Detectors for underwater experiments

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KM3NeT

Outline

- Introduction
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- Detection principle
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  - KM3NeT-Italia: the towers
  - KM3NeT-Italia: the strings (this afternoon S. Biagi)

The high energy neutrino telescopes

Array of optical sensors to detect neutrinos of extraterrestrial origin

Detection of the Cerenkov light produced by the particles

The faint expected fluxes and the low neutrino detection probability

↓

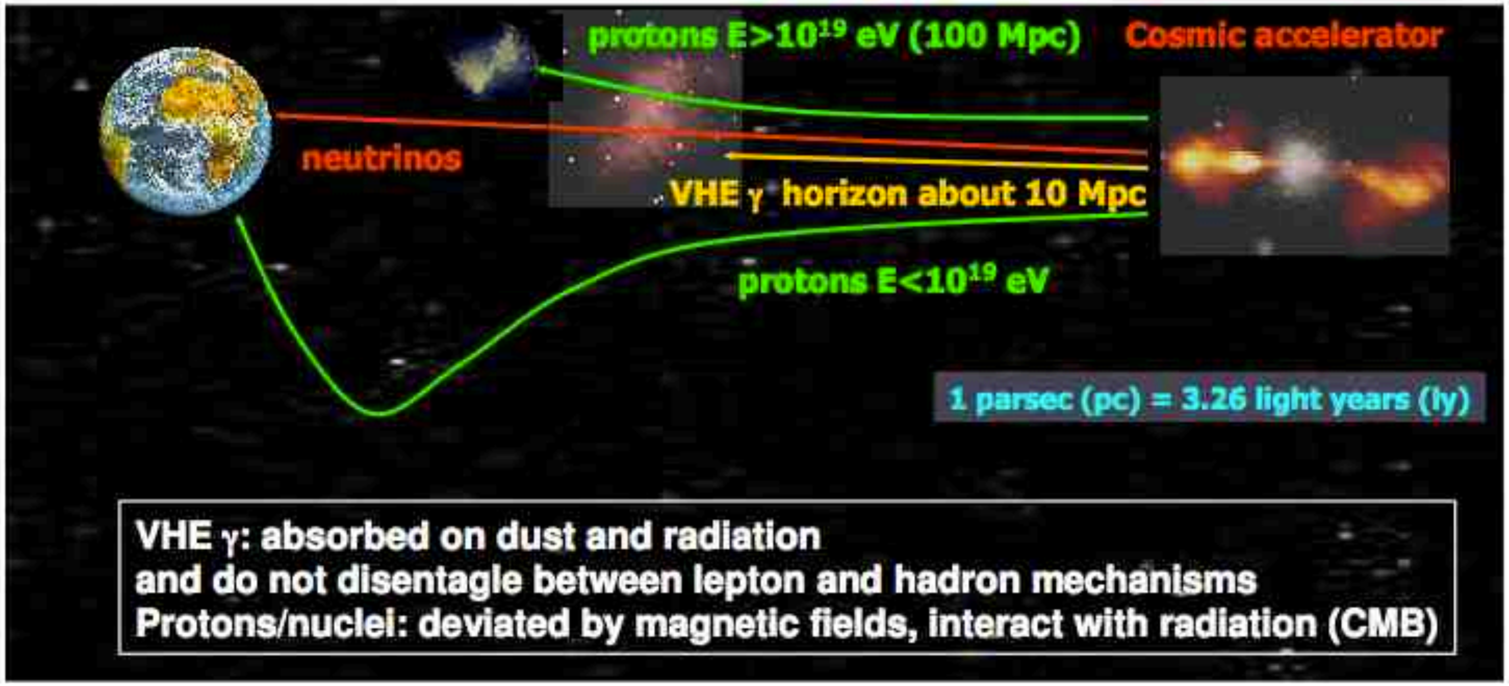
Detector with large volume (km3) installed in deep water or ice

Idea suggested by Markov in the '60

(to use the "beam" of atmospheric neutrinos)

High energy means -> from 10^2 GeV to 10^8 GeV

Why the neutrino detection?



The neutrino observation can give information on:

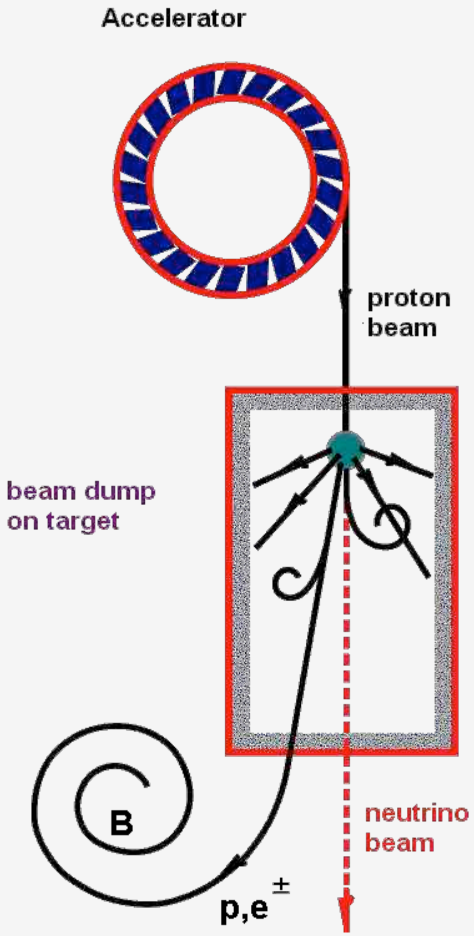
- ✓Origin of Cosmic Rays of high energies (astrophysics, cosmology and particle physics)
- ✓Production mechanism of high energy gammas (hadronic e/o leptonic mechanisms)
- ✓Properties and production mechanism in the core of sources

The observation of neutrinos is connected with the already observed gamma-ray fluxes in near low density sources and high not known high density sources.

The Astrophysical Beam Dump

Fermi acceleration of protons and electrons in astrophysical sources

Particle accelerator



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

Leptonic HE γ production

synchrotron radiation followed by IC

$e + \gamma_{Synchrotron} \rightarrow e' + \gamma'_{HE}$

Hadronic HE ν and γ production

p + p (SNR,X-Ray Binaries)→ X,π

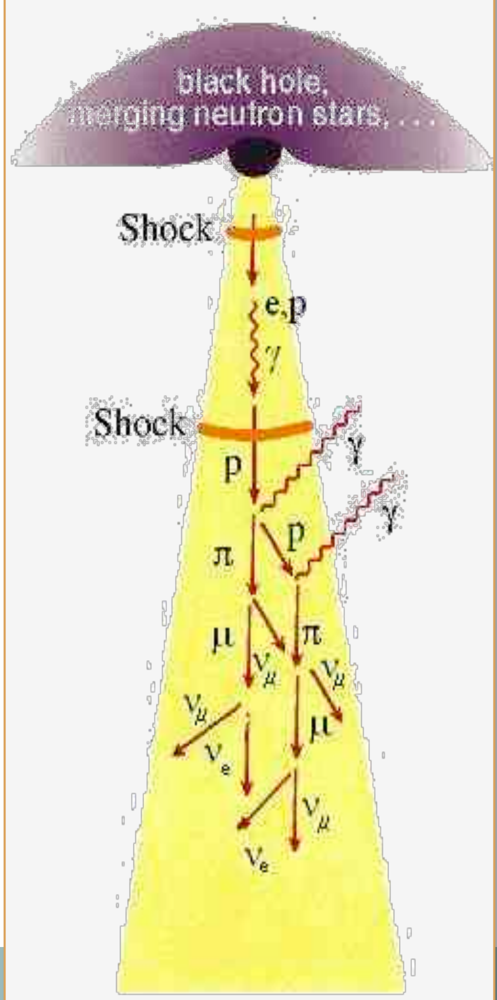
p + γ (AGN, GRB, μQSO) →Nπ

Decay of pions and muon

neutral pions → HE gammas

charged pions → **HE ν_μ ν_e**

Astrophysical jet



Why underwater/ice

The requirement of large neutrino interaction target induced Markov and Zheleznykh to propose the use of natural targets.

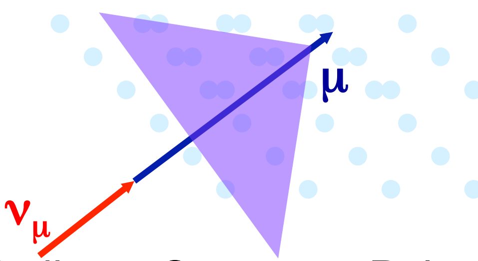
Deep seawater and polar ice offers:

- huge (and inexpensive) target for neutrino interaction;
- shielding from cosmic background;
- good characteristics as optical and radio Cherenkov radiators;

High Energy neutrinos detection techniques

1 TeV — 100 PeV — 1000 ZeV

Optical Detection (ICECUBE-KM3NeT)



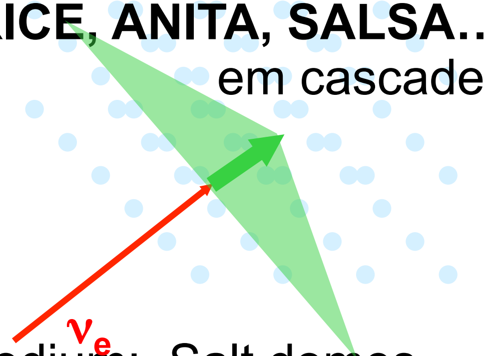
Medium: Seawater, Polar Ice

ν_μ (throughgoing and contained)
$\nu_{e,\tau}$ (contained cascades)

Carrier: Cherenkov Light (UV-visible)
Attenuation length: 100 m

Sensor: PMTs
Instrumented Volume: 1 km^3

Radio Detection (RICE, ANITA, SALSA…)



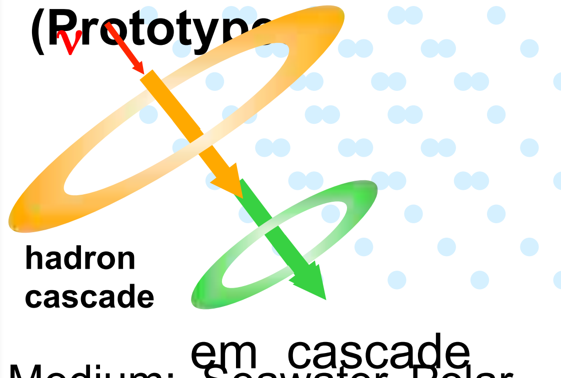
Medium: Salt domes, Polar Ice

ν(cascades)

Carrier: Cherenkov Radio
Attenuation length: 1 km

Sensors: Antennas
Instrumented Volume: >10 km^3

Acoustic Detection (Prototype)



Medium: Seawater, Polar Ice, Salt Domes

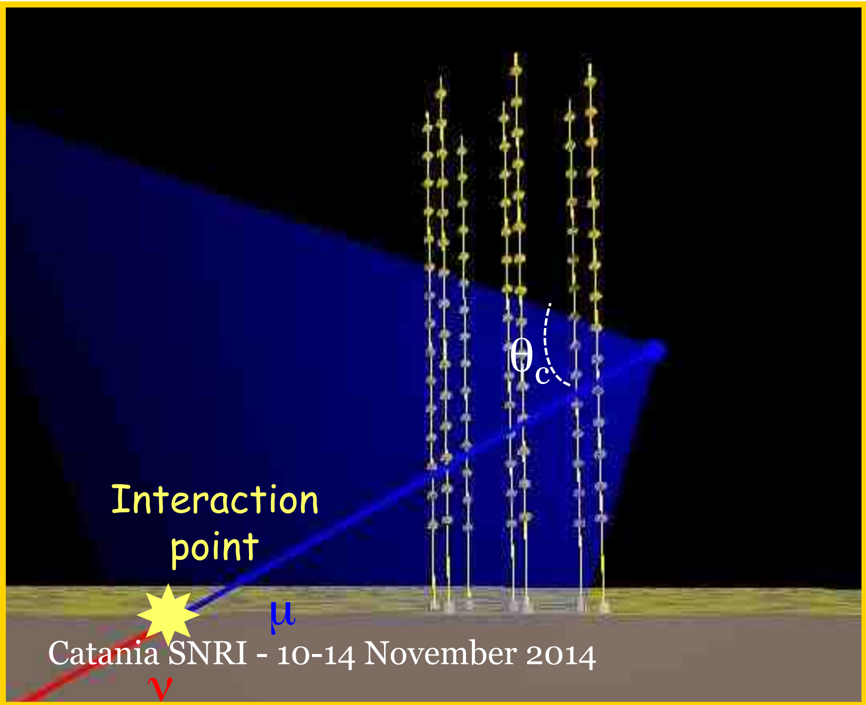
ν (cascades)

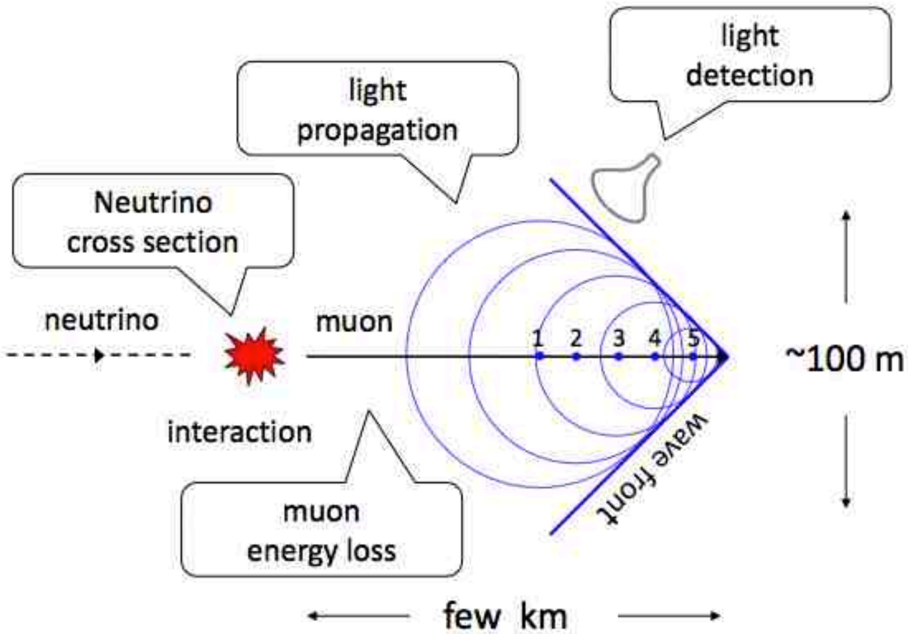
Carrier: Sound waves (tens kHz)
Attenuation length: ~ 10 km

Hydro(glacio)-phones
Instrumented Volume: >100 km^3

Detection principle of underwater/ice neutrino telescopes

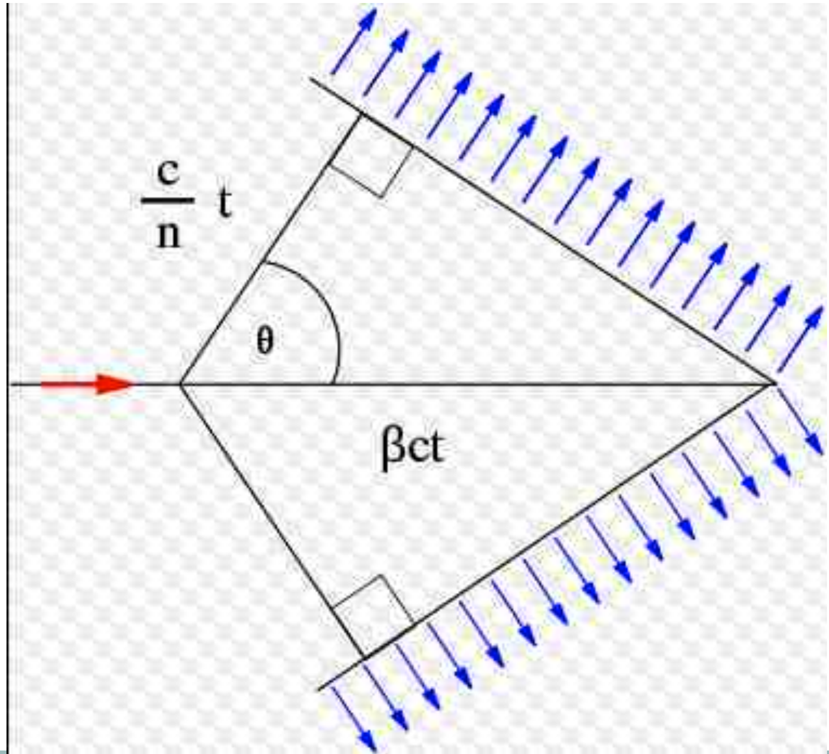
- The neutrinos interact in the water/ice or rocks around the detector and produce secondary particles that emit Cerenkov light in a cone at 42° w.r.t the particle direction.
- Light detected by means of optical sensors (photomultipliers)
- From the arriving time of photons and from the positions of the photomultipliers is possible to determine the direction of the secondary particles. If muons, generated by ν_μ, the precision in the reconstruction of the direction is very high (0.1°-0.2°). High energy neutrinos are collinear with muons

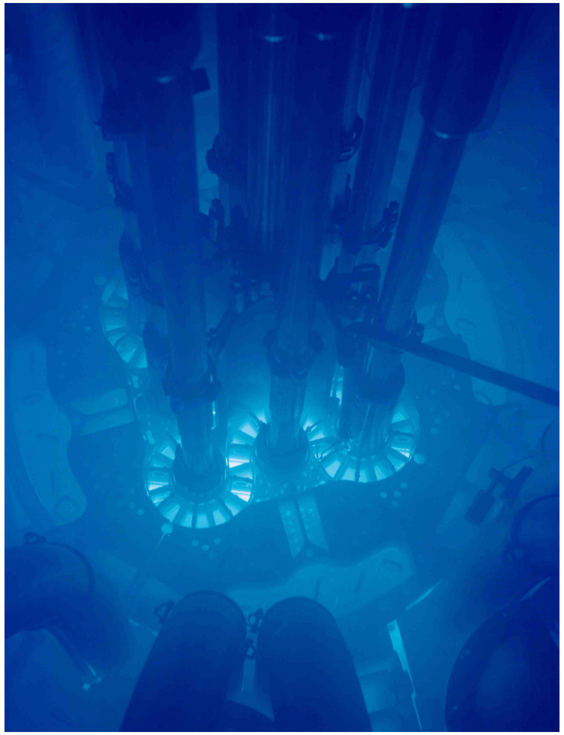




The Cerenkov radiation

- Electromagnetic radiation emitted when a charged particle traverses a medium with a velocity higher than the phase velocity of the light in the medium





The Cerenkov emission

The number of Cherenkov photons N emitted by a charged particle of charge ze per unit wavelength interval dλ and unit distance travelled dx

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \qquad v > \frac{c}{n}$$

High numbers of photons at low wavelength (blue)

The number of photons in the wavelength between 300 and 600 nm and distance unit:

$$\frac{dN}{dx} = 76500 \cdot \sin^2\theta_{ch} \approx 34500\, fotoni/m$$

Huge amount of photons

- Photons emitted at θ_{ch} w.r.t the track direction

$$\cos\theta_{ch} = \frac{1}{\beta n}$$

n water/ice refractive index

$$n = 1.35 \qquad \theta_{ch} = 42.2°$$

emission angle defined

Muon Neutrino interaction

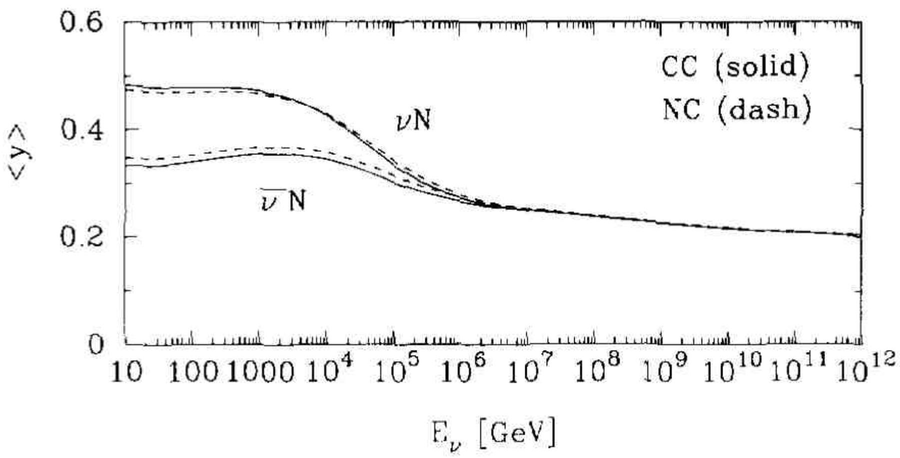
- Neutrino interaction

Charged Current $\nu_{\mu,}$ N -> μ^- + hadrons

Neutral Current ν_μ N -> ν_μ + hadrons

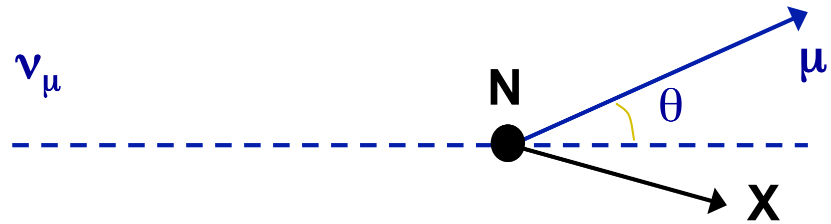
Inelasticity plot

$$\langle y \rangle = \left\langle \frac{E_\nu - E_\mu}{E_\nu} \right\rangle$$



Gandhi et al. Astr.Phys. 5 (1996) 81-110

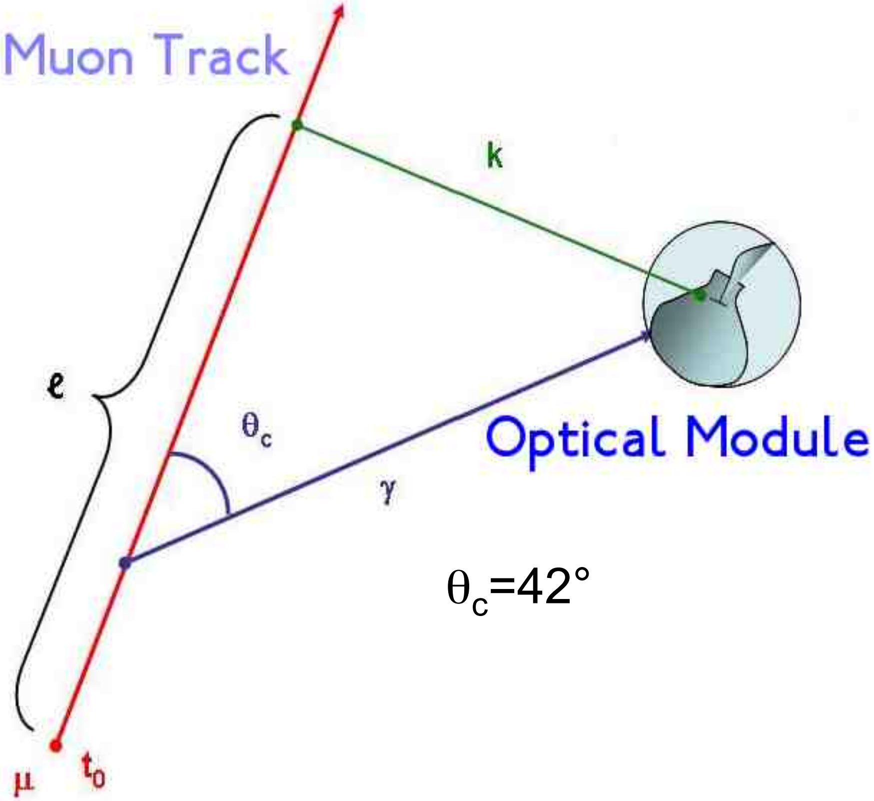
For neutrino energies >TeV neutrino and muon collinear



$$\langle \theta \rangle \approx \frac{1.5^\circ}{\sqrt{E_\nu [\mathrm{TeV}]}}$$

Muon track reconstruction

Based on the relation between the track direction and photon emission angle present in the Cerenkov emission



θ_c=42°

All the reconstruction codes are based on the same space-time relation

$$t_{teorico} = t_0 + \frac{1}{c}\left(l - \frac{k}{\tan\theta_c}\right) + \frac{1}{v_g}\left(\frac{k}{\sin\theta_c}\right)$$

$$\Delta t_{res} = t_{teorico} - t_{\exp}$$

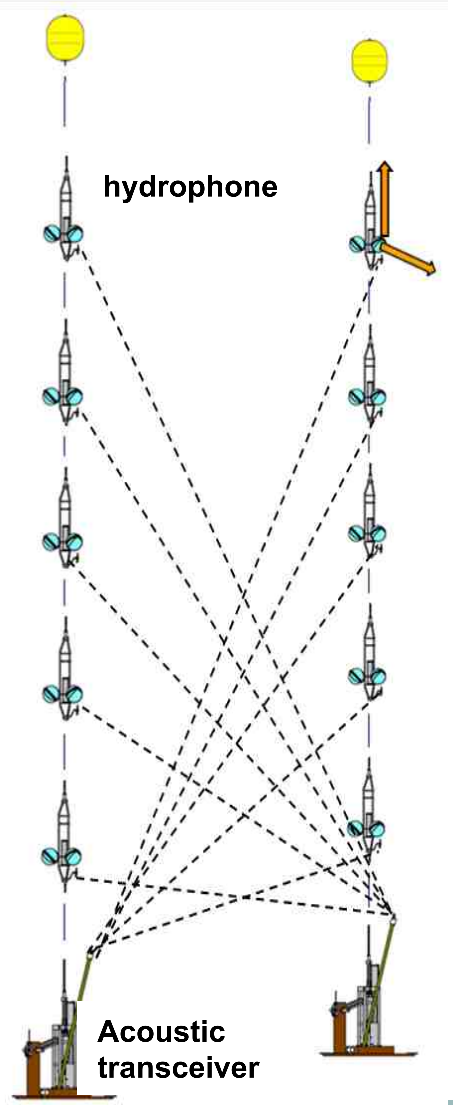
Track direction reconstructed with a precision of 0.1°-0.3°

Required resolution:

≈ 1 ns PMT TTS

≈ 10 cm in position of the PMT (good positioning system needed)

Measurement of the PMT positions in water telescope: the acoustic positioning system



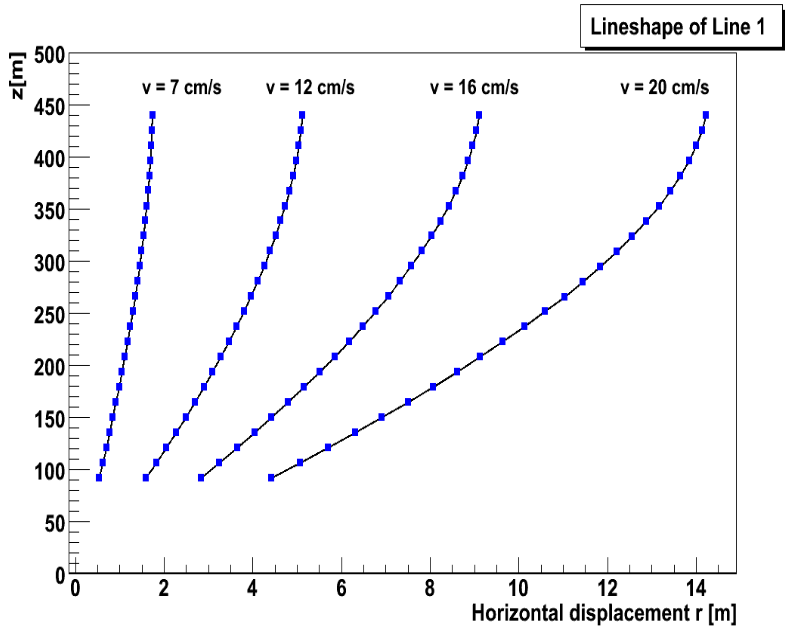
The strings are in continuous movement due to the sea currents

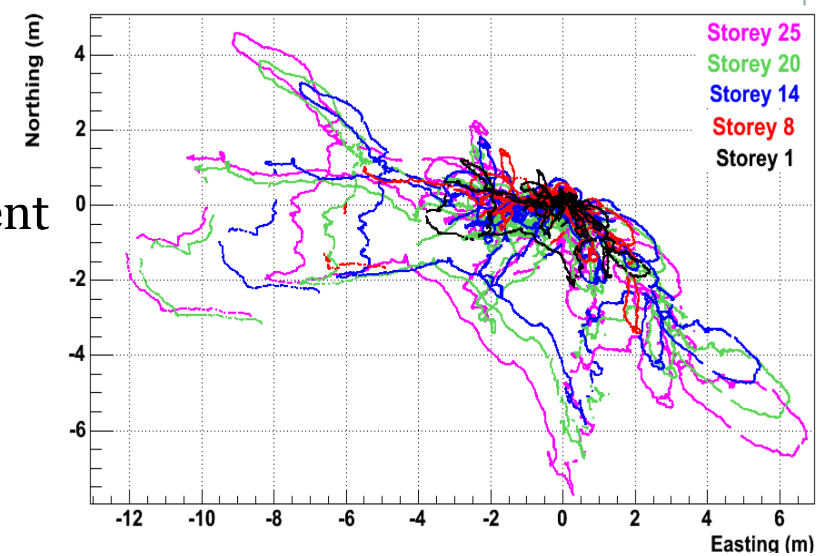
Hydrophones and transceivers located in several floors along the line

In each floor compass and tiltmeters

In ANTARES a measurement each 2 minutes

Position measured with an uncertainty of about 10cm





Water/ice optical properties

- The water/ice "transparency" is measured by the absorption length L_{abs} and the scattering length L_{sca}

The attenuation length is :

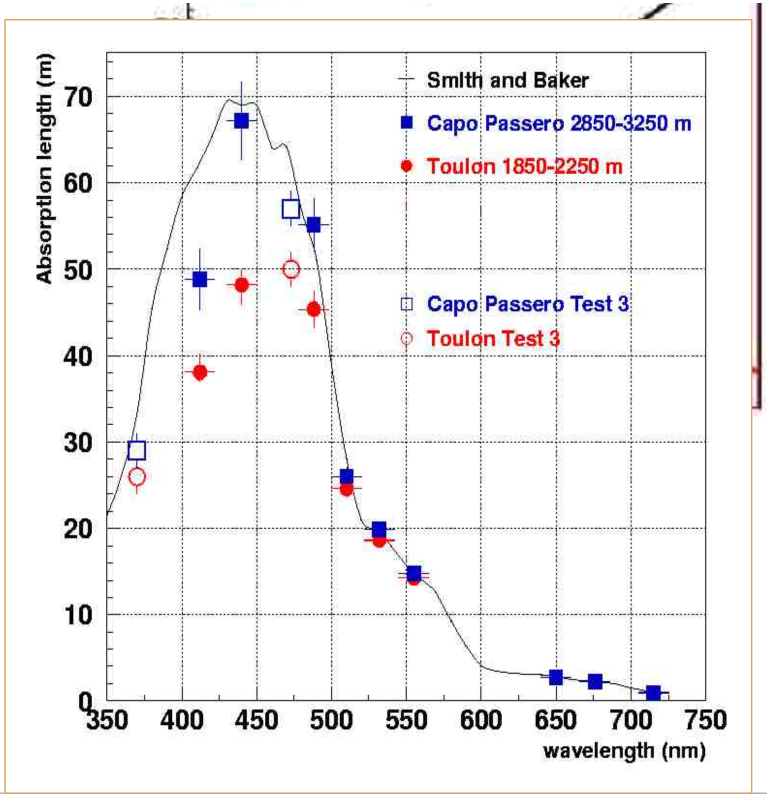
$$\frac{1}{L_{att}(\lambda)} = \frac{1}{L_{abs}(\lambda)} + \frac{1}{L_{sca}(\lambda)}$$

Attenuation coefficient

Absorption coefficient

Scattering coefficient

Measured L_{abs} as a function of the wavelength



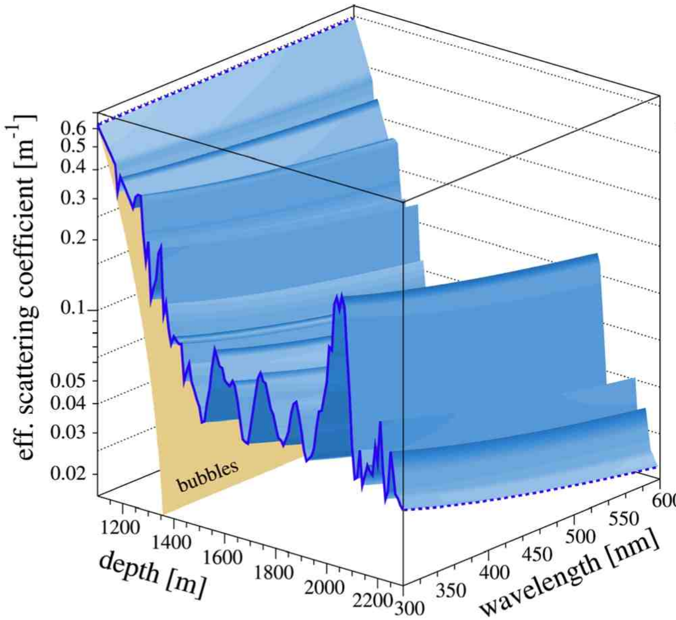
Scattering on molecules (Rayleigh scattering) or on particles (Mie scattering)

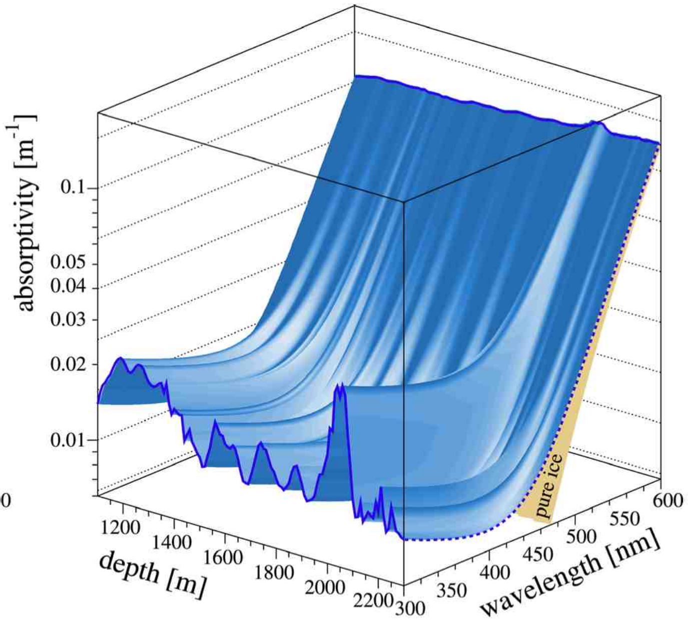
Used also the effective scattering length

$$L_{sca}^{eff} = \frac{L_{sca}(\lambda)}{1 - \langle \cos\theta_{scat} \rangle}$$

Water vs ice

- Water -> homogeneous medium:
  - Baikal water: L_{abs}=22-24m, L_{scat}=30-50m, low background
  - Sea water: L_{abs}=50-70m, L_{scat}=55m
- Ice ->not homogeneous medium :





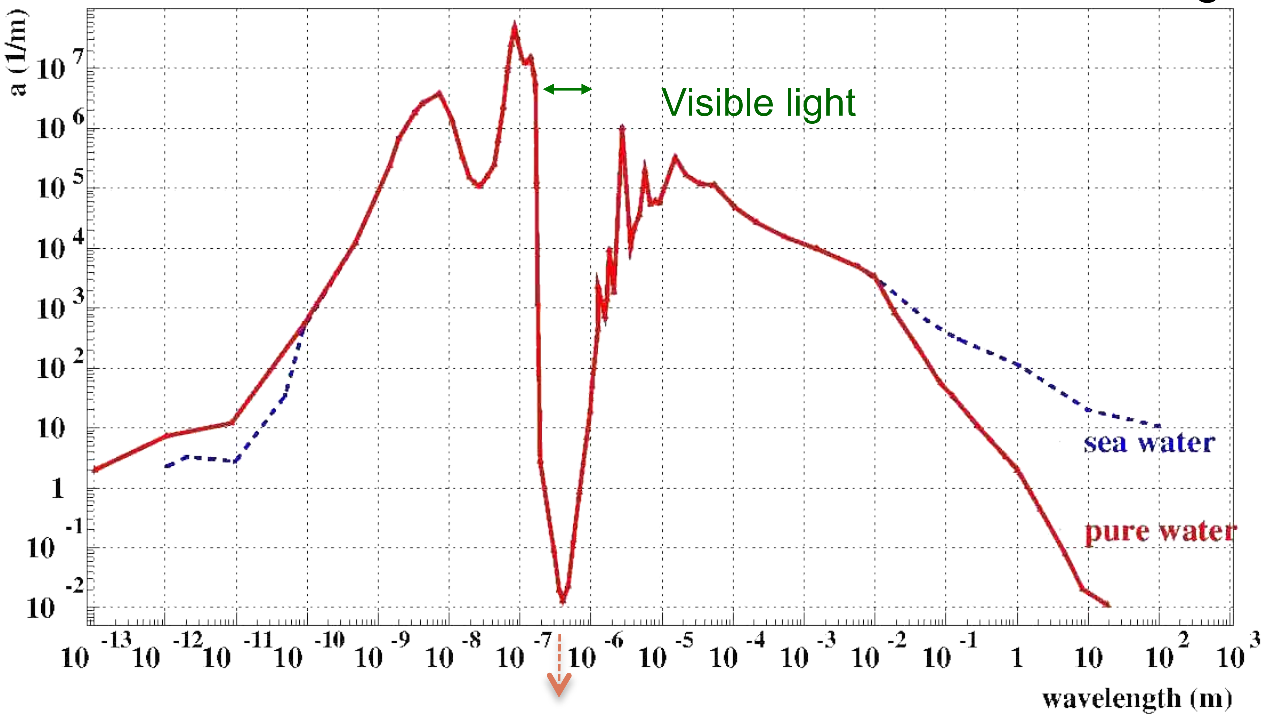
Scattering coefficient very different (up to a factor 7)
$\langle L_{scatt} \rangle \approx 30$ m

Absorption coefficient differs of a factor 3

Light propagation and detector granularity

Spacing of optical sensors inside the instrumented volume must be of the order of the light absorption lenght in seawater (≈70 m for blue light)

Attenuation coefficient as a function of the wavelength



Blu 450–495 nm

$$I = I_0 e^{-\frac{a(\lambda)}{D}}$$

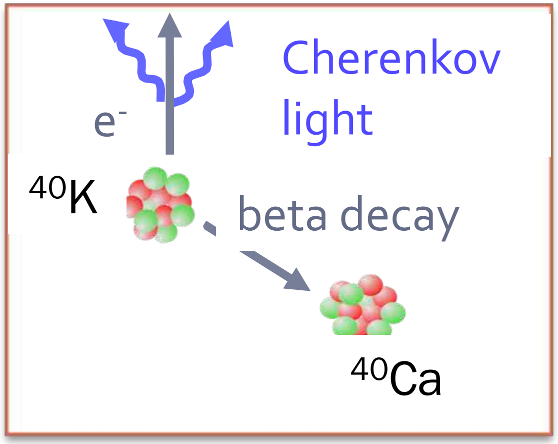
$$L_a(\lambda) = \frac{1}{a(\lambda)}$$

$$L_a(\text{blue}) \approx 70\text{m}$$

The ^{40}K and bioluminescence

In sea water telescope photons due to the beta decay of ^{40}K are present:

- beta decay of ^{40}K presents in the salt.



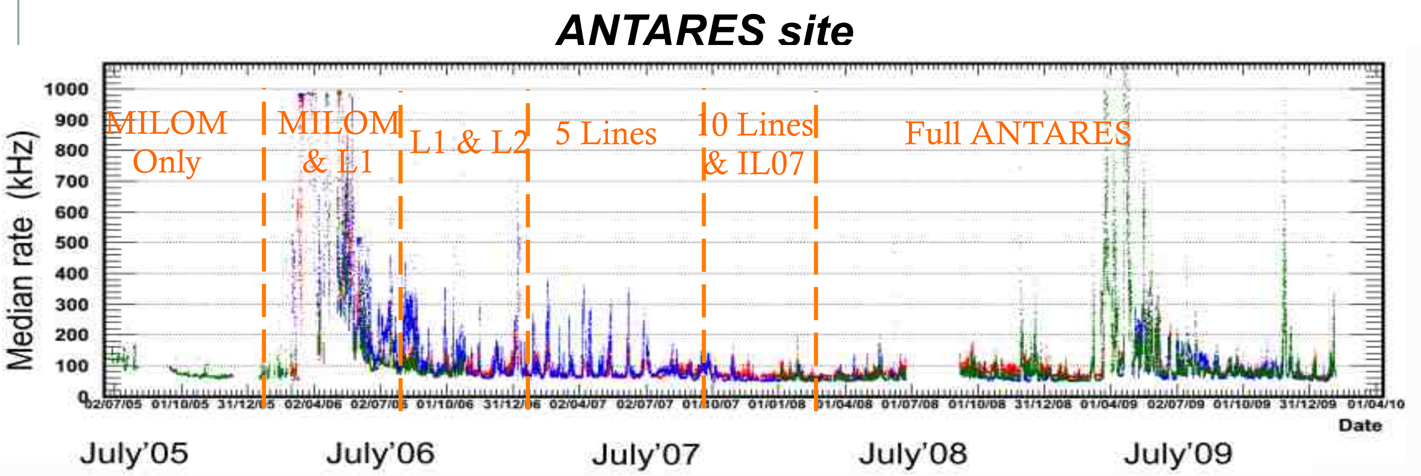
Rate of about 360 s^{-1} cm^{-2}
Baseline of about 60 kHz in 10" PMT (0.3 p.e.)
And 5 kHz in 3" PMTs

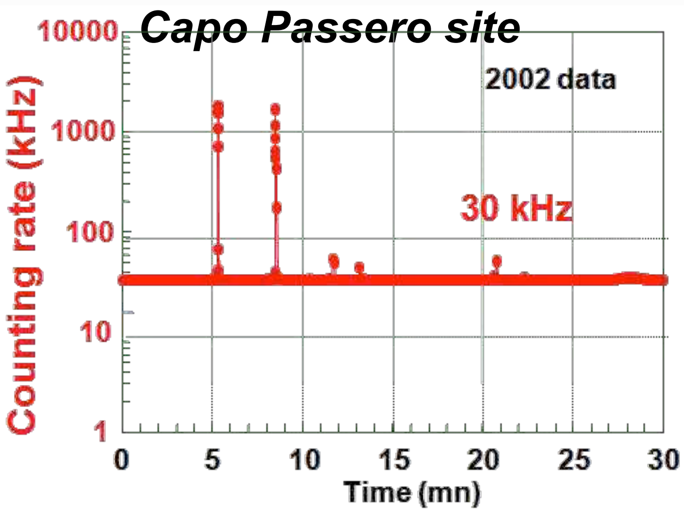
- Bioluminescence from micro-organisms (bacteria) → baseline + bursts
- Light from macro-organisms → bursts of MHz

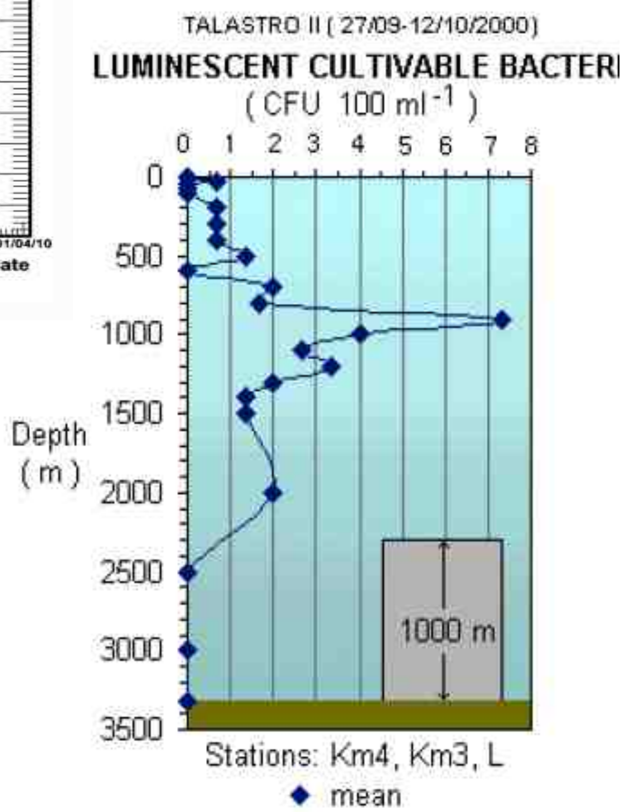
The bioluminescence if present is strongly correlated with the sea current.

Background Light in water

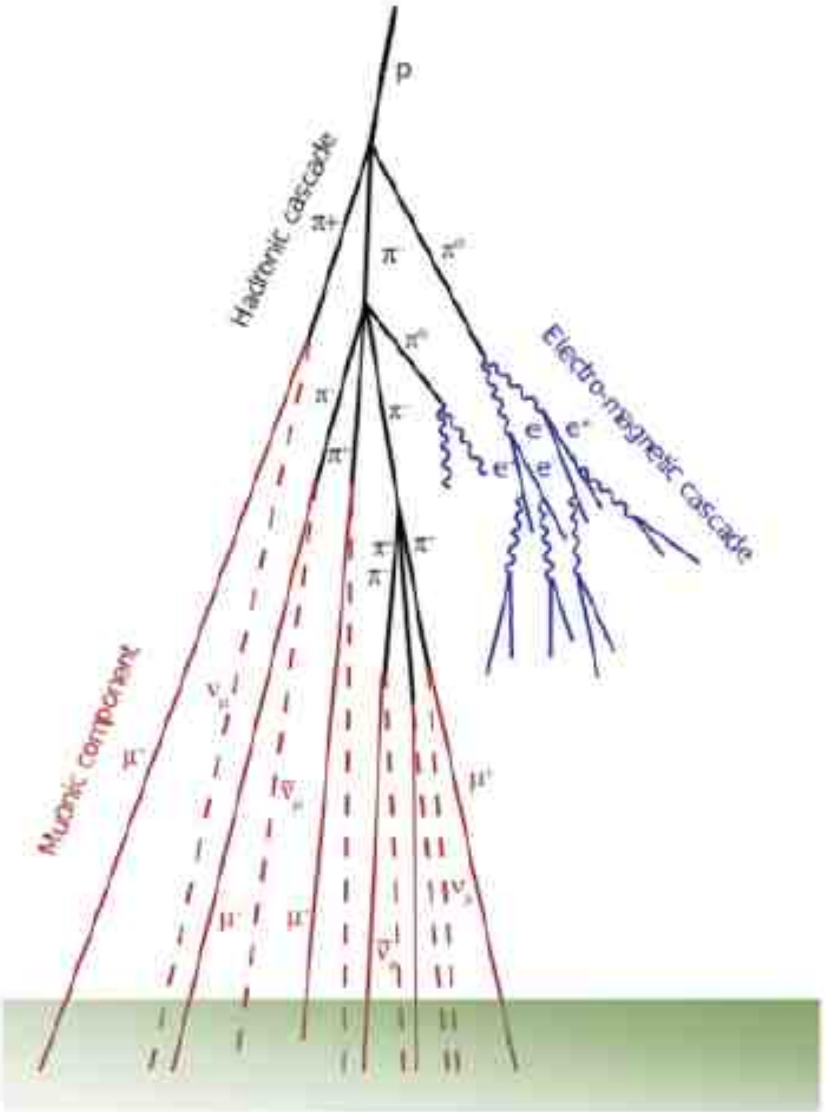
40K and bioluminescence not present in polar ice







Background: atmospheric neutrinos and muons

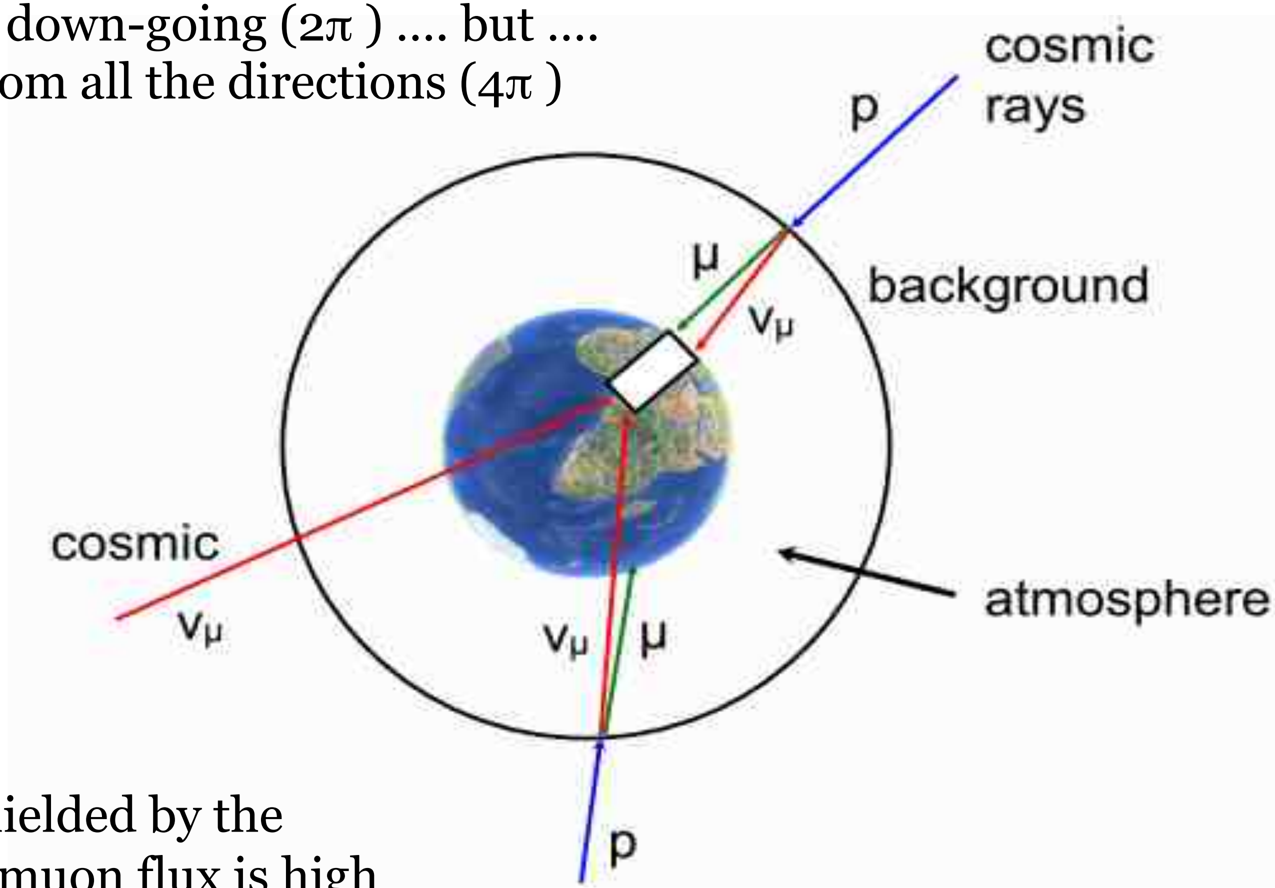


- Cosmic rays (mainly protons) interact with atmosphere and produces shower

Muons and neutrinos

Background of atmospheric muons and atmospheric neutrinos

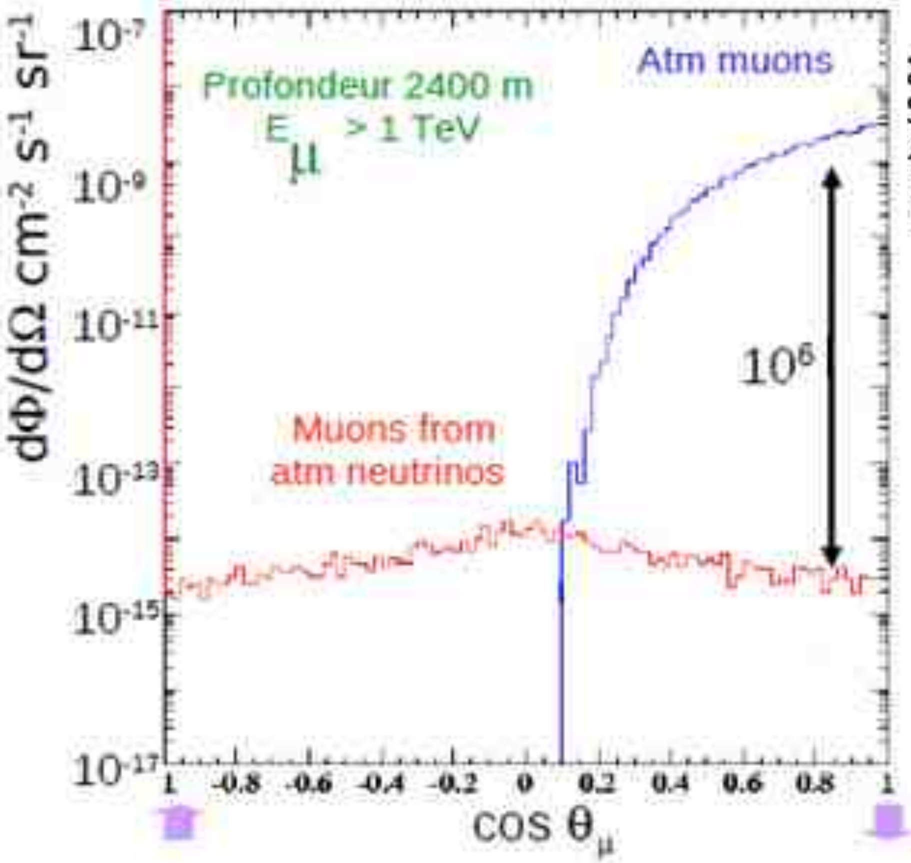
From the interaction of Cosmic Ray with the atmosphere:
- Atmospheric muons only down-going (2π) .... but ....
- Atmospheric neutrinos from all the directions (4π)



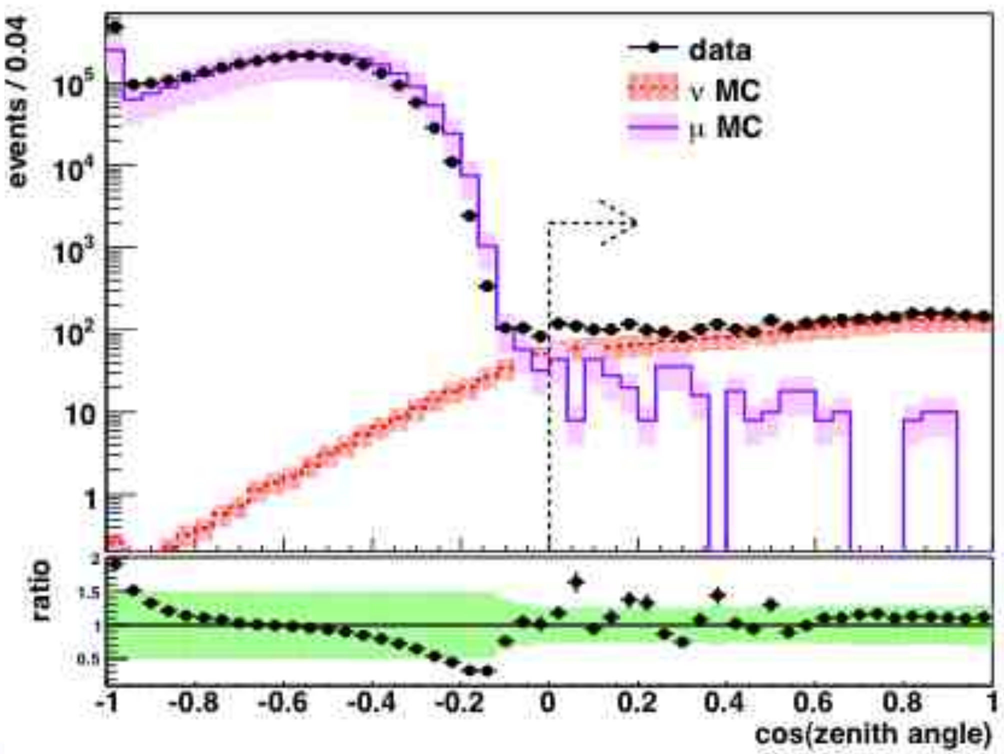
Even if the detectors are shielded by the water/ice the atmospheric muon flux is high
Search for extraterrestrial up-going neutrinos

Background of atmospheric muons and atmospheric neutrinos

MC at generation level



After the reconstruction and the cuts of the analysis



The search of the small number of events of cosmic origin is based in statistical methods

The international context

First attempt the Dumand project – Detector located in Hawaii in the ‘90
-> failed project

Baikal telescope - lake Baikal

- NT200 working since 1998

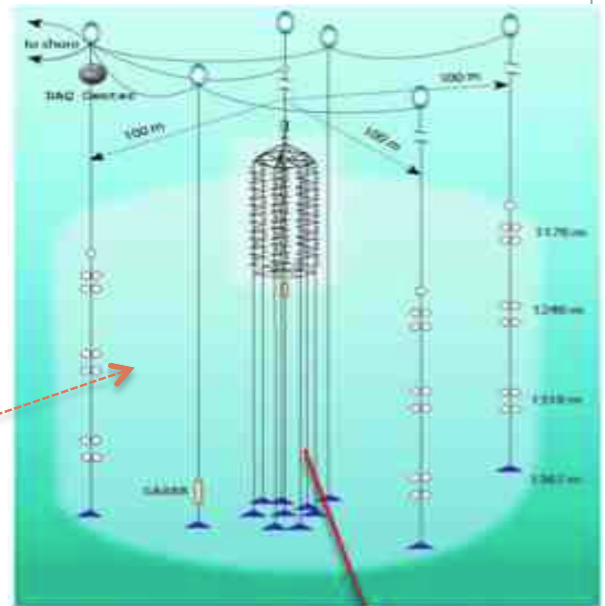
NT200: 8 strings (192 optical modules)
Height x ∅ = 70m x 40m, $V_{inst}=10^5 m^3$
Effective area: 1 TeV~2000 m²
Eff. shower volume: 10 TeV~ 0.2 Mton

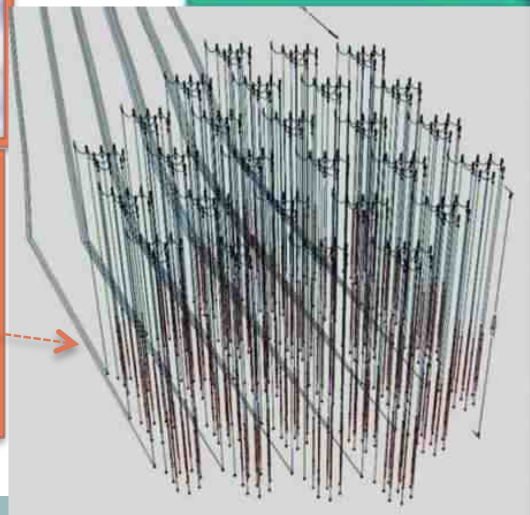
- NT200+ is taking data

NT200+ = NT200 + 3 outer strings (36 optical modules)
Height x ∅ = 210m x 200m, $V_{inst} = 5\times10^6 m^3$
Eff. shower volume: 10^4 TeV ~ 10 Mton

- GVT detector planned - Actually prototyping phase

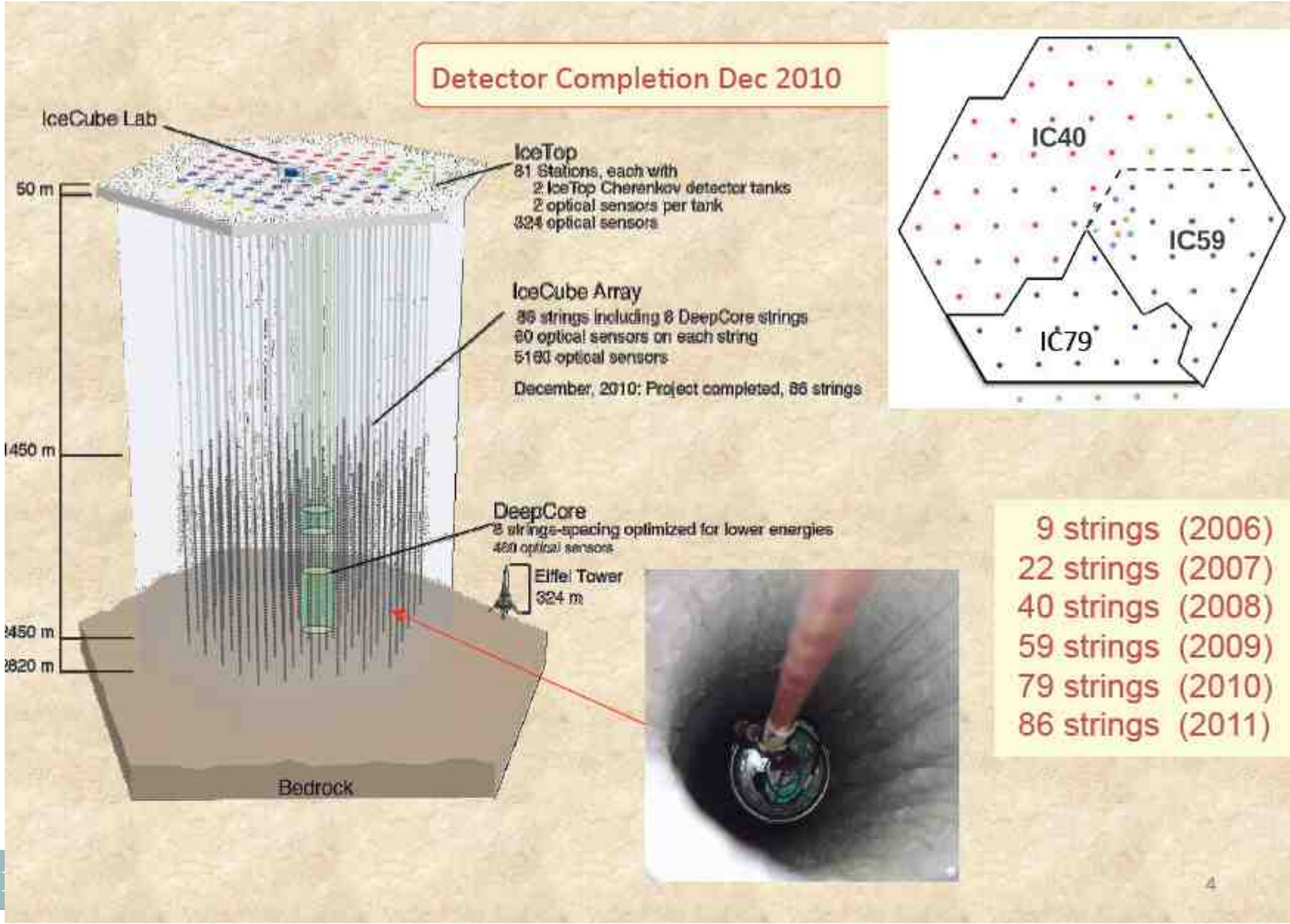
GVT = NT200+ and 27 clusters of 8 strings
Total volume 1.5 km^3





IceCube – South Pole

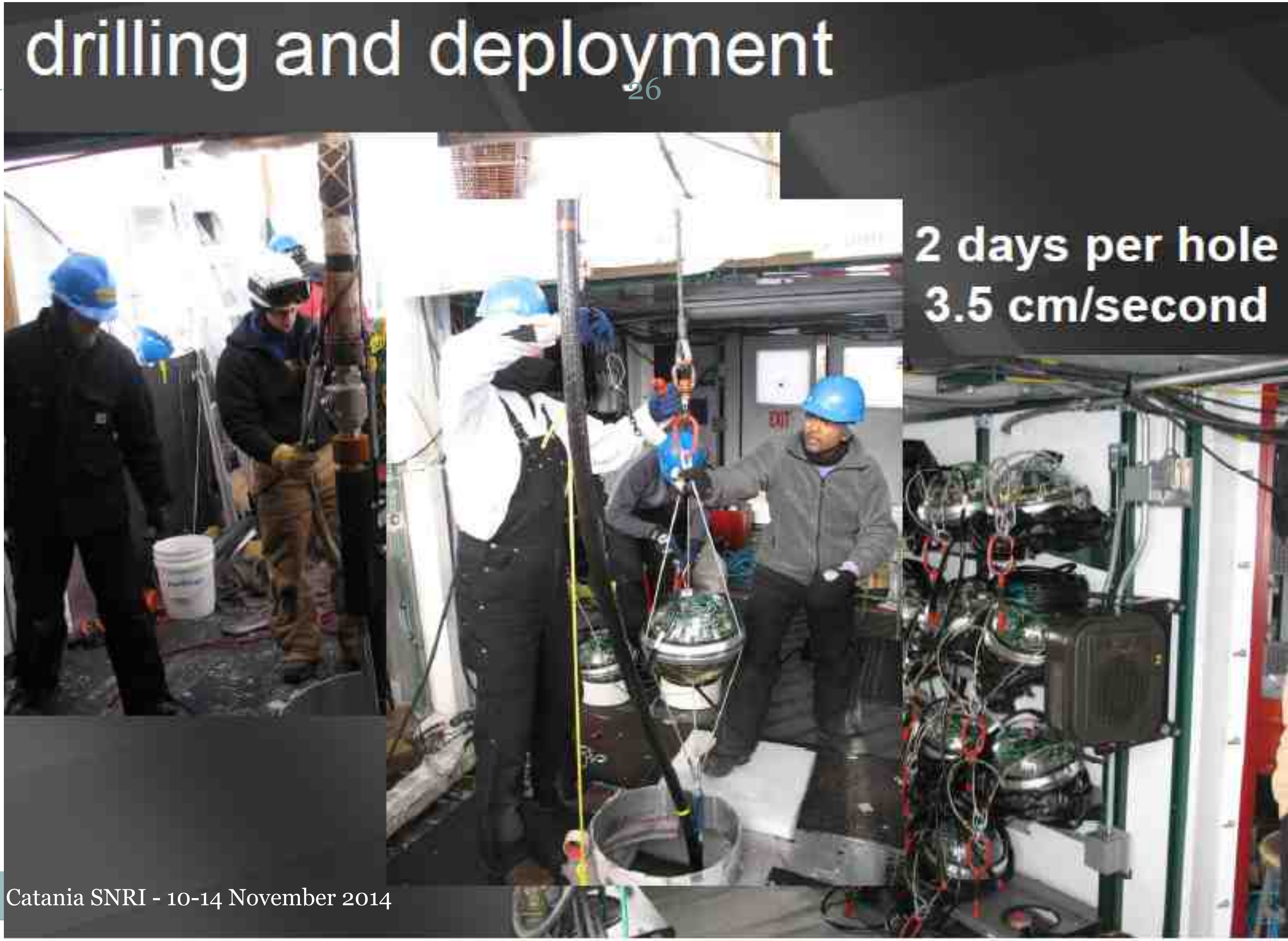
86 strings 60 PMTs each at the South Pole. Volume about 1km³. Depth 2500m



The IceCube Site: the Geographic South Pole

Only few weeks per year for the string deployment

IceCube Deployment

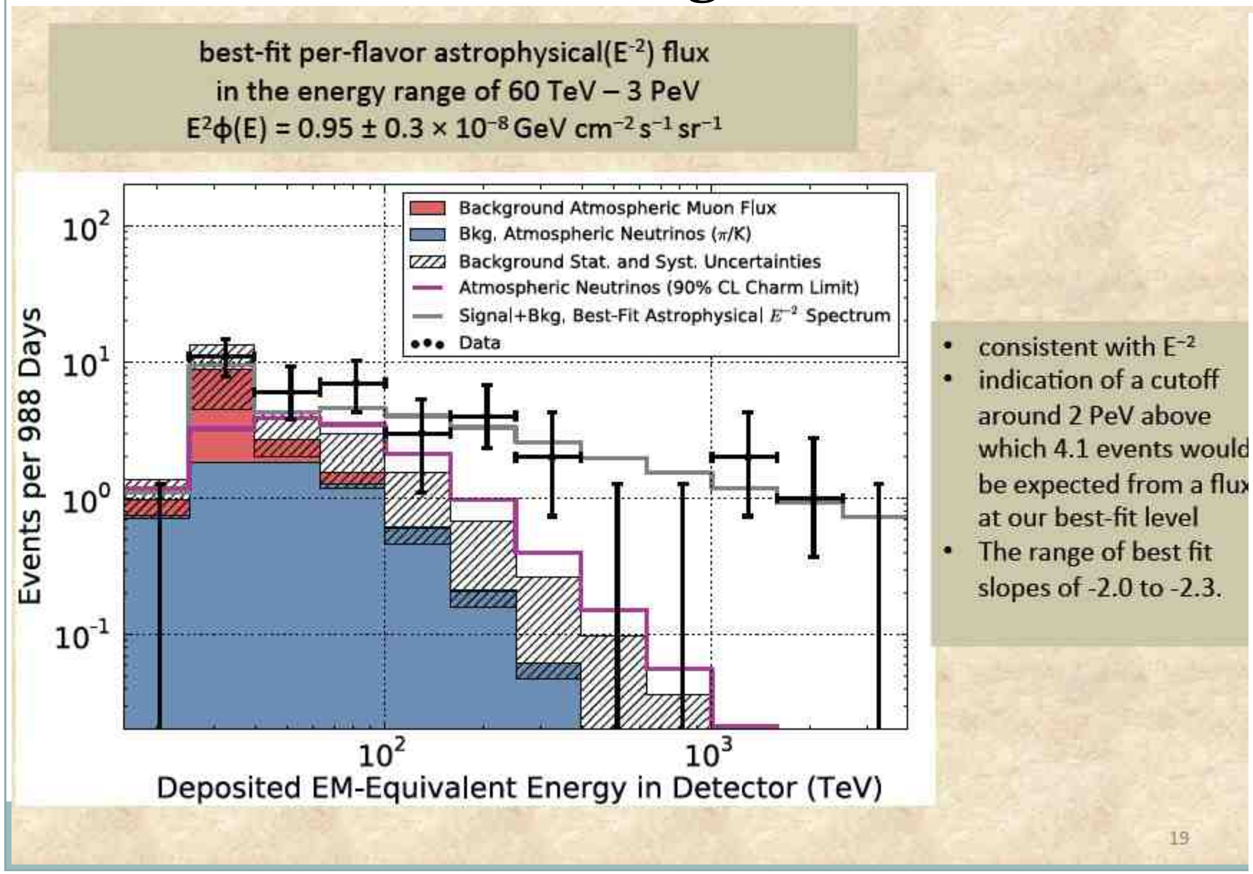


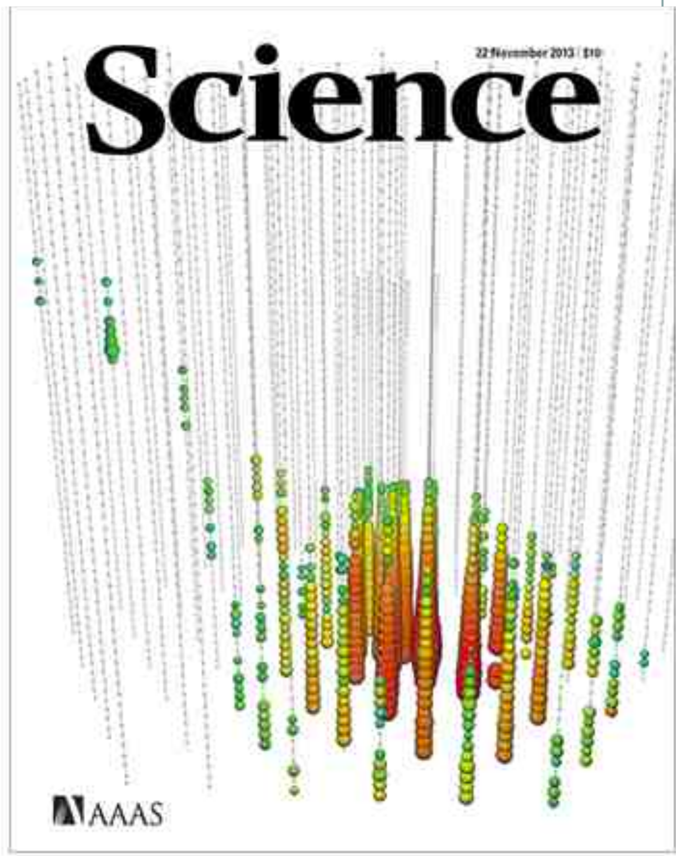
First astrophysical flux from IceCube

- Flux of astrophysical origin detected at 5.7 s.

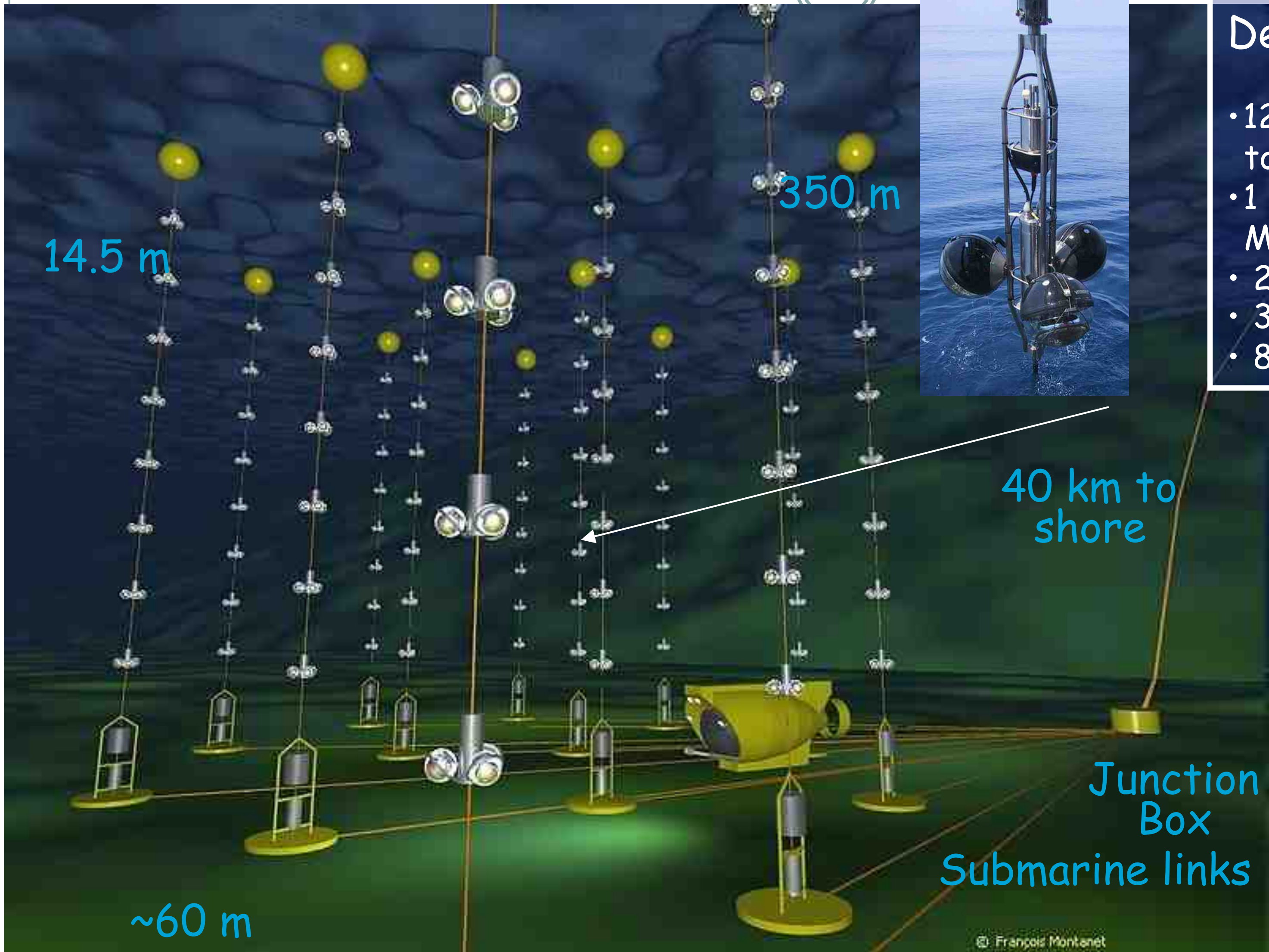
Not known the origin

Science nov 2013





ANTARES – Toulon (France)



Depth 2470m

- 12 lines of 75 PMTs (885 total)
- 1 line for Earth and Marine sciences (IL07)
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

Takes data in the complete configuration since 2008.
At the moment is the largest telescope in the Mediterranean sea

Antares deployment

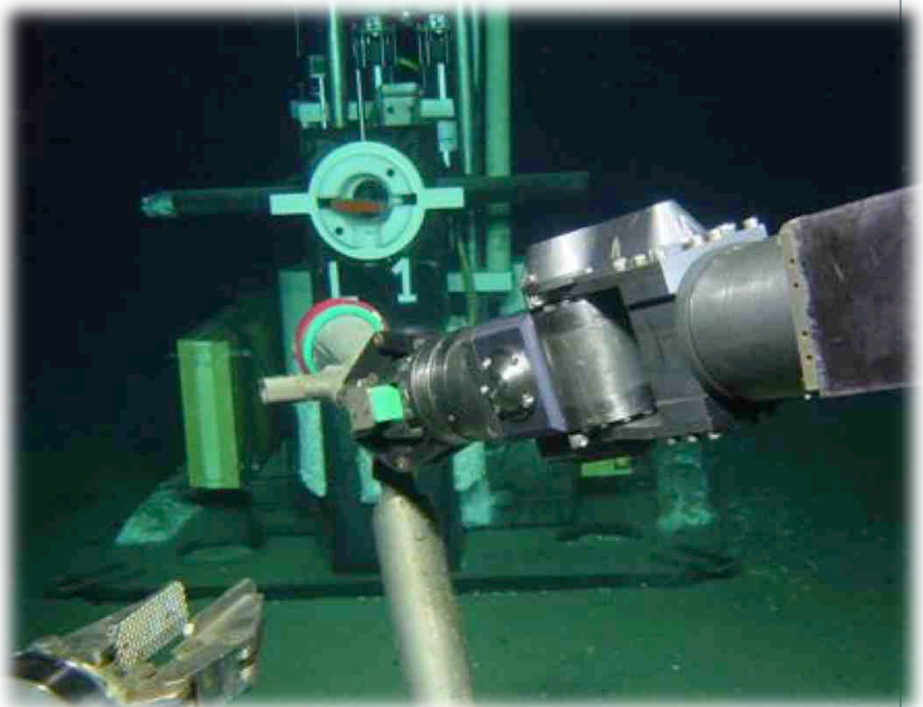
Line 1 deployment: February 2006

Time consuming and risky sea operation: "Open" structure deployed from surface

Antares connection

IFREMER 'VICTOR6000'
Remote controlled submarine

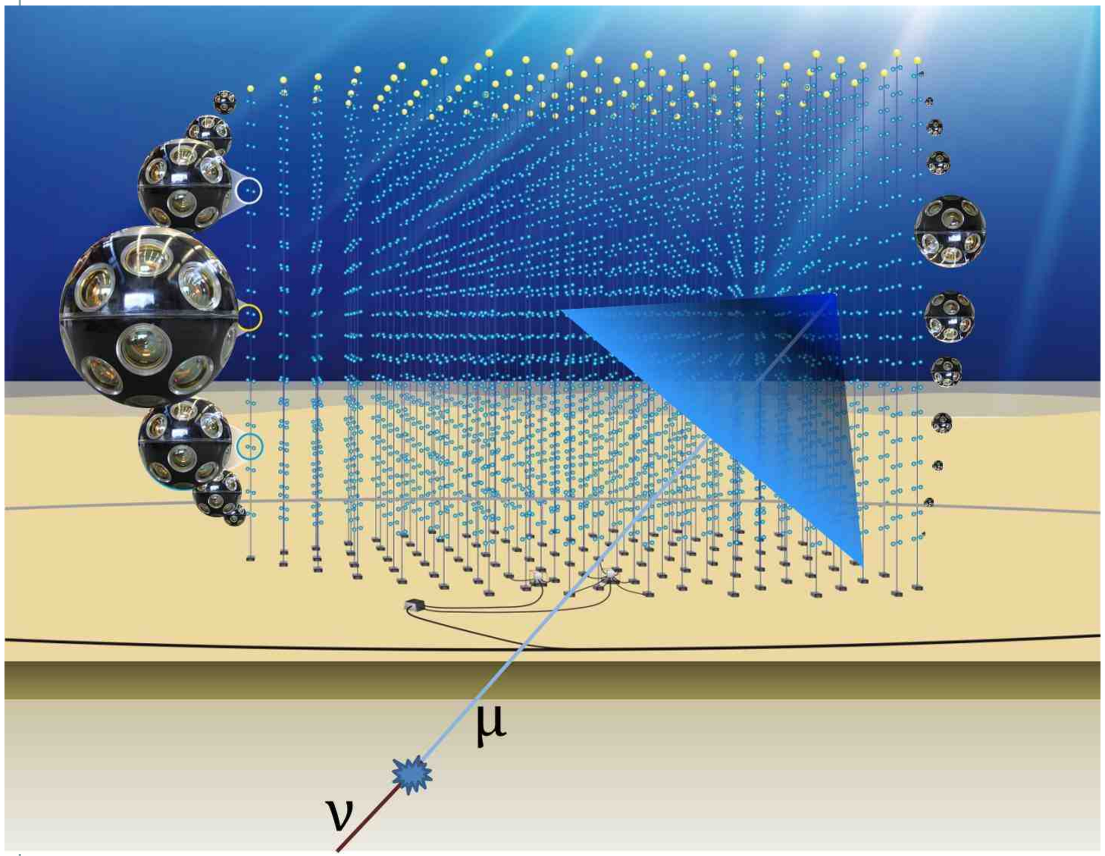
Line connection



Non-proprietary ROV ... Not always available

The KM3NeT detector

- Building block concept: the full detector is made of several blocks of Detection Units (DU).

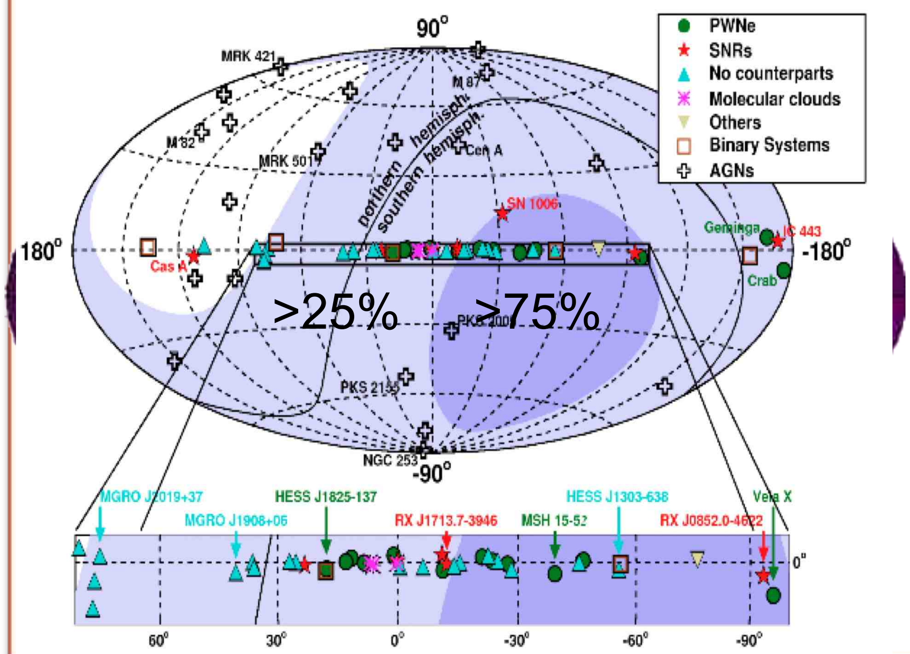


- A single block has 115 DU 90-120 m distant (0.5 - 0.8 km^3).
- Full volume ~ 3 - 5 km^3
- A DU is a vertical string equipped with 18 Optical Modules
- An Optical Module contains 31 3” PMTs
- The building block concept allows for a distributed detector

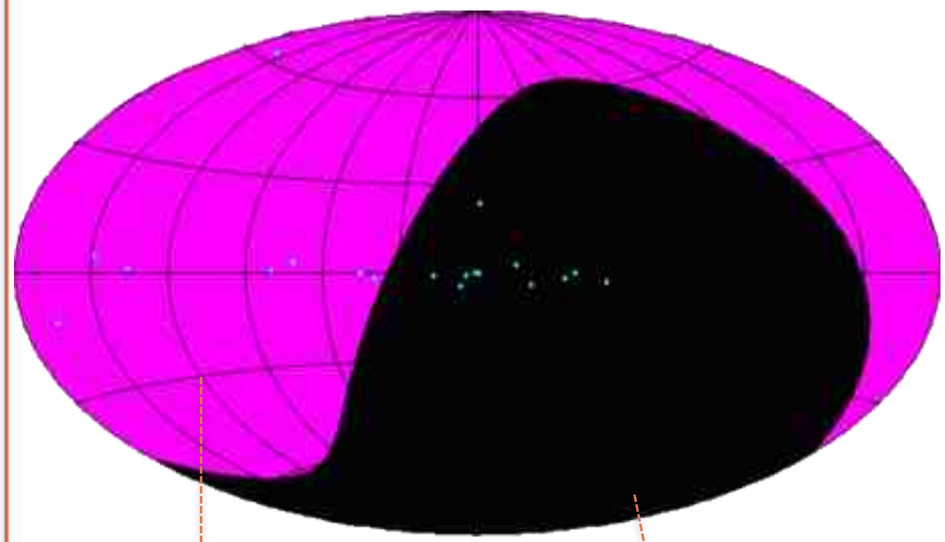
Why one more large detector in the Northern Hemisphere

Galactic coordinates

- ANTARES and KM3NeT



- IceCube



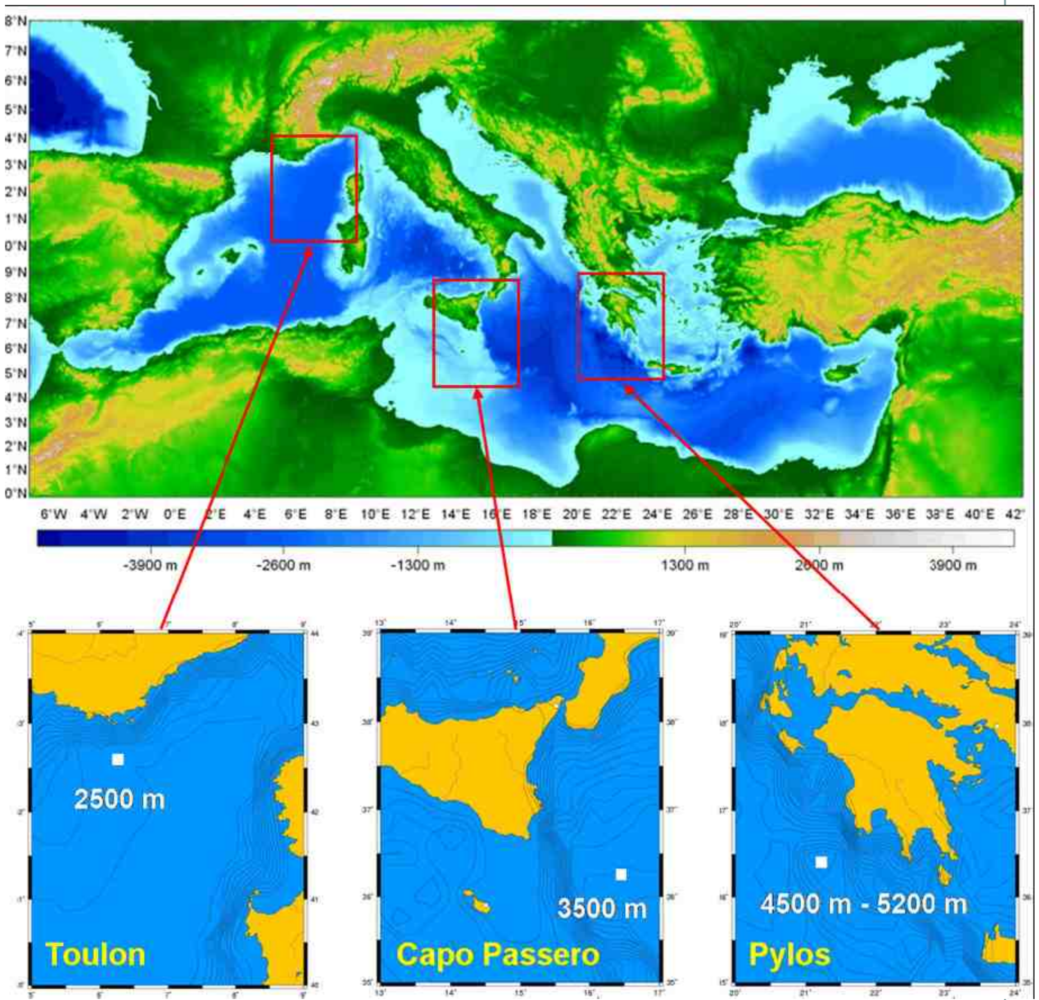
Northern hemisphere

Southern hemisphere

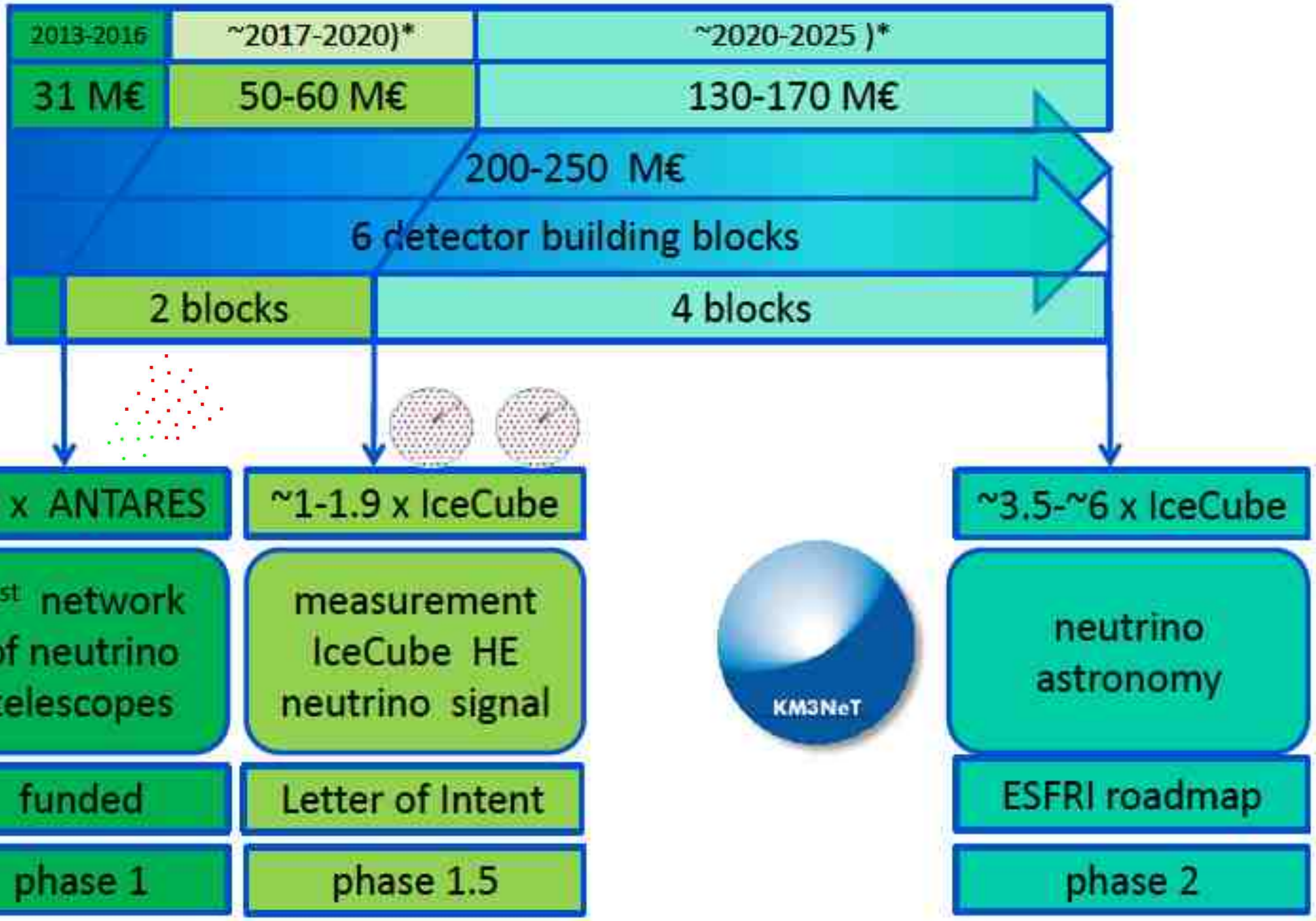
Complementary detectors

KM3NeT Installation in the Mediterranean

- KM3NeT-France: Toulon (~2500m)
  KM3NeT-Italy: Capo Passero (~3400m)
  KM3NeT-Greece: Pylos (~4500m)
- Long-term site characterisation measurements performed
- Shore distances: 15km-100km
- Power via Main Electro-Optical Cable MEOC
  - Short distances: (AC), long distances: (DC)
  - Transmission on optical fibers (24-36 optical fibres)
  - Common hardware, software and data handling



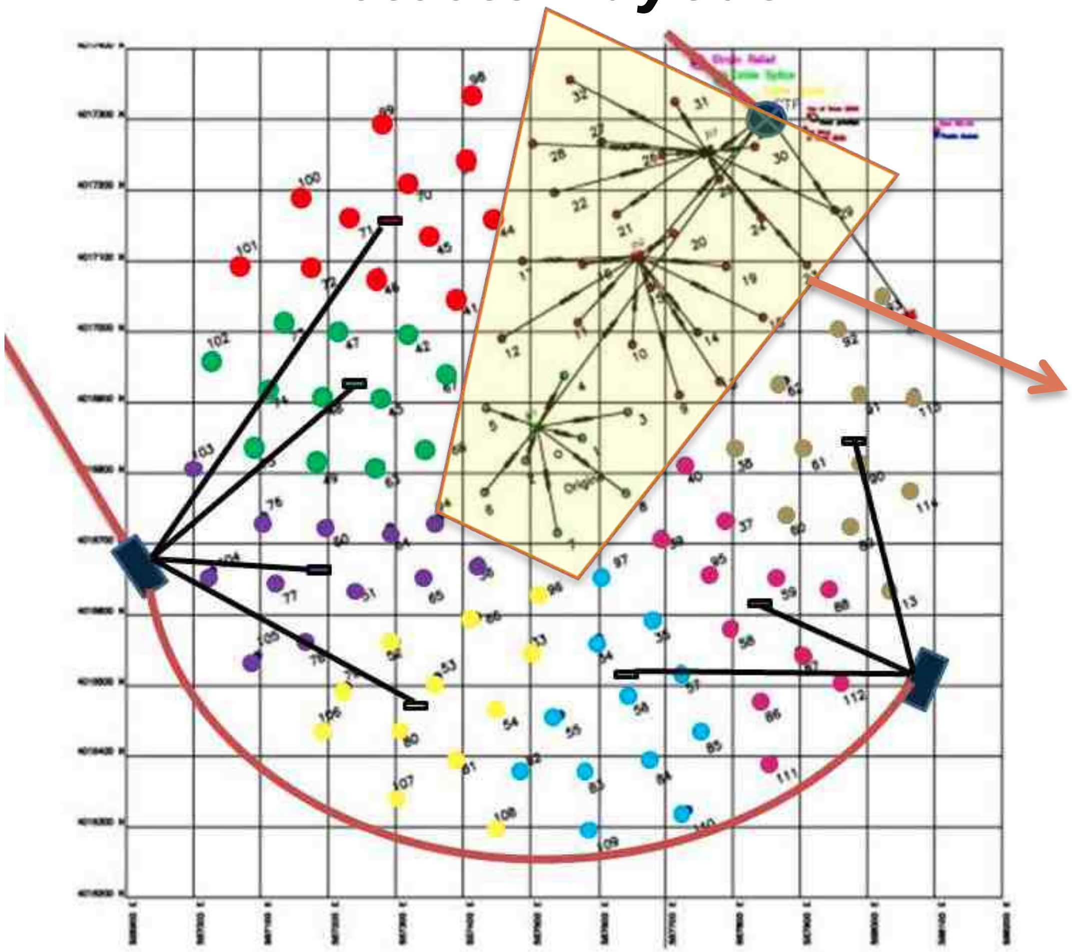
KM3NeT: a phased project



)* depending on funding

KM3NeT- Italia

Detector layout



Phase 1 in KM3NeT-Italia:

24 strings + 8 towers

Shore station in Capo Passero

Shore Laboratory:
Electronics Labs, Data Acquisition Room, Control Room, Guest House, Power Feeding Equipment (UPS protected)

Up to 10 Gbps direct Optical-fibre link GARR-X

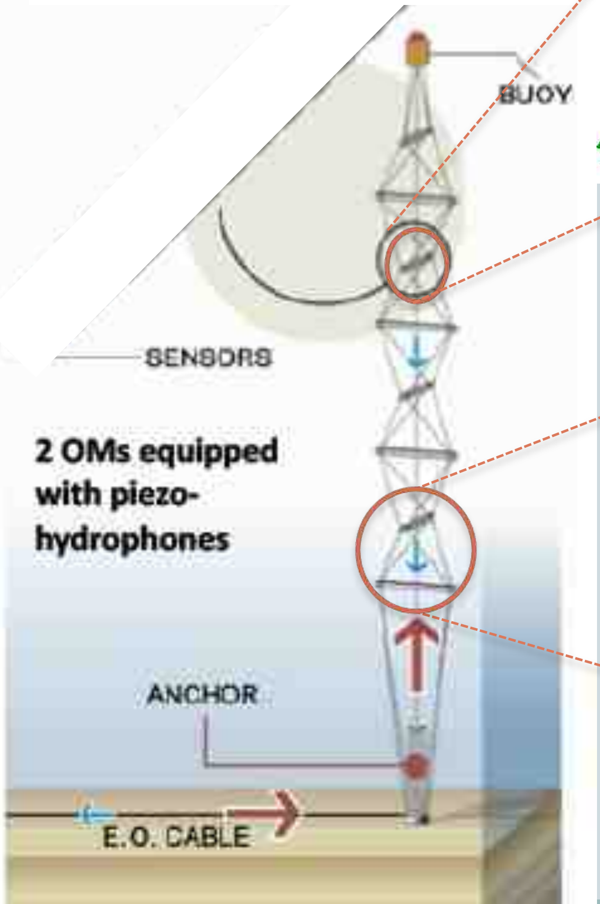
Submarine cable and infrastructure (now):
96 km - 20 fibres ITU655-NZDSF
Single conductor with DC-sea return
Phase 1: Cable Termination Frame
Medium Voltage Converter: 10kV to 375V

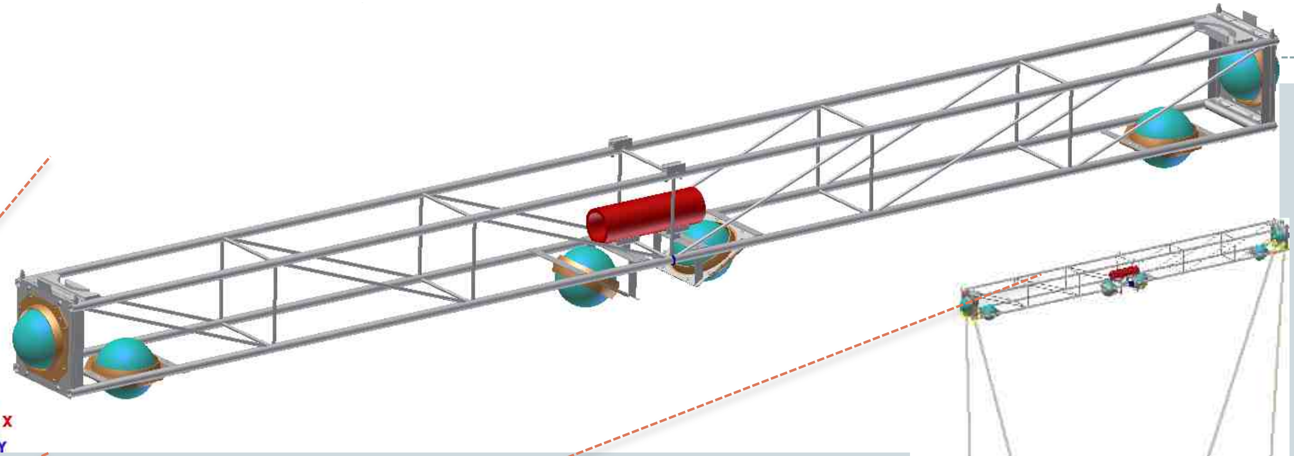
Shore Laboratory in Capo Passero harbour

The KM3NeT-Italia towers

The tower: the innovative mechanical structure

6 OM/floor
2 hydrophones

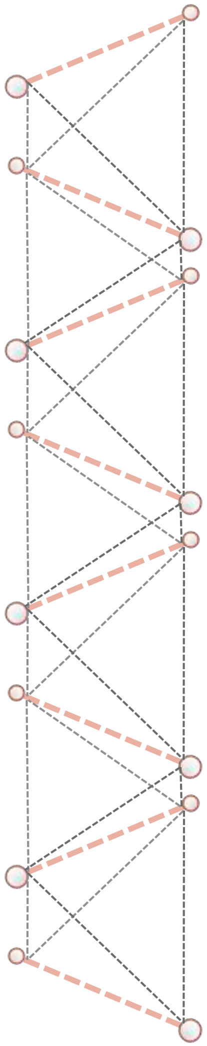




A three-dimensional vertical structure made of

- 14 floors (bar 8 m long)
- 84 10” PMTs (6 each bar)
- Distance between bars 20m
- Total height 260m

The deployment

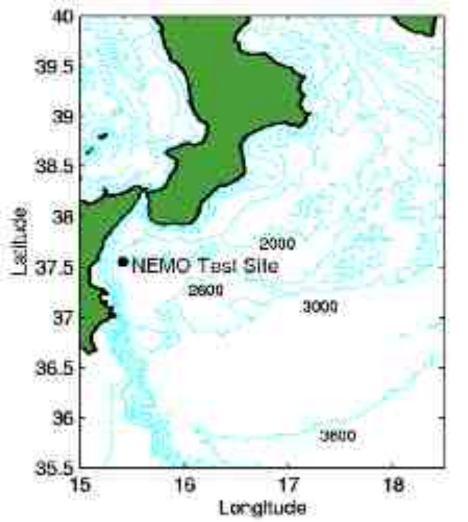


New deployment technique:
Transport detection Unit in a compact package easy to handle and unfurl once it is placed in the seafloor

First prototype

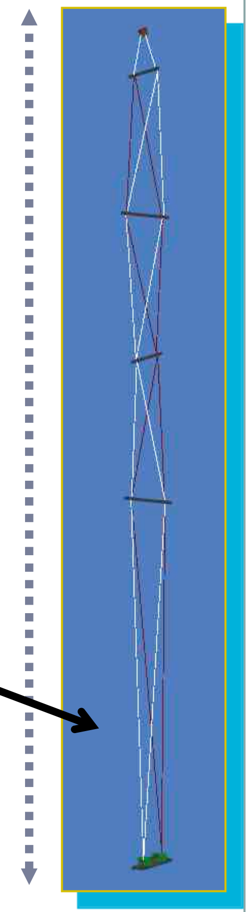
First prototype in Catania test site:

- Deployed December 2006
- Operational for about 5 months
- Muon tracks reconstructed (S. Aiello et al. Astrop. Phys. 33 (2010) 23)



25 km est off-shore Catania test site
2000 depth

4 floors
4 OM/floor
15 m bar length



Second prototype of the tower

- A second prototype of the towers was deployed 23/3/2013 at 3500 m and in data taking up to august 2014. More than one year of data taking

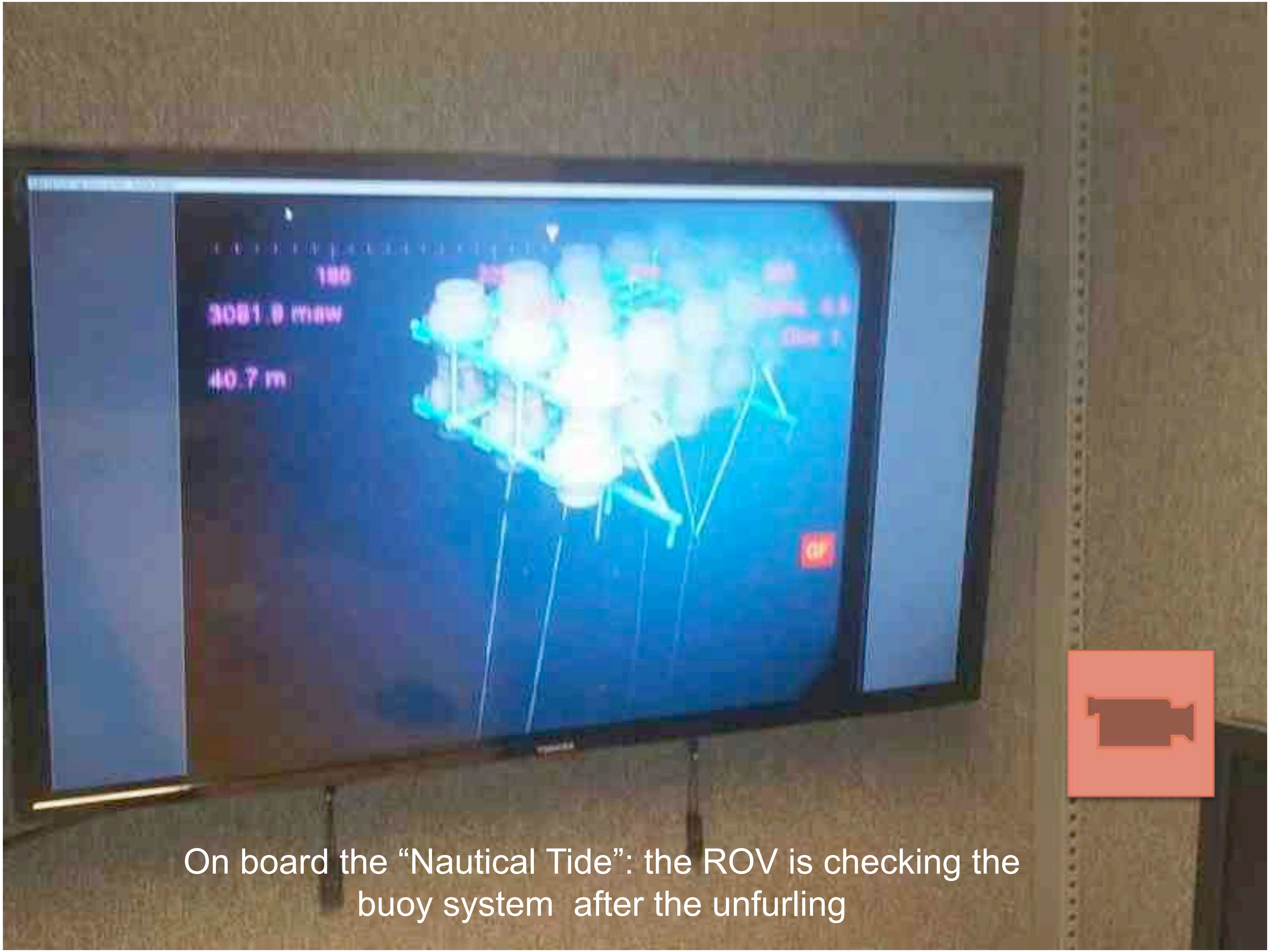
> - 8 floors
> - 8 m bars, vertical dist. = 40 m, H_{tot} = 450 m
> - 32 OM, 14 acoustic receivers
> - oceanographic instrumentation (CTDs, DCS...)

The deepest structure ever installed and operational

NEMO-Phase2 under test in Malta before boarding on “Nautical Tide”


The tower on the “Nautical Tide”

The “Nautical Tide” ROV
and its launching system



On board the “Nautical Tide”: the ROV is checking the buoy system after the unfurling

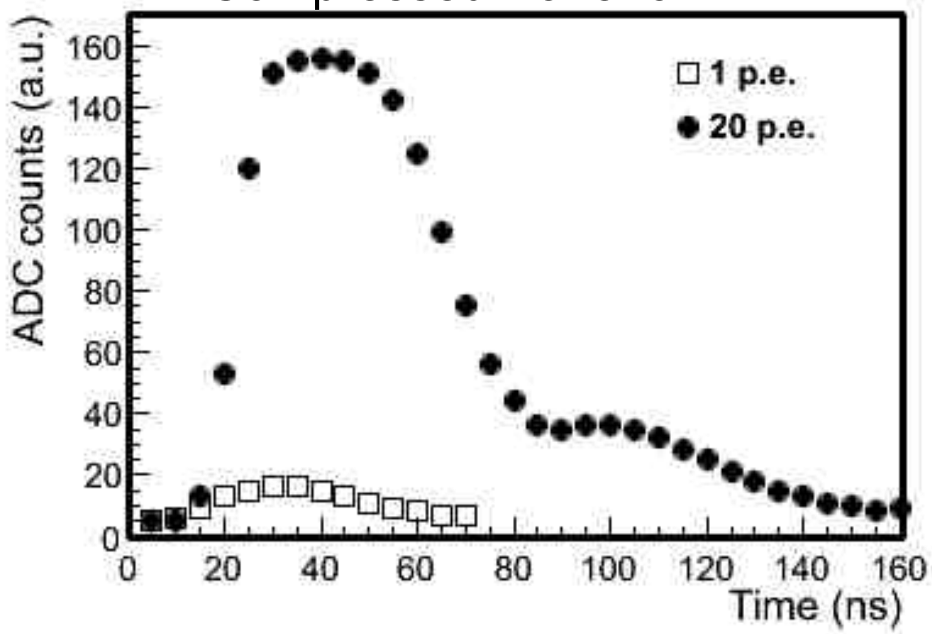
The Optical Module

Integration at Catania test site (Catania harbour)

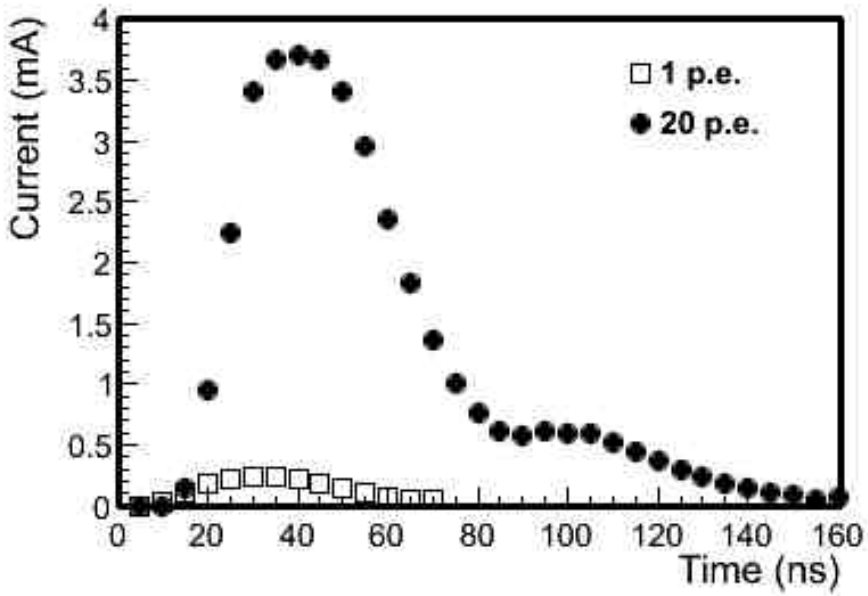
Signal digitization

- PMT signal is compressed with a quasi-log law to increase the ADC input “dynamics”
  - Low voltage signals (up to fes s.p.e.) sampled with high accuracy
  - High voltage signals sampled with lower accuracy

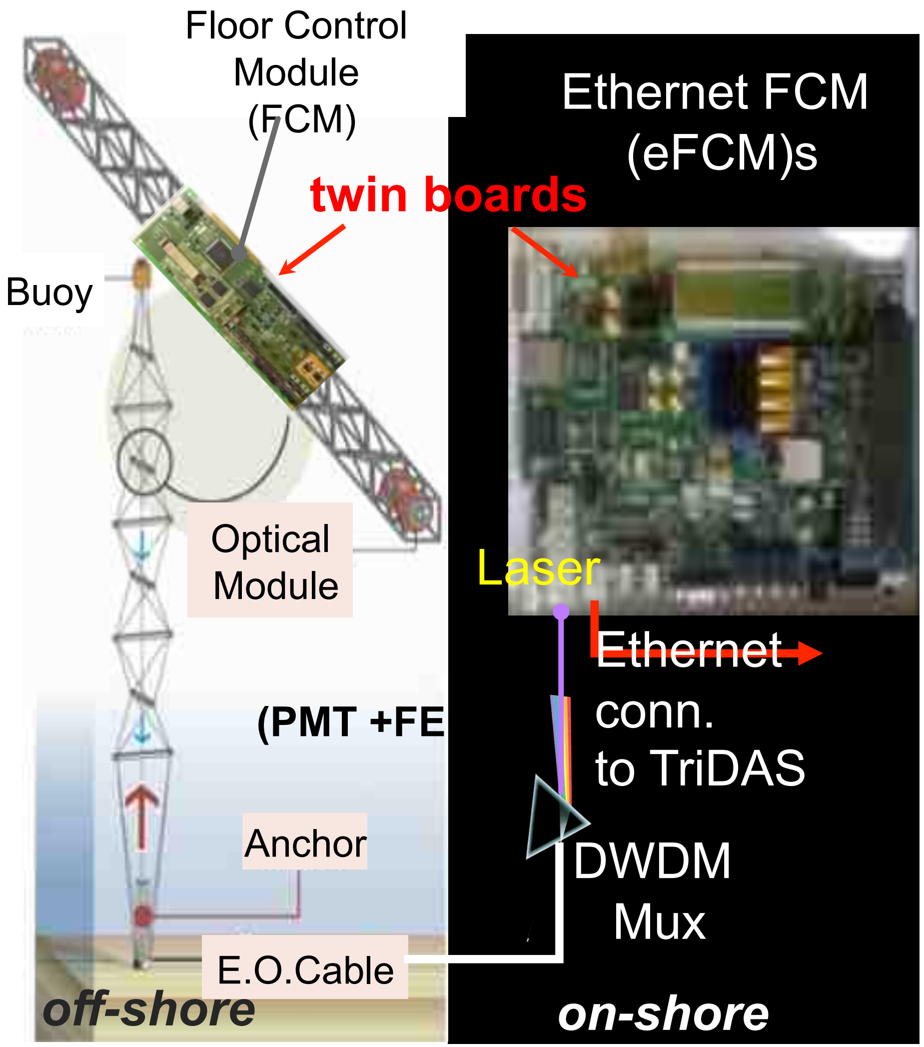
Compressed wave form



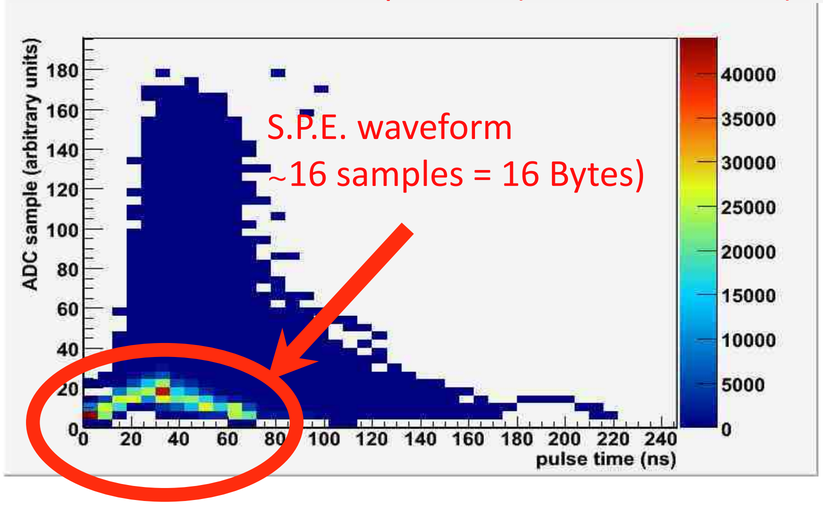
Decompressed wave form



Electronics and DAQ



Hit samples Vs. pulse time
on a 10" PMT with 0.5 p.e. thr. (NEMO Ph.1 data)

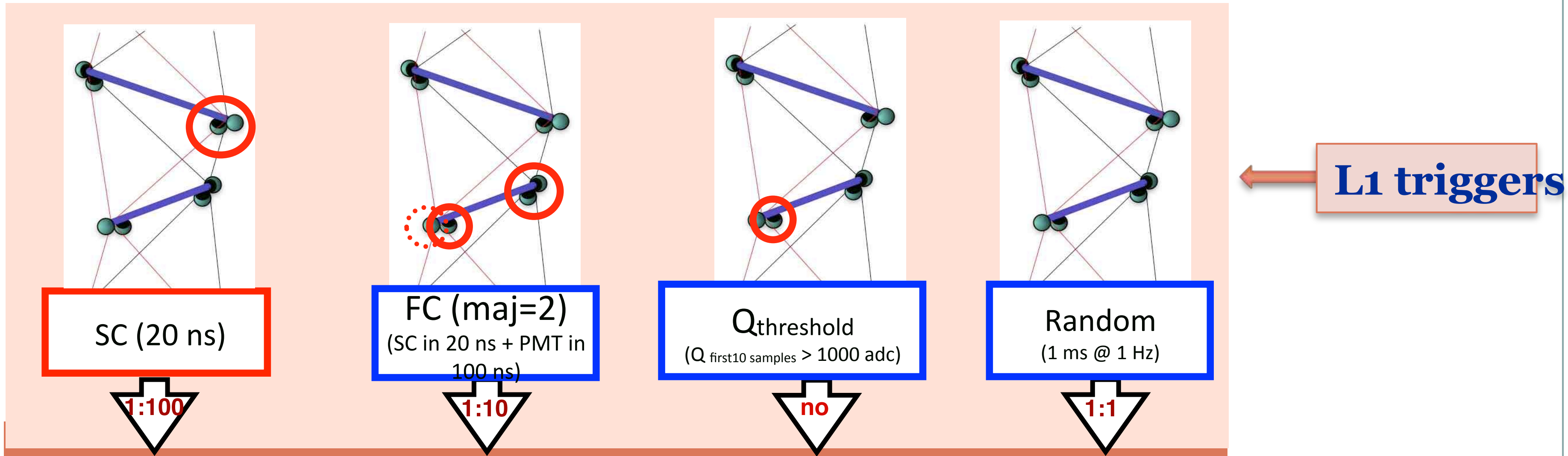


S.P.E. HIT SIZE

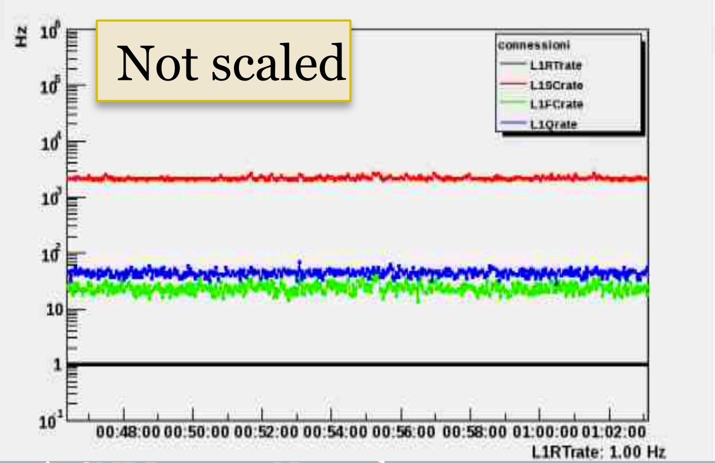
Hit PMT Info
+
Hit Time
+
Hit Charge
+
Hit Waveform (samples)

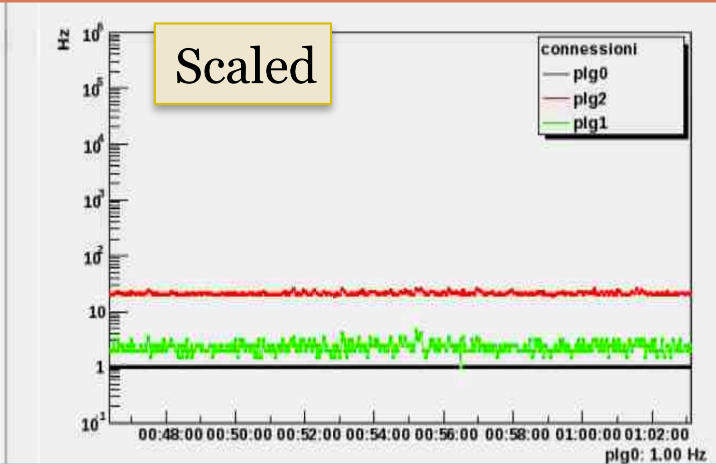
28 Bytes

Triggers



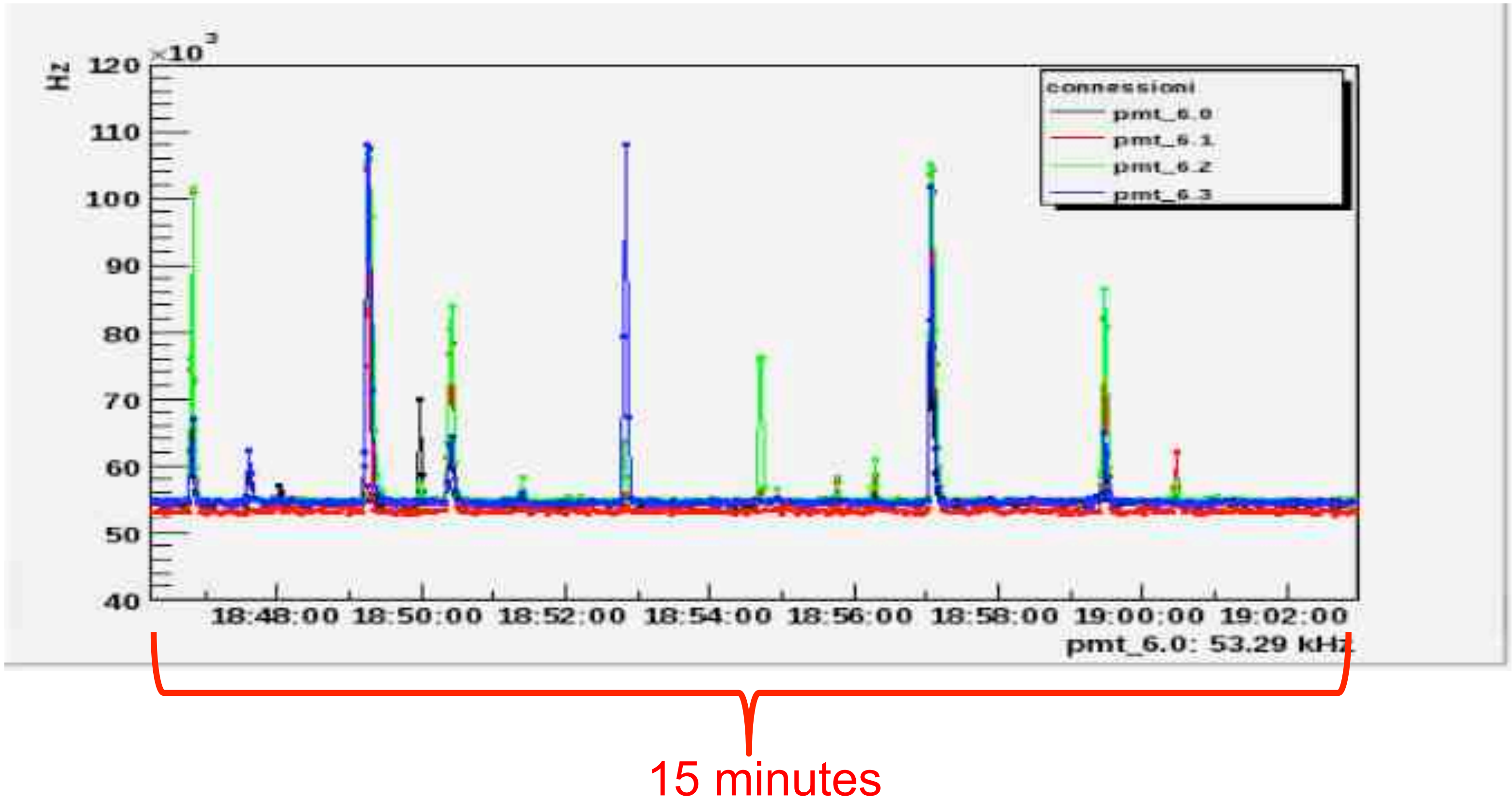
Draft: down-scale with L2 plugins





Background rates

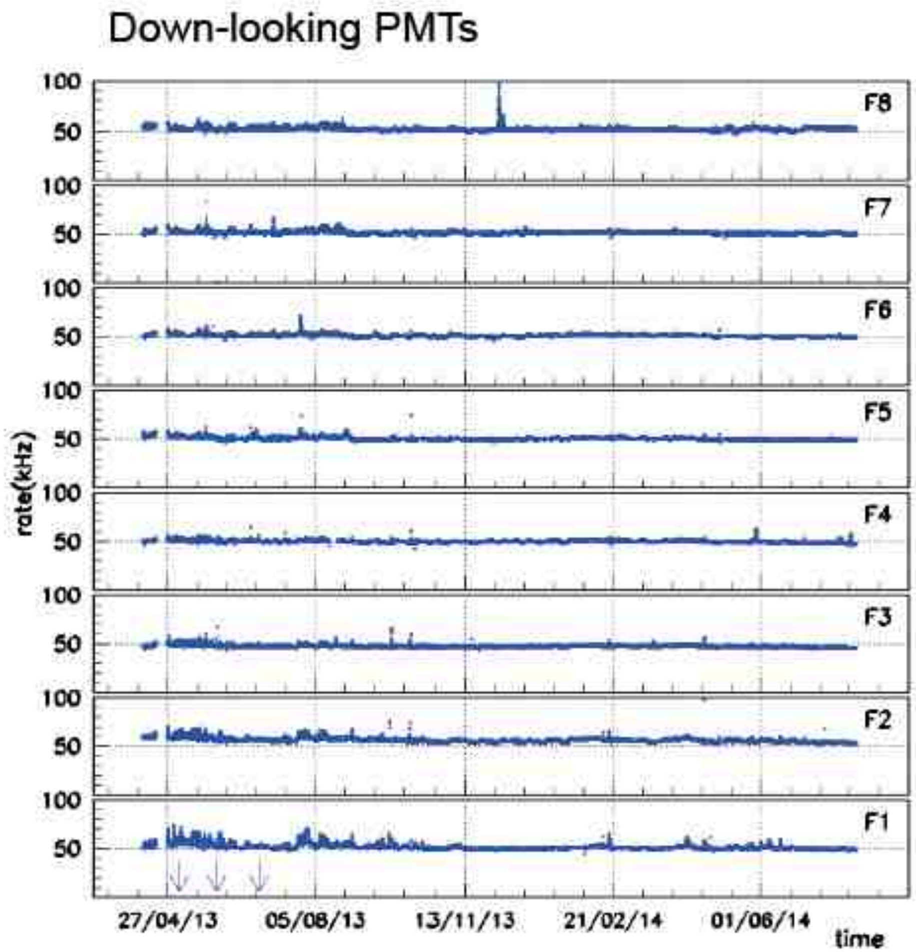
A typical snapshot of background rates from DAQ



Dead time = 0 for rates < 100kHz -- saturation effects above 120 kHz

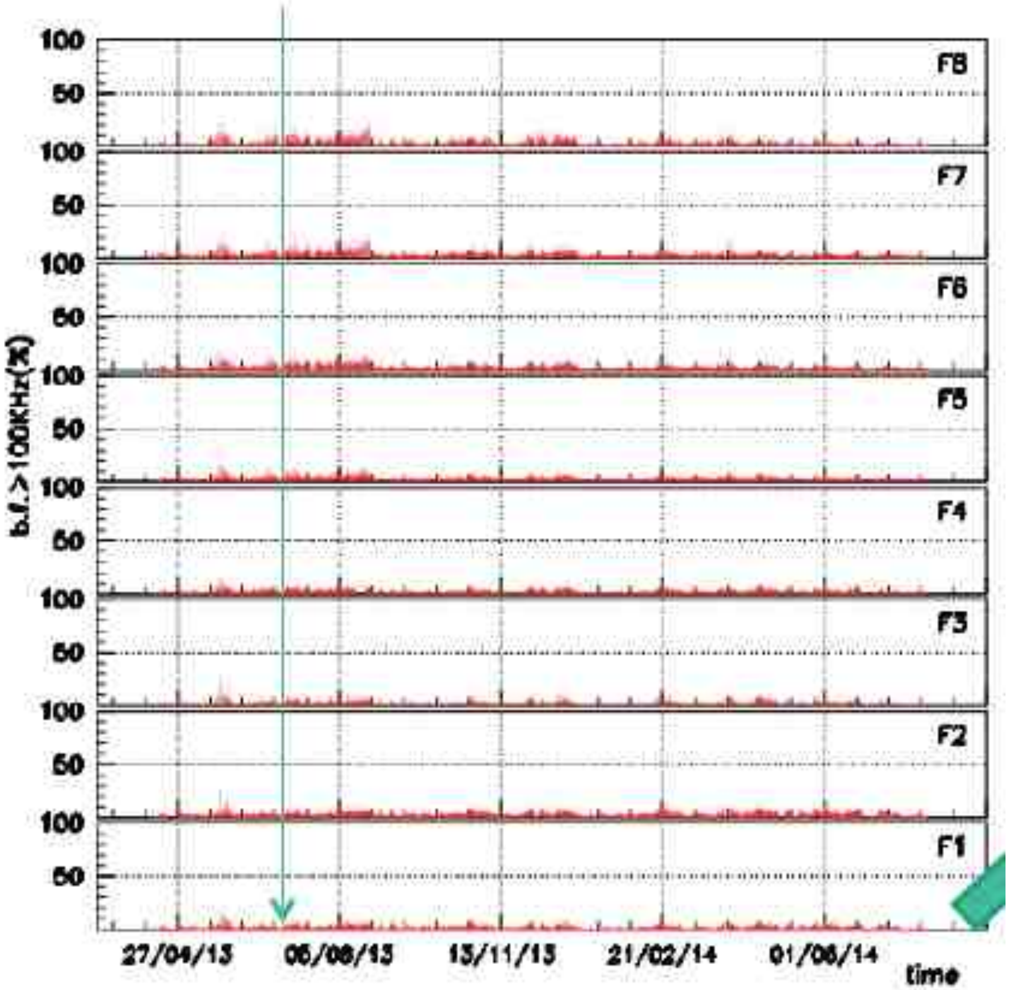
Long term measurement

40K rate



→ One year measurement
→ Median (kHz) over 15 min

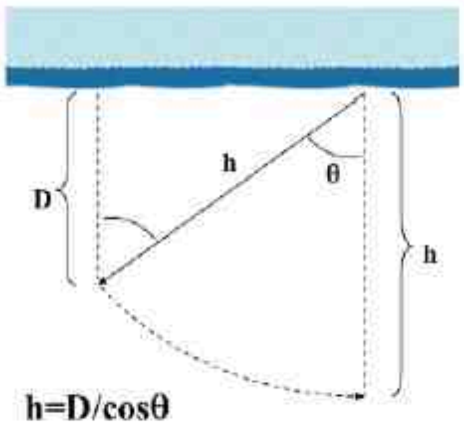
bioluminescence

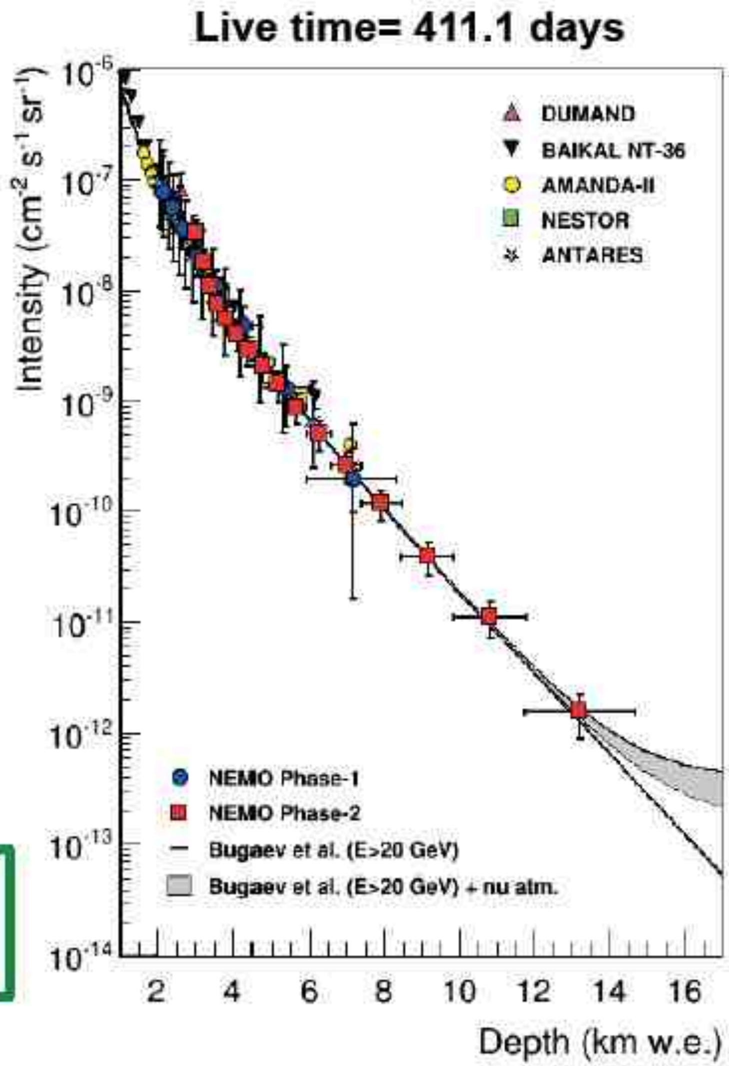


Last HV setting

The depth intensity relation

Vertical Muon Intensity as a function of Depth





DIR in water extended up to 13 km

First tower of KM3NeT-Italia

To first tower of KM3NeT-Italia will be deployed this week

The KM3NeT-Italia strings
This afternoon in Capo Passero

Per concludere

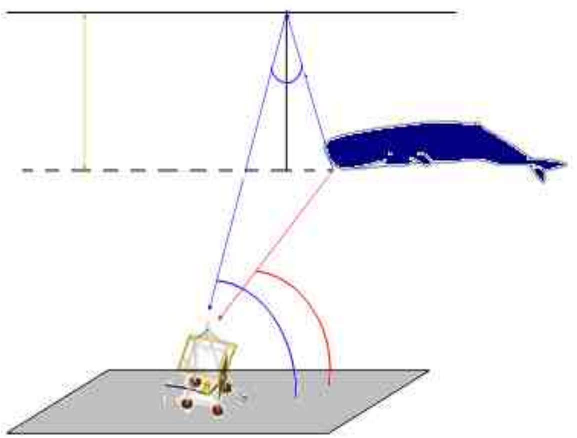
Non solo “underwater detector”… ma grandi infrastrutture in fondo al mare che offrono grandi opportunità per la ricerca in altre discipline ed il monitoraggio del mare e dei fenomeni legati alla scienza della terra
(SEA AND EARTH SCIENCE)

NEWS FEATURE

The neutrino and the whale

N. Nosengo, G. Pavan, G. Riccobene

NATURE Vol 462 - 3 December 2009



KM3NeT and EMSO

Common effort with the Earth and Sea Science Community

KM3NeT

european multidisciplinary seafloor observatory emso

Real Time Environmental Monitoring

Toulon, Sicily and Hellenic: sites of common interest for KM3NeT and EMSO

Oceanography (water circulation, climate change):
Current intensity and direction, Water temperature, Water salinity ,...

Geophysics (geohazard):
Seismic phenomena, low frequency passive acoustics, magnetic field variations,...

Biology (micro-biology, cetaceans,...):
Passive acoustic monitoring, Biofouling, Bioluminescence, Water samples analysis,...