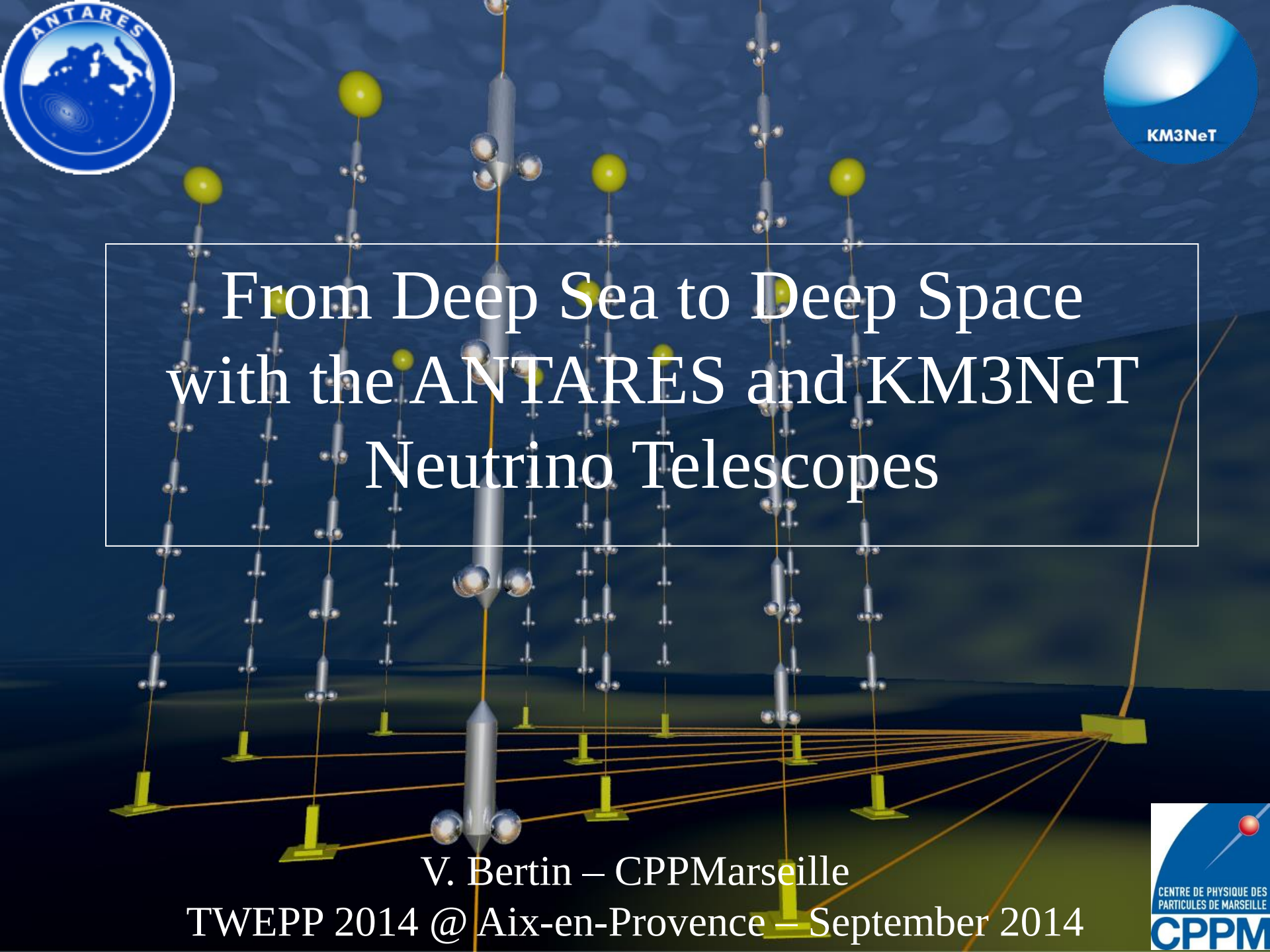
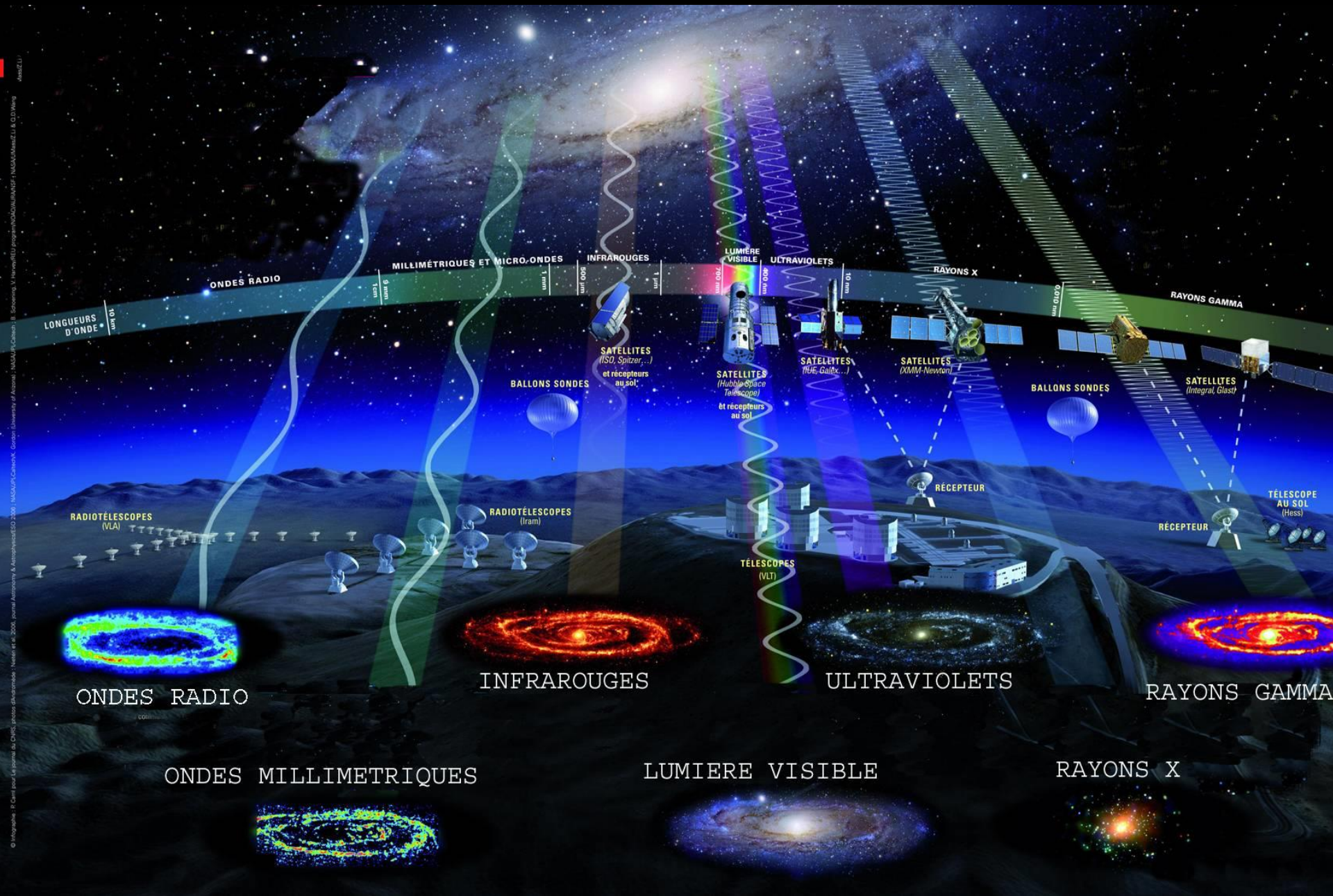


From Deep Sea to Deep Space with the ANTARES and KM3NeT Neutrino Telescopes

V. Bertin – CPPMarseille

TWEPP 2014 @ Aix-en-Provence – September 2014

Multi-Wavelengths Astronomy



Cosmic Rays

Interactions of cosmic rays in the high atmosphere produce showers of particles

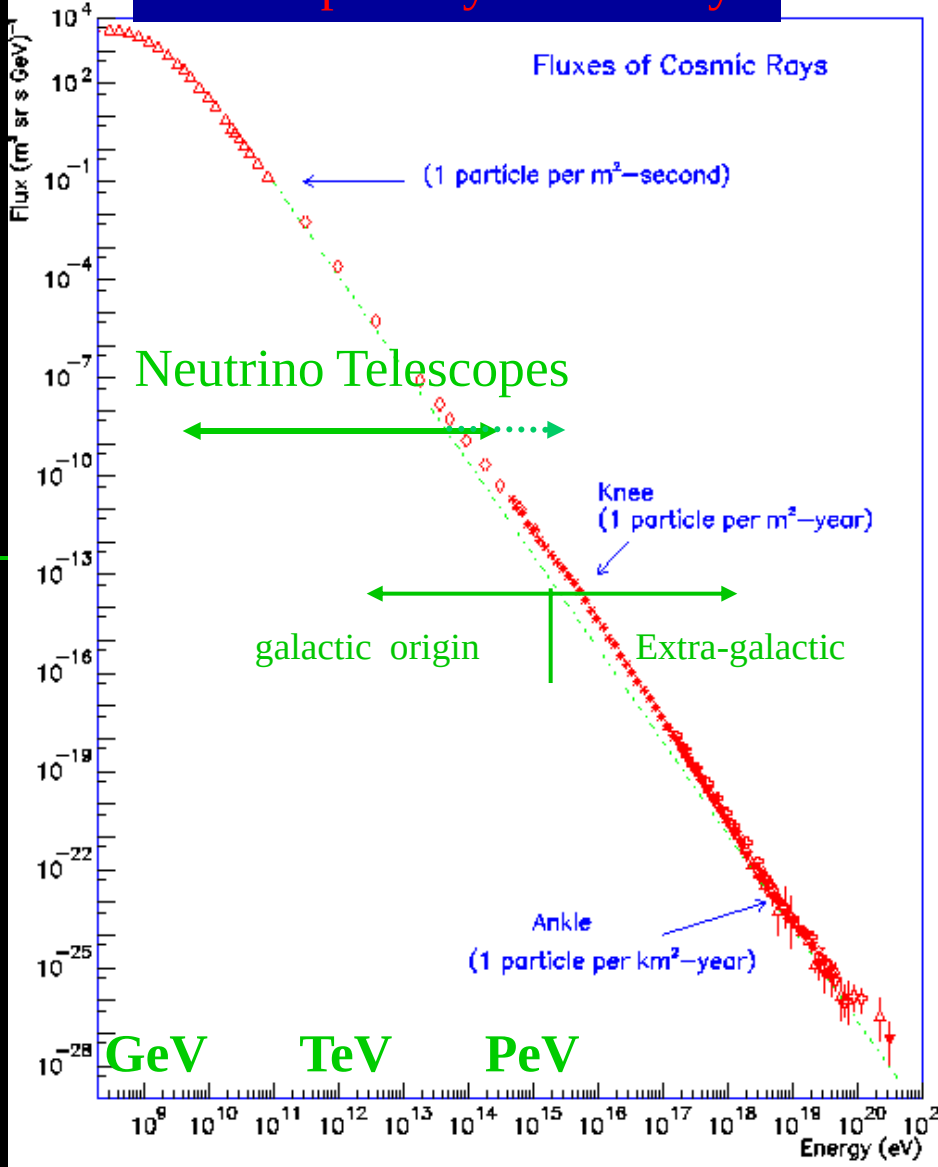
Charged particles
- protons
- ions
- electrons

Neutral particles
- photons
- **neutrinos**

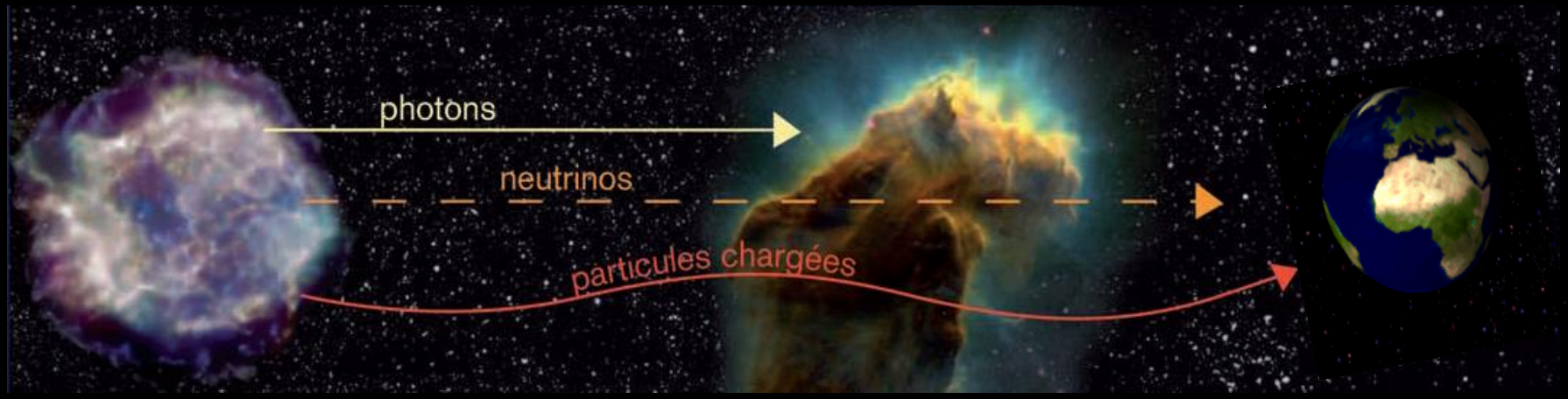
At ground level :**100 per minute and per m²**

100 years after their discovery, the origin of cosmic rays is still very unclear

Flux of primary cosmic rays



Why looking for neutrinos?



Avantages of neutrinos :

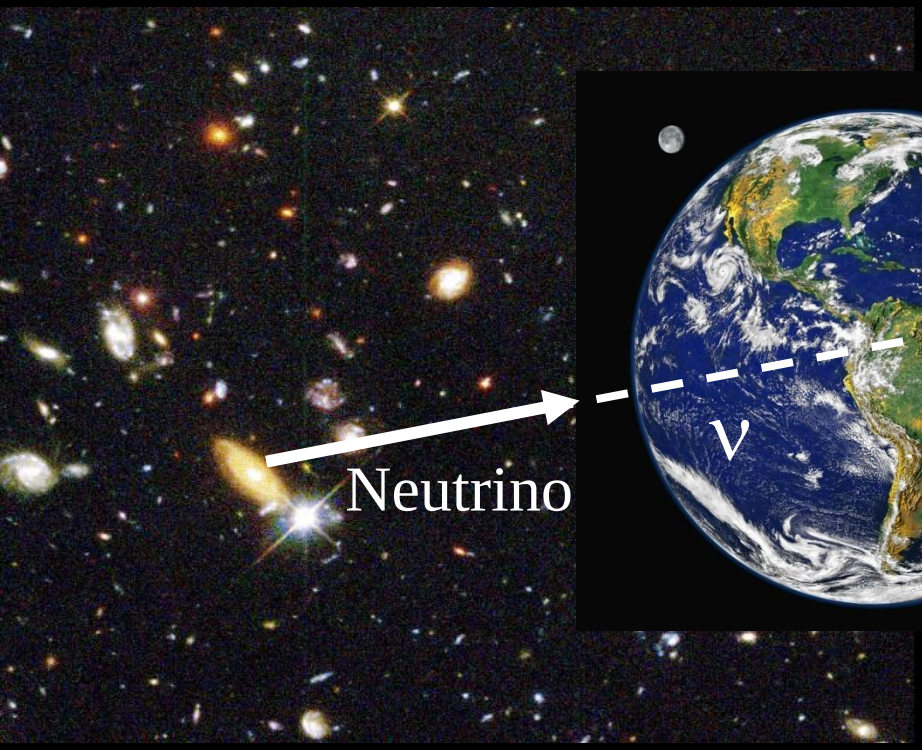
- Electrically neutrals, not deviated by magnetic fields ➔ astronomy
- No absorption ➔ observation over cosmological distances
- Very weakly interacting ➔ escape from dense regions of the 'Universe

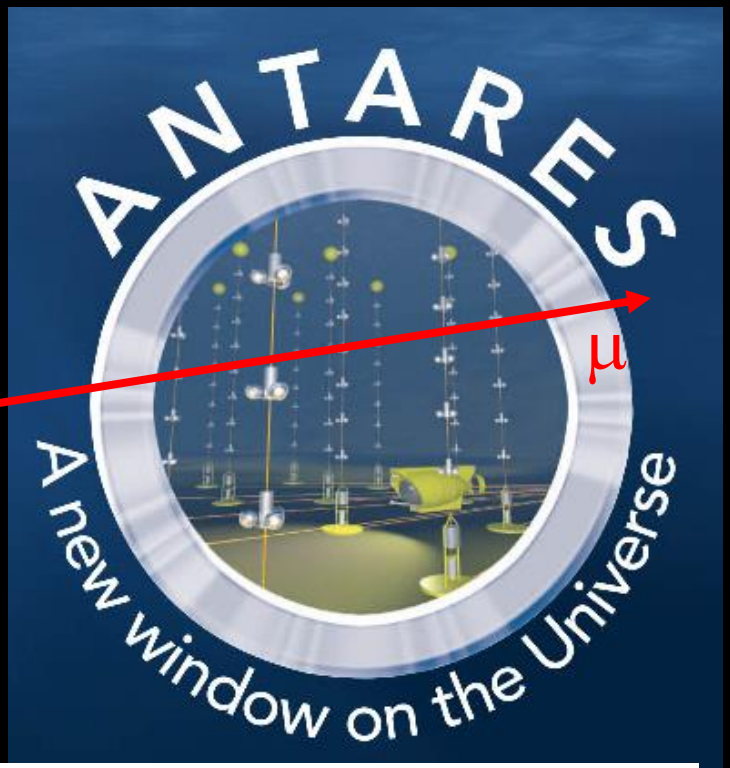
Cons :

Over 10 billions of neutrinos coming from the Sun and corssing the Earth, only 1 will interact !!!

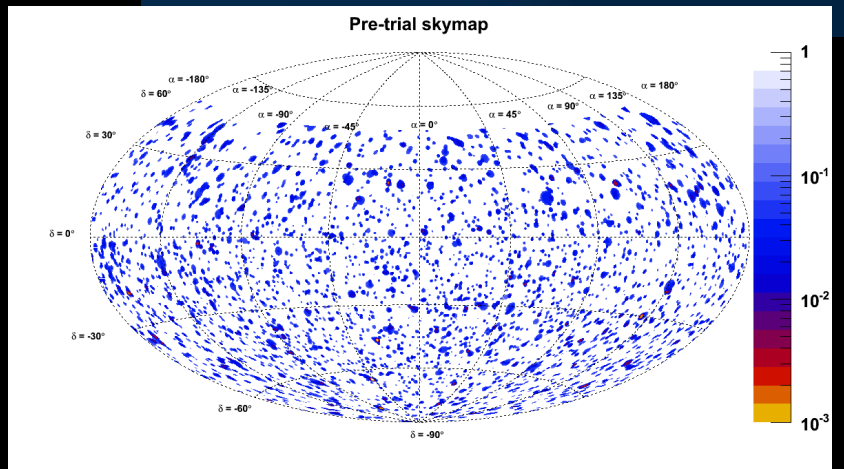
➔necessity of a very large detection volume

A new window over the HE Universe



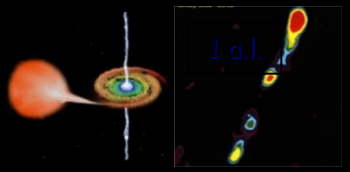


Neutrino Astronomy :
Skymap of the most catastrophic phenomena of the Universe



The sources of very high energy neutrinos

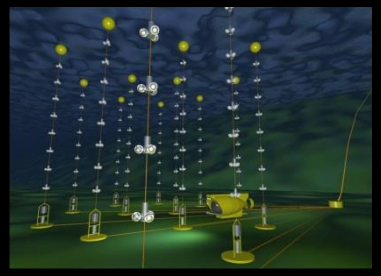
Microquasars



Active Galactic Nuclei

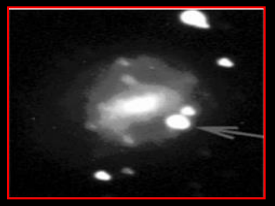
SN Remnants

Galactic sources



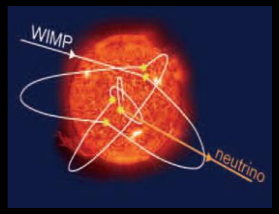
Extra galactic sources

Gamma-Ray Bursts



Pulsars

Dark Matter



Exotic Physics

Magnetic Monopoles

Nuclearites

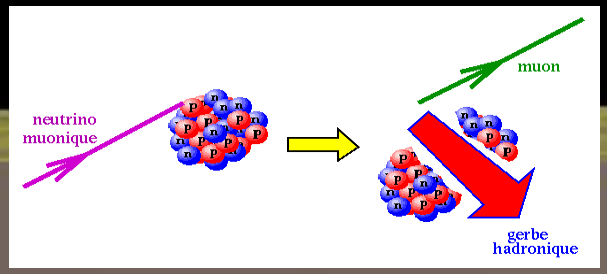
Detection Principe

3D array of
photomultipliers

γ

Cherenkov light
induced by the muon
travelling in water

43°



interaction

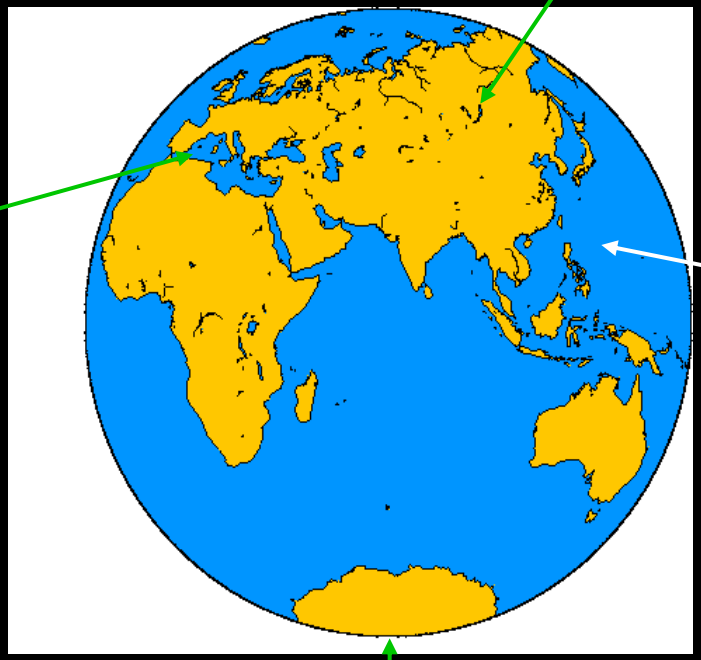
ν_μ

μ

Cherenkov light emitted by μ coming from ν propagation detected by PMT array
Time & position of photons allow the reconstruction of the μ (~ ν) trajectory

Existing Neutrino Telescopes

BAIKAL (1989) : Lake Baikal, Sibérie



DUMAND : Hawaii
(canceled in 1995)

NESTOR (1991): Grèce
ANTARES (1996): France
NEMO (2000): Italie

KM3NeT (2003): Mediterranean Sea

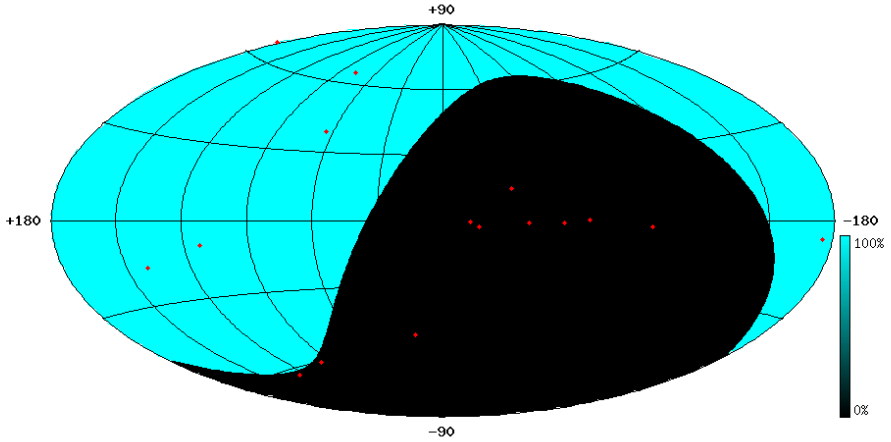
AMANDA: South Pole, Antarctica

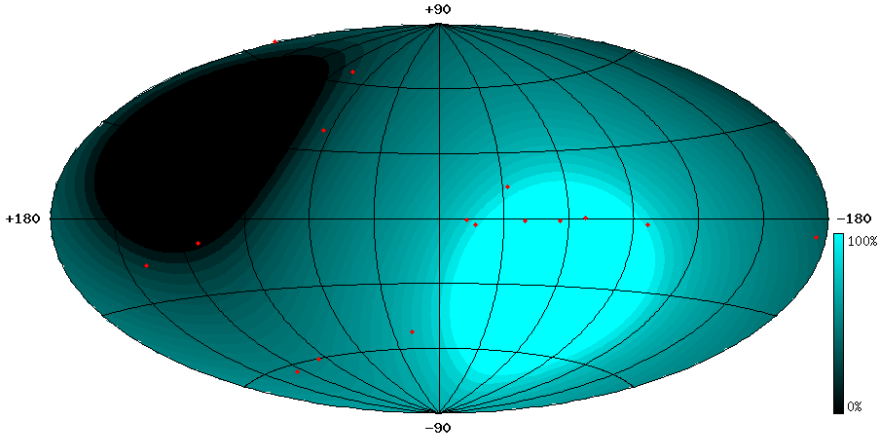
IceCube

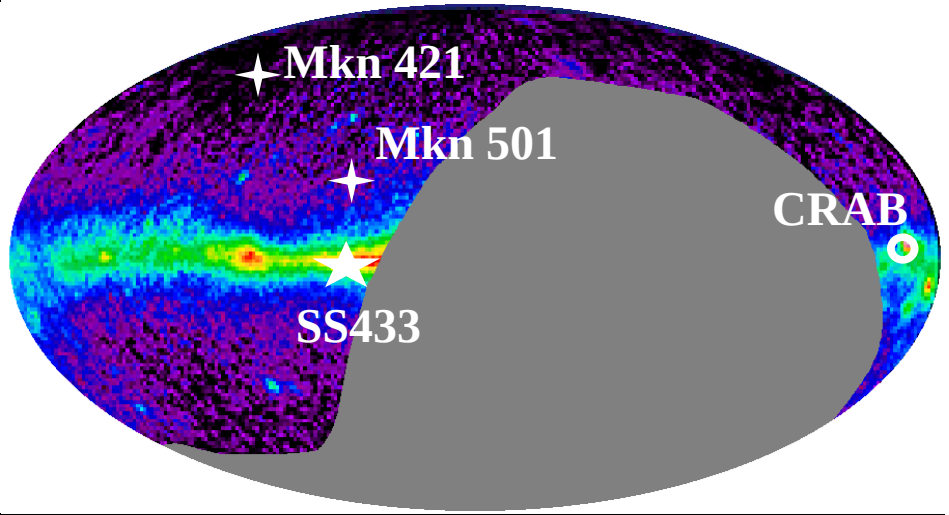
Region of Sky Observable by Neutrino Telescopes

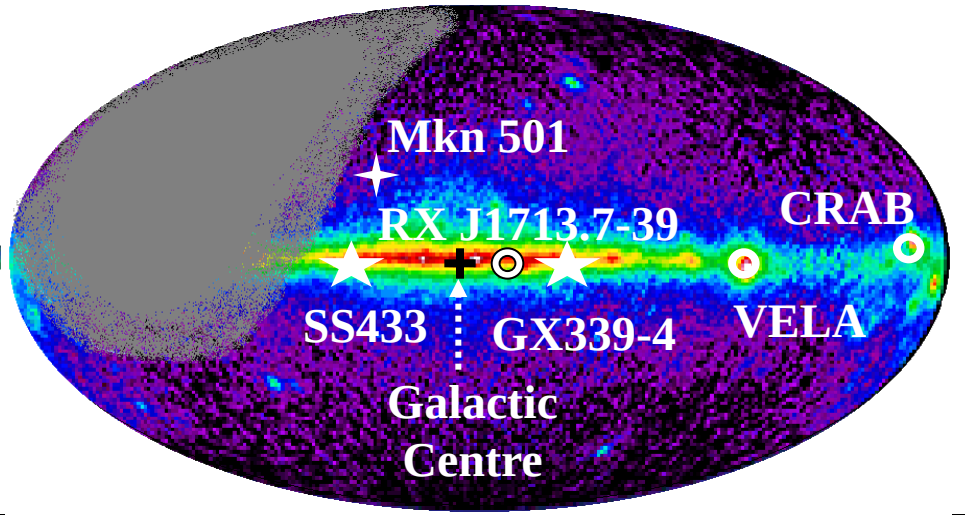
IceCube (South Pole) **ANTARES/KM3 (43° North)**

(ice: ~0.6°) Angular resolution (water: ~0.2°)



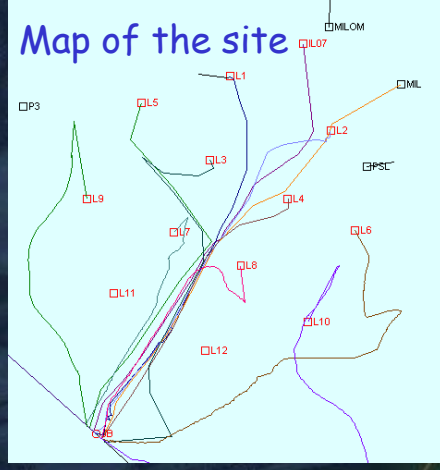






The ANTARES Detector

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



Bouy

14.5 m

Storey

350 m

Junction Box

100 m

~60-75 m

Electro-optical Cable

Depth: 2500m

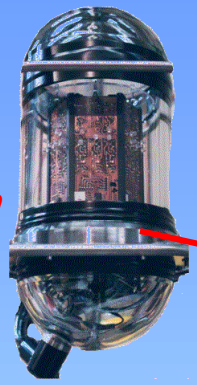
Detector completed in May 2008

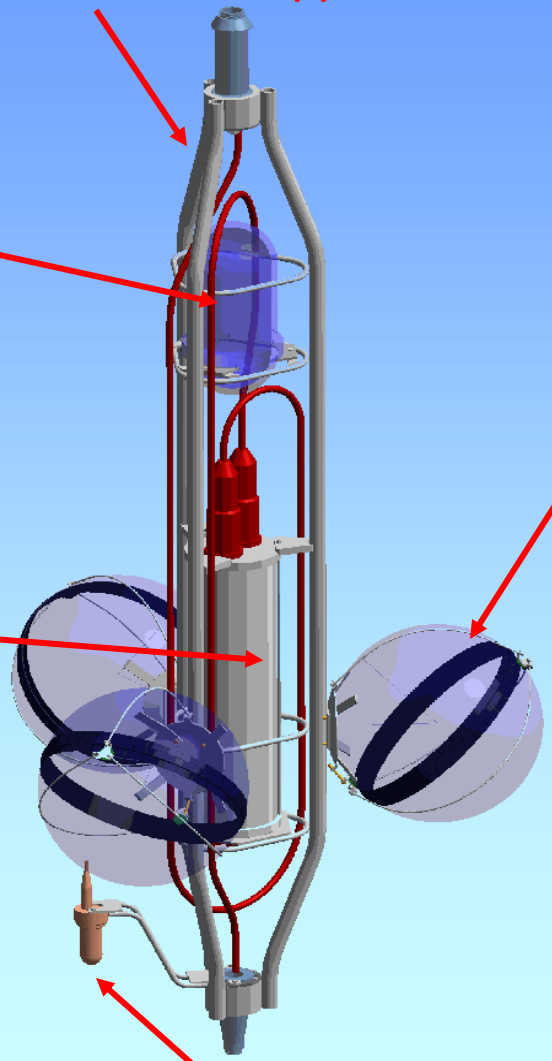
The ANTARES site

Basic detector element: storey

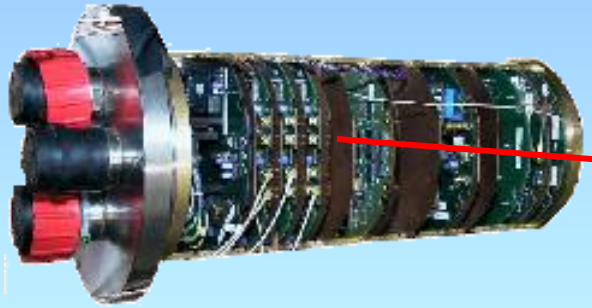
titanium frame: *support structure*

Optical Beacon with blue LEDs: *timing calibration*





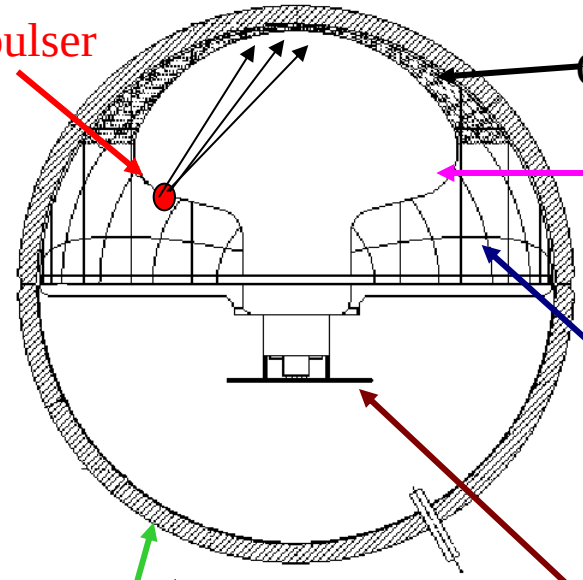
Optical Module: 10” Hamamatsu PMT in 17” glass sphere ($\sigma_{TTS} \approx 1.3$ ns) *photon detection*



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

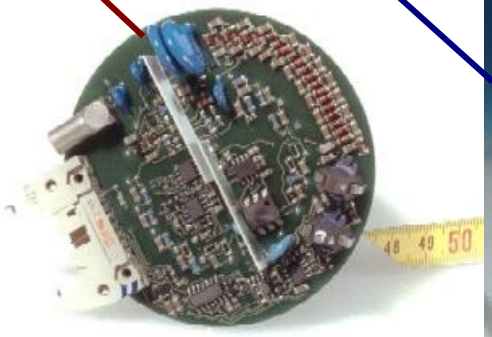
Hydrophone: *acoustic positioning*

The Optical Module



Photomultipler: 10” Hamamatsu R7081-20

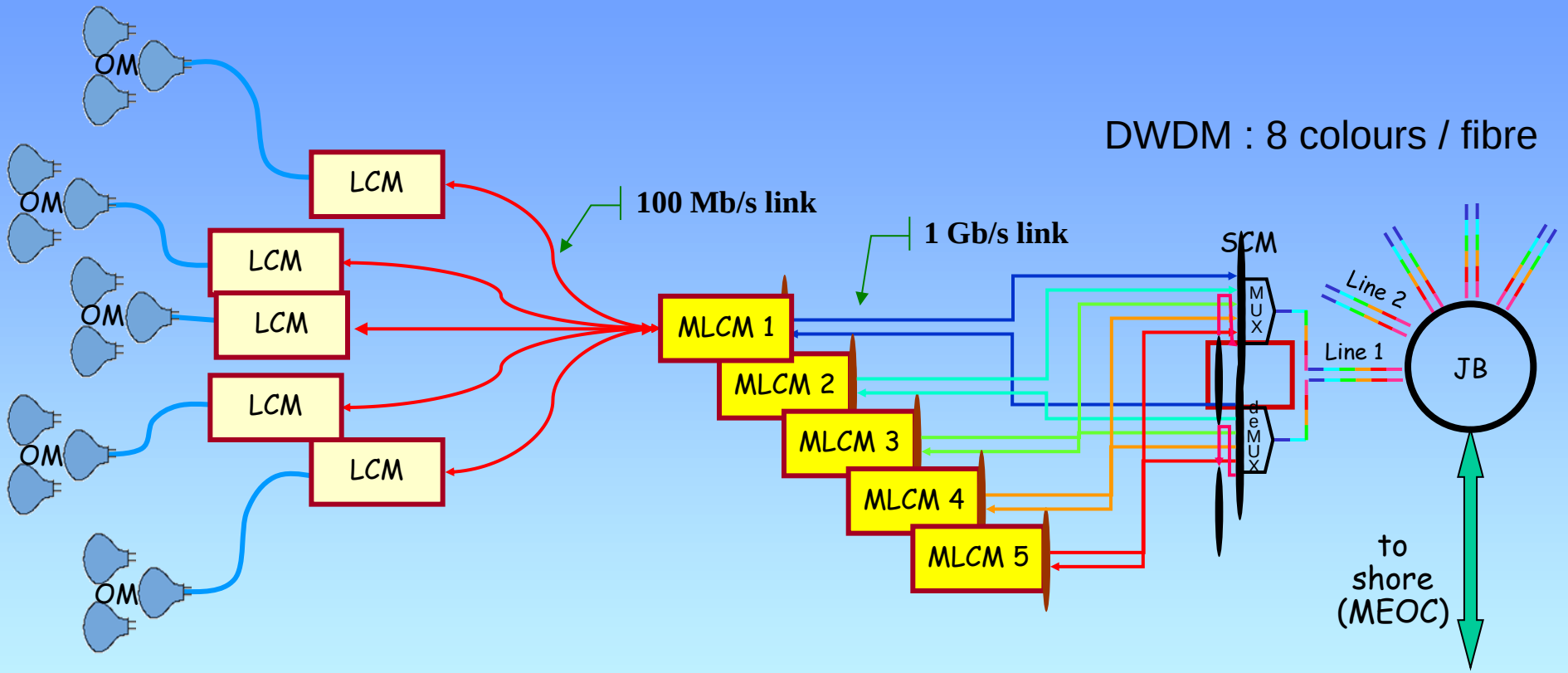
Glass sphere (Nautilus)



Active (C-W) PMT Base (ISEG)

Mu metal magnetic shield

Data acquisition architecture



ANTARES: a large undersea LAN…

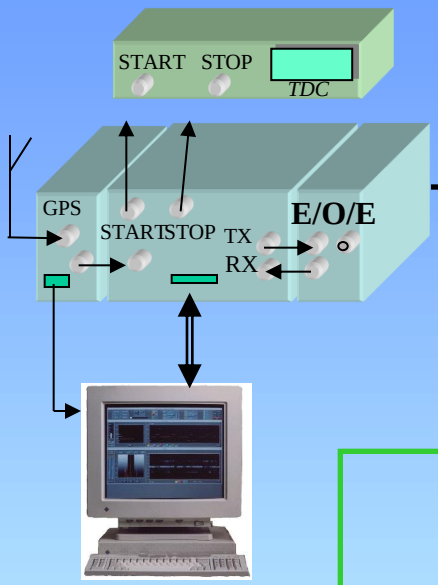
Shore Station
La Seyne-sur-mer

Demux/ Mux

Computer farm

Clock distribution

On-shore Station



Junction Box
1–16 passive splitter

Link Cables
200-500 m fibre

1534 nm⇆1549 nm

1310 nm⇆1550 nm

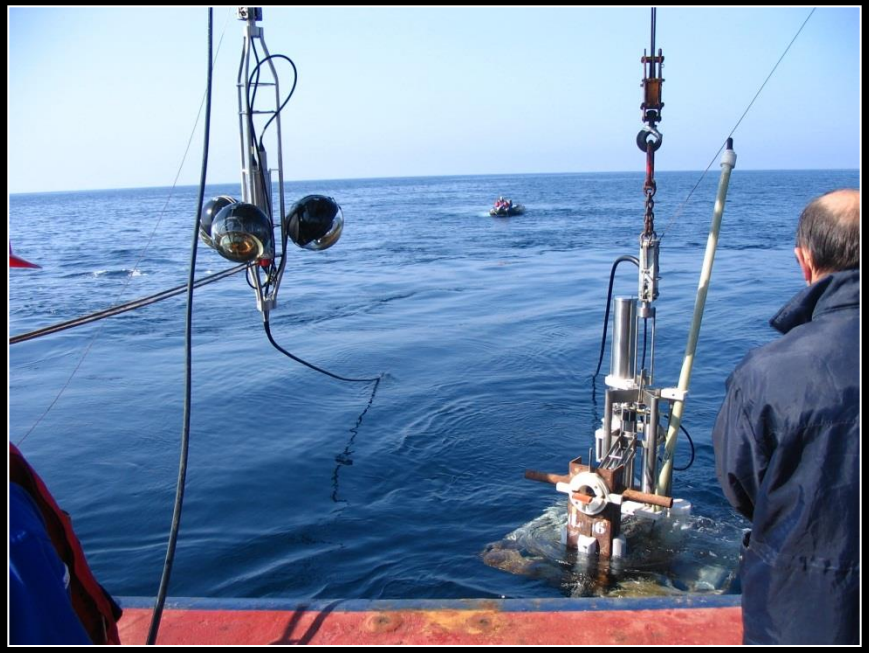
1534 nm⇆1549 nm

Main Electro-Optical Cable
40 km
from shore to Junction Box
Single bidirectional fibre
(1534 nm / 1549 nm)

String Control Module
BIDI modules
O/E and E/O converters
by sectors (5 storeys)

Local Control Modules
LCM clock boards

Line deployment operations

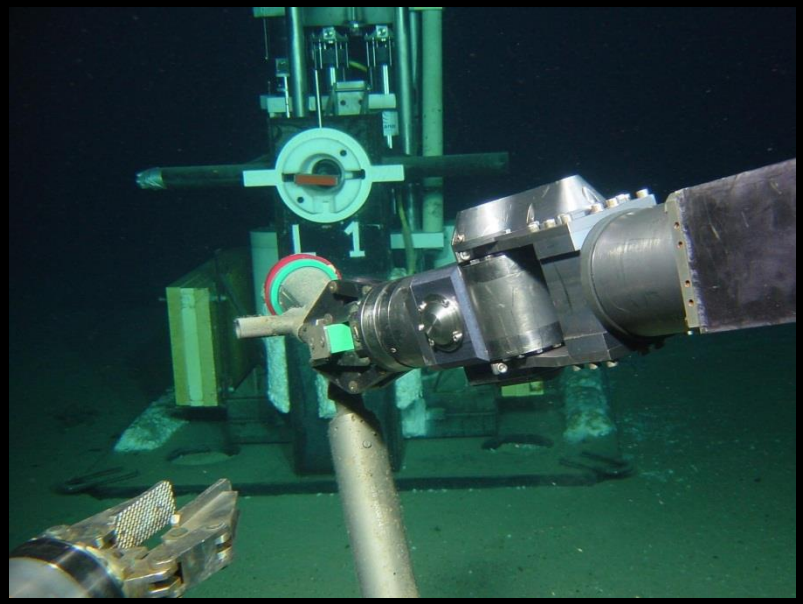


- DP Ship *Castor02*
- Precision of ~1m on the line position at sea bottom.
- ~7 hours operation

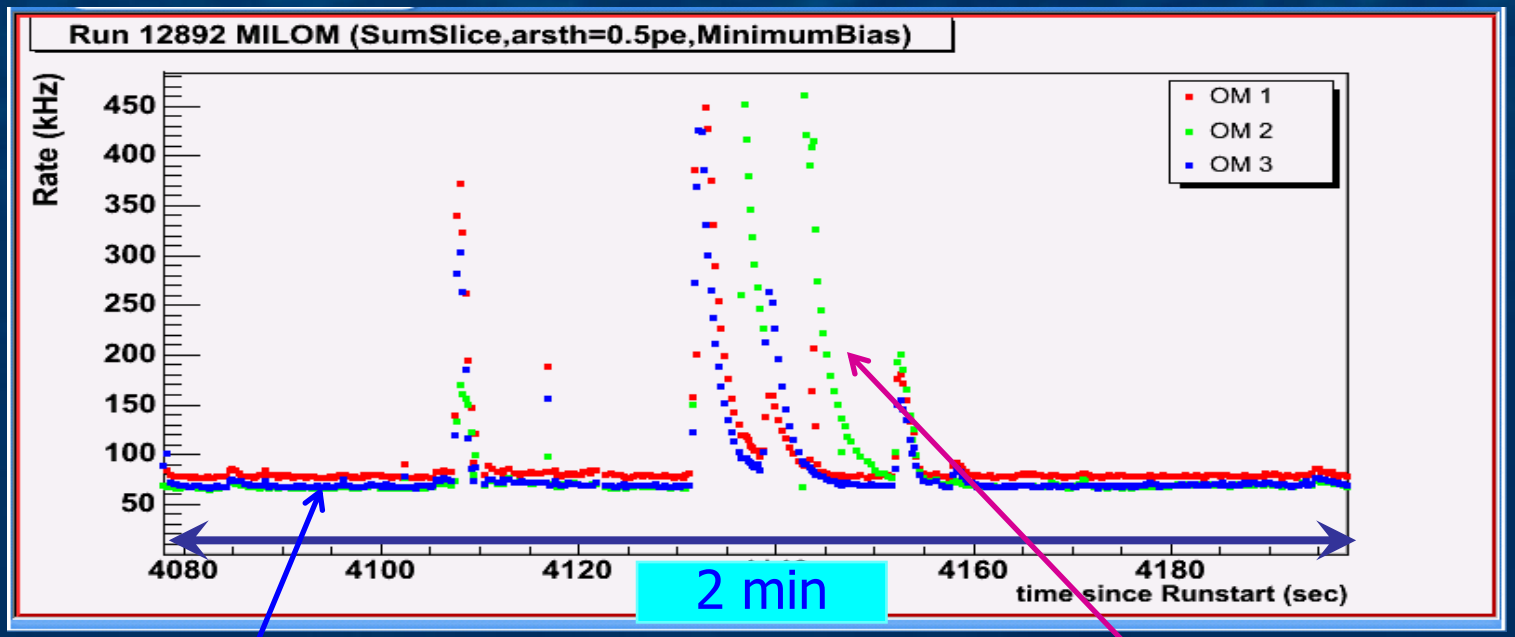
Undersea connection of lines with ROV

- Deep Sea ROV *VICTOR* of IFREMER

- ODI wate-metable connectors with:
  - 4 optical fibres
  - 2 electrical contacts



Counting Rates on Optical Modules

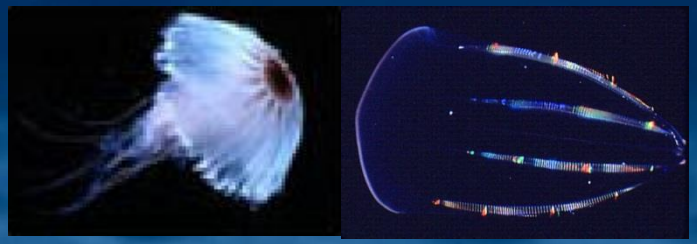


Continuous baseline:
Radioactivity in the sea (^{40}K)
+ bioluminescent bacteria

Bursts:
bioluminescence from
Macroscopic organisms

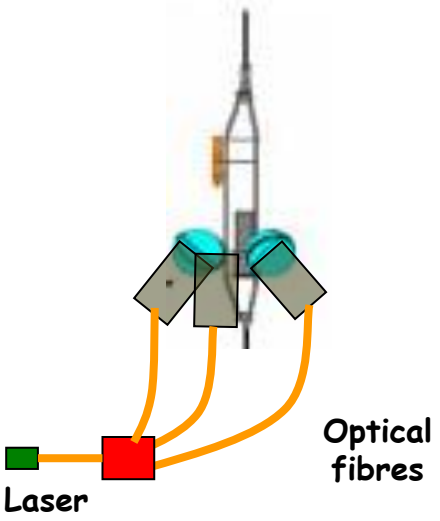
^{40}K

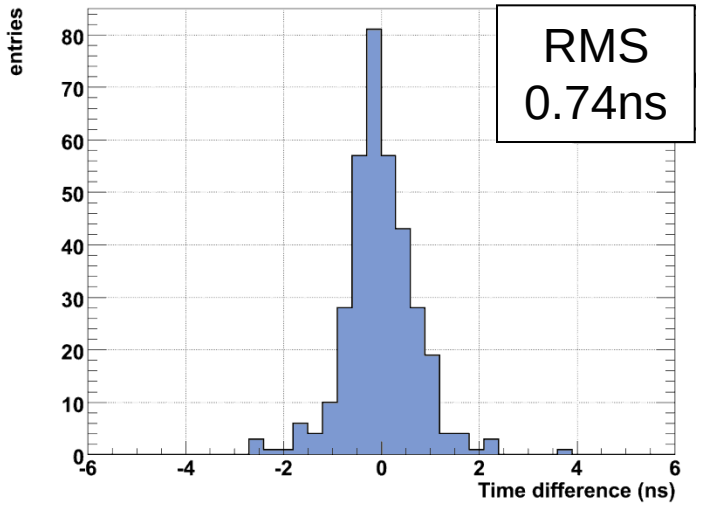
$$^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{20}\mathrm{Ca} + \mathrm{e} + \bar{\nu}_{\mathrm{e}}$$



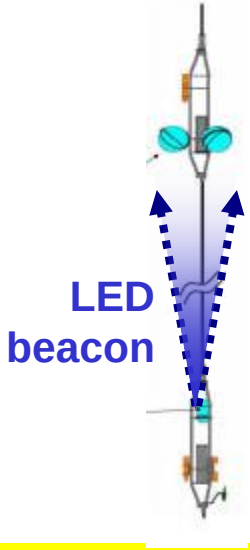
Time Calibration

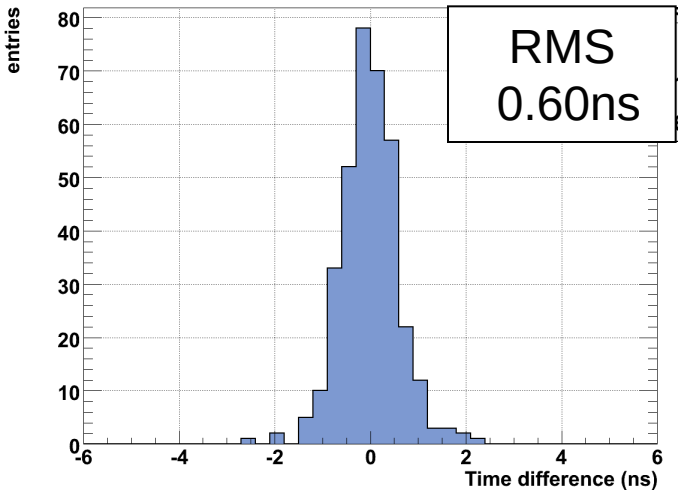
On shore laser system



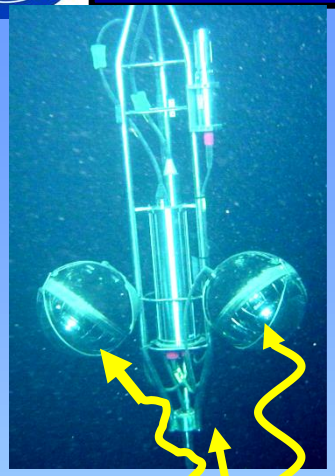


In sea LED beacon system





In situ calibration with Potassium-40



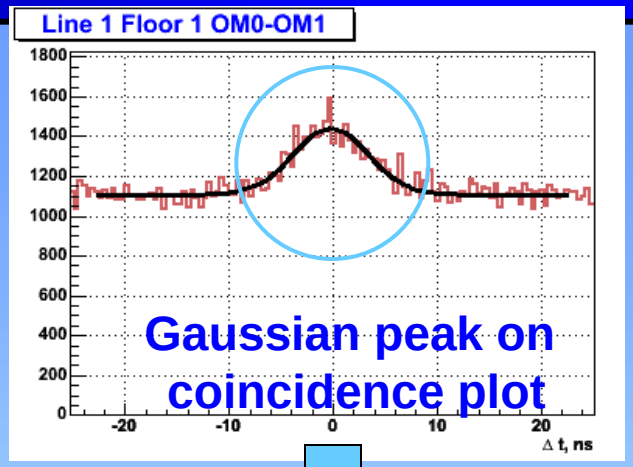
γ γ

Cherenkov

e^-
(β decay)

^{40}K

^{40}Ca



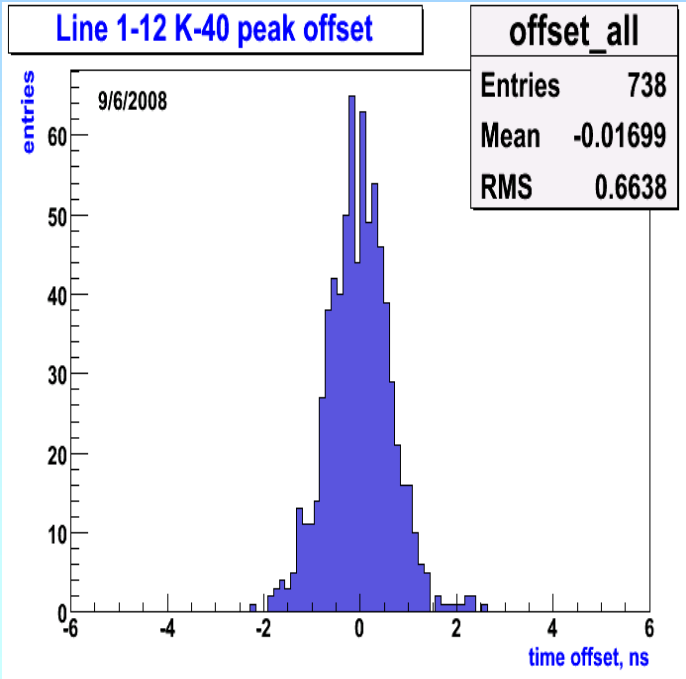
Integral under peak = rate of correlated coincidences

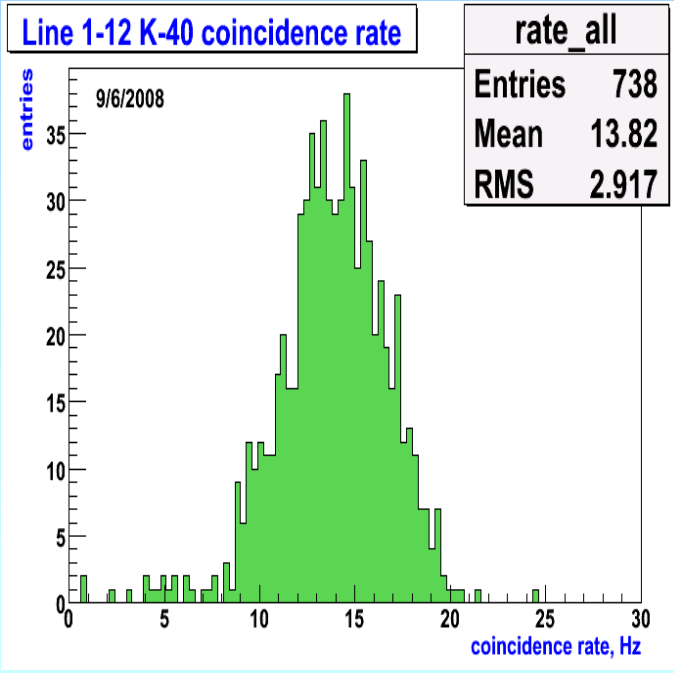
MC prediction =13 ± 4 Hz

High precision (~5%) monitoring of OM efficiencies

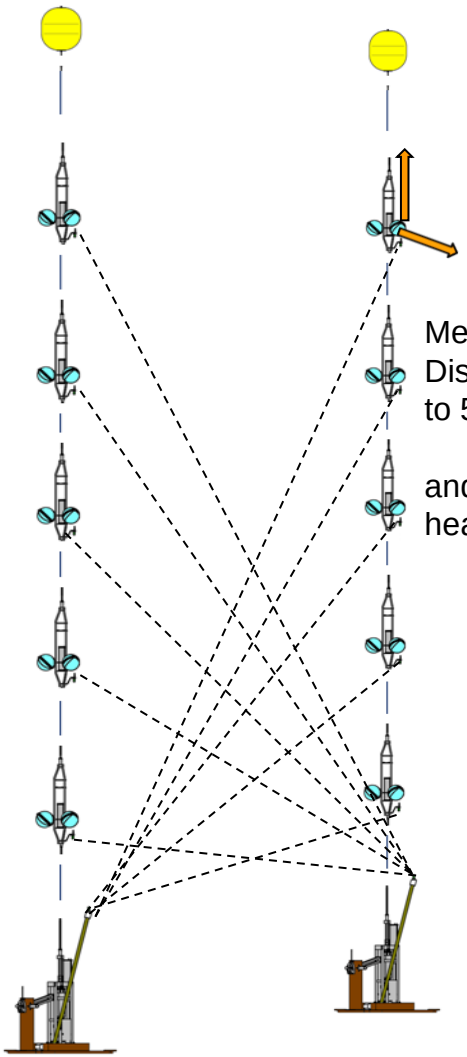
Peak time offset :

Cross check of time calibration



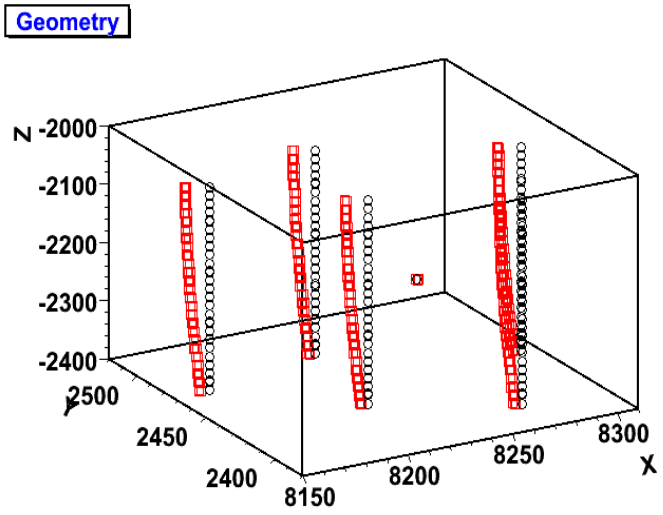


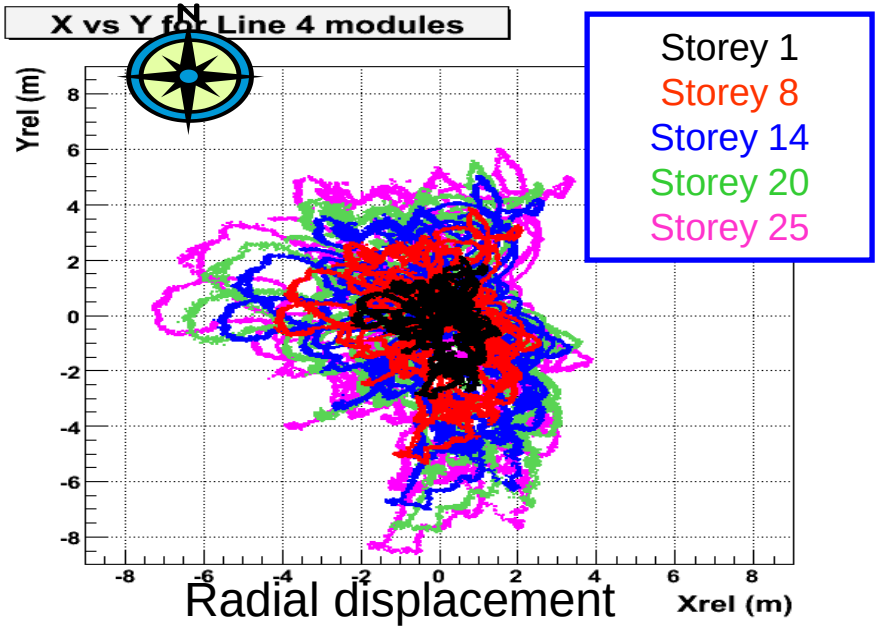
Acoustic Positioning



Measure every 2 min:
Distance line bases
to 5 storeys/line

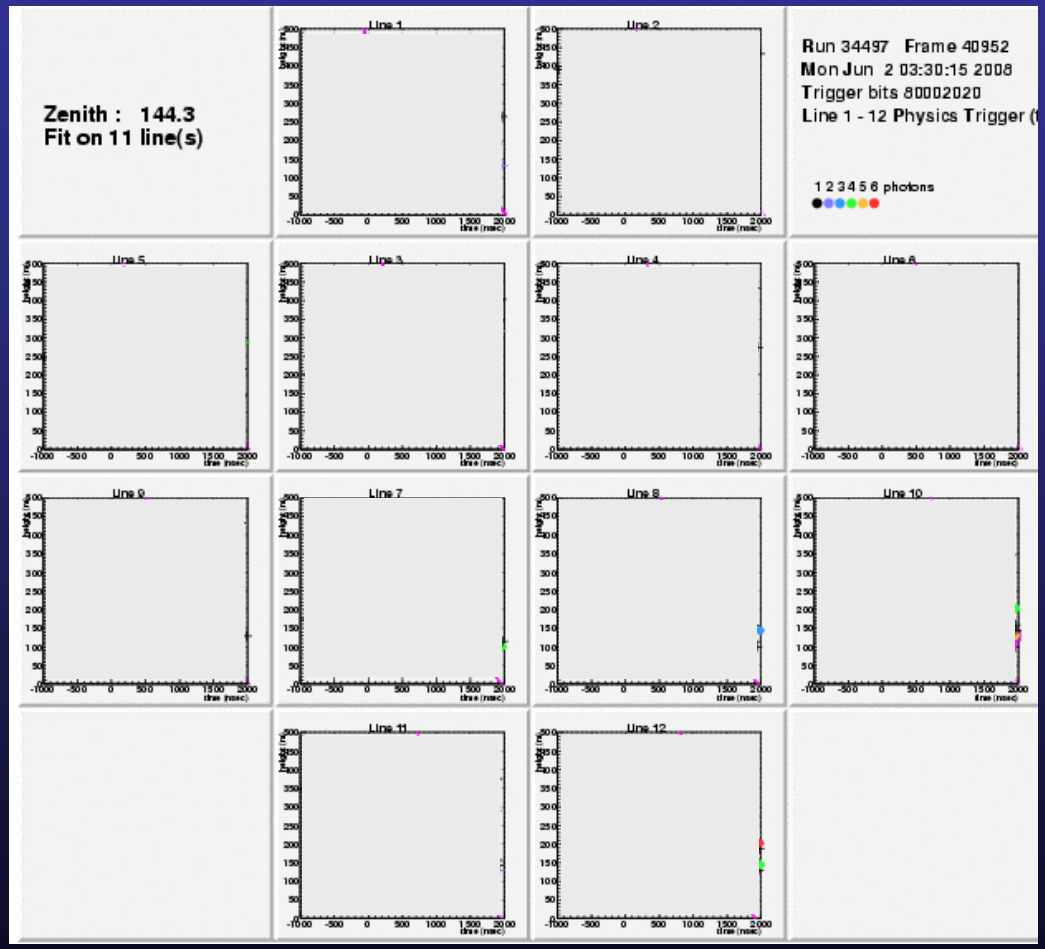
and also storey
headings and tilts



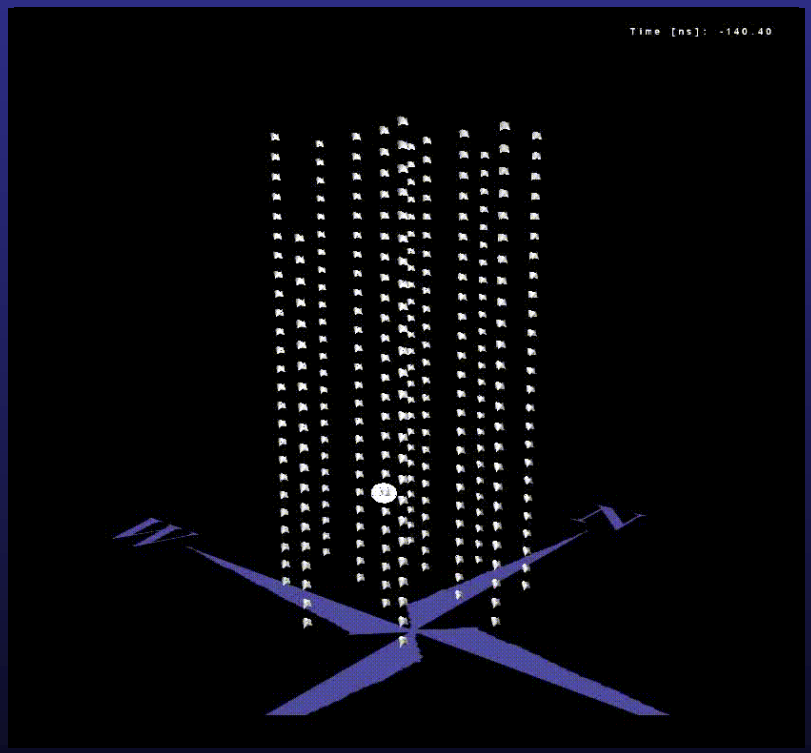


Radial displacement

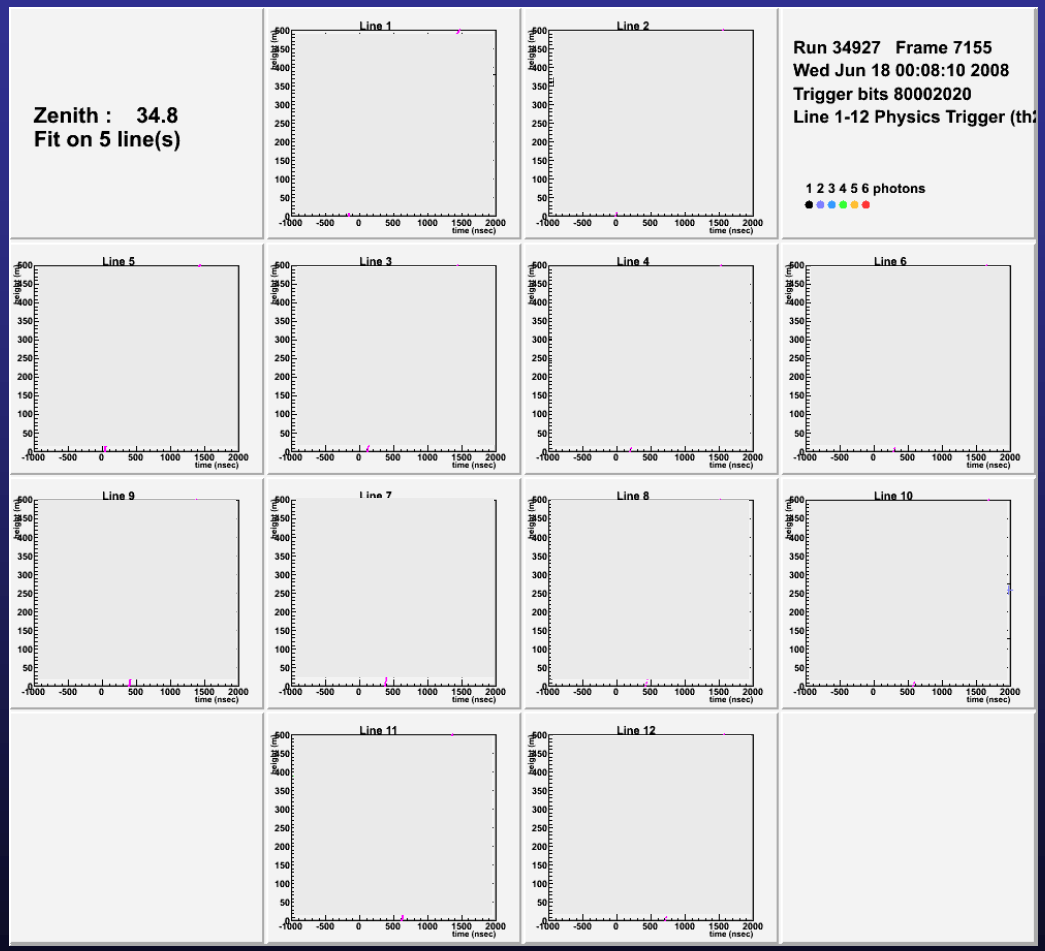
Example of a muon event



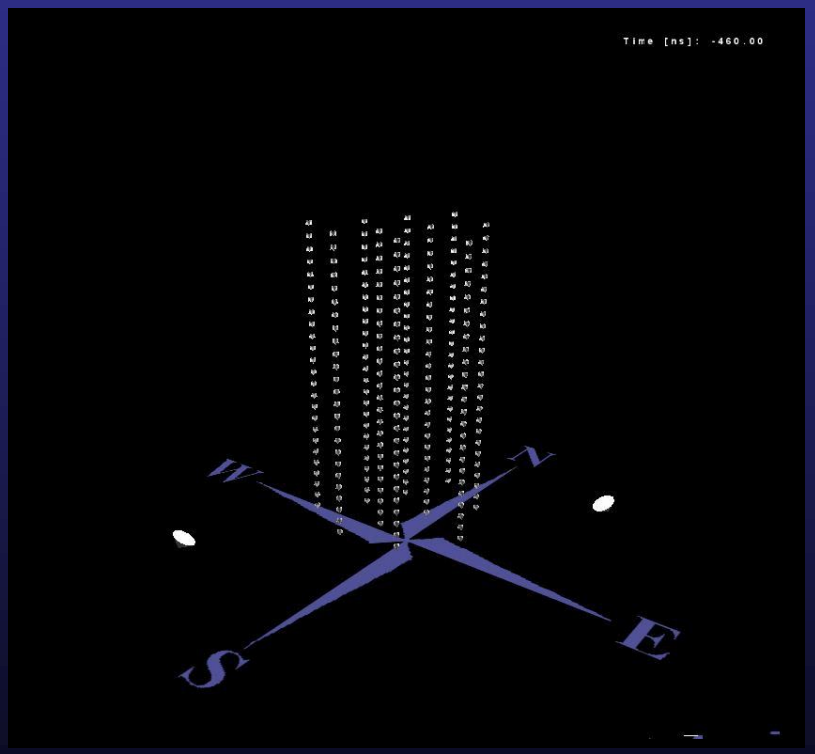
Example of a down-going muon event, détected over the 12 detector lines

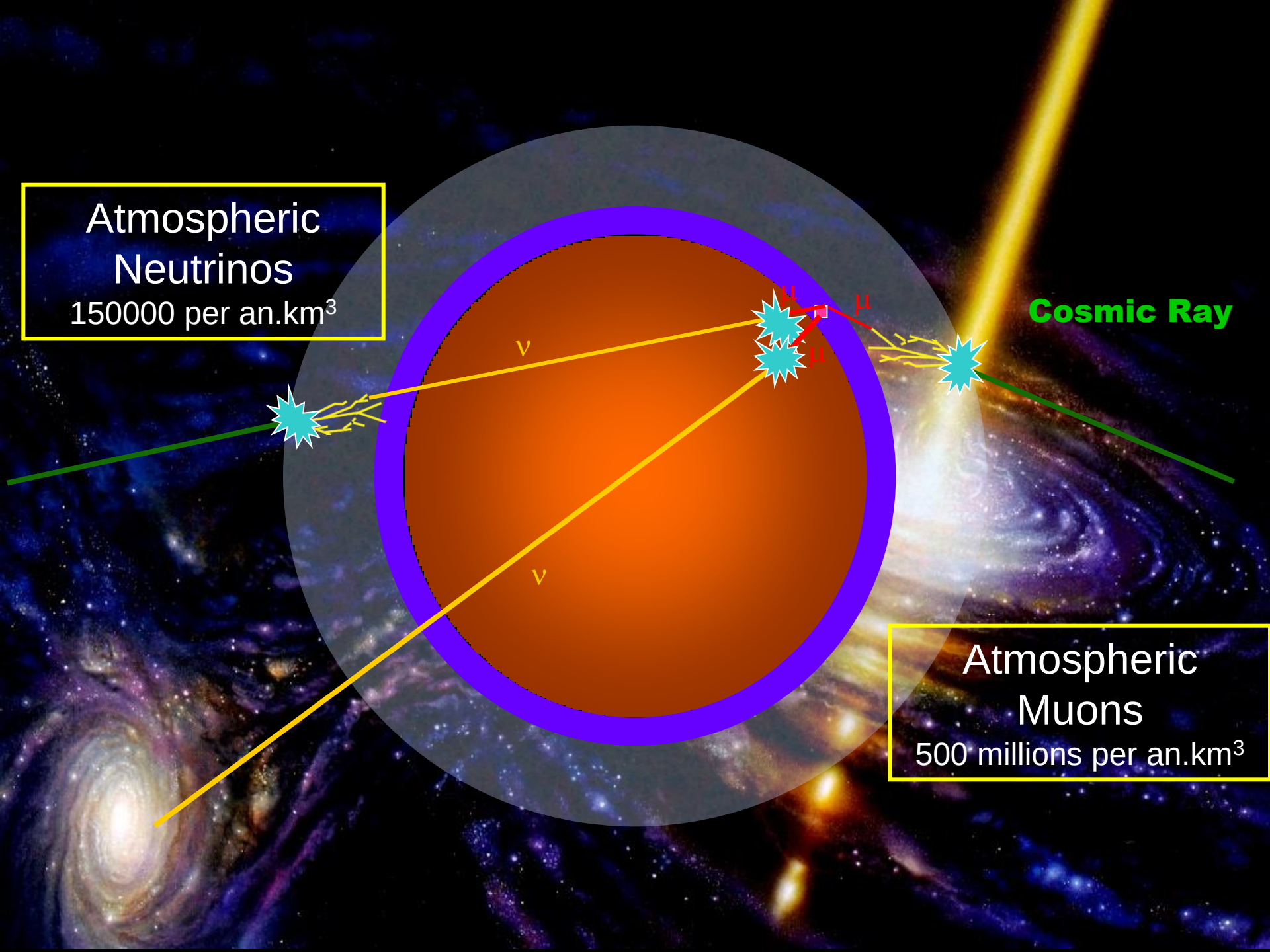


Example of a neutrino event

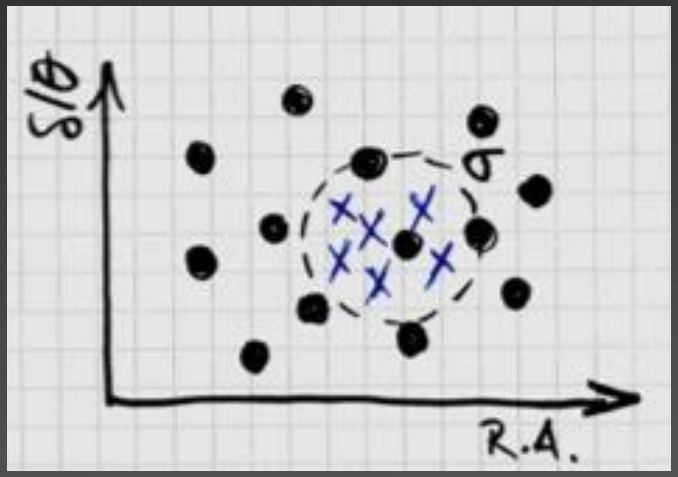


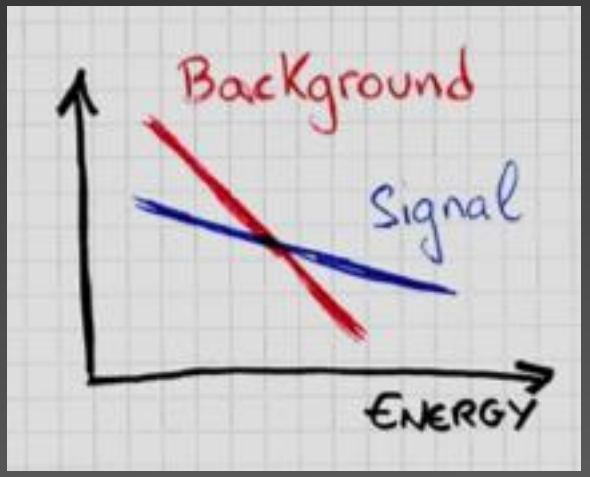
Example of an up-going muon event (i.e. a neutrino event) detected by 6/12 detector lines




Atmospheric Neutrinos
150000 per an.km3
Cosmic Ray
Atmospheric Muons
500 millions per an.km3

Cosmic Signal vs atmospheric background





Point Source

Diffuse Flux

Background suppression :

- atmospheric muons : look down, apply veto, use reconstruction quality
- atmospheric neutrinos : isotrope + lower energy spectrum

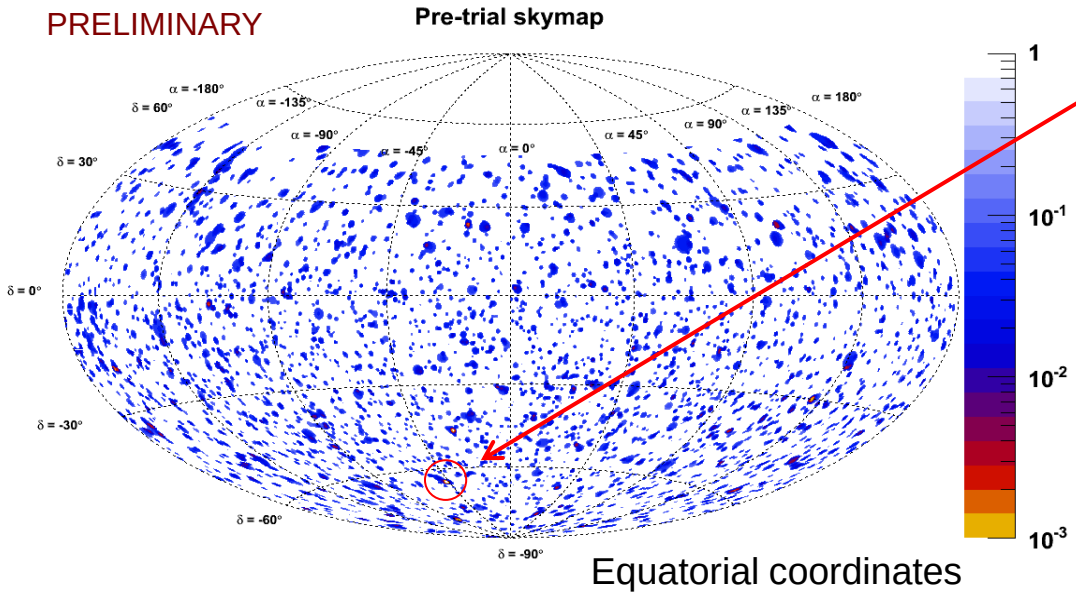
Signal:

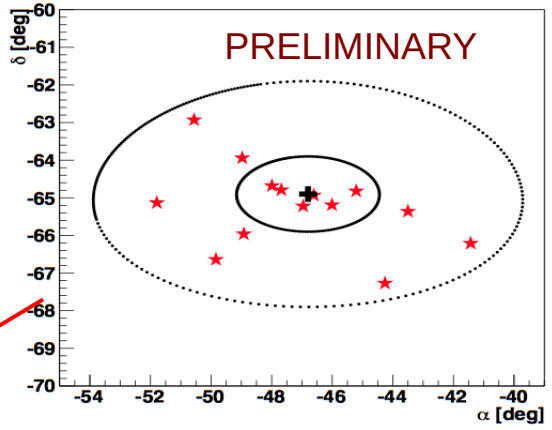
- distribution concentrated for point source + harder energy spectrum
- search for time/space coincidences with other cosmic messengers

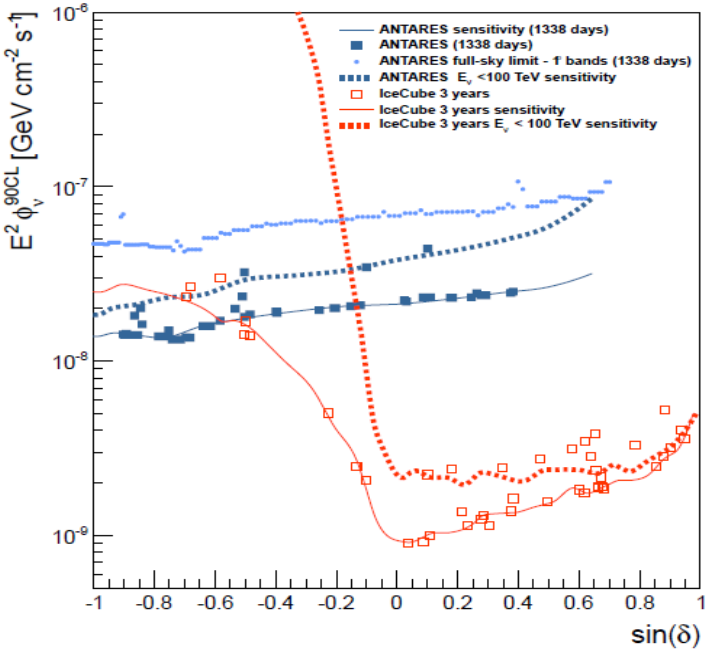
The ANTARES SkyMap

Search for cosmic neutrino sources with 2007-2012 data (1340 days)

- 5516 neutrino candidates : No significant excess
- Most significant cluster : 6 (14) neutrinos within 1° (2°)
- Compatible with bkg hypothesis: p-value = 2.1% (2.3 σ)



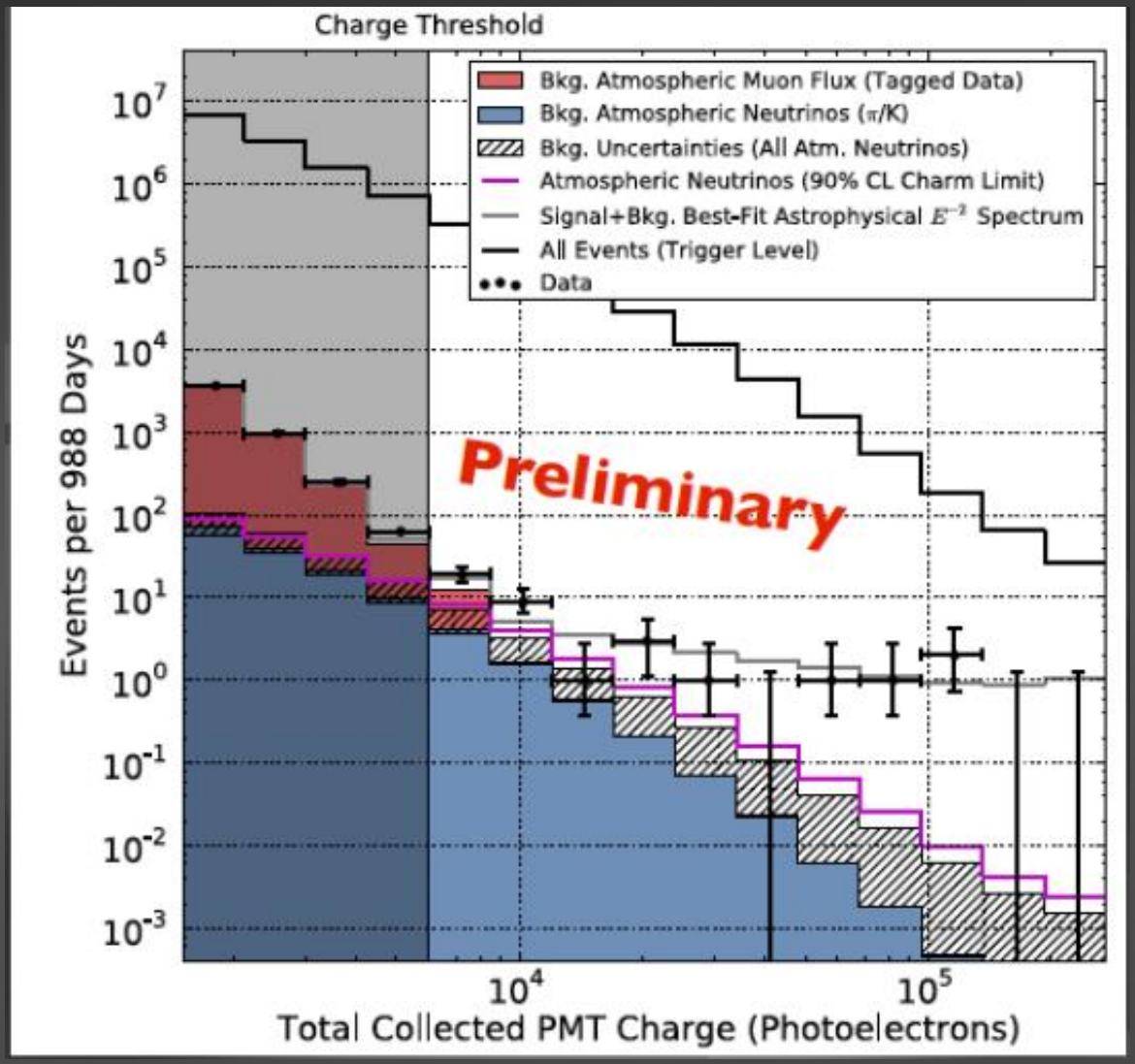


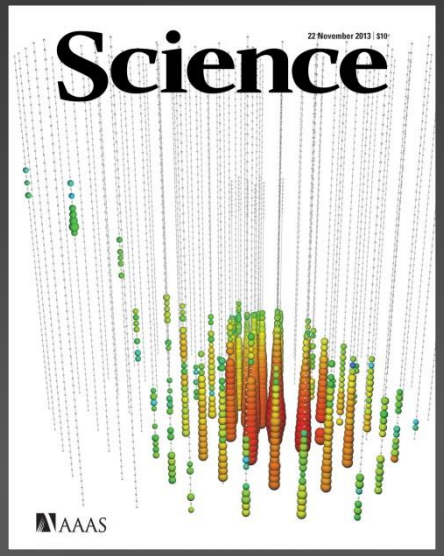


ANTARES is mostly sensitive
for 'galactic sources' (< 100 TeV)

Best world limits in South sky

Ice Cube : First signal of cosmic neutrinos !!





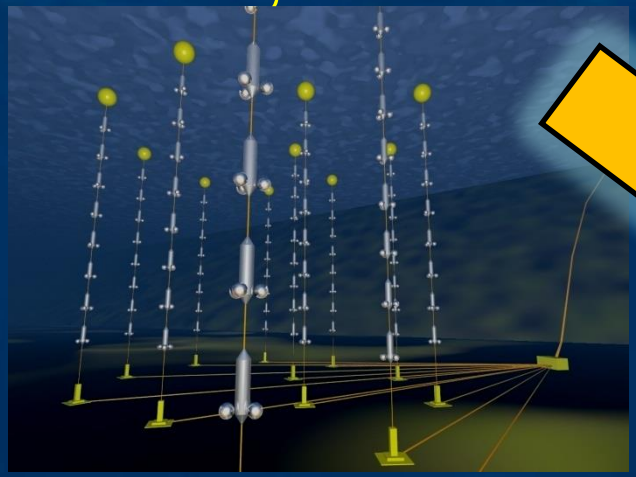
3 yr data: 988 days
Observed : 37 events
Expected background :
6.6 $^{+5.9}_{-1.6}$ atm. neutrinos
8.4 ±4.2 atm. muons
Significance 5.7 σ

Very small flux
→ to be studied with a multi-km^3 size detector

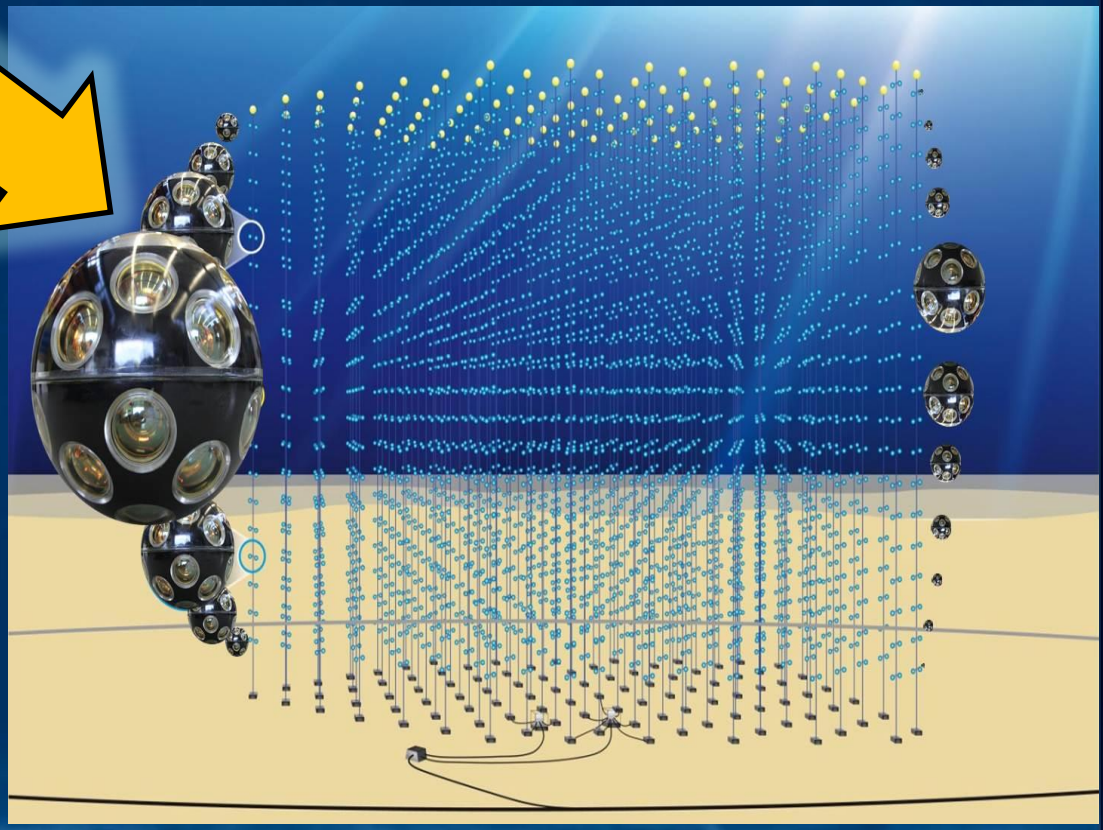
arXiv:1405.5303v1 [astro-ph.HE] 21 May 2014

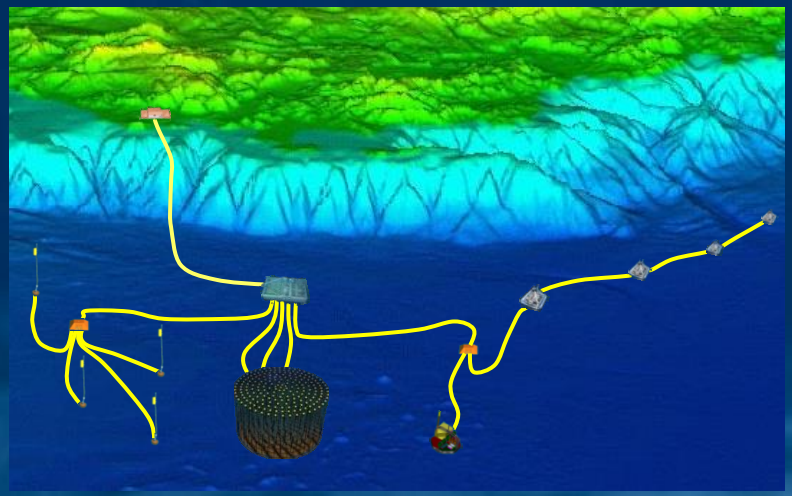
The KM3NeT Neutrino Telescope

12 lines, 900 PMTs



~600 lines, ~12 000 OMs

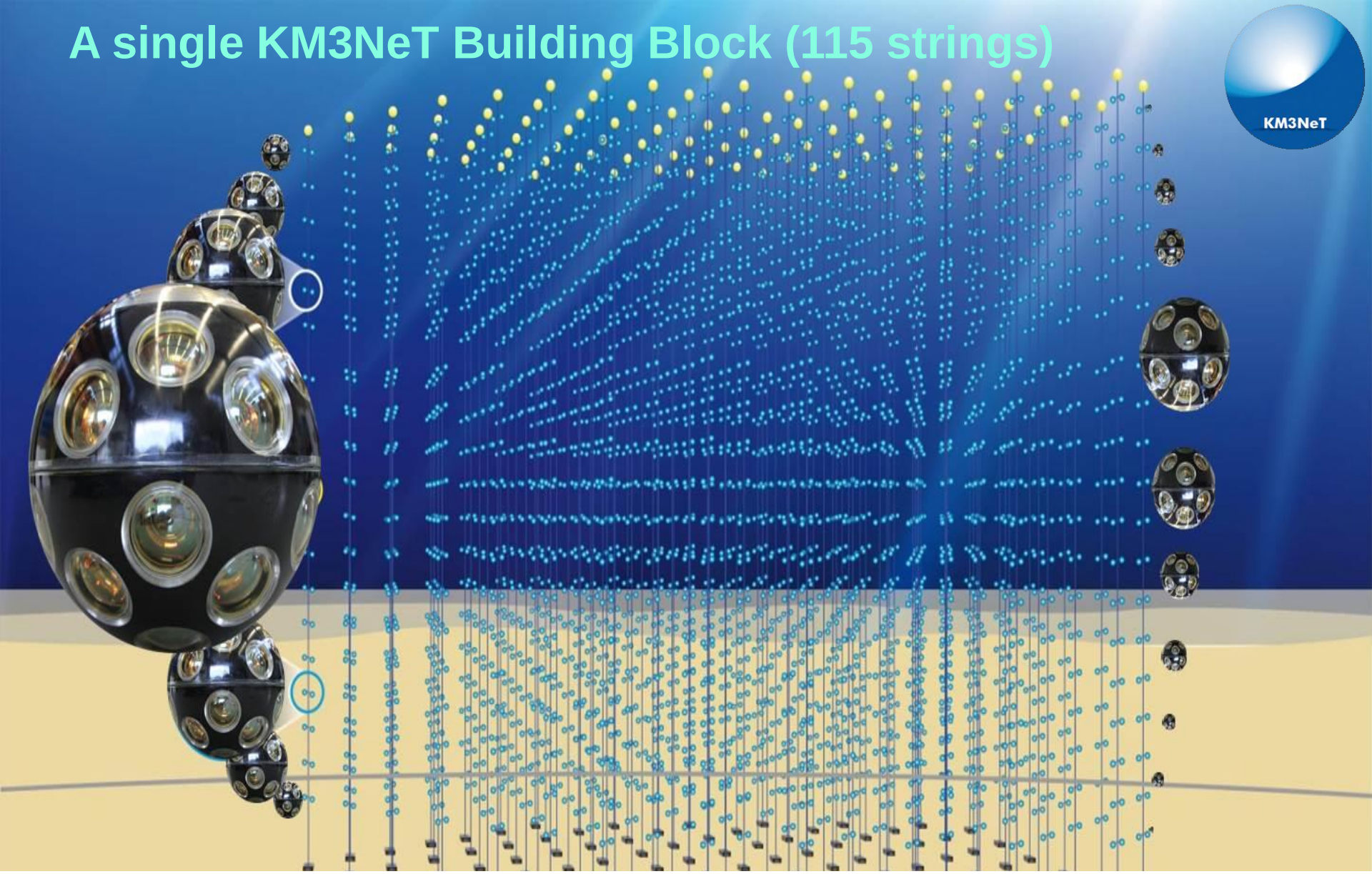




Permanent multidisciplinary observatory in the deep sea

Detector split on 3 deep sites in Mediterranean Sea offshore Toulon (France), Sicily and Greece

A single KM3NeT Building Block (115 strings)



Phase 1 (funded) : 2 sites (Toulon, Capo Passero), 31 lines total (~2016)

Phase 1.5 (LoI) : 2 sites with 1 building block each (~2020)

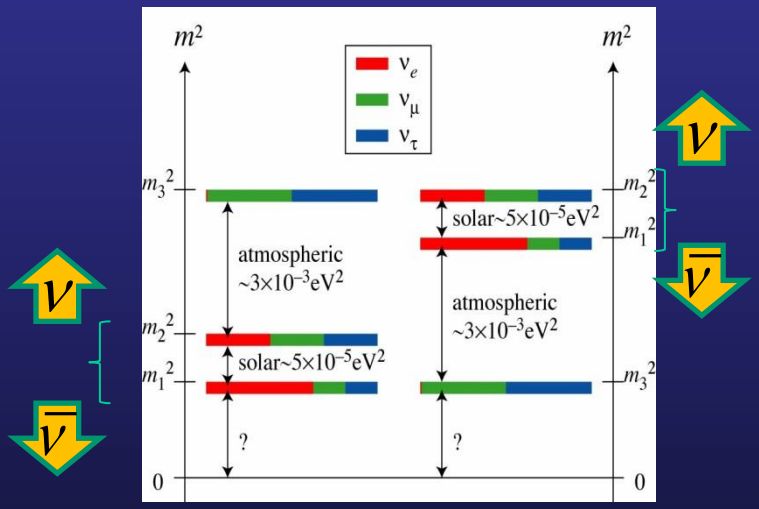
Phase 2 (ESFRI) : 2 (or 3 Greece?) sites with 6 blocks total (> 2020)

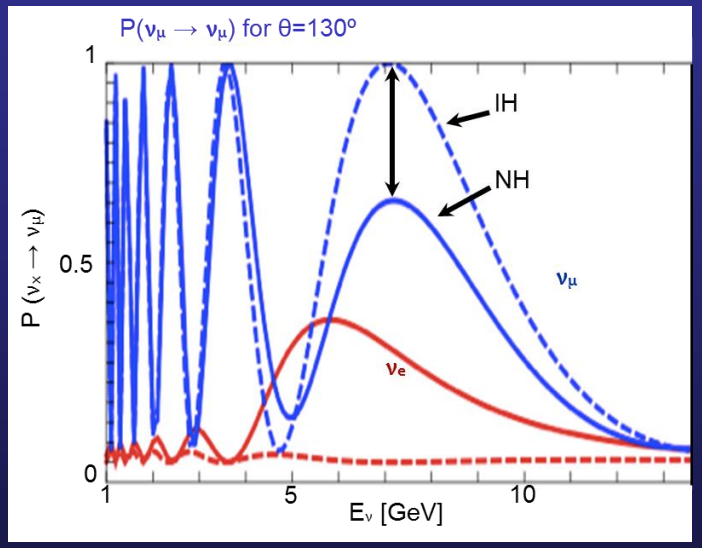
KM3NeT Collaboration

ORCA: measurement of the neutrino mass hierarchy with a dense undersea neutrino telescope

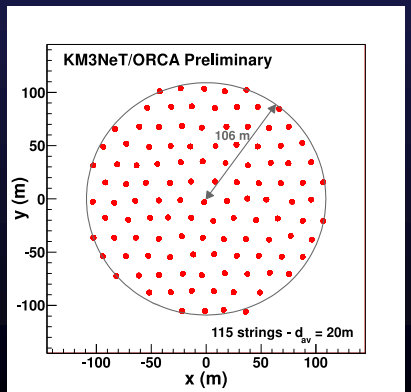
Measurement of the Daya Bay experiment in Spring 2012: $\sin^2 2\theta_{13} = 0.109 \pm 0.03 \pm 0.025$

→ Sensitivity to neutrino mass hierarchy (Normal vs Inverse) with oscillations of atmospheric neutrinos of few GeV interacting with the Earth





→ On-going faisability study of such measurement with a dense undersea neutrino telescope **(ORCA)**



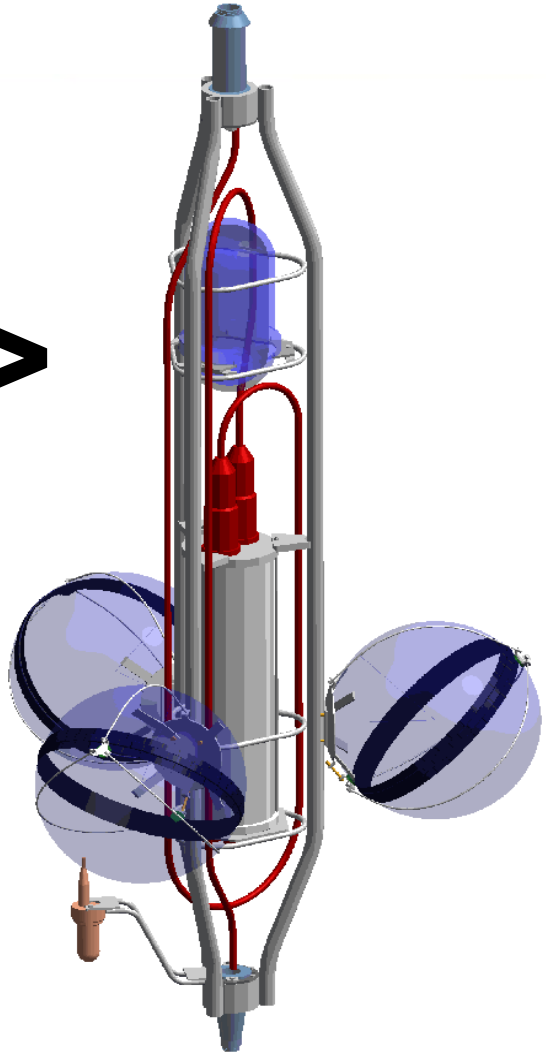
The Multi-PMT Digital Optical Module (DOM)

3-inch PMT
Hamamatsu
R12199

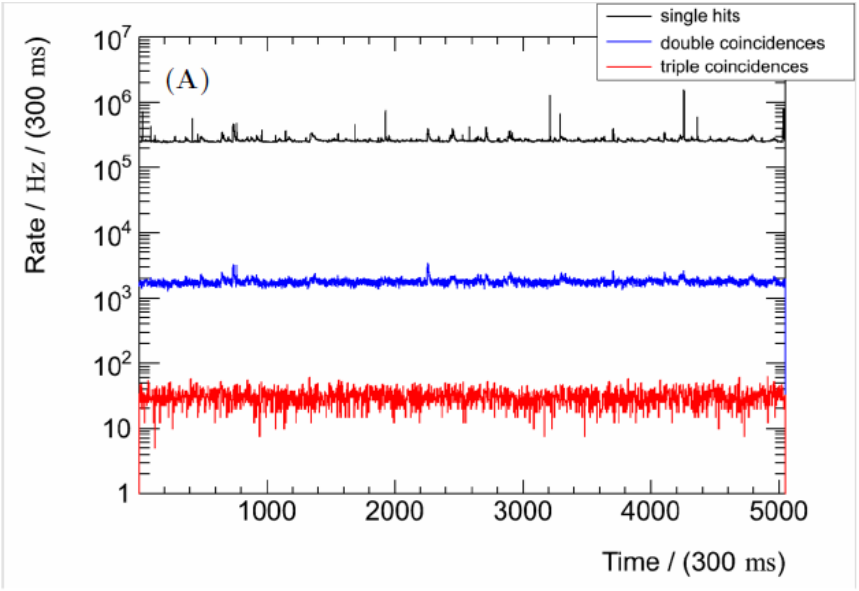
17 inch

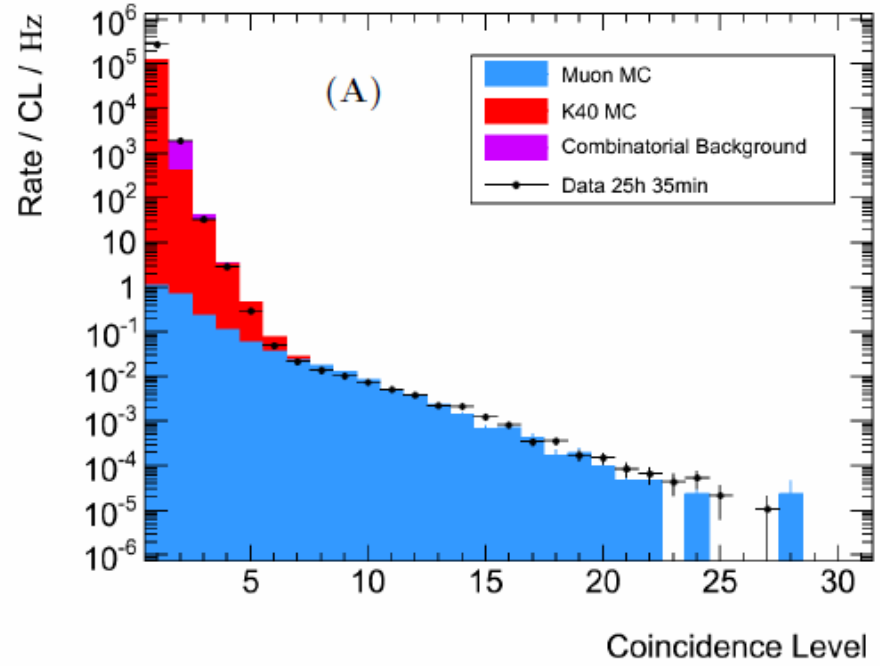
- Digital photon counting
- Directional information
- Wide angle of view
- Single pressure transition
- Cost reduction cf ANTARES

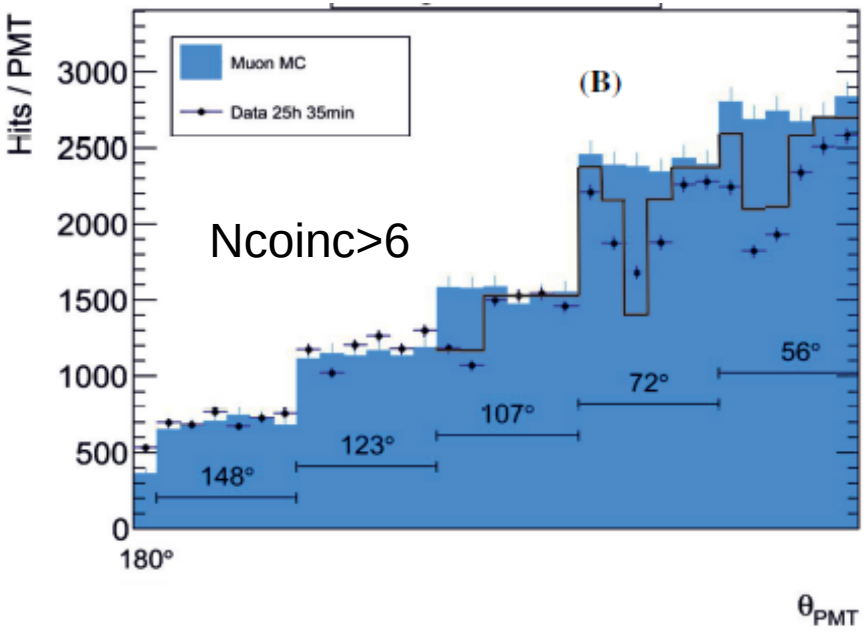
ANTARES Storey



KM3NeT DOM: works beautifully



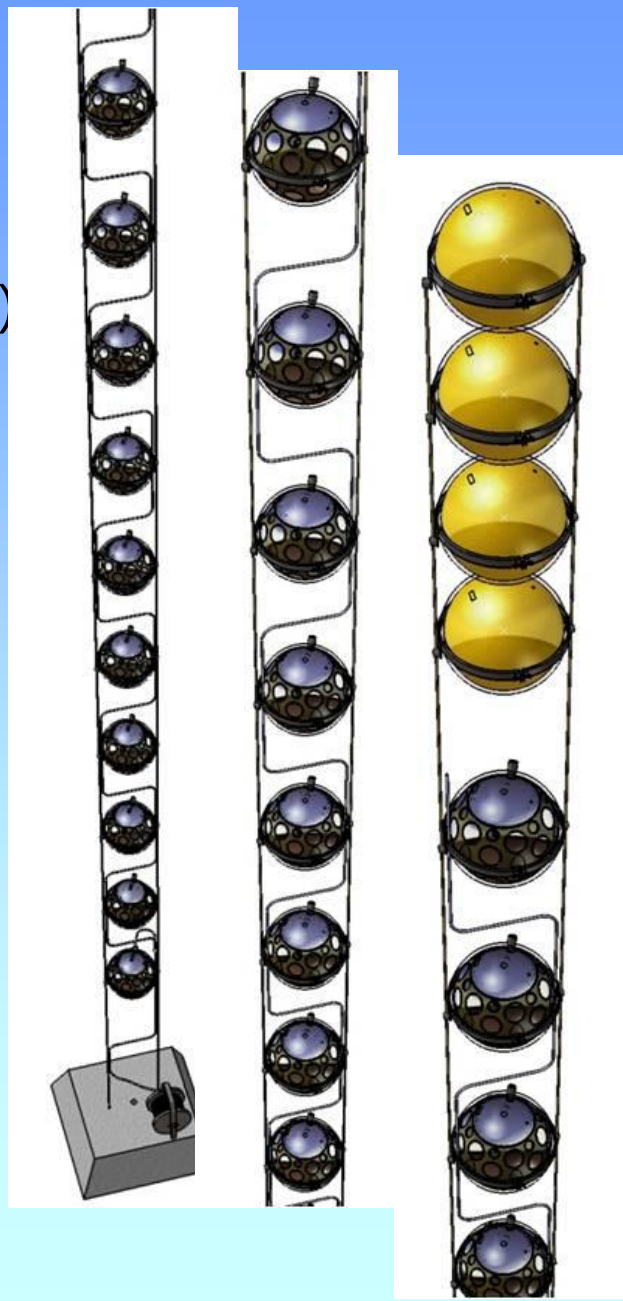




KM3NeT Detector Strings

- Mooring line:
  - Buoy
  - 2 Dyneema ropes (4 mm diameter, prestreched)
  - 18 storeys (one DOM each),
    36m spacing, 100m anchor-first storey

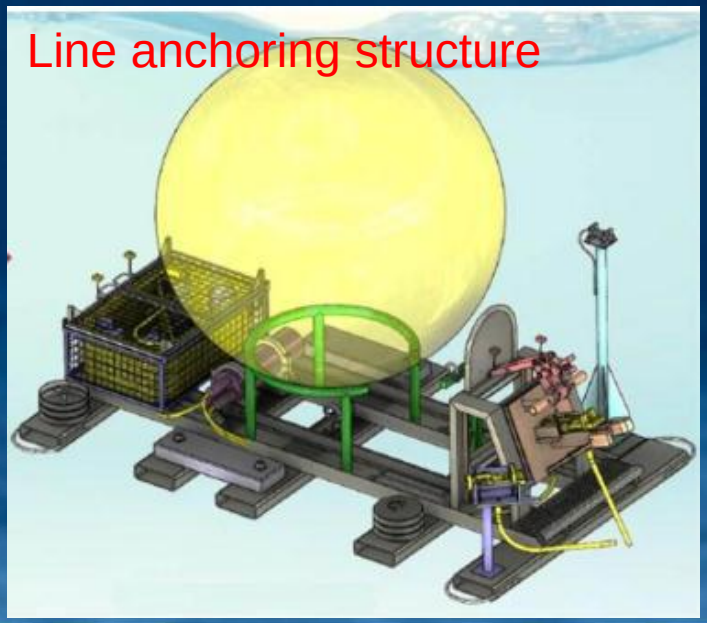
- Electro-optical backbone:
  - Oil filled flexible hose ~6mm diameter
  - 12 fibres and 2 copper wires
  - At each storey: 1 fibre+2 wires
  - Break out box with fuses at each storey:
    single pressure transition



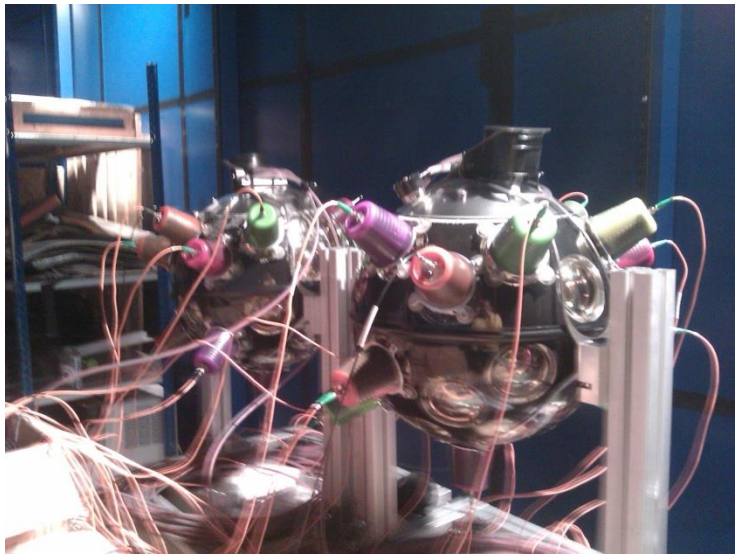
String Deployment

Multiple deployments with a single boat cruise

Autonomous unfurling

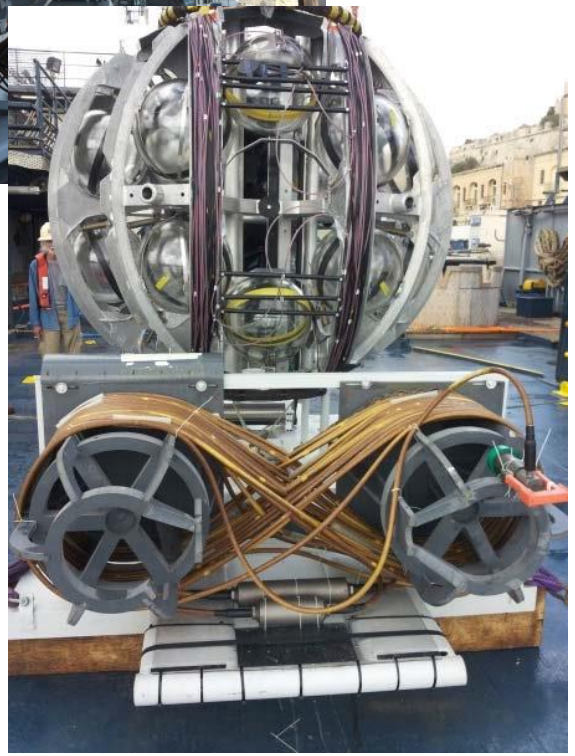


KM3NeT 'Mini-line' Deployed at Capo Passero (May 7, 2014)

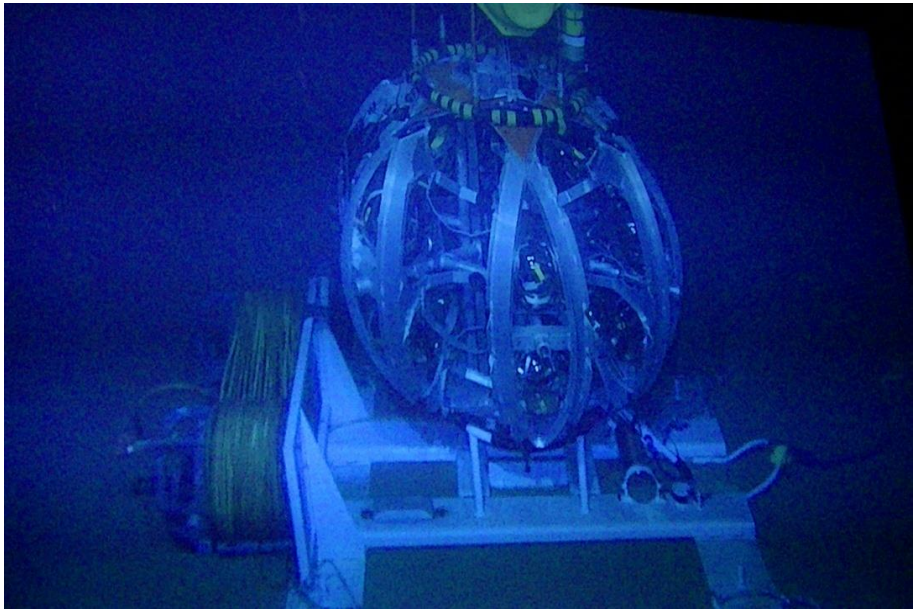


Integration
Nikhef +
CPPM

Deployment
Sicily

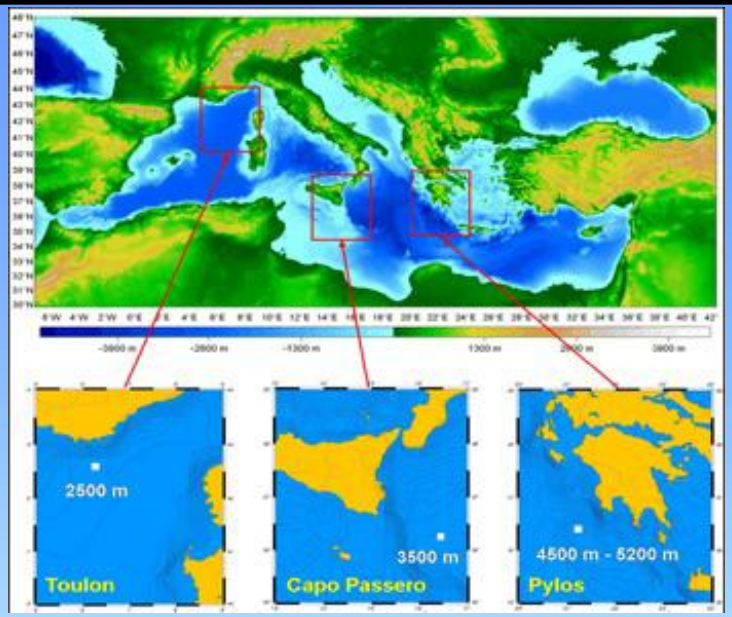


KM3NeT ‘Mini-line’



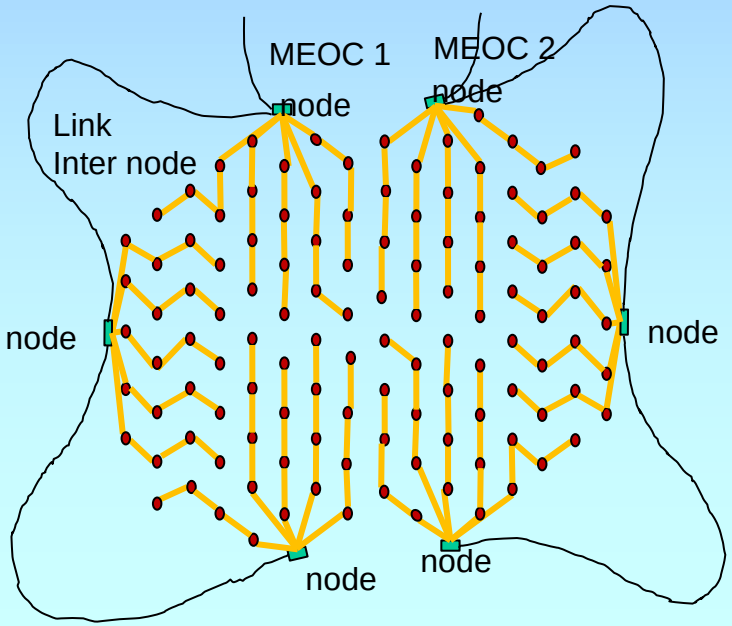
Seabed Infrastructure

- Distributed submarine infrastructure:
  - KM3NeT-France (Toulon)
    ~2500m
  - KM3NeT-Italy (Capo Passero)
    ~3400m
  - KMNeT-Greece (Pylos) Phase2
    ~4500m

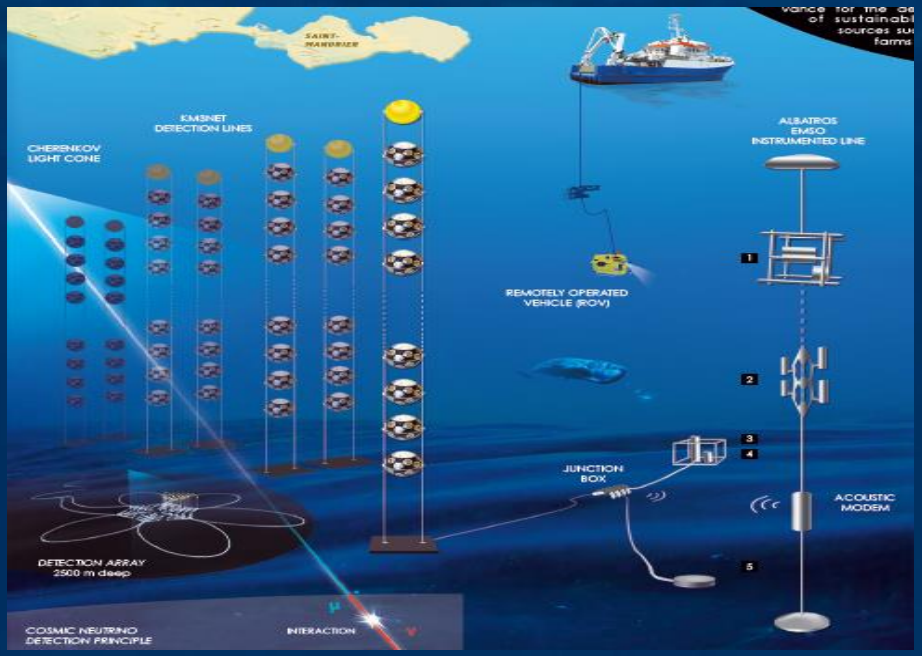


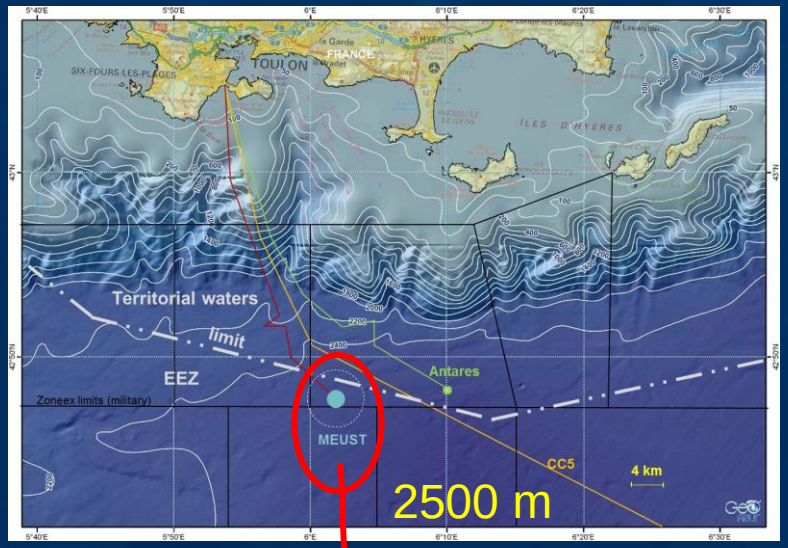
- Shore distances; 15km-100km
- Power via main electro-optical cable
  - short distances (AC), Long distances (DC)
  - 24-36 Optical fibres

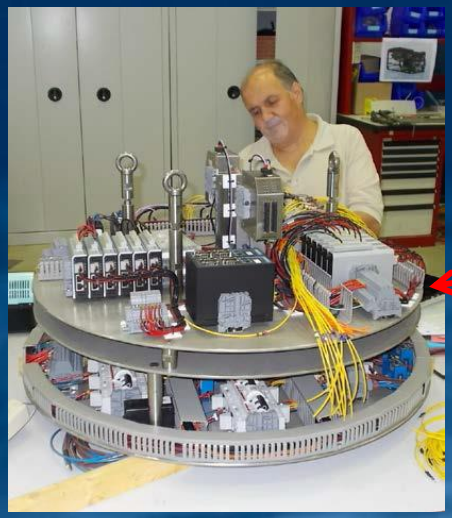
- e.g; KM3NeT-Fr
  - 3 nodes per MEOC
  - 20 strings per node
  - 4 strings in series

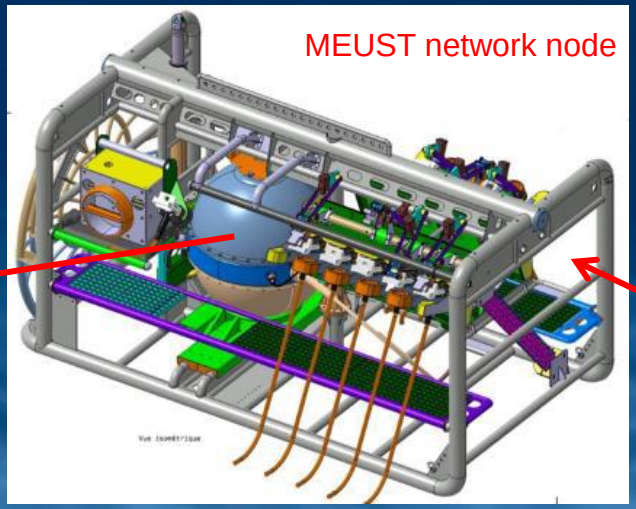


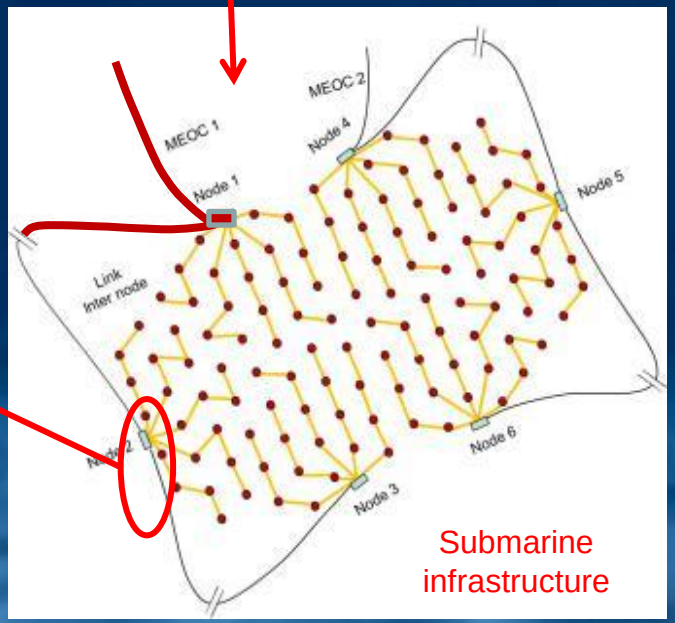
MEUST : a multi-disciplinary Deep Sea Observatory off Toulon for KM3NeT and EMSO





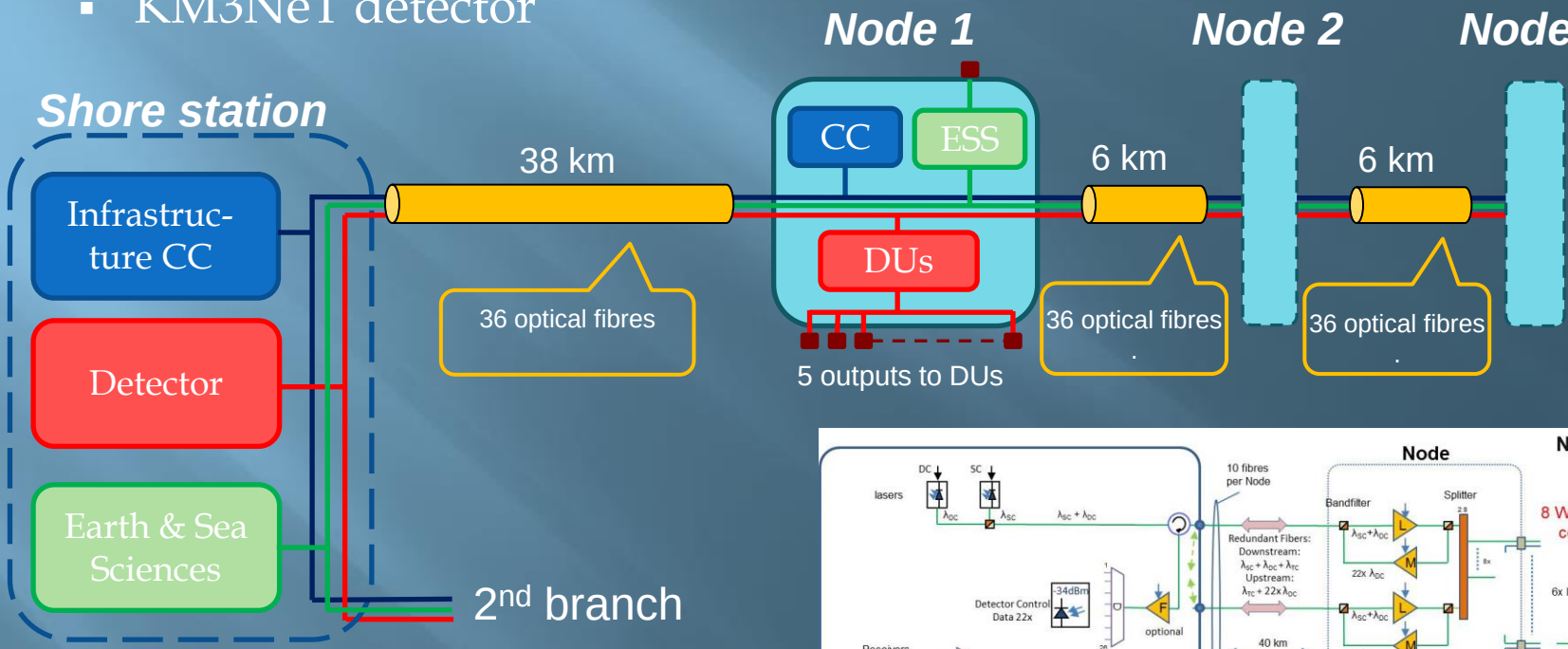


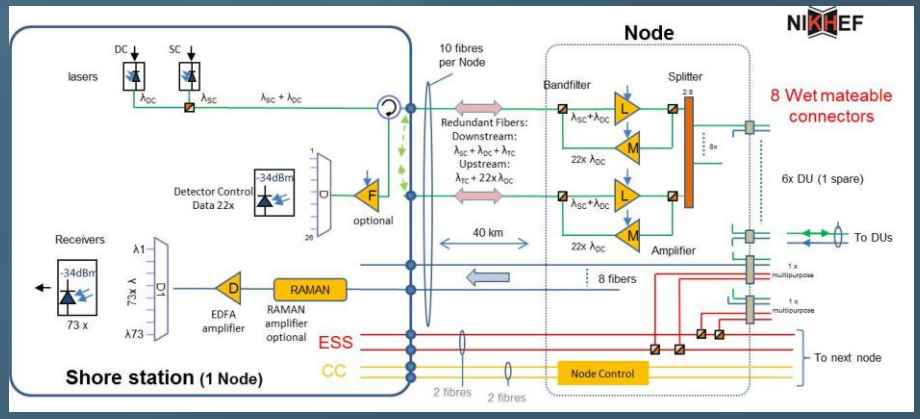




MEUST Optical network

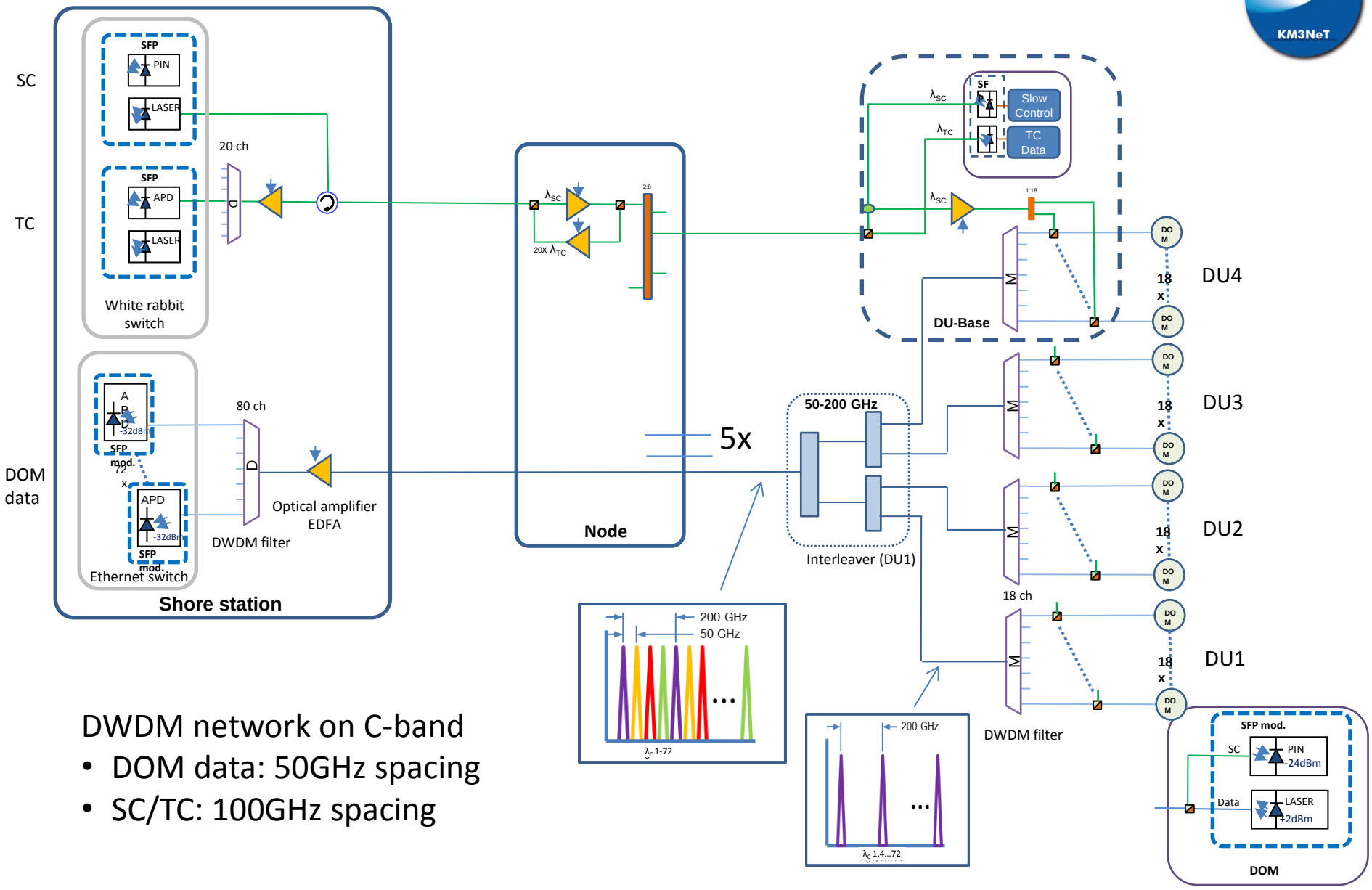
- 3 independent networks in the infrastructure:
  - Infrastructure control/command
  - Earth & Sea Sciences (EMSO)
  - KM3NeT detector





Optical scheme from shore to the node

Optical scheme for the KM3NeT detector

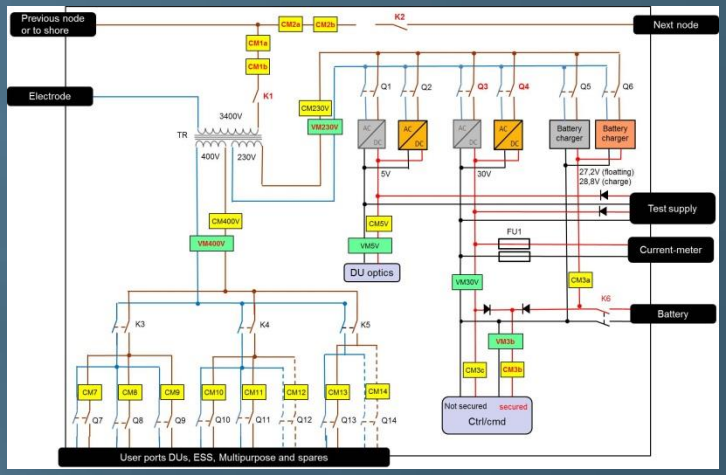


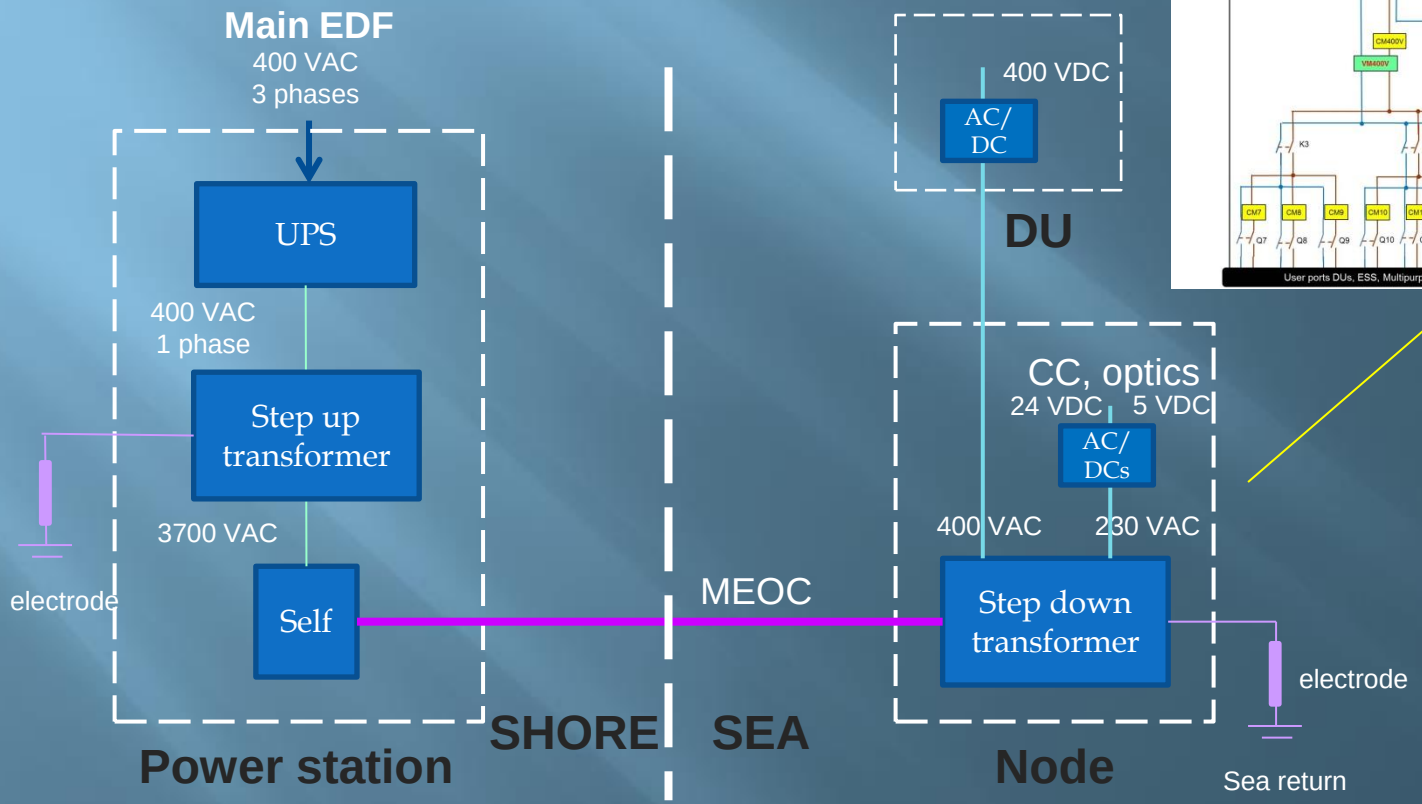
DWDM network on C-band

- DOM data: 50GHz spacing
- SC/TC: 100GHz spacing

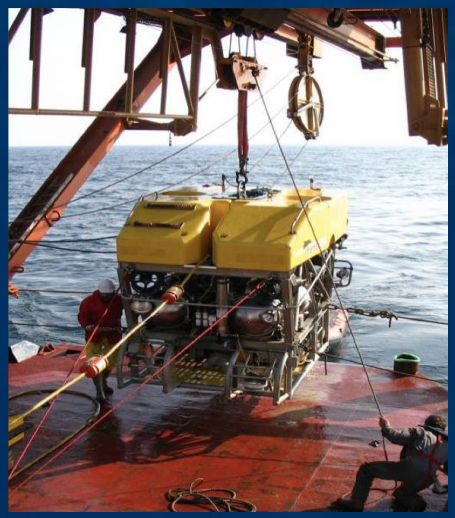
Power distribution system

- AC voltage distribution with sea return
- 10 kVA per node
- 400 VAC to feed DUs & ESS





Submarine Connections

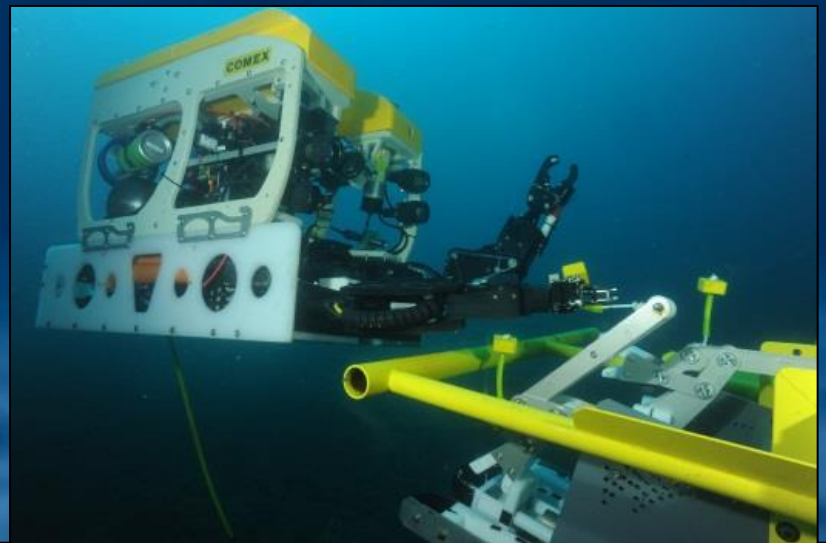


ROV VICTOR Ifremer

ODI wet-matable electro-optical connector :
4 optical fibres
2 electrical contacts

ROV Apache Comex

R&D connection with light ROV Apache

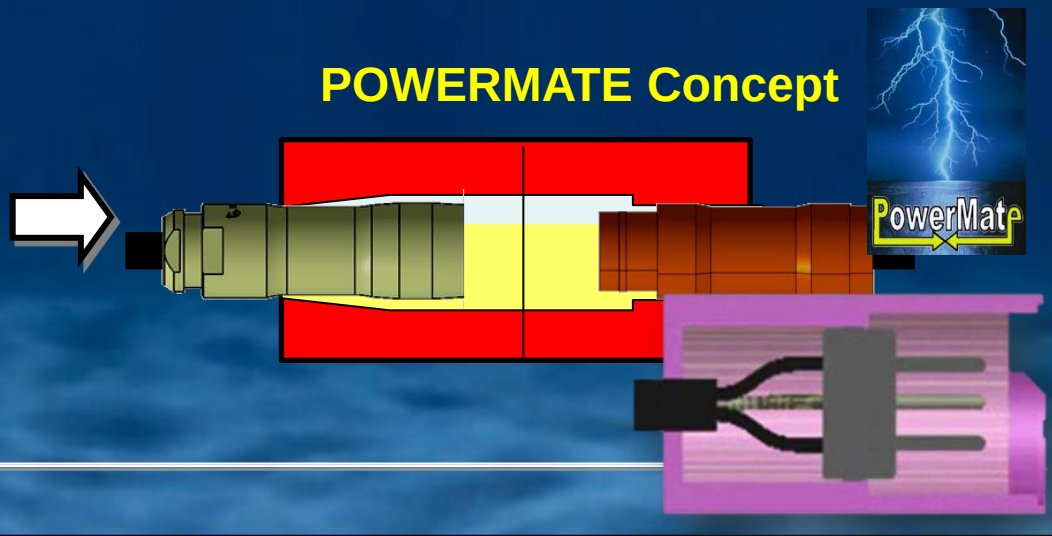


R&D on Submarine Connections

- Problems:
  - Submarine connections : ~10% of detector cost
  - 10% of connector failures
- R&D for :
  - Reduce the cost and improve reliability
  - Furnish electrical power in deep sea *(oil&gas, Marine energy)*
- Industrialisation : creation of **PowerSea,** Spin-off of CNRS

Exsisting wet-metable connectors

POWERMATE Concept



Summary and Outlook

- After decades of dream and intensive R&D, the Neutrino Astronomy is finally **opening a new window** over the Universe

- ANTARES is recording neutrino events everyday
  → ~8000 neutrinos recorded so far, more to come !
  → more analysis in progress **looking for origins of HE Cosmic Rays and for Dark Matter**

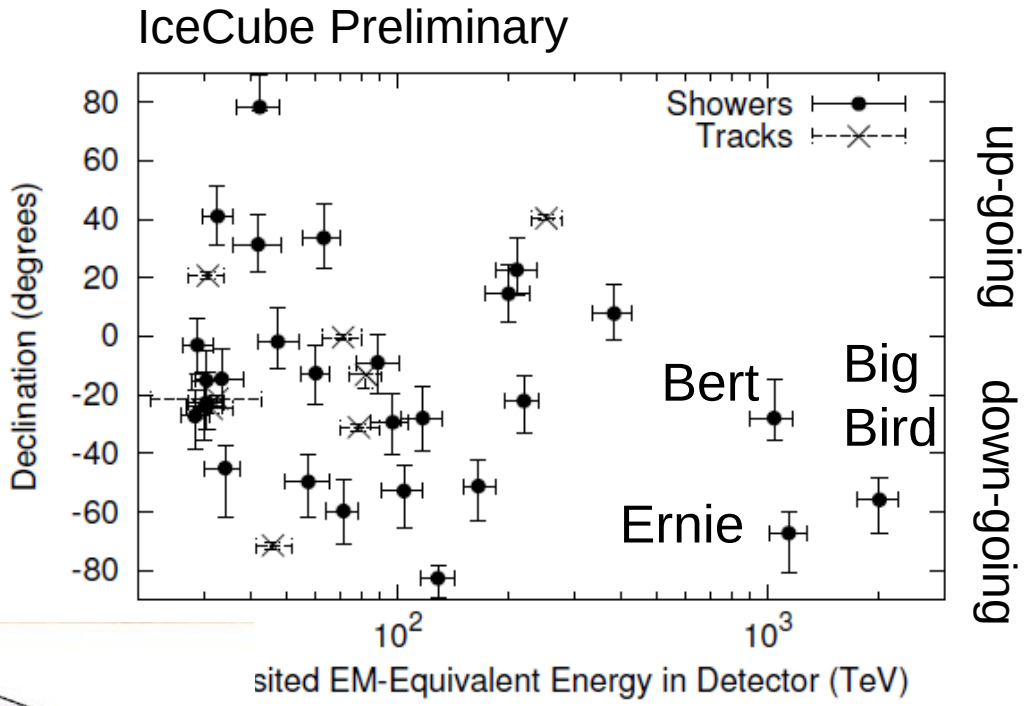
- KM3NeT R&D improved costs and reliability w.r.t. ANTARES
  →**Technology is mature to build within the next decade deep sea multi-science observatories for:**
  - Neutrino Astronomy (KM3NeT),
  - Neutrino mass hierarchy measurement (ORCA),
  - Earth, Sea and Environmental Science (EMSO)

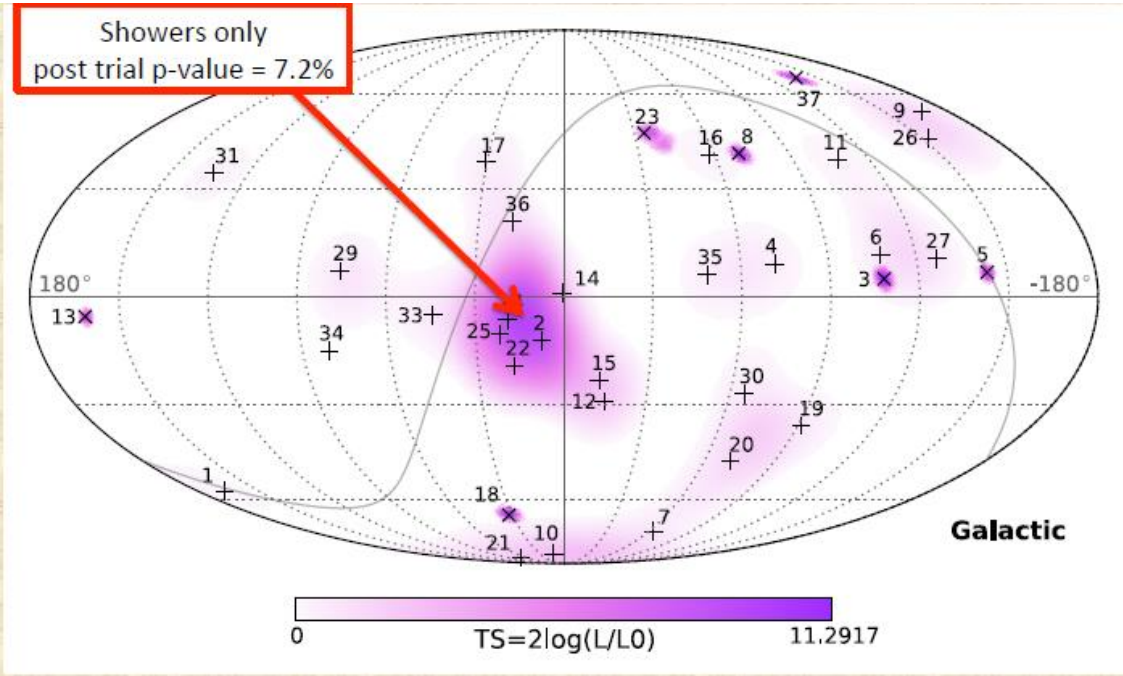
ANTARES : Fishing stars…or mysteries ??

IceCube Signal for Diffuse Flux

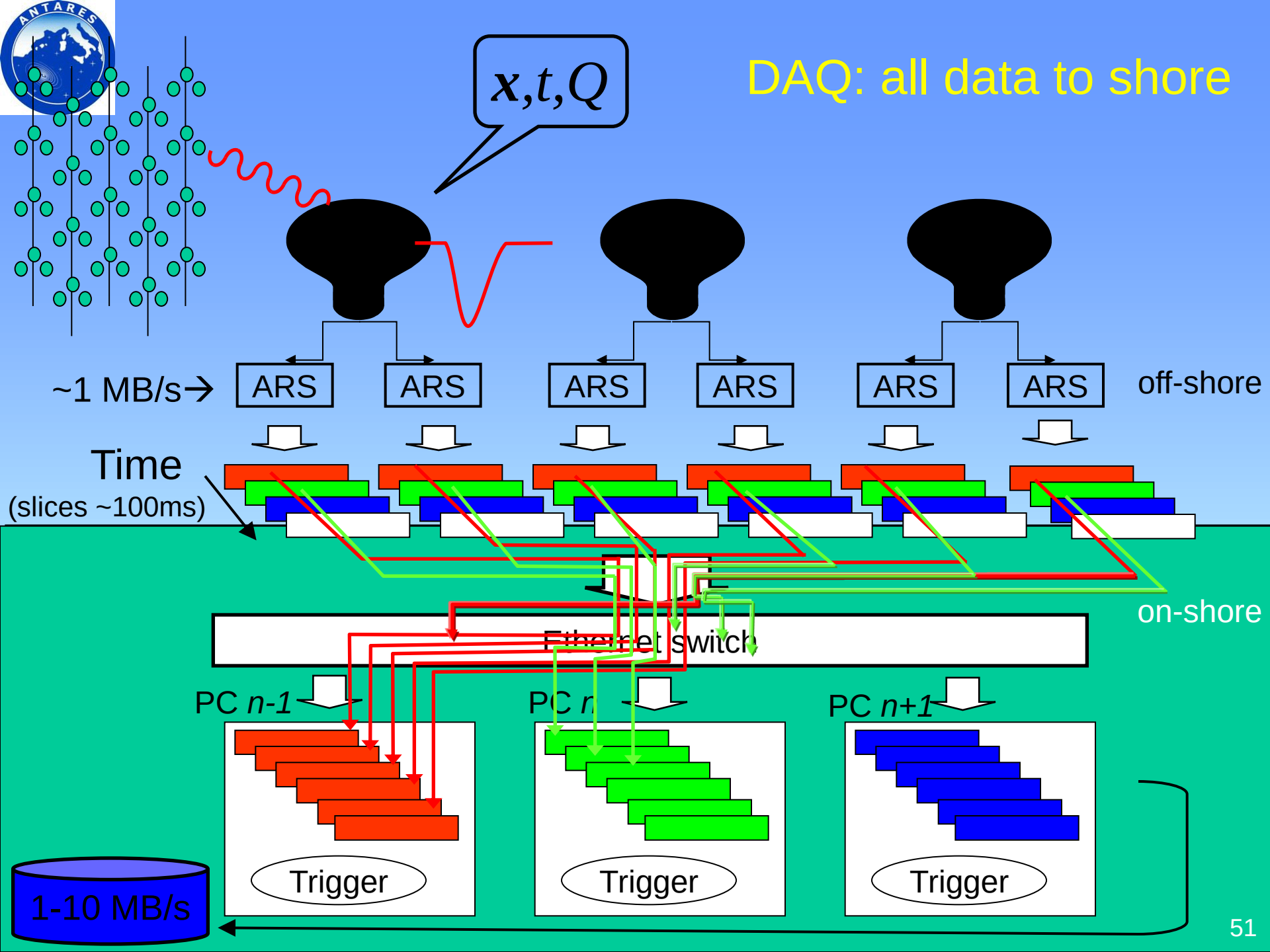
Mainly shower events with poor angular resolution (~15˚)

Shower events: clustering near Galactic Centre (7% prob)?

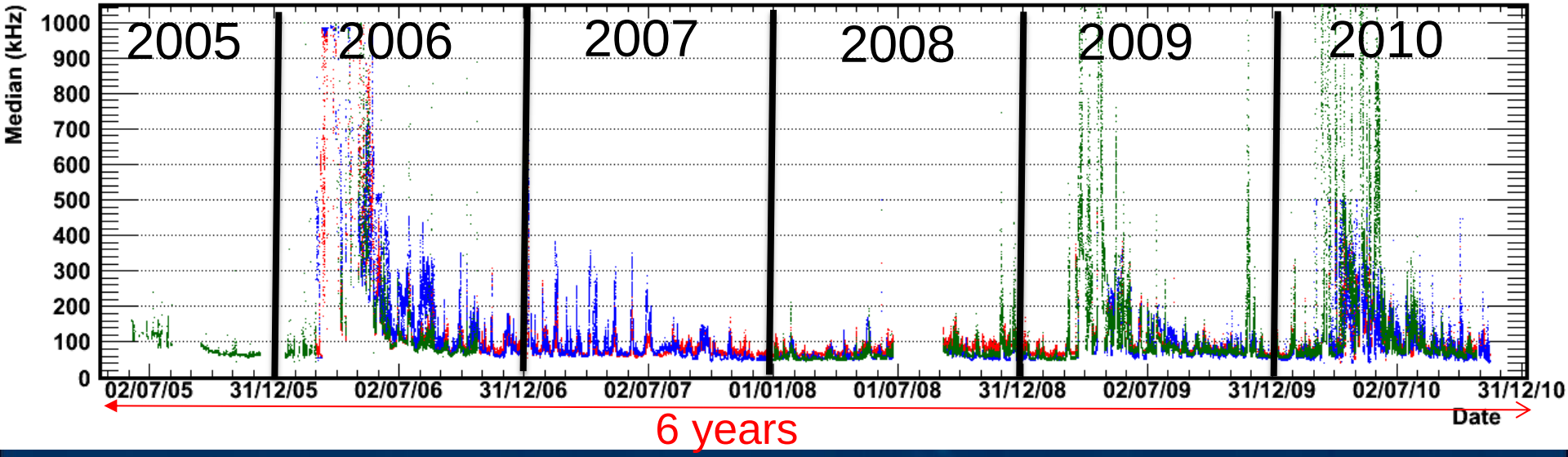




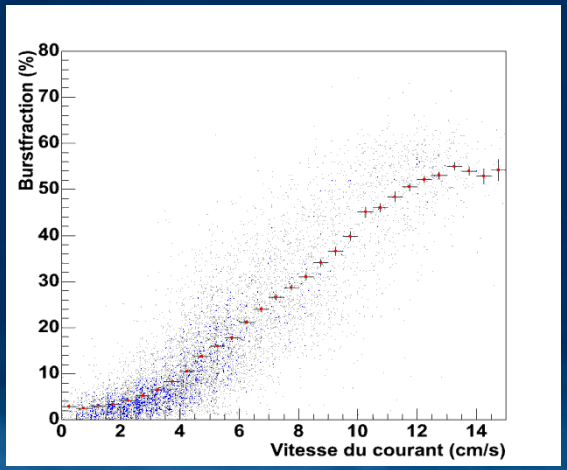
DAQ: all data to shore



Seasonal Variations in Counting Rates

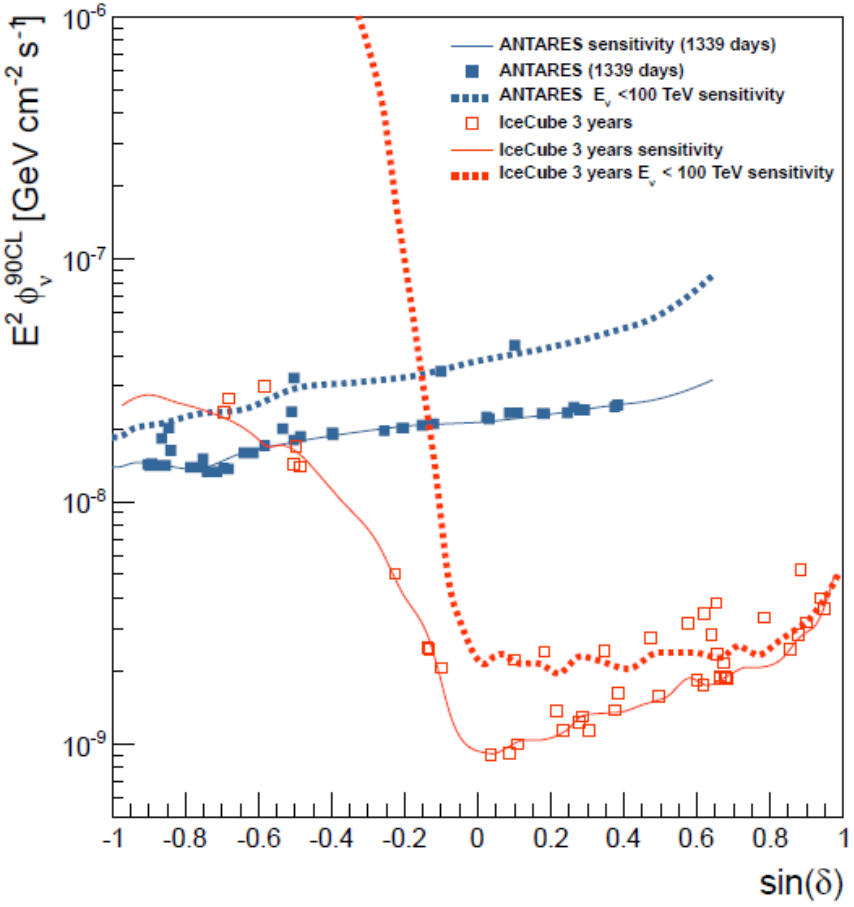


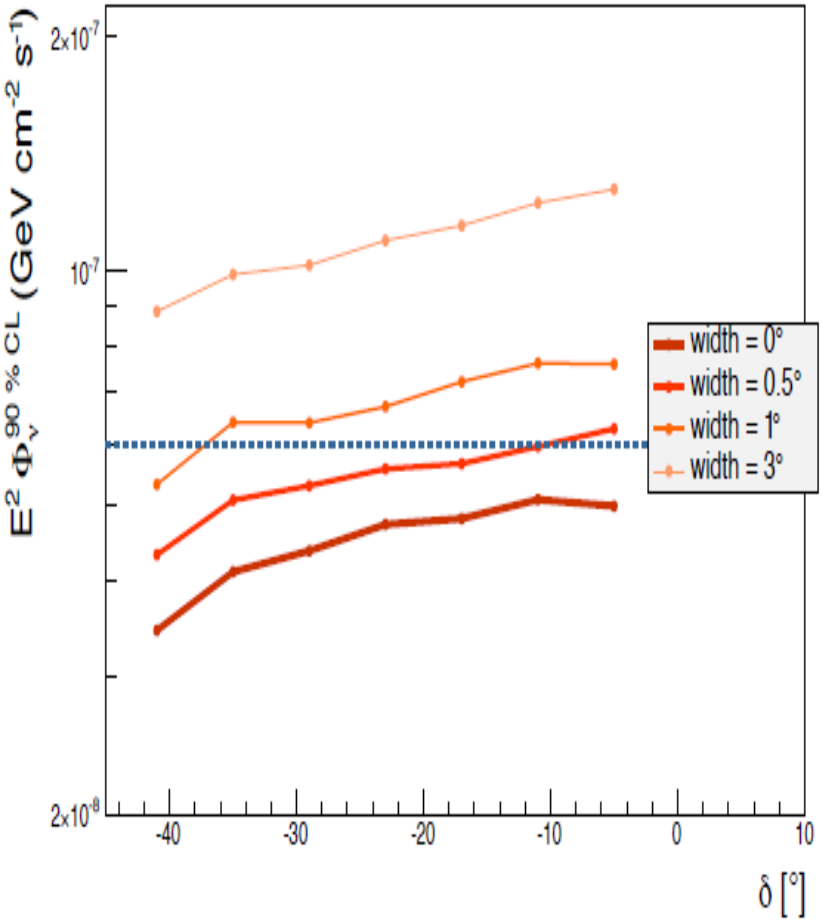
Burst fraction correlated with sea current – bioluminscence induced by Impact/turbulence of structure



'Spring' effect –observed in 2005, 2006, 2009, 2010, 2011

Search for neutrino point sources





Factor 2 improvement
cf 2 years ago

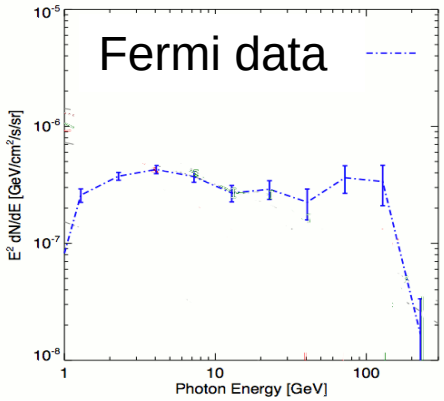
Exclude IceCube ‘cluster’ is due to a point source up to an extension of 1°

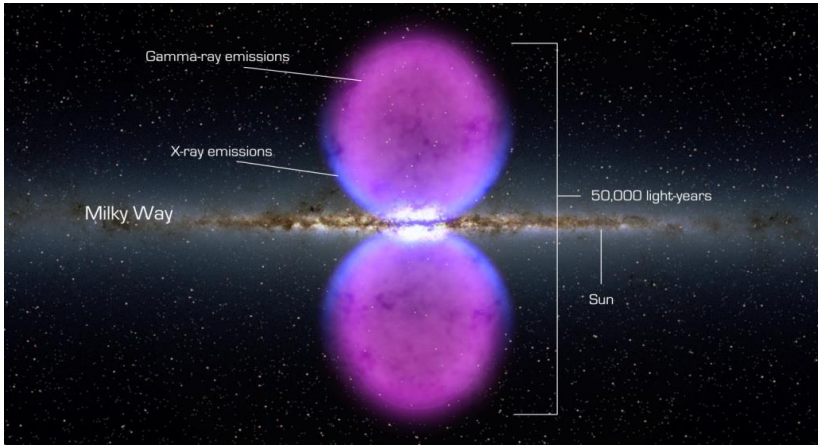
Search for a Diffuse Emission from the Fermi Bubbles I

➢Excess of γ- (and X-)rays in extended "bubbles" above and below the Galactic Center

➢ Homogenous intensity, hard (E^{-2}) spectrum with probable cutoff

📖 M. Su et al., Ap. J. 724 (2010)





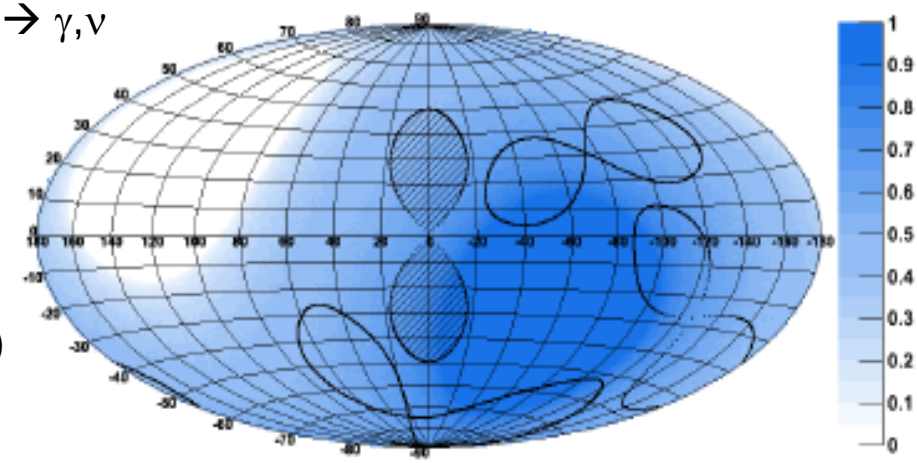
➢ Origin still debated;

promising Galactic wind model involves hadronic processes (📖 Crocker & Aharonian, PRL 2011):
accelerated cosmic rays interacting with ISM → π → γ,ν

$\Phi_\nu \approx 0.4 \times \Phi_\gamma$

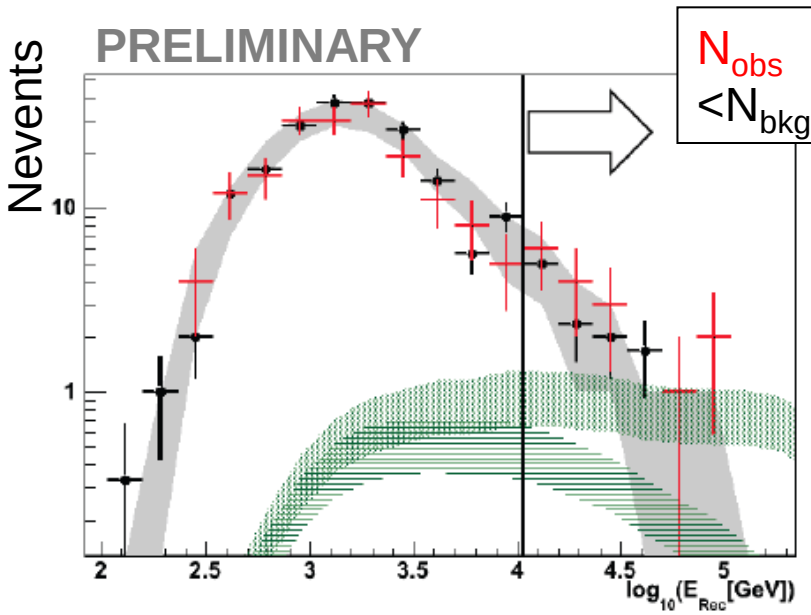
➢ In the field of view of ANTARES

background estimated from average of
3 non-overlapping "off-zone" data regions
(same size, shape and average detector efficiency)

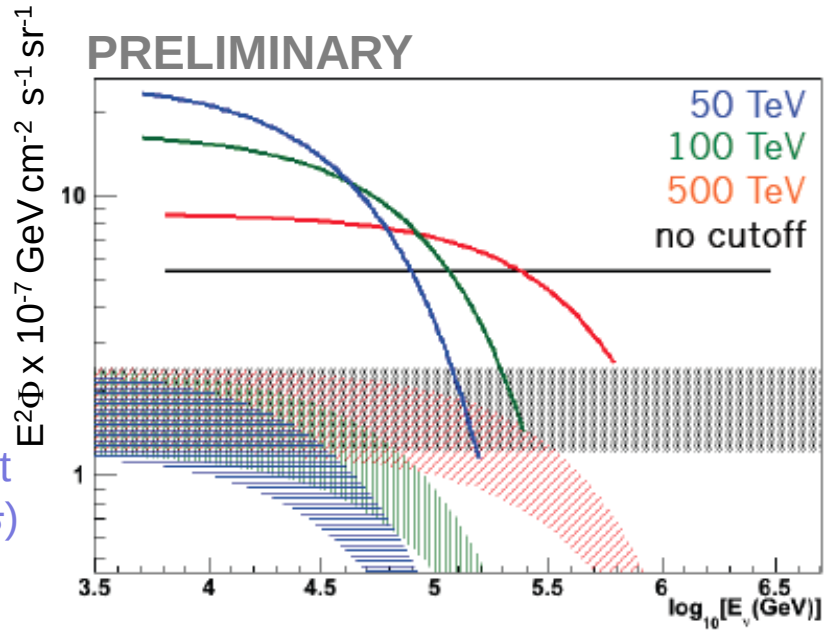


Search for a Diffuse Emission from the Fermi Bubbles II

- 12-line data sample: May 2008 - Dec 2011 (806 days livetime) muon neutrinos only
- E_ν estimation based on Artificial Neural Networks procedure
- Optimization tuned on off-zone background events (MRF)



No significant excess (1.2 σ)

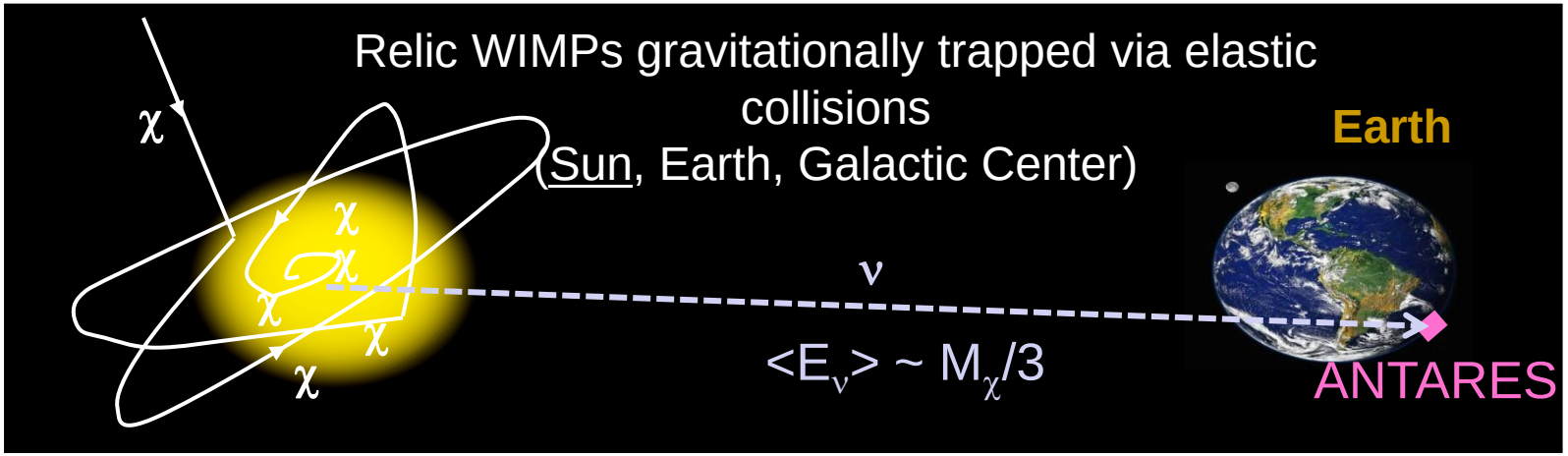


on-zone
off-zone average
expected signal (≠ cutoff, 50TeV cutoff)

Upper limits with respect to different models
65% improvement expected with 2012-2016 data

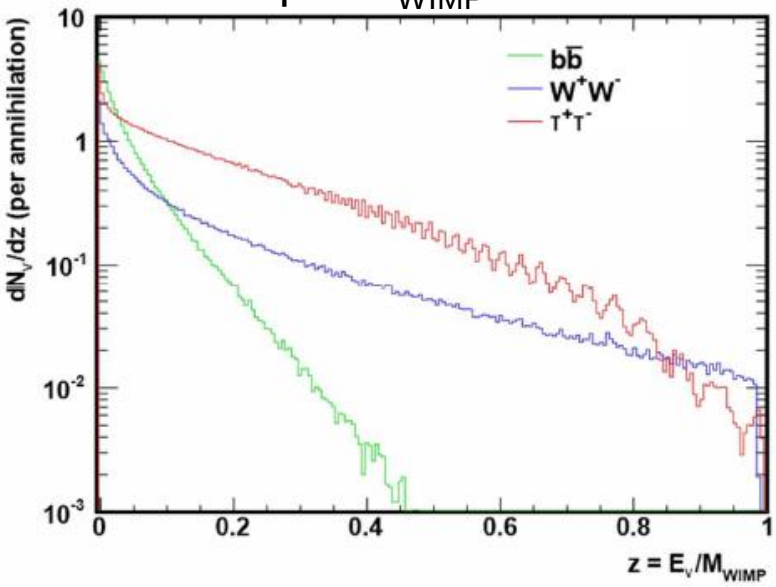
S. Adrián-Martínez et al., accepted for publication in European Physics Journal C.

Indirect search for Dark Matter



- HE neutrinos from the Sun → Clean DM signature
- Models where Lightest SUSY Particle (LSP) is stable (R-parity conservation) are considered
- Self-annihilation in c,b,t quarks, τ leptons or W, Z,H bosons induce HE neutrino flux → benchmarks
  - → b quarks (soft spectrum)
  - → τ leptons
  - → W bosons (hard spectrum)
- Model-independent simulation using WIMPSIM 🕮JCAP01(2008)021

Example M_{WIMP}= 350 GeV

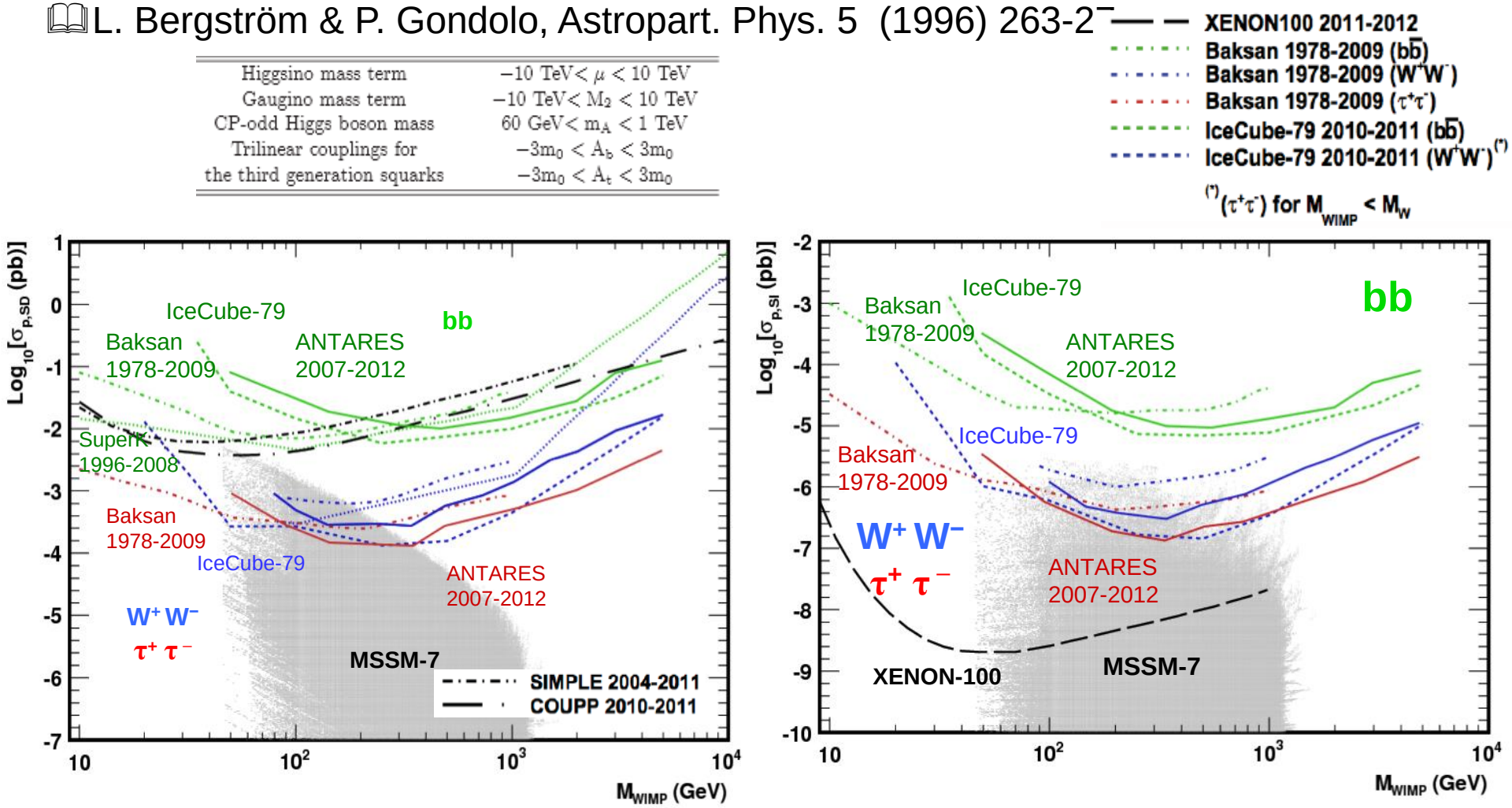


Indirect search for Dark Matter: Sun

➡ Limits on WIMP-proton SD/SI cross sections (equilib. capture/annihilation)
→ Much better sensitivity on SD cross sections w.r.t direct detection

Comparison to predictions of MSSM-7 phenomenological model
📖 L. Bergström & P. Gondolo, Astropart. Phys. 5 (1996) 263-2

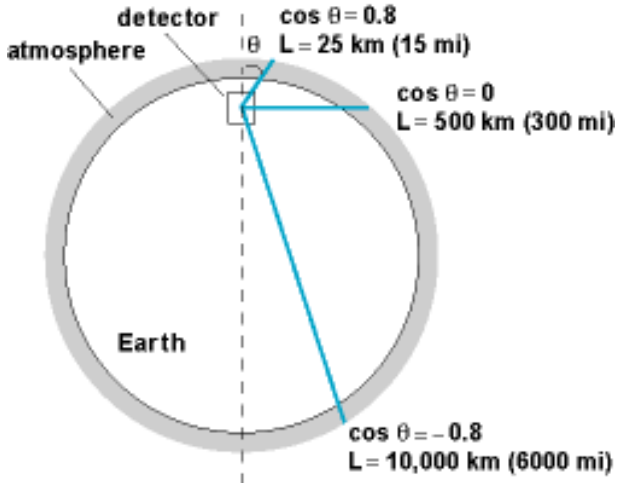
Higgsino mass term	$-10\ \text{TeV} < \mu < 10\ \text{TeV}$
Gaugino mass term	$-10\ \text{TeV} < M_2 < 10\ \text{TeV}$
CP-odd Higgs boson mass	$60\ \text{GeV} < m_A < 1\ \text{TeV}$
Trilinear couplings for	$-3m_0 < A_b < 3m_0$
the third generation squarks	$-3m_0 < A_t < 3m_0$

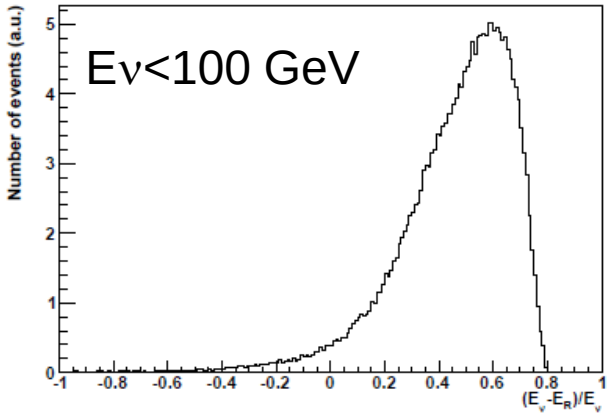


Oscillations with Atmospheric Neutrinos

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{16200\ \Delta m^2_{32} \cos\Theta}{E_\nu}\right)$$

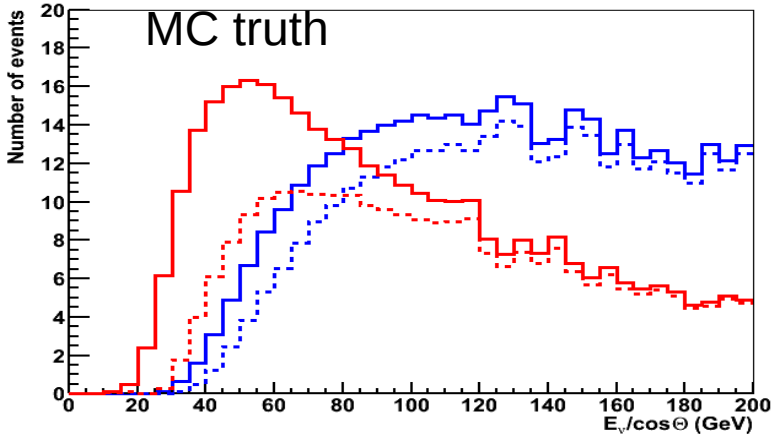
L=2 R_{Earth} cosθ, from track fit





Oscillations maximal at 24 GeV for vertical neutrinos (muon range~120m)

Larger effect on single-line (low energy) than multi-line (higher energy) events



Neutrino Oscillations: Result

2008-2010 data (863 days):

No oscillation: χ^2/NDF = 40/24 (2.1%)

Best fit: χ^2/NDF = 17.1/21

$\Delta m^2 = 3.1\ 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.00$

Systematics:

(Absolute normalisation free)

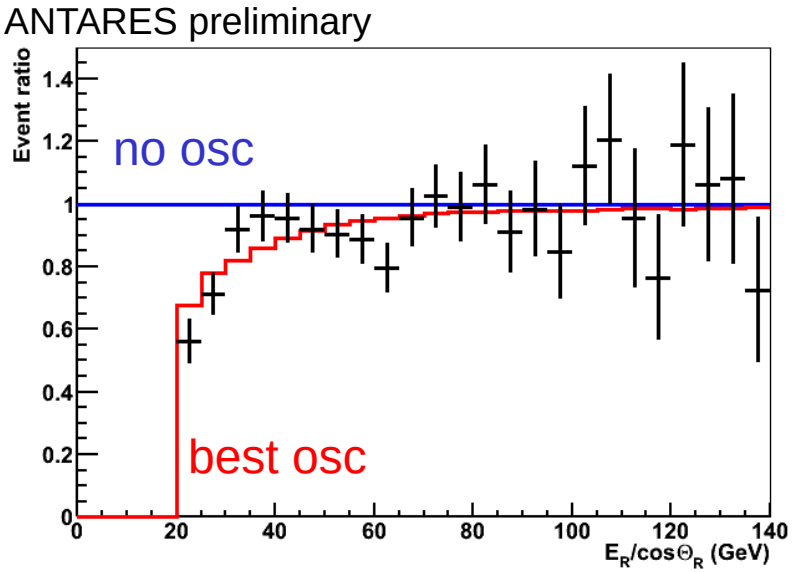
Absorption length: ±10%

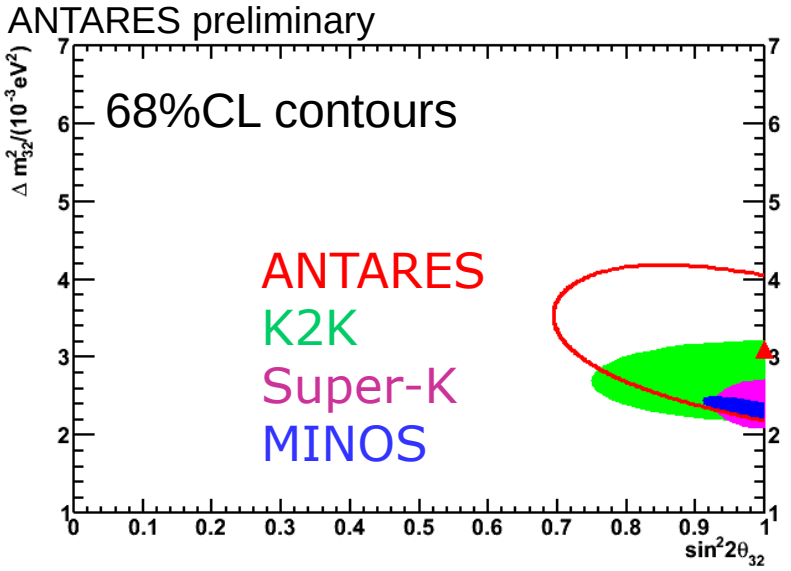
Detector efficiency: ±10%

Spectral index of ν flux: ±0.03

OM angular acceptance

5% error on slope vs $E_R/\cos\vartheta_R$





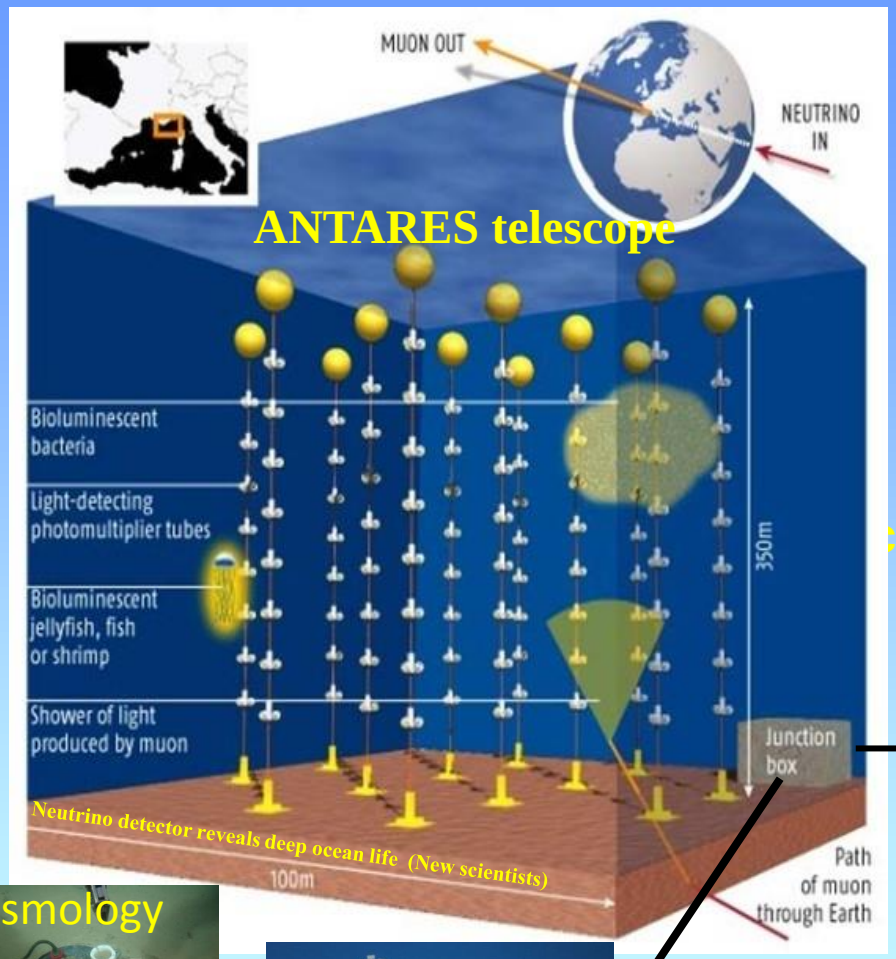
Assuming maximal mixing: $\Delta m^2=(3.1\pm0.9)\ 10^{-3}\ eV^2$

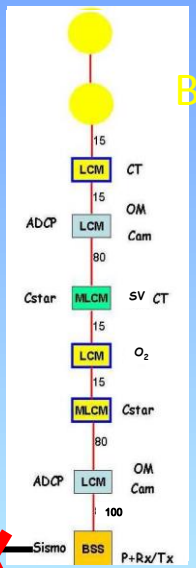
PLB: arXiv:1206.0645

Un Observatoire Pluridisciplinaire en Mer Profonde

Biology

Bioluminescence





Biogeochemistry

Oceanography

IL07

Microbial ecology

Since Nov 2010

Environmental research

Sismology

BJS

MII

Multidisciplinary research activity: The IL07 Instrumentation Line

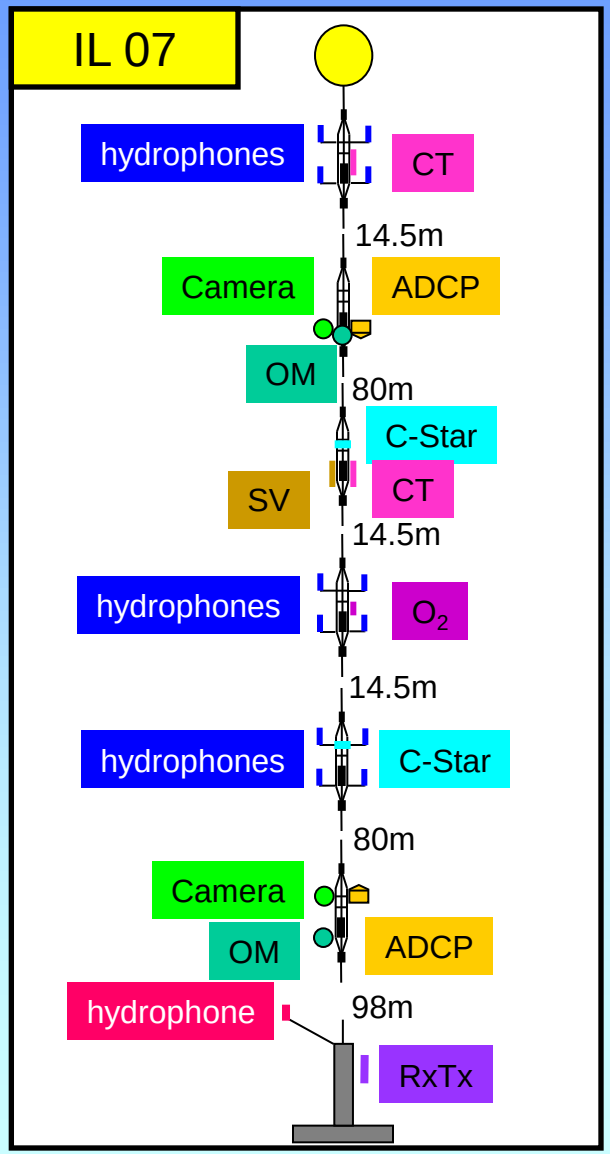
Goals:

- monitor of environmental sea parameters
- apparatus calibration

+ <u>acoustic detection prototyping</u>

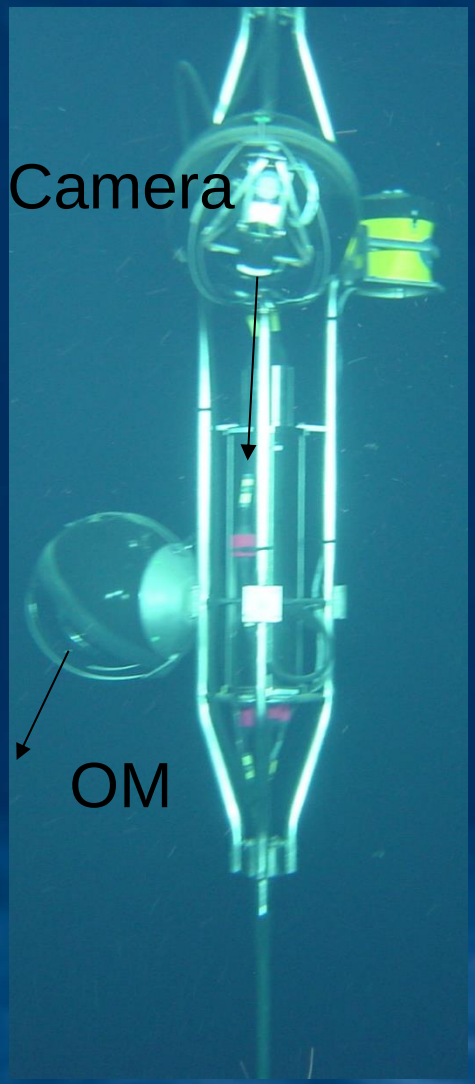
- WetLabs **CSTAR** light transmissometer
- **CT** = Seabird Conductivity-Temperature probe
- **SV** = Sound Velocimeter
- **ADCP** = Acoustic Doppler Current Profiler
- GURALP seismometer (moved to L12)
- 2 OMs
- Acoustic Positioning RxTx
- 0_2-probe
- 2 cameras

  +
- <u>Three floors equipped for acoustic detection R&D</u> (AMADEUS)



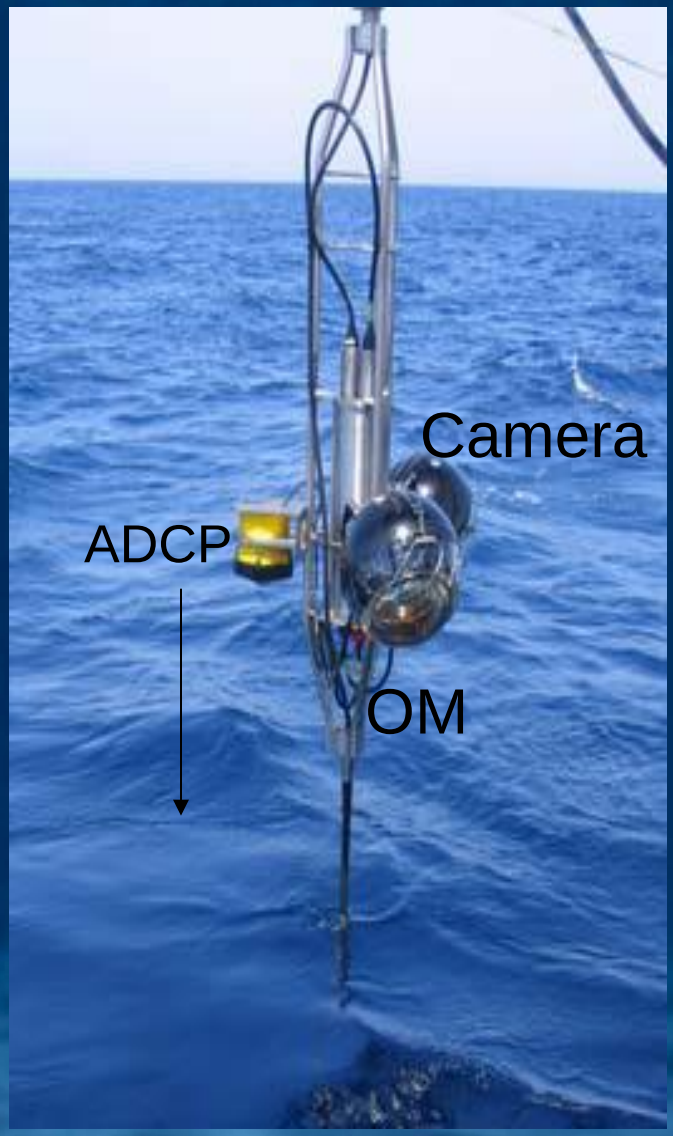
Real Time Video Cameras

Floor 1

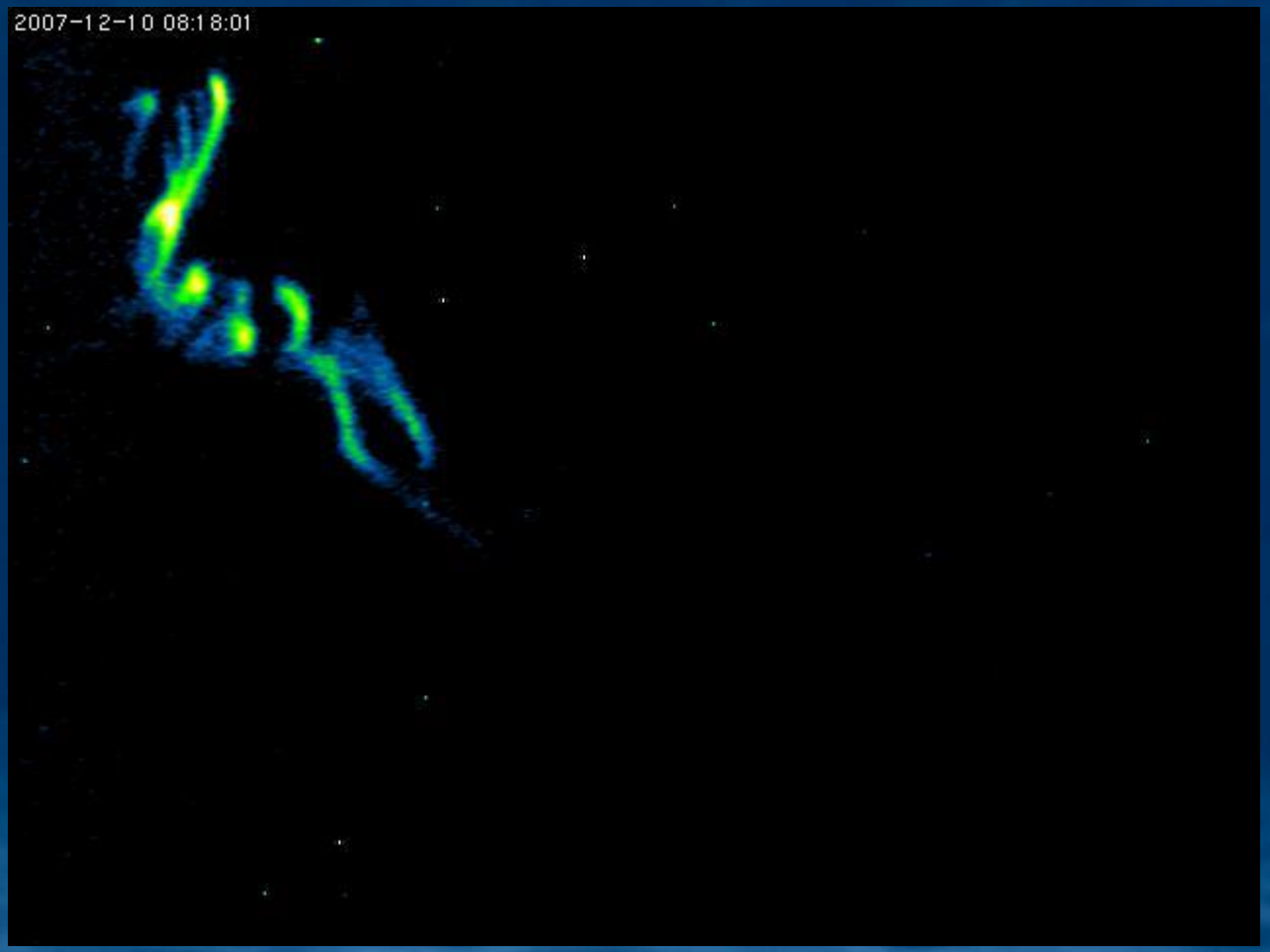


AXIS221 vidéosurveillance
Sensistivity: 0.1 lux
Field of view: up to 90 degrees
Self triggering
Infra red night vision

Floor 5

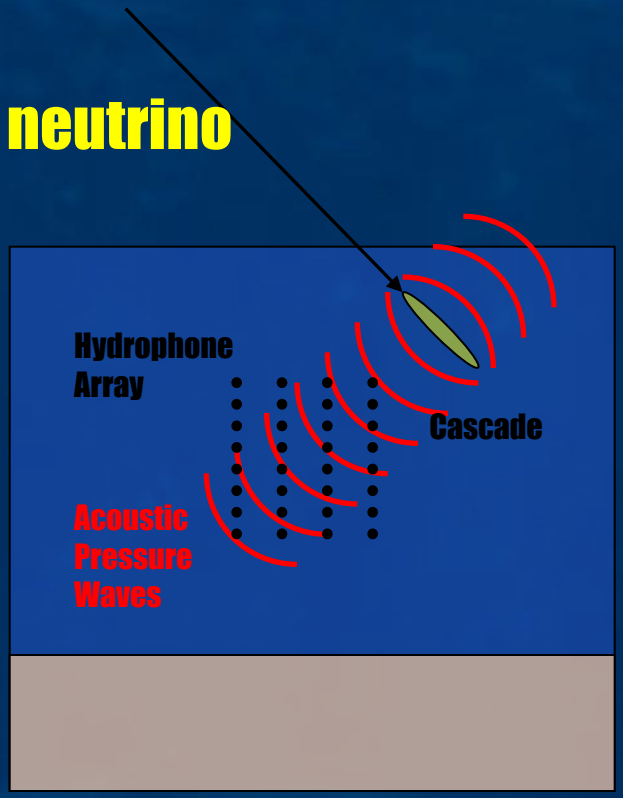


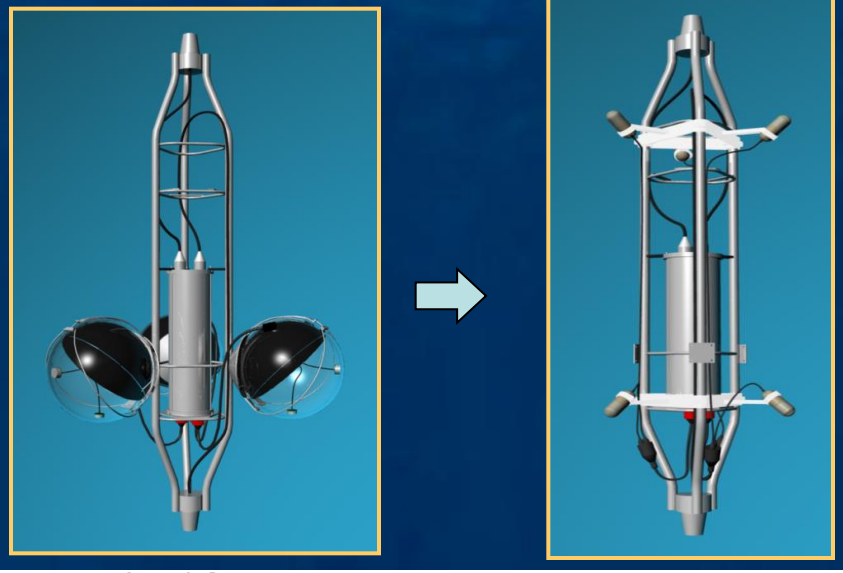
Early image 2sec exposure

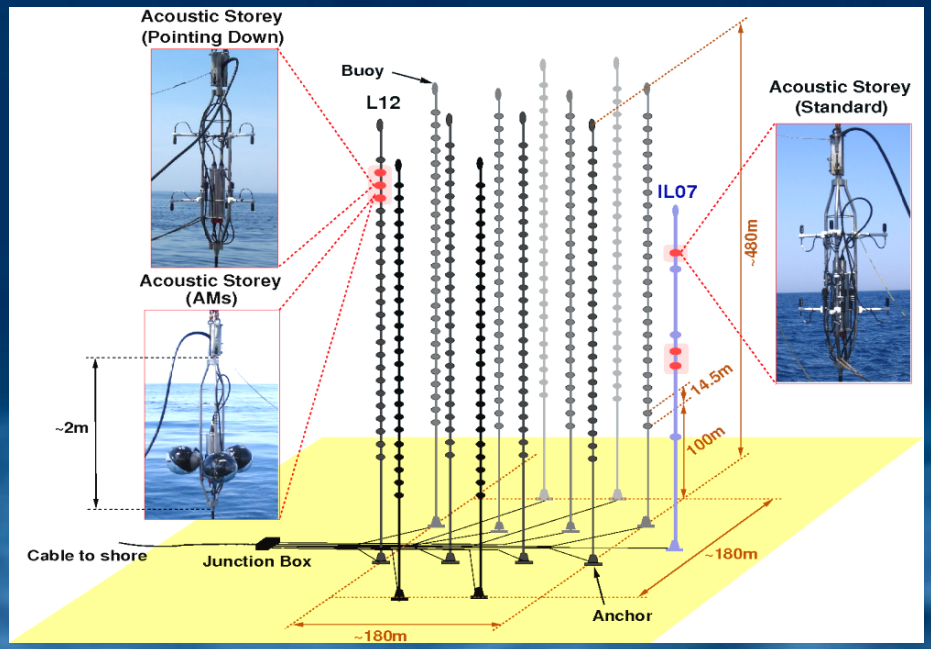


Extended object

AMADEUS: Acoustic Detection of Neutrinos



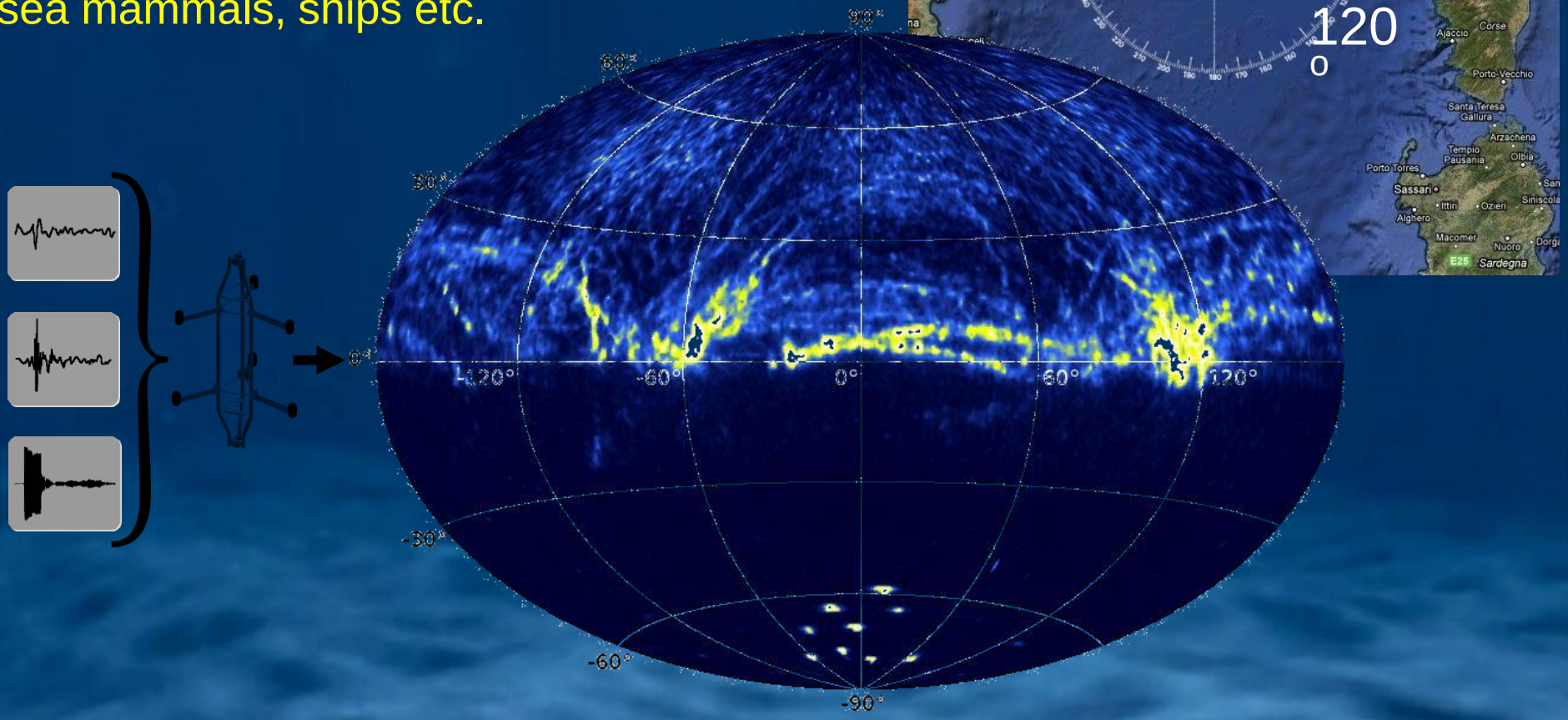




Acoustic Source Direction Distribution

Direction reconstruction from
one storey on L12

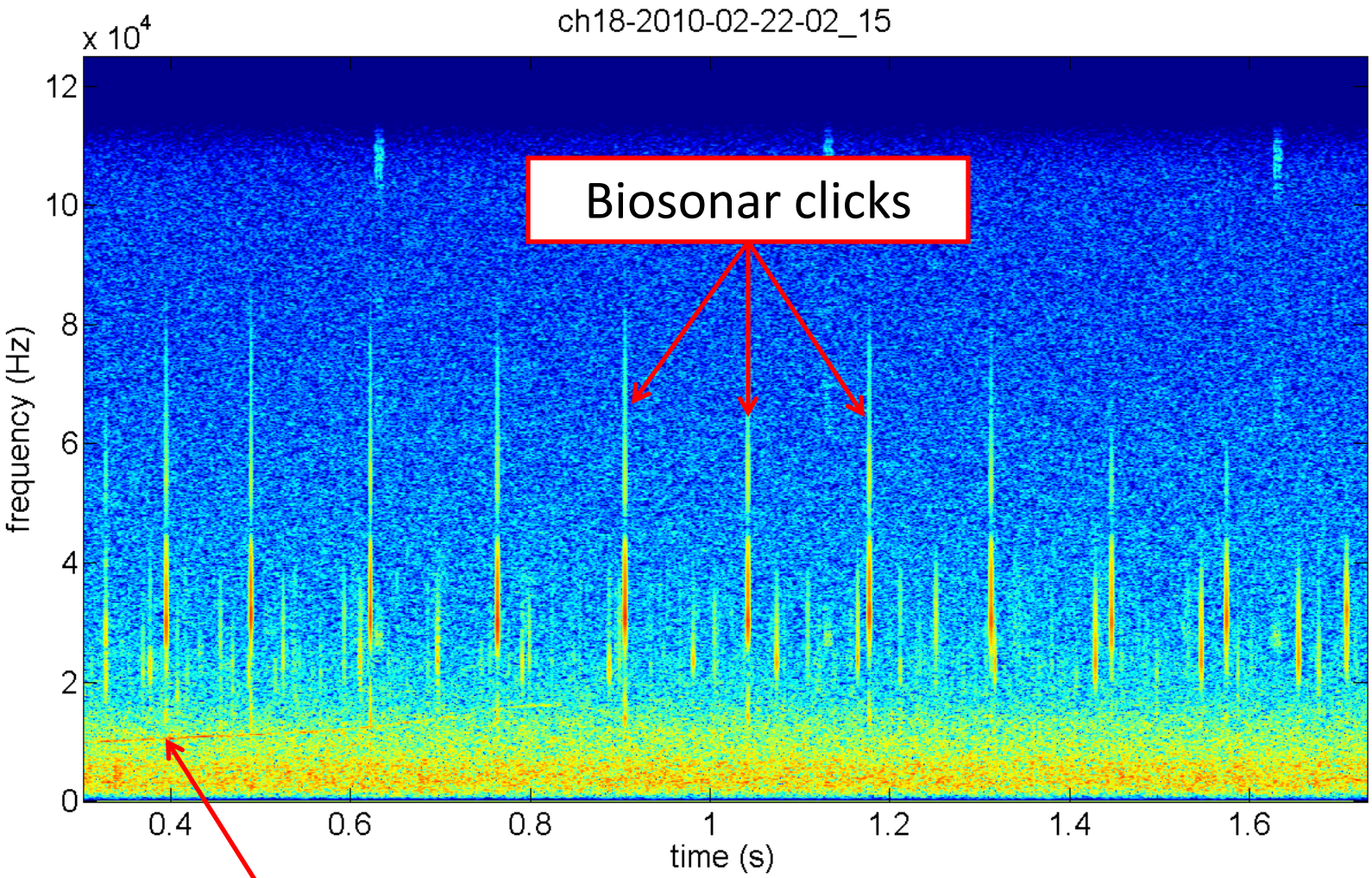
All types of transient signals included,
sea mammals, ships etc.



http://www.listentothedeep.com

LABORATORI D'APLICACIONS BIOACUSTIQUES
Universitat Politécnica de Catalunya

Dense series of ultrasonic clicks,
(biosonar) from beaked whales or dolphins



3-inch PMTs

Key features:

– timing	≤ 4.5 ns (FWHM)
– QE	≥ 25-30%
– collection efficiency	≥ 90%
– photon counting purity	100% (by hits, up to 7)
– price/cm^2	≤ 10” PMT

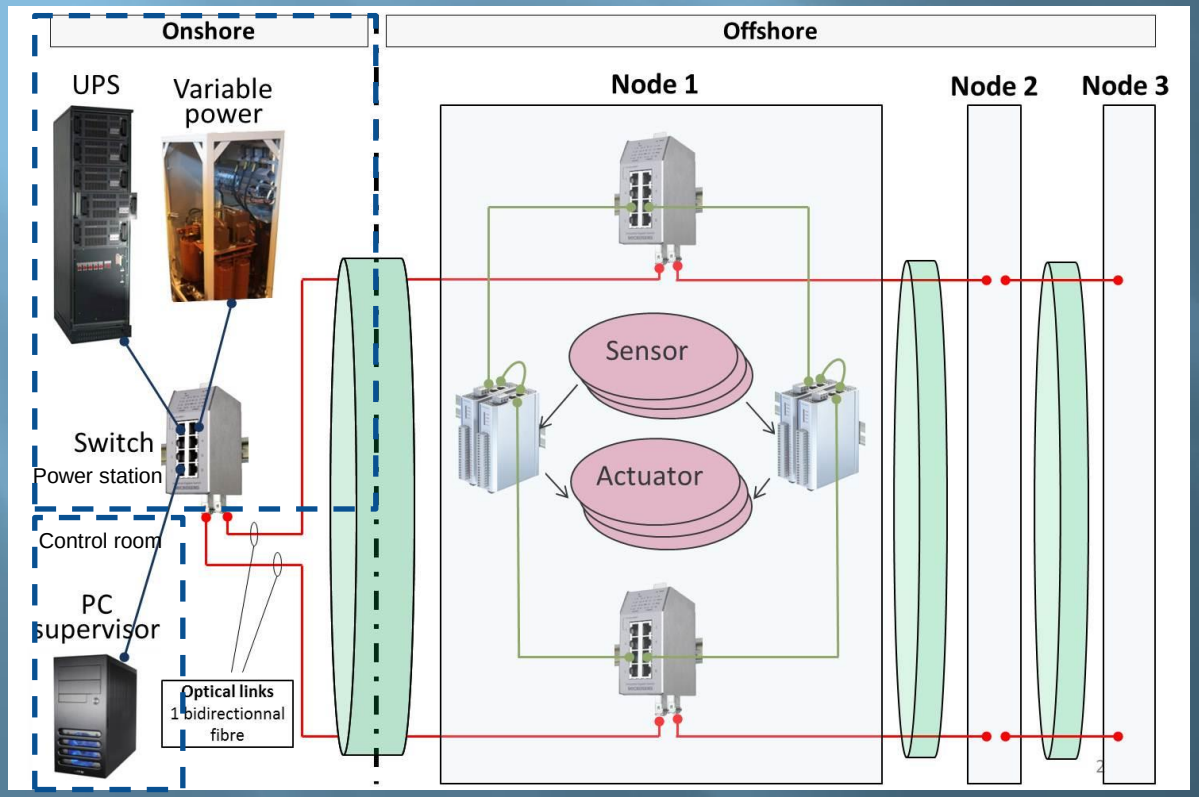
ETEL D792

Hamamatsu R12199

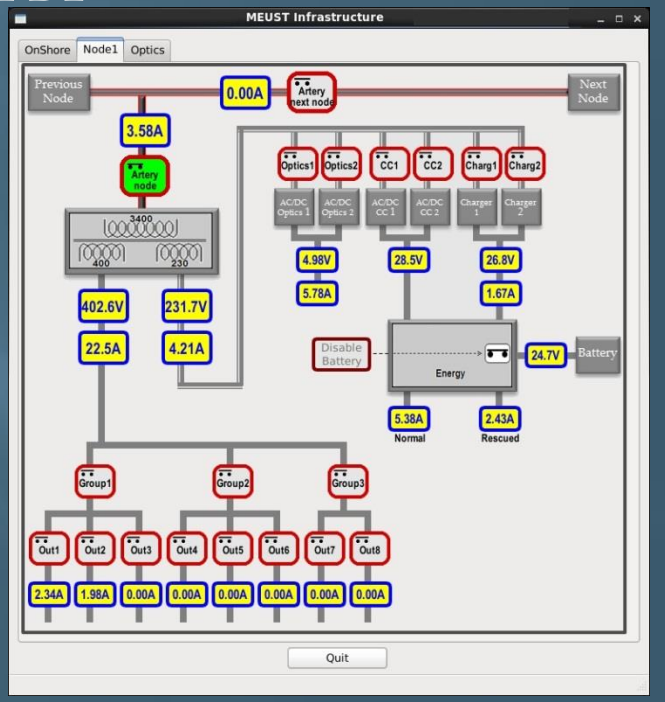
HZC XP53B20

Control/command

- Manage infrastructure (mainly the power system & DU optics in the node)
- Based on redundant Ethernet network
- Industrial components with high MTBF



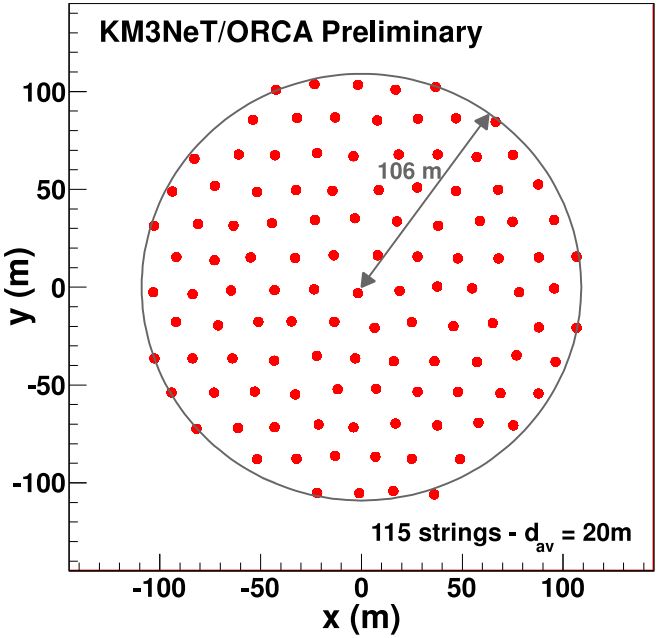
Scheme of the CC



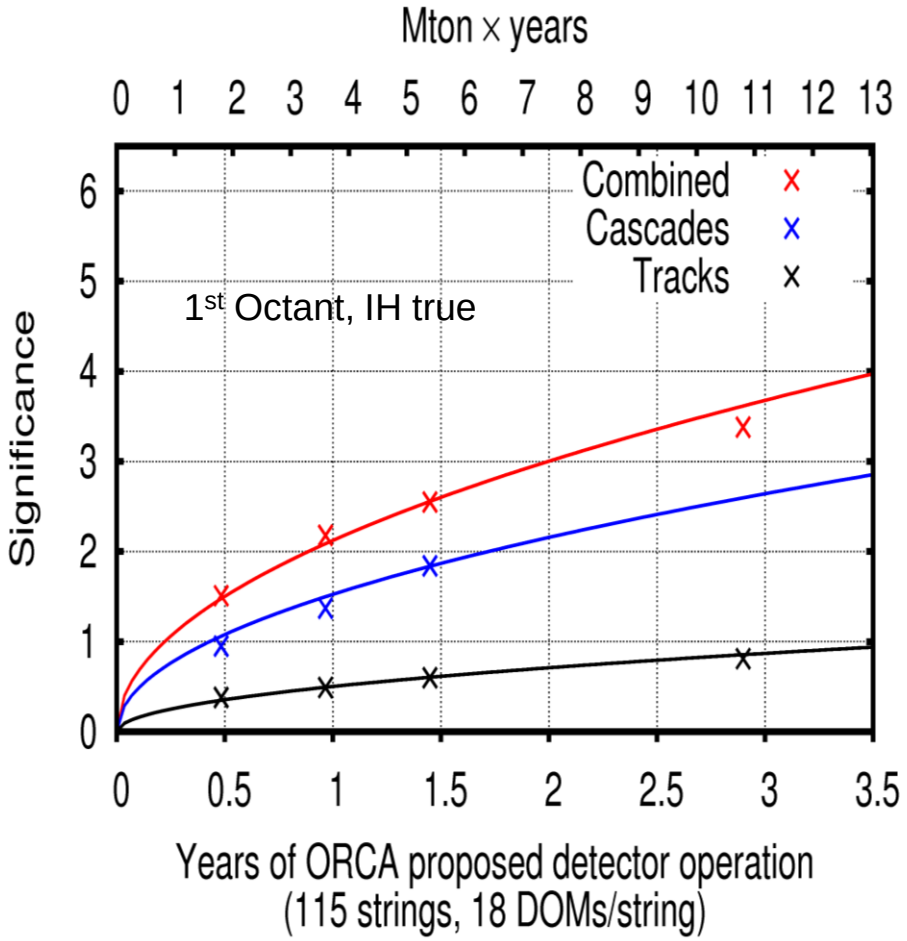
User interface for the node

ORCA: Mass Hierarchy Sensitivities

Oscillation Research with Cosmics in the Abyss (ORCA)



115 strings, 18 OM/string, 6m/20m



3.5 sigma in 3 years

+ Factor ~4 improvement on value of θ_{23}
+ Measurement of octant

ORCA competitive with other Expts

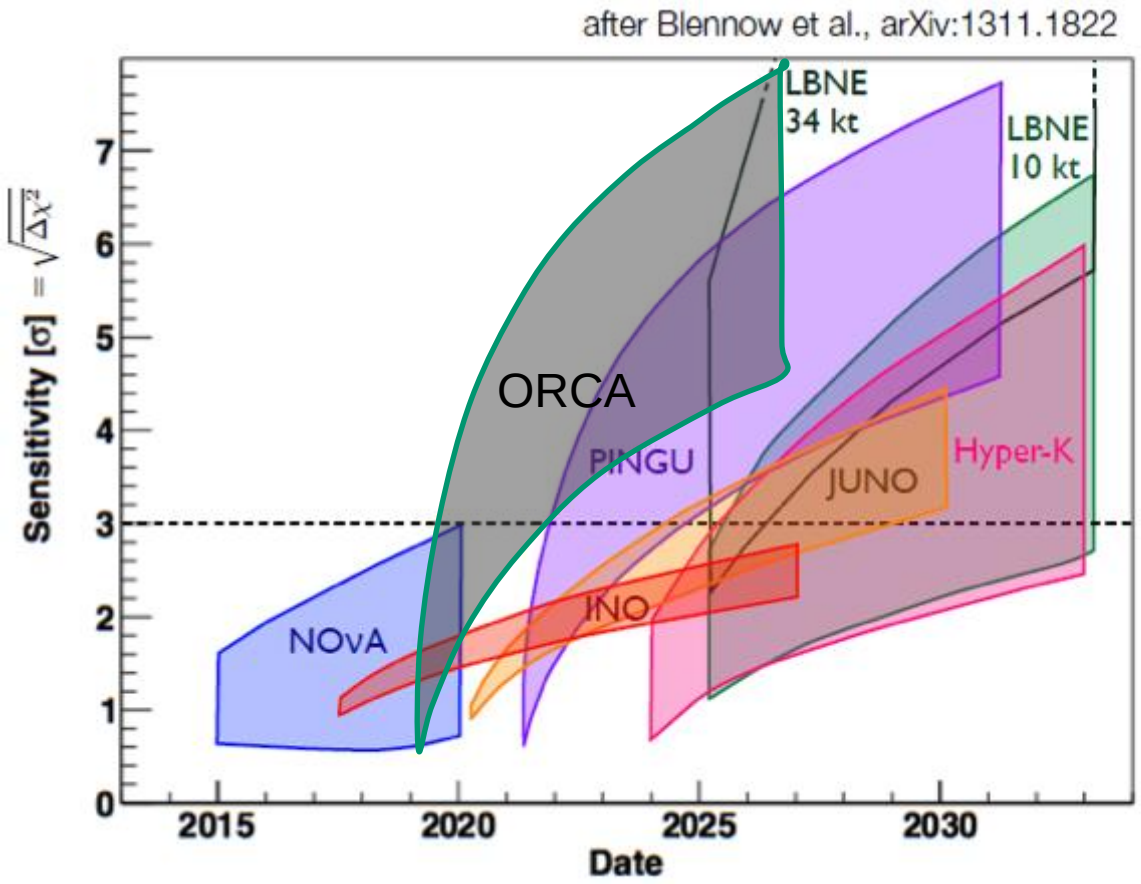
Several current experiments or planned experiments will have sensitivity to the neutrino mass hierarchy in the next 10-15 years

(NB: median outcomes shown, large fluctuations possible)

Widths indicate main uncertainty
LBNE/NOVA: δcp
JUNO: σE (3.0-3.5%)
ORCA/PINGU/INO: θ_{23}

Other projections assume worst case parameters (1st oct)

ORCA timeline, assumes start deployment 2016 for 3 years



LBNE from LBNE-doc-8087-V10
PINGU from DeYoung, Arlington, April 2014
Others Blennow