



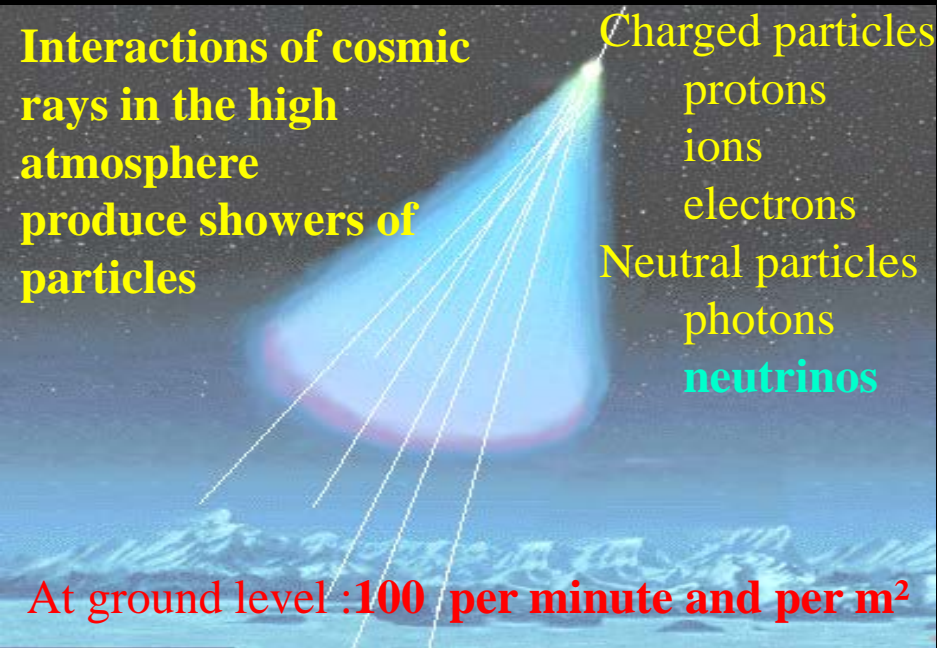
ANTARES and KM3NeT :

Deep Sea Telescopes to study the Universe

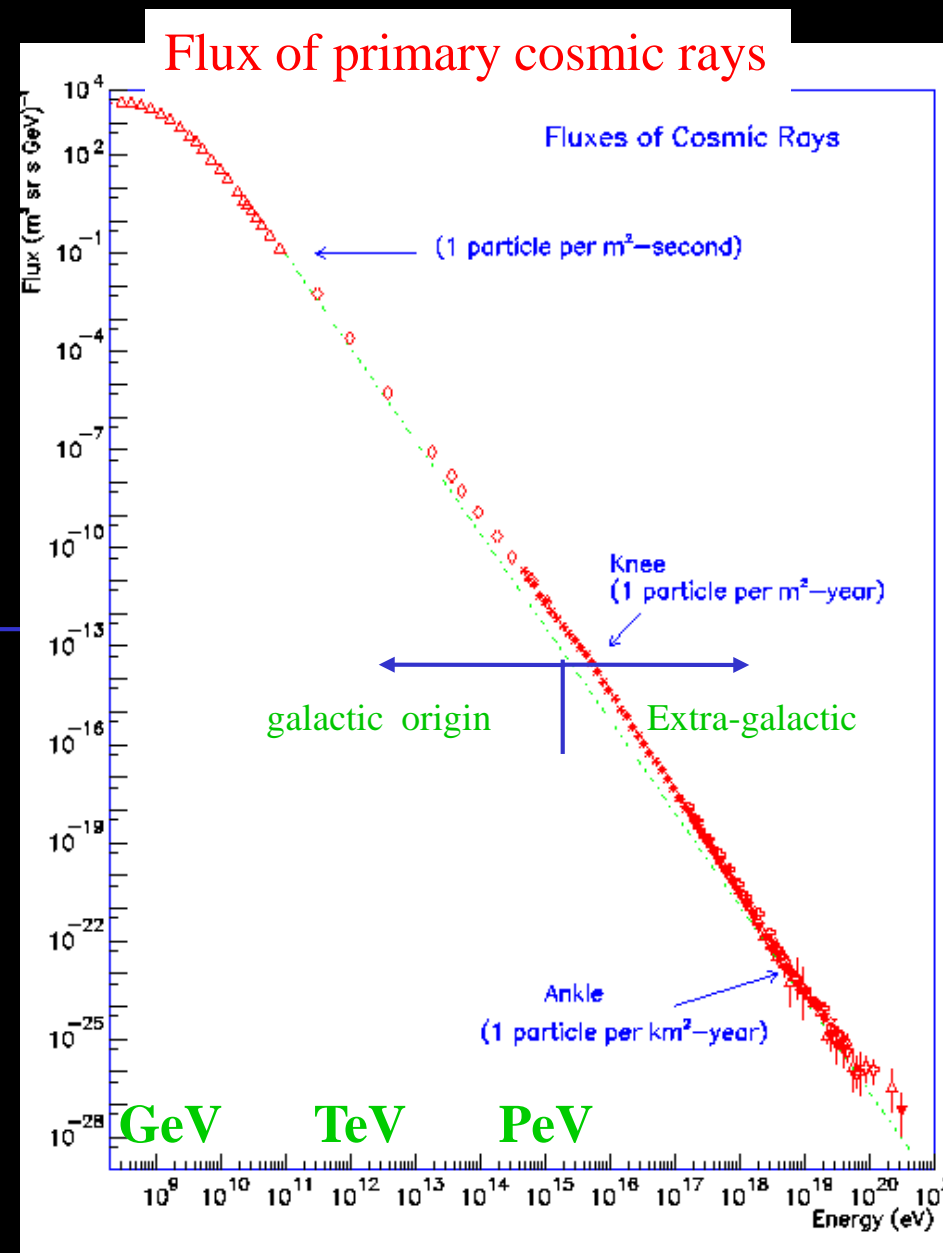
Massimiliano LINCETTO
Aix-Marseille Université
Centre de Physique des Particules de Marseille

Physics for both infinities @ CPPM - July 2018

Cosmic Rays



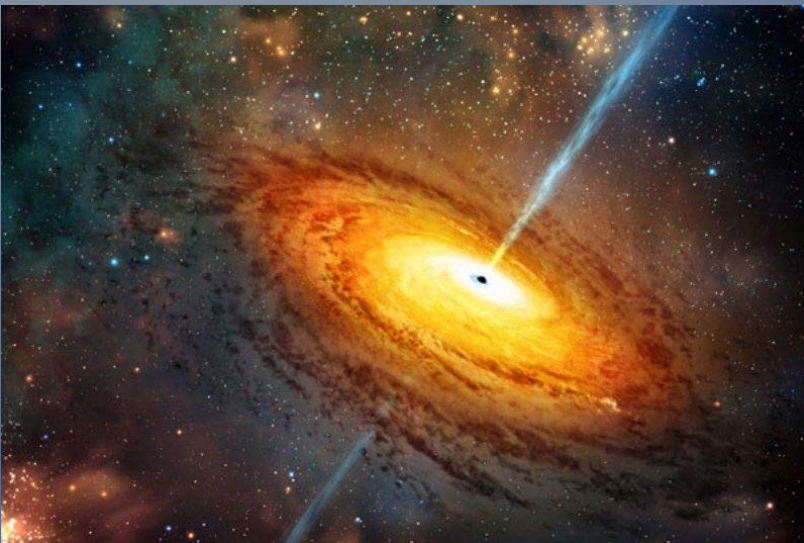
100 years after their discovery, the origin of cosmic rays is still very unclear



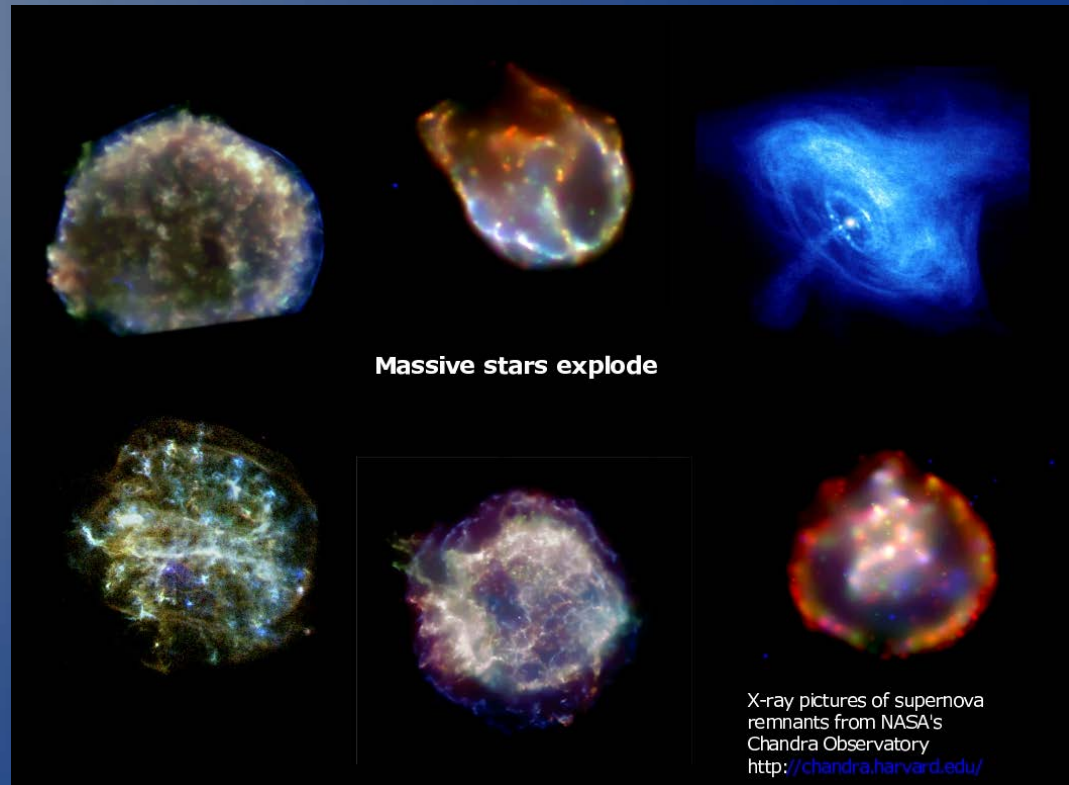
Potentiel Sources : Supernovae, Black Holes,...

High Energy Cosmic Rays come from the most violent phenomena of the Universe...

Massive star explosions (Supernovae)



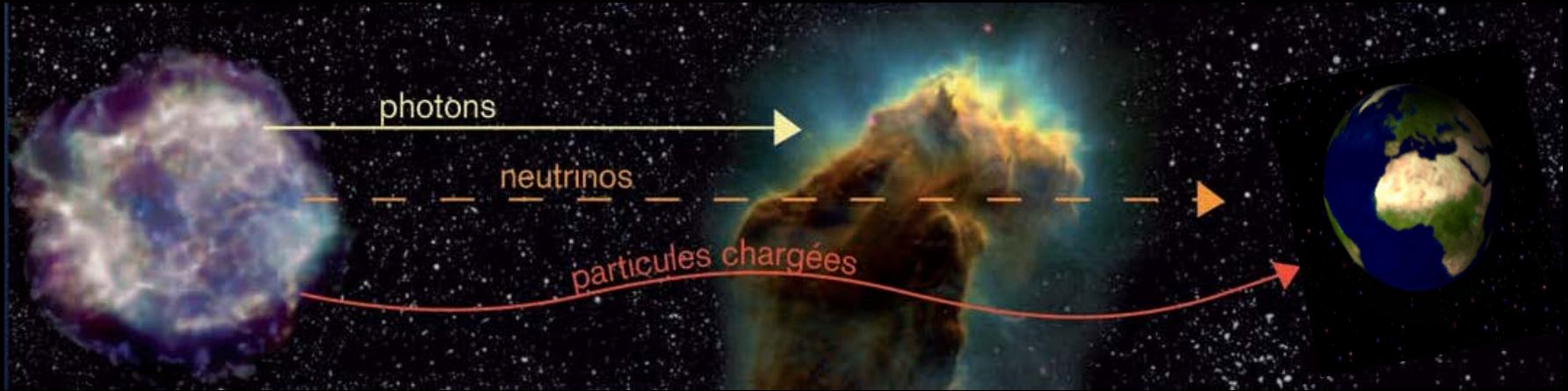
Super-massive Black Holes
(Active Galactic Nuclei)



Massive stars explode

X-ray pictures of supernova remnants from NASA's Chandra Observatory
<http://chandra.harvard.edu/>

Why looking for neutrinos ?



Pros for neutrino :

- Electrically neutral, not deviated by magnetic fields → **astronomy**
- No absorption → **observation over cosmological distances**
- Interacts VERY weakly → **escapes from dense regions of the Universe**

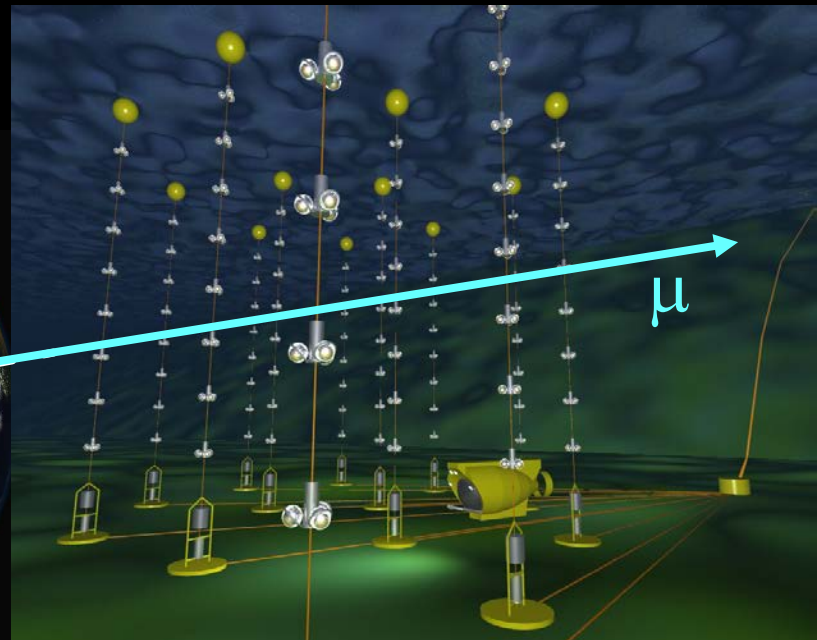
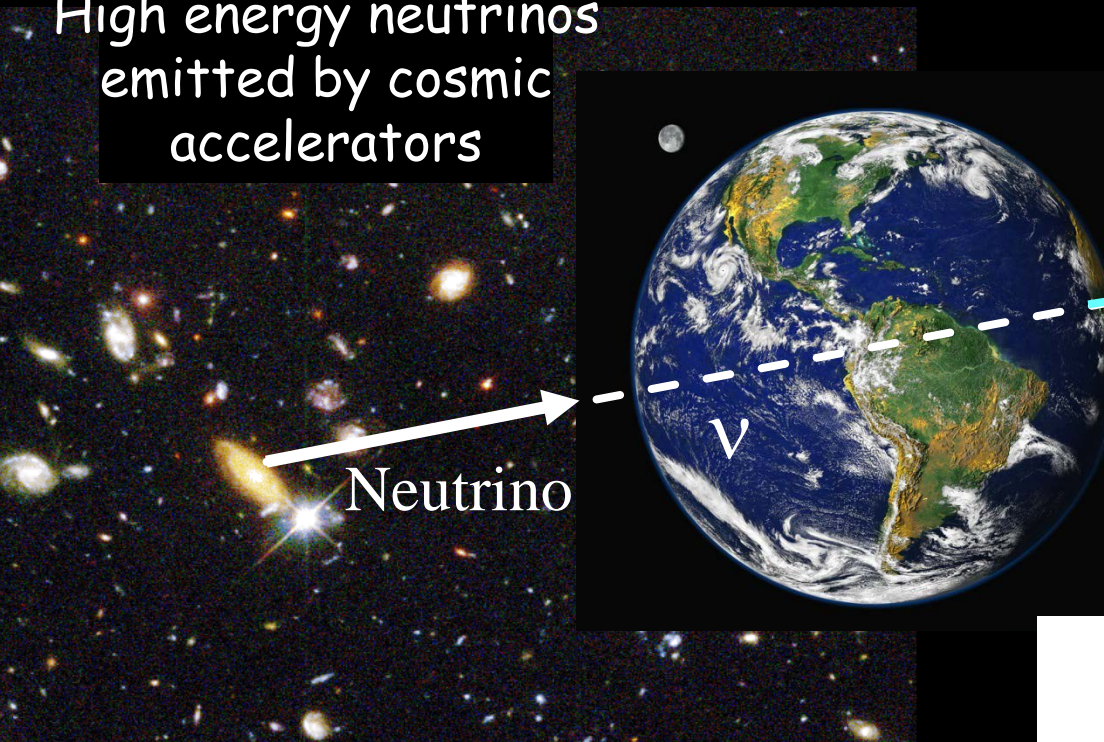
Cons :

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

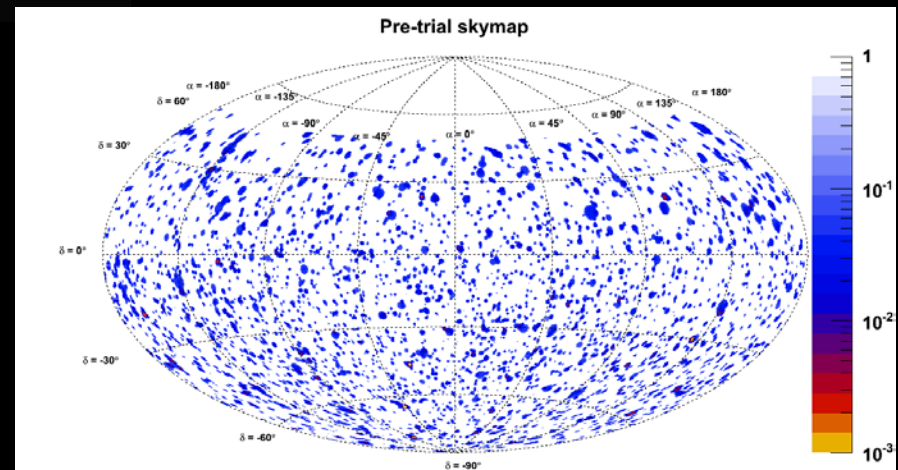
→ **Necessity of a HUGE detection volume**

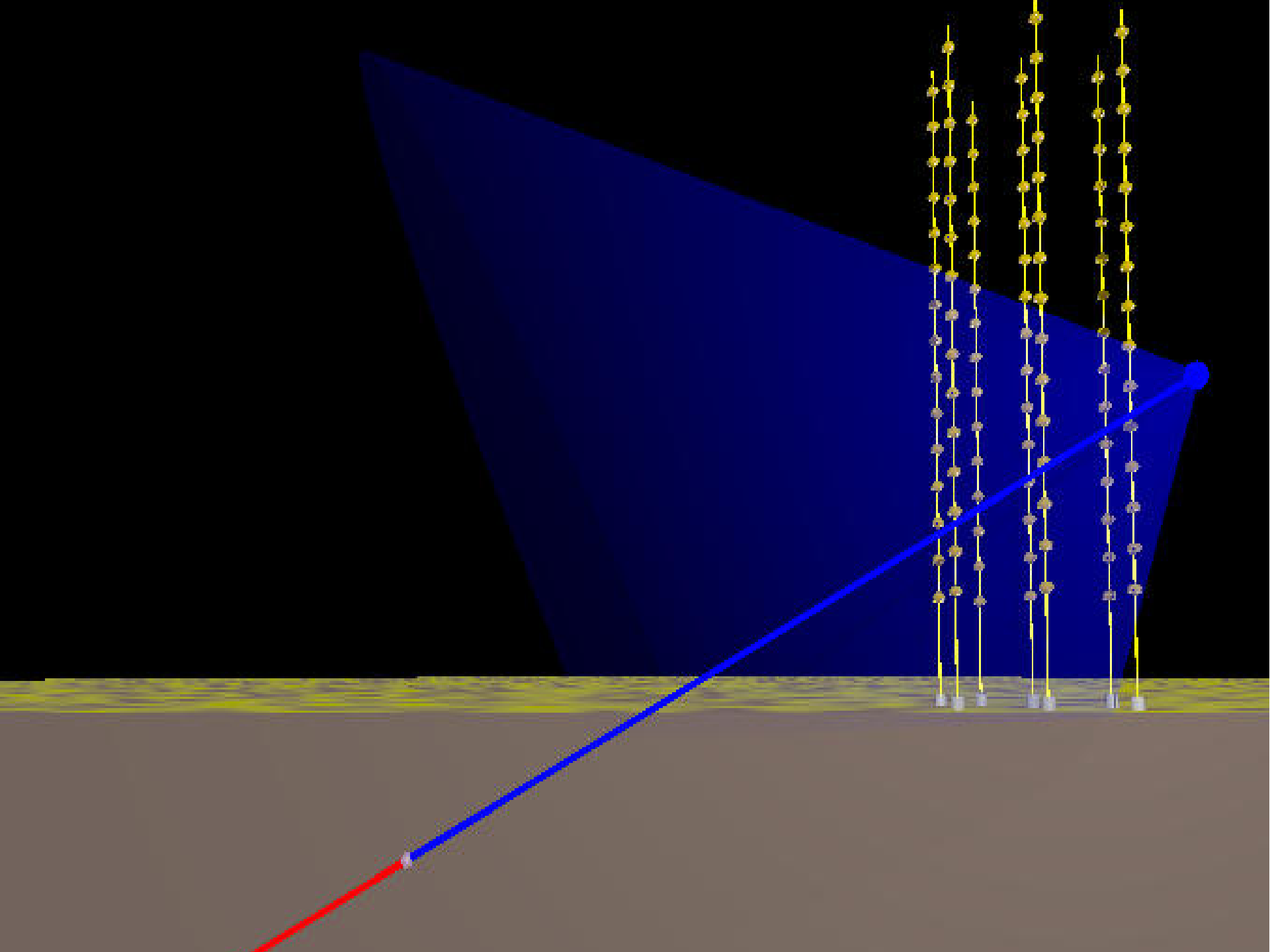
A new window over the Universe

High energy neutrinos emitted by cosmic accelerators



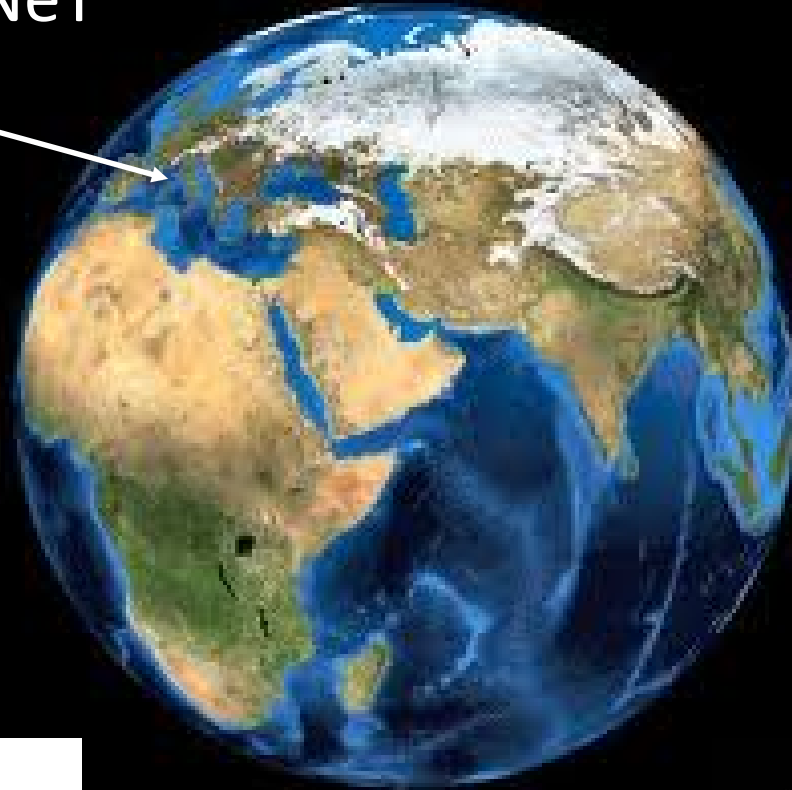
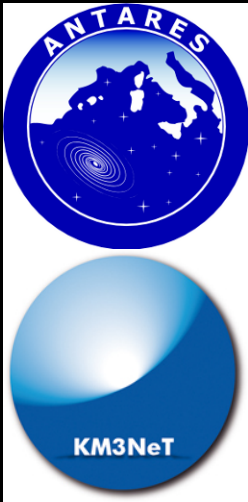
Neutrino Astronomy :
skymap of the most catastrophic
events of the Universe



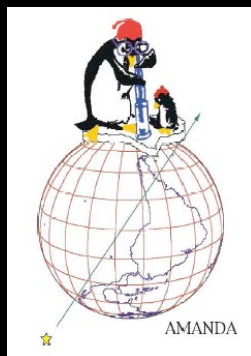


Existing Neutrino Telescopes

ANTARES/KM3NeT



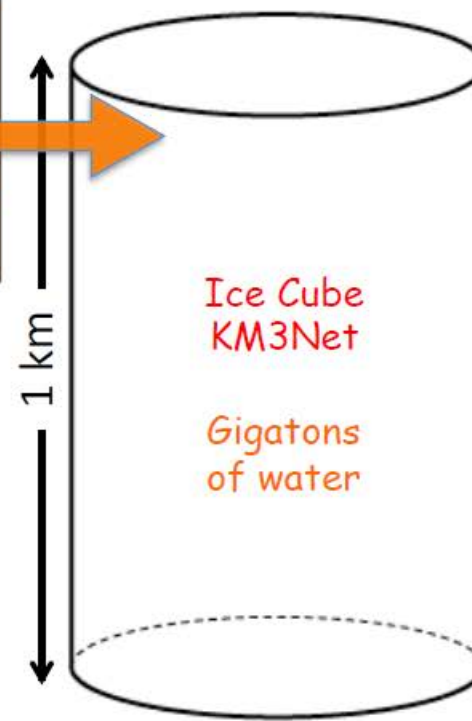
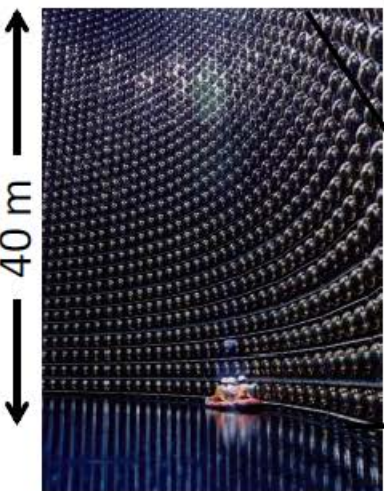
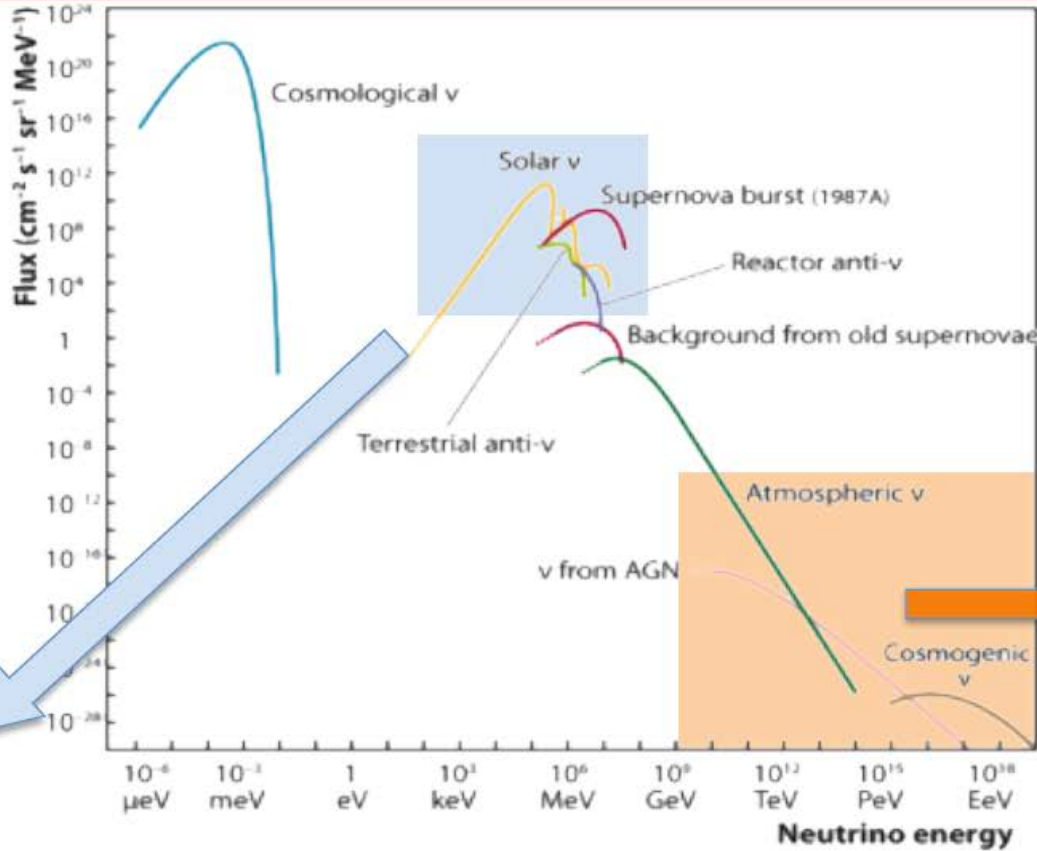
BAIKAL



AMANDA/Ice Cube

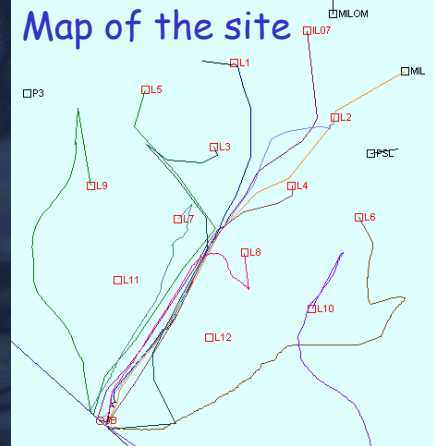


Neutrino spectrum



The ANTARES Detector

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



14.5 m

Bouy

Storey

350 m

Junction Box

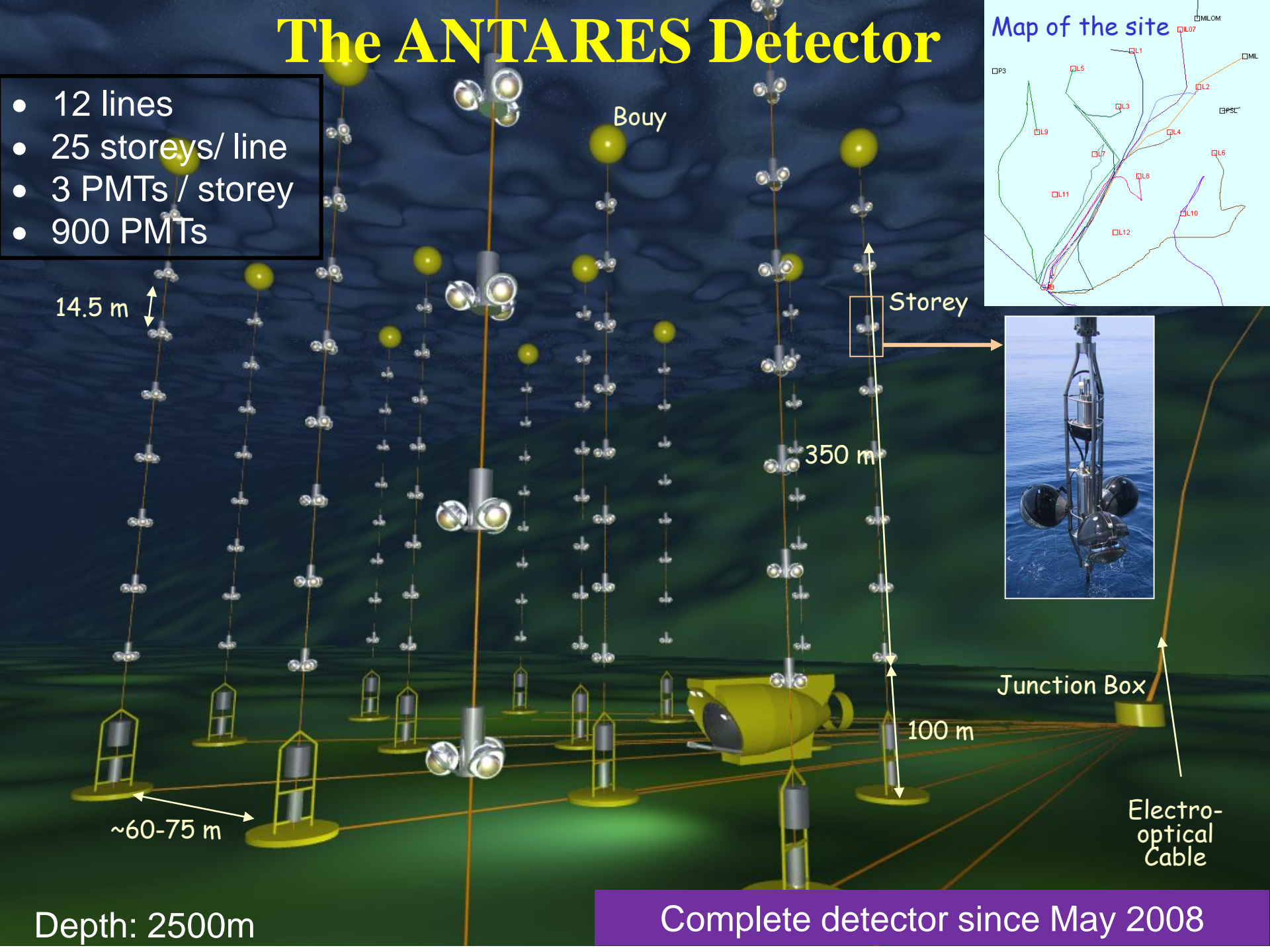
100 m

Electro-optical Cable

~60-75 m

Depth: 2500m

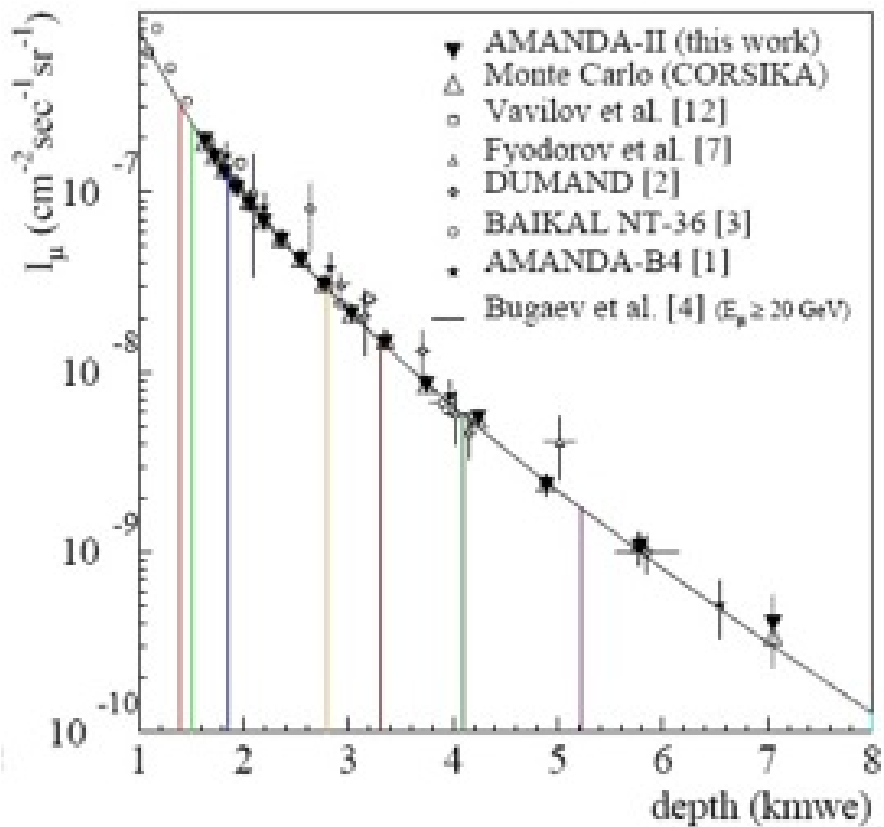
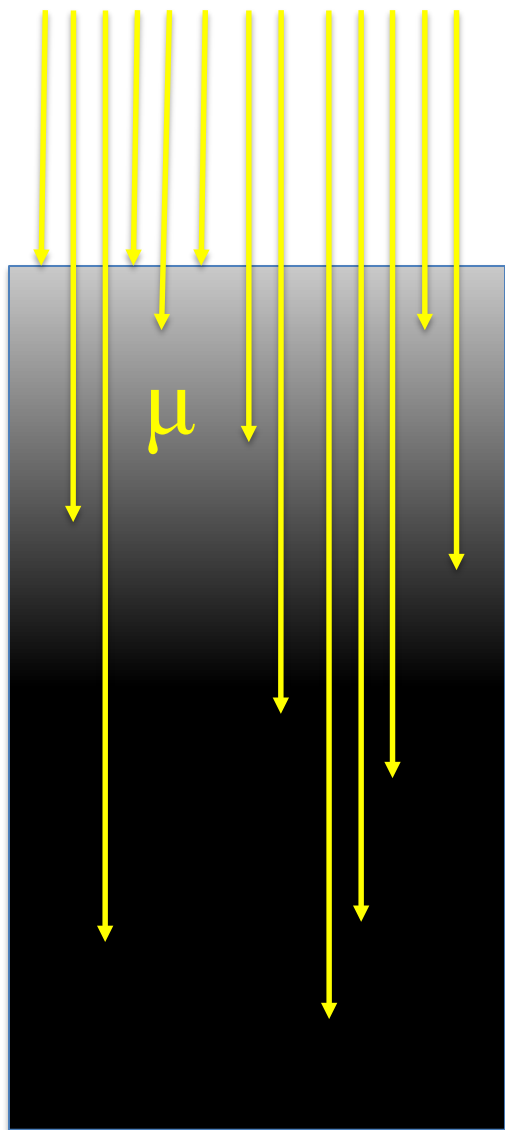
Complete detector since May 2008





The ANTARES site



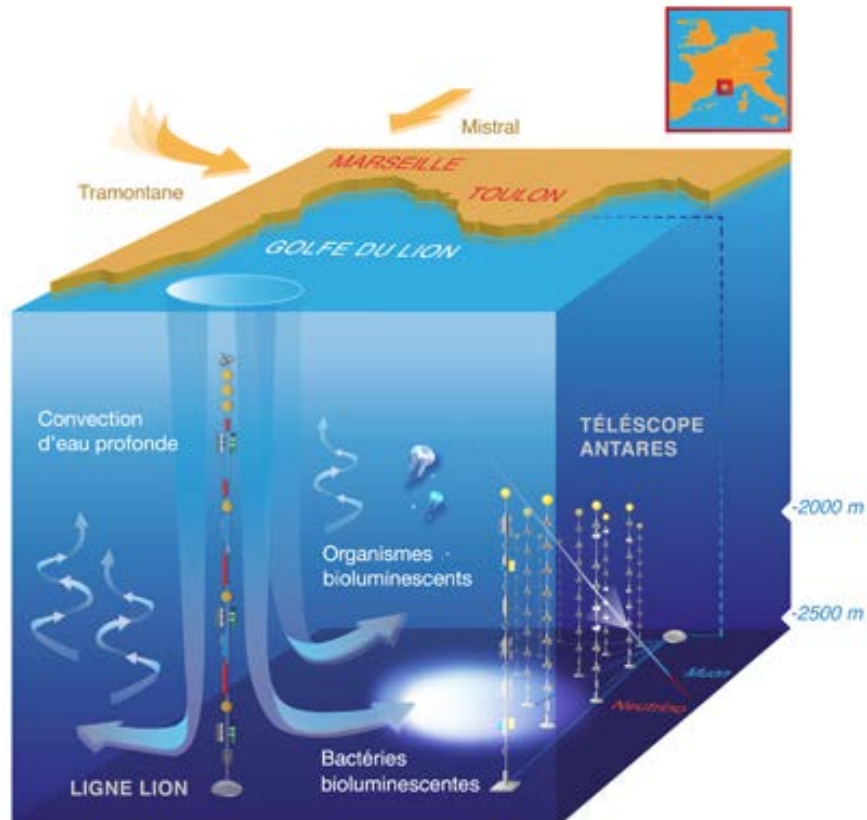


Synergies with deep-sea science

ANTARES awarded "La Recherche Prize" category "Coup de Coeur"

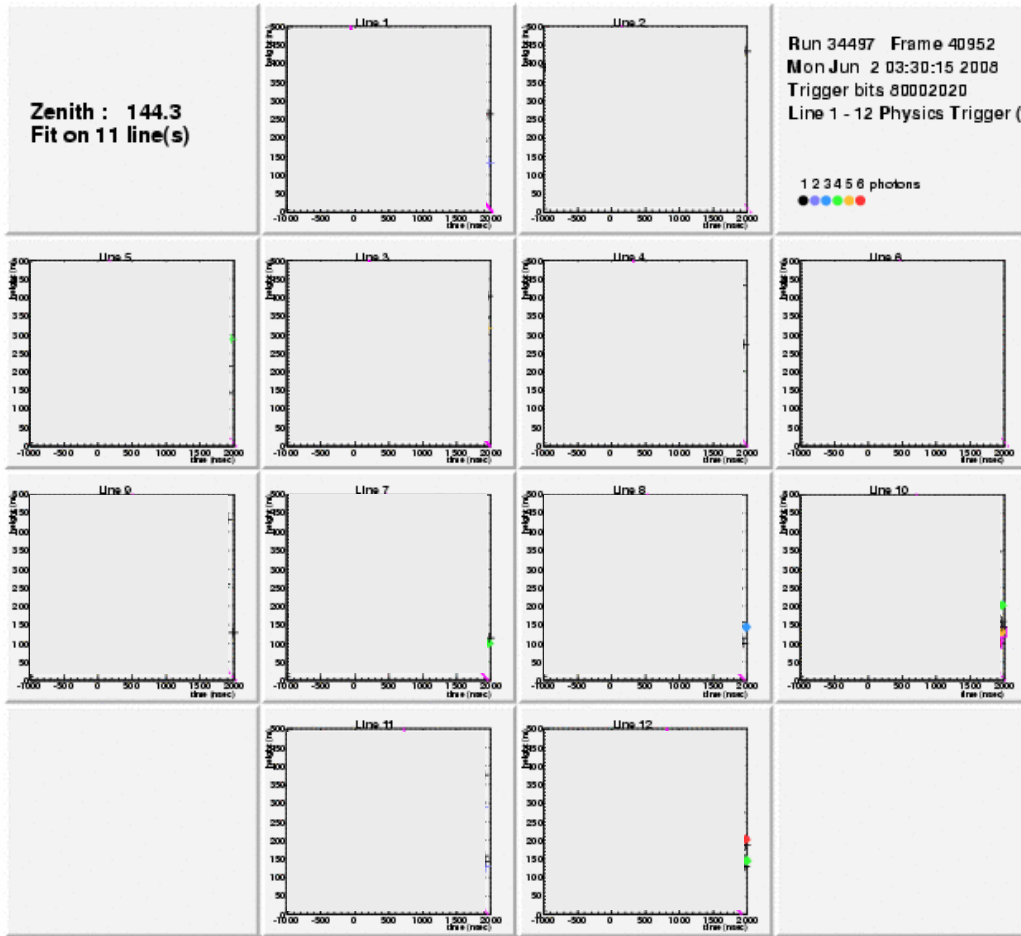
📖 C. Tamburini, S. Escoffier et al., PLoS ONE 8(7) 2013

Deep-sea bioluminescence blooms after dense water formation at the ocean surface



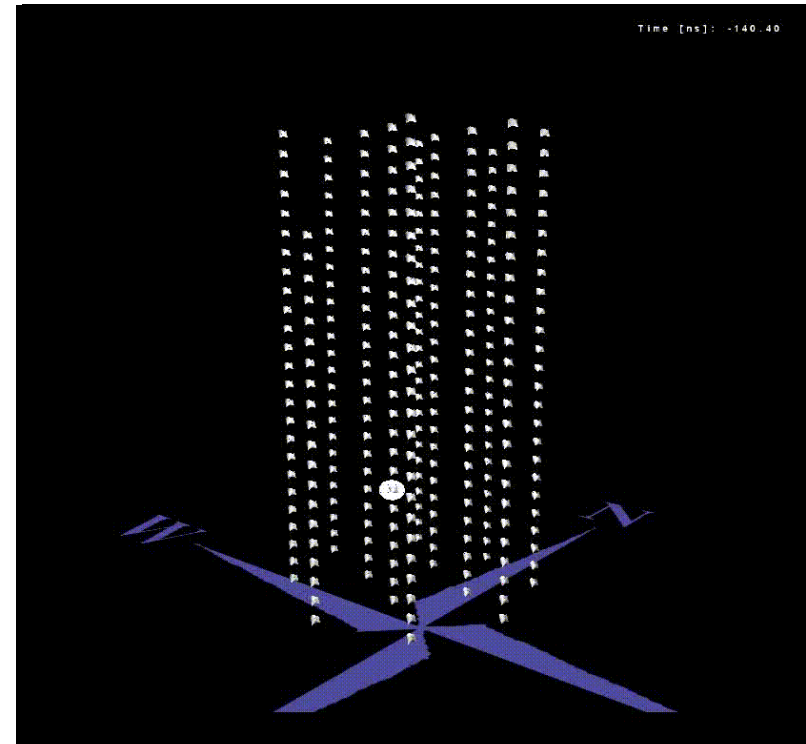
Example of a muon event

Few muons per second are detected



event

down-going muon



Example of a neutrino event

Few neutrinos per day are detected

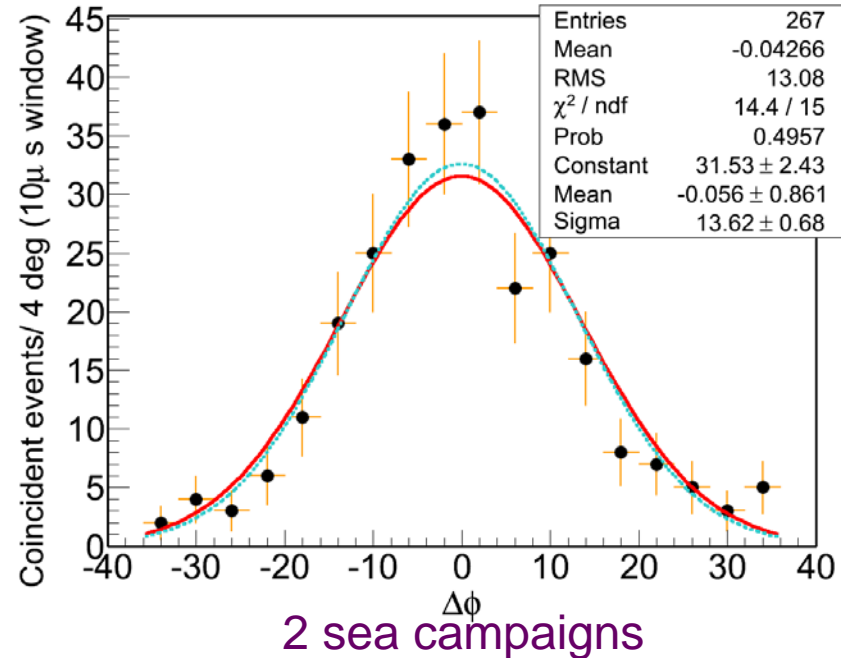
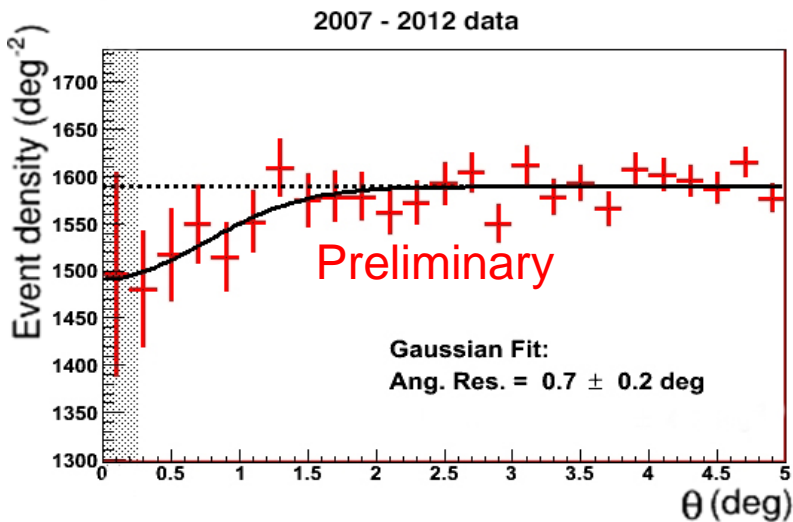
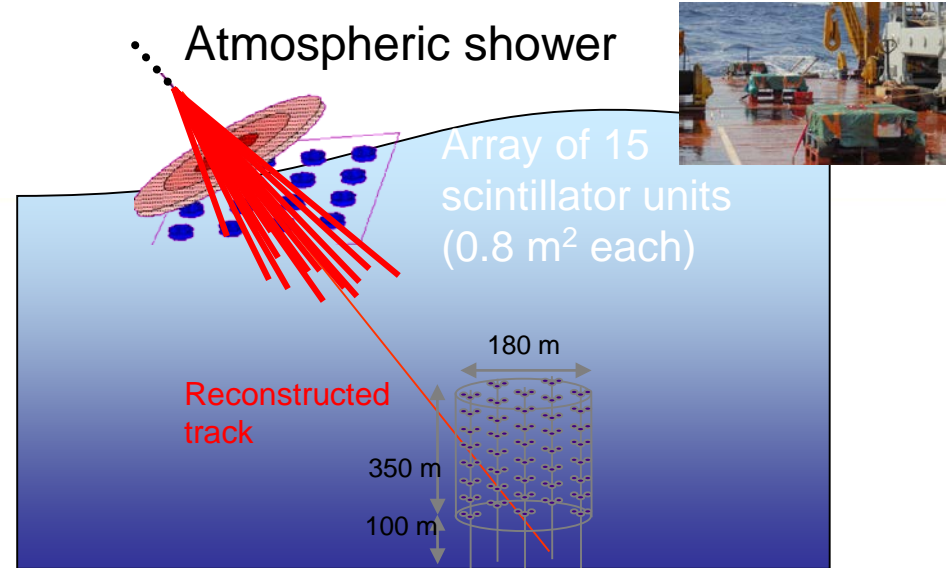
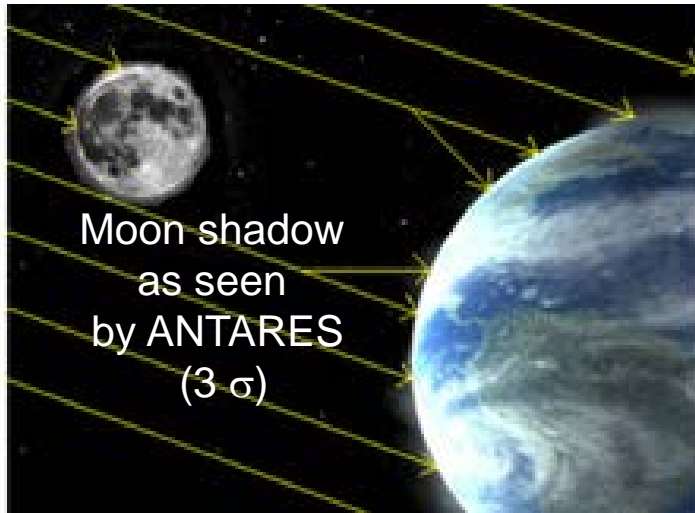


event

up-going muon



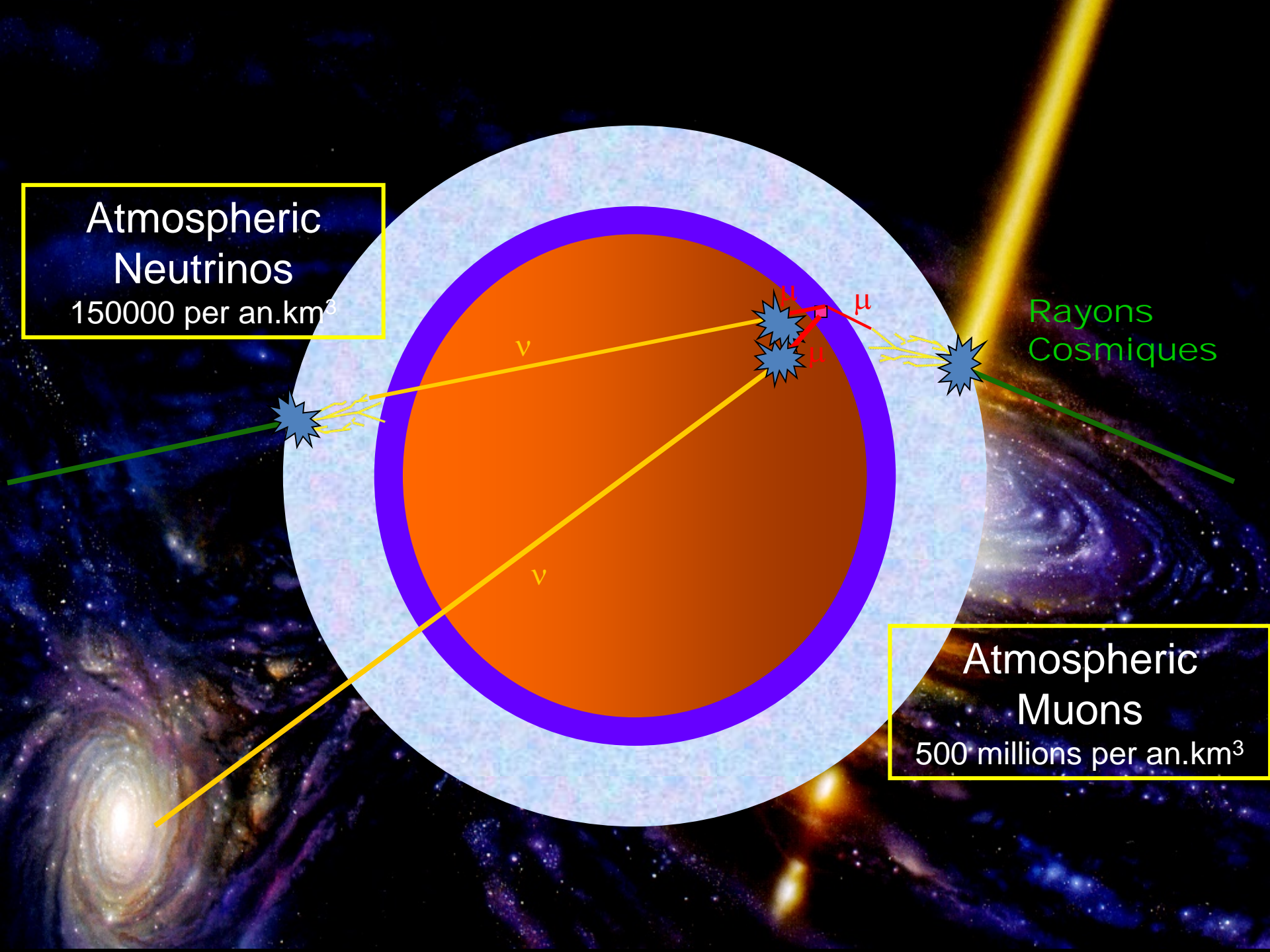
Check of Detector Absolute Pointing

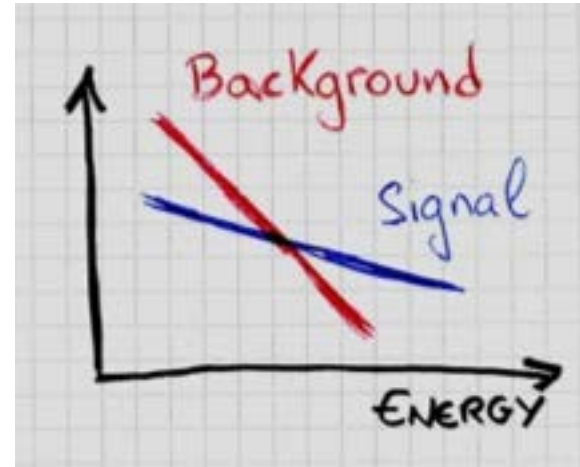
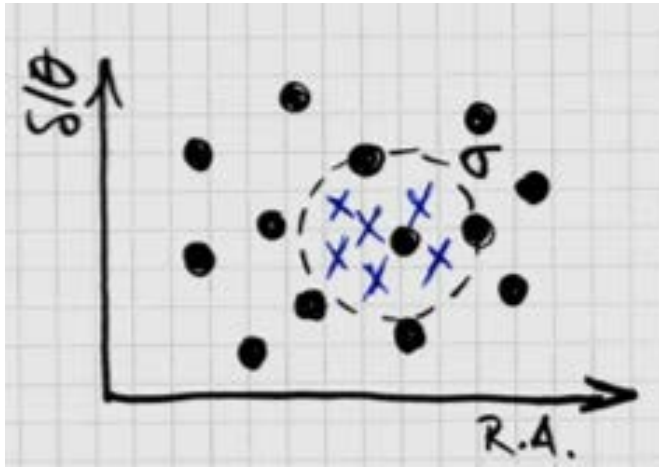


Atmospheric
Neutrinos
150000 per an.km³

Rayons
Cosmiques

Atmospheric
Muons
500 millions per an.km³





Background suppression :

- atmospheric muons : use reconstruction quality
- atmospheric neutrinos : isotrope + lower energy spectrum

Signal:

- distribution concentrated for point source + harder energy spectrum



Point Source

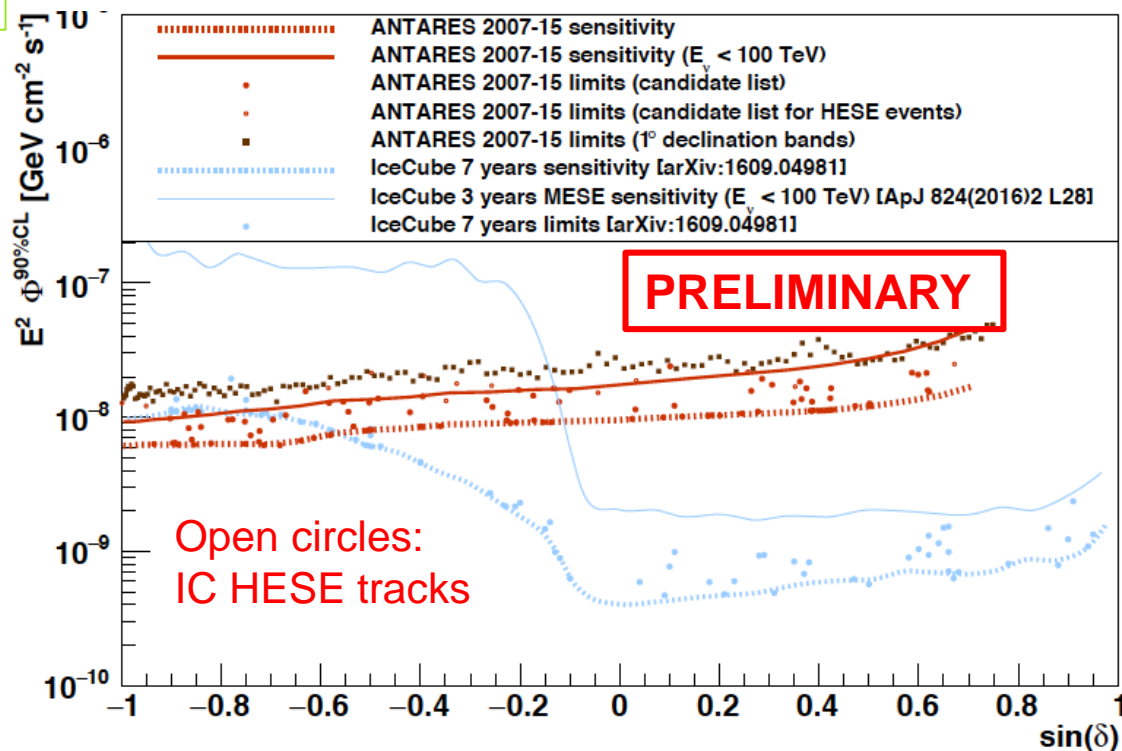
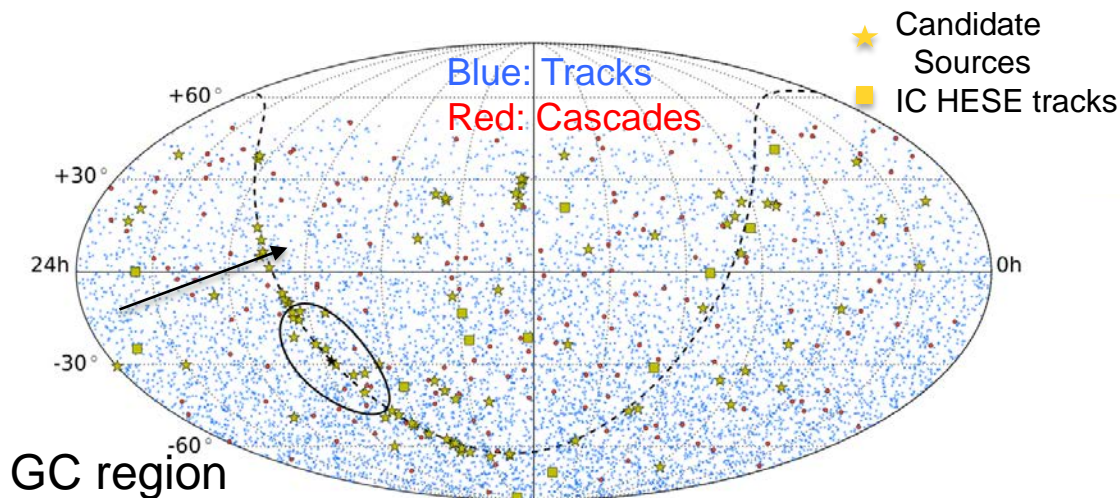


Diffuse Flux

All flavor search with ANTARES

- 2007-2015 (2424 days):
7629 tracks, 180 cascades
- Unbinned all-sky search
- 103 Candidate sources including 13 IceCube HESE tracks and HAWC sources

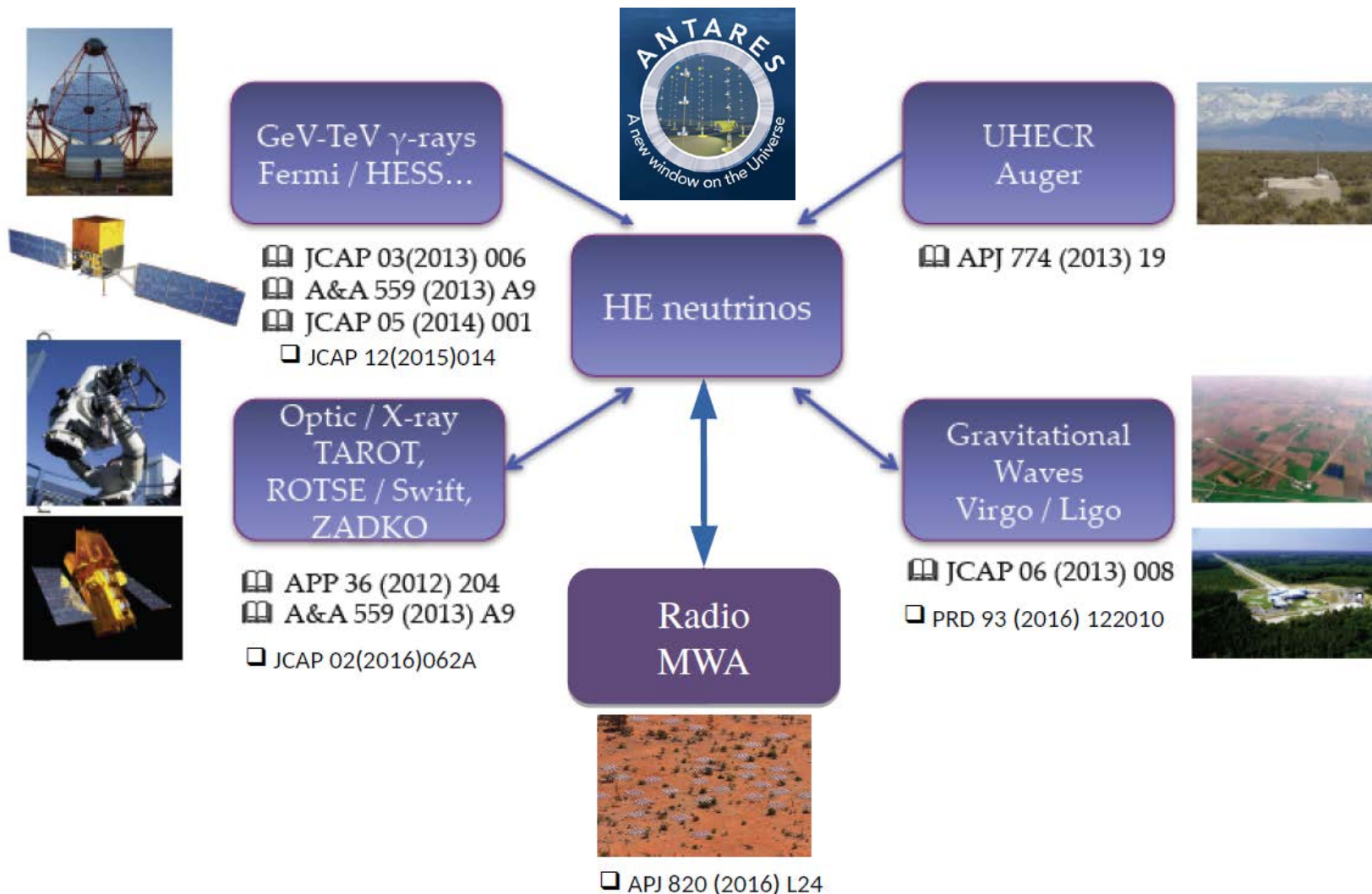
- No significant excess
- Best limits for part of Southern Hemisphere
- Excellent sensitivity for $E_\nu < 100$ TeV
- Results to be combined with latest IC search



Towards a multi-messenger astronomy...



→ Search for signals of transient catastrophic astrophysical events
(Gamma Ray Bursts, SuperNovae, flares of Active Galactic Nuclei,...)
with High Energy Neutrinos, Radio/Optical/X/ γ Photons, Cosmic Rays,
Gravitational Waves,...



Search for Coincidences with Gravitational Waves

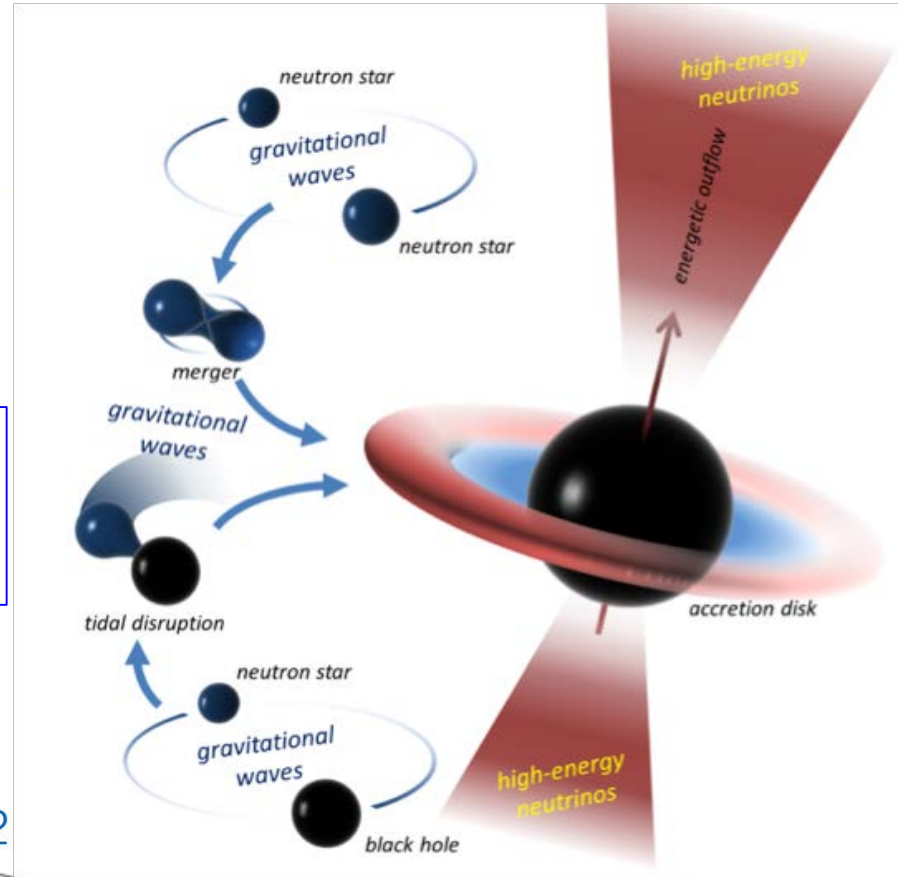
Mostly for BH/NS or NS/NS systems :

Gravitational waves
+ electromagnetic
+ neutrino emission (if baryonic ejecta)

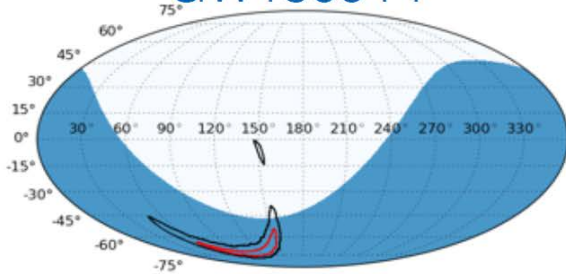
No counterpart observed so far

Limits from ANTARES dominate $E_\nu < 100$ TeV wrt IC

Limit on total energy radiated in neutrinos: $< 10\%$ GW

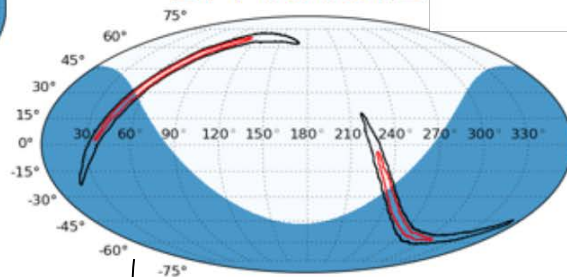


GW150914



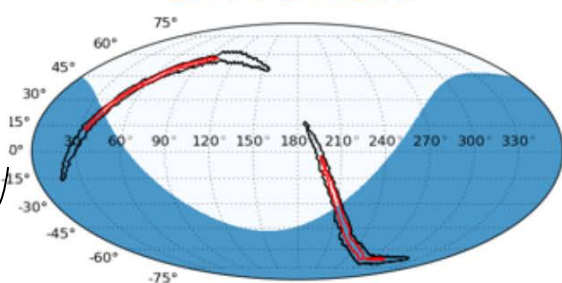
PRD 93, 2016

LVT151012



arXiv:1703.06298

GW151226



Real time follow-up
Of GW science runs

The multi-messenger program: TATOO

Telescope-Antares Target of Opportunity

2ND APPROACH:

Alert
triggering

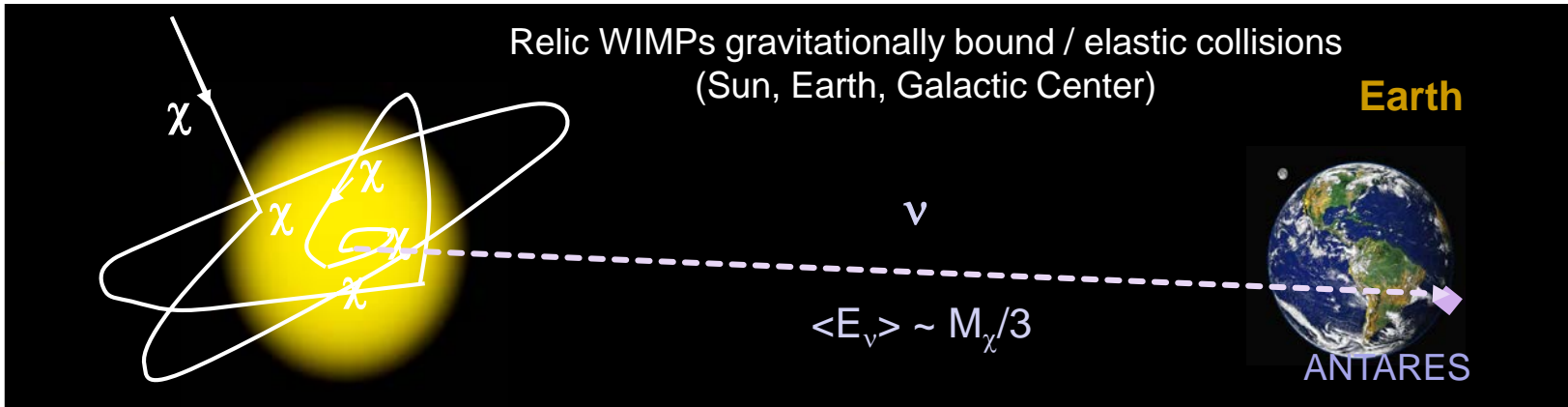


Real-time analysis



- Time to send an alert: ~ 5 s
- First optical image < 20 s
- Median angular resolution: $\sim 0.3^\circ$
- Triggers: single HE, preferred direction, multiplets

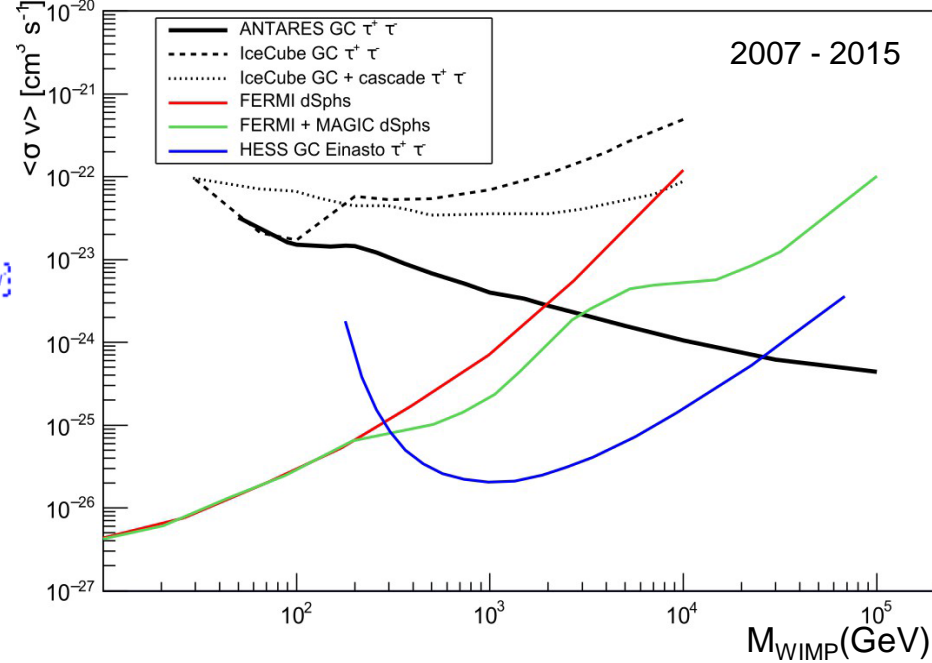
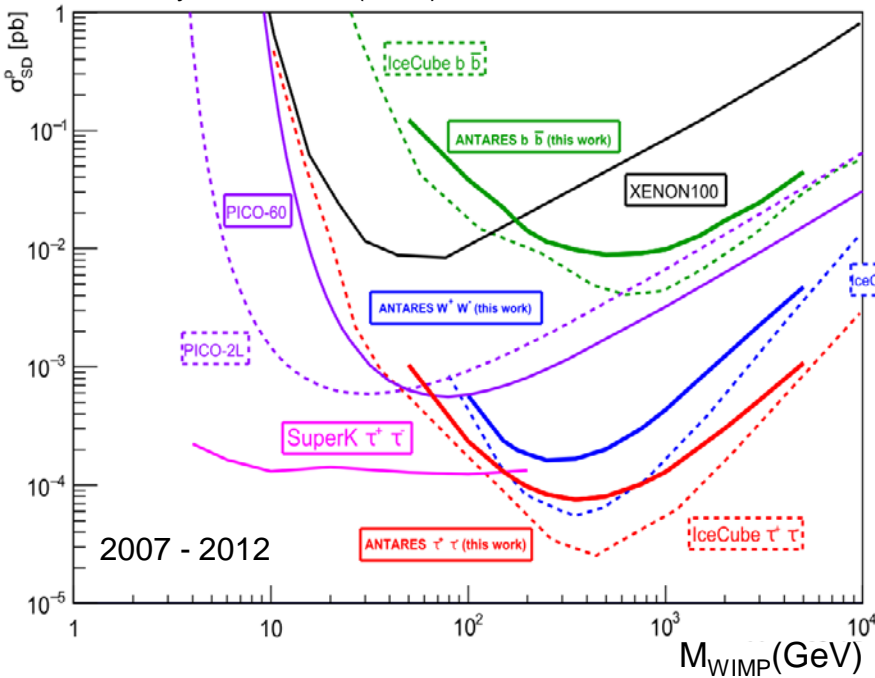
Indirect Search for Dark Matter



Phys.Lett. B759 (2016) 69-74

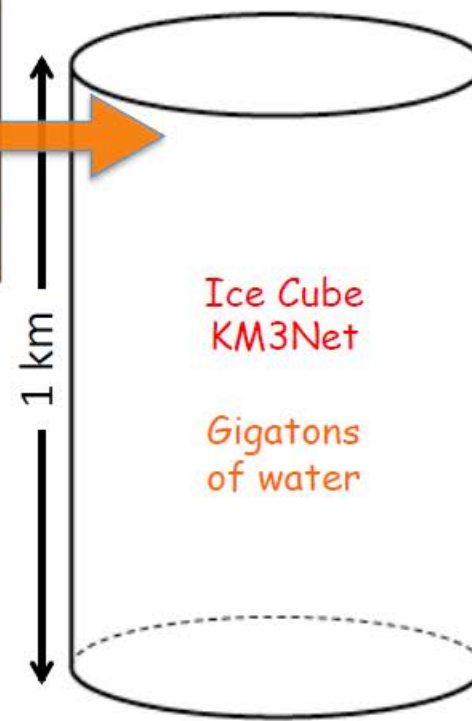
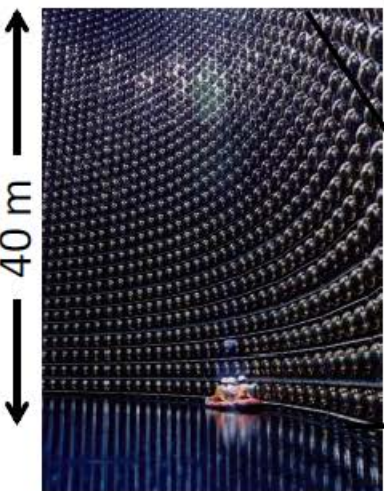
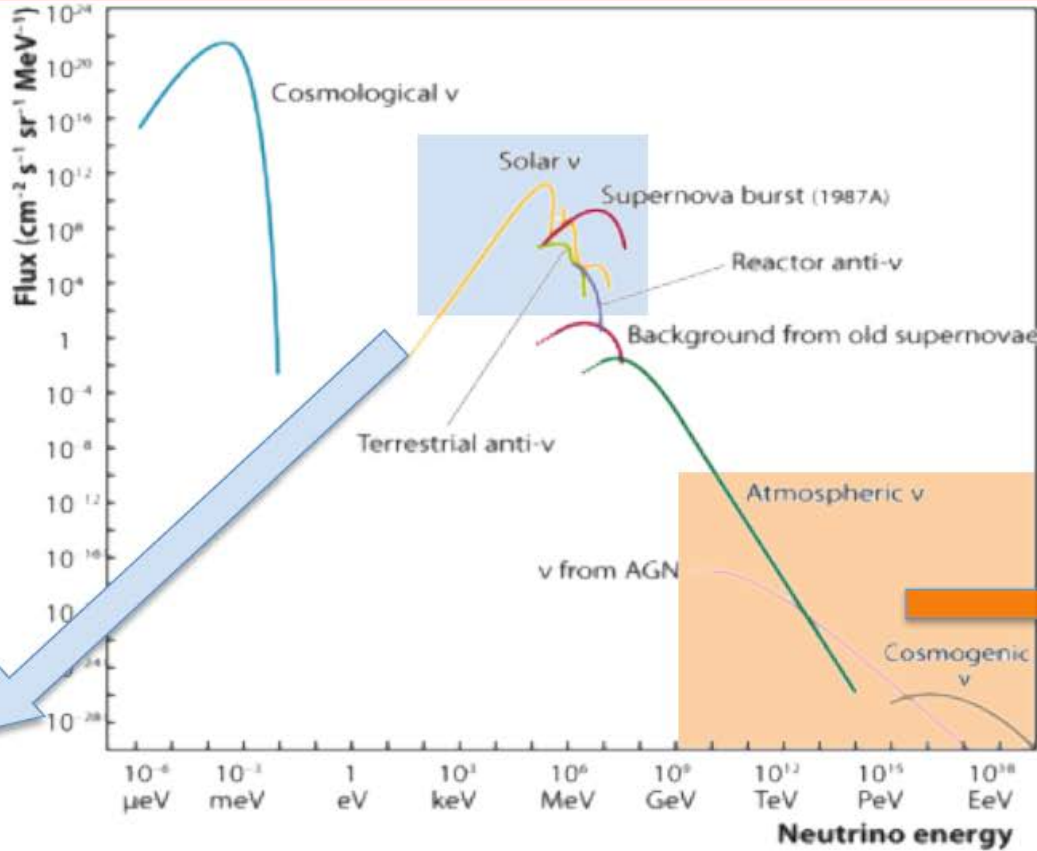
Track channel only

Phys. Let. B 769 (2017) 249



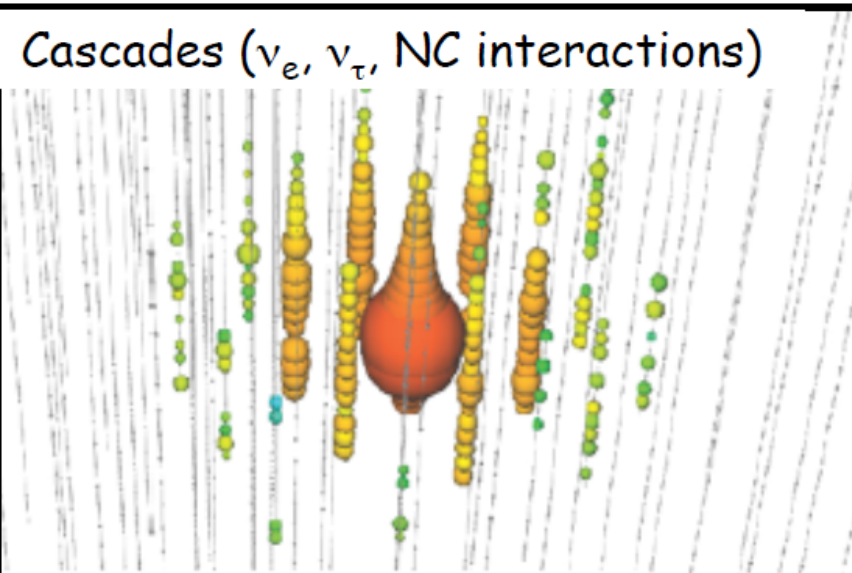
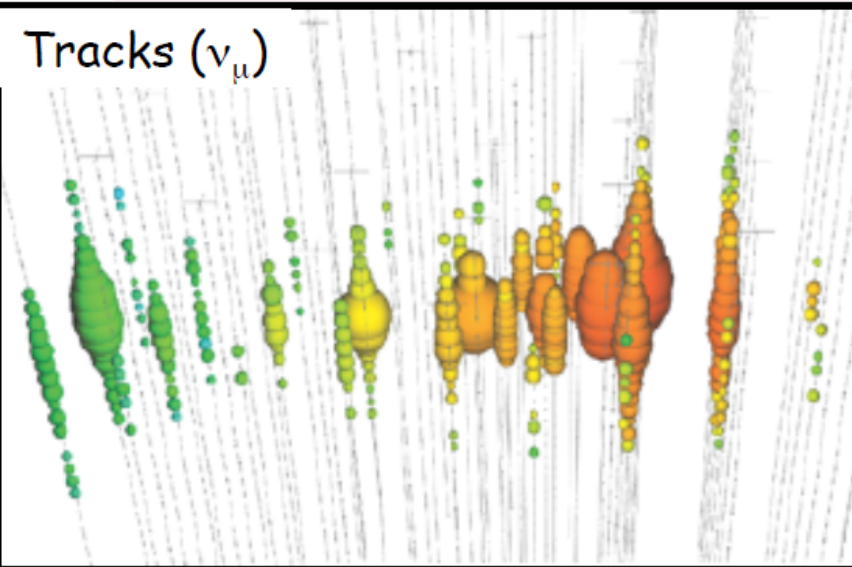
Also DM from the Center of the Earth : Physics of the Dark Universe, 16 (2017) 41-48

Neutrino spectrum

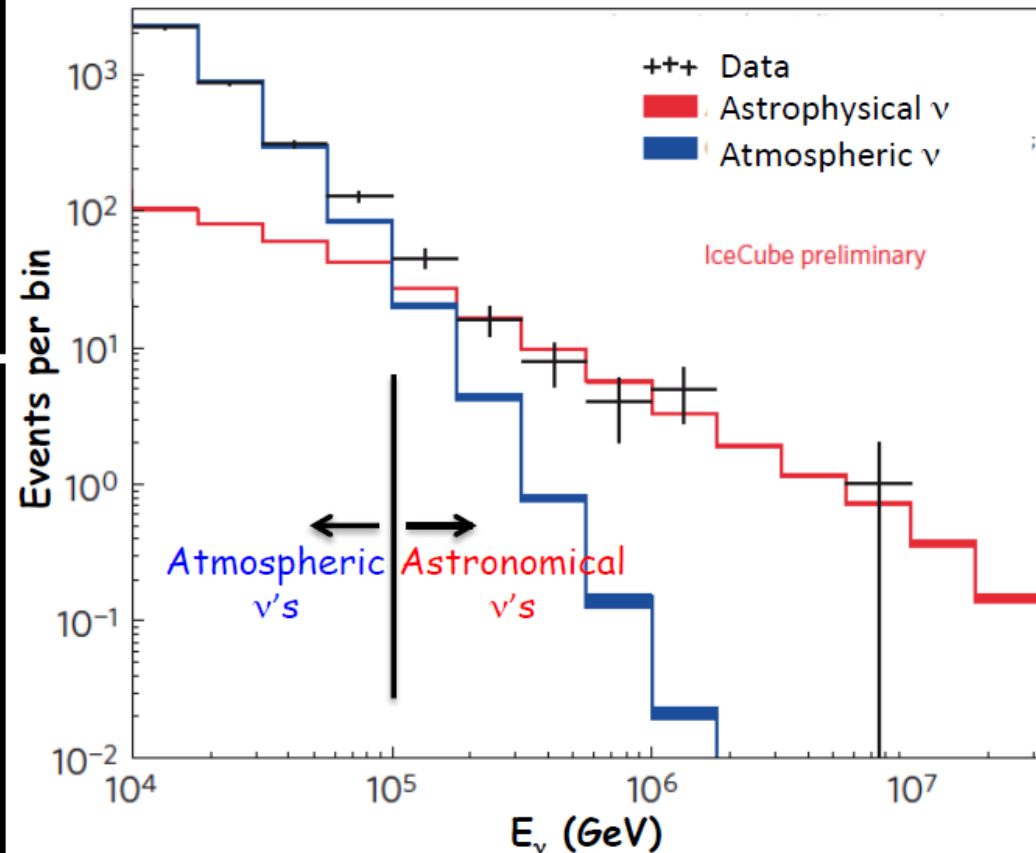


The IceCube Signal :

Birth of high-energy neutrino astronomy



28 events (after 2 years)
Deposited energy from 30 TeV to 1 PeV



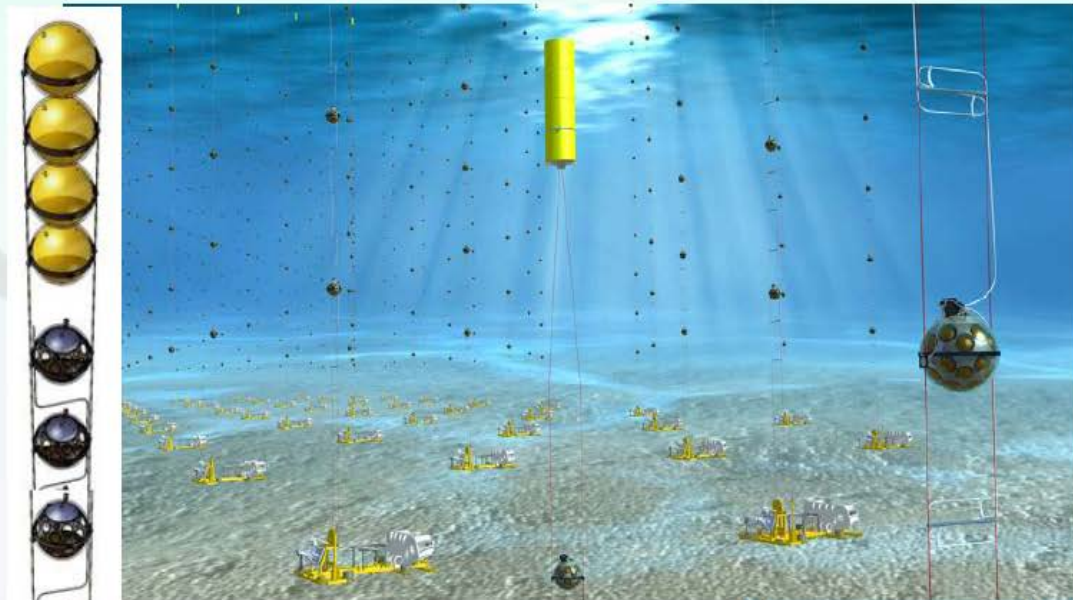
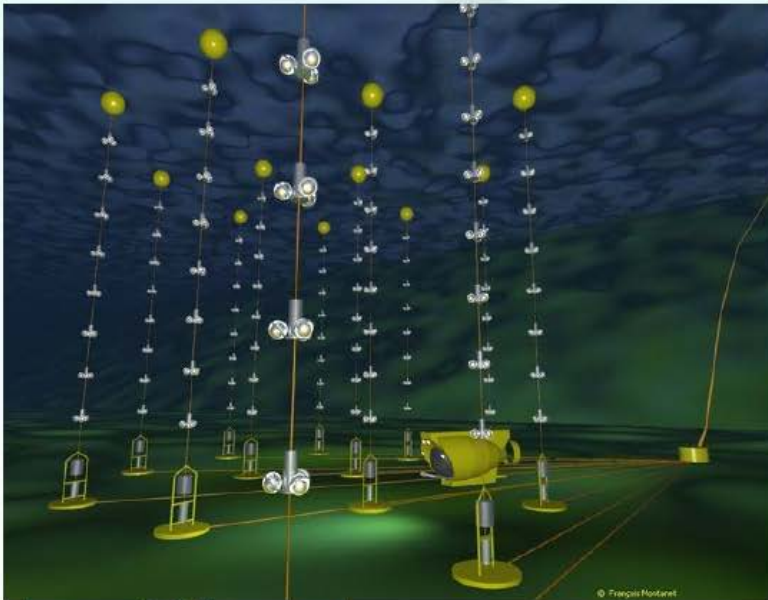
The future of Neutrino Astronomy in the Mediterranean Sea

ANTARES → KM3NeT

12 Lines, 885 OM

3 Building Blocks on 2 Sites

3*115 lines, ~6210 OMs, ~ 192510 PMTs



Basic active element:
Digital Optical Module
31 x 3" PMTs

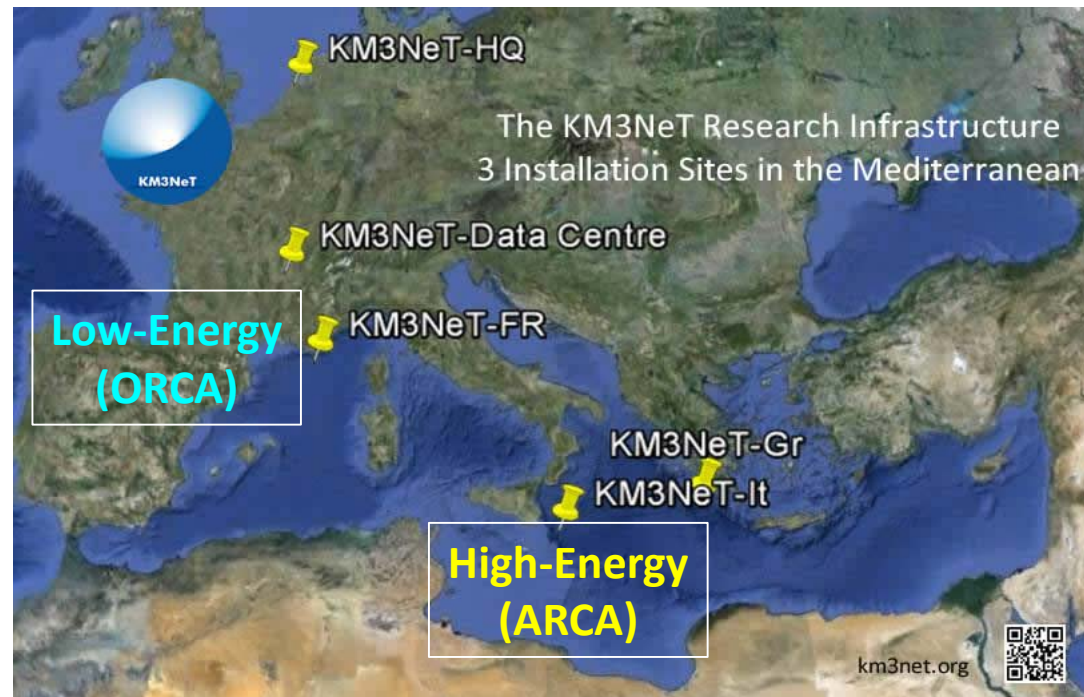
18 OMs/line



KM3NeT

KM3NeT is a distributed research infrastructure with 3 main science topics:

- The origin of cosmic neutrinos (high energy)
- Measurement of fundamental neutrino properties (low energy)
- Deep Sea Observatory - Oceanography, bioacoustics, bioluminescence, seismology



Single Collaboration
Single Technology

ARCA - Astroparticle Research with Cosmics in the Abyss

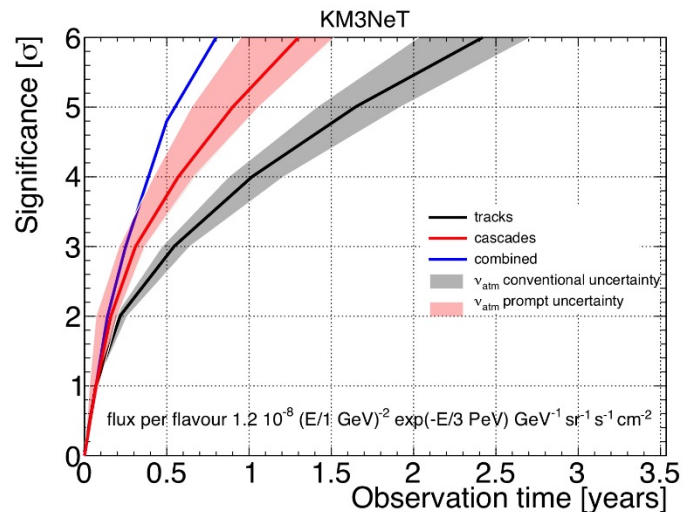
ORCA - Oscillation Research with Cosmics in the Abyss



KM3NeT Objectives

Astroparticle Research with Cosmics in the Abyss (ARCA):

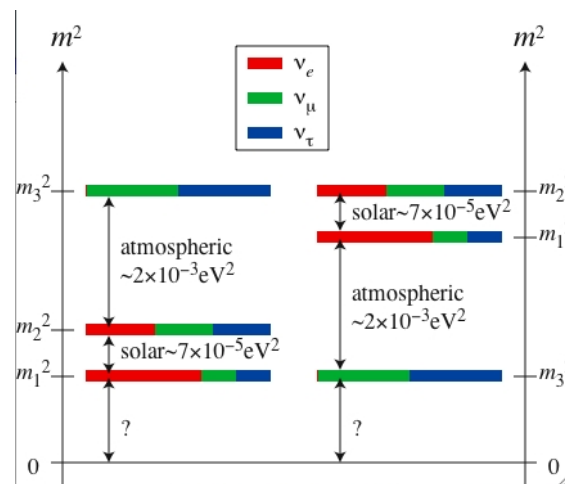
Sparse telescope optimised for TeV-PeV cosmic neutrinos



Discover/observe high-energy astrophysical neutrino sources

Oscillation Research with Cosmics in the Abyss (ORCA):

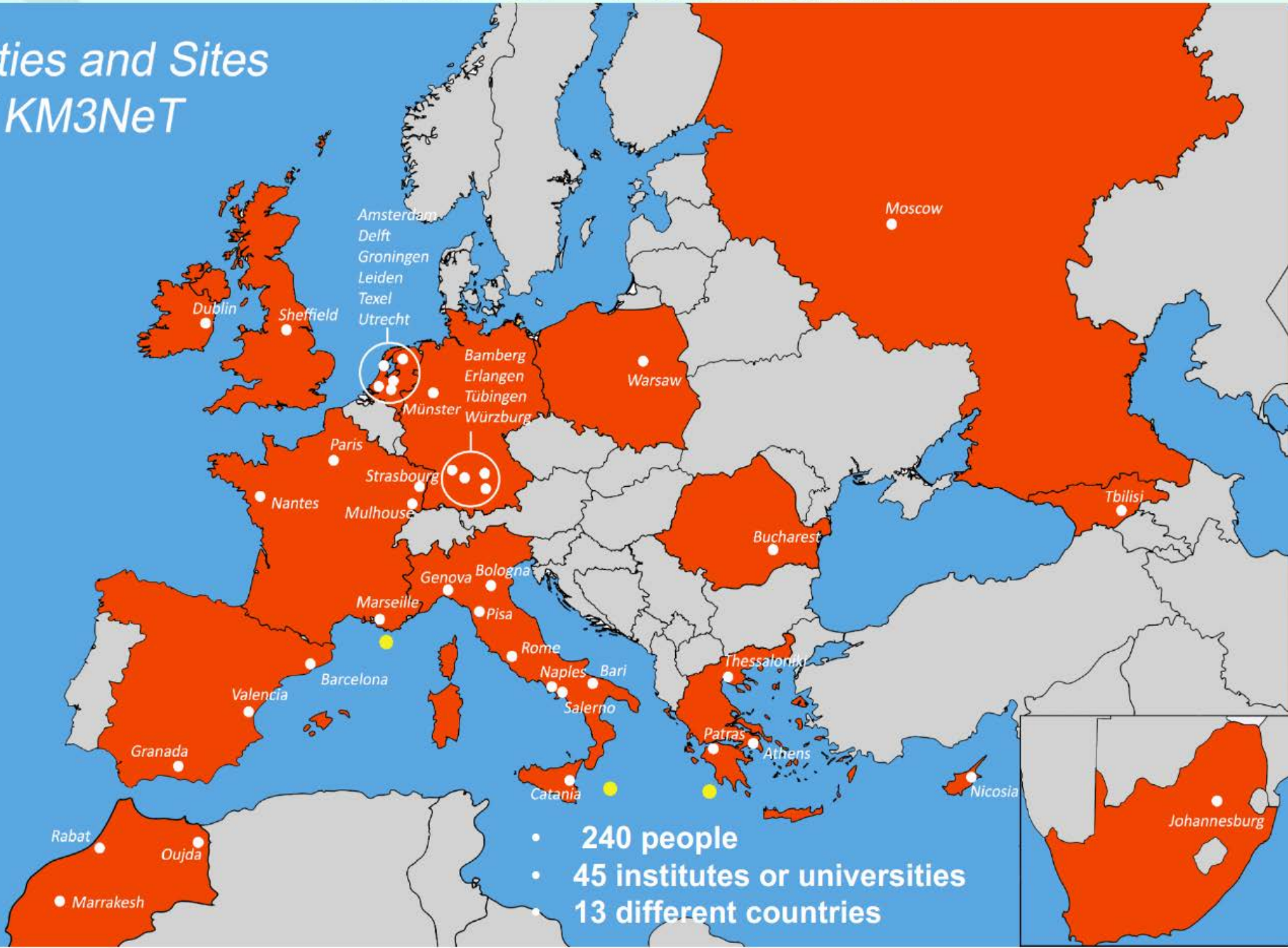
Dense detector optimised for GeV atmospheric neutrinos



Determine the Neutrino Mass Hierarchy

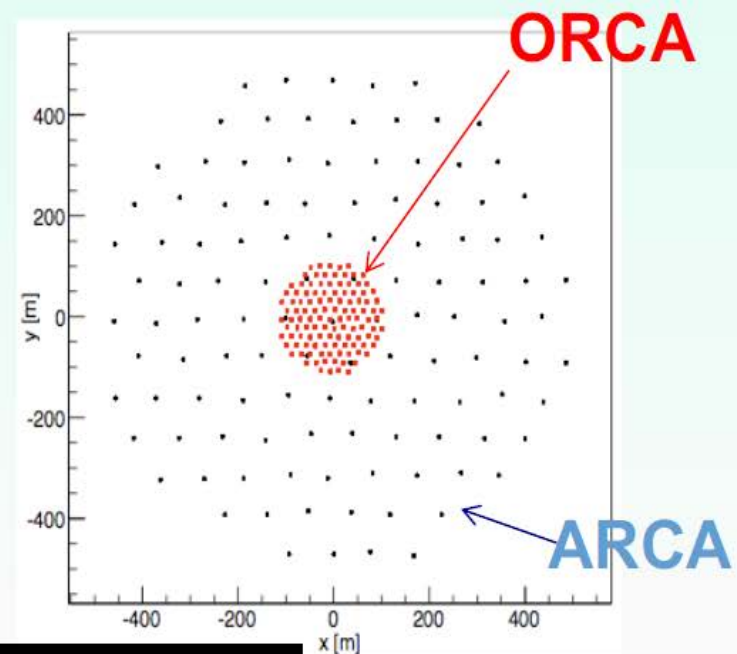
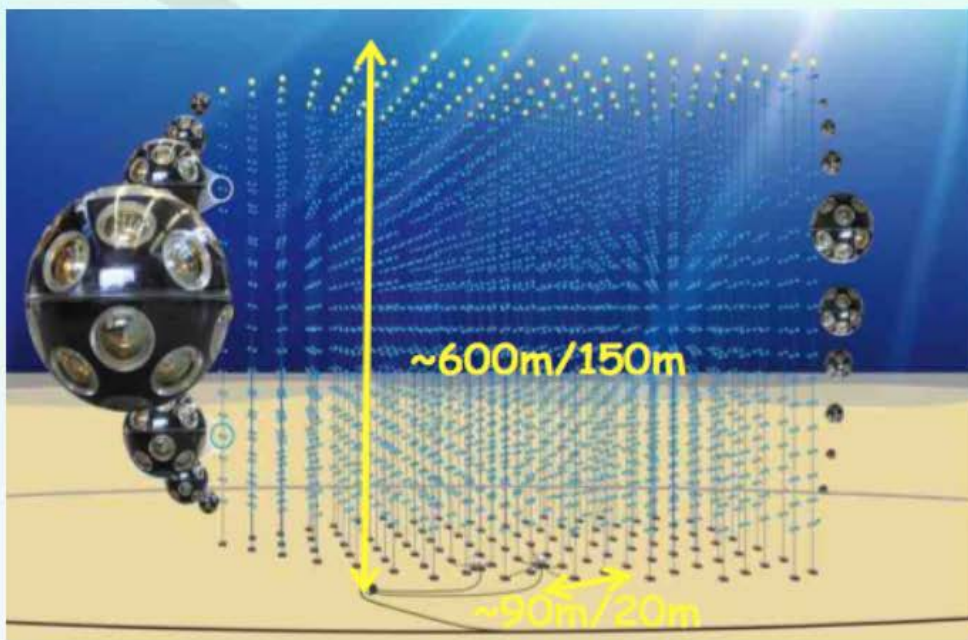
KM3NeT - Collaboration

Cities and Sites of KM3NeT



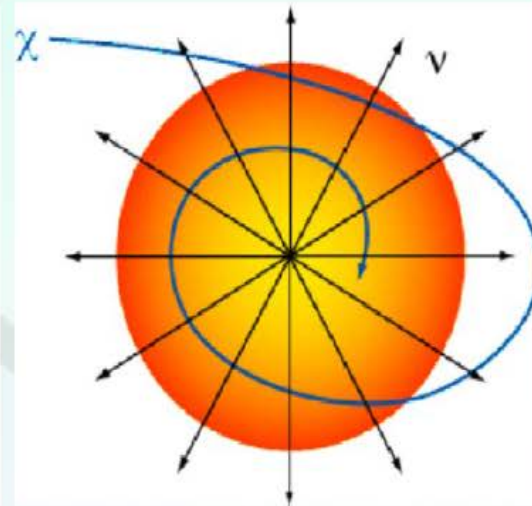
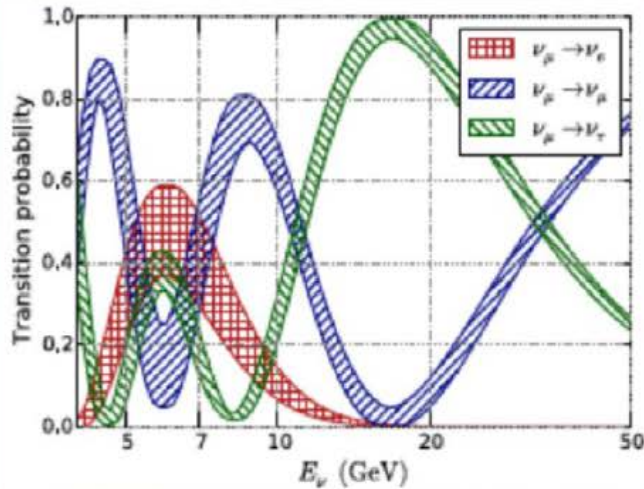
- 240 people
- 45 institutes or universities
- 13 different countries

KM3NeT Building Blocks



	ARCA	ORCA
Location	Italy – Capo Passero	France - Toulon
Detector Lines distance	90m	20m
DOM spacing	36m	9m
Instrumented mass	500Mton	5,7 Mton

KM3NeT Neutrino Telescope science scopes



Low Energy

$\text{MeV} < E_\nu < 100 \text{ GeV}$

- Neutrino Oscillations
- Neut. Mass Hierarchy
- Sterile neutrinos
- Neut. From Supernovae

Medium Energy

$\text{MeV} < E_\nu < 100 \text{ GeV}$

- Dark Matter search
- Monopoles
- Nuclearites

High Energy

$E_\nu > 1 \text{ TeV}$

- Neutrinos from extra-terrestrial sources
- Origin and production mechanism of HE CR

KM3NeT-ORCA

ANTARES

KM3NeT-ARCA

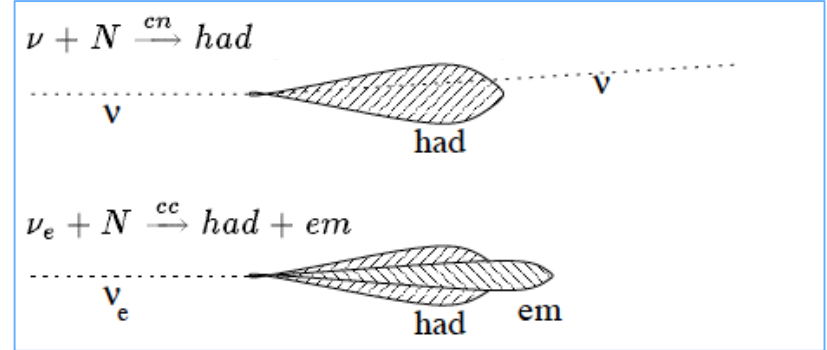
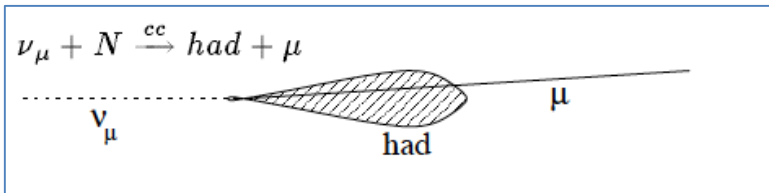
... and synergies with Sea-Sciences: oceanography, biology, seismology, ...



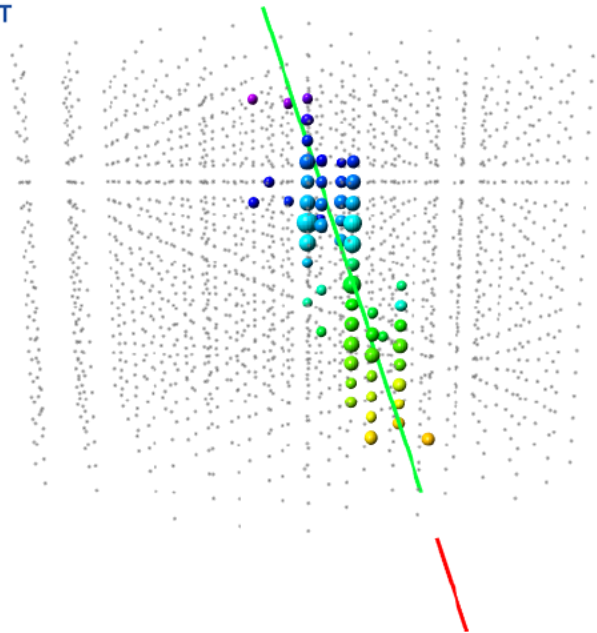
Event Topologies

Track-like (ν_μ^{CC})

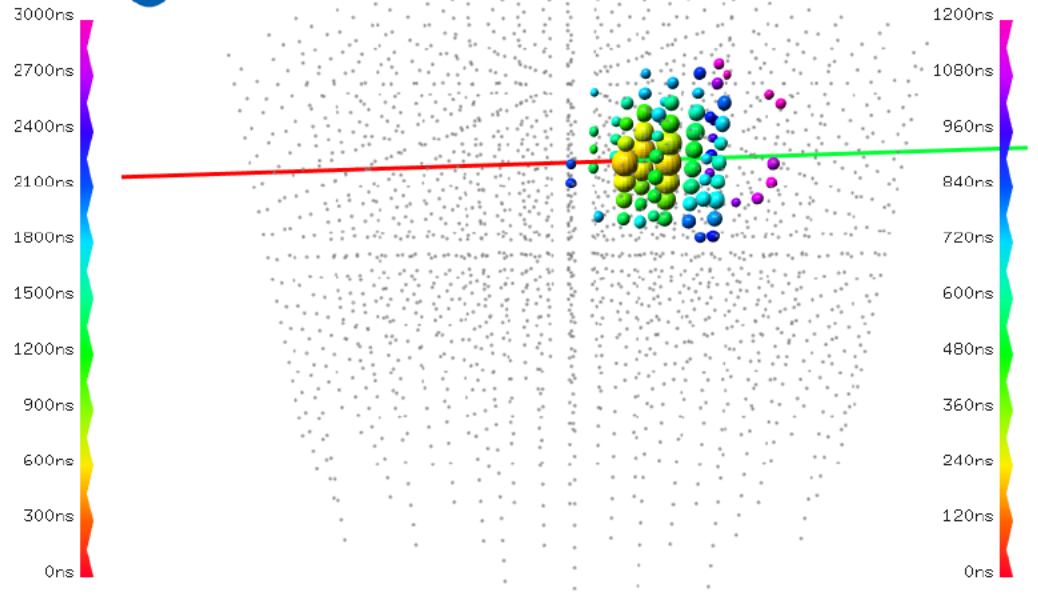
shower-like (ν^{NC}, ν_e^{CC})



KM3NeT



KM3NeT



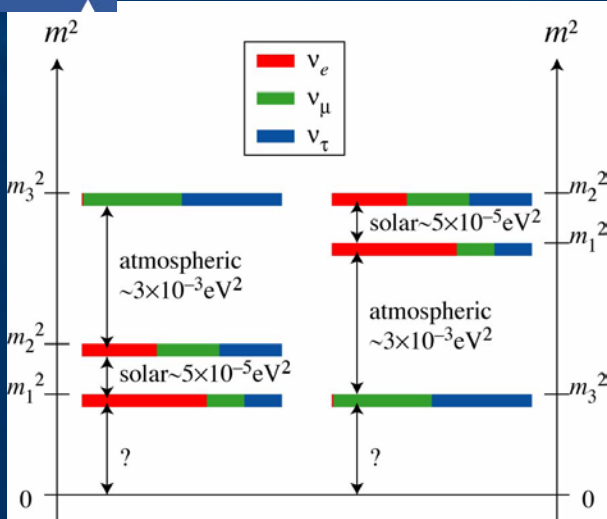
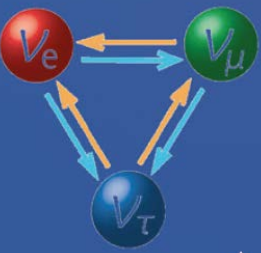
ARCA simulation, TeV neutrino energies

Determination of the Neutrino Mass Hierarchy using atmospheric neutrino oscillations

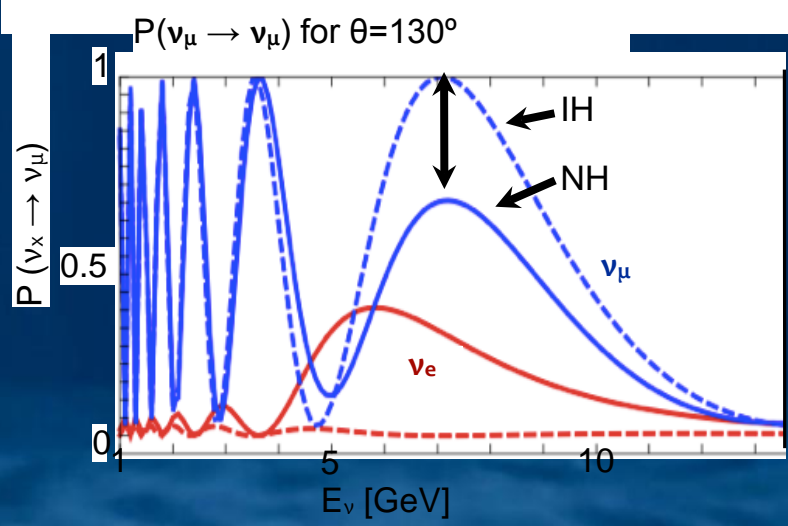
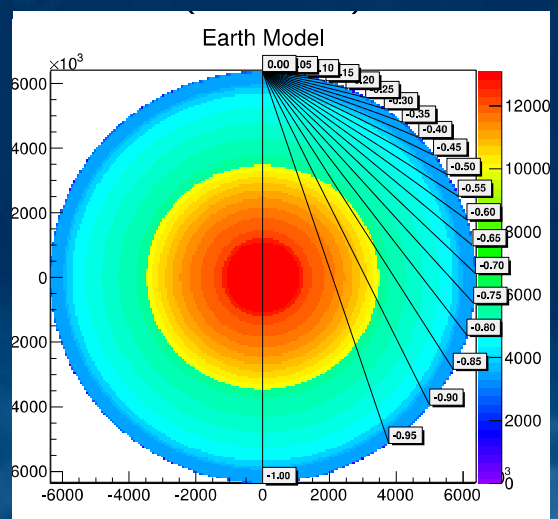
2015 NOBEL PRIZE
in Physics



NEUTRINO OSCILLATIONS
The discovery of these oscillations shows that neutrinos have mass.



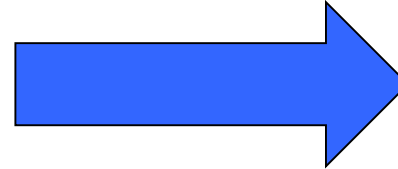
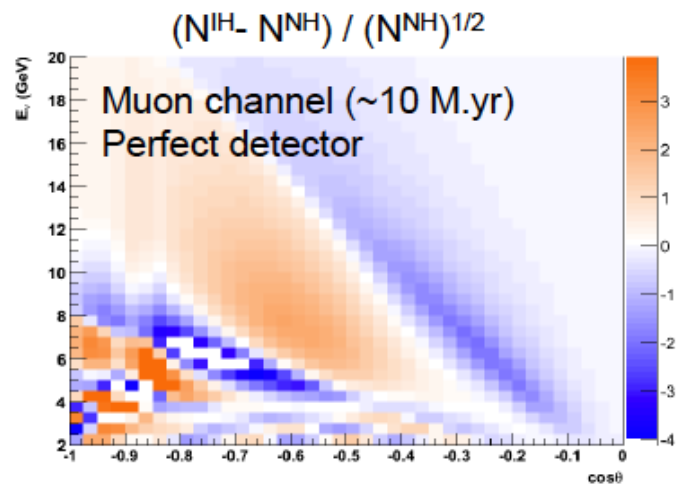
Fundamental parameter of the neutrino particles still unknown !!



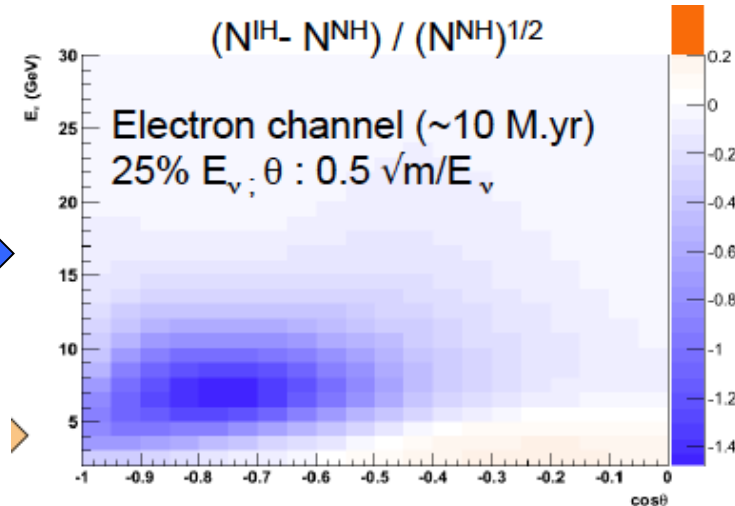
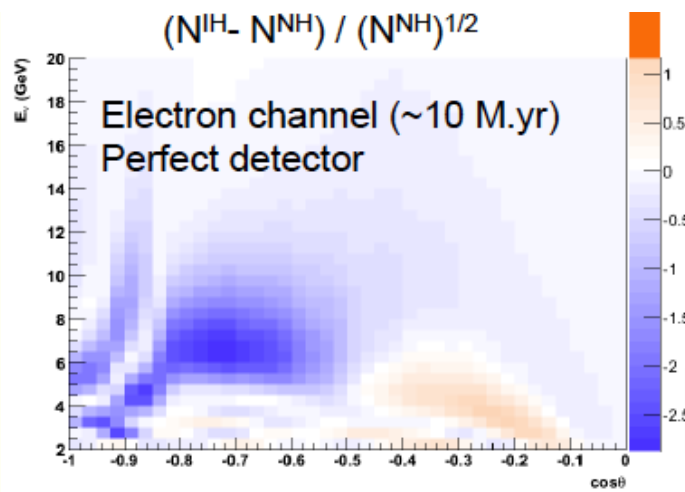
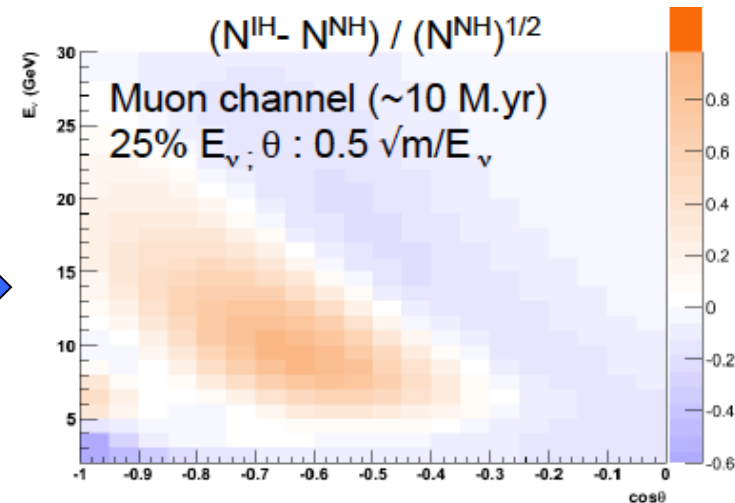
Precise study of the flux of atmospheric neutrinos of few GeV interacting in the Earth

Experimental signature

Both muon- and electron-channels contribute to net hierarchy asymmetry
electron channel more robust against detector resolution effects:



E, θ smearing
(kinematics
+ detector
resolution)

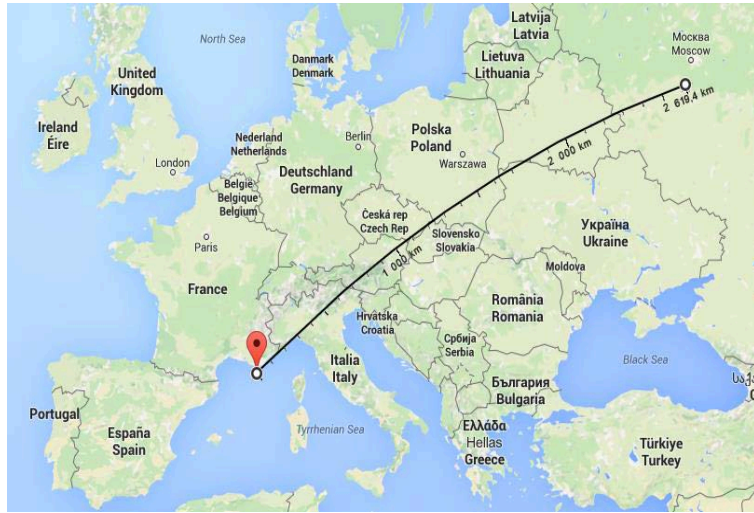




Additional ORCA Physics Topics

- Unitarity of PMNS matrix
- Exotic physics
 - sterile neutrino, Non-standard interactions
- Earth tomography
- Low energy neutrino astronomy
 - Transient phenomena
- Dark Matter indirect searches
- Supernovae monitoring
- Neutrino beam from Protvino
- Earth and Sea Science

P20: Protvino to ORCA



-U70 proton accelerator in Protvino

$$E = 70 \text{ GeV}$$

-Proposed intensity upgrade

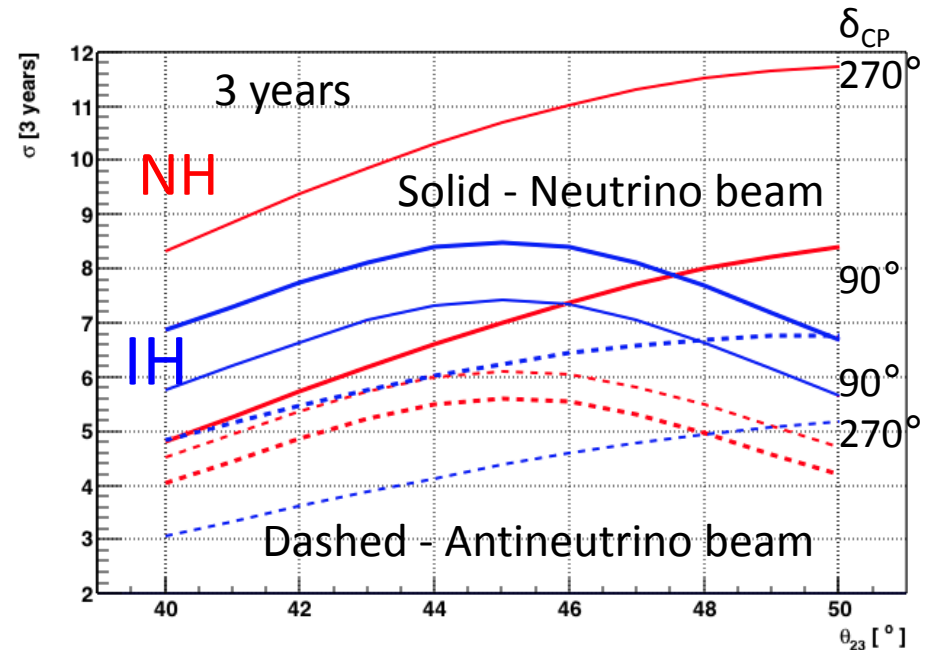
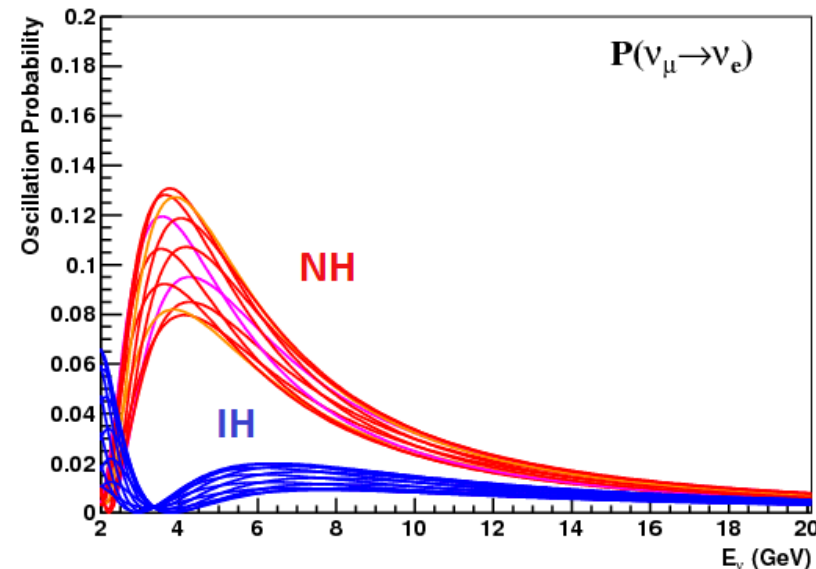
$$P = 450 \text{ kW}$$

➤ Up to 4.10^{20} POT / year

- ν_e appearance at $L = 2600 \text{ km}$

-Target energy range : 3-8 GeV

-Optimal baseline for separating NMH from δ_{CP}



KM3NeT technologies

DOM



-31 x 3" PMTs

Transmission Gbit/s on optical fibre

Synchro with Hybrid White Rabbit

Calib LED flasher & acoustic piezo

Position Tiltmeter/compass

➔ Uniform angular coverage

➔ Directional information

➔ Digital photon counting

➔ Wide angle of view

➔ Background rejection

➔ All data to shore

String



~ 700 or 200 m

LOM



- Rapid / safe deployment
- Multiple strings / campaign
- Auto/ROV unfurling
- Re-useable

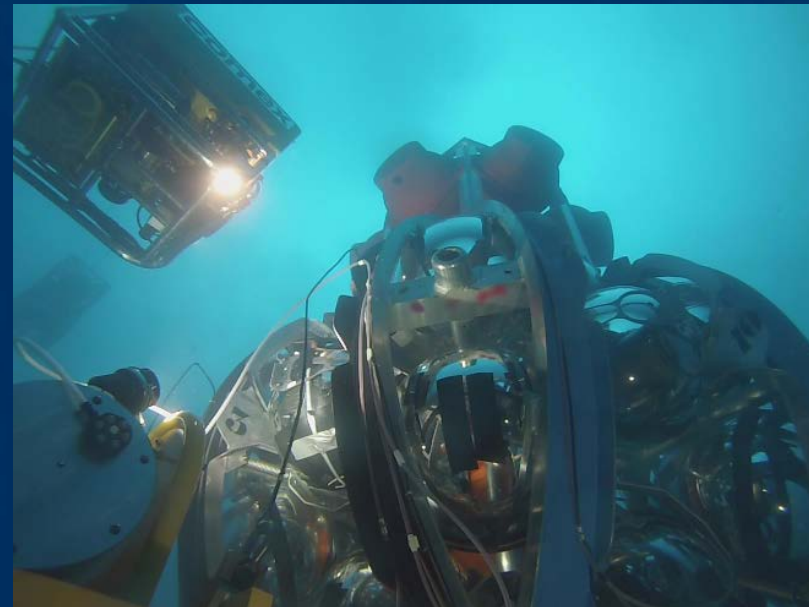
- 2 Dyneema ropes
- VEOC: Oil filled PVC tube
- Low drag
- Low cost



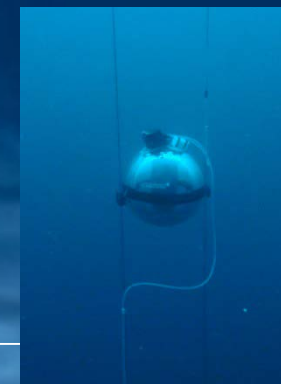
Construction of KM3NeT ORCA



- Configuration ORCA line defined (9m between DOMs)
- Deployment with LOM validated by shallow water tests

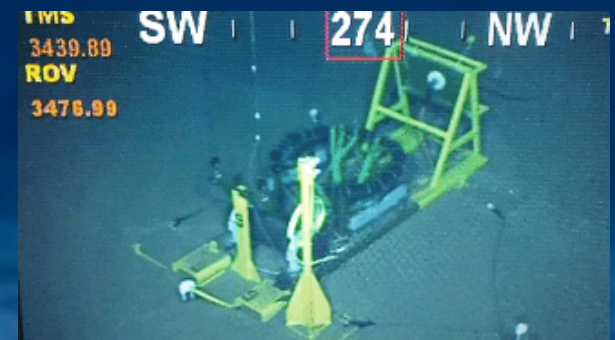
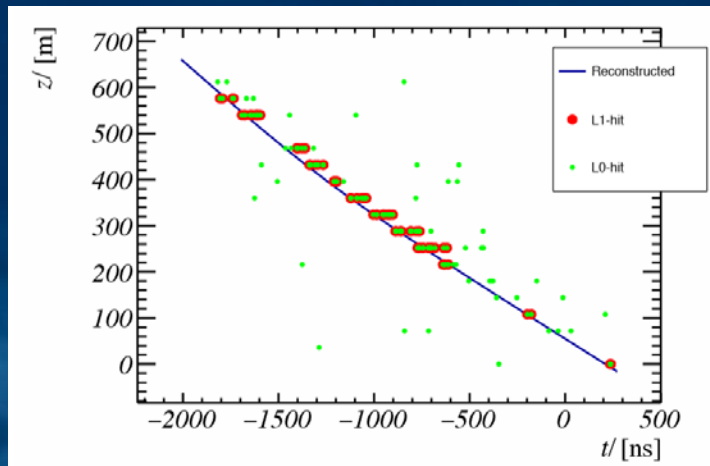
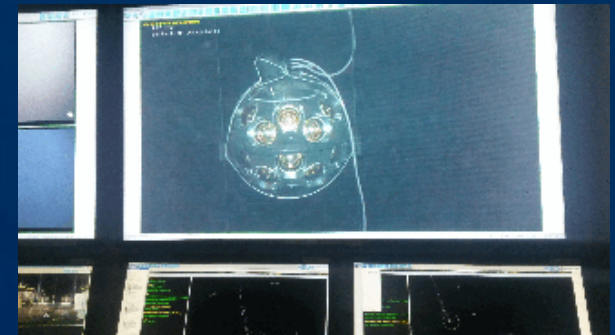
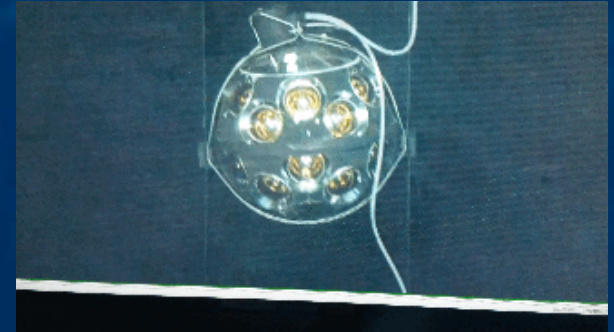
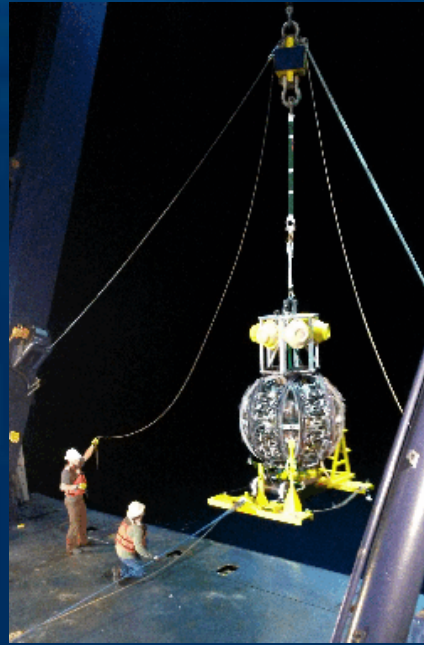
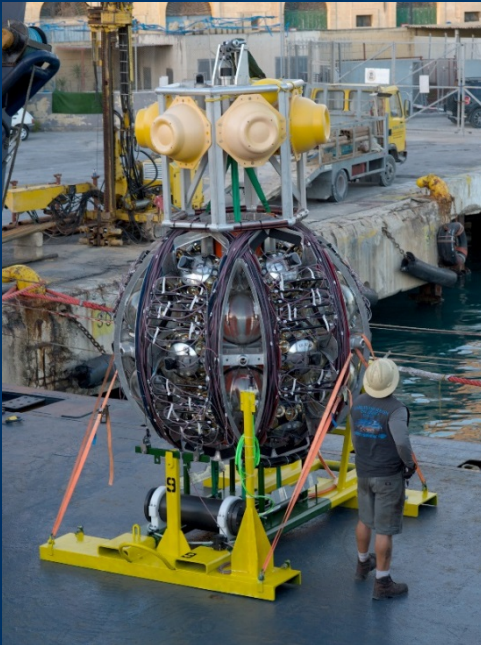


First ORCA line deployed on september 2017!



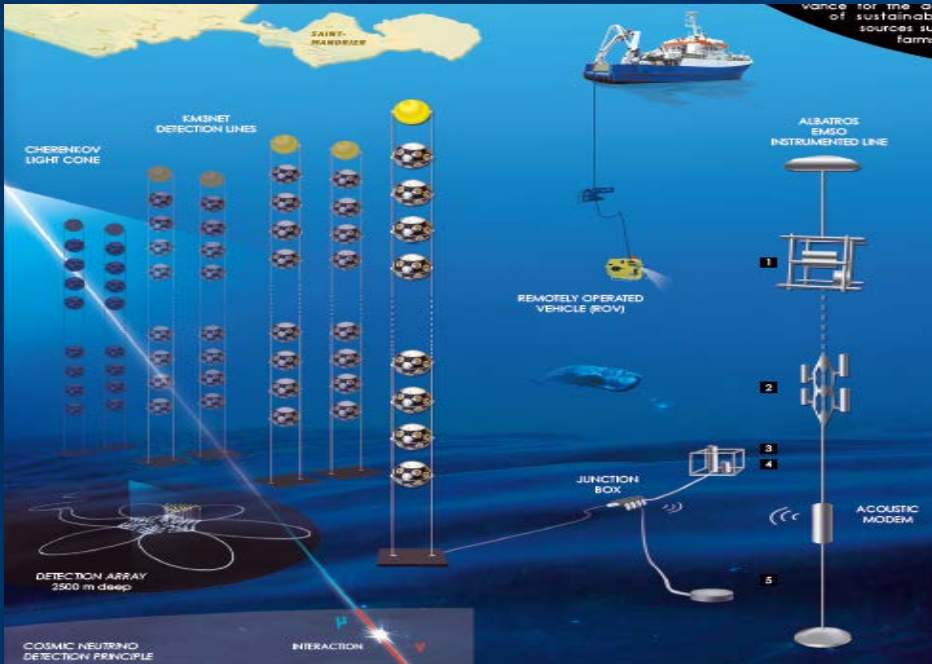
The first KM3NeT-ARCA detector lines

KM3NeT



First line in operation since December 2015, 2nd since May 2016

A Multidisciplinary Observatory in the Deep Sea

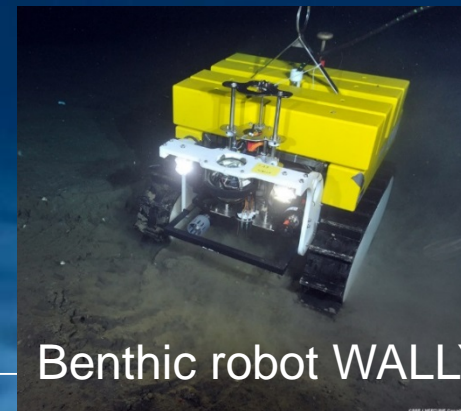


- Astronomy
- Neutrino physical properties
- Physico-chemical oceanography
- Marine Biology
- Bioacoustic
- Bioluminescence
- Microbiology
- Ecology, biogéochimie
- Sismology
- Environnement
- Renewable energies
- Underwater acoustic
- R&D marine technologies
- ...

Dolphins (Pilot Whales)
observed on ANTARES site



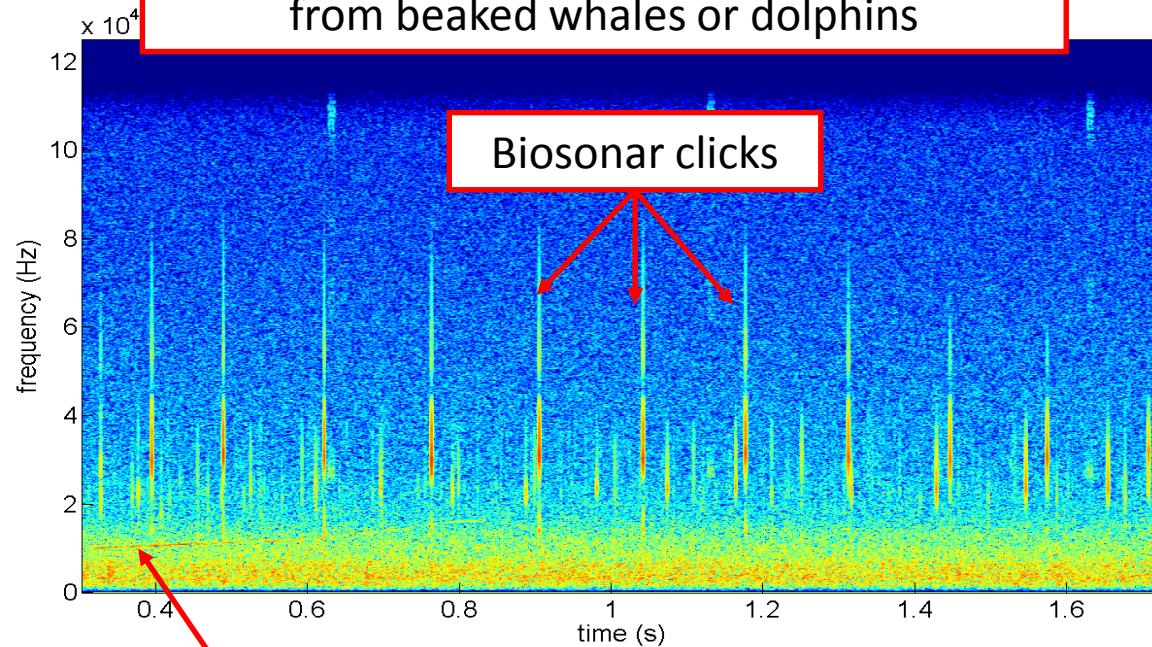
Deep sea sismometer



Benthic robot WALLY

Bioacoustic studies of Whales and Dolphins

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



Detection and localisation of bioacoustic sources (cetaceans)
using hydrophones integrated on ANTARES and KM3NeT detectors



Summary & Perspectives



- After decades of dream and intensive R&D, Neutrino Astronomy is finally opening **a new window over the Universe**
- ANTARES is recording new neutrino events every days
 - >10 000 neutrinos detected so far !
 - analyses are under progress looking for **the origine of HE Cosmic** and **discovering the nature of the mysterious Dark Matter**
- The building of the new generation neutrino telescope KM3NeT, based on an improved technology, **has started !**
 - it should lead to **fondamental results** during the next decade on :
 - **Neutrino Astronomy (ARCA)**
 - **Fundamental properties of neutrinos (ORCA)**
- The submarine infrastructure offers an unique potentiel of very rich **multidisciplinary researchs** in the deep sea

Lots of New, Rich and Great Physics !
→ Join us on this Adventure !!