The next generation of Neutrino telescopes -ICECUBE

Design and Performance, Science Potential

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Neutrino 2002

Munich

The IceCube Collaboration

Institutions: 11 US, 9 European institutions and 1 Japanese institution; ≈110 people

1. Bartol Research Institute, University of Delaware
2. BUGH Wuppertal, Germany
3. Universite Libre de Bruxelles, Brussels, Belgium
4. CTSPS, Clark-Atlanta University, Atlanta USA
5. DESY-Zeuthen, Zeuthen, Germany
6. Institute for Advanced Study, Princeton, USA
7. Dept. of Technology, Kalmar University, Kalmar, Sweden
8. Lawrence Berkeley National Laboratory, Berkeley, USA
9. Department of Physics, Southern University and A\&M College, Baton Rouge, LA, USA
10. Dept. of Physics, UC Berkeley, USA
11. Institute of Physics, University of Mainz, Mainz, Germany
12. University of Mons-Hainaut, Mons, Belgium
13. Dept. of Physics and Astronomy, University of Pennsylvania, Philadelphia, USA
14. Dept. of Astronomy, Dept. of Physics, SSEC, University of Wisconsin, Madison, USA
15. Physics Department, University of Wisconsin, River Falls, USA
16. Division of High Energy Physics, Uppsala University, Uppsala, Sweden
17. Fysikum, Stockholm University, Stockholm, Sweden
18. University of Alabama
19. Vrije Universiteit Brussel, Brussel, Belgium
20. Chiba University, Japan

Outline of Talk

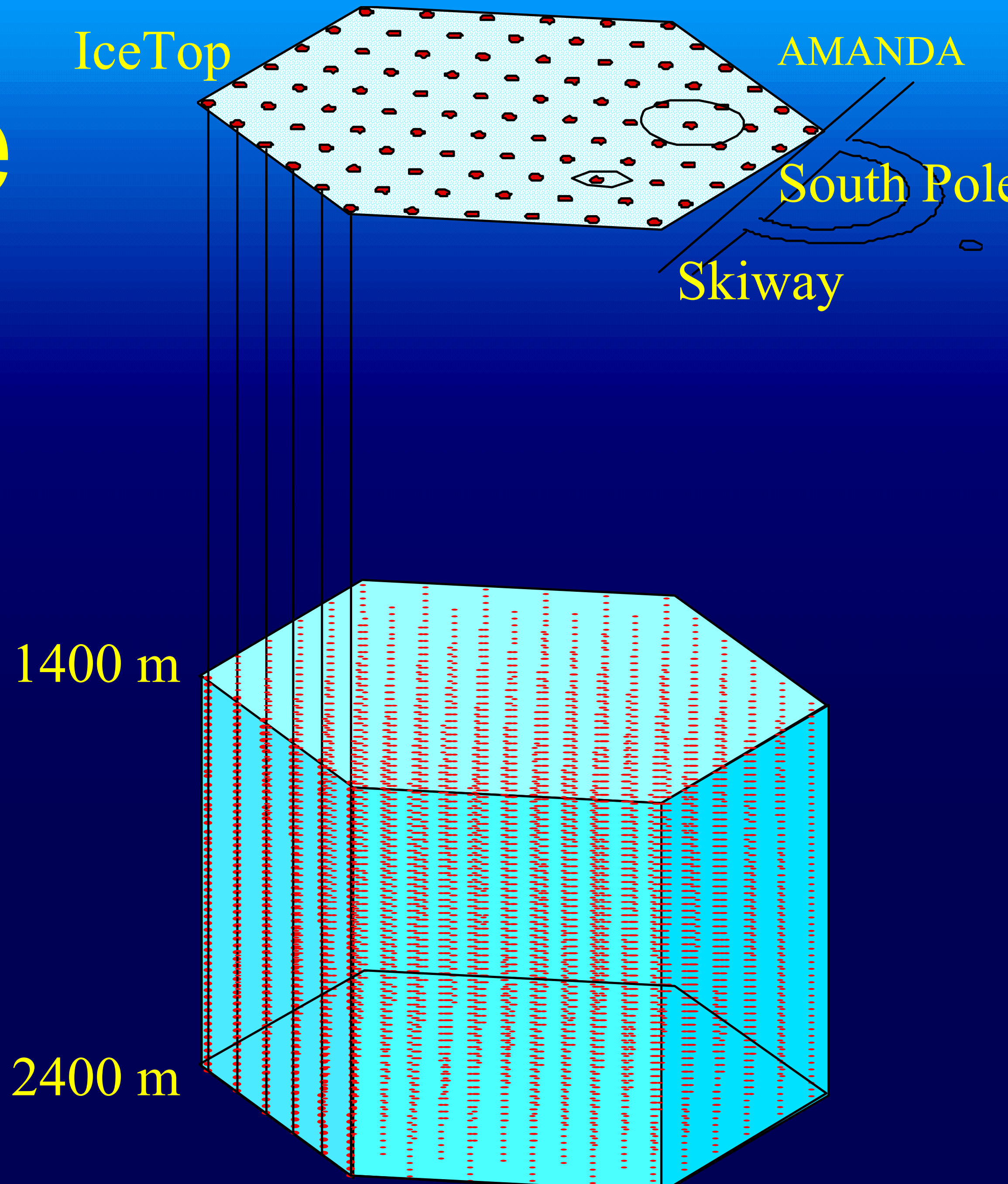
1. Overview
2. Muon neutrinos from:
   - a) diffuse sources
   - b) point sources
   - c) Gamma ray bursts
3. Electron Neutrinos: Cascades
4. Tau Neutrinos
5. The surface component: IceTop
6. Detector: Optical sensor
7. Summary

IceCube has been designed as a discovery instrument with improved:

- telescope area
- detection volume
- energy measurement of secondary muons and electromagnetic showers
- identification of neutrino flavor
- angular resolution

IceCube

- 80 Strings
- 4800 PMT
- Instrumented volume: 1 km^3 (1 Gt)

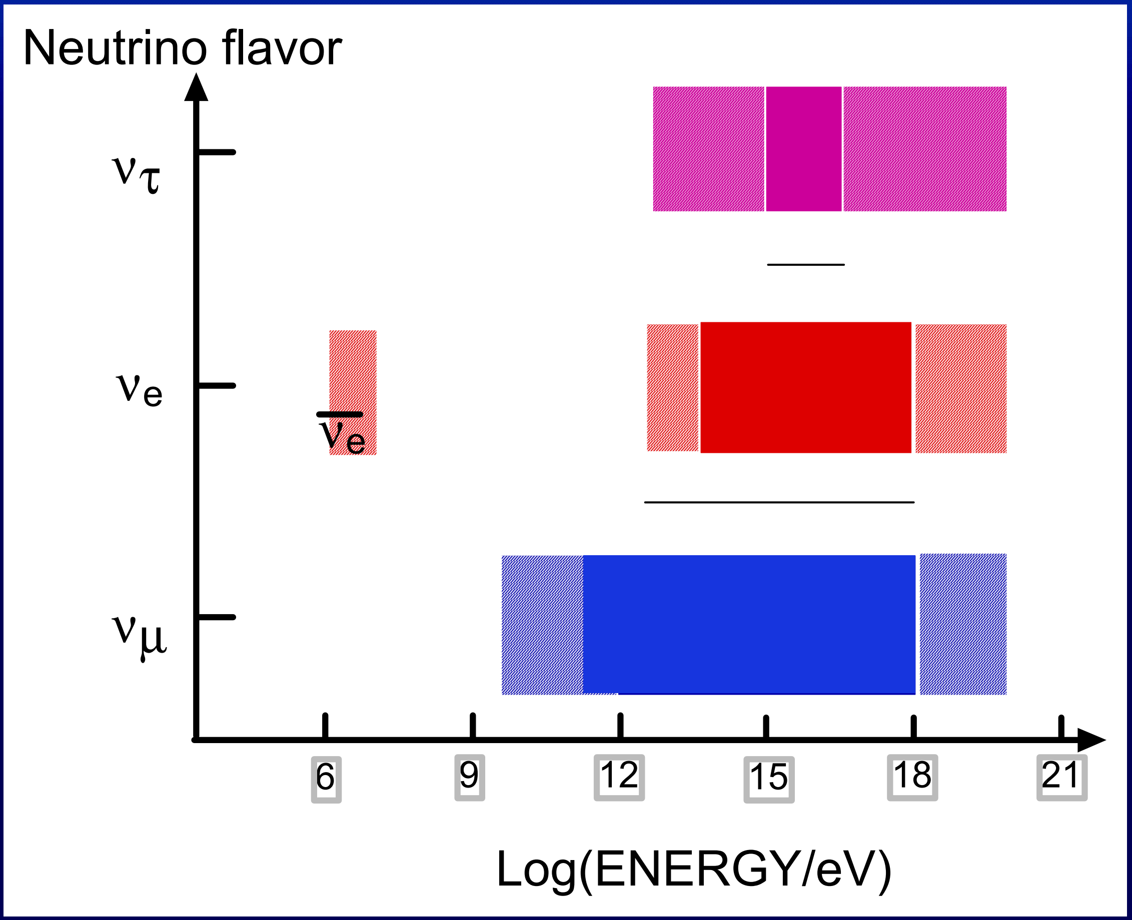


Project status

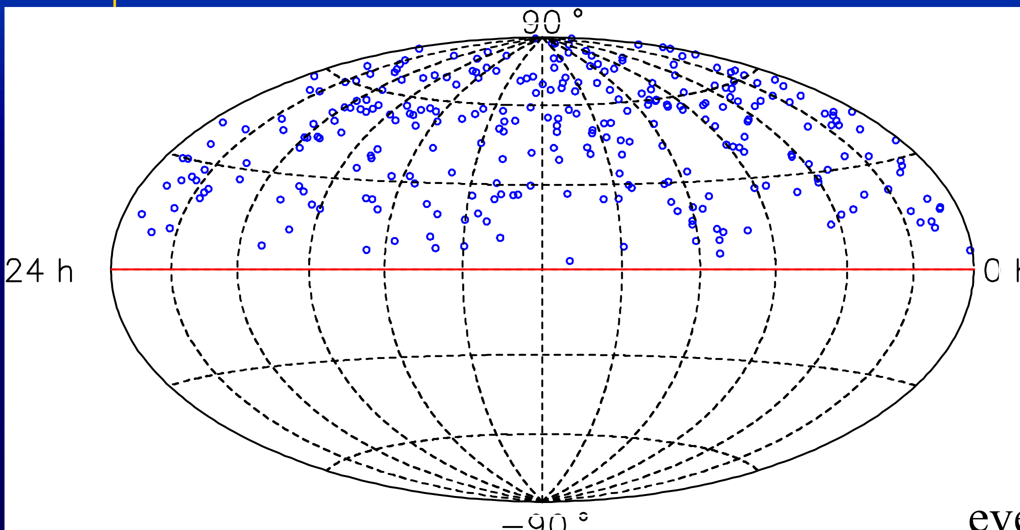
- Approved by the National Science Board
- Startup funding is allocated.
- Construction is in preparation (Drill, OM design, OM production, DAQ and test facilities).
- Construction start in 04/05; possibly a few initial strings in 03/04.

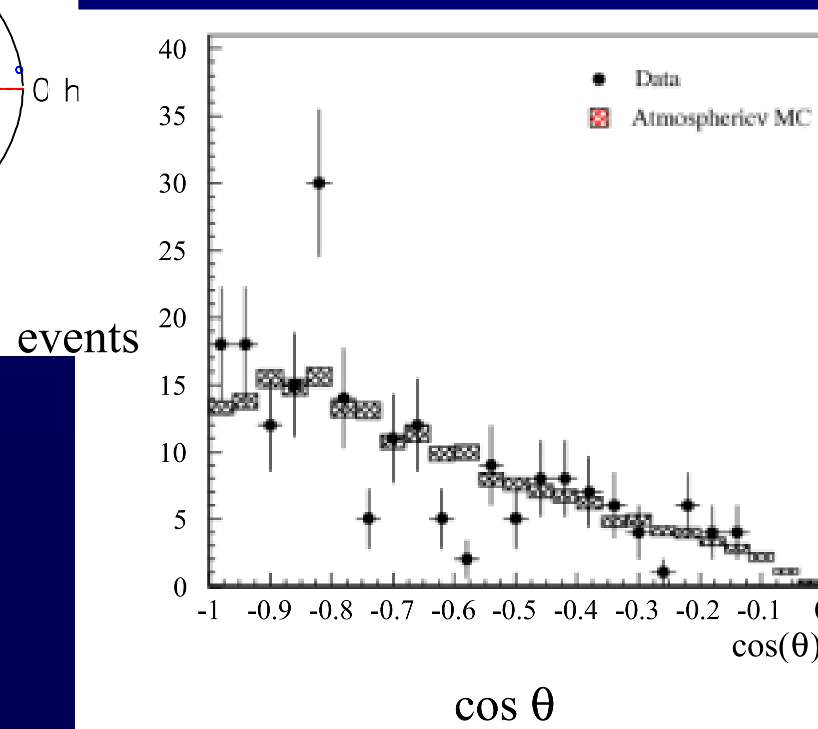
ν - flavours and energy ranges

- Filled area: particle id, direction, energy
- Shaded area: energy only
- Detect neutrinos of all flavours at energies from 10^7 eV (SN) to 10^{20} eV



Neutrino sky as seen by AMANDA





Monte Carlo methods are verified on data.

Methods are not yet optimized and fully developed for high energies.

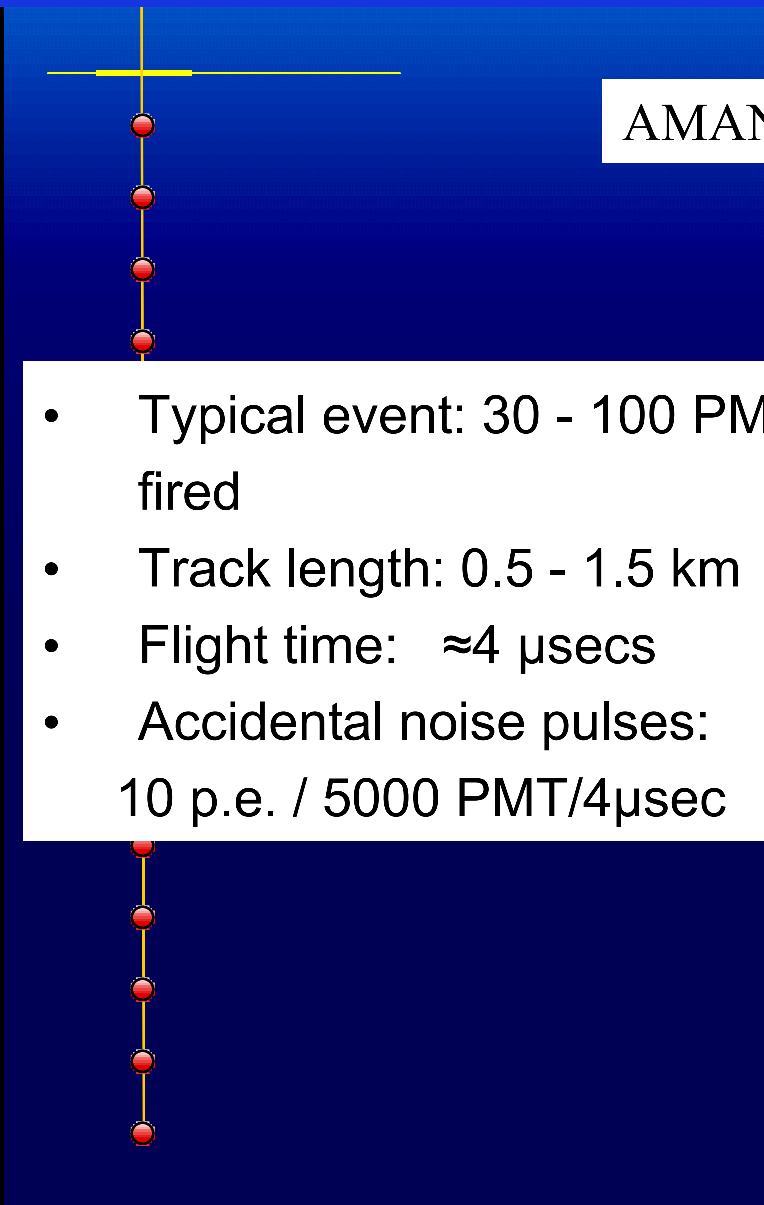
Signals and Background rejection

Backgrounds:
Atmospheric neutrinos
Cosmic ray muons (misreconstructed downgoing)

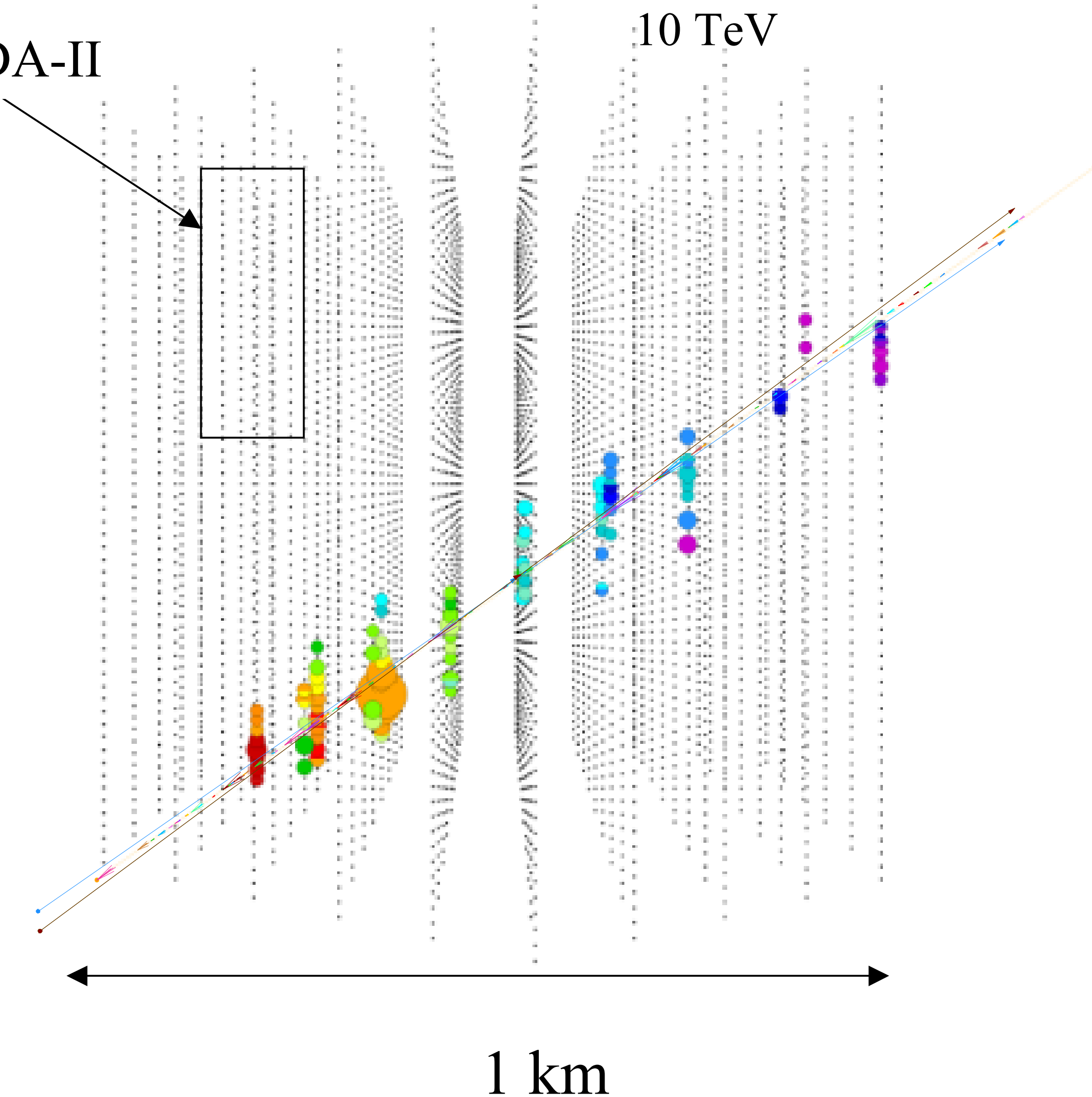
Type of Neutrino source	Rejection method
1. Diffuse source (AGN, GRB, ..)	Up/Down: <1E-8 and energy*
2. Point Sources (AGN, WIMP)	&& Direction
3. Burstlike Point Sources (GRB or AGN with time structure)	&& Time Stamp (GRB: secs, AGN: h,d)

*At very high energies (>≈PeV), the downgoing signals can be accepted

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/4μsec

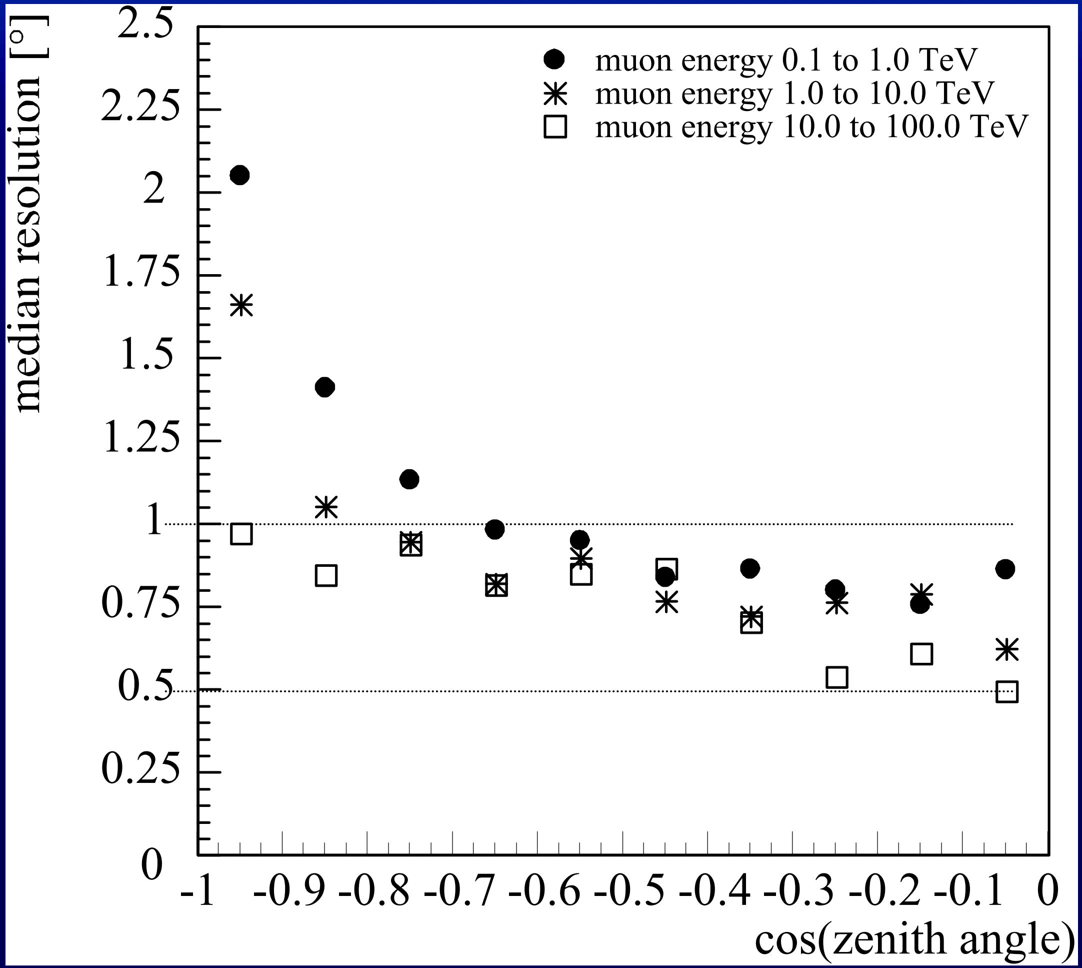


Angular resolution < 1° (med)

- Resolution ≈ 0.8 deg (median)
- Improves slightly with energy
- Better near horizon: ≈0.7° (Sample more strings)

Search bin ≈ 1.0°

Solid angle: 2π/6500



Effective area for muons

QuickTime™ and a
GIF decompressor
are needed to see this picture.

$\log_{10}(E/GeV)$

Geometric detector area = 1km2
Eff. area = $A_{gen} * (N_{det.}/N_{gen})$
Efficiency ≈ effective area/km2
Muon energy is the energy at closest approach to the detector

- Trigger: allows non contained events
- Quality cuts: for background rejection
- Point source selection: soft energy cut for atmos. neutrino rejection
  (Assumed spectrum: E-2, time of exposure 1 year)

Effective Area vs. cos(θ)

Muon energy

Effective areas are given after quality cuts (including up/down separation where needed)

QuickTime™ and a
GIF decompressor
are needed to see this picture.

Note that the detector is sensitive to downward going muons at energies above 1 PeV

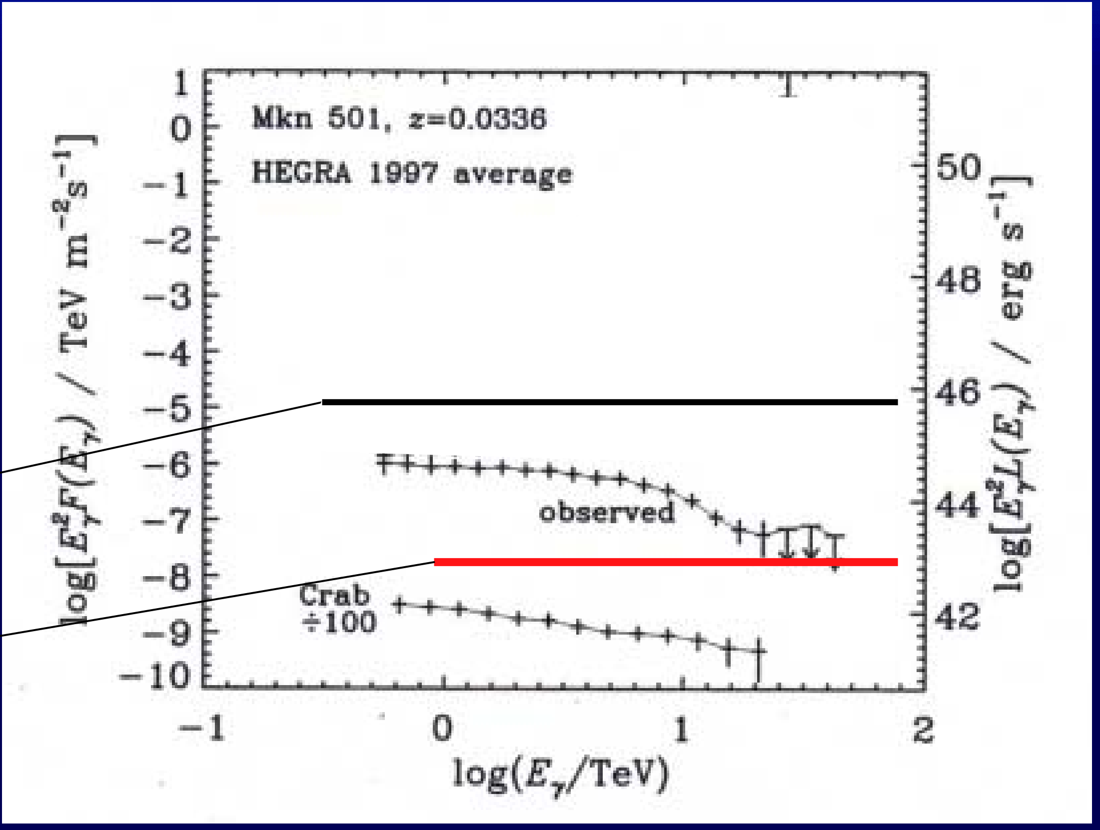
Point sources: event rates

Flux equal to current AMANDA limit
$dN/dE = 10^{-6} * E^{-2}/(cm^2\ sec\ GeV)$

	Atmospheric Neutrinos	AGN* (E^{-2})	Sensitivity ($E^{-2}/(cm^2\ sec\ GeV)$)
All sky/year (after quality cuts)	100,000		-
Search bin/year	20	2300	-
1 year: Nch > 32	0.91	610	5.3×10^{-9}
3 year: Nch > 43 (7 TeV)	0.82	1370	2.3×10^{-9}

Compare to Mrk 501 gamma ray flux

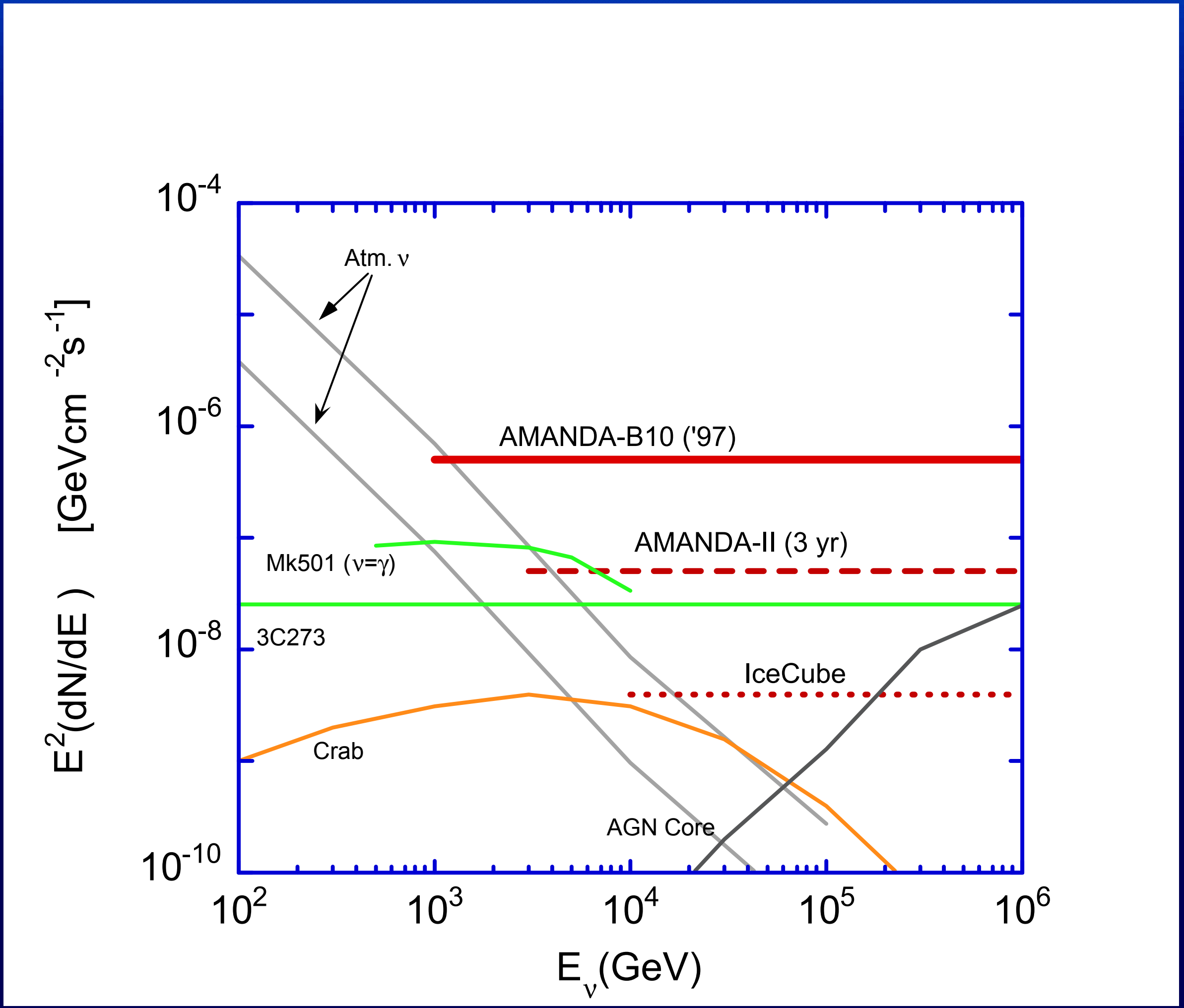
Field of view:
Continuous
24 h x 2 π sr
(northern sky)



AMANDA
prelim. limit

Sensitivity of
3 years of IceCube

Point source sensitivity



Search for diffuse ν-fluxes

Method:

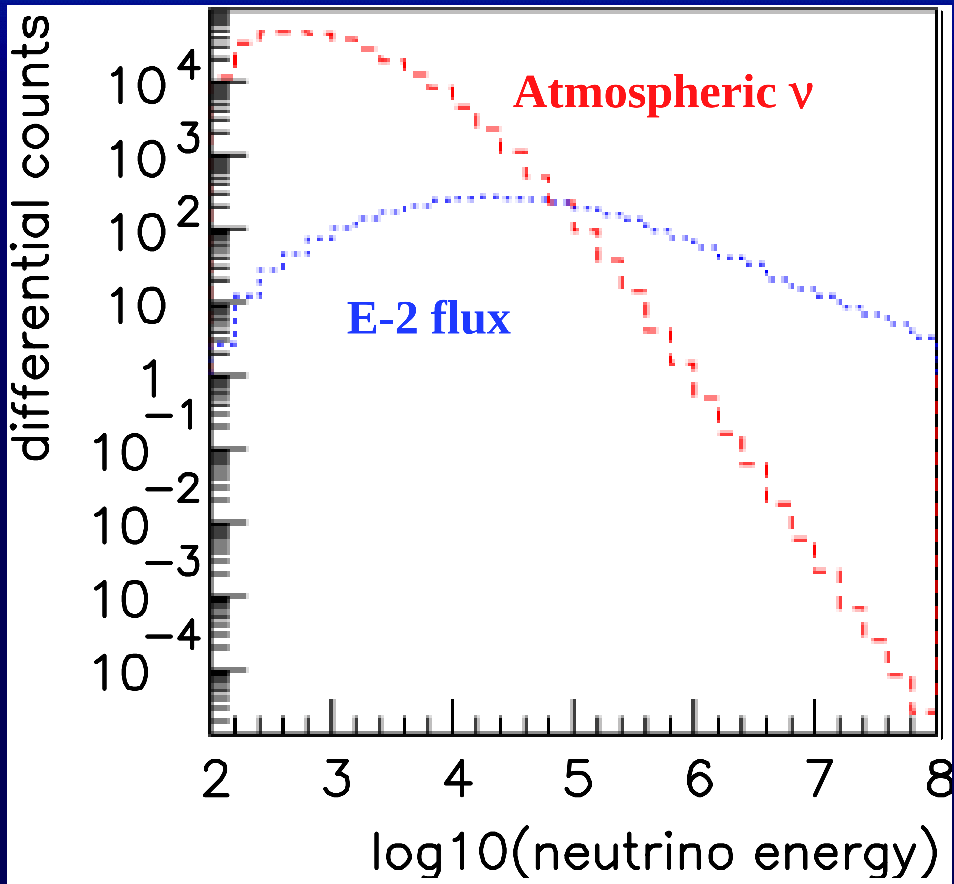
- Assume a diffuse neutrino flux (Hypothesis), e.g. the current AMANDA limit:

  $dN/dE = 10^{-6} \cdot E^{-2}/(cm^2\ sec\ GeV\ sr)$

  --> 11,500 events /year

- The background is the atmospheric neutrino flux (after quality cuts): = **100,000 events / year**

- Apply energy cut.

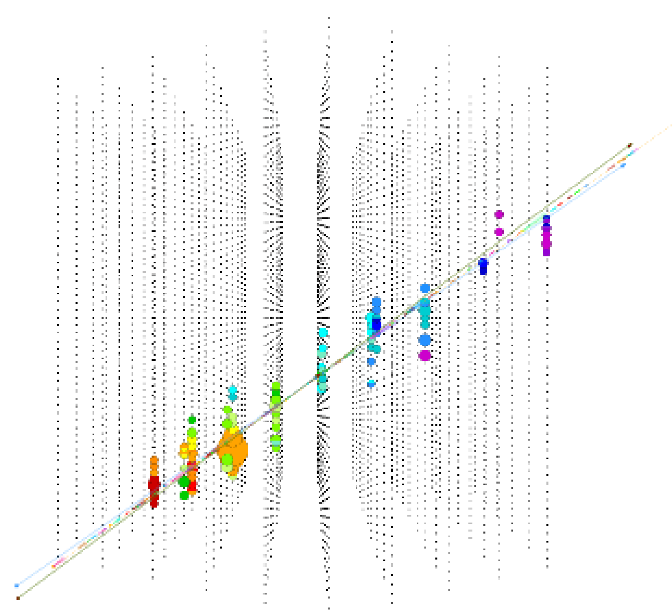


True neutrino energy

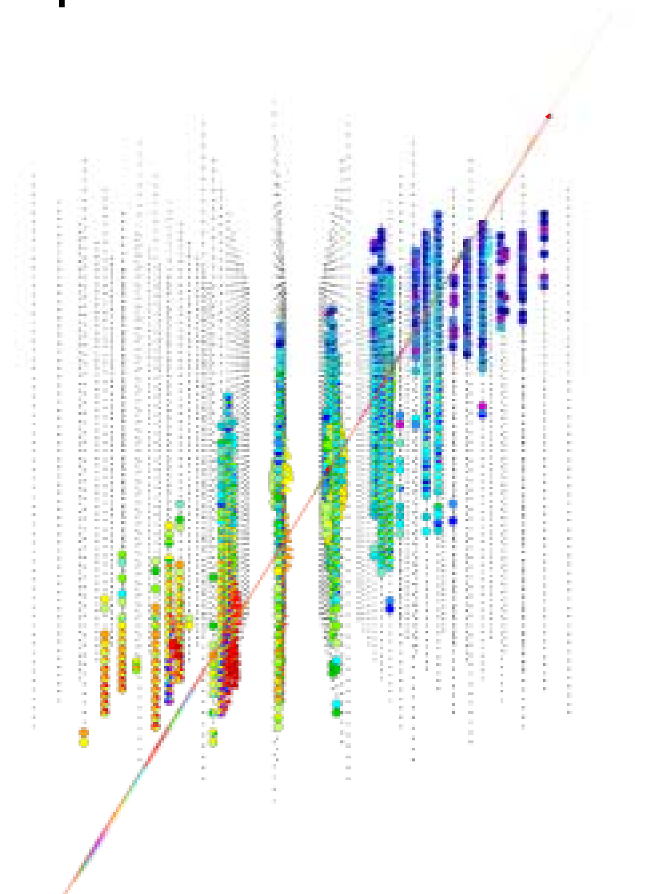
Energy reconstruction

Small detectors: Muon energy is difficult to measure because of fluctuations in dE/dx
IceCube: Integration over large sampling+ scattering of light reduces the fluctutions energy loss.

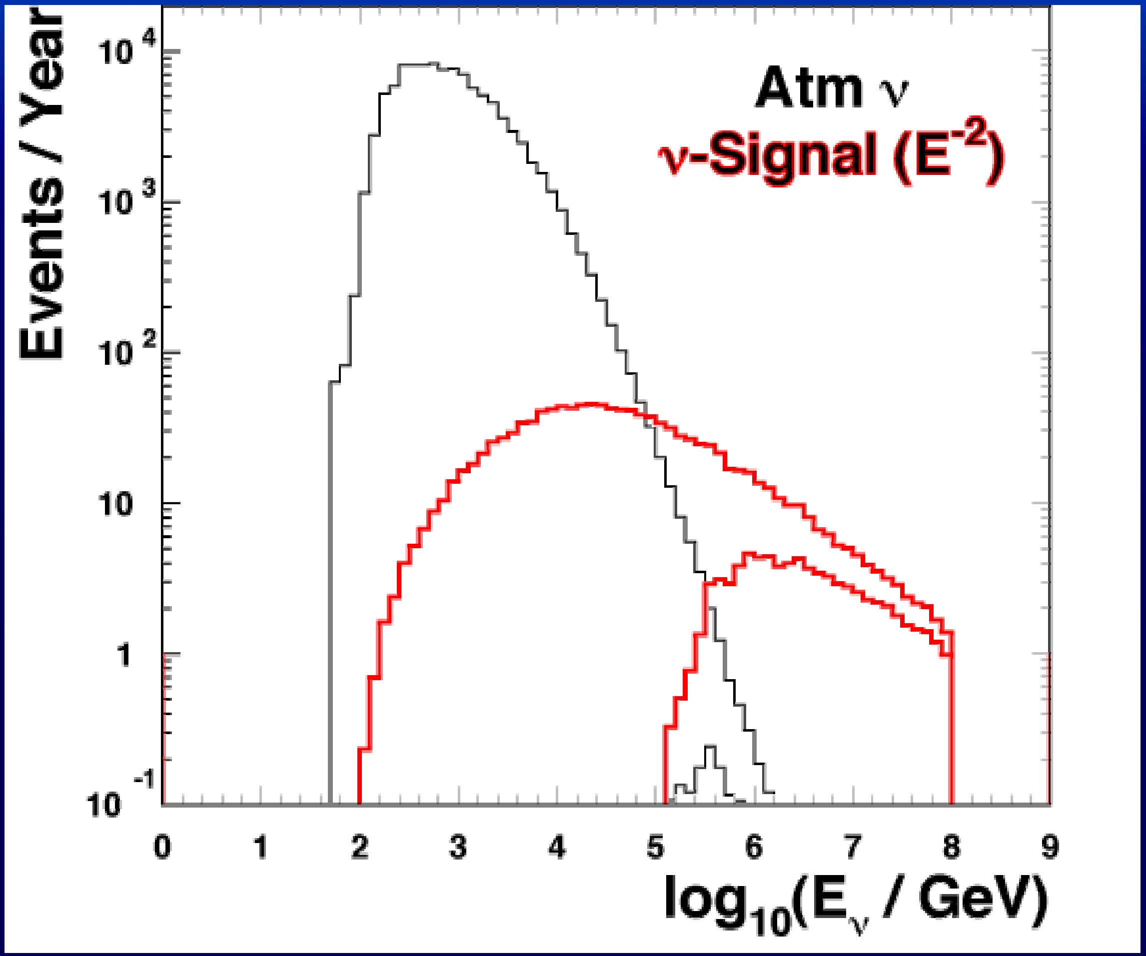
E_μ=10 TeV ≈ 90 hits



E_μ=6 PeV ≈ 1000 hits

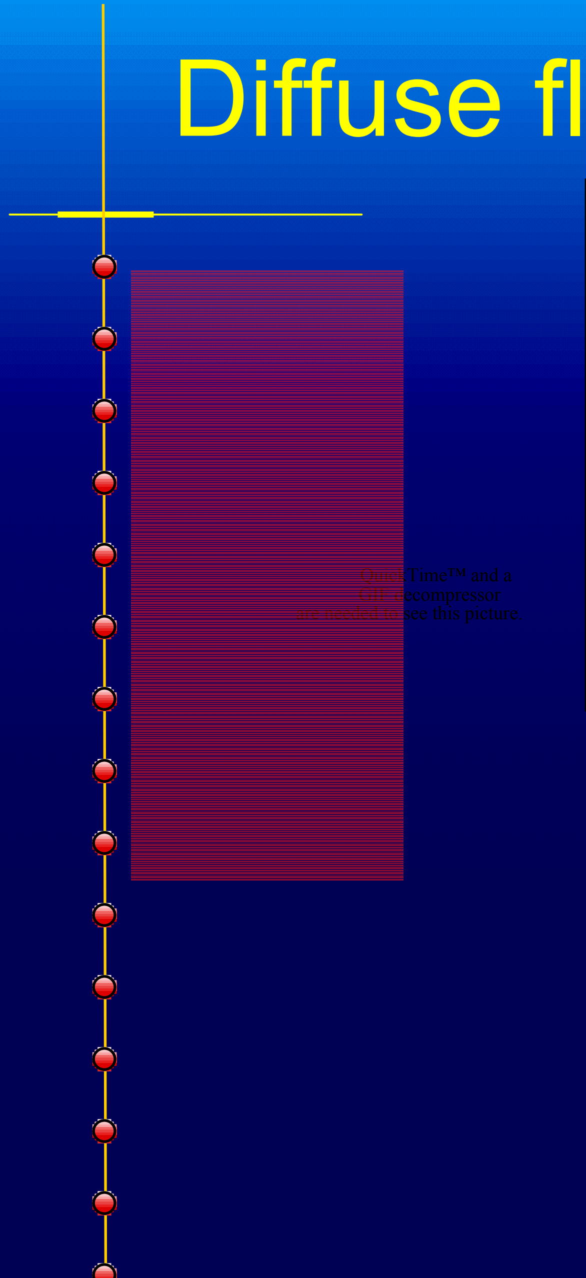


Event rates before and after energy cut



Note:
Neutrinos from Charm production included according to: Thunman, Ingelmann, Gondolo, Astropart. Phys. 5:309-332,1996

Diffuse flux, 3 years of IceCube

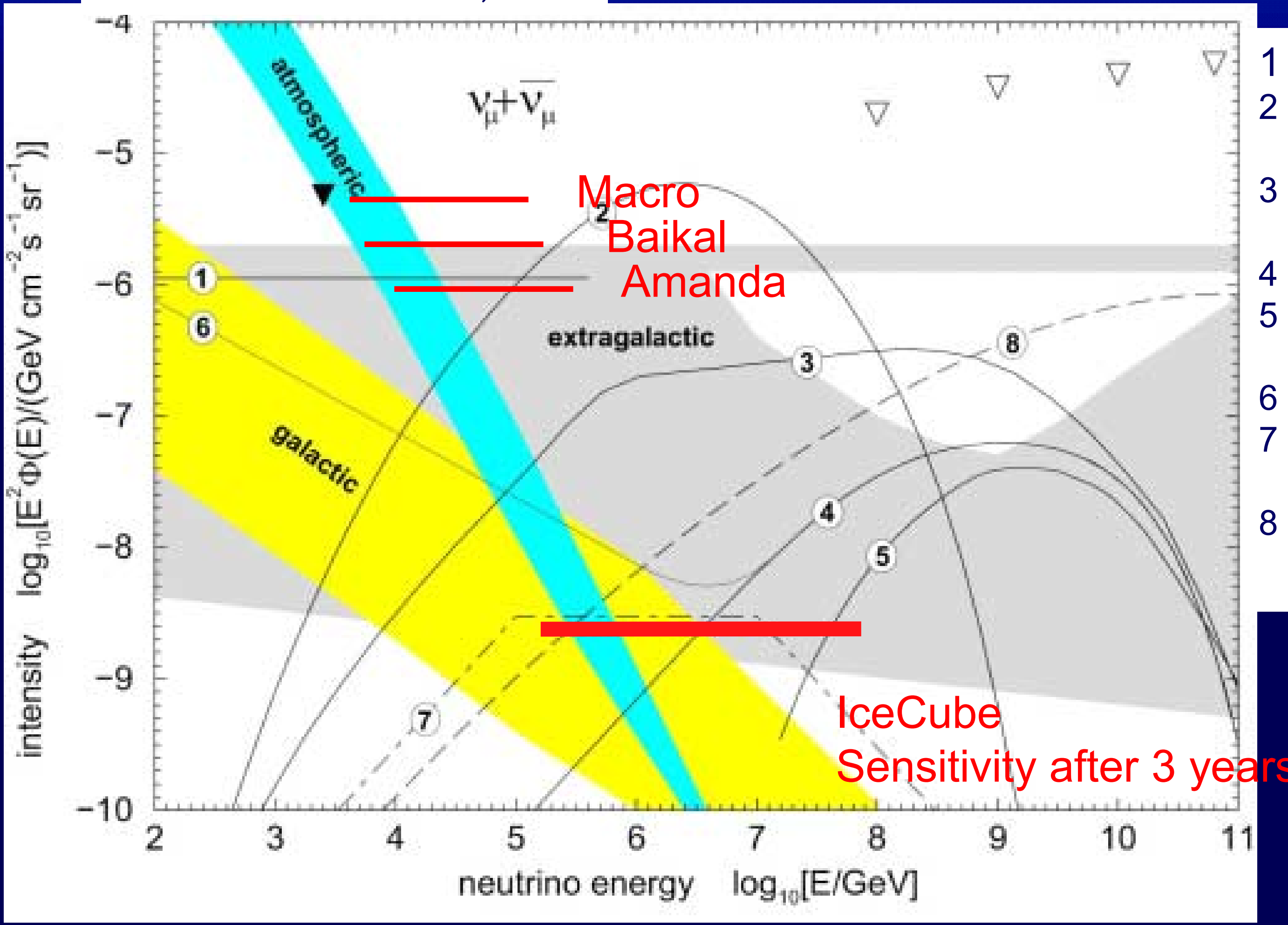


- Optimize energy cut.
- Sensitivity of IceCube after 3 years of operation (90% c.l.):

$$dN/dE_\nu \leq 4.8 \times 10^{-9} * E^{-2}/(cm^2 \; sec \; GeV)$$

Example: Diffuse Fluxes - Predictions and Limits

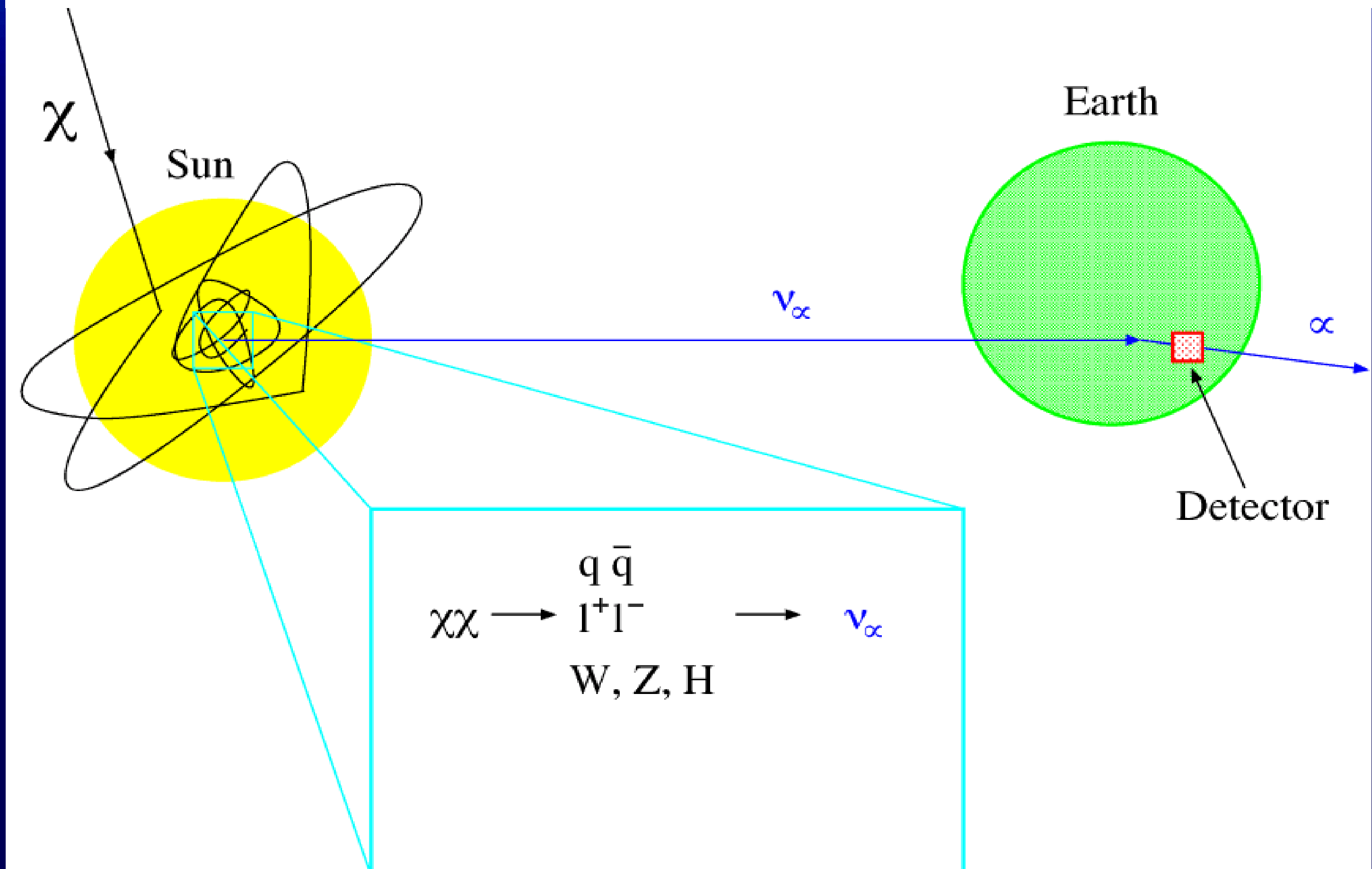
from
Mannheim & Learned,2000



1 pp core AGN (Nellen)
2 pγ core AGN
Stecker & Salomon)
3 pγ „maximum model"
(Mannheim et al.)
4 pγ blazar jets (Mannh)
5 pγ AGN
(Rachen & Biermann)
6 pp AGN (Mannheim)
7 GRB
(Waxman & Bahcall)
8 TD (Sigl)

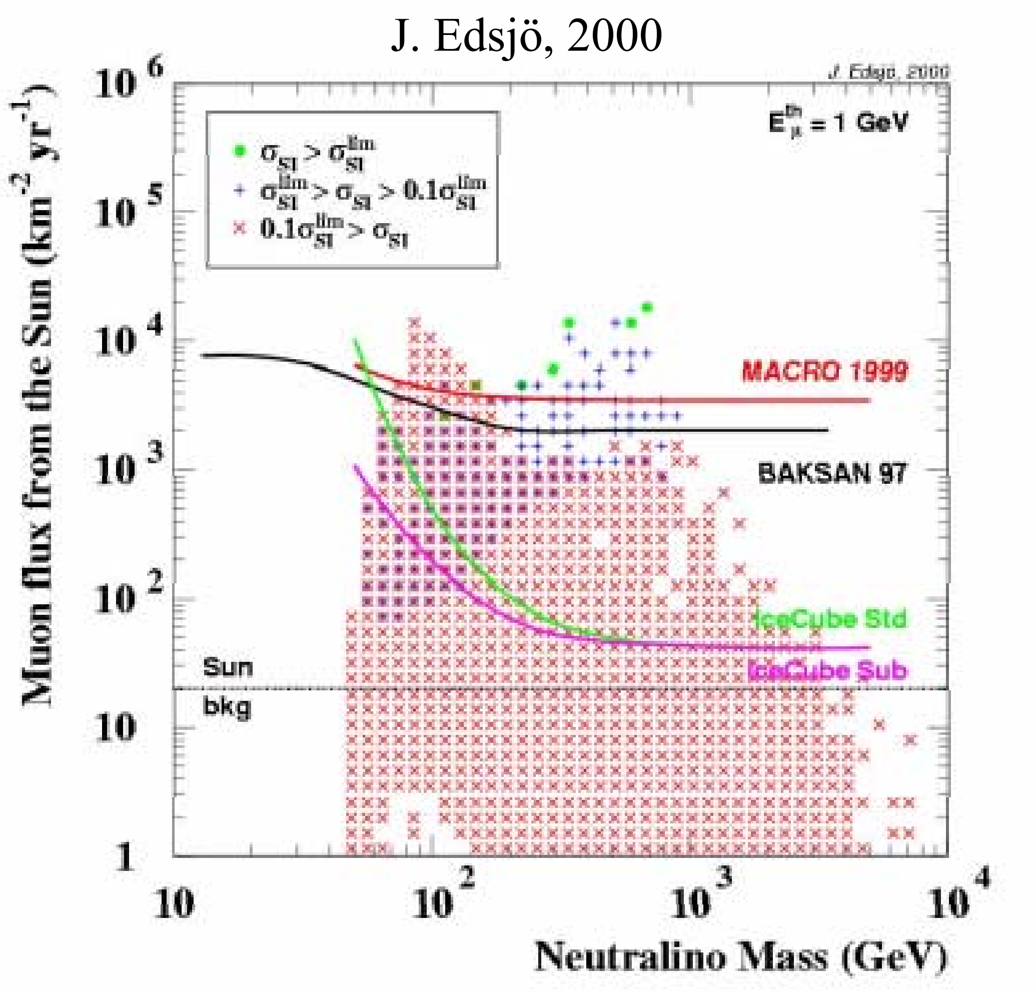
WIMPs from Sun/Earth

Look for excess of muons from the direction of the sun or the center of the earth



WIMPs from the Sun with IceCube

- IceCube will significantly improve the sensitivity.
- Similar sensitivity to GENIUS, …



Neutrinos from Gamma Ray Bursts

Reject background by:

- Energy (number of fired PMT)
- Angle (circular bin of 1º radius)
- Time (≈ 10 sec/ GRB, coincident to known GRB, gamma ray signal, e.g. from satellite detector)

Neutrinos from Gamma Ray Bursts

For 1000 GRB observed:

- **Expected signal: 11 upgoing muon events**
- **Expected background: 0.05 events**

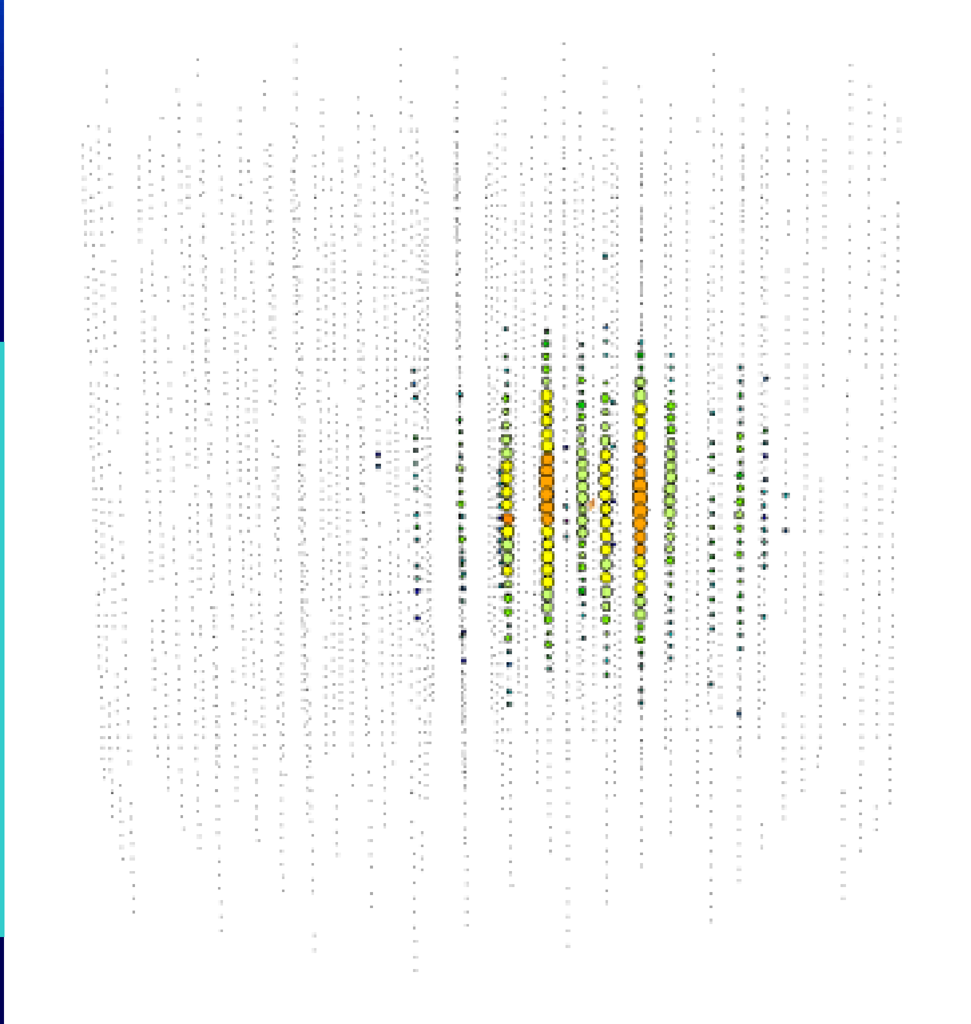
Essentially background free detector:
Only 200 GRB needed to detect standard fireball prediction (Waxman/Bahcall 99)

Cascade event

ν_e + N --> e- + X

- The length of the actual cascade, ≈ 10 m, is small compared to the spacing of sensors
- ==> ≈ roughly spherical density distribution of light
- 1 PeV ≈ 500 m diameter
- Local energy deposition = good energy resolution of neutrino energy

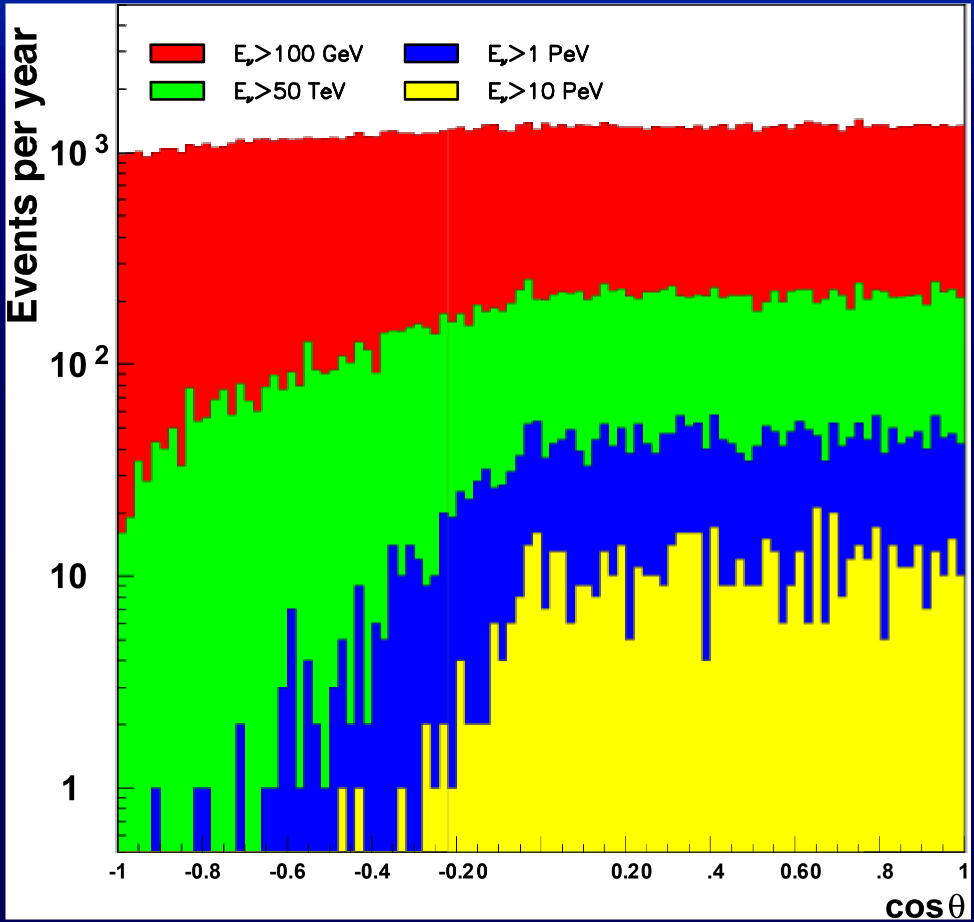
Energy = 375 TeV



Event rates of cascades (ν_e)

Assumed flux: $dN/dE = 10^{-7} * E^{-2} / (cm^2 \text{ sec GeV sr})$

Rates at trigger level
Effective volume after background rejection:
1 km^3 for E>30TeV



ν_τ . Double Bang

Learned, Pakvasa, 1995

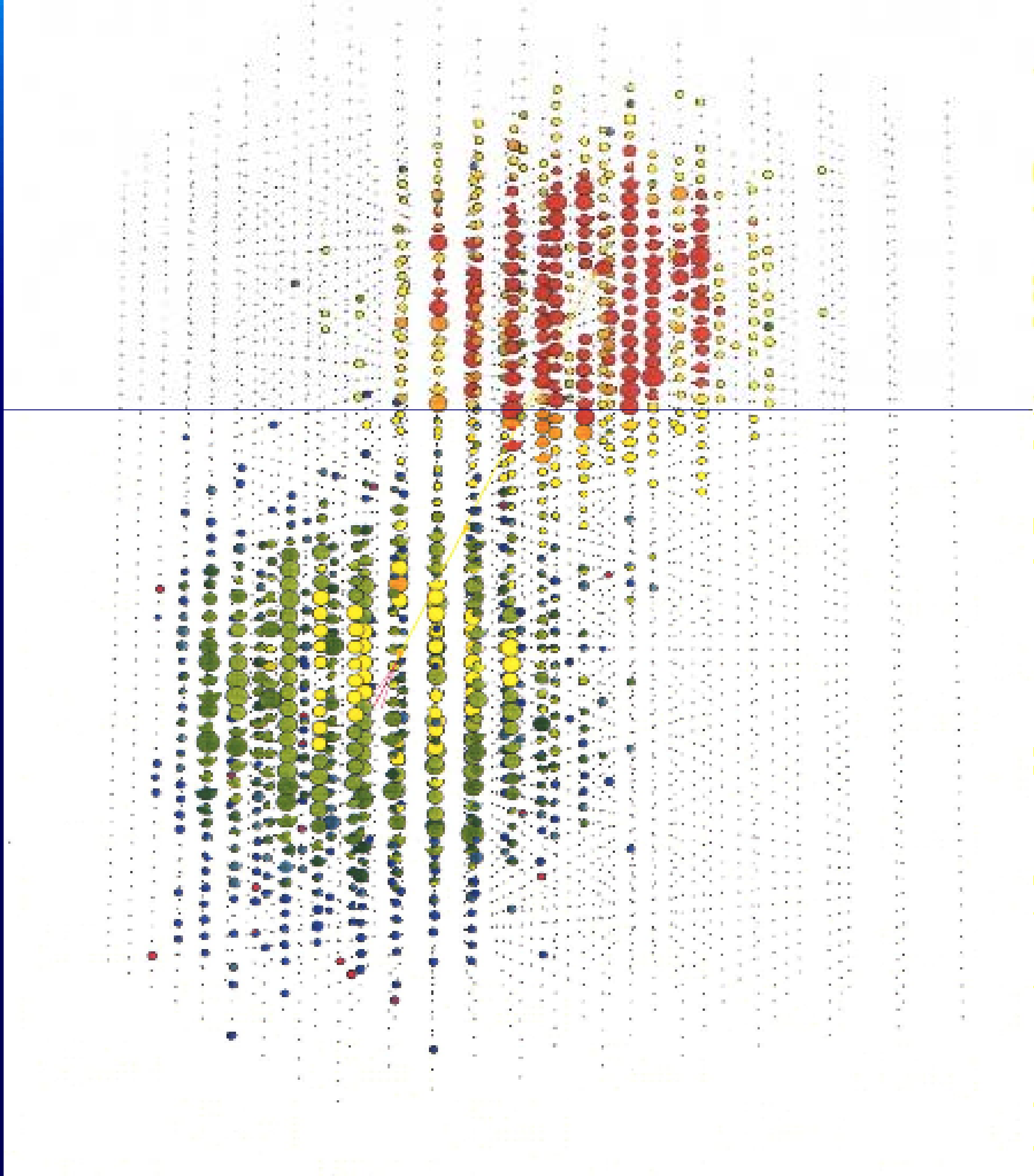
ν_τ + N --> τ- + X

↓

ν_τ + X (82%)

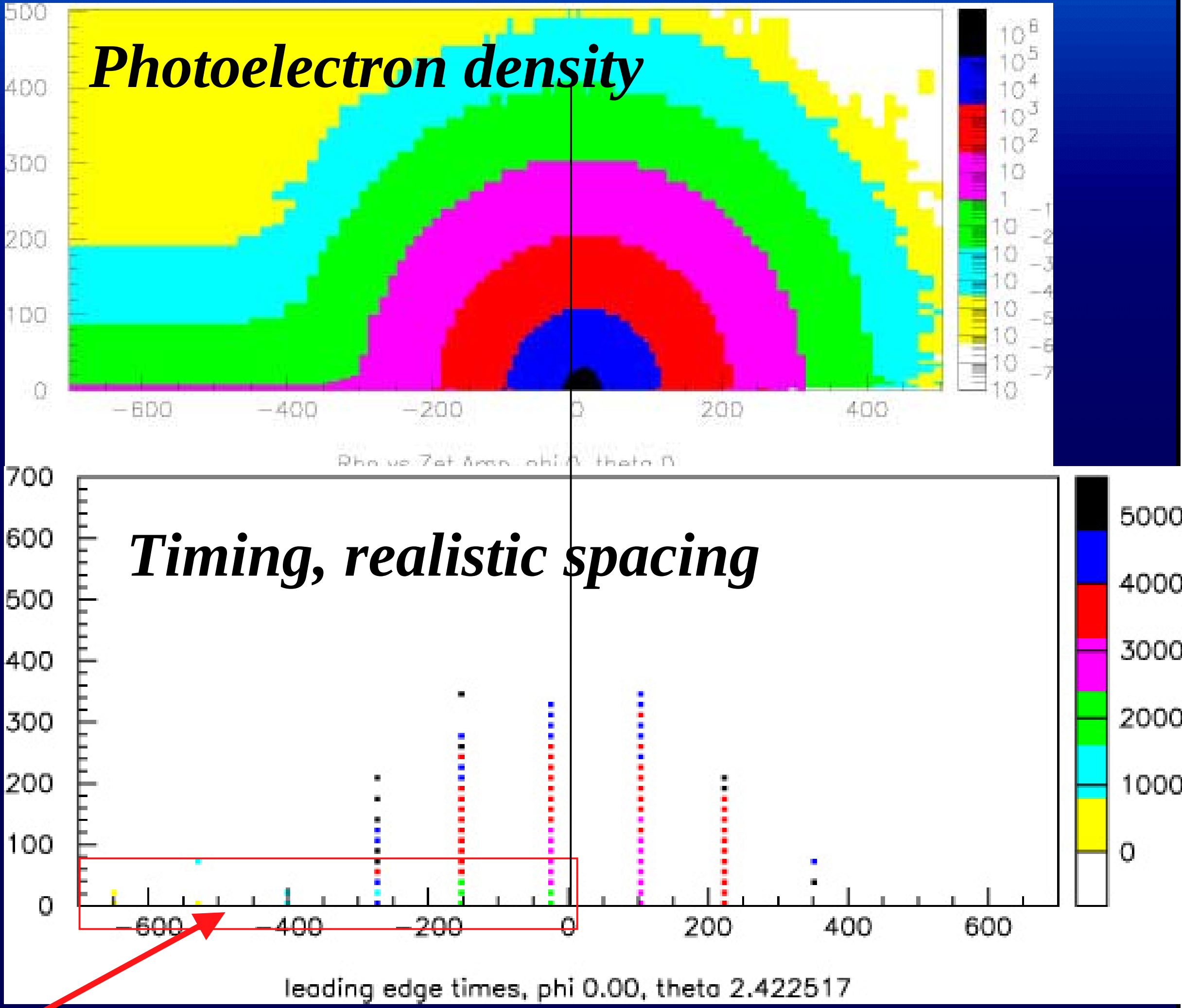
Regeneration makes Earth quasi transparent for high energie ν_τ;
(Halzen, Salzberg 1998, …)
Also enhanced muon flux due to Secondary μ, and ν_μ
(Beacom et al.., astro/ph 0111482)

E << 1PeV: Single cascade
(2 cascades coincide)
E ≈ 1PeV: Double bang
E >> 1 PeV: partially contained
(reconstruct incoming tau track and cascade from decay)



ν_τ at E>PeV: Partially contained

- The incoming tau radiates little light.
- The energy of the second cascade can be measured with high precision.
- Signature: Relatively low energy loss incoming track: would be much brighter than the tau (compare to the PeV muon event shown before)

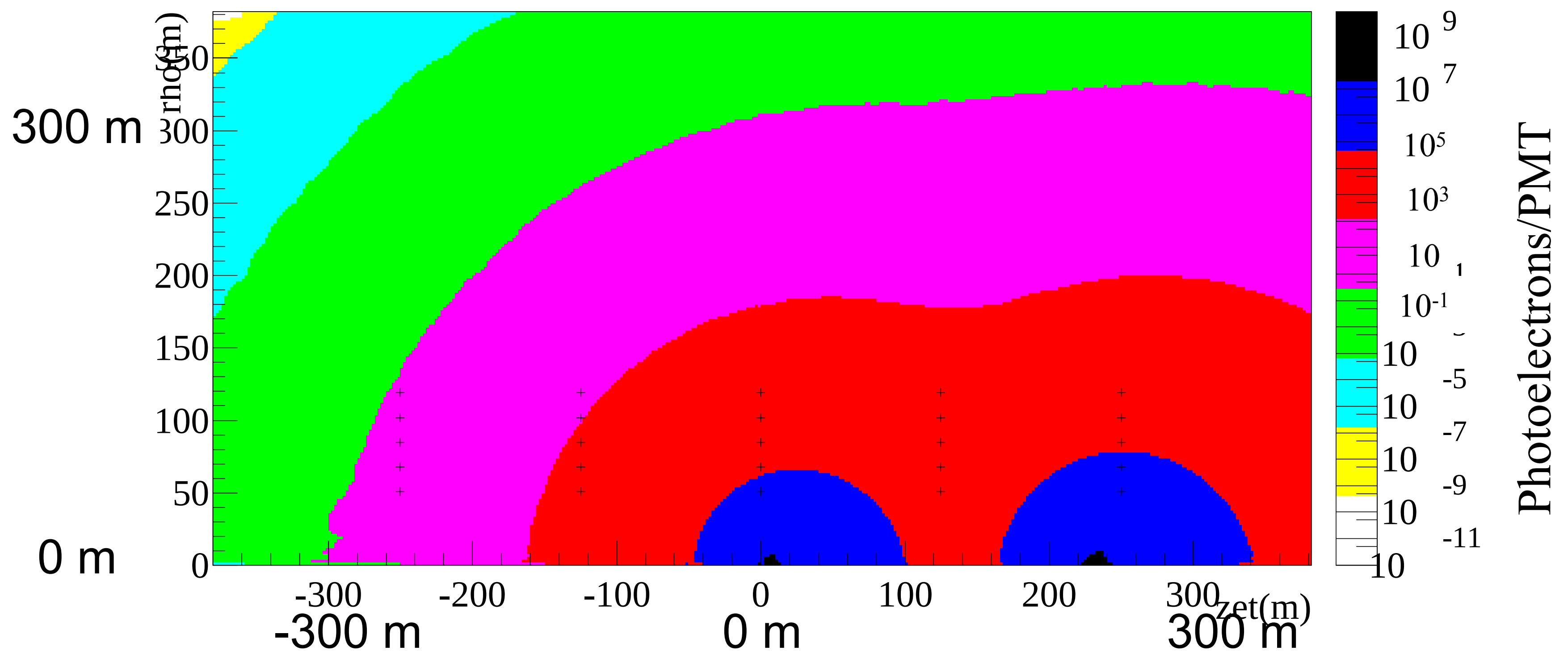


Result: high eff. Volume; Only second bang needs to be seen in Ice3

10-20 OM early hits measuring the incoming τ-track

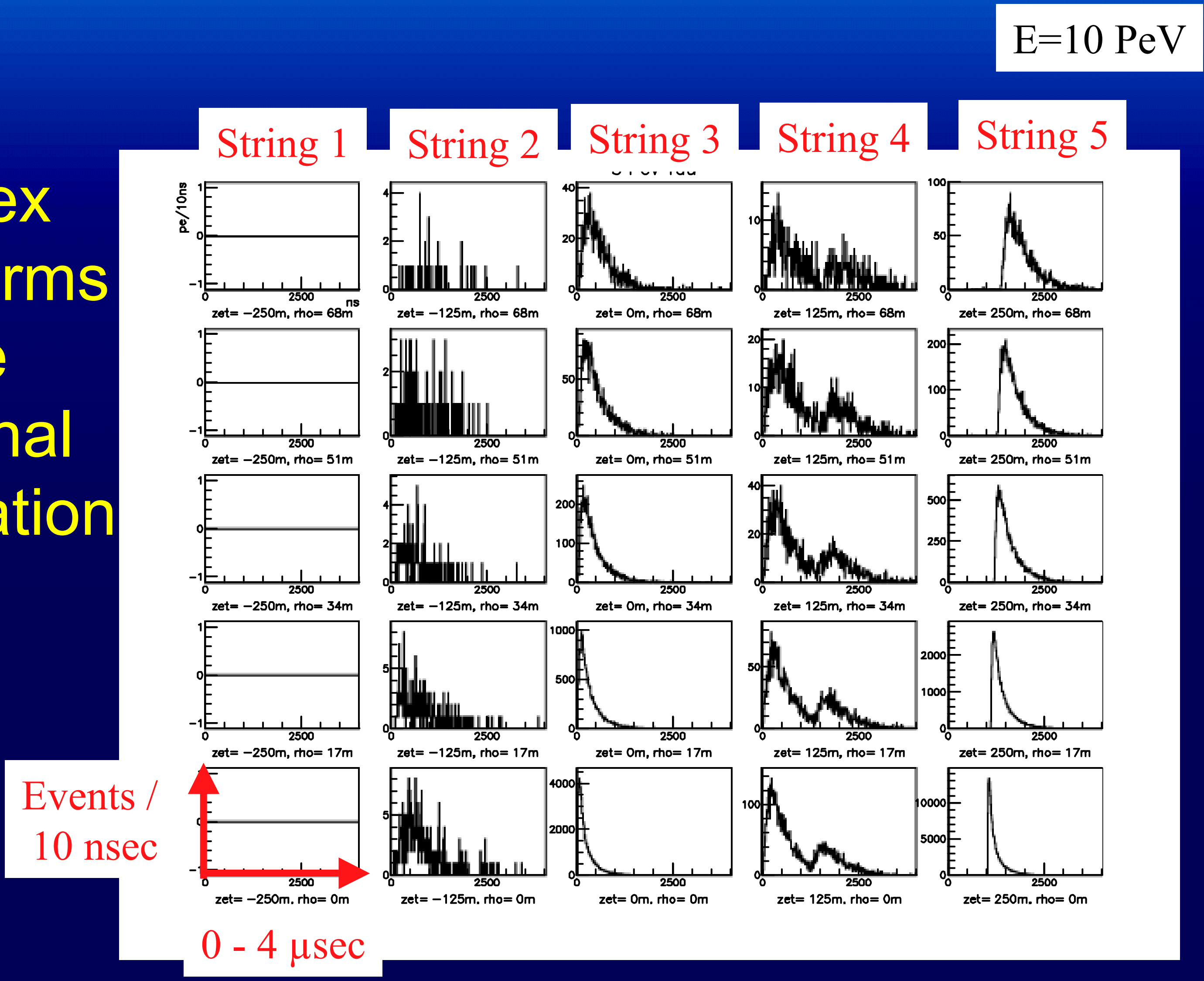
Density profile of double bang event

- Shown is the expected photoelectron signal density of a tau event.
- The first ν_τ interaction is at z=0, the second one at ≈225m.
- The diagram spans about 400m x 800m.



Capture Waveform information (MC)

- Complex waveforms provide additional information

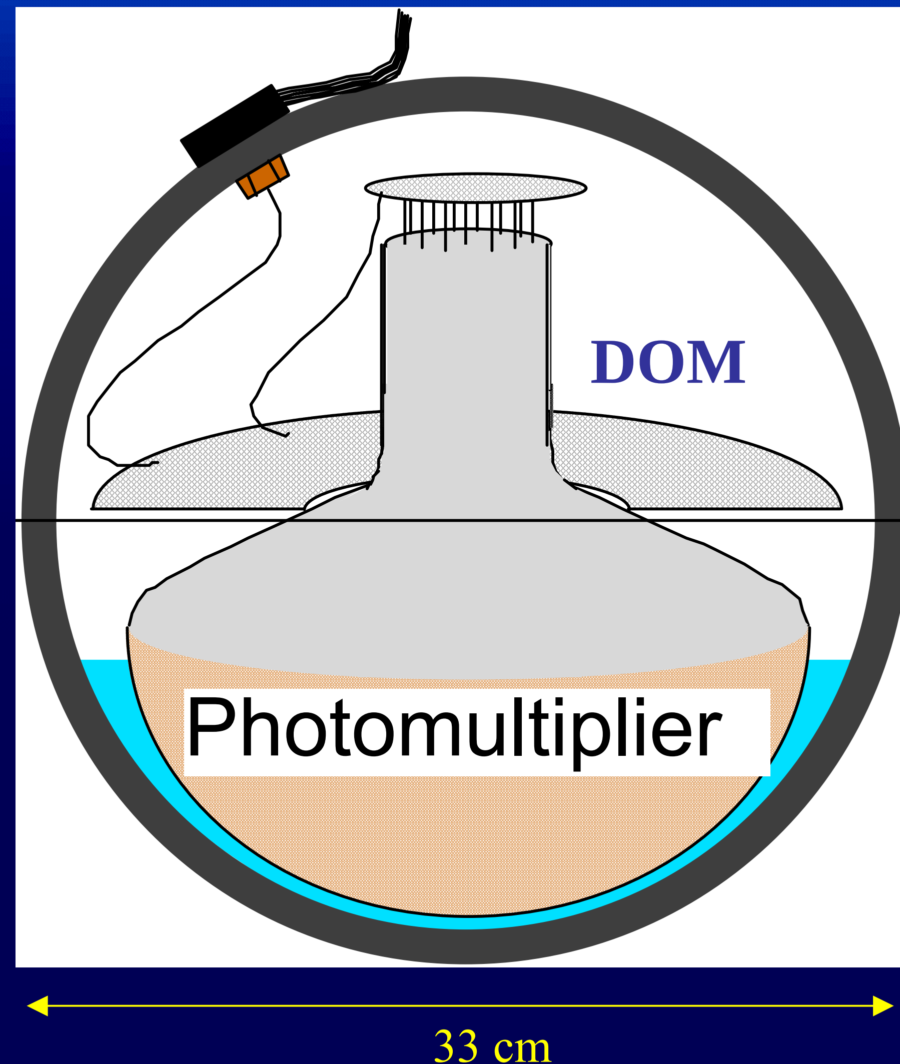


DAQ design: Digital Optical Module - PMT pulses are digitized in the Ice

Design parameters:

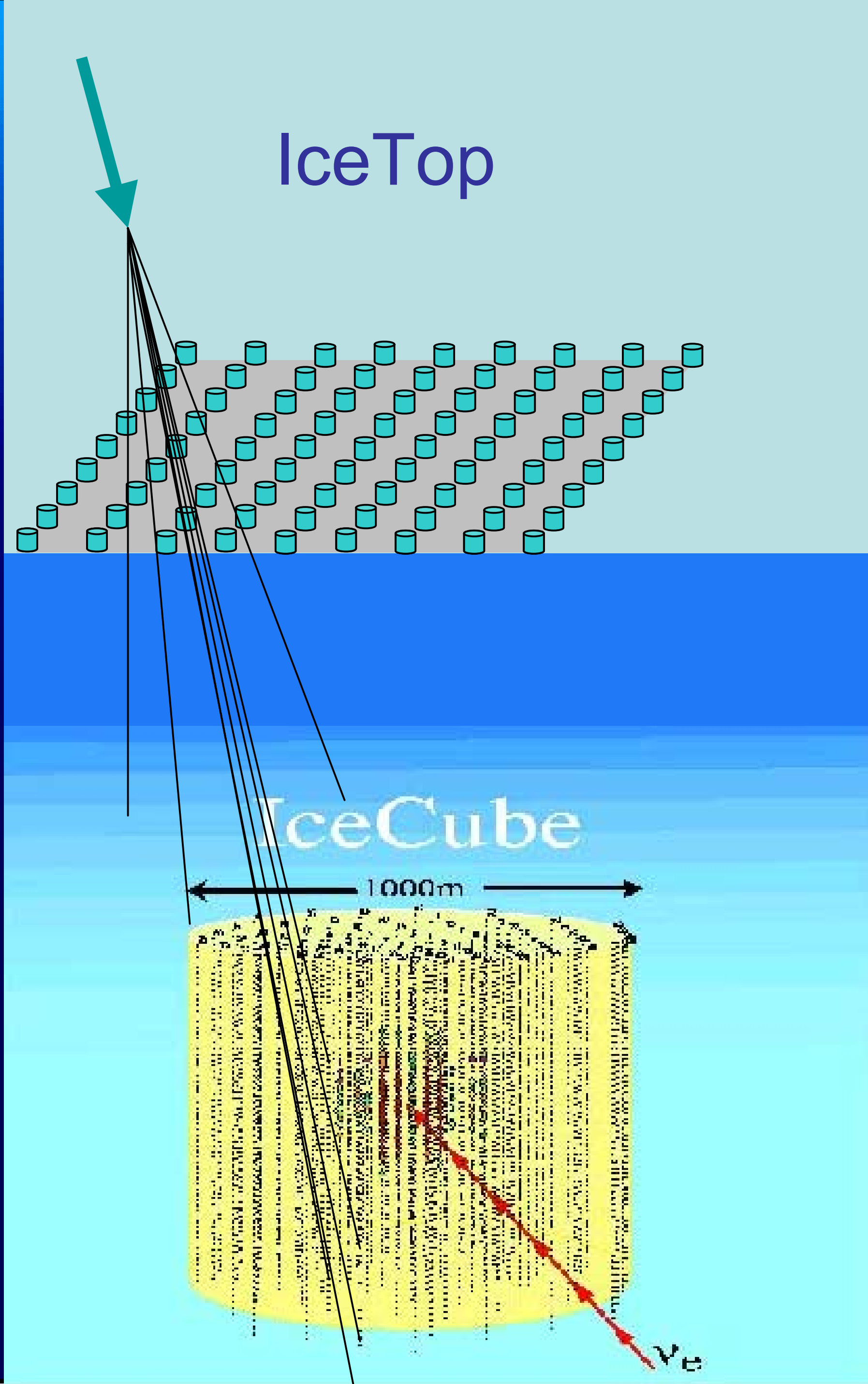
- Time resolution:≤ 5 nsec (system level)
- Dynamic range: 200 photoelectrons/15 nsec
- (Integrated dynamic range: > 2000 photoelectrons)
- Digitization depth: 4 μsec.
- Noise rate in situ: ≤500 Hz

For more information on the Digital Optical Module: see poster by R. Stokstad et al.



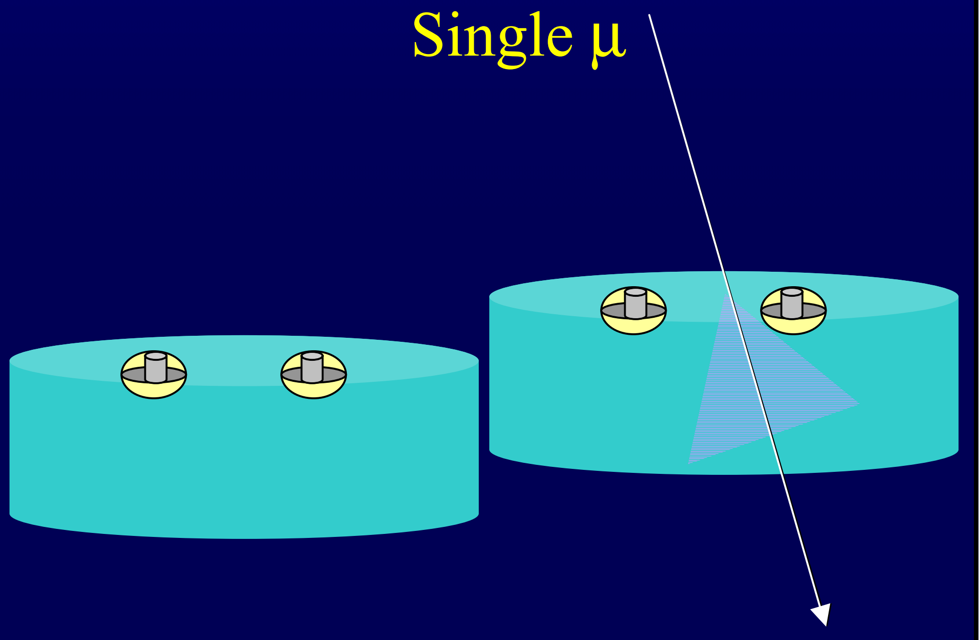
Coincident events

- Two functions
  - veto and calibration
  - cosmic-ray physics
- Energy range:
  - ~3 x 10^{14} -- 10^{18} eV
  - few to thousands of muons per event
- Measure:
  - Shower size at surface
  - High energy muon component in ice
- Large solid angle
  - One IceTop station per hole
  - ~ 0.5 sr for C-R physics with “contained” trajectories
  - Larger aperture as veto



Schematic of IceTop detector

- Two Ice Cherenkov tanks at top of each IceCube hole
  - Each 3.6 m^2; local coincidence for muon vs. shower discrimination
  - Calibration with single muons @ ~1KHz per tank
- Integrated into IceCube
  - construction
  - trigger
  - data acquisition
- Heritage:
  - Haverah Park
  - Auger



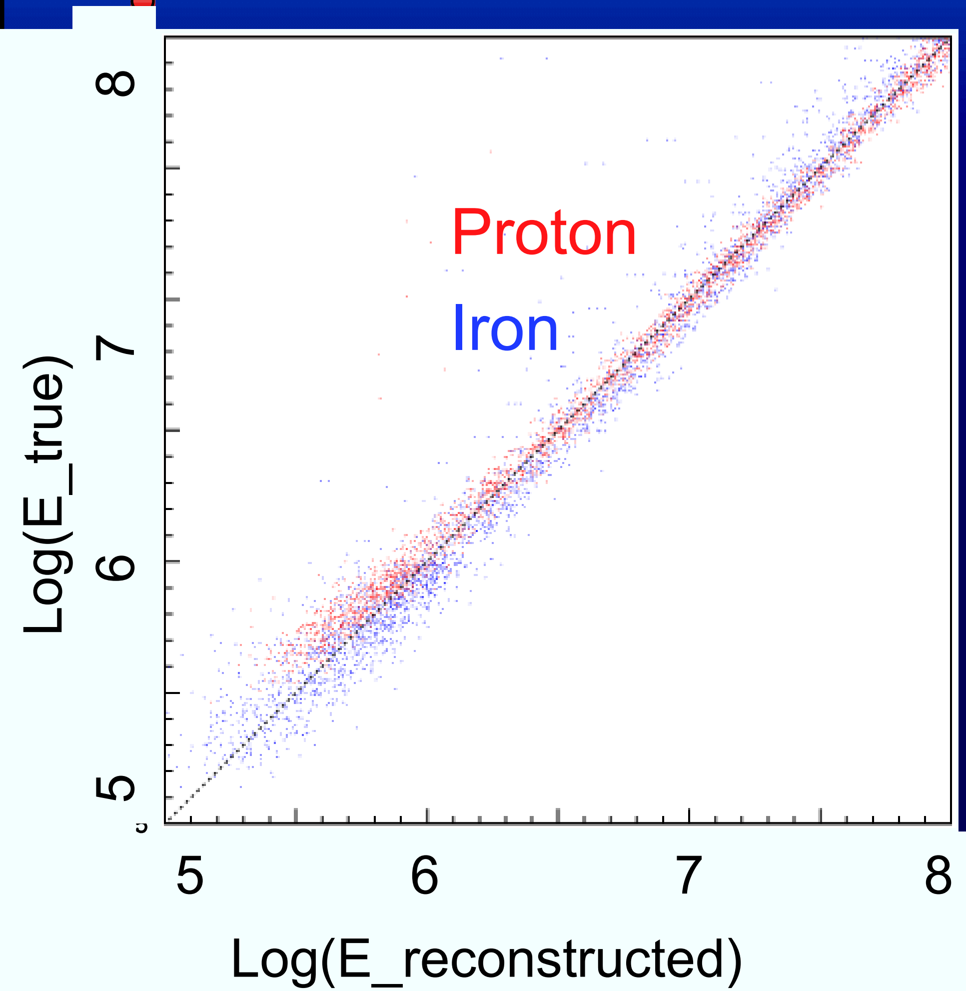
Expectation for coincident events

- ~10^9 IceTop-IceCube coincidences/year
- Calibration beam for IceCube
- ~100/day with multi-TeV μ in IceCube
- Air shower physics to 10^{18} eV

Some numbers:
Shower energy
Number of muons / shower
Number of events / year

E_{shower} log(E/eV)	Log(N_{μ}) (1500m)	Events/ year
15	20	5e7
16	130	5*105
17	700	5000
18	4000	50

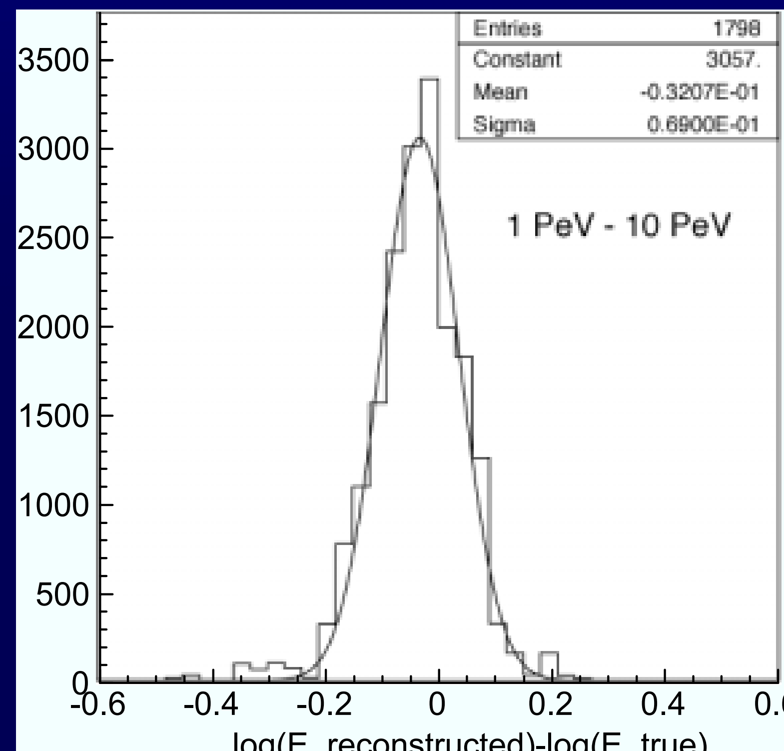
SPASE - AMANDA: Energy resolution of air shower primary



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

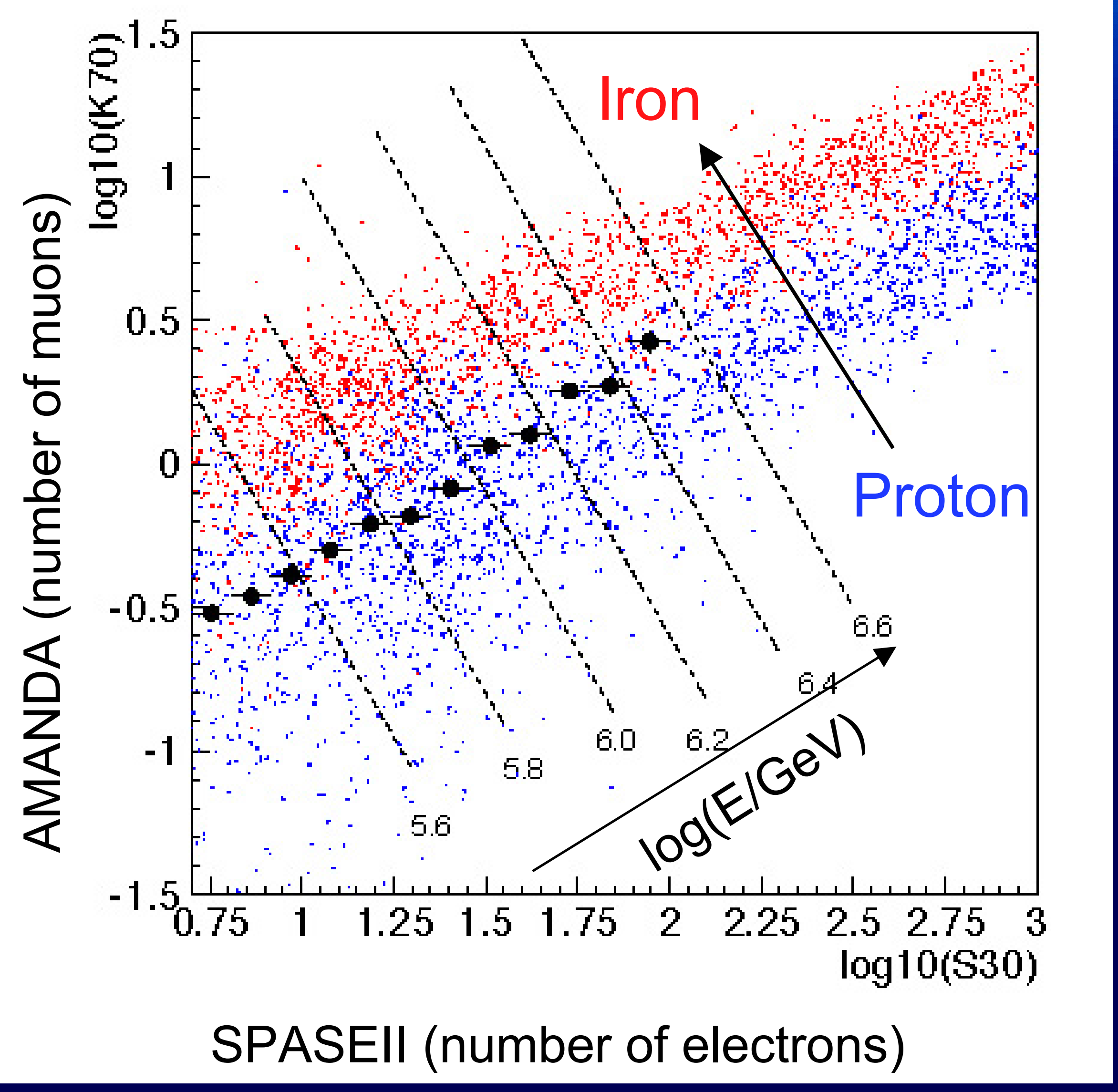
$\sigma_E \approx 7\% \log(E)$

(Mass independent; based on MC)



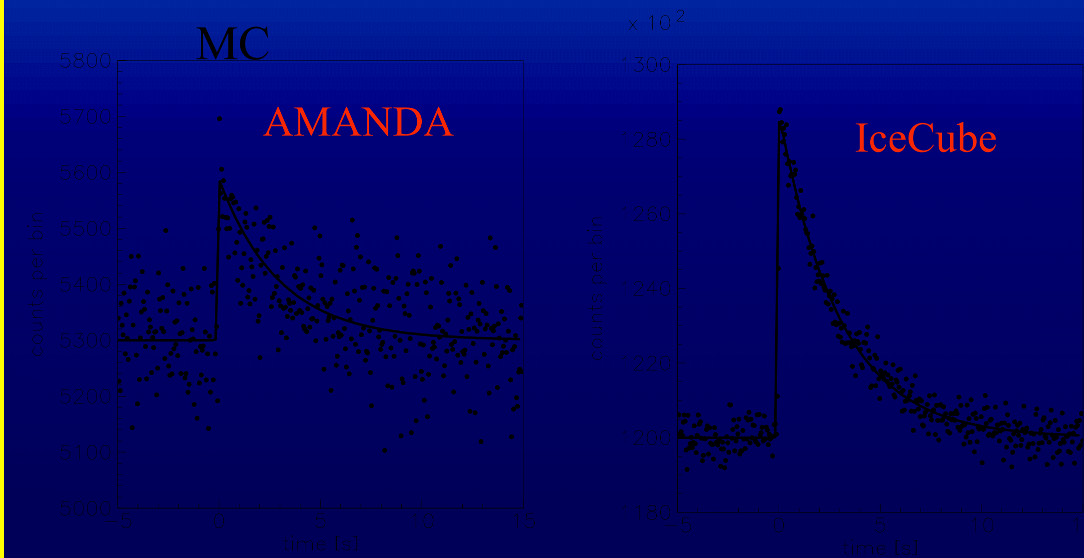
Measuring mass and energy of cosmic ray primary particle

Unfolding energy and mass using SPASE and AMANDA

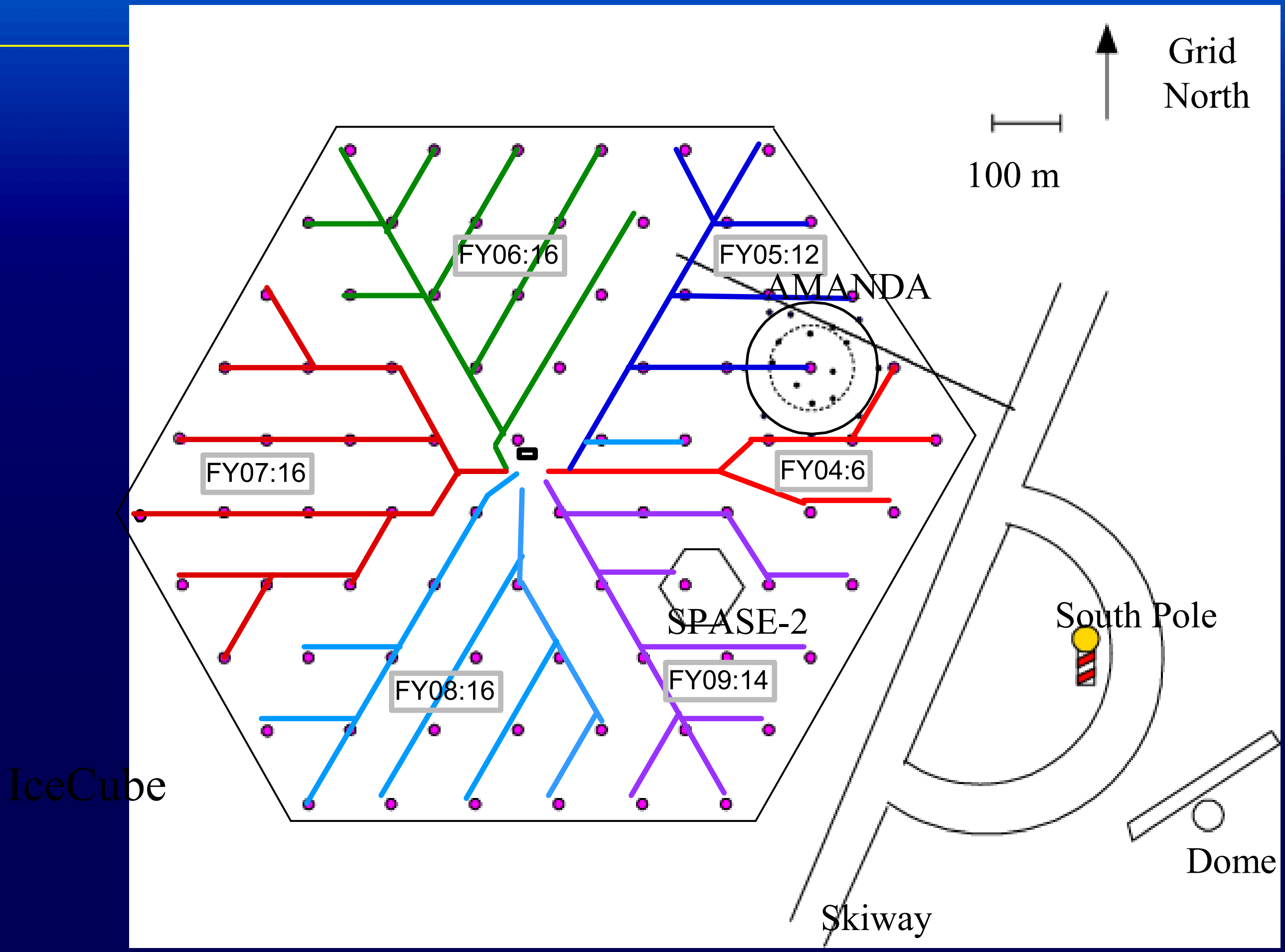


Supernova detection in IceCube

- $\bar{\nu}_e + p \rightarrow n + e^+$ (10-40 MeV)
- Low PMT noise (<500Hz) increase due to the positrons
- AMANDA/IceCube records noise on the PMTs over 0.5 sec and summing up total rate over 10 sec intervals.
- Detectors to be connected to Supernova Early Warning System



Construction: 11/2003-01/2009



South Pole

Project status

- Approved by the National Science Board
- Startup funding is allocated.
- Construction is in preparation (Enhanced Hotwater Drill, OM design, OM production facilties, DAQ and test facilities).
- Construction start in 04/05; possibly a few initial strings in 03/04.
- Then 16 strings per season, increased rate may be possible.

Summary

- IceCube array allows
  - Very good event reconstruction (E,θ,φ).
  - High sensitivity to muon-, electron-, tau-neutrinos.
  - Particle identification over wide energy range.
- IceCube is a multipurpose detector covering a wide range of energies, signals, discovery potentials.
- Size and quality of information provides sensitivity in discovery range.
- Construction is in preparation.