Antonio Capone
Univ. "La Sapienza"
INFN - Roma

Neutrino Telescopes status & perspectives

- KM3NeT ARCA-ORCA
- IceCube-Gen2
- Baikal-GVD

KM3NeT Collaboration

12 Countries
> 40 Institutes
> 220 Scientists

KM3NeT Collaboration

KM3NeT: originated by the common effort of European physicists (plus Morocco)

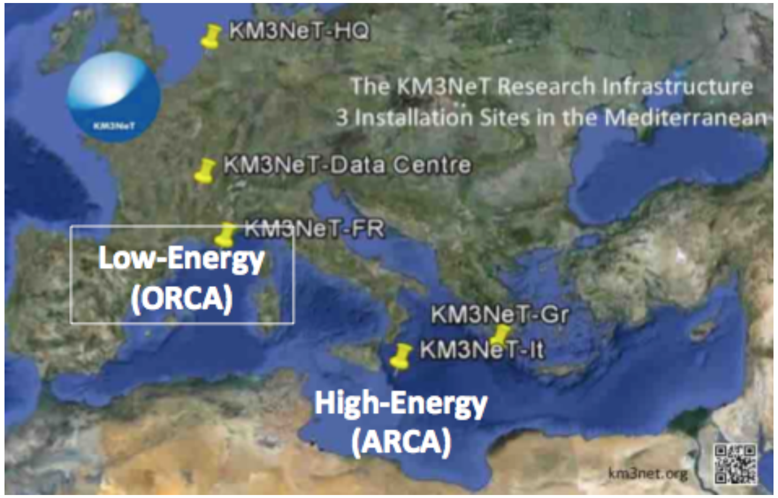
KM3NeT: a research infrastructure with 2 main physics topics

- high energy: the existence/origin of cosmic neutrinos, search for diffuse and point like sources (ARCA)
- low energy: study of the fundamental neutrino properties: oscillations and mass hierarchy (ORCA)

KM3NeT: as a research infrastructure will be a Deep Sea Observatory available for oceanography, bioacoustics, bioluminescence, seismology, …

It will consists of:

- a single Collaboration
- a single technology
- a multisite detector
- a single managements



ARCA: **A**stroparticle **R**esearch with **C**osmics in the **A**byss
ORCA: **O**scillation **R**esearch with **C**osmics in the **A**byss

KM3NeT – physics goals

ARCA

- Measure high-energy neutrino fluxes
  - Benchmark: the IceCube flux (isotropic and flavour symmetric)

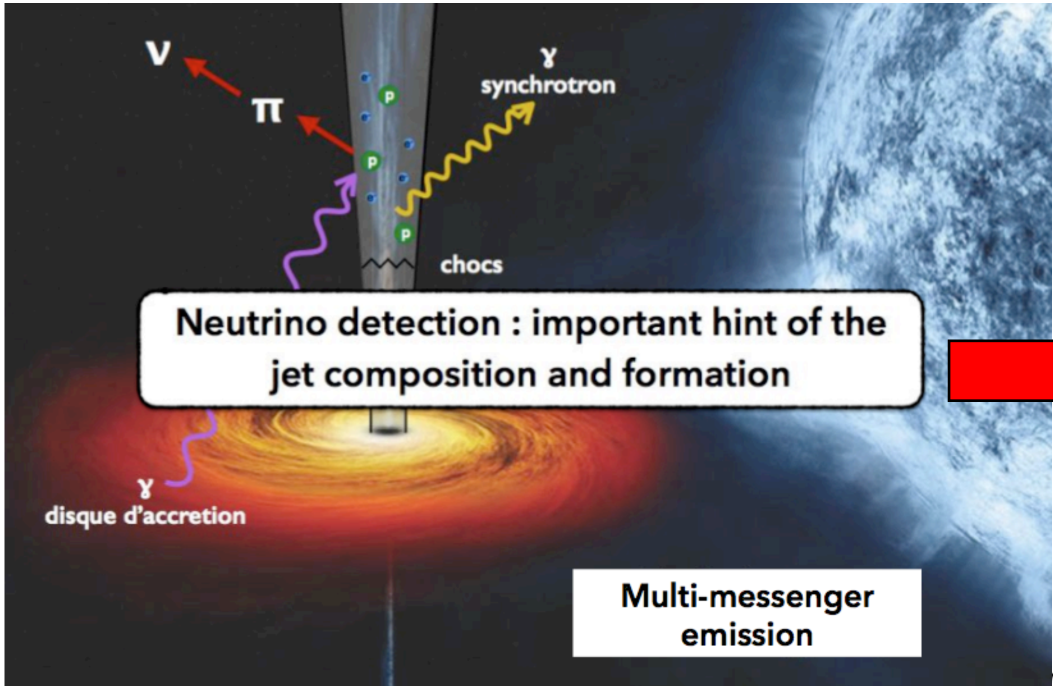
$$\Phi(E_\nu) = 1.2 \cdot 10^{-8} \left(\frac{E_\nu}{1GeV}\right)^{-2} e^{-\left(\frac{E_\nu}{3PeV}\right)} [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]$$

- Search for astrophysical neutrino point-like sources
  - Neutrino fluxes from intense galactic TeV gamma sources
  - Gamma Ray Bursts, Transient sources, indirect Dark Matter search, …
  - Multi-messenger studies

ORCA

- Determine the Neutrino Mass Hierarchy (NMH)
- Precise measurement of atmospheric neutrino parameters
- Indirect Dark Matter search

Multi-messenger astronomy: the ultimate approach



Offline

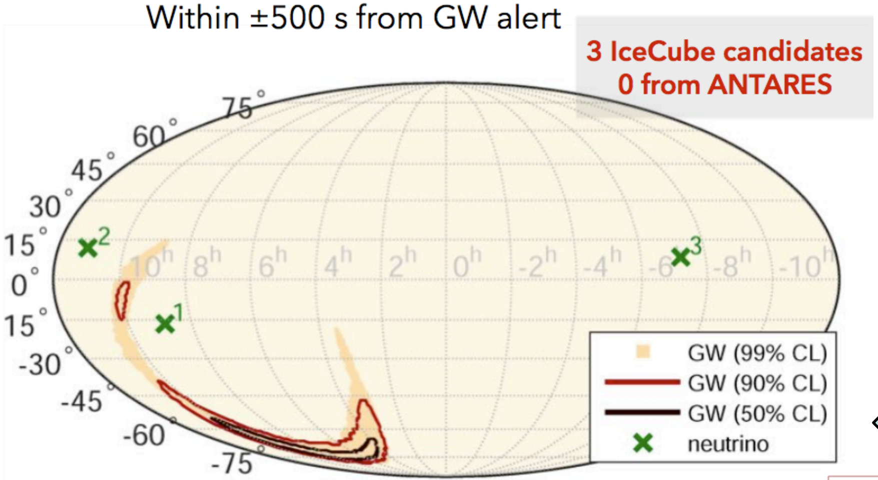
Time-dependent searches:
- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]
- Fast radio burst [radio telescopes]

Multi-messenger correlation:
- Correlation with the UHE events [Auger]
- Correlation with the gravitational wave [Virgo/Ligo]
- 2pt-correlation with 2FGL catalogue, loc. galaxies, BH , IceCube HESE

TAToO

Real-time analysis:
- TAToO: follow-up of the neutrino alerts with optical telescopes [TAROT, ROTSE, ZADKO, MASTER], X-ray telescope [Swift/XRT], GeV-TeV γ-ray telescopes [HESS] and radio telescope [MWA]
- Online search of fast transient sources [GCN, Parkes]

Within ±500 s from GW alert

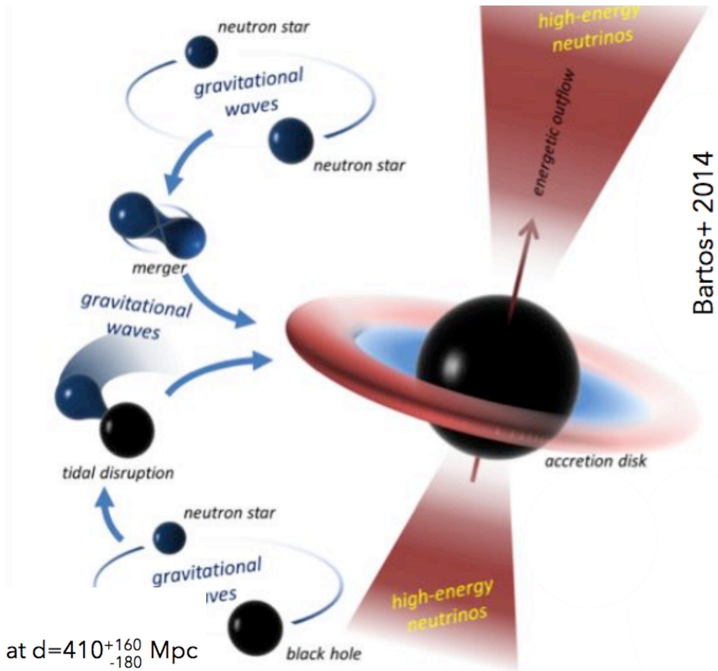


➜ Consistent with the background expectations (4.4 events for IceCube; 10^{-2} for ANTARES)

For BH/NS or NS/NS systems :

gravitational waves + electromagnetic + neutrino emission expected if ejection process with baryonic component

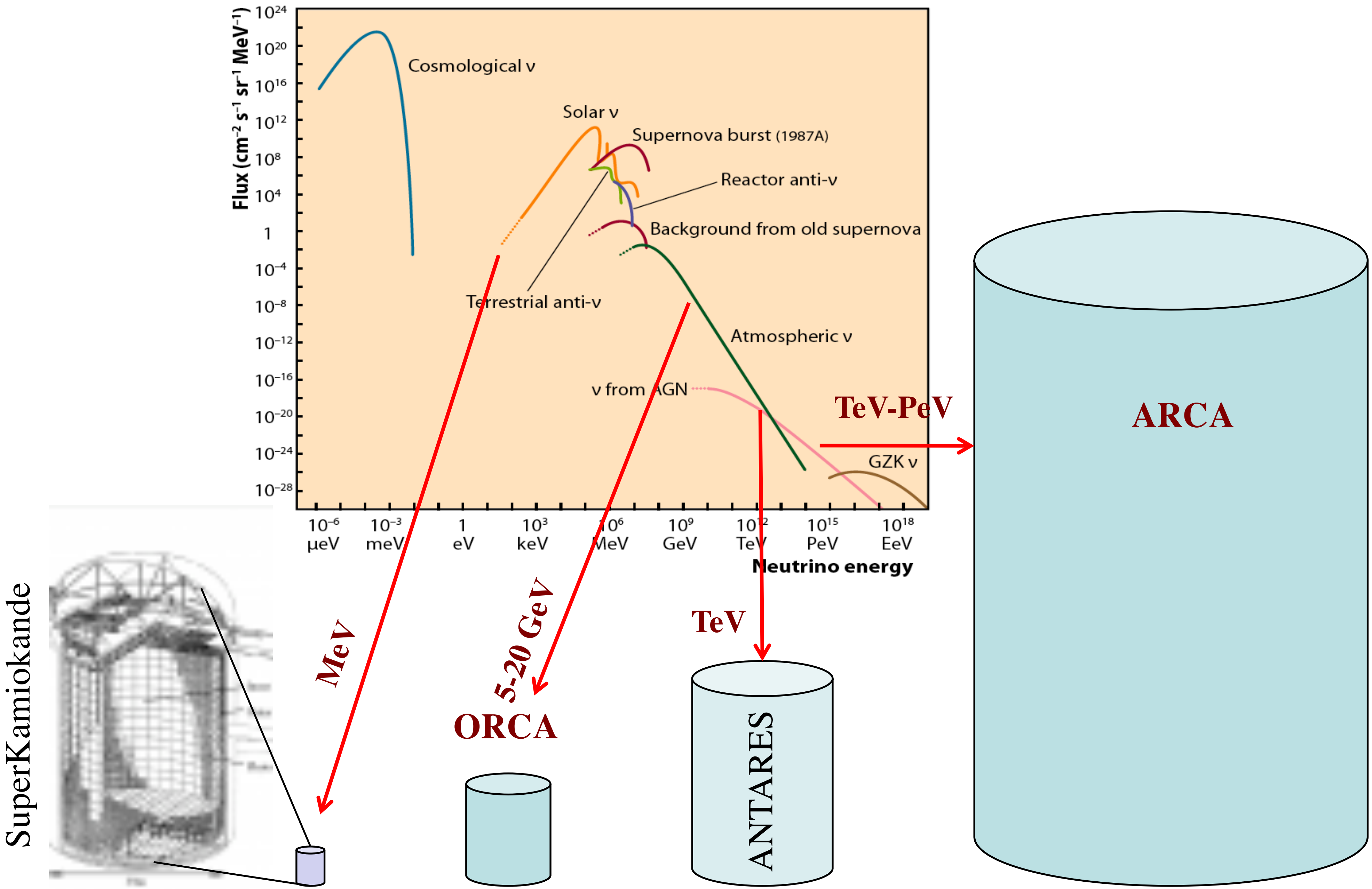
$$E^{ul}_{\nu,tot} = 5.4\times10^{51} - 1.3\times10^{54}\ \text{erg}$$
$$E^{ul(cutoff)}_{\nu,tot} = 6.6\times10^{51} - 3.7\times10^{54}\ \text{erg}$$



at d=410^{+160}_{-180} Mpc

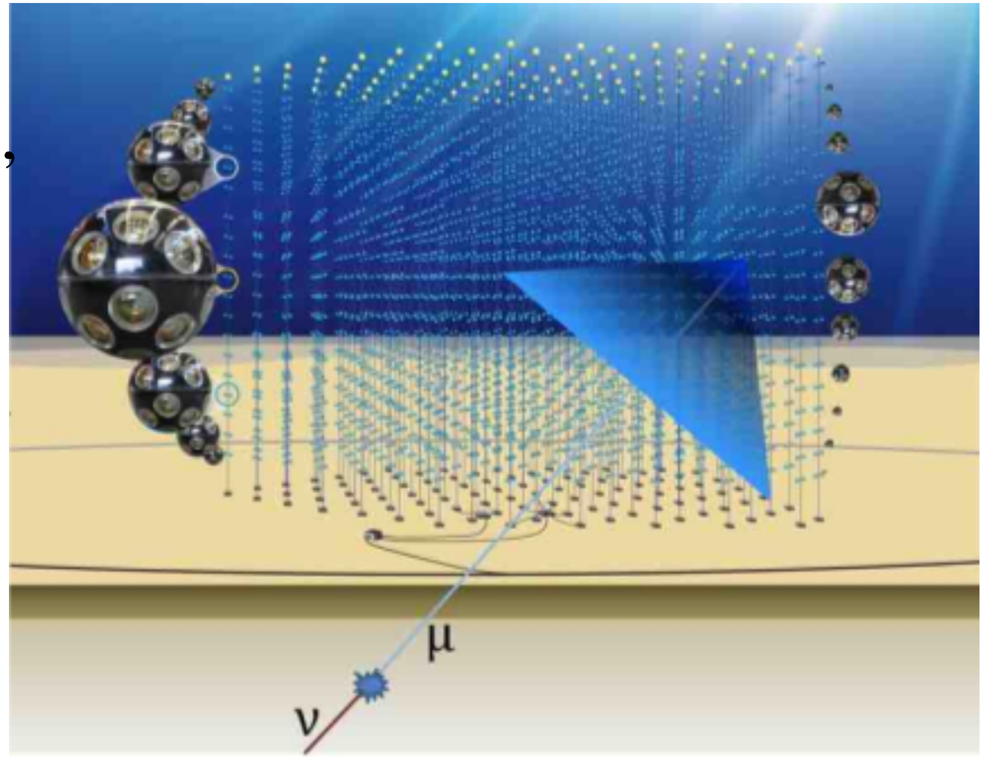
Bartos+ 2014

… yesterday, today, tomorrow …



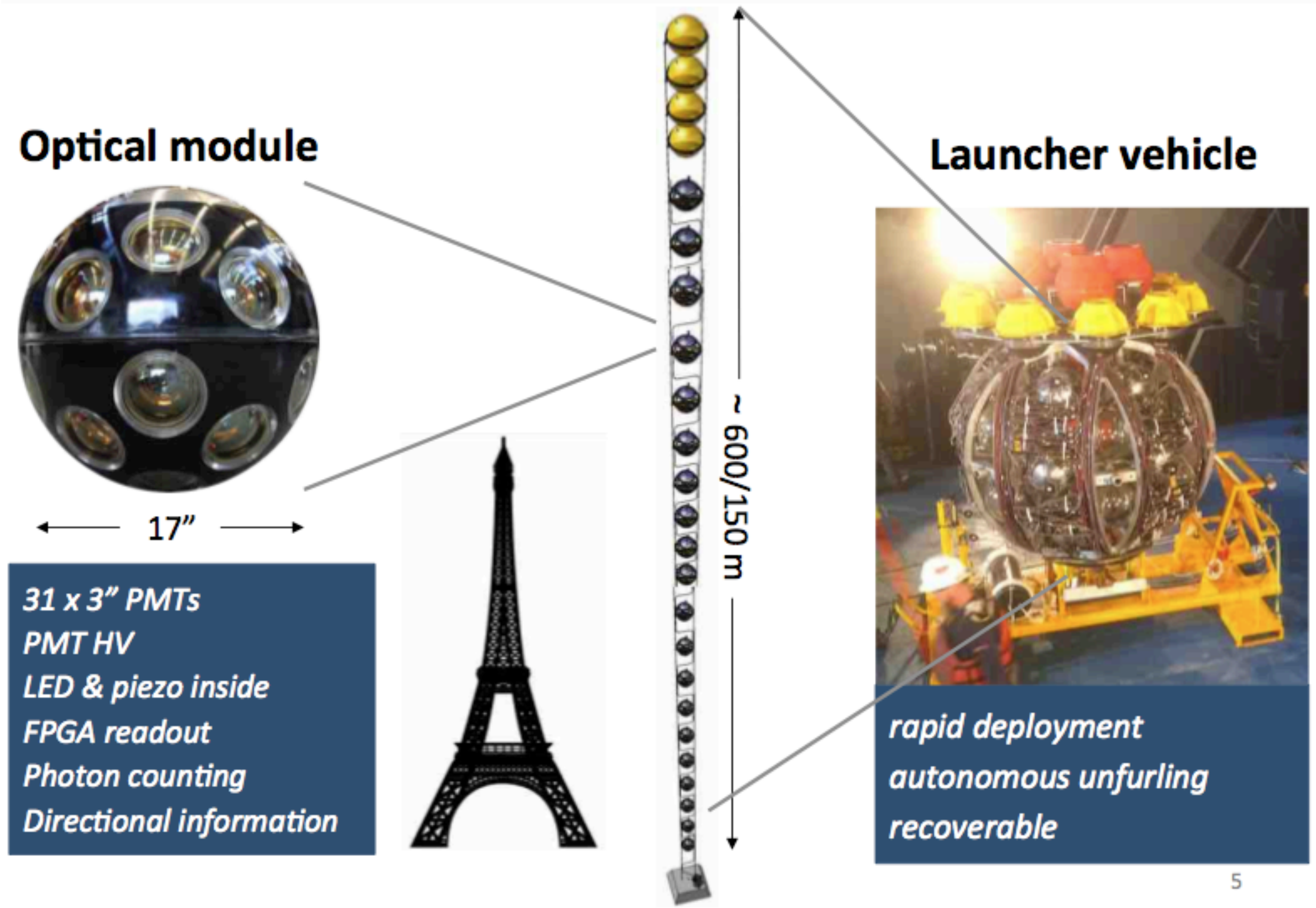
KM3NeT design

- **Basic detector module**: a multi-PMT digital optical module: 31 3" PMTs distributed in a glass sphere, looking at different solid angles
- **Basic Detector Units (DU)**: a vertical slender string with 18 DOMs. Power and data distributed by a single backbone cable with breakouts at DOMs.

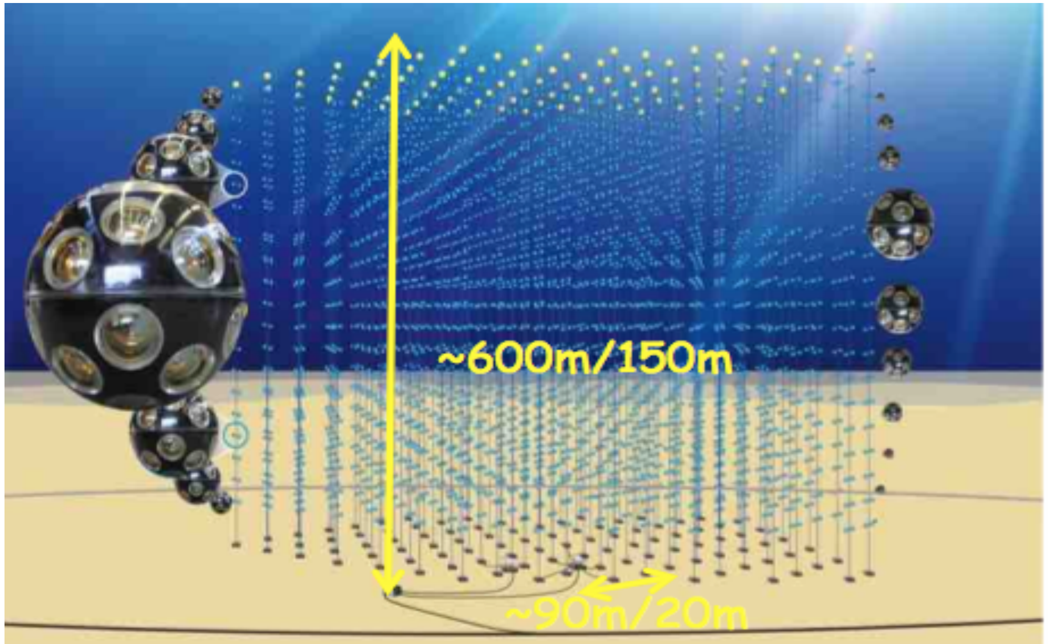


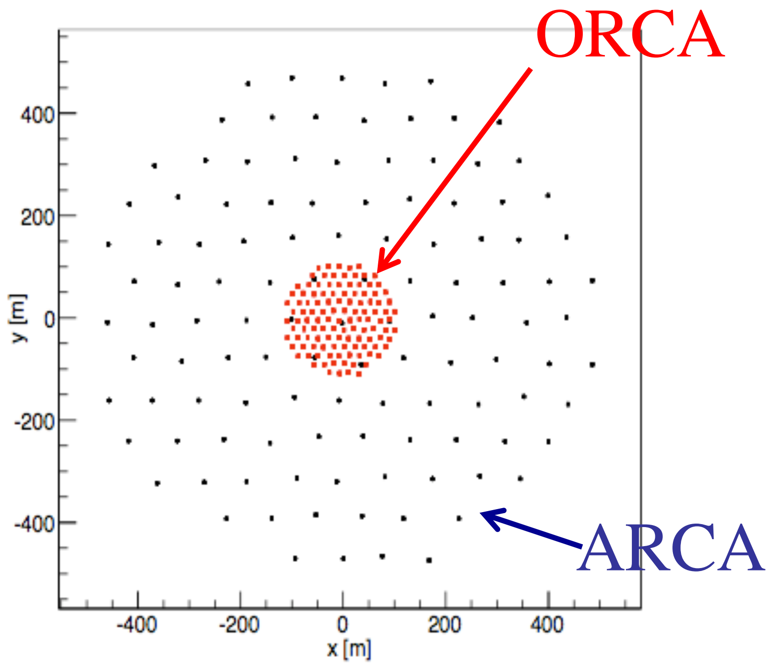
- **Building Blocks** of 115 DUs each, allow for a "distributed" detector
- Multi-site infrastructure
    - ARCA at KM3NeT-It site (2 building blocks)
    - ORCA at KM3NeT-Fr site

KM3NeT technology



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

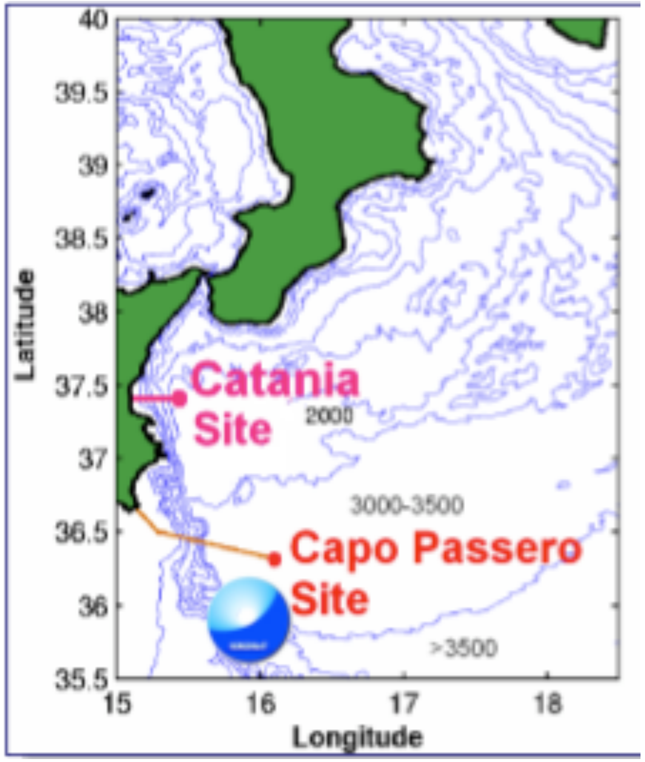
KM3NeT phased implementation

Phase	Building Blocks		Number of DUs		Phisics Goals		Status	
	ARCA	ORCA	ARCA	ORCA	ARCA	ORCA	ARCA	ORCA
1	0.2	0.06	24	7	Proof of feasibility and first science results. Joined analysis with ANTARES.		Fully funded. First 2 DUs acquiring data in Capo Passero.	
2.0	2	1	230	115	Study of the IceCube signal.	Determination of neutrino mass hyerarchy.	Not yet funded.	Not yet funded.
3	6	1	690	115	All flavour neutrino astronomy.			

L.O.I. KM3NeT ARCA and ORCA:

- J. Phys. G43 (2016) n. 8, 084001
- arXiv: 1601.07459

KM3NeT – ARCA infrastructure



The KM3NeT-It site:
- 80 km SE offshore Capo Passero
- 3450m depth
- excellent water optical properties
- low optical background
- negligible deep sea water current
- wide and flat abyssal plain

The KM3NeT-It site will host Earth and Sea science node

The Capo Passero Infrastructure:
- 100 km Electro-Optical cable: 20 fibres, 80 kW
- Cable Termination Frame, 3 Junction Boxes to serve 32 DUs
- 1 Junction Box to serve ESS

The Capo Passero Shore Lab.:
- Power Feeding Equipment
- DAQ centre + local Data Storage
- Guest House

KM3NeT – The Digital Optical Module

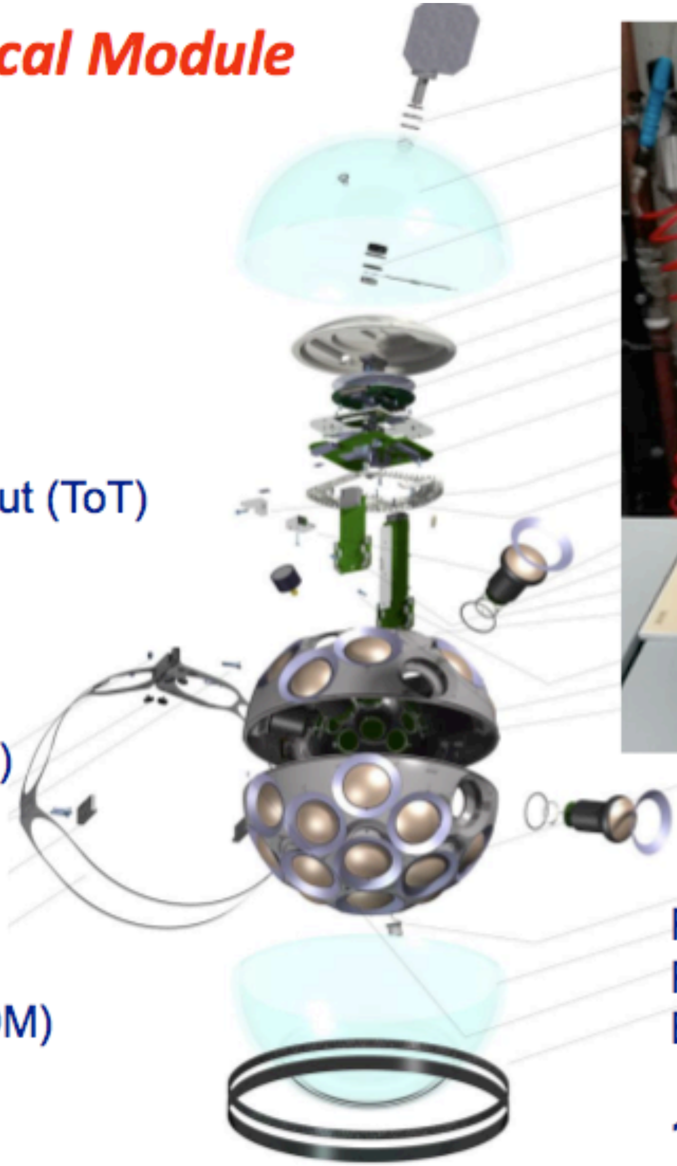
Multi-PMT Digital Optical Module

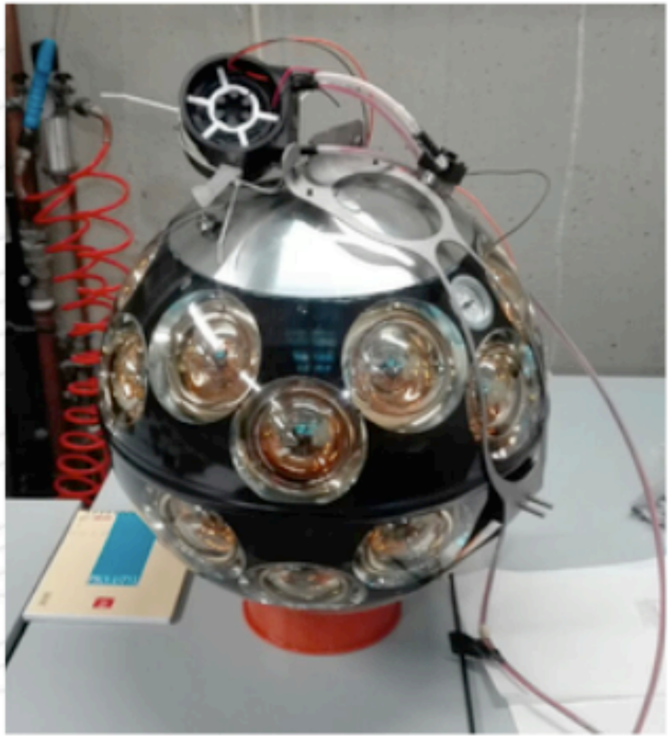
17" glass housing
e.o. penetrator
3d printed support structure
cooling structure (mushroom)

31 x 3" PMTs
light collection cone
active base & digital signal readout (ToT)
equalised PMT Gain ($3*10^6$)
Threshold 0.3 s.p.e.

AHRS (tilt, compass)
Digital piezo receiver (positioning)
LED emitter (time calibration)

Central logic board (CLB)
FPGA-based, white rabbit (T_{GPS})
DWDM optical comm (1 color/DOM)
power board
All data to shore





Photon counting
Particle direction reconstuction
Enhanced photocathode area

1DOM = 1 ANTARES Storey

About 100 components per DOM

KM3NeT – The Detection Unit

Detection Unit: vertical slender string with 18 DOMs

String

1 Buoy
2 Dyneema ropes
18 DOMs
Electro-optical backbone:
- Flexible hose 7mm
- Oil-filled
- 18 fibres
- 2 copper wires (375VDC)

36 m distance between DOMs
72 m anchor-first storey
700+ m total height from seabed
ARCA dimensions

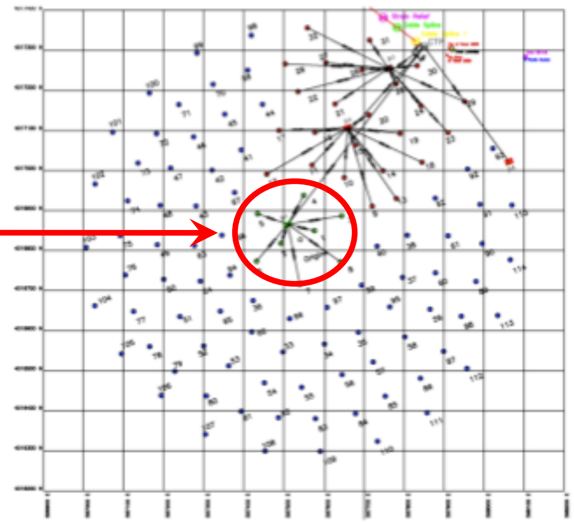
DU Base

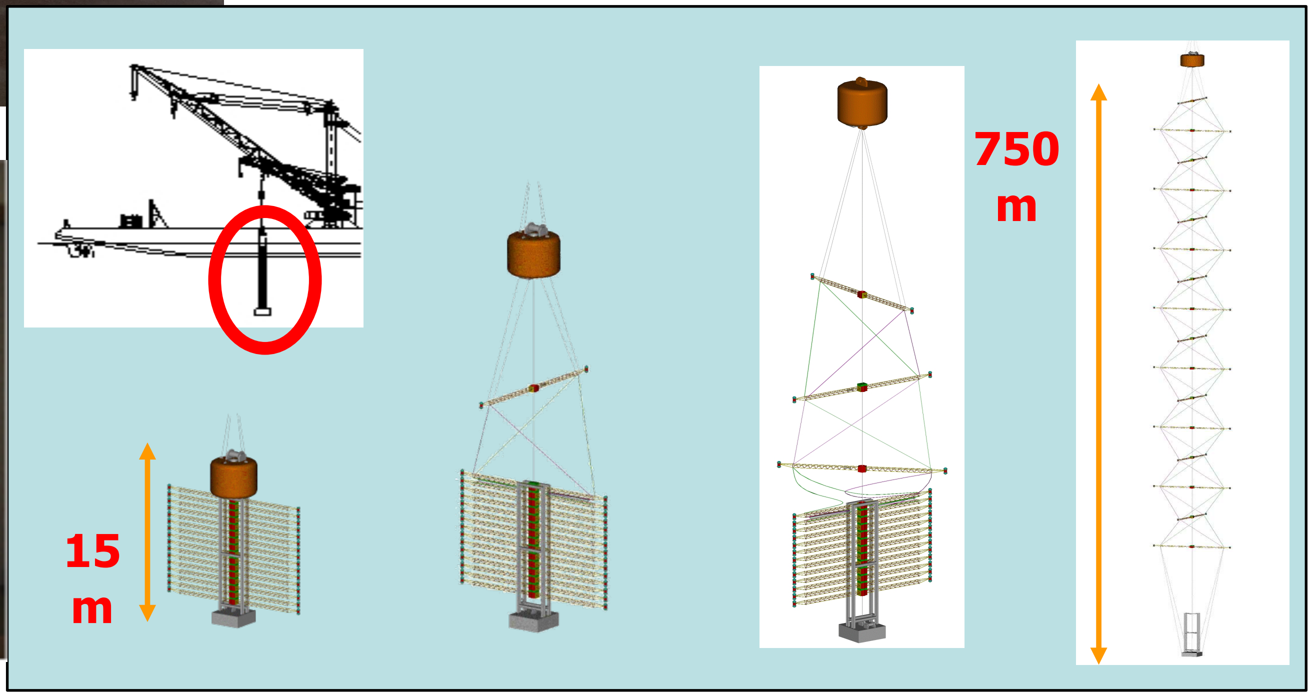
Anchor with electro-optical ROV mateable connector
Base Module:
- CLB (white rabbit)
- Power control board
- Optical amplifier

Hydrophone
LBL beacon

LOM (DU launch only)

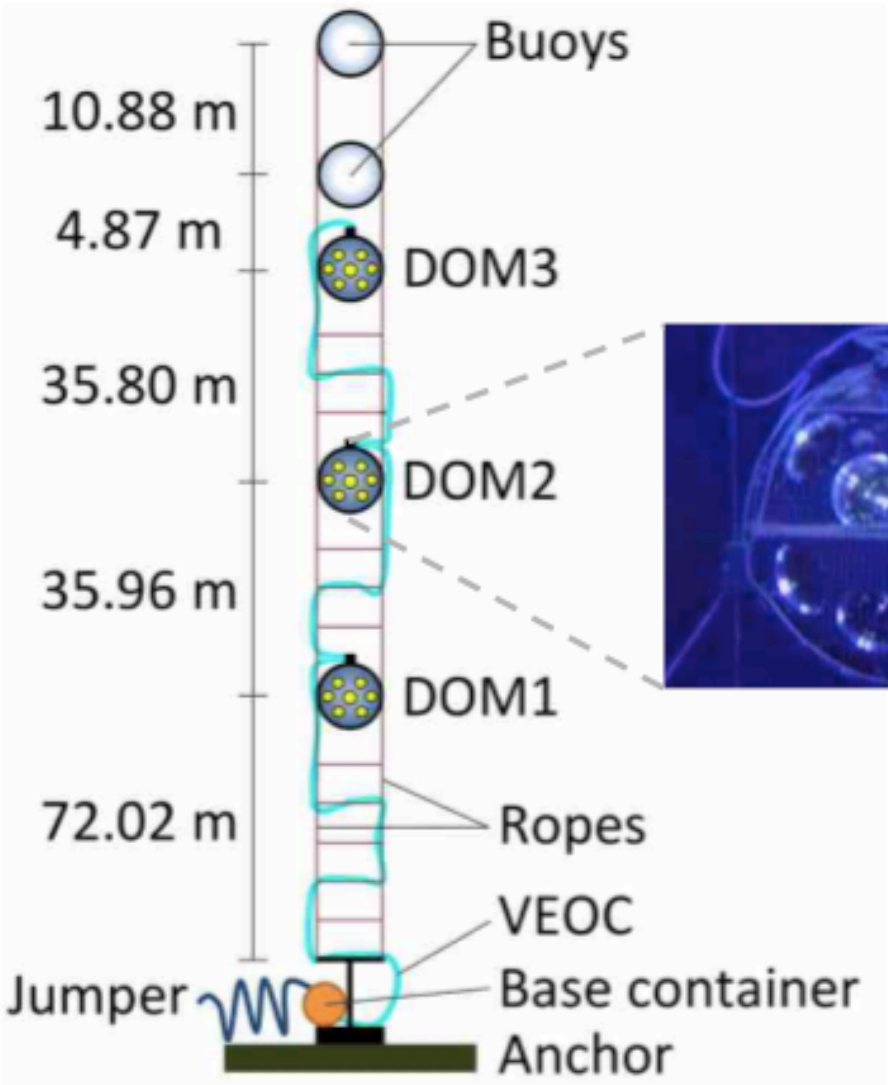
Not only strings, also 8 "Towers"

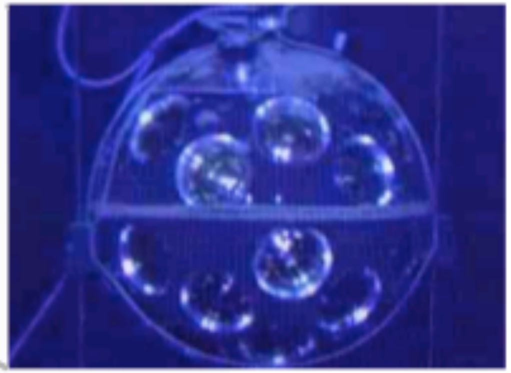




KM3NeT – prototype

A prototype DU with 3 DOMs in KM3NeT site





Prototype Line with three DOMs

Deployed at the KM3NeT-It site at 3500m depth

Followed successful operation of prototype DOM at the ANTARES site

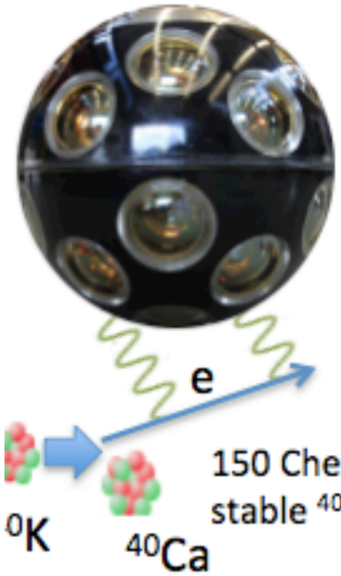
Operational from May 2014 to July 2015

Proof of concept functionality

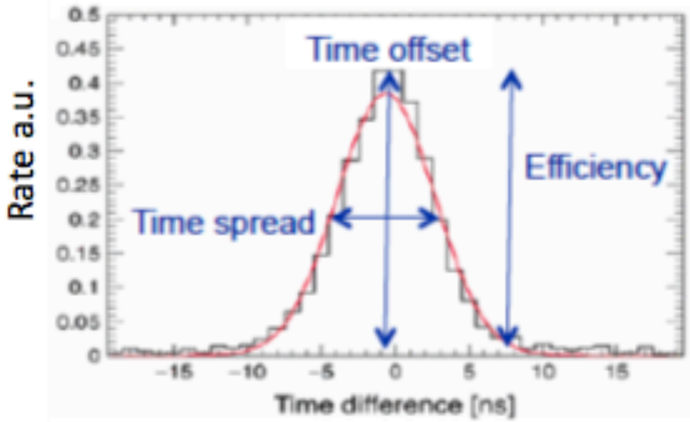
Test of readout, DAQ, connection, intra-DOM and inter-DOM synchronization

KM3NeT – results from prototypes

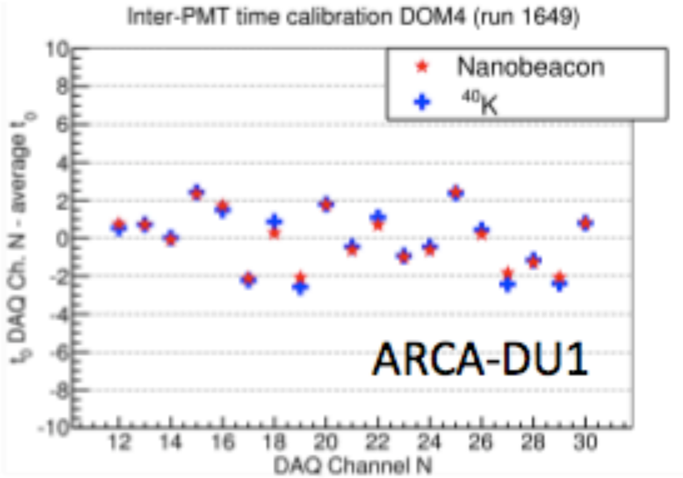
One DOM in ANTARES site



150 Cherenkov photons per decay
stable ^{40}K concentration



L1 trigger
Intra-DOM calibration

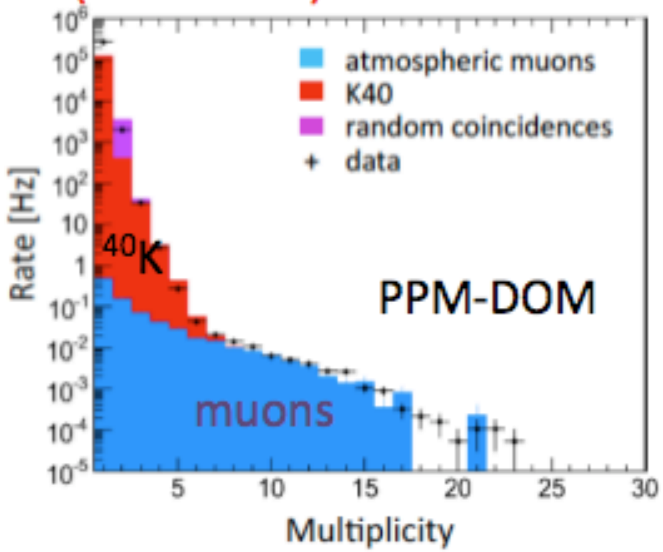


Muon/background separation with the DOM in ANTARES (PPM-DOM)

Photon counting + coincidences

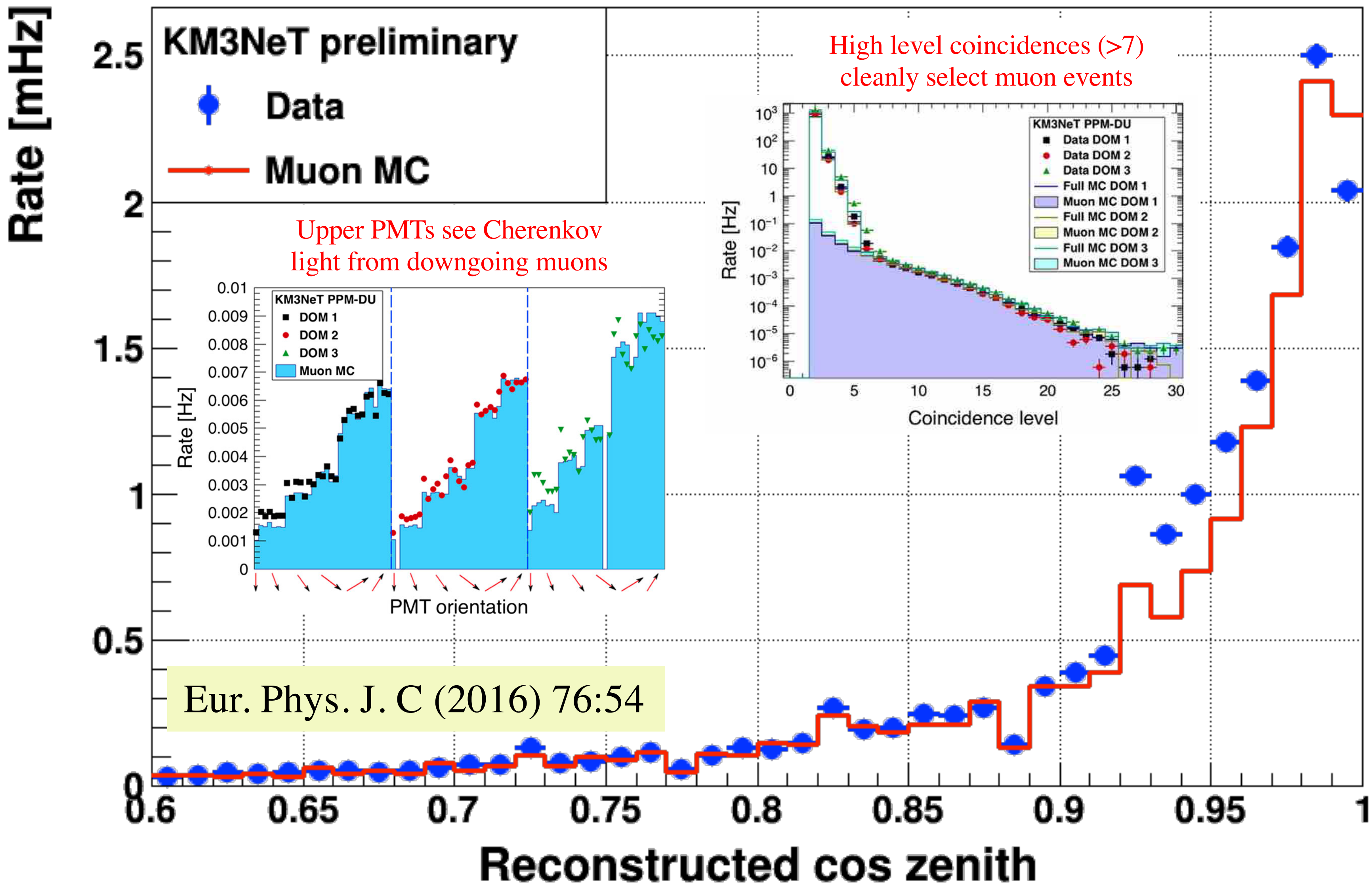
N_{coinc}>6 suppress ^{40}K
^{40}K rate: 5kHz

Eur. Phys. J.
C (2014) 74: 3056



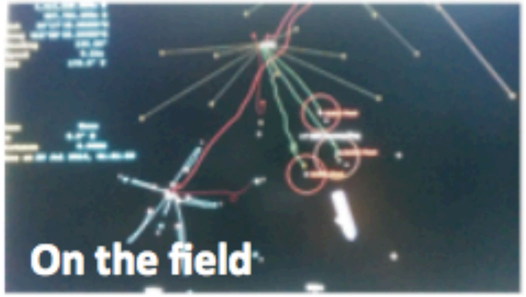
KM3NeT – results from prototypes

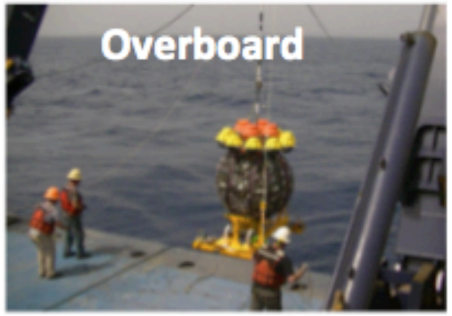
3 DOMs in the prototype DU in KM3NeT-It



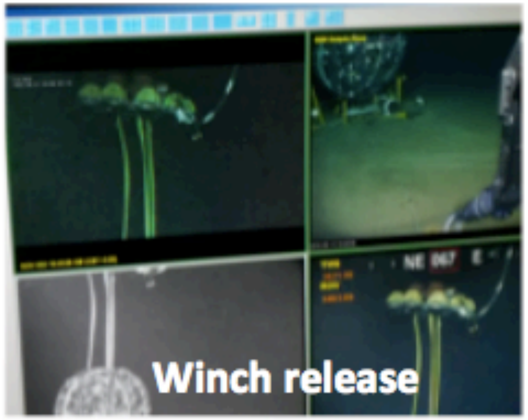
KM3NeT – DU deployment

December 2015 – Installation of the first DU in KM3NeT-It





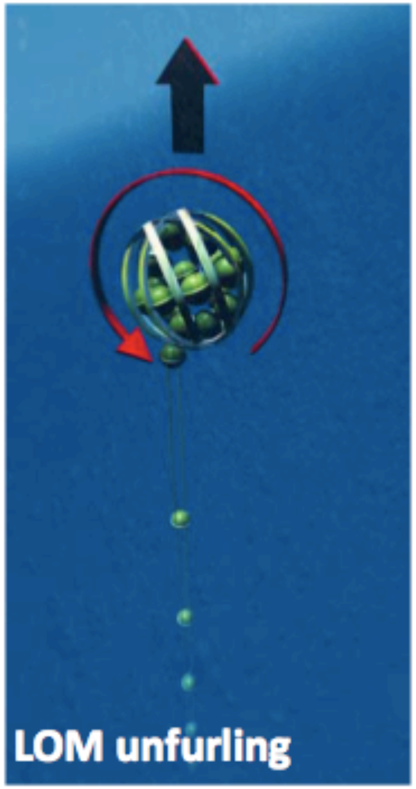
4 DUs fits on the ship

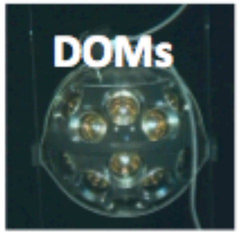


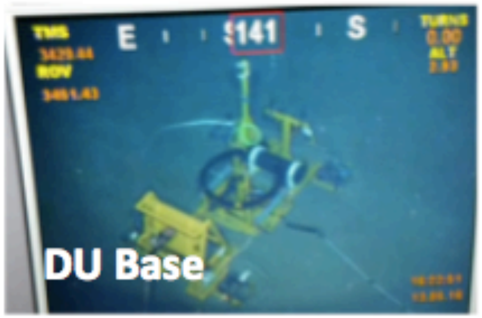
Winch and ROV guided DU landing ±2 m accuracy

May 2016 – DU2 and DU3 installed in KM3NeT-It.
D1 and DU2 in data taking. DU3 recovered after failure

KM3NeT – DU unfurling





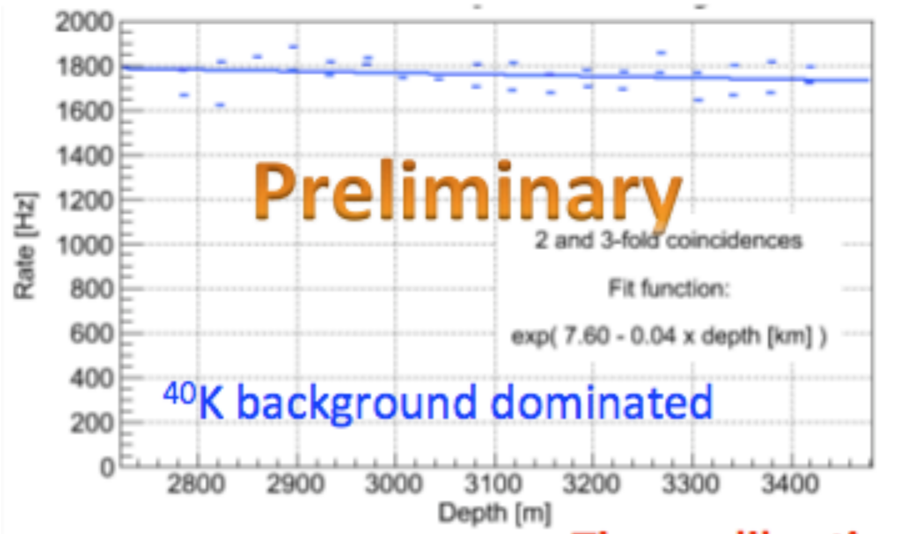


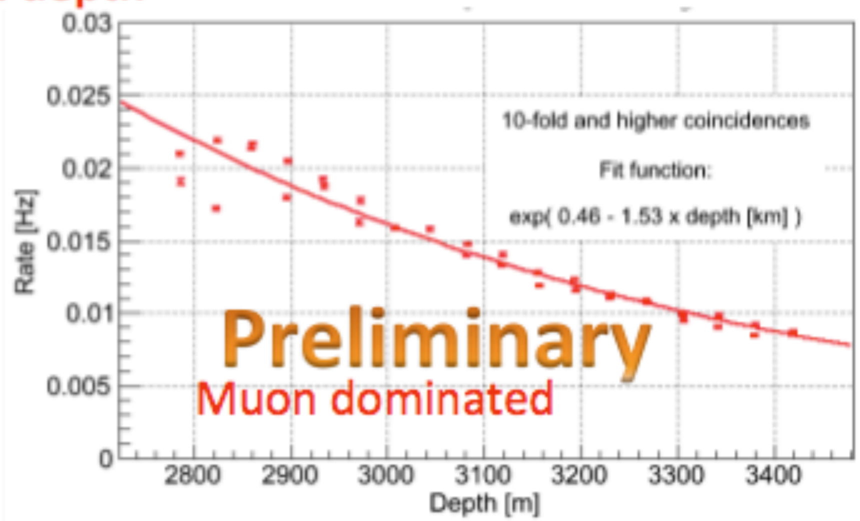
The deployment operation tested several times: ARCA DU in KM3NeT-It

2 ARCA DU already operational in KM3NeT-It site

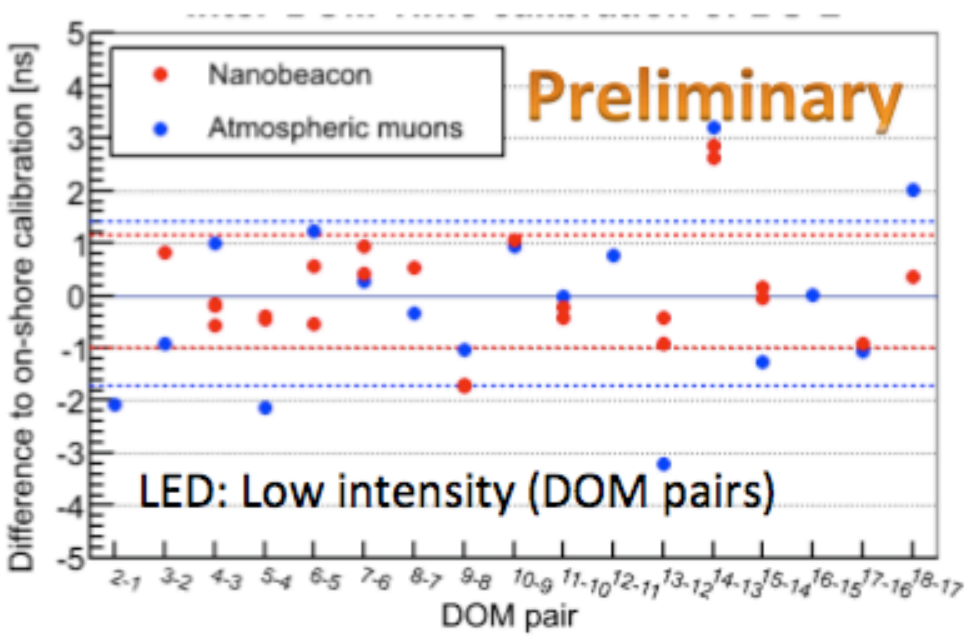
ARCA: DU1 and DU2 first data

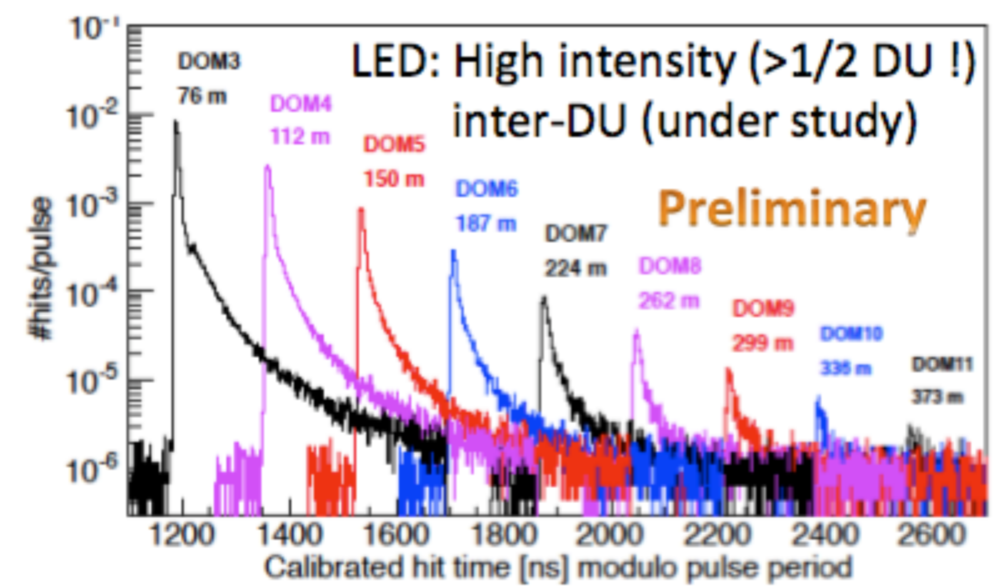
Coincidence rate vs. depth





Time calibration check with nanobeacons



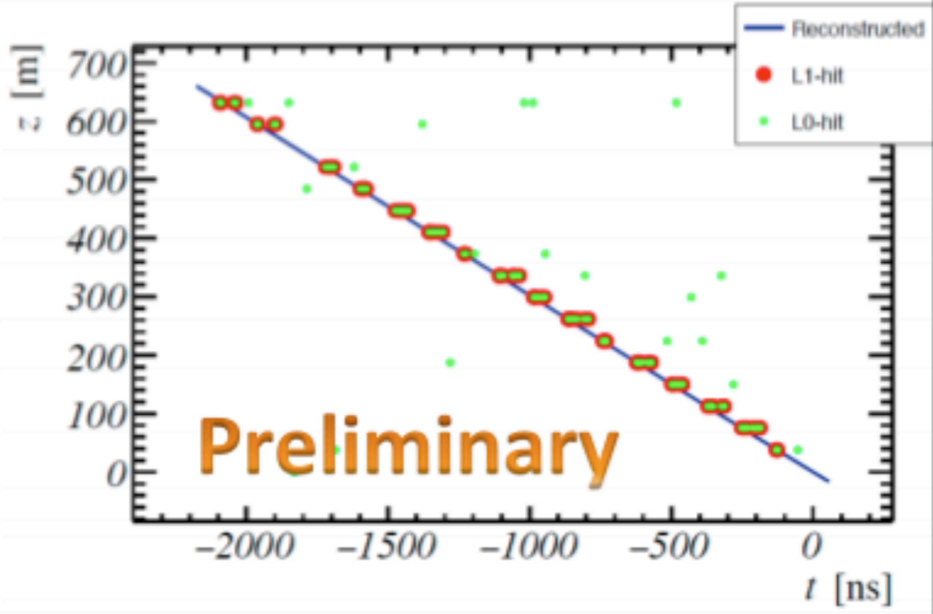


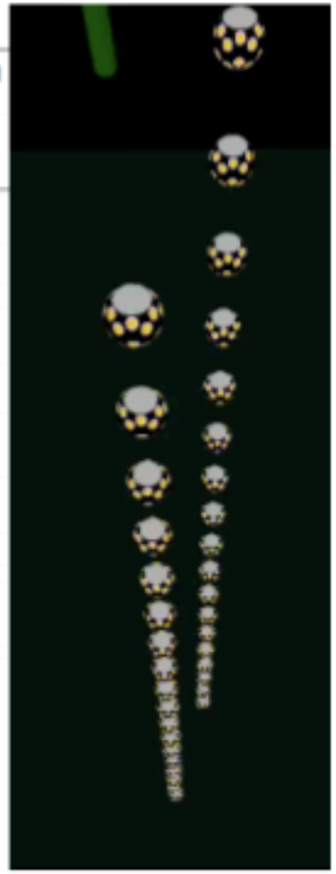
ARCA DU1 and DU2 first muon tracks

Cosmic muon (downgoing) reconstruction

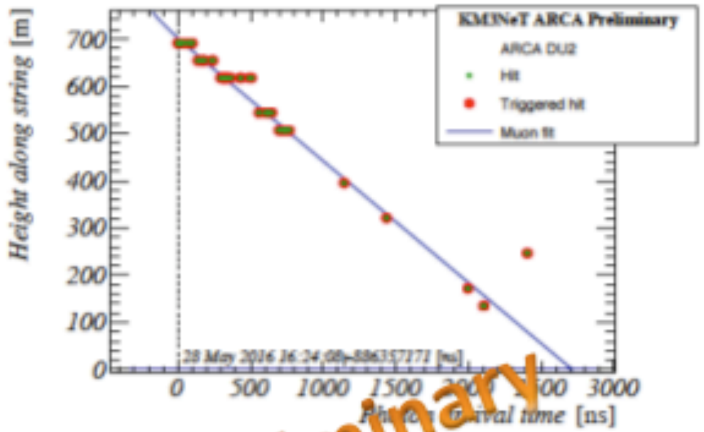
$$t = \frac{(z - z_0)\cos\theta + \sqrt{n^2 - 1}\cdot\sqrt{d_0^2 + (z - z_0)^2 \sin^2\theta}}{c} + t_0$$

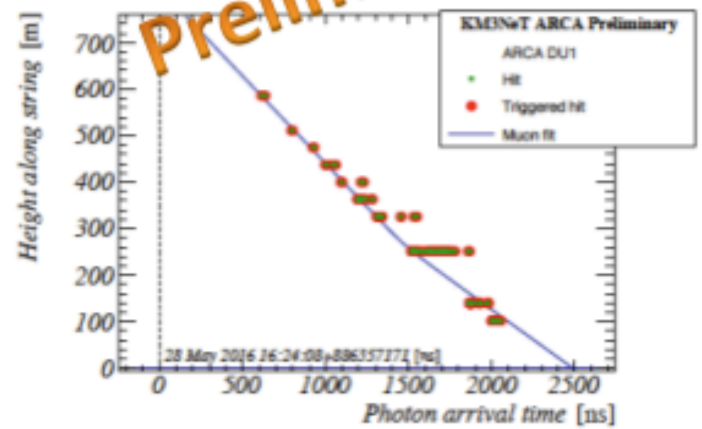
1 string





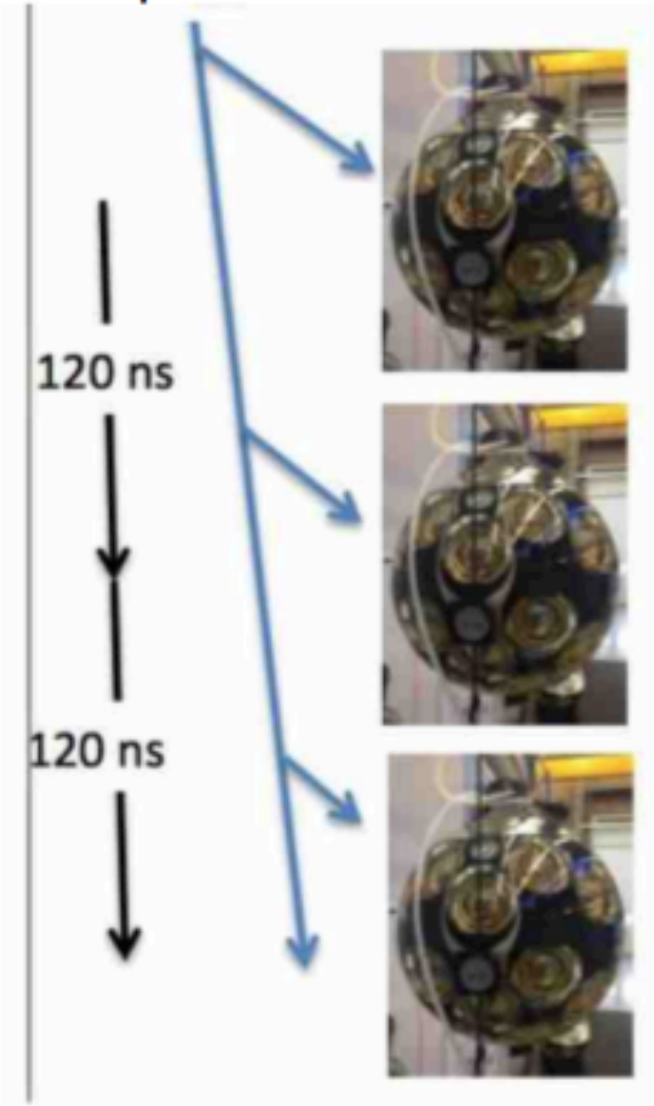
2 strings

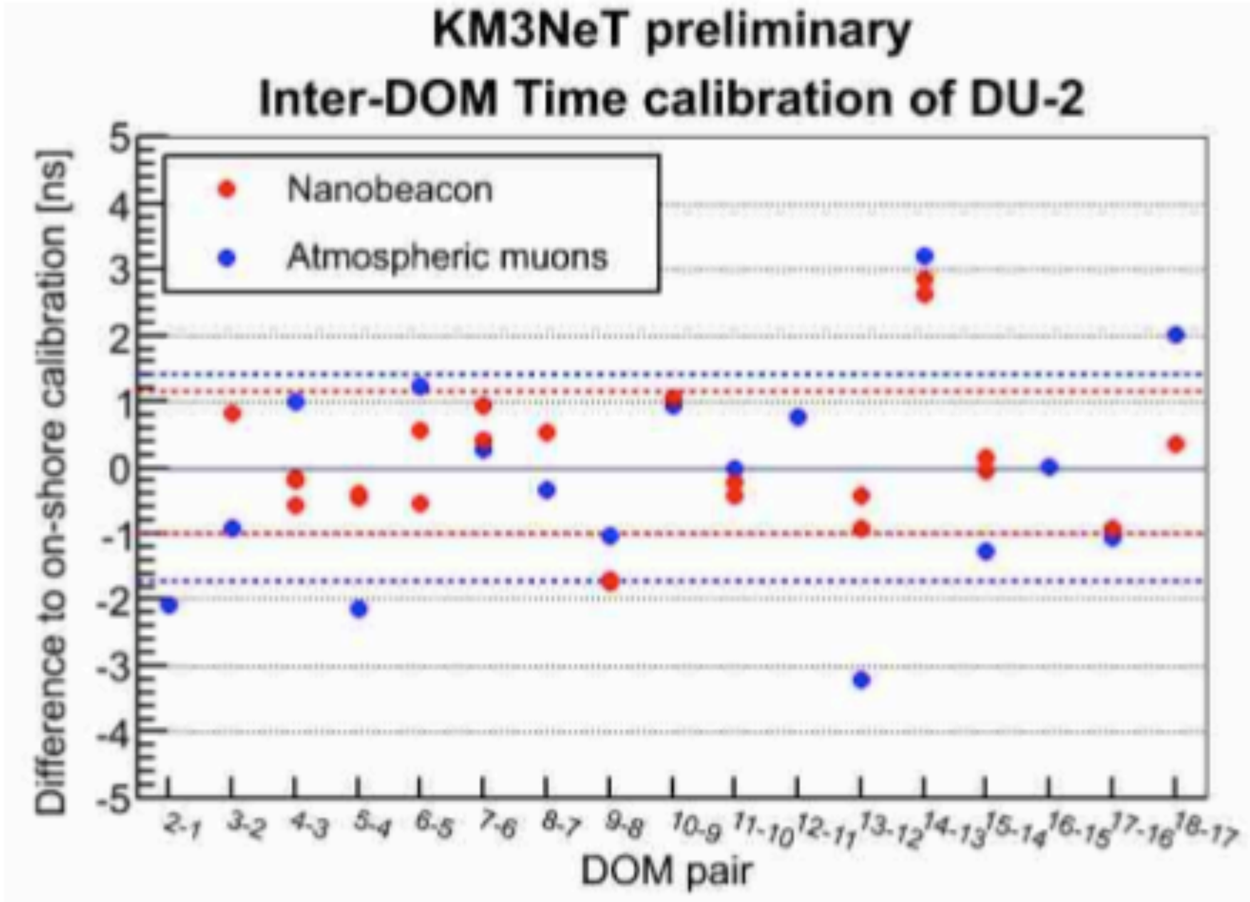




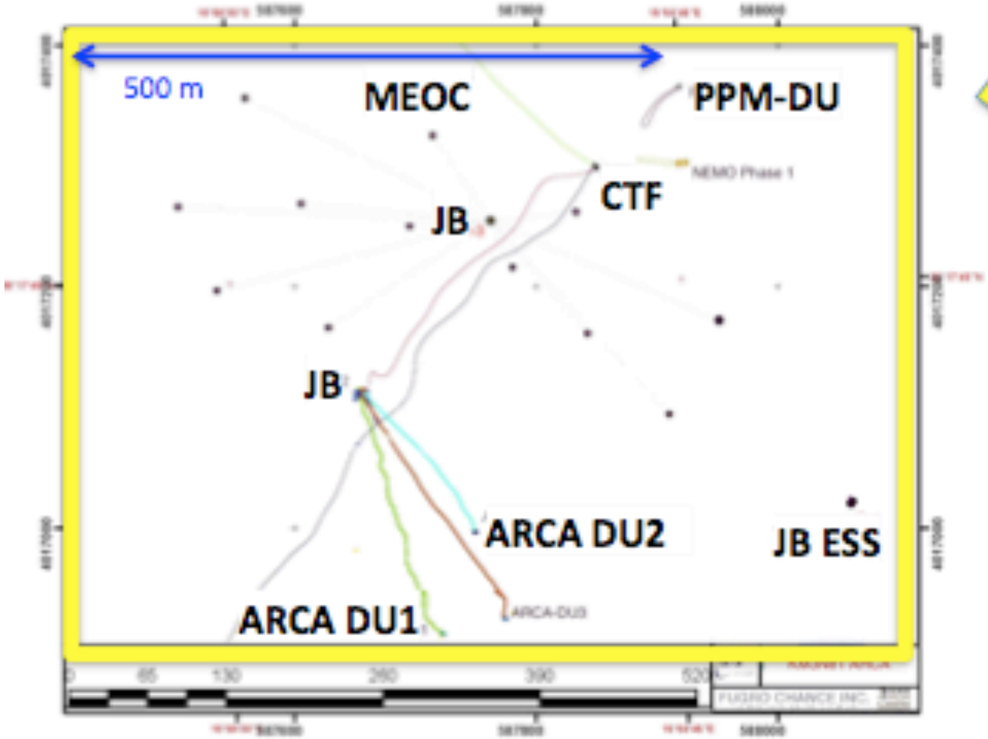
ARCA DU1 and DU2: calibration tests

Comparison of calibration with LED nanobeacons and atmospheric muons

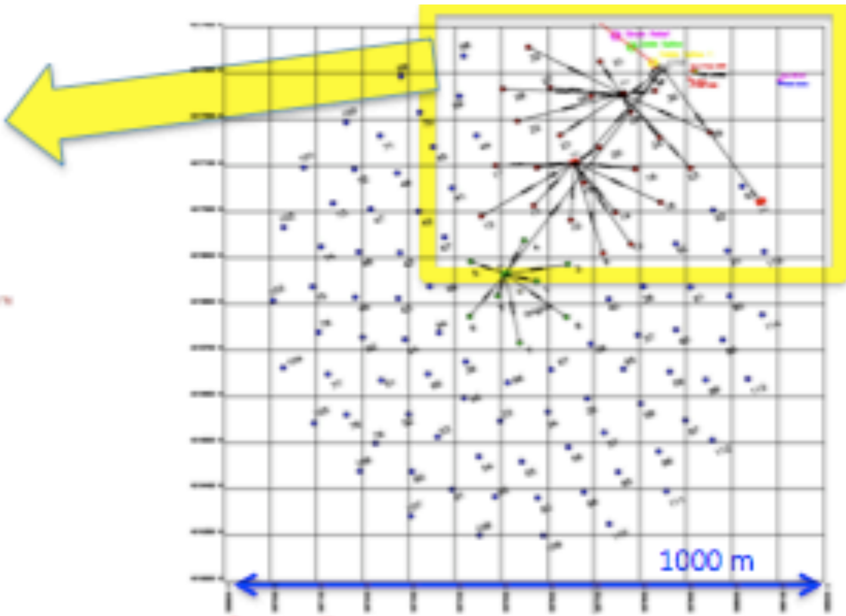




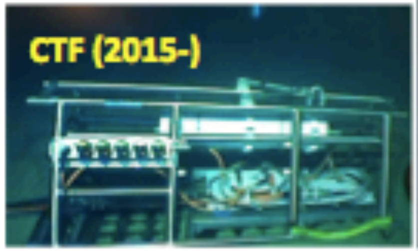
KM3NeT – ARCA footprint and seabed network



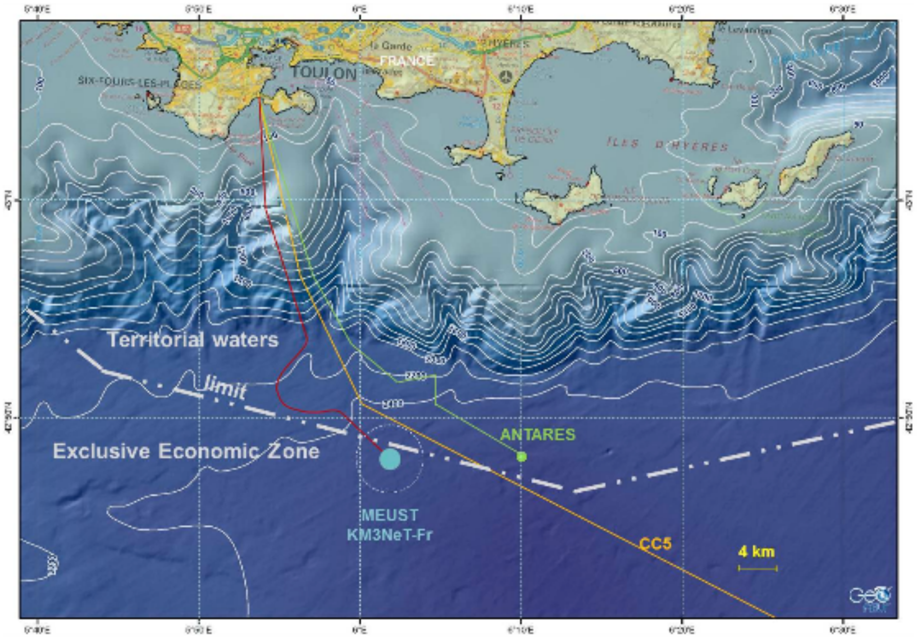
ARCA Phase 1

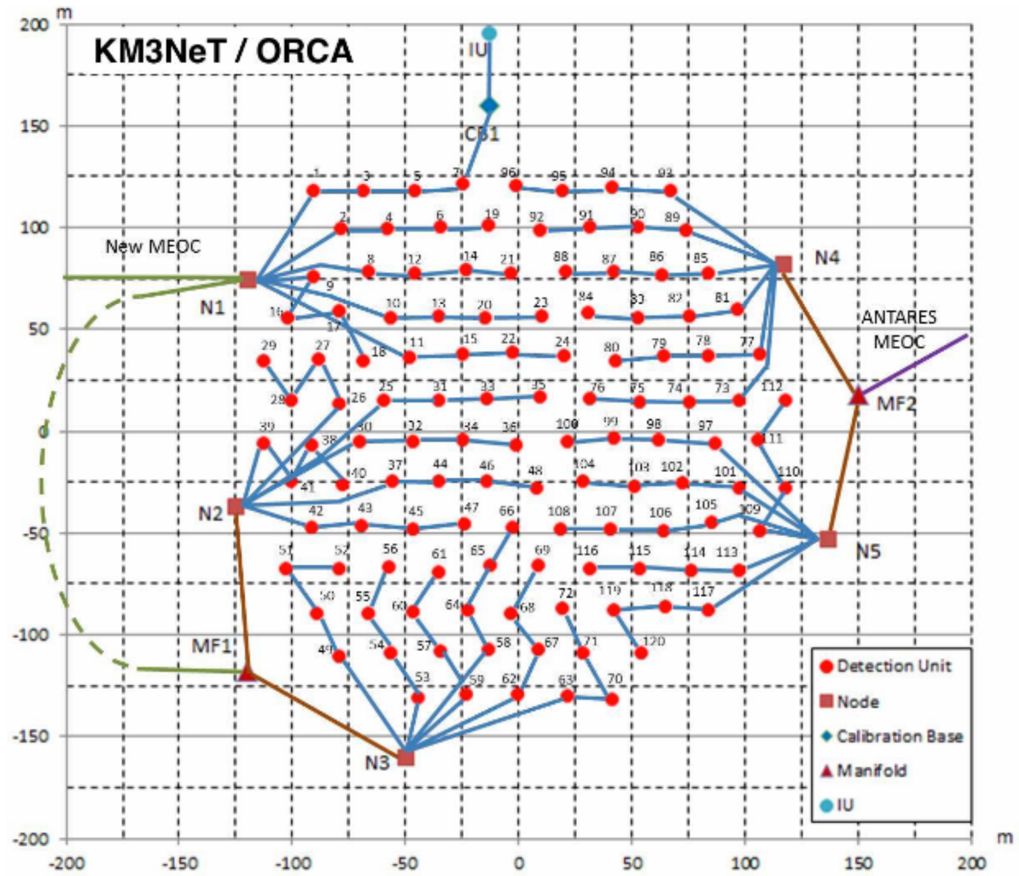


Capo Passero
ARCA Buliding block 1



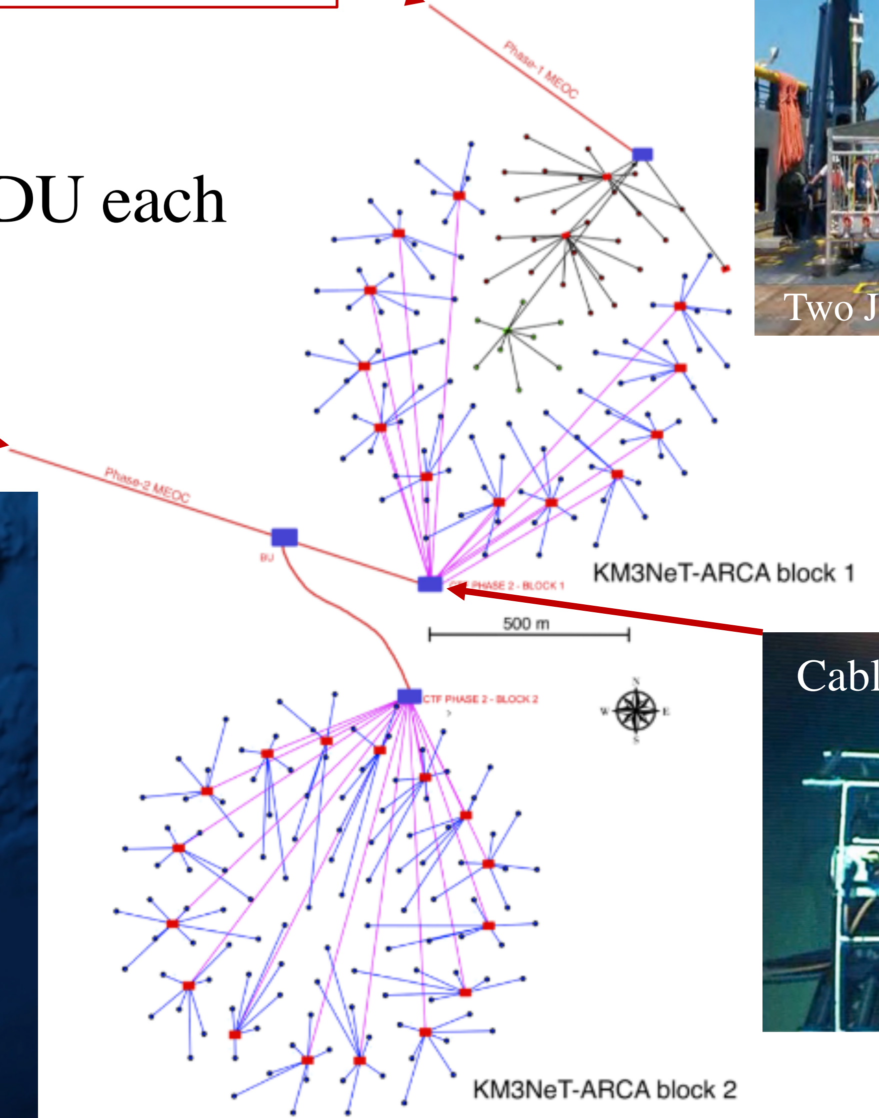
KM3NeT – ORCA footprint and seabed network





KM3NeT – ARCA Phase 2

Present Main Electro-Optical Cable



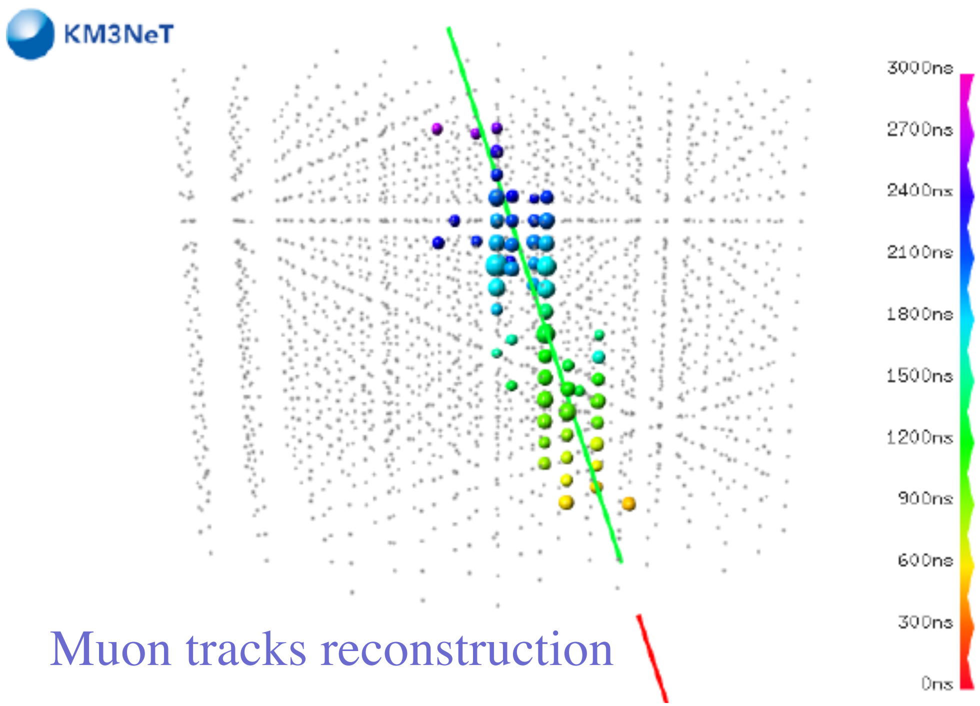
Two JBs ready for deployment

Two Building Blocks 115 DU each

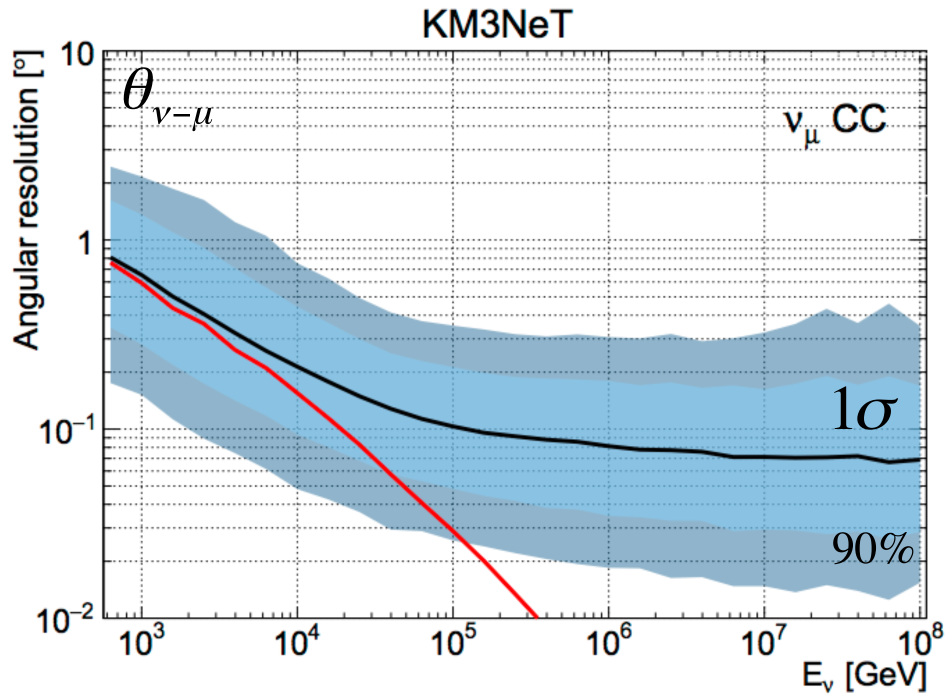
New Main Electro-Optical Cable

Cable Termination Frame

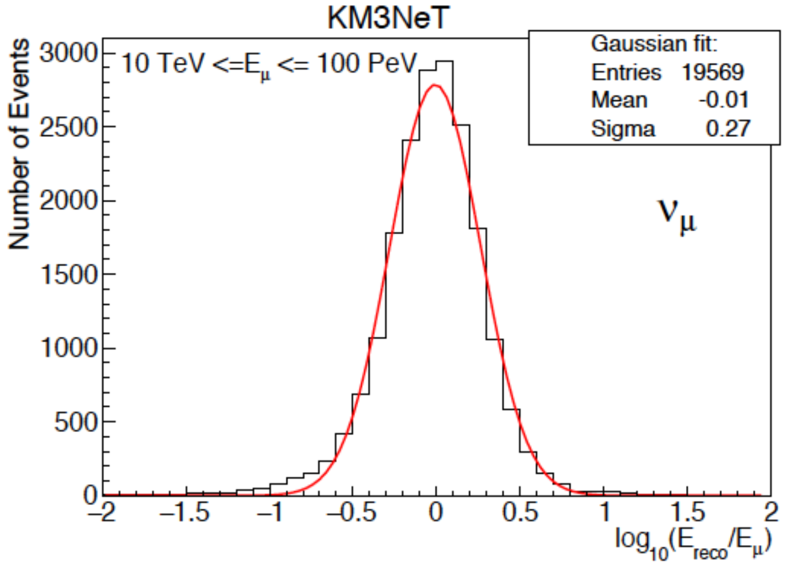
ARCA (Phase 2) performances for tracks



Muon tracks reconstruction



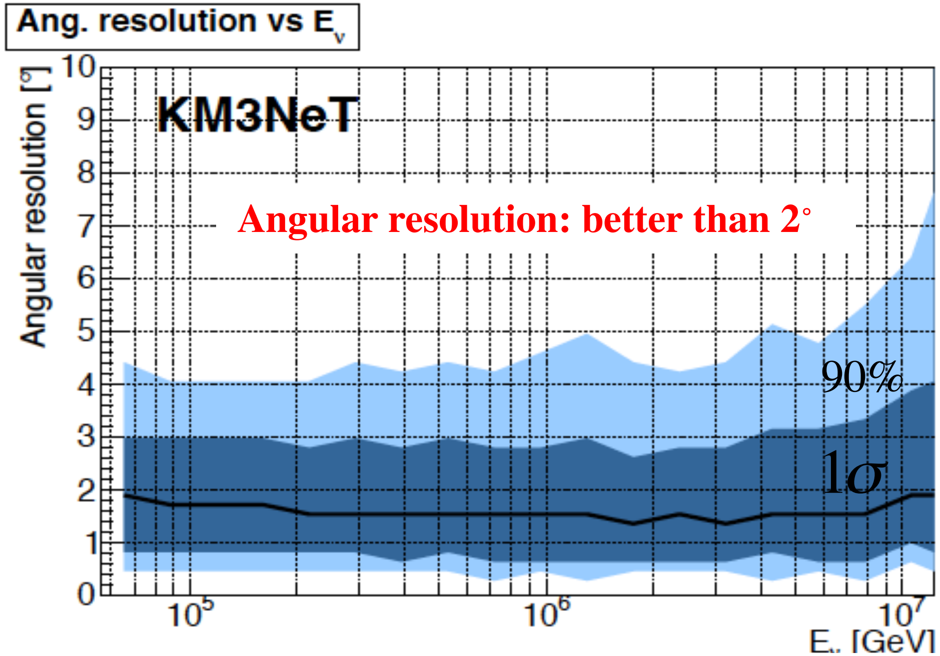
Angular resolution ~ 0.1° for E_ν >10 TeV

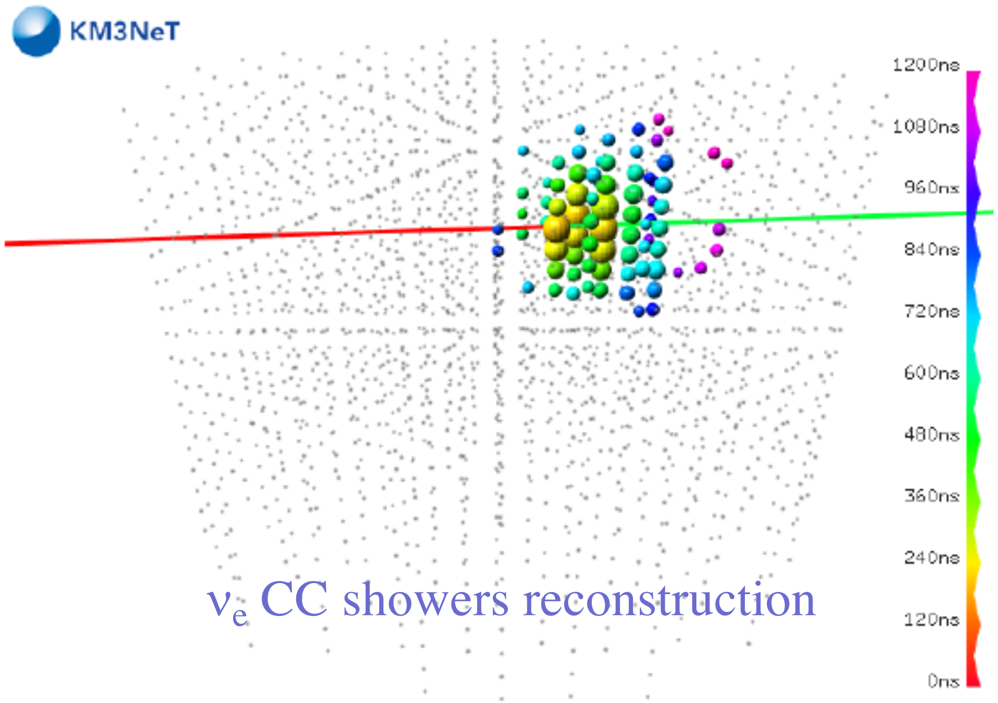


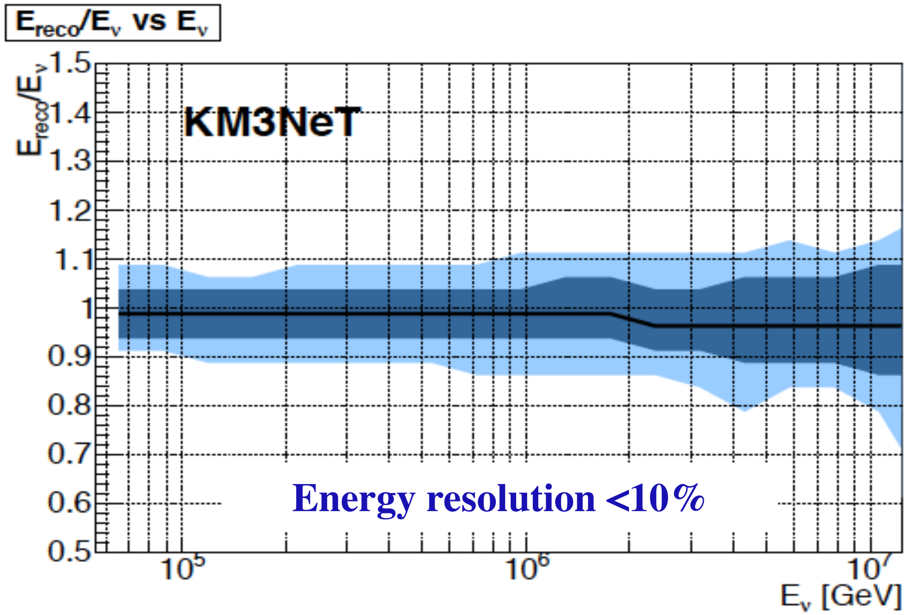
Angular and energy resolution, after cuts, for the analysis of diffuse ν_μ neutrino CC events

Energy resolution ~ 0.27 in logE_μ 1 1TeV<E_ν <100 PeV

ARCA (Phase 2) performances for showers

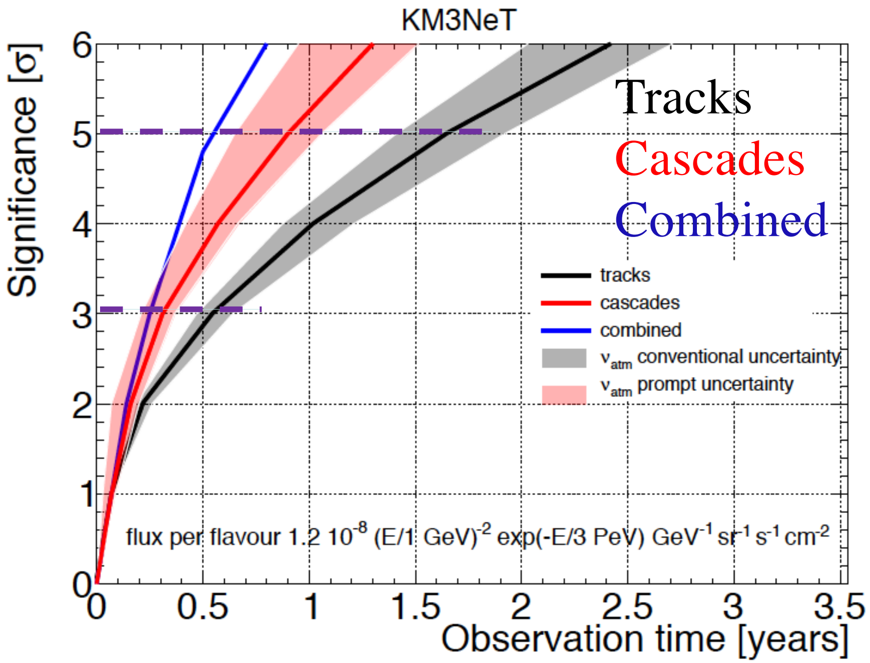






Angular and energy resolution, after cuts, for the analysis of diffuse neutrino cascade events

ARCA (Phase 2) discovery potential for ν diffuse fluxes



Tracks:

- up-going tracks $\theta_{zenit} > 80^\circ$
- analysis based on Maximum Likelihood
- cuts on reconstruction quality parameter Λ
- cuts on N_{hits} (→ muon energy)

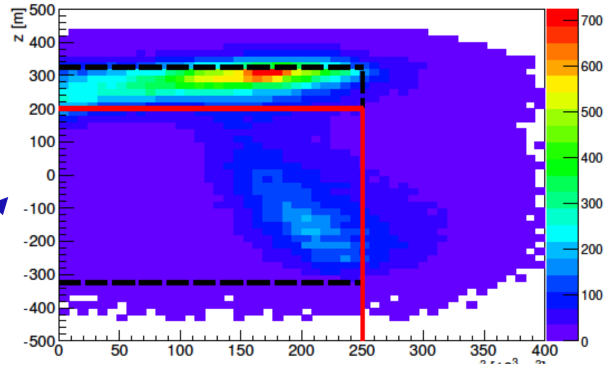
Cascades:

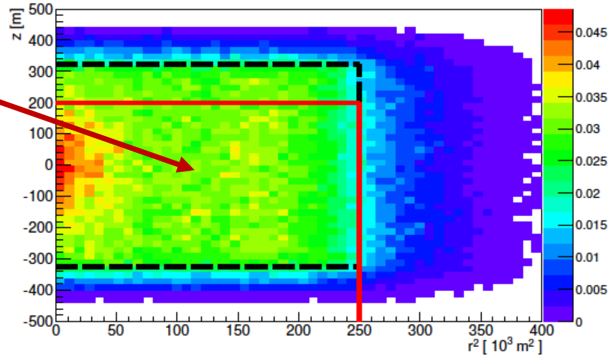
- Containment cut on reconstructed vertex to remove atmospheric muons

Discovery at 5σ significance (50% probability) in less than one year (combined analysis)

Reconstructed vertex position for atm. muons and for ν_e CC cascades.

MUON VETO





ARCA (Phase 2) search for diffuse fluxes from Galactic Ridge

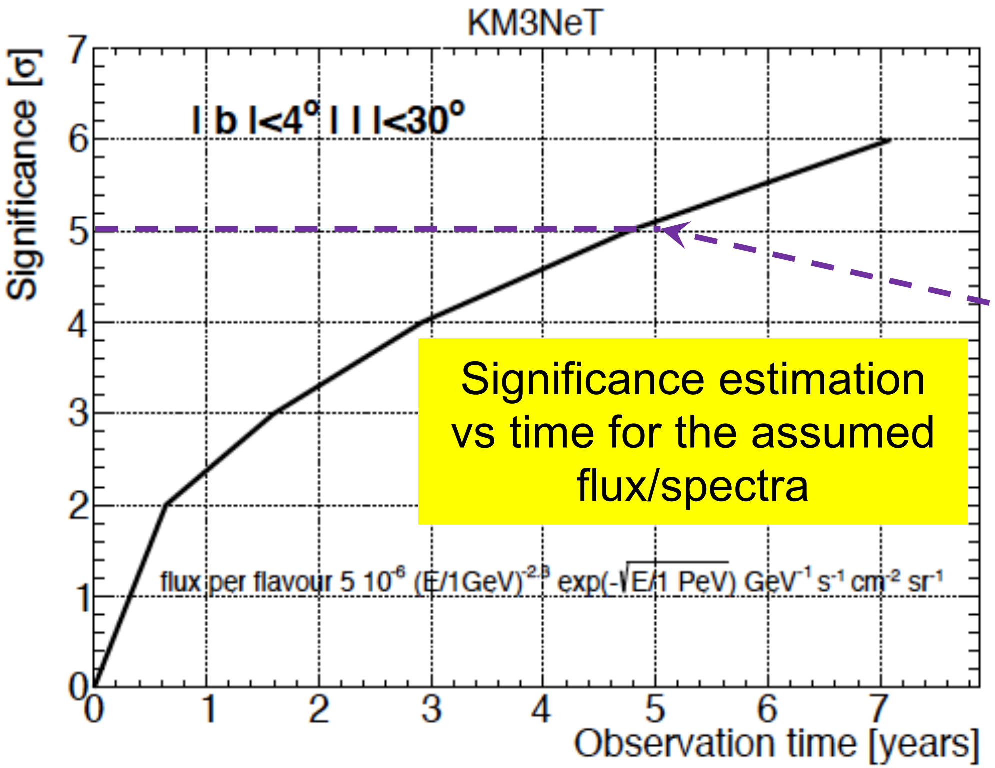
Hypothesis:

- neutrinos produced in the interactions of the galactic cosmic rays with the interstellar medium and radiation fields.
- D. Gaggero et al. arXiV 1508.03681 (2015)
- flux for each flavour:

$$\Phi(E_\nu) = 5.\cdot 10^{-6} \left(\frac{E_\nu}{1GeV}\right)^{-2.3} e^{-\left(\sqrt{\frac{E_\nu}{1PeV}}\right)} [GeV^{-1}cm^{-2}s^{-1}sr^{-1}]$$

Only muon tracks analysed.
Events selection:

- $-30^\circ <$ Galactic latitude $< 30^\circ$
- $-4^\circ <$ Galactic longitude $< 4^\circ$
- up-going tracks $\theta_{zenit} > 80^\circ$
- analysis based on Maximum Likelihood
- cuts on reconstruction quality parameter Λ
- cuts on N_{hits} (→ muon energy)

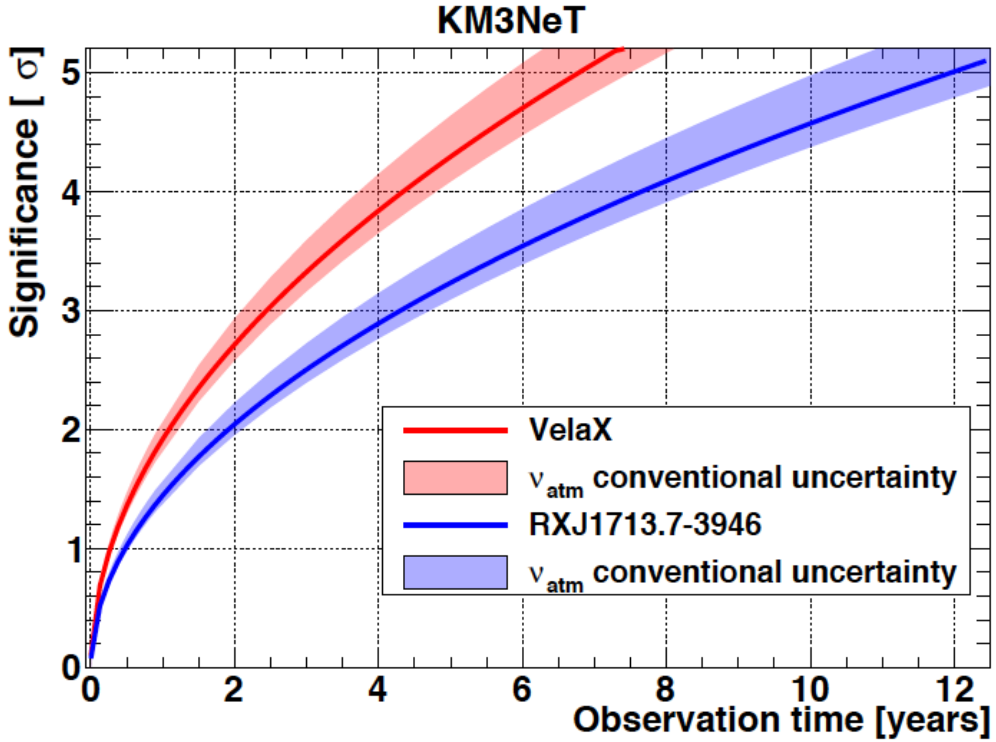


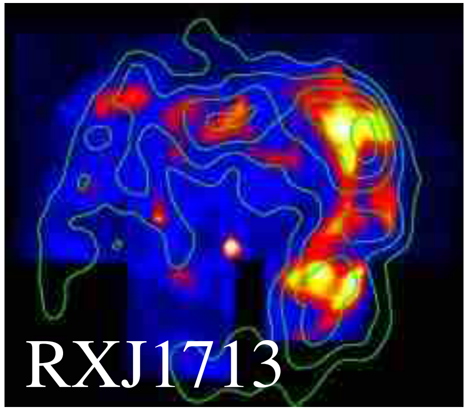
5σ discovery to be achieved after 5 years of operation

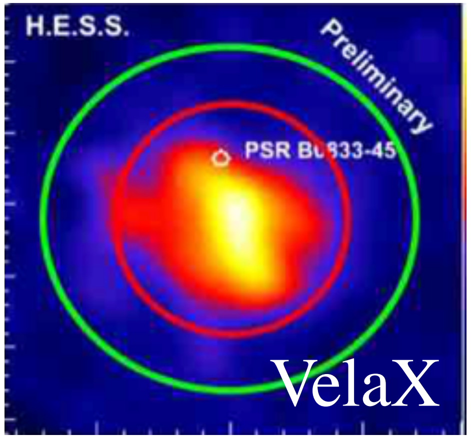
ARCA (Phase 2) search for point-like Galactic sources

Hypothesis:

- Neutrino fluxes/spectra inferred from gamma-rays data .
- S.R. Kelner, et al. PRD 74 (2006) 034018
- F.L. Villante and F. Vissani, PRD 78 (2008) 103007
- 100% hadronic source
- transparent source





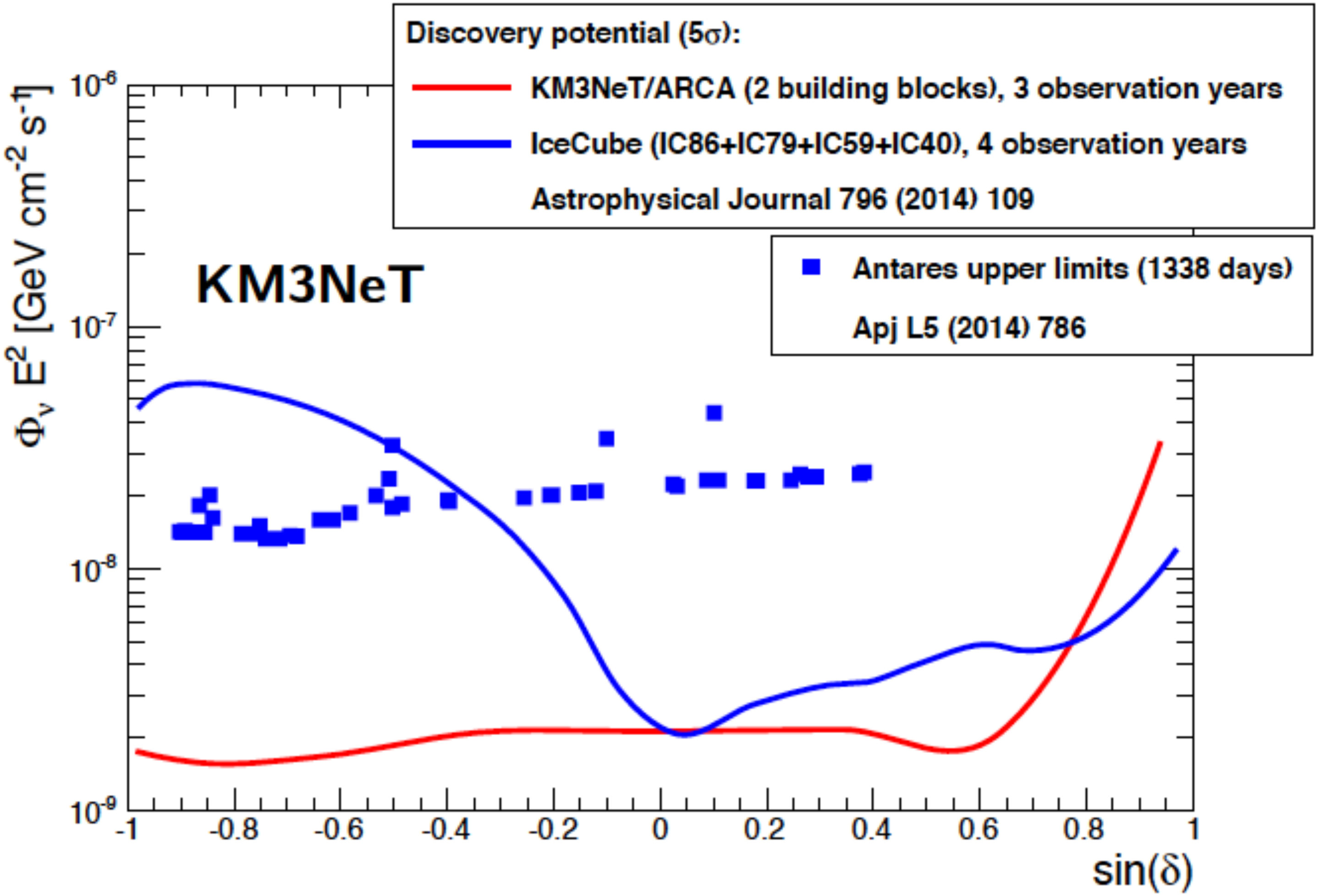


VelaX : 3σ discovery in ~ 2 years
RX1713: 3σ discovery in ~ 4 years

ARCA (Phase 2) discovery potential for point-like sources

Hypothesis:

- Neutrino spectra ~ E_ν^{-2}.
- 3 years observation time

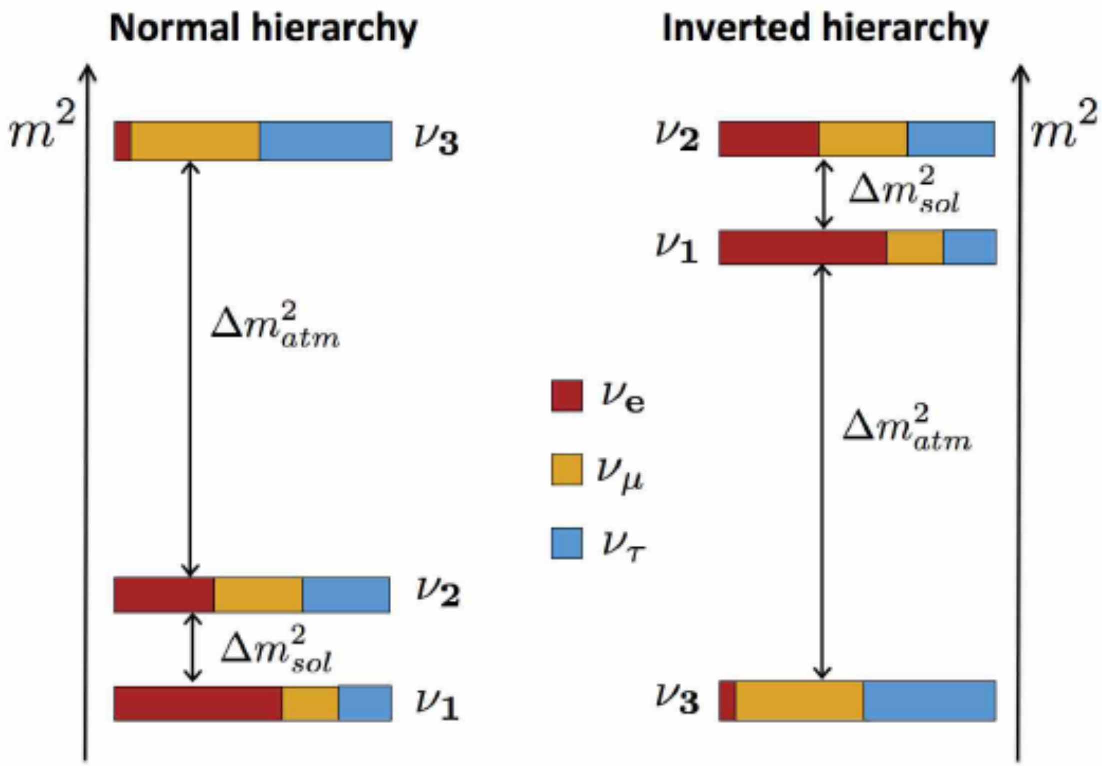


KM3NeT – ORCA physics goals

The Pontecorvo–Maki–Nakagawa–Sakata matrix

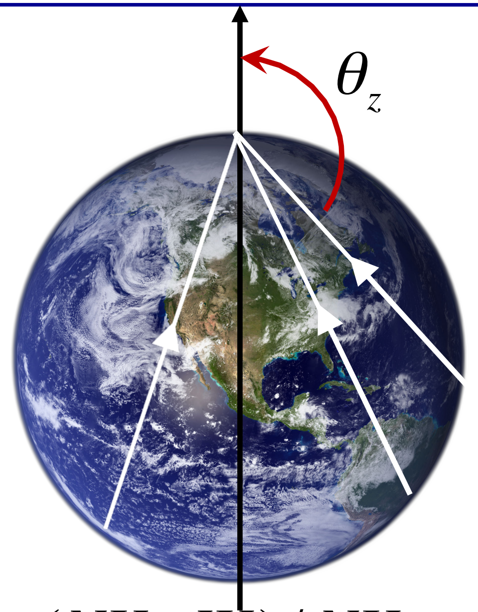
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Determine the Neutrino Mass Hierarchy (NMH)
- Precise measurement of atmospheric neutrino parameters
- Indirect Dark Matter search



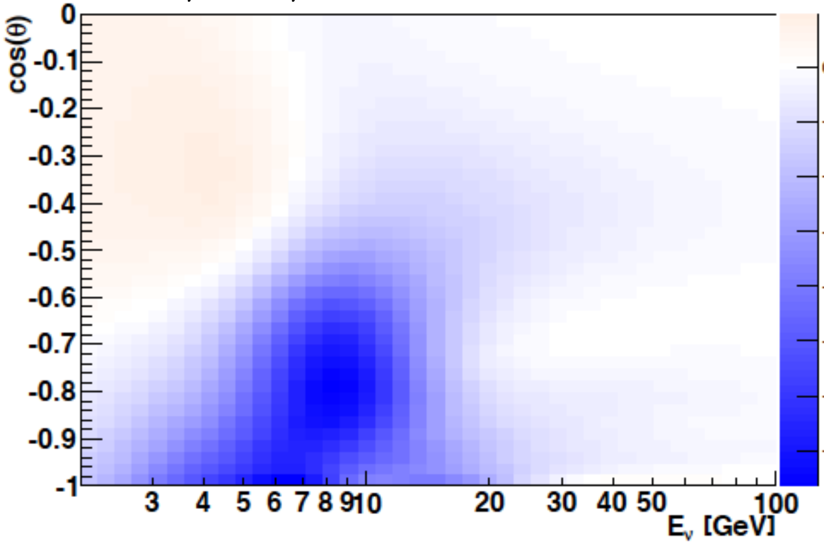
KM3NeT – ORCA observable quantities

- The propagation of neutrinos in matter is sensitive to the NMH.
- To investigate the NMH we need to know the Energy and the length (the angle θ_z) of the path into the matter of neutrinos.
  - Required good energy resolution (~25%)
  - Required good angular resolution ($\sigma(\theta_z) = m_p/E_\nu)^{1/2}$)
  - Required large statistics

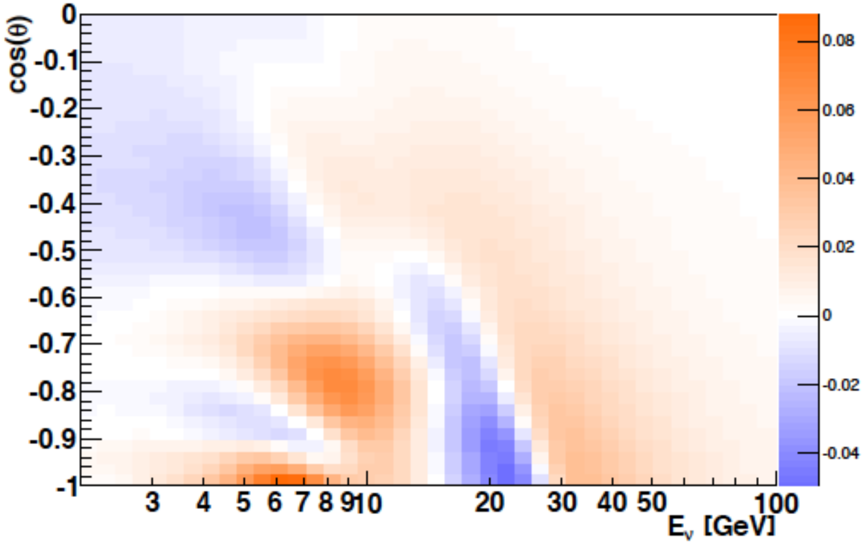


Fractional difference

$\nu_\mu + \bar{\nu}_\mu \quad (NH - IH)/NH$

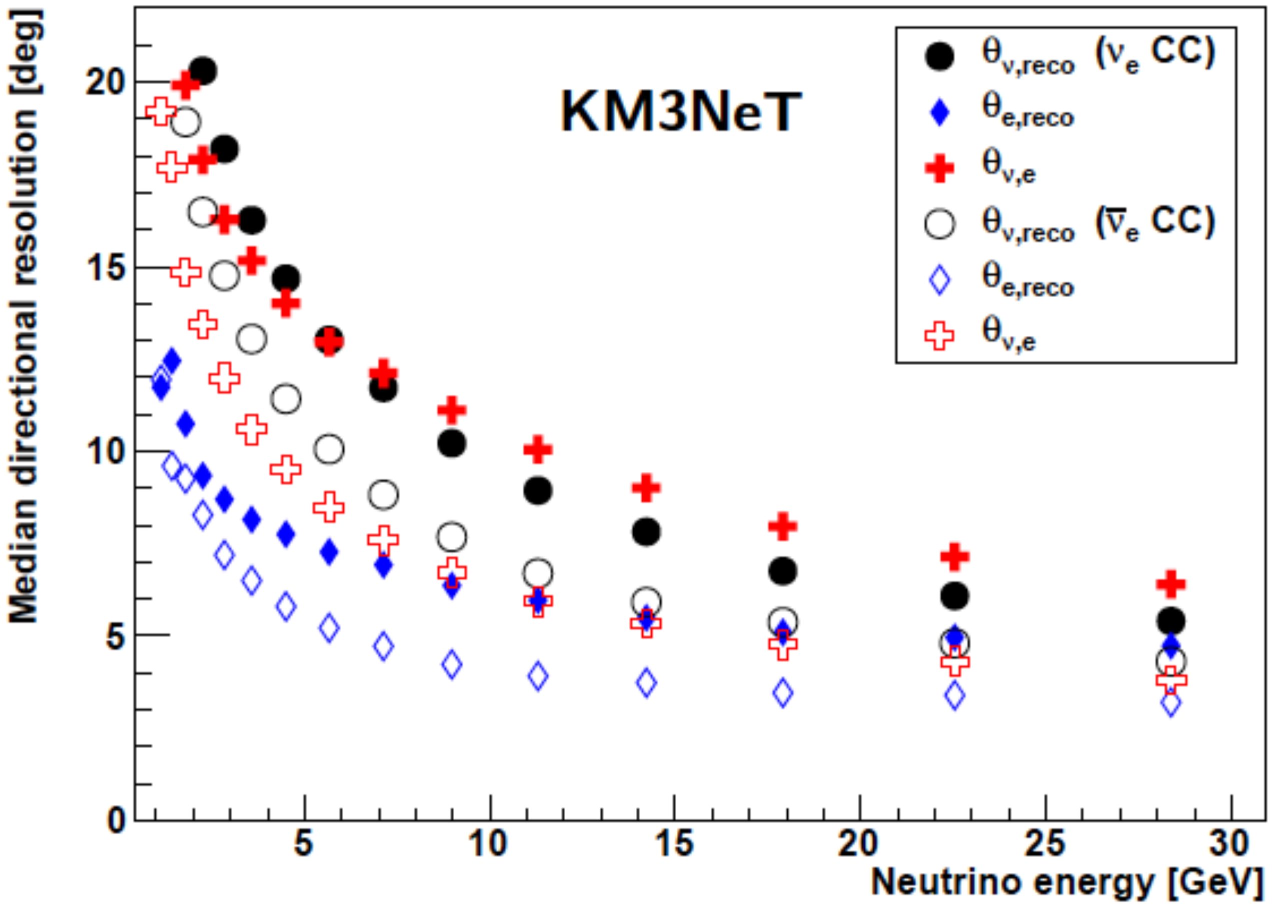


$\nu_e + \bar{\nu}_e \quad (NH - IH)/NH$



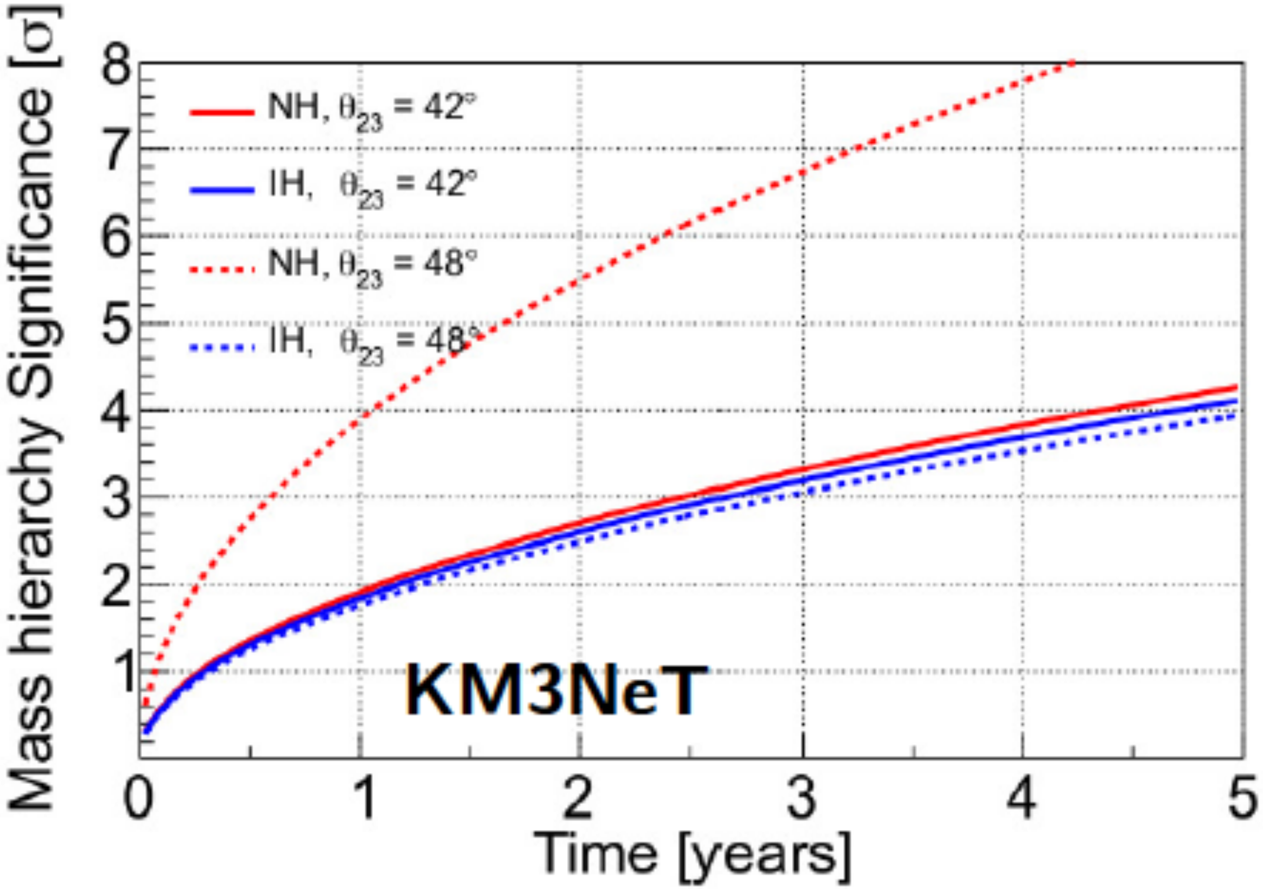
KM3NeT – ORCA resolutions

- Both for electron and muon channels the angular resolution is dominated by kinematics
- Largely independent from spacing between DOMs and DUs



KM3NeT – ORCA sensitivity to NMH

- Time dependence of the KM3NeT sensitivity
- ORCA Mass Hierarch determination significance for $\delta_{CP} = 0^\circ$



at the South Pole

PINGU

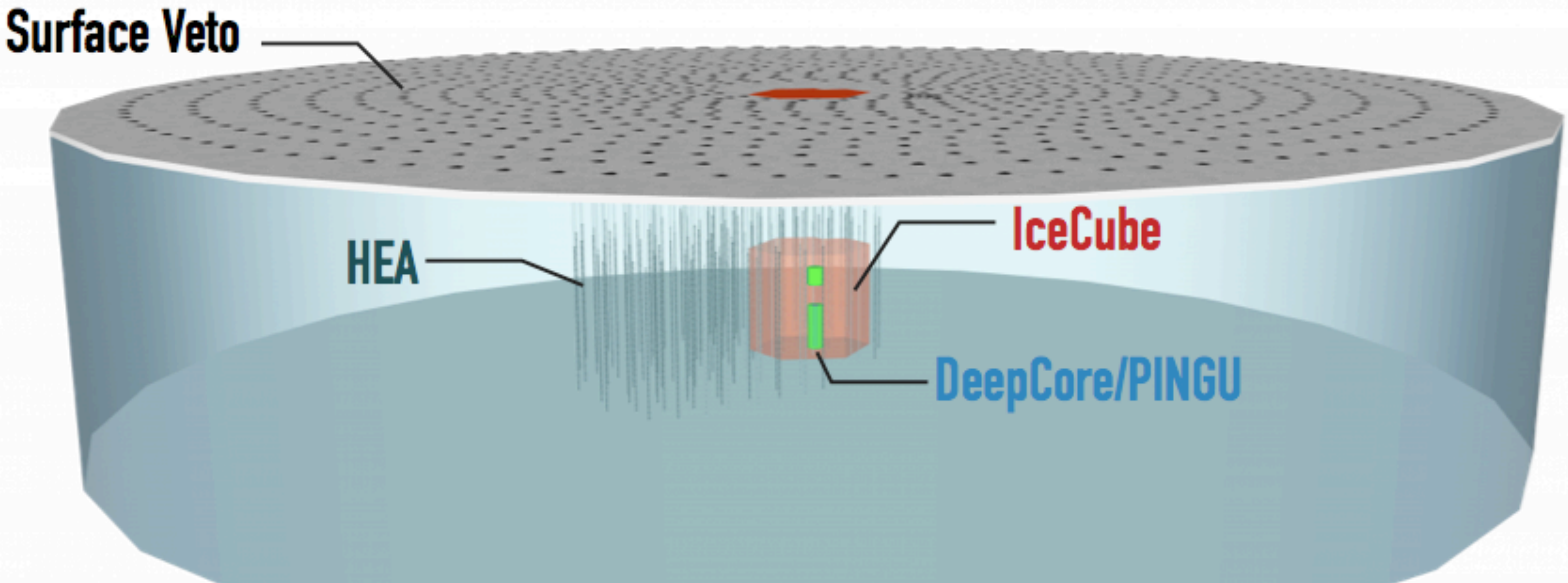
Further in-fill
Lower the energy threshold few GeV
Neutrino Mass Hierarchy
Dark Matter + Solar Flares

High Energy Array (HEA)

Extension of IceCube array
Look for high-energy events
GZK and astrophysical neutrinos

Radio Array: 100-300 km^2 for extremely high energies ($\geq 10^{18}$ eV)

Surface Veto: Air showerdetector with 75 km^2 / 100 TeV threshold

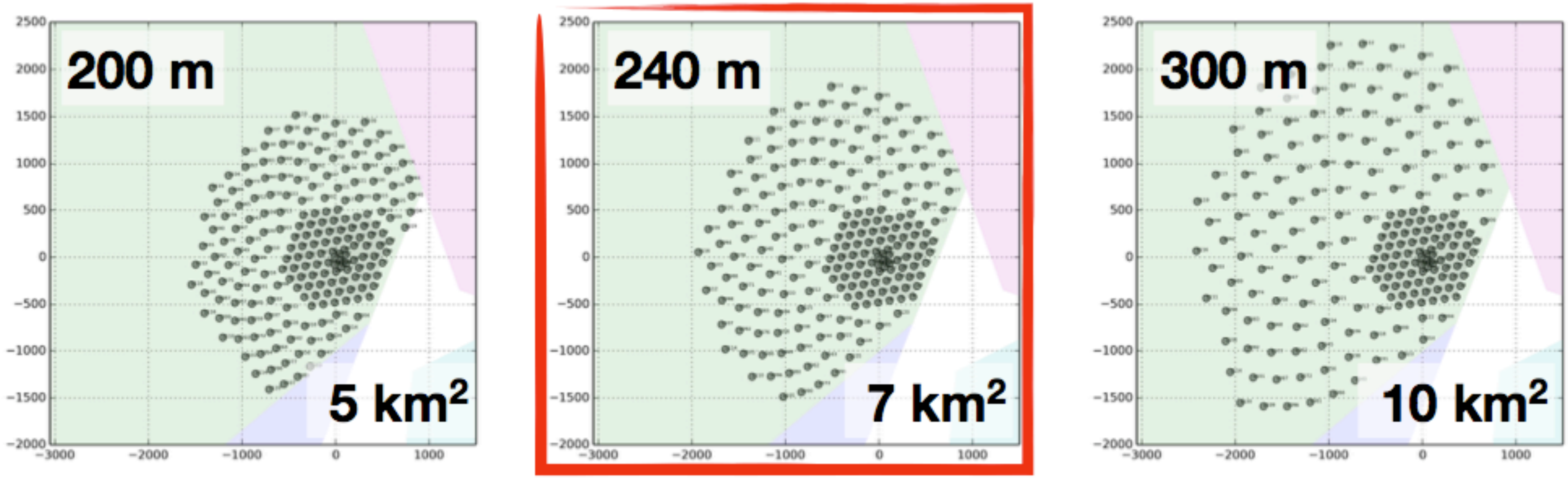


White paper:submitted in Dec. 2014 [arxiv.org:1412.5106]

RICAP 2016 Juan A. Aguilar

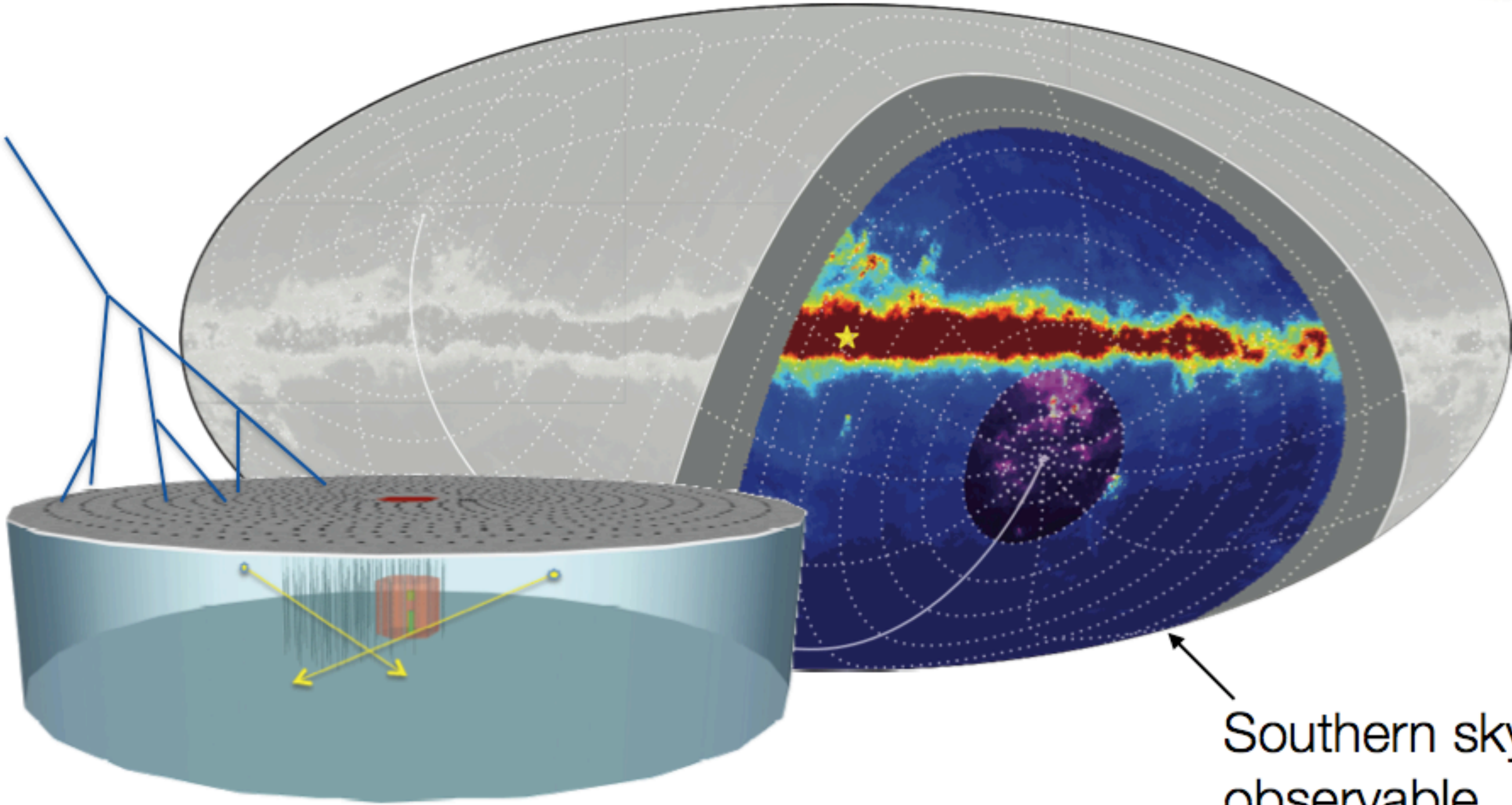
IceCube Gen2

- Several layouts under evaluation
- Example: “Sunflower” geometry with different string spacings



- ~120 new strings, 80 DOMs per string, instrumented over 1.25 km
- ~10 x IC volume for contained event analysis above 200 TeV

a unique facility: vetoing downgoing events

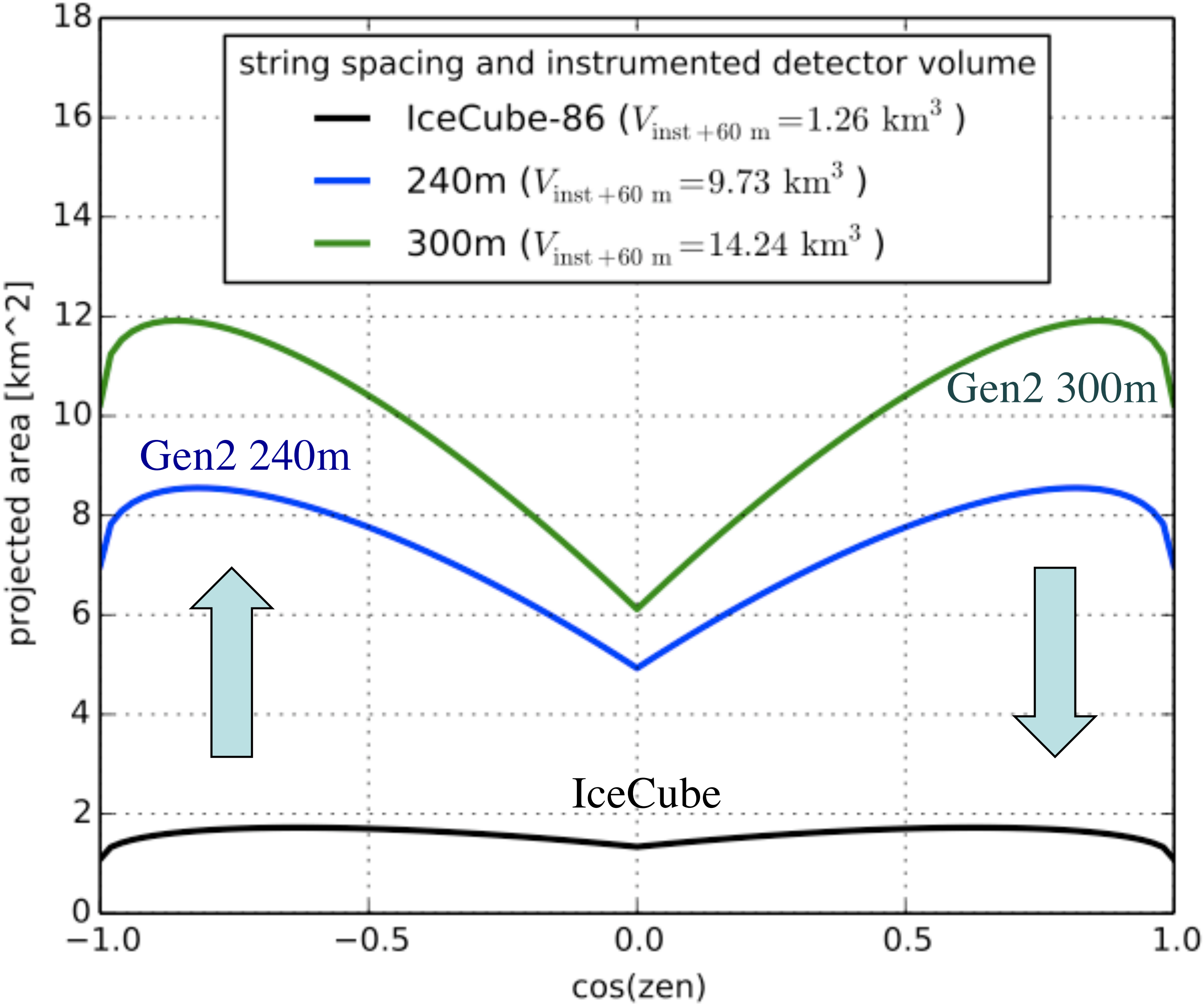


Potential gain for e.g. 75 km^2 veto:

~2x number of PeV tracks

~2x precision in spectral index

IceCube Gen2 – instrumented area/volume



IceCube Gen2 – expected event rates

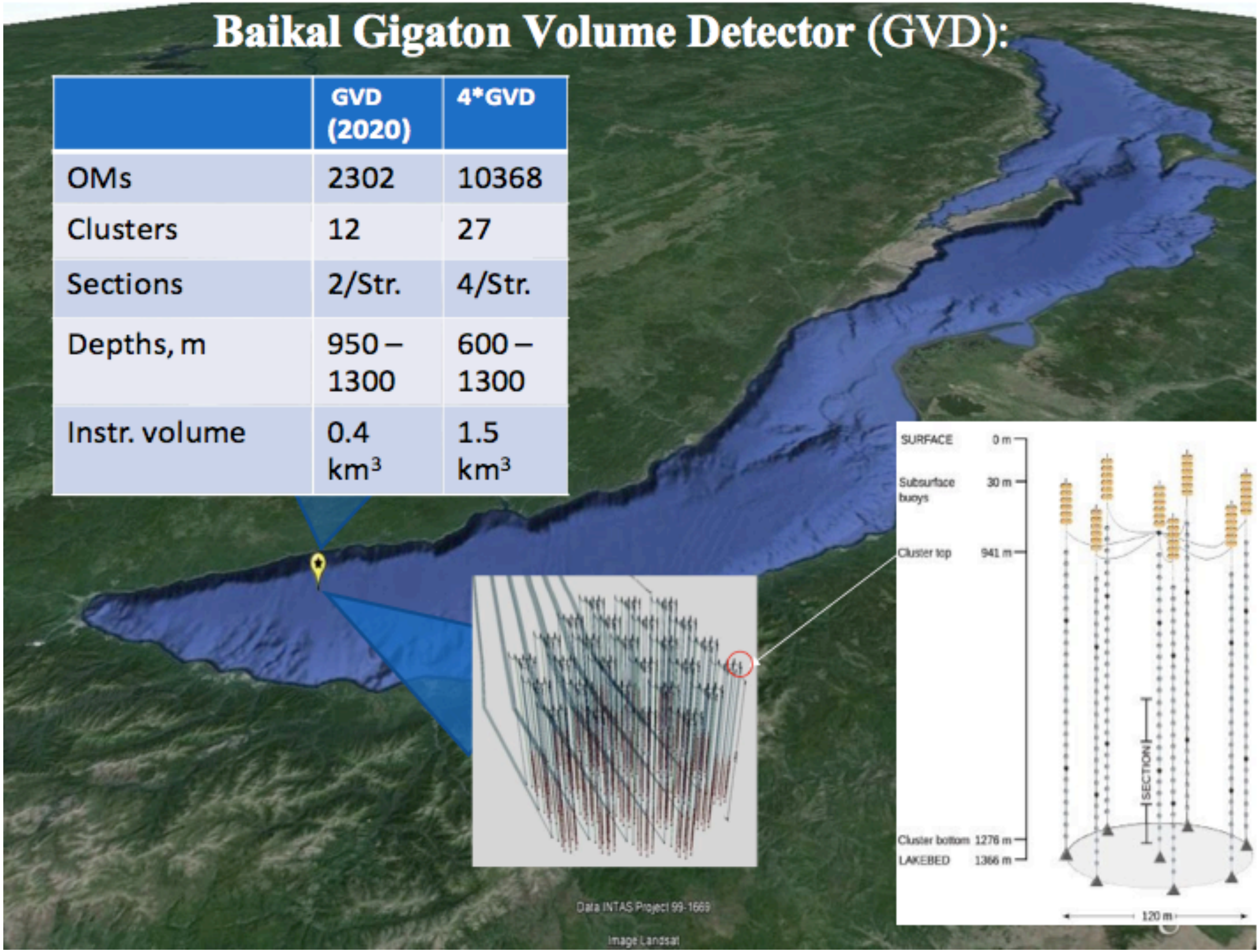
Event type	10–100 TeV	100–1000 TeV	1–10 PeV	>10 PeV
Contained cascades	0 (2.6)	**20** (4.4)	**15** (1.6)	**2** (0.2)
Surface vetoed muons	0 (0)	**9.7** (0.06)	**4.8** (0.051)	**1.2** (0.014)
Upgoing muons	**100** (37)	**55** (16)	**11** (3.2)	**1.6** (0.47)

Number of neutrinos per year in **Gen2** (IceCube), assuming $E^2\Phi_\nu = 0.95\times10^{-18} (E\nu/100\ \mathrm{TeV})^{-0.13}\ \mathrm{GeV\ cm^{-2}\ sr^{-1}\ s^{-1}}$ per flavor

The Baikal – GVD project

Baikal Gigaton Volume Detector (GVD):

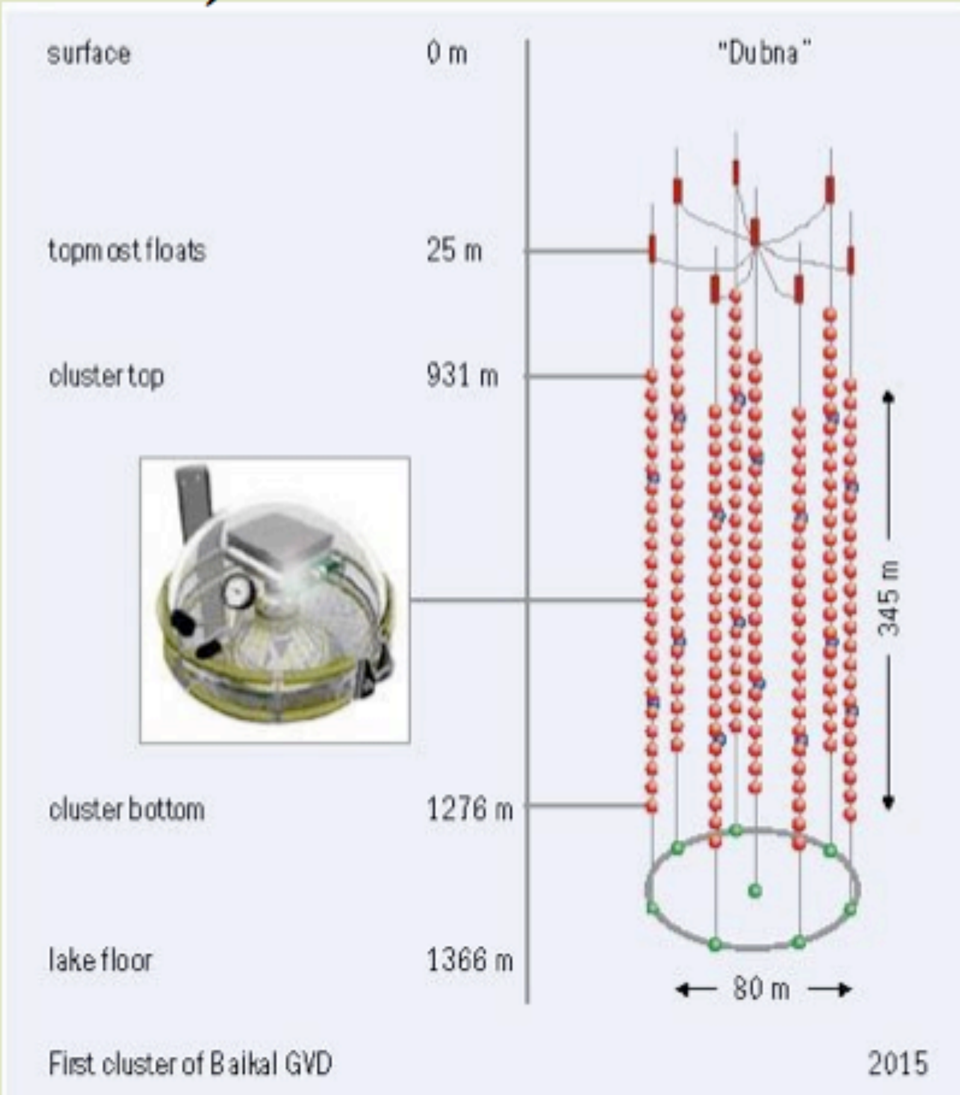
	GVD (2020)	4*GVD
OMs	2302	10368
Clusters	12	27
Sections	2/Str.	4/Str.
Depths, m	950 – 1300	600 – 1300
Instr. volume	0.4 km³	1.5 km³



The Baikal – GVD project, the prototype

First Demonstration Cluster "DUBNA" (April 2015)

- 192 OMs at 8 Strings 2×12 OMs per String.
- Acoustic Positioning System
- Instrumentation String for environment monitoring
- LED beacon for inter-string time calibration

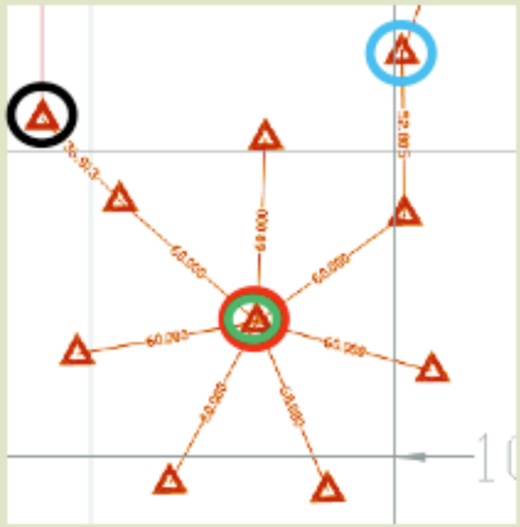


Active depth 950 – 1300 m
Instrumented volume 1.7 Mt

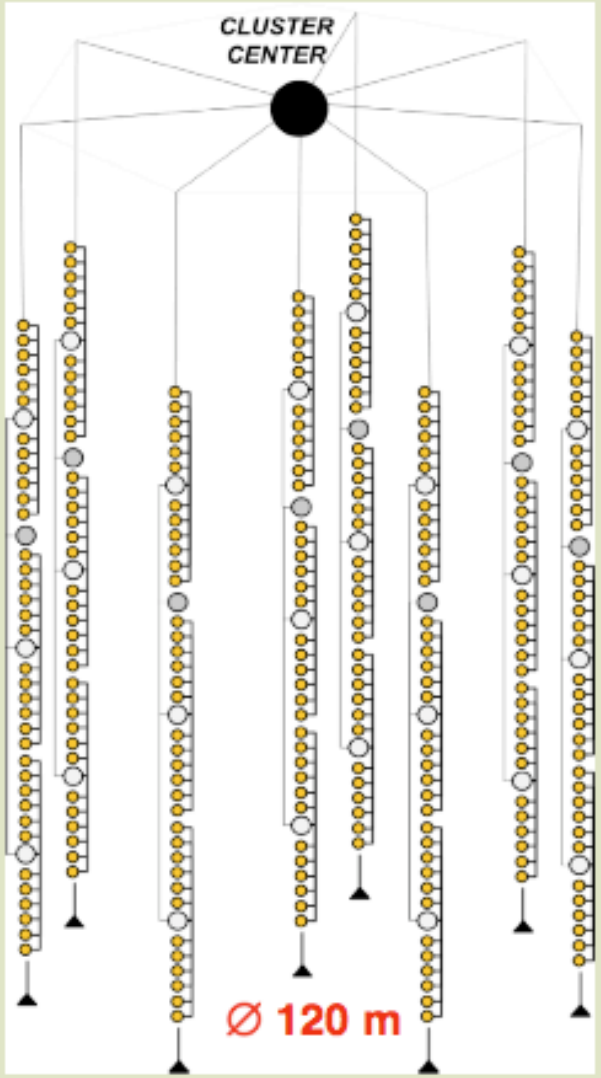
Vladimir Aynutdinov

The Baikal – GVD, improved detector

Upgraded cluster "DUBNA"



- DAQ center
- Instrumentation string
- Cable Buoy Station

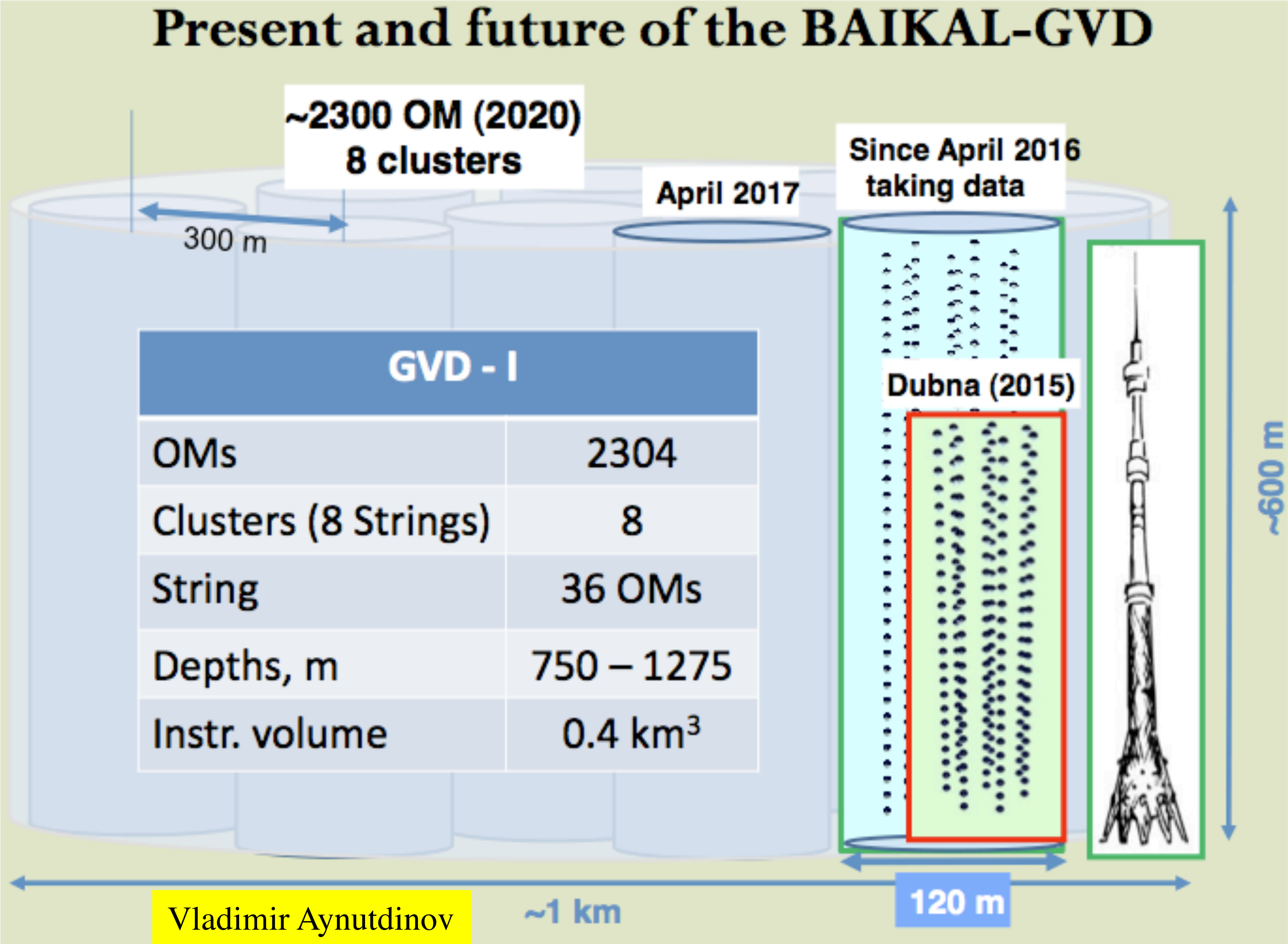


- 288 OMs at 8 Strings 3×12 OMs per String.
- Acoustic Positioning System on each string.
- 4 LED beacons for inter-string calibration.
- Instrumentation String for environment monitoring.

Active depth 750 – 1275 m
Instrumented volume 6.0 Mt

Vladimir Aynutdinov

The Baikal – GVD, next steps



GVD - I	
OMs	2304
Clusters (8 Strings)	8
String	36 OMs
Depths, m	750 – 1275
Instr. volume	0.4 km^3

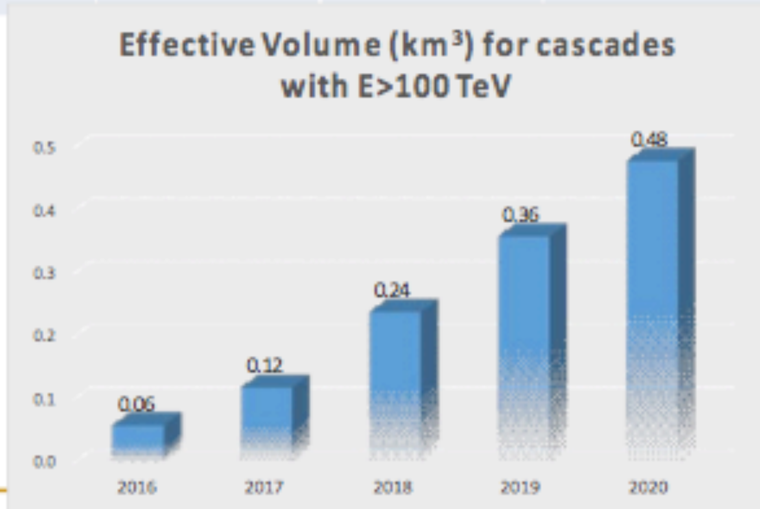
The Baikal – GVD, time schedule

Baikal-GVD

The GVD-1 timeline

Cumulative number of clusters vs year

Year	2015	2016	2017	2018	2019	2020
Cluster 192 OM	***1*** ***192***	***1*** ***192***	***3*** ***576***	***5*** ***960***	***7*** ***1344***	***10*** ***1920***
Cluster-288 OM	***2/3*** ***192***	***1*** ***288***	***2*** ***576***	***4*** ***1152***	***6*** ***1728***	***8*** ***2304***

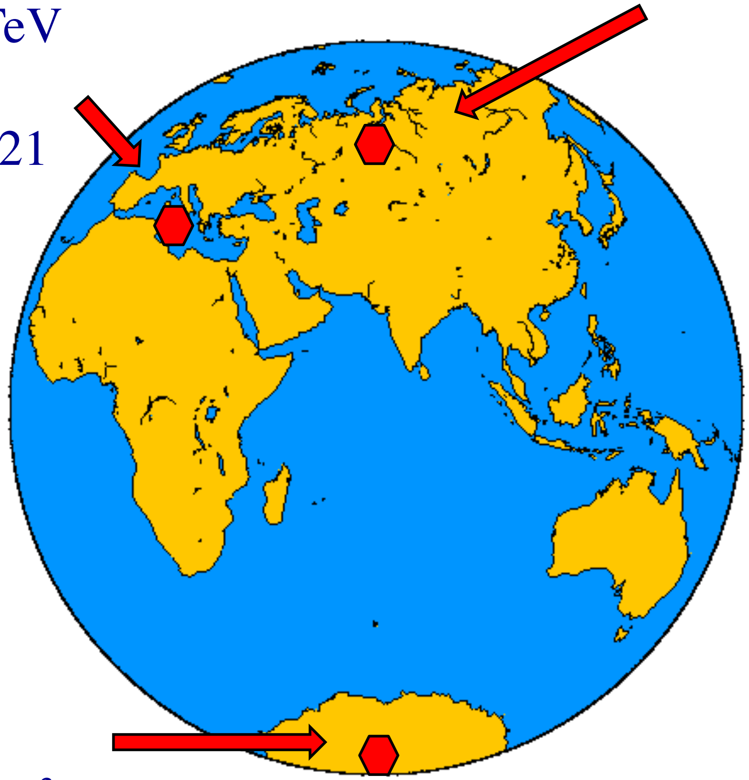


Olga Suvorova – RICAP 2016

The global approach to neutrino Telescopes

ARCA
optimized ~1.4 km^3 → >1 TeV
(4-5 km^3)
construction 2015(18) – 2021
Deep – Sea water
high angular resolution
depth 2.7 – 3.3 km
no veto available

GVD
optimized ~0.4 km^3 → >10 TeV
(1.5 km^3)
construction 2015 – 2021
Lake fresh water
good angular resolution
depth 0.7 – 1.2 km
no veto available



IceCube-Gen2
optimized ~ 1 km^3 → >1 TeV
~ 10 km^3 → > 30 TeV
Operating 2021 – 2031
Ice (scattering, medium homogeneity, …)
Moderate angular resolution
Depth 1.4 – 2.7 km
Surface Veto !!!

from a collection of C.Spiering slides at MANTS-2016