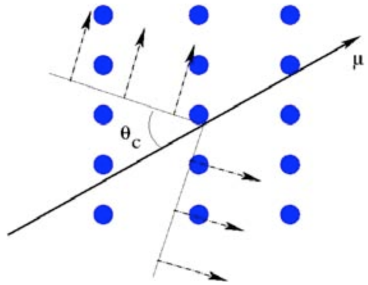
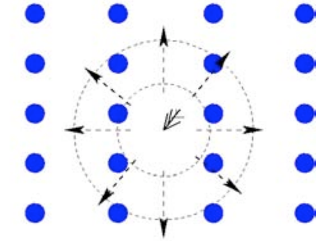
Lecture 3 Physics at Neutrino Telescopes

- Detectors
- Event Topologies and reconstructions
- Example of analyses



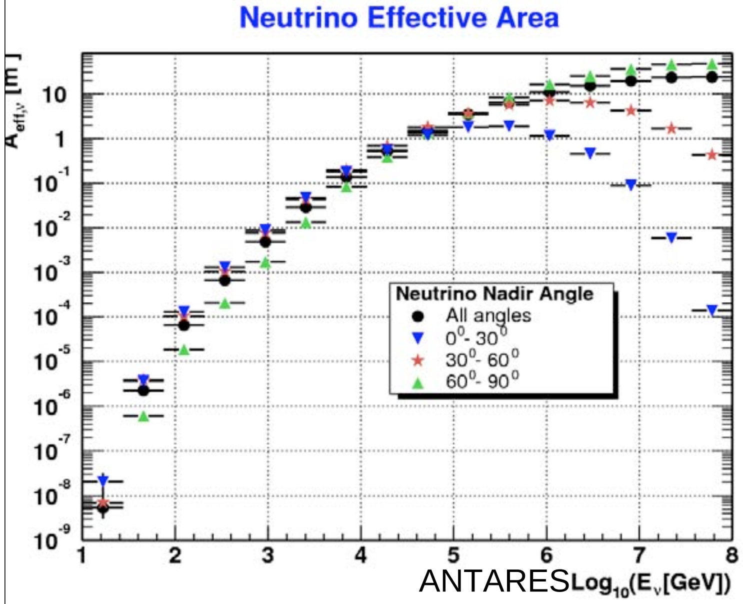
Muon, with a Cherenkov cone

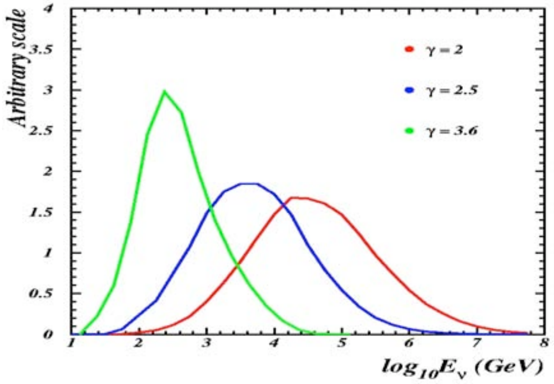


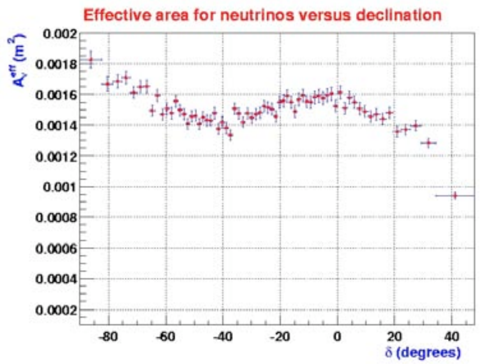
Electromagnetic cascade, with spherical Cherenkov front.

- Point-source analysis and current results
- Atmospheric neutrino analysis
- Current physics results
- SN Collapses

Effective area







Neutrino-nucleon cross-section

Neutrinos flux model

$$N_\mu = \int V_{eff}(E_\nu,\theta_\nu,\phi_\nu)\,(\rho\, N_A)\,\sigma(E_\nu)\,\frac{d\Phi_\nu}{dE_\nu d\Omega_\nu}\,dE_\nu\, d\Omega_\nu$$

Target nucleon density

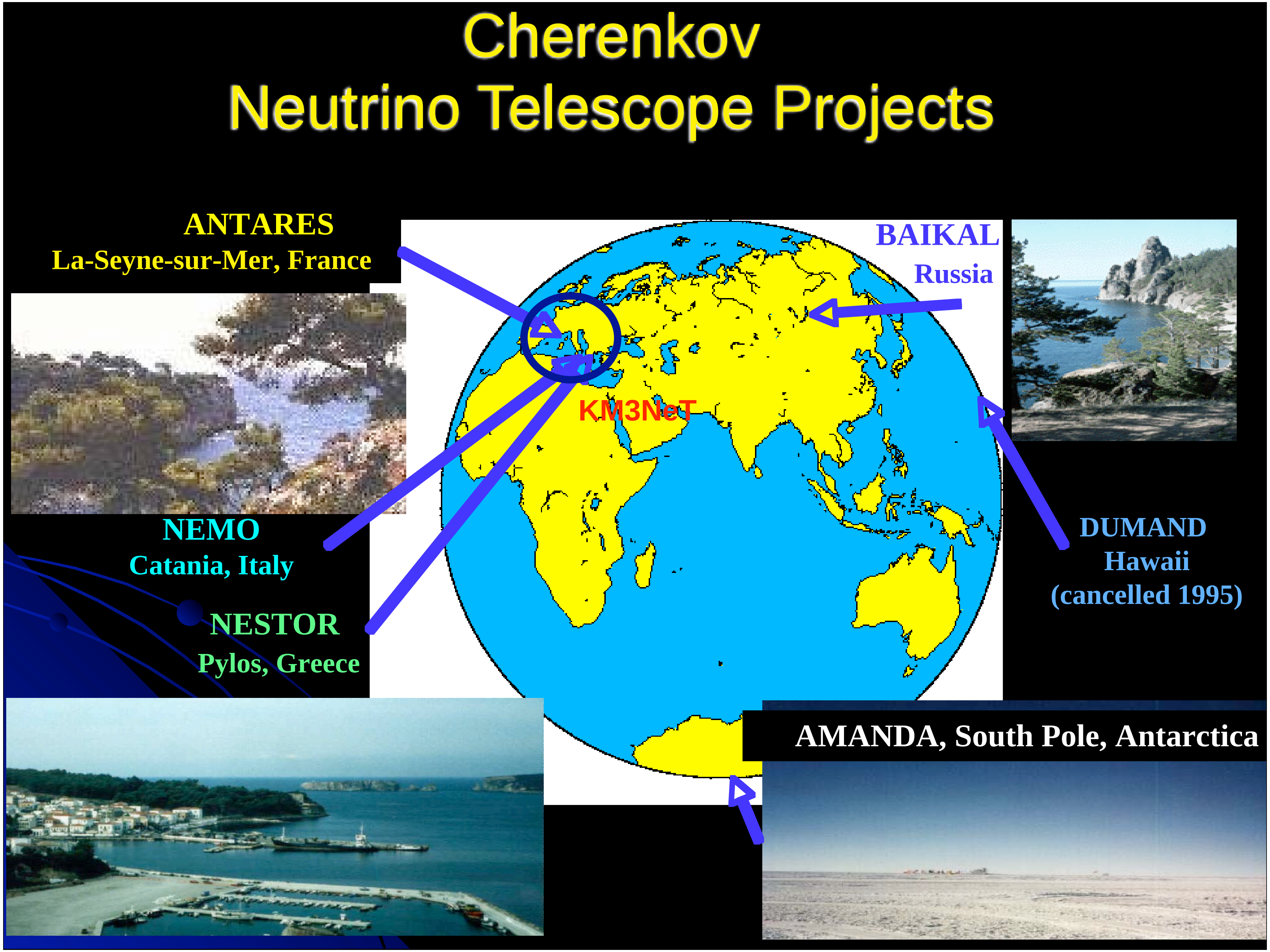
Shadowing effect

$$A^\nu_{eff} = V_{gen} \times \frac{N_{xxx}(E_\nu,\theta_\nu,\phi_\nu)}{N_{gen}(E_\nu,\theta_\nu,\phi_\nu)} \times (\rho\, N_A)\,\sigma(E_\nu) \times P_{earth}(E_\nu,\theta_\nu)$$

$$P_{earth}(E_\nu,\theta_\nu) = e^{-N_A\,\sigma(E_\nu)\int \rho\, dl}$$

Event rate

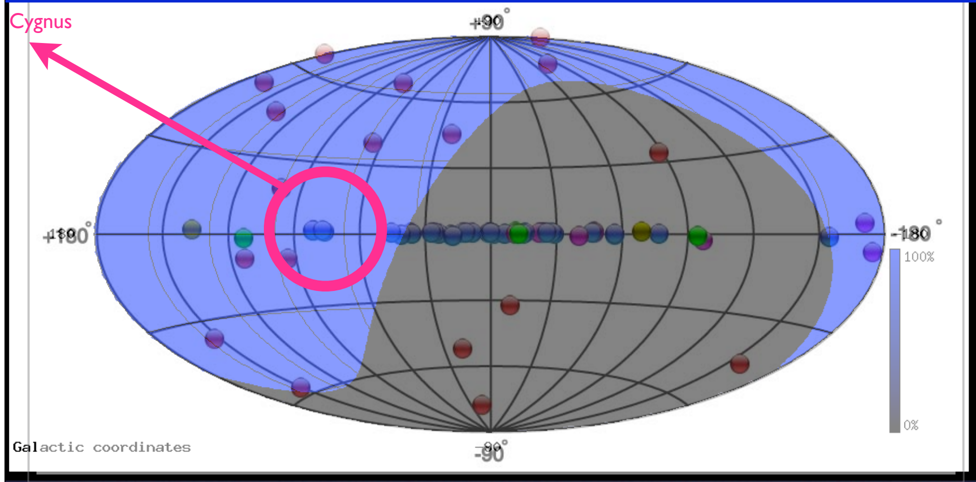
$$N_\mu = \int A^\nu_{eff}(E_\nu,\theta_\nu,\phi_\nu)\,\frac{d\Phi_\nu}{dE_\nu d\Omega_\nu}\,dE_\nu\, d\Omega_\nu$$



Cherenkov
Neutrino Telescope Projects
ANTARES
La-Seyne-sur-Mer, France
BAIKAL
Russia
KM3NeT
NEMO
Catania, Italy
NESTOR
Pylos, Greece
DUMAND
Hawaii
(cancelled 1995)
AMANDA, South Pole, Antarctica

Full Sky Coverage with upgoing neutrinos

To cover better galactic sources we need Med detectors

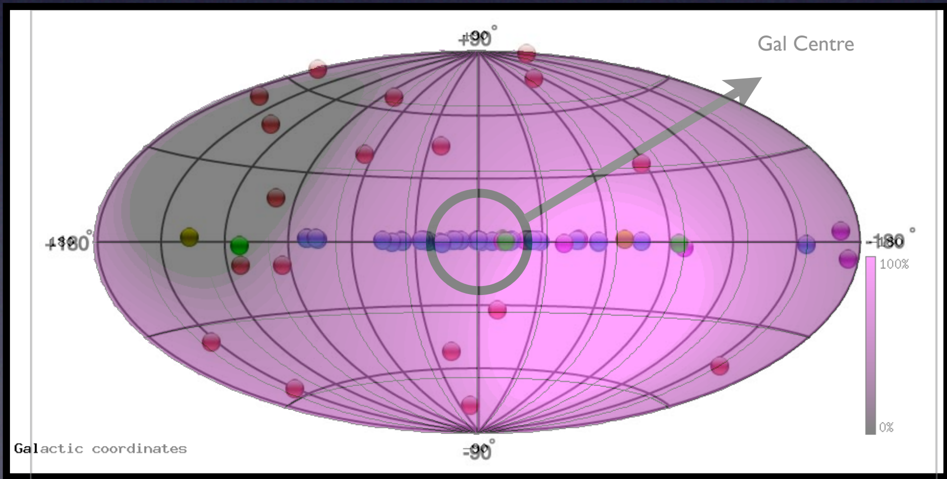


ANTARES 43° N

Galactic Centre 2/3 of day

IceCube/AMANDA

at South Pole



TeV sources from tevcat.uchicago.edu > 70 TeV sources

IceCube

http://icecube.wisc.edu

United states

- Univ Alaska, Anchorage
- UC Berkeley
- UC Irvine
- Clark-Atlanta University
- U Delaware / Bartol Research Inst
- University of Kansas
- Lawrence Berkeley National Lab
- University of Maryland
- Pennsylvania State University
- University of Wisconsin-Madison
- University of Wisconsin-RiverFalls
- Southern University, Baton Rouge

Europe

University Utrecht

- Uppsala University
- Stockholm University

- University of Oxford

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

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

Japan

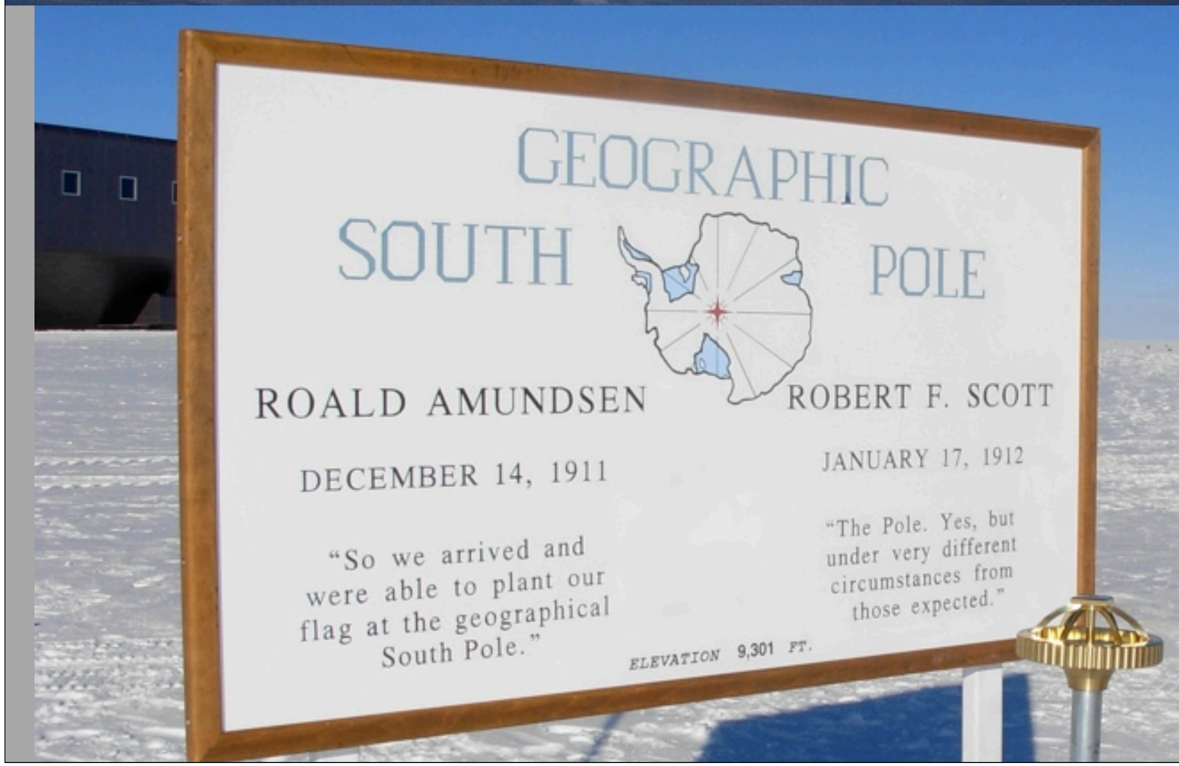
Chiba University

New Zealand

Univ. of Canterbury, Christchurch

The dome, the old station

new South Pole station



IceCube Neutrino Observatory

IceCube

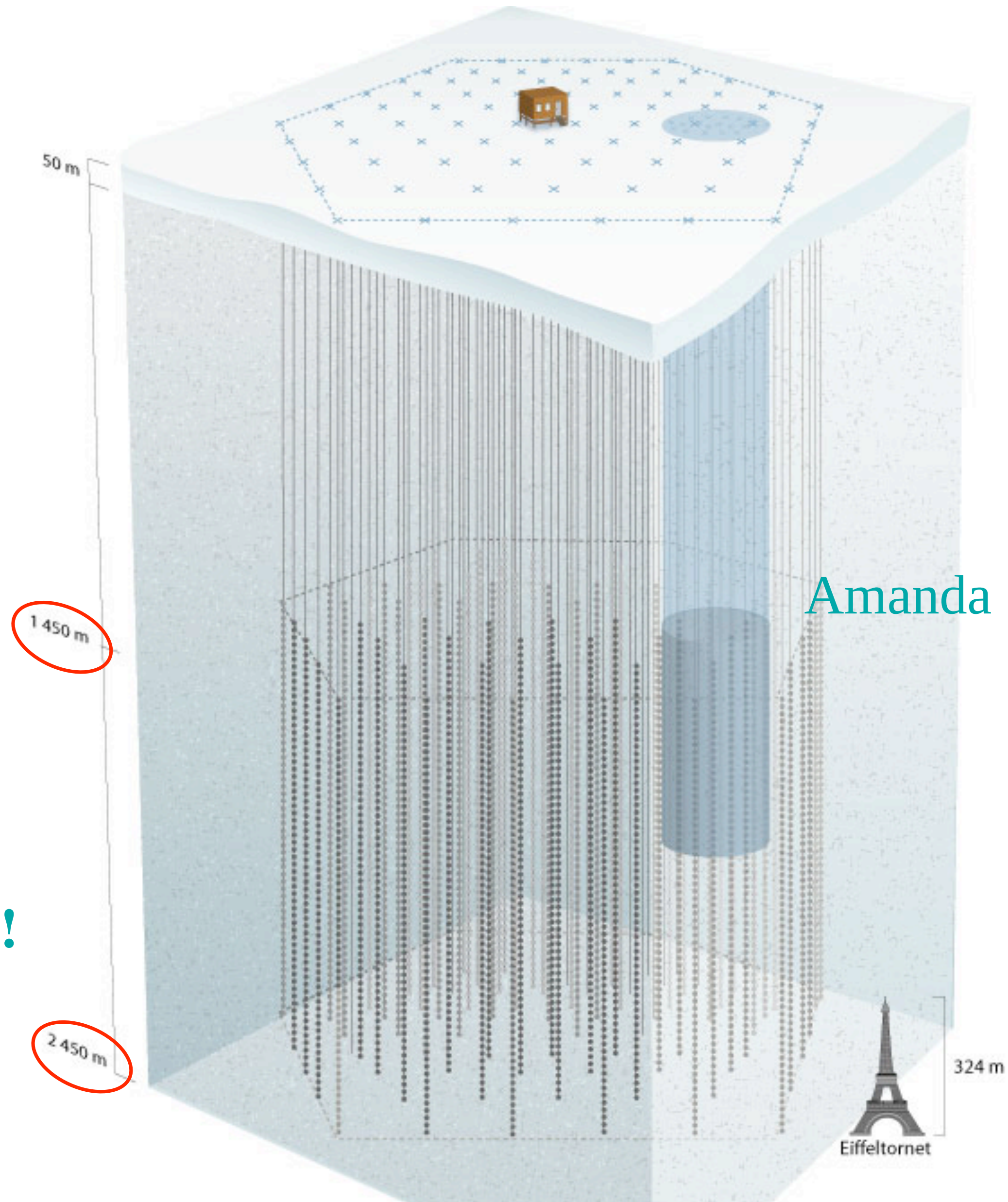
up to 80 strings with 60 Digital Optical Modules
4800 DOMs
17 meters between them
125 meters between strings
1 Giga Ton Detector
No single point failure in a string!
DOM failure rate about 1%

Now: 2400 DOMs on 40 strings!

IceTop Air shower array

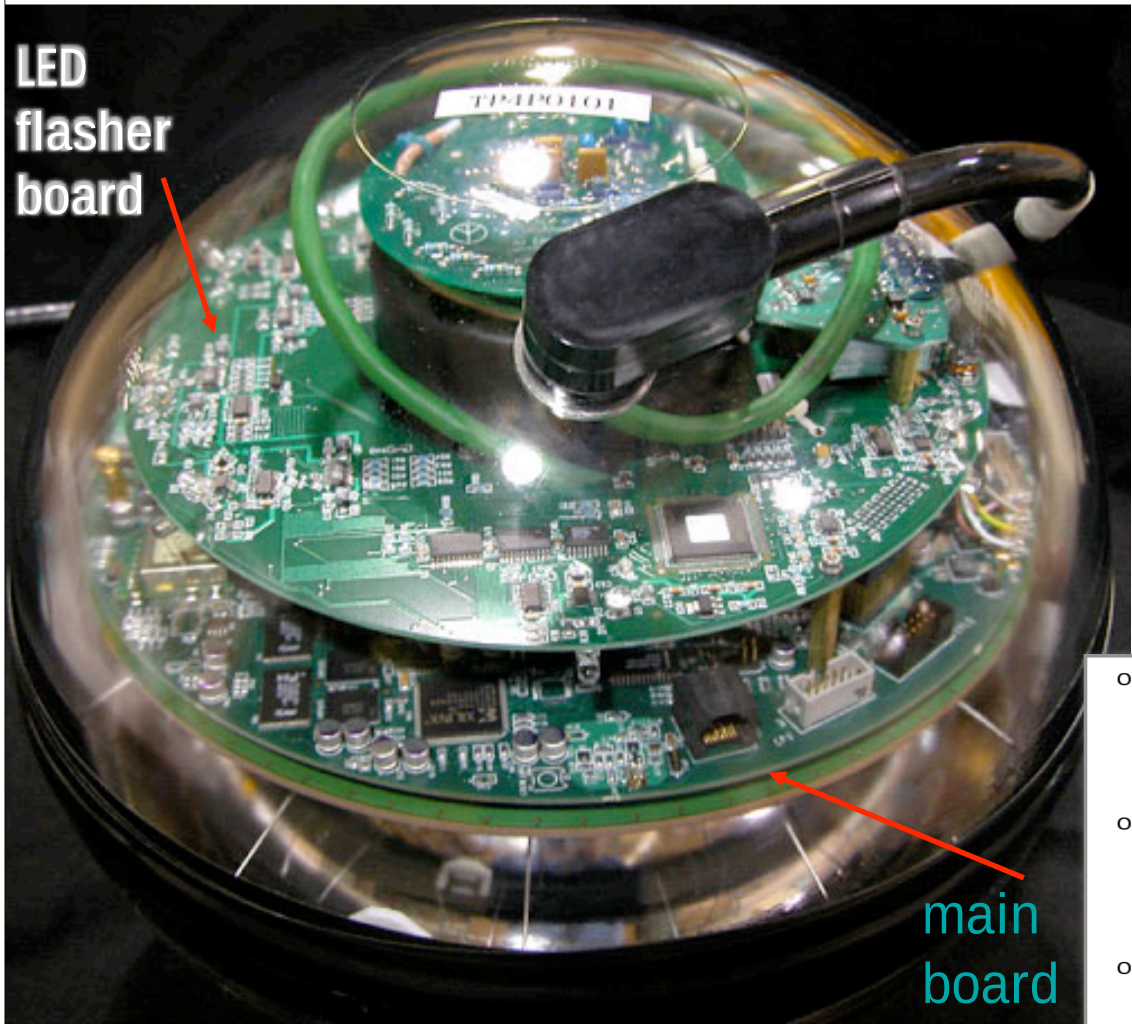
80 Pairs of Ice Cherenkov Tanks 10 m apart each with 2 DOMs

Now: 80 tanks => 160 DOMs!



The Site
ICL
Drilling Tower
IceCube
AMANDA
1500 m
road to work
Skiway
South Pole
Dome
Summer camp
http://icecube.wisc.edu

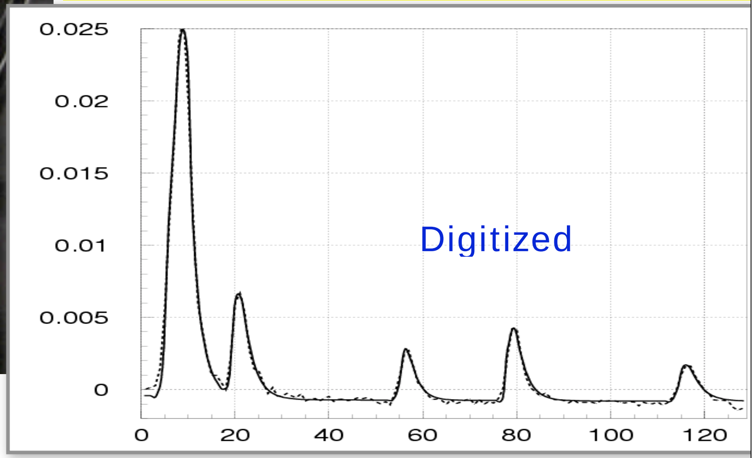
Digital Optical Module (DOM)



PMT: 10 inch Hamamatsu
Power consumption: 3 W
Digitize at 300 MHz for 400 ns with custom chip
40 MHz for 6.4 µs with fast ADC
Dynamic range 200pe/15 nsec

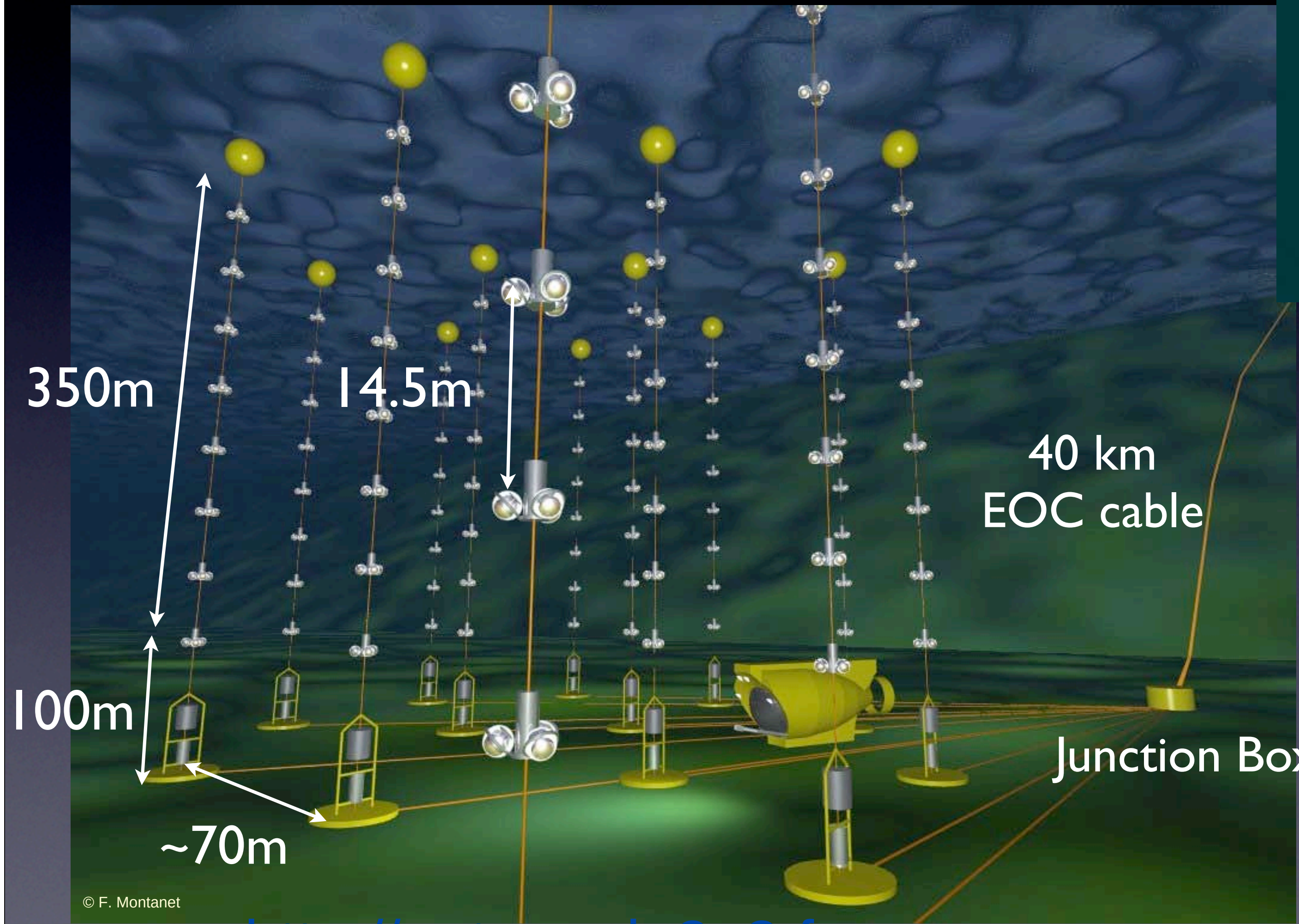
Send all data to surface over copper
2 sensors/twisted pair.
Flasherboard with 12 LEDs
Local HV

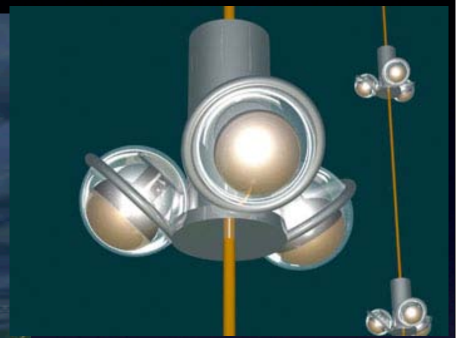
Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS time every ≈10 sec
Time calibration resolution = 2 nsec



ANTARES

- The largest underwater NT in the Northern Hemisphere and the first undersea NT, an invaluable step towards KM3 in the Mediterranean Sea



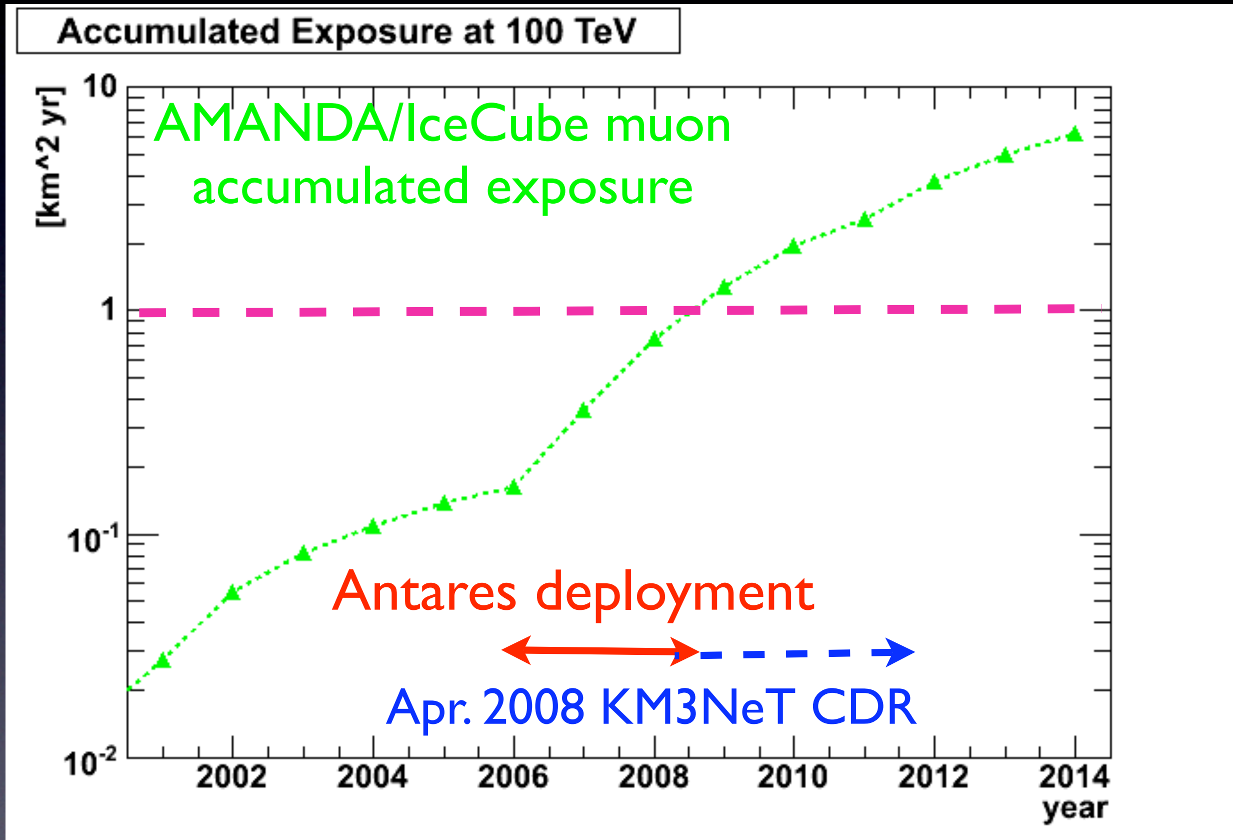


Storey: 10 inch PMT
Front end electronics: pulse shape discrimination, time stamp and digitization above a threshold

http://antares.in2p3.fr

- Consortium of 40 Institutions from 10 European countries in European Strategy Forum on Reasearch Infrustructures roadmap
- Propose a facility for Deep Sea Science
- CDR ready
- Site decision still open

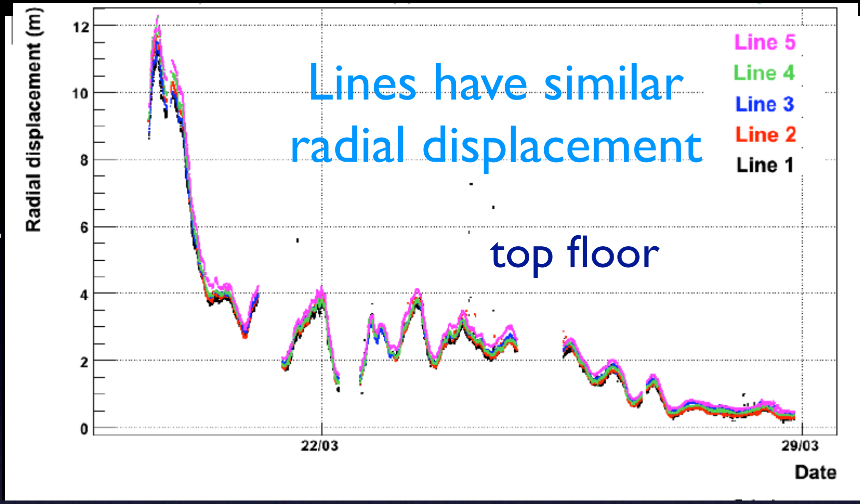
Entering the km^3 era

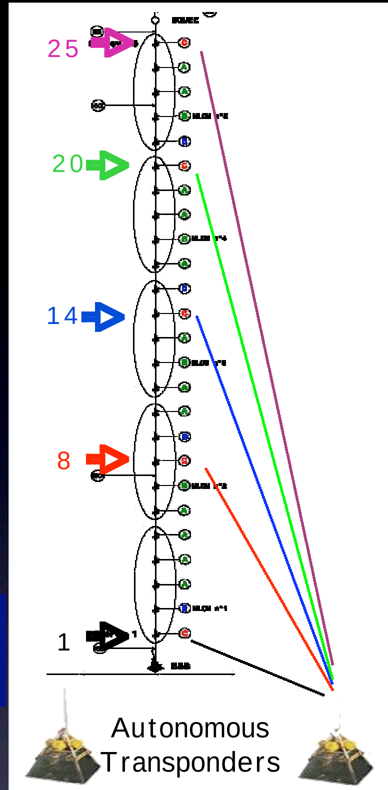


this yr IceCube/ AMANDA integrated exposure about 1 km^2 yr at 100 TeV

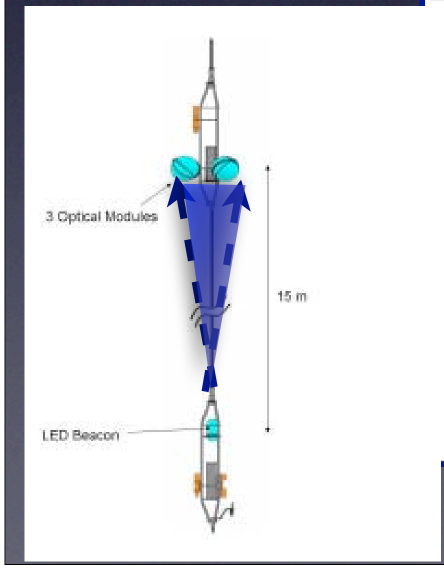
Calibrations in sea water

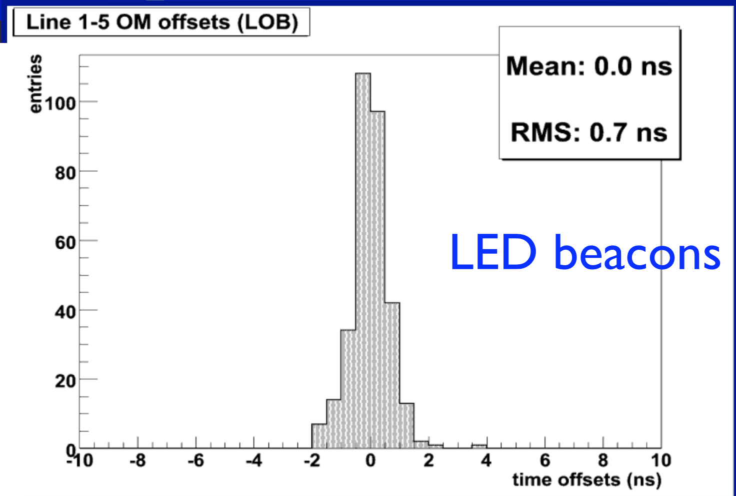
Lines move:
acoustic triangulation and tiltmiter-compasses reconstruct line shape





Measured position resolution < 10 cm





Electronics+calibration σ~0.5ns

TTS PMTs σ~1.3ns

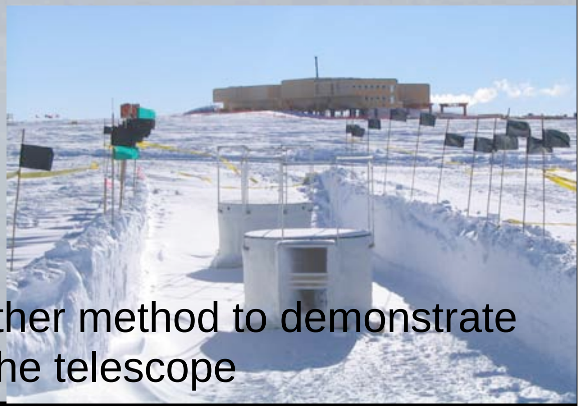
Light scattering+chromatic dispersion σ~2ns

Angular resolution limitation ~ 0.2°-0.3°

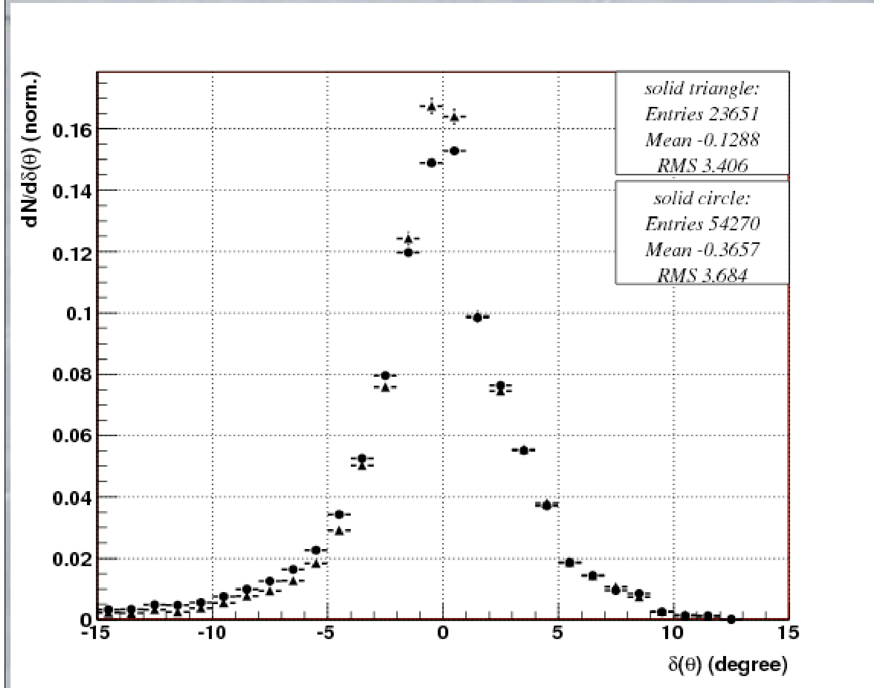
IceCube - IceTop coincident events

26 stations (52 tanks)

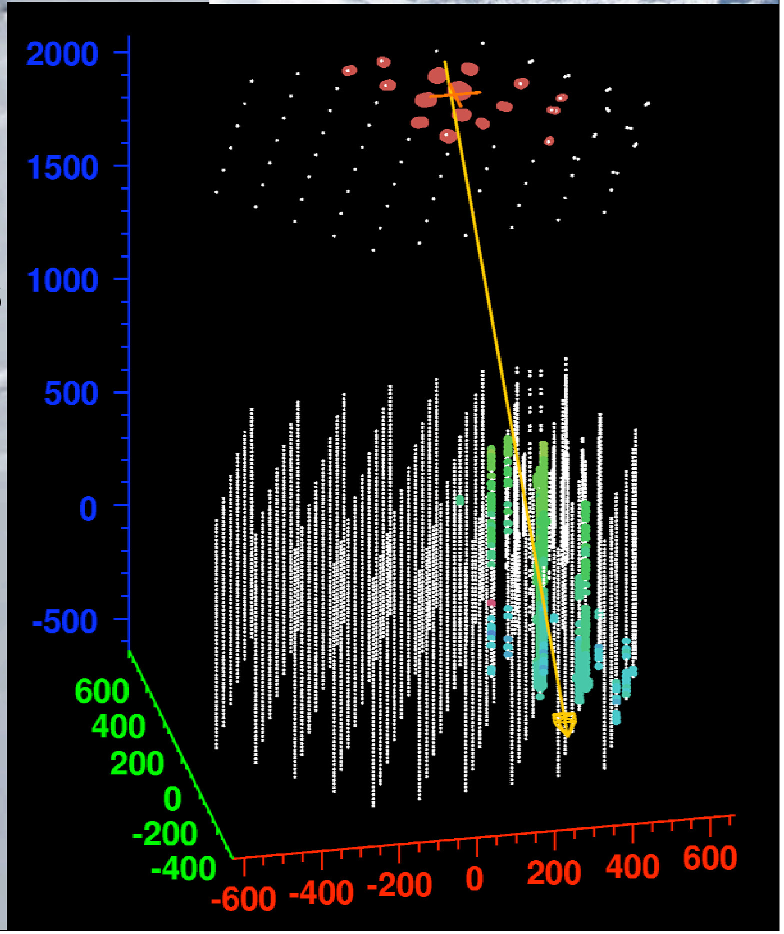
- Muon direction given by position of station and Center Of Gravity of InIce Signals.
- Comparison of InIce reconstruction to "known" muon direction.



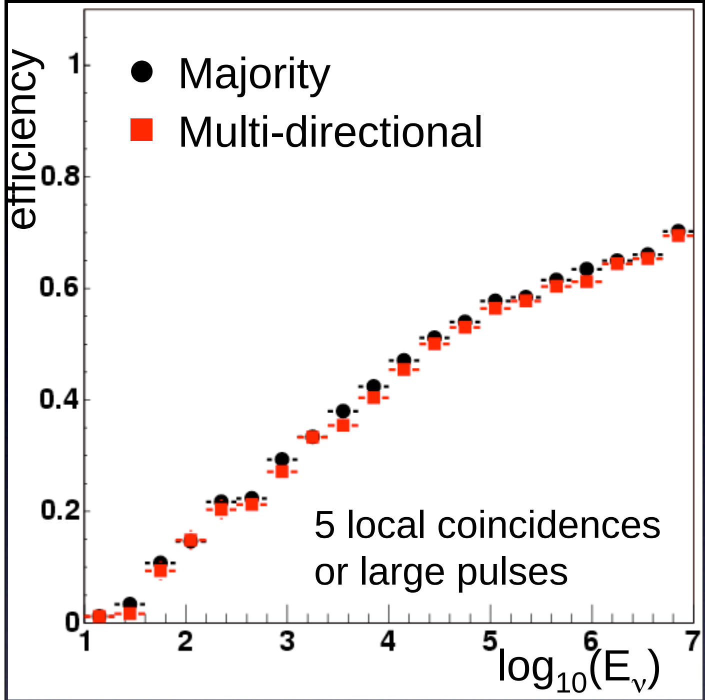
Moon shadow is another method to demonstrate absolute pointing of the telescope



6 μs



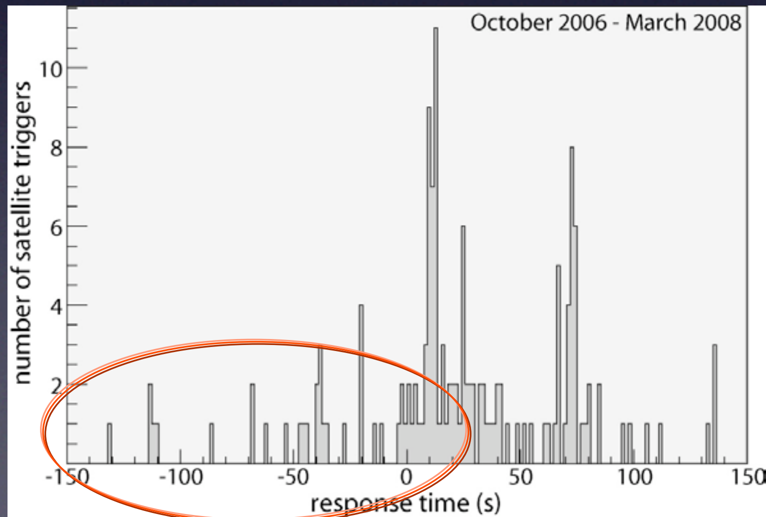
Trigger/hit filtering in sea water



- L0: PMT hit above 1/3 p.e.
- L1: local coincidence (2 L0 in the OM triplet in Δt<20 ns) or a large pulse (> 3 p.e.)

TRIGGER:
- ≥ 5 L1
- causal connection between L1:

Trigger rate: ~1 Hz (5 lines)
~2-3 Hz (10 lines)



GRB trigger
data can be buffered
delay time of start of observation respect to astronomical event time

Out of 198 GCN triggers 176 have been handled by Antares DAQ

What science with these fluxes?

Astrophysics

- Extragalactic sources: AGN & GRBs
- Galactic sources: SNRs, pulsar wind nebulae, magnetars, micro-quasars, unidentified sources, galactic plane
- GZK neutrinos (CRs interacting with CMWB)
- SN collapse
- Large scale anisotropies with muons

Physics beyond the SM and Dark Matter

- Dark Matter: WIMPs, Monopoles
- cross sections at EeV energy
- test of Lorentz invariance and equivalence principle, cross sections at UHE

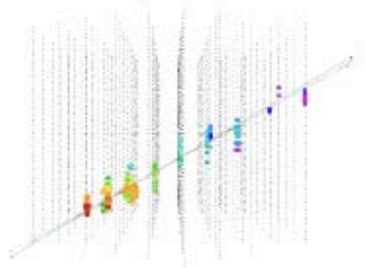
Standard particle physics and Hadronic interactions

- pion, K and charm physics at TeV energies in the Lab
- Neutrino oscillations
- Climatology with muons

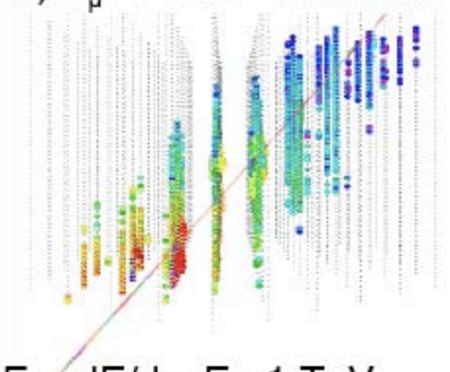
Neutrino Topologies

Muon neutrino

a) E_μ=10 TeV ~ 90 hits



b) E_μ=6 PeV ~1000 hits

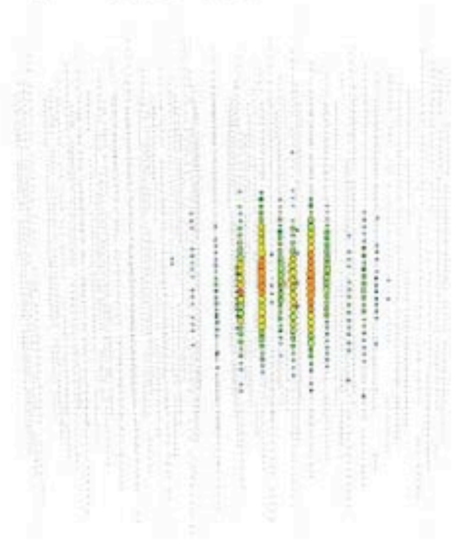


E ~ dE/dx, E> 1 TeV

Energy Res. : log(E)~0.3
Angular Res.: 0.8 -2 deg

Electron neutrino

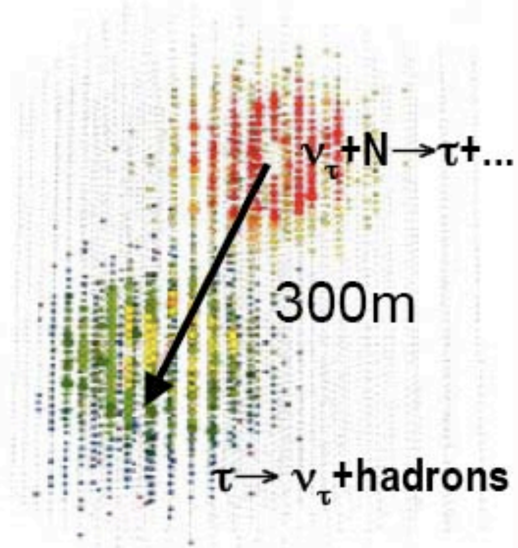
E = 375 TeV



Energy Res. log(E)~0.1-0.2
Poor Angular Resolution

Tau neutrino

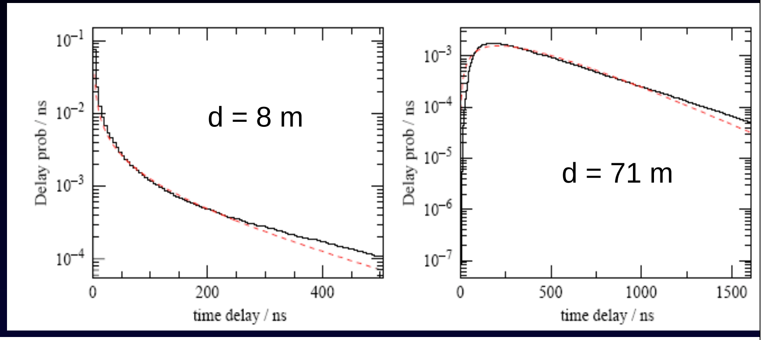
E = 10 PeV

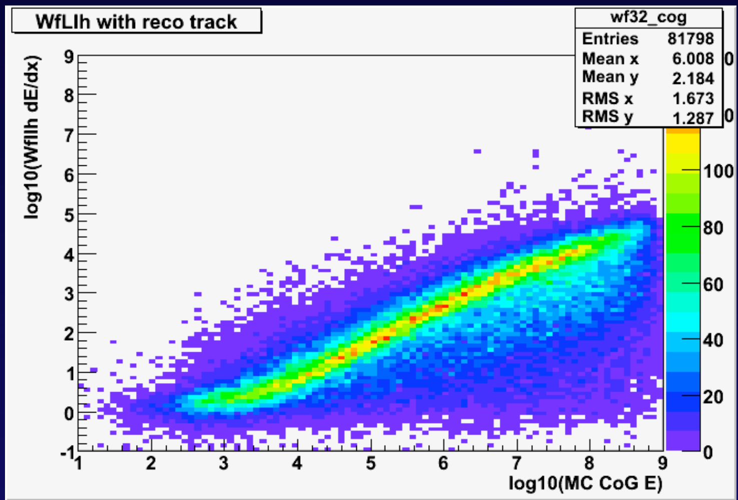


Double-bang signature above ~ 1 PeV
Very low background
Pointing capability
Best energy measurement

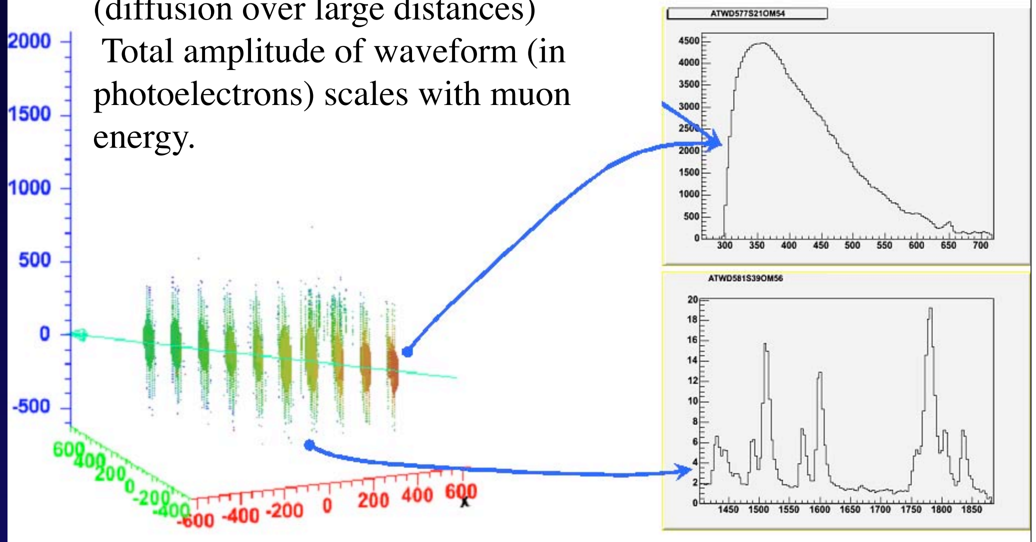
Track Reconstruction

Max LH reconstruction
pdf is time delay

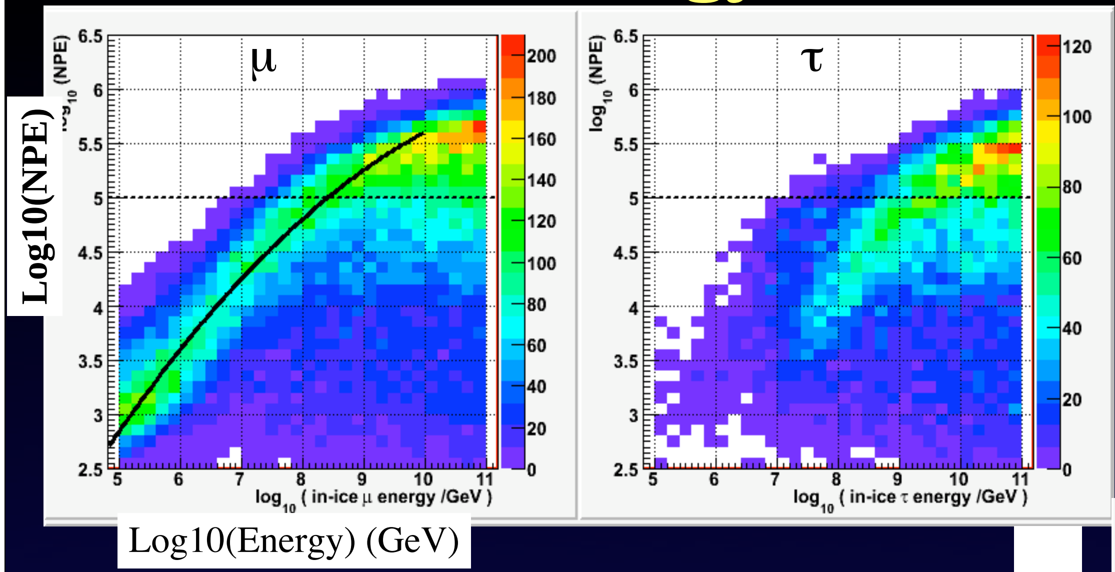




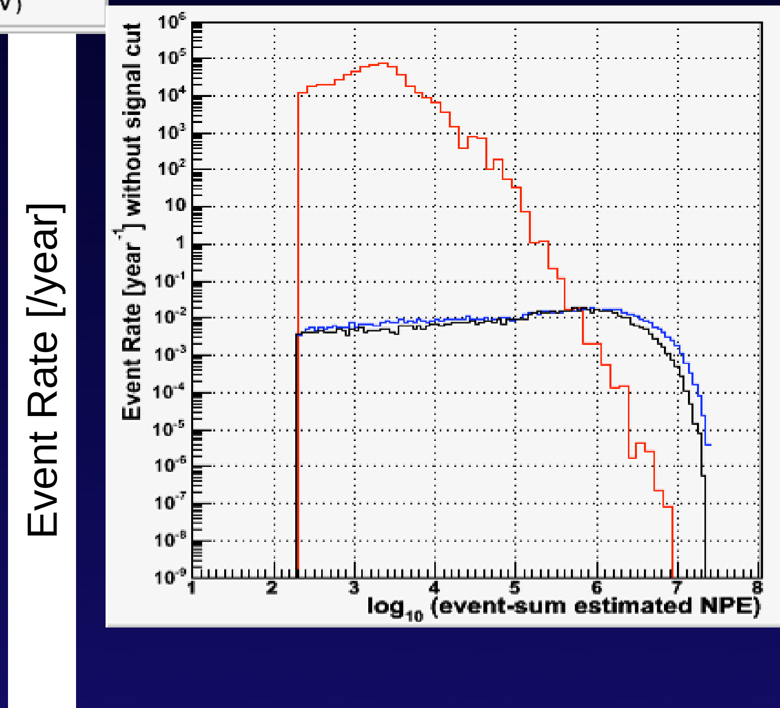
Width of WF scales with distance (diffusion over large distances)
Total amplitude of waveform (in photoelectrons) scales with muon energy.



Energy reconstruction



IC80

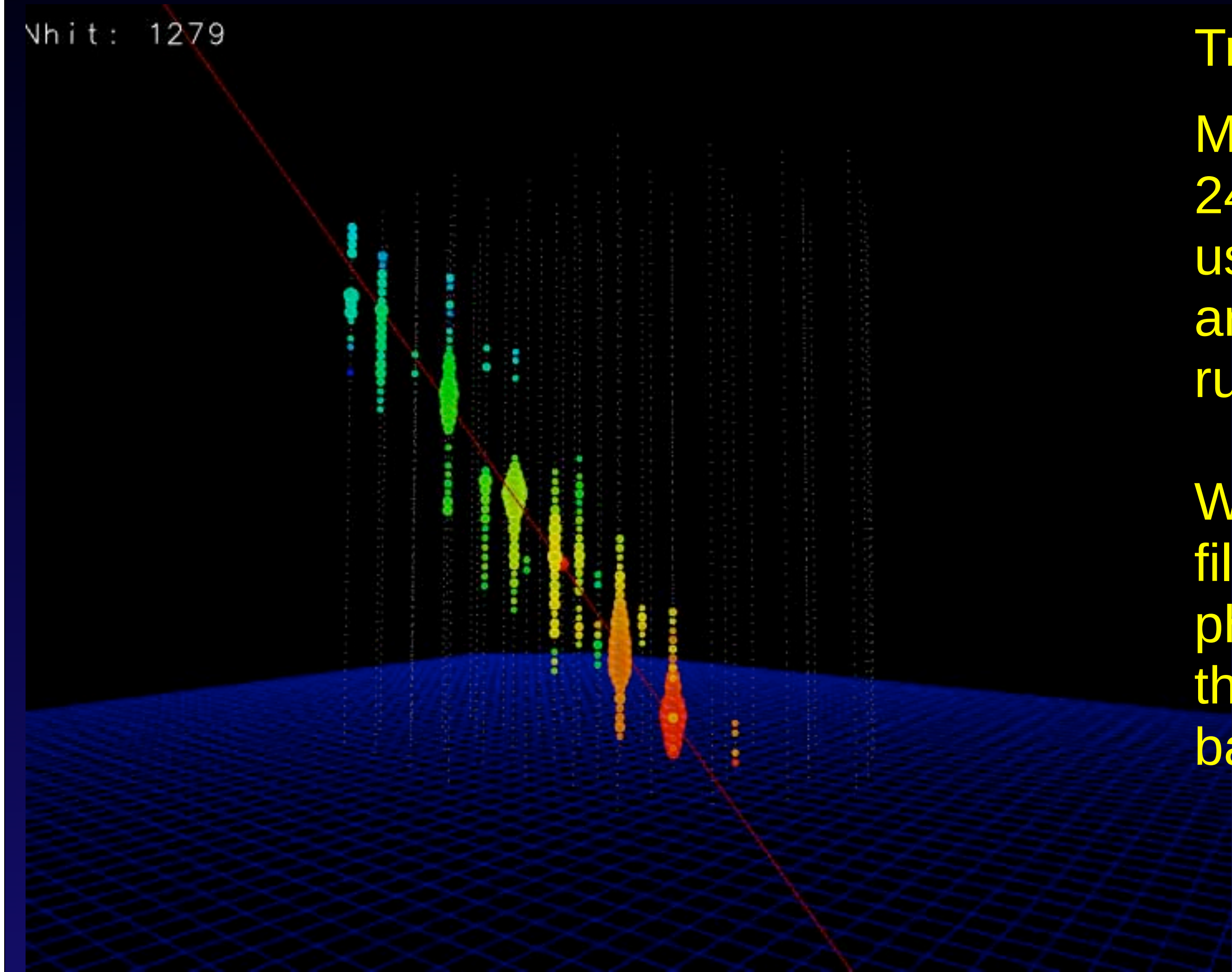


IceCube Preliminary

GZK μ	0.35	events/year
GZK τ	0.31	events/year
Atmospheric μ	0.033	events/year

GZK: S. Yoshida et. al. (1997) ApJ 479:547 (m=4, Zmax=4)

Icecube 40 strings muon

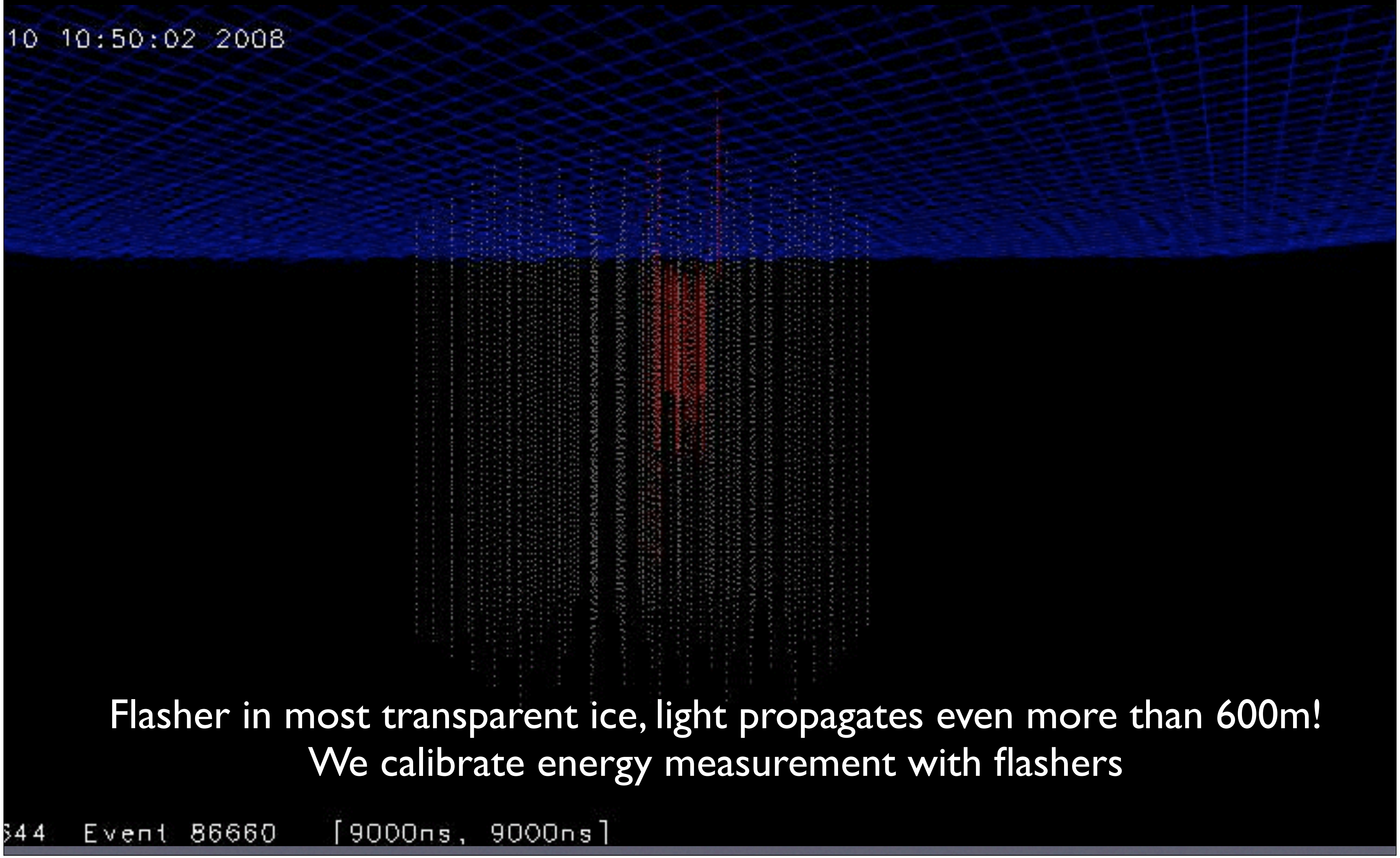


Trigger rate~ 1 kHz

Muon Filter rate 24 Hz (events we use for high level analisys), Physics run started

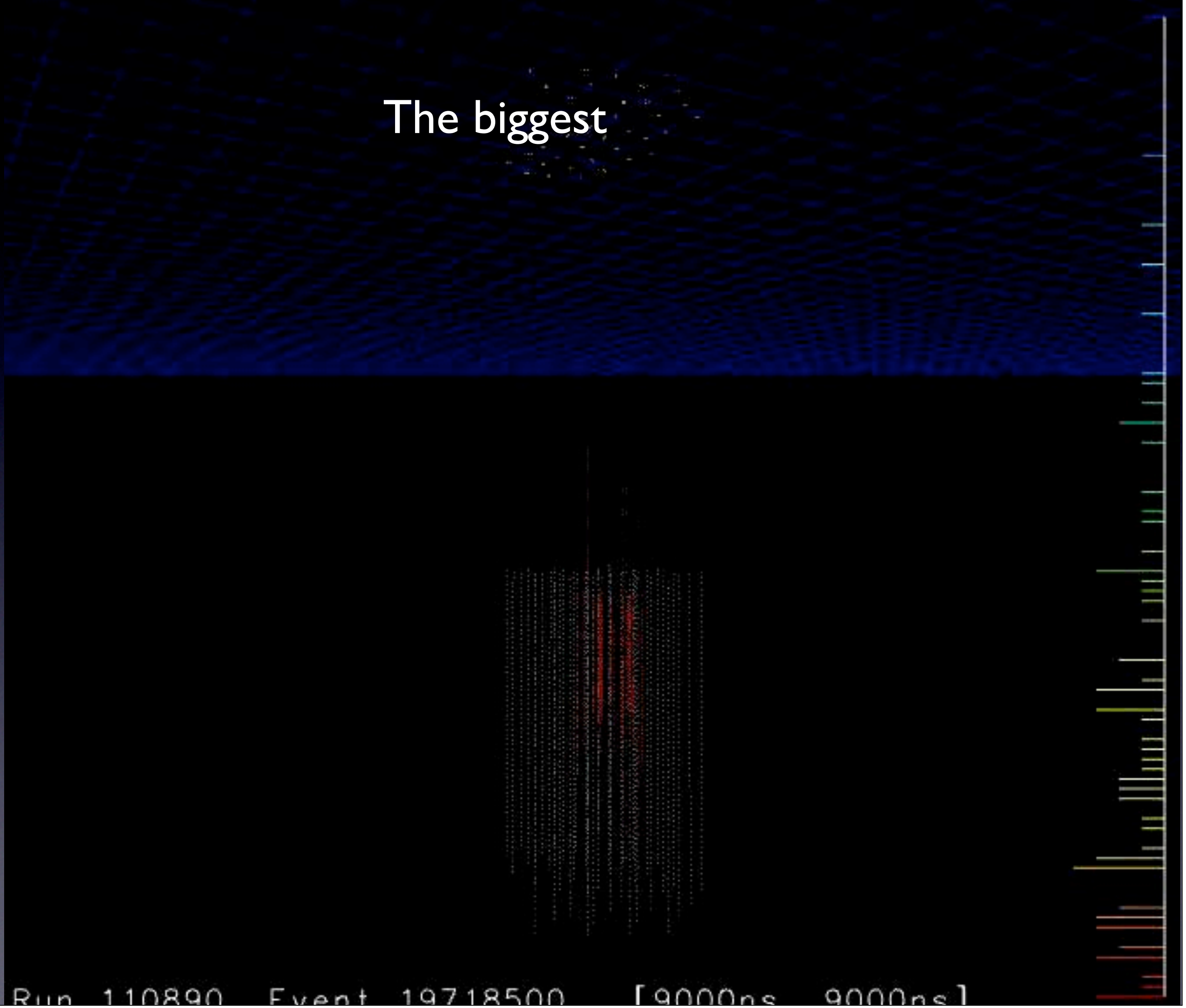
We send 40Gb/d of filtered streams for physics analysis on the satellite bandwidth

A flasher and muon in IC40

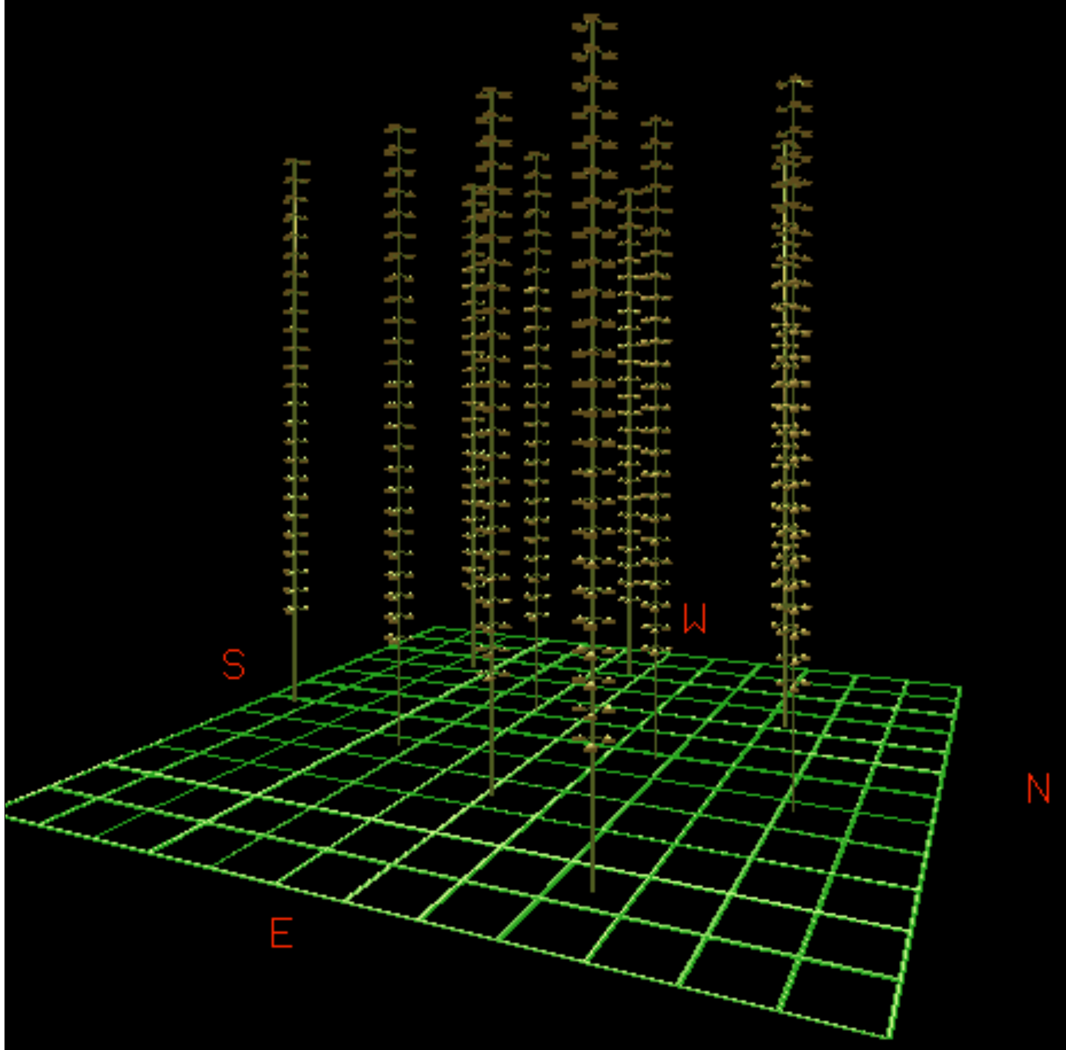


Flasher in most transparent ice, light propagates even more than 600m!
We calibrate energy measurement with flashers

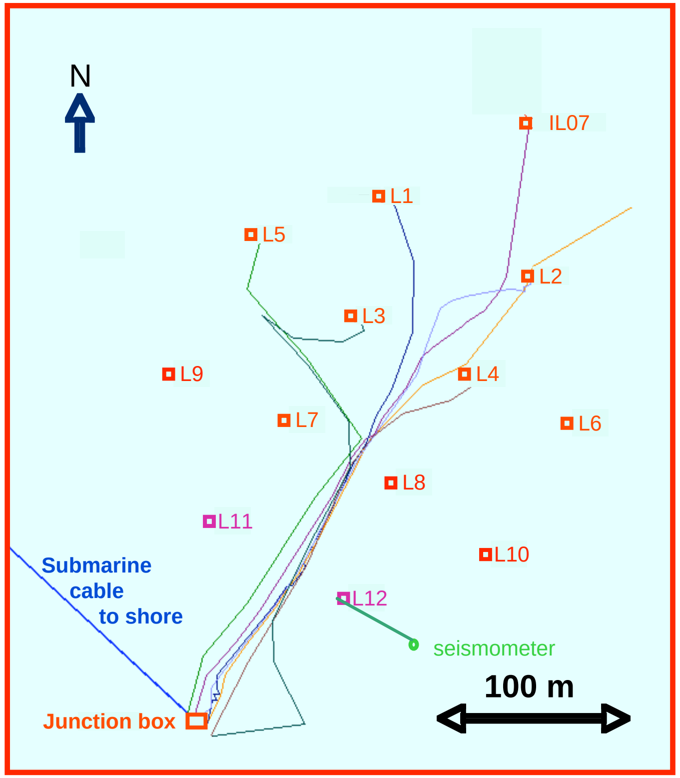
The biggest



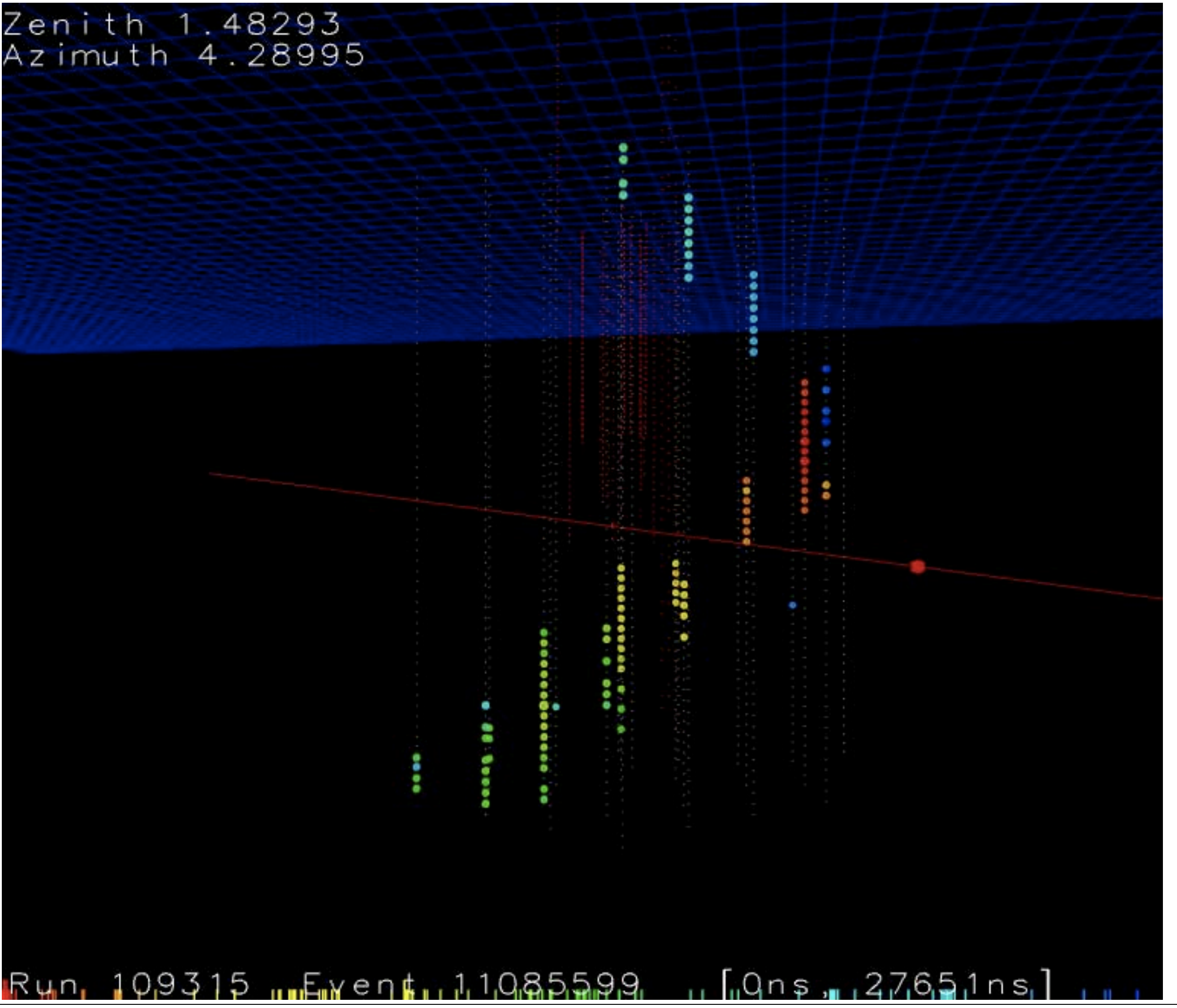
ANTARES 10 line event



2001-2: EOC and Junction box
2006: Line 1 (March)
Line 2 (Oct.)
2007: Lines 3,4,5 (Jan.)
Lines 6,7,8,9,10 + instr. line
Apr 2008: Line 11 deployed
Completion soon

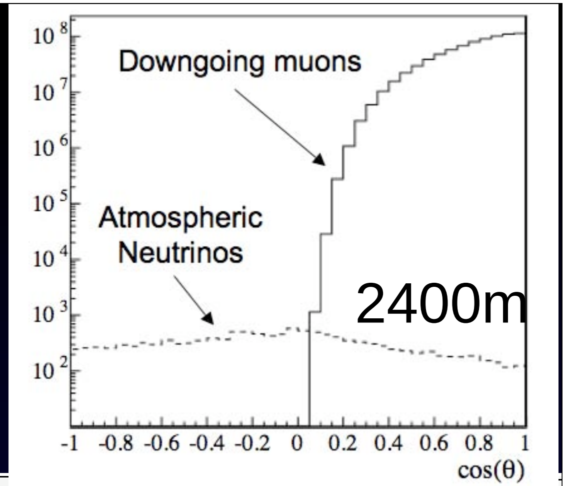


The most dangerous background: coincident muons

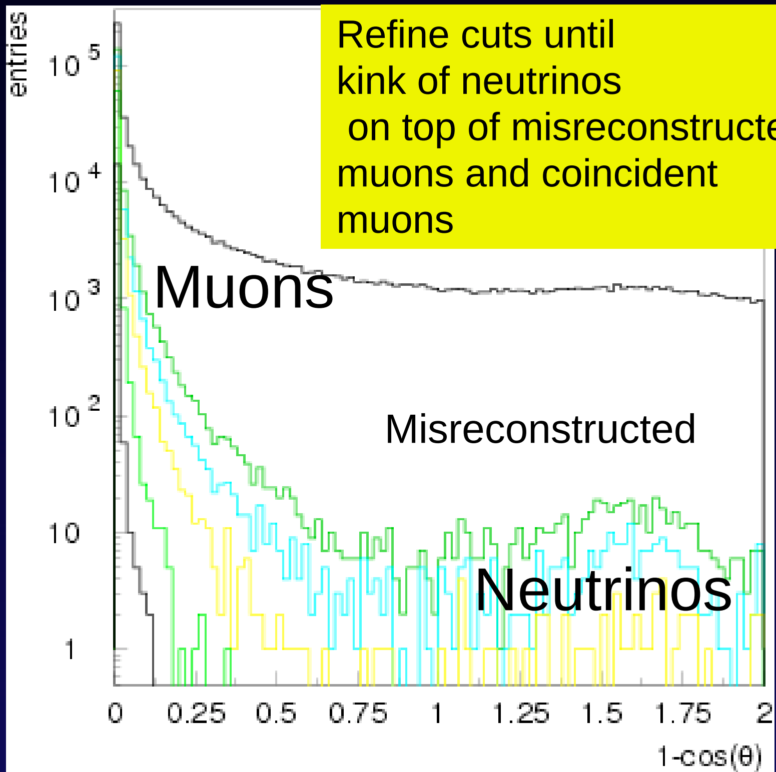


Analysis cuts: the kink

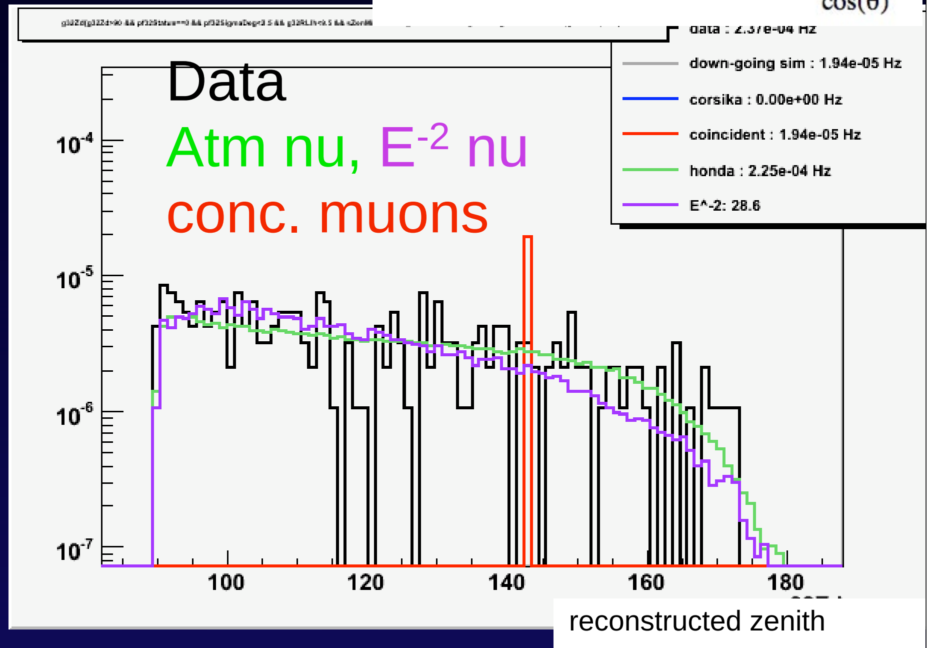
- 290 d of IC22 being analyzed. At cuts level about 20 atmospheric neutrinos/day.



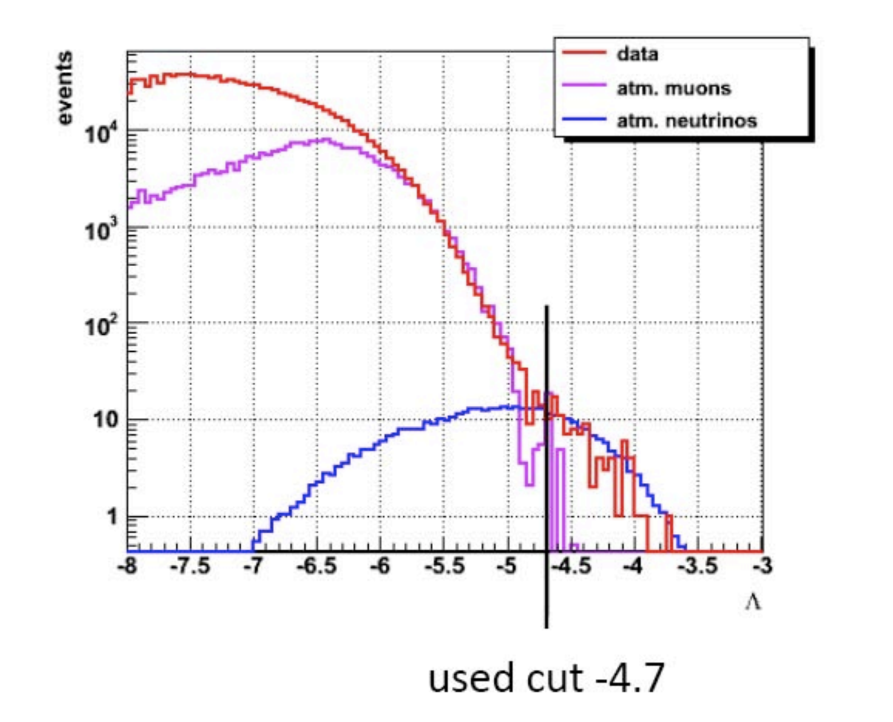
Refine cuts until kink of neutrinos on top of misreconstructed muons and coincident muons

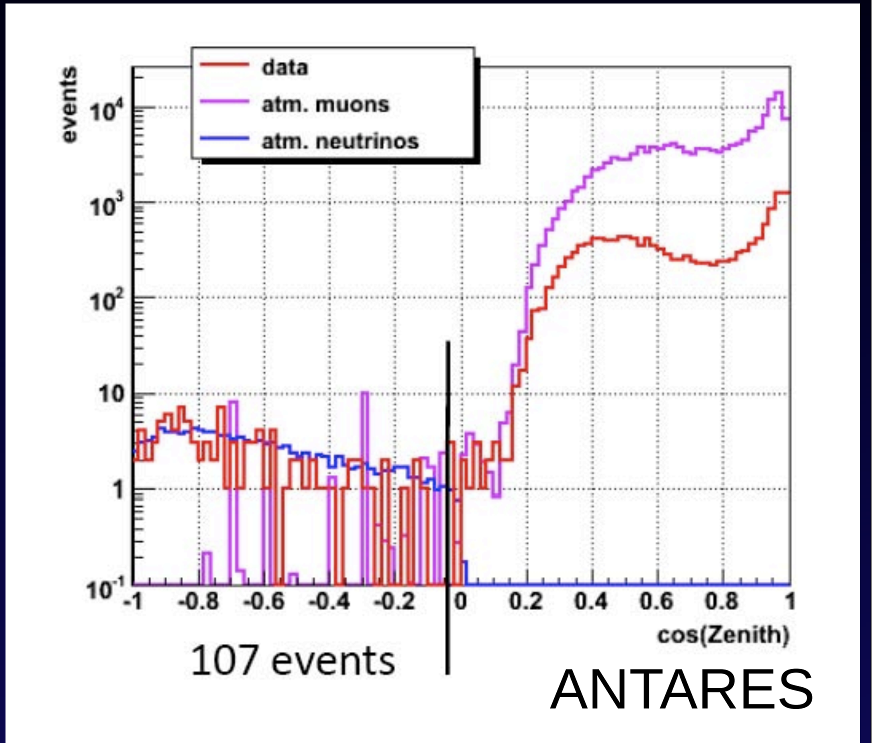


After L3 and close to final analysis cuts

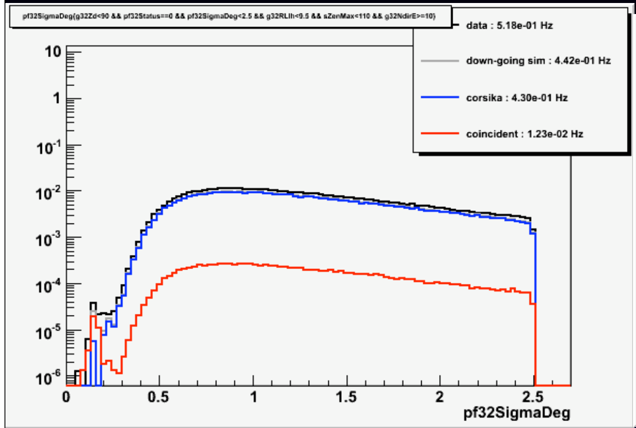


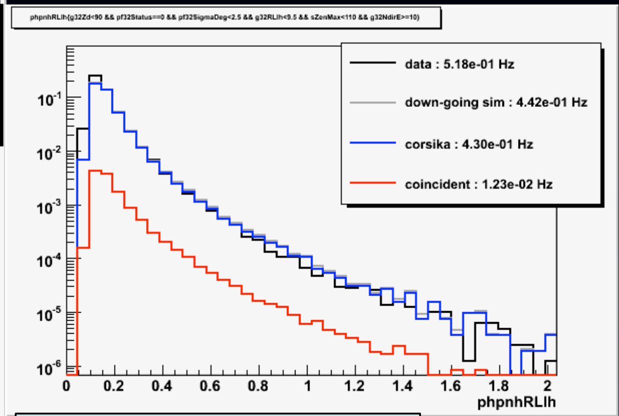
Cuts: reconstruction quality

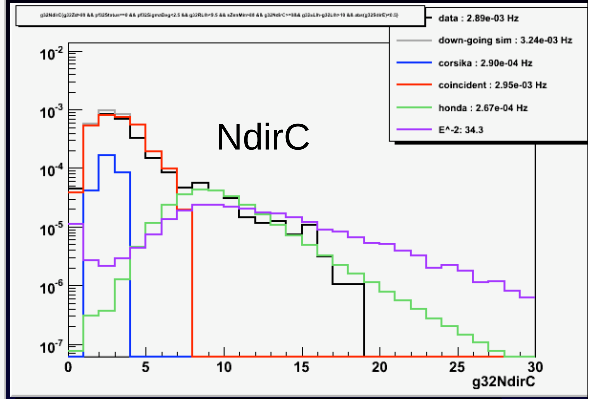




Other variables



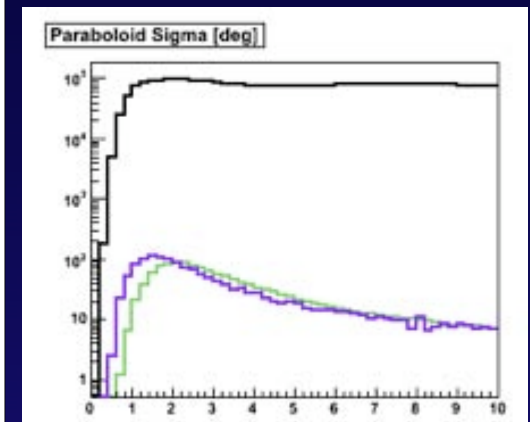




Fitting the width of the llh space gives estimate in track uncertainty

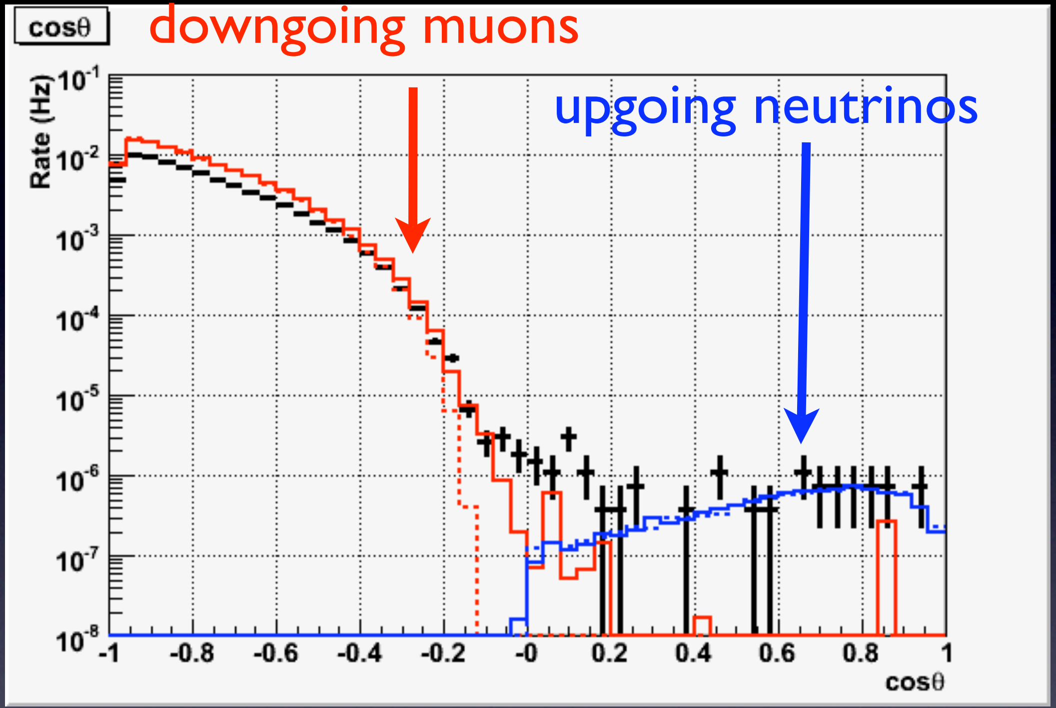
Calculate a likelihood based on whether DOMs should or should not be hit by a muon

A hit is direct_C if:
-15ns < T_res < 75ns



Data-MC agreement

ANTARES 5 lines, 40 days



Systematics: PMT effective **area and angular acceptance ~30% (lower on neutrinos since PMTs are down-looking)**

20-25% absorption length

Hadronic Models + Primary spectrum 30-50% depending on energy

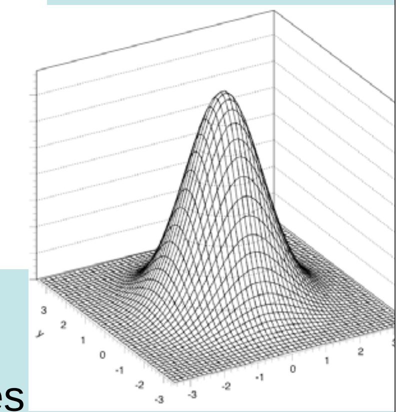
Point-like source searches

- Partial Prob for each event
- Likelihood function
- Log Likelihood Ratio

$$P_i(x, n_s) = \frac{n_s}{N} S_i(x) + \frac{N - n_s}{N} B_i(x)$$

$$L(n_s) = \prod P_i(x_i, n_s)$$

$$\log \lambda = \log \frac{L(\hat{n}_s)}{L(n_s = 0)}$$



$\hat{n}_s$ number of signal events which maximize the likelihood

$S_i(x)$ signal pdf, based on individual reconstructed uncertainty estimates

$B_i(x)$ background pdf, based on dec. distribution of data

$$\mathcal{S}_i = \frac{1}{2\pi {\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

Determine significance by evaluating Log Likelihood Ratio over background-only (scrambled) datasets

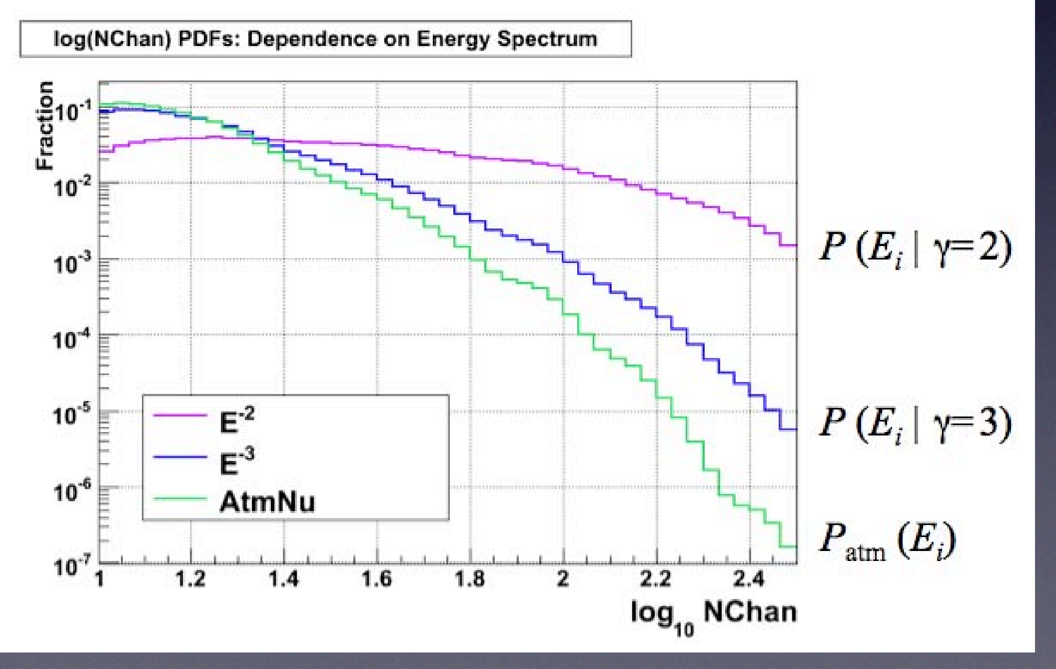
Braun et al, arXiv:0801.1604

$$\mathcal{B}_i = B_{\text{zen}} \cdot P_{\text{atm}}(E_i)$$

LH method

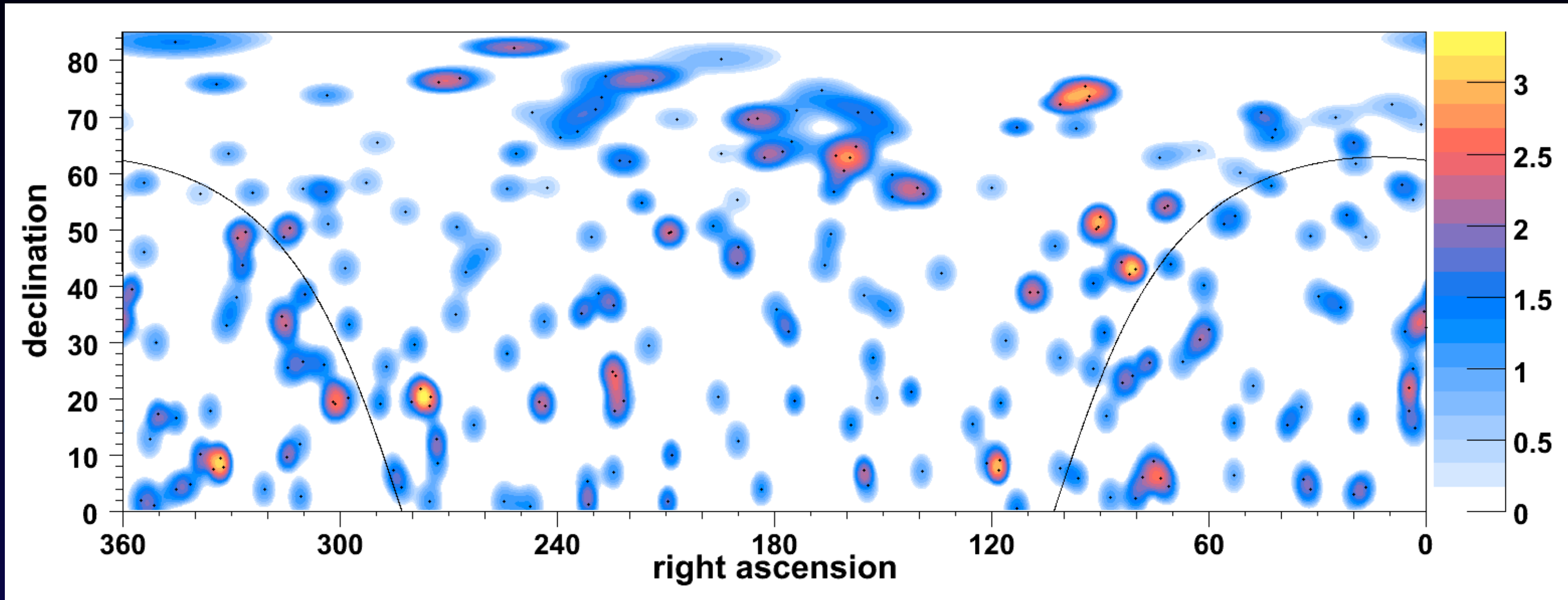
Any observable that distinguishes signal from background can be incorporated into the likelihood analysis

First try something easy - the number of channels hit.



1st IceCube data Sky Map: Icecube9

233 in 137d, expected 227



Random clustering of background: **60%** of simulated background trials (data scrambled in right ascension), have a maximum deviation (anywhere) of **3.35 sigma** or greater.

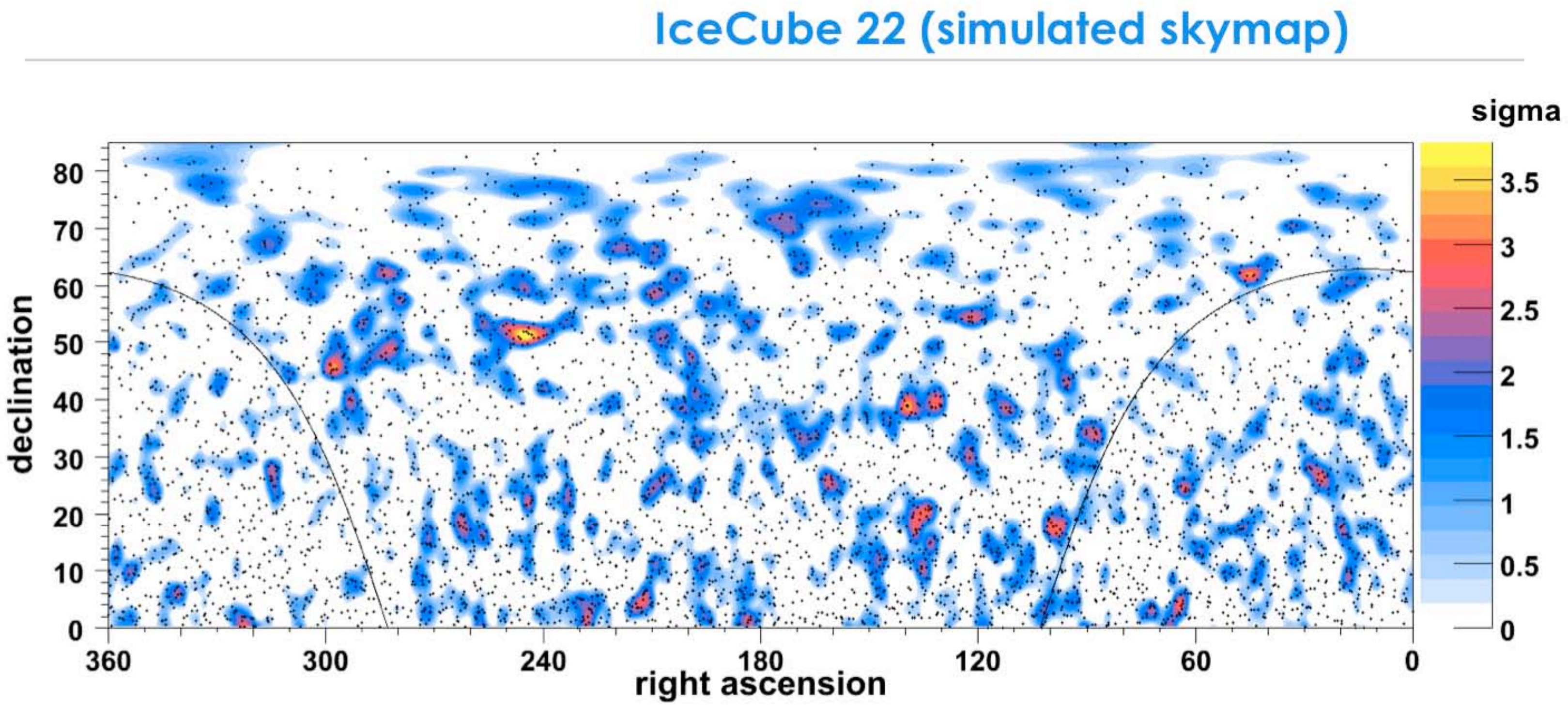
Largest deviation from background: sigma = 1.77 (one-sided p-value = 0.04), in the direction of the Crab Nebula when looking at IC9 26 source list.
Chance to obtain a p-value of 0.04 or lower with 26 independent trials is **65%.**

presented at ICRC2007 and TAUP2007

C. Finley, J Dumm, TM

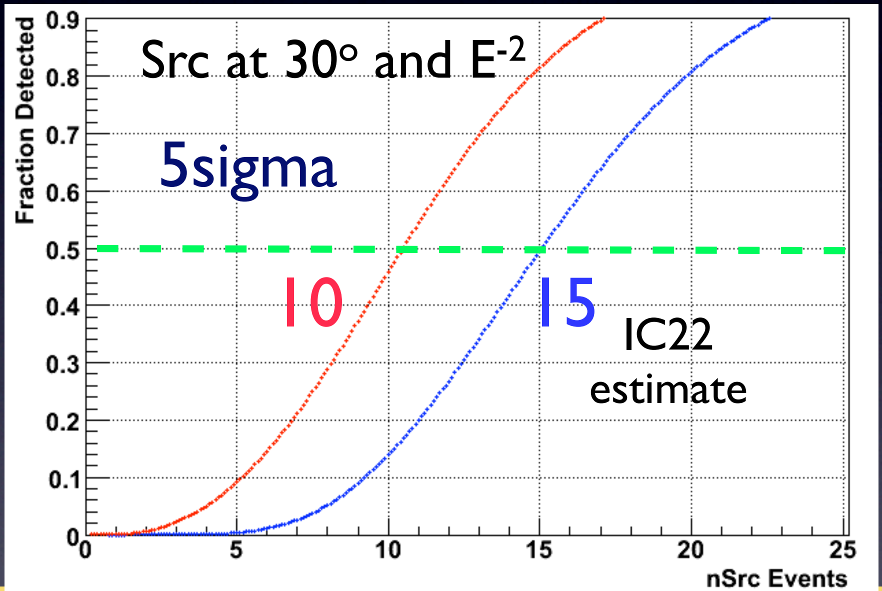
IceCube 22 strings

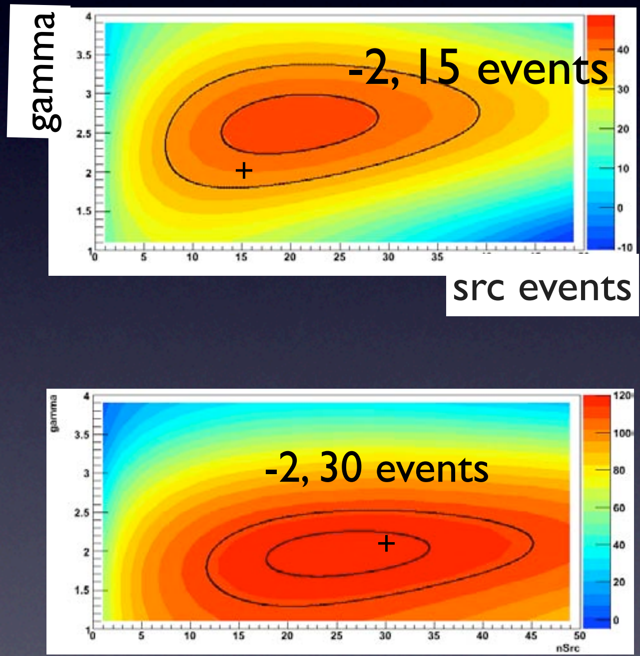
IC9 1.7 neutrino events/day, 134.7 d, median ang res 2º
IC22: 20 events/day at cut level, **287 days** median ang res 1.5º
IC80: 200 events/day, median and res 0.8º



IceCube 22 strings discovery potential

- ★ likelihood method: compare null hypothesis (all atmospheric neutrinos with source hypothesis using detector PSF + energy estimator (eg Nch), + time dependencies (eg lightcurve from X-ray, TeV, optical telescopes)
- ★ unbinned method improves up to 40% binned method





Discovery potential:

without energy term in likelihood: **6.1 10^{-8}** GeV^{-1} cm^{-2} s^{-1} (E/GeV)$^{-2}$
(mean number of source events: **15**)

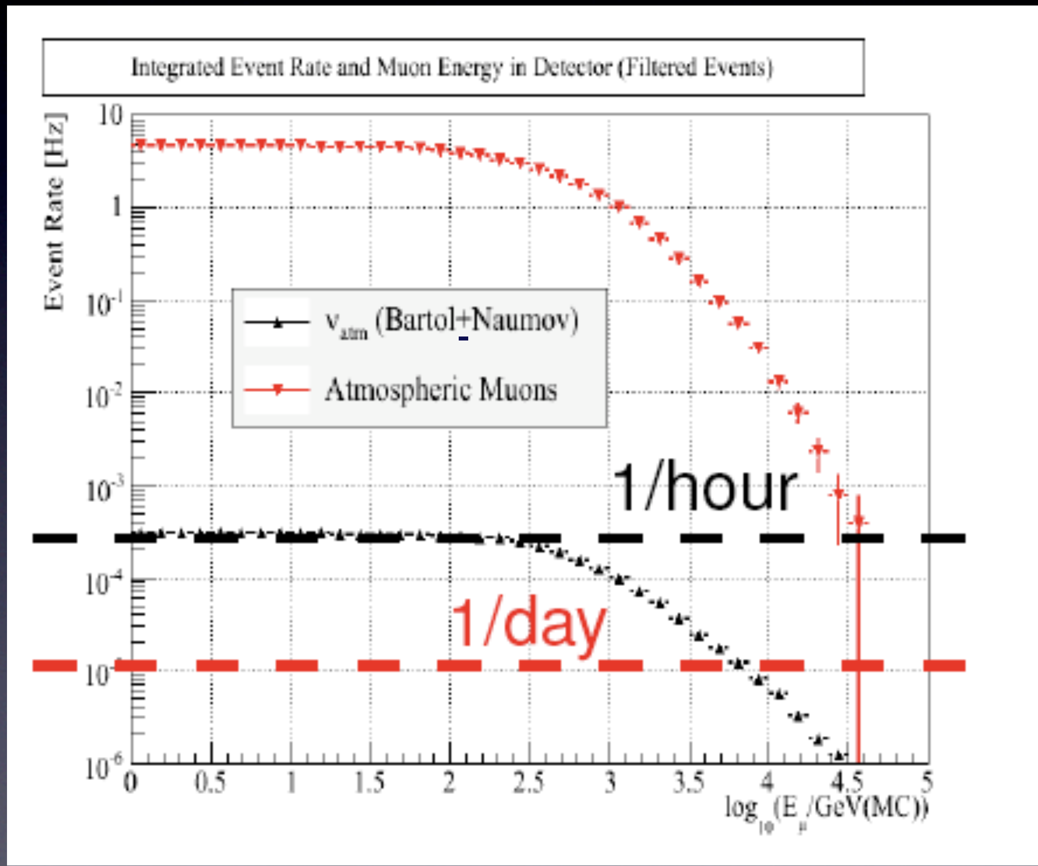
with energy term in likelihood: **4.2 10^{-8}** GeV^{-1} cm^{-2} s^{-1} (E/GeV)$^{-2}$
(mean number of source events: **10.5**)

Braun et al, arXiv:0801.1604

Atmospheric neutrinos and muons: the spectrum

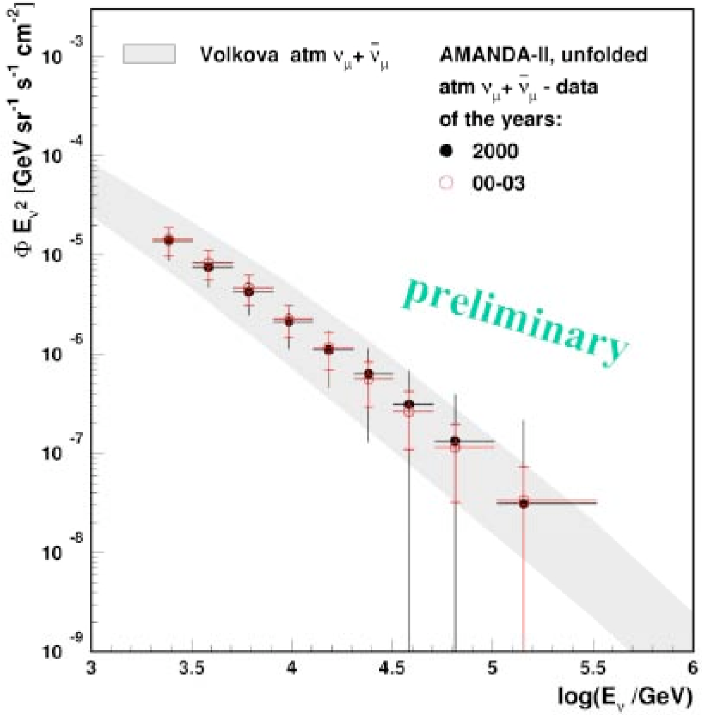
Testing high energy hadronic interactions

IC22

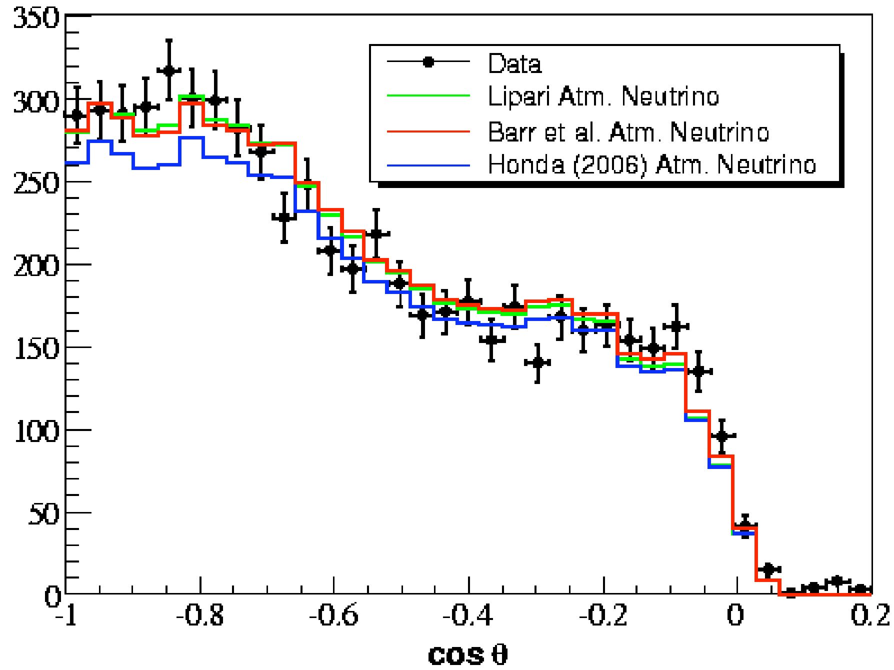


Atmospheric Neutrinos

comparison: result 2000 with 2000-2003

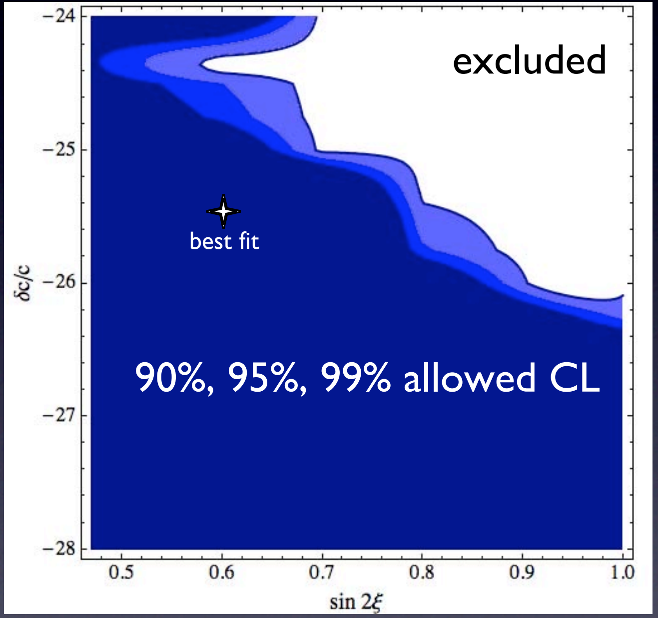


AMANDA final sample: 6163

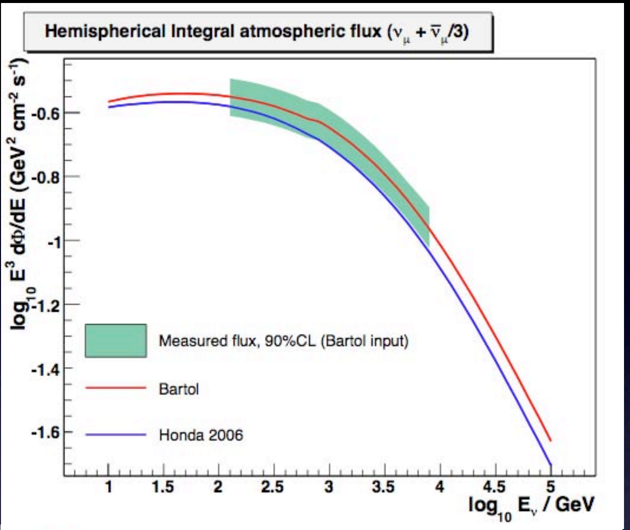


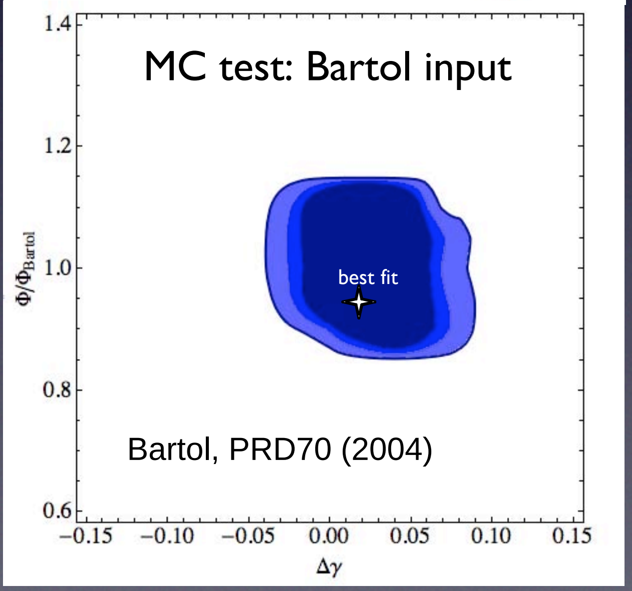
Atmospheric neutrinos: angular distribution is the observable

6099 events in 1387 d of AMANDA-II:
unblinding coming soon



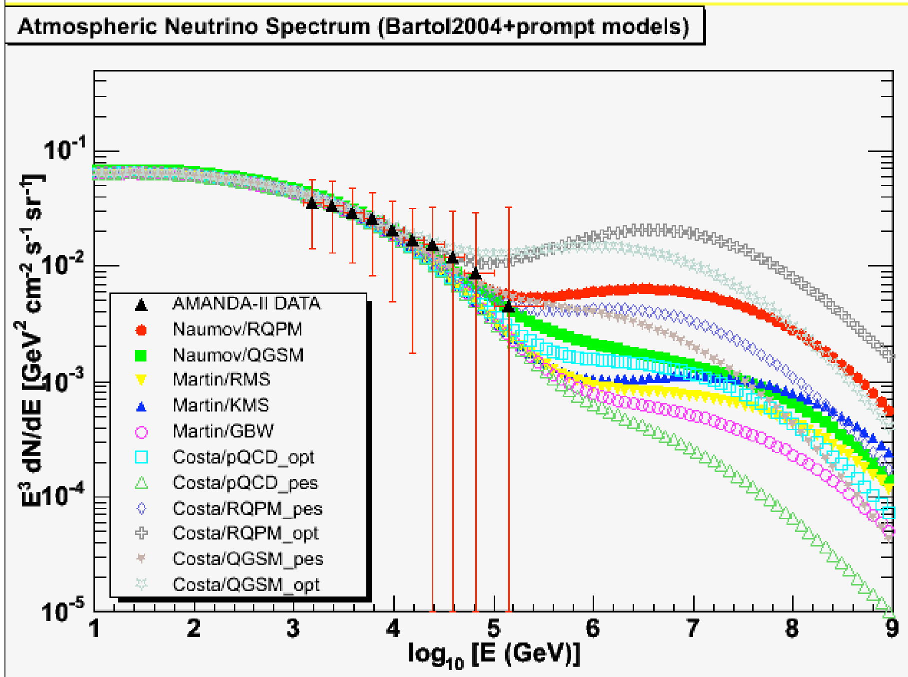
Estimated sensitivity for VLI (LE dependence)

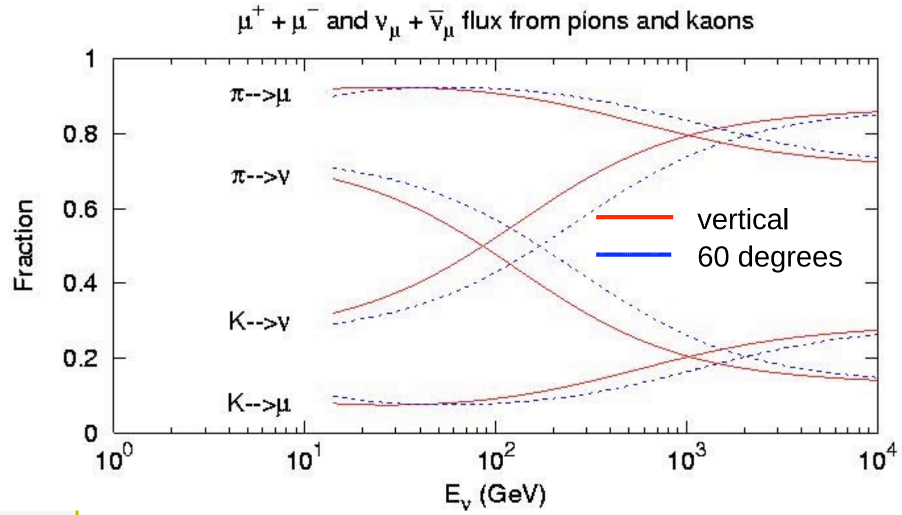


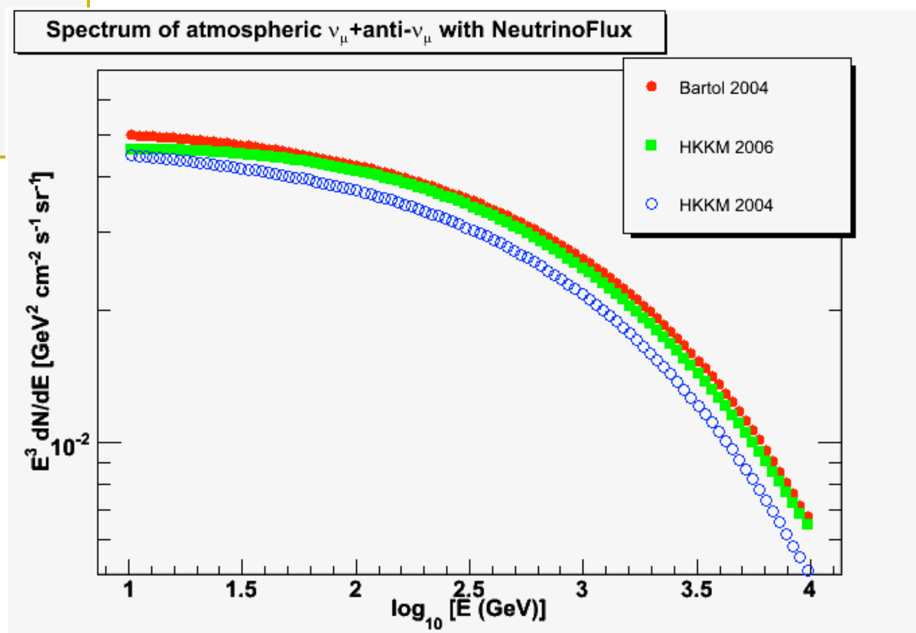


How does the measured angular distribution constrain the Bartol flux calculation? Fit angular dr with 2 free parameters
±15% in normalization and ±0.07 in slope

NeutrinoFlux code







Good agreement on
summed fluxes of numu+anumu
Kaons are the main source of
neutrinos > 100 GeV

Honda et al., PRD75 (2007)
Bartol, PRD70 (2004)