Astronomia con neutrini di alta energia: verso un telescopio da 1 km3

***Ne**utrino **M**editerranean **O**bservatory*

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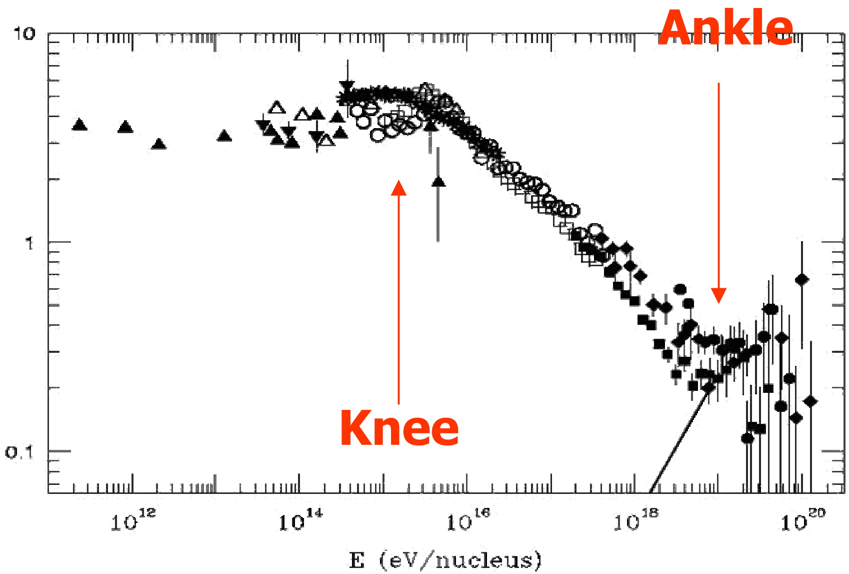
High energy astrophysics

The detection of high energy gammas and cosmic rays are milestones in modern astrophysics but there are still open questions:

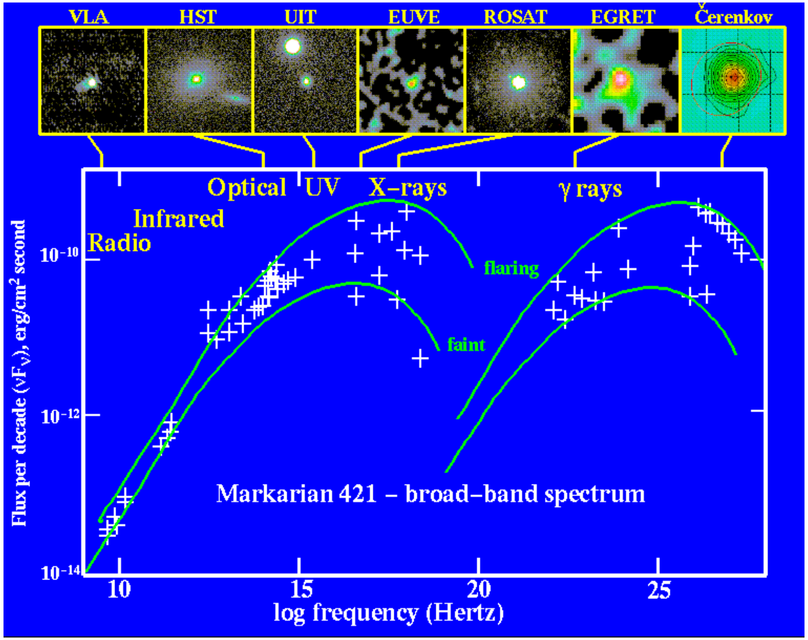
- *Identification of high energy CR sources*
- *Solution of the UHECR puzzle*
- *Particle acceleration mechanisms in astrophysical sources*
- *Dark matter content in the Universe*

Motivations for neutrino astronomy

Cosmic rays

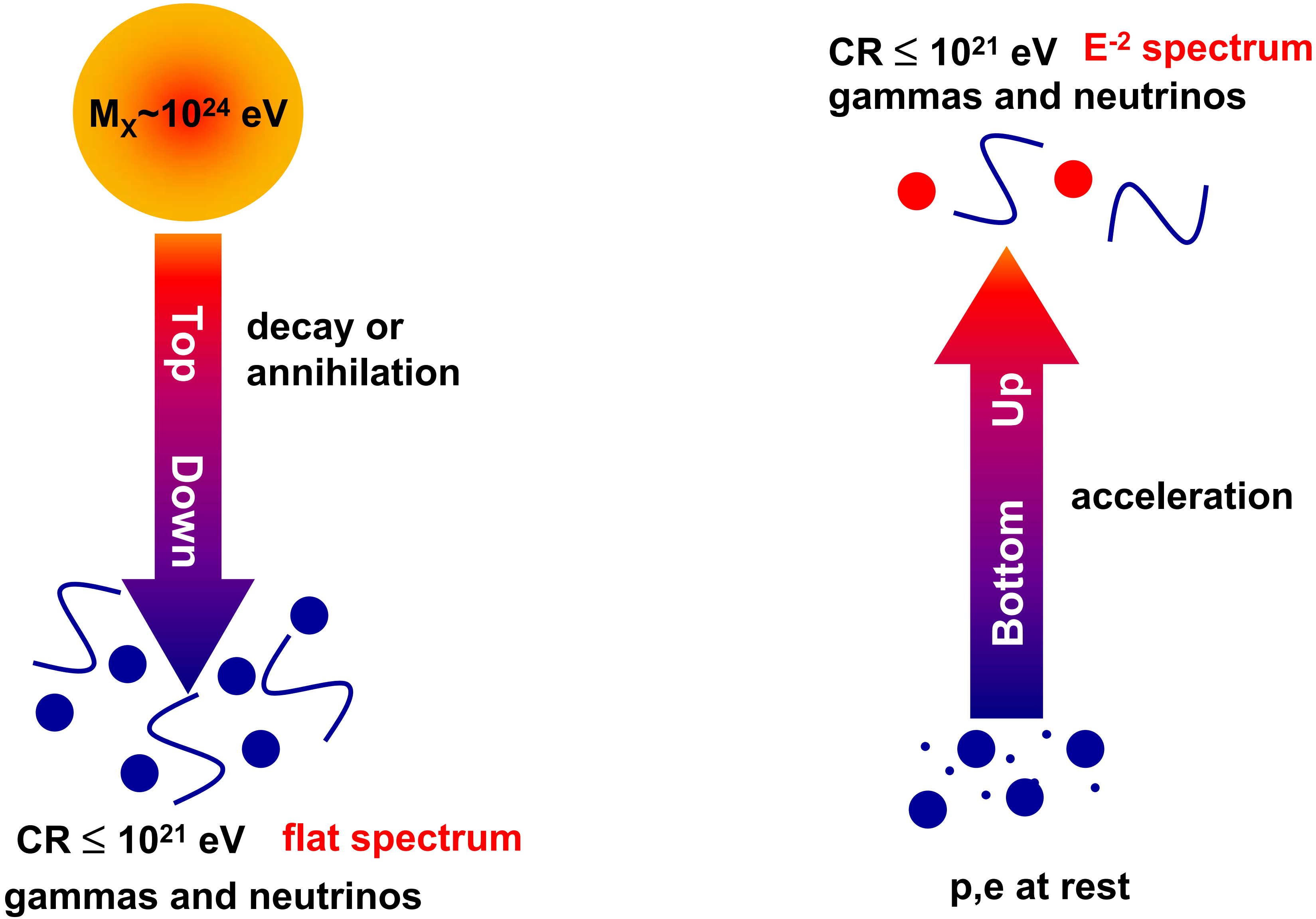


Gamma rays

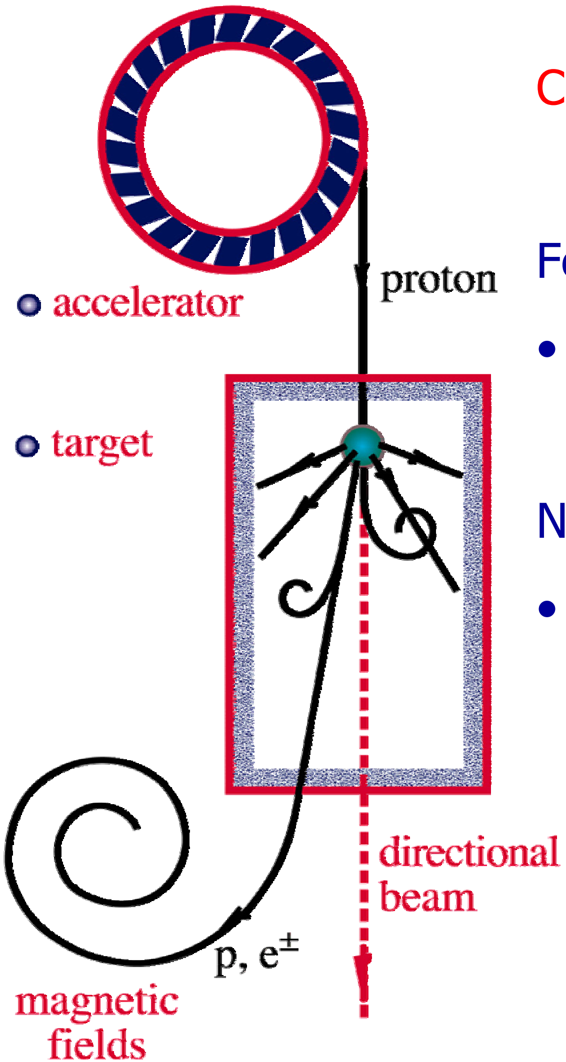


- **protons dominate CR at E>10^{18}eV**
- **1-10 TeV γ rays detected from nearby sources**

Mechanisms for HE cosmic ray production



Motivations for neutrino astronomy



Cosmic accelerators

Fermi acceleration mechanism

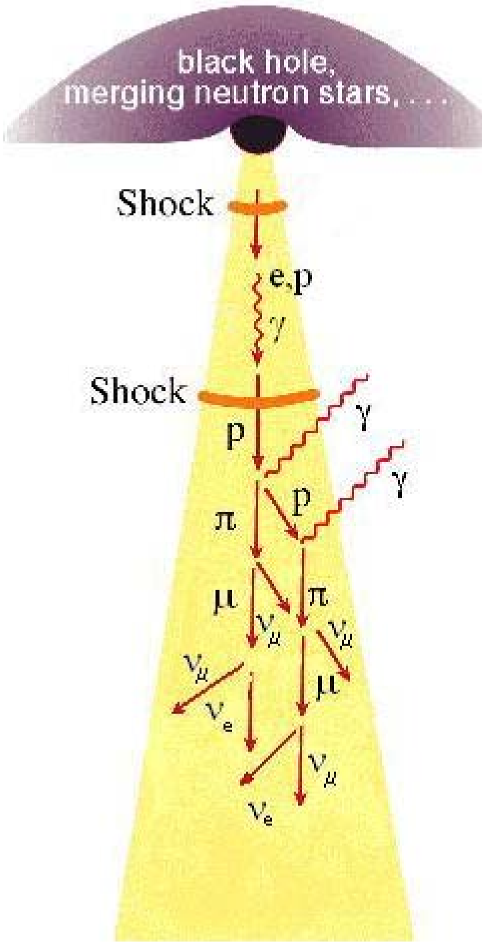
- Accelerated protons $dN_p/dE \sim E^{-2}$

Neutrino production

- Interaction target:

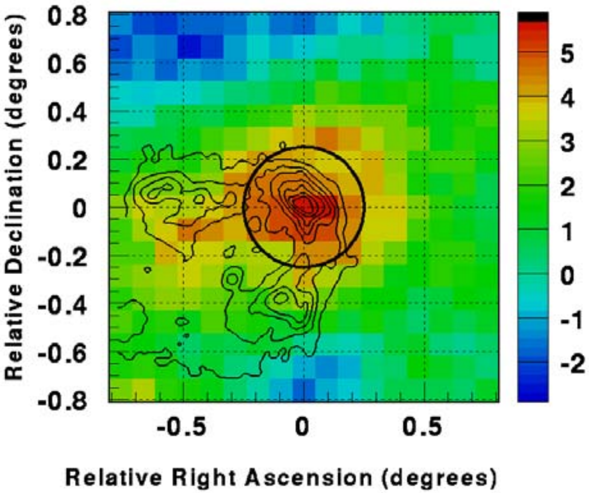
  p → p (SNR,X-Ray Binaries)

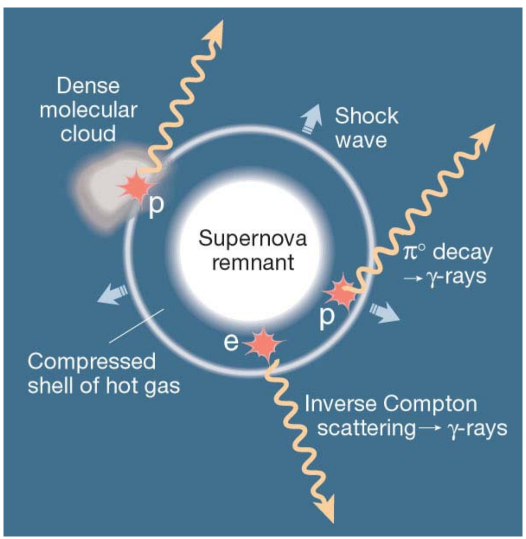
  p → γ (AGN, GRB, μQSO)

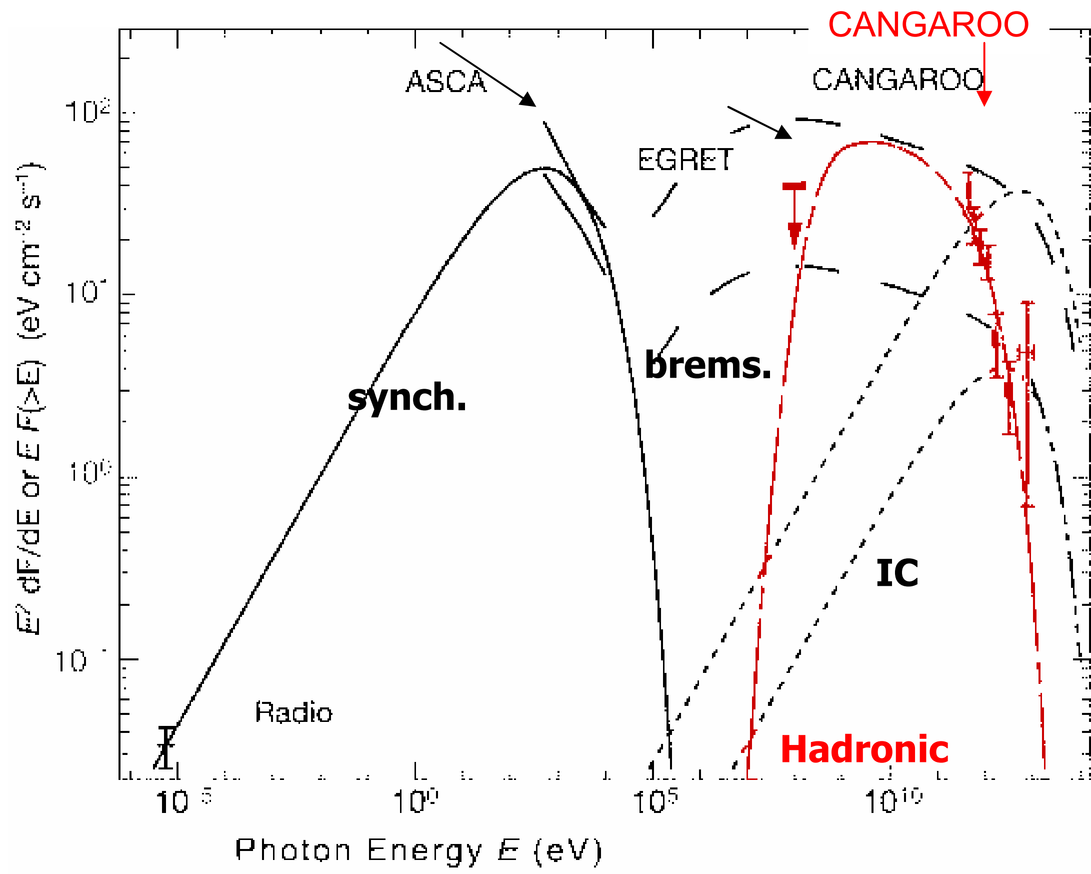


Gamma rays from π^0 decay in SNR?

RXJ1713.7-3946







CANGAROO observations fit with TeV gamma ray production originated by π^0 decay

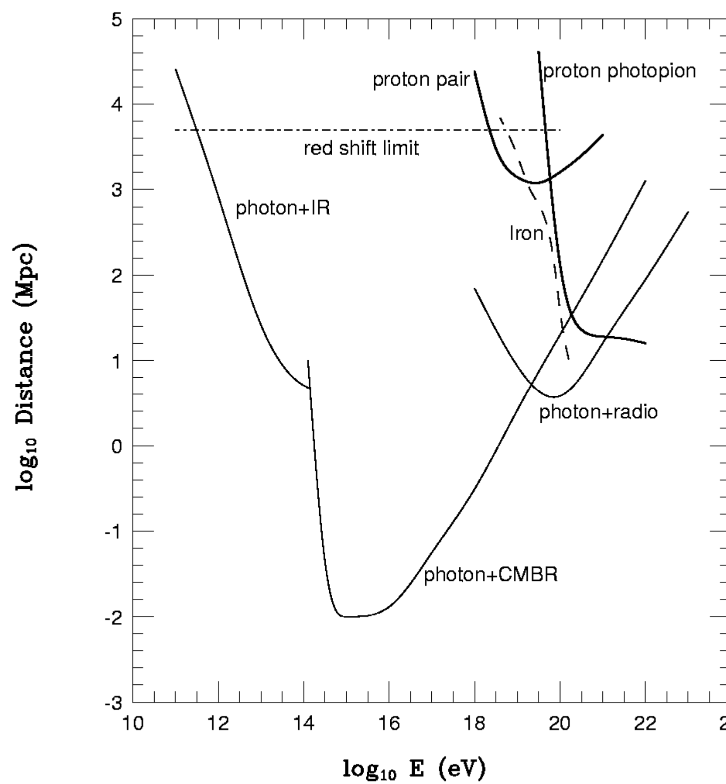
Enamoto et al., 2002, Aharonian, 2002

Absorption of photons and protons

Photomeson interaction (GZK cutoff)

$N\gamma_{CMBR} \rightarrow N\pi$

$D_p\ (E_p > 10^{19.5}\ eV) \sim (\sigma \cdot \rho_{CMBR})^{-1} \sim 50\ Mpc$



pair production

$\gamma\gamma_{IR,MW} \rightarrow e^+e^-$

$D_\gamma\ (E_\gamma > 10^{13}\ eV) \sim (\sigma_{\gamma\gamma} \cdot \rho_{IR,MW})^{-1} \sim 10\ Mpc$

Only neutrinos can reach the Earth from cosmological sources

Candidate neutrino sources

The most luminous astrophysical sources could also produce high energy neutrinos0

Extragalactic sources:

AGN: e.m. models fairly explain observed gamma ray emission (Mkn 421)
but also discussed...
acceleration of protons in the jet (Biermann, Mannheim, Dermer)

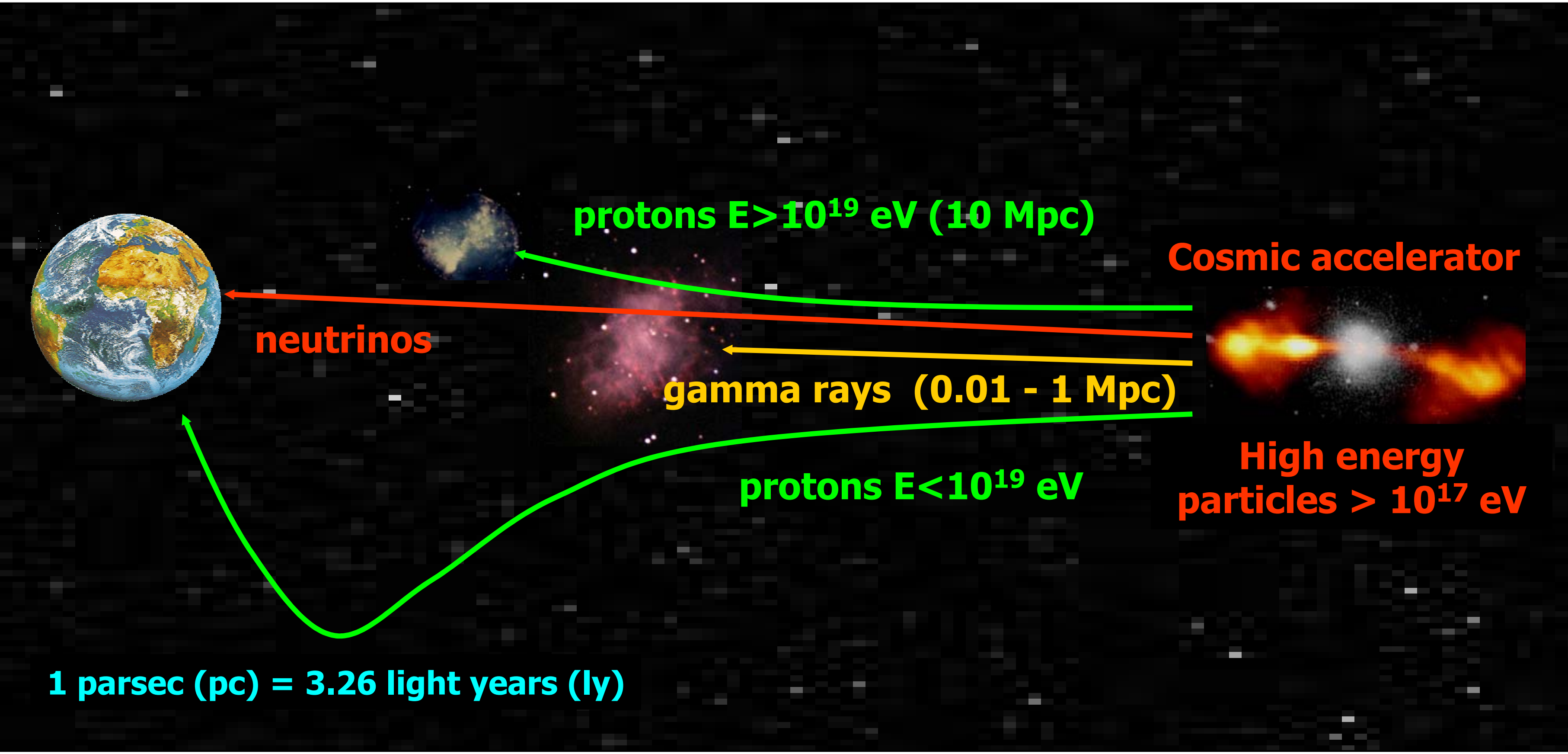
GRB: the standard scenario foresees the acceleration of UHECR and the production of E>TeV neutrinos (Waxman, Vietri)

Galactic sources:

μQSO: the presence of an hadronic component in the jet (SS433) may lead to neutrino fluxes detectable by underwater/ice neutrino detectors (Levinson, Distefano)

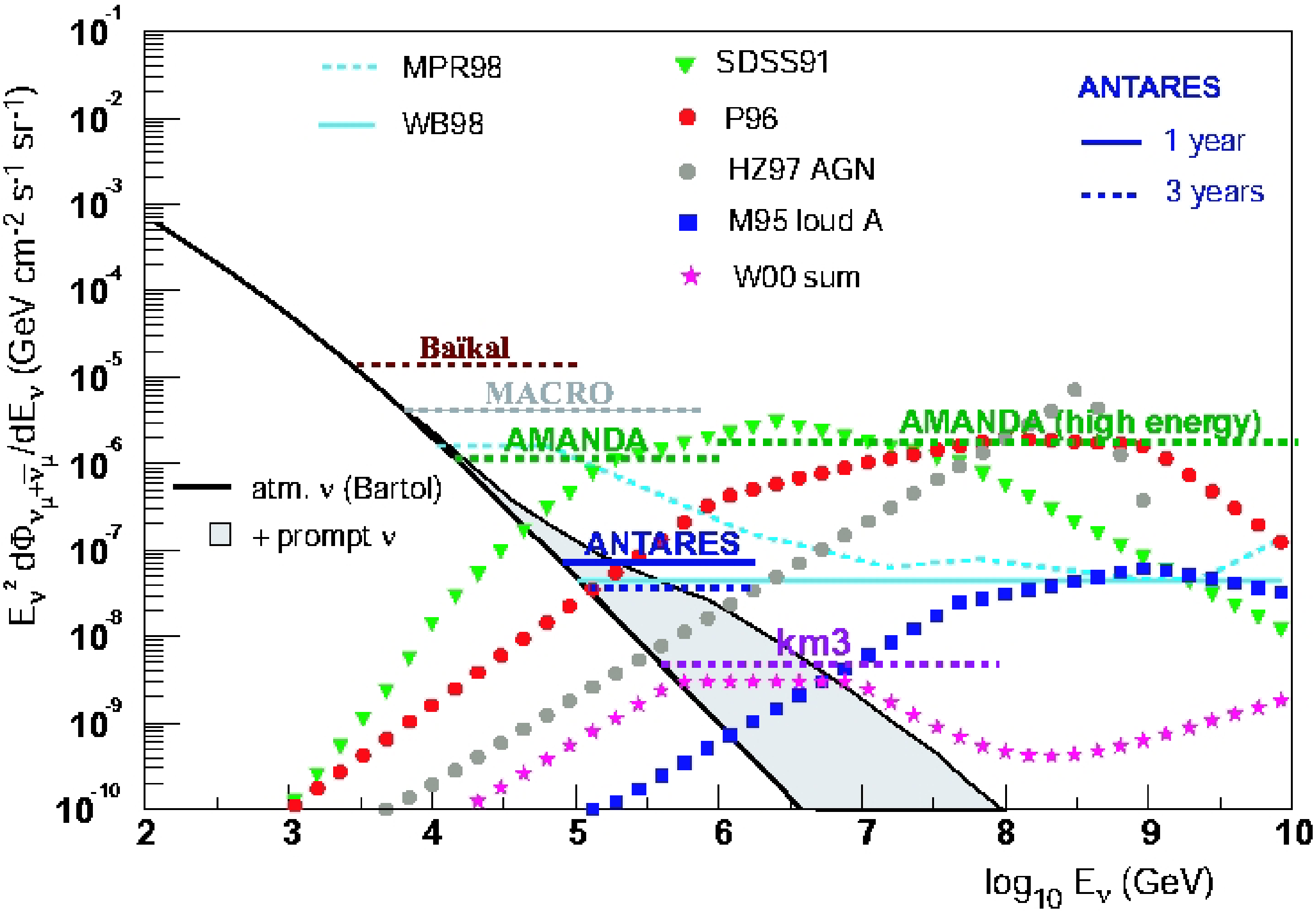
SNR: p-p interaction may produce neutrinos and TeV gamma rays, recently observed by CANGAROO (Enamoto)

Particle propagation in the universe



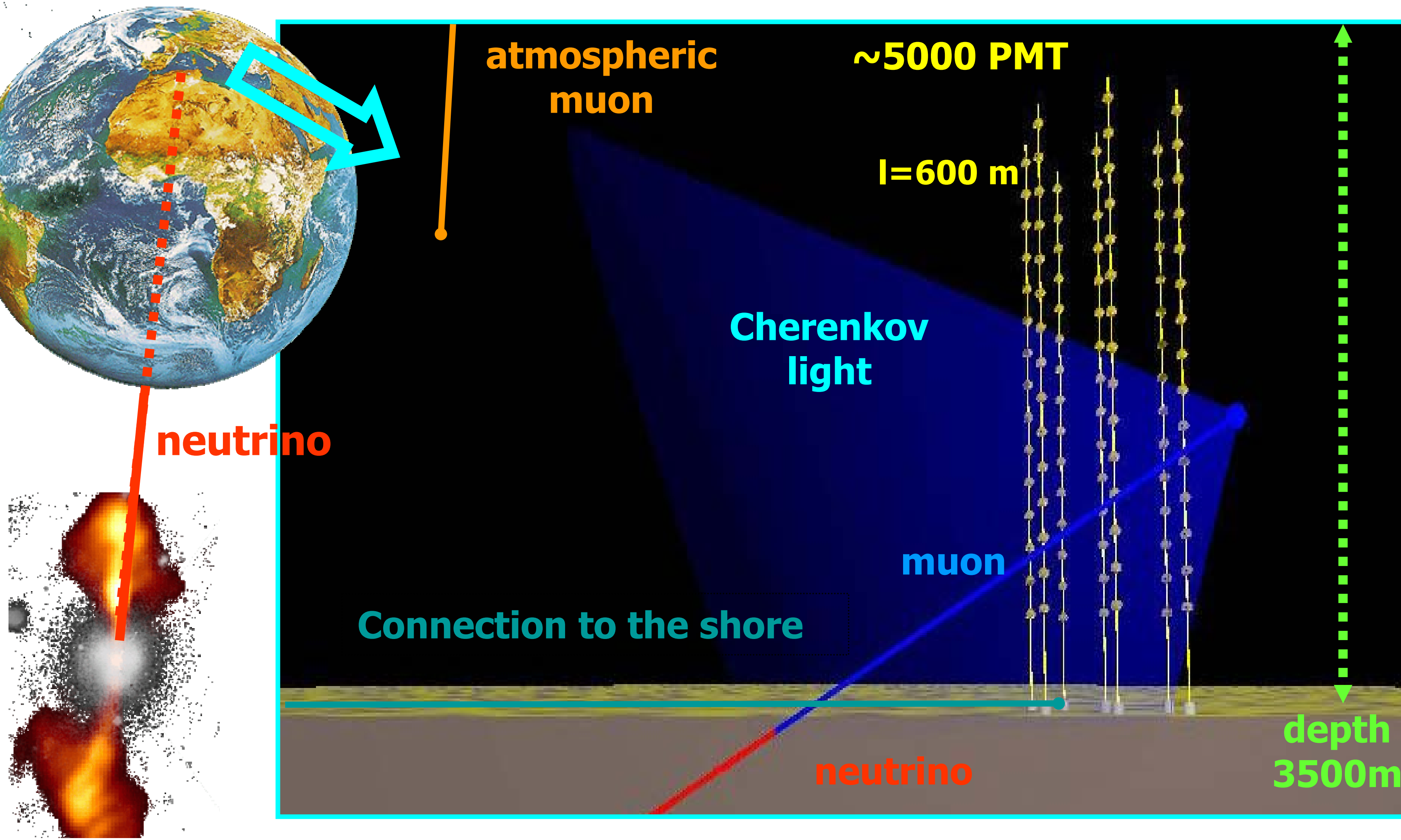
Photons are absorberd on dust and radiation
Protons are deviated by magnetic fields
Extremely high energy protons interact with background radiation
Only neutrinos are direct

Diffuse neutrino fluxes sensitivity

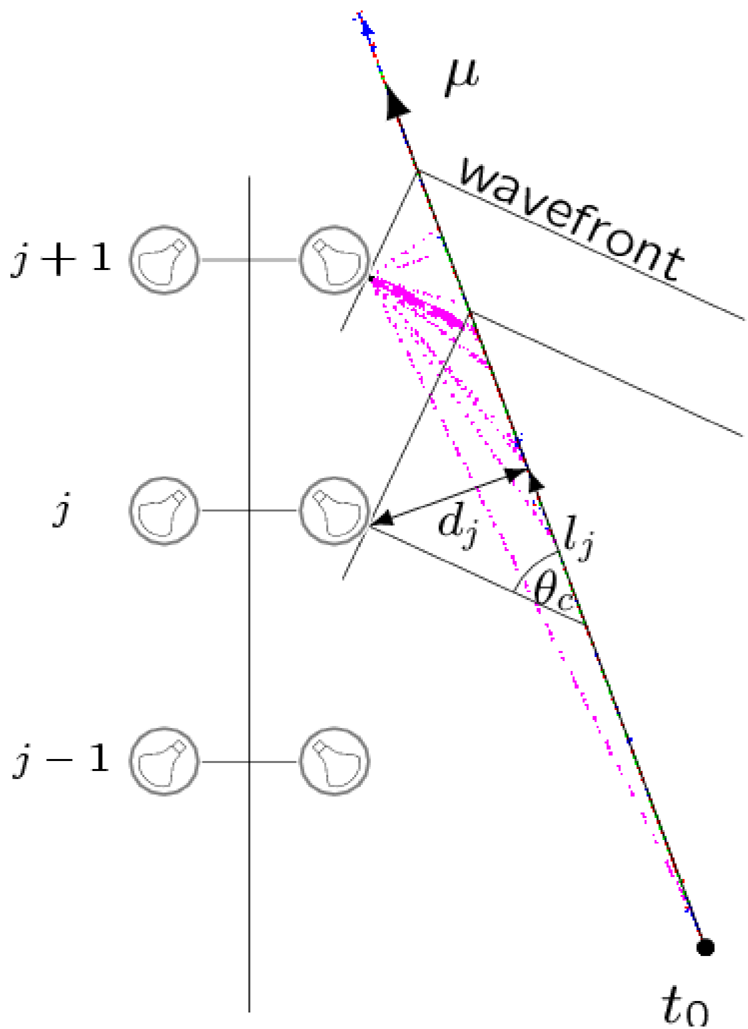


Principles of neutrino astronomy

Flux estimate → need km3 scale detectors



Neutrino detection principle



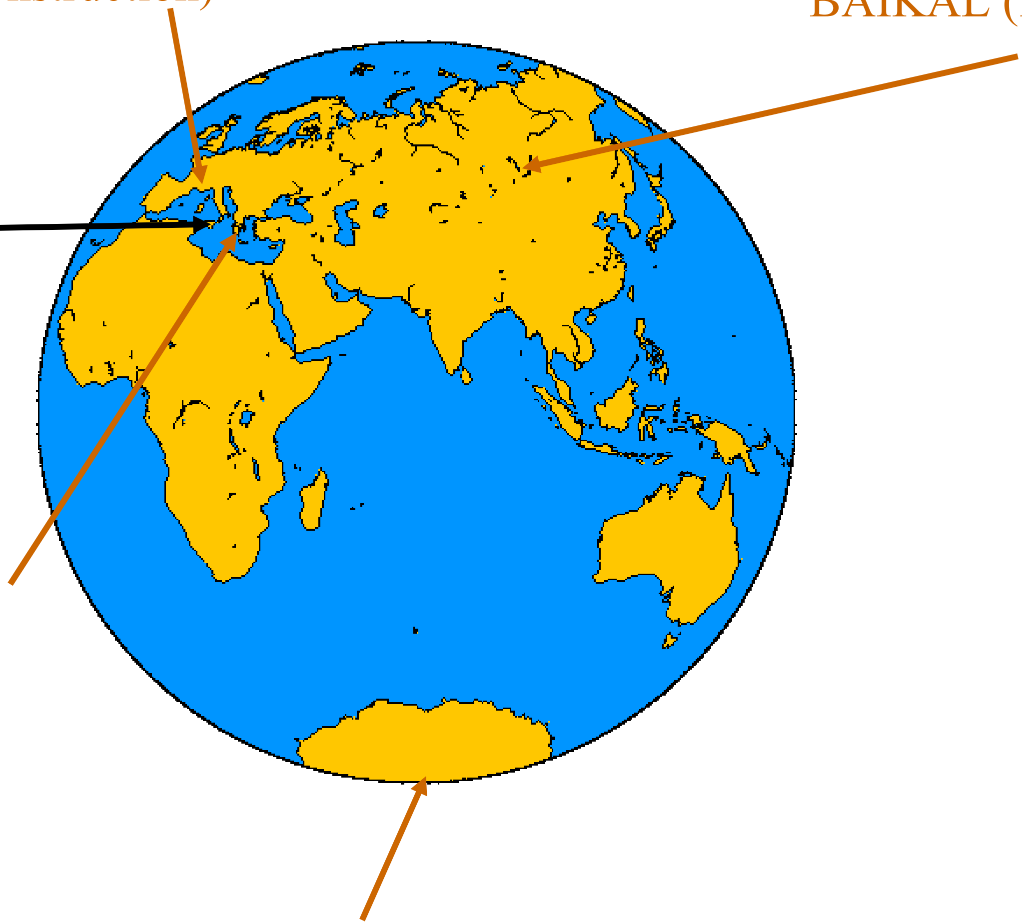
$$\nu_\mu + N \rightarrow \mu + X$$

$$c(t_j - t_0) = l_j + d_j \tan(\theta_c)$$

medium properties

$$\left.\begin{aligned}\delta x &= 20\ \text{cm}\\ \delta t &= 1\ \text{ns}\end{aligned}\right\}\ \delta\theta = 0.2\ \text{deg.}$$

Underwater neutrino telescope projects

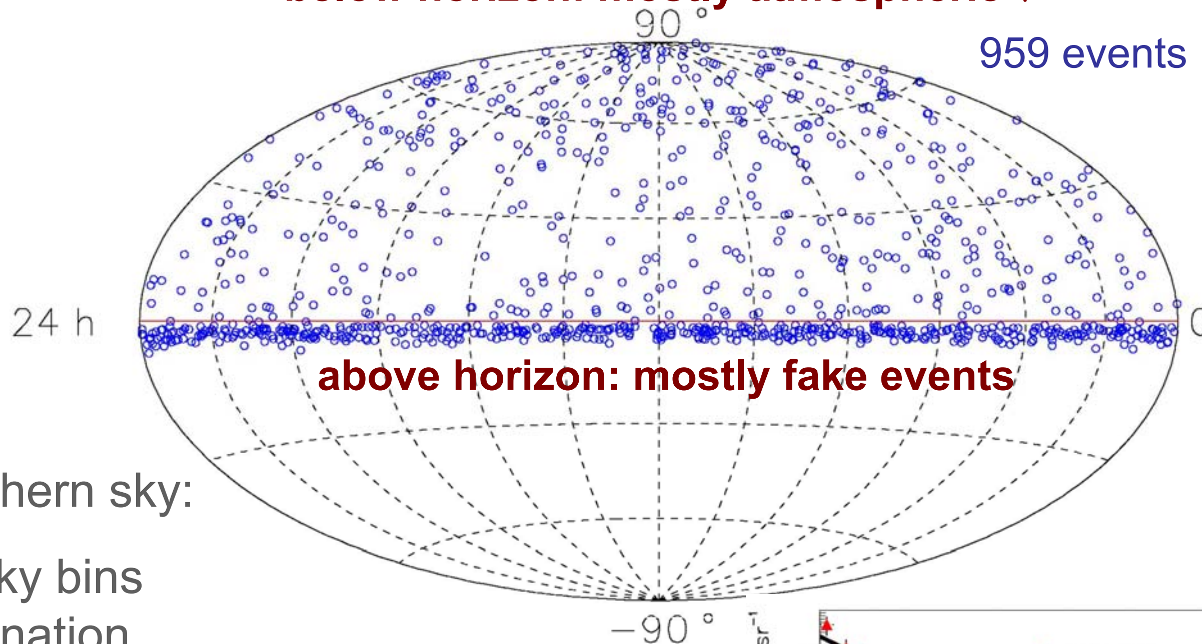


AMANDA neutrino sky map

Livetime
2000: 197 days
2001: 194 days
2000+2001: 959 events
465 below horizon

below horizon: mostly atmospheric ν

959 events



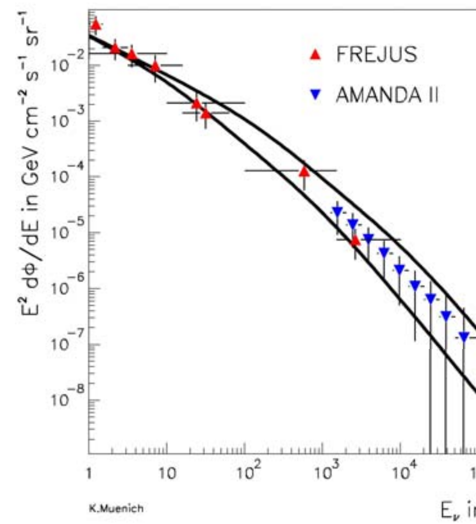
above horizon: mostly fake events

Step 2:

Search for clustering in Northern sky:

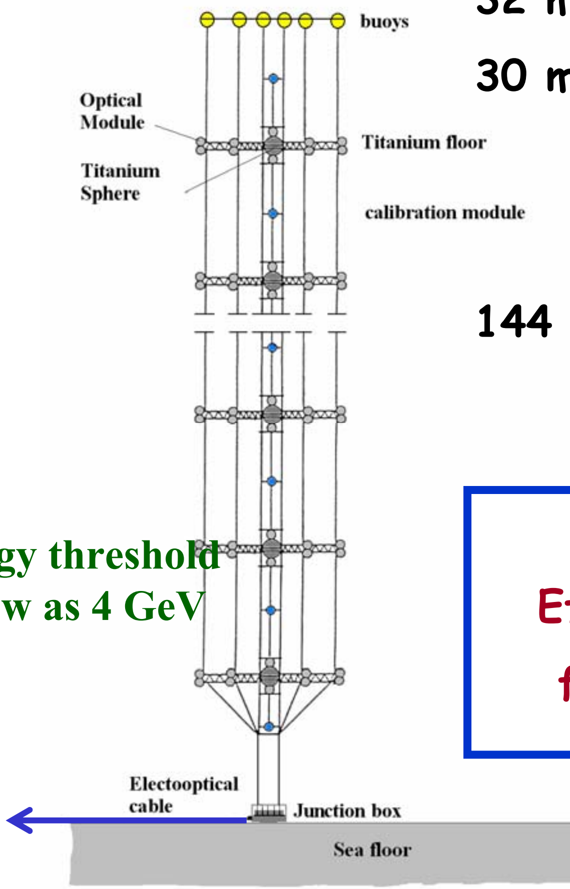
Grid search in rectangular sky bins
- bin size depends on declination
- shift grid 4 times to cover boundaries

No evidence for point sources
with an E^{-2} energy spectrum
based on first 2 years of AMANDA-II data



Consistent with atmospheric ν

NESTOR



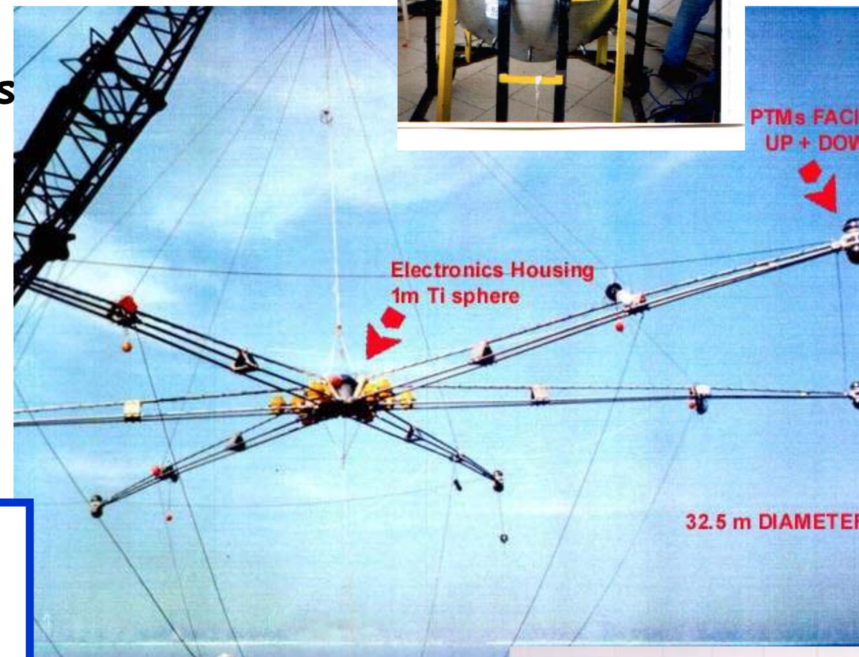
32 m diameter

30 m between floors

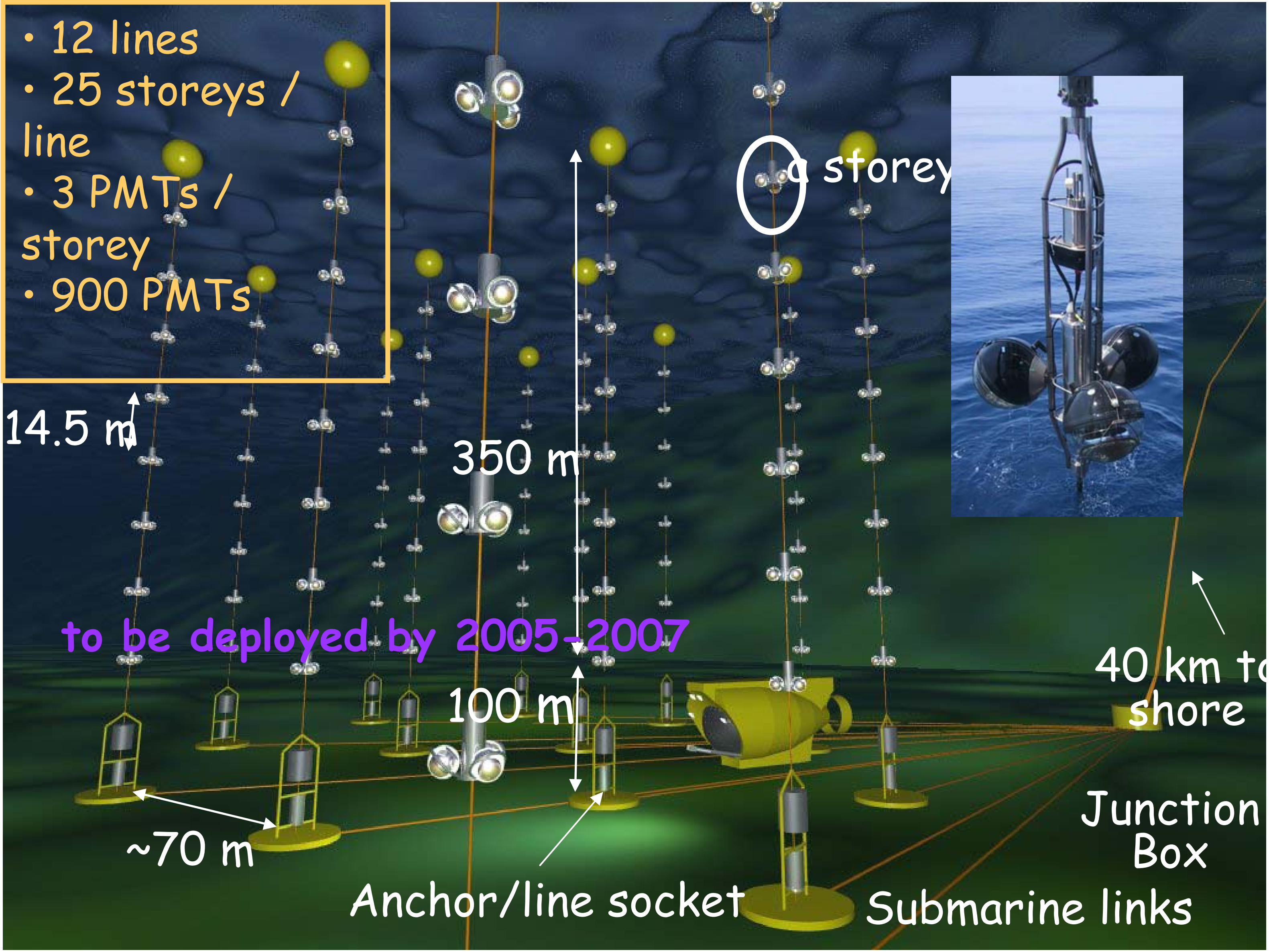
144 PMTs

ergy threshold
s low as 4 GeV

20 000 m^2
Effective Area
for E>10TeV



The ANTARES neutrino telescope



The ANTARES prototype line

ICECUBE

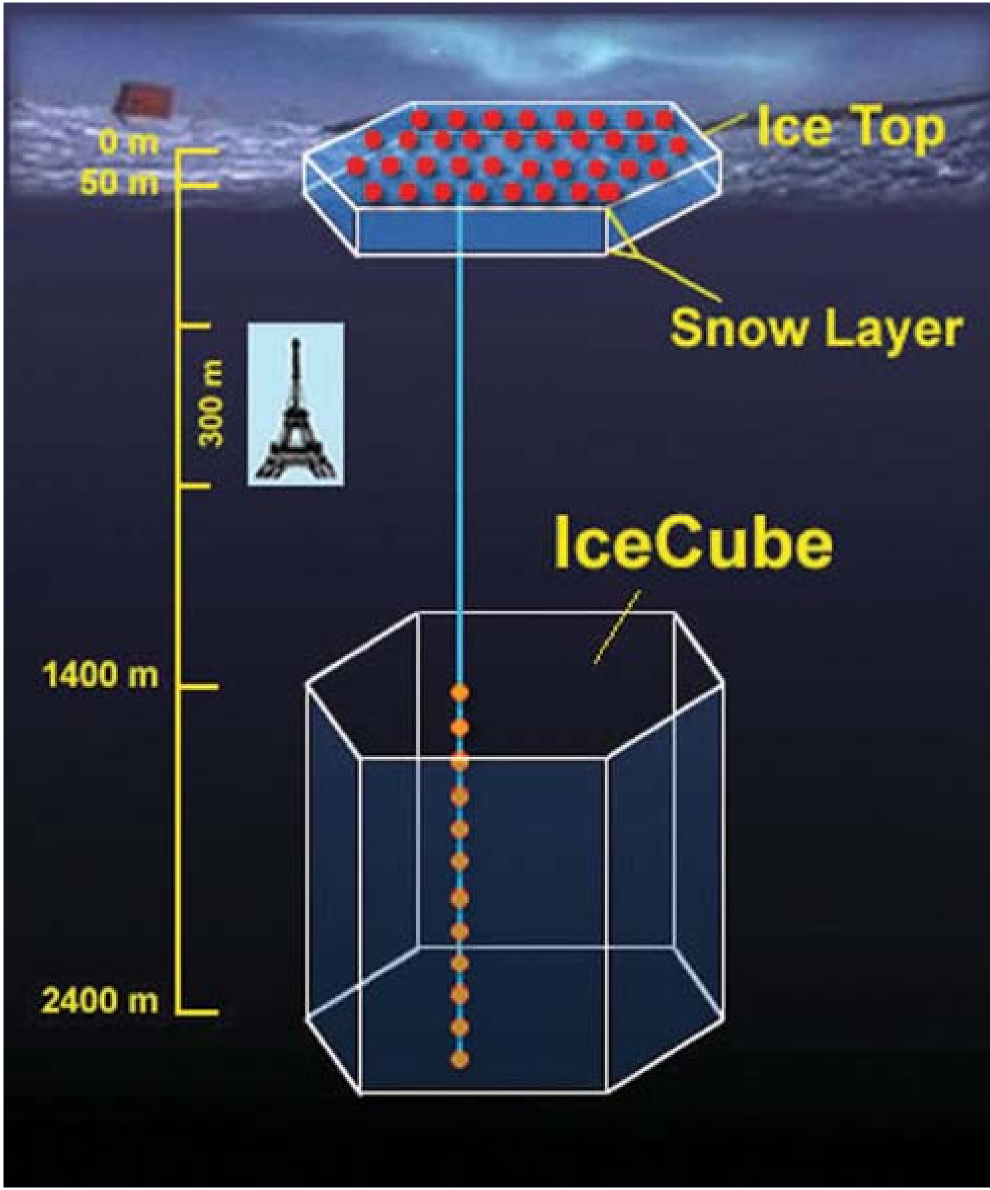
Deep ice array

- 80 strings / 60 OM's each
- 17 m OM spacing
- 125 m between strings
- hexagonal pattern over 1 km²

geometry optimized for detection of TeV – PeV (EeV) ν's based on measured absorption & scattering properties of Antarctic ice for UV-blue Cherenkov light

Surface array IceTop

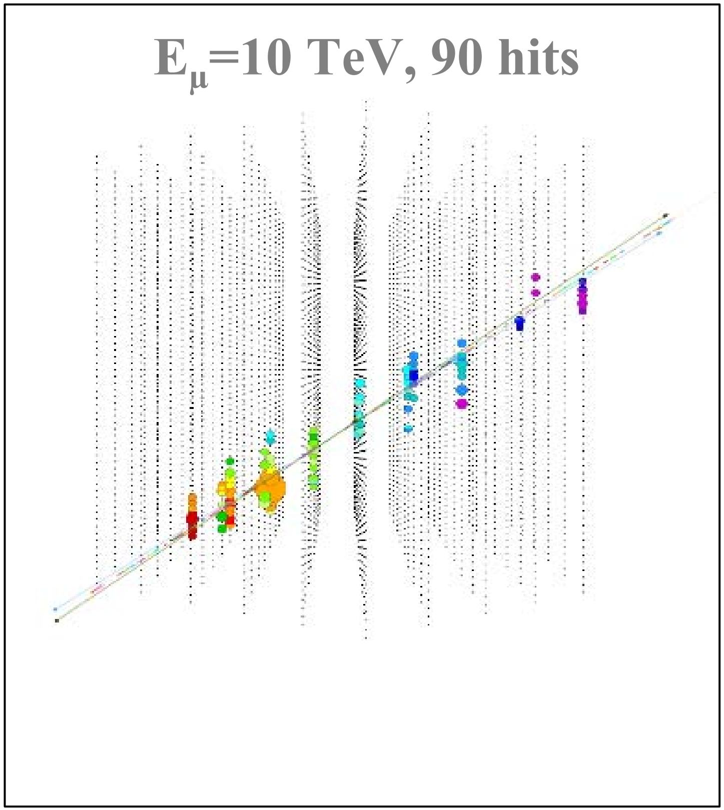
2 frozen-water tanks (2 OM's each) on top of every string

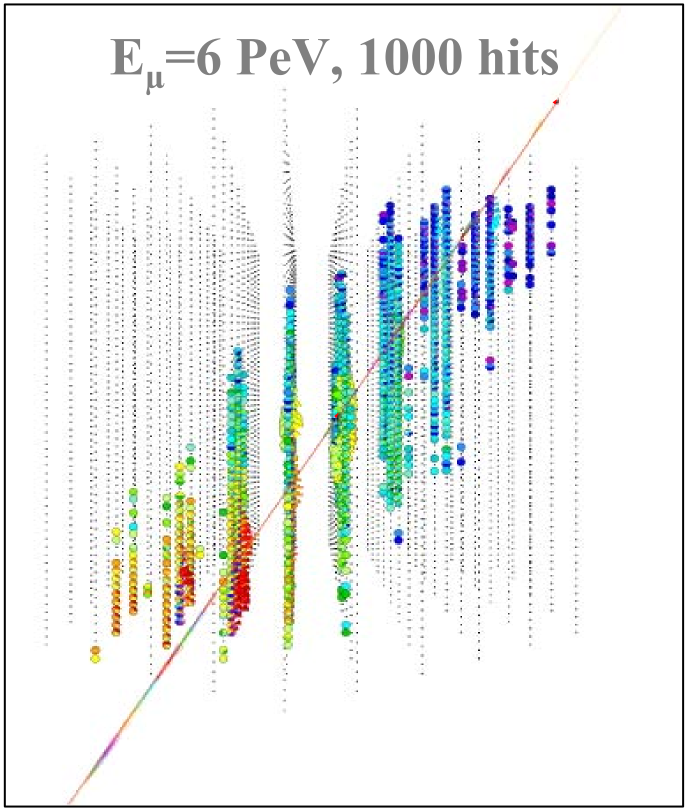


ICECUBE physics performances

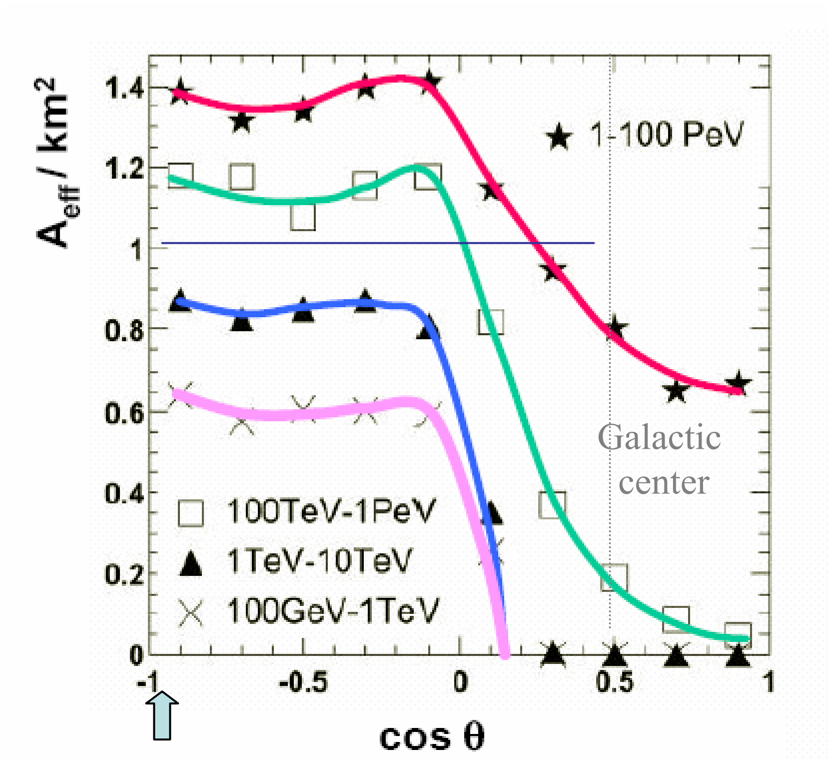
IceCube will be able to identify

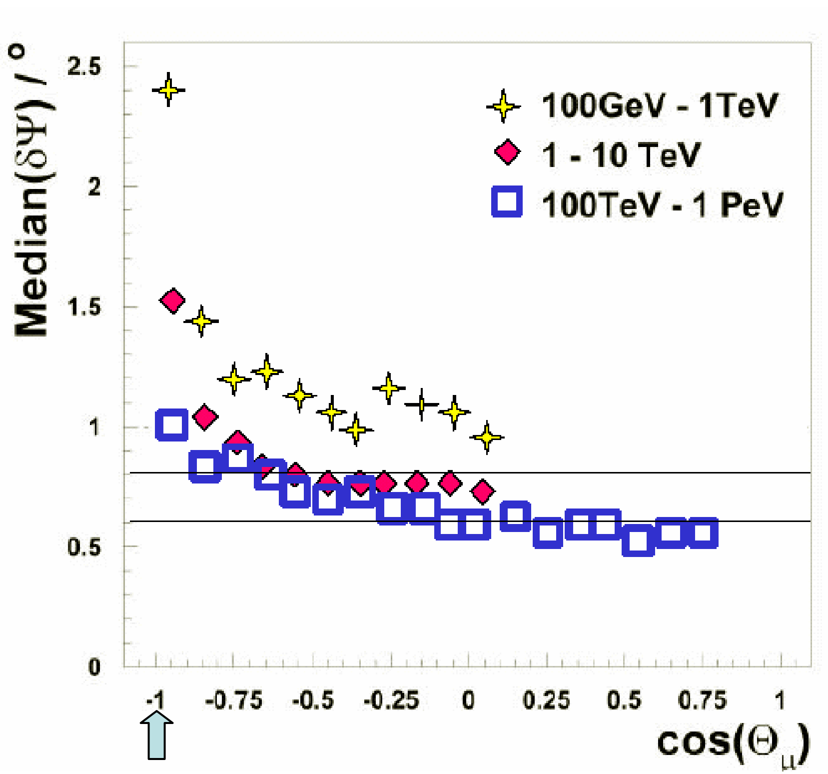
* μ tracks from ν_μ for $E_\nu > 10^{11}$ eV
* cascades from ν_e for $E_\nu > 10^{13}$ eV
* ν_τ for $E_\nu > 10^{15}$ eV





ICECUBE Aeff and angular resolution

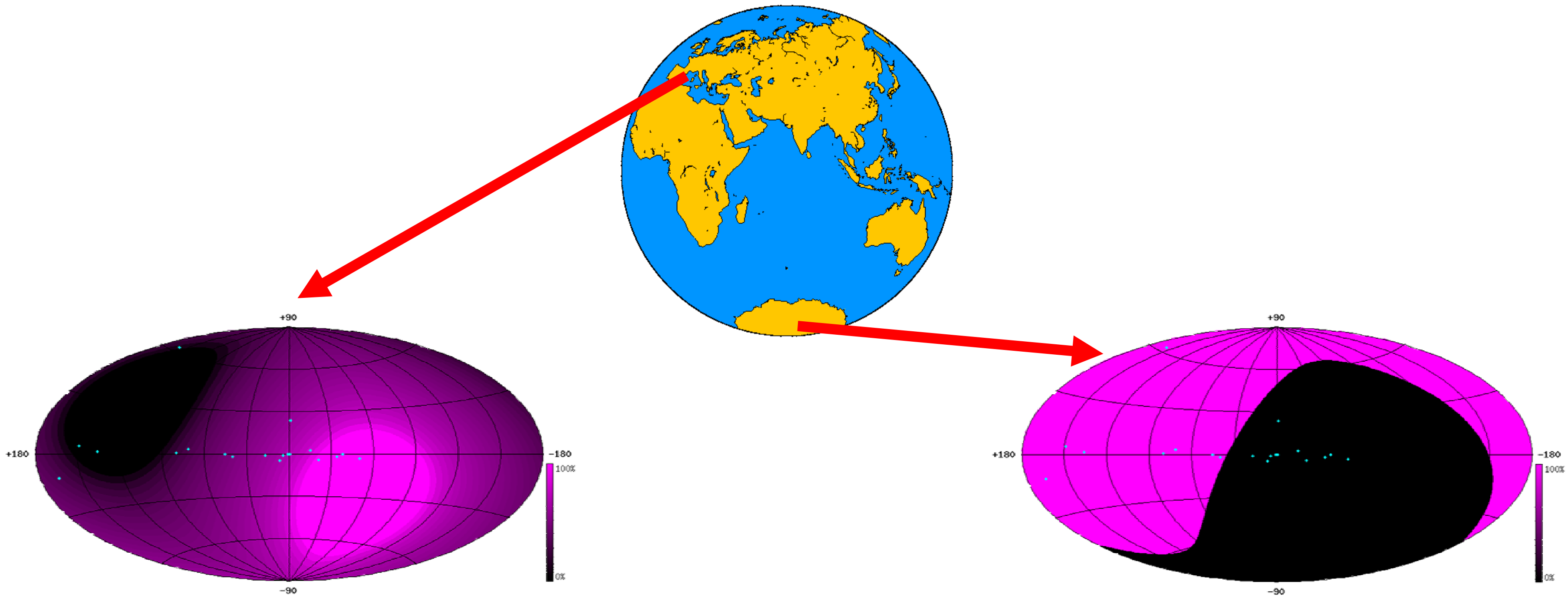




Median angular reconstruction uncertainty ~ 0.8°

- E^{-2} ν_μ spectrum
- quality cuts and bkgr suppression (atm μ reduction by ~10^6)

Sky view



Mediterranean km3
37° North
2/3 of time: Galactic Centre

ICECUBE
South Pole

0.5 π sr instantaneous common view
1.5 π sr common view per day

NEMO

Towards the km3 detector

- **R&D phase (1999 - 2002)**
  - ***Site selection and characterization***

    Several sites close to the italian coasts have been studied. A site close to Capo Passero (Sicily) at 3500 m with optimal water characteristics has been identified for the installation
  - ***R&D activities***

    Development of specific ASICS for the underwater front end electronics

    Large area hybrid photomultipliers
  - ***Feasibility study of the km3 detector***

    A complete feasibility study has examined all the detector critical components and the deployment procedures

    A preliminary project for the km3 has been developed
- **Phase 1: Advanced R&D and prototyping (2002 - 2006)**
  - ***Realization of a detector subsystem including all critical components***

    The system under realization at the Underwater Test Site of the LNS at 2000 m
- **Km3 detector realization (2007 ? - ...)**

The NEMO Collaboration

INFN

Bari, Bologna, Cagliari, Catania, Genova, LNF, LNS, Messina, Roma

CNR

Istituto di Oceanografia Fisica, La Spezia
Istituto di Biologia del Mare, Venezia
Istituto Sperimentale Talassografico, Messina

Istituto Nazionale di Geofisica e Vulcanologia

Istituto Nazionale di Oceanografia e Geofisica Sperimentale

Universities:

Bari, Bologna, Cagliari, Catania, Genova, Messina, Roma *"La Sapienza"*

Site selection criteria

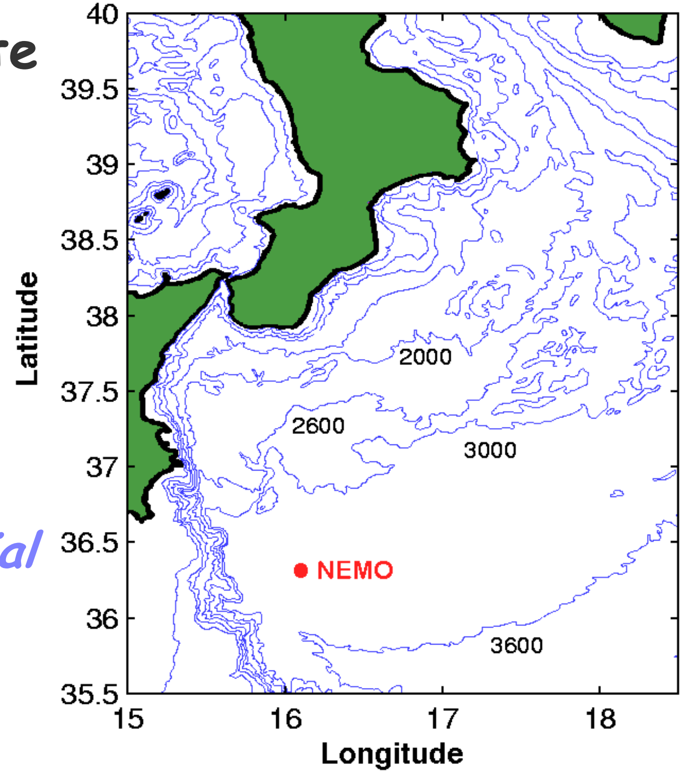
- **Depth**
  Reduction of atmospheric muon flux
- **Water optical transparency**
  Optimisation of detector performances (efficiency and angular resolution)
- **Weak and stable deep sea currents**
  Reduce stresses on mechanical structures
  Reduce stimulation of bioluminescent organisms
- **Low biological activity**
  Low optical background (bioluminescence) $\Rightarrow$ detector performances
  Low biofouling and sedimentation on OM
- **Distance from the shelf break and from canyons**
  Installation safety
- **Proximity to the coast and to existing infrastructures**
  Easy access for sea operations
  Reduction of costs for installation and maintenance

Site exploration activities

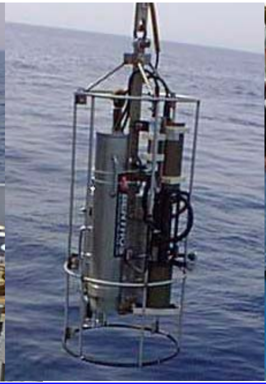
Since 1998 continuous monitoring of a site close (≈80 km) to the coast of Sicily (Capo Passero)

More than 20 sea campaigns on the site to measure

- water optical properties
- optical background
- deep sea currents
- nature and quantity of sedimenting material

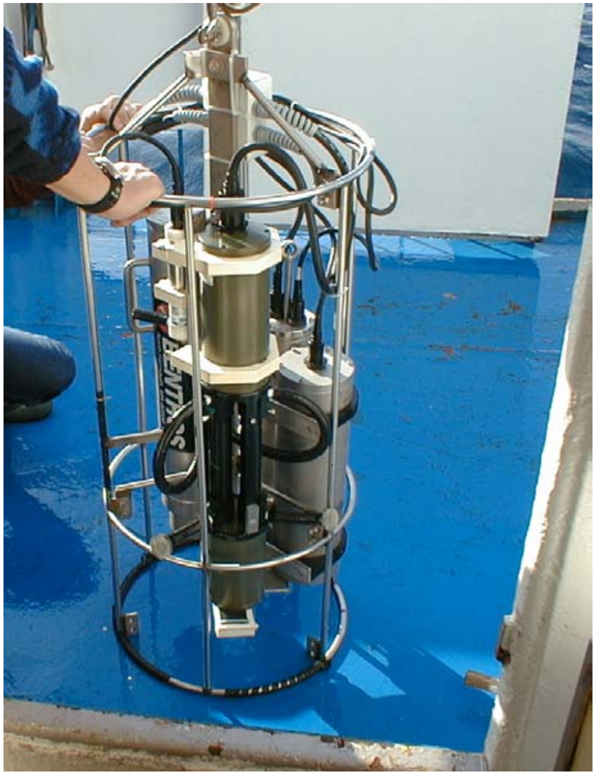


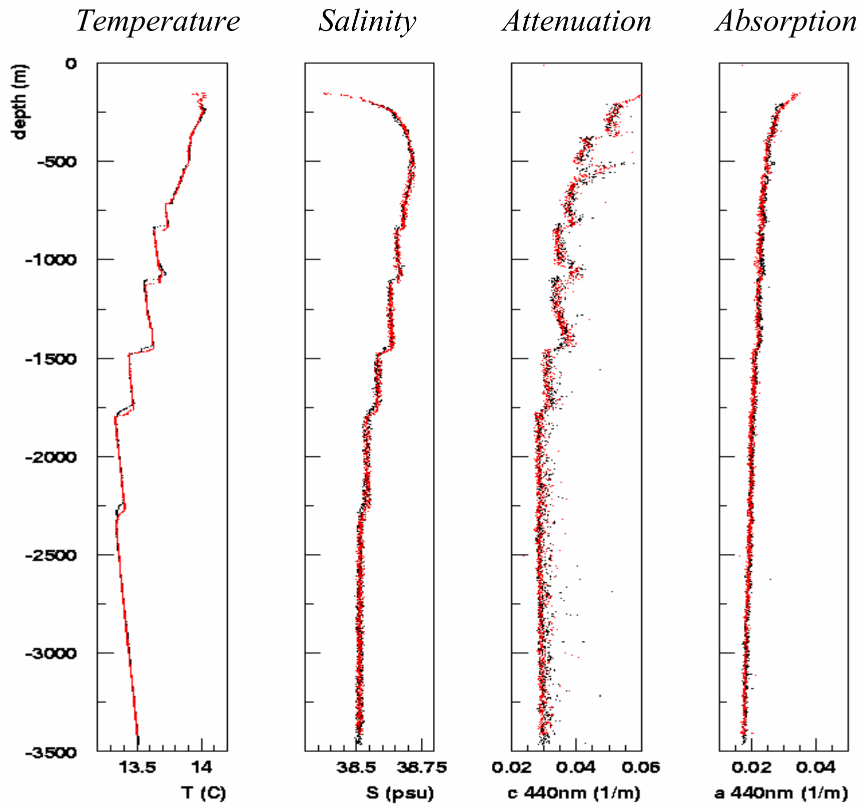



Water optical properties

Measure of profiles of water optical properties





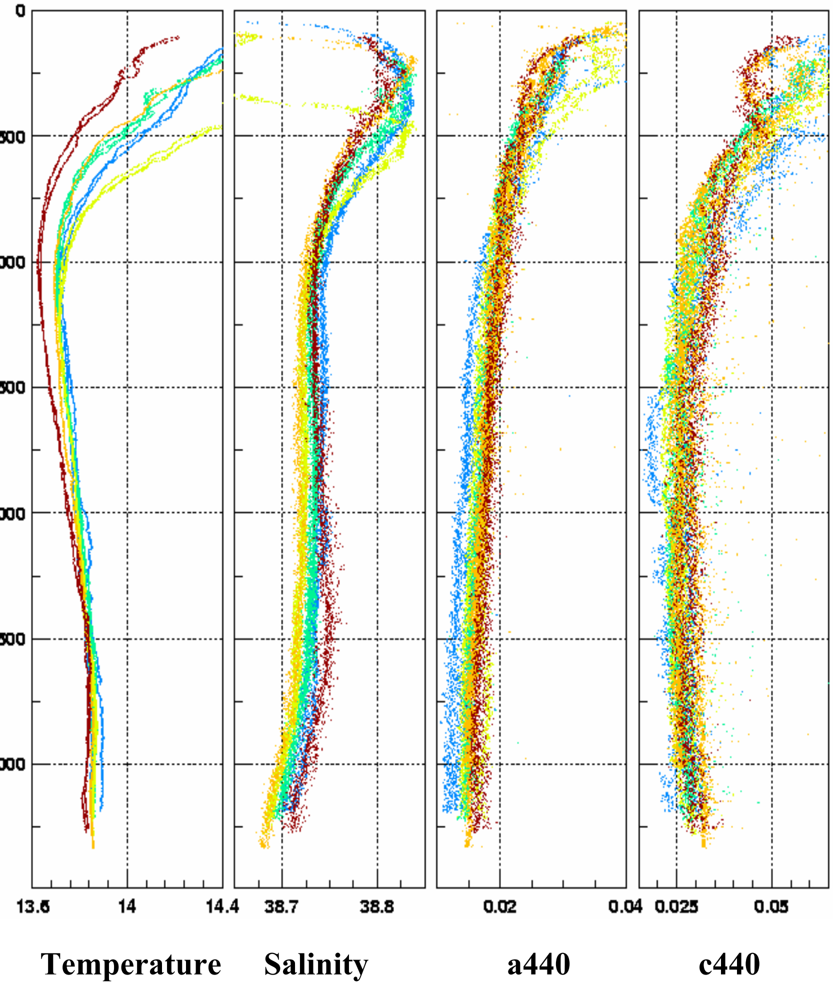
Data taken in th South Thyrrenia Sea (Alicudi)

Strong layering of waters

The setup used (AC9+CTD) measures oceanographical (temperature, salinity, pressure) and optical (absorption and attenuation coefficients at 9 wavelengths) parameters along the whole water column

Water optical properties

Seasonal dependence of optical parameters in Capo Passer

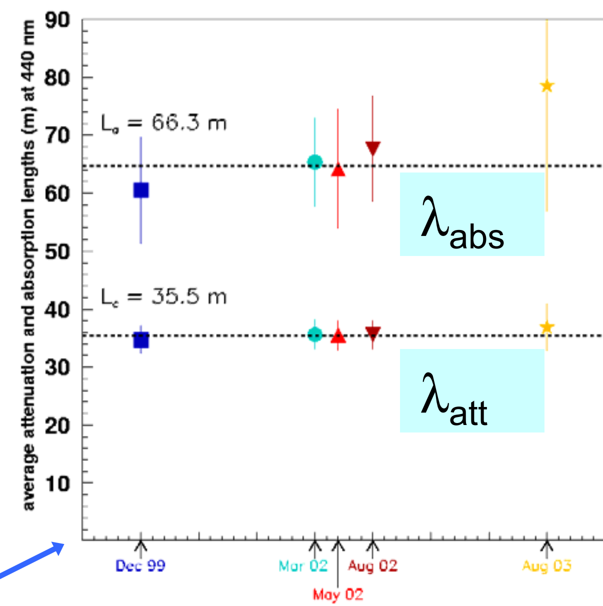


Seasonal dependence of oceanographica (Temperature and Salinity) and optical (absorption and attenuation) properties has been studied

Variations are only observed in shallow water layers

Data taken in:

Aug 03 (2)
Aug 02 (3)
Mar 02 (4)
May 02 (2)
Dec 99 (2)

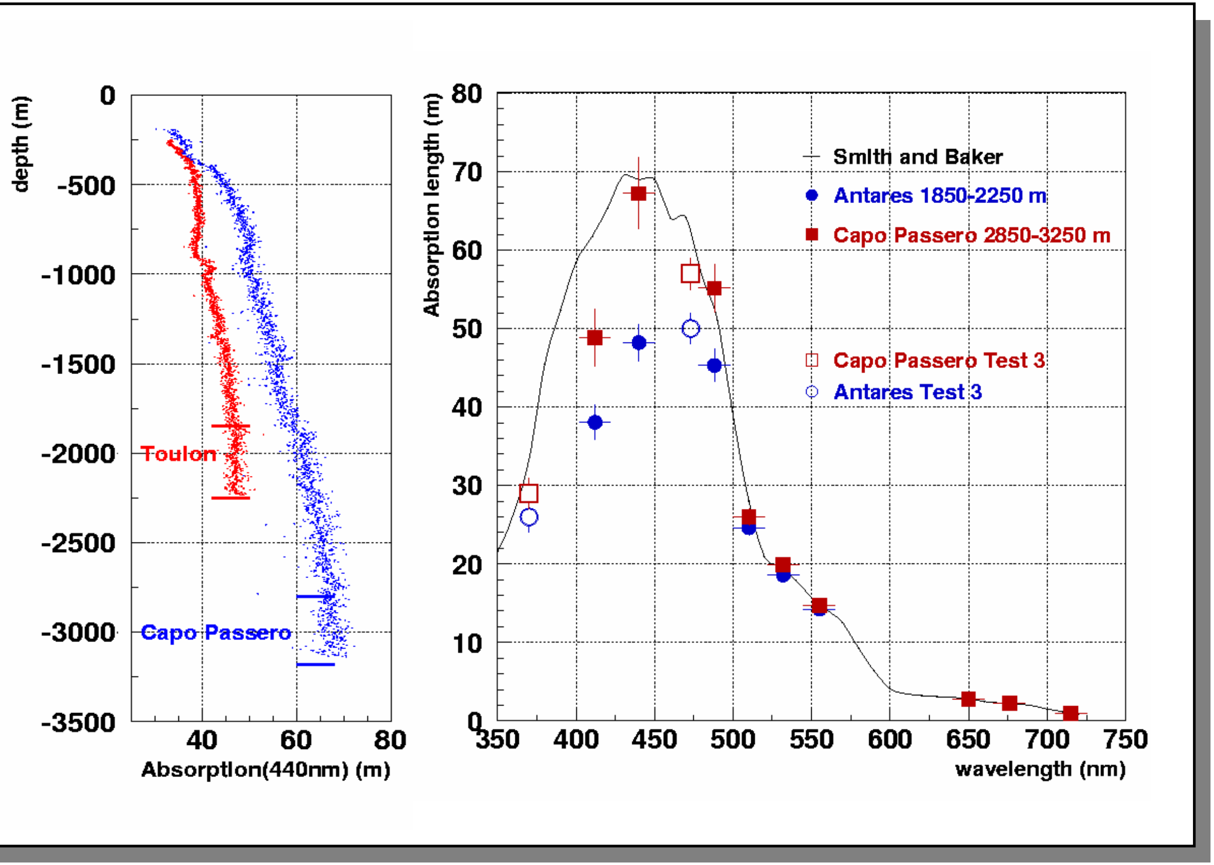


Average values 2850÷3250 m

Water optical properties

Comparison of NEMO and Antares data

Optical water properties have been mesured in the summer 2002 in Capo Passero and Toulon in two joint NEMO-ANTARES campaigns



Absorption lengths measured in Capo Passero are compatible with optically pure sea water data

Large differences between Toulon and Capo Passero are observed in the blue region

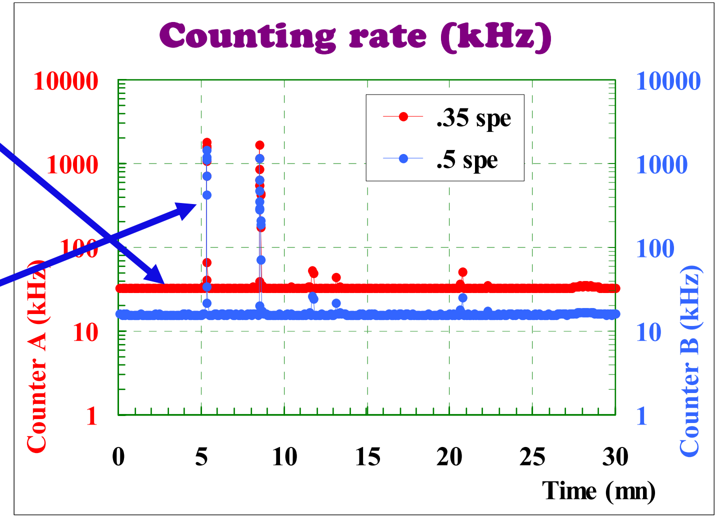
Values measured with the Antares Test 3' setup are in good agreement with the AC9 data

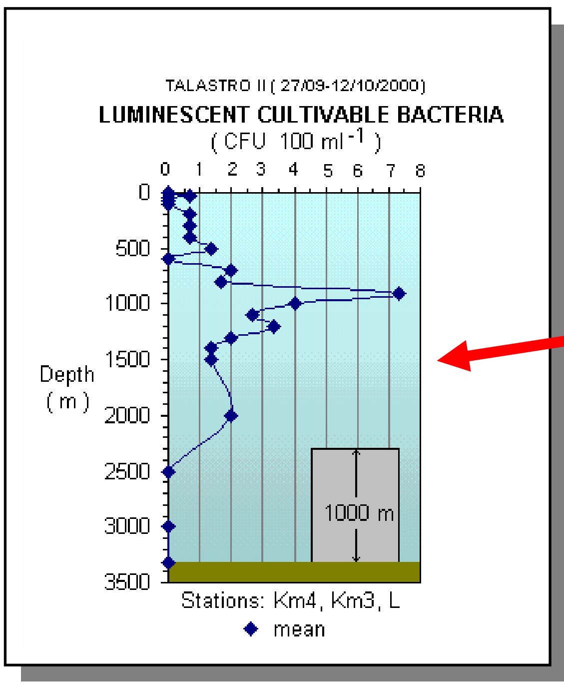
Optical background

Sources of optical background

Decay of radioactive elements (mainly ^{40}K) → stable frequency noise (≈30 kHz on a 8" PMT at 0.3 p.e. threshold)

Light produced by biological entities (bioluminescence) → random bursts with very high counting rate

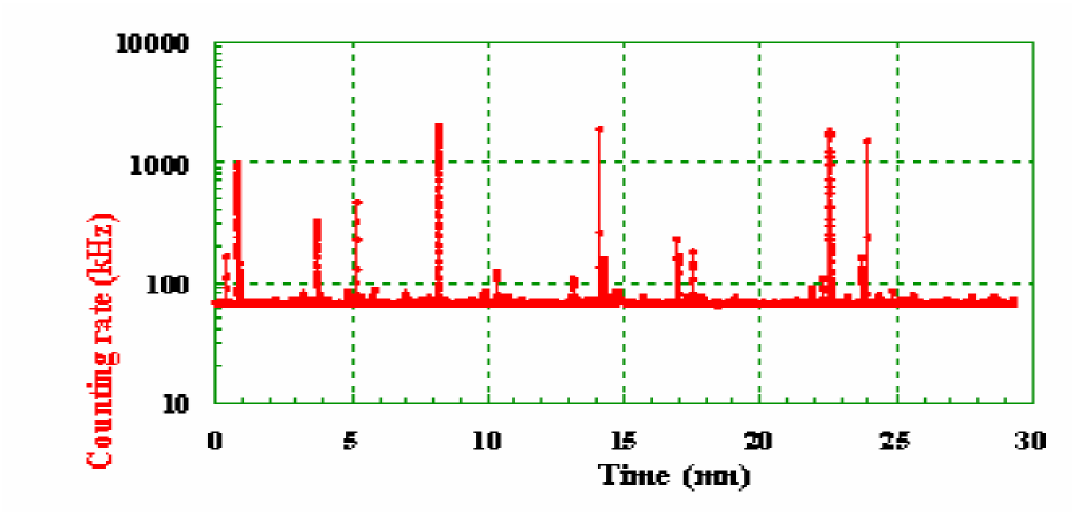




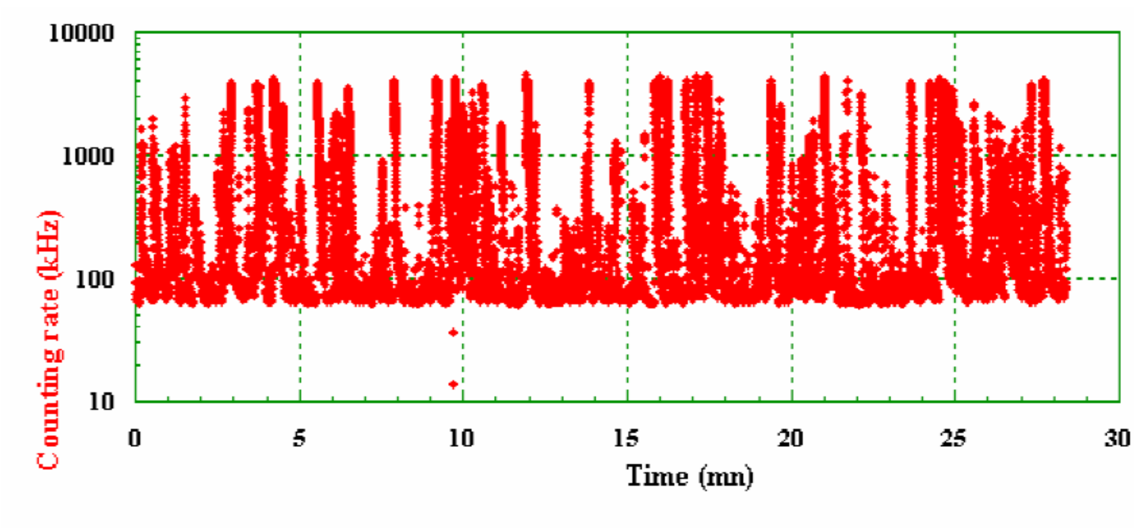
No luminescent bacteria have been observed in Capo Passero below 2500 m

Data taken by Istituto Sperimentale Talassografico, CNR, Messina

Optical background



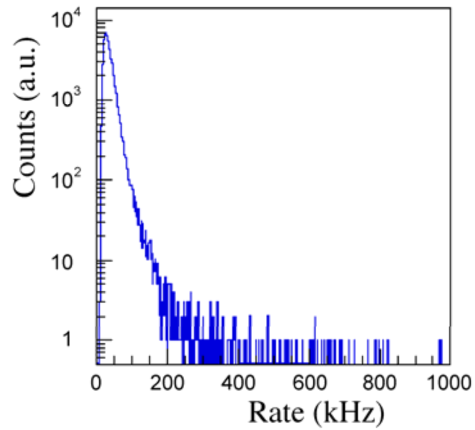
Example of background rates in Toulon with different bioluminescence contribution



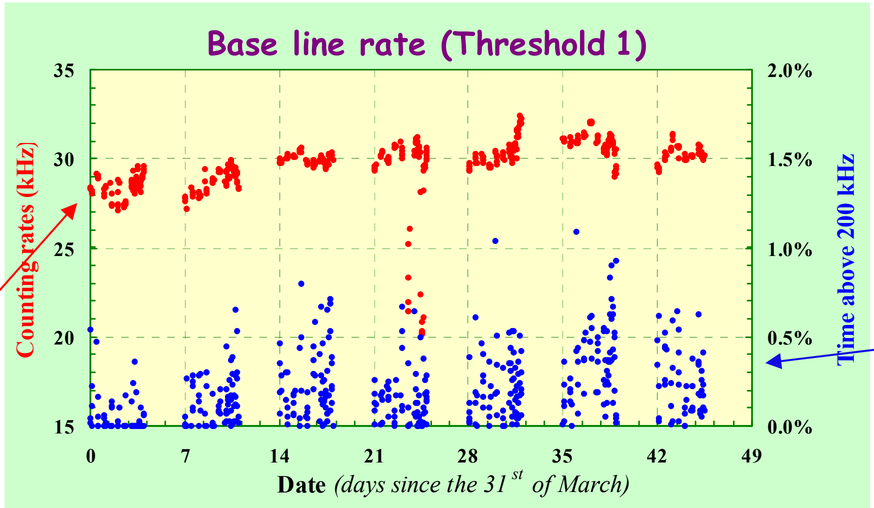
Optical background

Long period measurements in Capo Passero

NEMO setup (8" PMT) data



Noise on a 8" PMT
28.5 ± 2.5 kHz



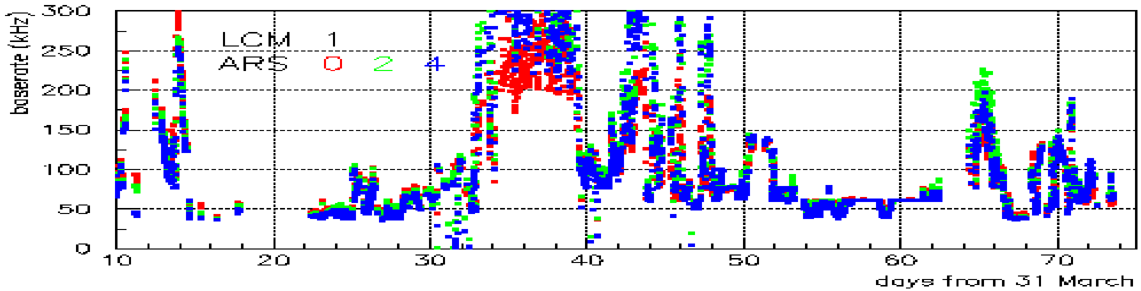
Baseline rate
28÷31 kHz

Burst fraction
- 0.2 %

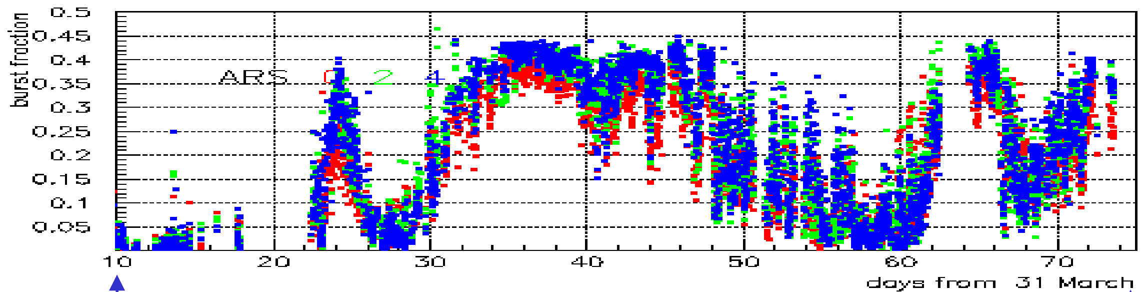
Data taken in spring 2003 (45 days) with the Antares setup

Counting rates from the ANTARES PSL

Baserate: median of rate in 15 min for 65 days



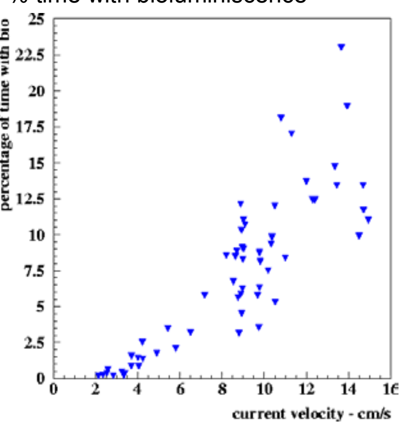
BurstFraction: fraction of time in 15 min in which rate >1.2xbaserate



April 10th

June 12th

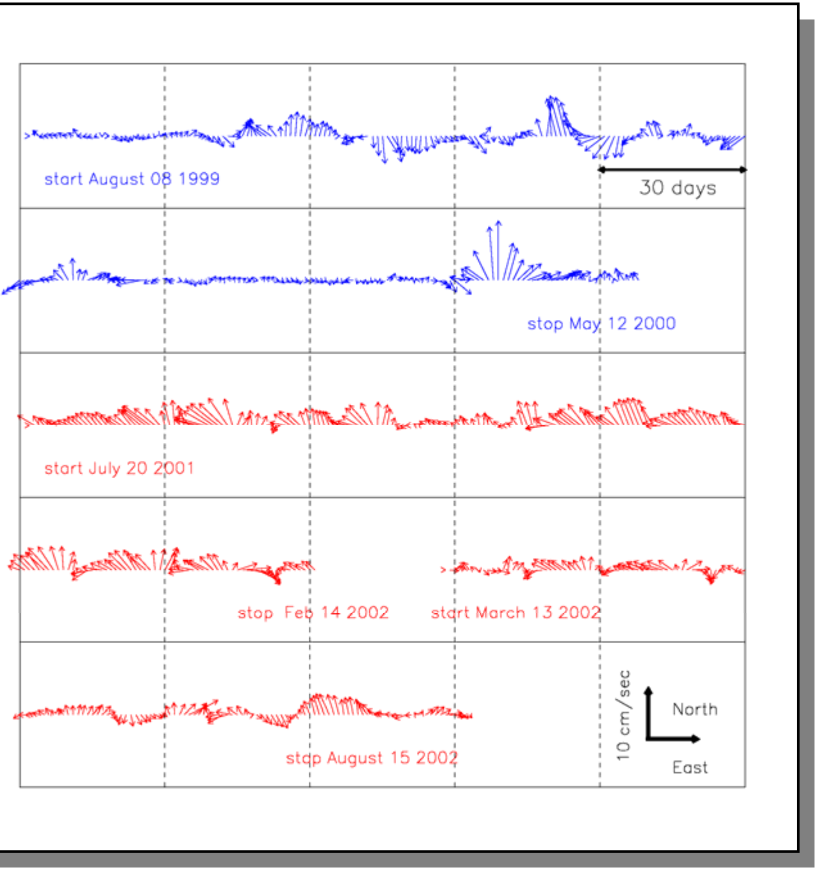
% time with bioluminiscence



The count monitoring showed large variations in the optical background rates.

- Sometimes bioluminescence bursts increase the baseline (mainly due to ^{40}K decays).
- Correlation between bioluminescence and current velocity has been measured.

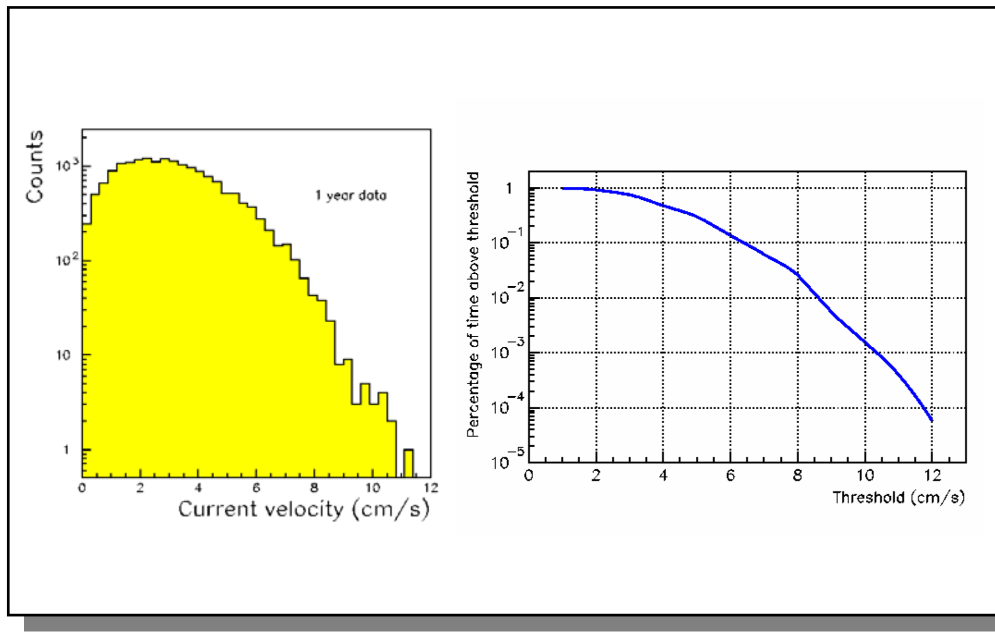
Deep sea currents



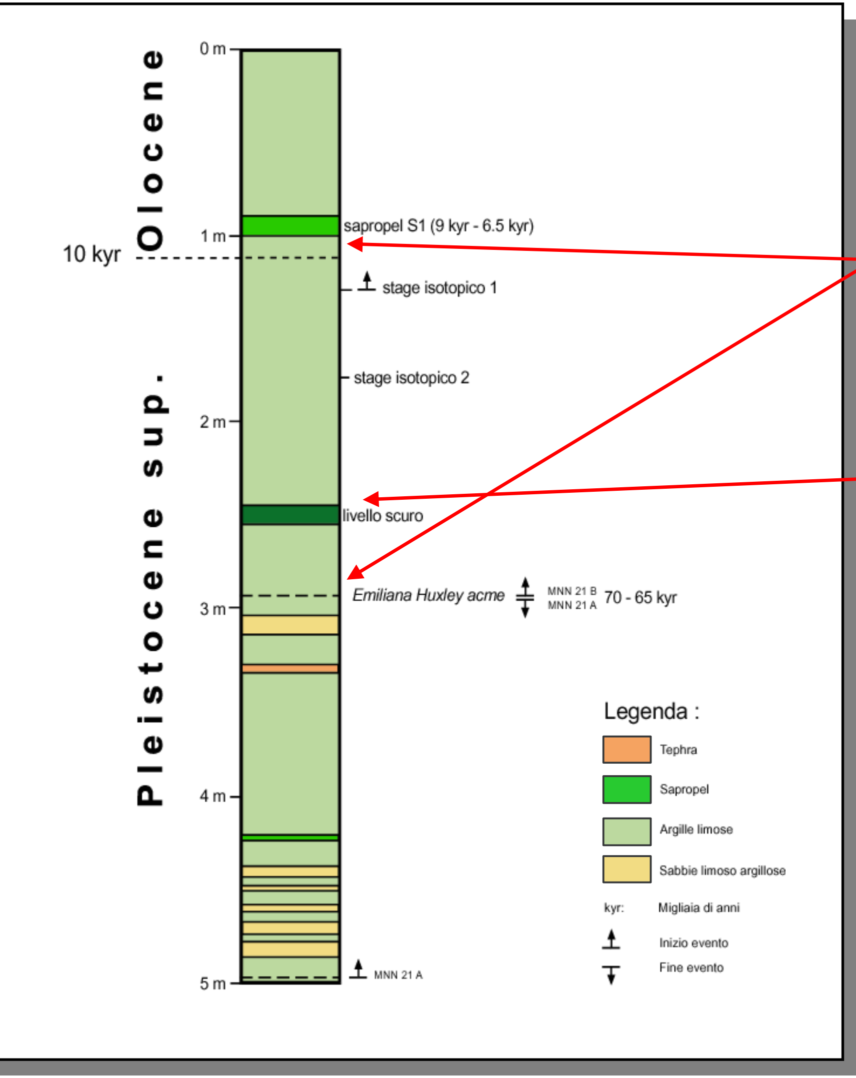
Currents have been continuosly monitored over more that four years

Average value measured is ≈ 3 cm/s

Intensities never exceed 12 cm/s

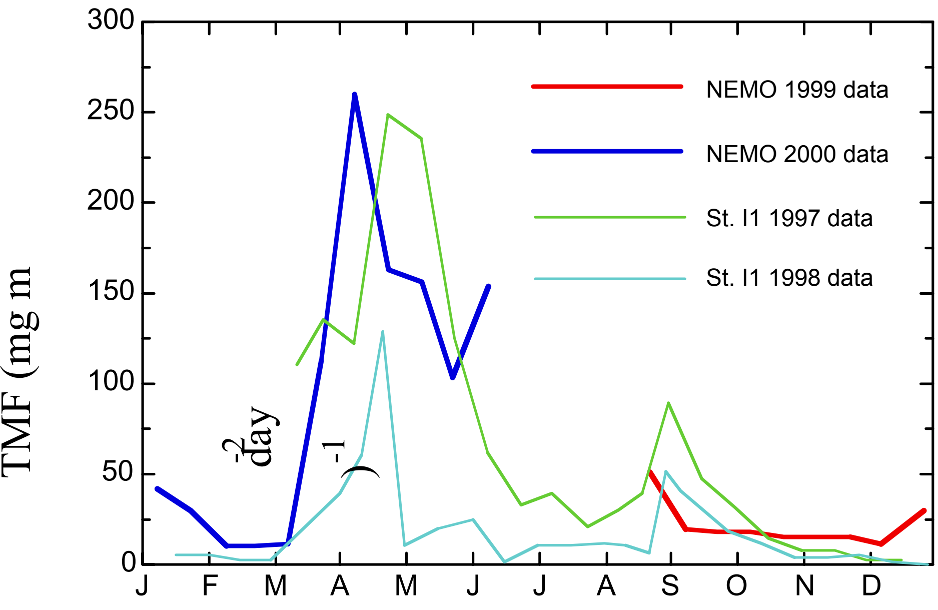


Seabed geology from core analysis



- All the collected cores show the same stratigraphy
- Some features, associated to well known geological events, allow for a dating of the cores
- Only one evidence of a turbidity event is present, but it can be dated at about 60 kyr BP
- The average sediment accumulation rate is estimated to be 3-4 cm/kyr

Downward sediment flux



Data analysed by Istituto di Biologia del Mare, CNR, Venezia

- Two series of collected data span an interval of about 1 year
- The mass flux is low (average of 62 mg m^{-2} d^{-1}), as expected in an oligotrophic enviroment such as the Ionian Sea, with an strong seasonal behaviour (spring bloom peak)
- Data are comparable to those measured in the Northern Ionian which show the same features
- Interannual variability can also occurr

The Capo Passero site

Site optical and oceanographical characteristics

- Absorption lengths (~70 m @440 nm) are compatible with optically pure sea water values
- Measured values are stable troughout the years *(important: variations on La and Lc will directly reflect in changes of the detector effective area)*
- Optical background is low (consistent with ^{40}K background with only rare occurrences of bioluminescence bursts)
- The site location is optimal (close to the coast, flat seabed, far from the shelf break and from canyons, far from important rivers)
- Measured currents are low and regular (2-3 cm/s average; 12 cm/s peak)
- Sedimentation rate is low (about 60 mg m^{-2} day^{-1})
- No evidence of turbidity events (from core analysis)

Feasibility study for the km3 detector

Aim: *demonstrate that an underwater Cherenkov detector with effective area of more than 1 km^2 is technically feasible and can be constructed with a "reasonable" budget*

Aspects that have been analysed in detail

- Mechanical structures
- Power distribution
- Front end electronics
- Data transmission to shore
- Cable network (submarine cables and connectors)
- Deployment of the structures and cables

The study shows that a km3 detector is presently technologically feasible

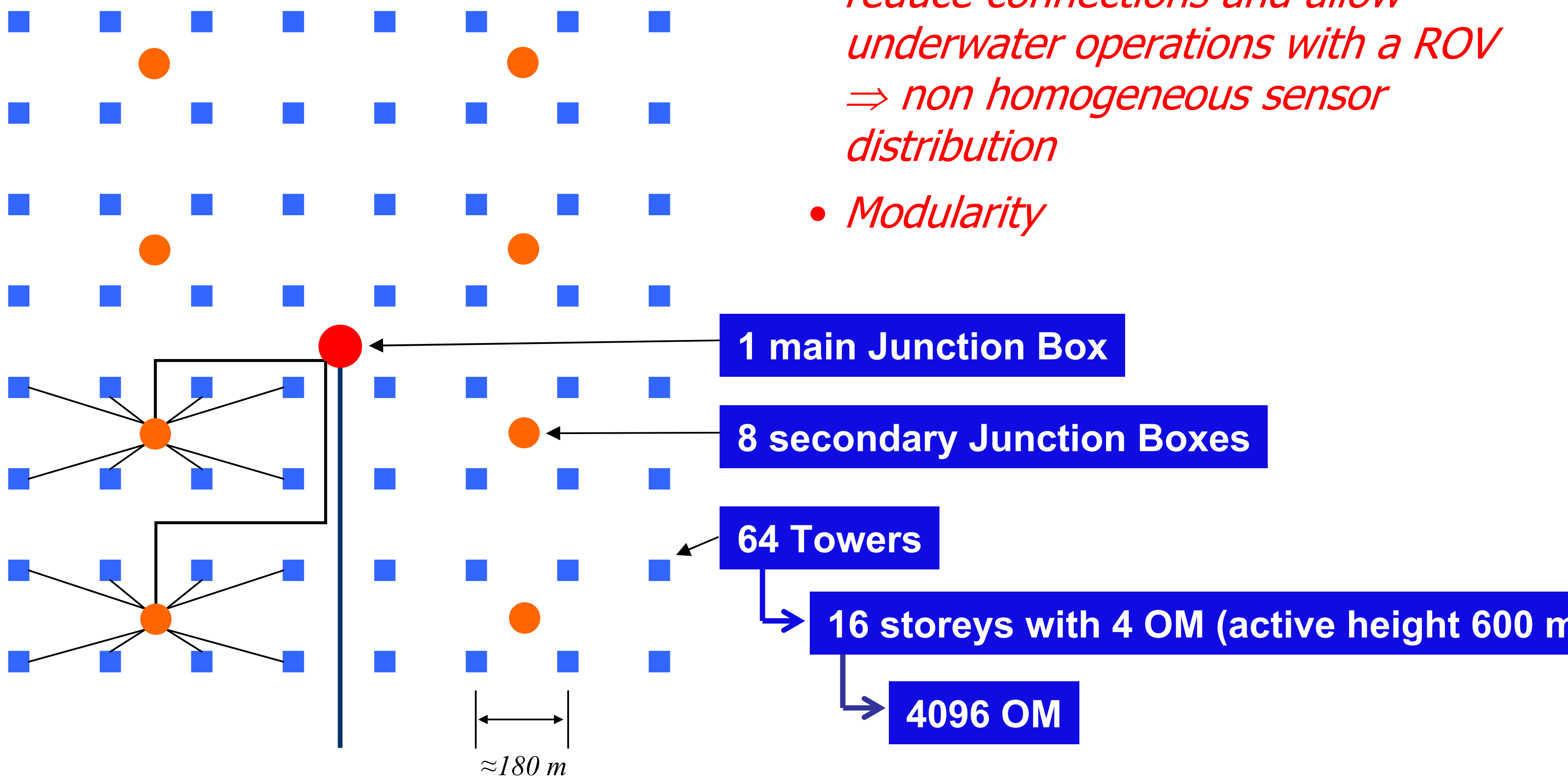
Preliminary project for a km^3 detector

Schematic detector layout

Detector architecture

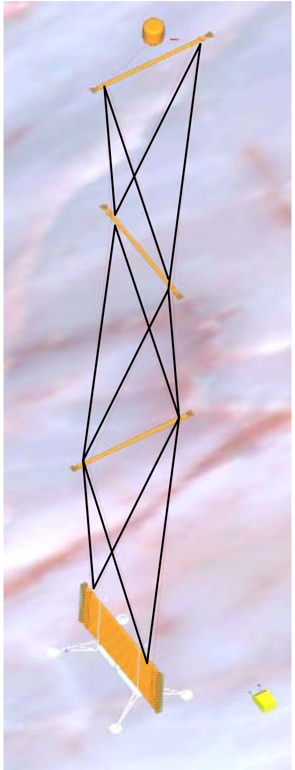
Reference layout used for the feasibility study

- *Reduce number of structures to reduce connections and allow underwater operations with a ROV $\Rightarrow$ non homogeneous sensor distribution*
- *Modularity*

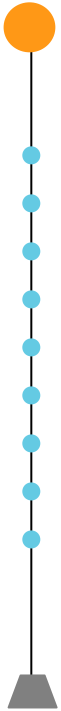


Total instrumented volume ≈1 km^3

Comparison of different km3 architectures



Simulations have been performed with the ANTARES simulation package



Tower architecture (5832 OM)

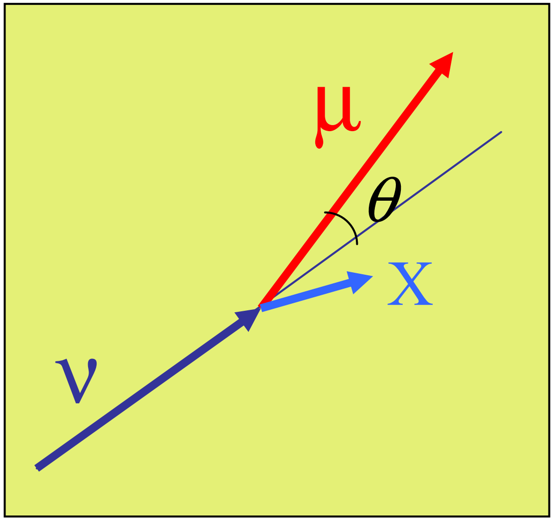
18 storey towers with 4 OM per storey
20 m storey length
40 m spacing between storeys
81 towers arranged in a 9x9 square lattice
140 m spacing between towers
≈ 0.9 km3 instrumented volume

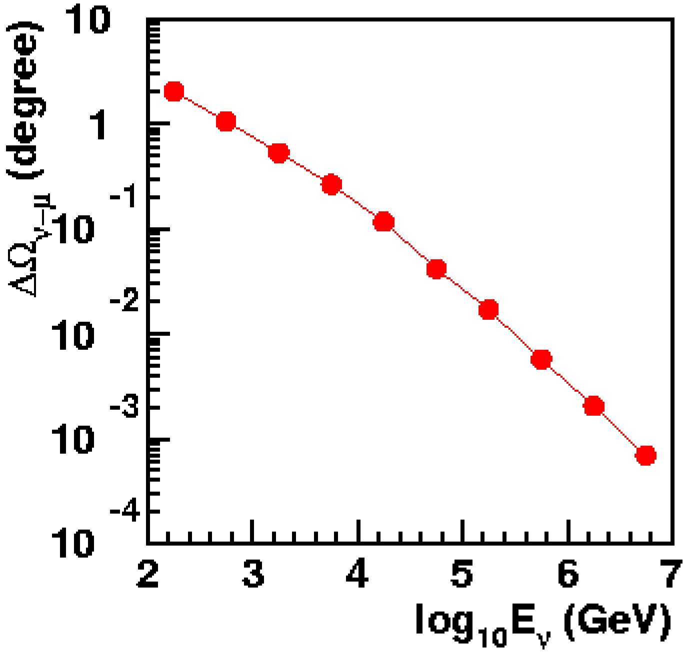
Lattice architecture (5600 OM)

Strings with 58 downlooking OM spaced by 16 m
100 strings arranged in a 10x10 lattice
125 m spacing between string
≈ 1.2 km3 instrumented volume

Angular resolution

$$\theta \leq \frac{1.5\,\mathrm{deg}}{\sqrt{E_\nu[\mathrm{TeV}]}}$$





Sensitivity for point-like sources

A effective area

T exposition time

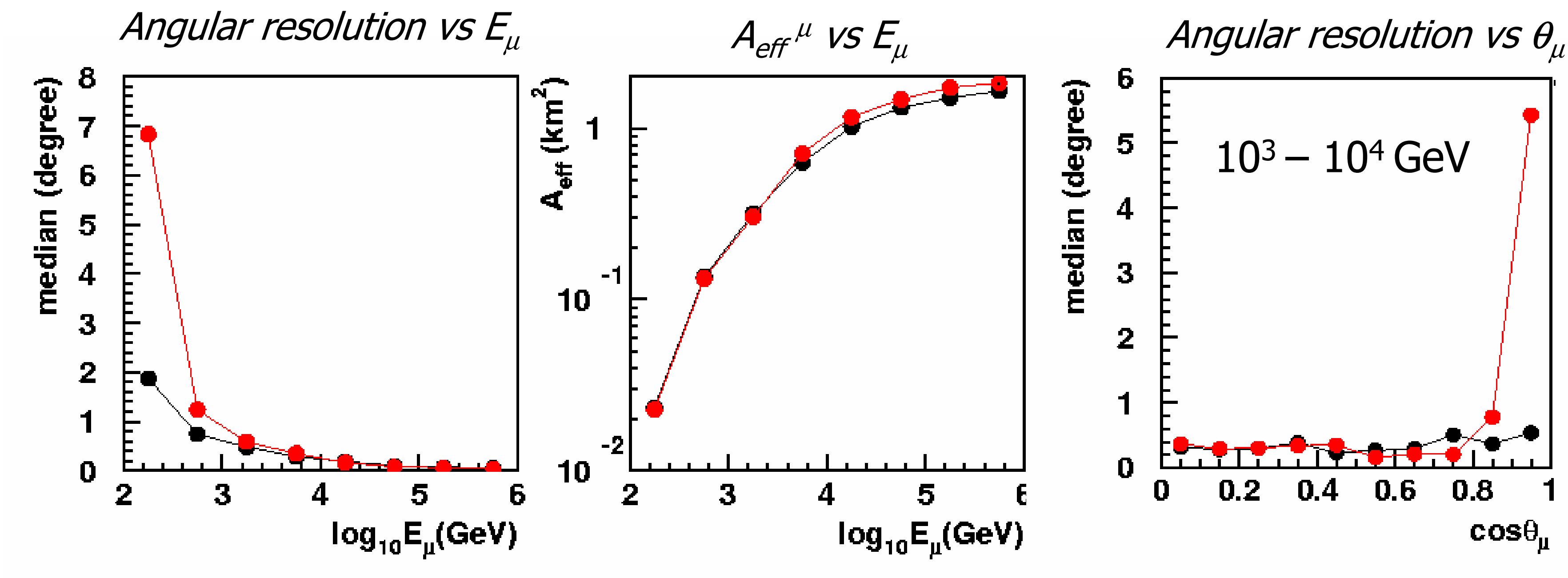
$\langle\theta\rangle$ angular resolution

$$sensitivity = \frac{signal}{\sqrt{signal + bckg}} = \frac{\phi_s AT}{\sqrt{\phi_s AT + \phi_b AT \langle\theta\rangle^2}} \propto \frac{\sqrt{AT}}{\langle\theta\rangle}$$

Comparison of string and tower geometries

- ✓ **Up-going muons with E^{-1} spectrum**
- ✓ **60 kHz background**
- ✓ **Reconstruction + Quality Cuts**

● **Nemo20m 140 (5832 OM)**
● **Lattice 125 16 (5600 OM)**



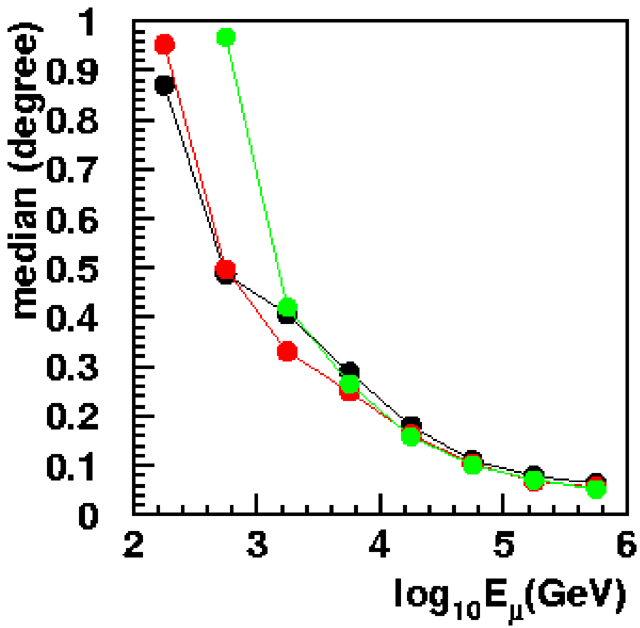
Comparison of different background rates

- Up-going muons with E^{-1} spectrum
- Tower architecture (5832 OM)
- Reconstruction + Quality Cuts

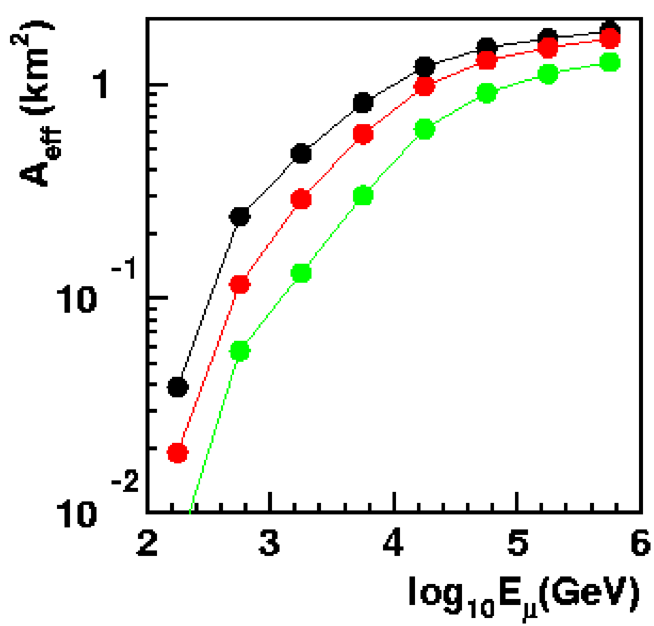
Optical background rate

- 20 kHz
- 60 kHz
- 120 kHz

Angular resolution vs E_μ



A_{eff}^μ vs E_μ



Sensitivity to point like sources

- Simulation of the km3 response to high energy neutrino fluxes from microquasars
- Simulation of background
  - *Atmospheric muon background*
  - *Atmospheric neutrino background*
- Background rejection
- Detector angular resolution

Atmospheric muon background rejection

No QC

N_μ=41117

isreconstructed uons in equatorial oordinates

QC> –10

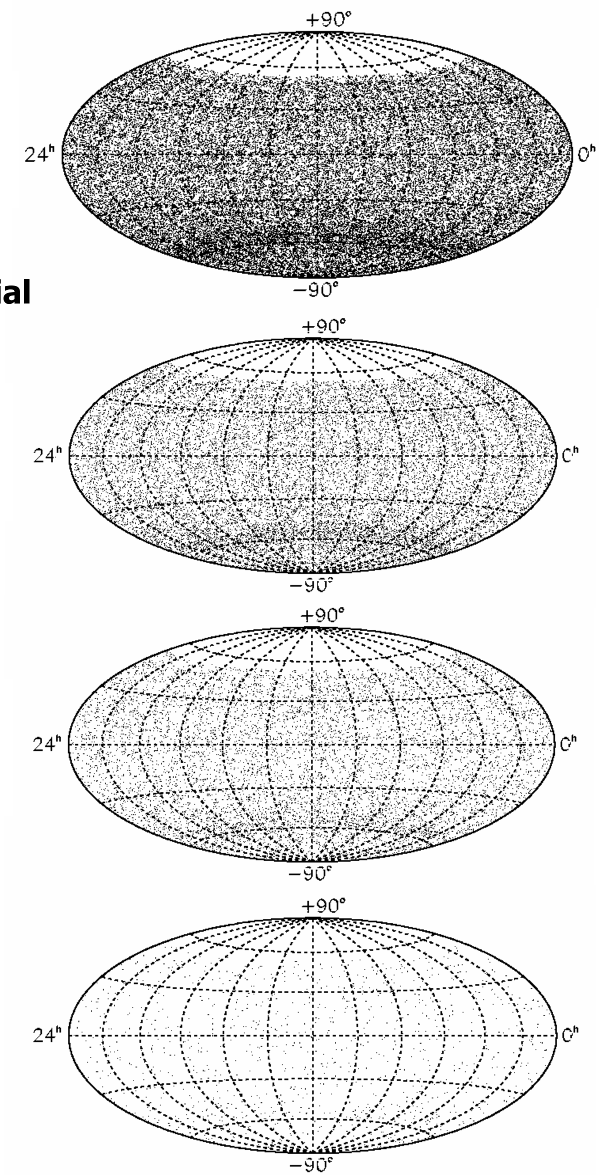
N_μ=20761

QC> –9

N_μ=11011

QC> –8

N_μ=1374



$1.8 \cdot 10^7$ downgoing muons simulated (Okada parameterization)

$1.1 \cdot 10^6$ reconstructed (using Antares code)

Rejection with quality cuts

The value of the logarithm of the likelihood function, at the fitted maximum, divided by the number of degrees of freedom:

$$QC = \log(L)/NDOF$$

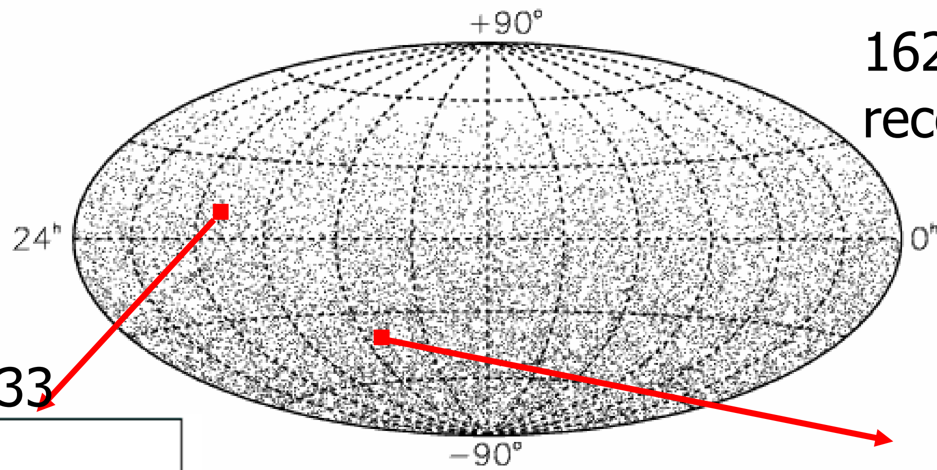
is used as a *goodness of fit criterion*.

Selection cuts increase the angular resolution but decrease effective area.

Sensitivity to point-like sources

Source and atmospheric neutrino background

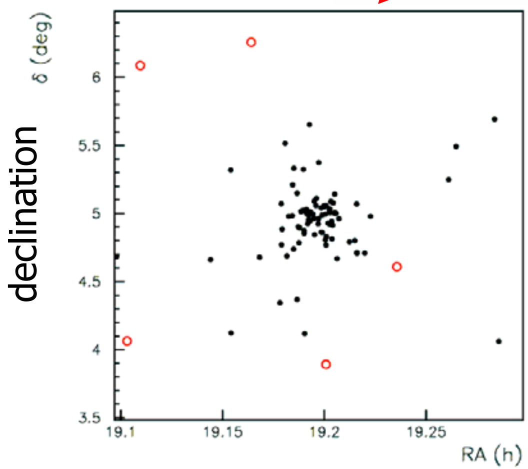
Equatorial coordinates



16204 atm. ν_μ event
reconstructed in 1 yea

Simulated spectrum from Learned & Mannaheim, 2000

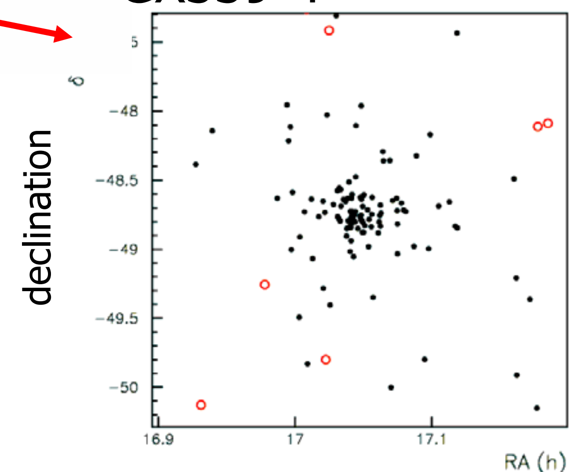
SS433



right ascension

Simulated microquasars spectrum from Distefano et al., 2002

GX339-4



right ascension

in the 3°x3° bin= 84+5

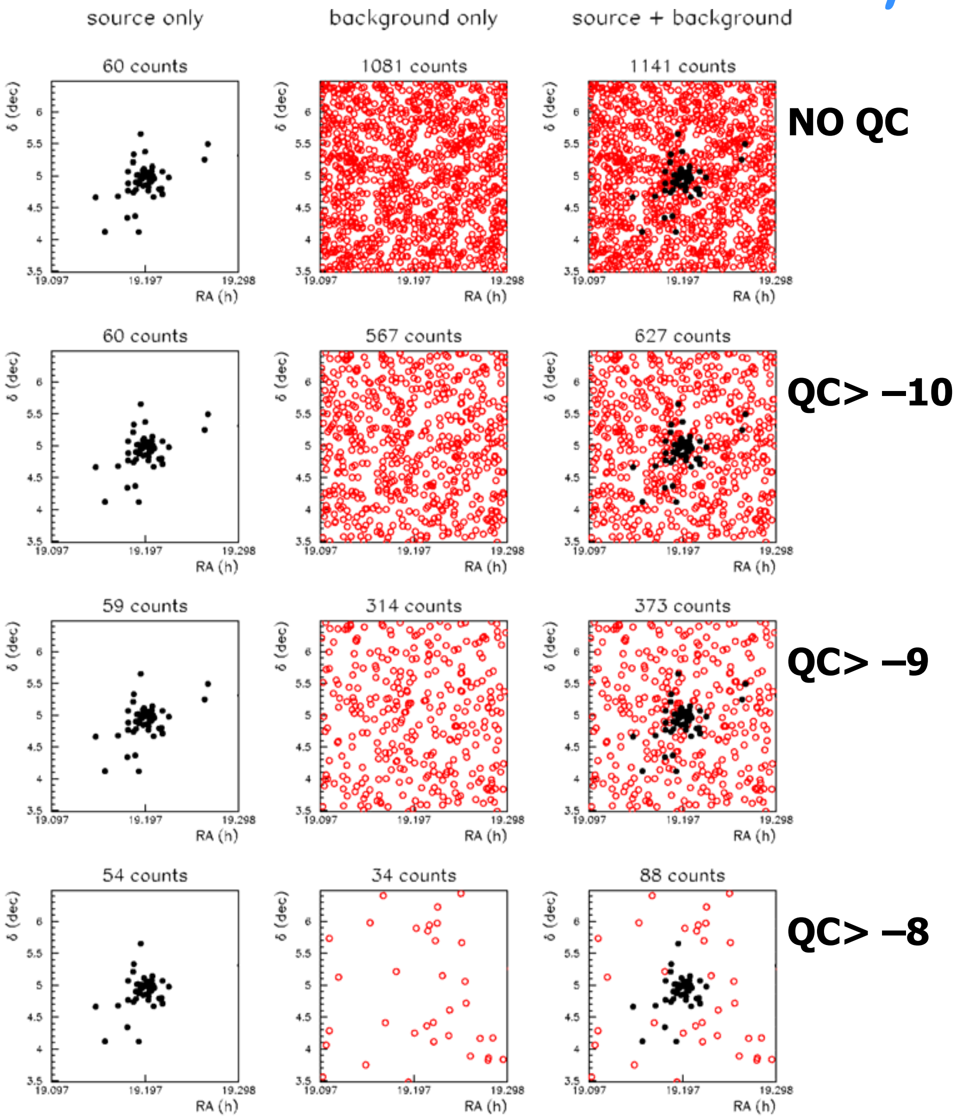
circular (r=1°) bin= 79+1

in the 3°x3° bin= 106+6

circular (r=1°) bin= 97+0

Sensitivity to point-like sources

The case of the SS433 microquasar



250 days time integration

counts 1° radius circular bin around the source

source	bkg	source+bkg	cut level
58	354	412	NO QC
58	195	253	QC –10
57	115	172	QC –9
53	15	68	QC –8

At QC > -8:

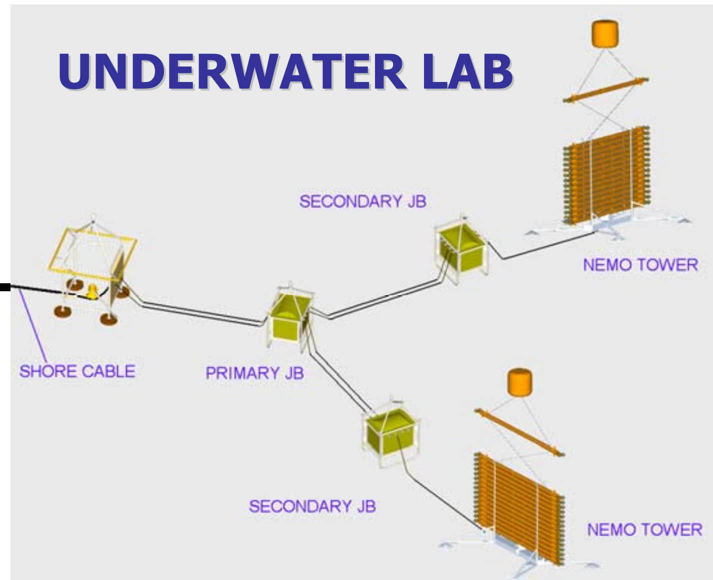
$$\frac{source}{\sqrt{source + bkg}} = \frac{53}{\sqrt{68}} = 6.4$$

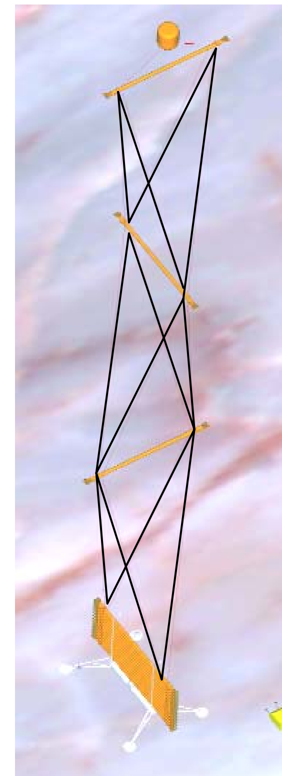
Background is the sum of atmospheric μ and ν

The NEMO Phase 1 project

A step towards the km3 detector

Realization of a detector subsystem including all critical components





EO CABLE

Length – 25 km
10 Optical Fibres ITU- T G-652
6 Electrical Conductors Φ 4 mm^2

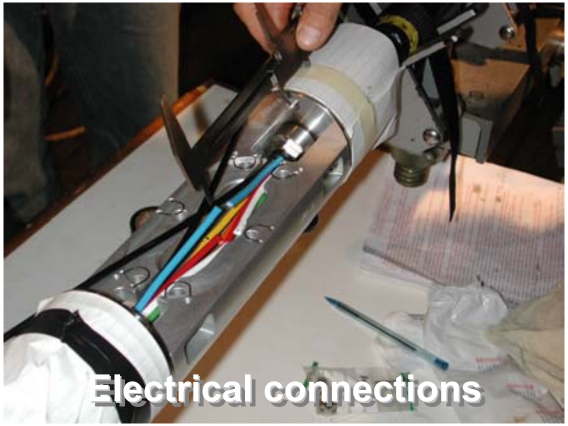
Project jointly funded by INFN and MIUR
Completion foreseen in 2006

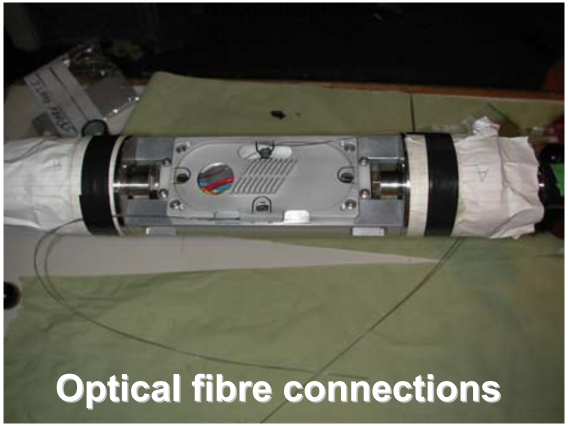
The LNS Test Site

Deployment of the electro-optical cable

Cable deployed in september 2001


Deployment of the branching unit

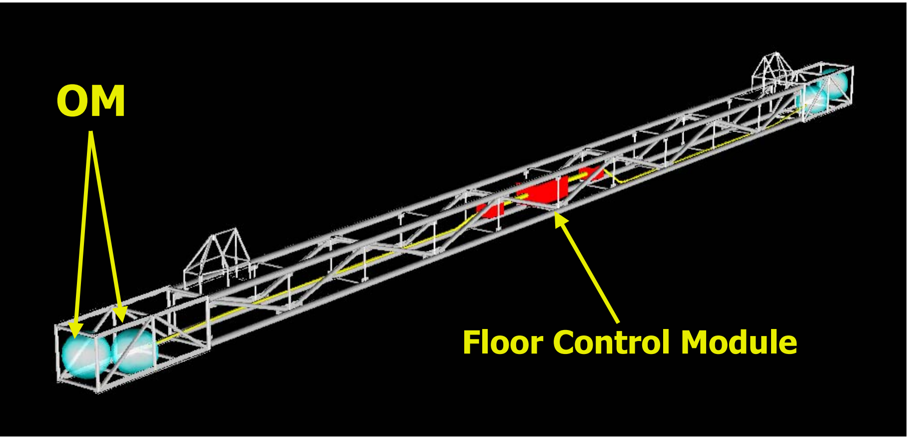

Electrical connections

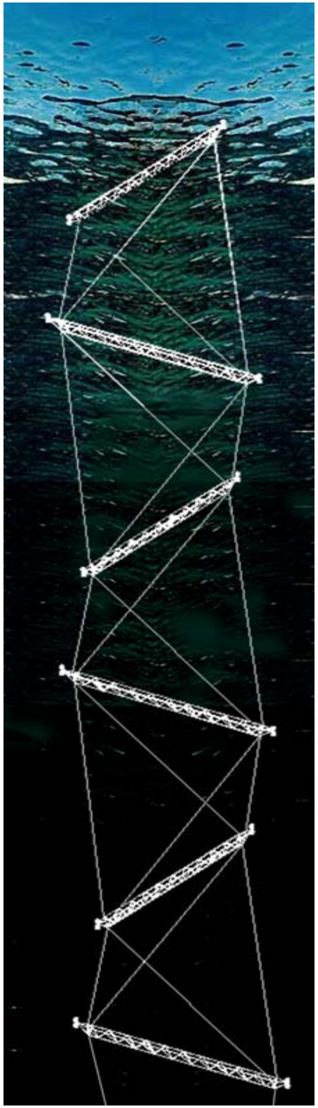

Optical fibre connections

The NEMO tower

"Tower" structure

Semi rigid structure
Tensioning and electro-optical cables are kept separated
The structure can be packed for transportation and deployment



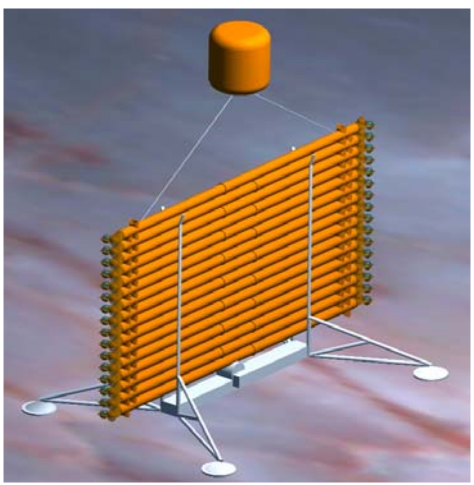


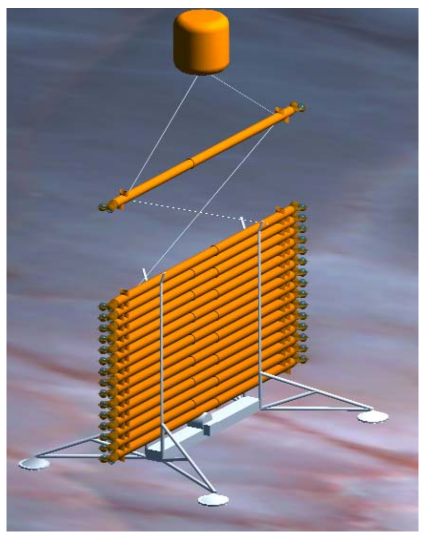
16 storeys spaced by 40 m
4 OM per storey
64 OM per tower
600 m active length

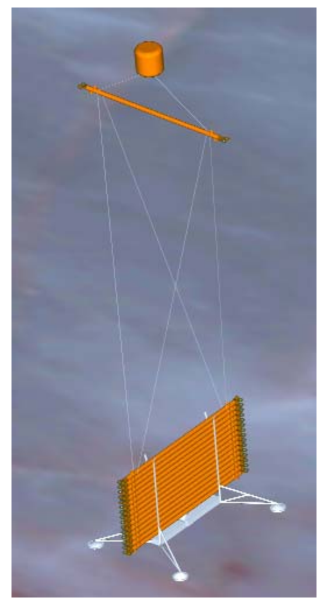
The NEMO tower

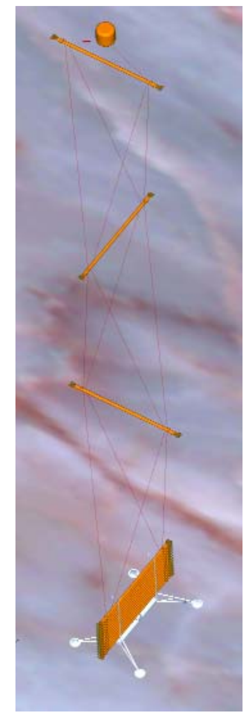
Deployment of the tower

Tested in shallow waters with a 1:5 scale model of the tower





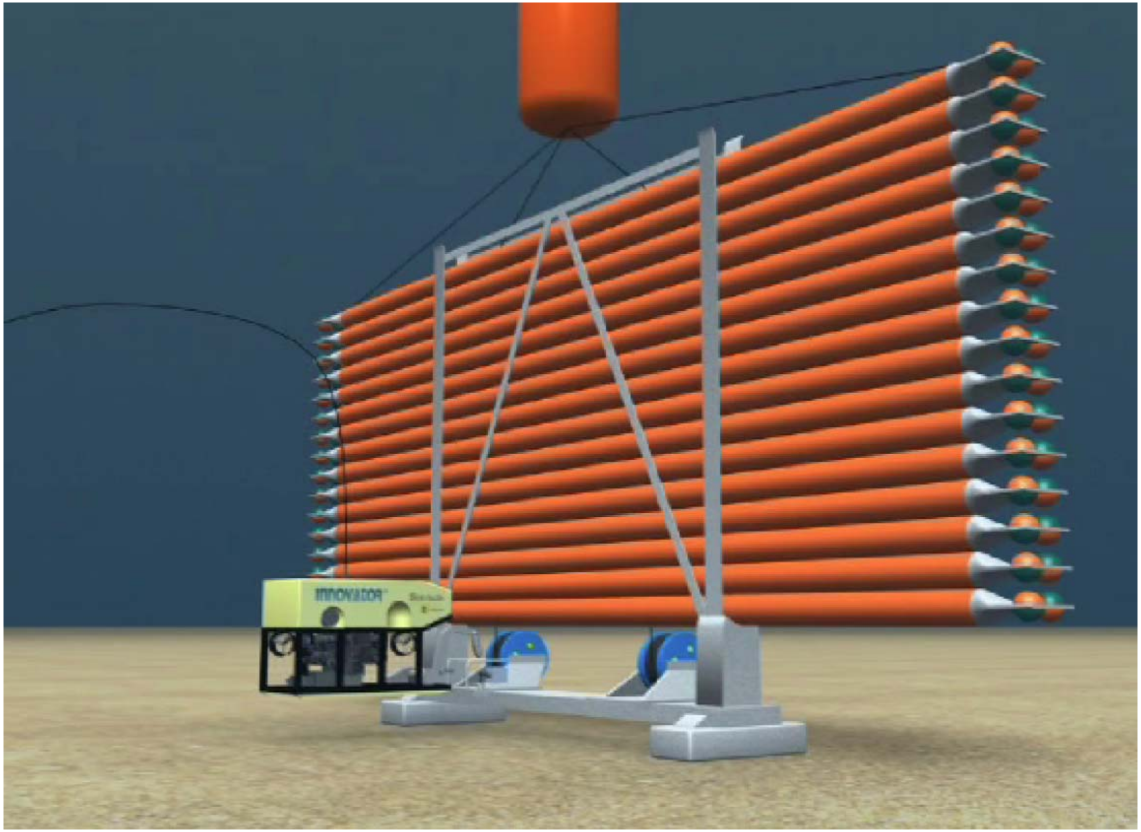




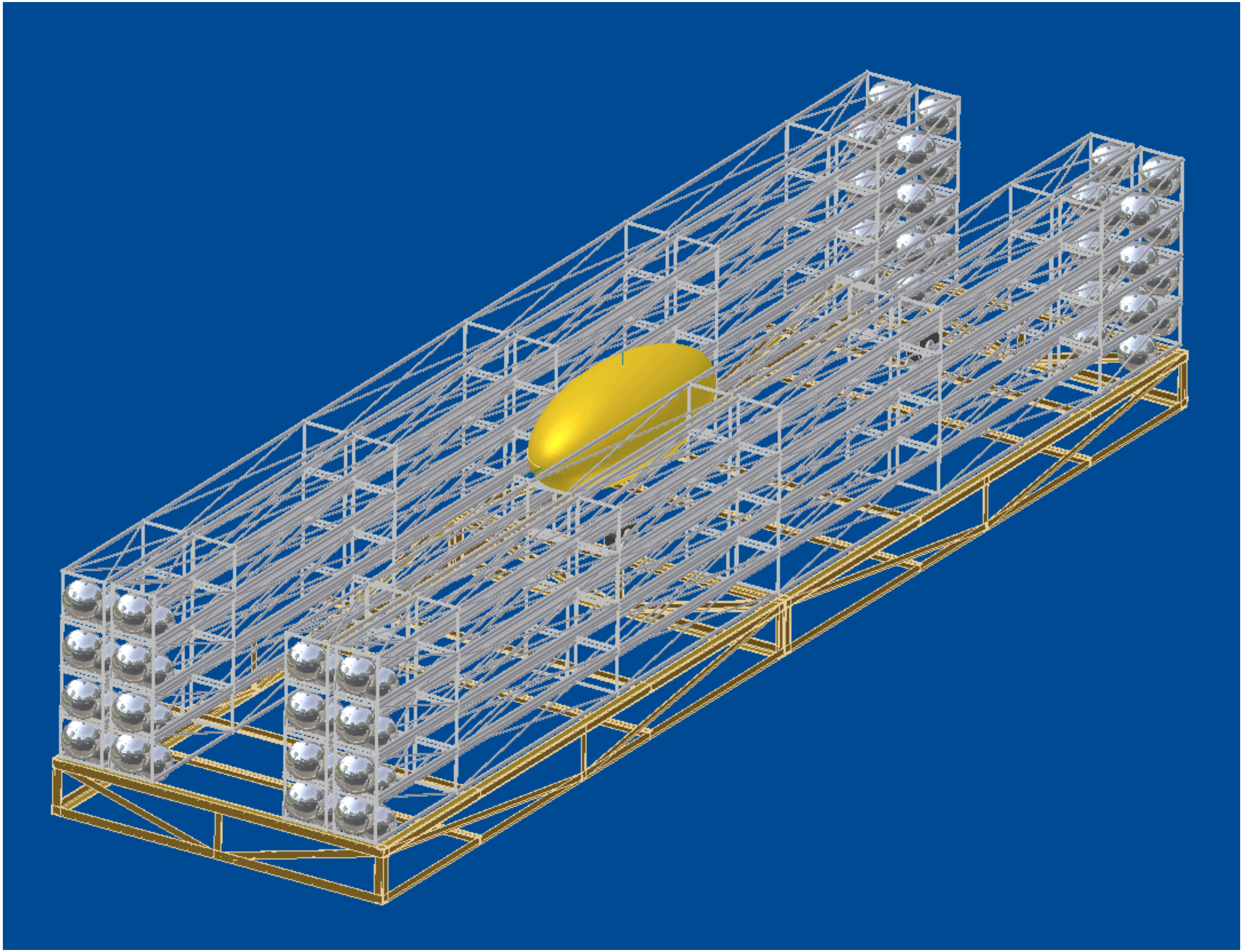
Deployment and submarine operations

Deployment will be performed by double positioning surface vessels

Unfurling of the tower and connections will be performed by means of submarine Remoted Operated Vehicles (ROV)



The NEMO tower

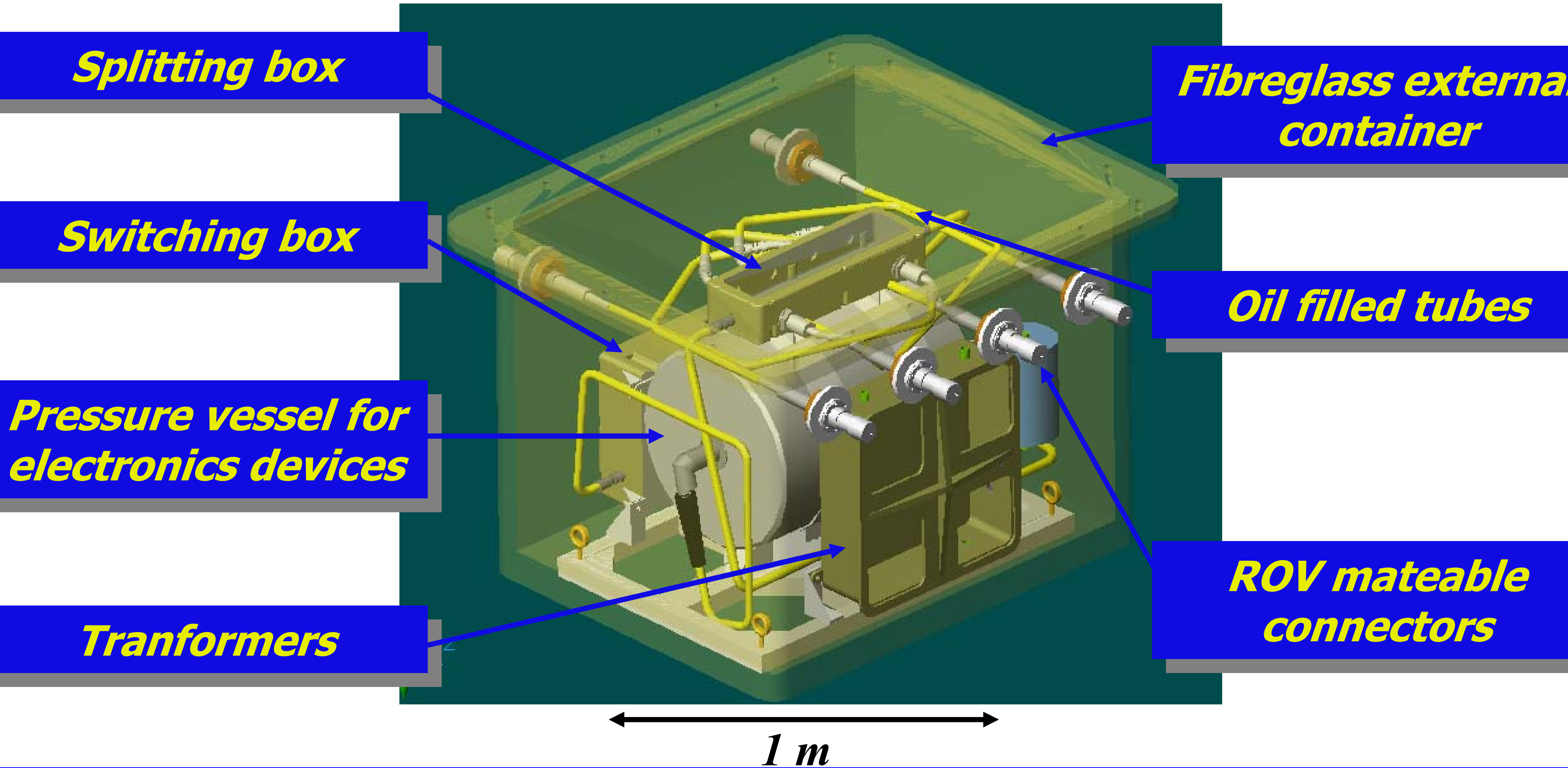


Junction Boxes

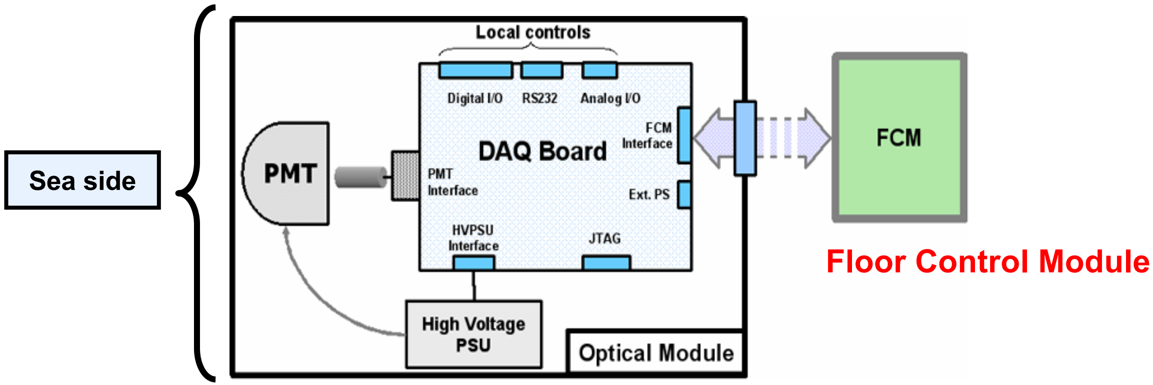
Alternative design to the Titanium container (Antares-like)

Aim

Decouple the two problems of pressure and corrosion resistance



Optical module electronics

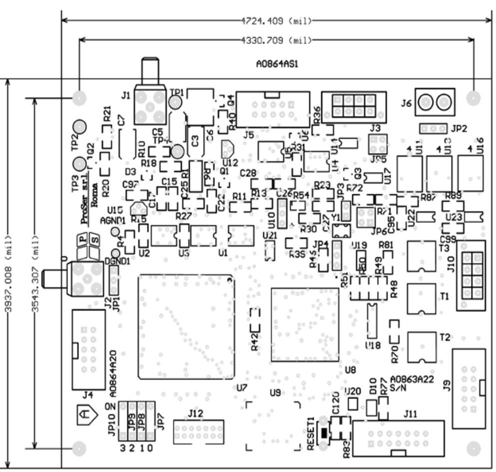


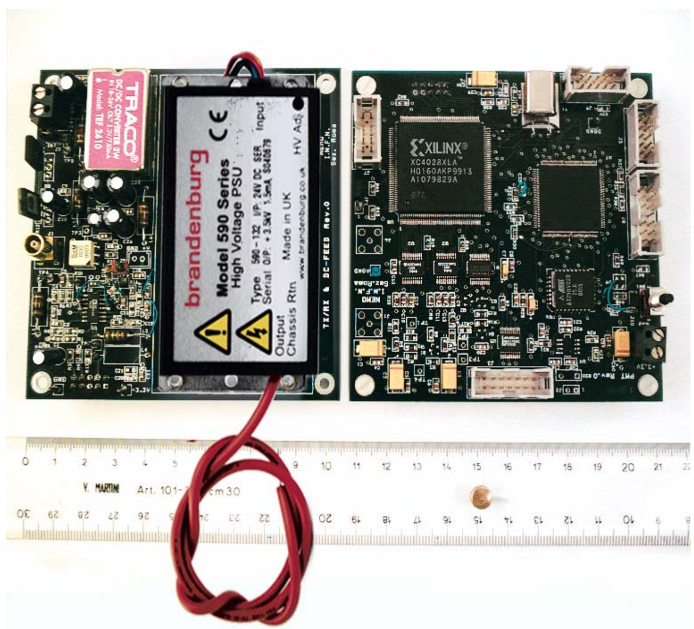
Data Acquisition:

- **200Msample/s**
- **8bit** (logarithmic compression)
- User programmable **digital threshold** level

On-board sensors:

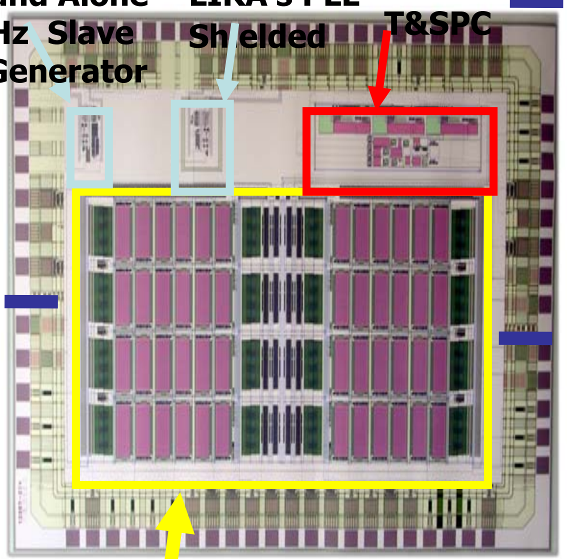
- Temperature
- Humidity

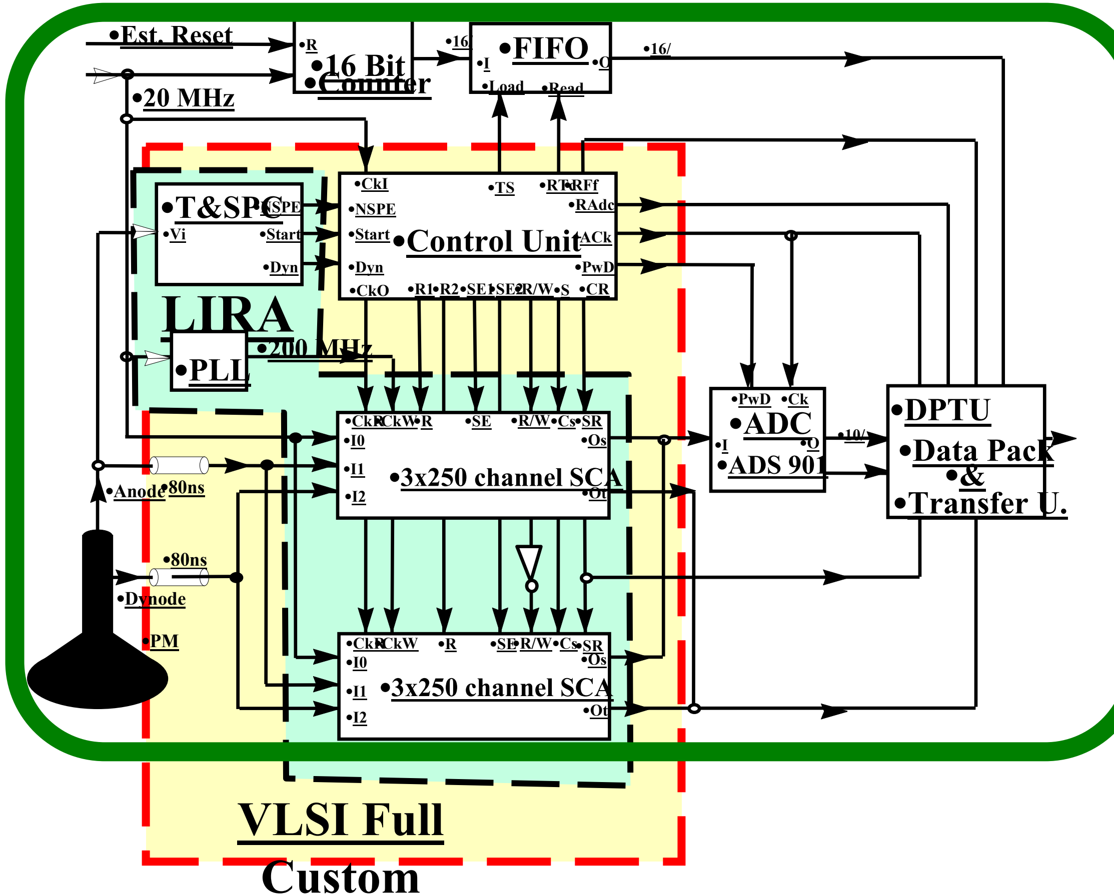




New low power electronics for the OM

- Sampl .Freq.: 200MHz
- Trigger level remote controlled;
- Max Power dissipation less than 200 mW
- Input dynamic range 10 bit
- Dead time < 0.1%.
- Time resolution < 1 ns





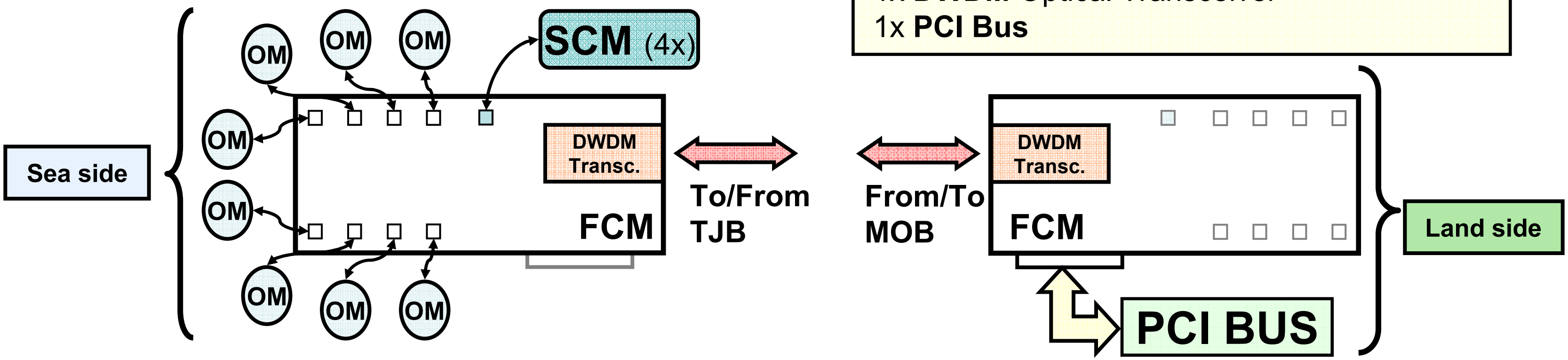
New full custom VLSI ASIC

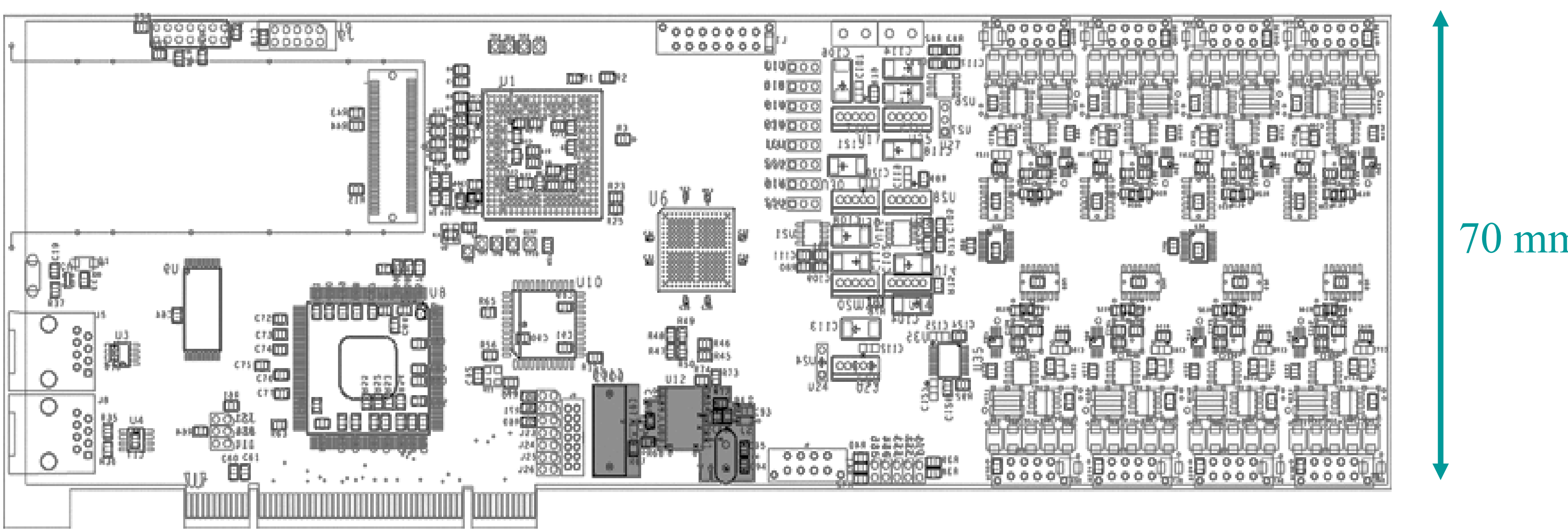
Presently under final laboratory testing

Will be tested in some optical modules in Phase 1

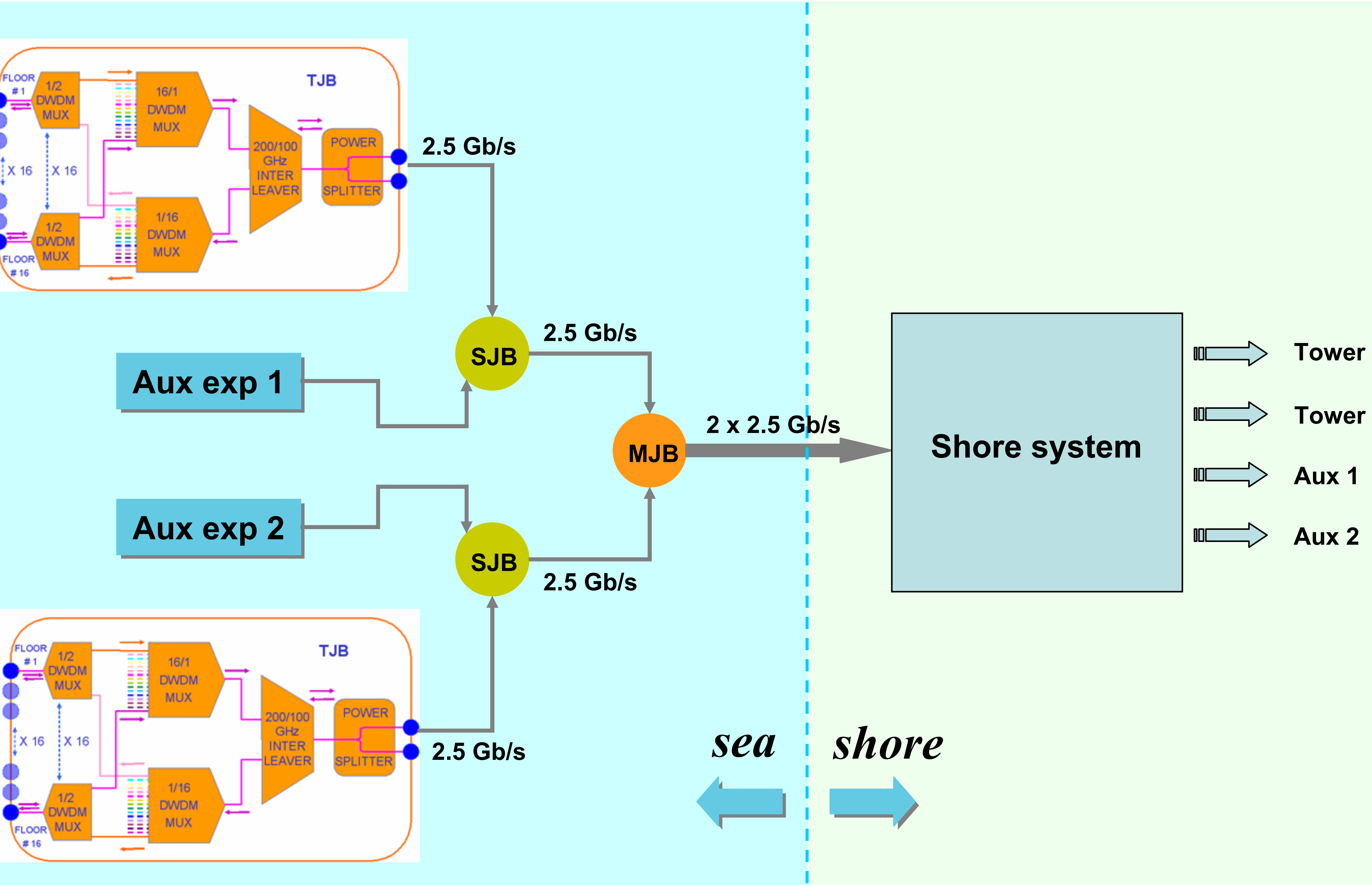
Floor electronics

MAIN INTERFACES
8x **O**ptical **M**odule (LVDS)
4x **S**low **C**ontrol **M**odule (SPI bus)
1x **DWDM** Optical Transceiver
1x **PCI Bus**

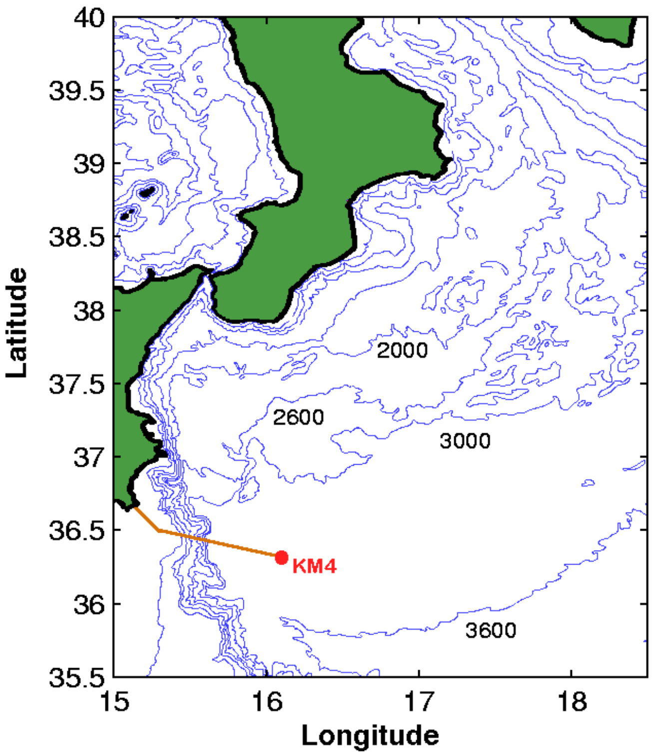




Data transmission system



Phase 2 project

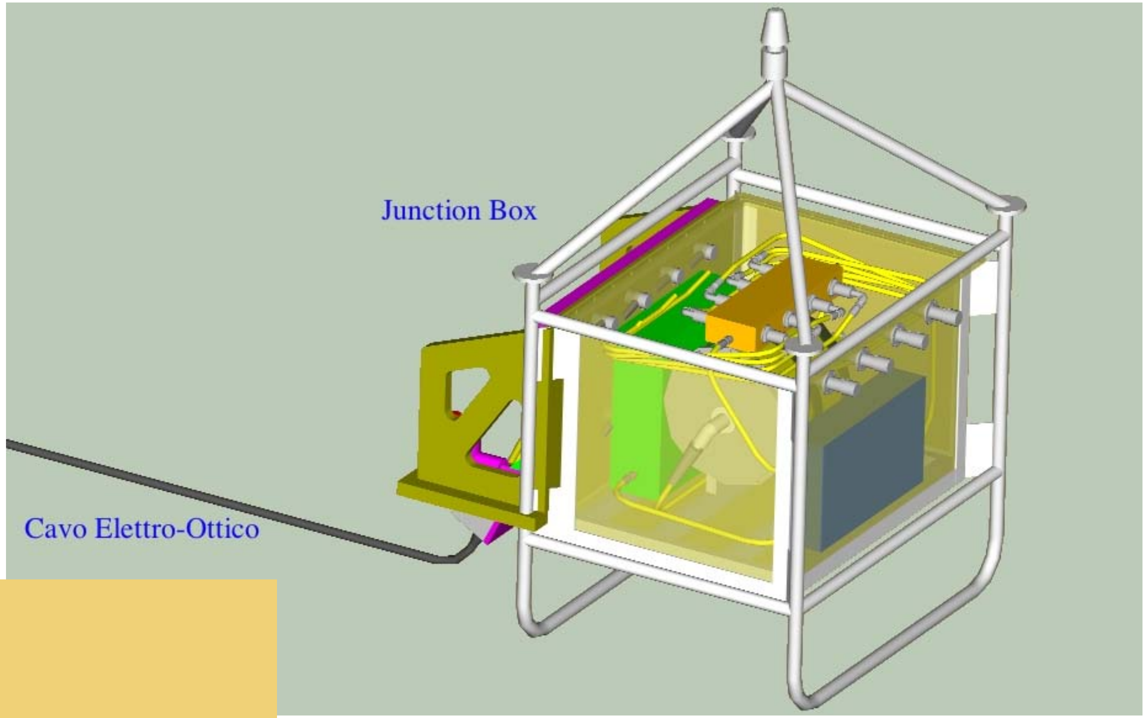


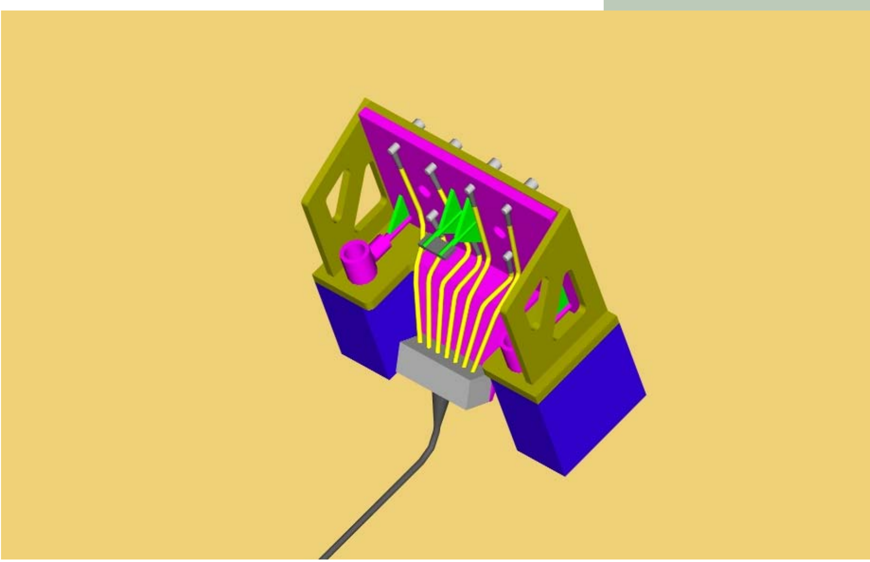
INFRASTRUTTURA PROPOSTA

- Stazione di terra a Portopalo di Capo Passero per l'alimentazione degli apparati sottomarini, acquisizione dati e montaggio degli apparati
- Cavo elettro-ottico di circa 100 km
- Struttura sottomarina composta da una Junction Box, dal sistema di connessione tra cavo elettro-ottico principale e JB e da una docking station per AUV/ROV

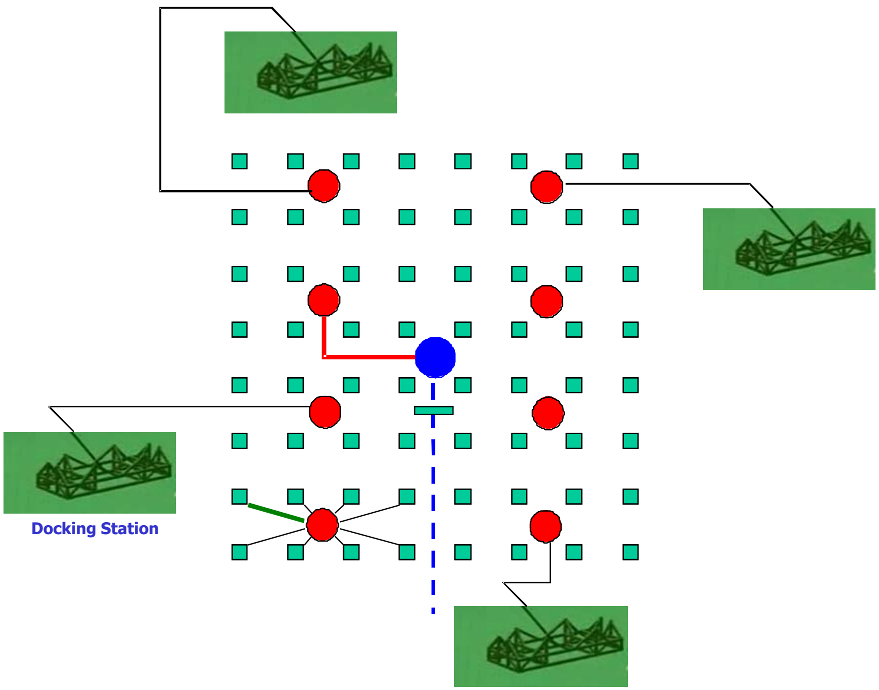
Capo Passero

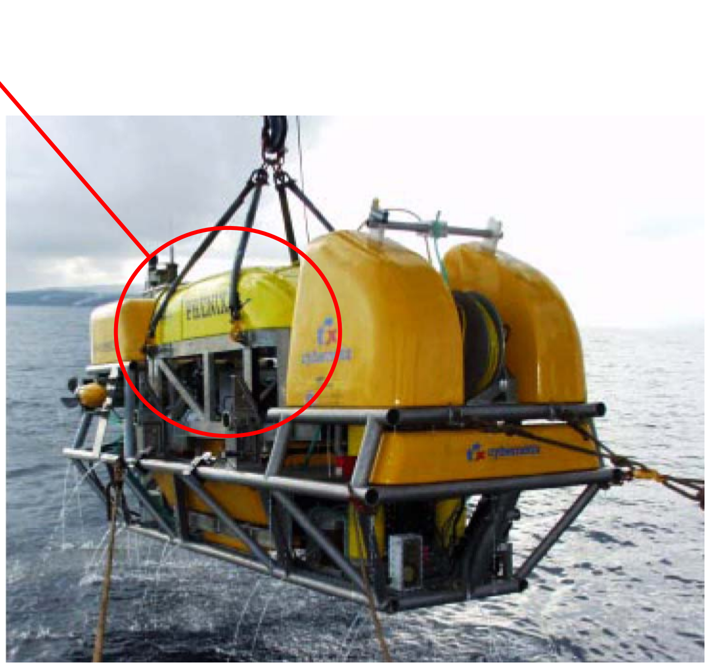
Connessione cavo EO - Junction Box





Test di sistemi ibridi AUV/ROV





Conclusions

- A km3 detector is needed to open the neutrino astronomy field
- The NEMO collaboration has carried out an advanced R&D activity towards the realization of the km3
- Studies of the Capo Passero site have shown that it is an excellent location for the km3
- A feasibility study has analysed in detail all the km3 components
- A Phase 1 project, aiming at the realization of a subset of the detector including all the critical components, is currently in realization; completion is foreseen for 2006
- Future plans:
  - *Completion of R&D activities*
  - *Design study for the km3 (KM3NeT)*
  - *NEMO Phase 2*
  - *Construction of the km3 within a large international collaboration*