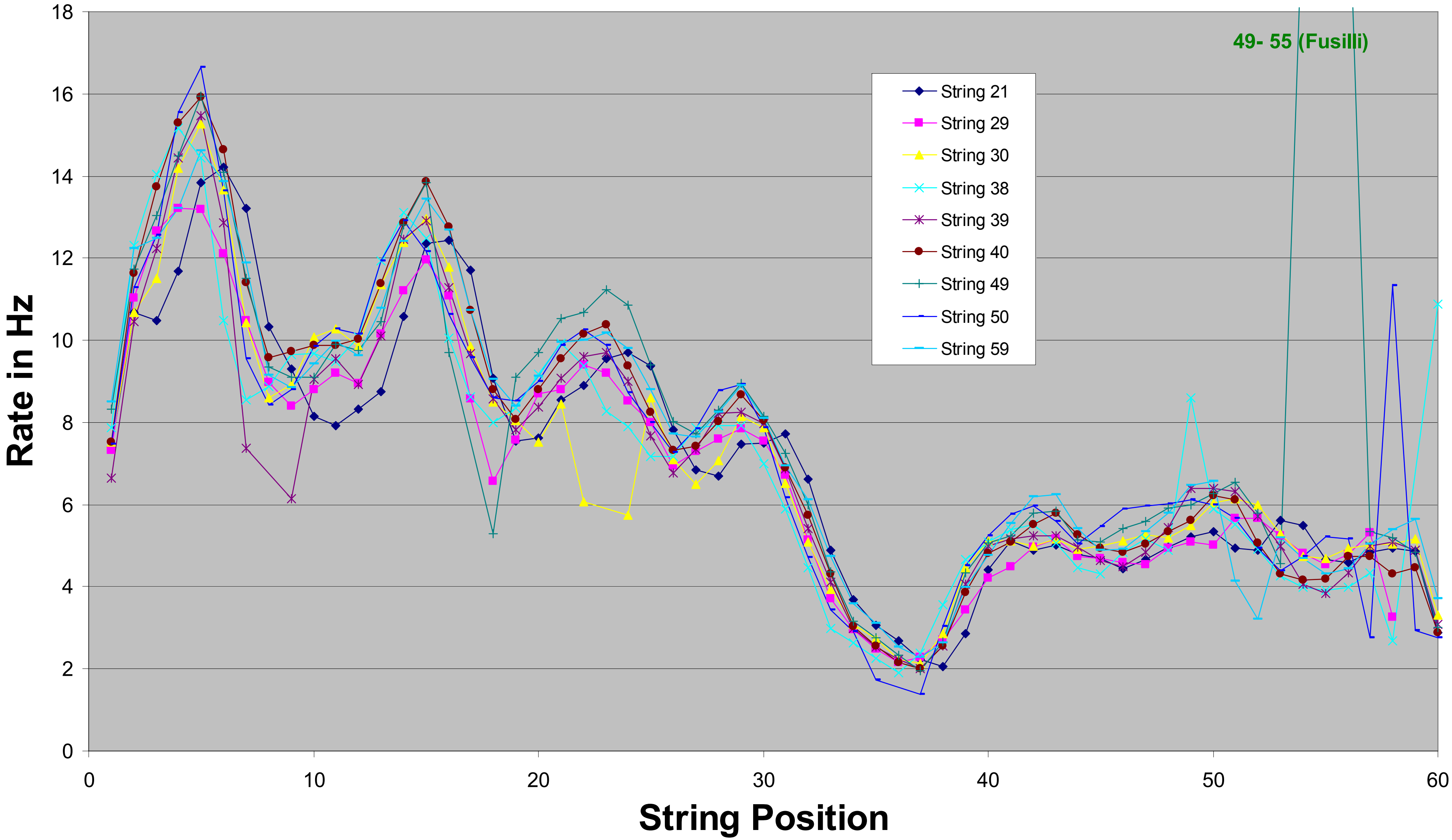
Importance of noise rates:

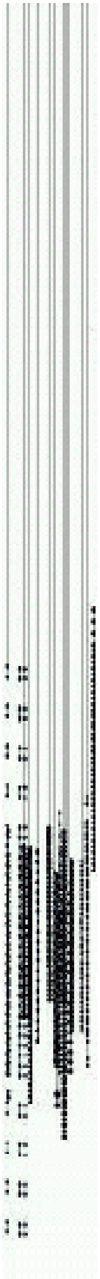
1.) noise rate w/o dead time: 700 Hz, important for DAQ bandwidth

2.) noise rate w/suppression of 50µs: 300Hz, important for event reconstruction and in particular for supernova sensitivity.

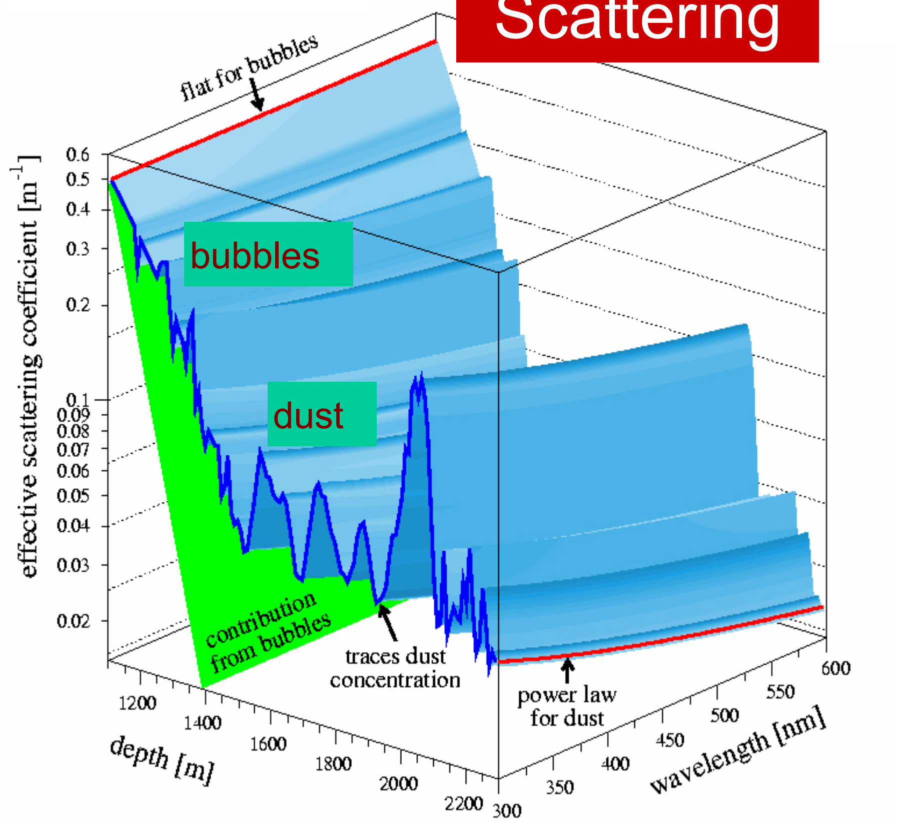
Two Icecube strings probably more sensitive than all of AMANDA.

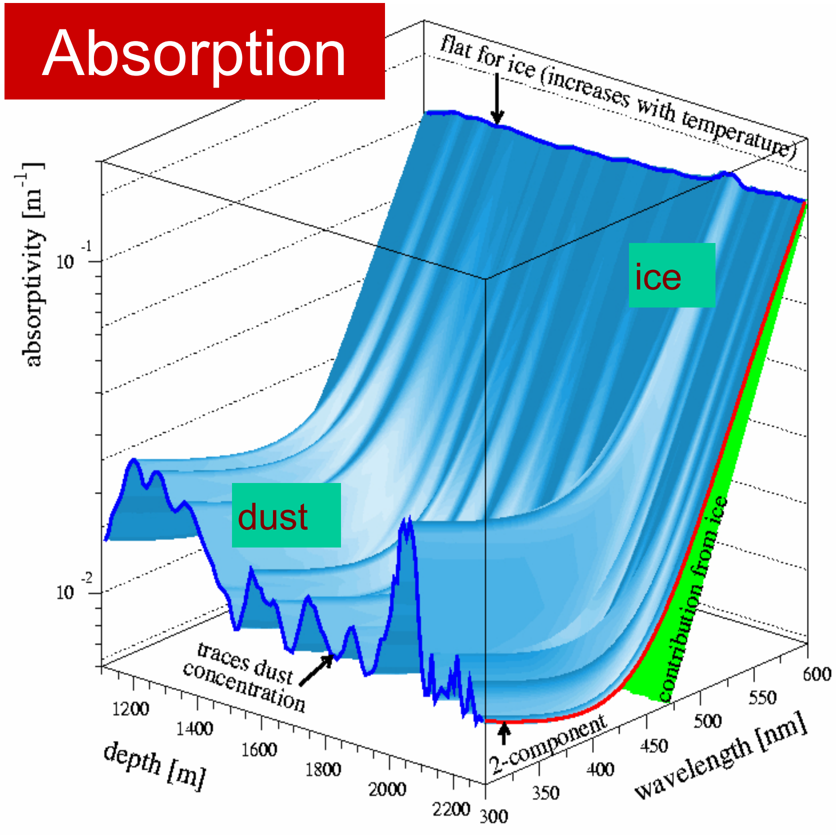
Local Coincidence Rates by String Position 3/15/06





Polar Ice Optical Properties





Measurements:

- in-situ light sources
- atmospheric muons

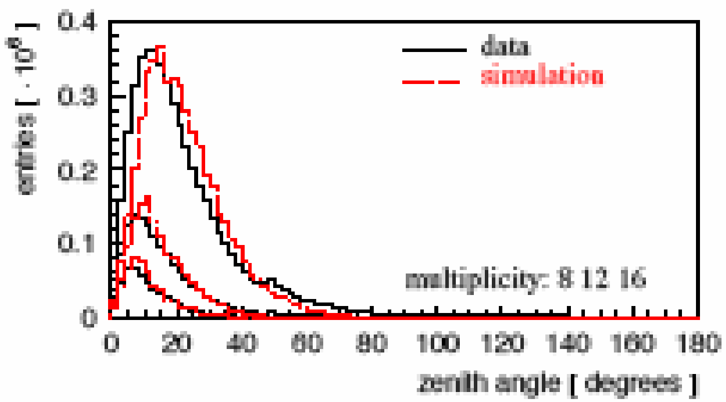
Average optical ice parameters:

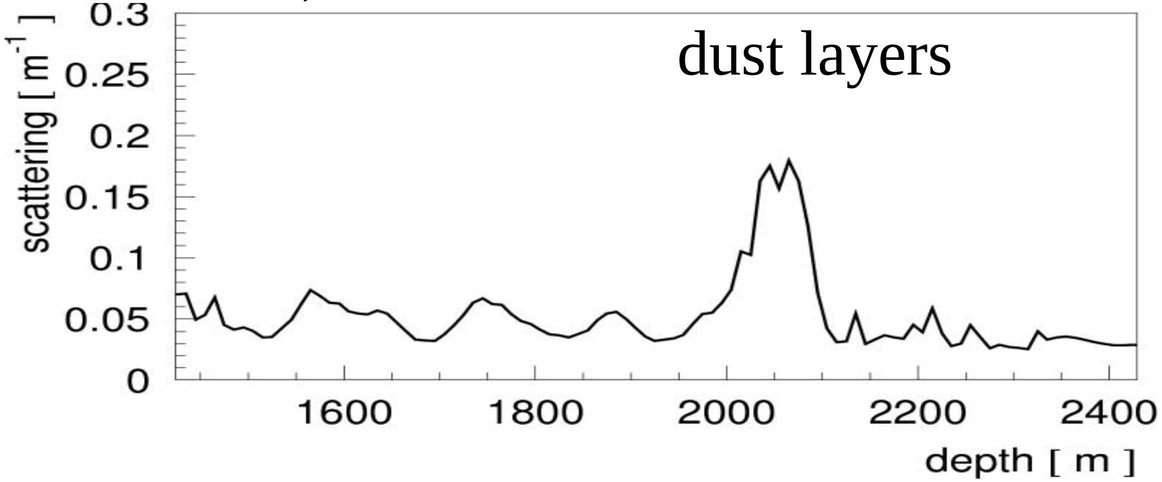
$\lambda_{abs} \sim$ 110 m @ 400 nm

$\lambda_{sca\_eff} \sim$ 20 m @ 400 nm

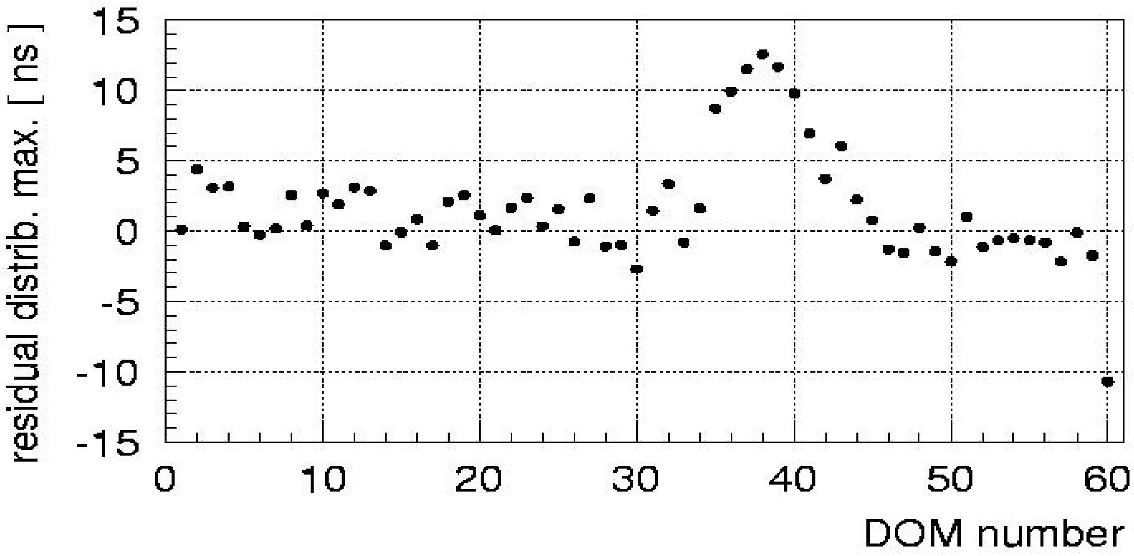
Muon calibrations

STRING 21 (**astro-ph/0604450, SUBM. TO ASTROP. PHYS)**:



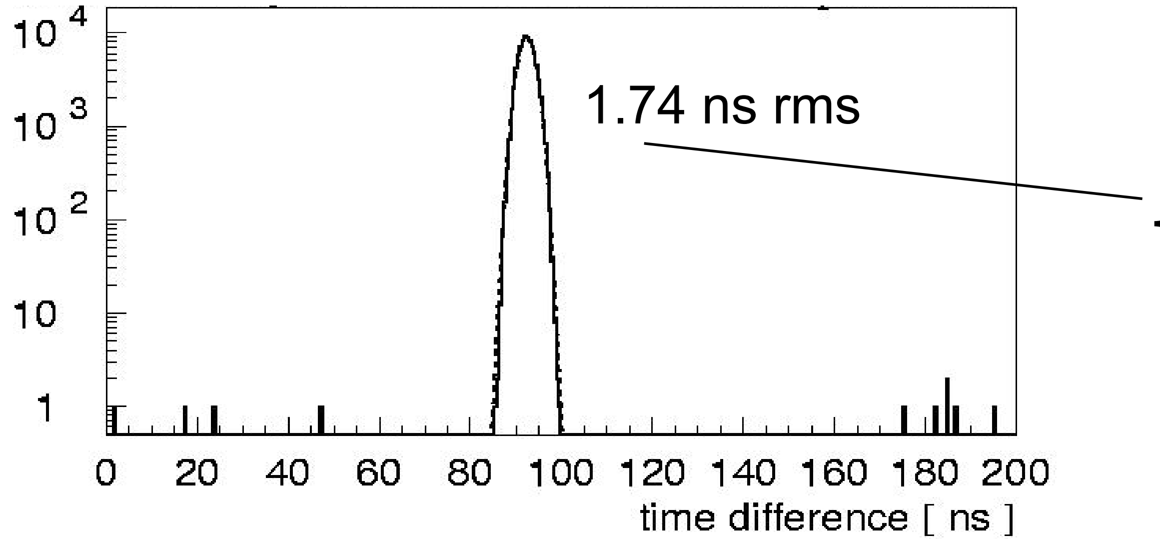


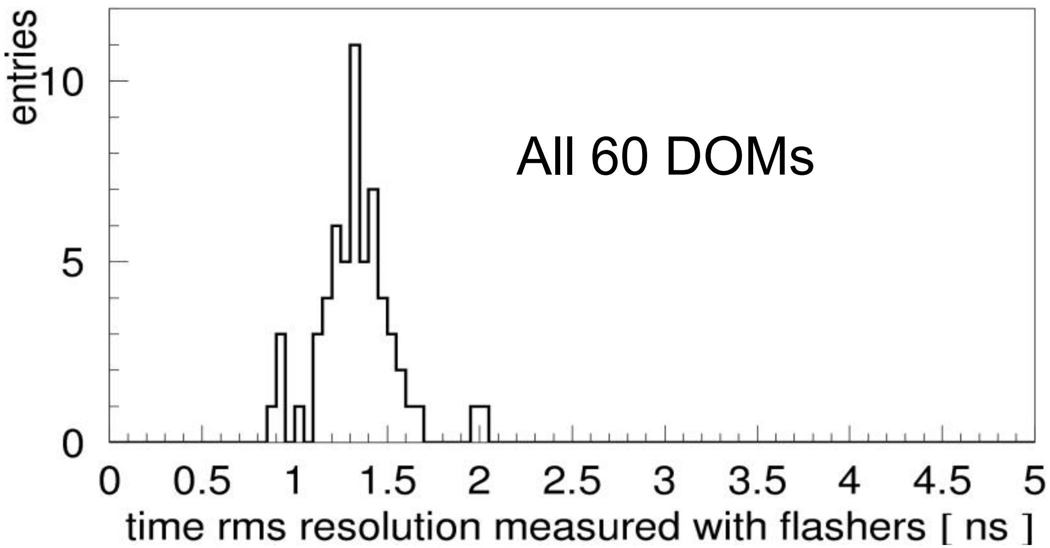
1st IceCube string: time residual peaks < ±3ns for all DOMs outside dust layer

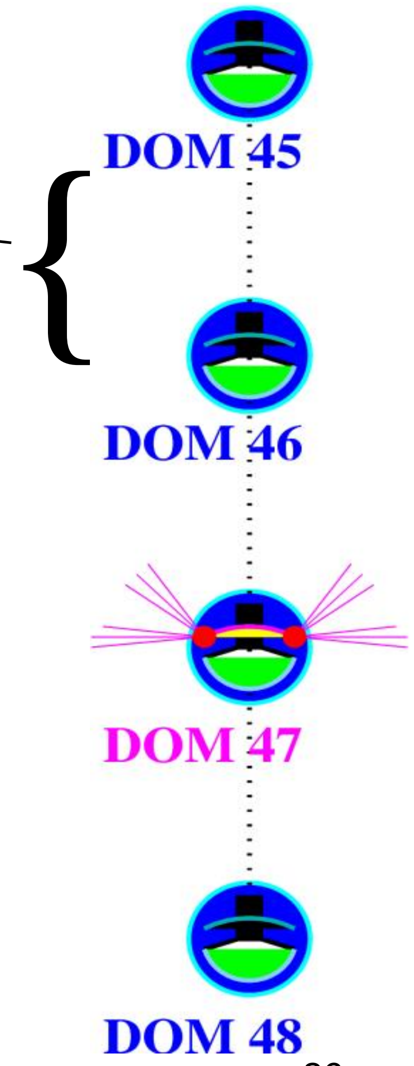


First Results: timing resolution from flashers

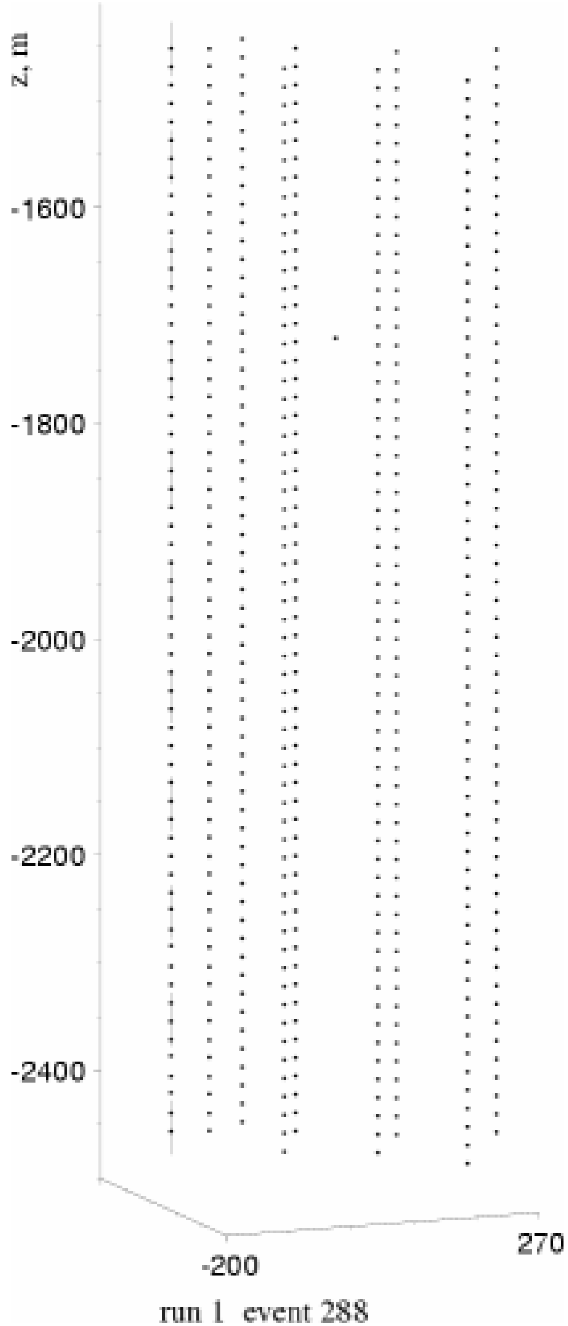
Photon arrival time difference between DOMs 45 & 46

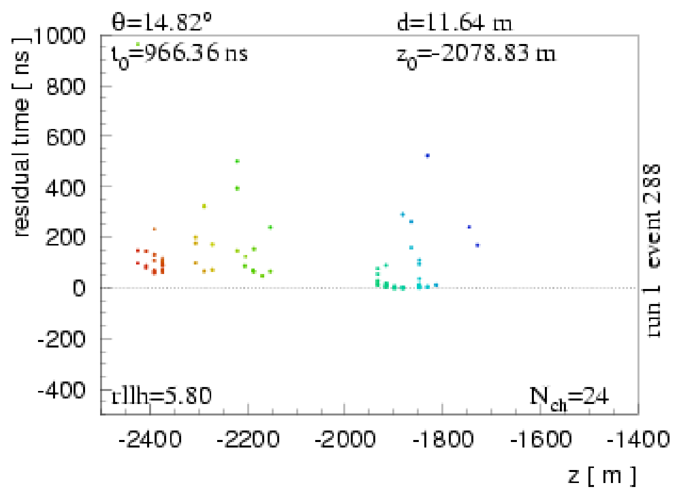






Neutrino candidate in 9 strings

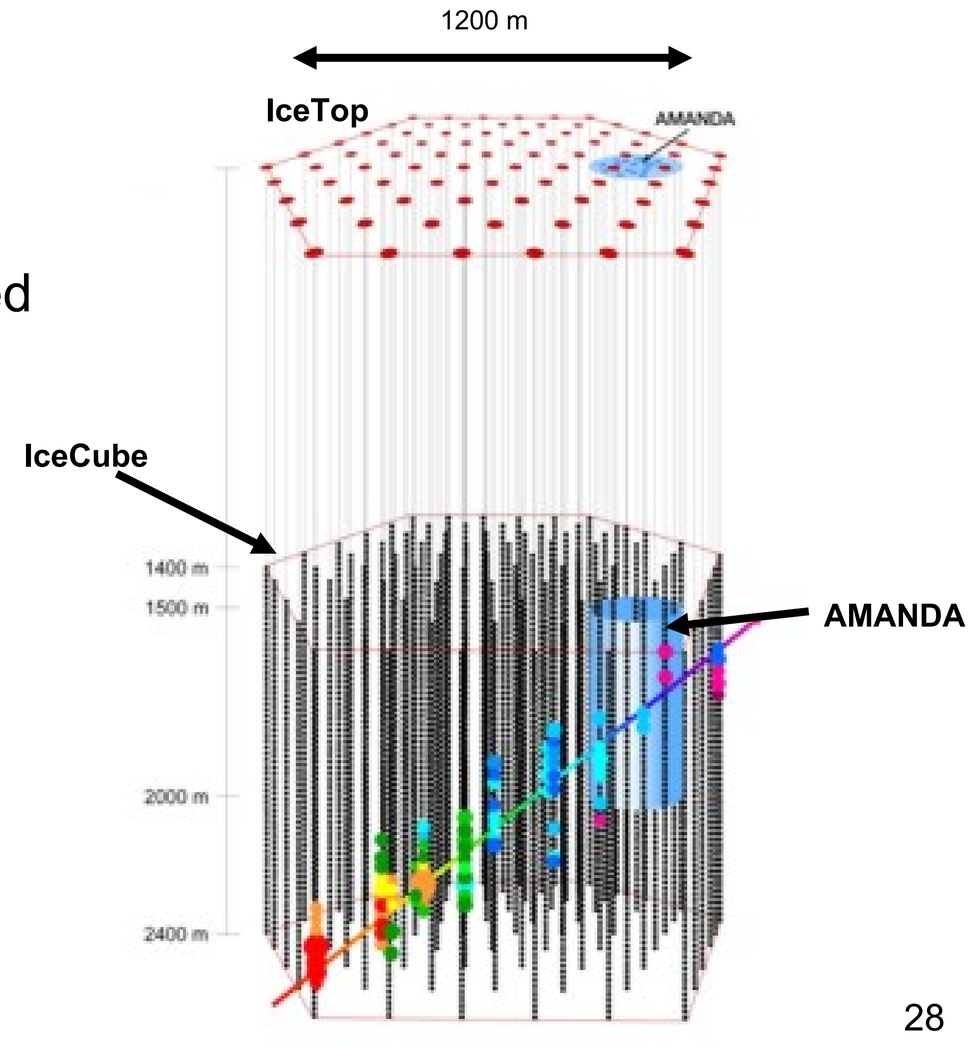




Track Reconstruction in Low Noise Environment

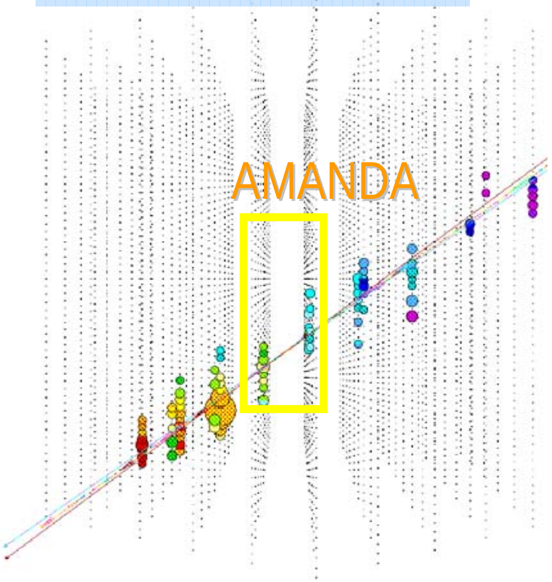
- Typical event: 30 - 100 PMT fired
- Track length: 0.5 - 1.5 km
- Flight time: ≈4 μsecs
- Accidental noise pulses:

  10 p.e. / 5000 PMT / 4 μsec

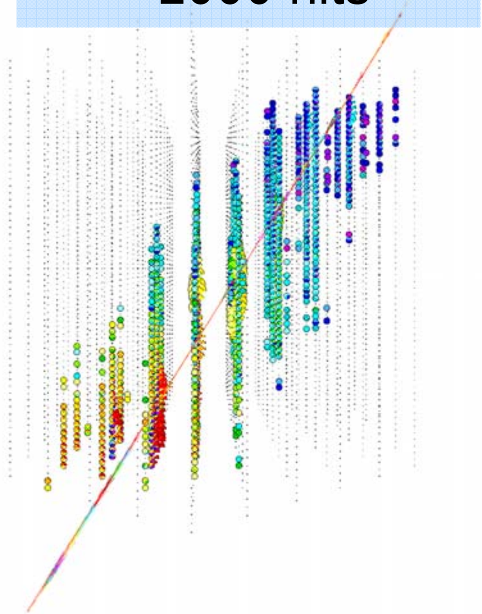


Event Signatures in IceCube

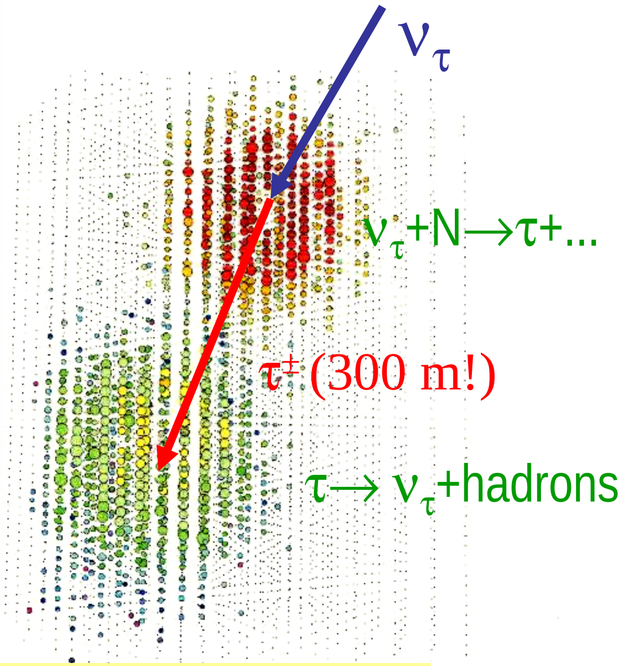
10^{13} eV (10 TeV)
~90 hits



6×10^{15} eV (6 PeV)
~1000 hits



Multi-PeV



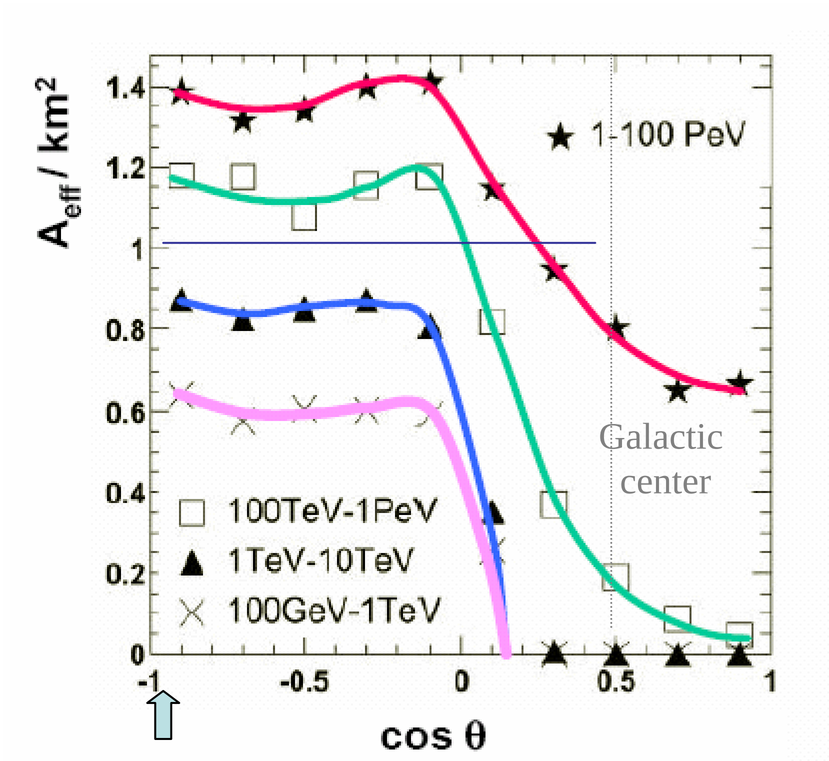
ν_μ signature

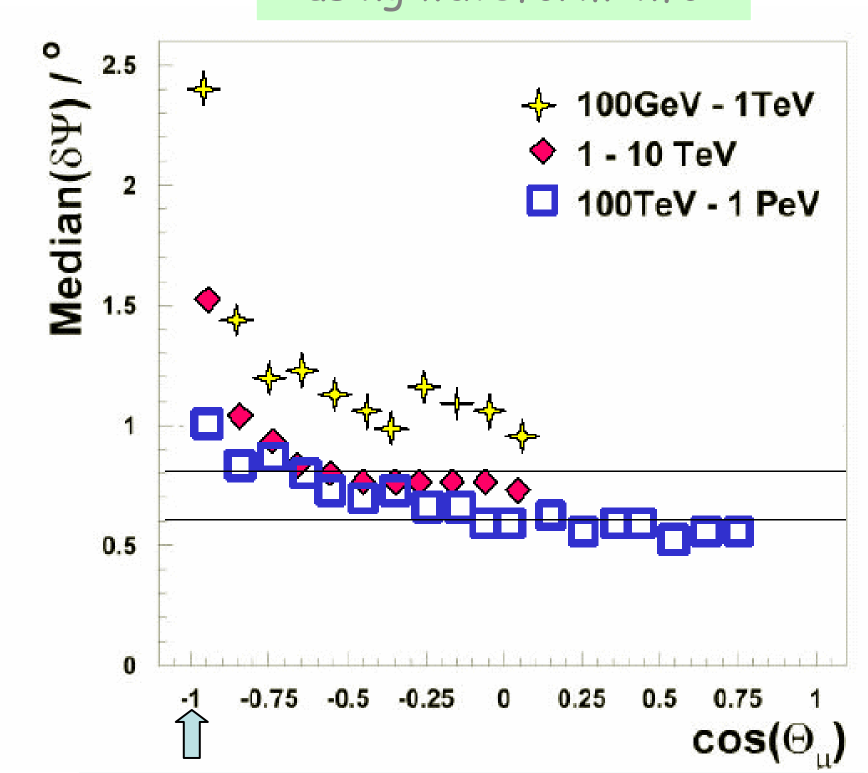
ν_τ signature

Expect about 100,000 events/yr

IceCube effective area and angular resolution for muons

further improvement expected using waveform info





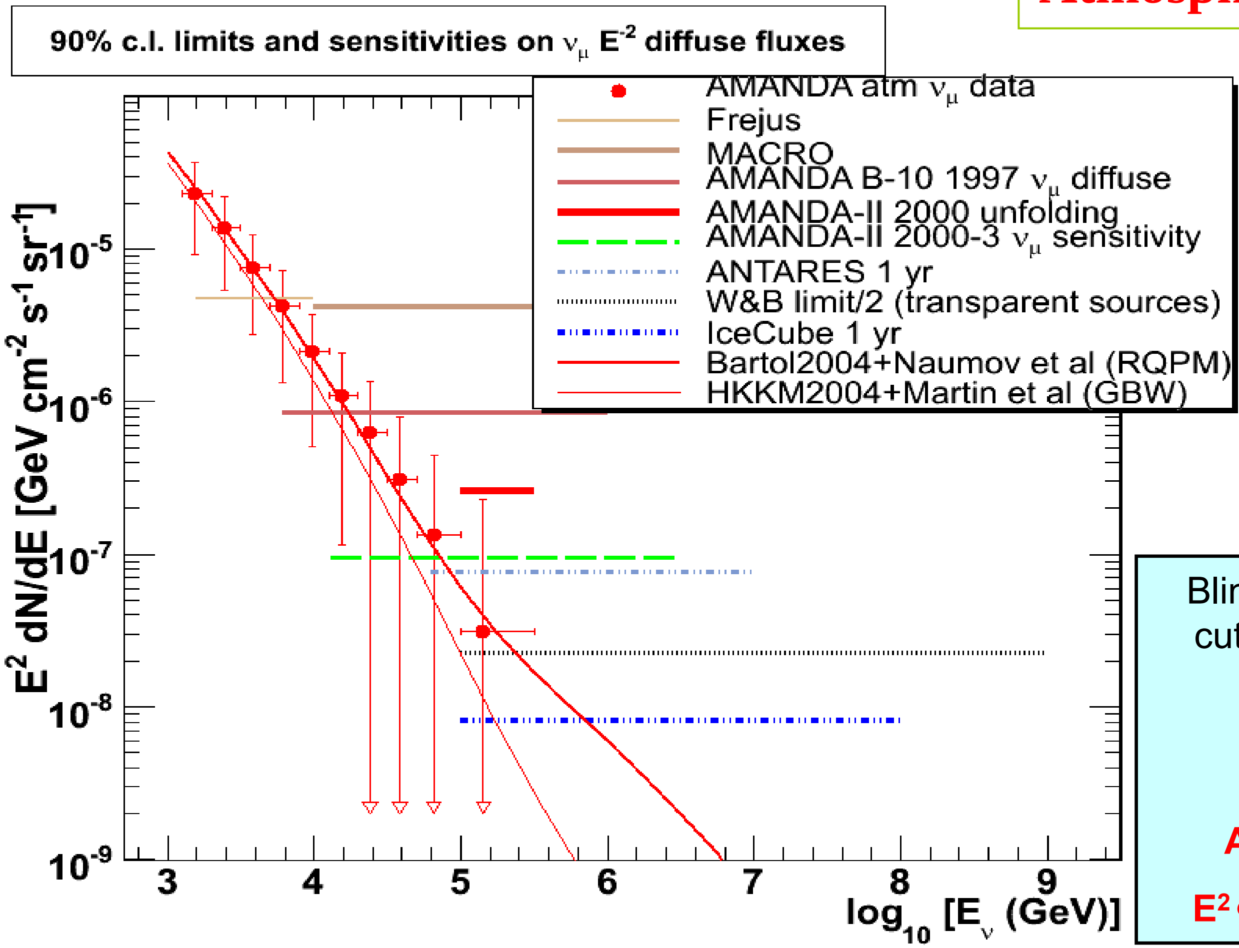
Median angular reconstruction uncertainty ~ 0.8°

- E^{-2} ν_μ spectrum
- quality cuts and background suppression (atm μ reduction by ~10^6)

Diffuse fluxes with AMANDA

IceCube preliminary UHE

GZK μ	0.35 events/year
GZK τ	0.06 events/year
Atmospheric μ	0.03 events/year



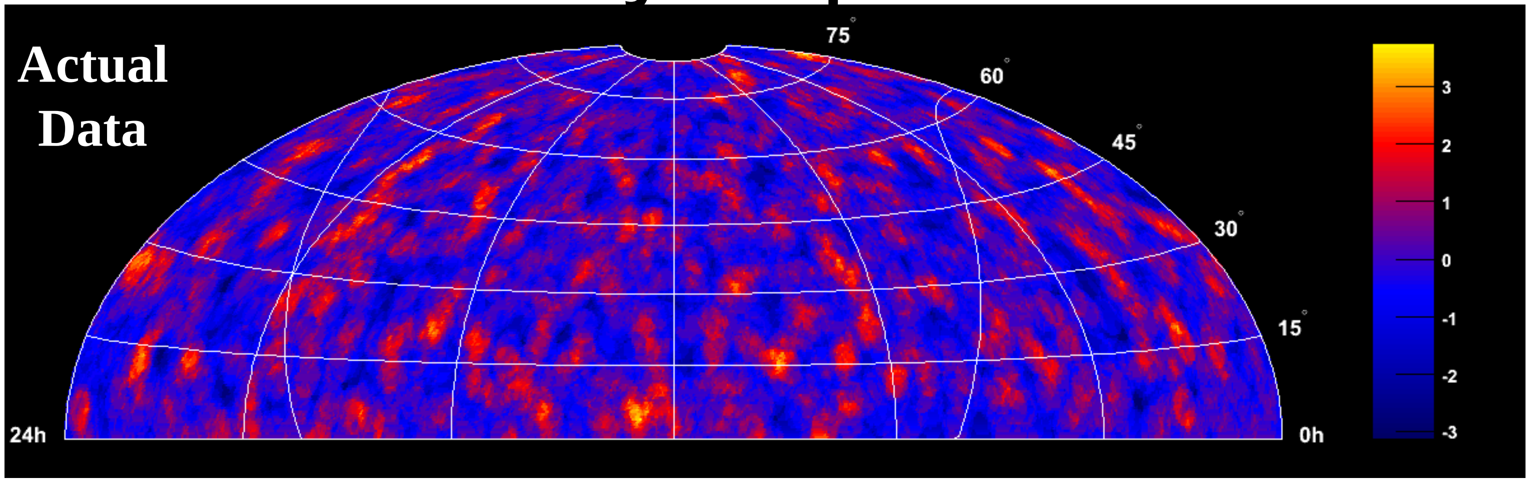
Cosmic ray muon rate is 80-90 Hz

Atmospheric muon neutrino rate is four per day

Blind analysis: optimize and determine cuts before looking at the high energy data.

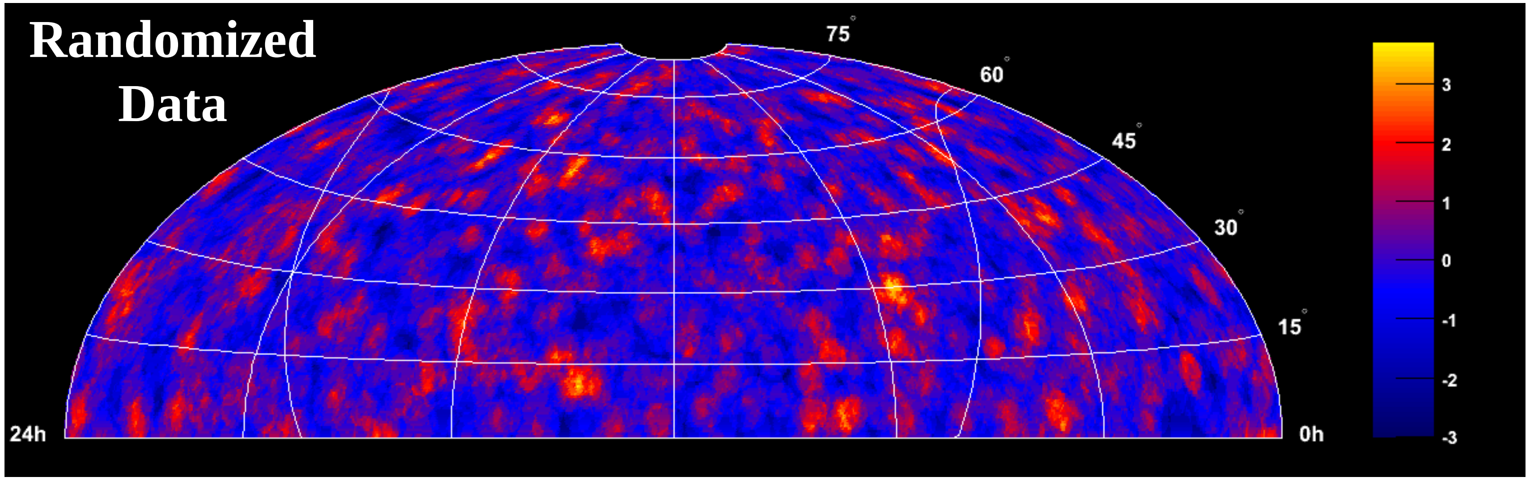
Sensitivity for
AMANDA-II: 2000 - 2003 (806d)
$E^2 \Phi(\nu_\mu) \approx 1.1 \times 10^{-7}$ GeV s^{-1} sr^{-1} cm^{-2}

AMANDA-II Skymap – Point Sources

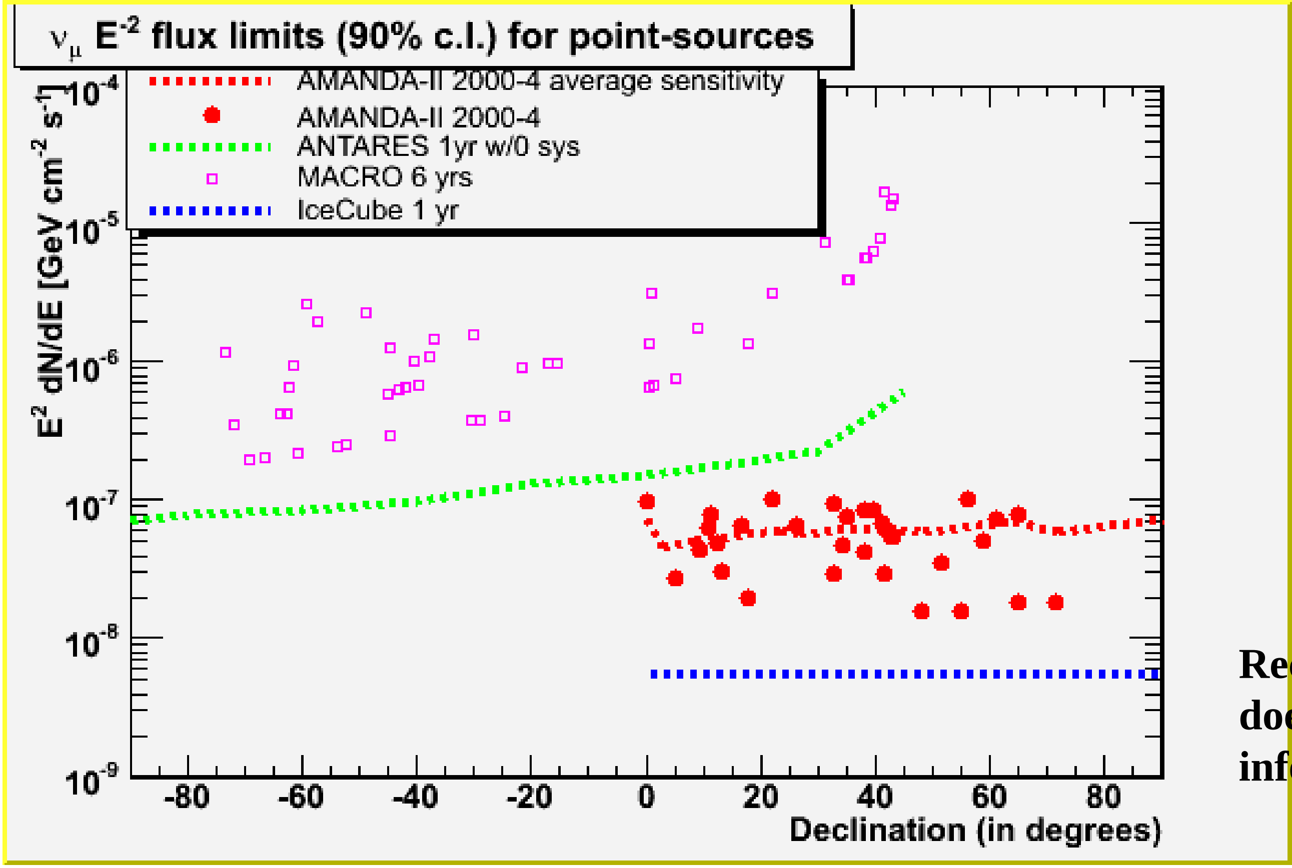


Data sample is AMANDA-II 2000-2004 (1001 days)
4282 ν from northern hemisphere

Several "hotspots" identifiable – however, running the MC on this shows that the maximum significance detection of 3.74 σ (or higher) would occur in 69 % of experiments with random fluctuations of background.

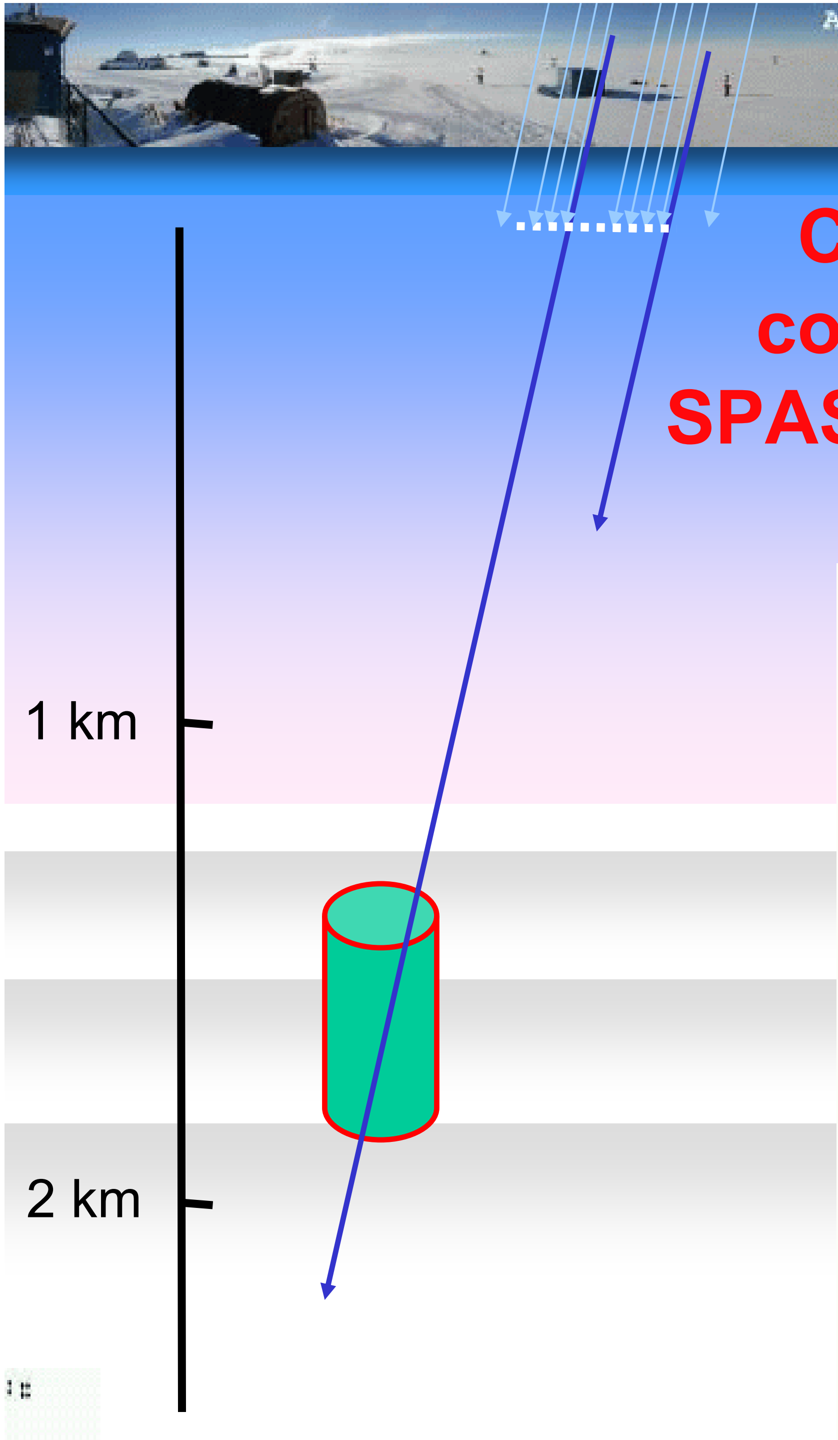


Limits and sensitivities



Reconstruction does not use WF information yet

IceCube: about 100000 atmospheric neutrinos/full yr
Better angular resolution: about 1 deg cones 15 events/yr
(compared to average 3 deg in AMANDA-II and 1 ev/200 days)



Cosmic rays air showers: coincident observation with SPASE-II (South Pole Air Shower Array) and AMANDA

Calibration:

- combined angular resolution ~ 0.5^o
- absolute pointing calibration < 1^o

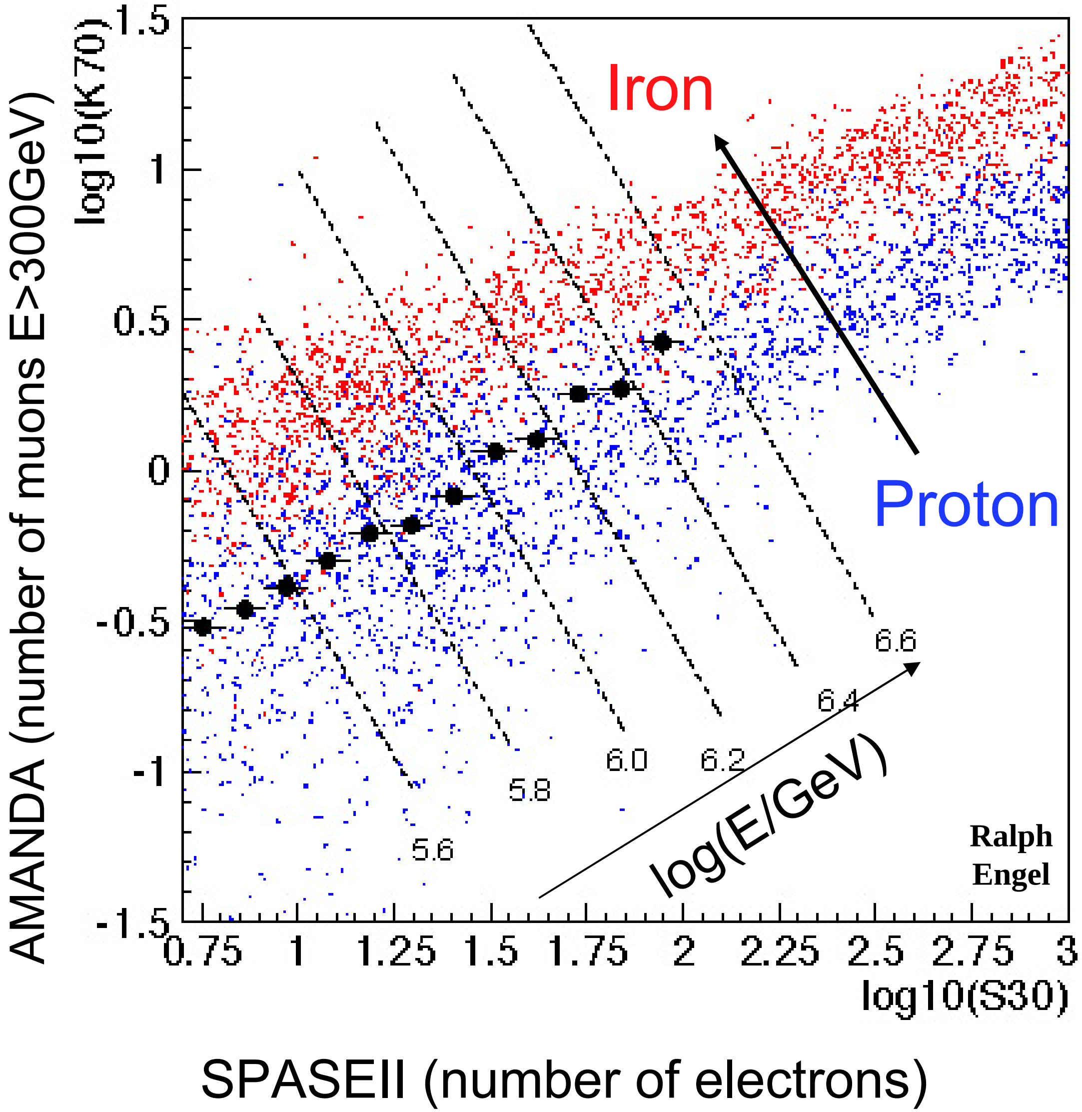
Cosmic Ray shower physics:

- SPASE-II: measure electrons at the surface (670g)
- AMANDA: measure high energy muons (>300 GeV)

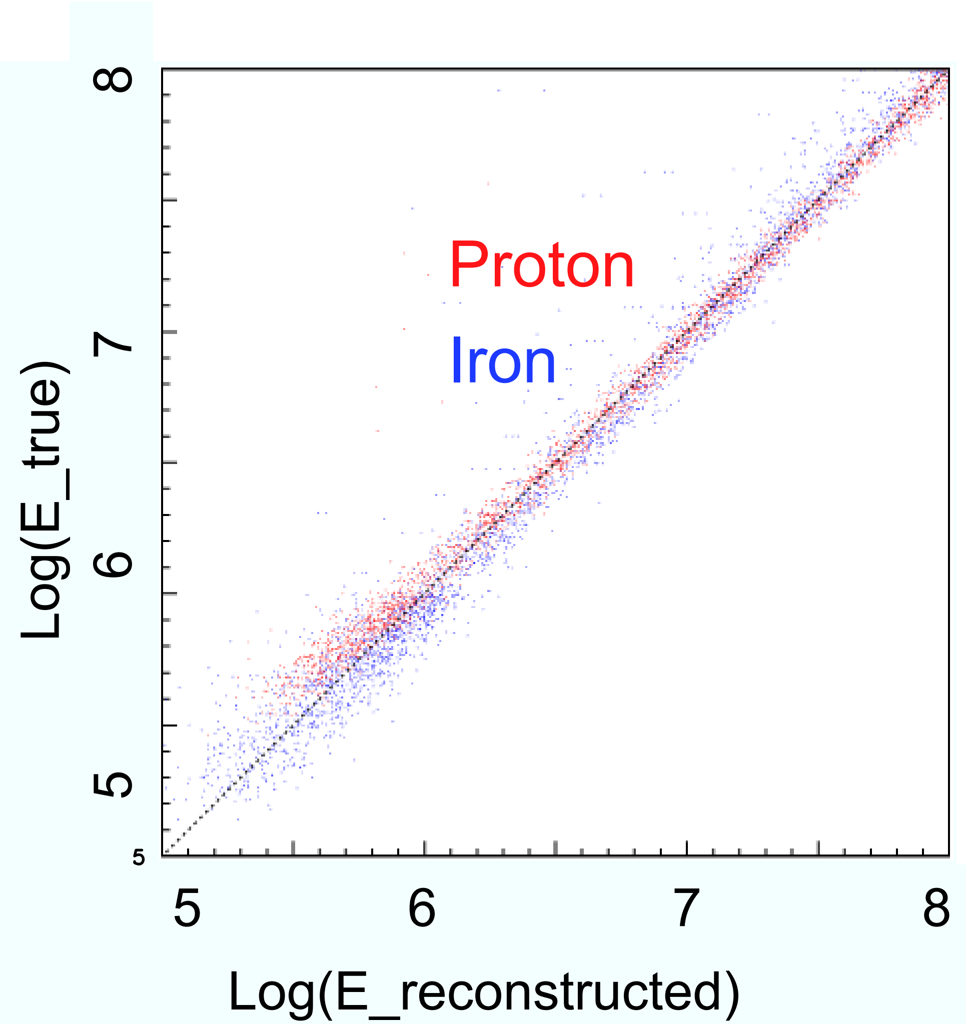
$(N_\mu, N_e) \Leftrightarrow$ (Energy, Mass)

Measuring mass and energy of cosmic ray primary particle

Unfolding energy and mass using SPASE and AMANDA



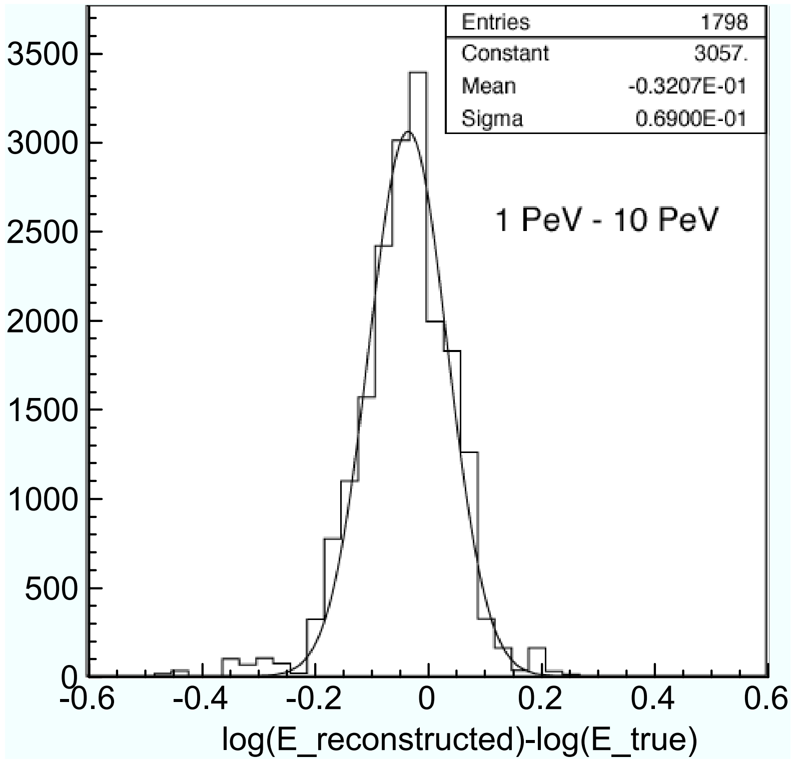
SPASE - AMANDA: Energy resolution of air shower primary



Energy resolution of air shower primary for 1<E/PeV<10:

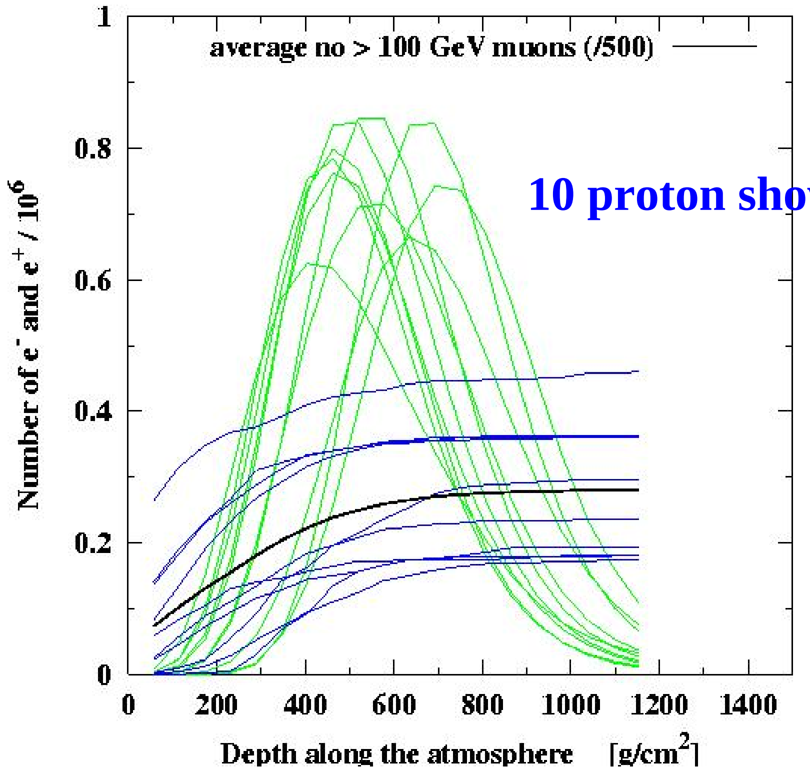
$\sigma_E \approx 7\% \log(E)$

(Mass independent; based on MC)



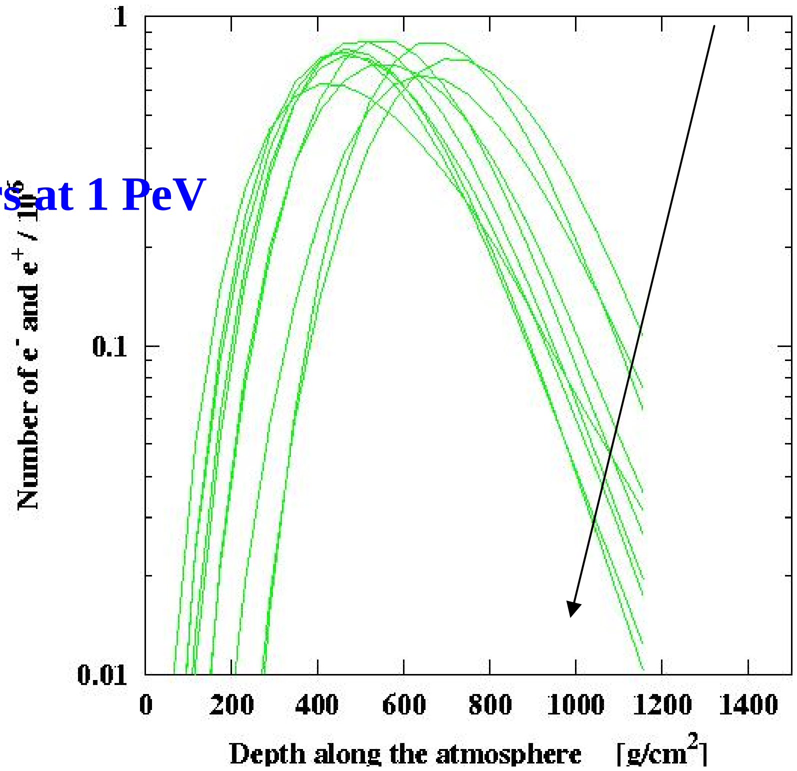
Large fluctuations in the knee region are worse at sea level

Linear plot: green = e+/e-; blue = μ

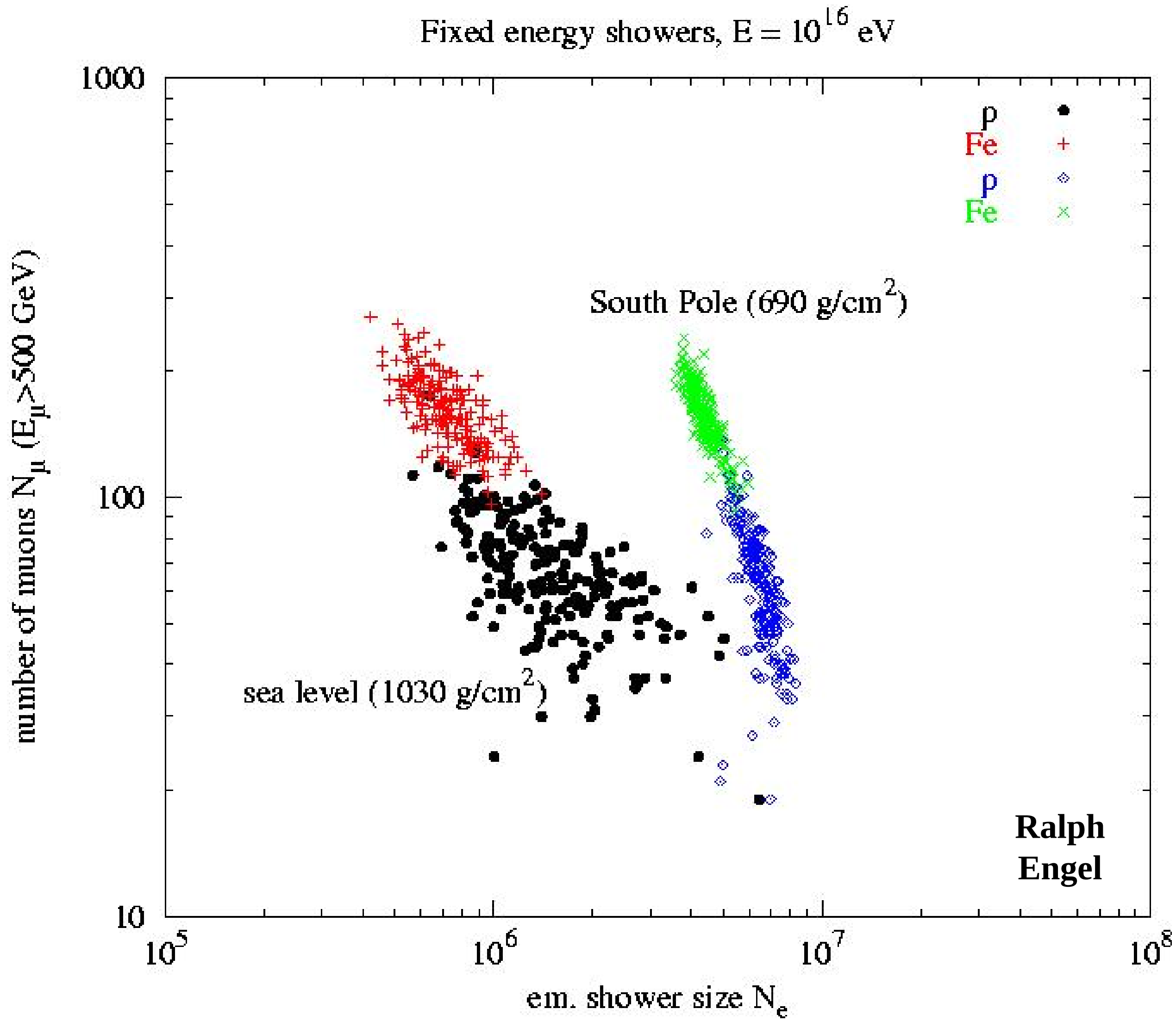


10 proton showers at 1 PeV

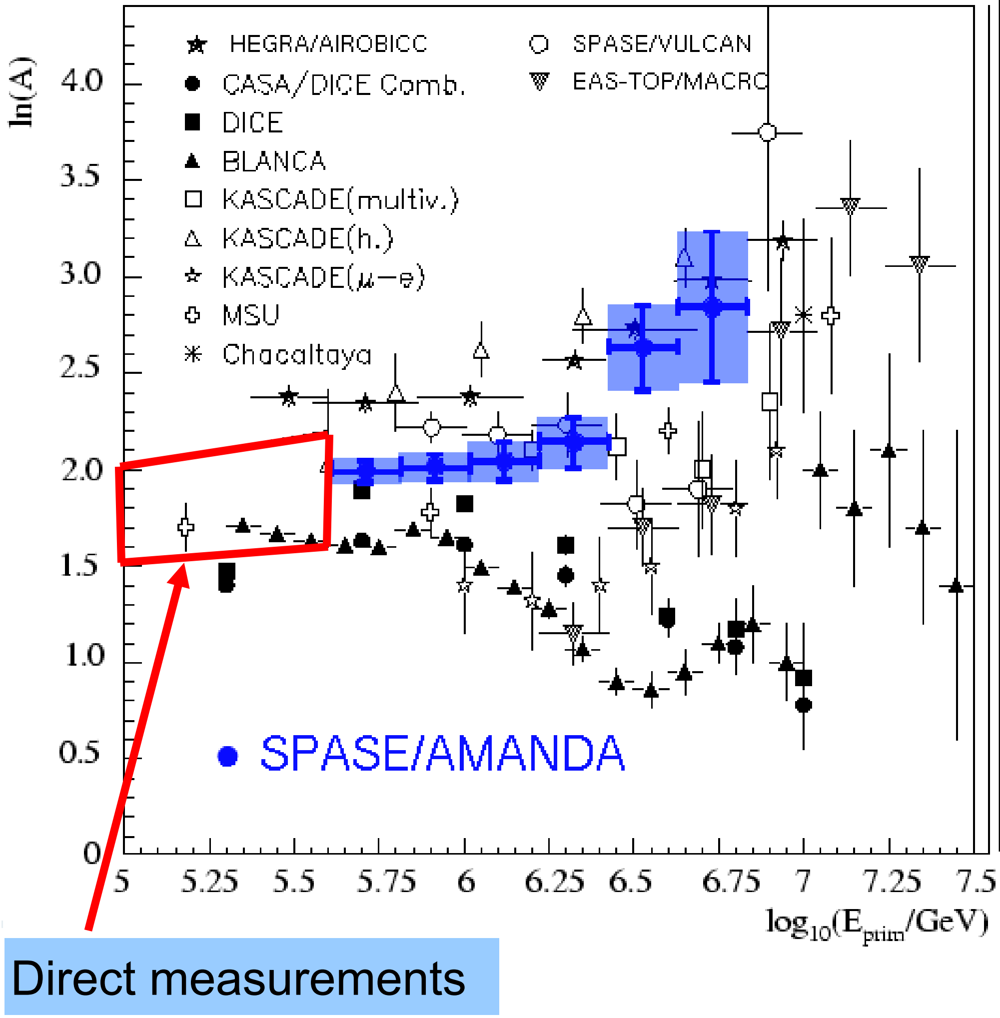
Log plot: fluctuations bad at sea level



Example: Fluctuations in N_μ, N_e at two depths



Cosmic ray composition

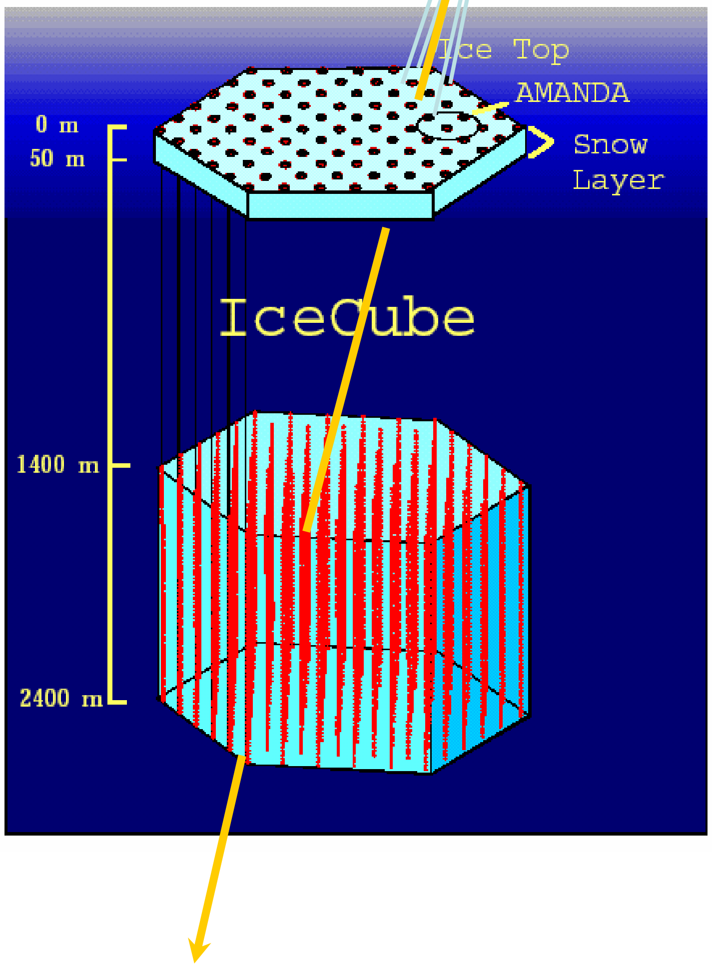


Data:
- electrons at surface and muons at depth.
- lowest energy data point normalized to 2.0.
- Method has strong fundamentals: excellent energy resolution.
- robust against many systematic uncertainties.

Future improvements:
- AMANDA-II (rather than Amanda-B10)
- IceCube-IceTop

Rates of contained, coincident events

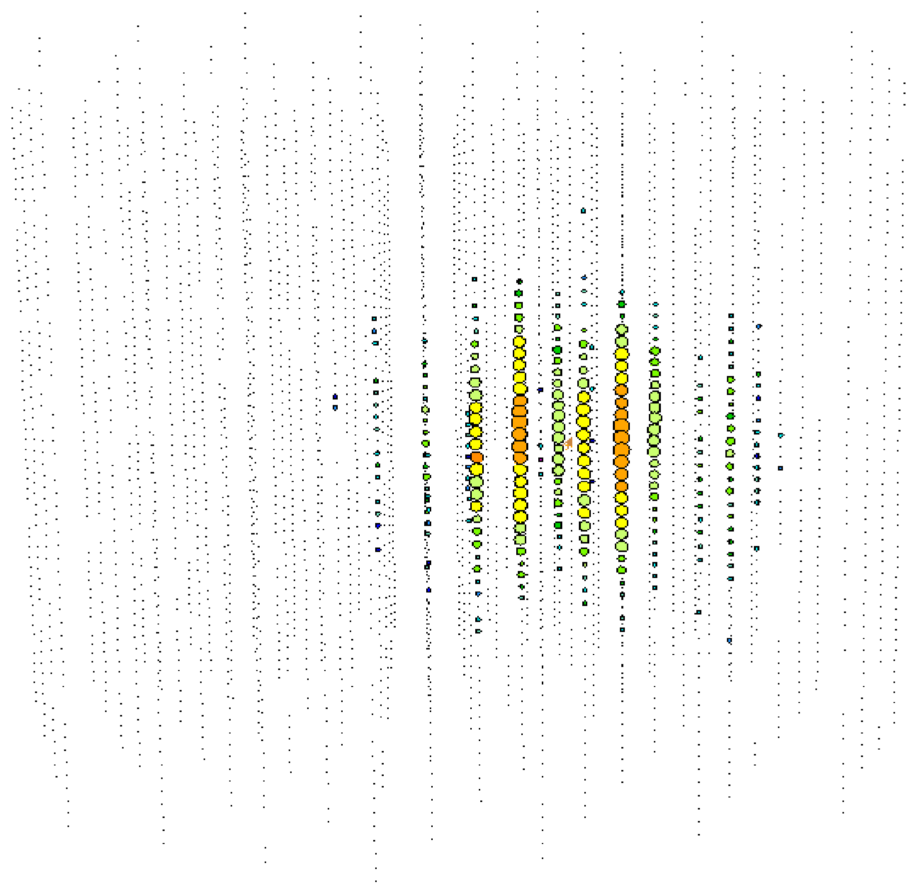
Area--solid-angle ~ 1/3 km^{2}sr



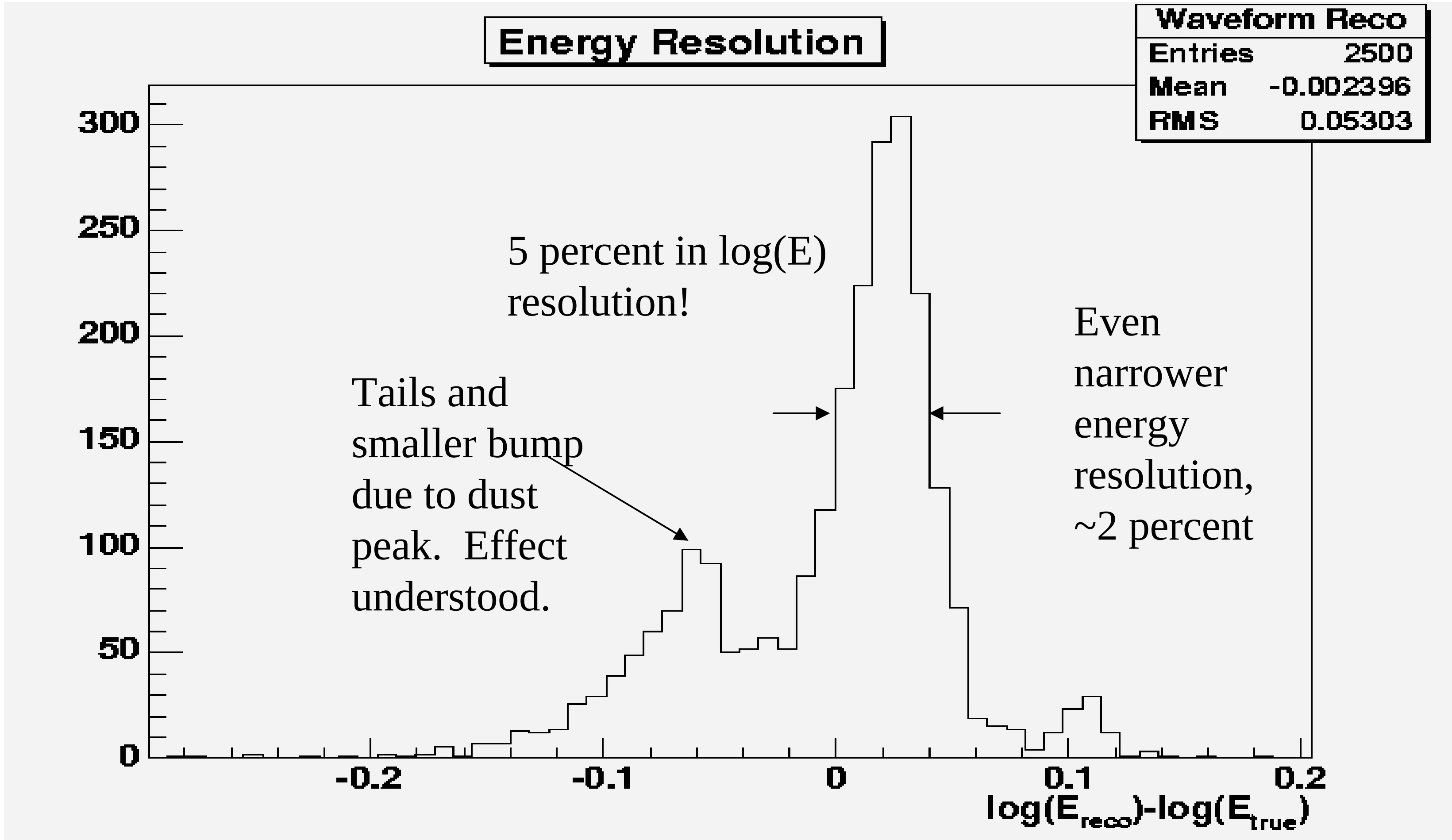
With IceCube we will be able to measure the mass component of cosmic showers up to energies of 10^{18} eV

Sample ν_e (375 TeV)

- Spherical, pointlike because extent of electromagnetic cascade small compared to DOM spacing.



Sample Cascade Results, Energy Resolution



Conclusions:

the first km^3 detector is becoming a reality!

- **Important Milestones:**

  - **Drilling works**

  - **At 1/20th km^3 IceCube is already the world's largest neutrino detector**

  - **Timing calibration system works to precision of 2 nsec.**

  - **DOM survival rate of freeze-in: 99%.**

  - **excellent noise rates (350Hz, 50µs deadtime)**

  - **IceCube "calorimeter" is well-suited to measure**

    composition of air showers

    energy of neutrino-induced cascades

- **We expect to deploy 12-14 strings per year**
- **IceCube construction ends in 2011. Physics results will come soon!**

The IceCube Collaboration

250 scientists from 30 Institutions

- Bartol Research Institute, Delaware, USA
- Univ. of Alabama, USA
- Pennsylvania State University, USA
- UC Berkeley, USA
- Clark-Atlanta University, USA
- Univ. of Maryland, USA

- IAS, Princeton, USA
- University of Wisconsin-Madison, USA
- University of Wisconsin-River Falls, USA
- LBNL, Berkeley, USA
- University of Kansas, USA
- Southern University and A&M College, Baton Rouge, USA

- Chiba university, Japan
- University of Canterbury, Christchurch, NZ

- Universite Libre de Bruxelles, Belgium
- Vrije Universiteit Brussel, Belgium
- Université de Mons-Hainaut, Belgium
- Universität Mainz, Germany
- DESY-Zeuthen, Germany
- MPIfK Heidelberg, Germany
- Universität Dortmund, Germany

- Universität Wuppertal, Germany
- Uppsala university, Sweden
- Stockholm university, Sweden
- Imperial College, London, UK
- Oxford university, UK
- Utrecht,university, Netherlands