

# Status of ANTARES and perspectives for the Mediterranean $\text{km}^3$ Neutrino Detector

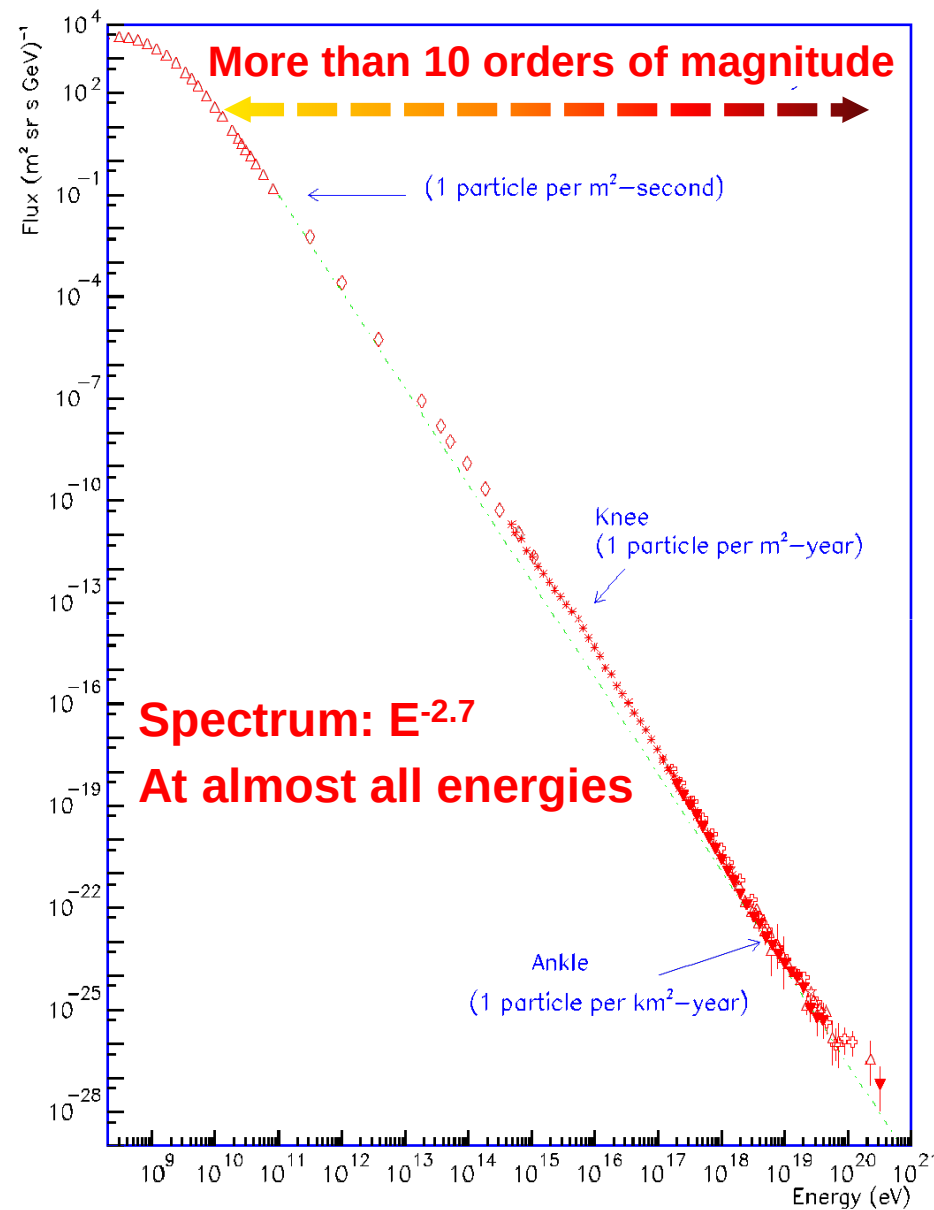


**Giorgio Riccobene**  
**INFN-LNS**  
**Spåtind 2010**

**Nordic Conference in Particle Physics**



# The Cosmic Ray (CR) Spectrum



**The CR  
sources are  
still unknown**



# The Fermi Acceleration Mechanism

*Observed  $E^{-2.7}$  spectrum*

*Non-thermal spectrum. Statistical acceleration*

*Fermi's idea:*

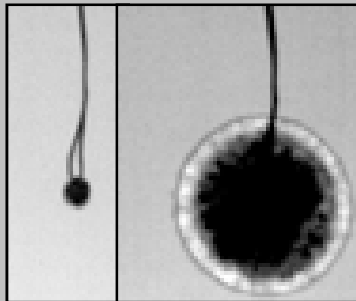
*Particles gain energy hitting on clouds moving at  $V \ll c$  (inefficient)*

*Bell's shock acceleration:  $E^{-(2-2.1)}$  ( $\times E^{-0.6}$  factor from confinement in the Galaxy)*

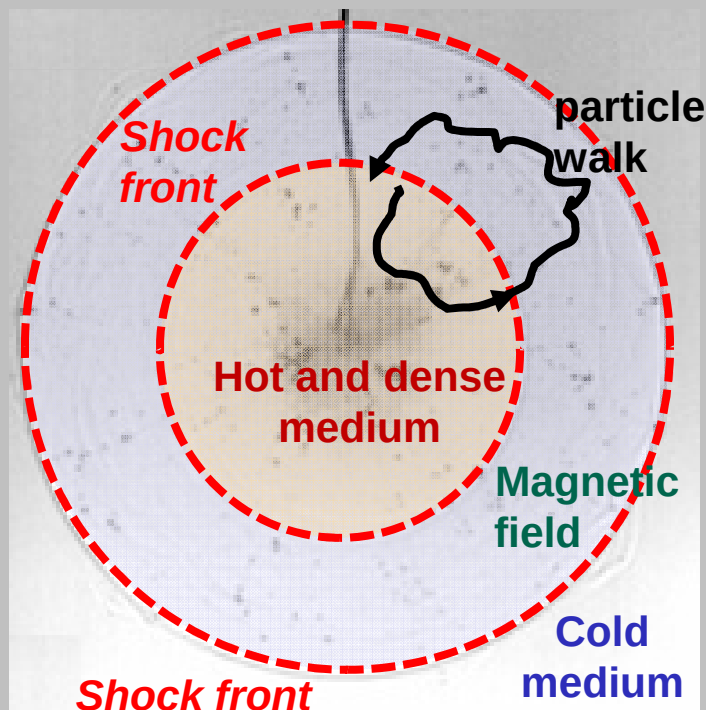
*Each time a particle hit on the shock front it gains energy*

*charged particles are confined by the object magnetic field*

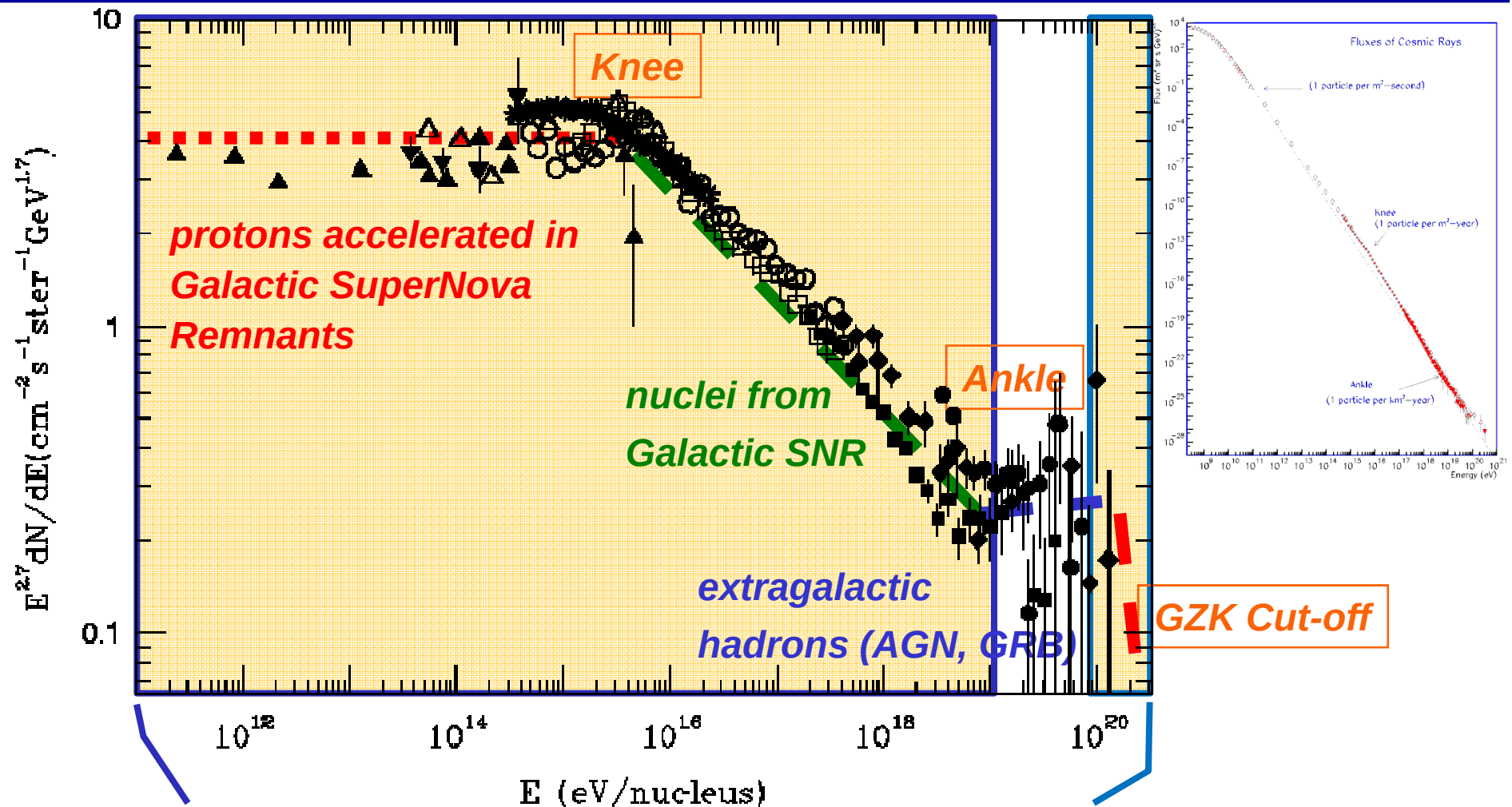
*maximum energy  $\propto$  number of hits  $\propto$  (confinement)  $B \times R$*



*Shock wave produced by the detonation of a TNT charge*



# CR Origin: the Standard Scenario



Hadrons deflected by the Galactic magnetic fields

Hadrons absorbed by the interaction with CMBR:  $p + \text{CMBR} \rightarrow \Delta^+$

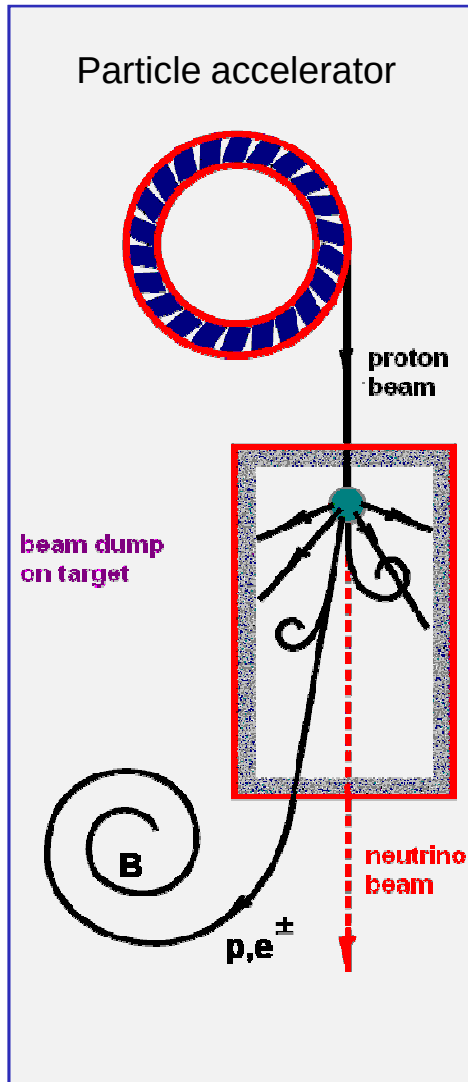
*Sources of high energy hadrons exist*

*but just a little energy window for proton astronomy*



# The Astrophysical Beam Dump

*Fermi acceleration of protons and electrons in astrophysical sources*



Spectrum  $dN_{p,e}/dE \propto E^{-2}$

**Hadronic HE  $\nu$  and  $\gamma$  production**

$p + p$  (SNR, X-Ray Binaries)  $\rightarrow X, \pi$

$p + \gamma$  (AGN, GRB,  $\mu$ QSO)  $\rightarrow N\pi$

Decay of pions

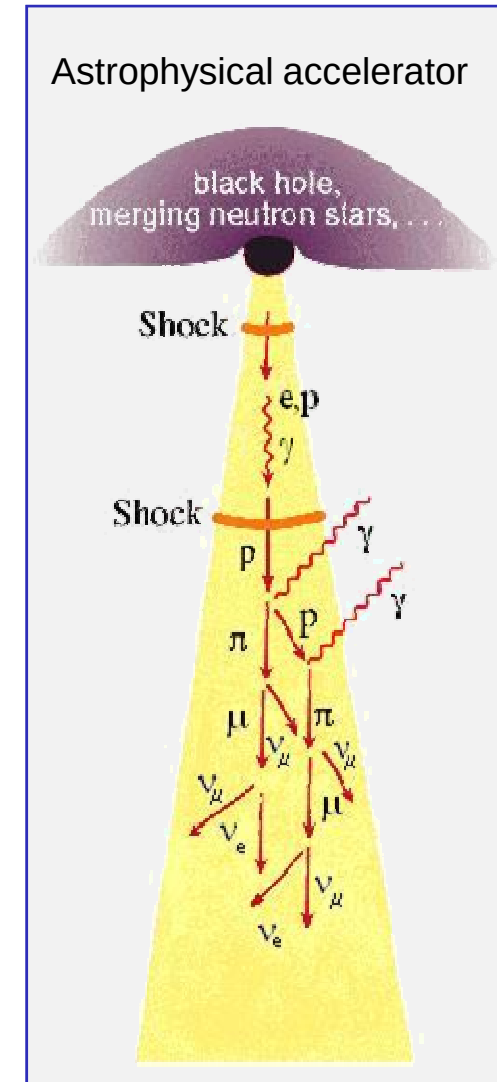
**neutral pions  $\rightarrow$  HE gammas**

**charged pions  $\rightarrow$  HE neutrinos**

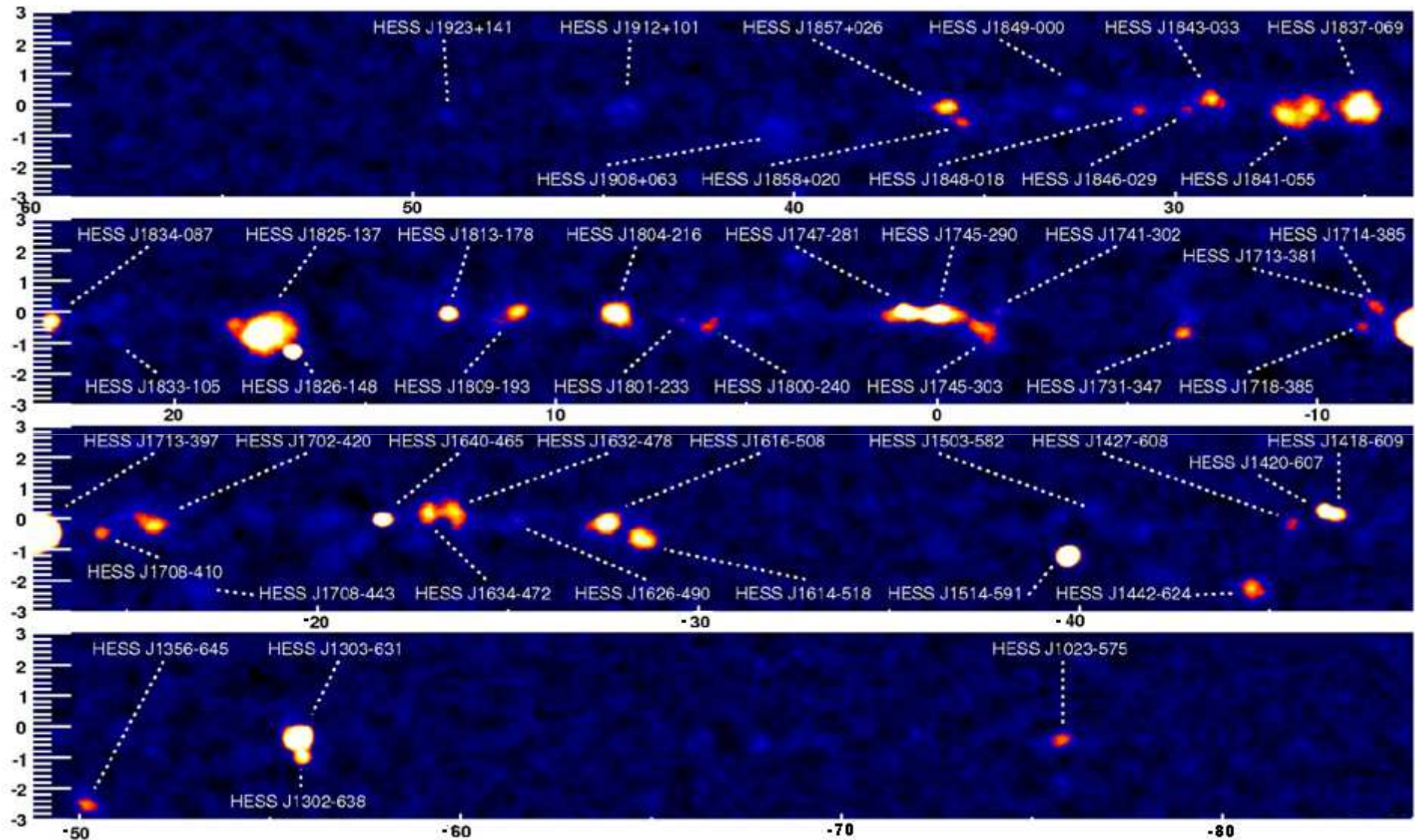
**Leptonic HE  $\gamma$  production**

synchrotron radiation followed by IC

$e + \gamma_{\text{Synchrotron}} \rightarrow e' + \gamma_{\text{HE}}$



# The TeV gamma ray sky



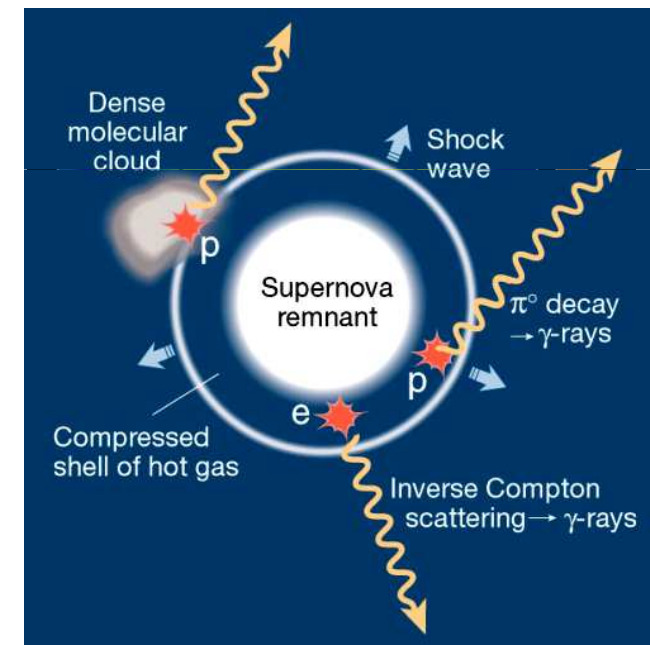
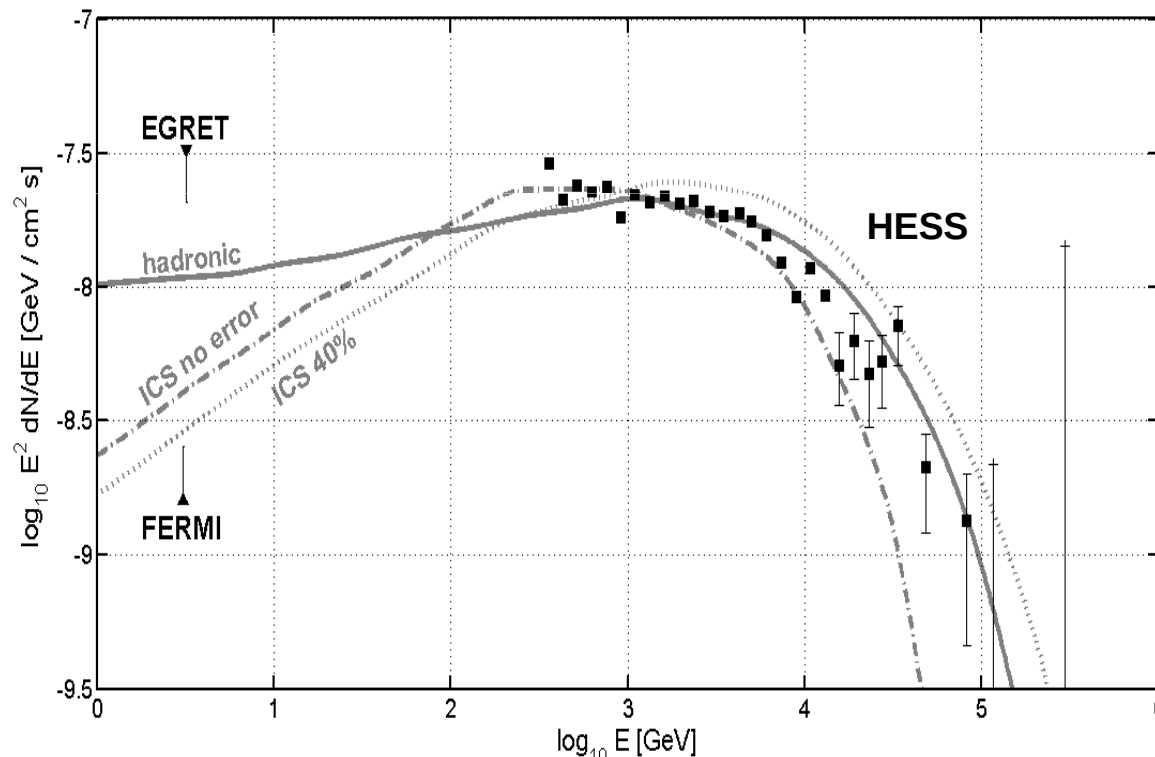
Galactic plane survey by HESS (2009)

# First Hadronic Gamma Ray Sources detection ? (HESS)

*The Galactic SNR RXJ1713.7-3946:*

*proton acceleration + beam dump on nearby molecular clouds*

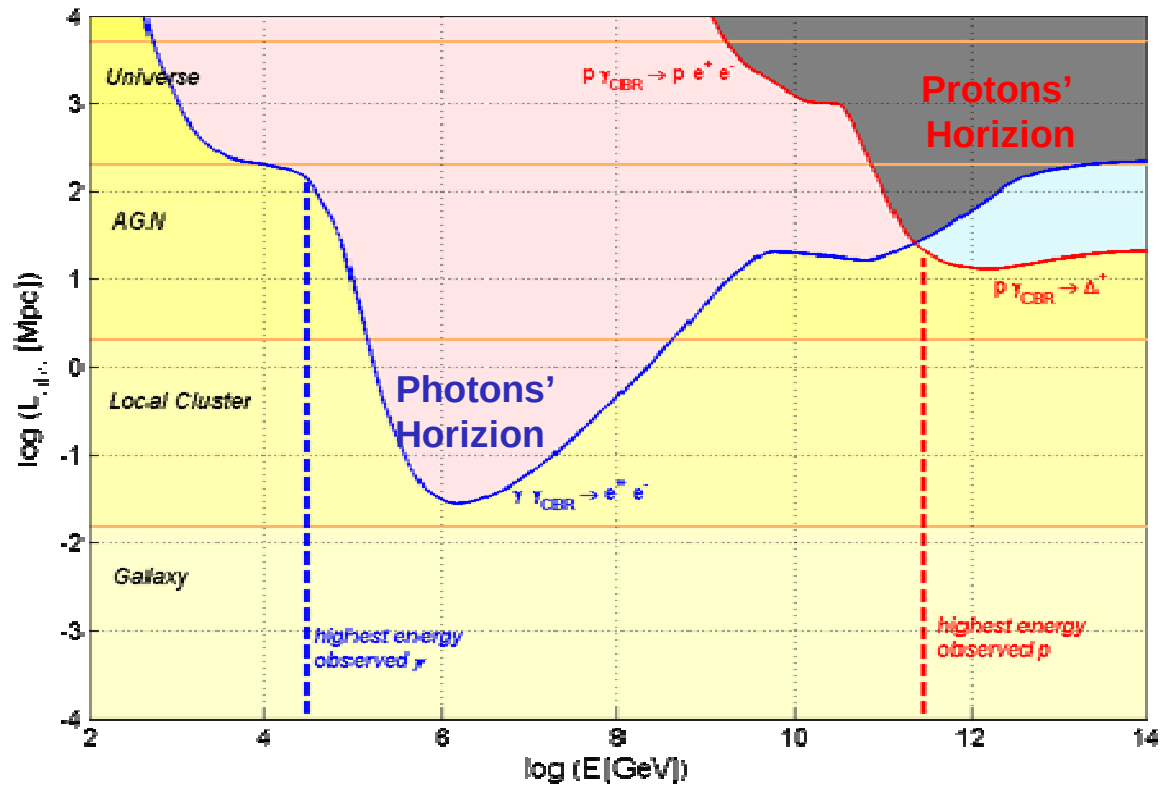
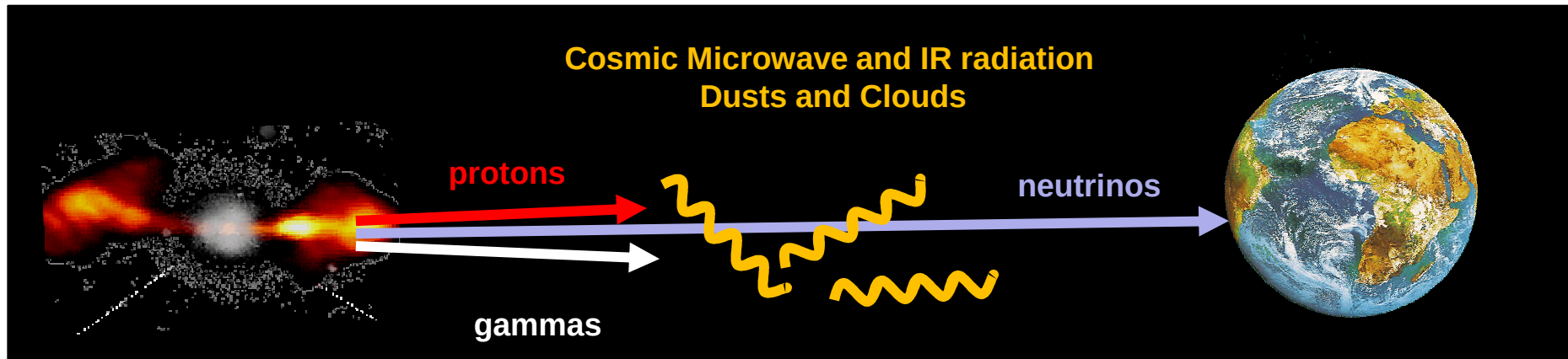
- Power law spectrum  $E^{-\gamma}$  observed up to 30 TeV
- Spectral index  $\gamma \approx 2$  implies acceleration of primaries up to 1000 TeV
- Spectrum hardly explainable with IC mechanisms



*Neutrinos are the ultimate smoking gun for hadronic processes*

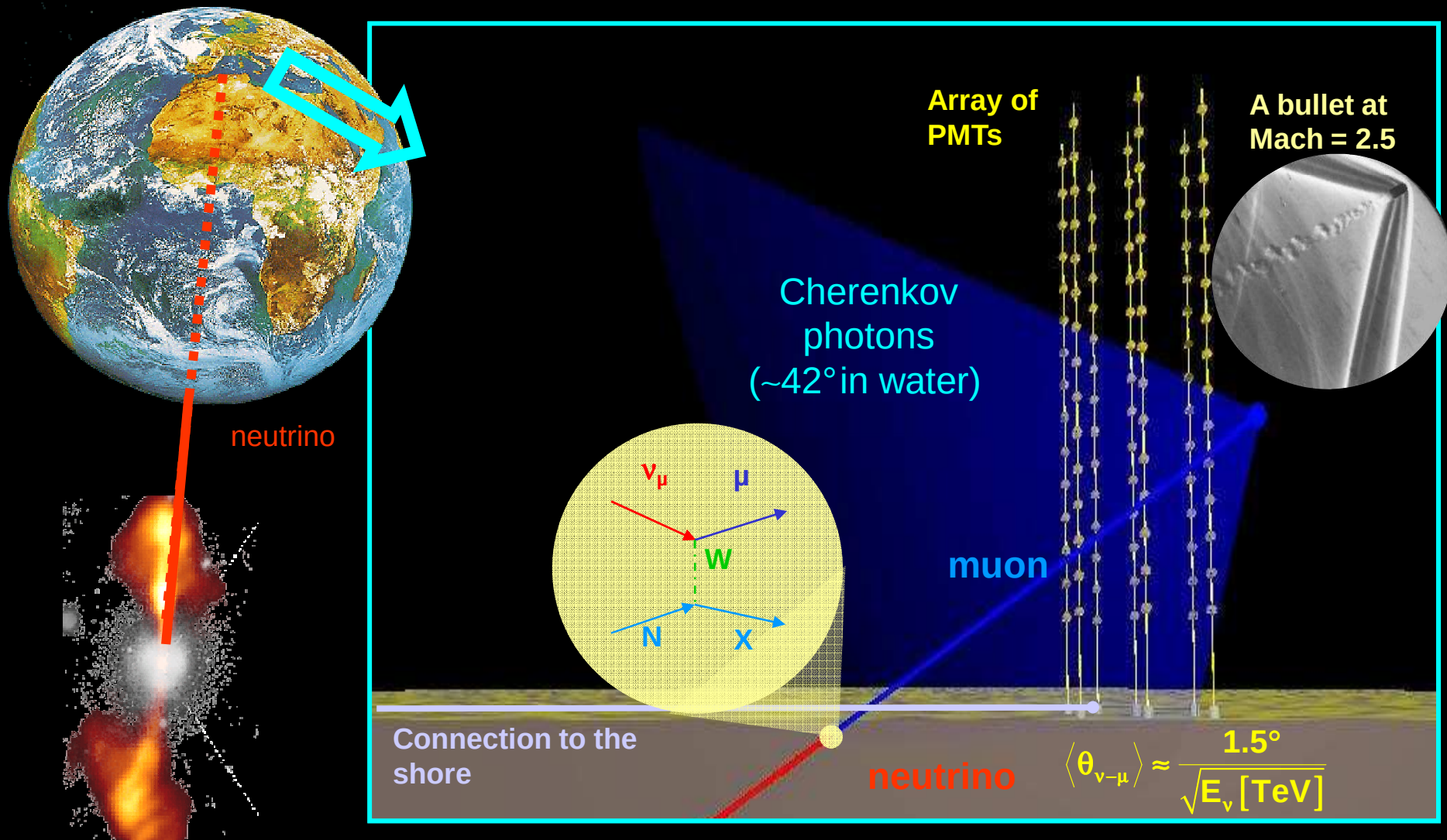


# Absorption length of protons and gammas in the Universe



**Neutrinos can probe the far and violent Universe**

# Underwater Cherenkov HE neutrino detectors

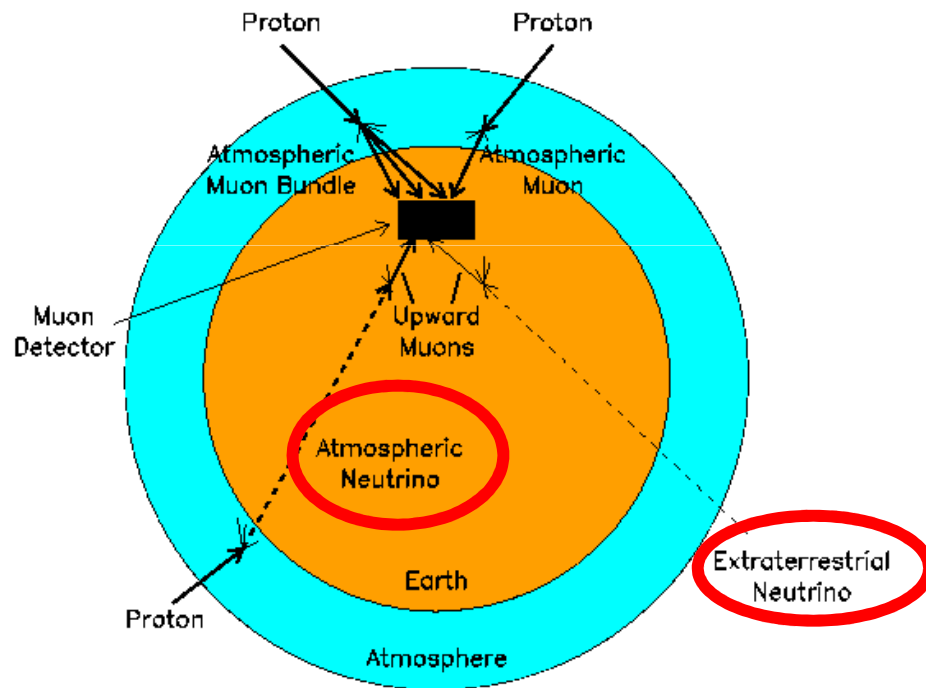


# The neutrino telescope: a downward looking detector

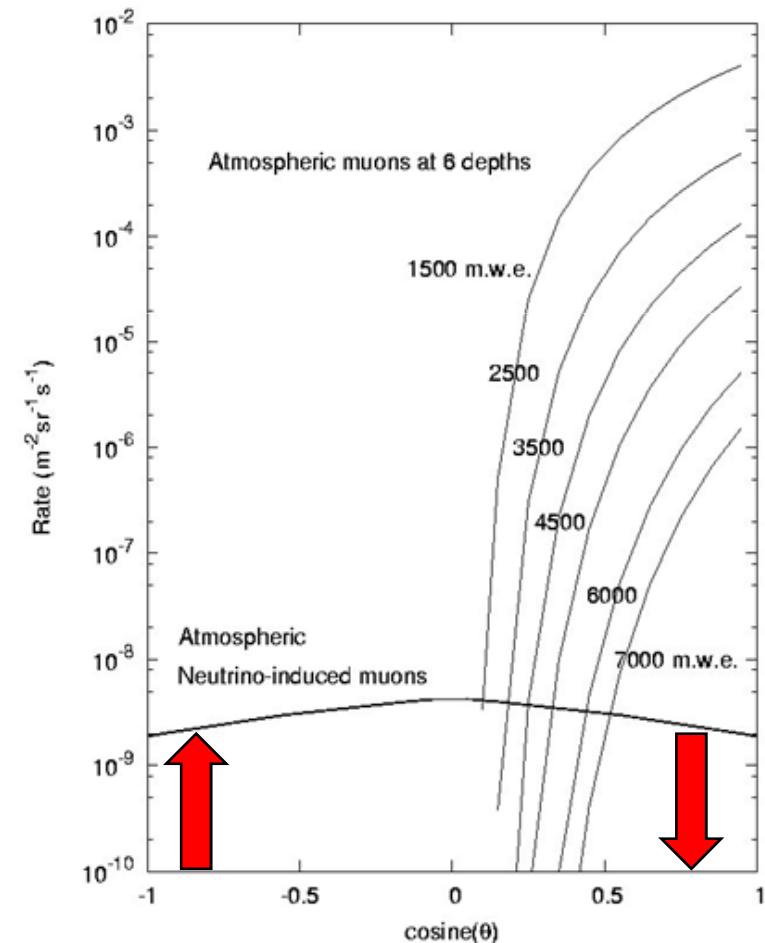
Neutrino telescopes search for muon tracks induced by neutrino interactions

The downgoing atmospheric  $\mu$  flux overcomes by several orders of magnitude the expected  $\mu$  fluxes induced by  $\nu$  interactions.

Look at upgoing muon tracks: **Use the Earth as a muon filter**



**Upgoing and horizontal muon tracks are neutrino signatures**





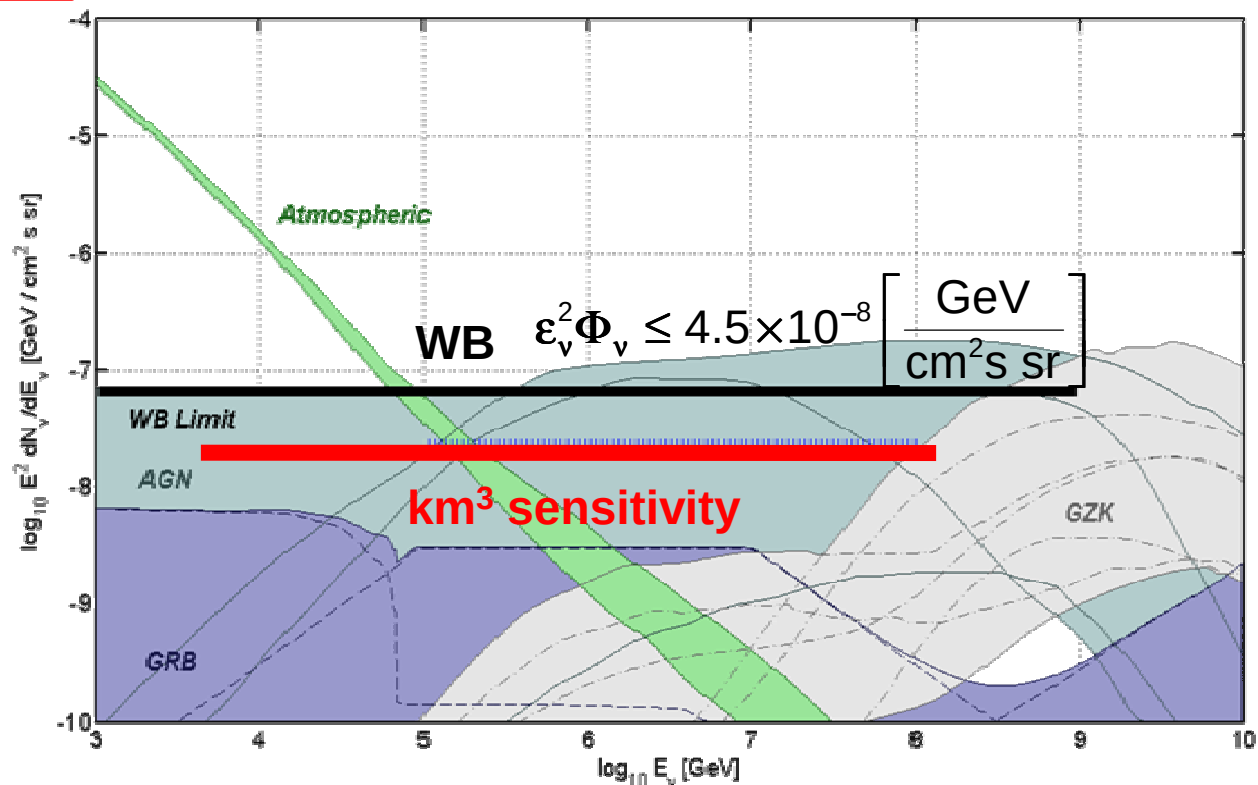
# The size of the detector

Expected number of upgoing astrophysical neutrino events per year (assuming the Waxman Bahcall (WB) reference flux):

$$N_{\mu}|_{E_{\nu}=100\text{TeV}} \approx \frac{4.5 \cdot 10^{-8} [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]}{10^5 [\text{GeV}]} \cdot 10^{-4} \cdot (10^{10} A^{\text{eff}} [\text{km}^2]) \cdot (3 \cdot 10^7 T [\text{y}]) \cdot 2\pi$$

$$N_{\mu}|_{E_{\nu}=100\text{TeV}} \approx 70 \cdot A^{\text{eff}} T [\text{km}^2 \text{y}]$$

The observation of TeV neutrino fluxes requires km<sup>3</sup> scale detectors !



# Neutrino telescopes brief history

80's: DUMAND R&D

90's: BAIKAL, AMANDA, NESTOR, ANTARES

2k's: NEMO R&D, completion of ANTARES

2011: ICECUBE (now running at about  $\frac{3}{4}$  of full size)

2015: Mediterranean KM3NeT



Pylos



La Seyne



Capo Passero



BAIKAL

Mediterranean  
km<sup>3</sup>

DUMAND

AMANDA  
ICECUBE



# The IceCube Site: the Geographic South Pole

*Only few weeks per year for the string deployment*





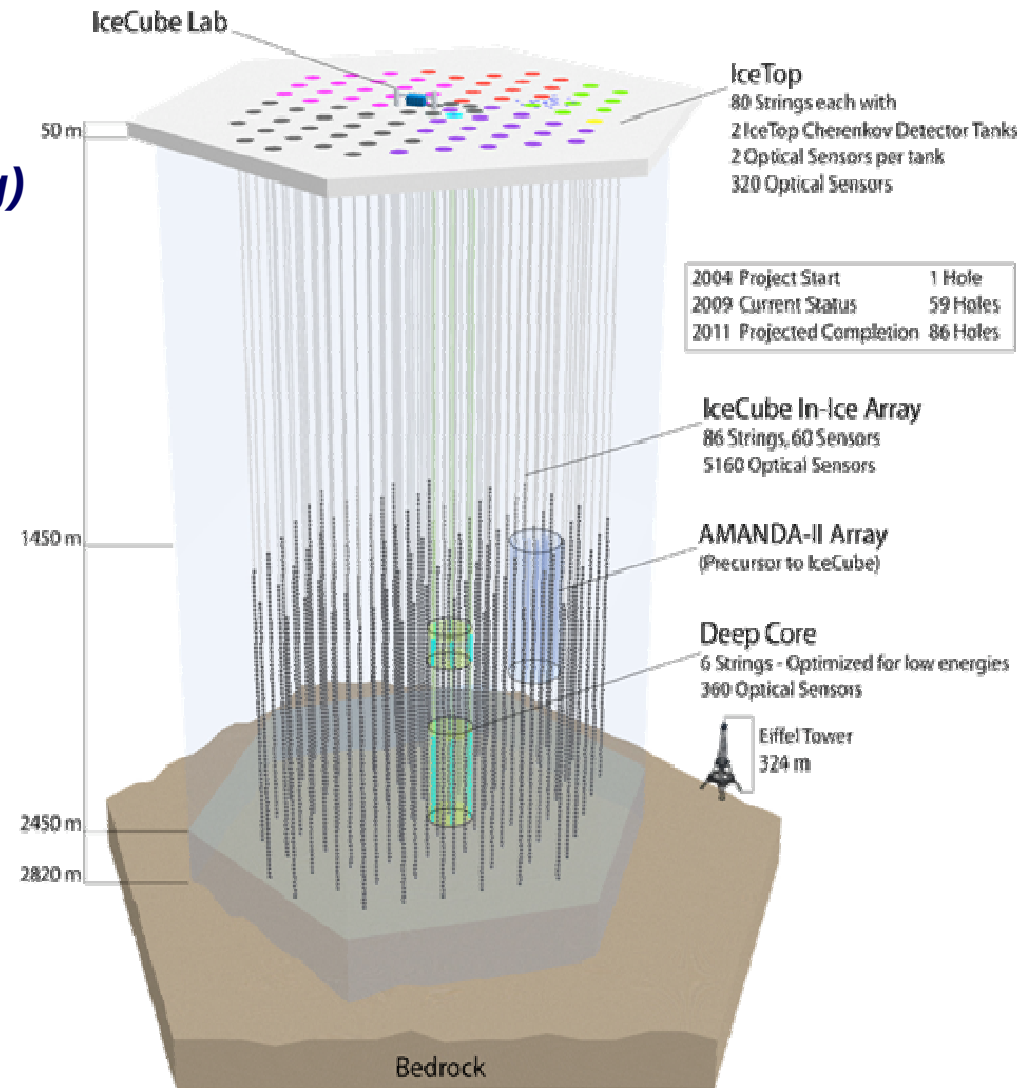
# IceCube: The first km<sup>3</sup>-scale neutrino telescope

**Completion January 2011:**  
**80 strings (60 PMT each)**  
**4800 10" PMT (only downward looking)**  
**125 m inter string distance**  
**16 m spacing along a string**  
**Instrumented volume: 1 km<sup>3</sup> (1 Gton)**

## **Present Status**

**More than 3/4 of the full detector in few months**

**The Detector is taking data during the construction phase.**

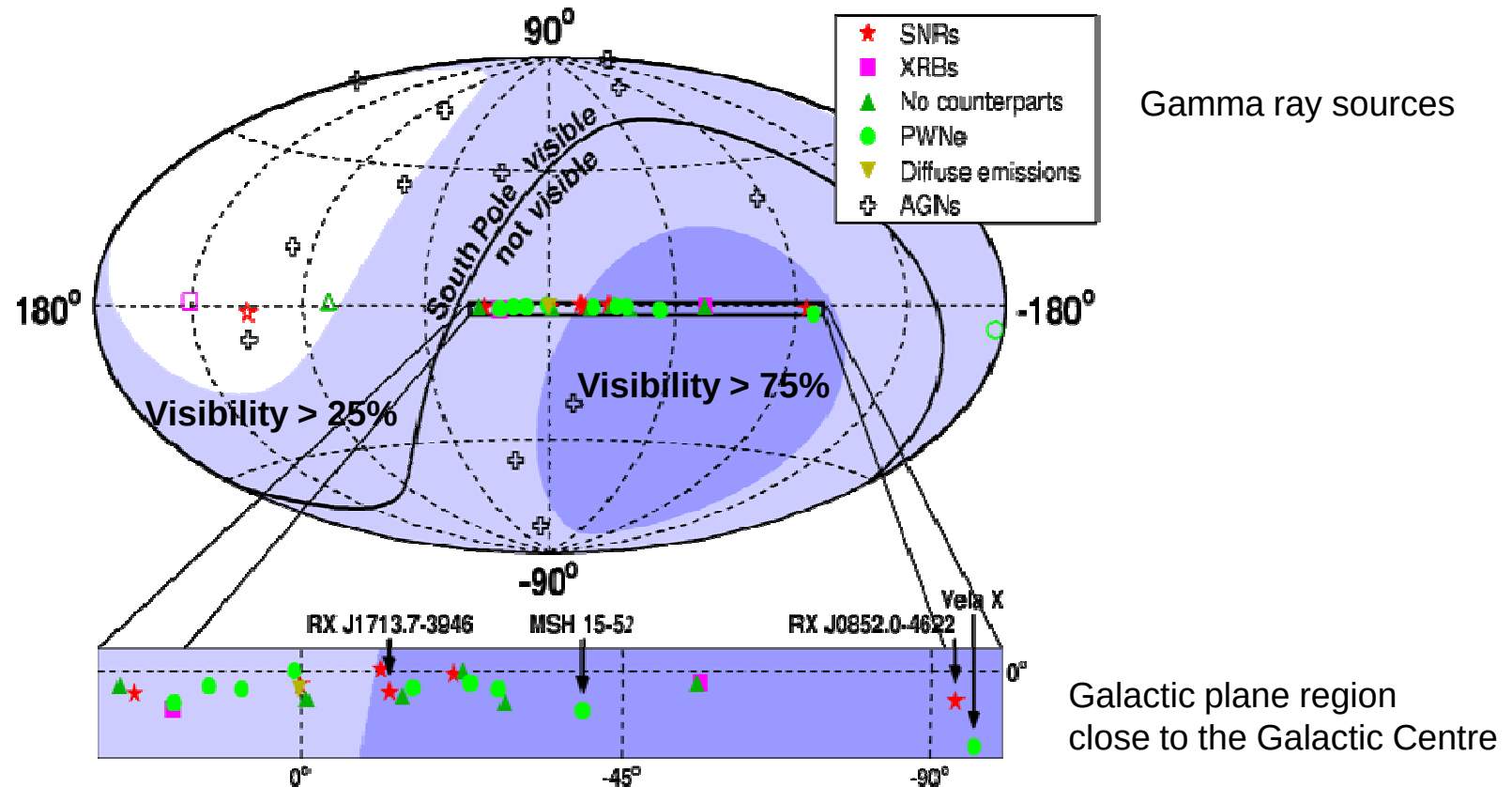


**No  $\nu$  source found yet**

# The Mediterraneanan-km3 and Icecube

Need two telescopes to cover the whole sky.

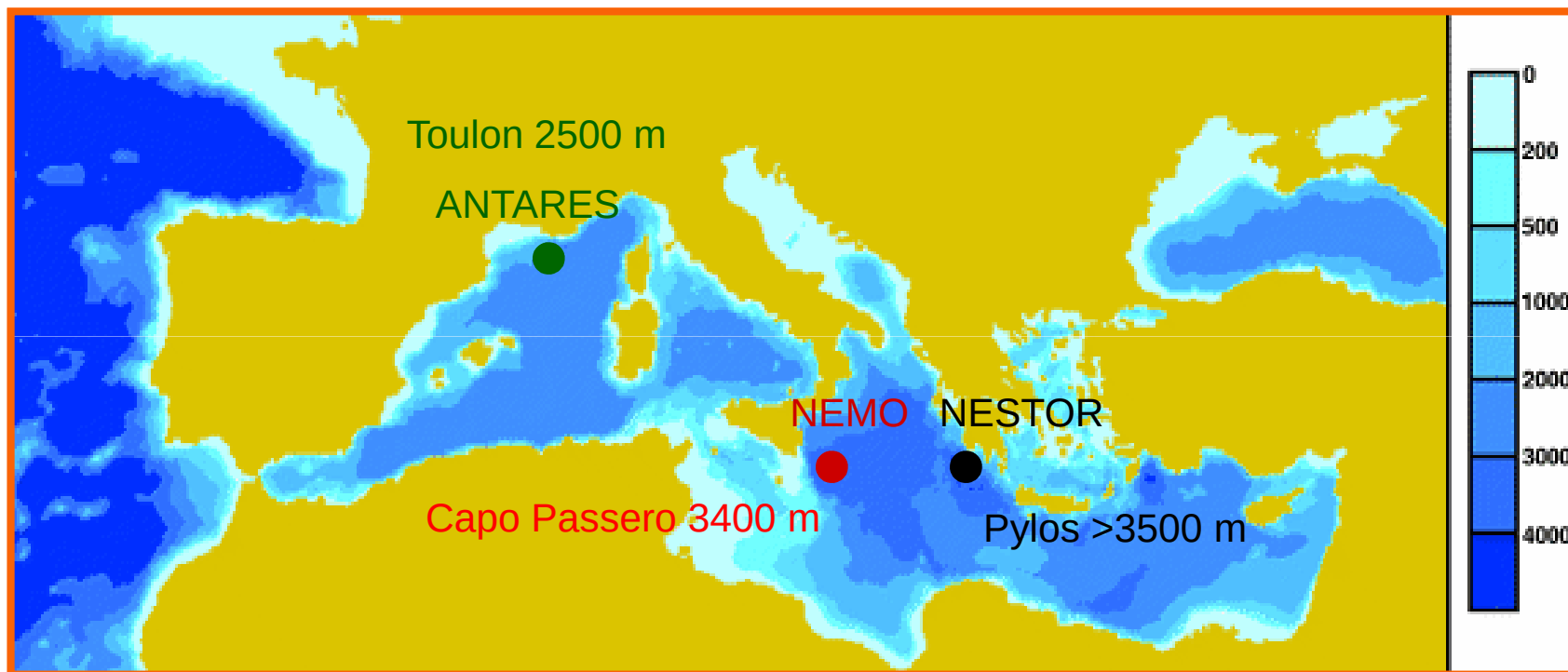
The Galactic Centre can be seen only from the Northern Hemisphere



*The most favorable site for the Northern km<sup>3</sup> detector is the **Mediterranean Sea**:*

- *vicinity to science infrastructures*
- *good water quality → improve angular resolution w.r.t. Icecube*

# Towards the Mediterranean km<sup>3</sup>



# What is ANTARES

**The largest neutrino telescope in the Northern Hemisphere, with 0.1 km<sup>2</sup> footprint**

**The first neutrino telescope under the sea**

**A high-depth real-time platform for multidisciplinary observations**

**A major step toward the km<sup>3</sup> detector in the Mediterranean Sea**





# Who is in ANTARES

7 countries  
27 institutes  
150 scientists+engineers



NIKHEF, Amsterdam  
KVI Groningen  
NIOZ Texel



University of  
Erlangen



IFIC, Valencia  
UPV, Valencia



CPPM, Marseille  
DSM/IRFU/CEA, Saclay  
APC, Paris  
LPC, Clermont-Ferrand  
IPHC (IReS), Strasbourg  
Univ. de H.-A., Mulhouse  
IFREMER, Toulon/Brest  
C.O.M. Marseille  
LAM, Marseille  
GeoAzur Villefranche



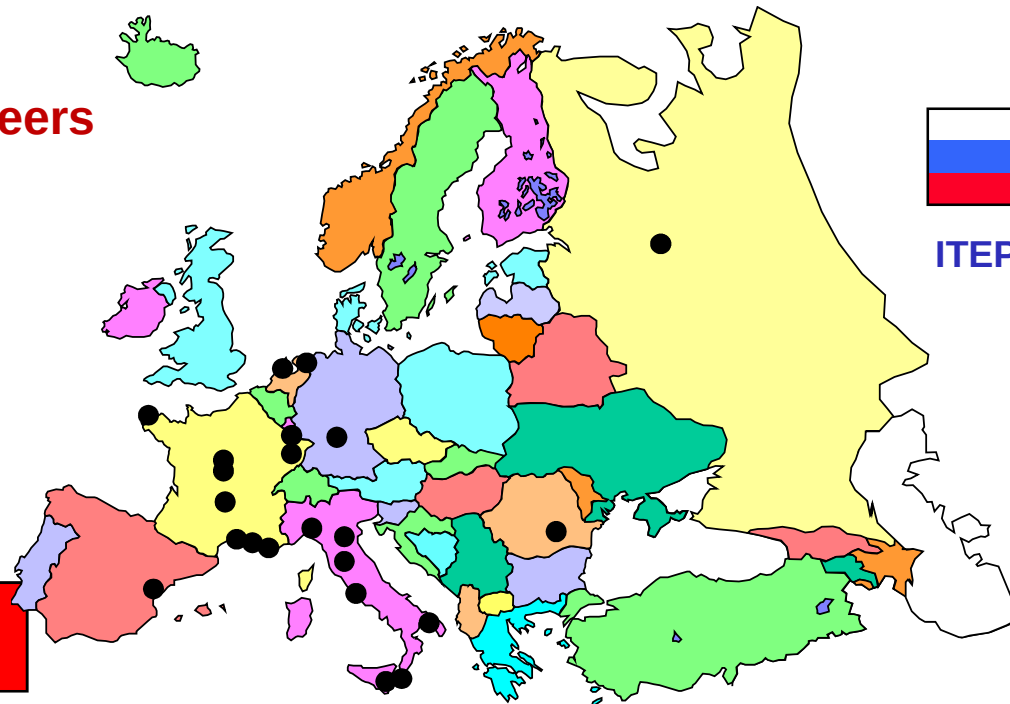
University/INFN of Bari  
University/INFN of Bologna  
University/INFN of Catania  
LNS – Catania  
University/INFN of Pisa  
University/INFN of Rome  
University/INFN of Genova



ITEP, Moscow



ISS, Bucarest



# The ANTARES Site infrastructures



**IFREMER Toulon Centre**



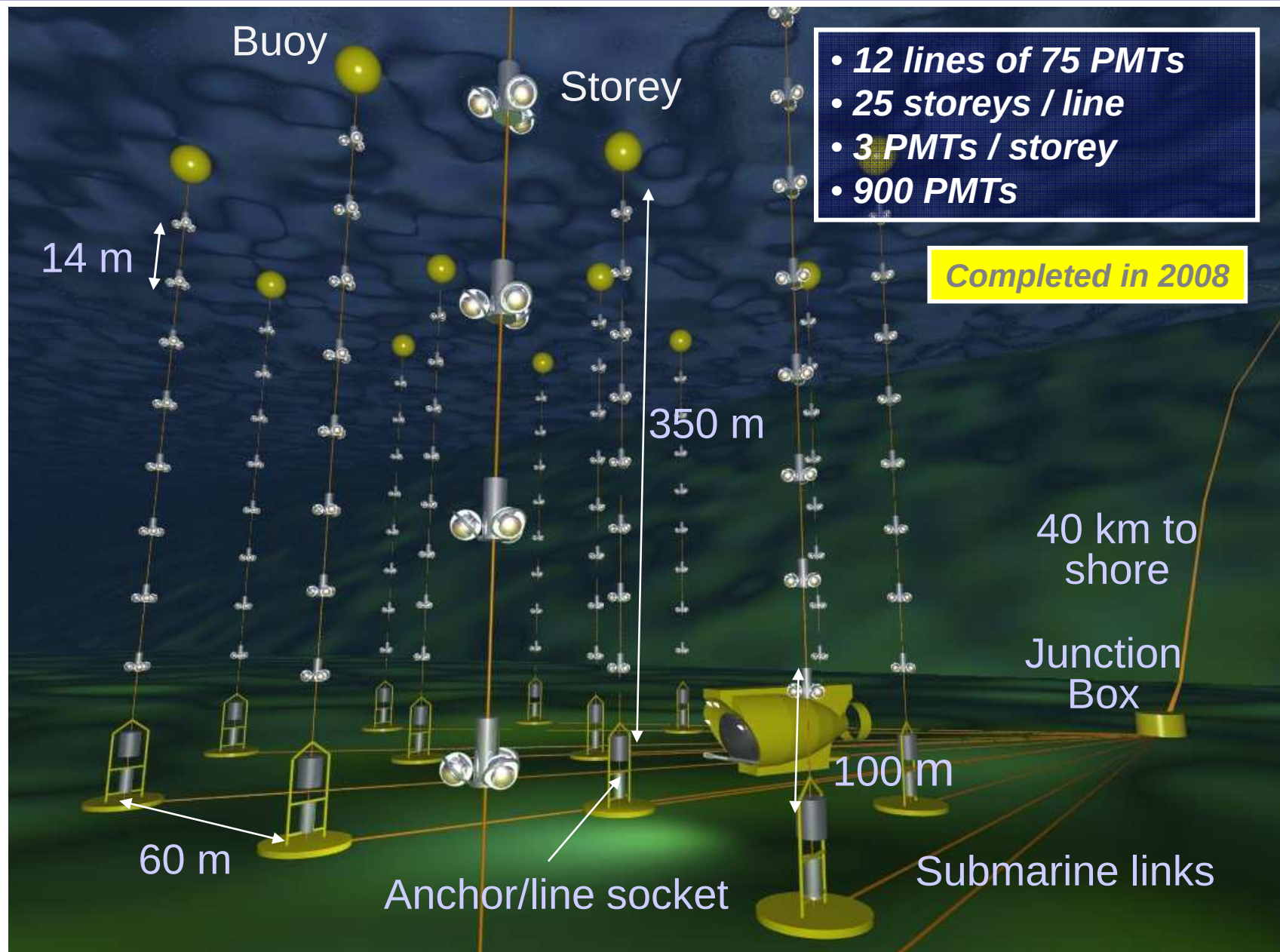
**Onshore station,  
Institut Michel Pacha, La Seyne s/M**



**FOSELEV Marine Shipyard, La Seyne s/M**



# ANTARES: the detector

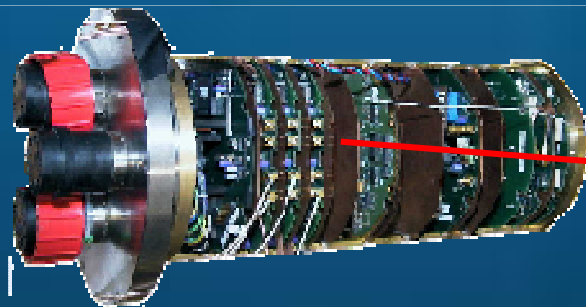
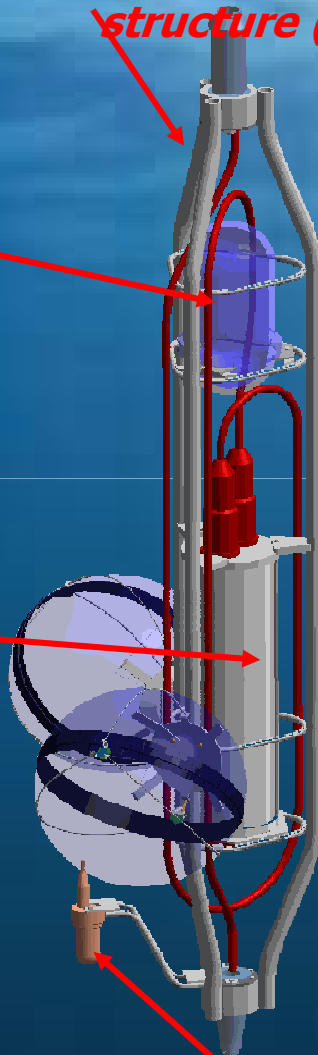


# The ANTARES Storey

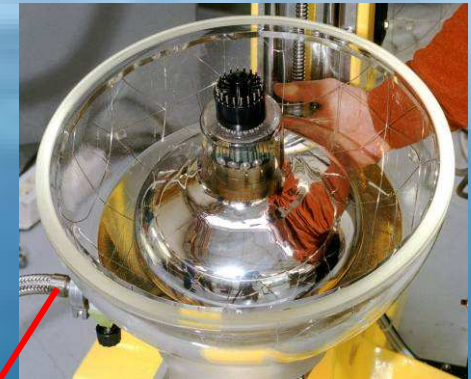
**Optical Beacon  
with blue LEDs:  
timing  
calibration**



**titanium frame: support  
structure (2m)**



**Local Control Module  
(in Ti cylinder):  
Front-end ASIC,  
DAQ/SC, DWDM,  
Clock, tilt/compass,  
power distribution...**



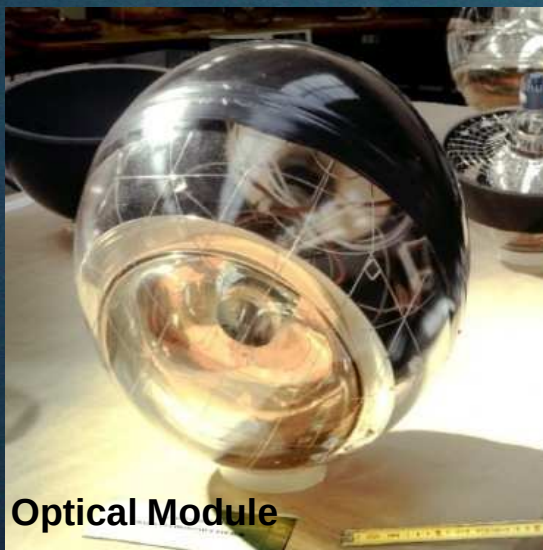
**Optical Module:  
10" Hamamatsu PMT  
in 17" glass sphere  
( $\sigma_{TTS} \approx 1.3$  ns)  
photon detection**



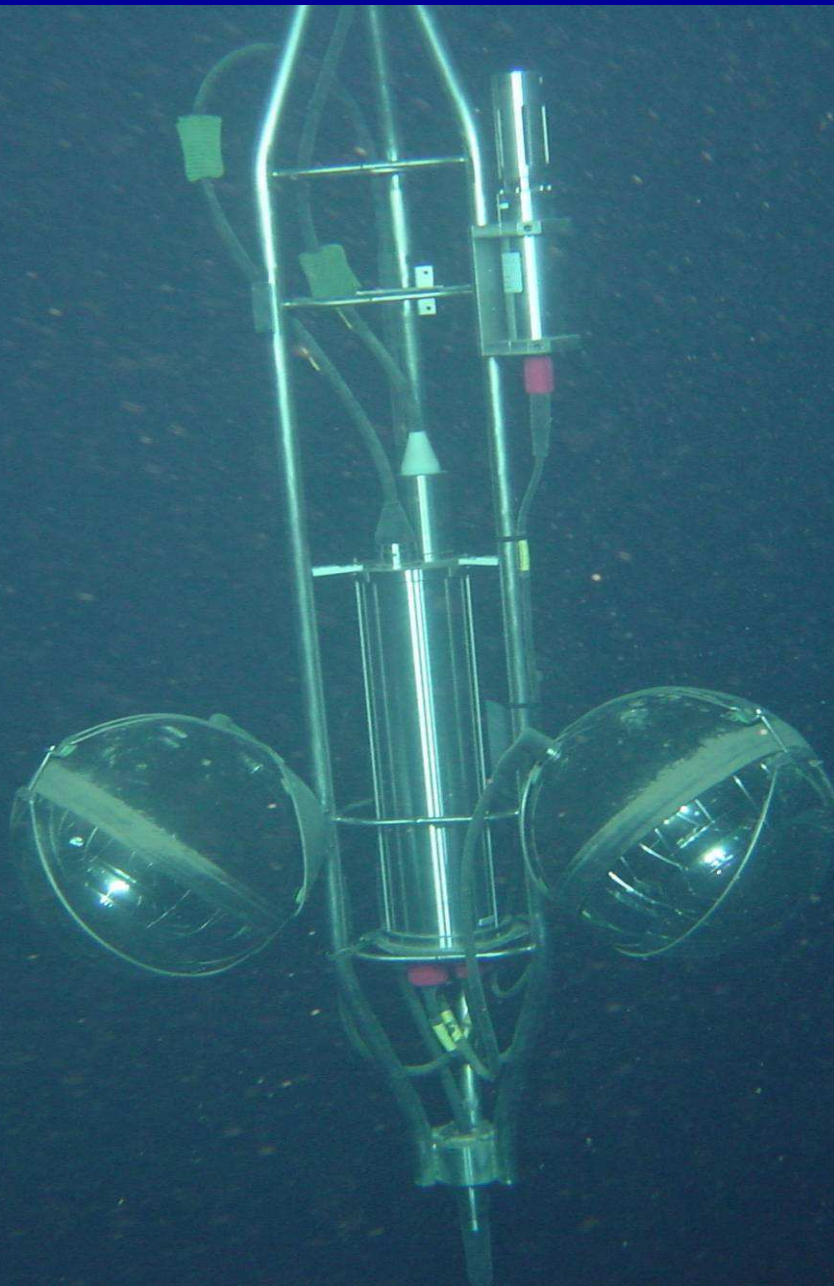
**Hydrophone:  
acoustic positioning**



# The ANTARES Storey

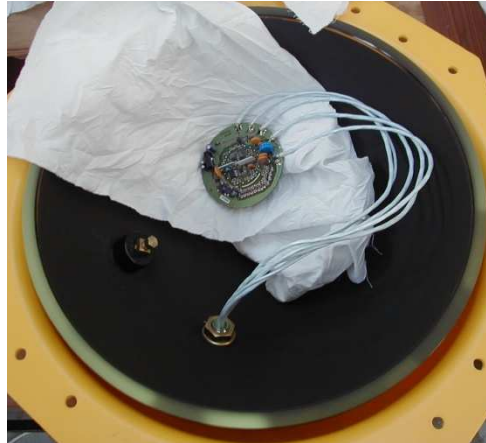
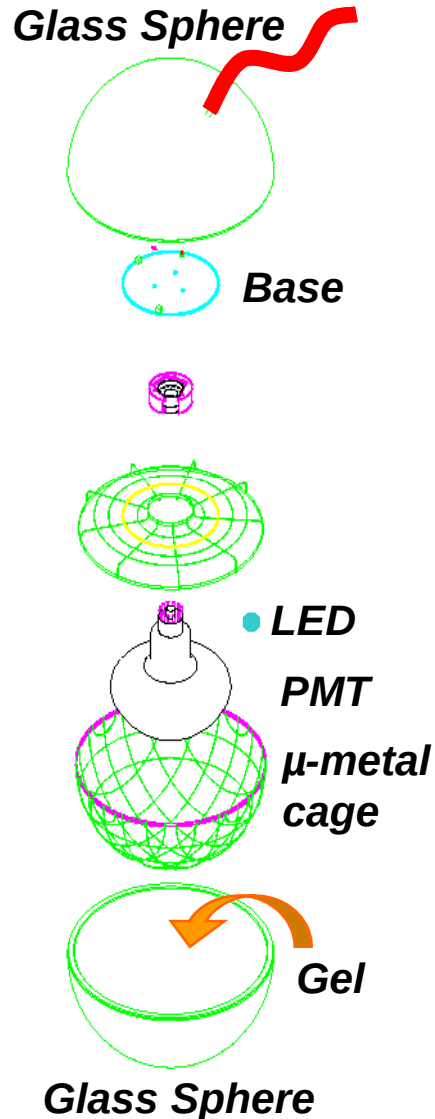


Optical Module



# The ANTARES Optical Module

## Blow-up of an Optical Module

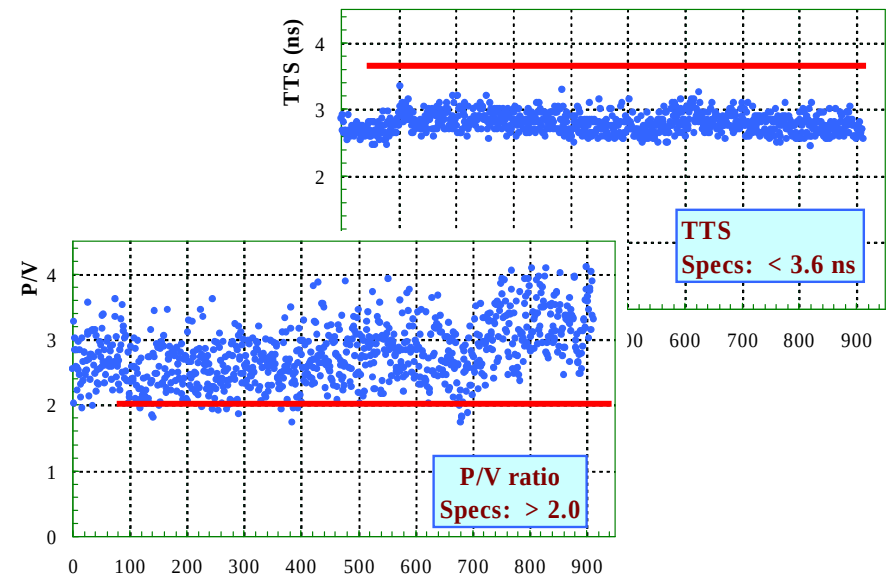


**PMT: 10"**  
Hamamatsu R7081-20

### Main features

- ❖ Sensitive area  $\cong 500 \text{ mm}^2$
- ❖ Transit time spread  $< 3.6 \text{ ns}$  (FWHM)
- ❖ Dark count (@ 0.3 spe)  $< 10 \text{ kHz}$
- ❖ Peak/valley  $> 2$

**All 900 PMT's have been characterized**

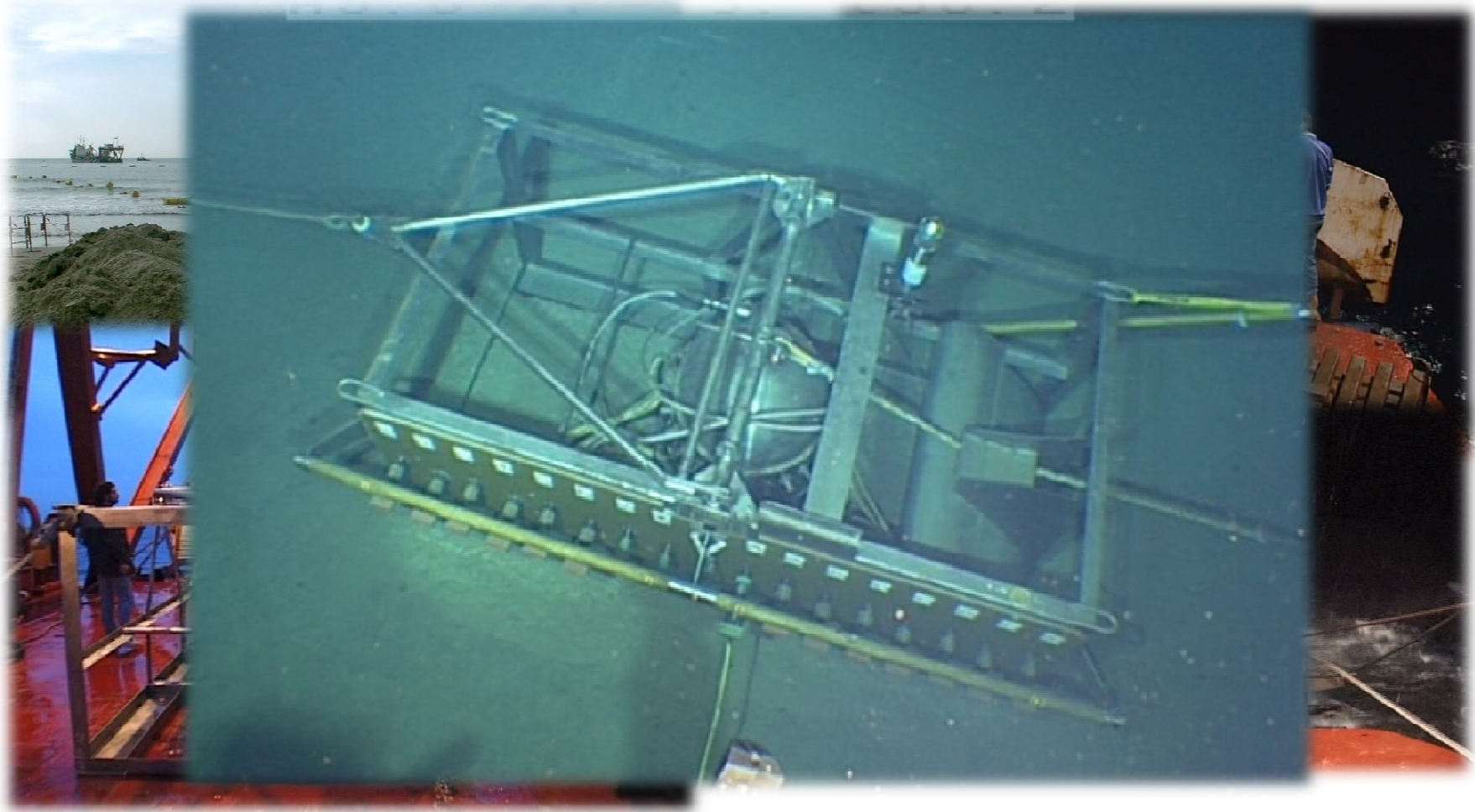




# Construction Milestones

2001 Deployment of 45 km electro-optical cable (Alcatel)

2002 Deployment of Junction Box



# Construction Milestones

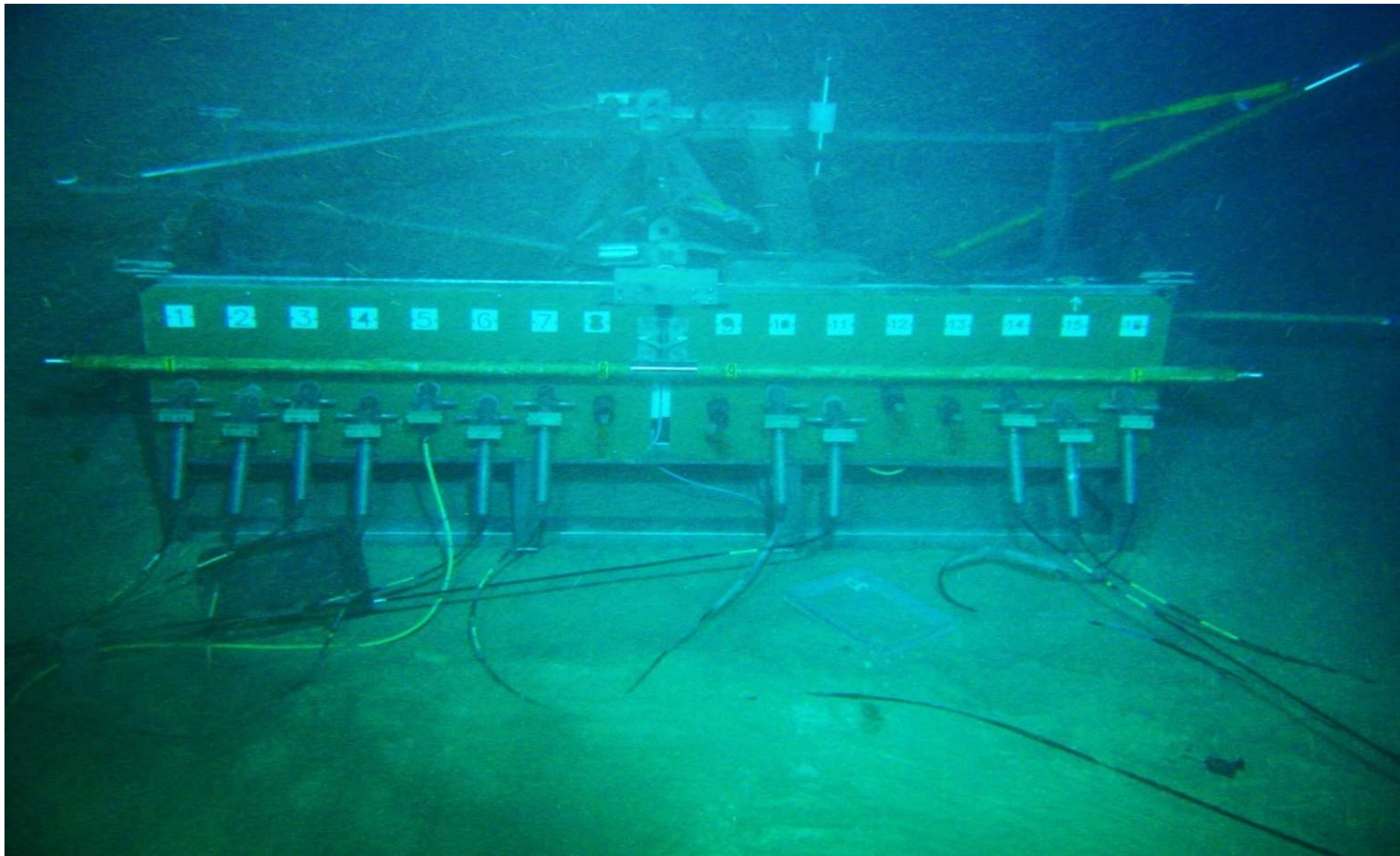
- 2003-2005: Prototype lines + MILOM
- 2006: Lines 1, 2
- 2007: Lines 3, 4, 5, 6, 7, 8, 9, 10
- 2008: Lines 11, 12



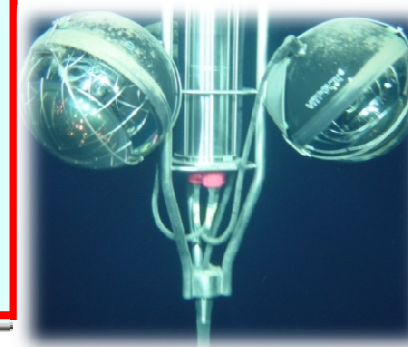
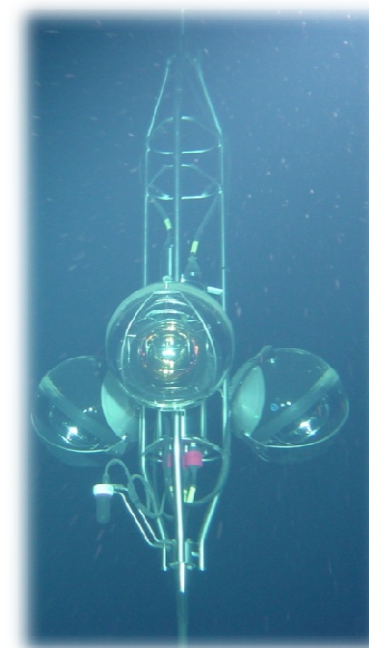
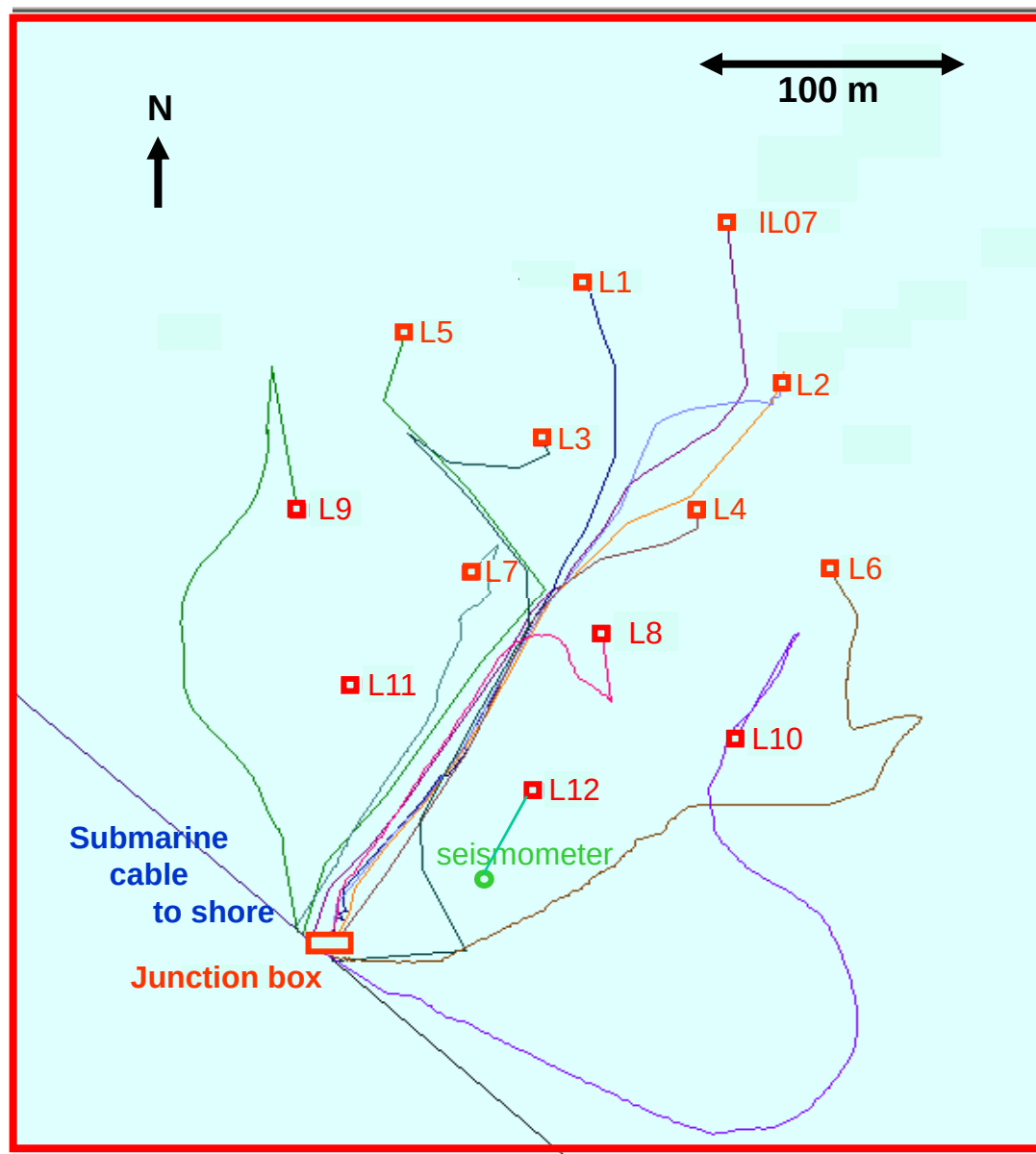
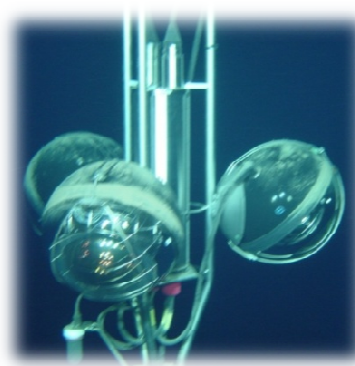
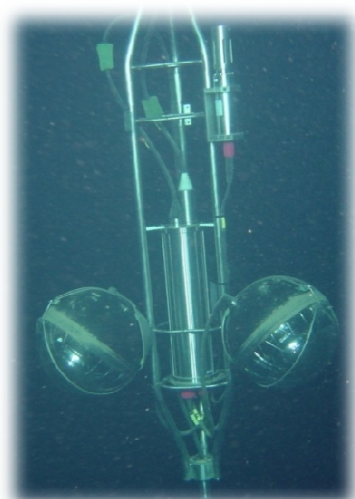


# Construction Milestones

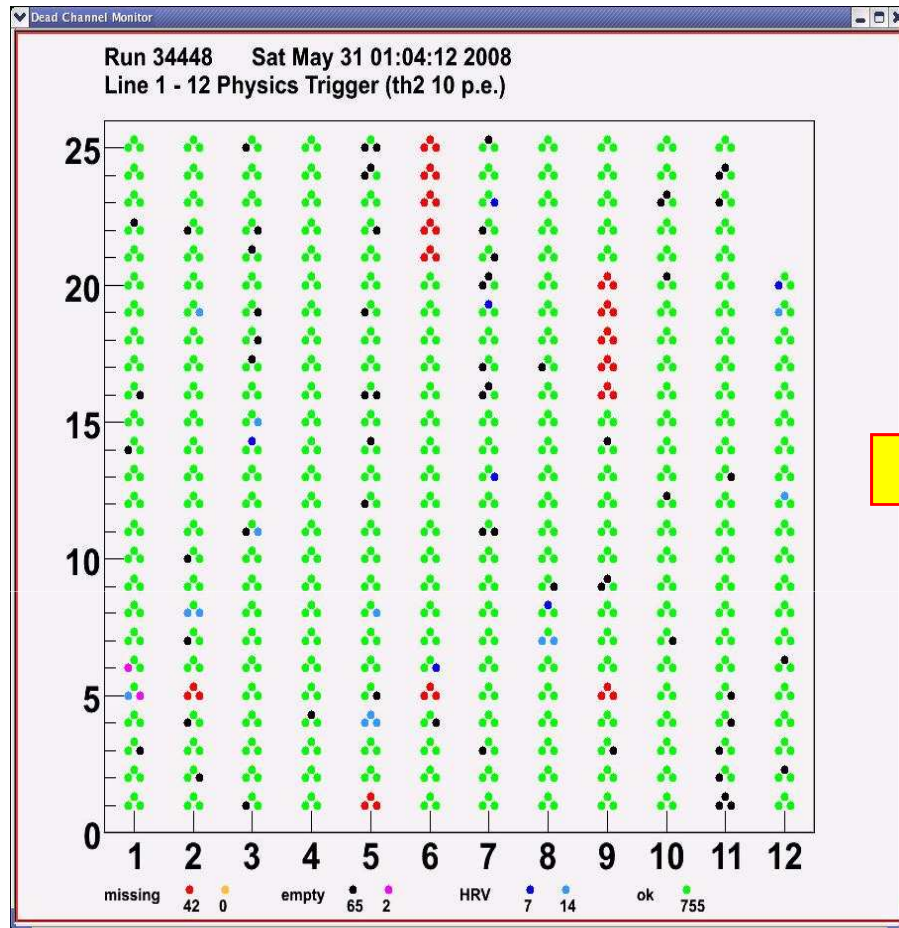
- Connection operations



# The full detector on Seabed



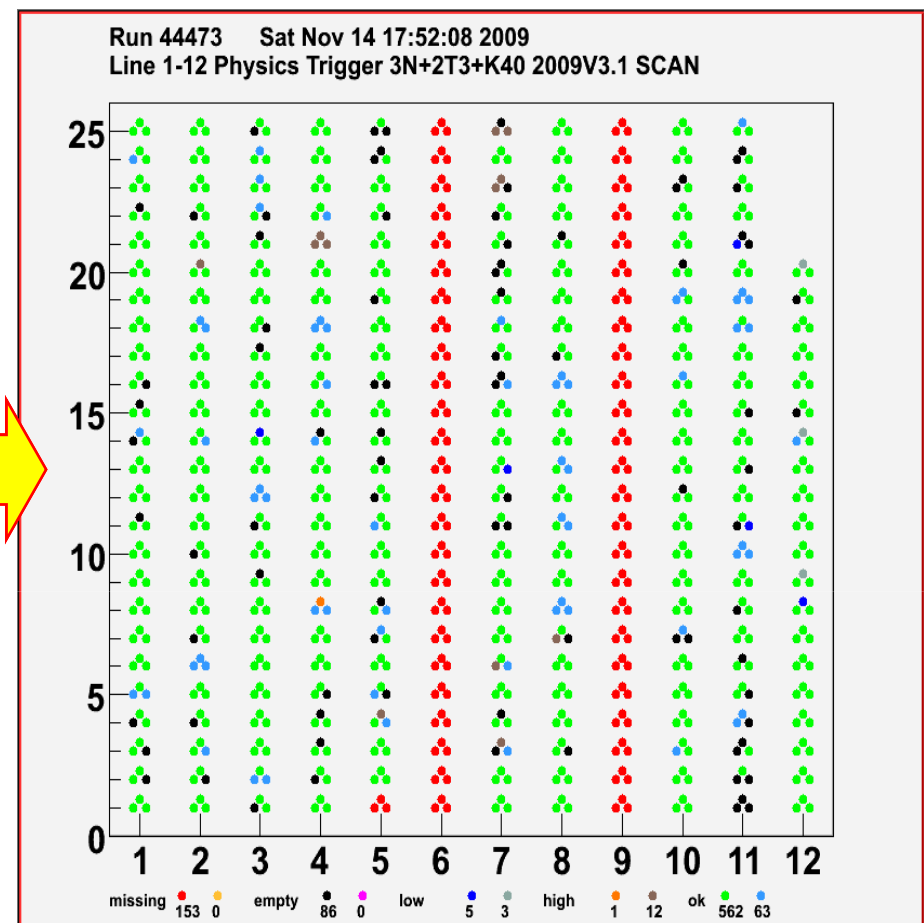
# Status of the apparatus



At end of construction

- ~90% of optical modules operational

Regular maintenance of in-situ infrastructure

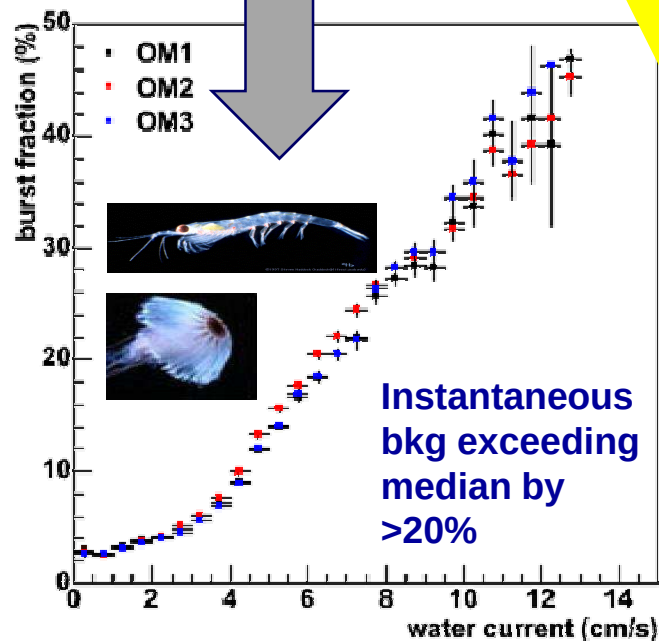
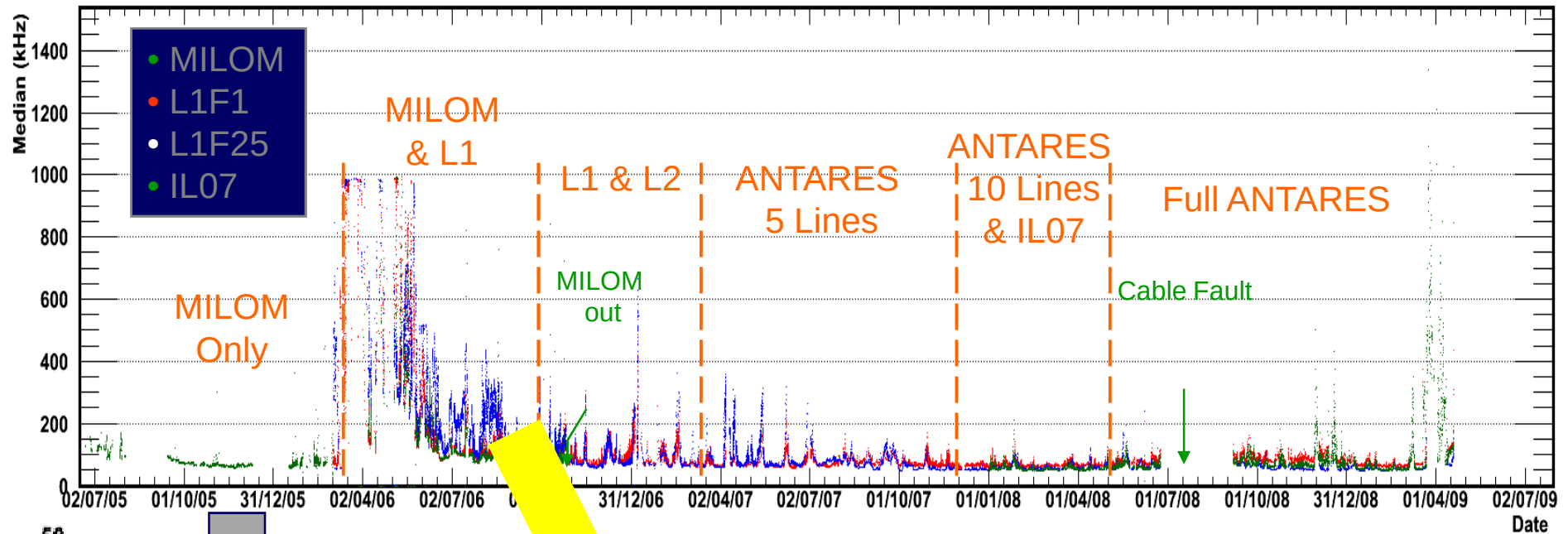


Today

- Line 6 recovered, Line 9 planned to be recovered
- Line 12 repaired and reconnected



# Optical Modules Counting Rates



$^{40}\text{K}$  decays and bioluminescence of micro-organisms (rate  $\sim 70$  kHz)

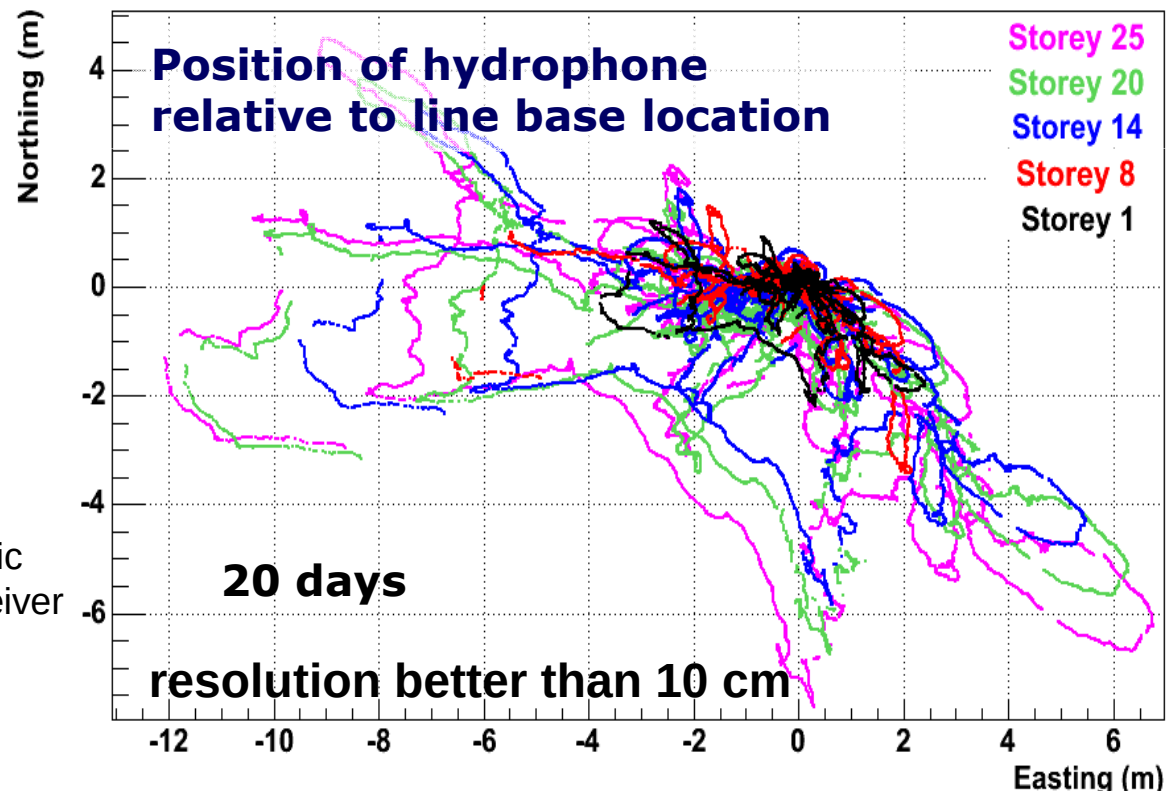
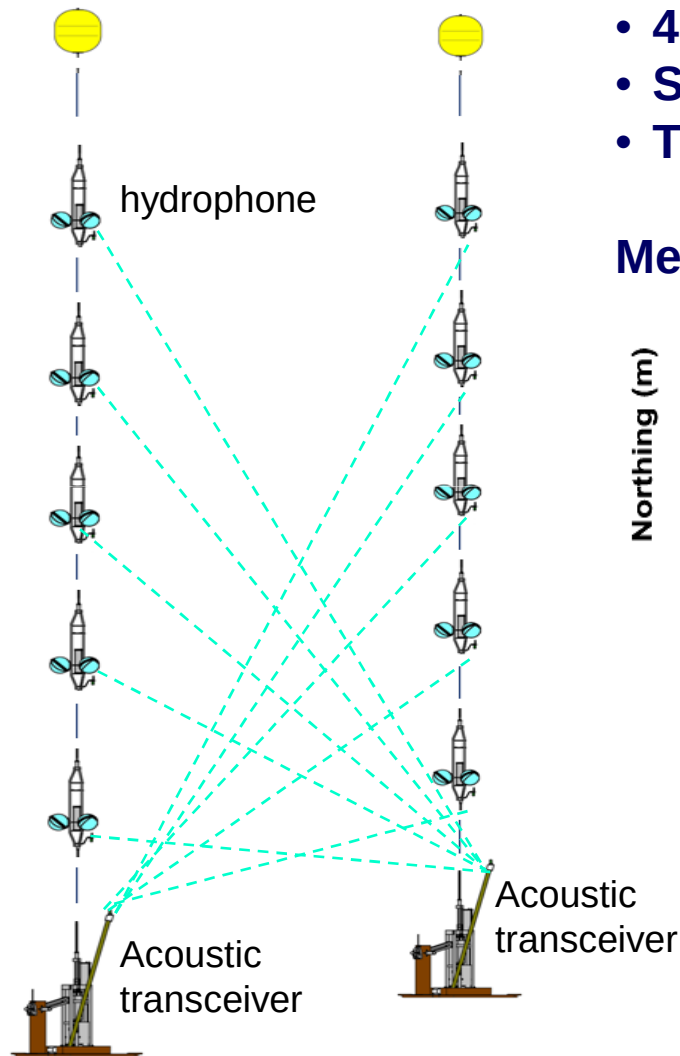
Plus bursts from macro-organisms (strongly affected by sea currents)

**Theory: cold winter caused descent of nutrient-bearing colder water (correlated change in salt content)**

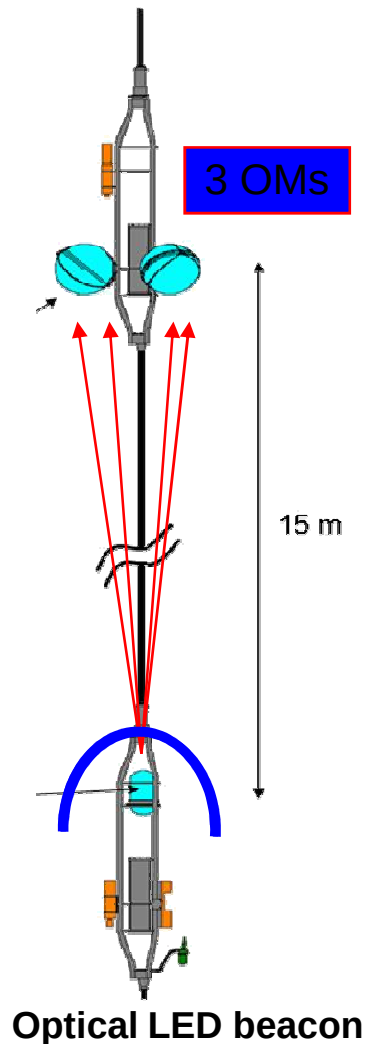
# Calibration: detector acoustic positioning

- Transceivers on the bottom of each line
- 5 hydrophones at specific heights on each line
- 4 autonomous transponders around the apparatus
- Sound velocimeters installed at various depths
- Tiltmeter and compass at each storey

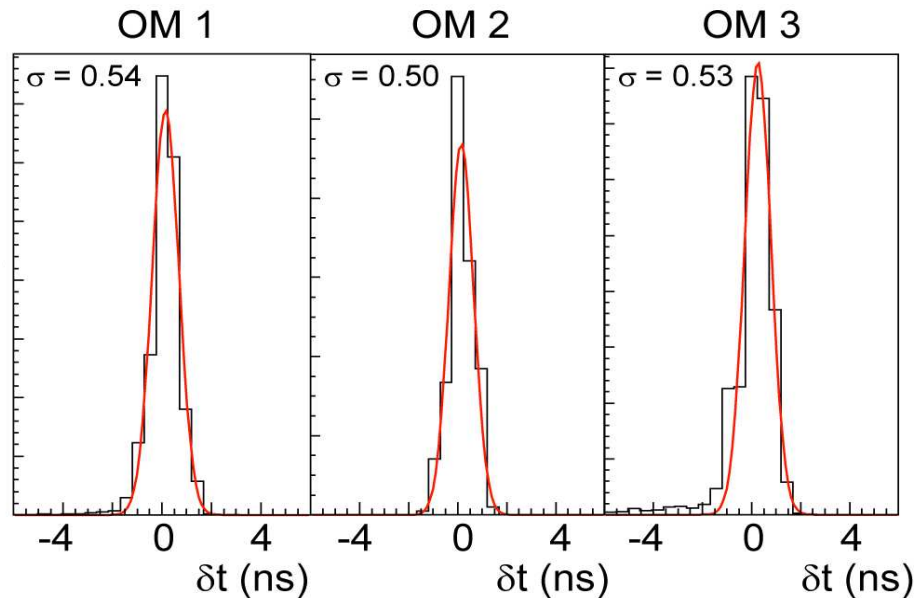
Measurements performed every 2 minutes



# Calibration: timing and PMT resolution



Time of signal in OMs relative to reference PMT  
for optical beacon flashes



- Electronics + calibration  $\rightarrow \sigma < 0.5$  ns
- TTS in photomultipliers  $\rightarrow \sigma \sim 1.3$  ns
- Light scattering + dispersion in sea water  $\rightarrow \sigma \sim 2$  ns

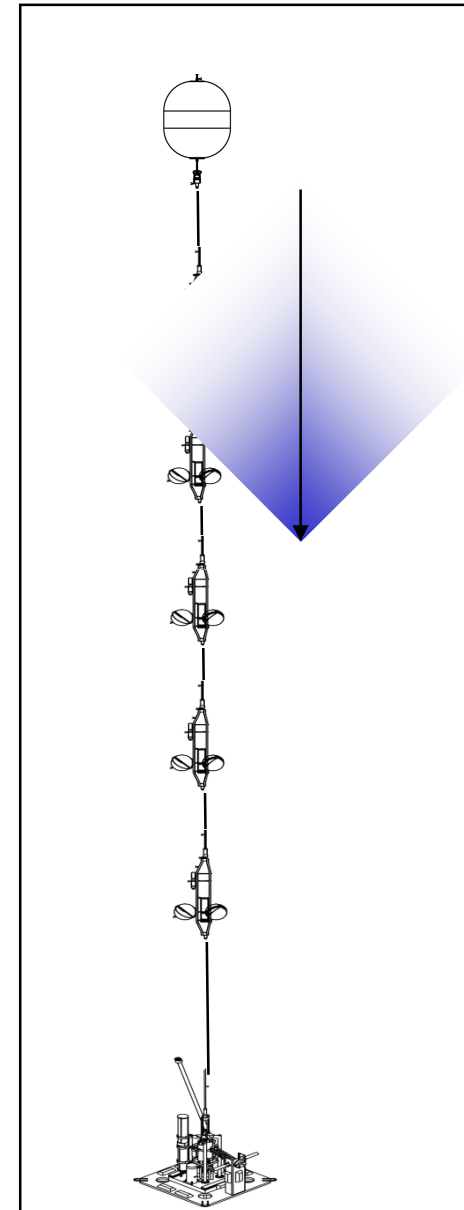
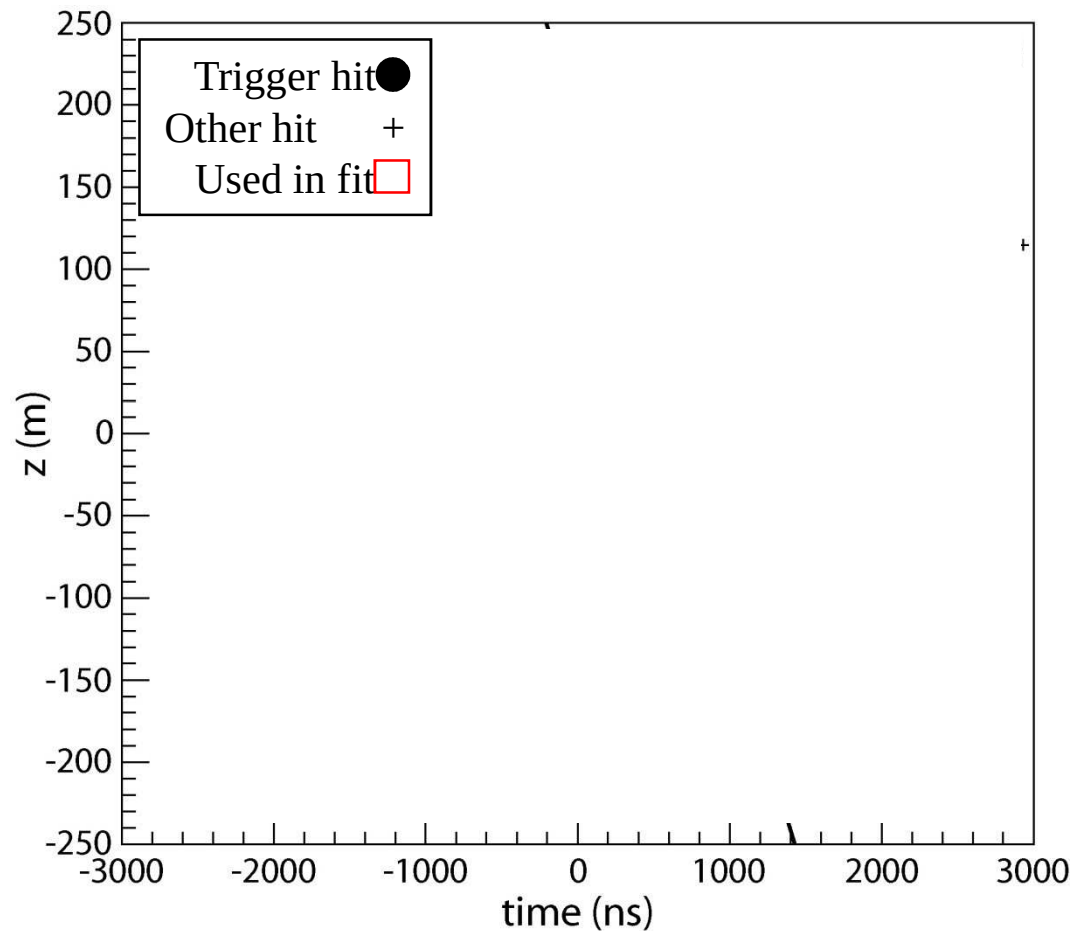
**Angular resolution  $\rightarrow 0.2^\circ - 0.3^\circ$  (above few TeV)**

Including the acoustic position resolution and the  $\nu$ - $\mu$  angle



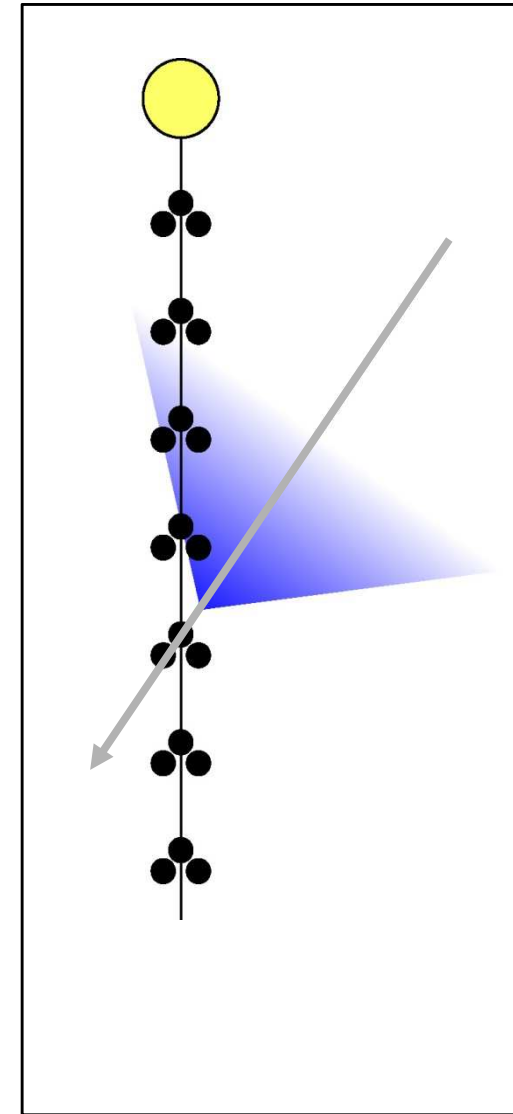
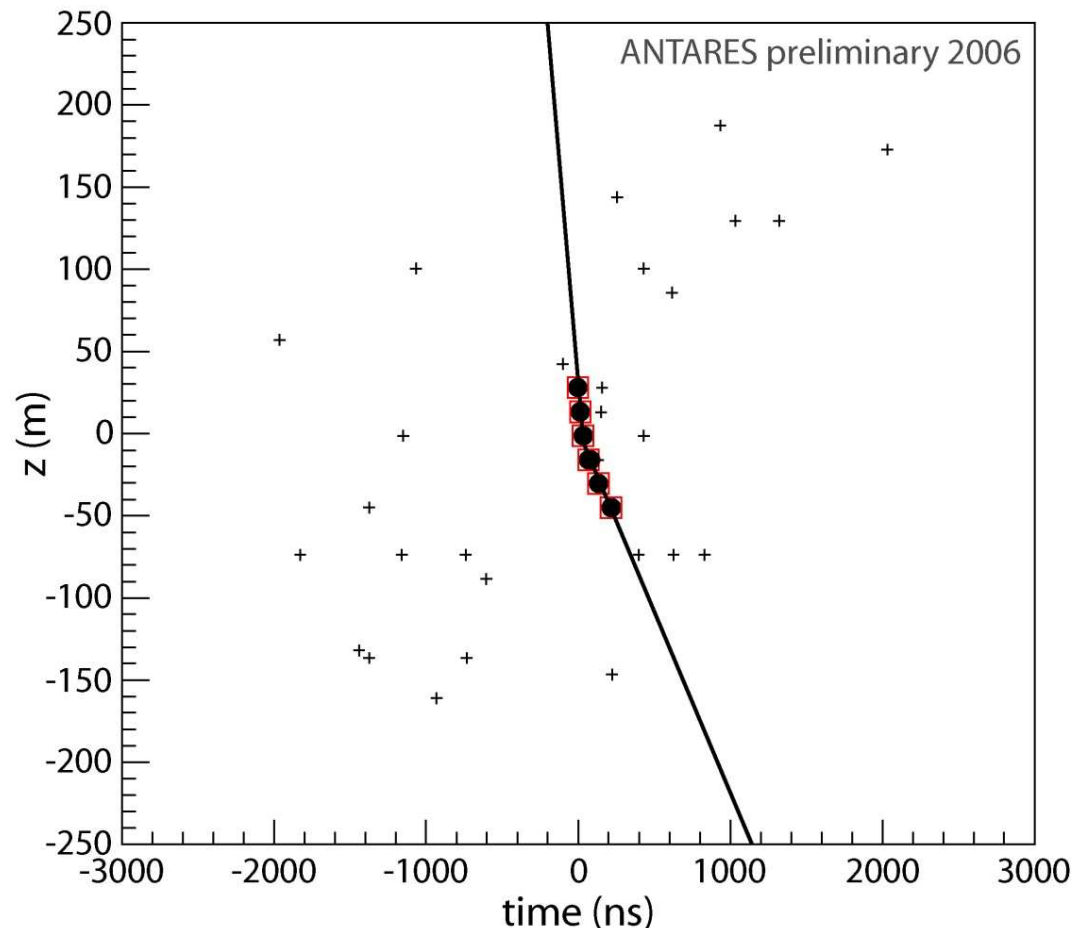
# Muons tracks: event display principle

Characteristic pattern depending on zenith angle and distance of closest approach

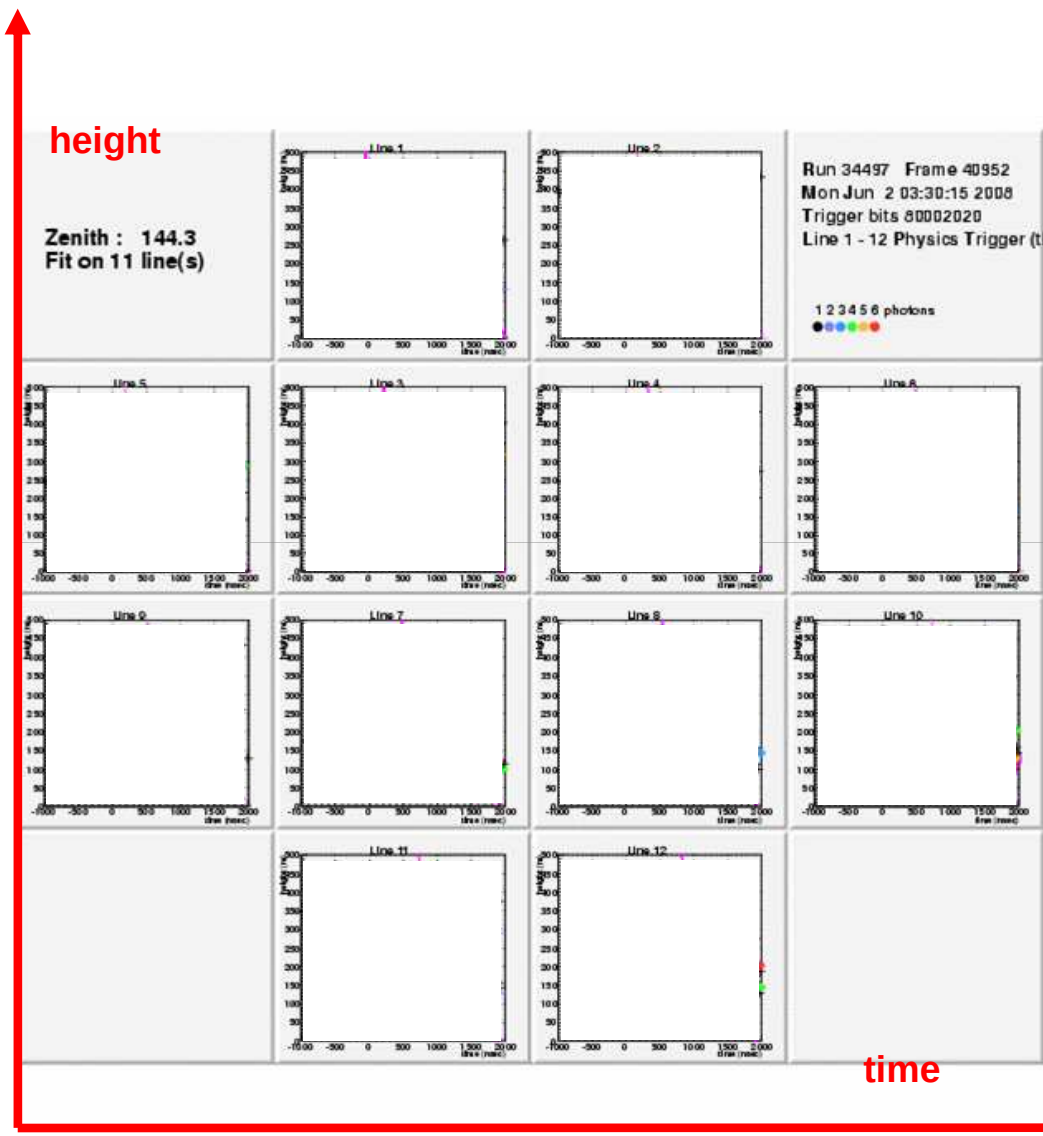


# Muons tracks: event display principle

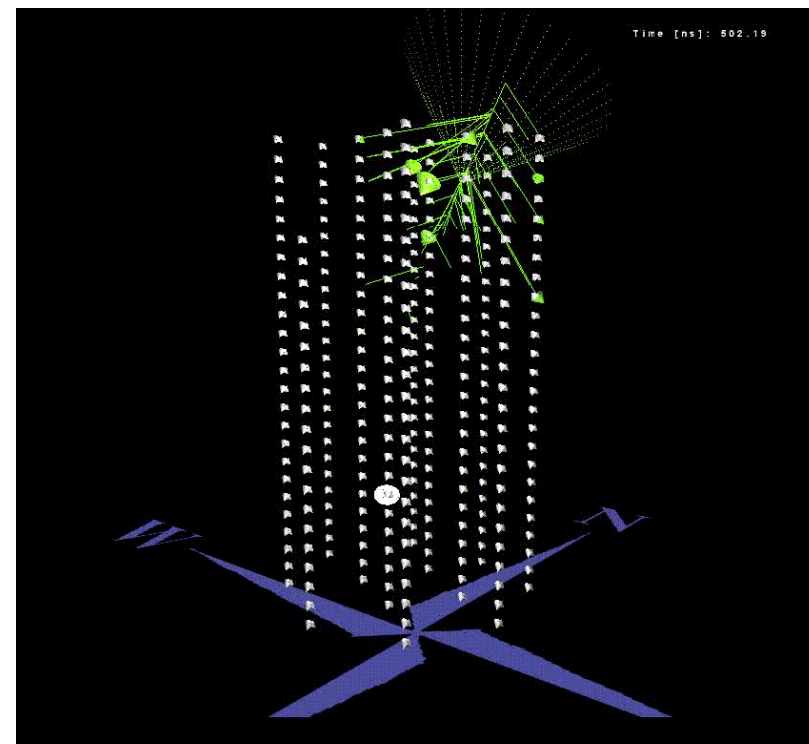
Characteristic pattern depending on zenith angle and distance of closest approach



# Reconstruction: a downgoing muon (atmospheric)



Example of a **reconstructed down-going muon**, detected in all 12 detector lines:

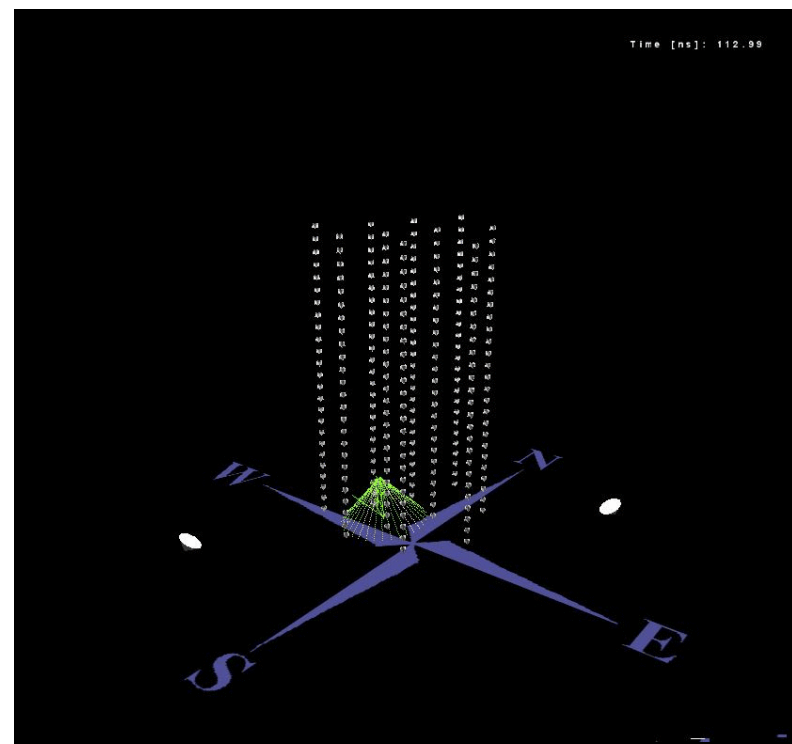




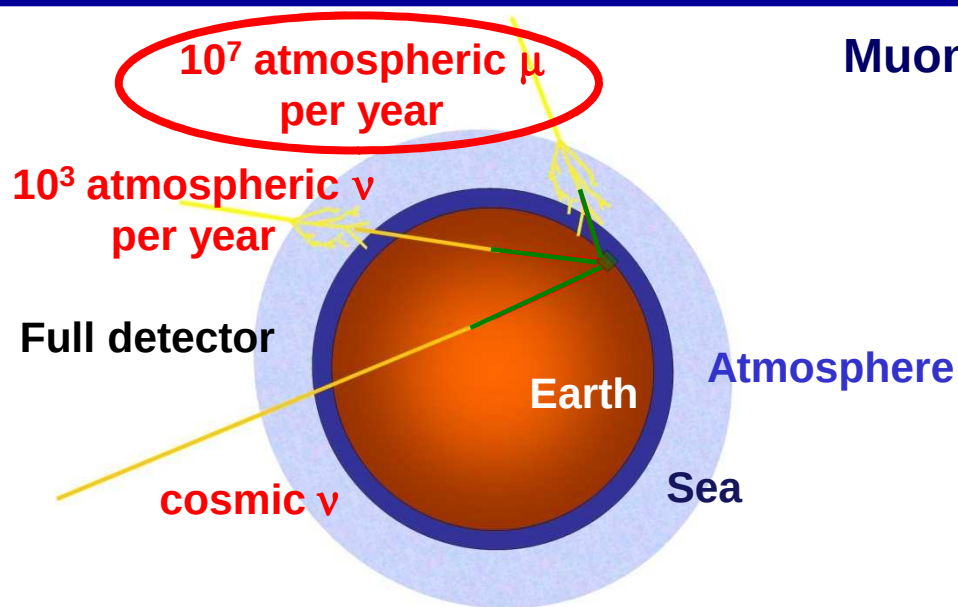
# Reconstruction: an upgoing muon (neutrino induced)



Example of a **reconstructed up-going muon** (i.e. a neutrino candidate) detected in 6/12 detector lines:



# Analysis: Atmospheric muons

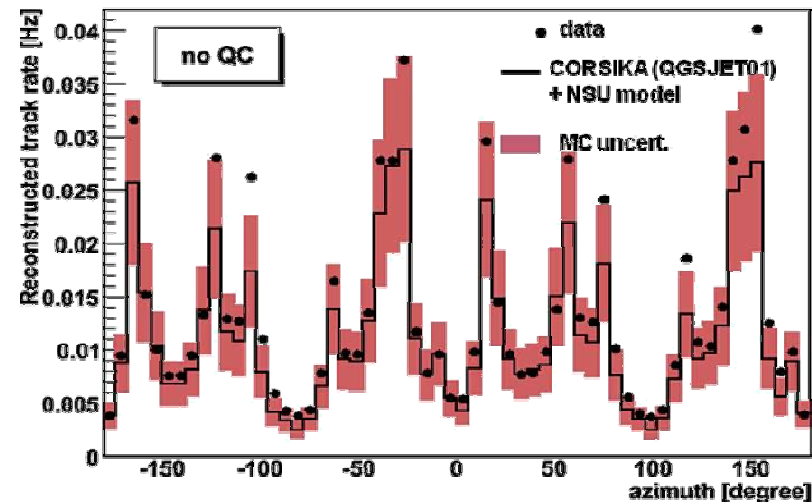
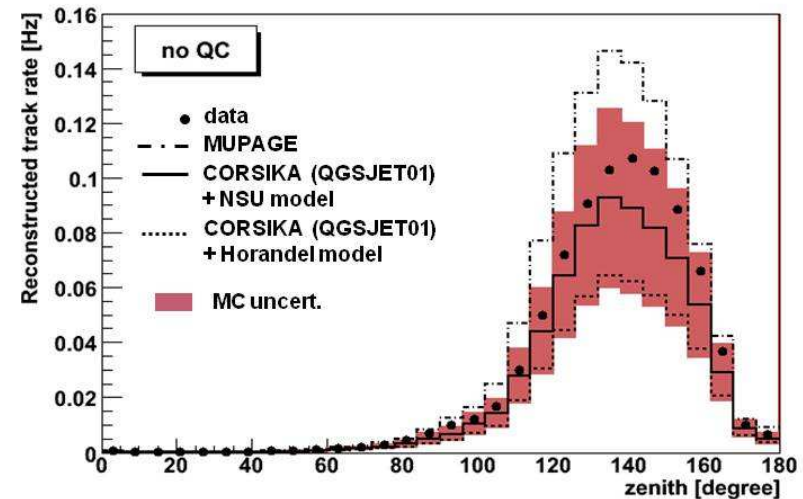


Muon trigger rate (with full detector):  $\sim 10$  Hz

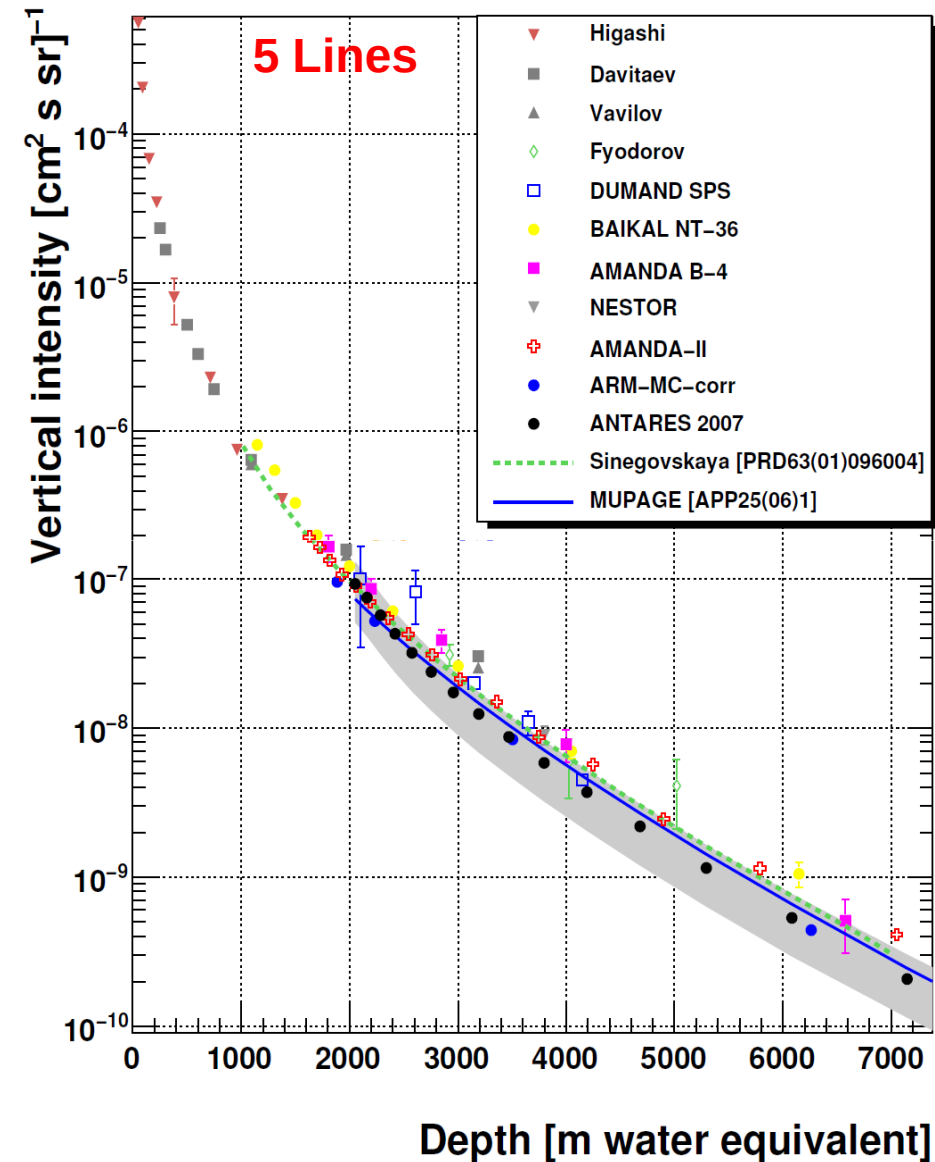
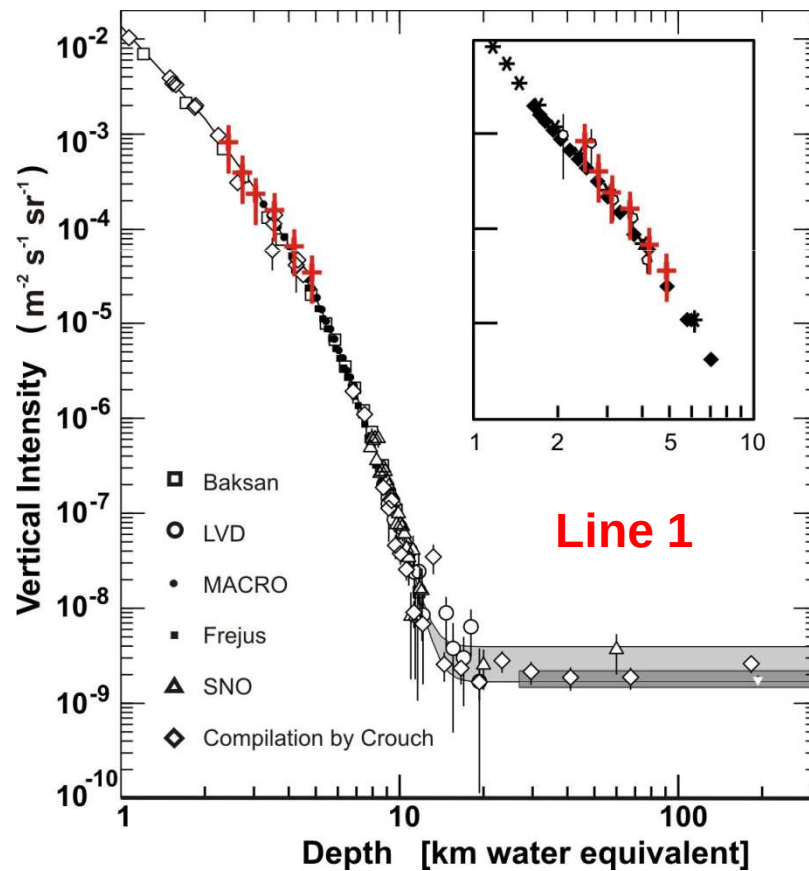
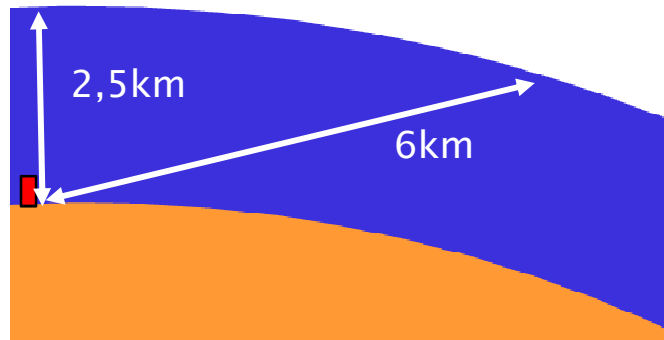
5 lines (2007)  $\rightarrow 19 \cdot 10^6$  muons

$>10$  lines (2008)  $\rightarrow 65 \cdot 10^6$  muons

- Agreement between simulations and data is satisfactory
- Details of apparatus geometry and performance well understood
- Main sources of simulation uncertainty are:
  - optical module response
  - absorption length of light in water

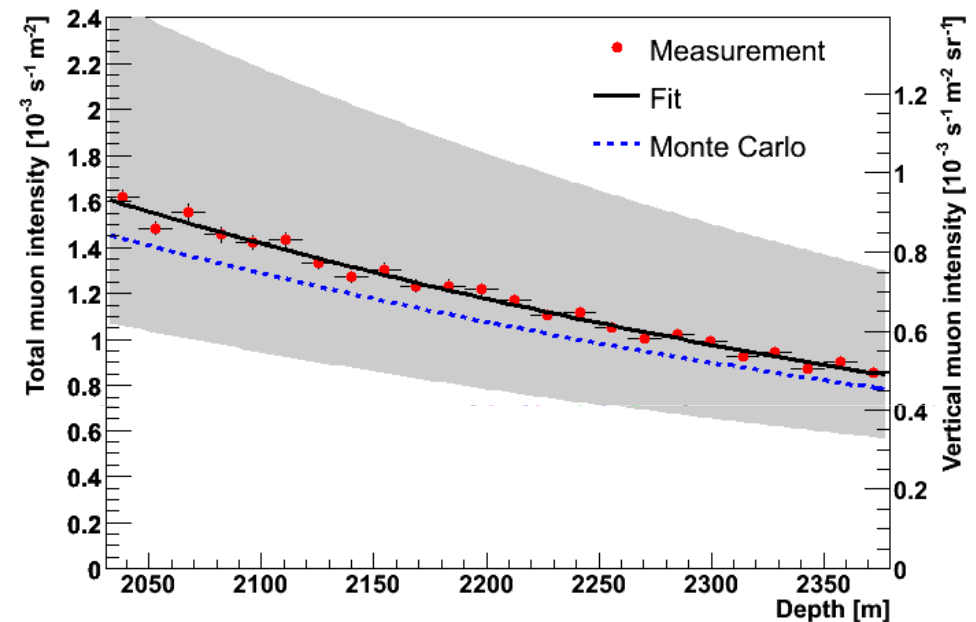
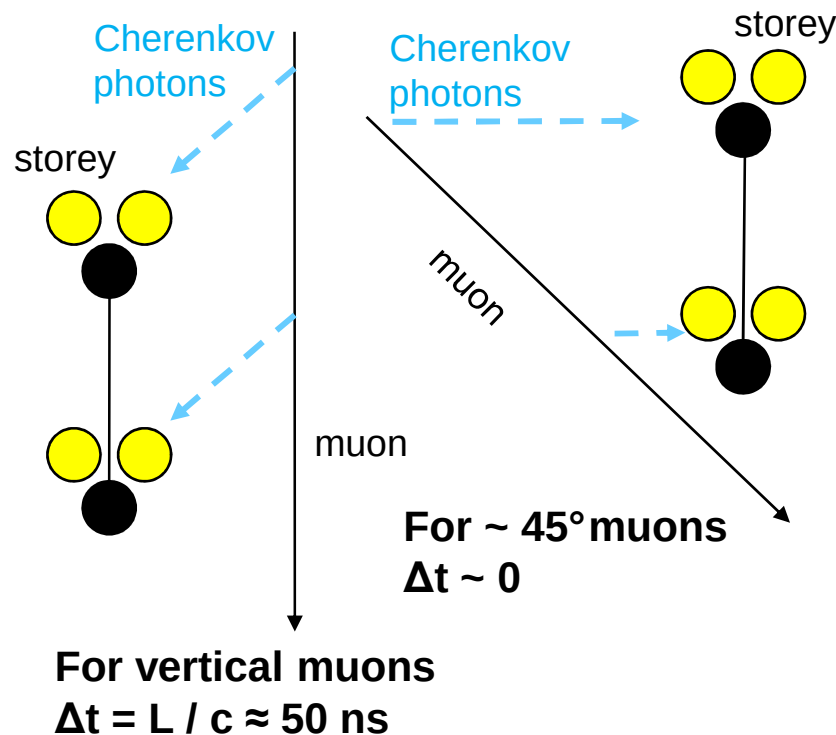


# Depth intensity Relation



# Depth intensity Relation without muon reconstruction

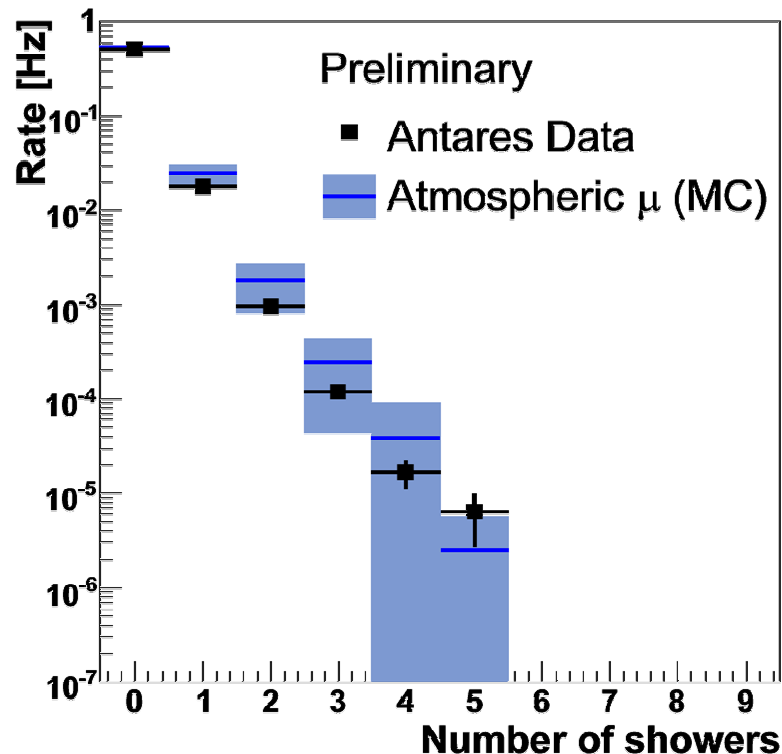
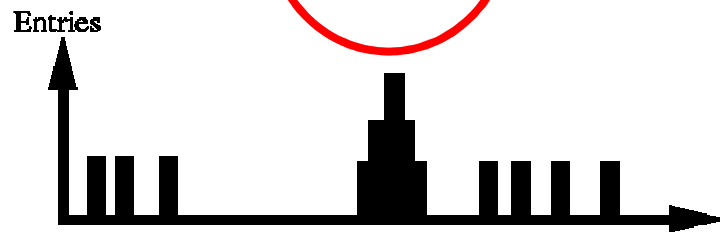
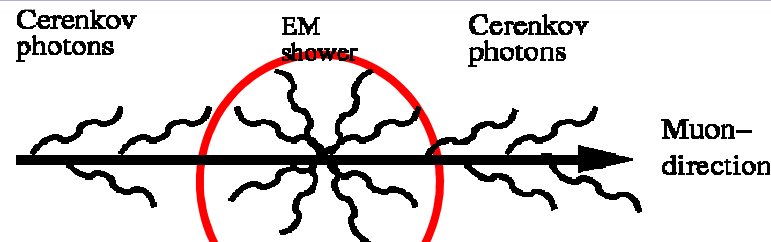
Simple method based on **coincidences on adjacent or next-to adjacent storeys**. No reconstruction needed.



Rate vs. depth distribution can test optical module efficiency and acceptance  
Method allows to measure the depth-intensity relation of muons with no systematic errors from trigger or reconstruction algorithms (main uncertainty: optical module acceptance)



# Electromagnetic showers from muons: CR composition

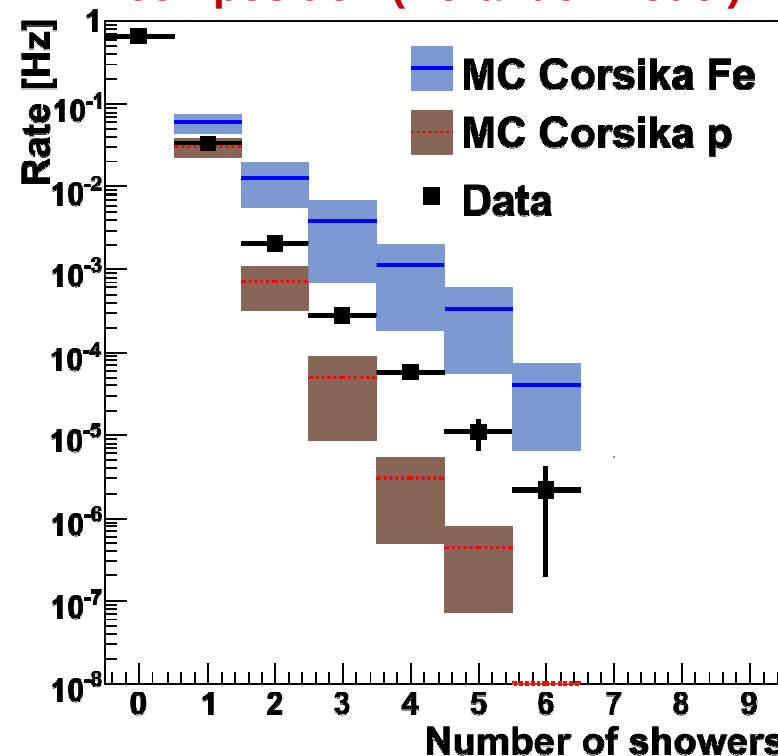


Muon emission :

- Cherenkov light (continuum)
- Discrete electromagnetic showers (bright point sources)

Peak gives shower position

Data compatible with mixed composition (Hörandel model)



# Neutrino Events

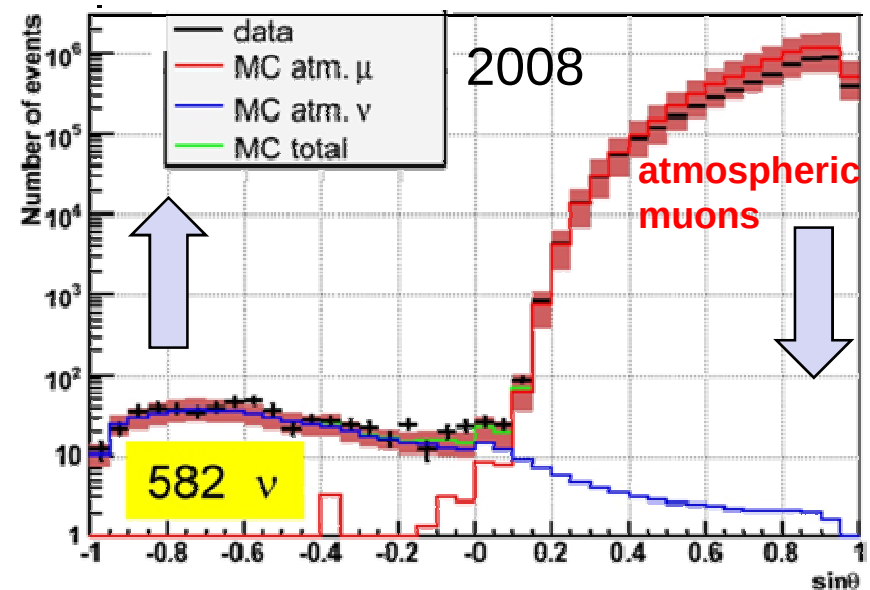
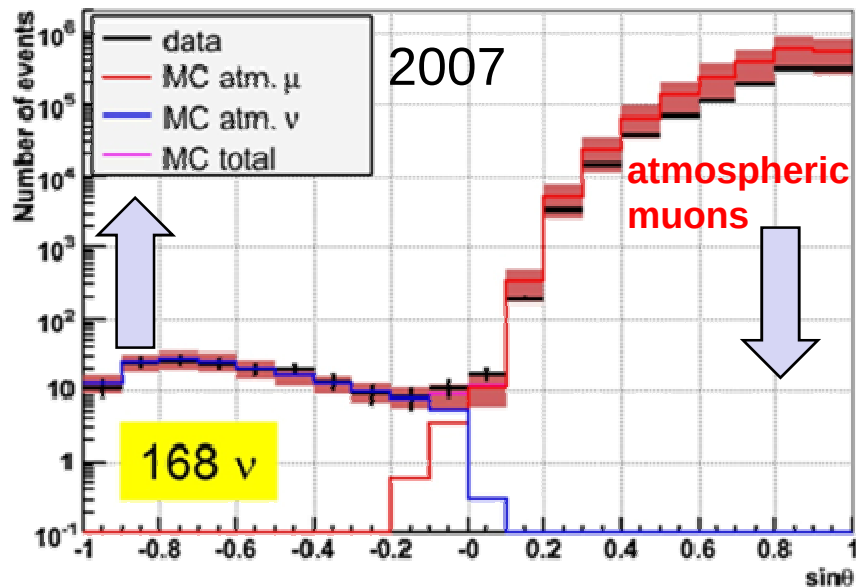
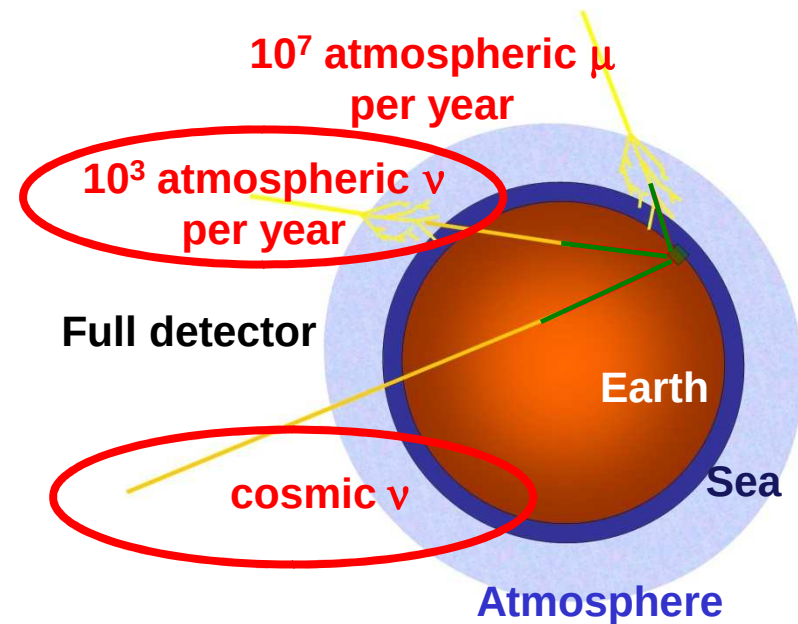
2007

5-line apparatus, 168 days 168 events

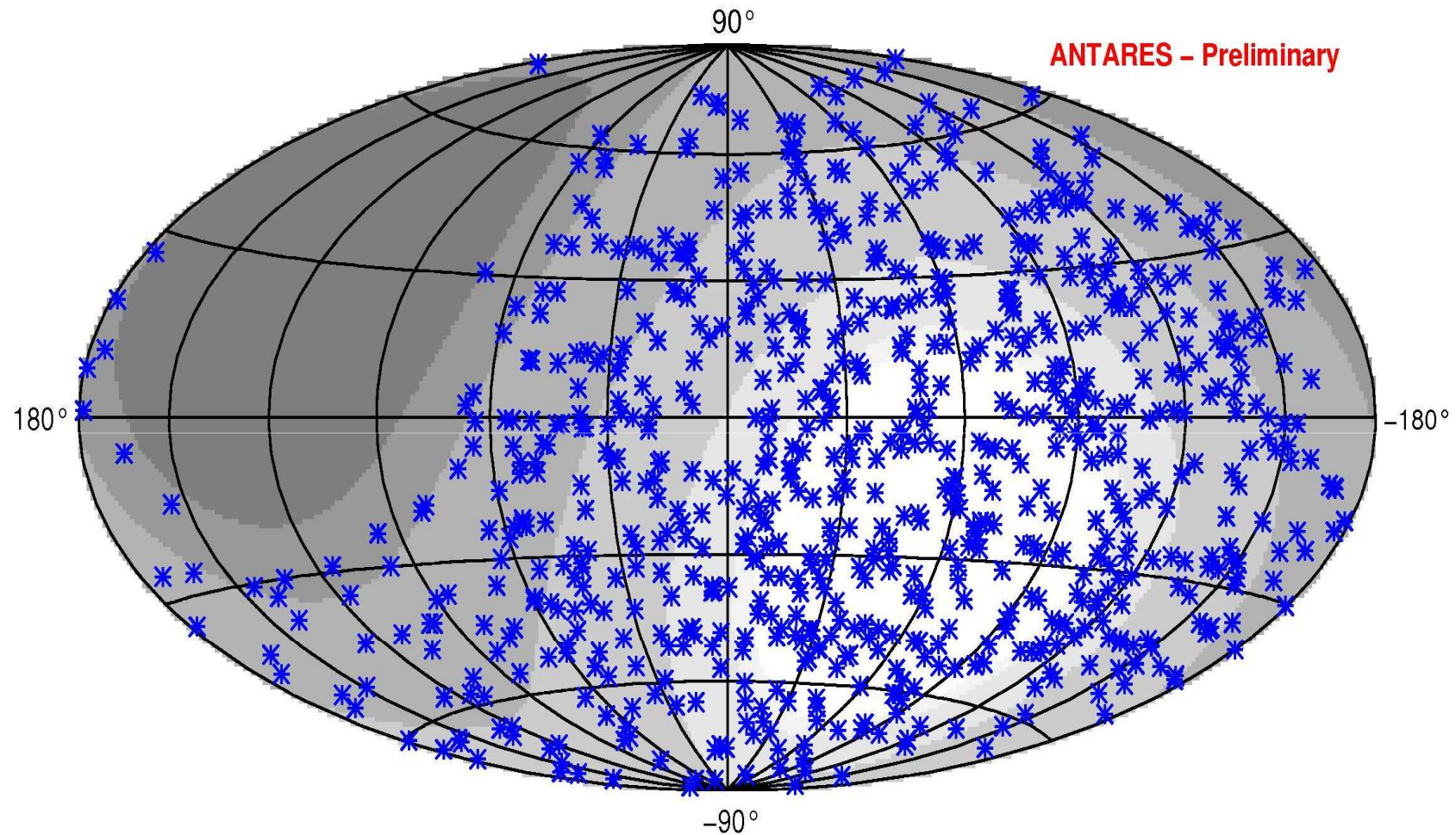
2008

9/10/12-line apparatus, 174 days 582 events

Up to today: more than 1500 neutrino events



# Neutrino Events: sky map



750 upgoing neutrinos: 2007+2008 data

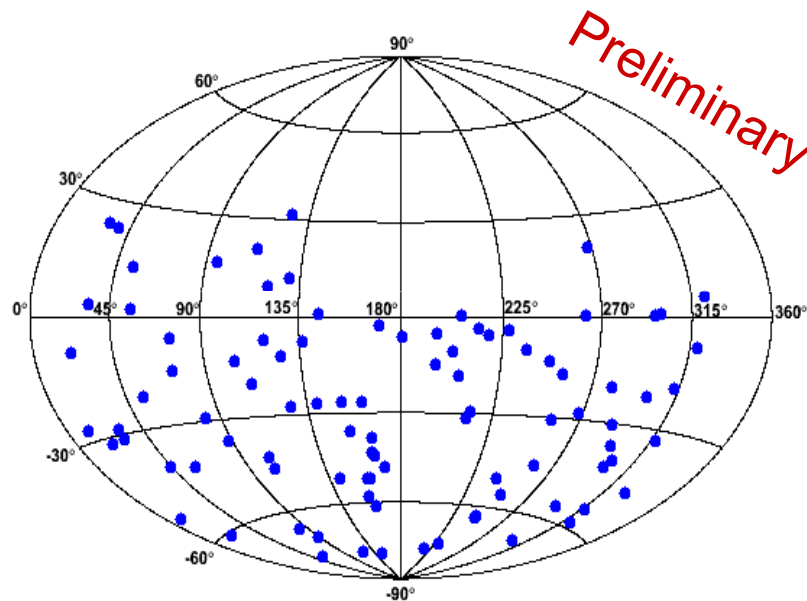
# Search for point sources

Definition of a list of 25 potential sources

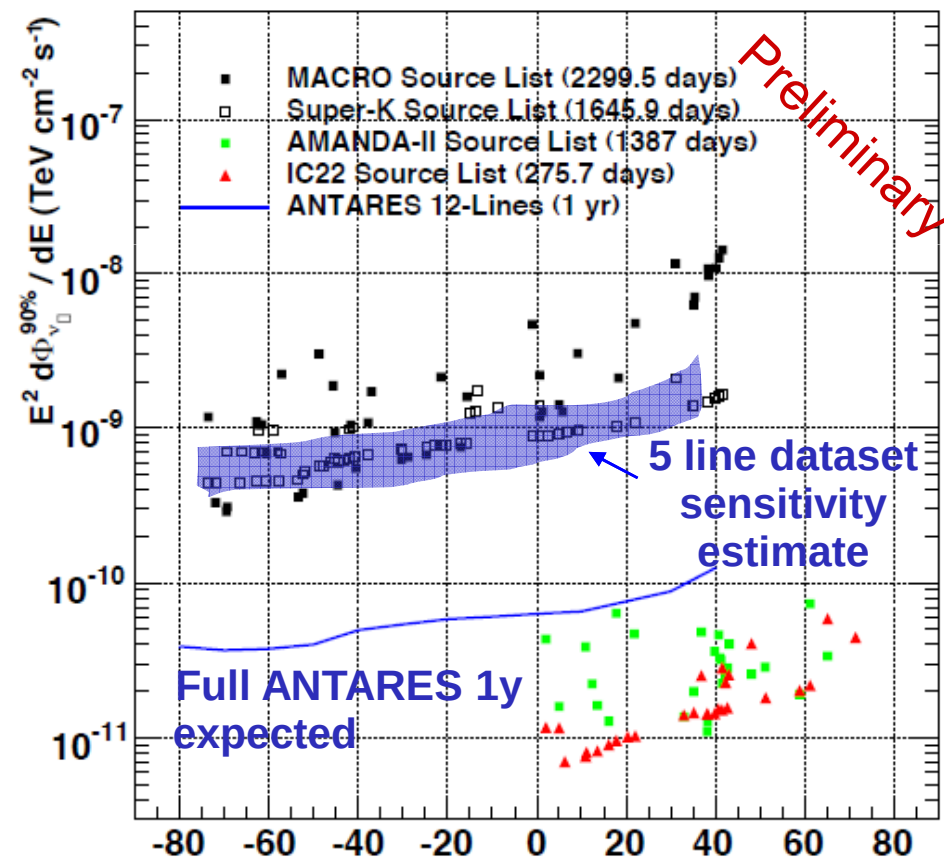
(stringent cuts to reduce background)

Analysis optimization based on simulations

Data unblinding...and...no excess ... no surprise !

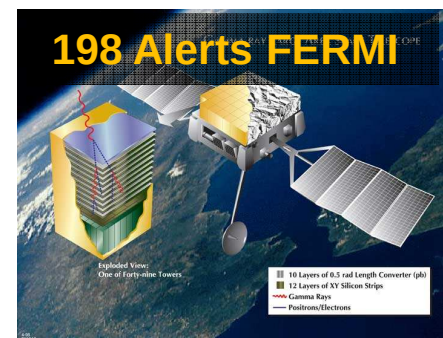
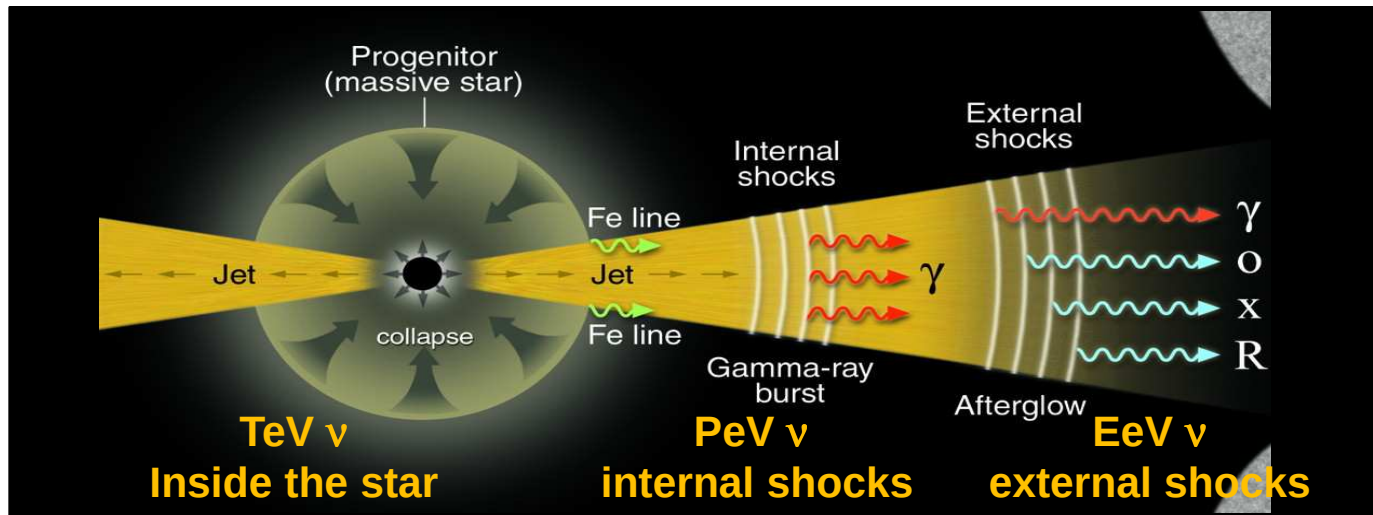


**Effective livetime of 140 days  
(with reduced apparatus)  
competitive with multi-year  
exposures of previous experiments**





# GRB Neutrino events: time correlation



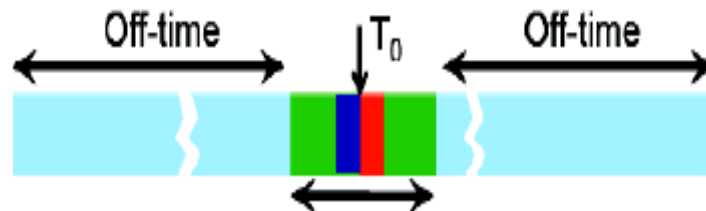
## Triggered search

Uses Satellite trigger list

Low backgrounds due to direction and time coincidences

Low signal per GRB, use stacking

Currently just muon neutrinos



Standard data storage:

Only filtered events  
(all hits within 2.2  $\mu$ s)

GRB data storage:

All data without filtering  
during 2 minutes

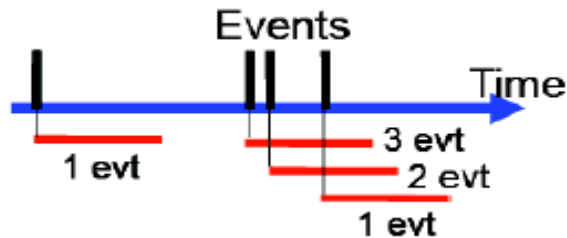
Till May 2009

# GRB Neutrino events: time correlation

## Rolling search plus TAROT optical follow up

- Sliding window around events
- Sensitive to dark bursts
- Fast online reconstruction optical follow up to identify source

Operational since May 2009



- Single High Energy Neutrino  $>20$  TeV
- Multiplets of events in the same direction and in a short time

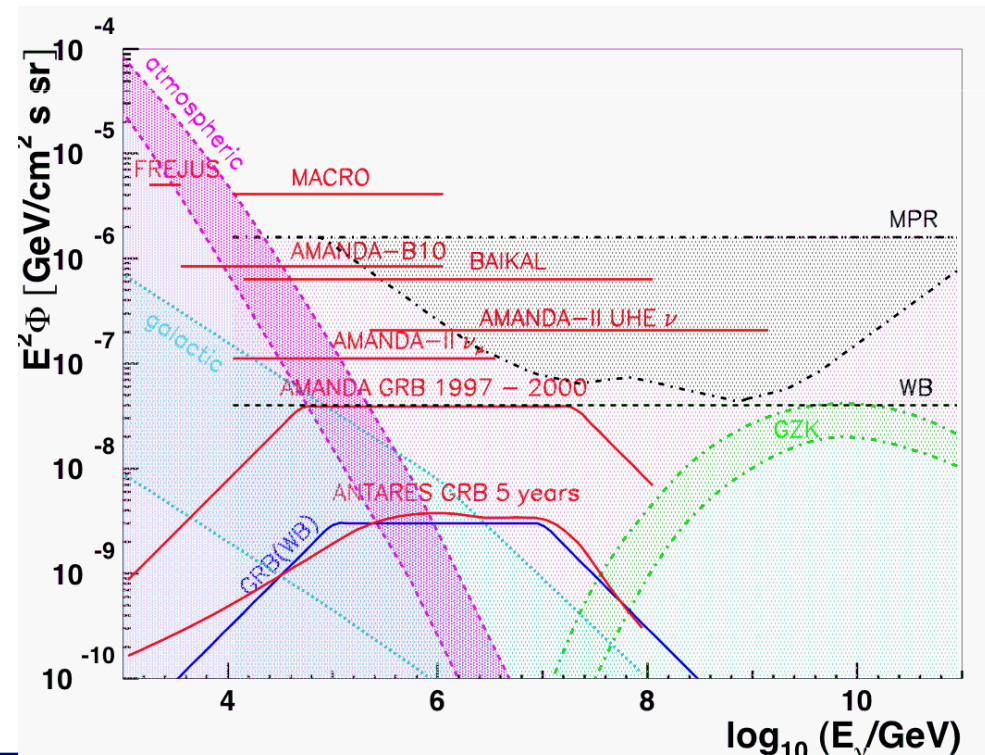
### TAROT

two 25 cm telescopes France and Chile

FOV  $1.86^\circ \times 1.86^\circ$

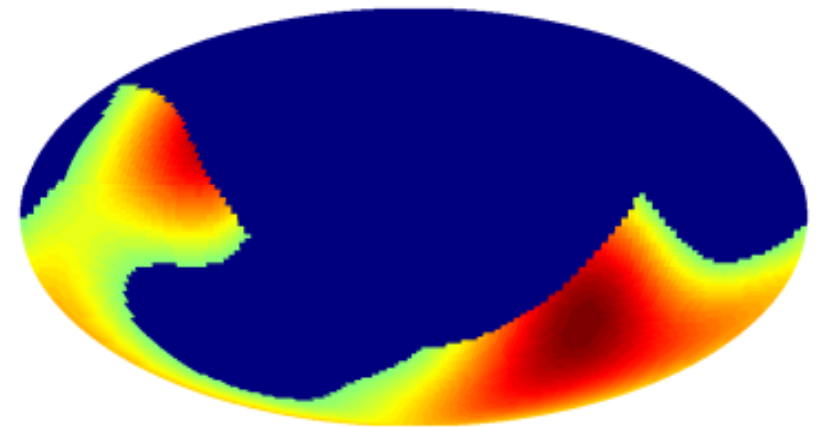
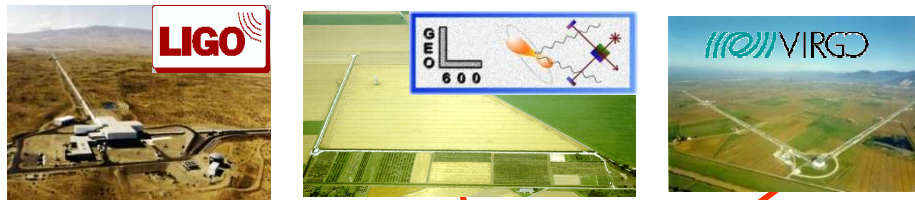
$\sim 10$  s repositioning after alert

ANTARES alert: two events with  $\Delta\Omega < 3^\circ \times 3^\circ$  in  $\Delta t < 15$  min  
[rate(atm) =  $0.05 \text{ yr}^{-1}$ ]



# ANTARES and Gravitational Waves detectors

Memorandum of understanding ANTARES-VIRGO-LIGO signed  
plausible common sources GRBs (core collapse into BH or coalescing  
neutron stars), SGRs (magnetars), microquasars...)  
potential for discovery of hidden sources (e.g. failed GRBs)

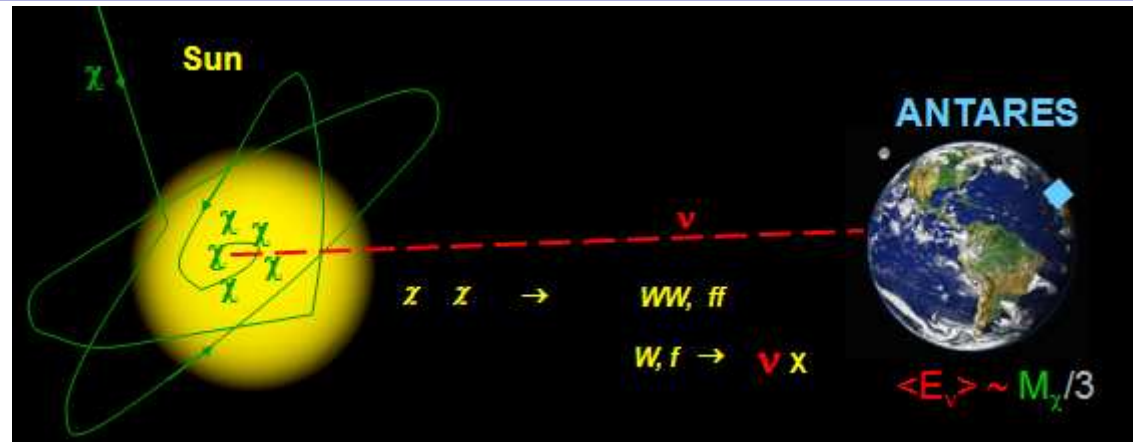


Common sky coverage for  
VIRGO+LIGO+ANTARES  
In geocentric coordinates ~ 30%

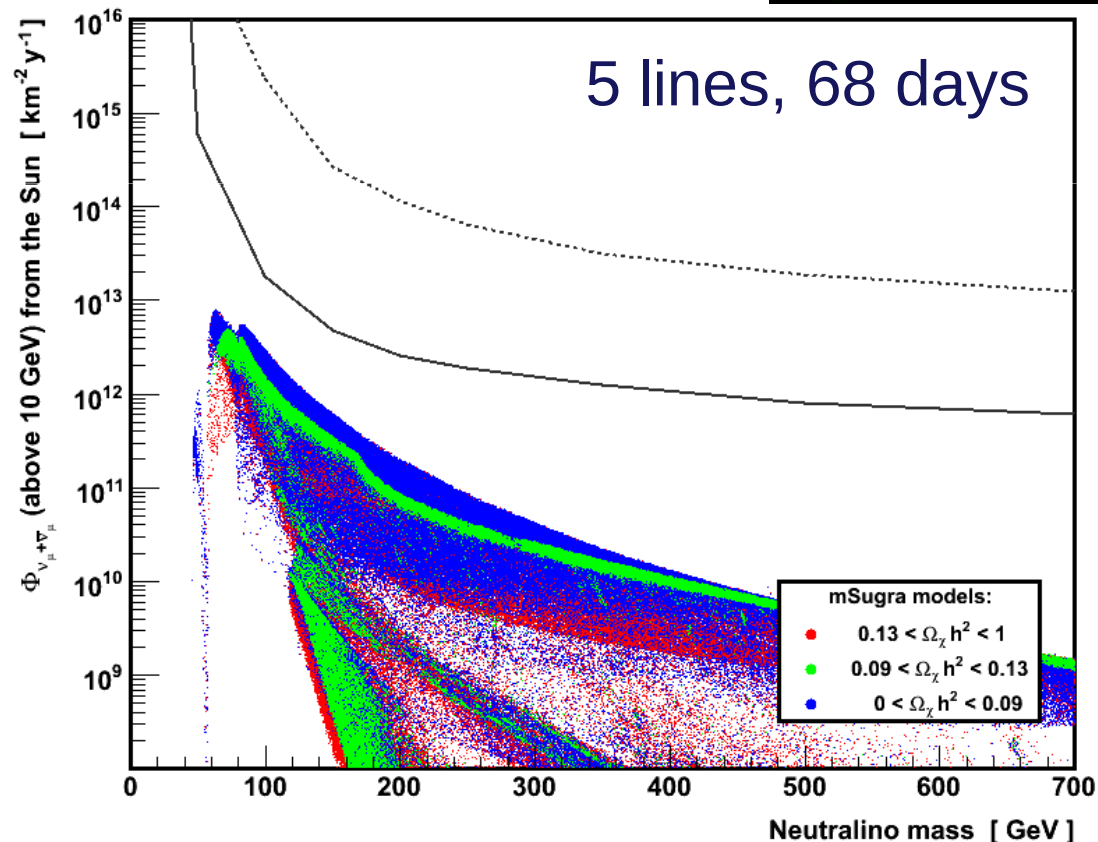


# Dark Matter Search

WIMPs gravitational trapped via elastic collisions in the Sun



$\Phi_{\nu_\mu + \bar{\nu}_\mu}$  from the Sun



168 days  
+ 51% Sun under horizon  
+ trigger corr.

No excess observed (90% C.L. limits) à la Feldman-Cousins

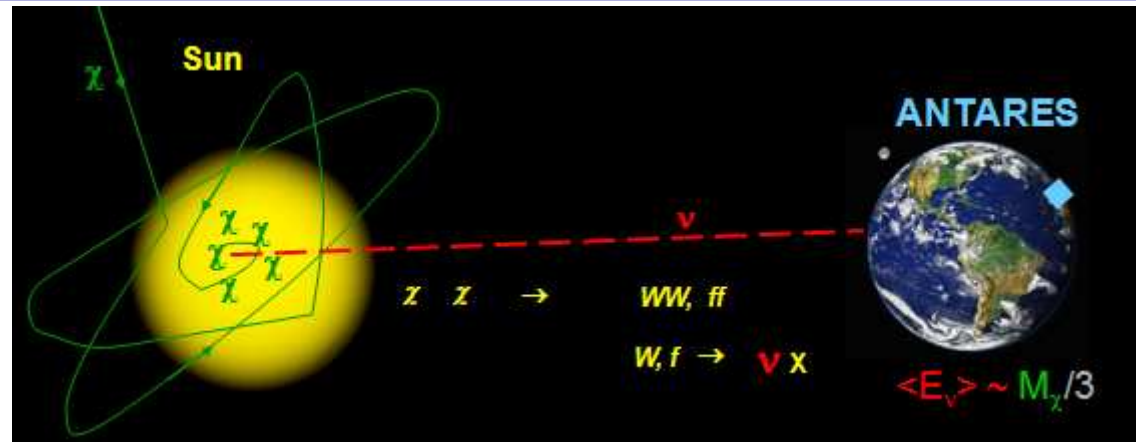
mSugra model predictions

green : WMAP favoured relic density  
red : > WMAP favoured relic density  
blue : < WMAP favoured relic density

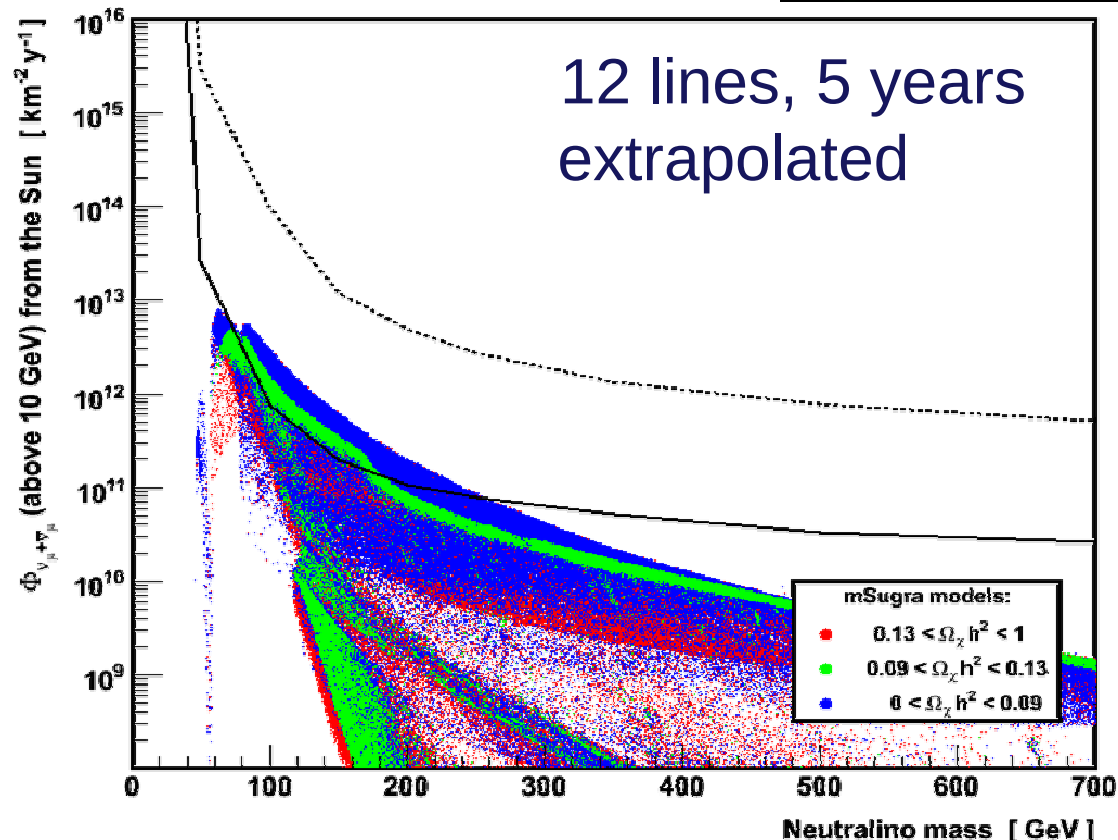


# Dark Matter Search

WIMPs gravitational trapped via elastic collisions in the Sun



$\Phi_{\nu_\mu + \bar{\nu}_\mu}$  from the Sun

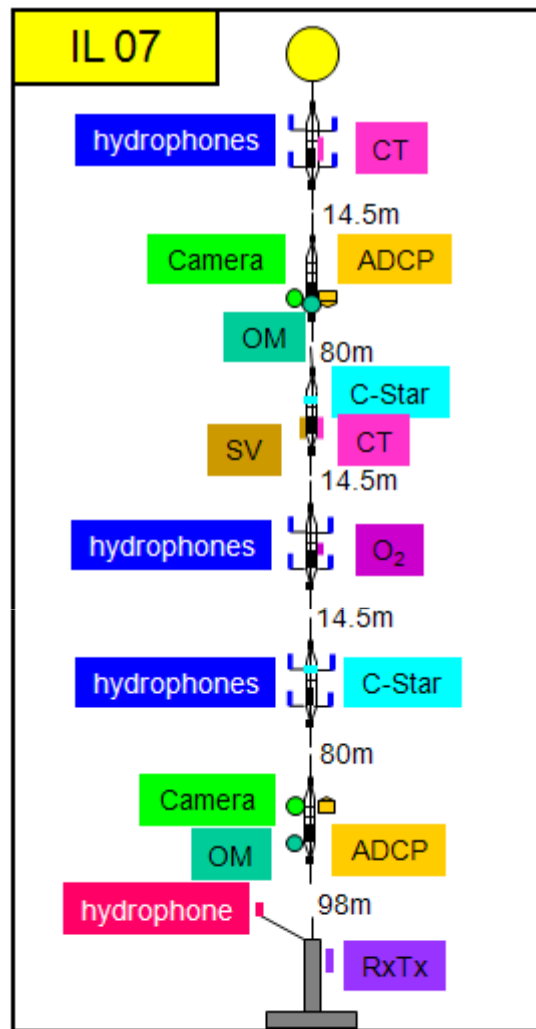


Simple extrapolation to full detector and 5 years

mSUGRA model predictions

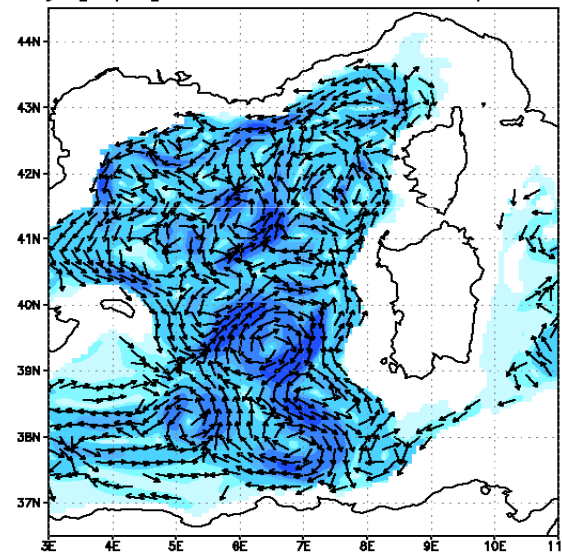
green : WMAP favoured relic density  
red : > WMAP favoured relic density  
blue : < WMAP favoured relic density

# Earth and Sea Science with the Instrumentation Line



- Bioluminescence
- Environmental Monitoring
- Seismology
- Oceanography (Med Sea Circulation)

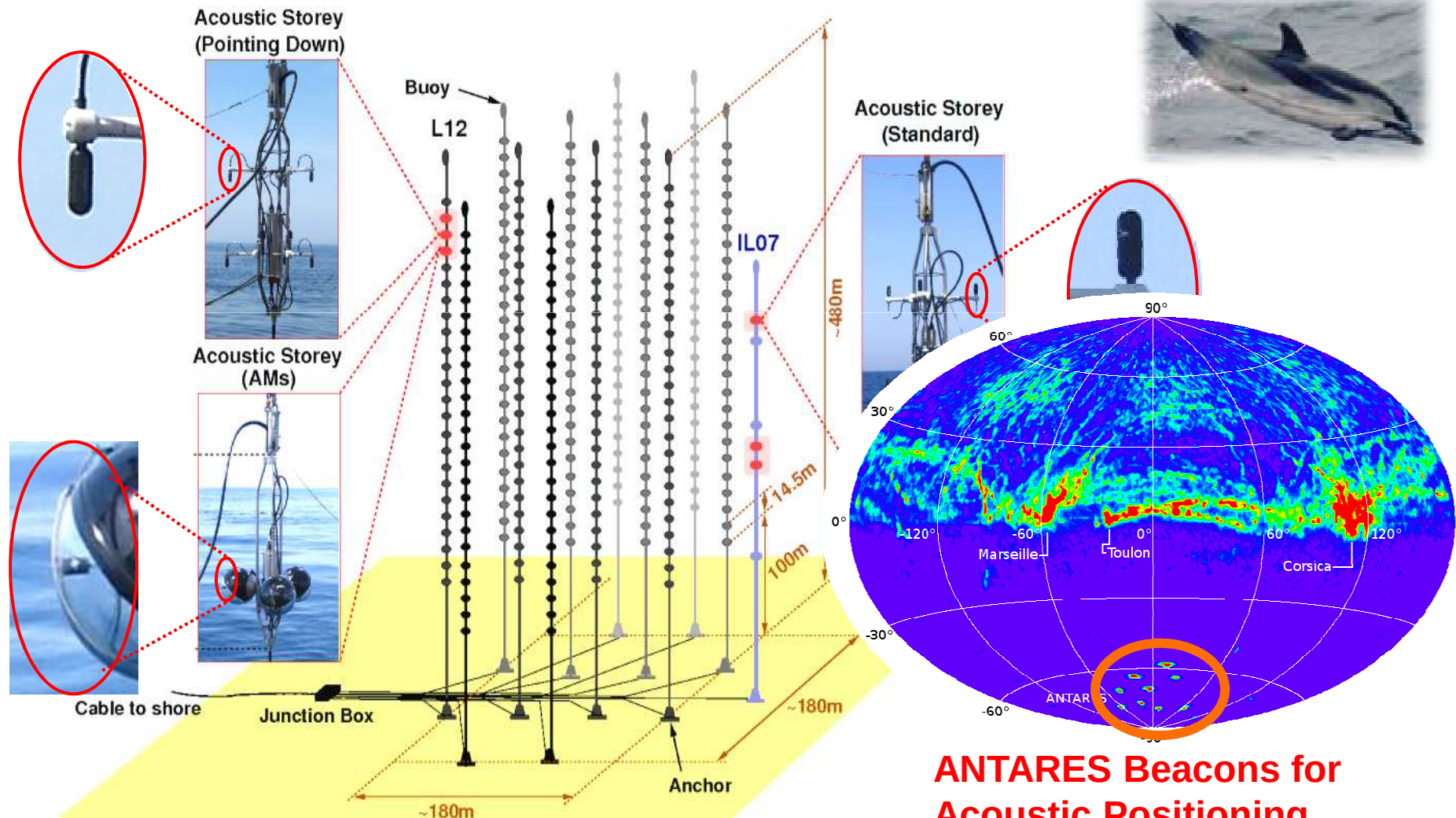
velocity [m/s] – date 070129 depth 1000 m



2010: Deployment of a secondary JB for Scientific and technological applications IFREMER/CNRS

# Acoustic Detection: AMADEUS

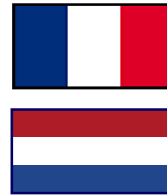
- AMADEUS comprises a series of hydrophones on the IL and Line 12
- A test bench to study the feasibility of a large acoustic UHE neutrino detector
- Study of acoustic environment and backgrounds
- Methods to reconstruct direction



**ANTARES Beacons for  
Acoustic Positioning**

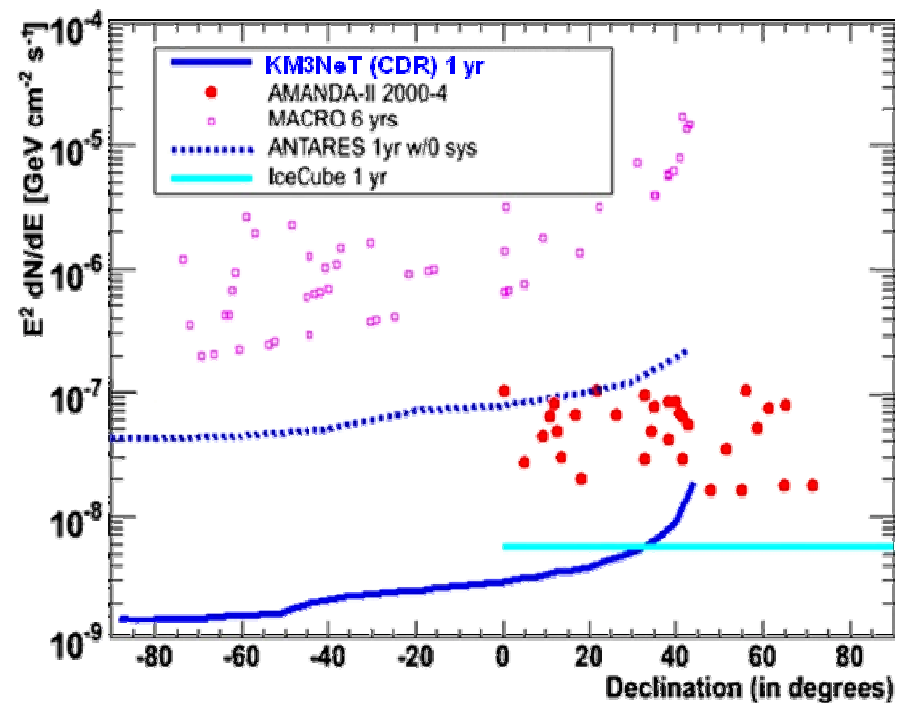
# The KM3NeT European Design Study

*KM3NeT is a European Consortium of 41 Universities and Research Institutes from 10 European Countries, working in the fields of nuclear and particle physics, astrophysics, geophysics and deep sea science.*



**The first step is a Technical Design Report for a cubic kilometre Detector in the Mediterranean Sea having better performances than IceCube (under completion).**

- Based on muon detection
- Factor ~50 more than ANTARES
- Factor ~3 more sensitive than IceCube  
larger photo-cathode area  
better direction resolution

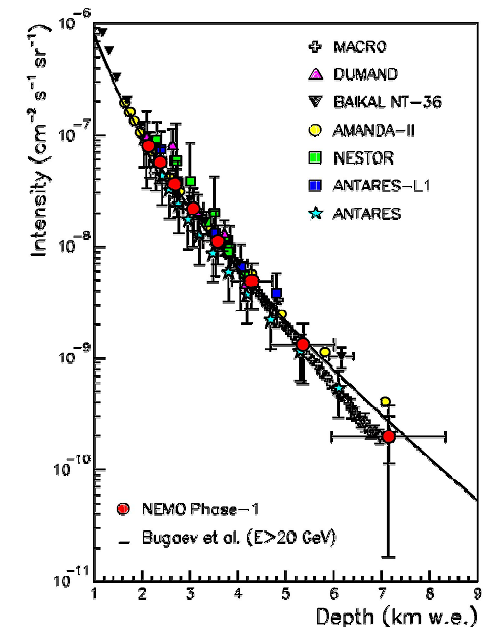
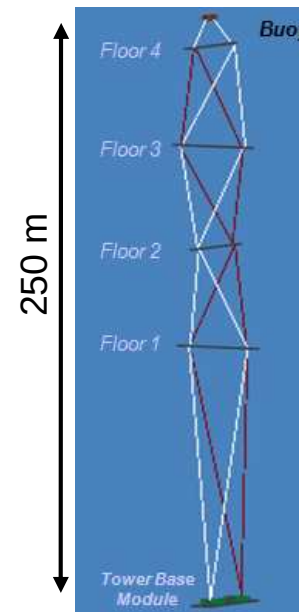
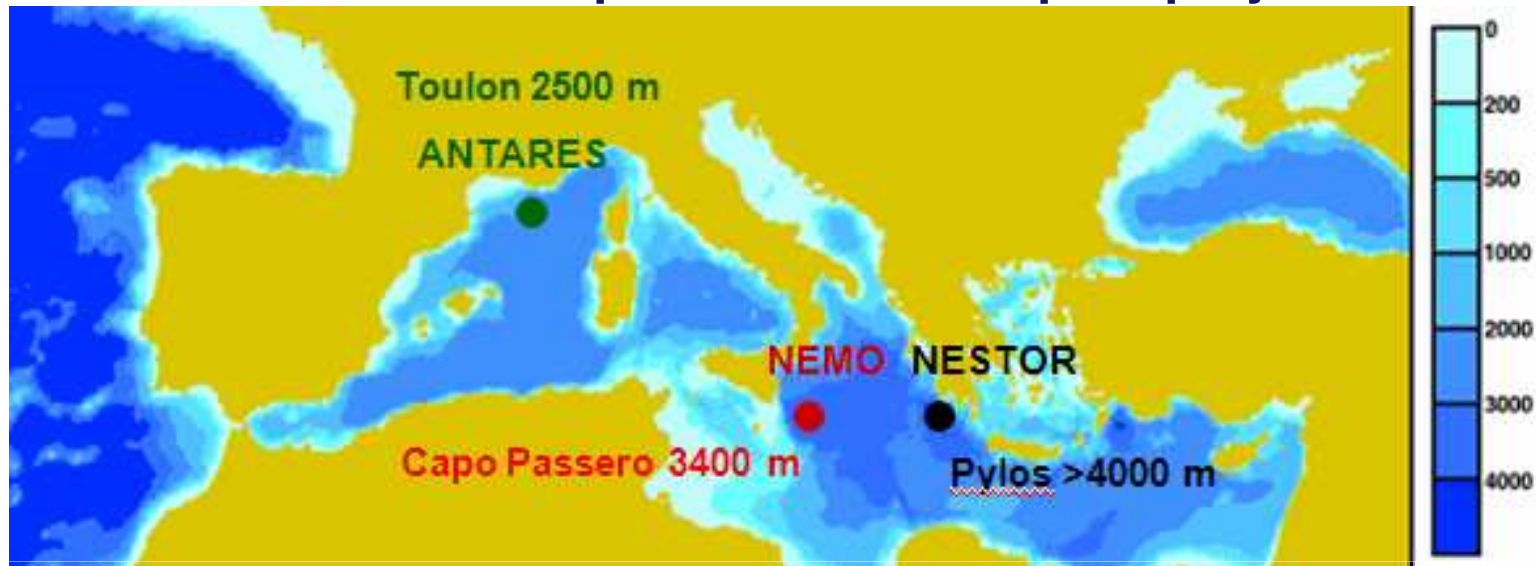


**Preparatory Phase started in 2009**



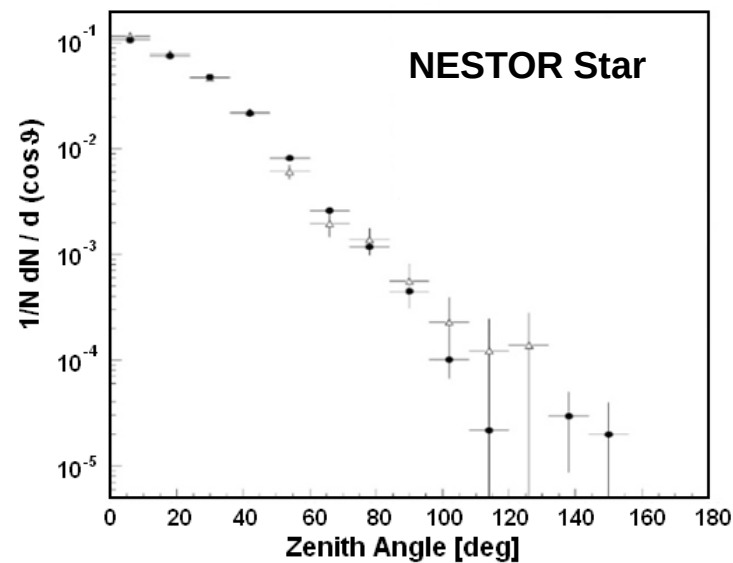
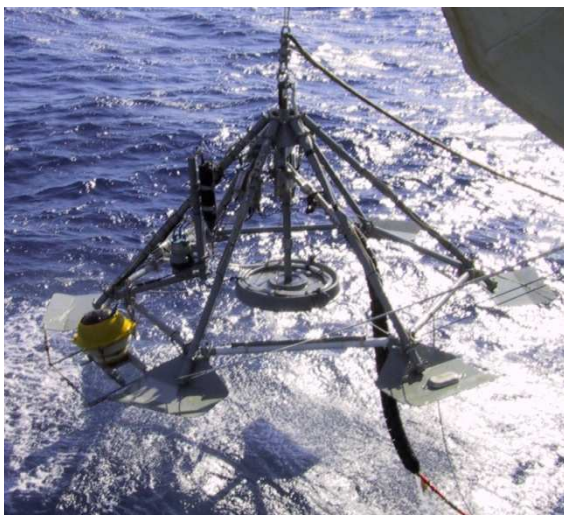
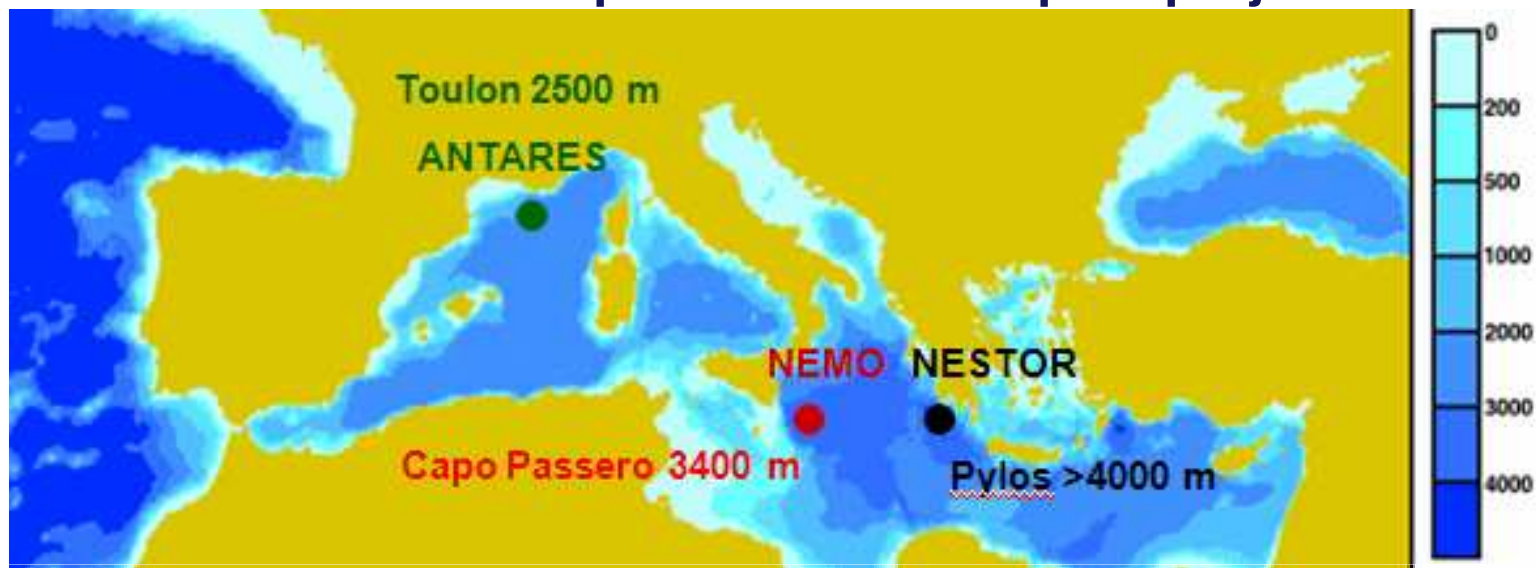
# Towards the Mediterranean km<sup>3</sup>

Born from the experience of three pilot projects



# Towards the Mediterranean km<sup>3</sup>

Born from the experience of three pilot projects





# Towards the km<sup>3</sup> detector

## Maximise physics potential

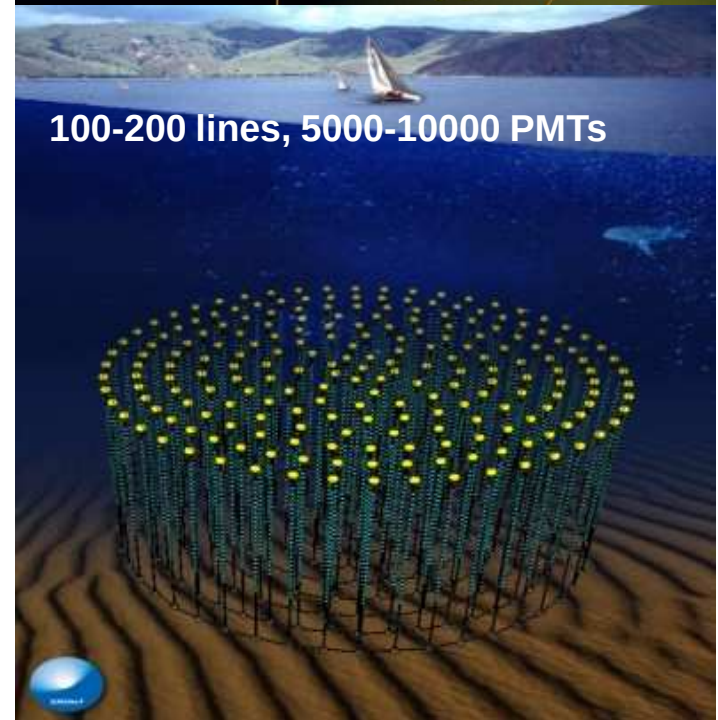
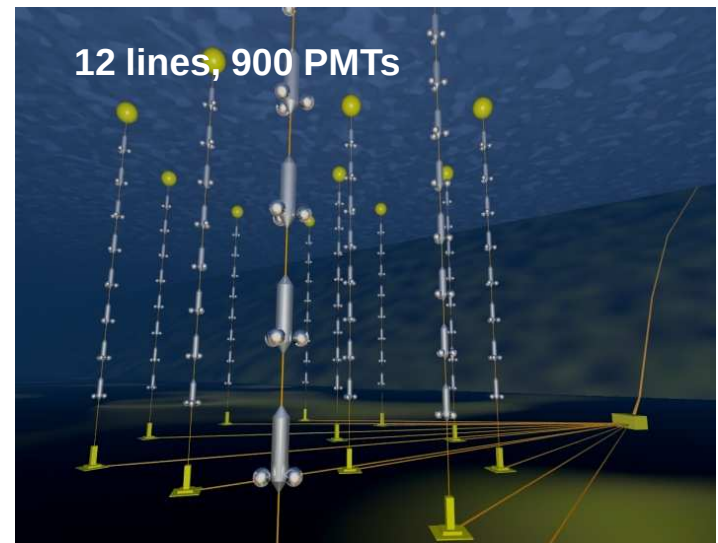
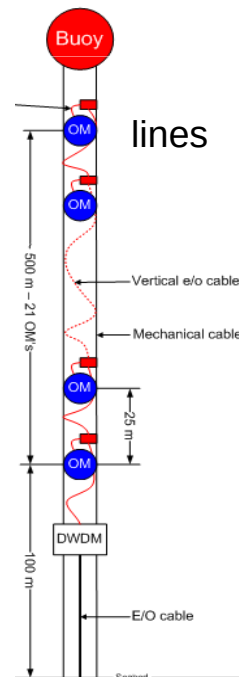
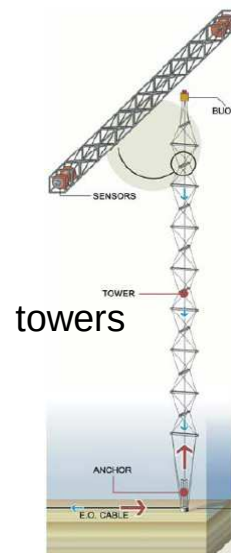
- Substantial improvement over ICECUBE
- Instrumented volume >1 km<sup>3</sup>
- Angular resolution ~0.1 degrees

## Build in a reasonable time ~ 4 years

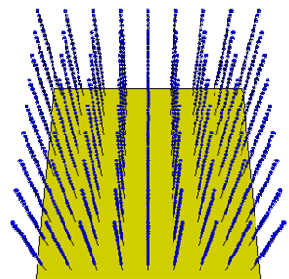
- New deployment techniques
- Speed-up integration time
- Sub contract part of the production

## At a reduced cost

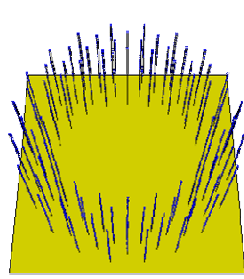
- Factor 2 reduction cf ANTARES
- Simplified architecture
- Reduced maintenance
- Multi-line deployments



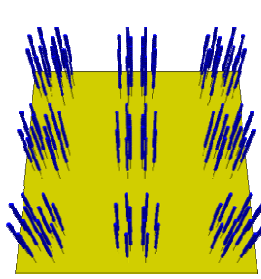
homeneous



ring



clusters



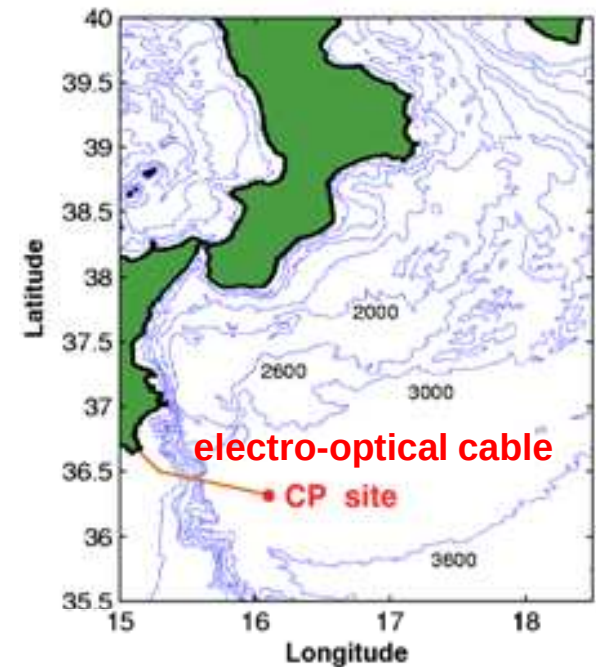
# The ANTARES Mini Line at the Capo Passero Site

## Goal

- Long term monitoring of the site with the ANTARES line (response known in Toulon waters)
- Test of the infrastructure

## Infrastructure

- Shore station in Capo Passero (power and data acquisition)
- 100 km electro optical cable (DC- 100 kW max)
- ROV and Deep Sea Shuttle for deployment and connection
- Underwater infrastructures:
  - Medium Voltage Converter 10 kV/400 VDC
  - ROV Operable Connectors





# The ANTARES Mini Line in the Capo Passero Site

*Comparison in the same environmental conditions of the two presently available detector designs (tower and line) with respect to:*

*Response to the external solicitations (sea current)*

*Sea operations and ROV connections*

*Bioluminescence stimulated by the structure*

*Monitoring of the NEMO site with a similar apparatus used in ANTARES*

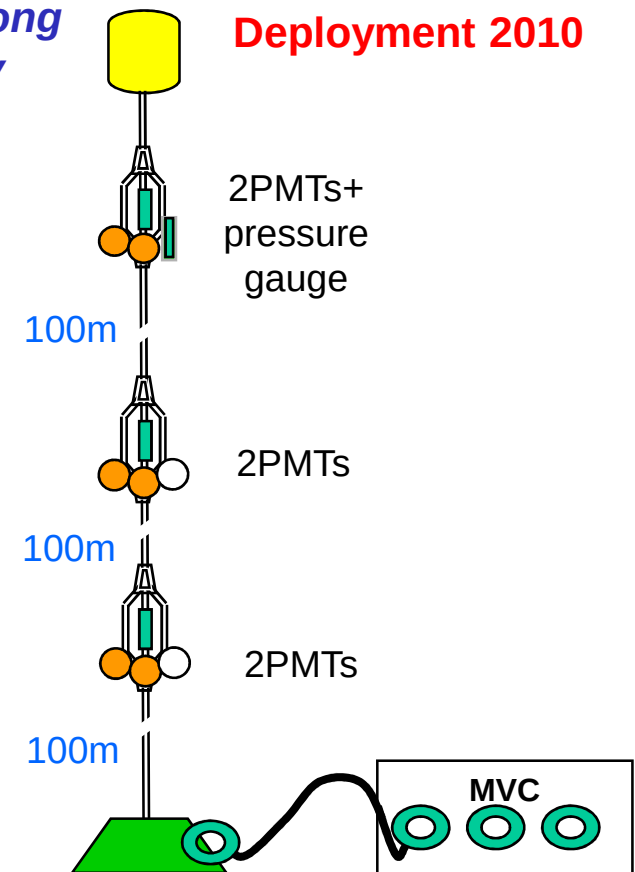
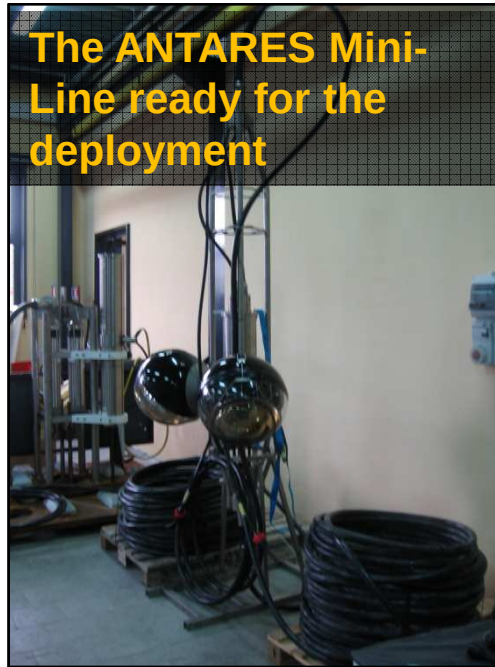
*3 electro optical cables 100m long*

*1 pressure gauge on top storey*

ROV for 4000 m (INFN/INGV) *2 OM's /storey for coincidence*



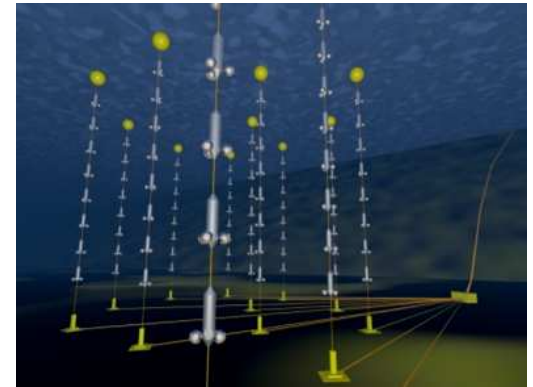
**The ANTARES Mini-Line ready for the deployment**



# Conclusions and Outlook

## ANTARES detector completed in May 2008

Detector operation and calibration under control  
Maintenance capability demonstrated



## Exciting physics program ahead

Over a thousand neutrino already reconstructed  
Unexplored regions of sensitivity  
astronomical sources, dark matter, oscillations, .....  
Multi-messenger approach strongly encouraged

## Real-time readout and in-situ power capabilities facilitates

a large program of synergetic multi-disciplinary activities: acoustics, biology, oceanography, seismology.....

## A multidisciplinary deep-sea research infrastructure

## A Major step towards the KM3NeT

