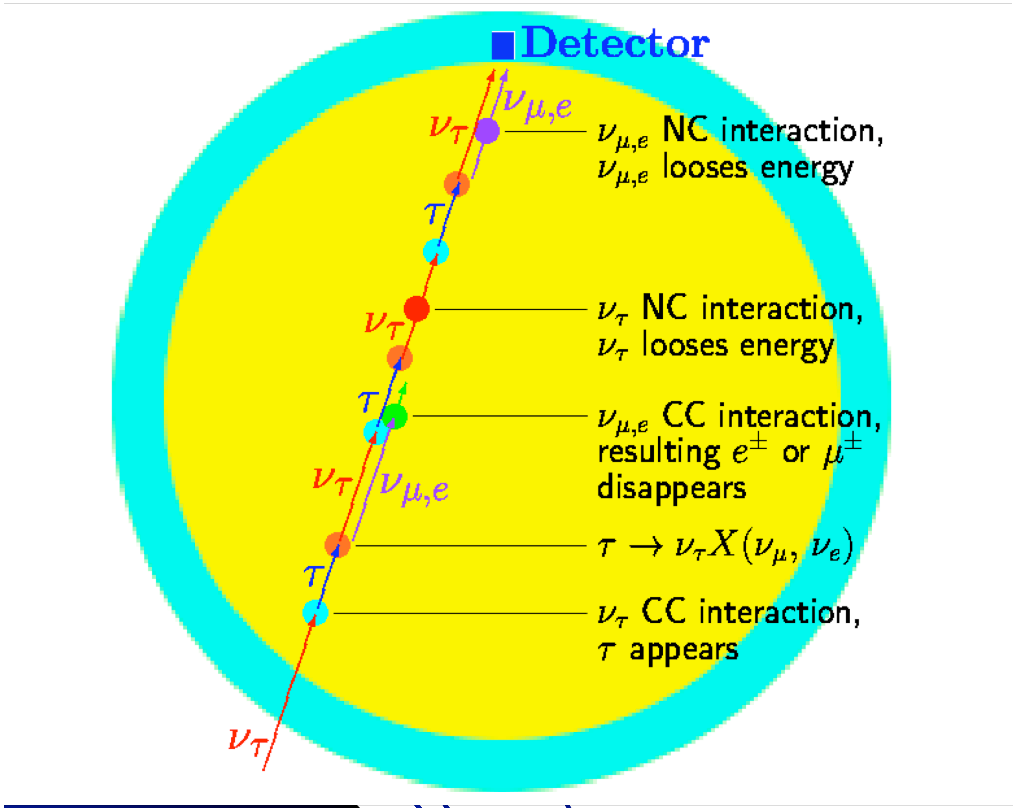
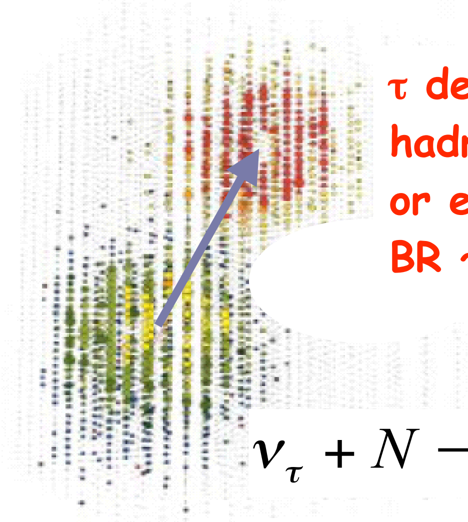
# Tau neutrinos

Never absorbed but loose energy

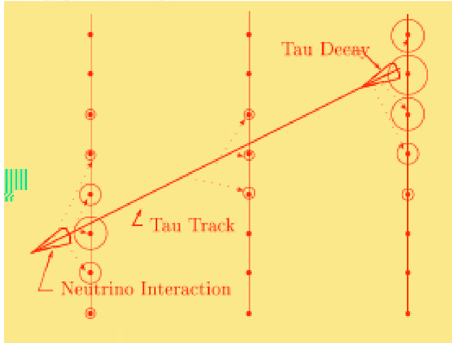
A topology for km$^3$
Double bang events
$E_\tau$ > 2 PeV $R_\tau$ ~100 m





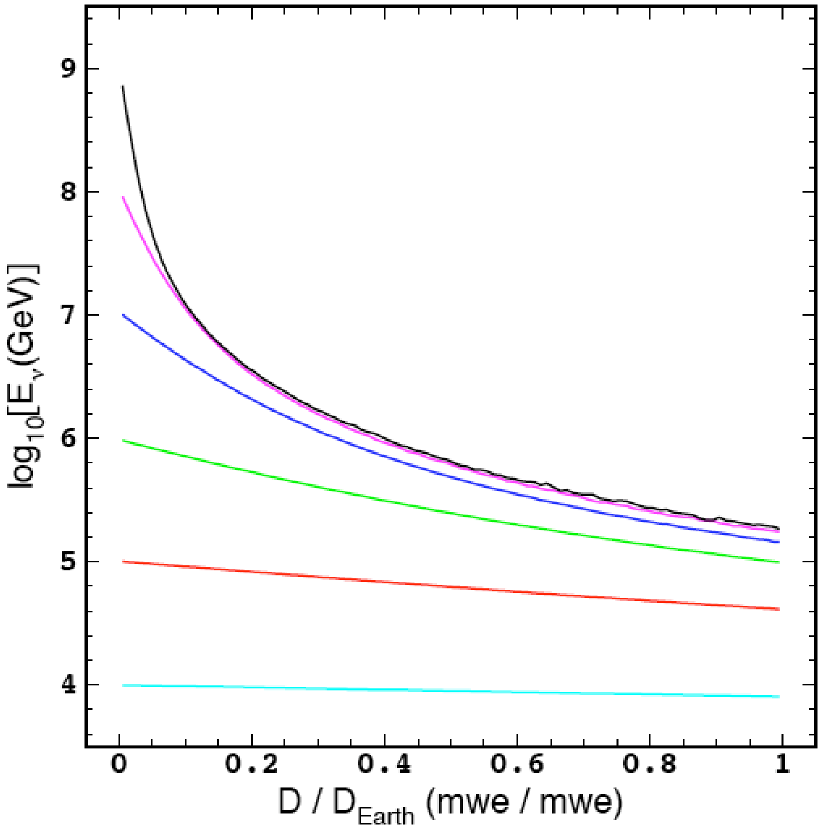
τ decay into
hadrons
or electrons
BR ~83%

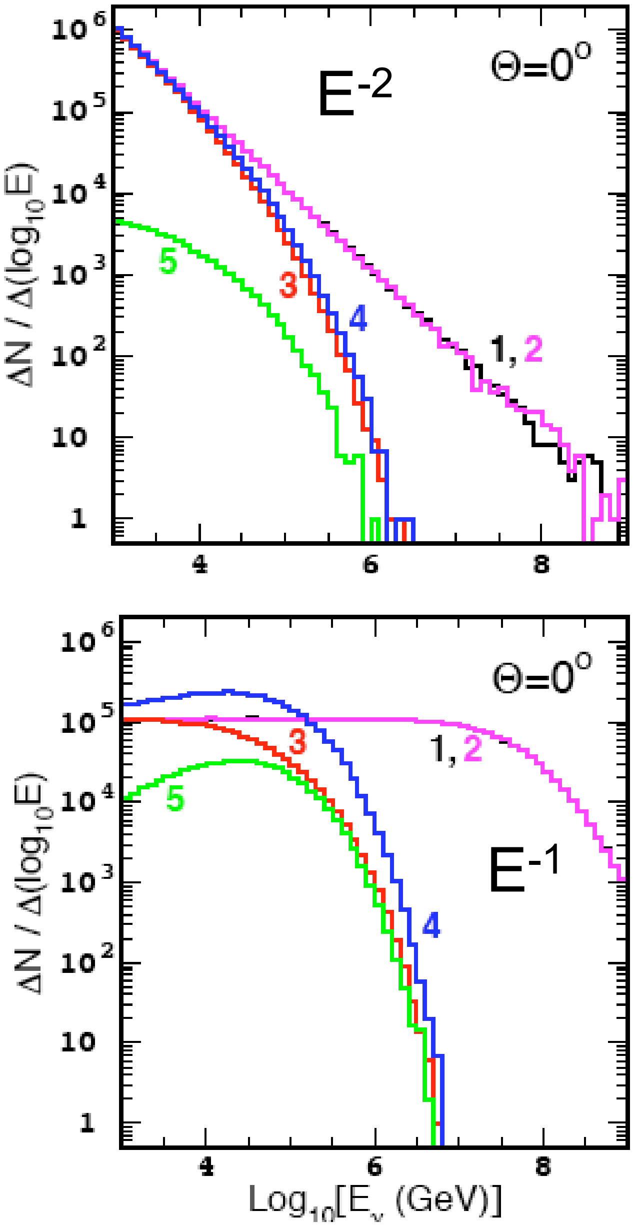
$$\nu_\tau + N \to \tau + X$$



# The Pile-up and regeneration

Mean rate of energy degradation for $\nu_\tau$ of $10^4$, $10^5$, $10^6$, $10^7$, $10^8$, $10^9$ GeV (bottom to top) vs fraction of Earth

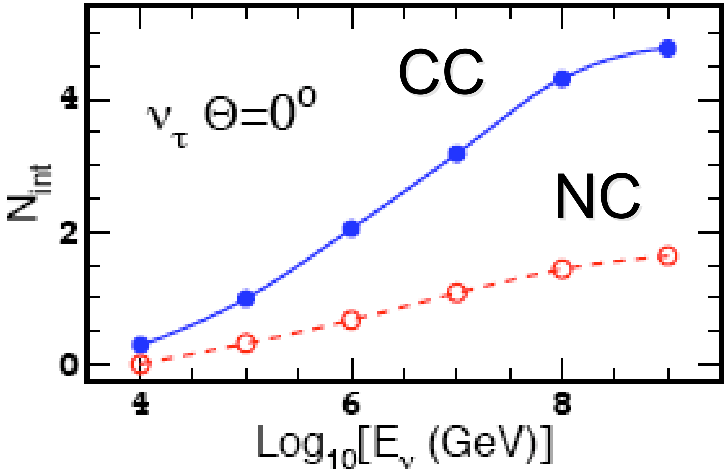


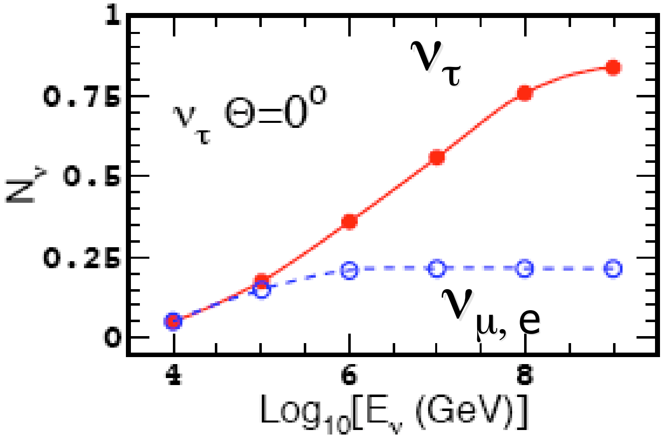


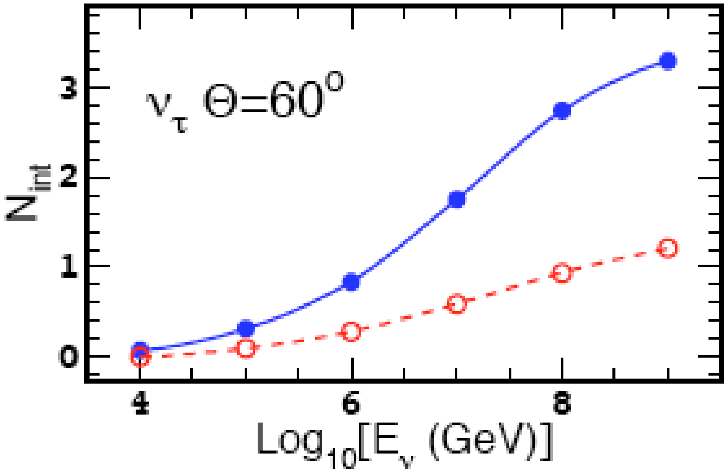
1,2 incoming $\nu_\mu$, $\nu_\tau$  3,4 outgoing $\nu_\mu$, $\nu_\tau$
5 secondary neutrinos from $\nu_\tau$

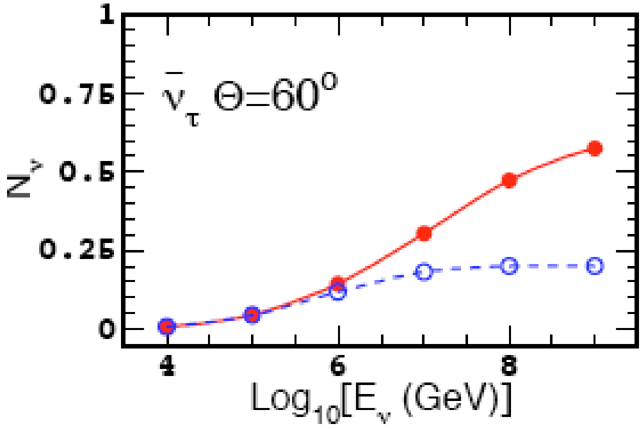
# Tau neutrino propagation in the Earth

Secondary $\nu$s from $\nu_\tau$





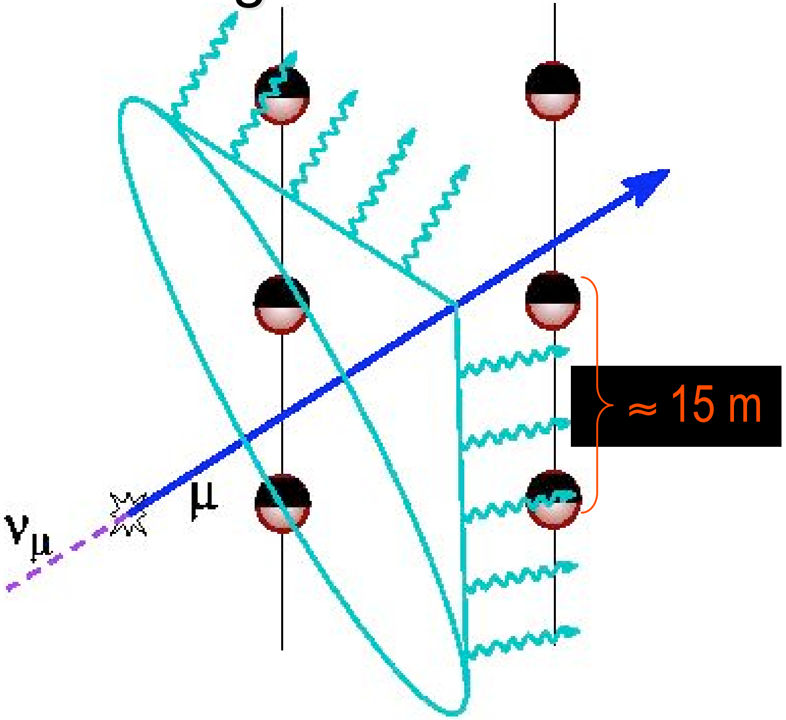




# Detection of $\nu_e, \nu_\mu, \nu_\tau$

## O(km) long muon tracks

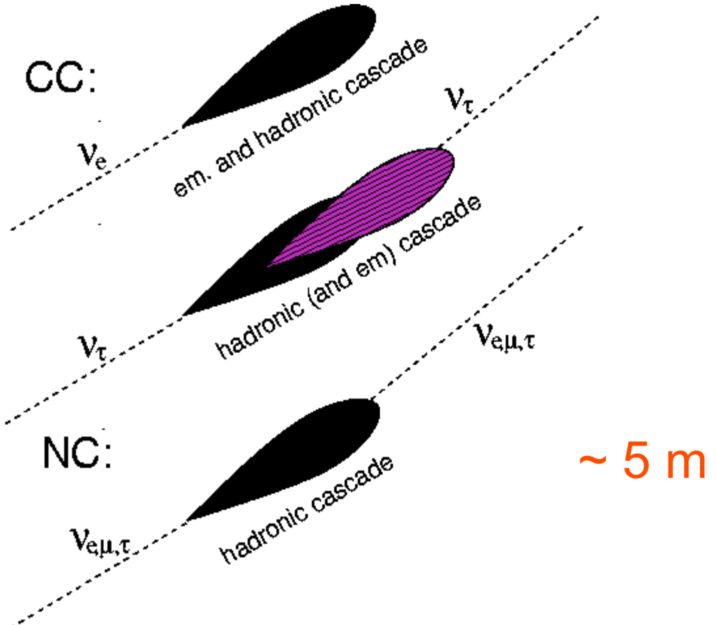
2π coverage



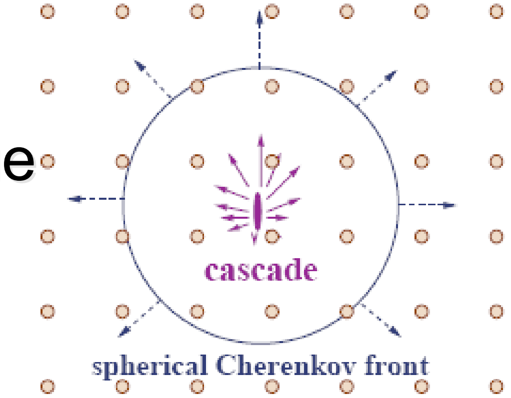
direction determination
by cherenkov light timing

Teresa Monta

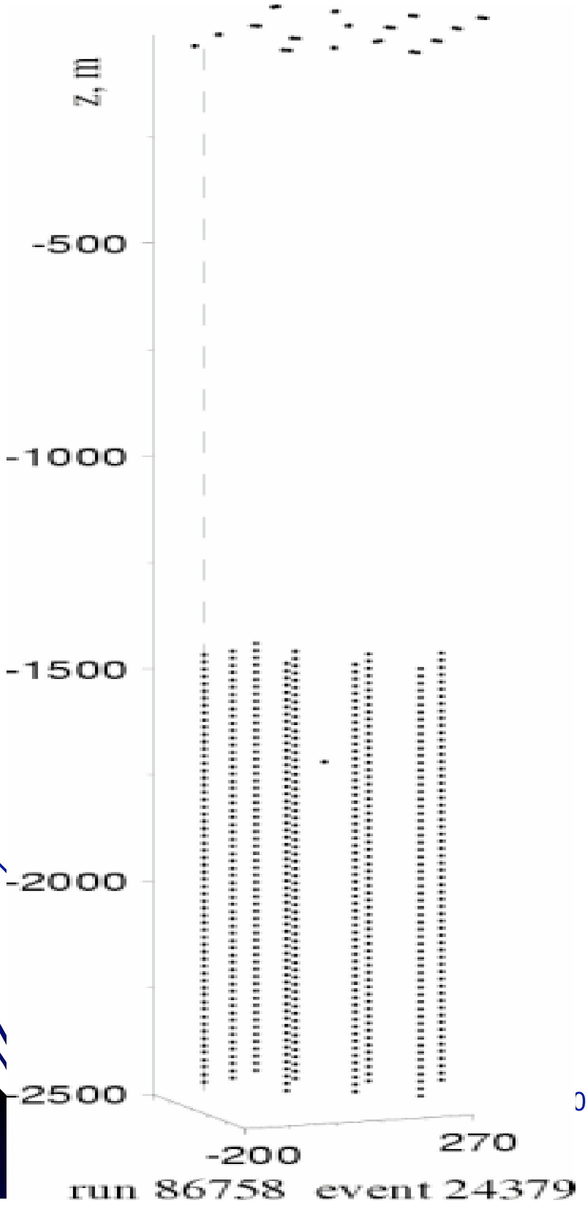
## Electromagnetic and hadronic cascades



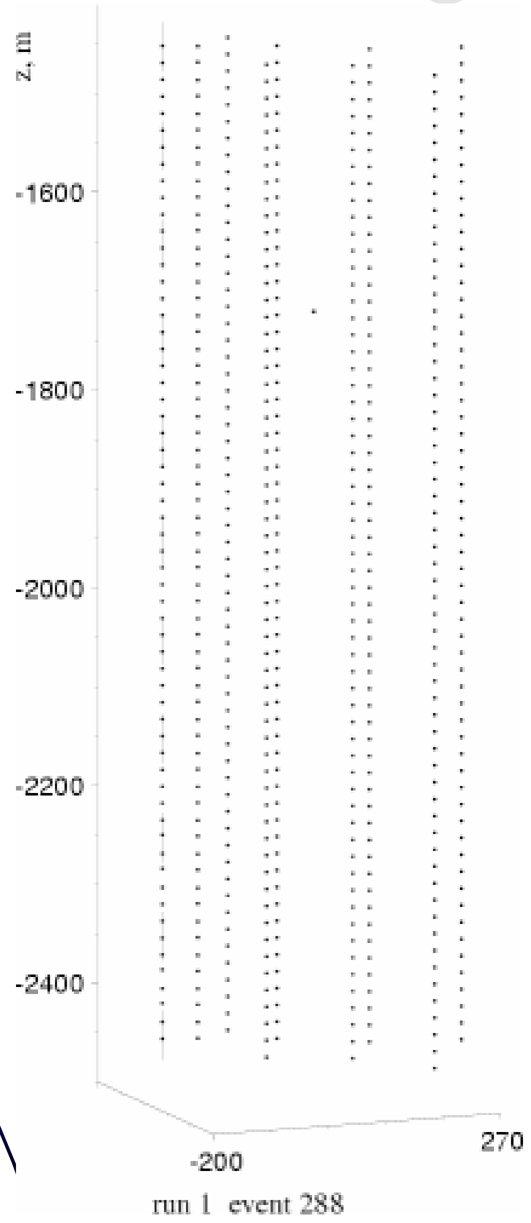
4π coverage



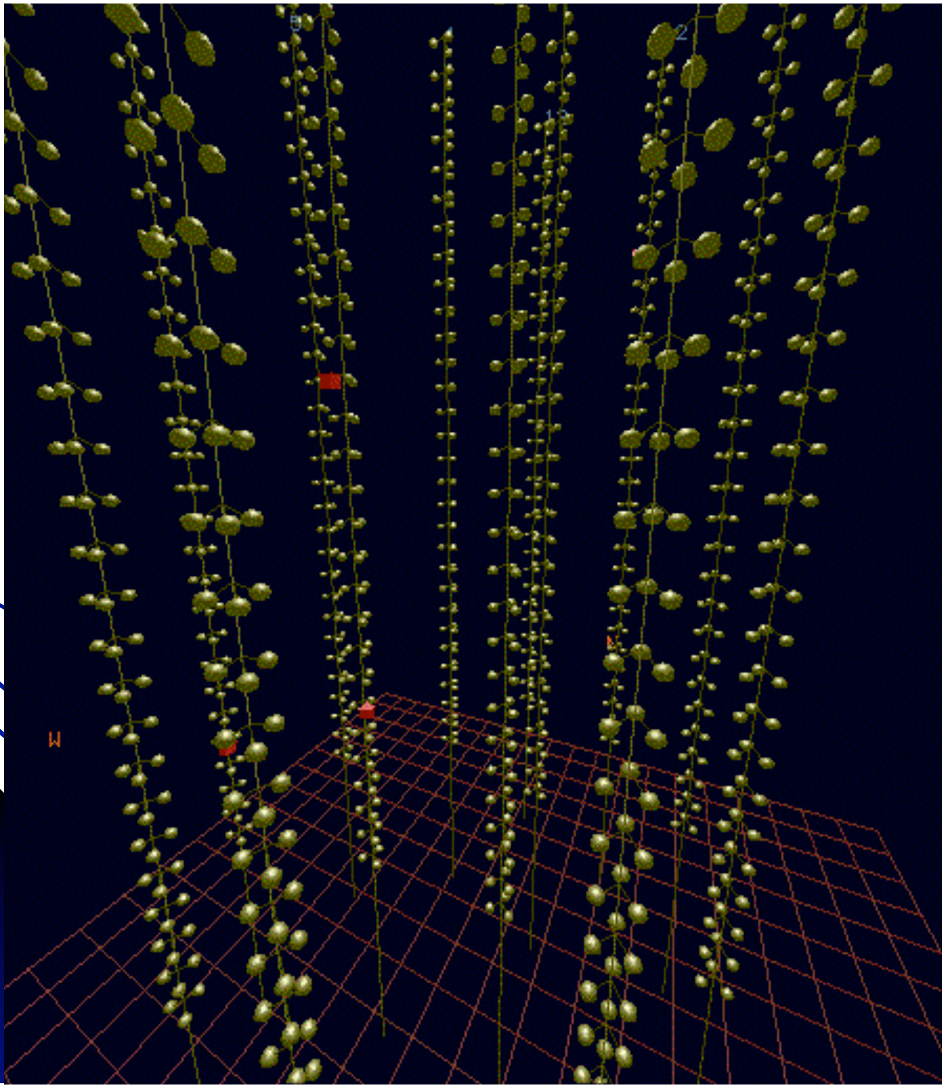
# Events in 9 IceCube strings+18 Icetop Stations



# Neutrino in 9 strings of icecube



# Simulated Muon in ANTARES



# The Cherenkov effect

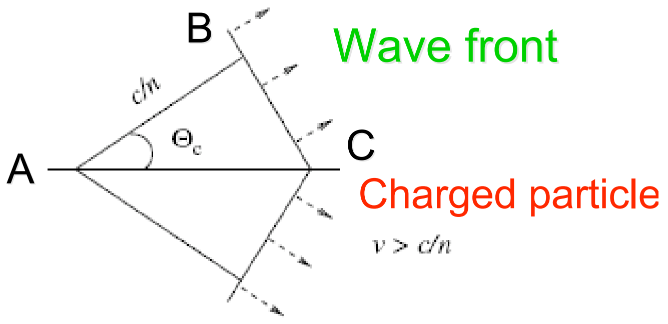
A charged particle radiates if its velocity is larger than the phase velocity of light v>c/n or $\beta > 1/n$

Electrons start vibrating due to particle em field and some of the particle energy is converted in light

If the media is transparent the Cherenkov light can be detected

If the particle is ultra-relativistic $\beta \sim 1$ $\Theta_c$ = const

In water $\Theta_c = 43^\circ$, in ice $41^\circ$



$$\cos\theta_c = \frac{AB}{AC} = \frac{\frac{c}{n}t}{\beta c t} = \frac{1}{\beta n}$$

$$\frac{d^2N_\gamma}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) = \frac{2\pi}{\lambda^2}\,\alpha\sin^2\theta_c$$

Using light detectors (photomultipliers) sensitive in 300-600 nm

$$\varepsilon_{pm}(\lambda) = 1 \Rightarrow \frac{dN_\gamma}{dx} = 350 \text{ photons/cm}$$

for an ideally 100% efficient detector

$$\frac{d^2N}{dE\,dx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$
$$\approx 370\sin^2\theta_c(E)\ \mathrm{eV}^{-1}\mathrm{cm}^{-1} \qquad (z = 1)\ ,$$

**About $10^4$ less than 2 MeV/cm in water from ionization but directional effect**

# The Cherenkov radiators

**In radiators $\gamma$s are absorbed and scattered**

**Absorption** affects light signal **amplitude** ⇒ determines **detector granularity**

**Scattering** affects $\gamma$ **arrival time distribution** ⇒ **angular resolution**

**Sea water: $\lambda_{att}$ ~ 40-50 m $\lambda_{abs}$ ~ 50-60 m $\lambda_{scatt}$ > 200 m (Blue 450 nm)**
**Lake Baikal $\lambda_{att}$ ~20 m $\lambda_{abs}$ = 15-30 m $\lambda_{scatt}$ > 100 m**
**Polar ice: $\lambda_{abs}$ ~ 100 m $\lambda_{scat}$ ~ 25 m**

$$I = I_0 \frac{A}{4\pi R^2} e^{-R/\lambda_{att}}$$

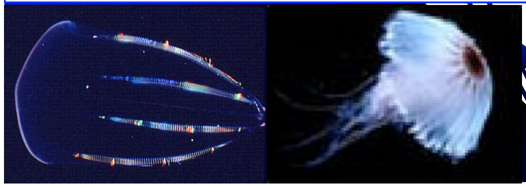
For an isotropic source of light:
$I_0$ = intensity of source
I = intensity at distance R

$$\frac{1}{\lambda_{att}} = \frac{1}{\lambda_{abs}} + \frac{1}{\lambda_{scatt}}$$

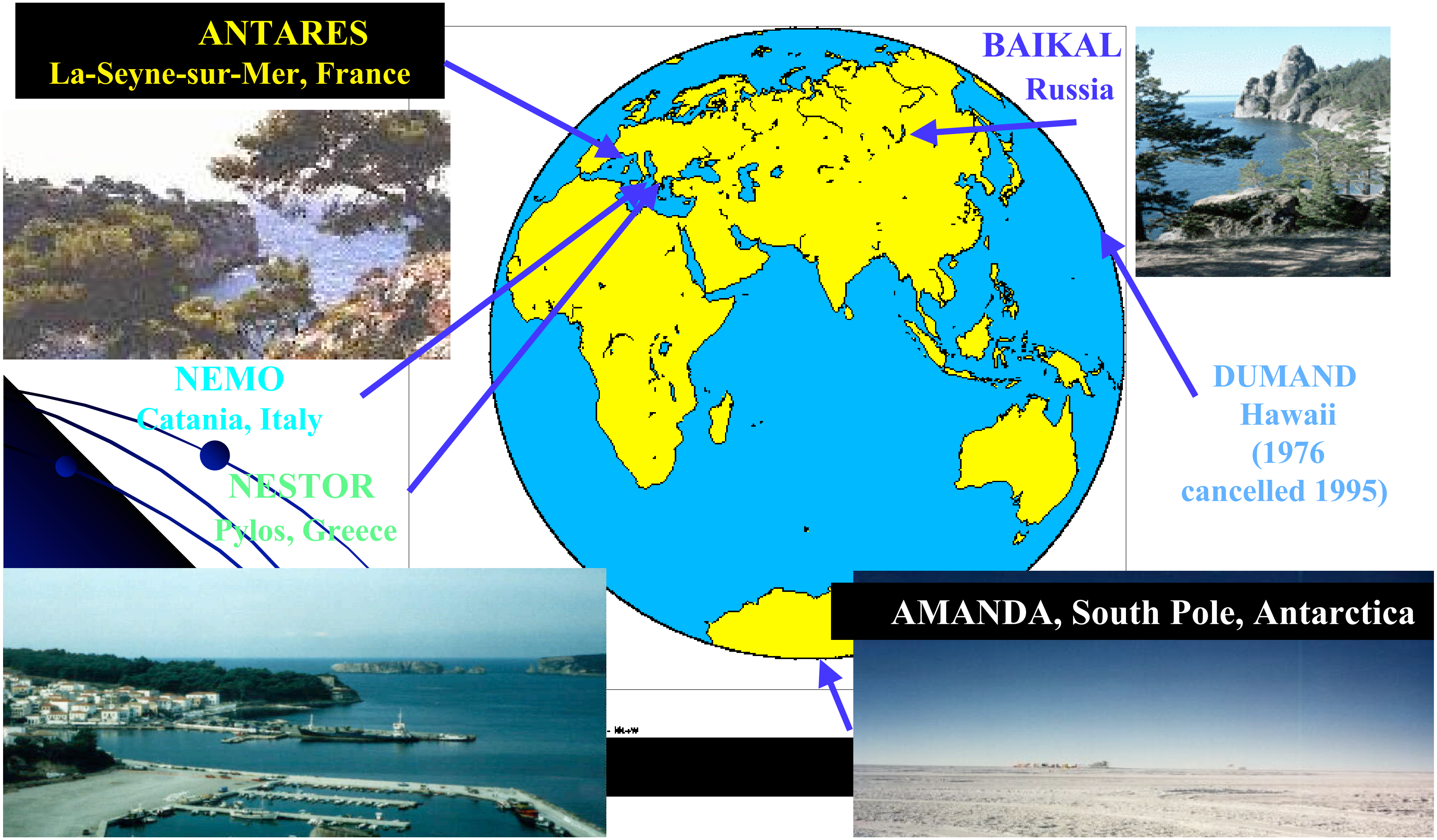
Ice is a more quiet environment than the sea (less optical backgrounds like $^{40}$K $\beta$ decay that produces light due to e$^+$, no currents, no sediments, no fishes!!)

South Pole is far and expensive to carry the material

Ice has more scattering than water, affecting the pointing capability, and more dependency on its properties with depth



# Cherenkov
# Neutrino Telescope Projects



**ANTARES**
La-Seyne-sur-Mer, France

**BAIKAL**
Russia

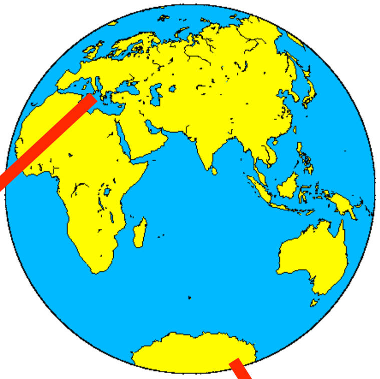
**NEMO**
Catania, Italy

**NESTOR**
Pylos, Greece

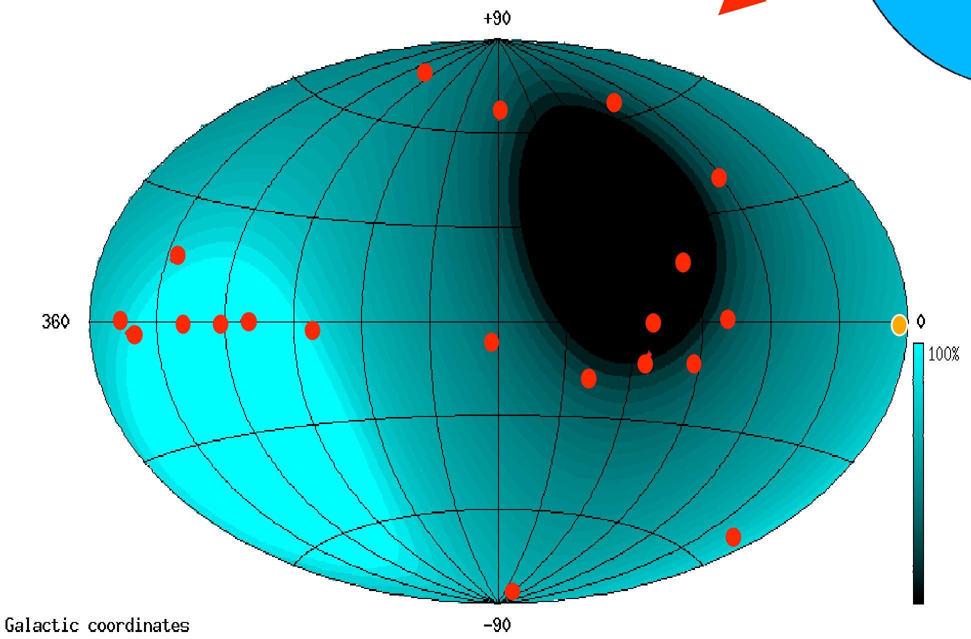
**DUMAND**
Hawaii
(1976
cancelled 1995)

**AMANDA, South Pole, Antarctica**

# Sky Visibility for upgoing μs

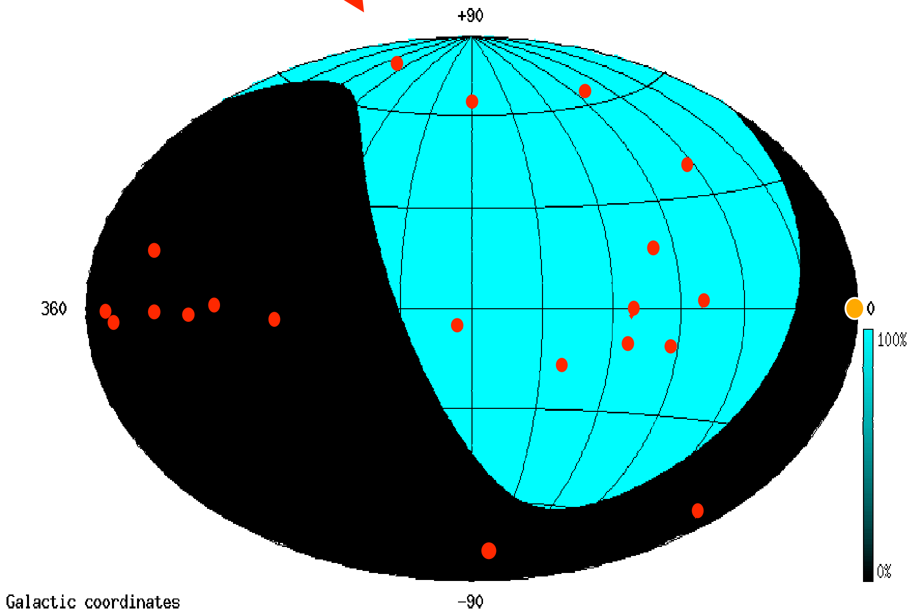


Hw for extra credits
Calculate for which percentage of the day your source is visible by the detector you chose



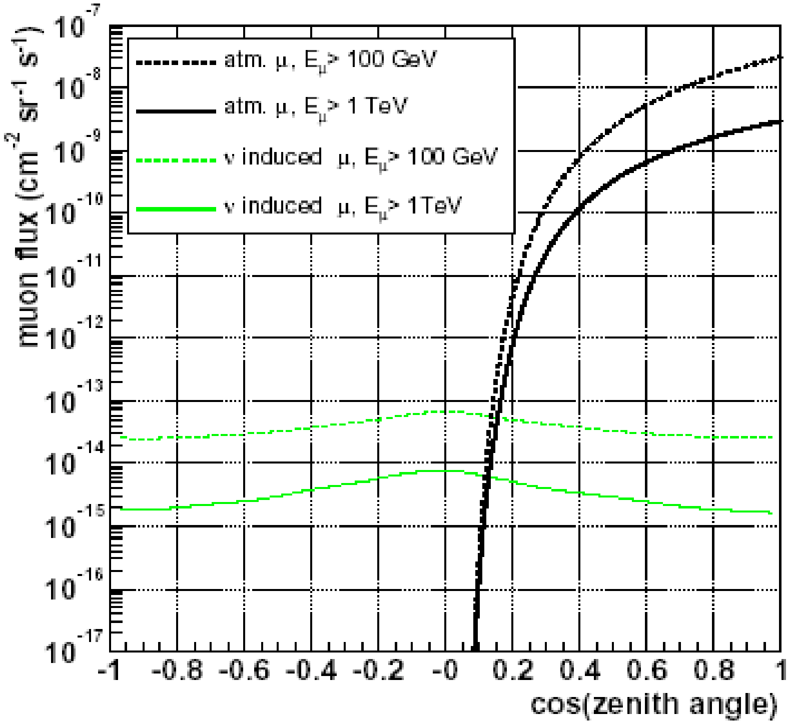
Mediterranean
France 43° North
2/3 of time: Galactic Centre

$0.6\,\pi$ sr instantaneous view



TeV γ sources

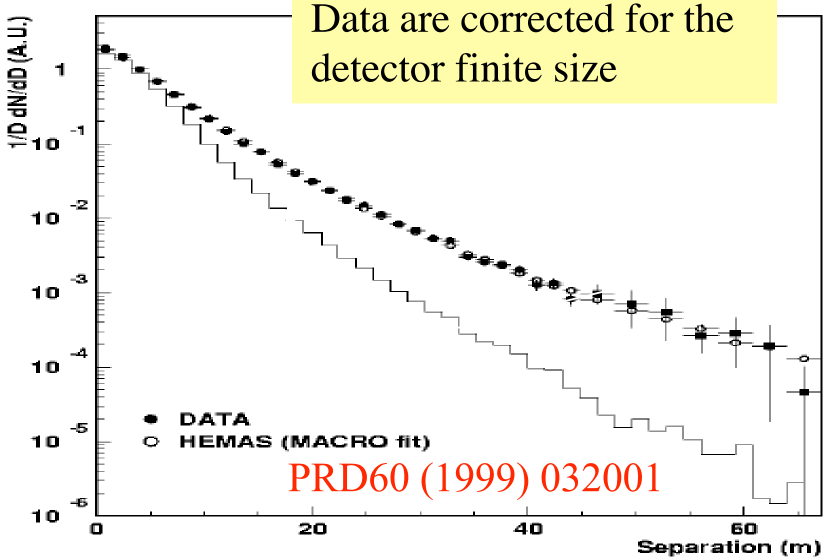
# Atmospheric μ background



2.4 km depth

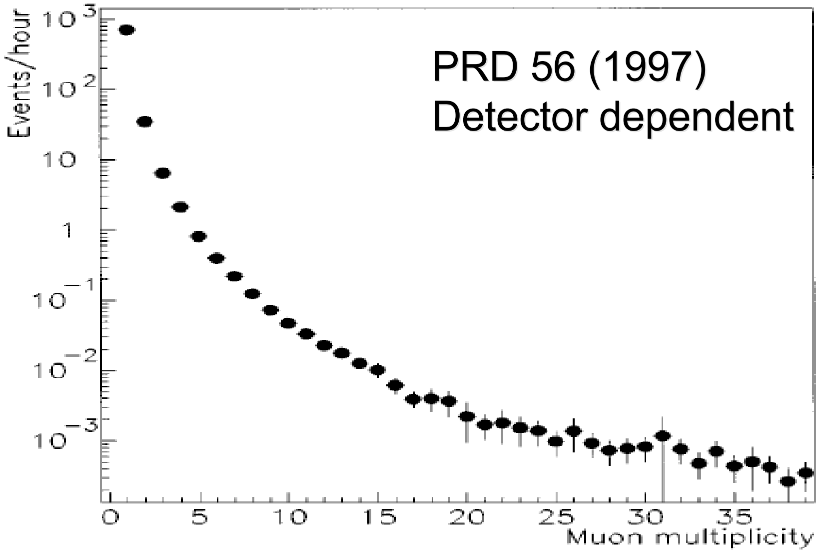
Only upward going muons or showers in the instrumented region can be distinguished from atm muons

MACRO results in 1000 m$^2$ at 1100 m under surface



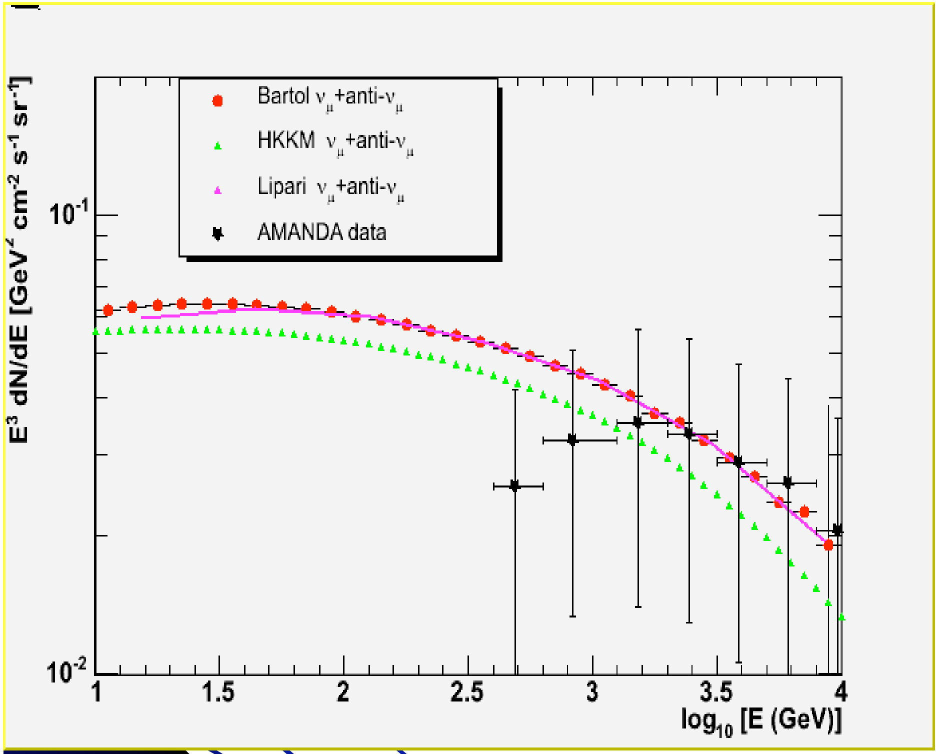
Data are corrected for the detector finite size

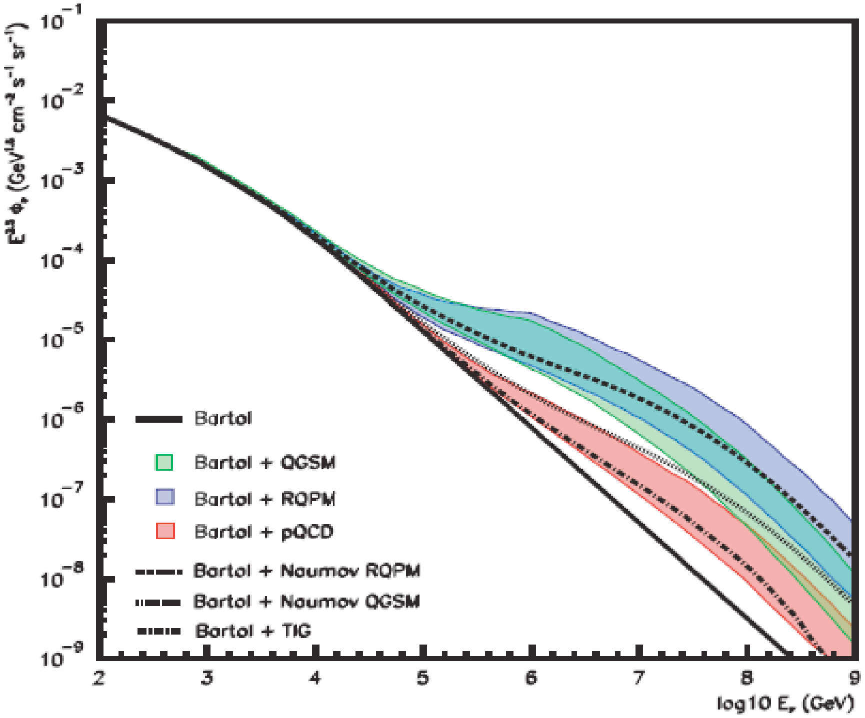
PRD60 (1999) 032001



PRD 56 (1997)
Detector dependent

# Atmospheric νs: a background and a calibration source



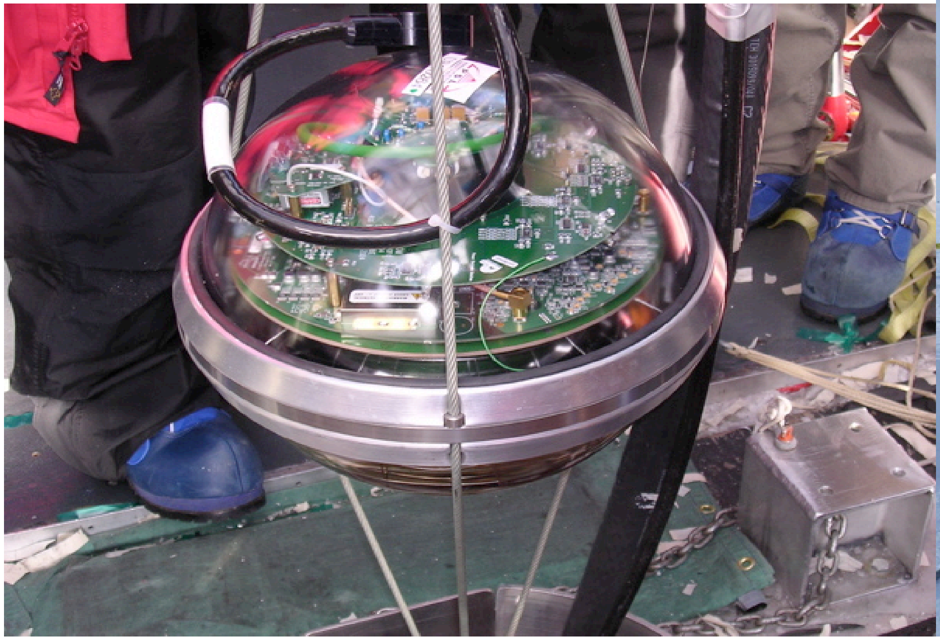


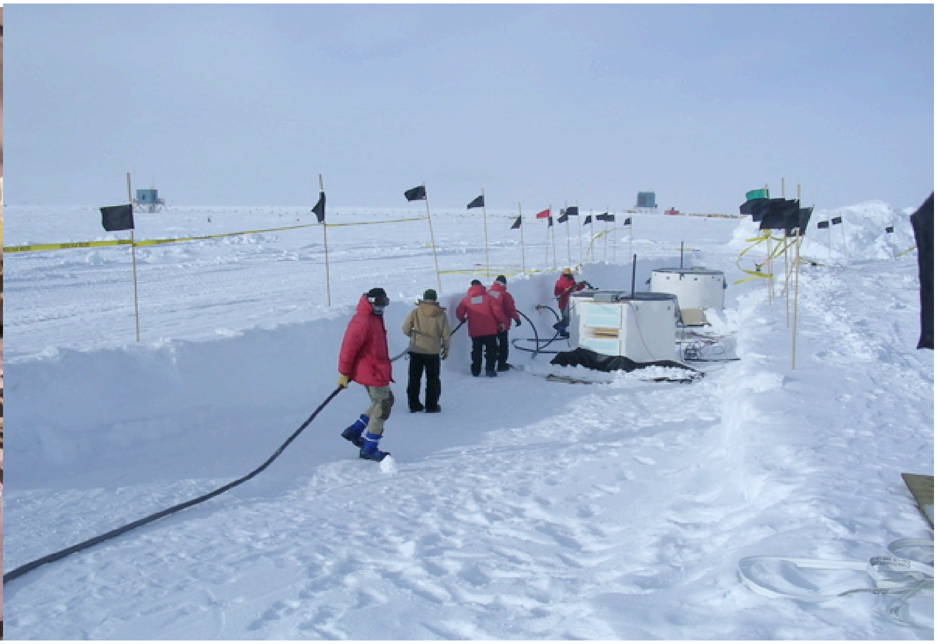
Large uncertainty due to CR flux knowledge around the knee and K physics/charmed meson decays

# Building detectors: towers/lines in the ice


6t for 1 string

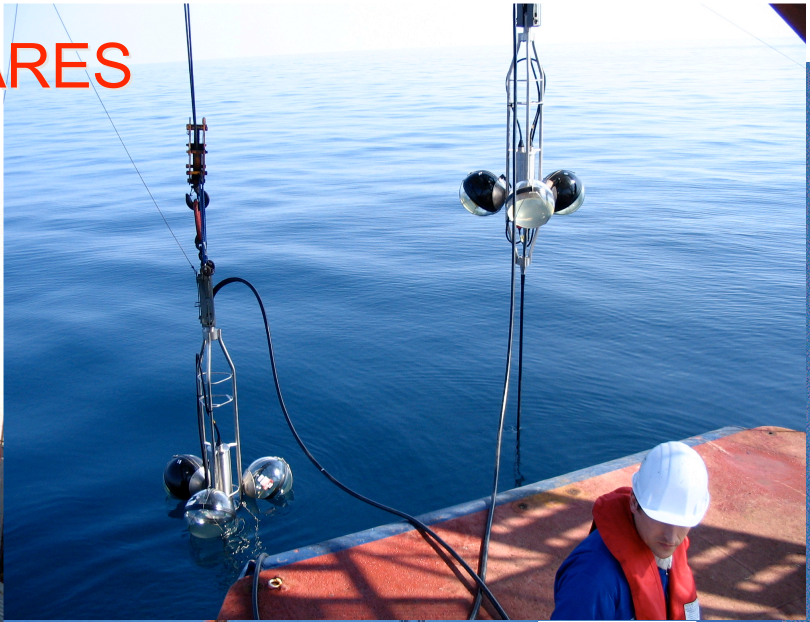

Drilling with hot water jet

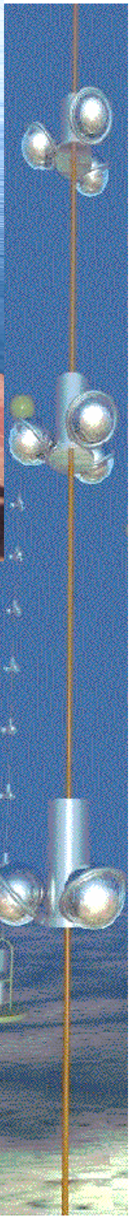


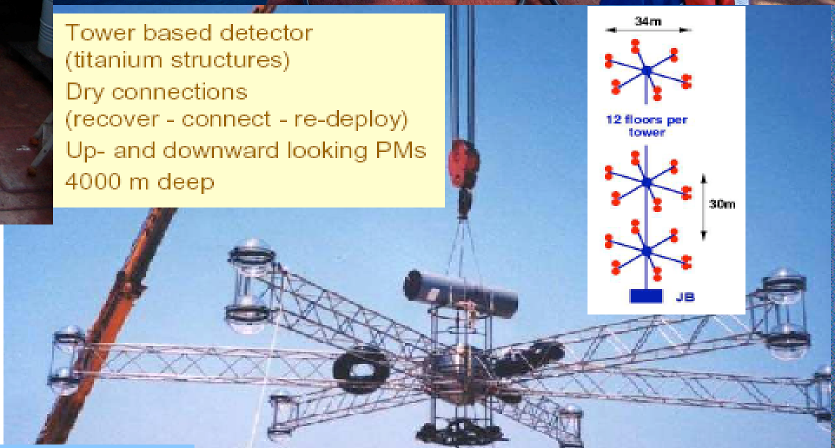


# Building detectors: towers/lines in the sea

ANTARES



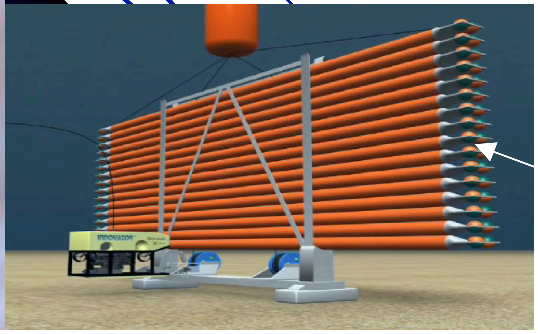


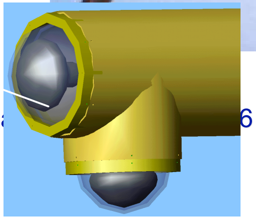


Tower based detector
(titanium structures)
Dry connections
(recover - connect - re-deploy)
Up- and downward looking PMs
4000 m deep

NESTOR

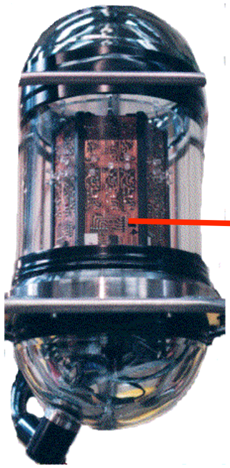
NEMO



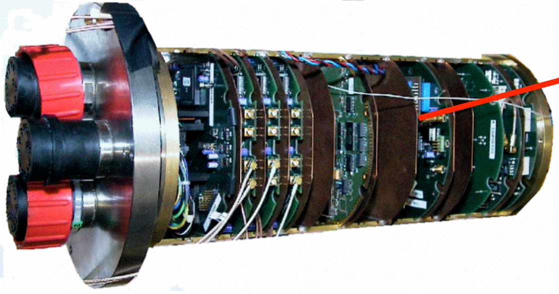


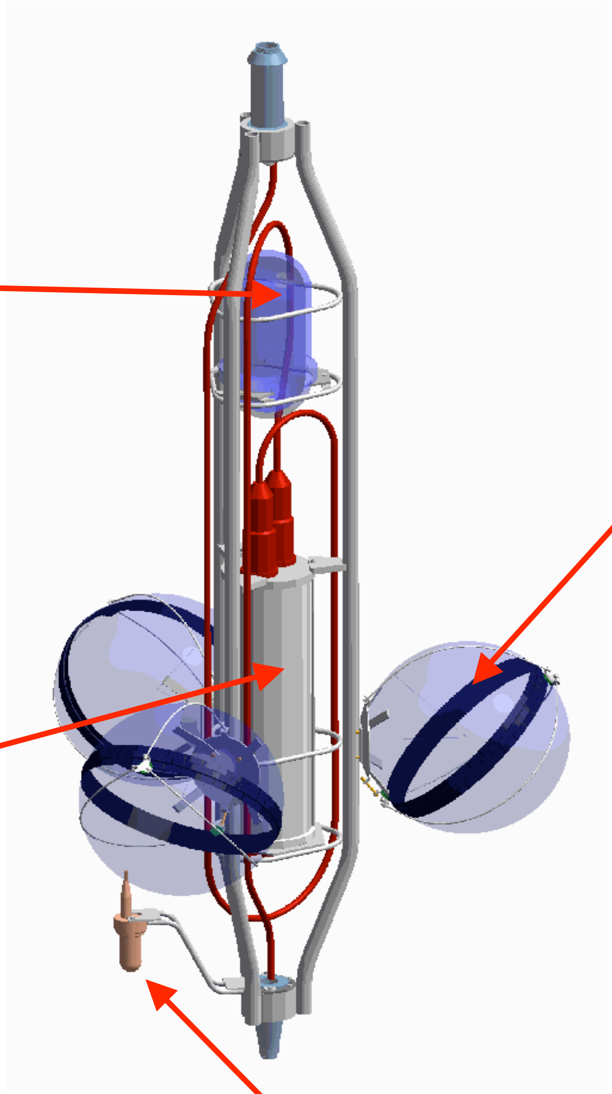
# Basic detector element in the sea

Optical
Beacon
for timing
calibration
(blue LEDs)
1/4 floors



Local Control Module
(in the Ti-cylinder)



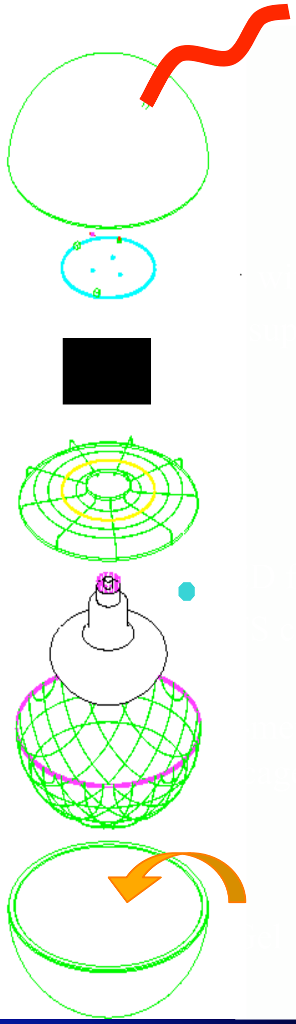


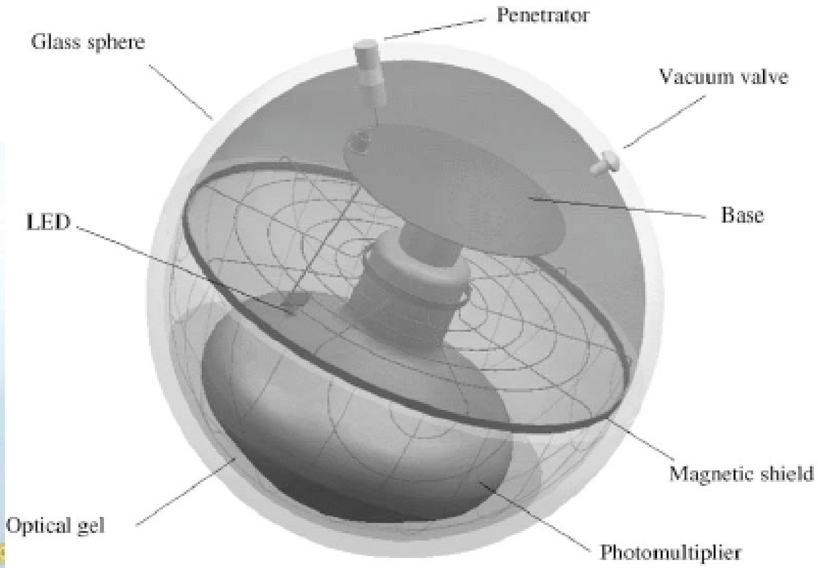
17″ glass sphere
10″ PMT Ham. R7081-20
14 stages

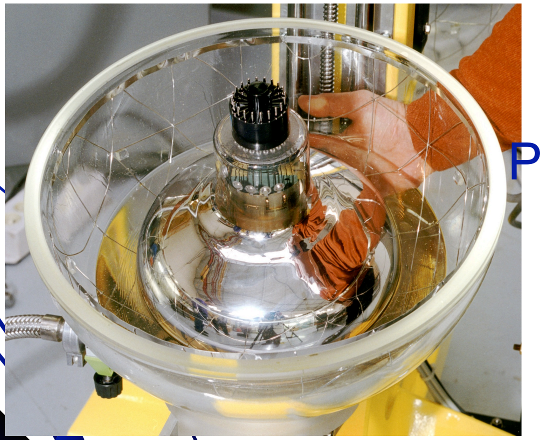
Hydrophone RX

# Optical Modules

Blow-up of an **O**ptical **M**odule







Resistant to >>260 bars

transparent 400-500 nm

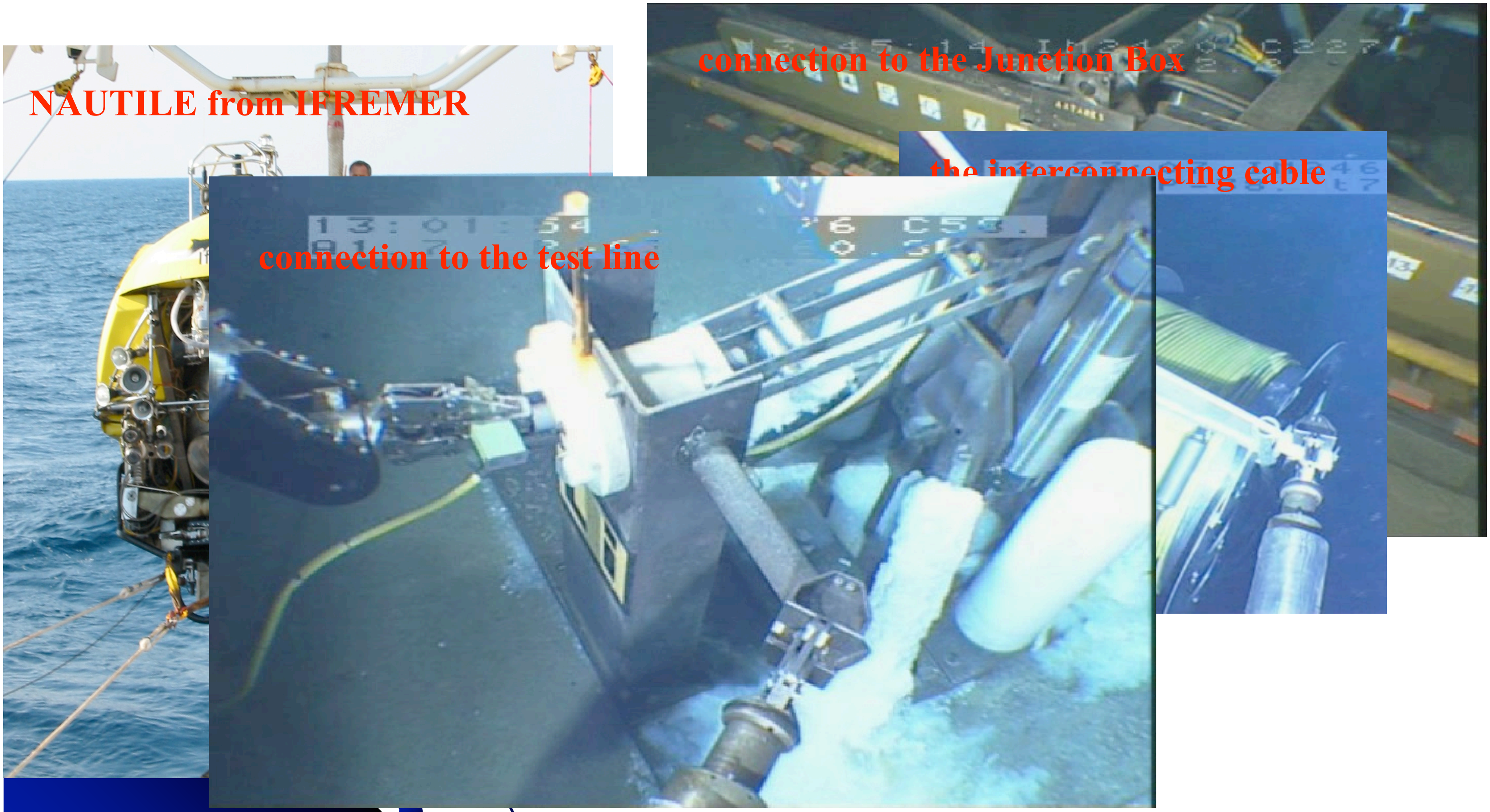
Pressure relation with depth in a media of density ρ

$$p_{\text{at depht h}} = p_{\text{atm}} + \rho g h$$

Weight of liquid column at depth h

About 1 atm / 10 m

# Sea operations: submarine connections



NAUTILE from IFREMER

connection to the Junction Box

the interconnecting cable

connection to the test line

# Monitoring of storey position and orientation

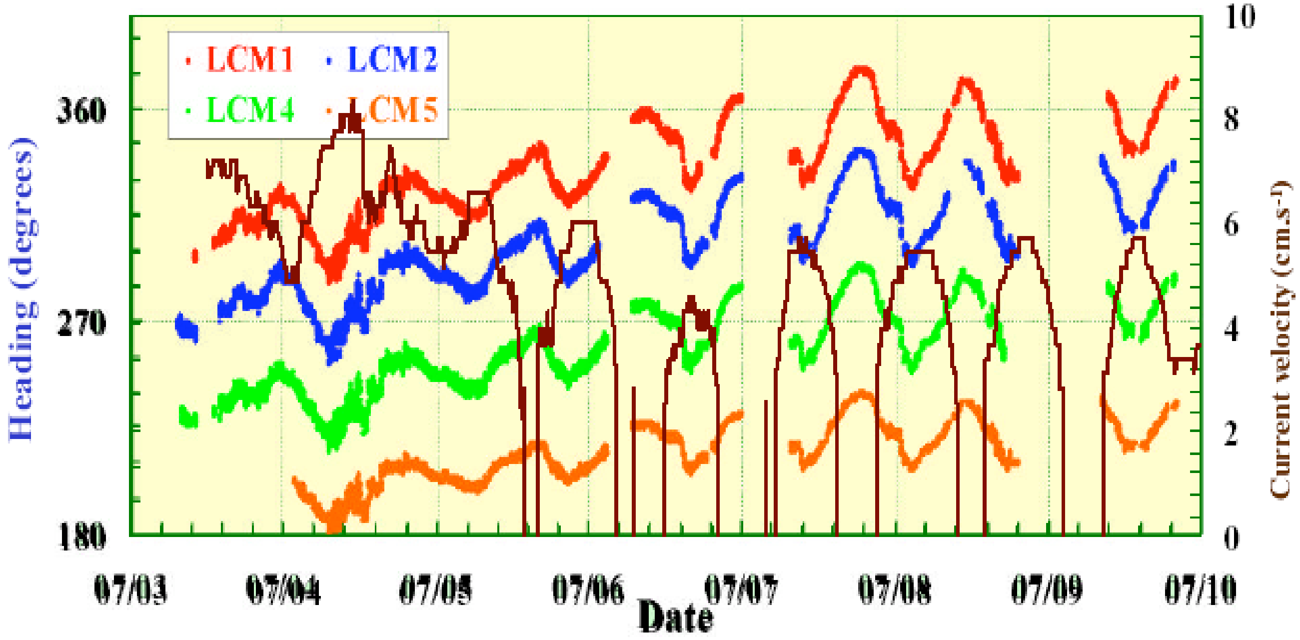
Absolute time: clock system + GPS ⇒ msec accuracy

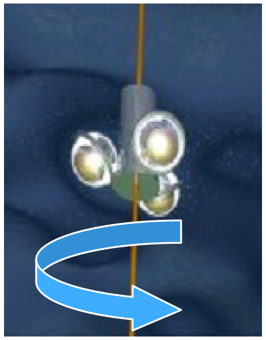
Absolute orientation: <0.1° accuracy through set of transponders whose position is determined with respect to a boat positioned by GPS system

Relative positioning: acoustic triangulation (acoustic beacons at sea floor + hydrophones at storeys)

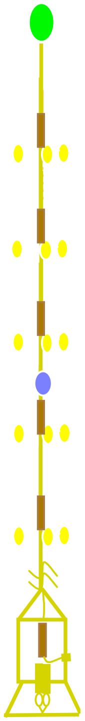
Orientation: compass and tiltmeters in storeys

Accuracy: ~0.5 ns ⇒ ~10 cm





Heading vs time at 4 positions along line ⇒ it moves coherently. Movements correlated to sea current (inertial oscillations due to Coriolis). Line is essentially vertical



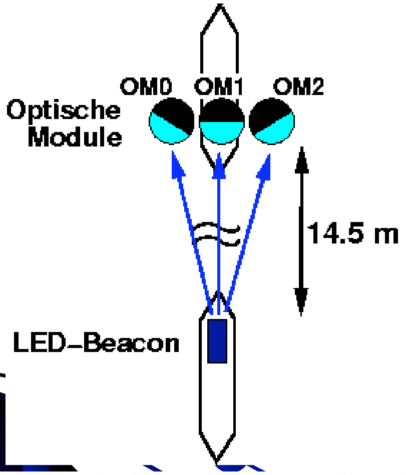
# Some results from the MILOM

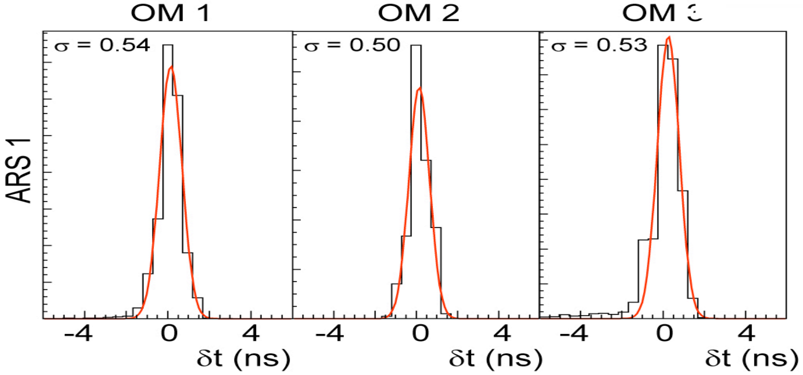
**LED beacons**

**Time calibration with LED beacons:**

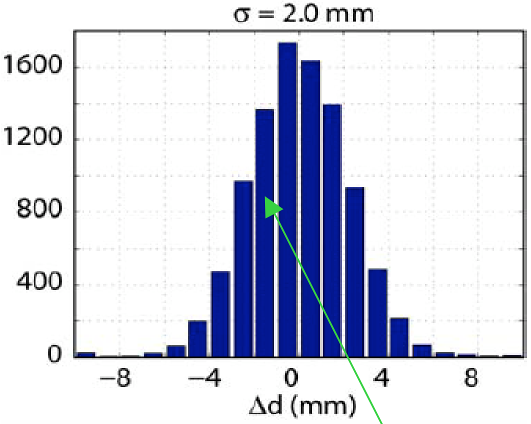
large light pulses (effect of electronic, TTS of PMTs small)

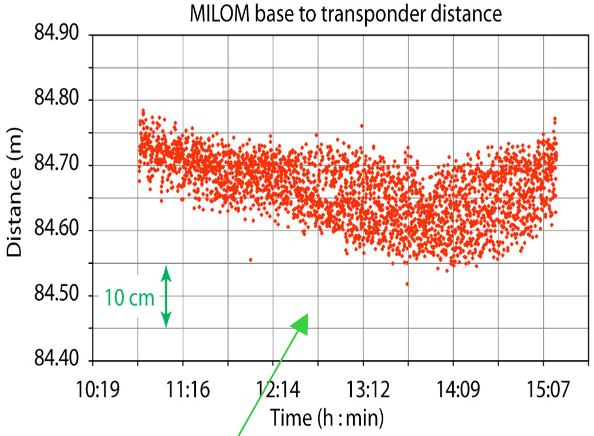
Time difference between OMs and internal PMT of LED beacons

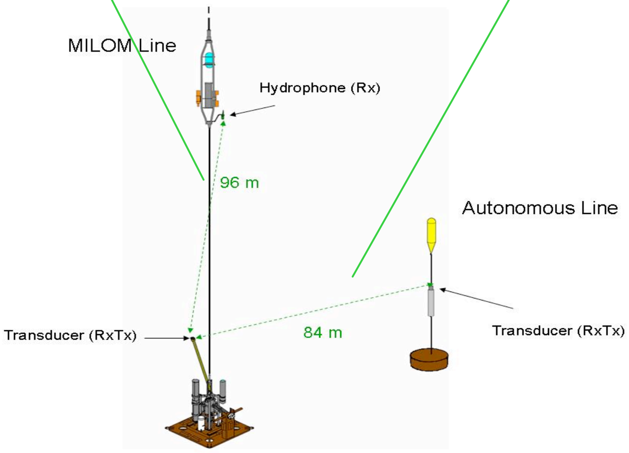


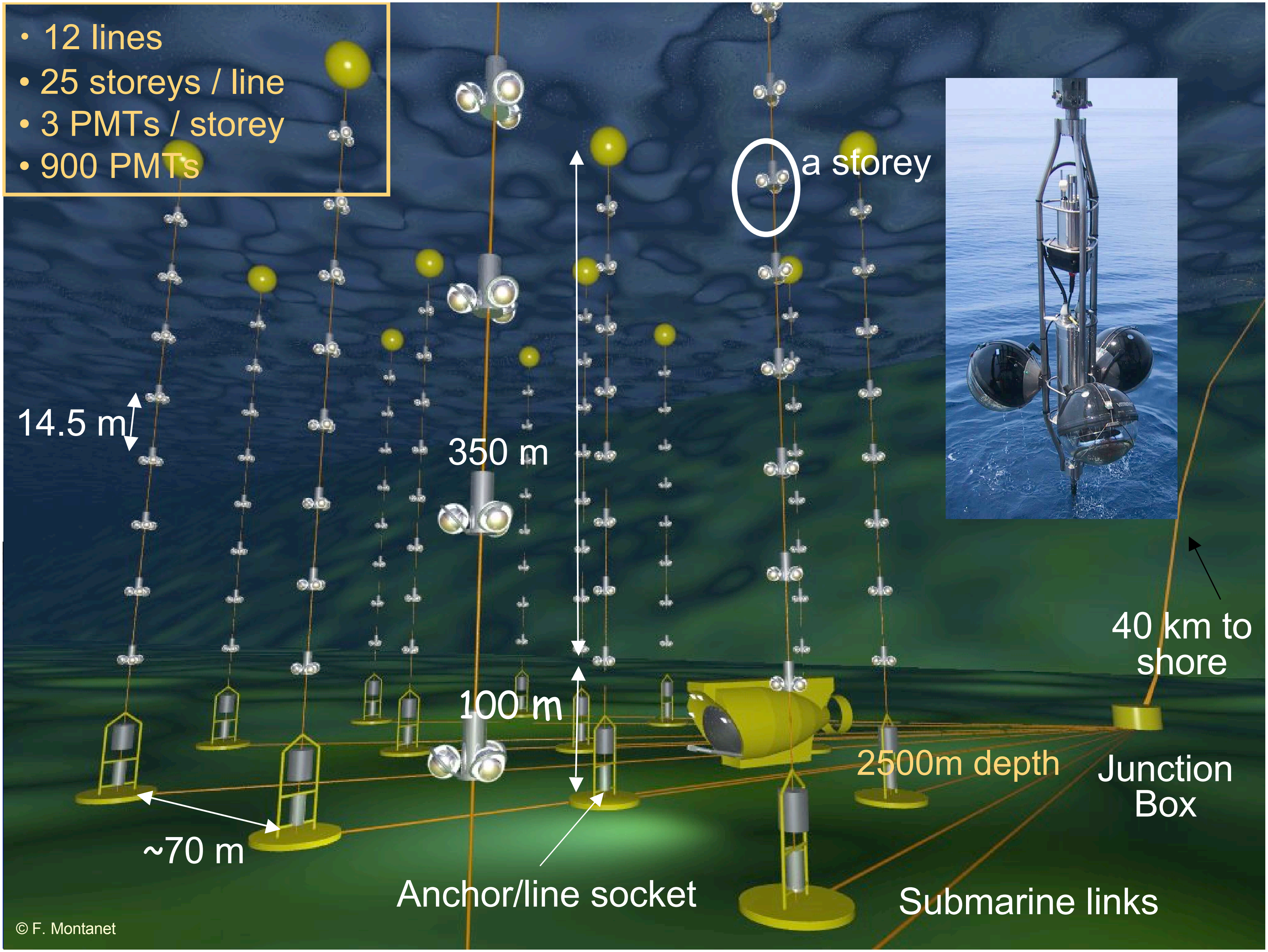


**Acoustic positioning: required precision on 3D position of the OMs is ~10 cm.**









- 12 lines
- 25 storeys / line
- 3 PMTs / storey
- 900 PMTs

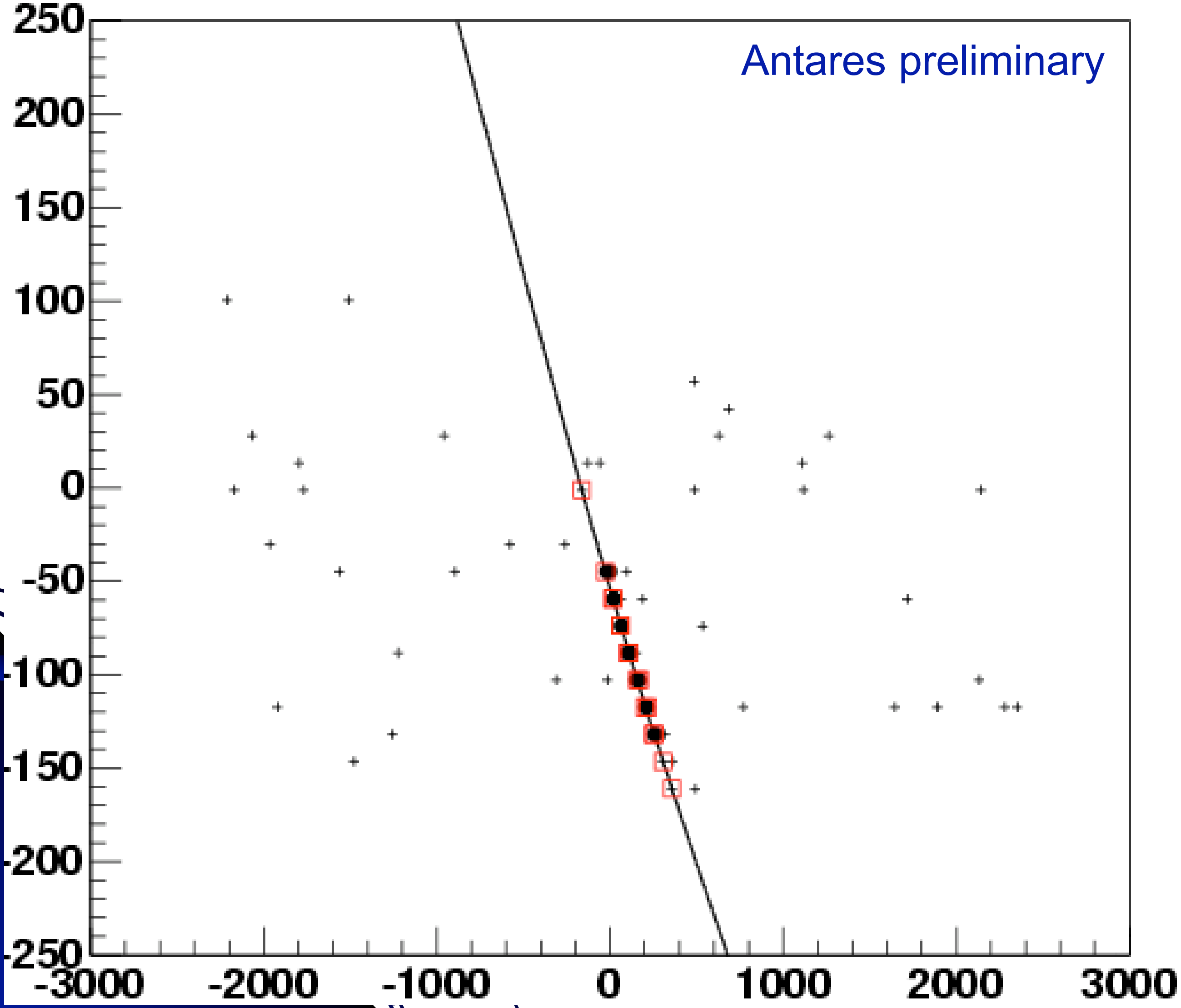
© F. Montanet

# The first line

Deployed on Feb 14

Connected to JB on Mar 2

# Reconstructed muons



- 21240 / 12527
- $\theta = 172^{o}$
- $P(\chi^2,\mathrm{ndf}) = 0.94$

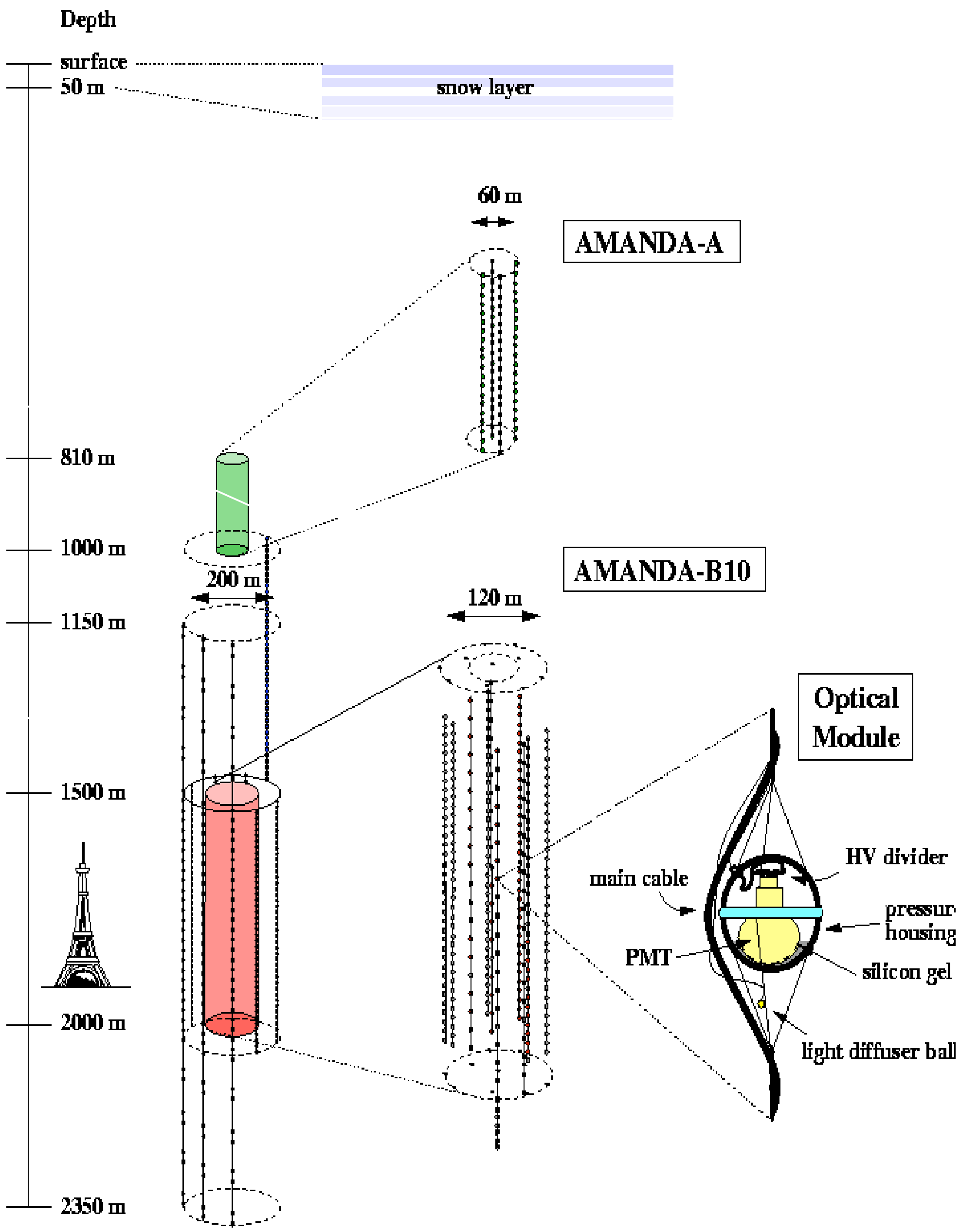
# AMANDA

## AMANDA-B10

- 10 strings
- 302 OM
- 102 diameter
- Years = 1997-99

## AMANDA-II

- 19 strings
- 677 OM
- 200 m diameter
- 400 m tall
- Years >=2000
- Trigger rate 80 Hz



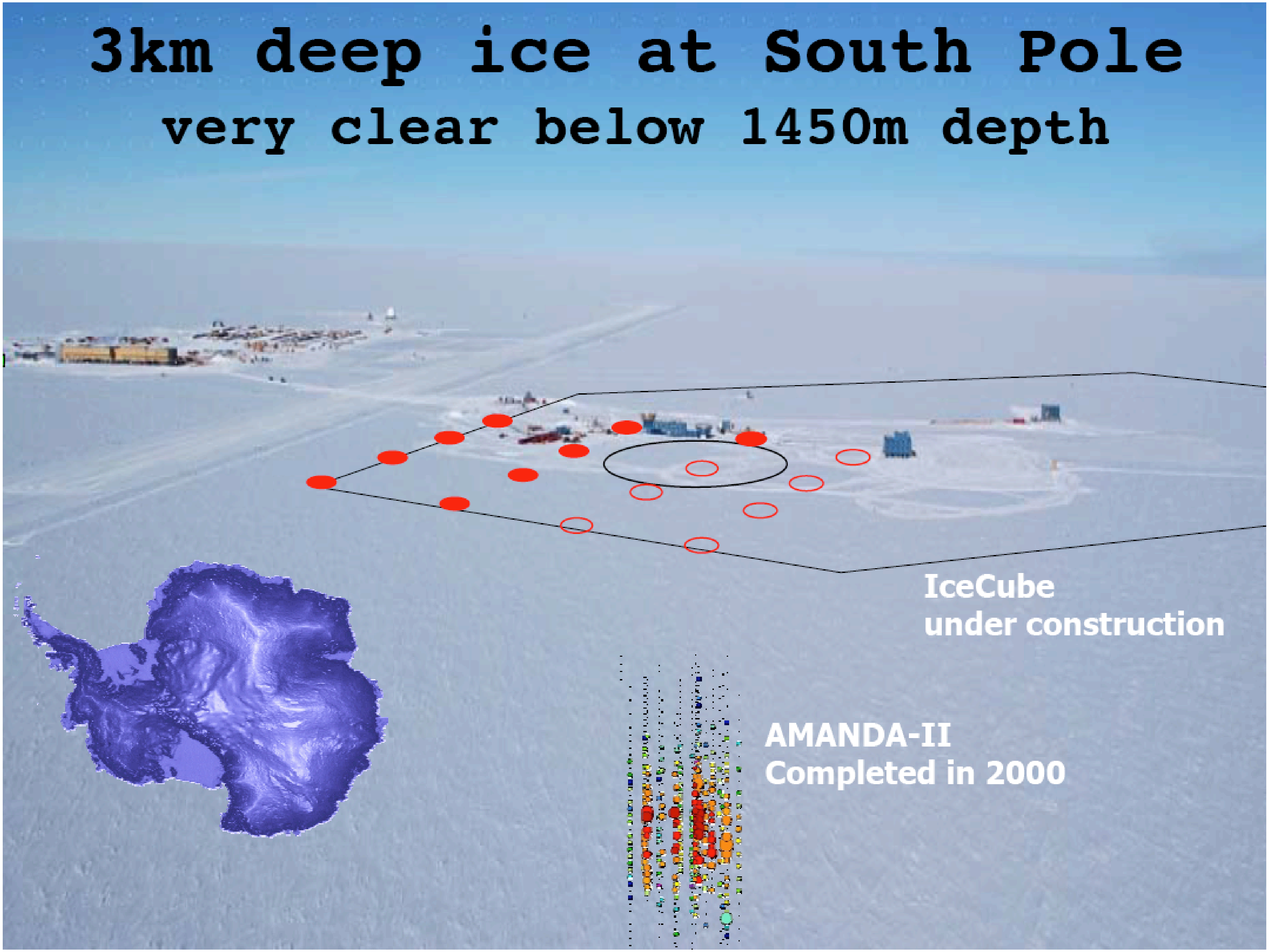
AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

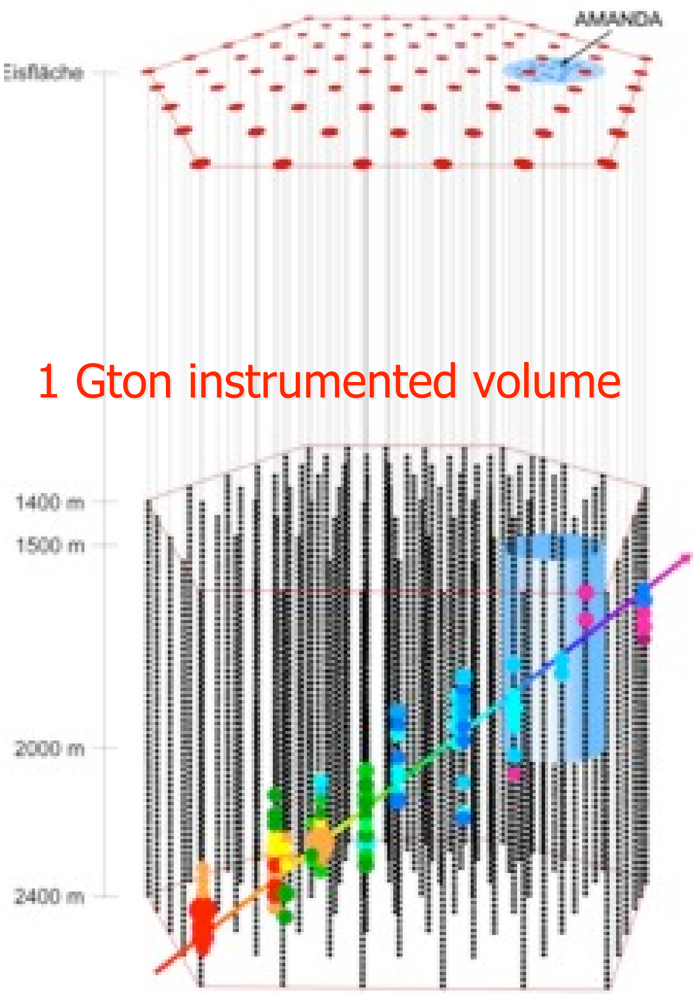
zoomed in on one
optical module (OM)

# 3km deep ice at South Pole

## very clear below 1450m depth



# IceCube: the 1st km$^3$ detector



1 Gton instrumented volume

**4800 OMs/80 strings (60 OM/string spaced by 17 m) DOM: 10 inch Hamamatsu R-7081 (digitized data)**

**IceTop: $E_{th}$ = 300 TeV**
**80 pair of 2m diameter tanks close to each hole filled by 1m ice instrumented with 2 DOMs**
**veto and calibration for angular response, CR composition**
**100 events/d with coincident $\mu$s**

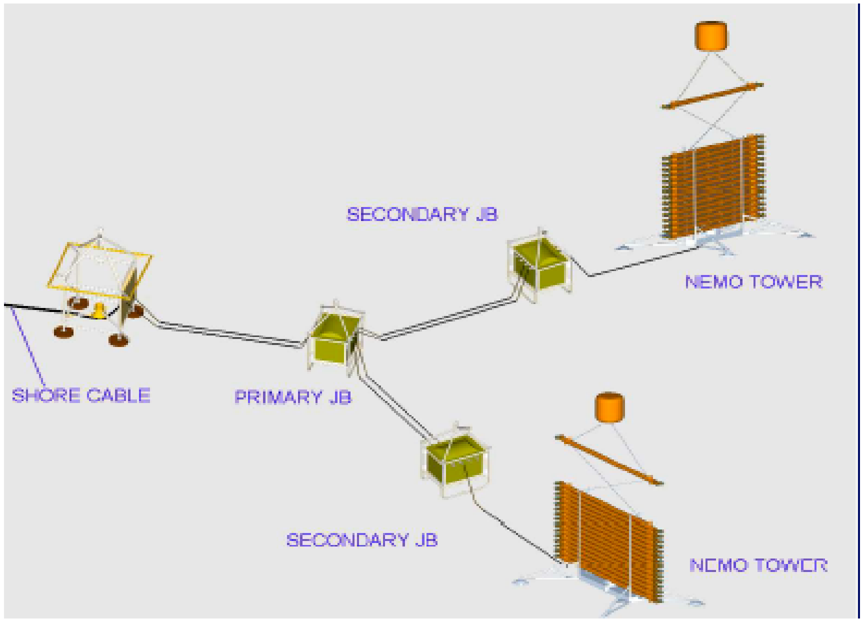
**Last season: 76 DOMs working and successfully deployed: 1st IceCube string 8 IceTop tanks deployed.**

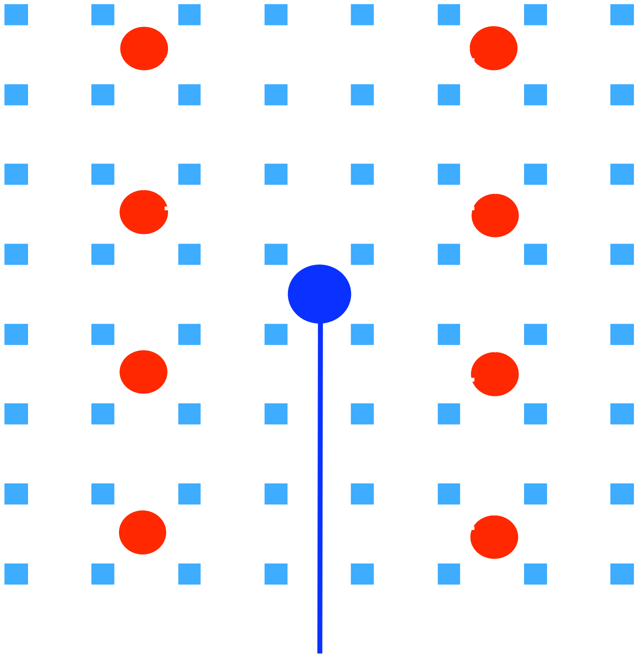
# NEutrino Mediterranean Observatory

http://nemoweb.lns.infn.it

- **R&D Phase (1999-2002):** >20 sea campaigns ⇒ optimal site Capo Passero 3500 m depth , 80km offshore; R&D on materials, large area PMTs and mechanical structures for long-term measurements in sea water, low power consumption electronics; feasibility study and simulations

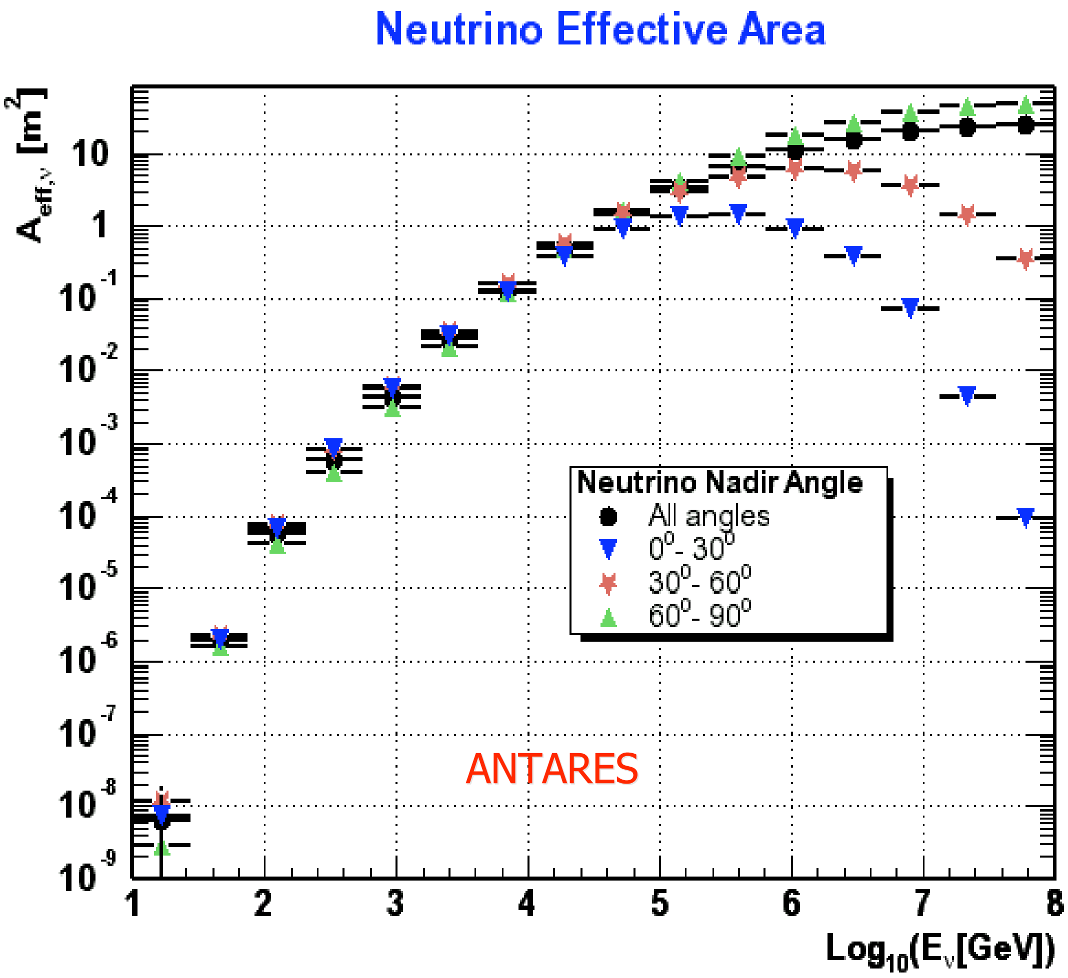
•Phase 1 (2002-2006) Advanced R&D:
1st multi-purpose underwater Lab

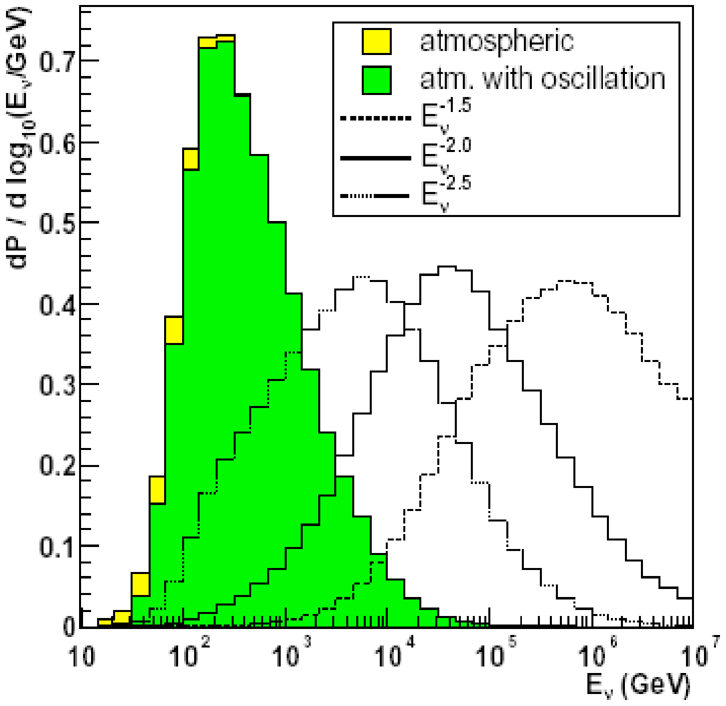




Montaruli, Apr. 2006

# Detector Parameters

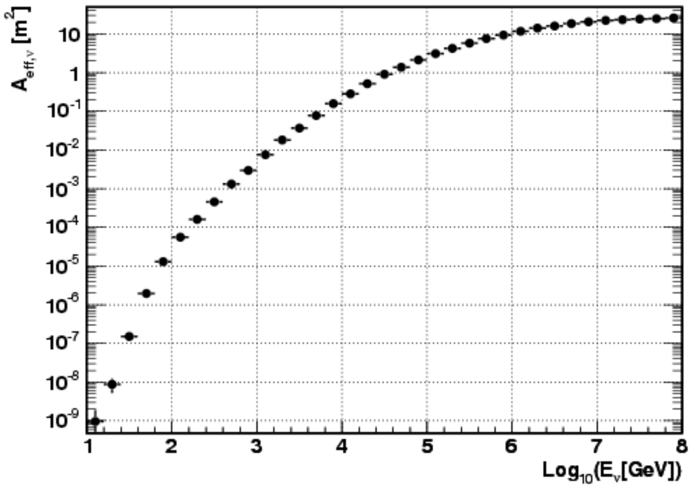




$$N_\mu = \int A^{\nu}_{eff}\,(E_\nu,\theta_\nu,\phi_\nu)\,\frac{d\Phi_\nu}{dE_\nu\, d\Omega_\nu}\, dE_\nu\; d\Omega_\nu$$

ntaruli, Apr. 2006

# Effective areas for $\nu_\mu$

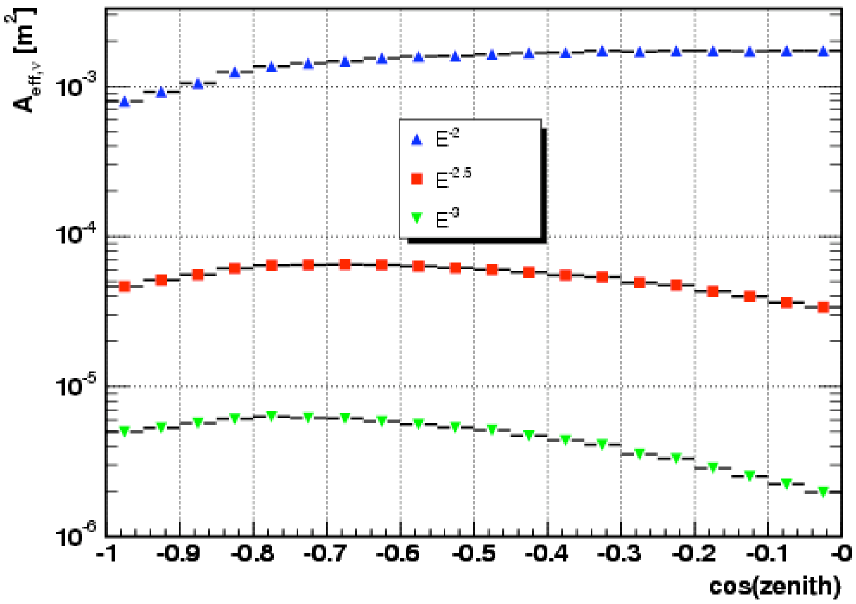


Neutrino Effective Area vs logE

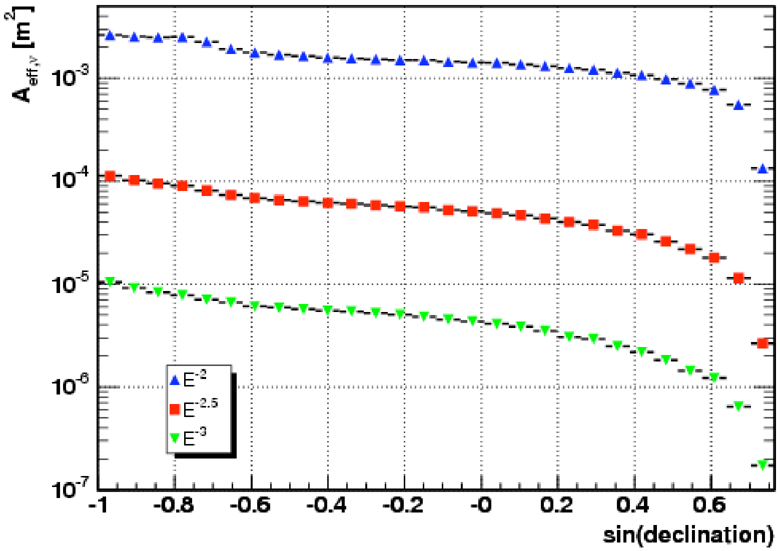
$$A^{\nu}_{eff}\left(E_\nu,\vartheta_\nu,\phi_\nu\right)=\boxed{V^{\nu}_{eff}}\cdot\rho N_A\sigma\left(E_\nu\right)\cdot P_{Earth}\left(E_\nu\right)$$

$$\Big\downarrow$$

$$\frac{N_x\left(E_\nu,\vartheta_\nu,\phi_\nu\right)}{N_{gen}\left(E_\nu,\vartheta_\nu,\phi_\nu\right)}\cdot V_{gen}$$

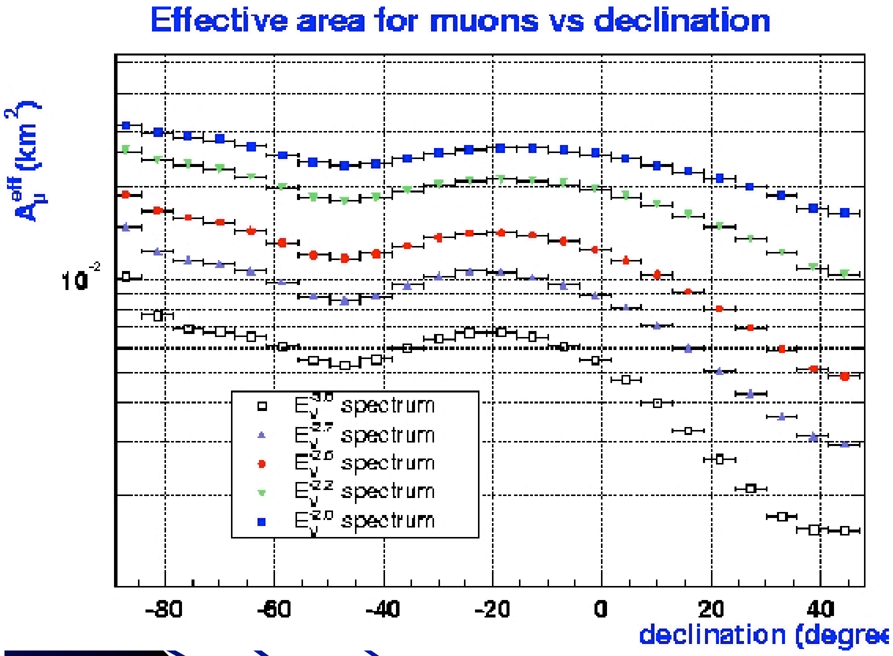


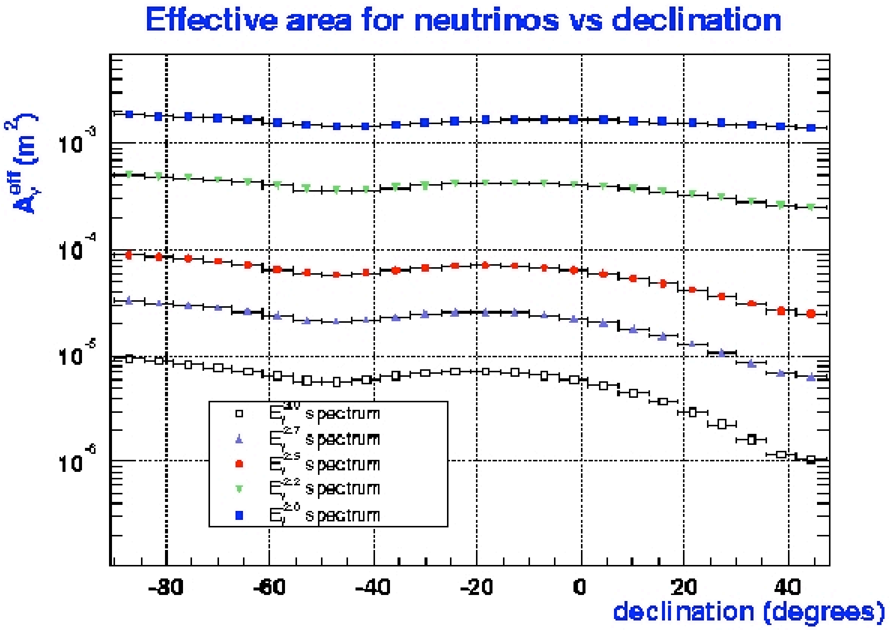
Neutrino Effective Area vs cos(zenith)



Neutrino Effective Area vs sin(declination)

# Effective areas for muons and neutrinos


Effective area for muons vs declination

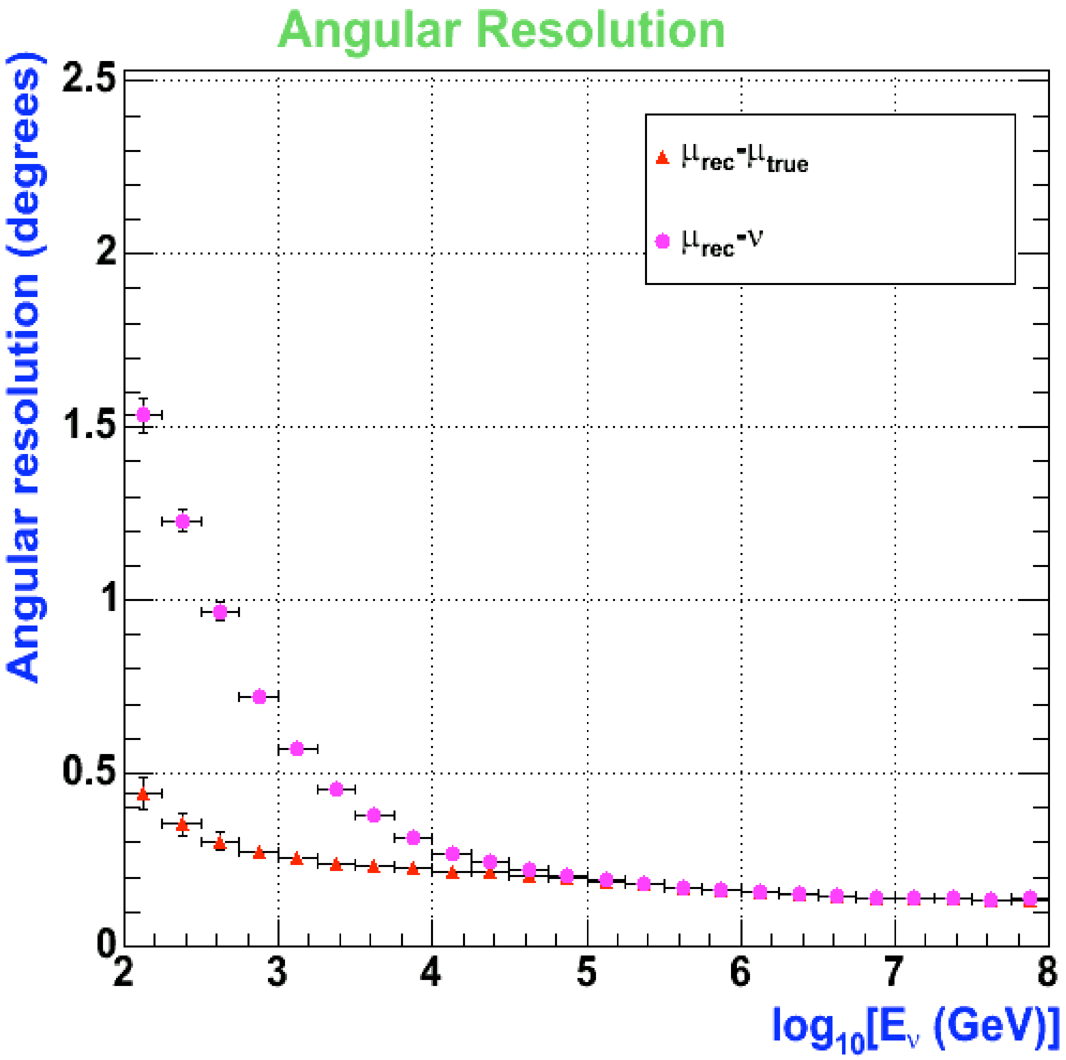

Effective area for neutrinos vs declination

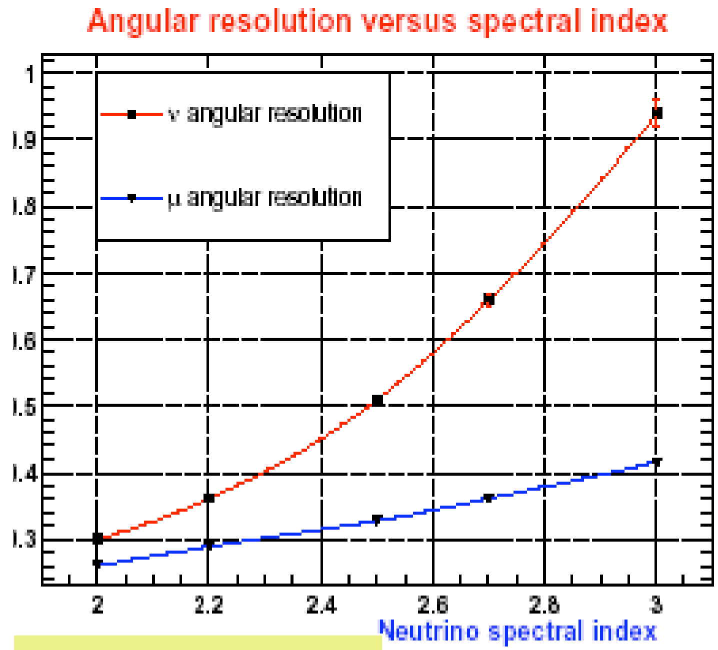
Teresa Montaruli, Apr. 2006

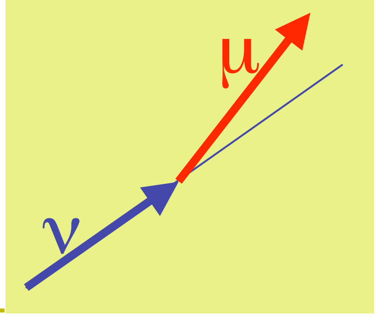
# Detector Parameters

Sensitivity for point-like sources: $N/\mathrm{sqrt}(B) \propto \sqrt{(A^{eff}T)}/\Delta\theta$

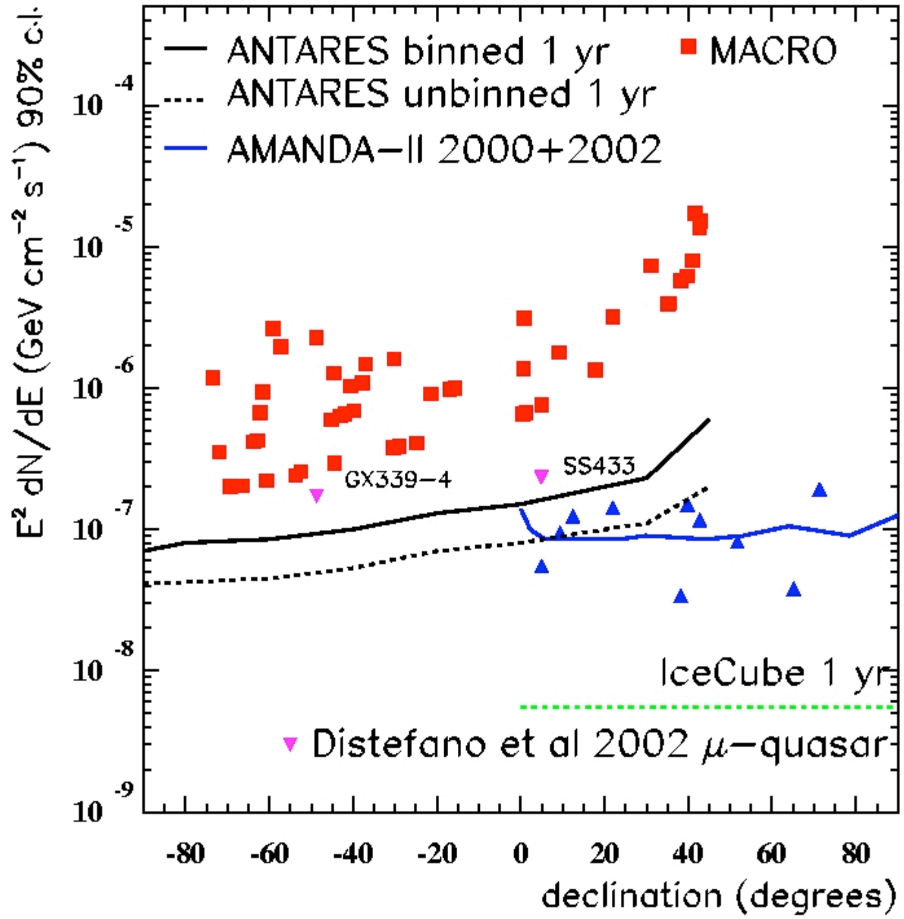
$N = A^{eff}\, T$ $B = A^{eff}\, T\, \Delta\theta^2$


Angular Resolution


Angular resolution versus spectral index



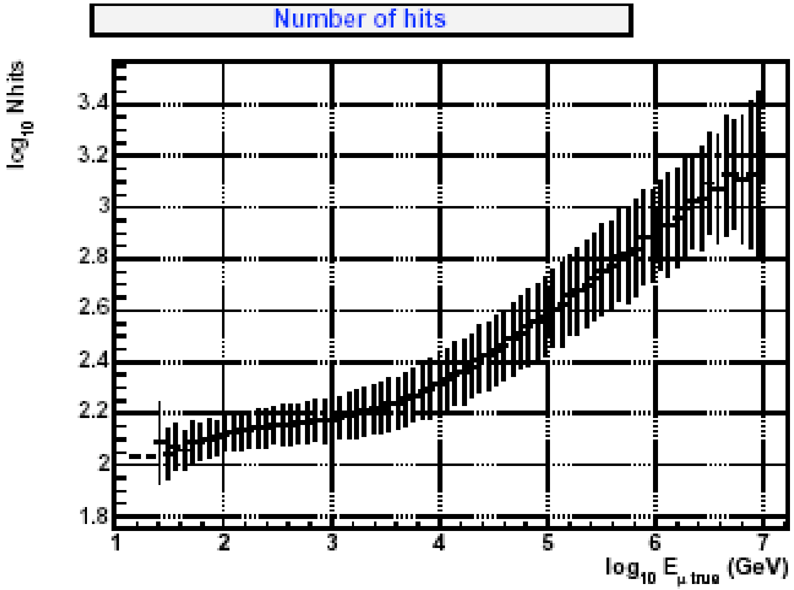
# Point-like sources

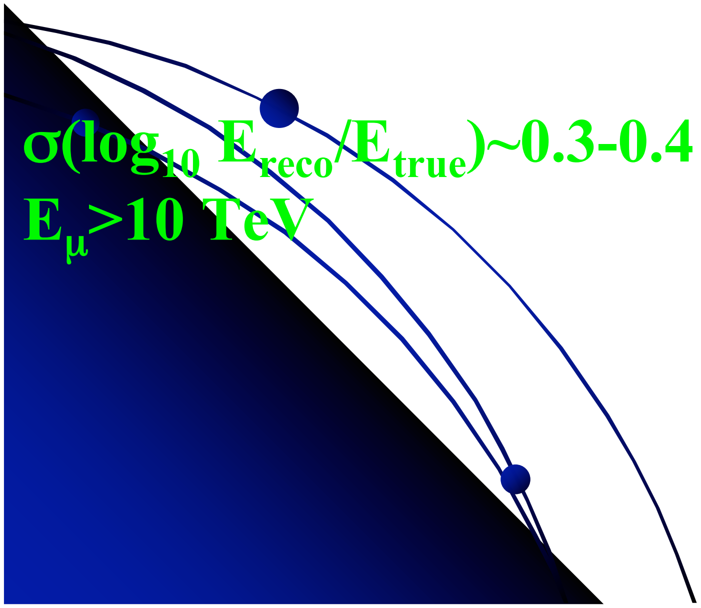


# Energy Estimators and spectra unfolding

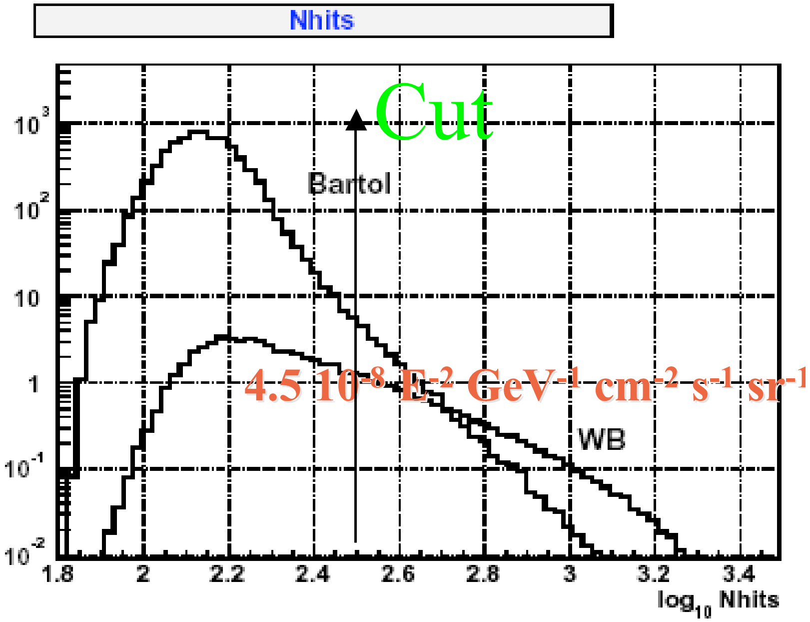
Various estimators:

- Number of Hits
- hit amplitude compared to MIP expected one
- dE/dx = amplitude/track length



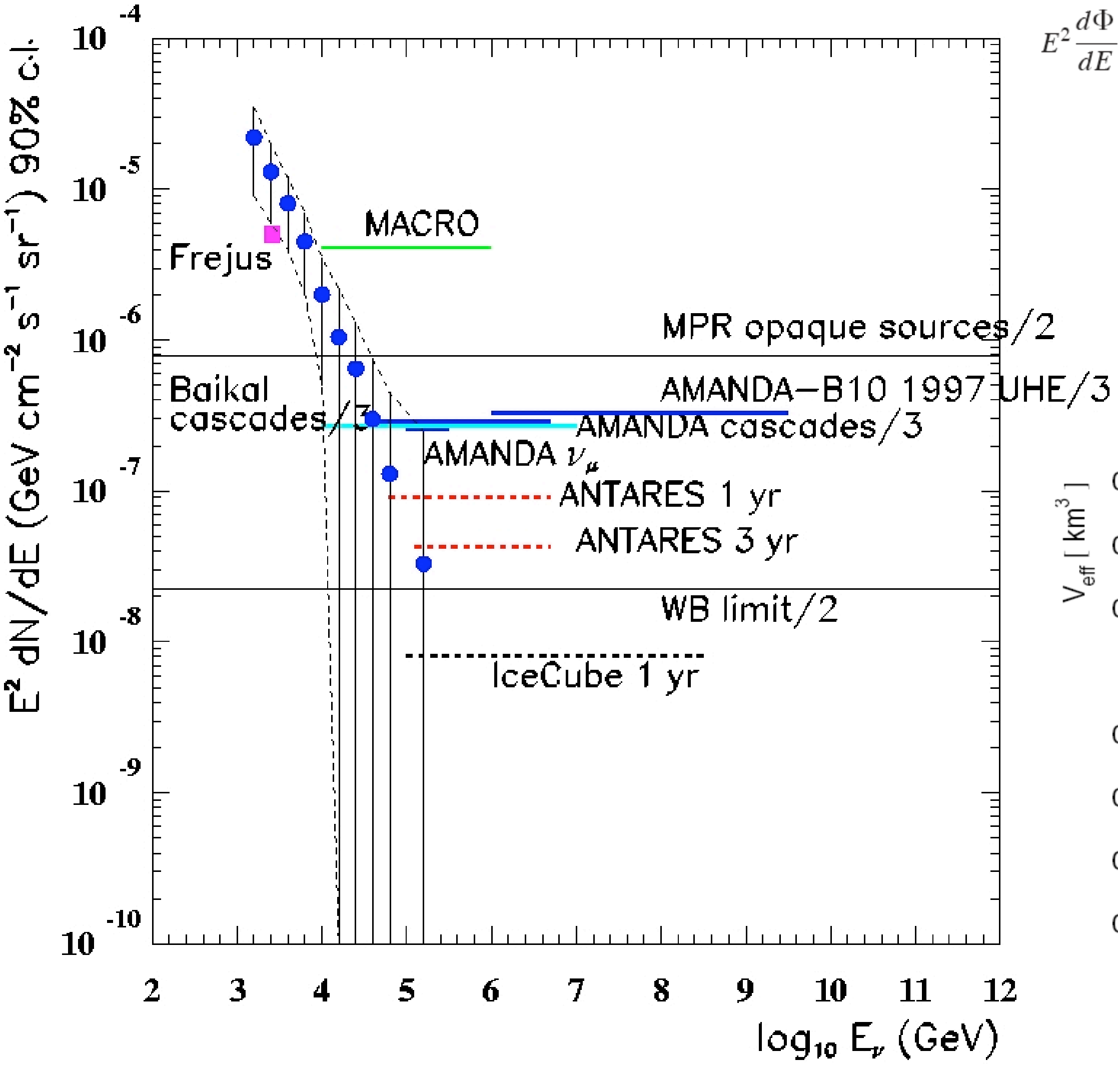


$\sigma(\log_{10} E_{reco}/E_{true})$~0.3-0.4 for $E_\mu$>10 TeV

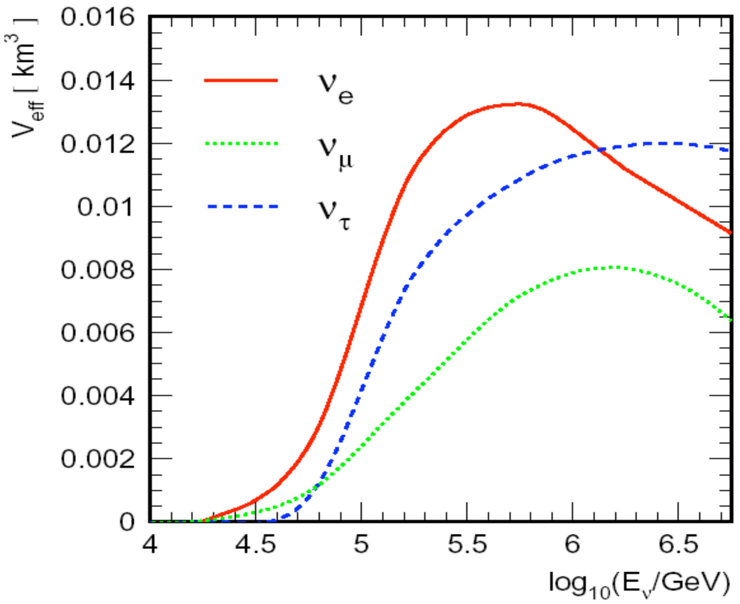


# Diffuse $\nu_\mu$ Fluxes

## 90% cl $E^{-2}$ $\nu$ flux



$$E^2\frac{d\Phi}{dE} = \frac{N_{90\%}}{T N_A \rho_{ice}\sum_l f_l \int E^{-2}\xi_l(E,\theta)\sigma^l_{tot}(E)V^l_{eff}(E,\theta)\,d\Omega\,dE}$$



Neutrino astronomy is a new adventure towards our understanding