ANTARES and KM3NeT
Deep Sea Telescopes to study the Universe

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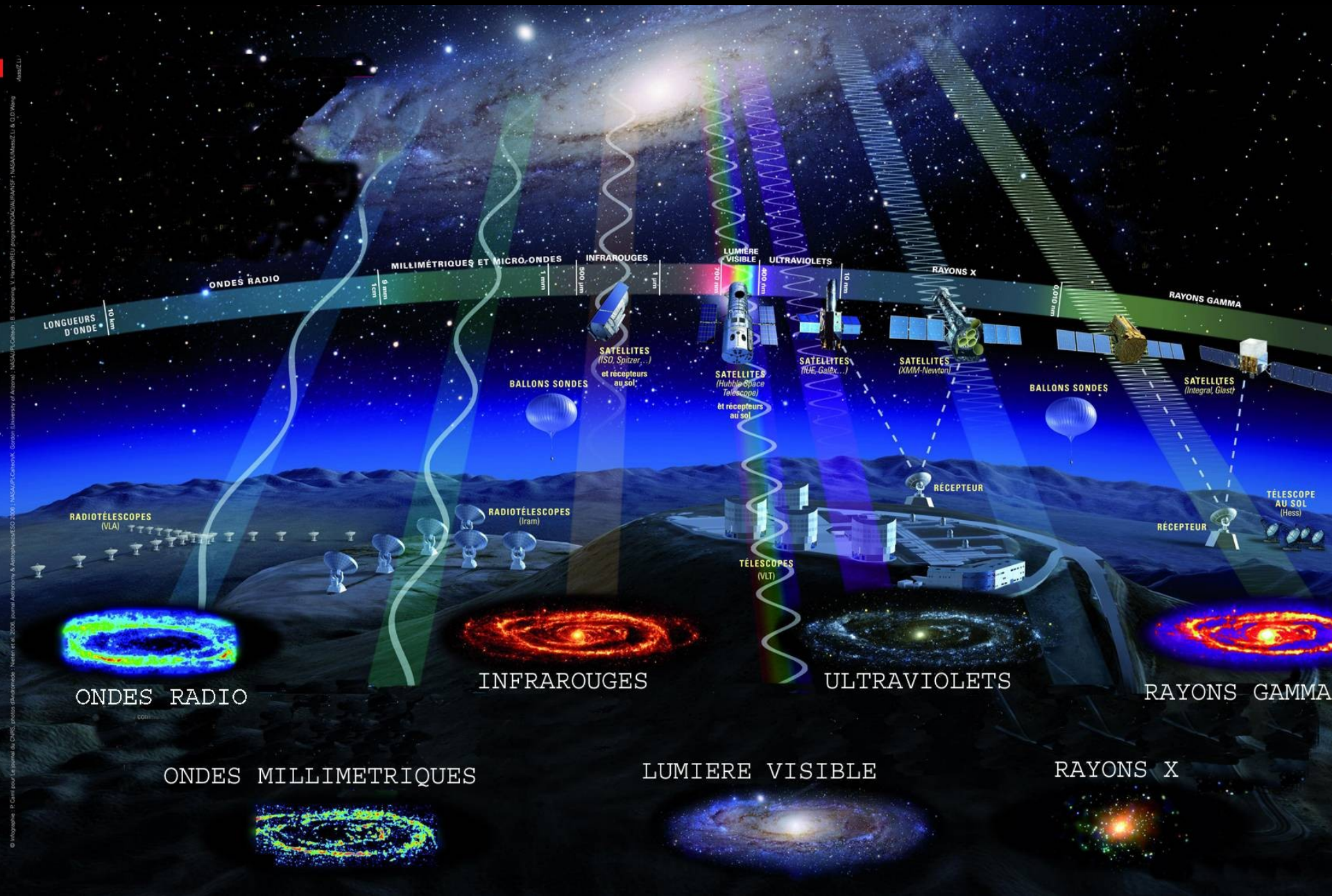
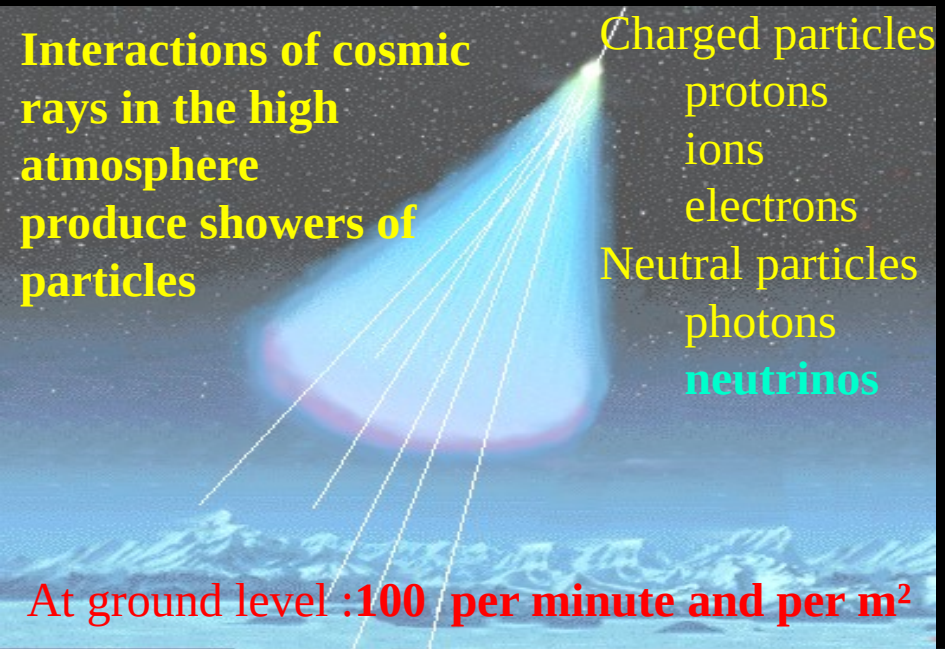
Physics of the two infinities: École d'été France Excellence 2019 @ CPPM - July 2019

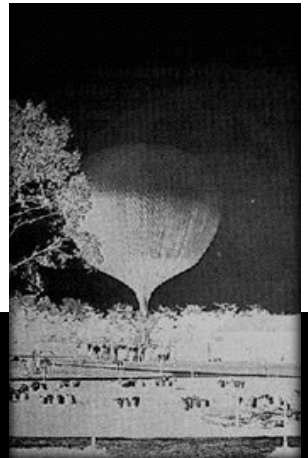
Multi-Wavelengths Astronomy



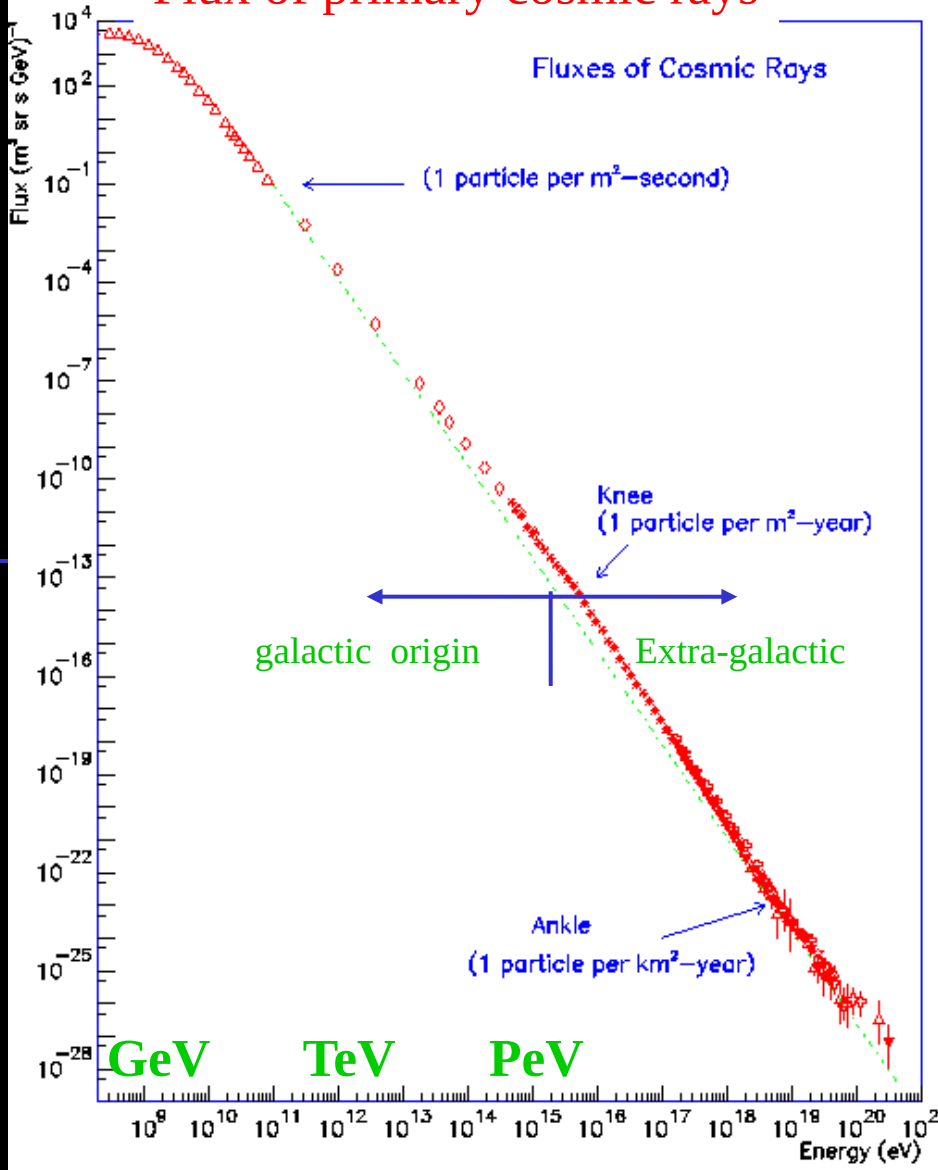
Cosmic Rays



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

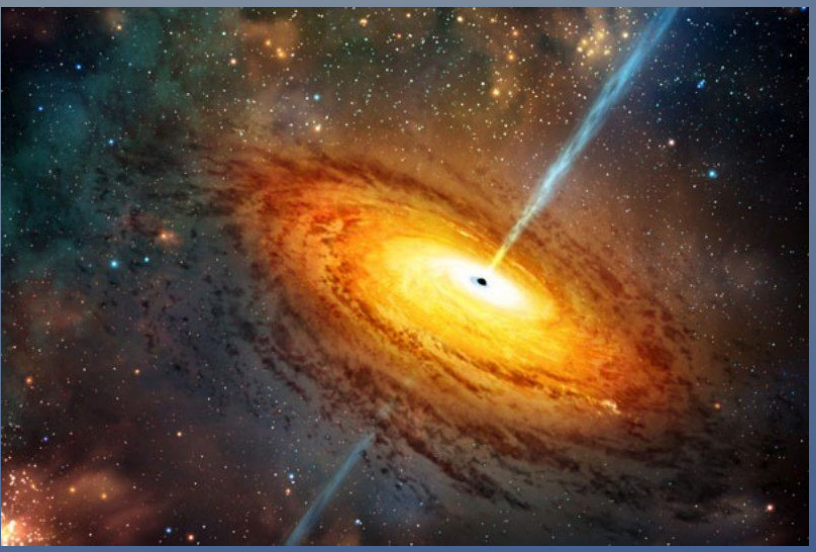


Flux of primary cosmic rays



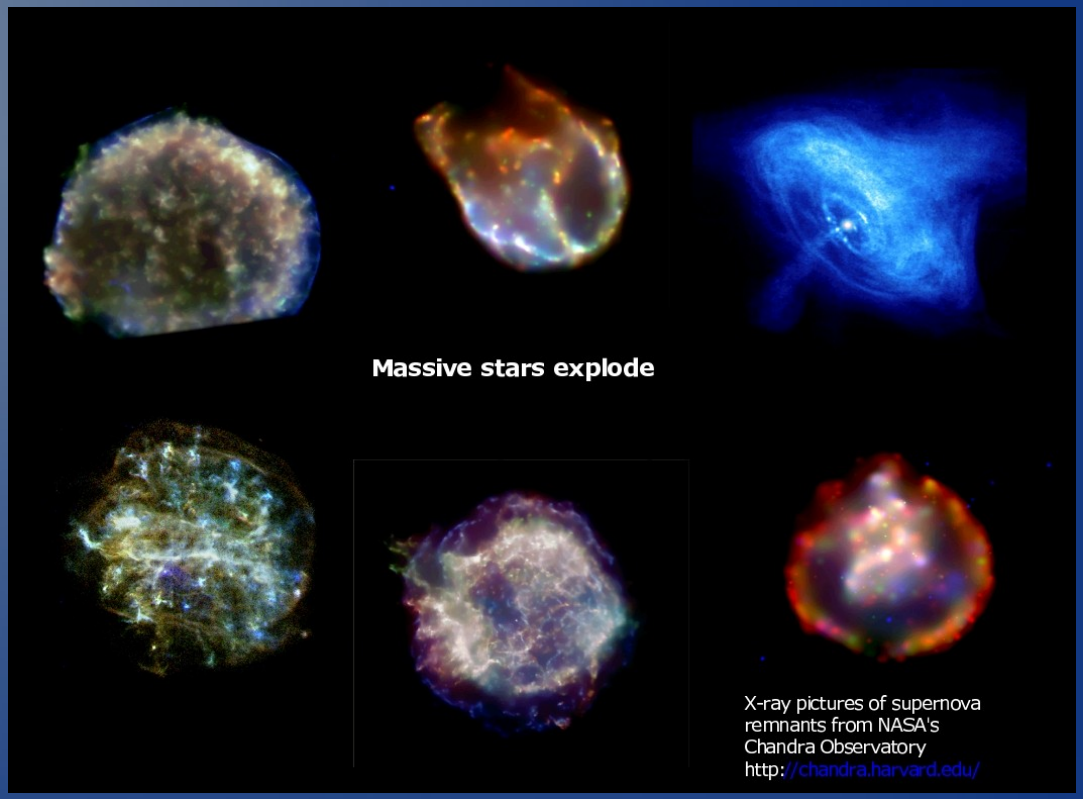
Potential Sources: Supernovae, Black Holes,…

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

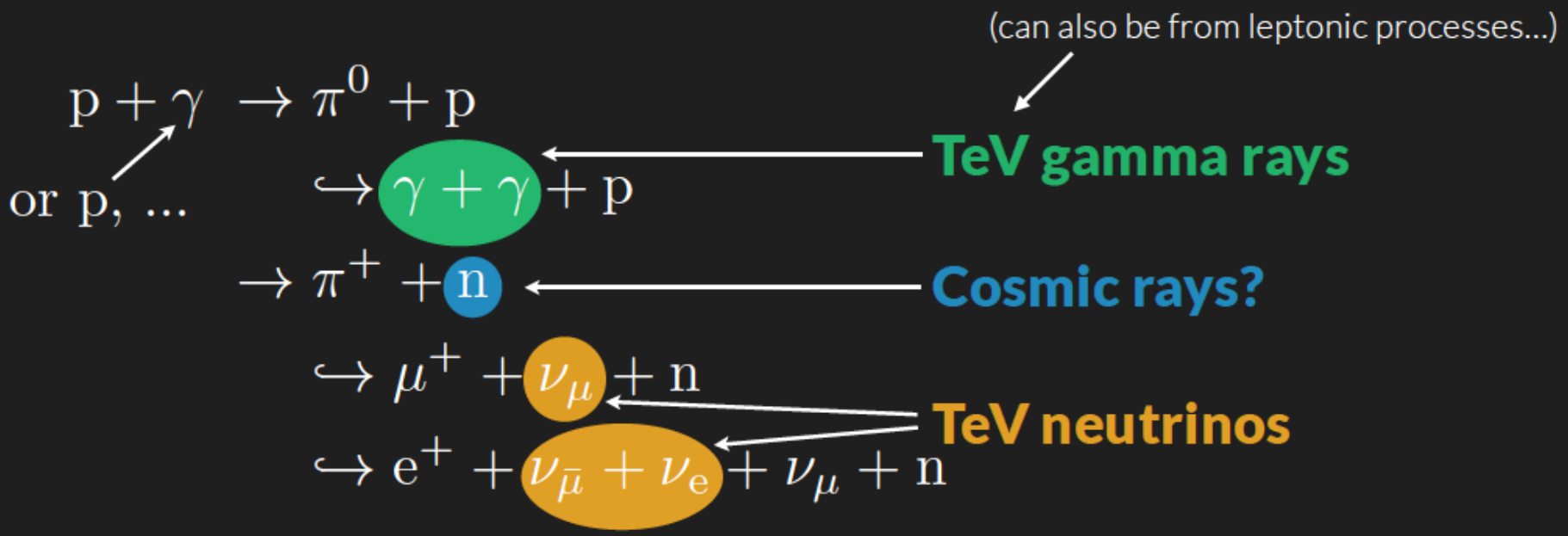


Super-massive Black Holes
(Active Galactic Nuclei)

Massive star explosions (Supernovae)



The CR-Gamma-Neutrino Connection



$\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ source —oscillations→ $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ Earth

$$E_\nu \approx \frac{1}{20} E_P \approx \frac{1}{2} E_\gamma$$

High-energy neutrino astronomy?

High-energy neutrino production processes

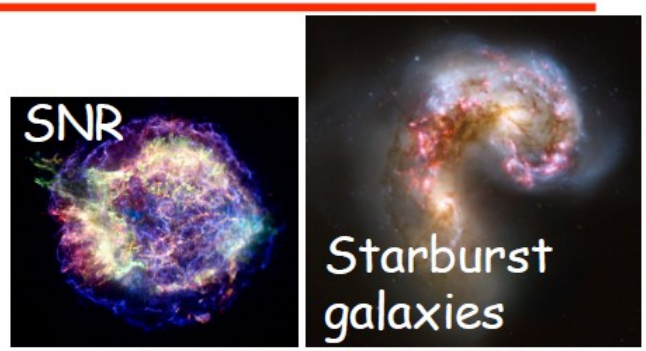
- **Hadronuclear** (e.g. galactic cosmic rays)

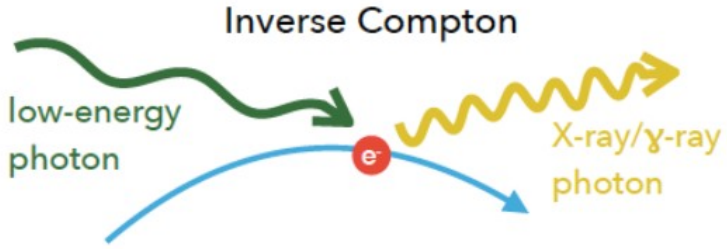
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

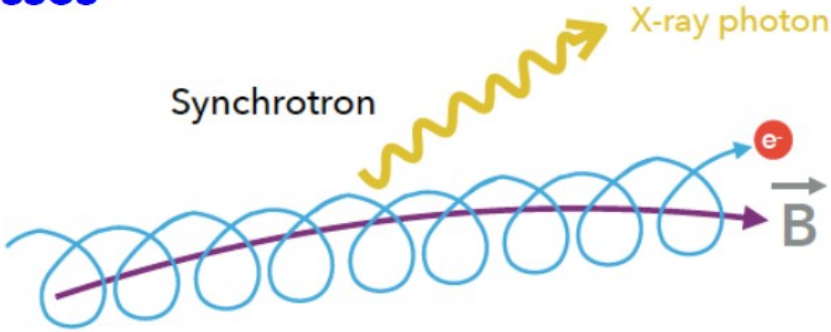
- **Photohadronic** (e.g. gamma-ray bursts, AGNs)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

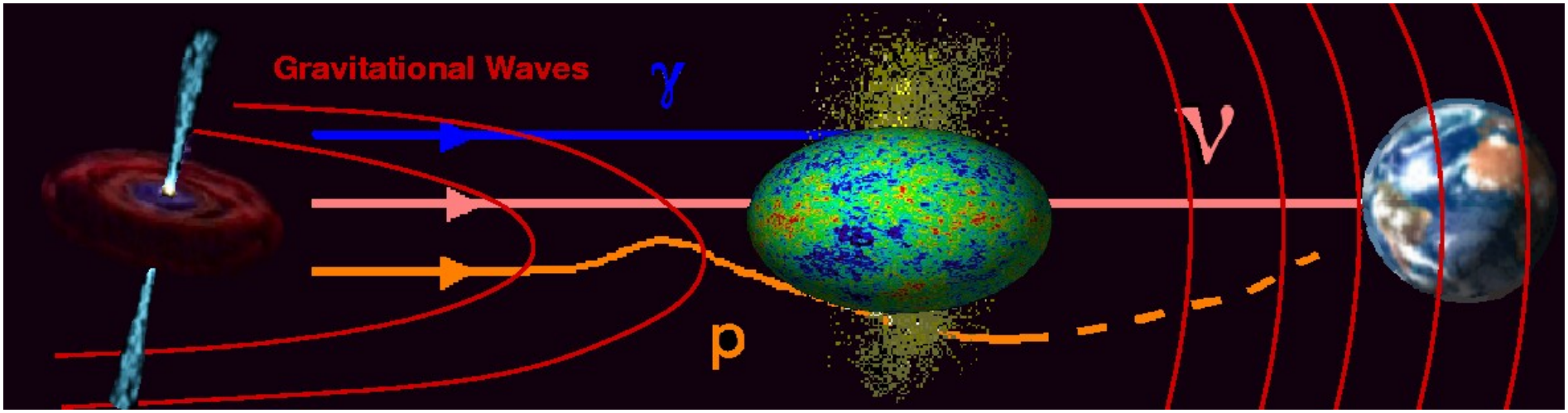
- **But γ-rays also from leptonic processes**







Neutrinos and Multi-Messenger Astronomy



Cosmic Rays

Subject to deflection by magnetic fields
Horizon limited by GZK cutoff
Large time delay w.r.t. optical signals

Photons

leptonic and hadronic processes-> confusion
Absorbed at high energies and large distances

Neutrinos

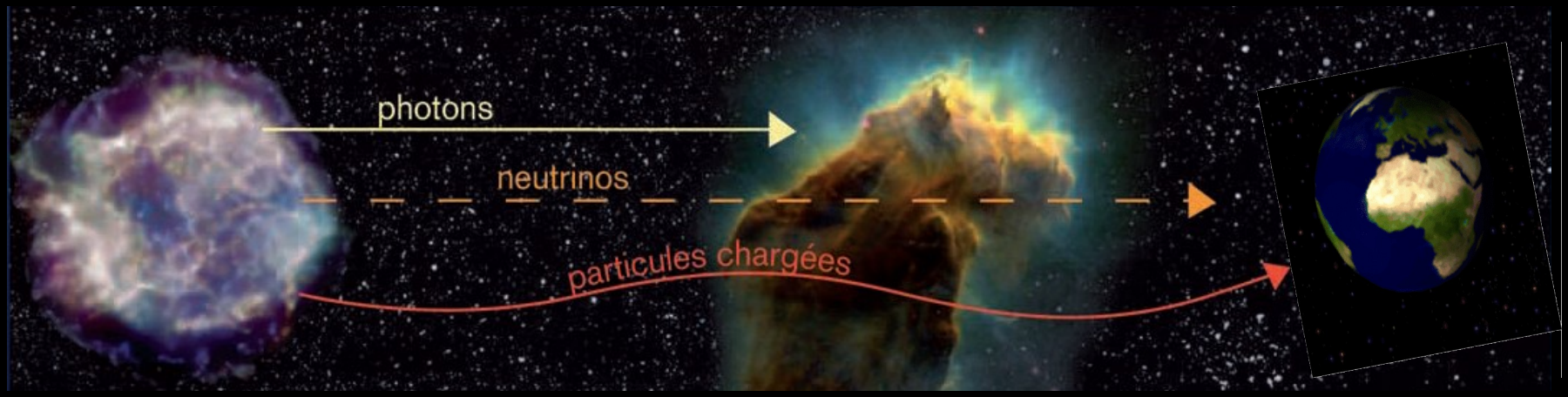
Unambiguous signature of hadronic acceleration
Not deflected by magnetic fields or absorbed by dust
Horizon not limited by interaction with CMB/IR
Escape from region of high matter density
Time correlated with EM signals

-> identify the cosmic ray sources

Large sky survey

24/24, 7/7

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

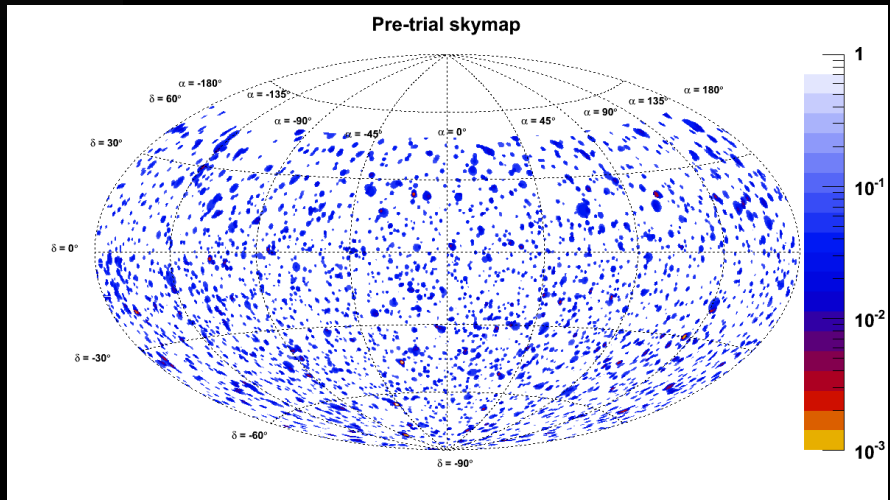
A new window over the Universe

High energy neutrinos emitted by cosmic accelerators

Neutrino

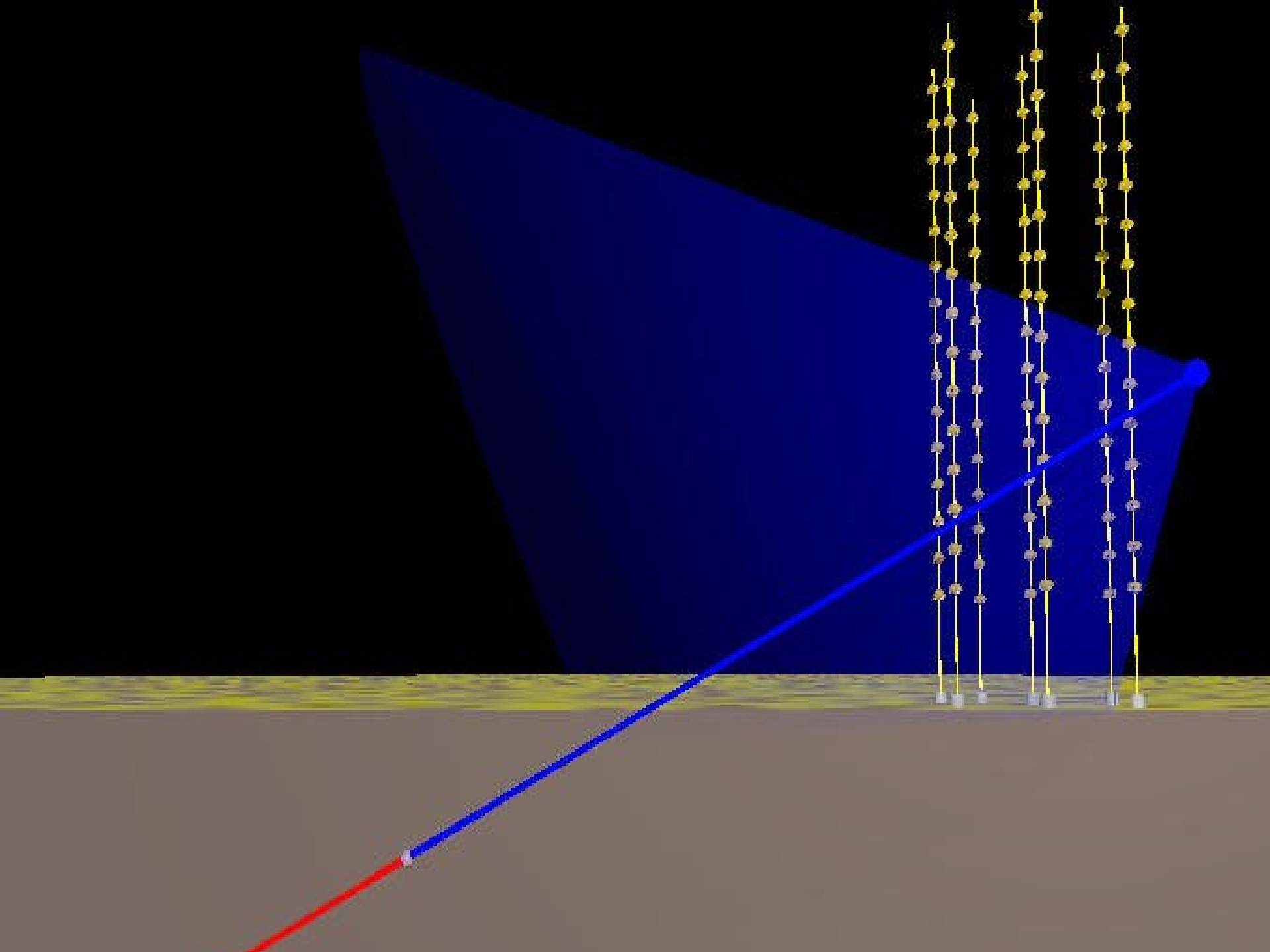
ν

μ



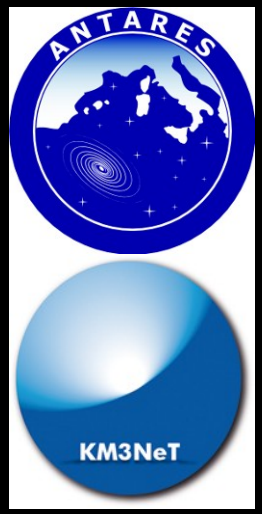
Neutrino Astronomy :

skymap of the most catastrophic events of the Universe

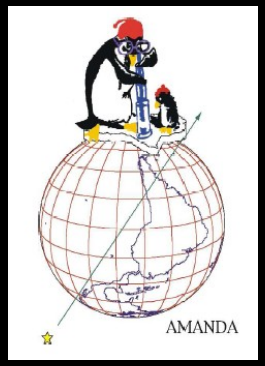


Existing Neutrino Telescopes

ANTARES/KM3NeT

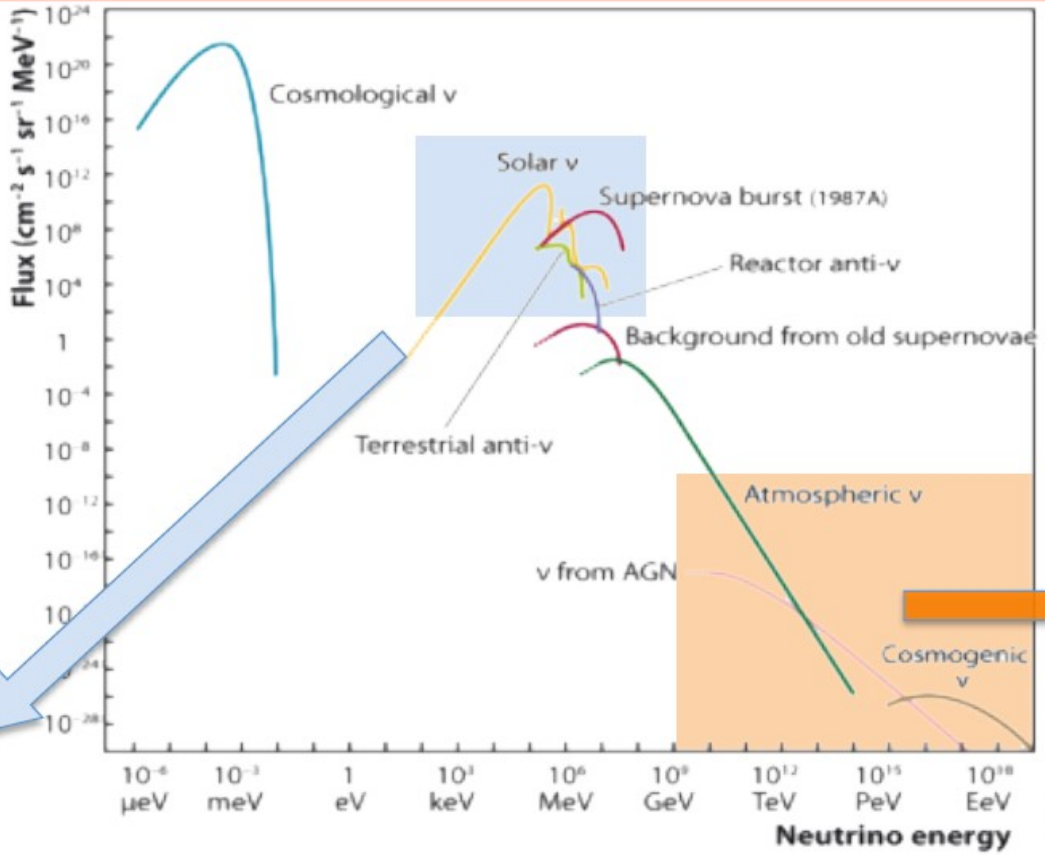


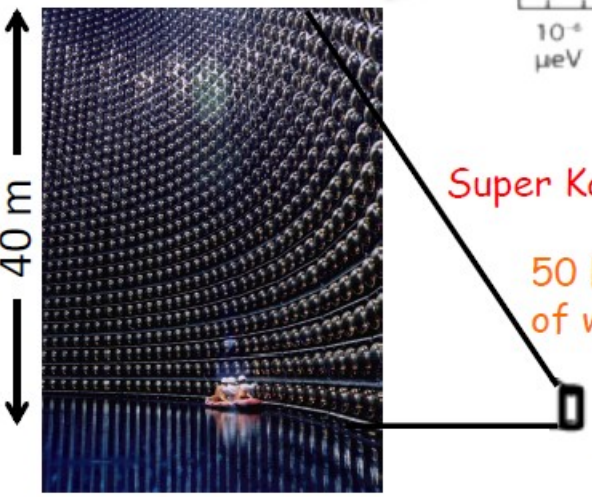
BAIKAL



AMANDA/Ice Cube

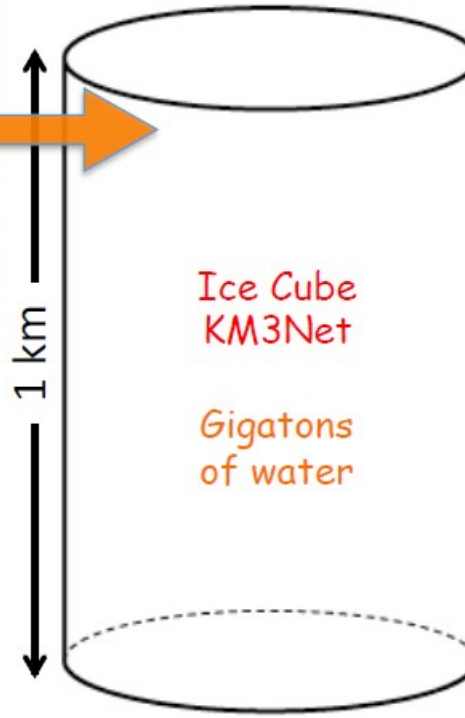
Neutrino spectrum





Super Kamiokande

50 ktons
of water

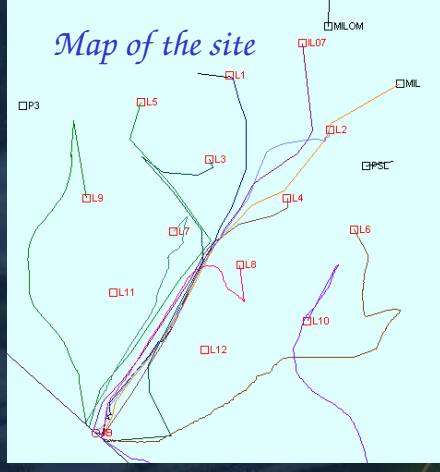


Ice Cube
KM3Net

Gigatons
of water

The ANTARES Detector

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



Bouy

14.5 m

Storey

350 m

Junction Box

100 m

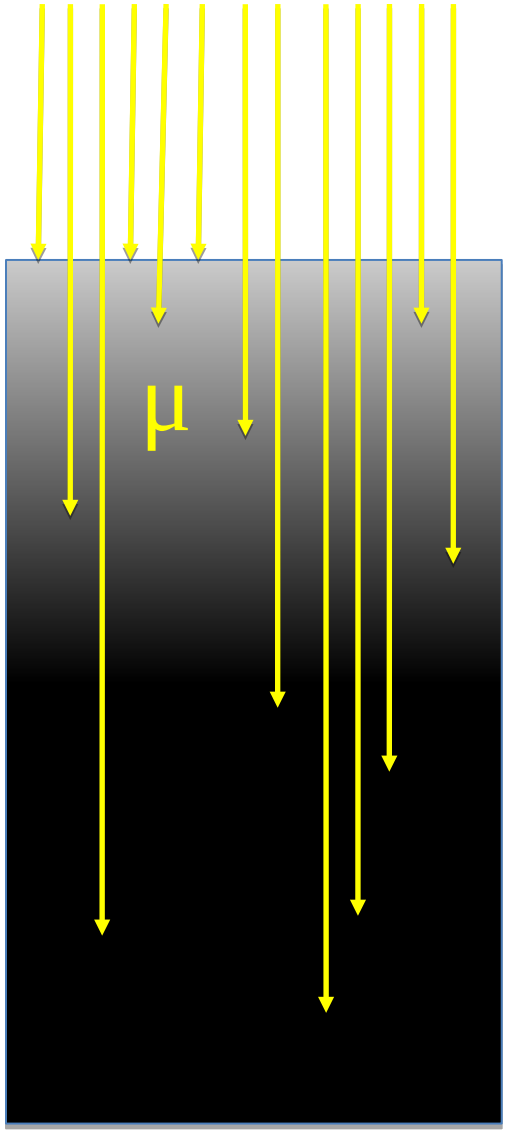
~60-75 m

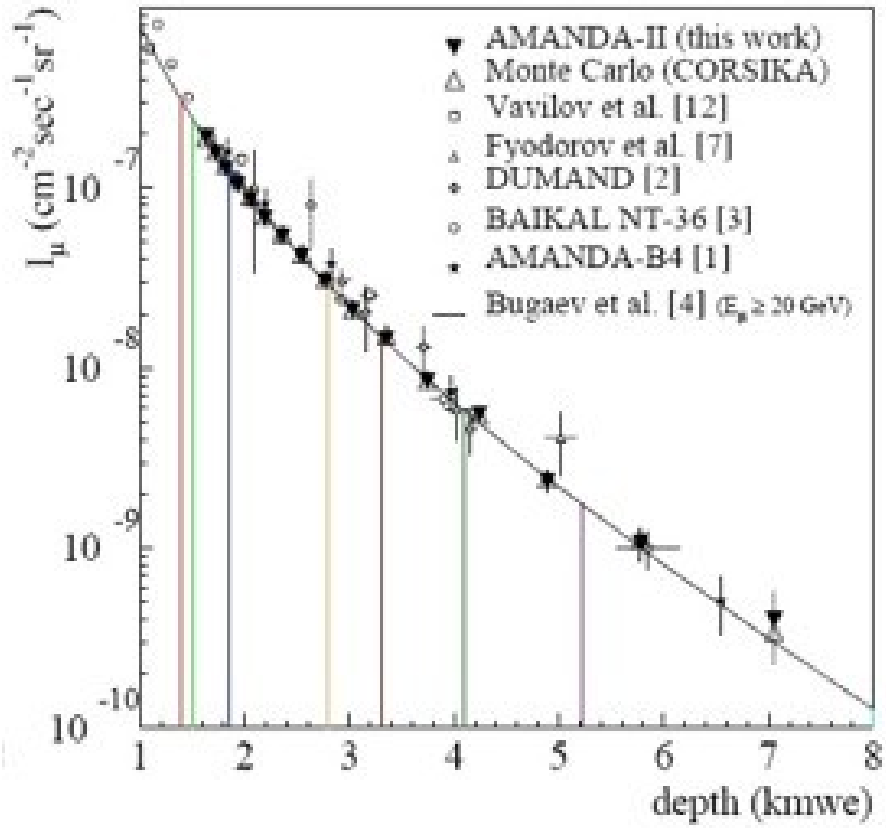
Electro-optical Cable

Depth: 2500m

Complete detector since May 2008

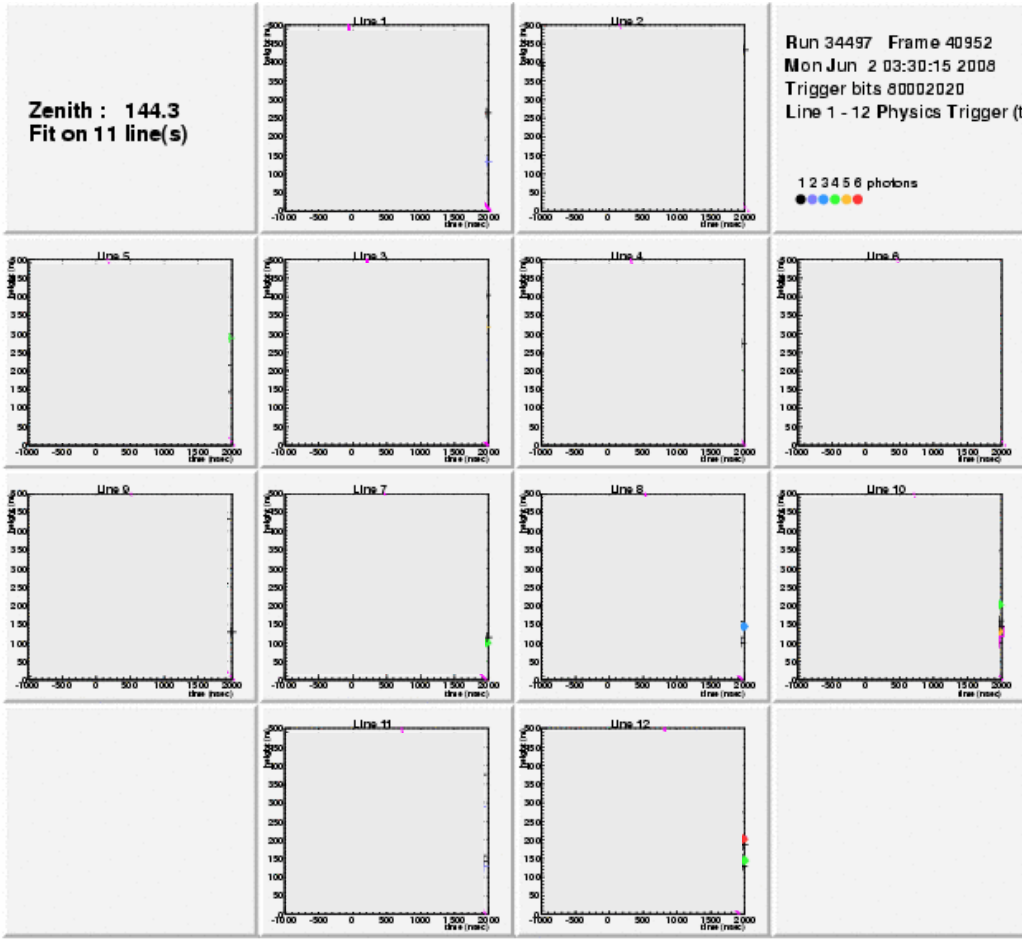
The ANTARES site


μ

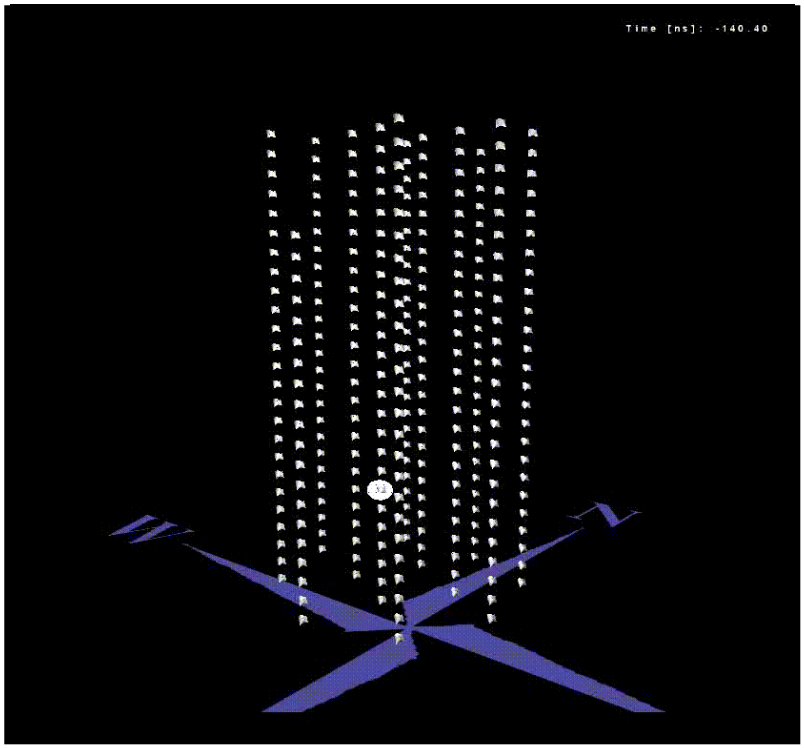

AMANDA-II (this work)
Monte Carlo (CORSIKA)
Vavilov et al. [12]
Fyodorov et al. [7]
DUMAND [2]
BAIKAL NT-36 [3]
AMANDA-B4 [1]
Bugaev et al. [4] (E_μ ≥ 20 GeV)
I_μ (cm^-2 sec^-1 sr^-1)
10^-7
10^-8
10^-9
10^-10
1
2
3
4
5
6
7
8
depth (kmwe)

Example of a muon event

Few muons per second are detected



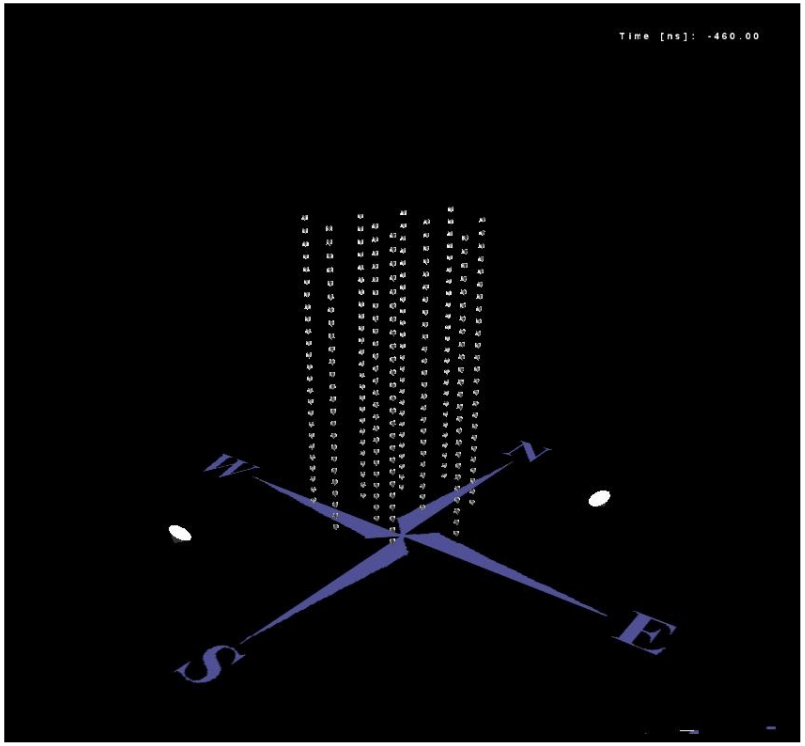
down-going muon event



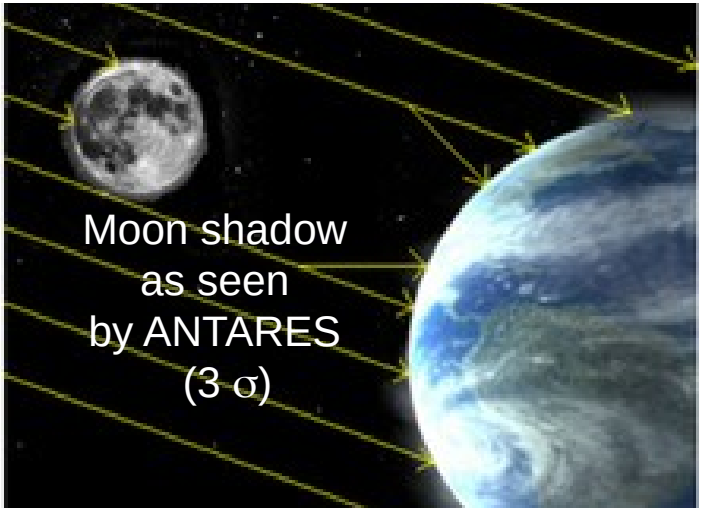
Example of a neutrino event

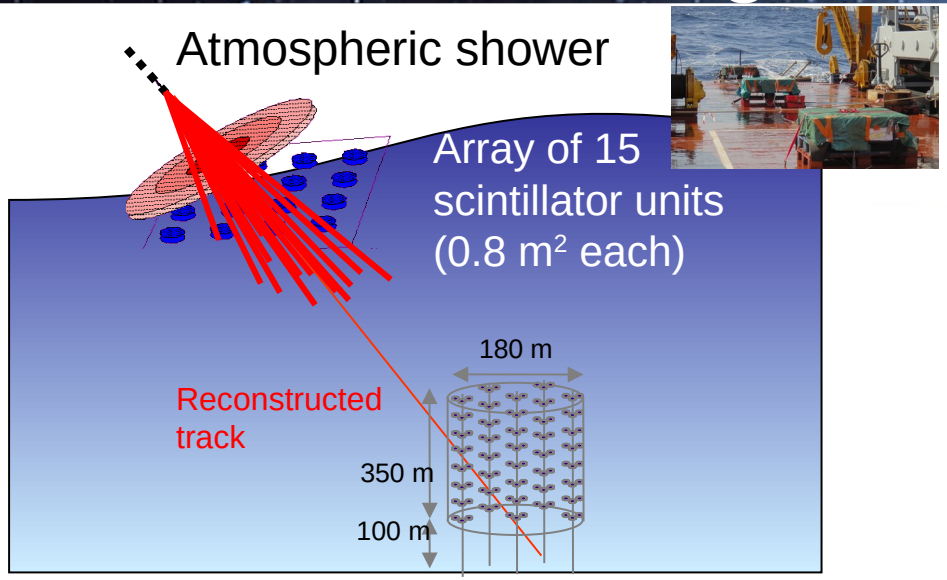
Few neutrinos per day are detected

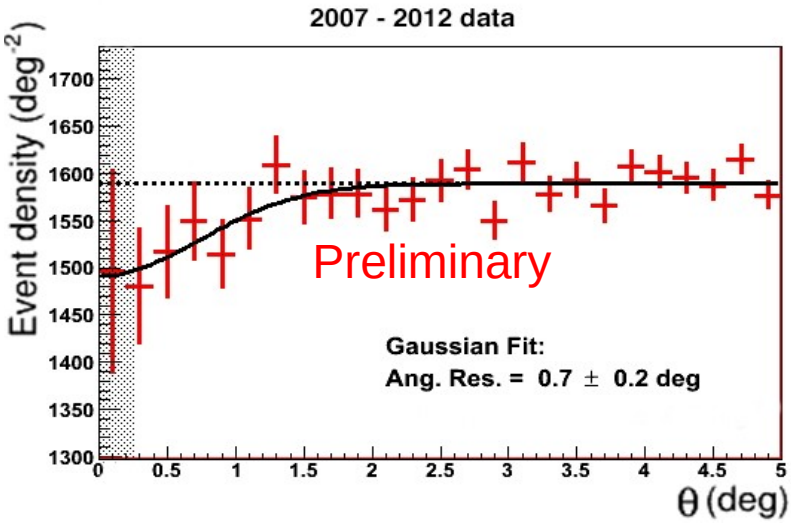
up-going muon event

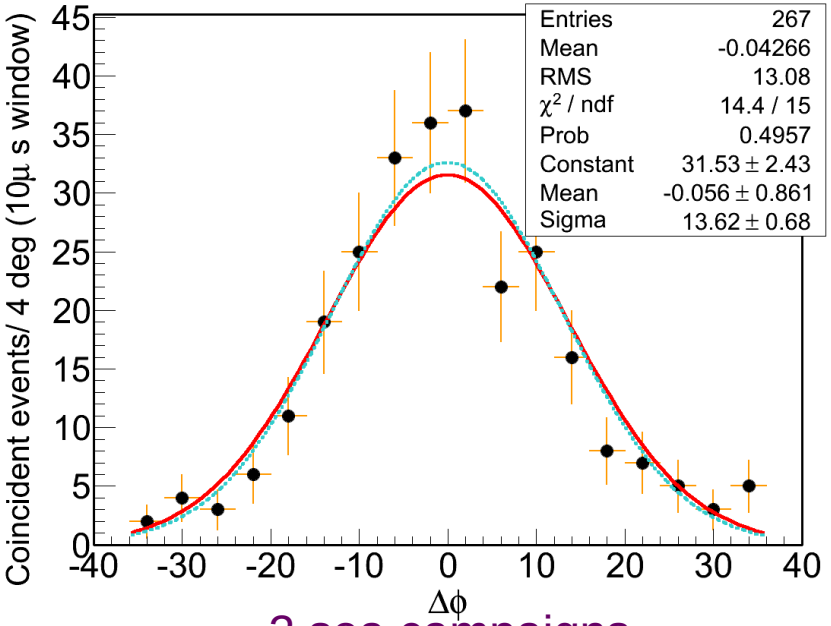


Check of Detector Absolute Pointing

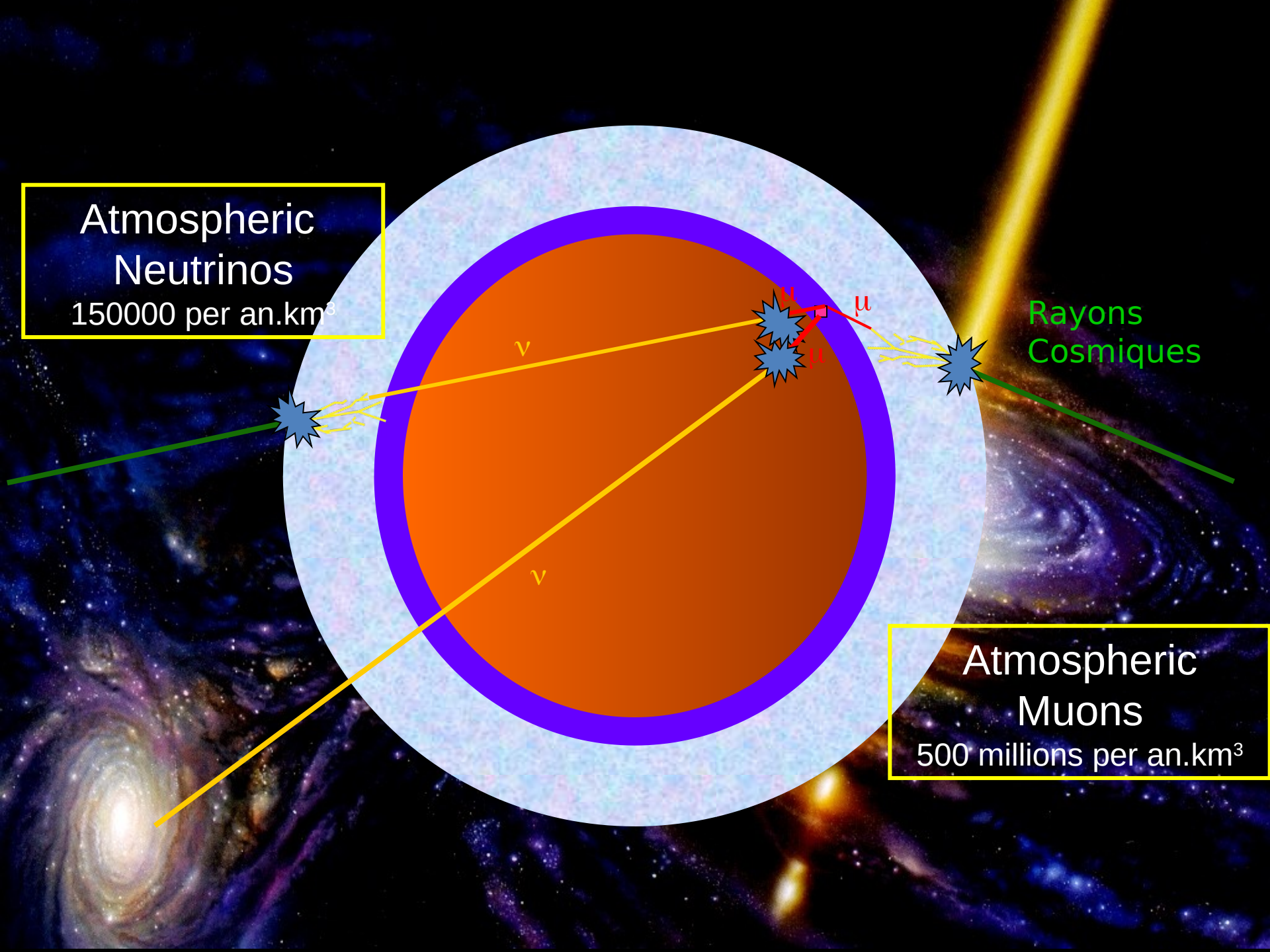


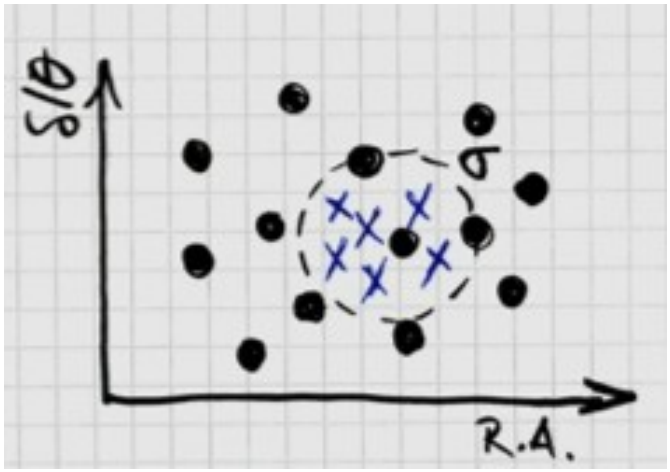


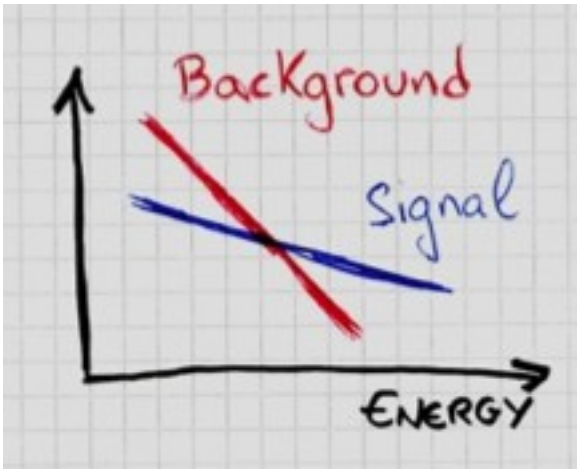




2 sea campaigns


Atmospheric
Neutrinos
150000 per an.km3
ν
ν
μ
μ
μ
Rayons
Cosmiques
Atmospheric
Muons
500 millions per an.km3





Background suppression :

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

Signal:

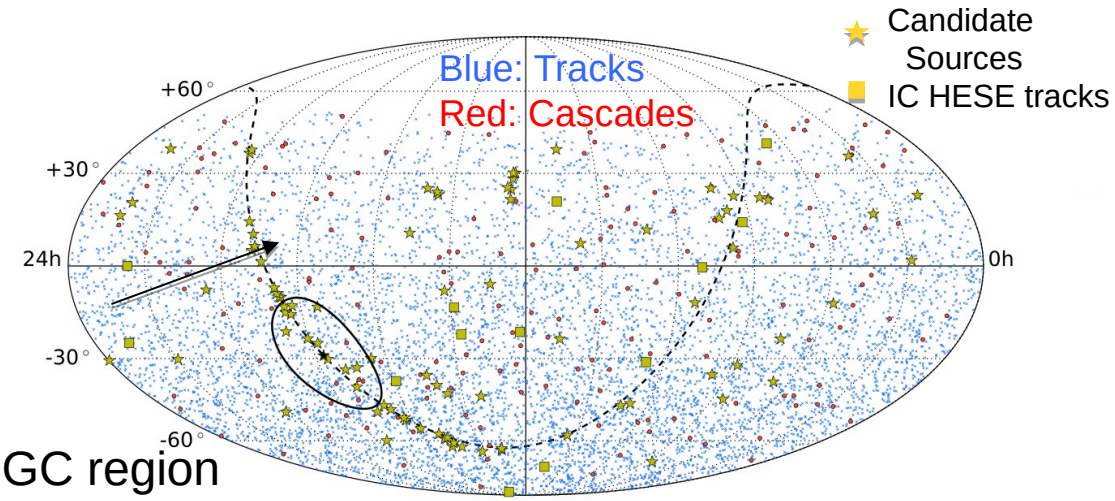
- distribution concentrated for point source + harder energy spectrum

Point Source

Diffuse Flux

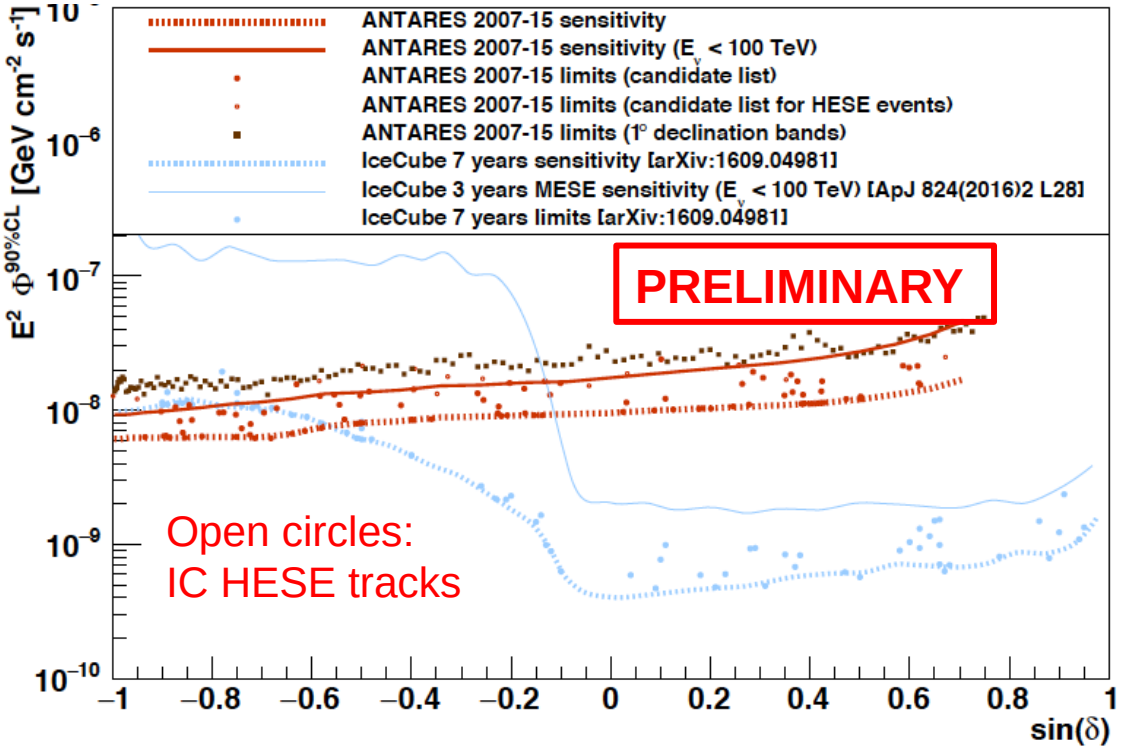
All flavor search with ANTARES

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



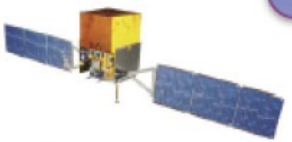
GC region

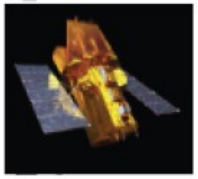
- No significant excess
- Best limits for part of Southern Hemisphere
- Excellent sensitivity for E_ν <100 TeV
- Results to be combined with latest IC search



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,…





GeV-TeV γ-rays
Fermi / HESS…

📖 JCAP 03(2013) 006
📖 A&A 559 (2013) A9
📖 JCAP 05 (2014) 001
❑ JCAP 12(2015)014

Optic / X-ray
TAROT,
ROTSE / Swift,
ZADKO

📖 APP 36 (2012) 204
📖 A&A 559 (2013) A9
❑ JCAP 02(2016)062A

HE neutrinos

Radio
MWA

❑ APJ 820 (2016) L24

UHECR
Auger

📖 APJ 774 (2013) 19

Gravitational
Waves
Virgo / Ligo

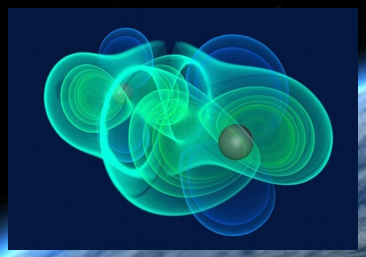
📖 JCAP 06 (2013) 008
❑ PRD 93 (2016) 122010

The multi-messenger program

1ST APPROACH:

Time dependent searches

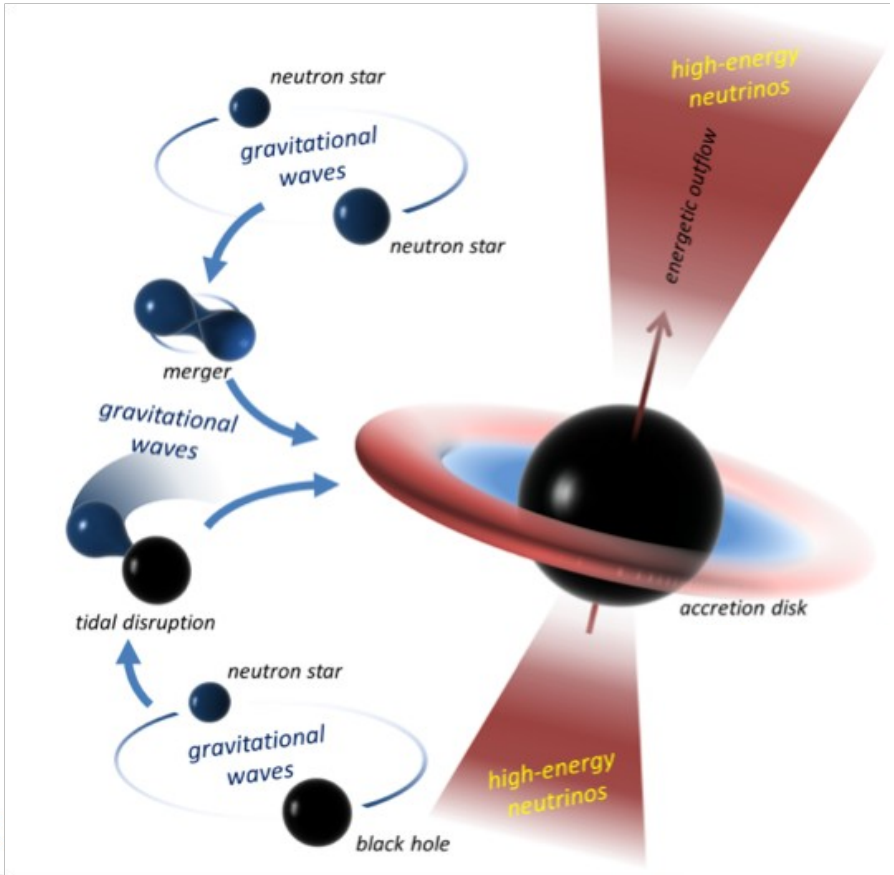
GRB
Microquasar
Gamma-ray binaries
Blazars
Supernovae Ib,c
Fast Radio Bursts



Search for Coincidences with Gravitational Waves

Mostly for BH/NS or NS/NS systems :

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

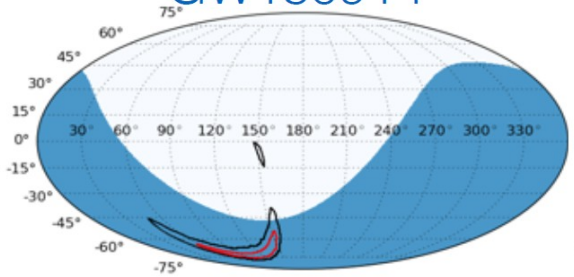


No counterpart observed so far

Limits from ANTARES dominate Eν < 100 TeV wrt IC

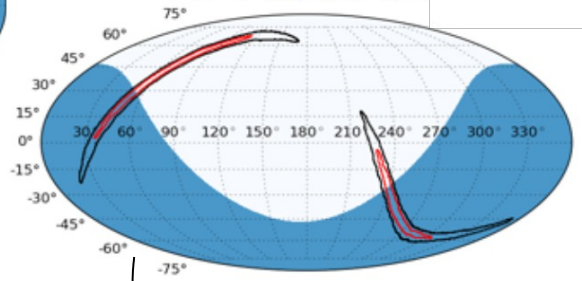
Limit on total energy radiated in neutrinos: <10% GW

GW150914

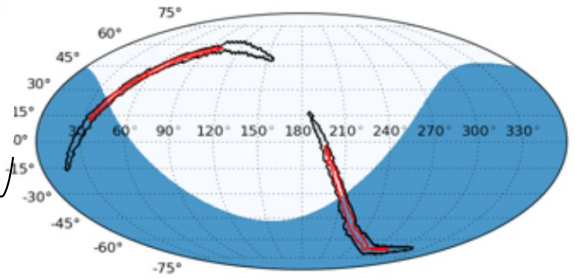


 PRD 93, 2016

LVT151012



GW151226



Real time follow-up
Of GW science runs

 arXiv:1703.06298

The multi-messenger program: TATOO

Telescope-Antares Target of Opportunity

2ND APPROACH:

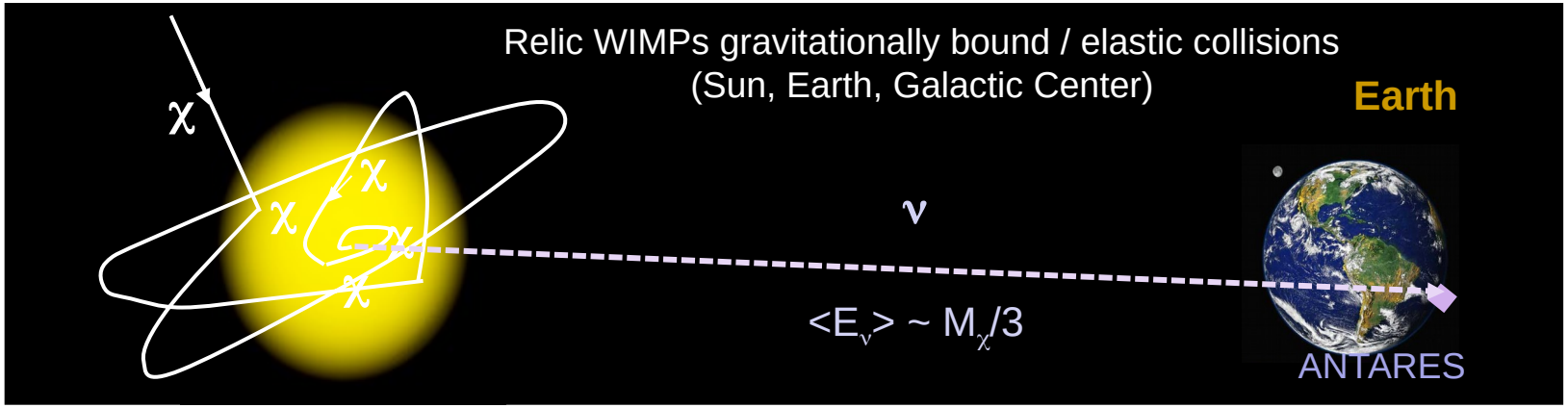
Alert triggering

Real-time analysis

H.E.S.S.

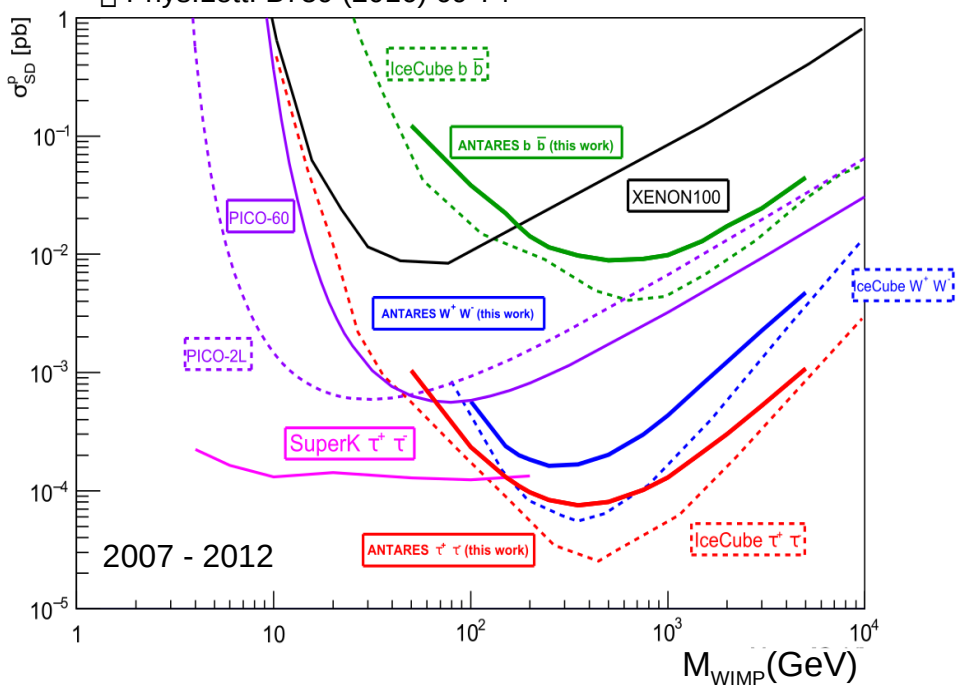
- Time to send an alert: ~5 s
- First optical image <20 s
- Median angular resolution: ~0.3°
- Triggers: single HE, preferred direction, multiplets

Indirect Search for Dark Matter

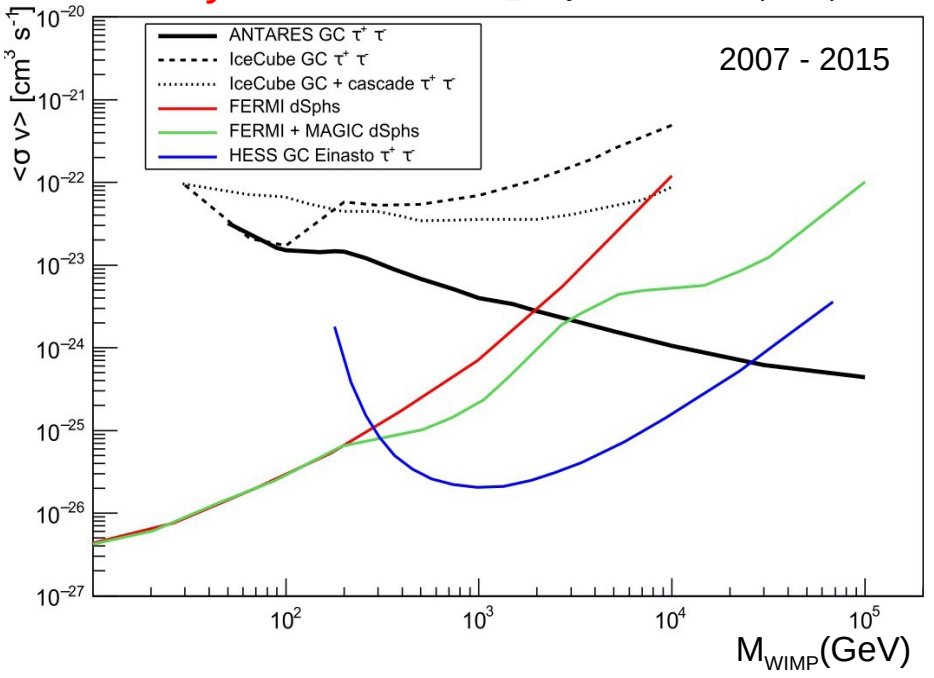


Track channel only

Phys.Lett. B759 (2016) 69-74

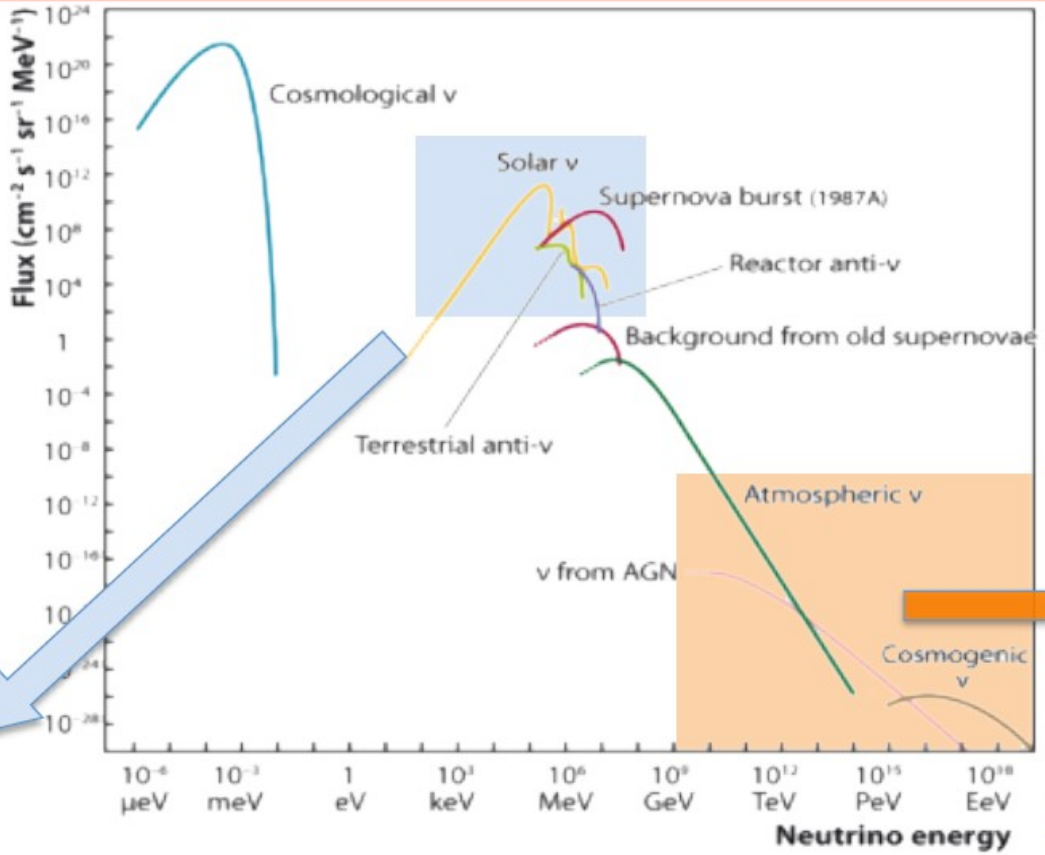


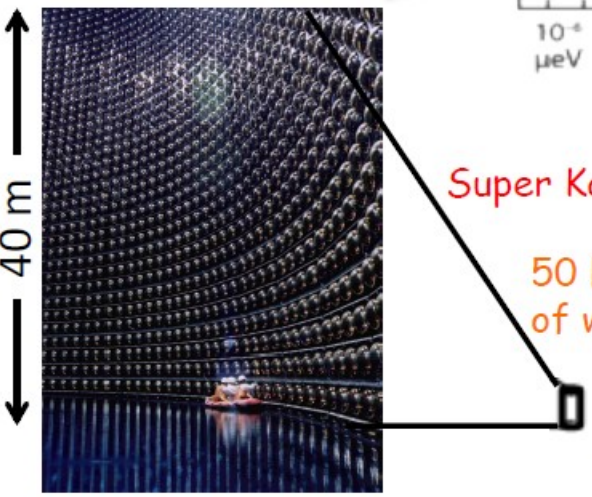
Phys. Let. B 769 (2017) 249



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

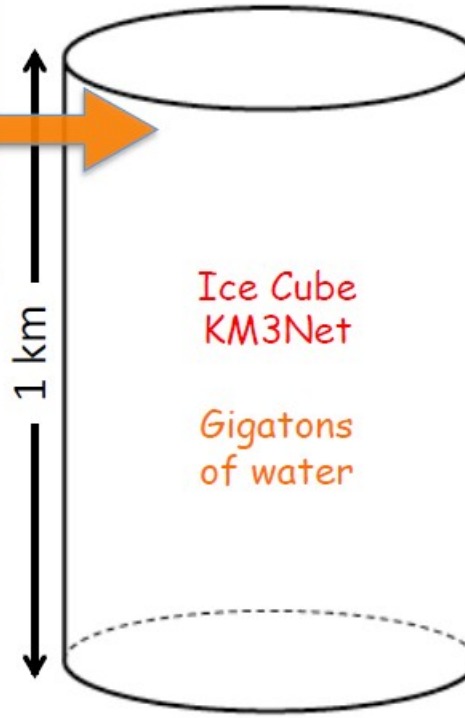
Neutrino spectrum





Super Kamiokande

50 ktons
of water

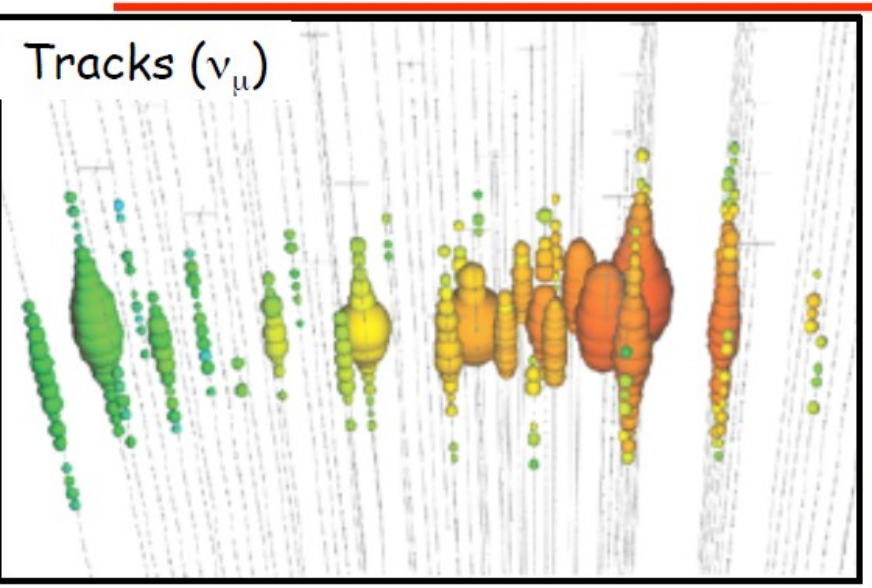


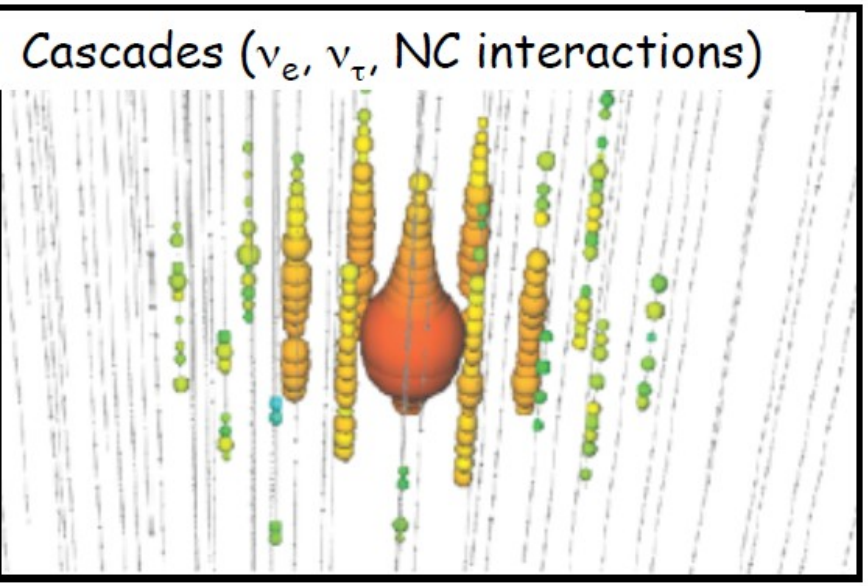
Ice Cube
KM3Net

Gigatons
of water

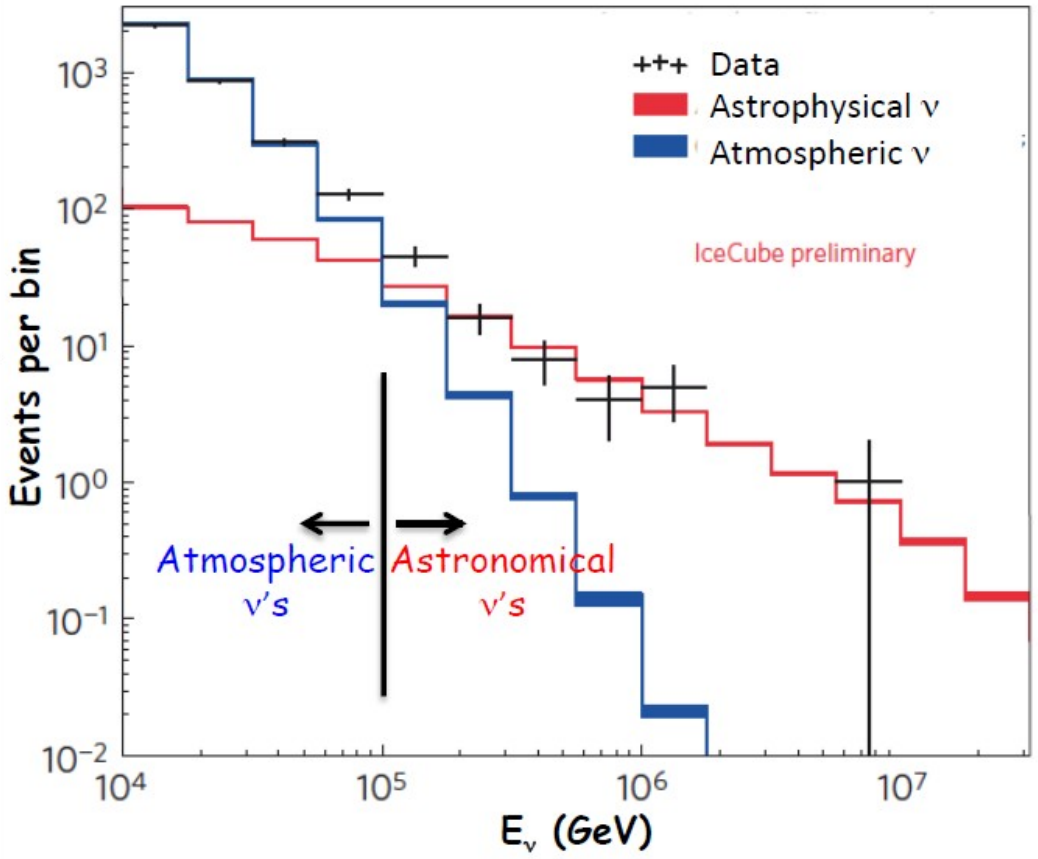
The IceCube Signal :

Birth of high-energy neutrino astronomy





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



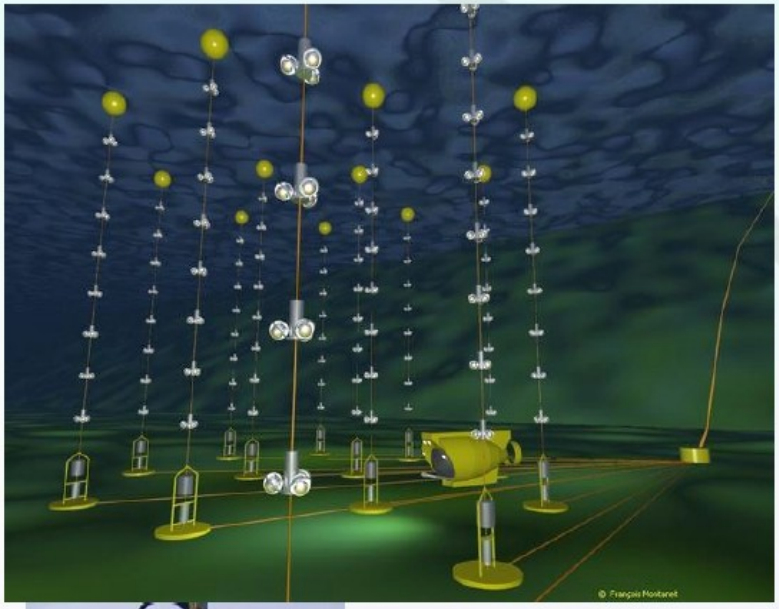
Halzen (2016) and refs. therein

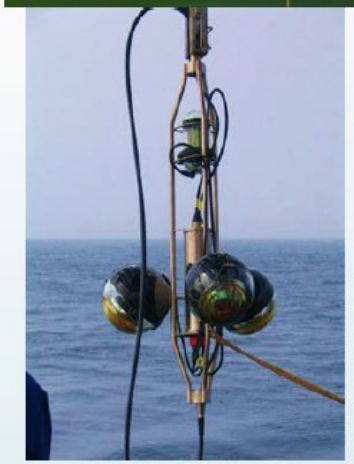
The future of Neutrino Astronomy in the Mediterranean Sea

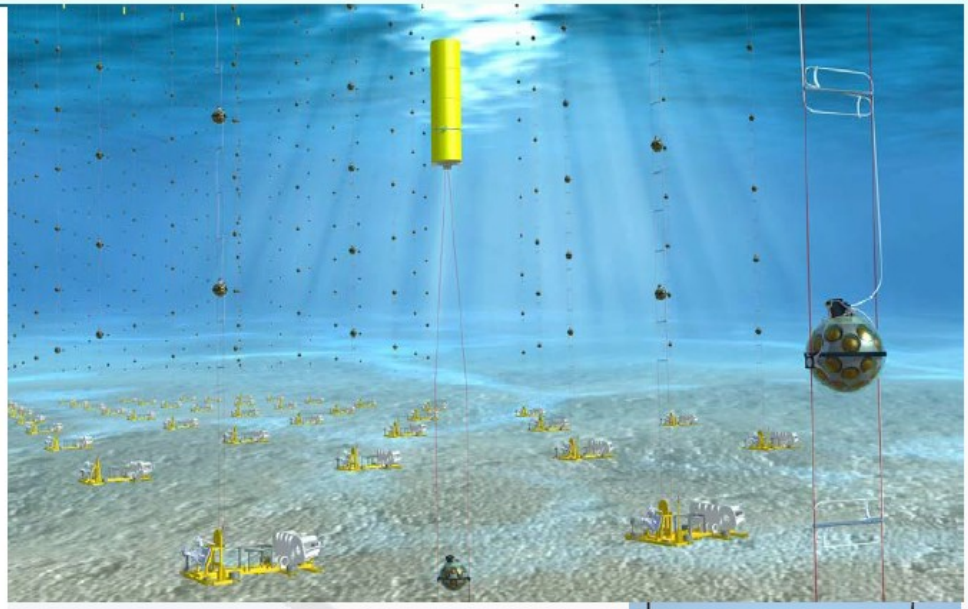
ANTARES → KM3NeT

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

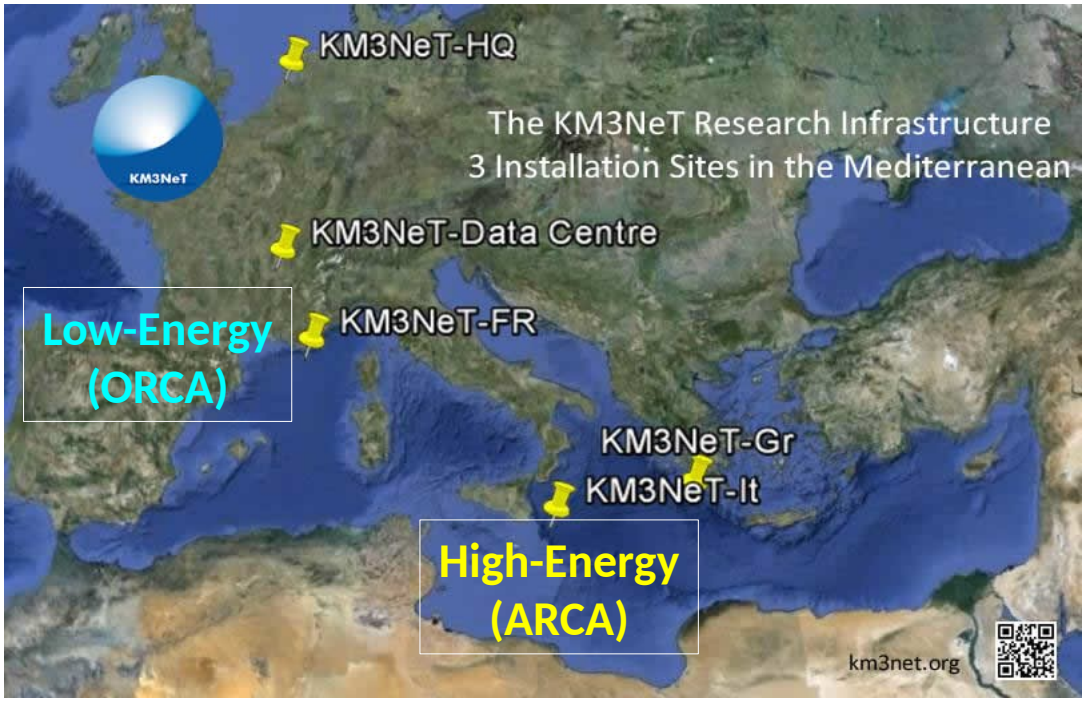
KM3NeT

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



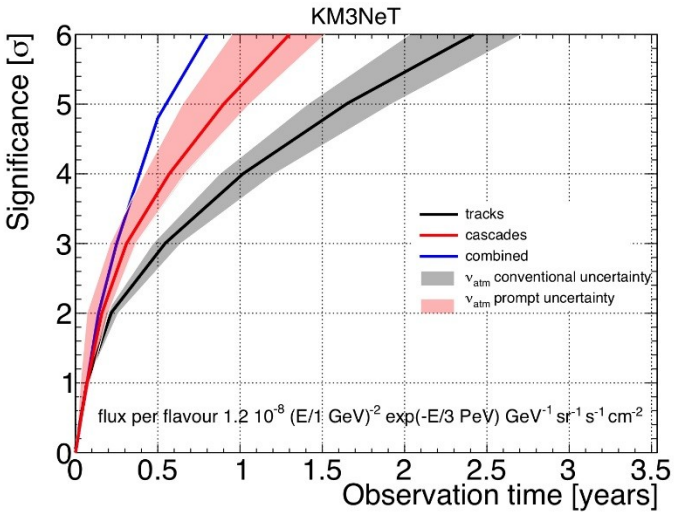
ARCA - Astroparticle Research with Cosmics in the Abyss

ORCA - Oscillation Research with Cosmics in the Abyss

KM3NeT Objectives

Astroparticle Research with Cosmics in the Abyss (ARCA):

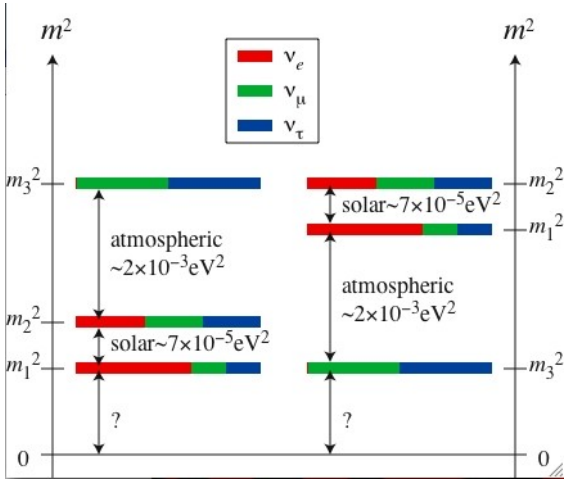
Sparse telescope optimised
for TeV-PeV cosmic neutrinos



Discover/observe high-energy
astrophysical neutrino sources

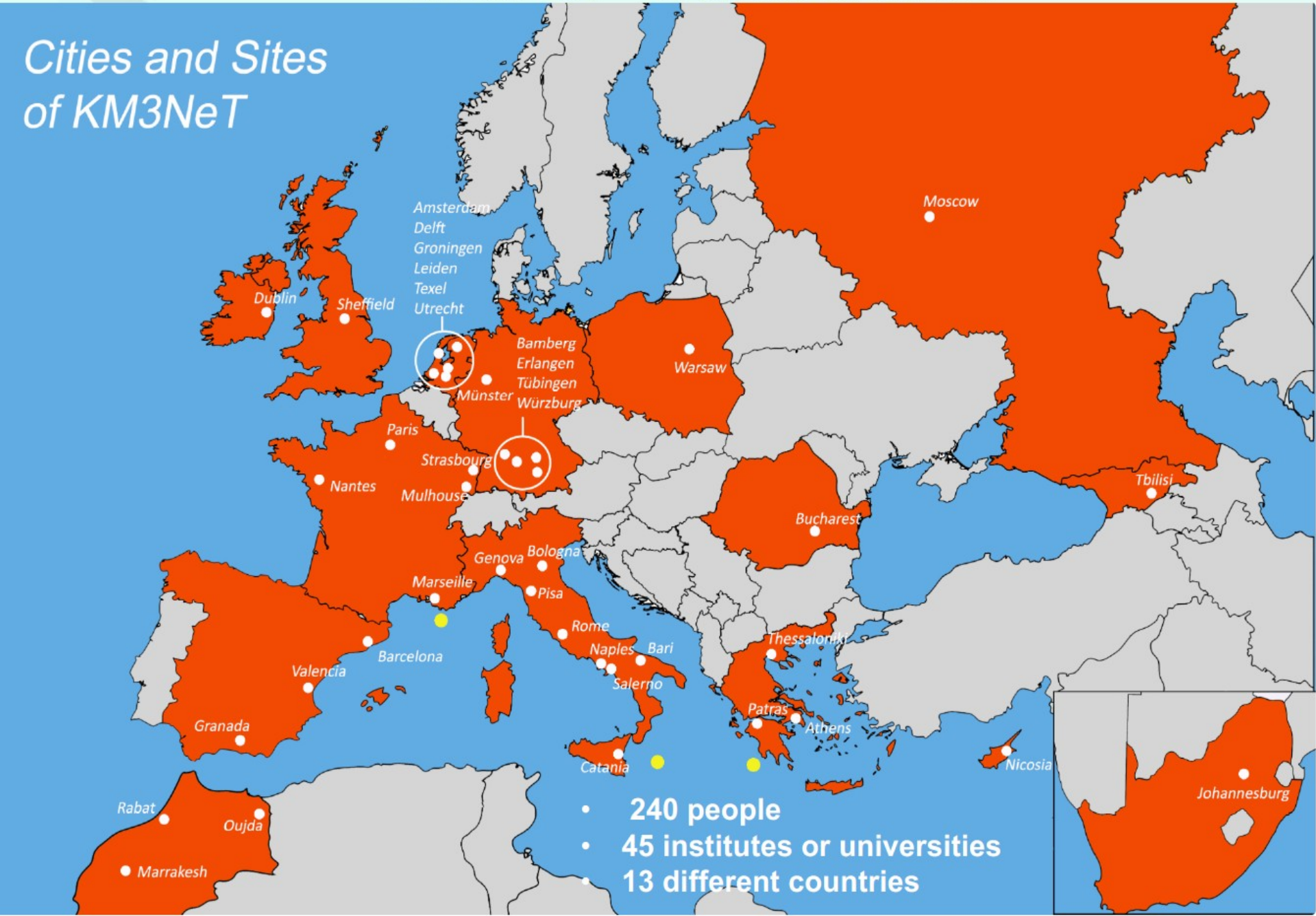
Oscillation Research with Cosmics in the Abyss (ORCA):

Dense detector optimised
for GeV atmospheric neutrinos

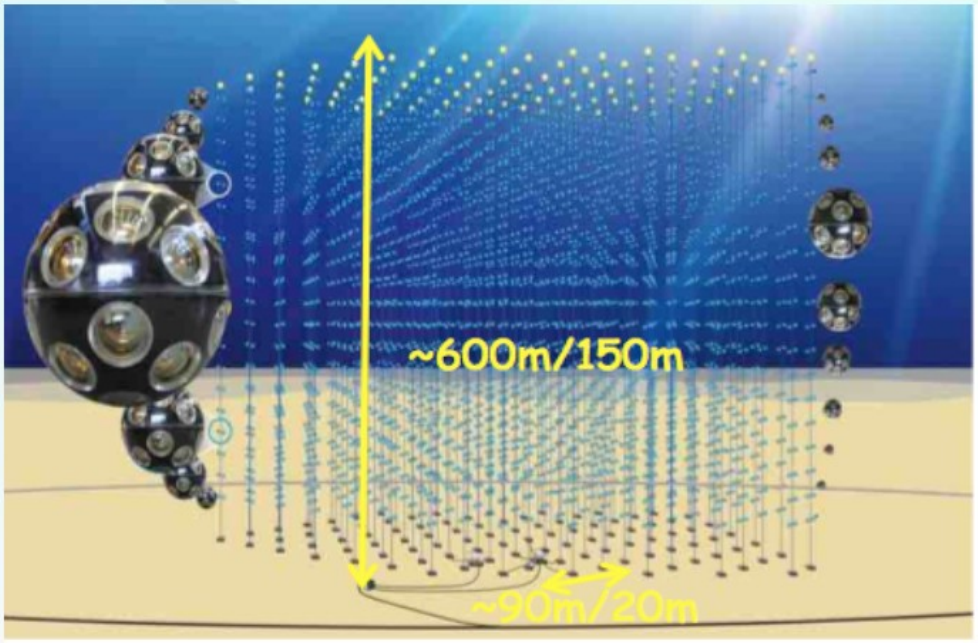


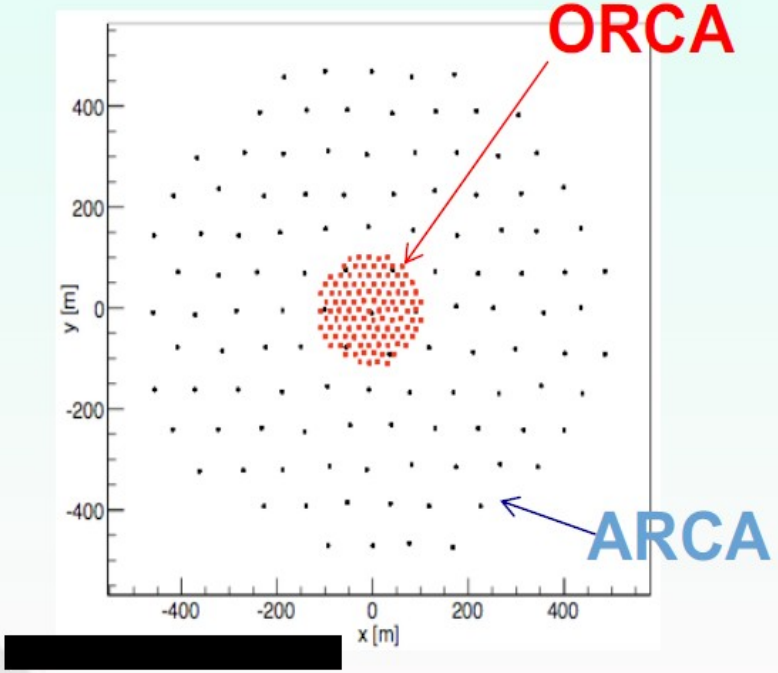
Determine the
Neutrino Mass Hierarchy

KM3NeT - Collaboration



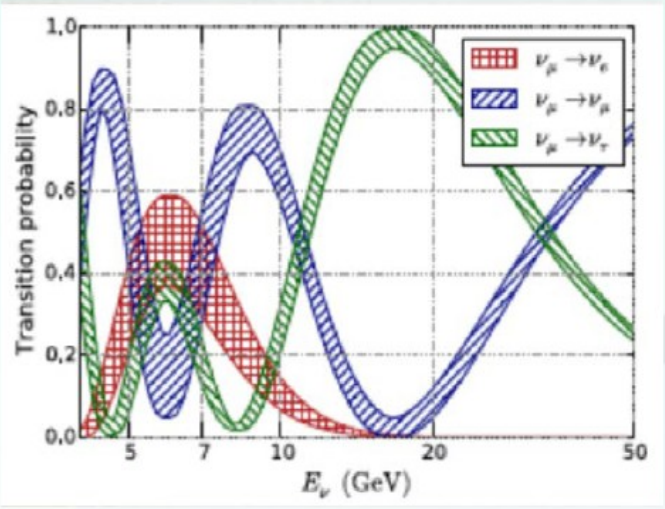
KM3NeT Building Blocks

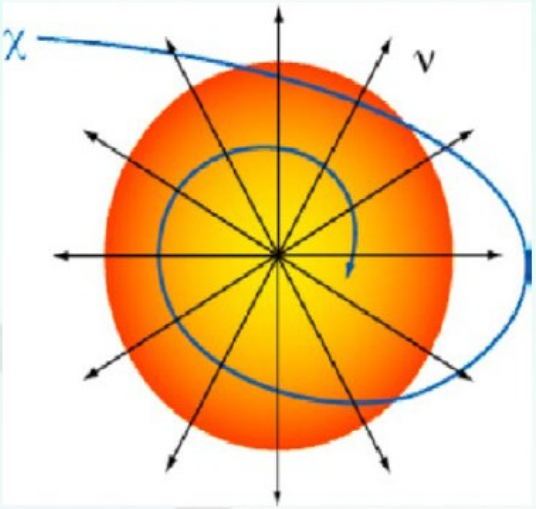




	ARCA	ORCA
Location	Italy – Capo Passero	France - Toulon
Detector Lines distance	90m	20m
DOM spacing	36m	9m
Instrumented mass	500Mton	5,7 Mton

KM3NeT Neutrino Telescope science scopes






Composite View of the Crab Nebula

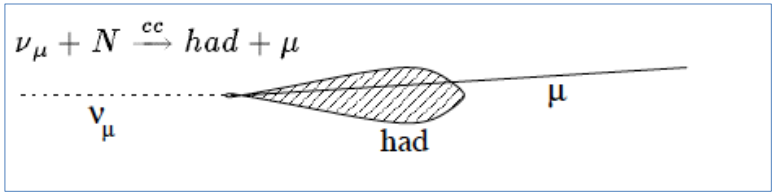
Low Energy	Medium Energy	High Energy
MeV < E_ν < 100 GeV	M eV < E_ν < 100 GeV	E_ν > 1 TeV
- Neutrino Oscillations	- Dark Matter search	- Neutrinos from extra-terrestrial sources
- Neut. Mass Hierarchy	- Monopoles	- Origin and production mechanism of HE CR
- Sterile neutrinos	- Nuclearites	
- Neut. From Supernovae		

KM3NeT-ORCA ANTARES KM3NeT-ARCA

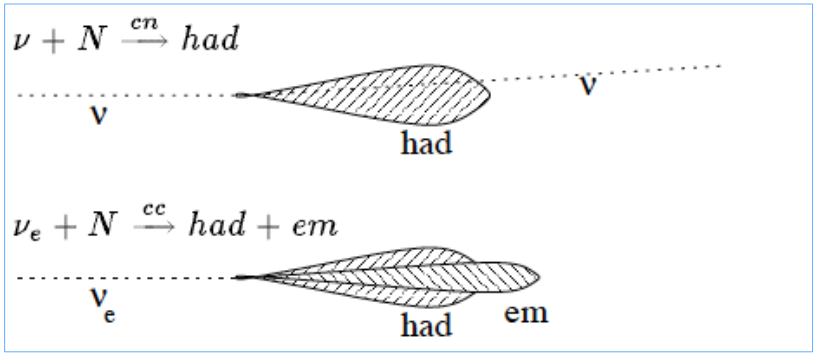
… and synergies with Sea-Sciences: oceanography, biology, seismology, …

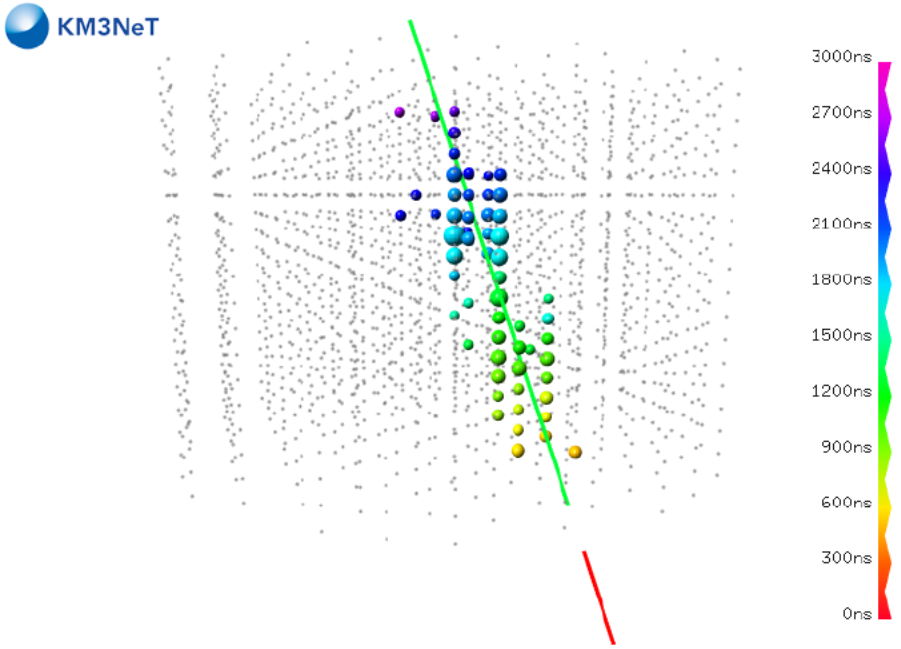
Event Topologies

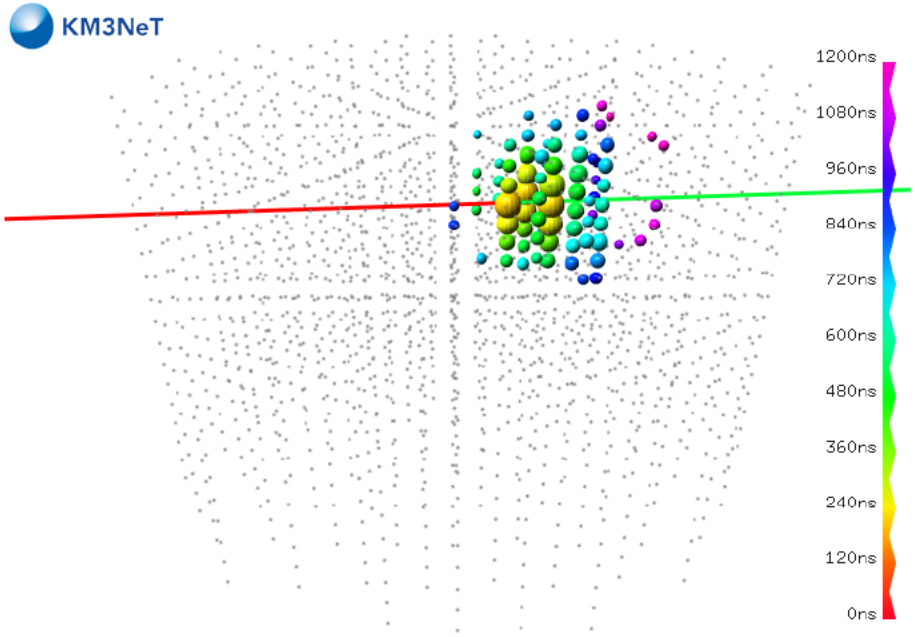
Track-like (ν_μ CC)



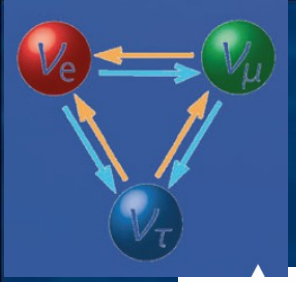
shower-like (ν NC, ν_e CC)



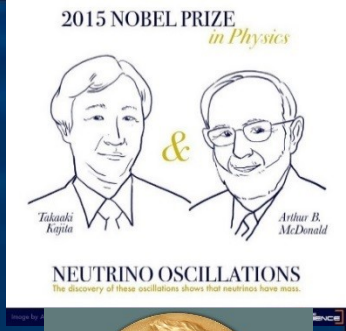


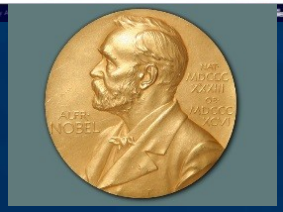


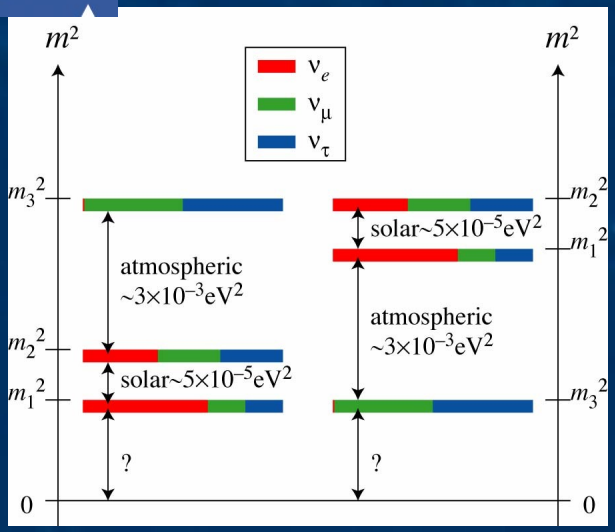
ARCA simulation, TeV neutrino energies



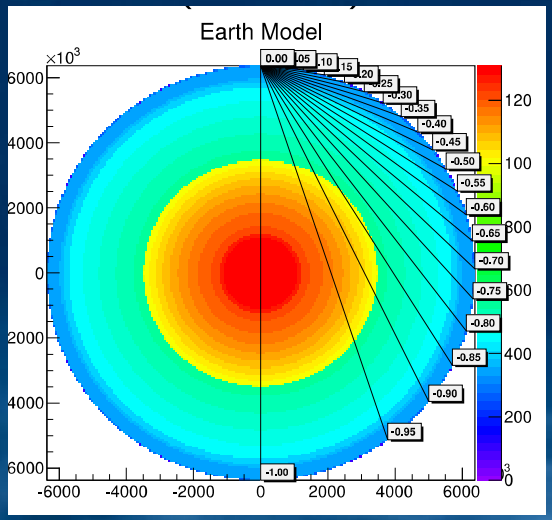
Determination of the **Neutrino Mass Ordering** using atmospheric neutrino oscillations

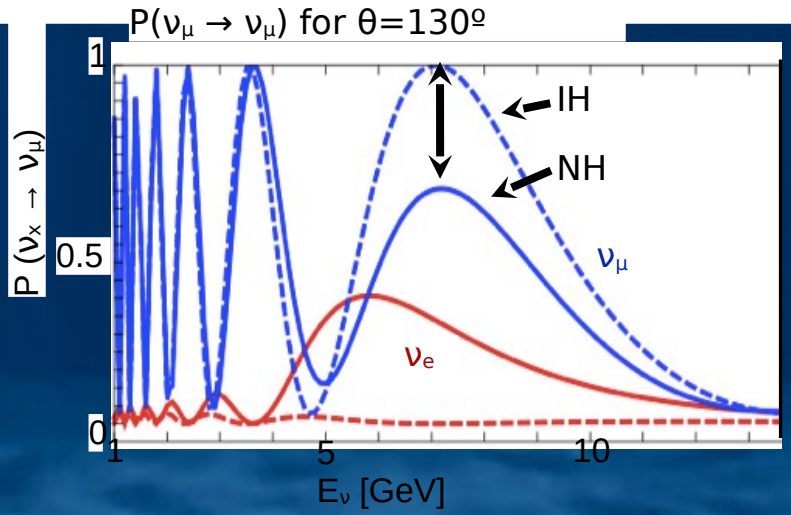






Fundamental parameter of the neutrino particles still unknown!

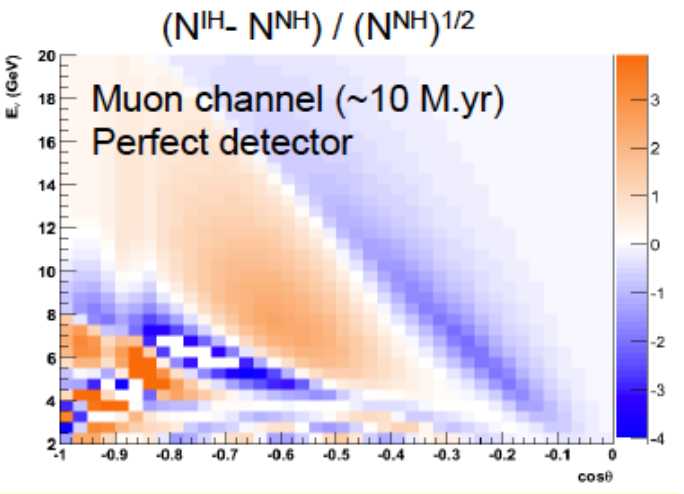


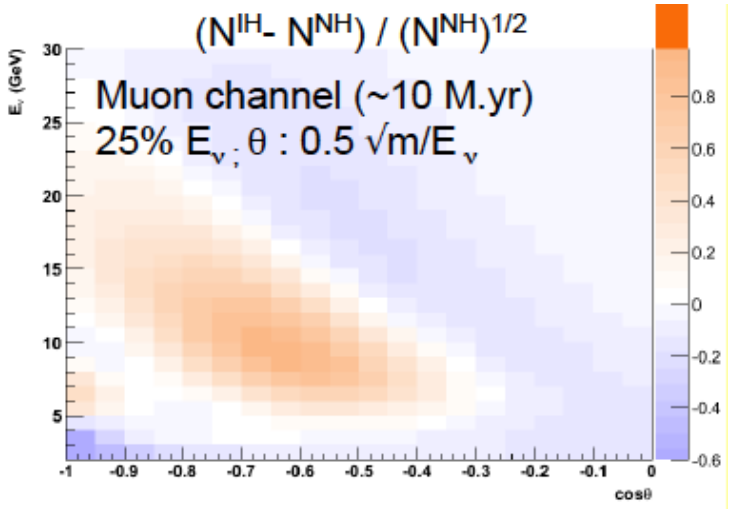


Precise study of the **flux of atmospheric neutrinos of few GeV** interacting in the Earth

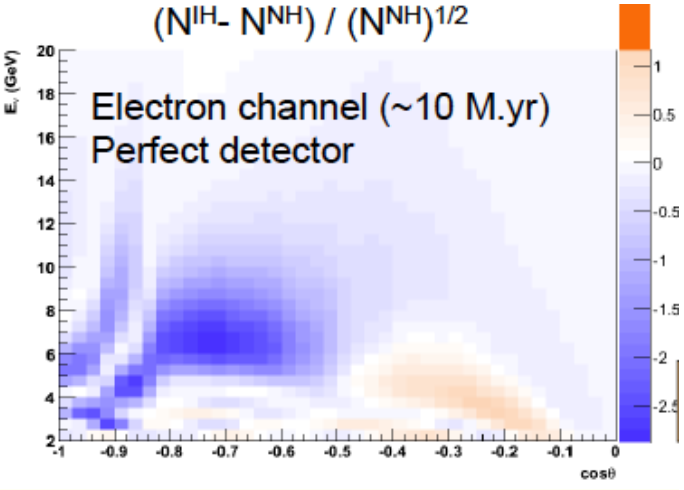
Experimental signature

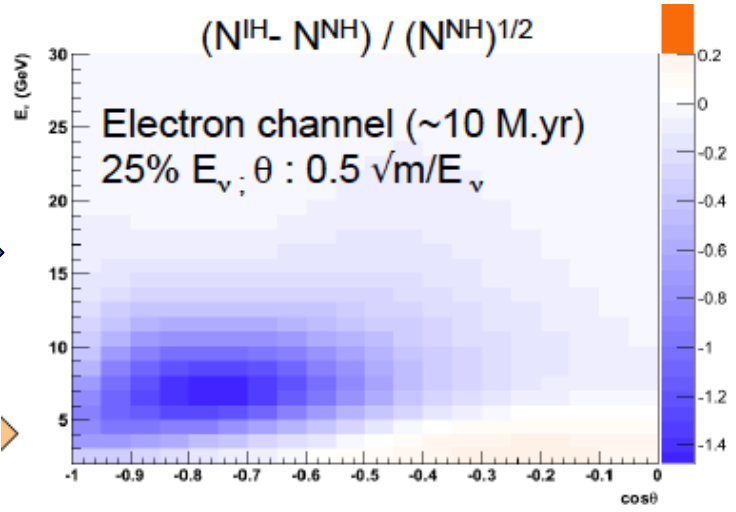
Both muon- and electron-channels contribute to net hierarchy asymmetry
electron channel more robust against detector resolution effects:





E, θ smearing
(kinematics
+ detector
resolution)

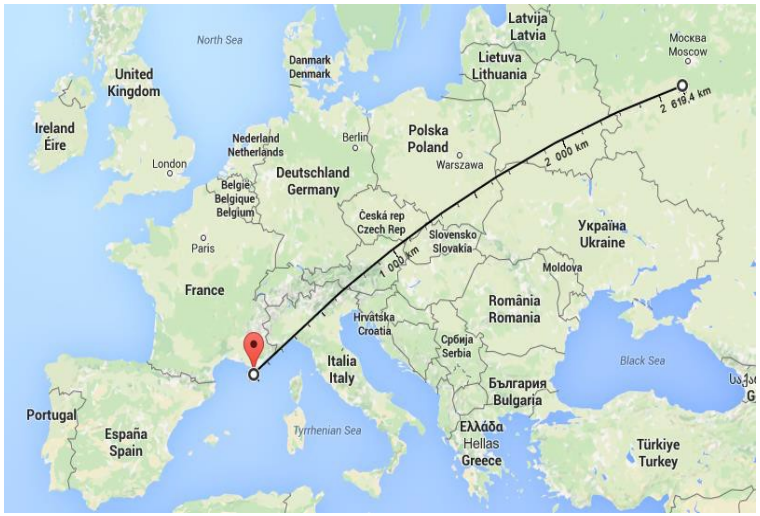




Additional ORCA Physics Topics

- 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 GeV

-Proposed intensity upgrade

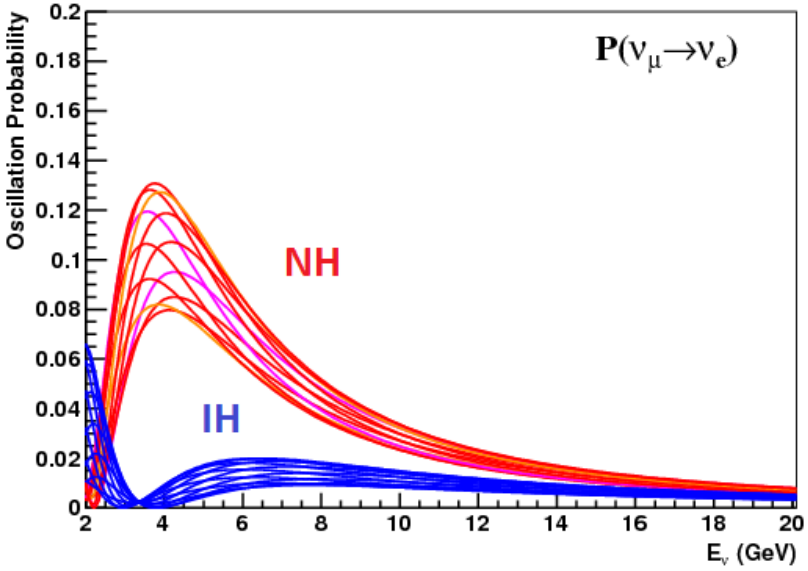
P = **450 kW**

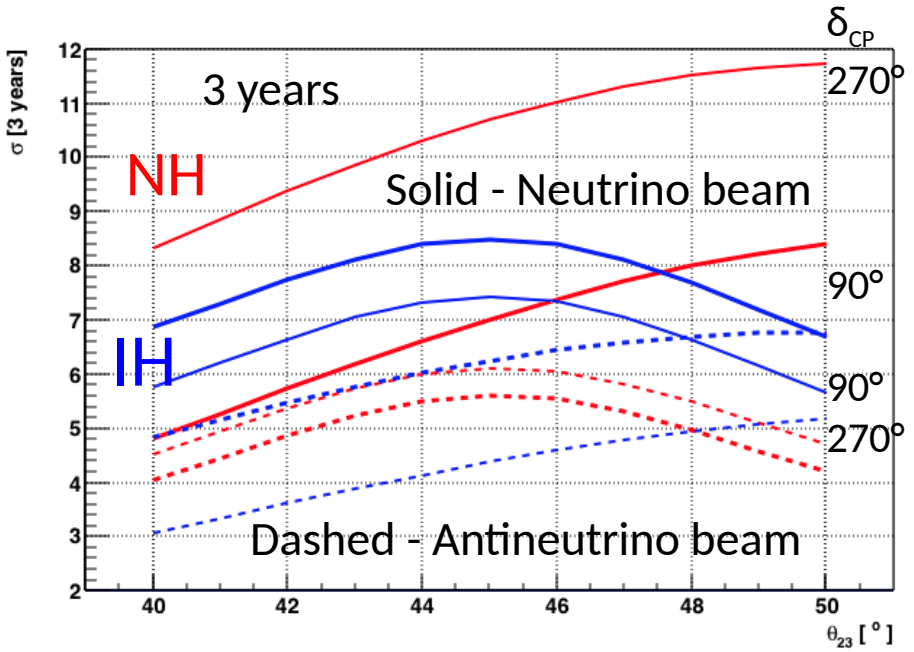
Up to **4.10^{20} POT / year**

-ν_e appearance at **L = 2600 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

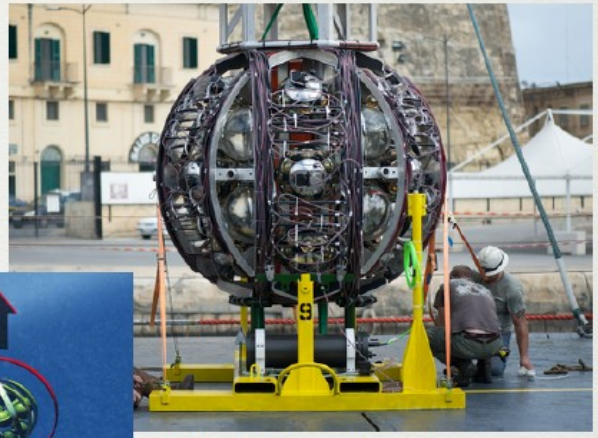
- ➡ Uniform angular coverage
- ➡ Directional information
- ➡ Digital photon counting
- ➡ Wide angle of view
- ➡ Background rejection
- ➡ All data to shore

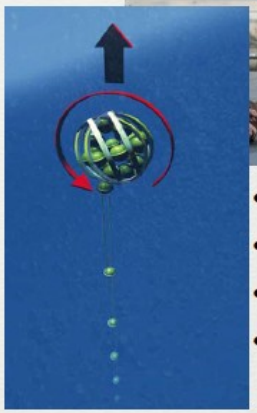
String

~ 700 or 200 m

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

LOM

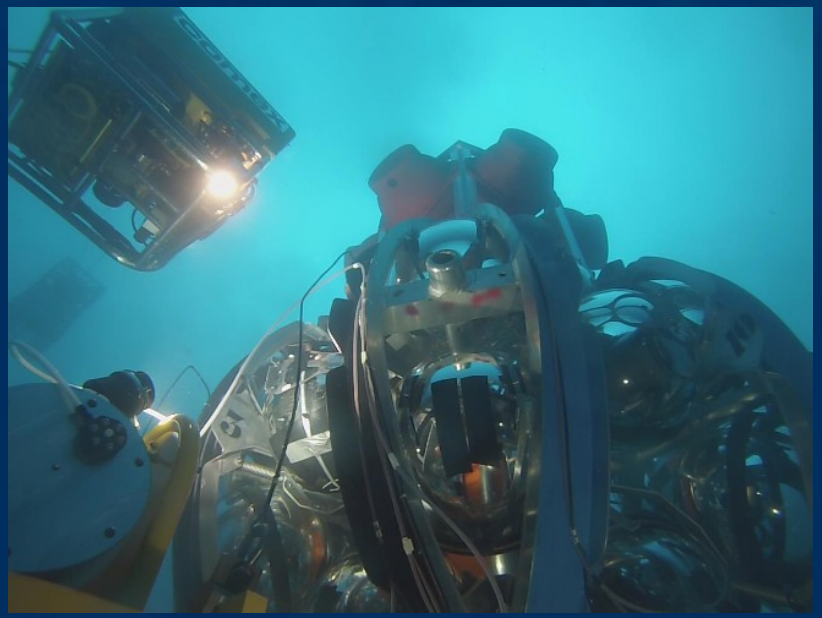




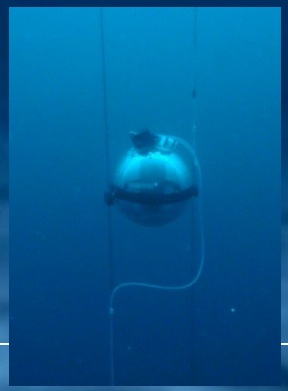
- Rapid / safe deployment
- Multiple strings / campaign
- Auto/ROV unfurling
- Re-useable

Construction of KM3NeT ORCA

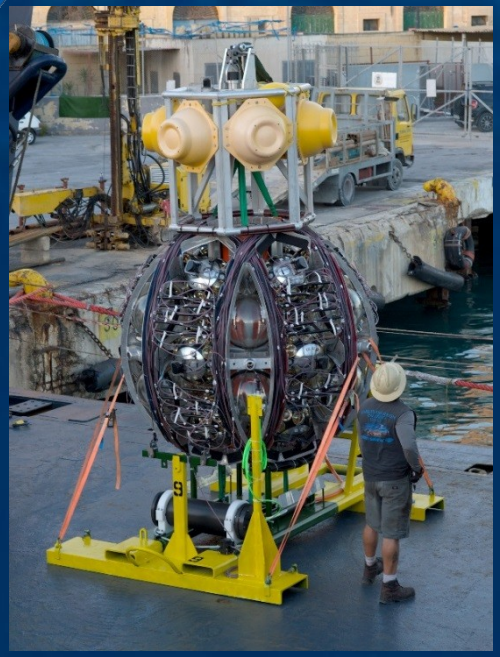
- Configuration ORCA line defined (9m between DOMs)
- Deployment with LOM validated by shallow water tests

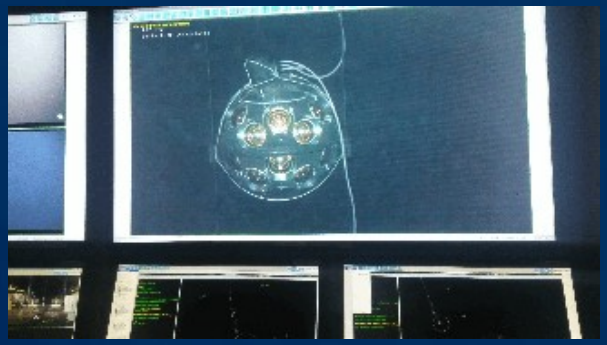


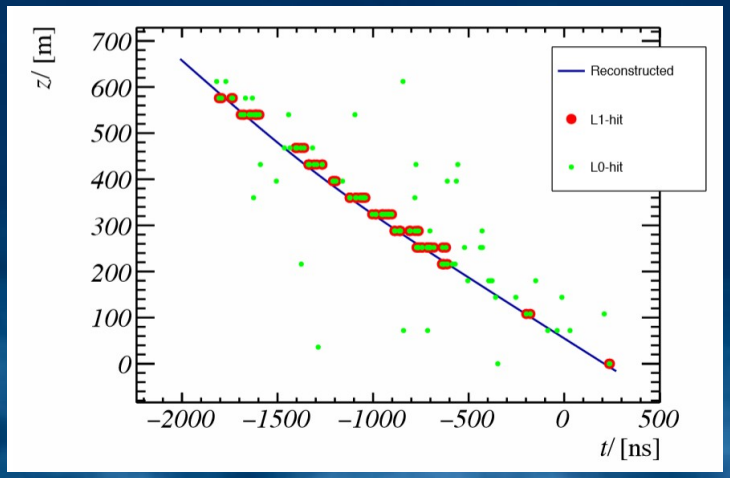
First ORCA line deployed on september 2017!



The first KM3NeT-ARCA detector lines

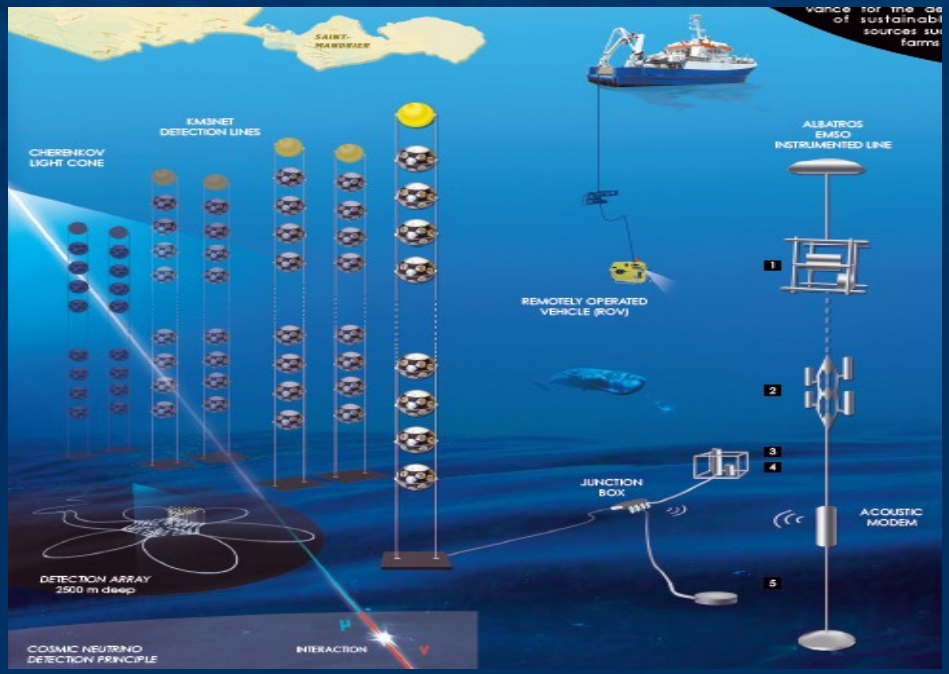






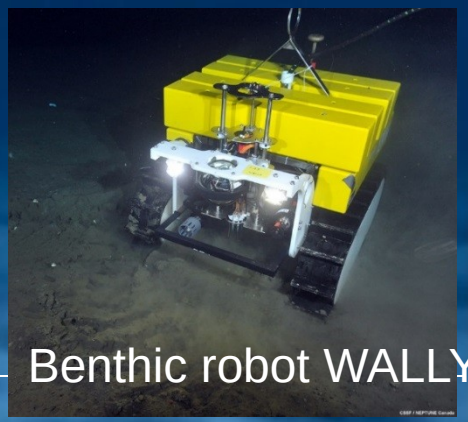
First line in operation since December 2015, 2nd since May 2016

A Multidisciplinary Observatory in the Deep Sea



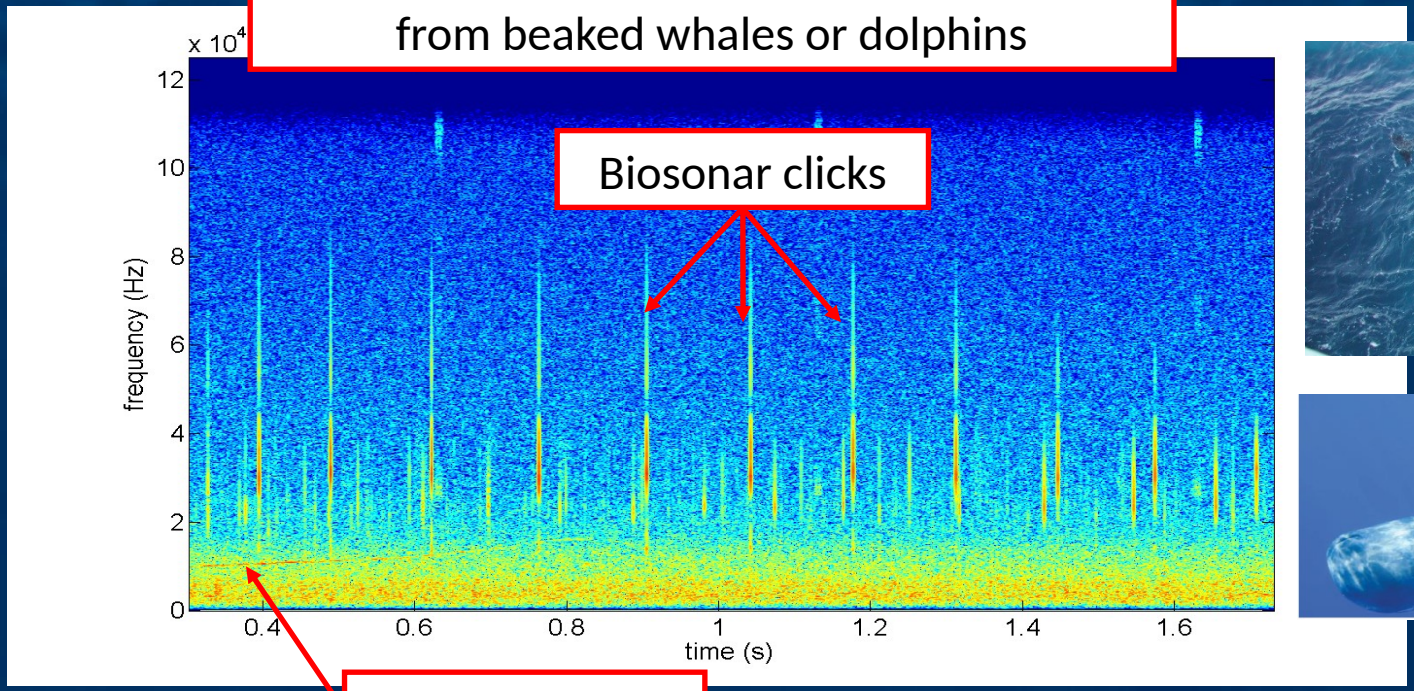
- Astronomy
- Neutrino physical properties
- Physico-chemical oceanography
- Marine Biology
- Bioacoustic
- Bioluminescence
- Microbiology
- Ecology, biogeochimie
- Sismology
- Environnement
- Renewable energies
- Underwater acoustic
- R&D marine technologies
- …

Dolphins (Pilot Whales) observed on ANTARES site



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 !!