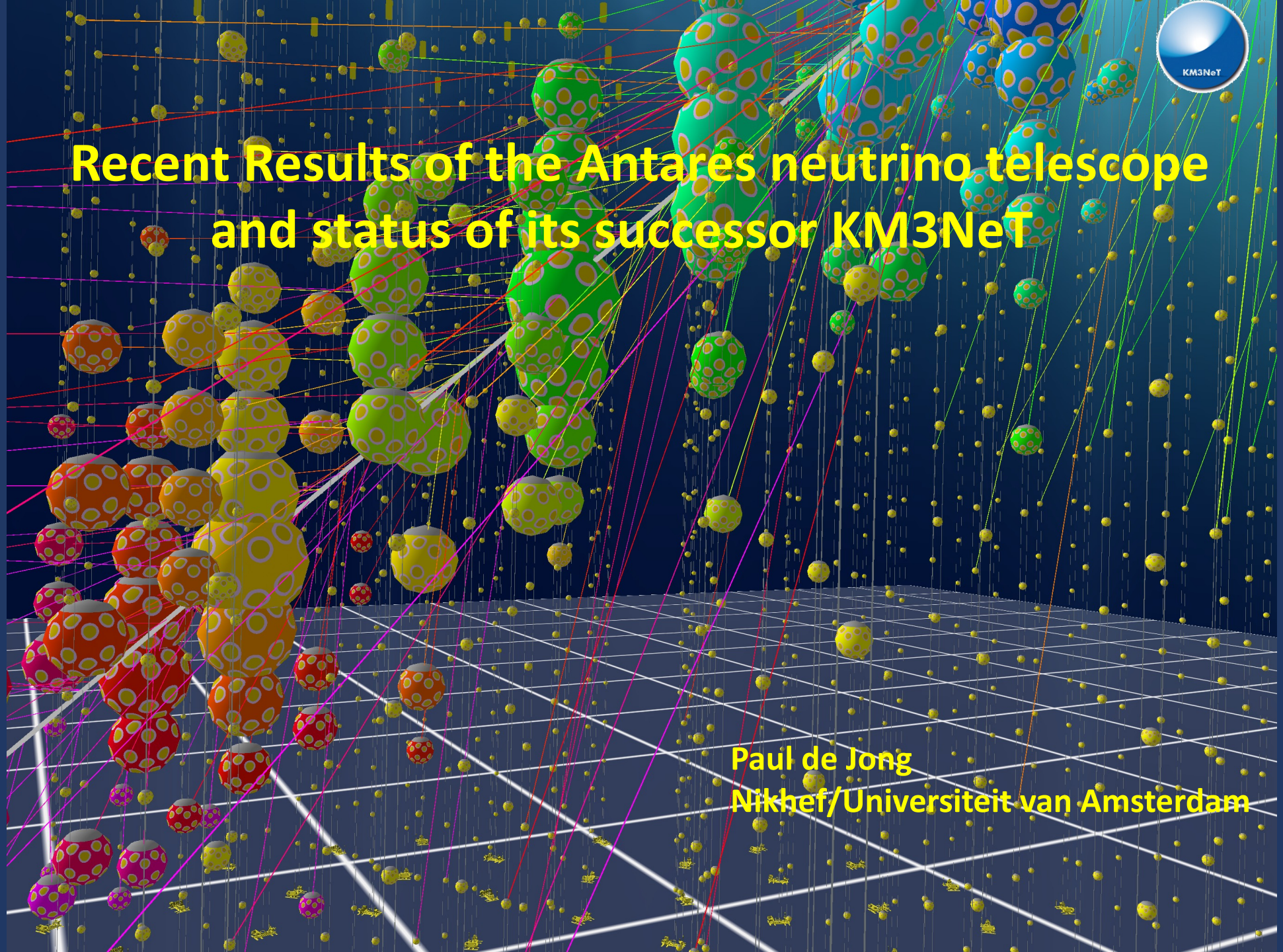
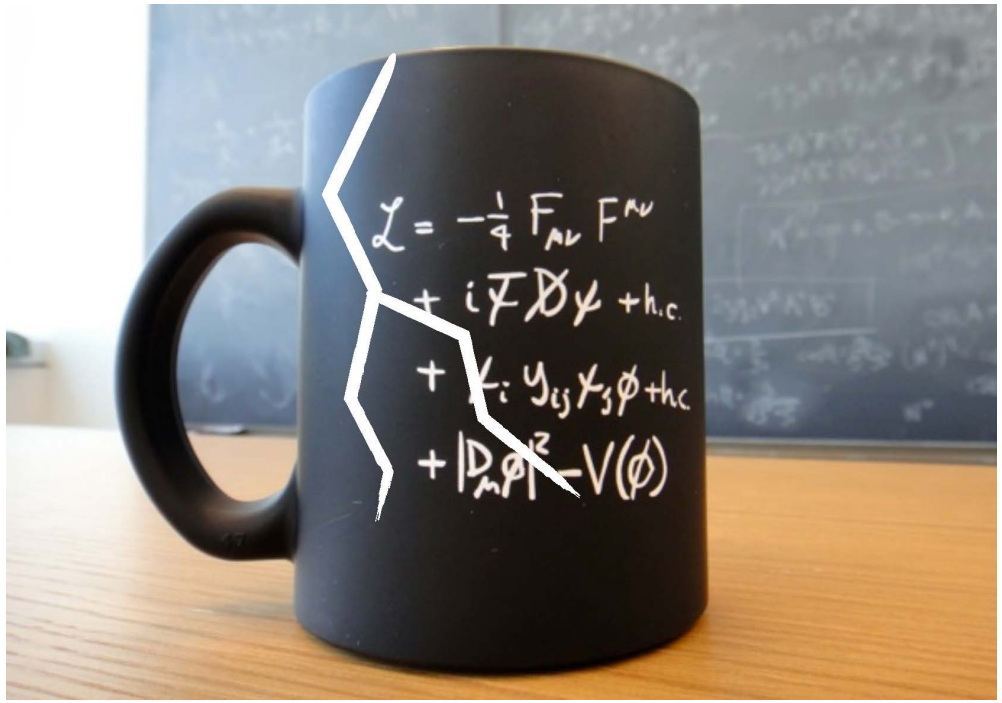


Recent Results of the Antares neutrino telescope and status of its successor KM3NeT

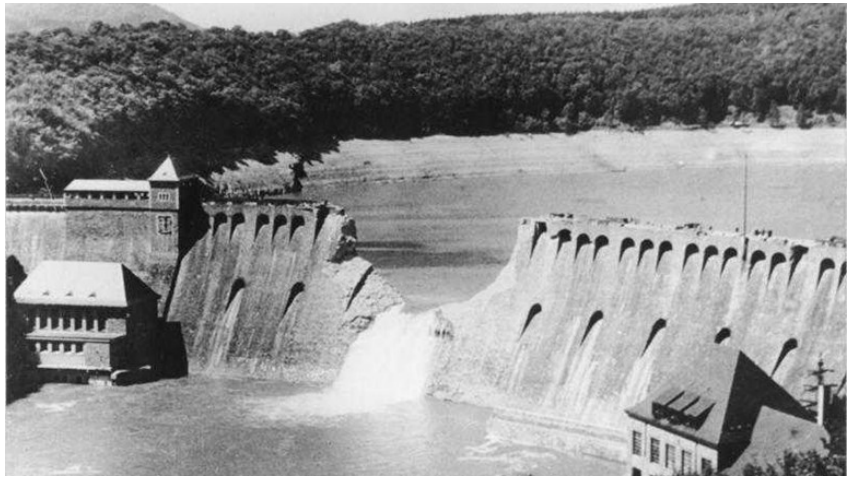
Paul de Jong
Nikhef/Universiteit van Amsterdam

In order for particle physics to advance, we need to identify the cracks in the Standard Model



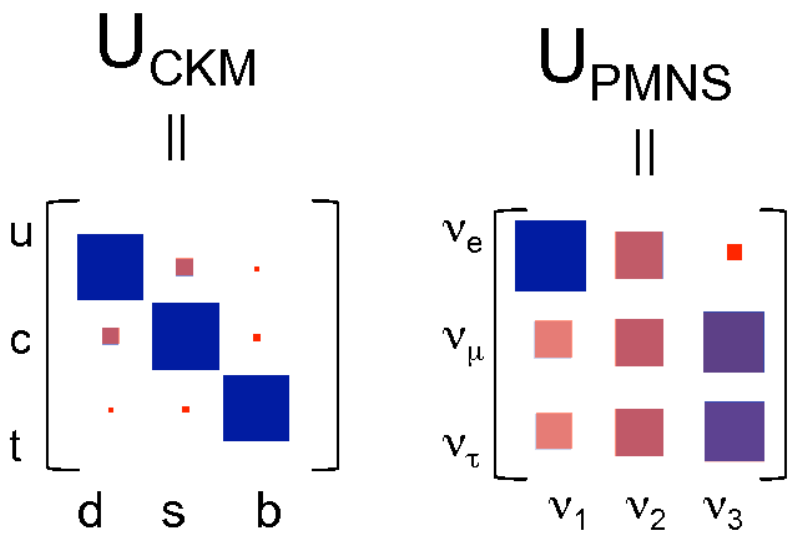
Many complementary approaches:

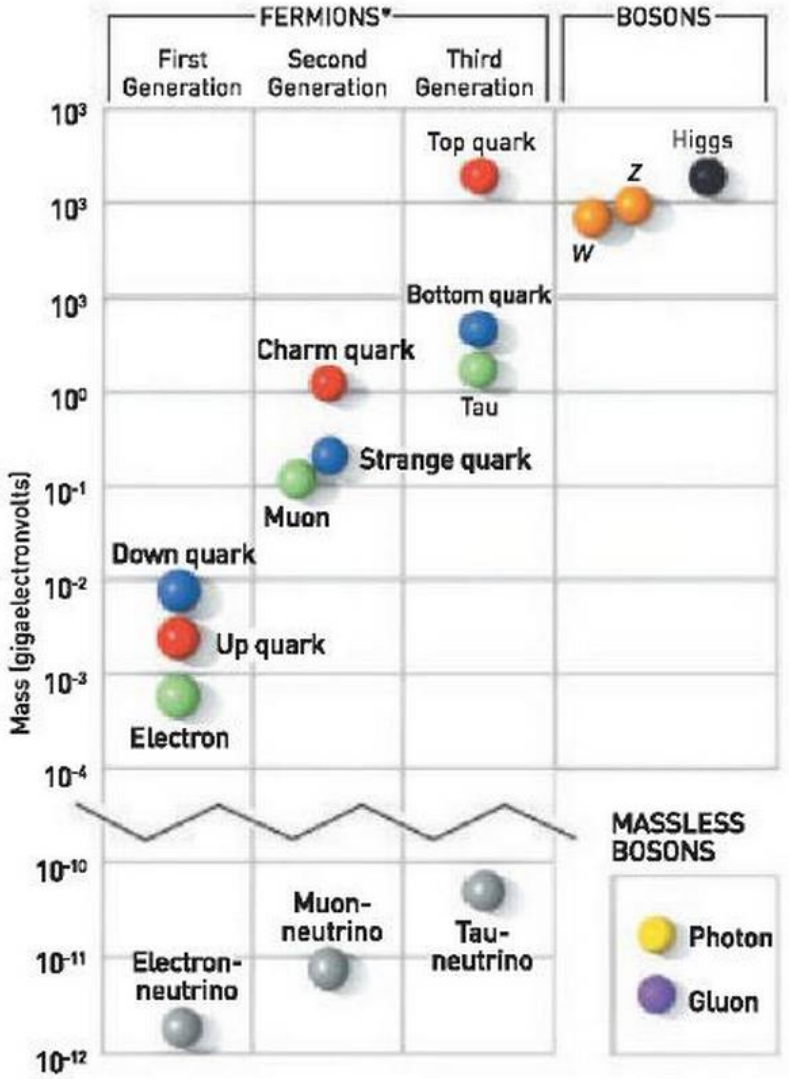
- Energy frontier: LHC and beyond
- Intensity frontier: rare decays, EDMs, etc.
- Cosmic frontier: dark matter, ΛCDM, etc.
- Neutrinos



Neutrinos:

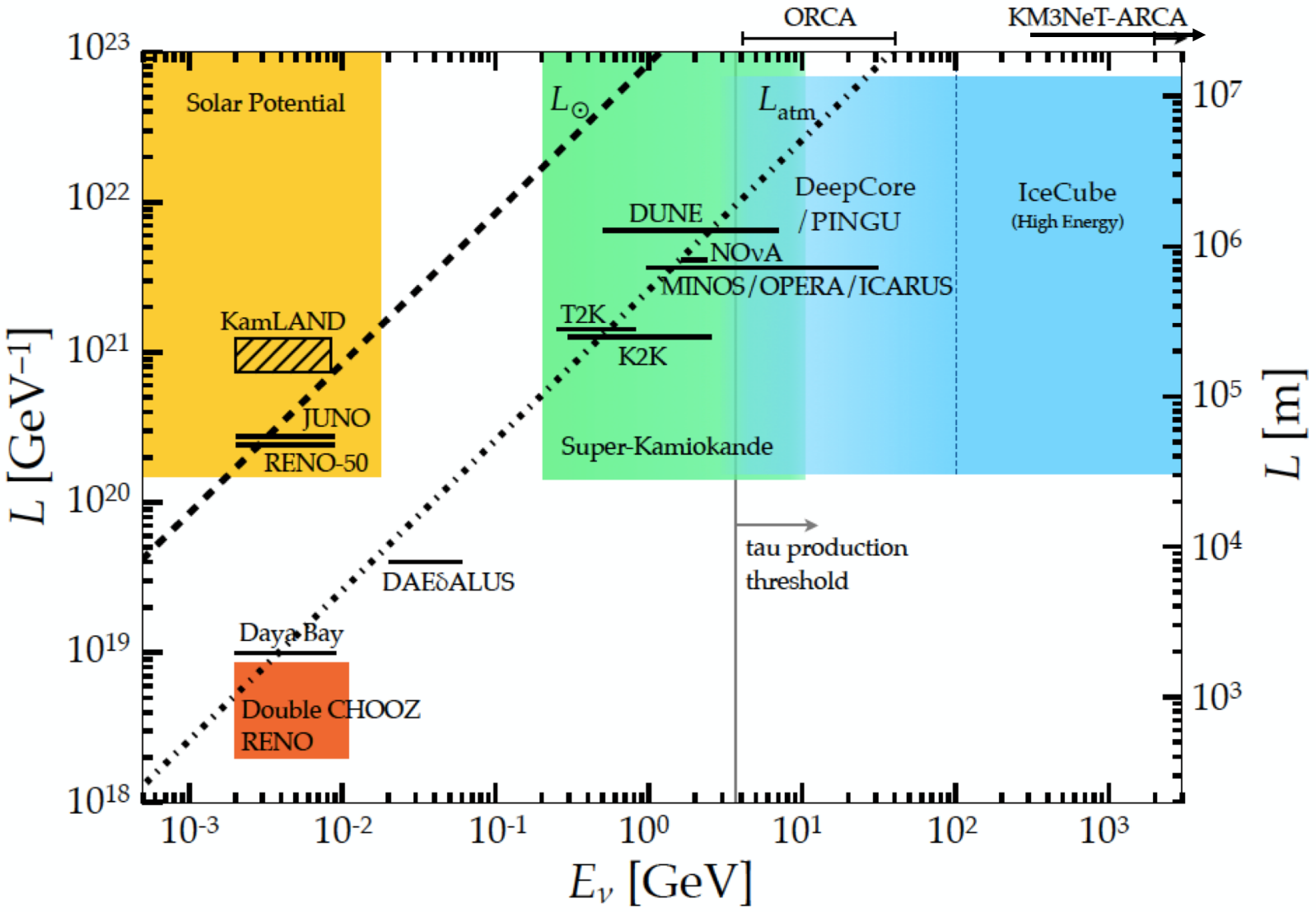
- Only left-handed, ν_R absent or sterile: P violation
- Masses remarkably small
- Possibly Majorana: new mass generation mechanism
- Flavor mixing: pattern unlike quarks
- Evidence for CP-violation: leptogenesis?
- Sterile: dark matter candidate





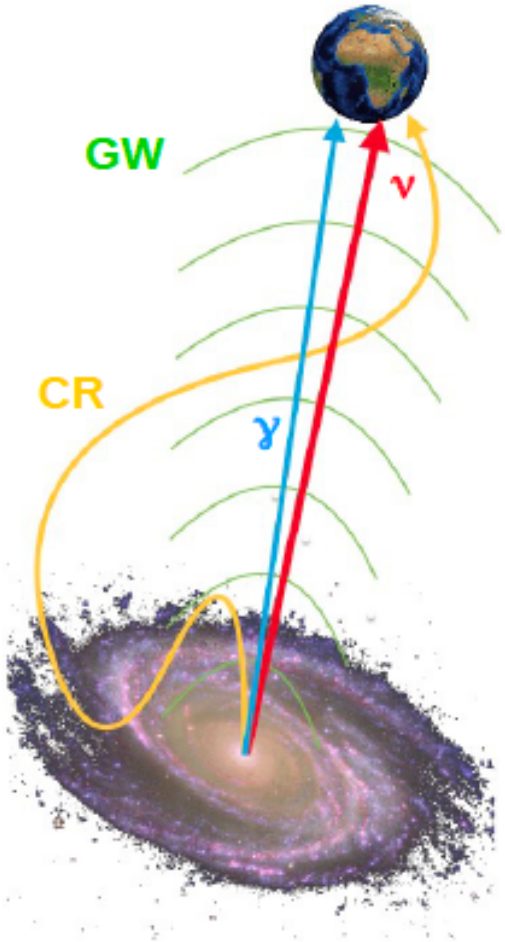
Neutrino oscillations: baselines and energies

Neutrino telescopes can do oscillation physics

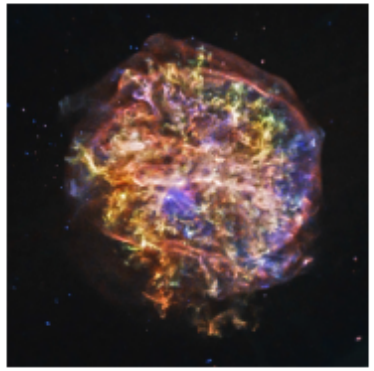


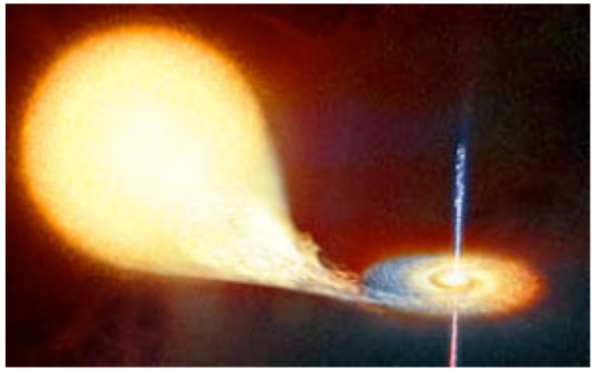
earth

Astrophysical neutrinos



Galactic:
Supernova Remnants (SNRs), Microquasars,...

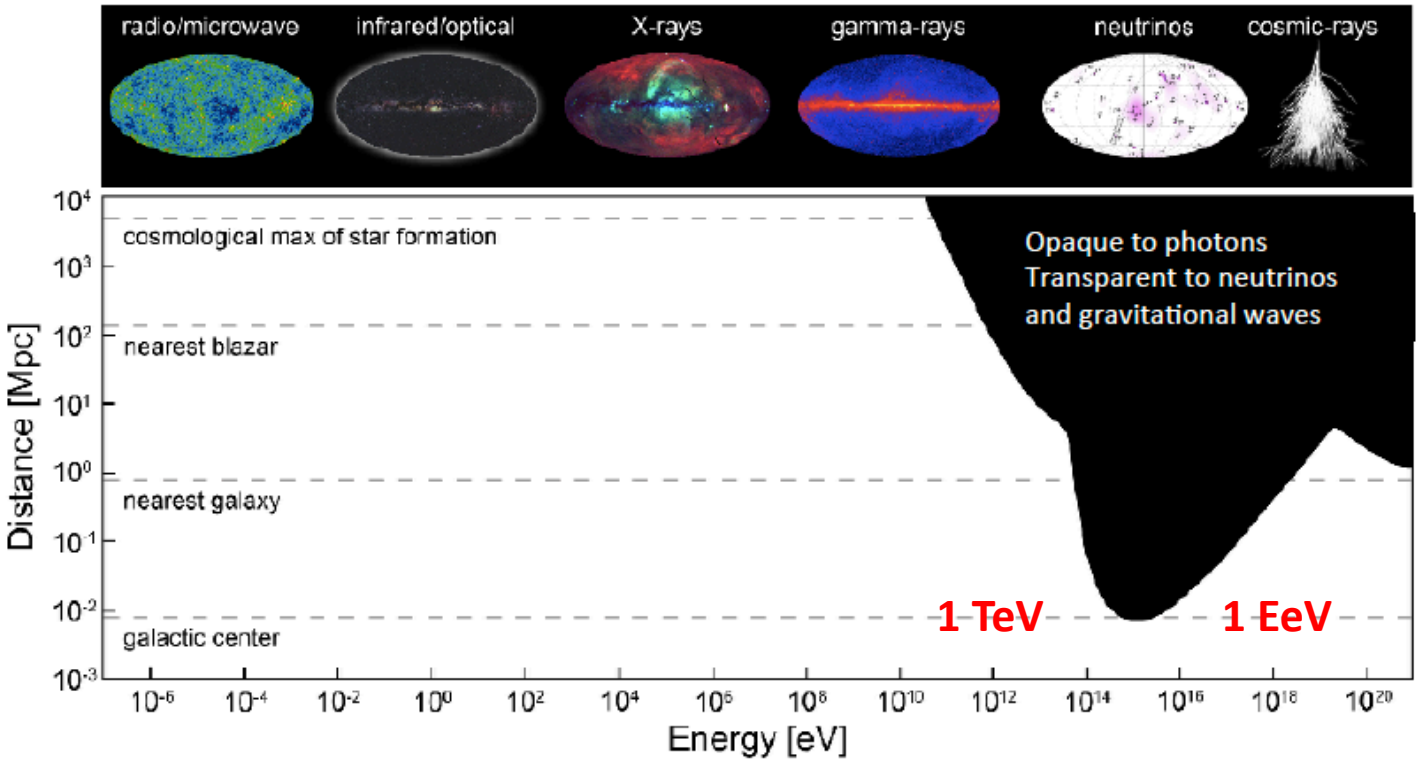




Extragalactic:
Active Galactic Nuclei (AGNs),
Gamma Ray Bursts (GRBs), ...

Messengers of the most violent processes in the Universe, in which fundamental physics is put to stress

Astrophysical neutrinos



Related to gamma ray flux:

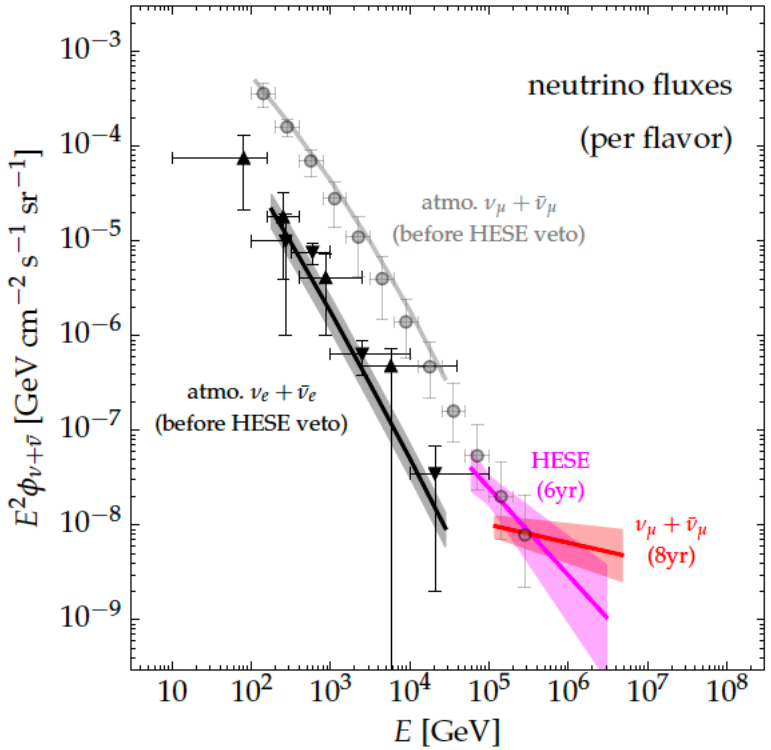
$$p+\gamma \rightarrow \Delta^{+} \begin{cases} \rightarrow p+\pi^{0} \\ \rightarrow n+\pi^{+} \end{cases}$$

$\pi^{0} \rightarrow \gamma\gamma$ ⟸ Observable as TeV photons

$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$

$\mu^{+} \rightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$

⟸ High energy neutrinos



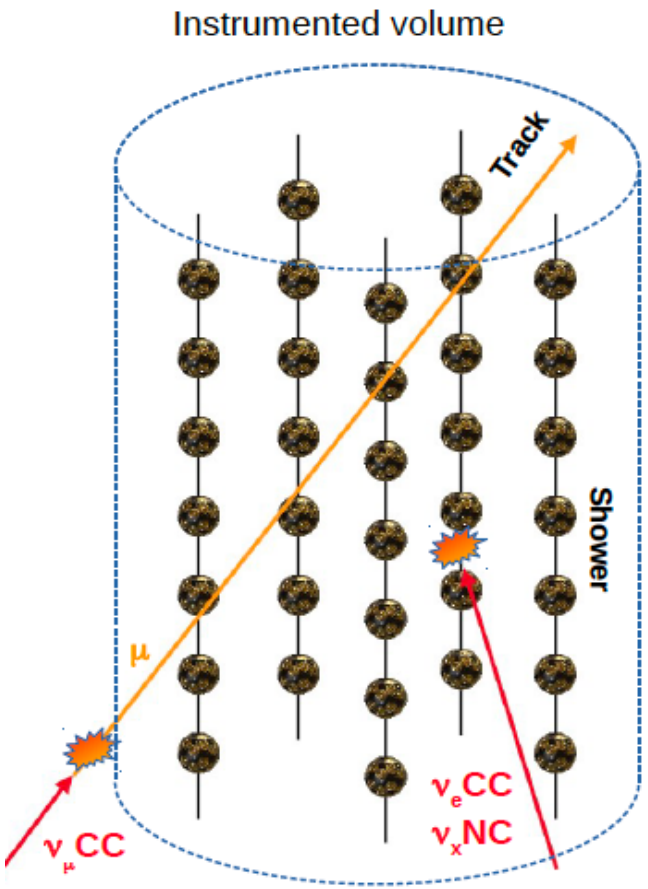
But low interaction rates:
huge detectors needed

2013++ : IceCube detects cosmic neutrinos
(excess of high energy neutrinos)

2018: IceCube announces discovery of first cosmic high energy neutrino source

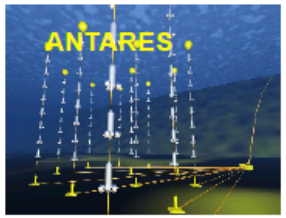
=> For the first time multimessenger observations including neutrinos!

Neutrino telescopes

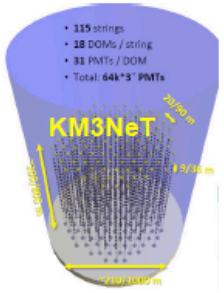


Deep sea or ice

Running since 2007

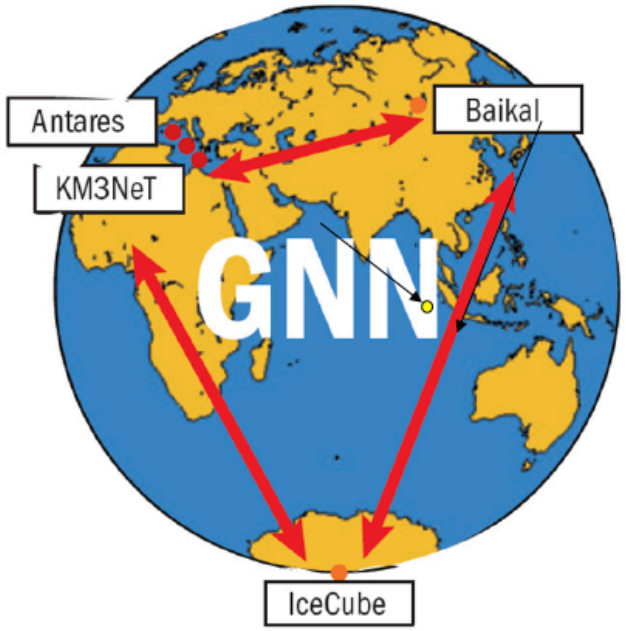


0.01 km^3

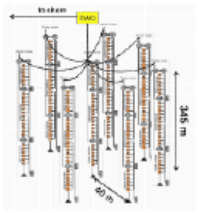


1 + 0.008 km^3

GNN
The Global Neutrino Network



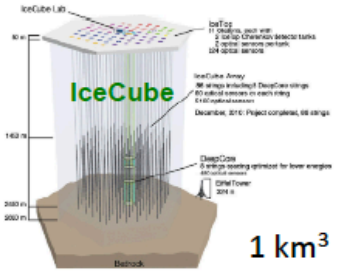
GVD (Baikal)



1 km^3

3 of 8 clusters installed
2015-2018
(to be finished 2021)

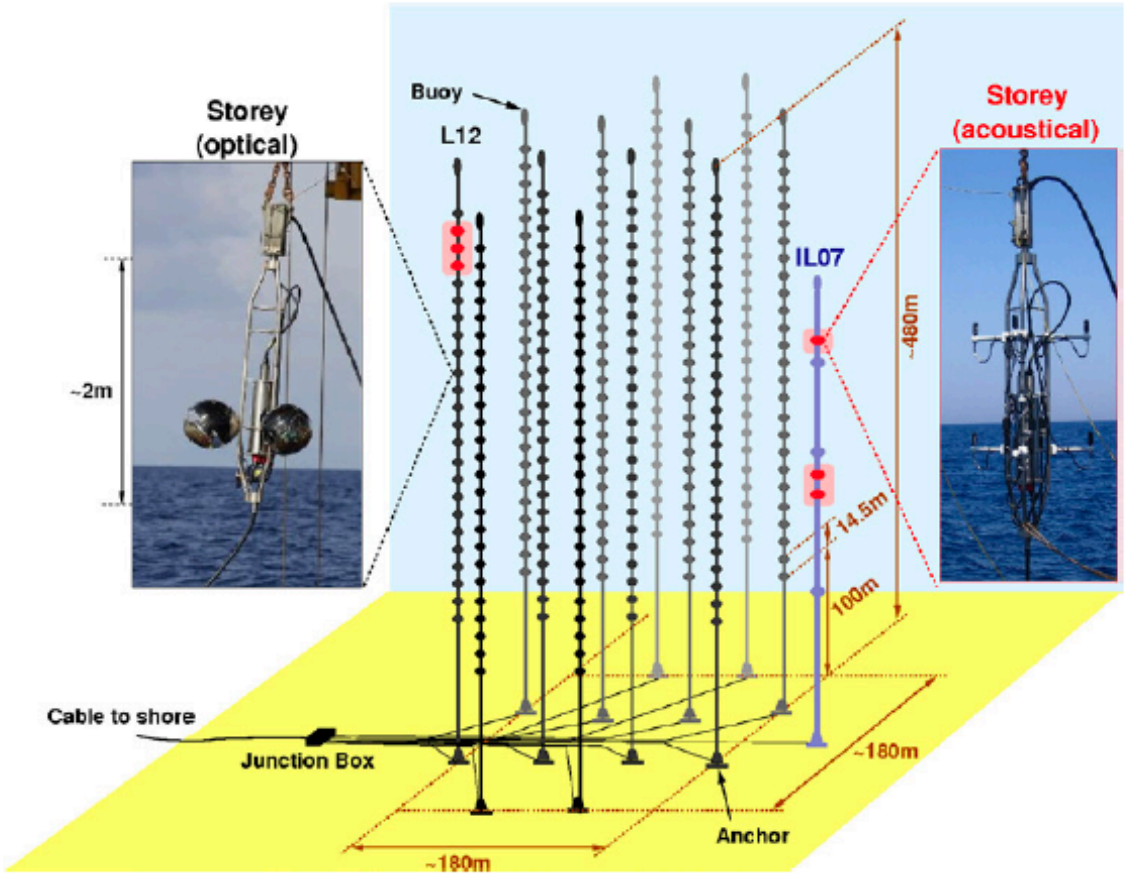
Running since 2009

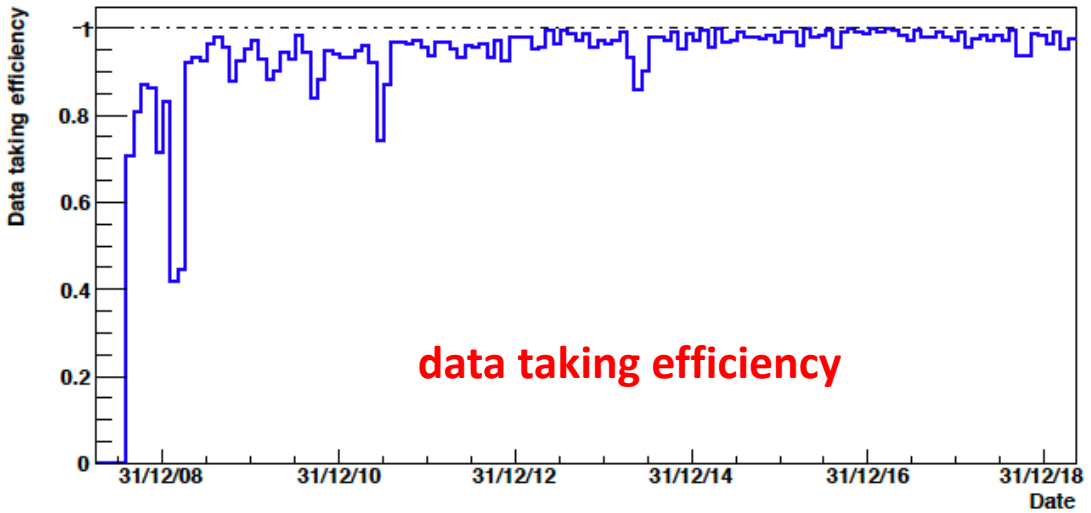


1 km^3

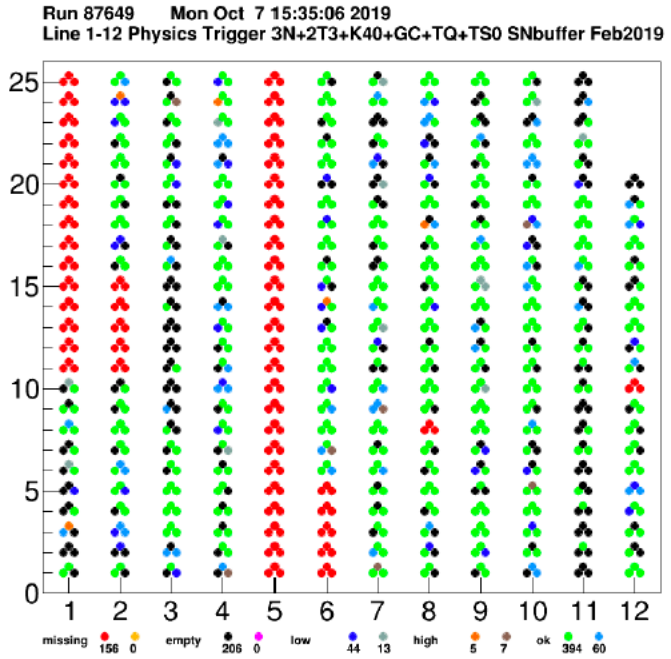
Antares

40 km south of Toulon, 2475 m depth





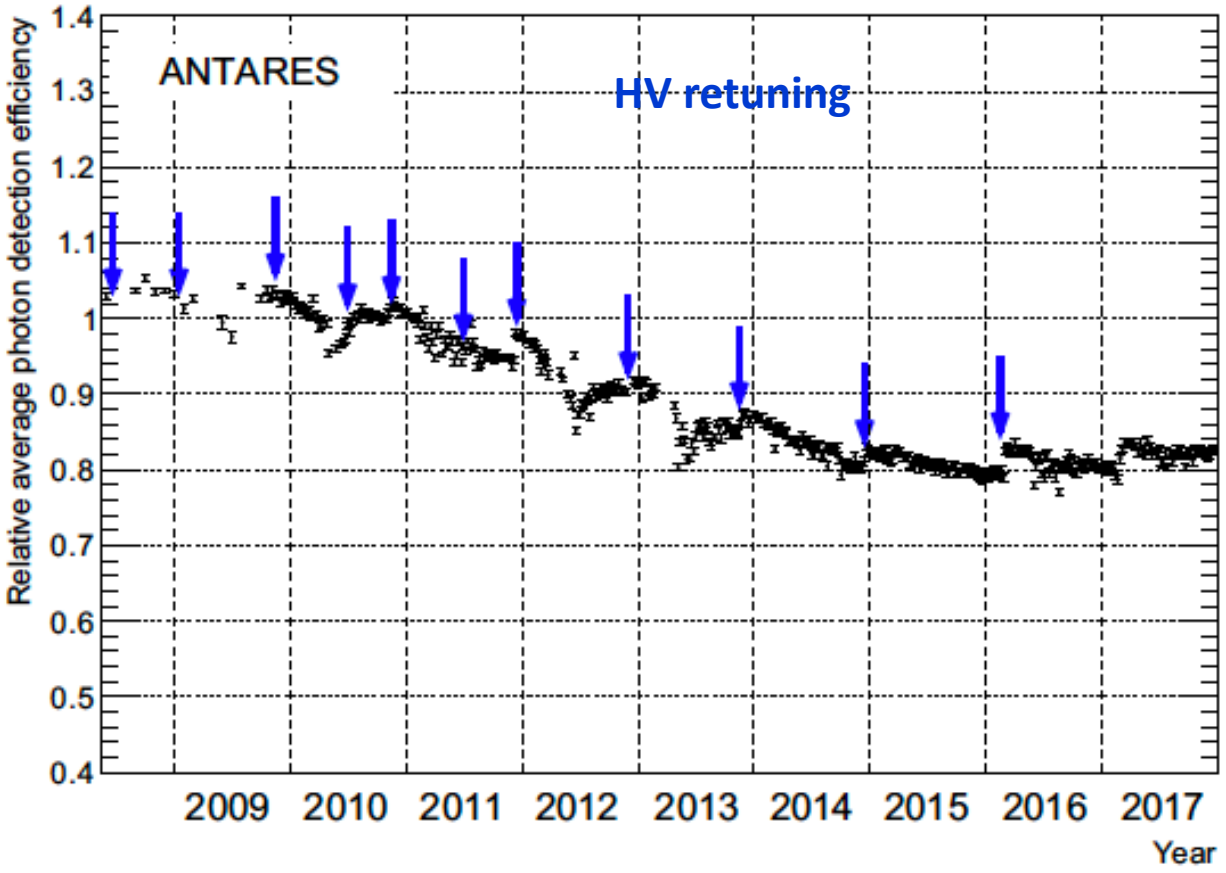
data taking efficiency

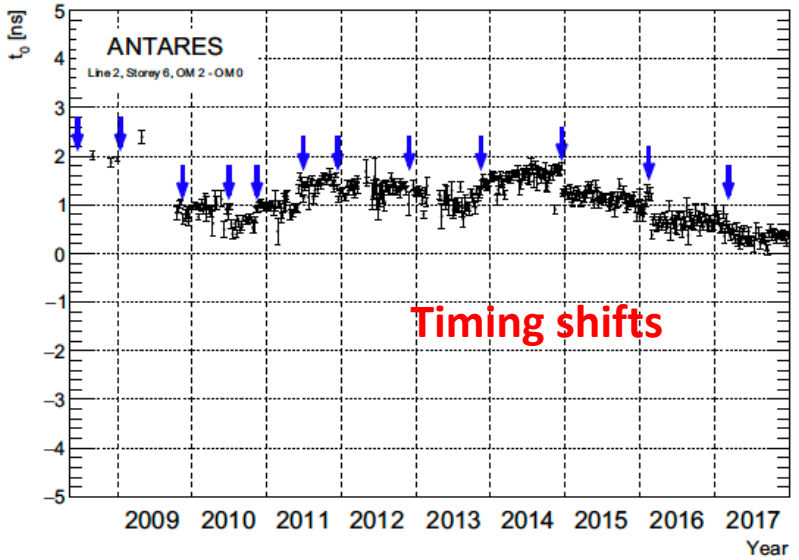


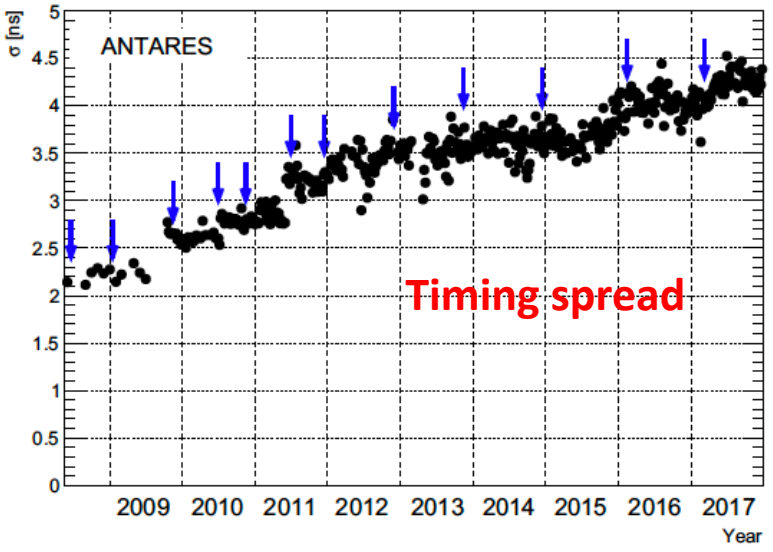
configuration

Antares

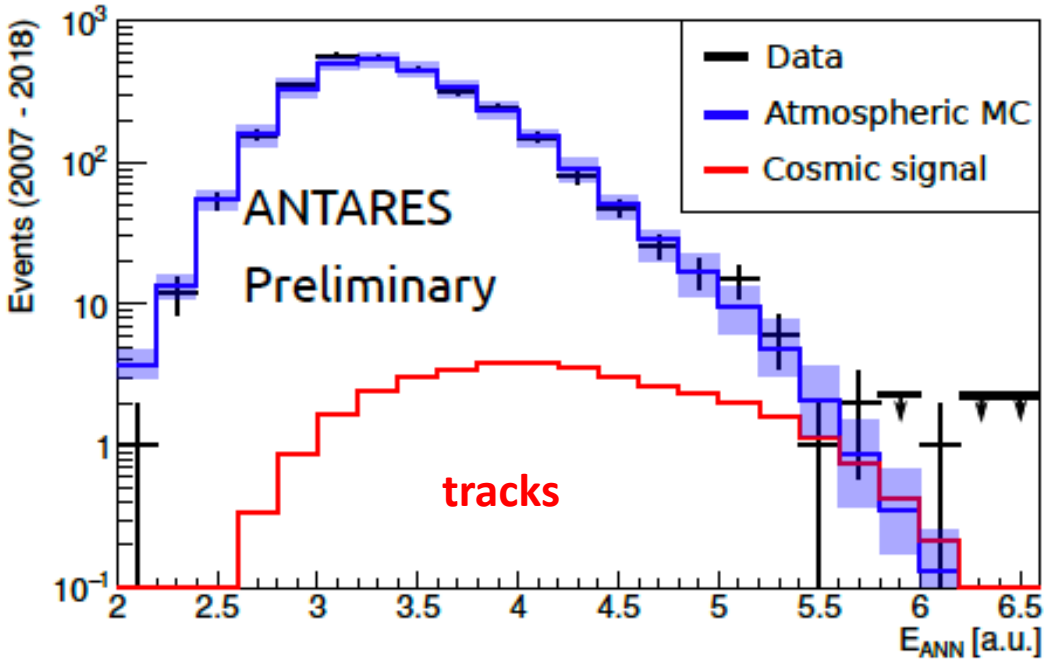
Photon detection efficiency

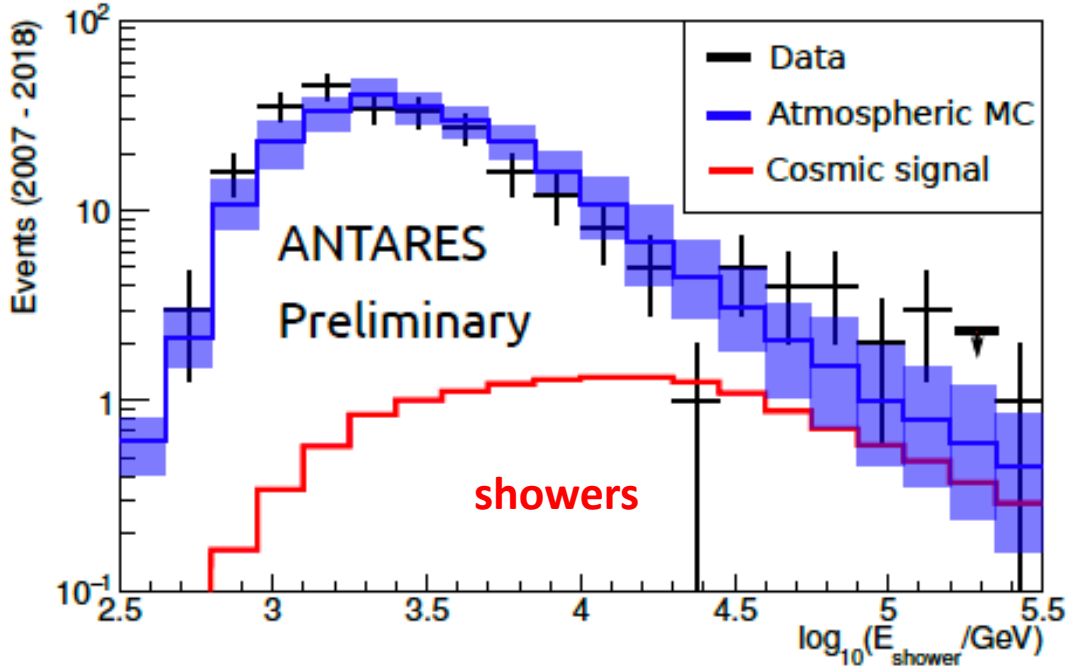






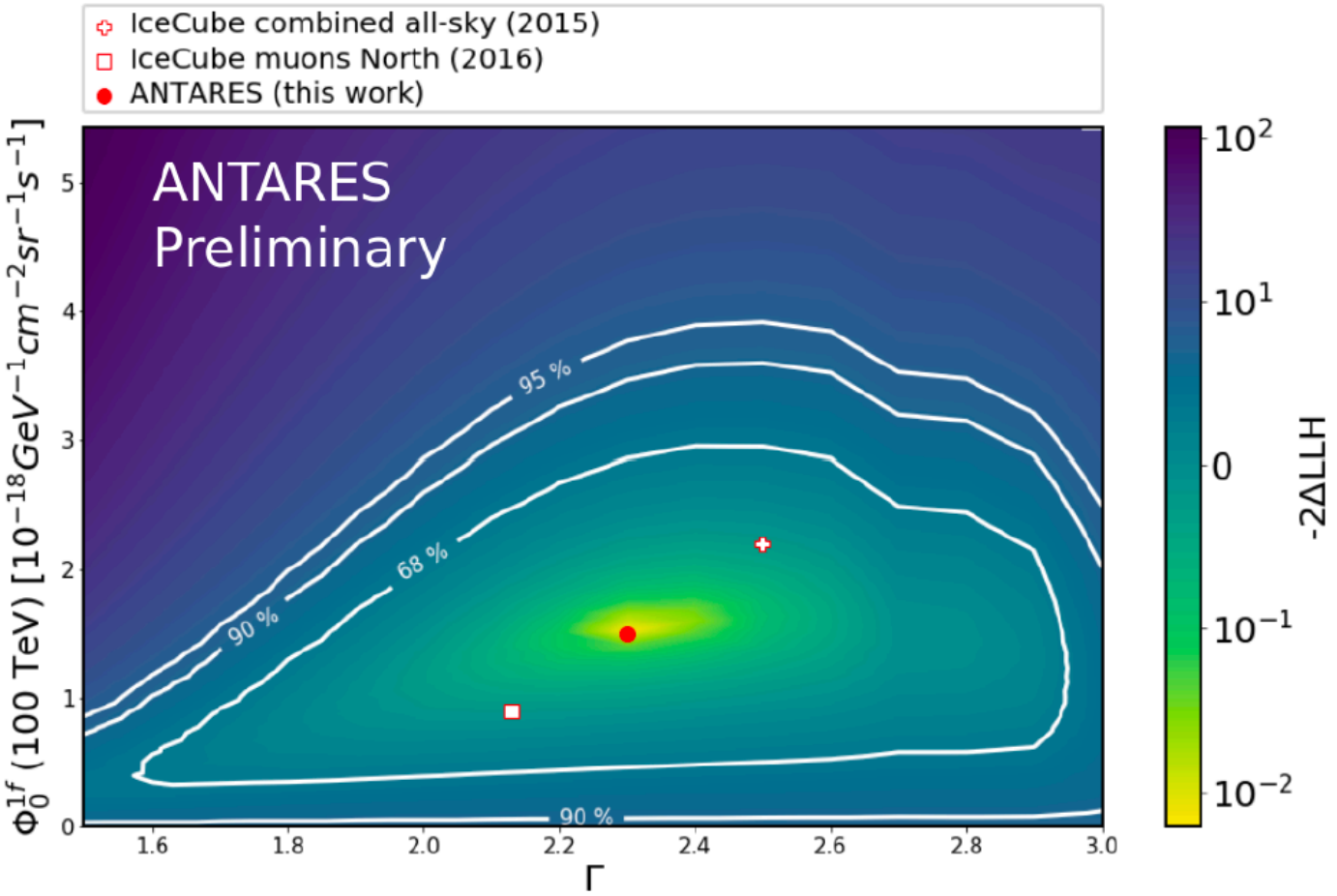
Diffuse cosmic neutrino flux





Data corresponding to 3330 days, 2007-2018

Diffuse cosmic neutrino flux



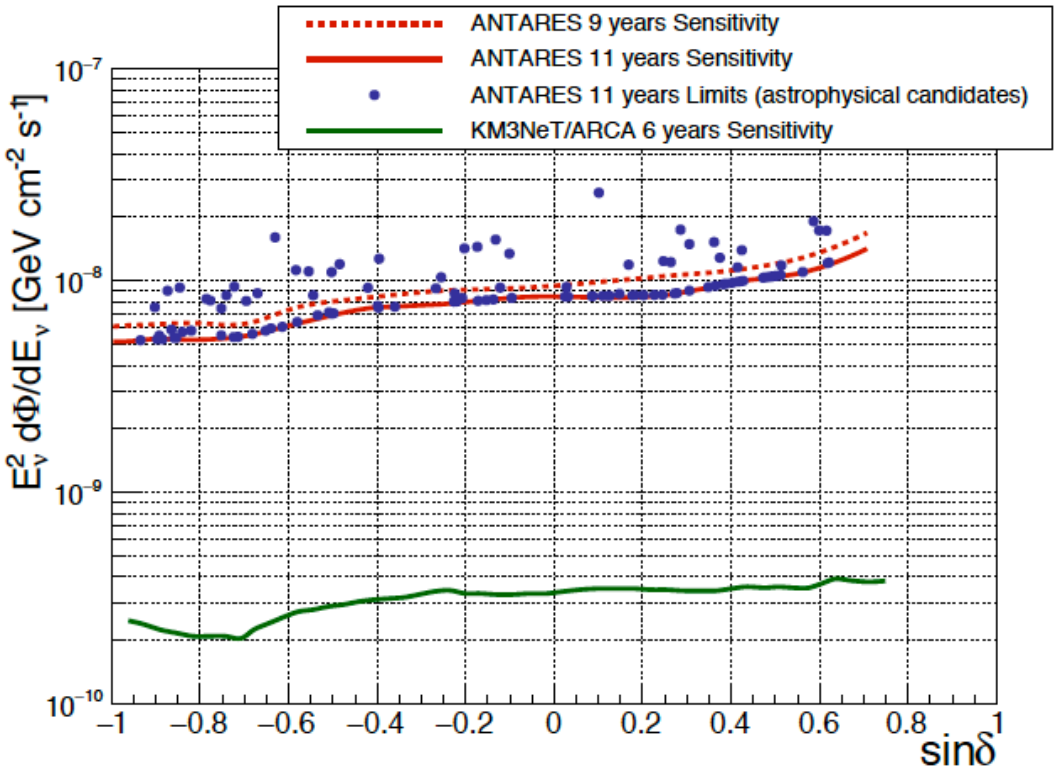
Null hypothesis excluded at 1.8σ

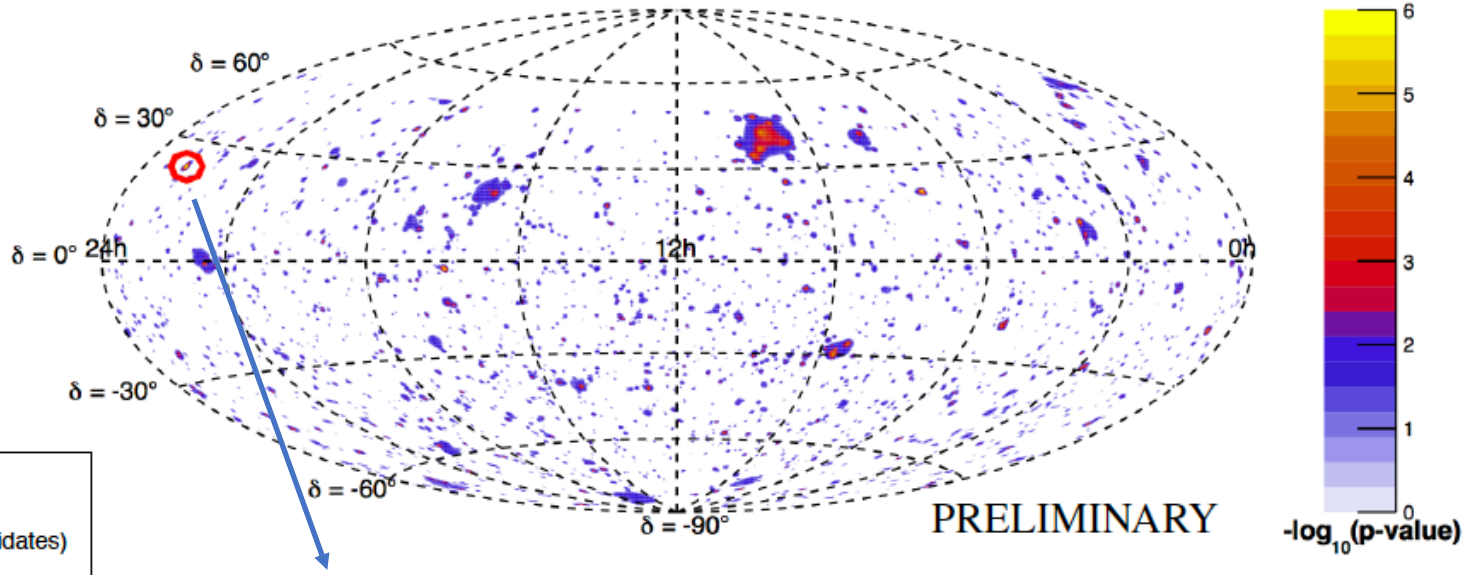
$$\Phi_0(100\,\mathrm{TeV}) = (1.5 \pm 1.0) \times 10^{-18}\ [\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}]$$

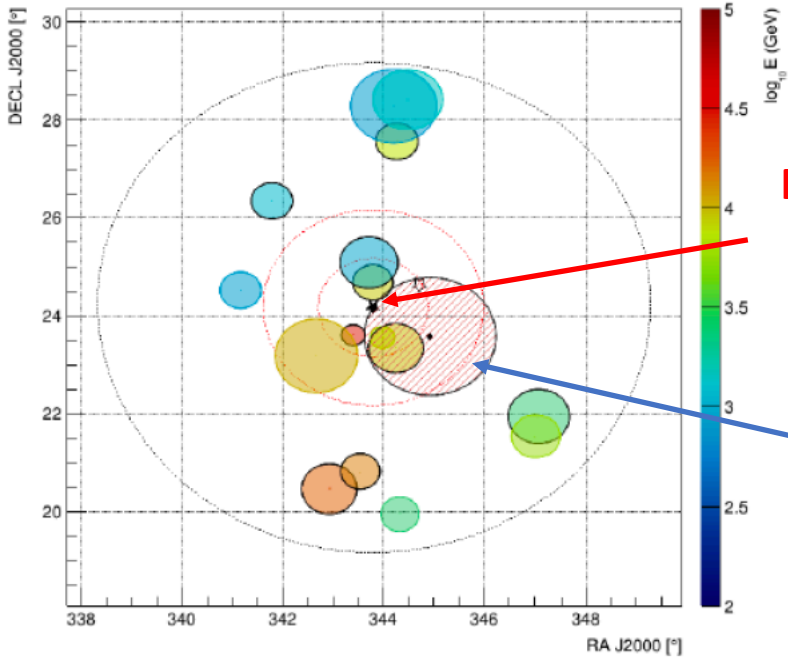
$$\Gamma = 2.3^{+0.4}_{-0.4}$$

Antares point source search

11 years of data





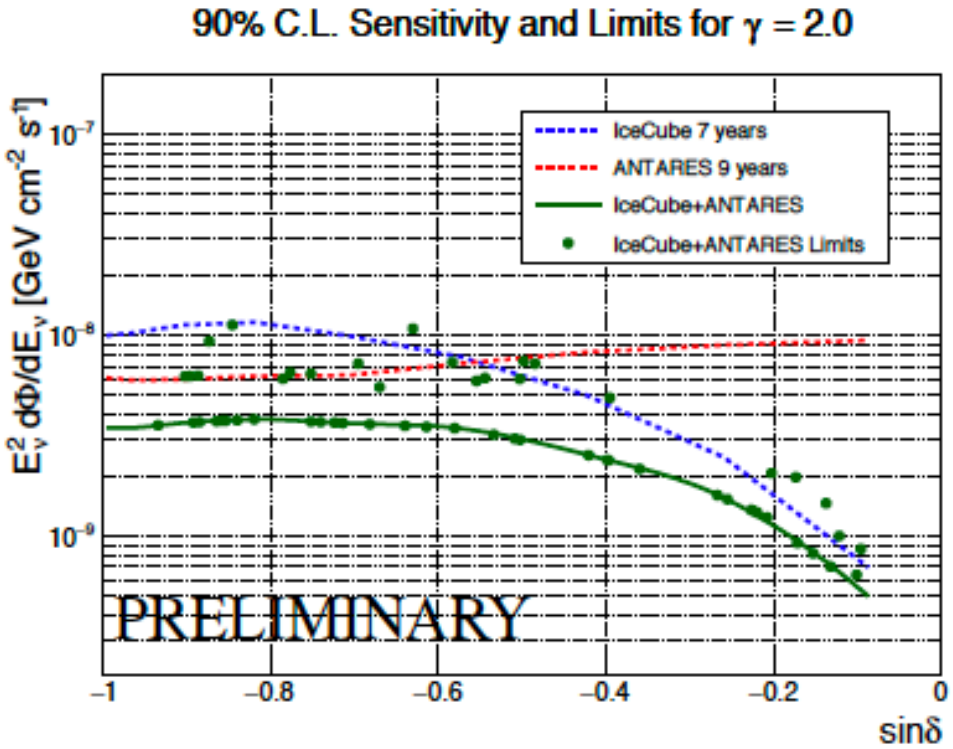


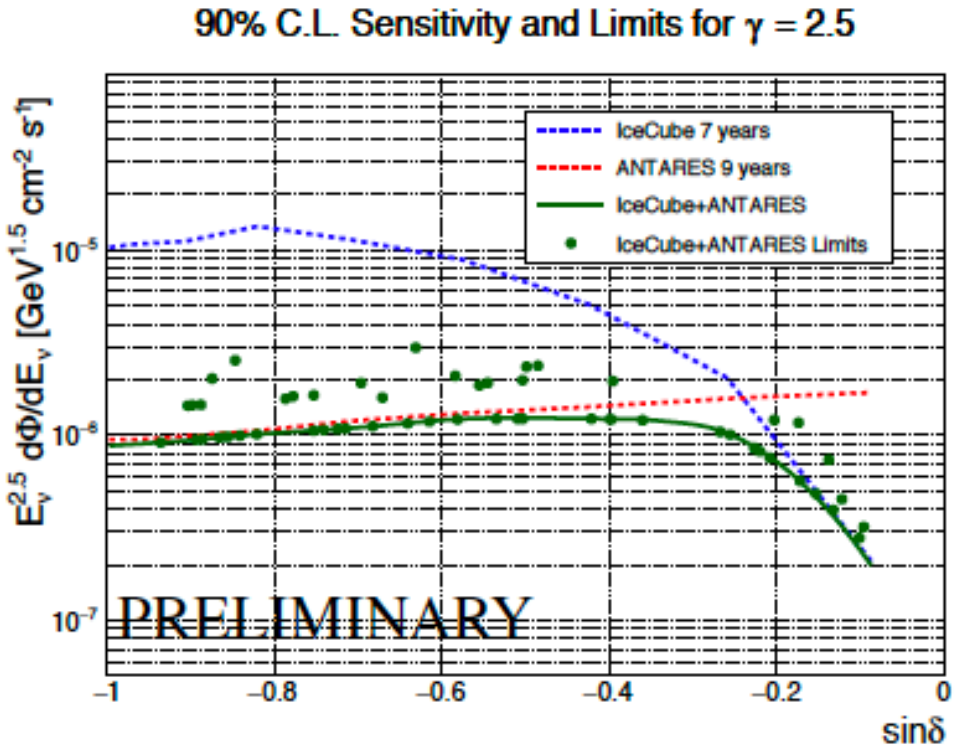
Summary of source searches:

Analysis	Source	α [°]	δ [°]	pre-trial (σ)	post-trial (σ)
full sky		343.5	+23.6	$1.5\ 10^{-6}$ (4.8)	0.23 (1.2)
candidate list	HESSJ0632+057	98.24	+5.81	$1.5\ 10^{-2}$ (2.4)	0.16 (1.4)
IceCube tracks	EHE ID3	343.5	+23.6	$1.5\ 10^{-6}$ (4.8)	0.015 (2.4)
TXS0506+056		77.36	+5.69	$3.4\ 10^{-2}$(2.1)	0.87 (0.16)
ANT-IceCube Southern sky		213.2	-40.8	$1.3\ 10^{-5}$ (4.3)	0.18 (1.3)
ANT-IceCube RXJ1713		258.25	-39.75	$4.0\ 10^{-1}$ (0.84)	
stacking Radio-galaxies		-	-	$4.8\ 10^{-3}$ (2.8)	0.10 (1.6)
stacking Radio-galaxies	3C403	298.06	+2.5	$2.3\ 10^{-4}$ (3.7)	0.013* (2.5)
stacking 3LAC BL Lacs		-	-	$8.8\ 10^{-2}$ (1.7)	0.64 (0.5)
stacking 3LAC BL Lacs	MG3J225517+2409	343.78	+24.19	$1.4\ 10^{-4}$ (3.8)	0.16* (1.4)
Time Analysis	MG3J225517+2409	343.78	+24.19	$1.4\ 10^{-4}$ (3.7)	0.16* (1.4)
Time Analysis ANT-IceCube	MG3J225517+2409	343.78	+24.19	$2.2\ 10^{-7}$ (5.2)	-

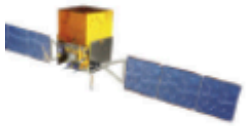
Complementarity Antares – IceCube in southern sky

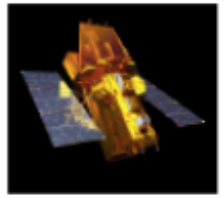
ANTARES sample	Livetime [days]	# of events
Tracks	2415	5807
Showers	2415	102
IceCube sample	**Livetime [days]**	**# of events**
IC40	376	22779
IC59	348	64257
IC79	316	44771
IC86	333	74931
2012-2015	1058	119231

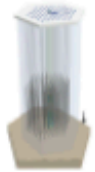




Multimessenger network







neutrinos
IceCube, GVD, SNEWS

GeV-TeV γ-rays
Fermi, HESS, HAWC, CTA

ANTARES, KM3NET

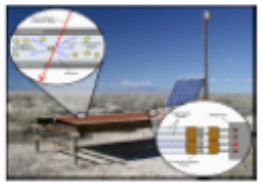
UHECR
Auger, TA

only spatial coincidence

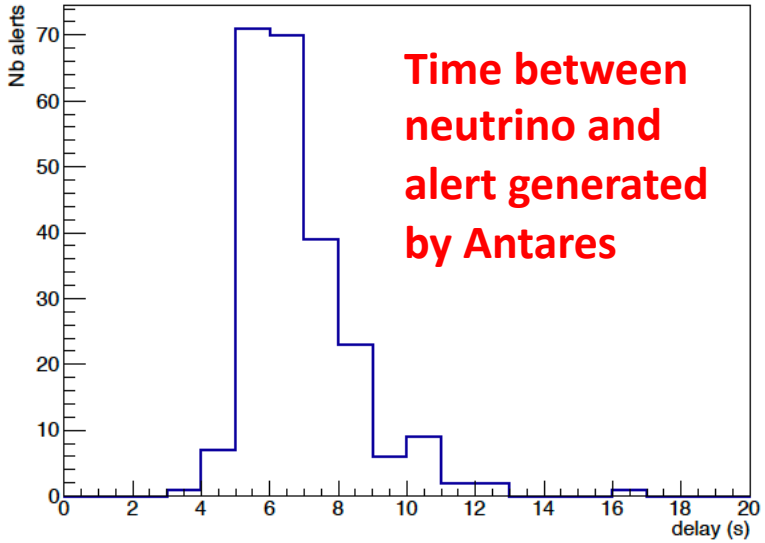
Receive alerts
Generate alerts

Radio/Optic /X-ray
TAROT, MASTER, Swift, INTEGRAL, MWA

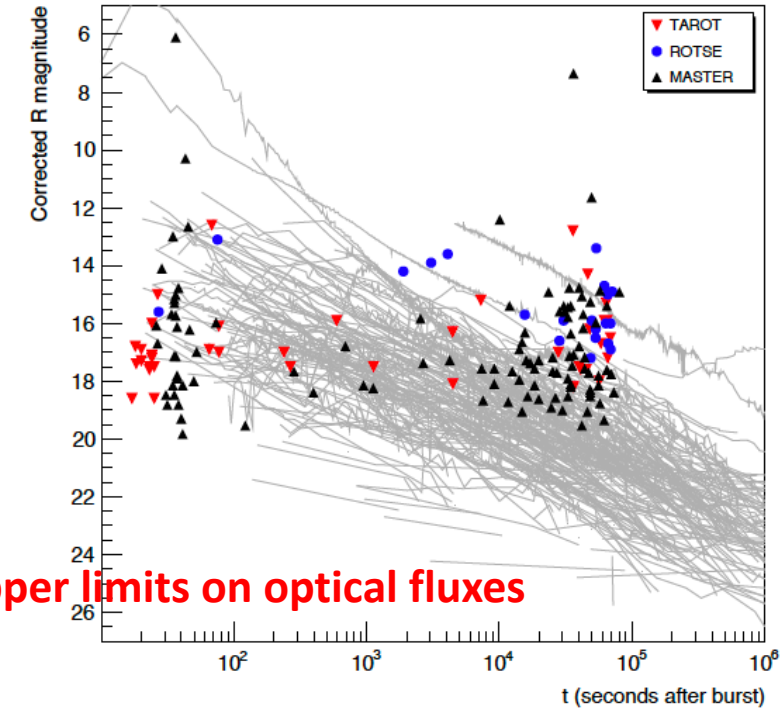
Gravitational Waves
VIRGO, LIGO



A selection of multimessenger results

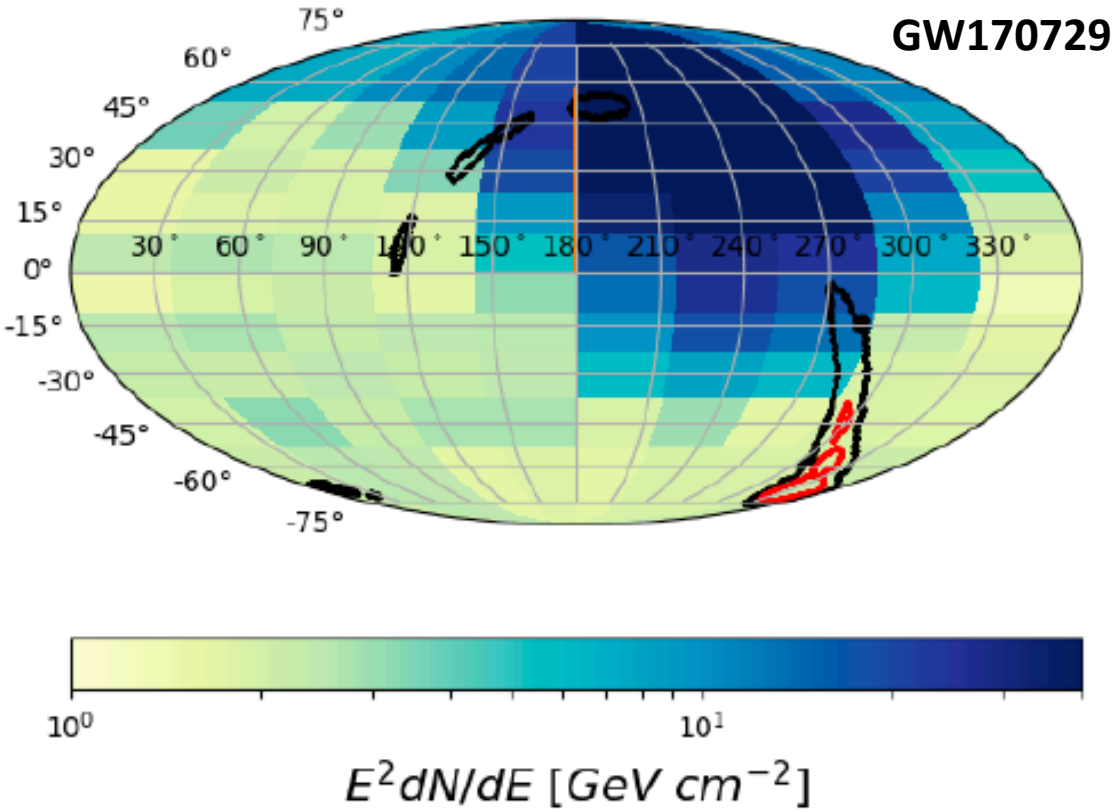


311 alerts 2009-2019

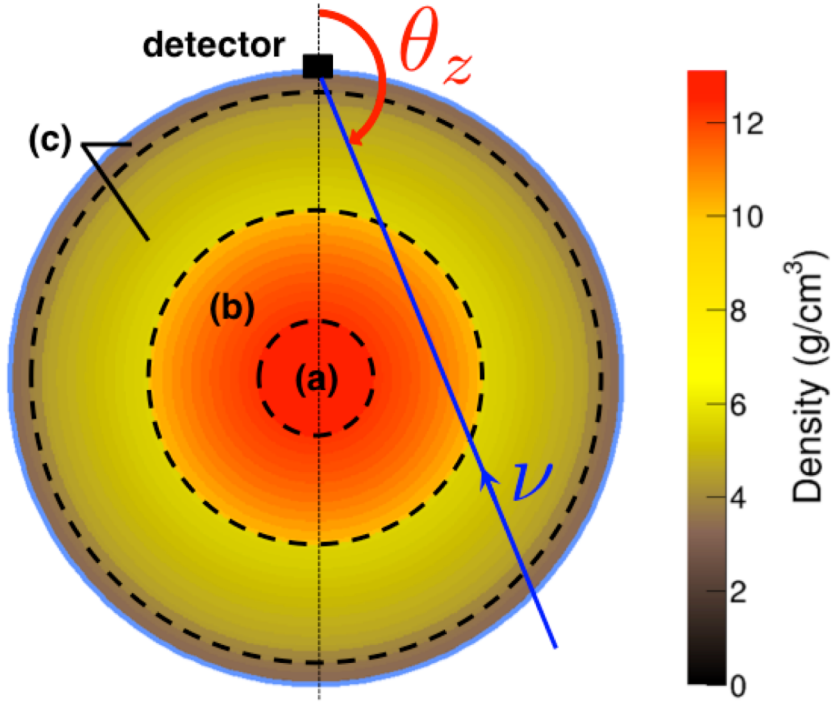


Upper limits on optical fluxes

Upper limits on neutrino flux from LIGO/VIRGO alerts



Neutrino oscillations



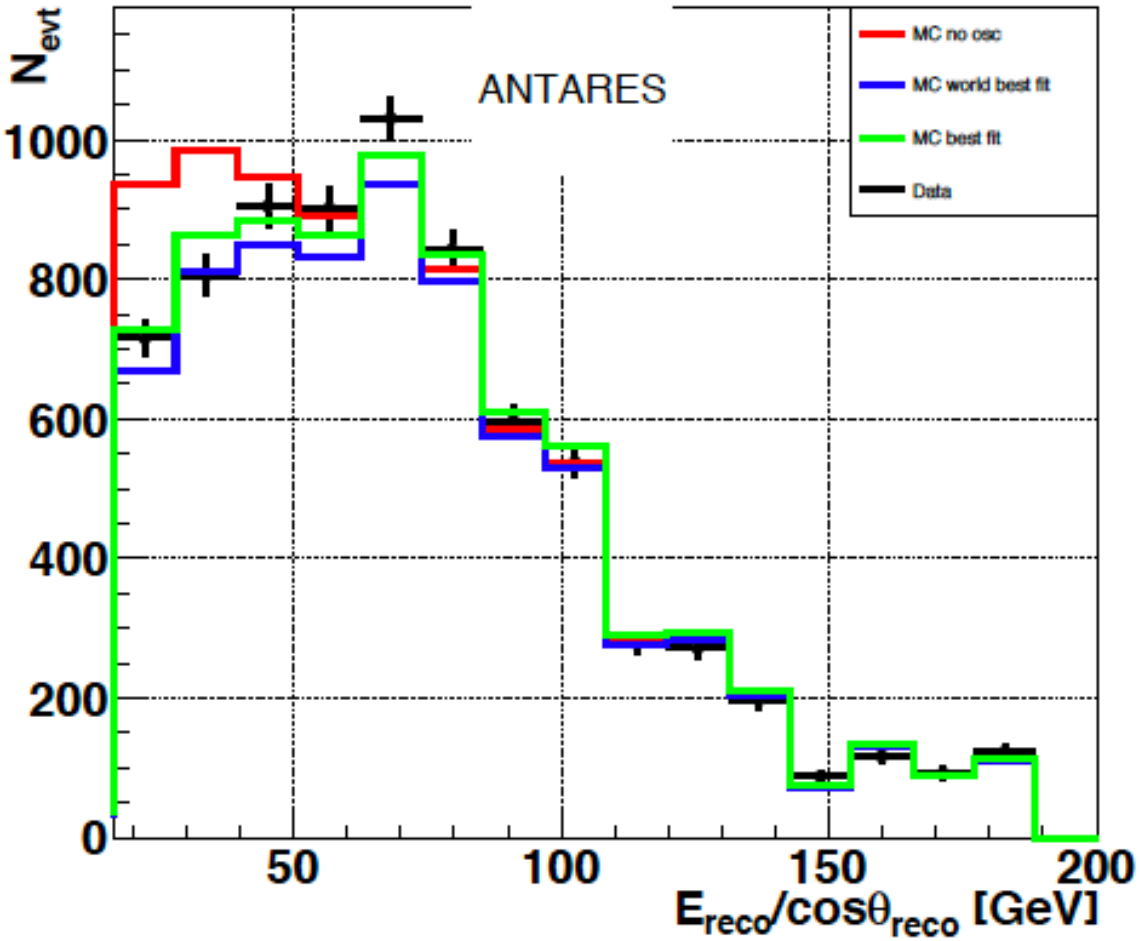
Oscillations ~ $\sin^2 \Delta m^2 \frac{L}{E}$

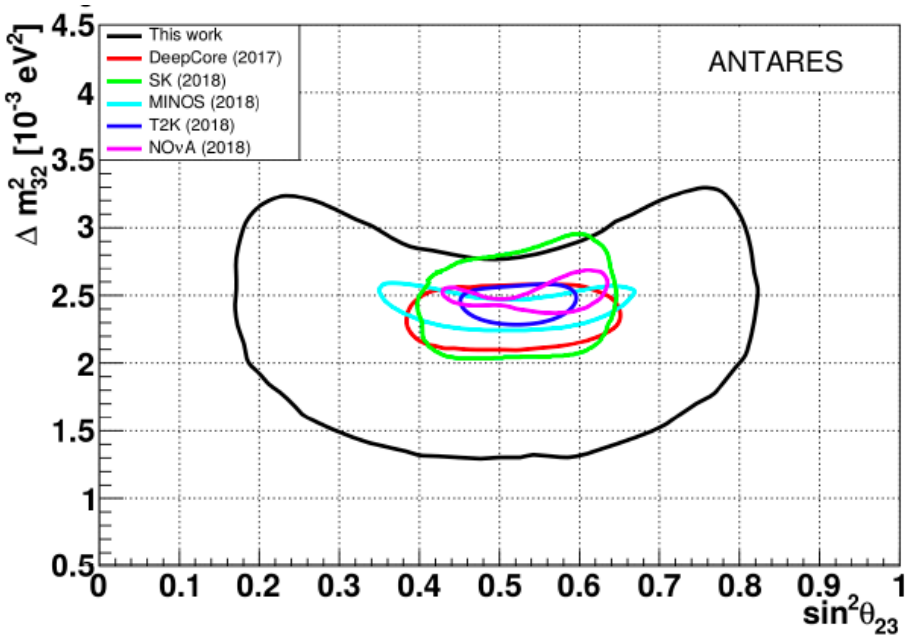
$\cos \theta_z$ is a measure of L

Full earth is baseline.

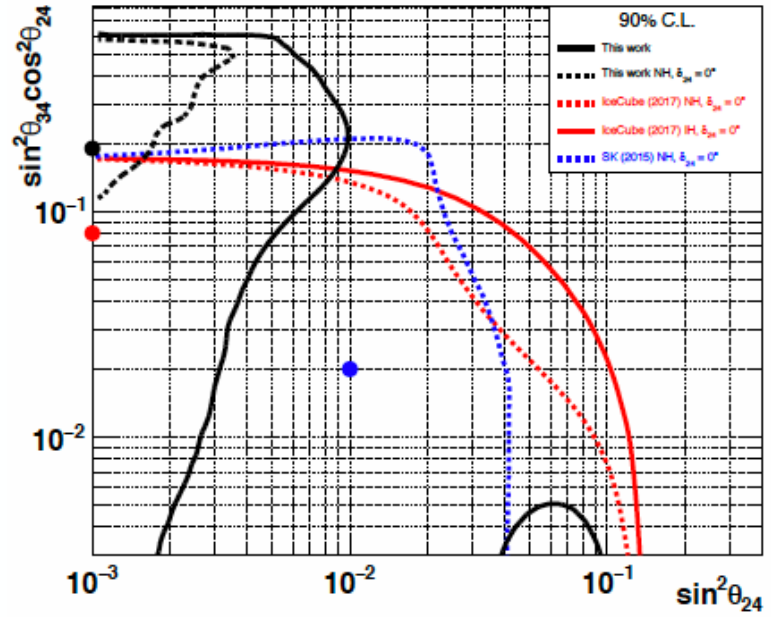
Antares oscillation results

10 years of data

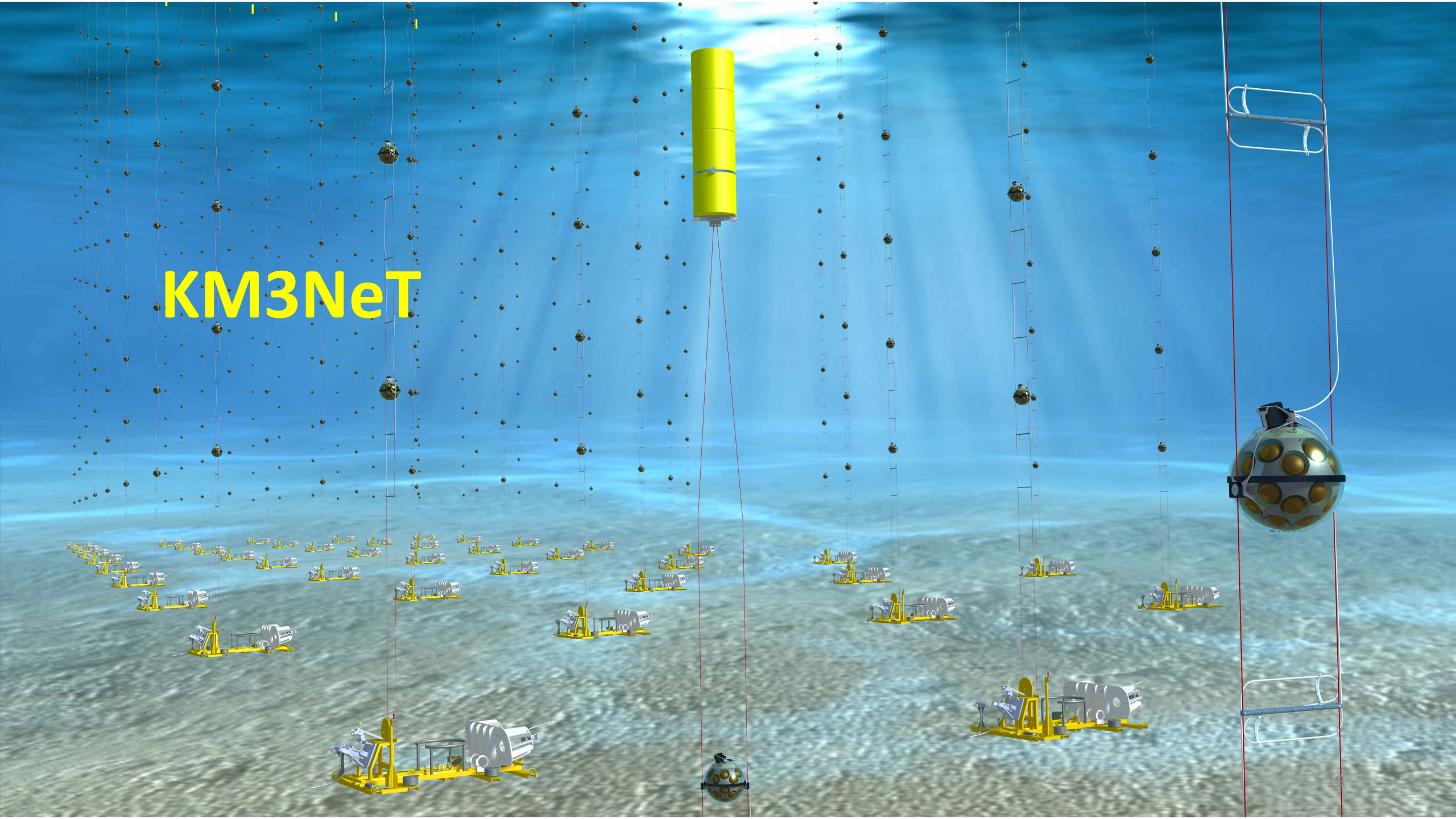


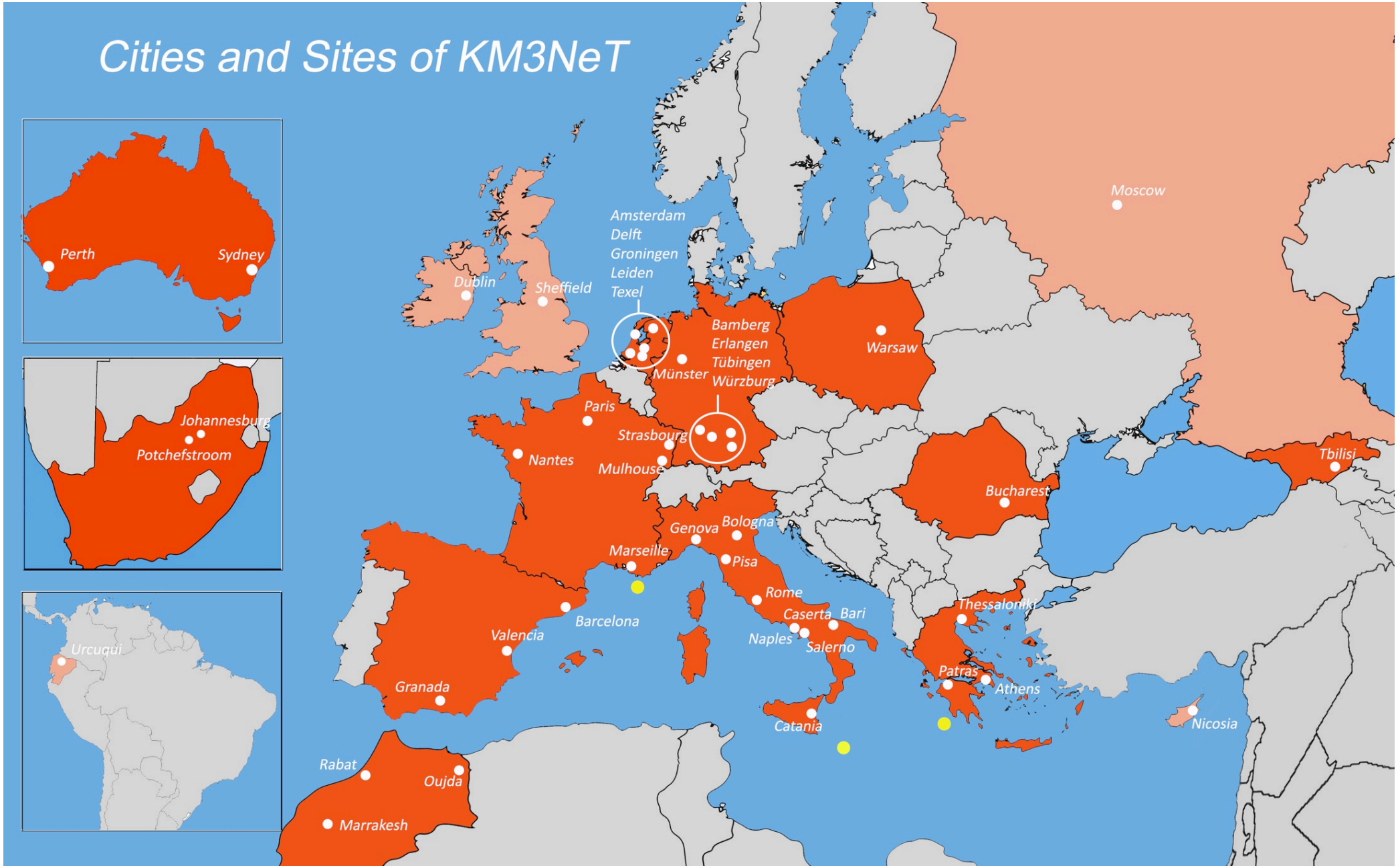


3-generation fit



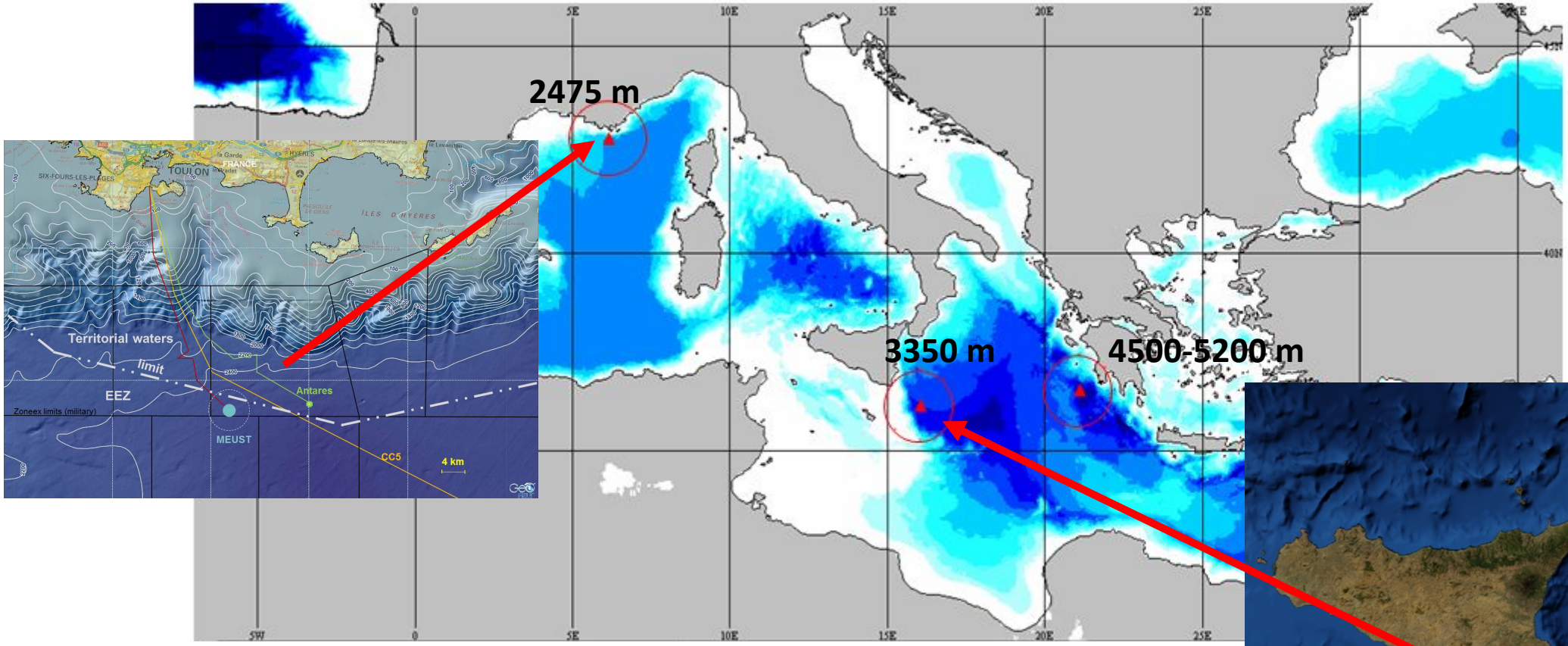
1 extra sterile ν


KM3NeT



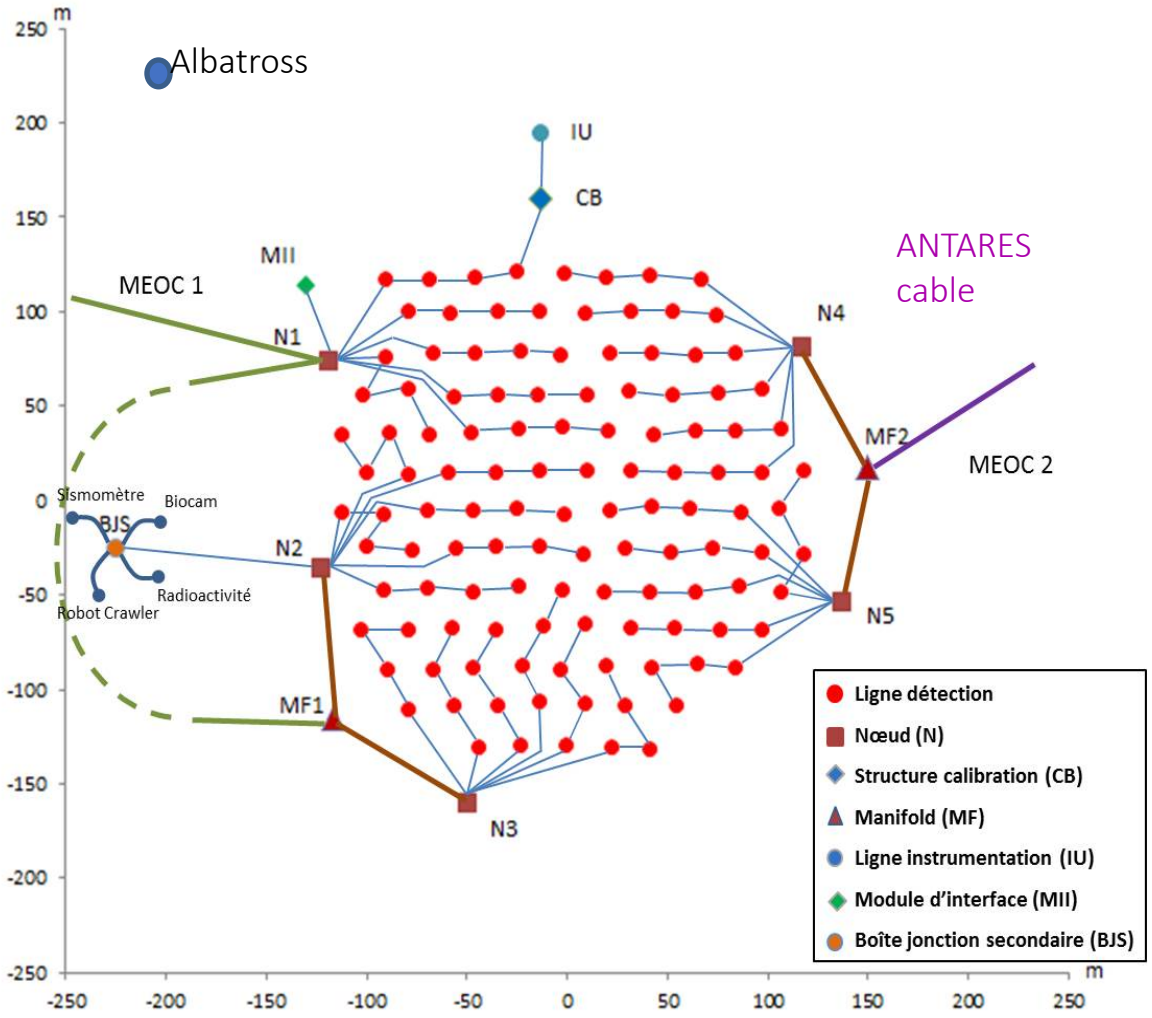
+ observer
Sun Yat-Sen univ.
Guangzhou
China

Location, location, location



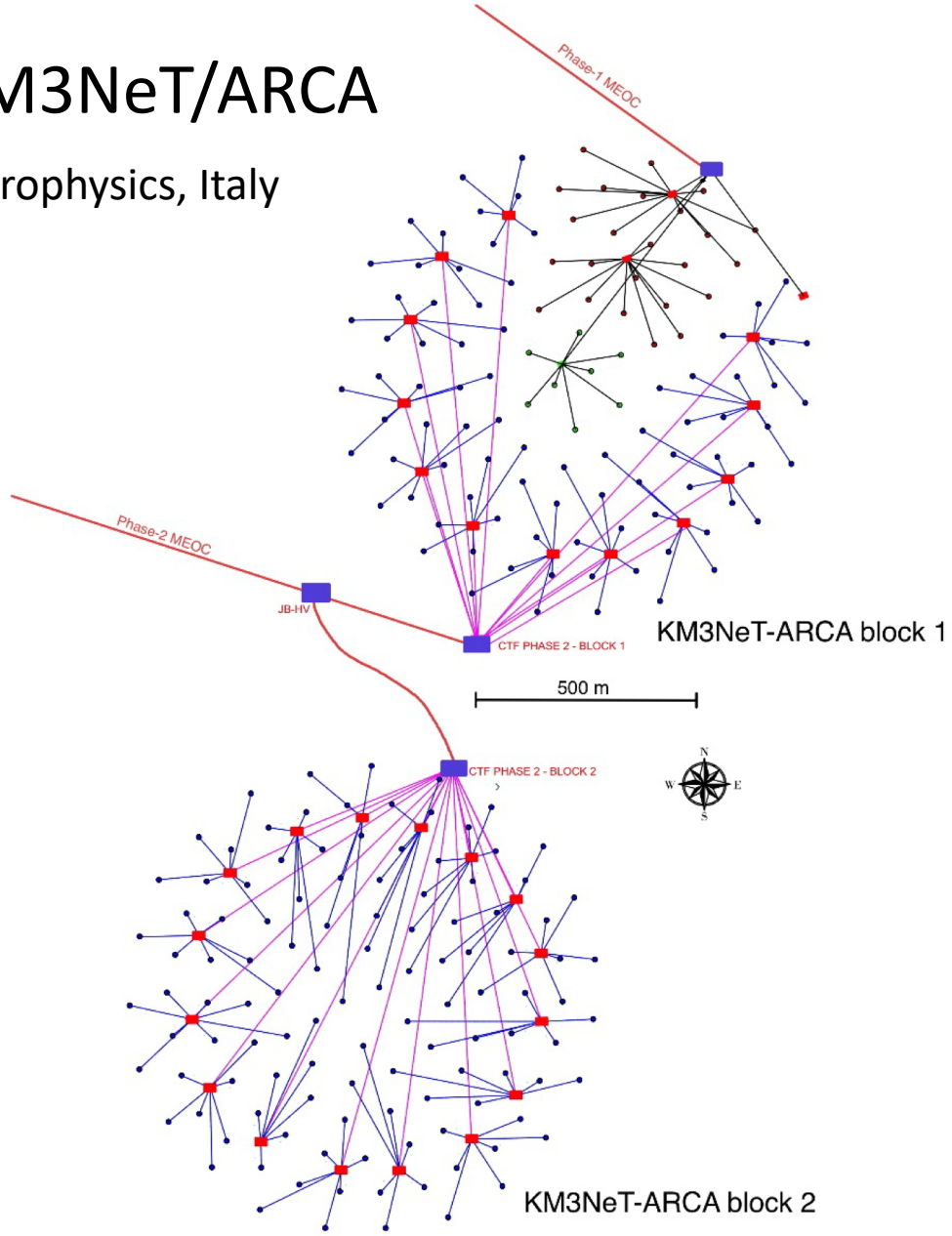
KM3NeT/ORCA

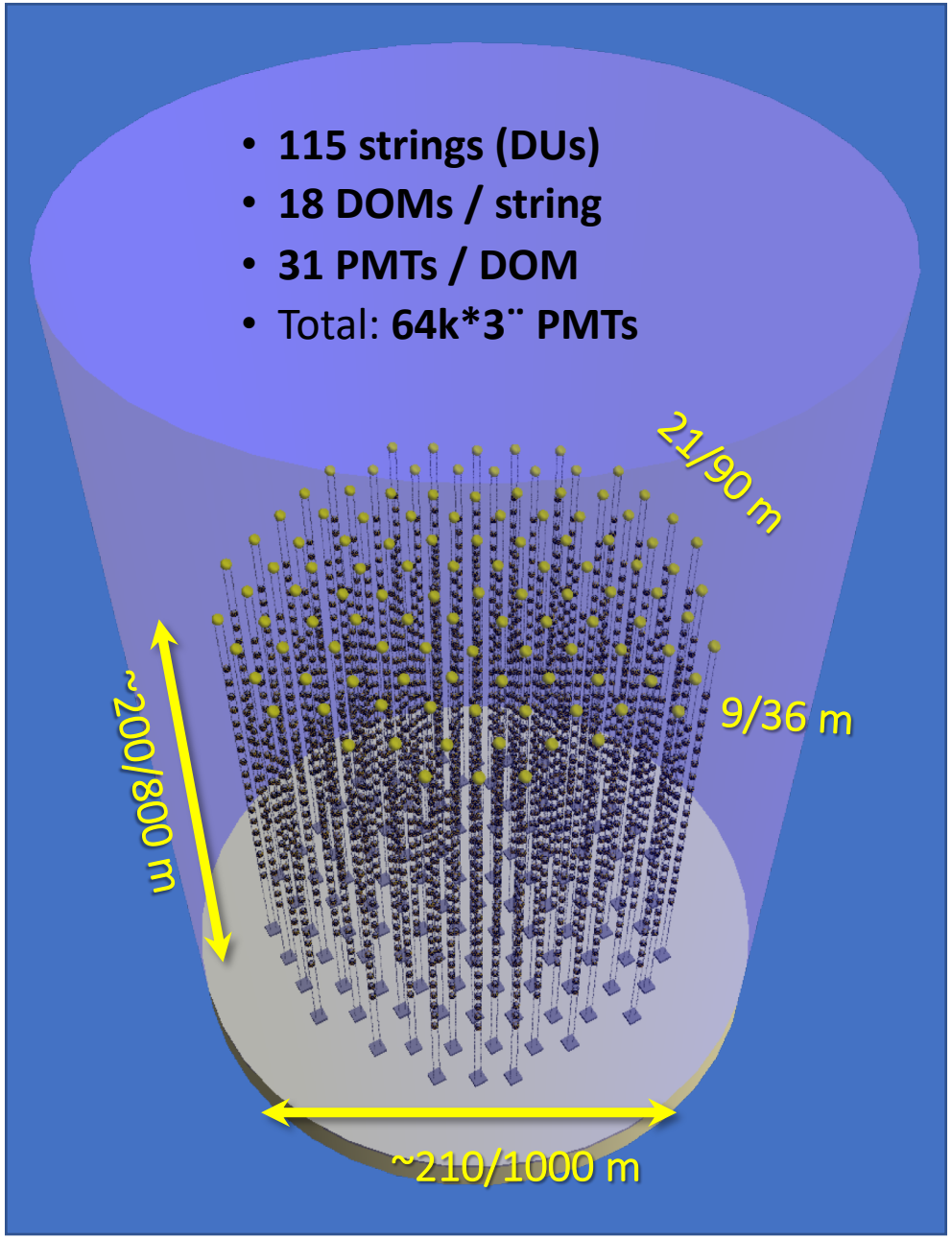
Oscillation research, France

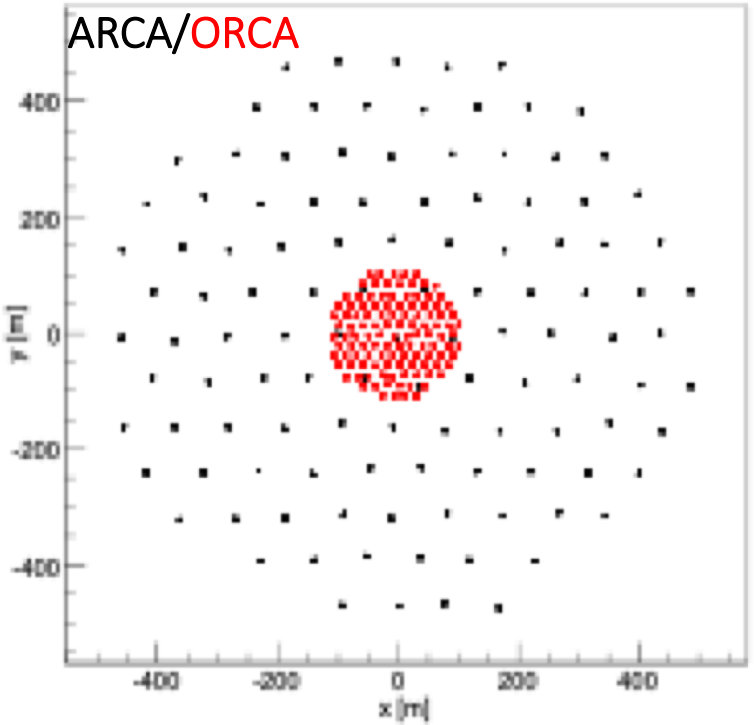


KM3NeT/ARCA

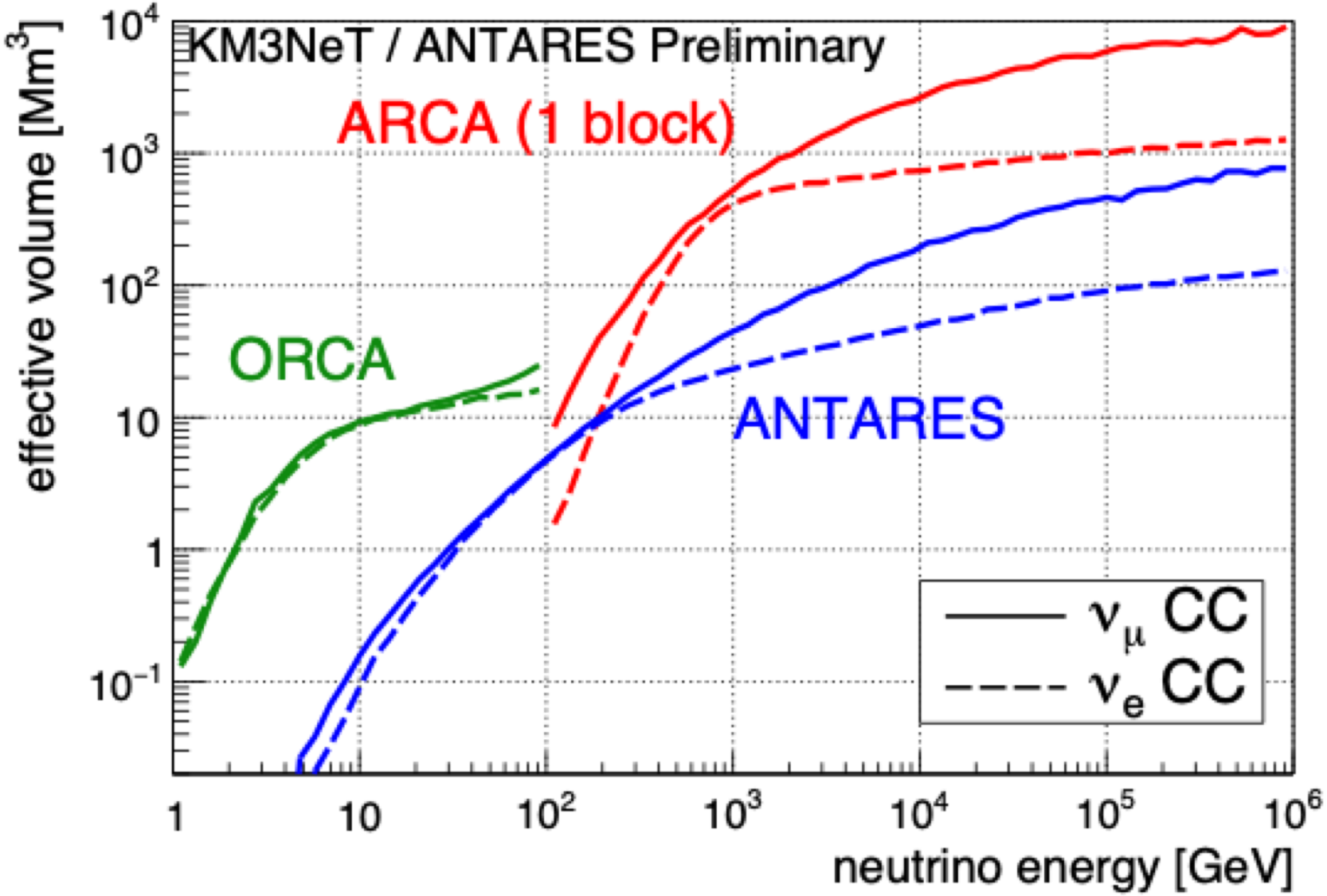
Astrophysics, Italy



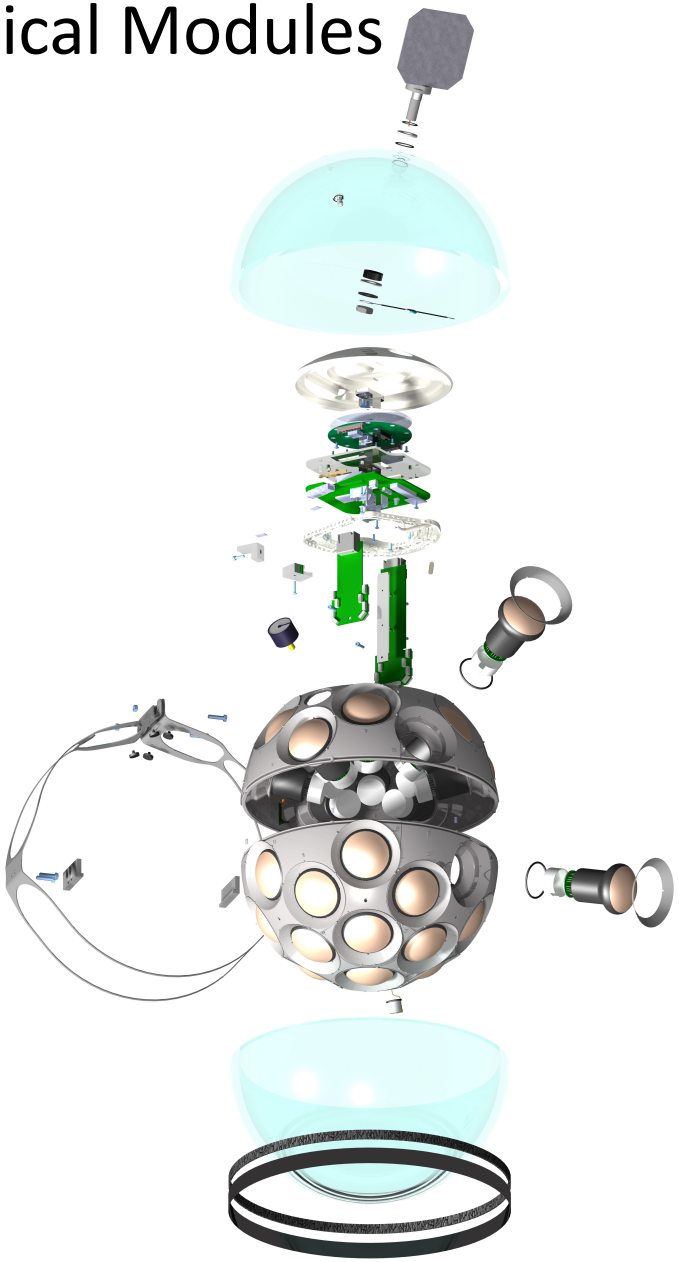




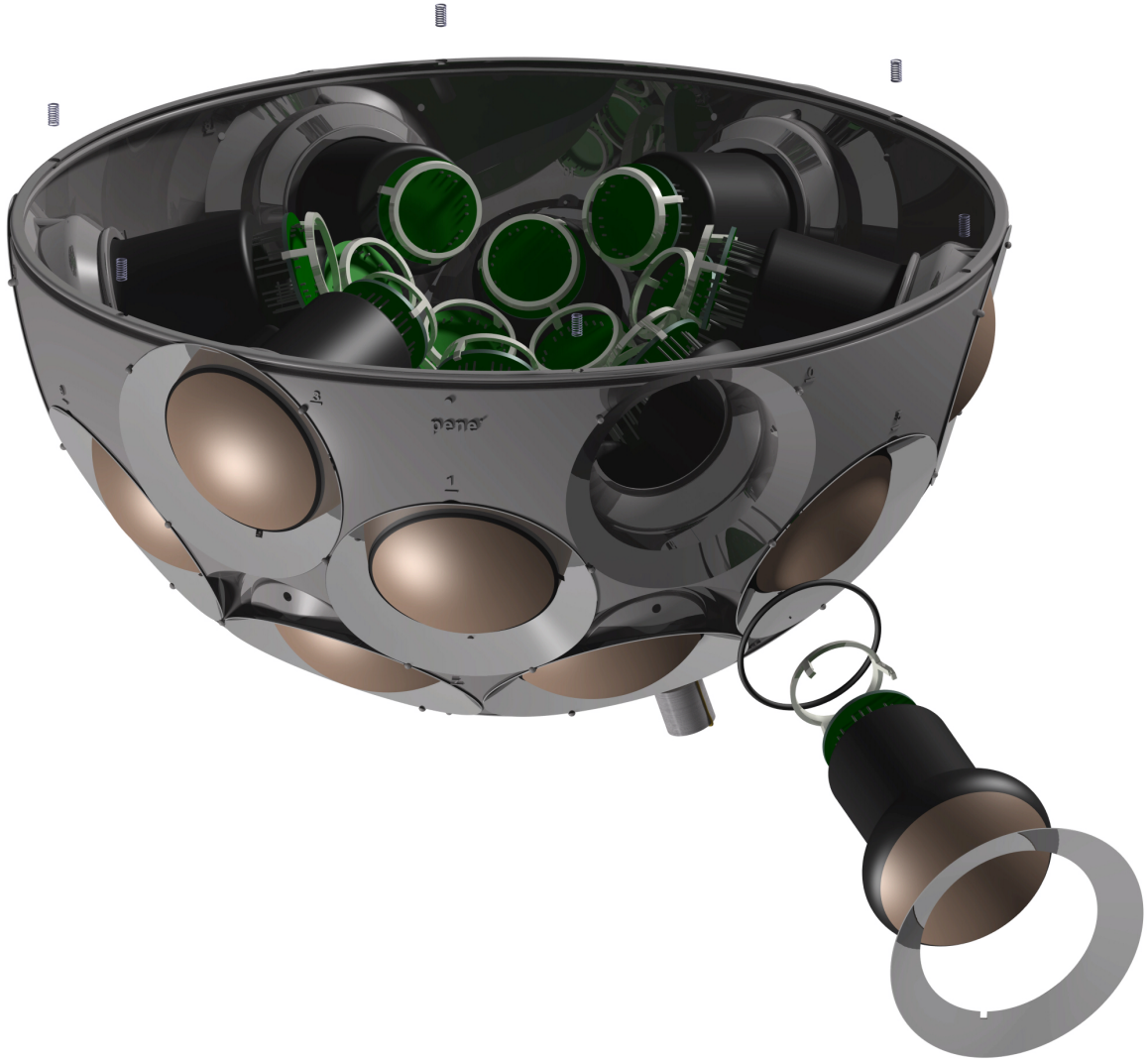
	ORCA	ARCA
String spacing	21 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3400 m
Instrumented mass	8 Mton	500*2 Mton

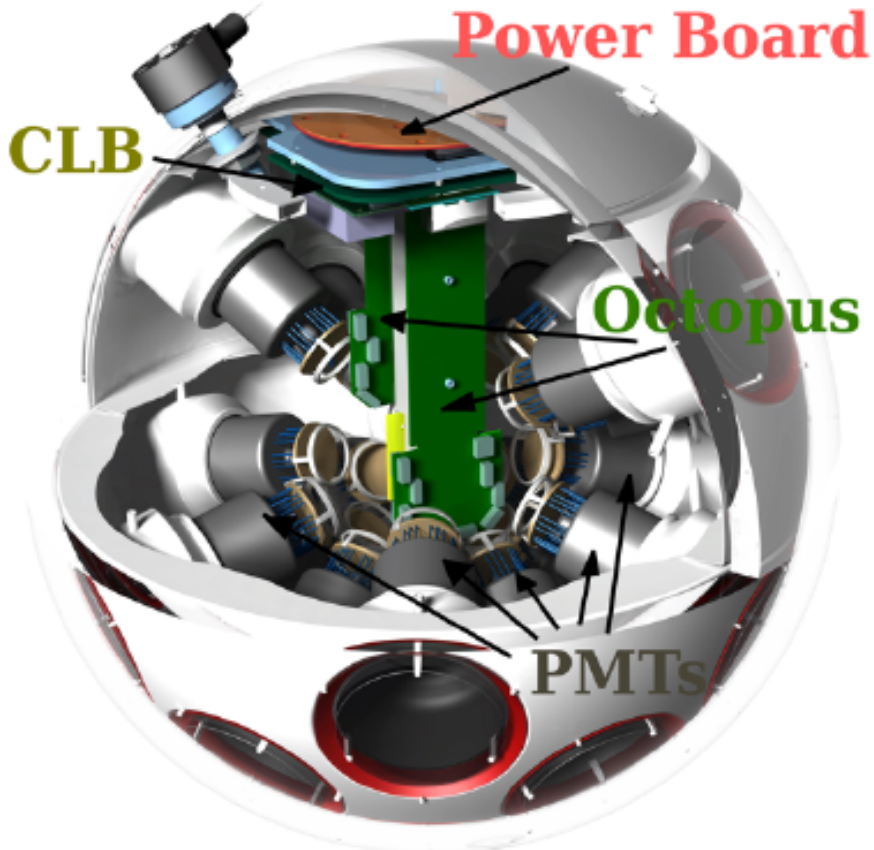

KM3NeT / ANTARES Preliminary
ARCA (1 block)
ORCA
ANTARES
ν_μ CC
ν_e CC
effective volume [Mm^3]
neutrino energy [GeV]
10^4
10^3
10^2
10
1
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6

Digital Optical Modules



31 3-inch PMTs per DOM
(Hamamatsu R14374)




Power Board
CLB
Octopus
PMTs

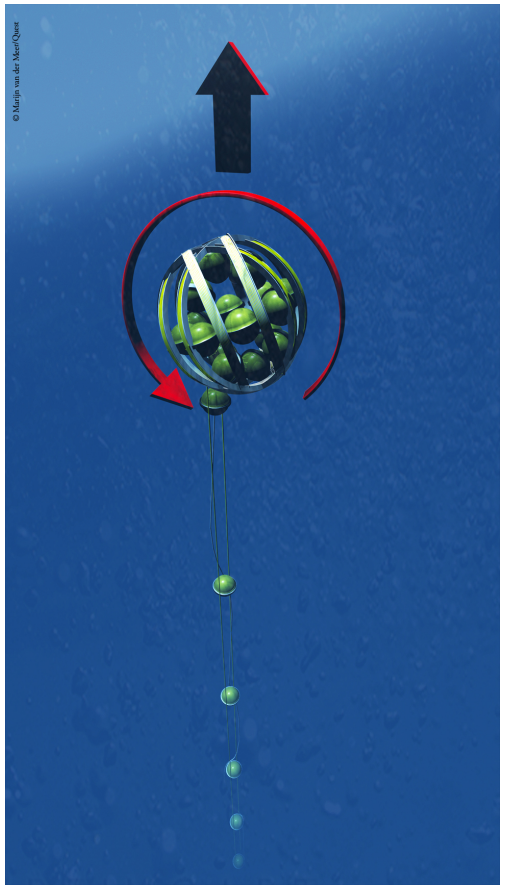
8 DOM production sites

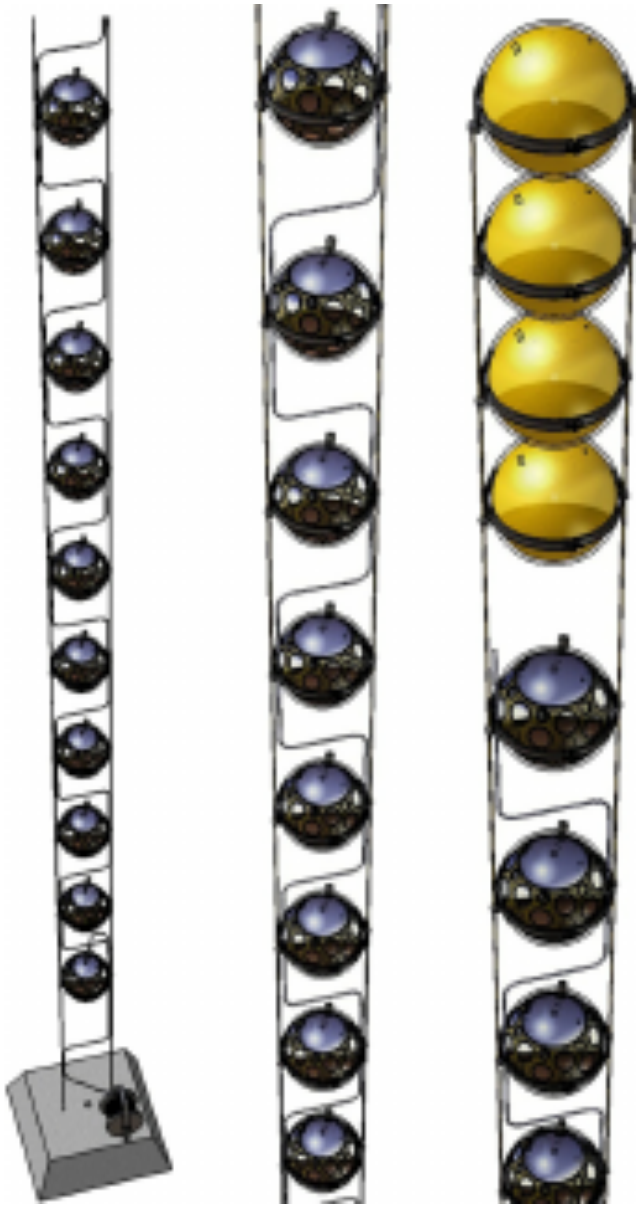
KM3NeT-Phase1 DOMs				
Site	n. of DOMs Integrated	On bench	To be done	Total
Amsterdam	218	0	0	218
Naples	73	0	0	73
Catania	75	15	18	108
Erlangen	36	0	18	54
Athens	38	0	18	56
Strasbourg	9	0	6*	15
Nantes	9	0	6	15
Rabat	0	0	1	1
TOTAL	**458**	**15**	**67**	**540**

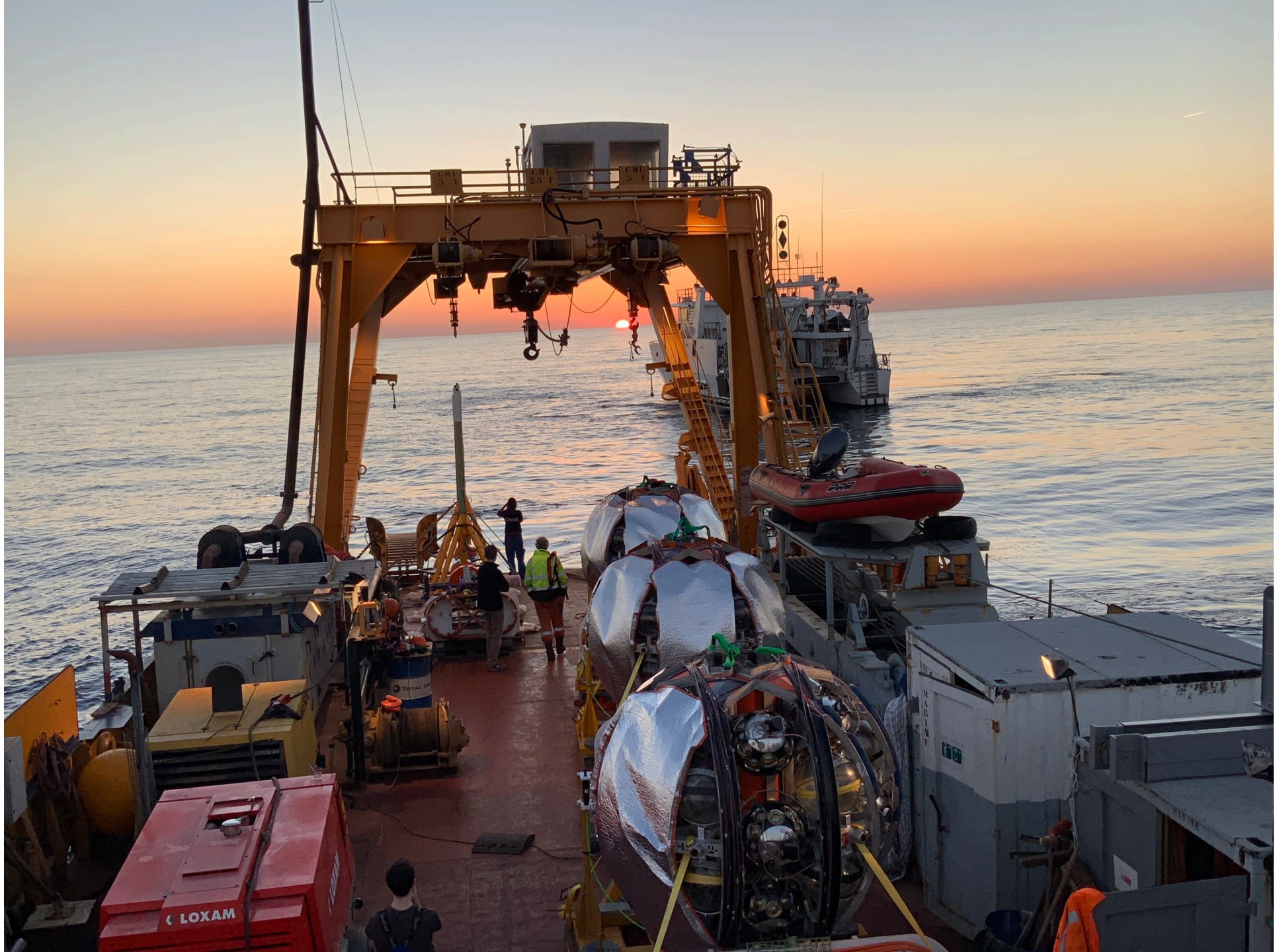
Sufficient DOMs for 25 DUs (strings) at the moment, 30 soon (= phase 1)

Detection Unit (DU) integration

5 sites: Amsterdam, Catania, Genova, Marseille, Napoli






LOXAM

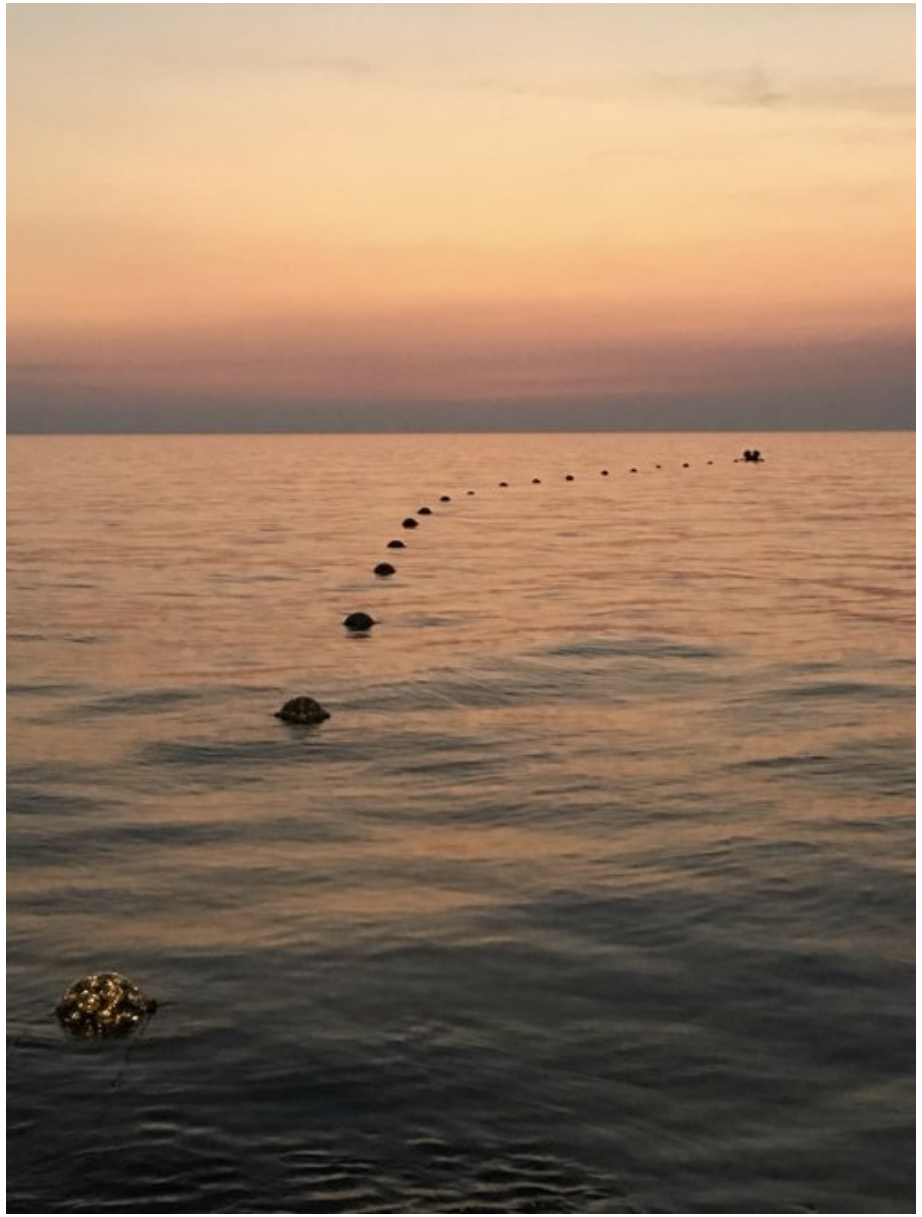

comex

https://www.youtube.com/watch?v=omlFkdCkbYk

Status at **ORCA** site (F)

- First DU deployed Sept 2016
- Dec. 2016: short in power cable to shore
- Cable replaced 2018, DU had to be retrieved
- 5 DUs deployed since, but 1 retrieved
  (VEOC cable cut when deploying other DU)
- Now operational with 4 DUs
- 2 DUs ready for deployment Nov 2019

Currently procuring for phase 2
Restart production and deployment in 2020
End of 2020: 13 DUs
End of 2021: ~40 DUs
Completion 2024

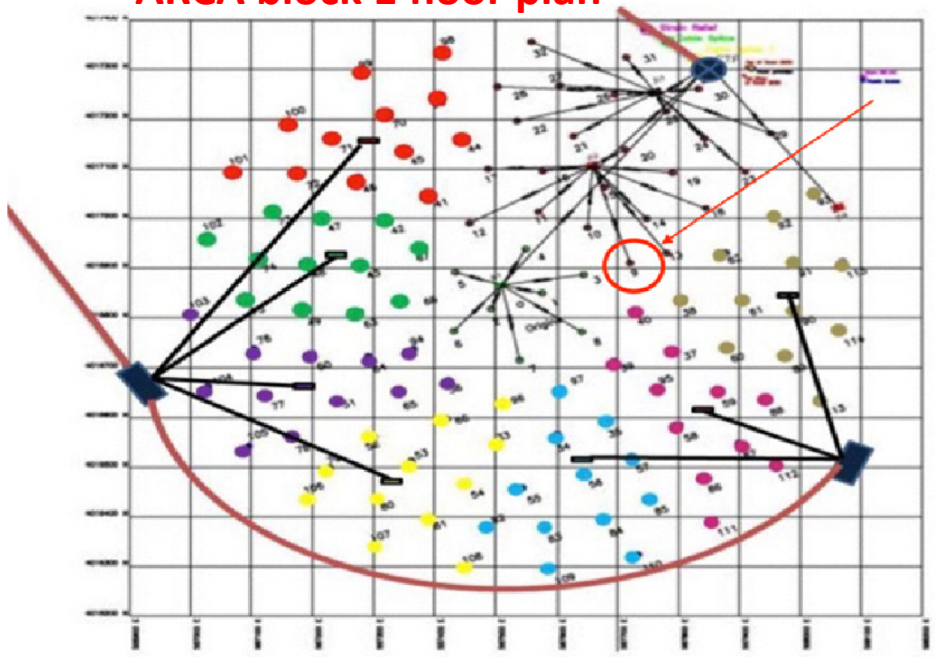


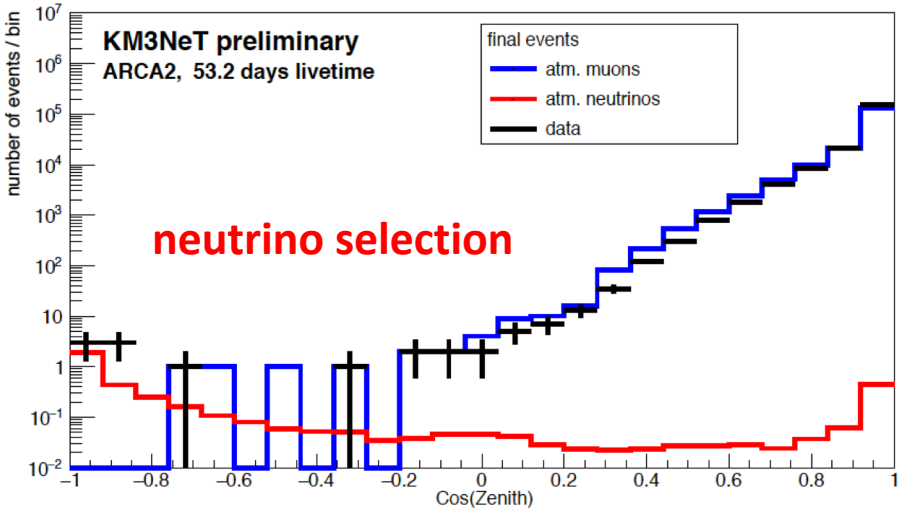
Status at **ARCA** site (I)

- 1 DU operational
- Work on seafloor network in progress
- Spring 2020: temporary Junction Box (6 DUs)
- Fall 2020-Summer 2021: final JBs for 24 DUs

Procurement for phase 2 in progress
More advanced optical network
DOM and DU construction to start during 2020
Completion block 1 in 2024
Completion block 2 in 2026

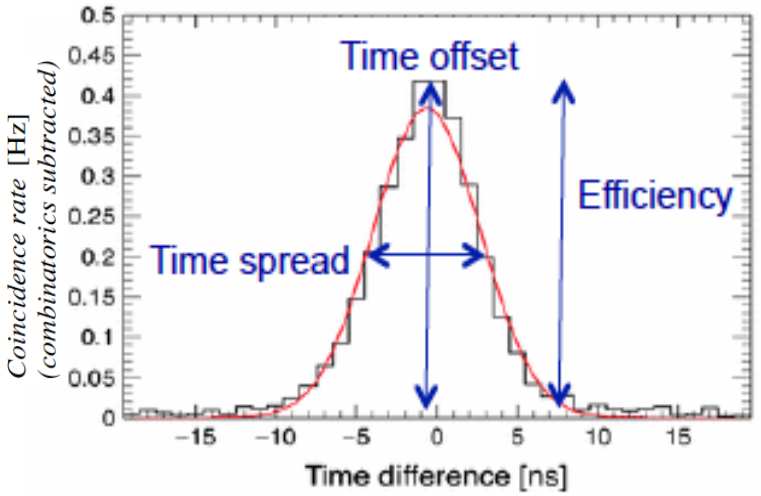
ARCA block 1 floor plan

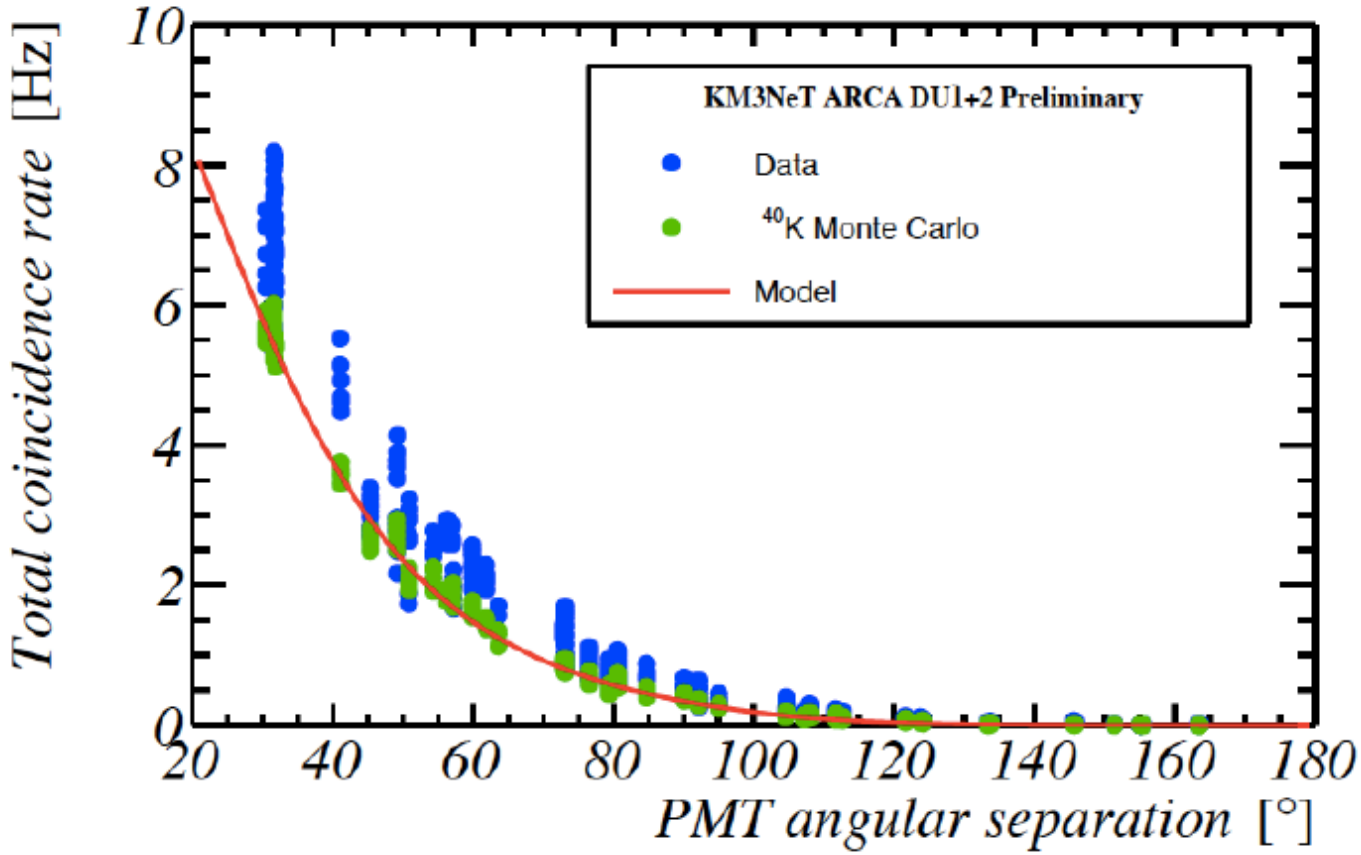




Calibration with ^{40}K decays in seawater

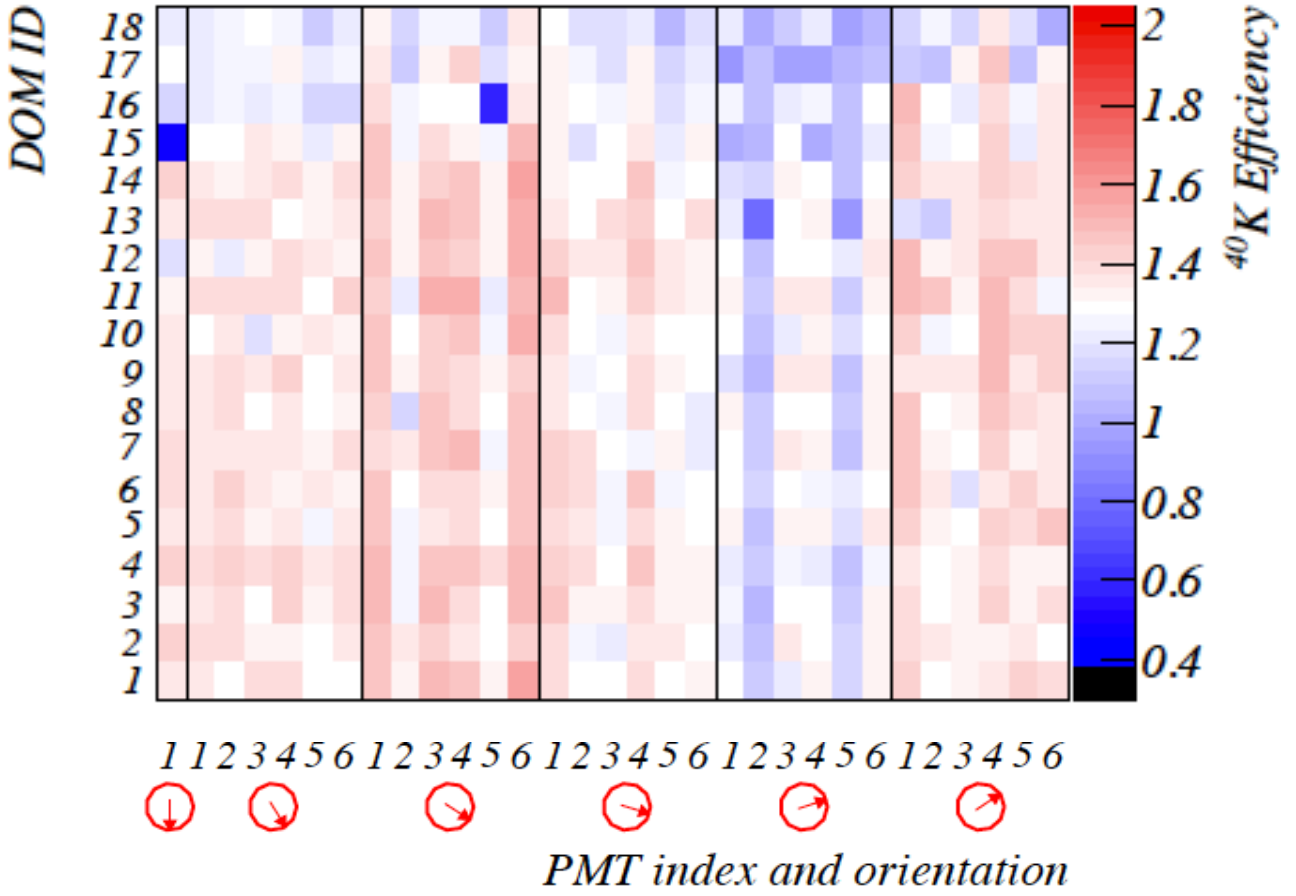
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e \quad (89.3\%)$$
$$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar}^* + \nu_e \quad (10.7\%)$$
$$\hookrightarrow {}^{40}\mathrm{Ar} + \gamma$$



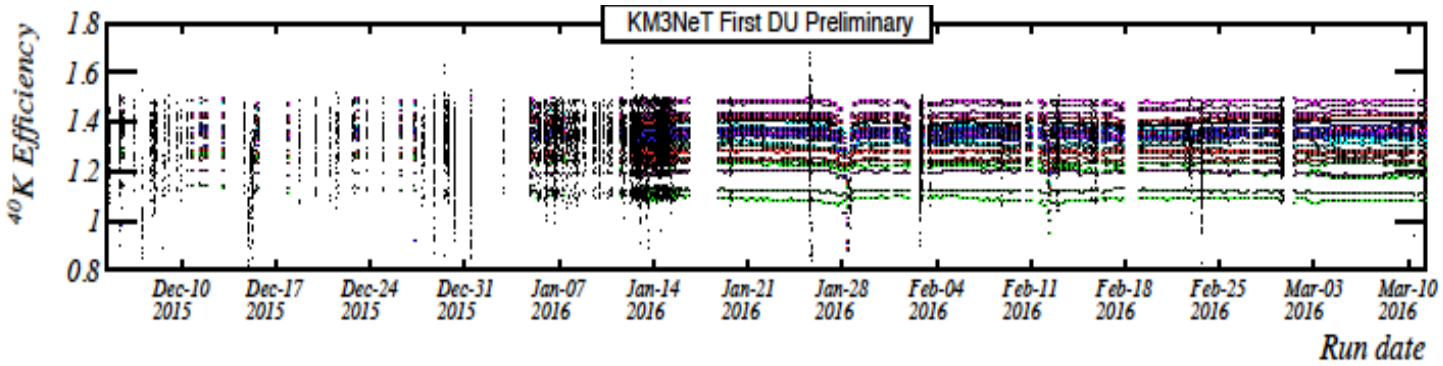


Single PMT rate ~ 6 kHz, two-fold coincidence on a DOM ~ 500 Hz

PMT efficiency
(relative to simulation)

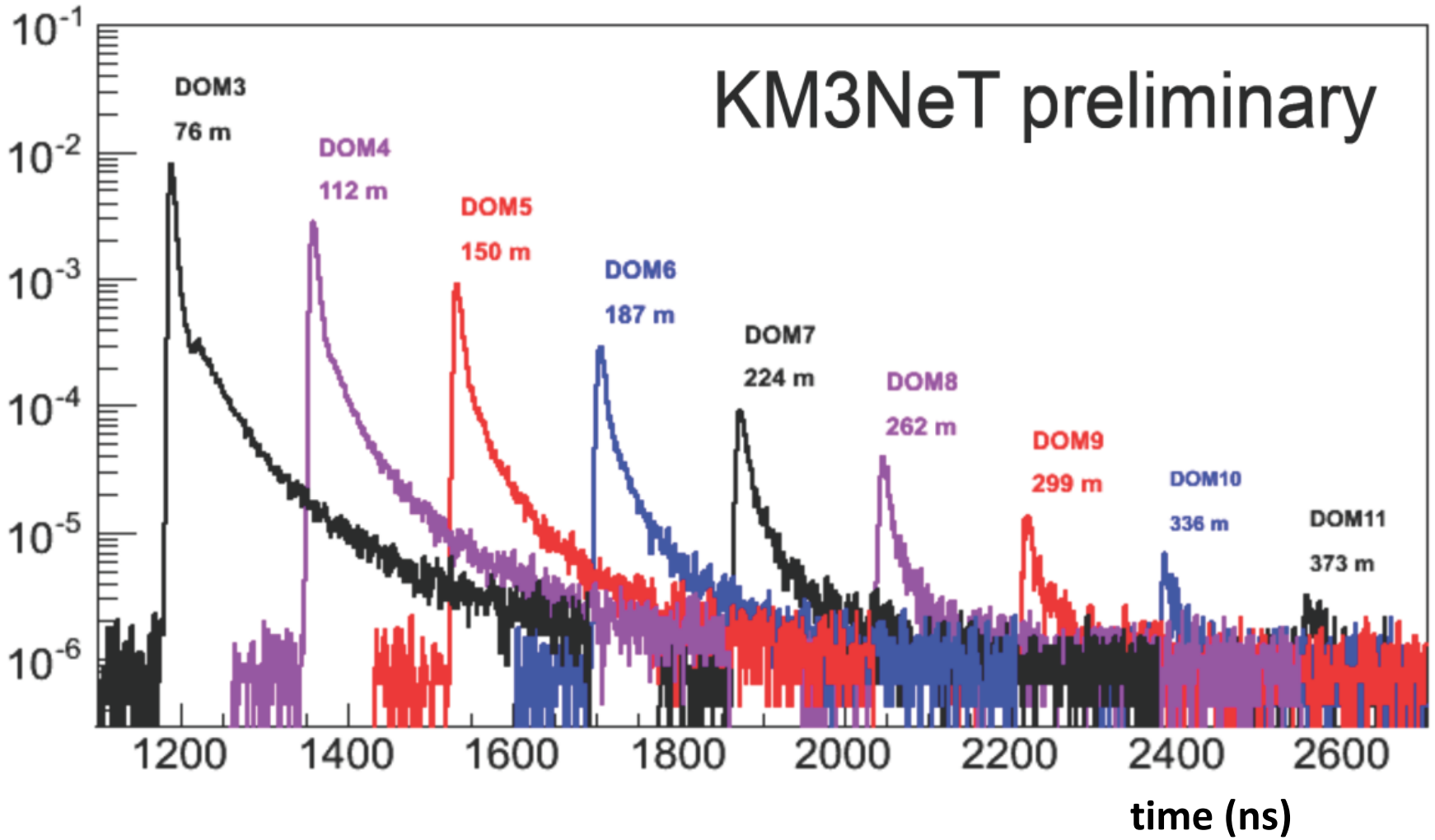


Stability monitoring



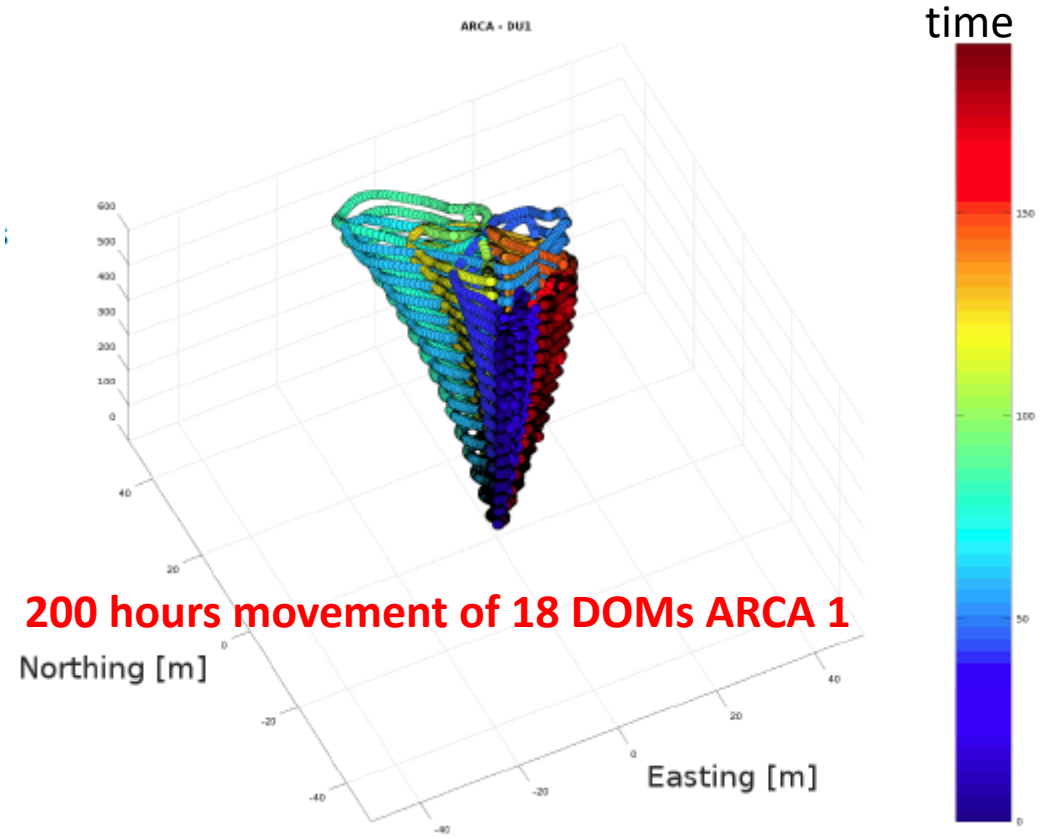
LED flashers: timing between different DOMs

Timing check with LED flashers

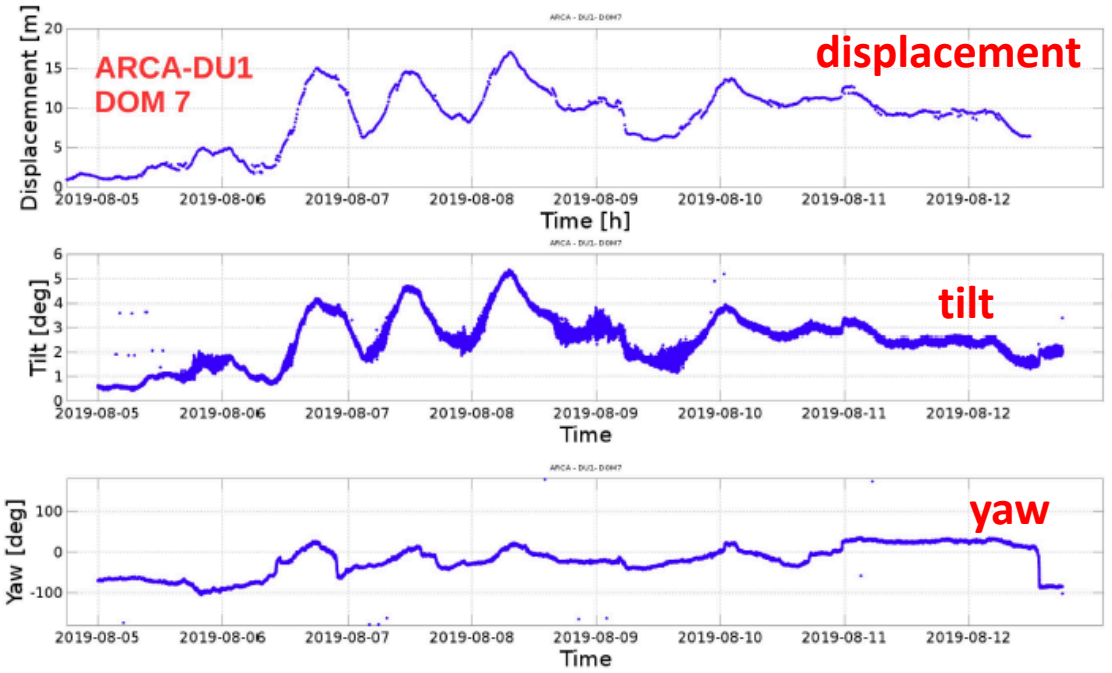


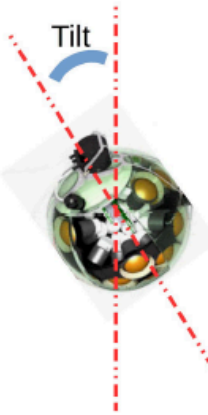
Positioning: acoustic triangulation, and compass

Acoustic emitters on sea-floor
Hydrophones in DOMs, triangulation



200 hours movement of 18 DOMs ARCA 1

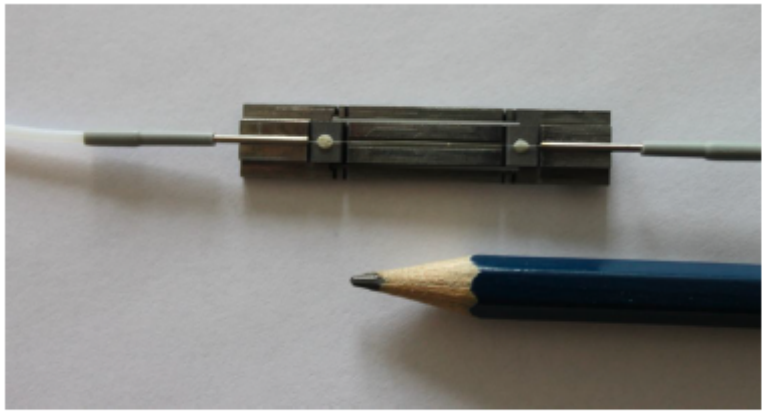


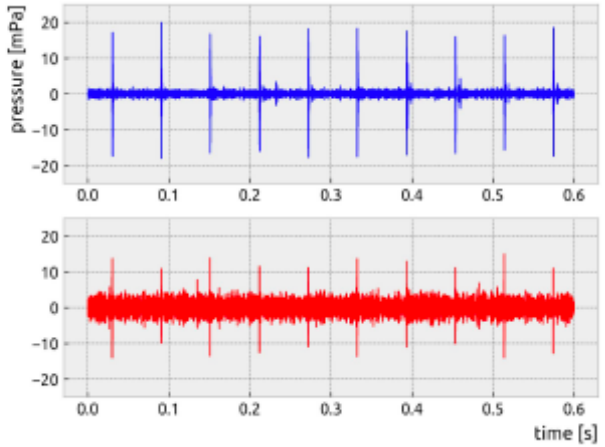


Correlation between acoustic positioning and compass

Aim for ~10cm accuracy in DOM positions

Future: acoustic detection of neutrinos (with TNO, Delft)



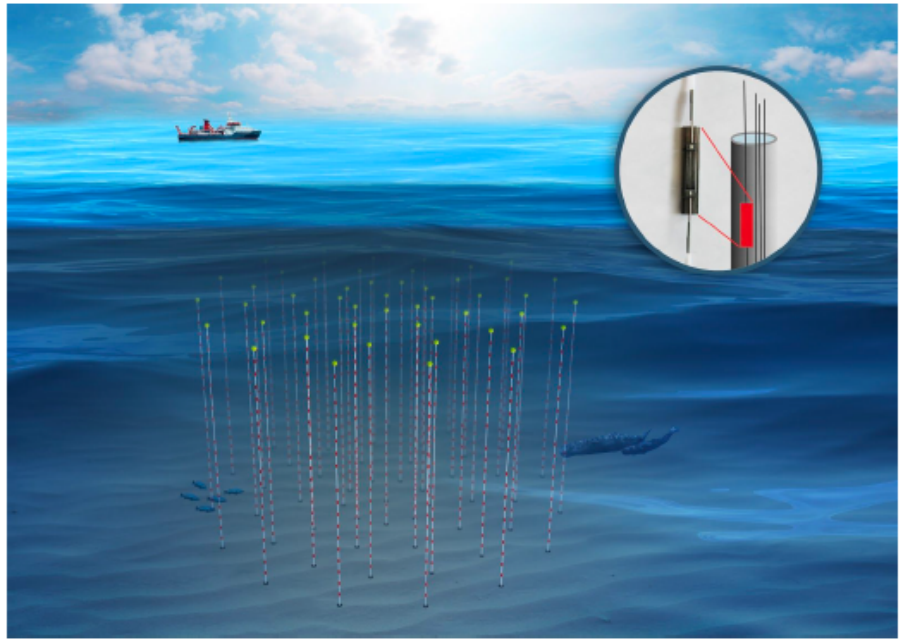


New fiber-optic hydrophone

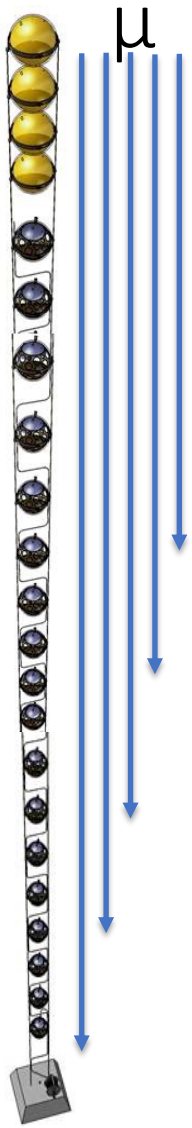
Commercial hydrophone as reference

Dream: future 100 km^3 array
Neutrinos above 10^{18} eV

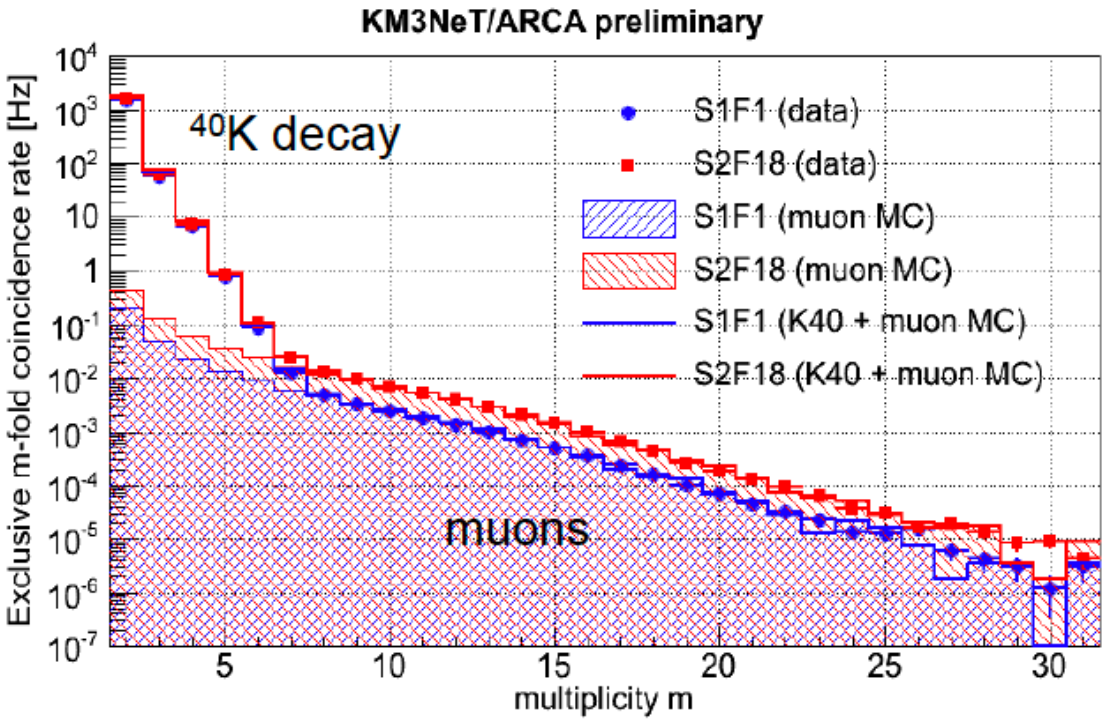
Also interest from biologists



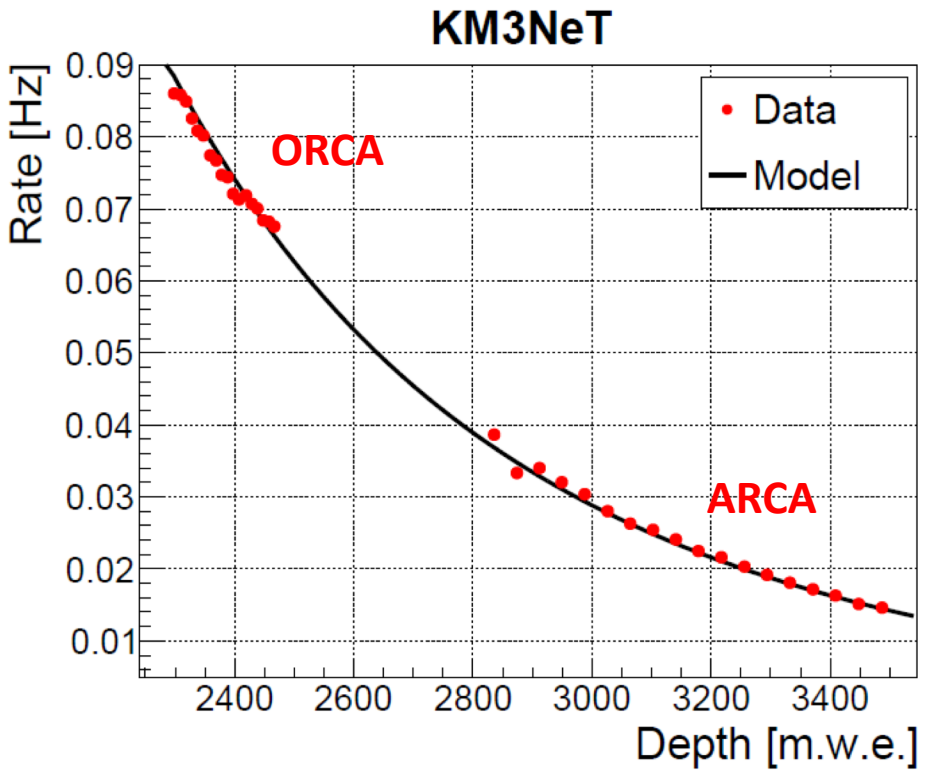
Depth dependence of the atmospheric muon flux



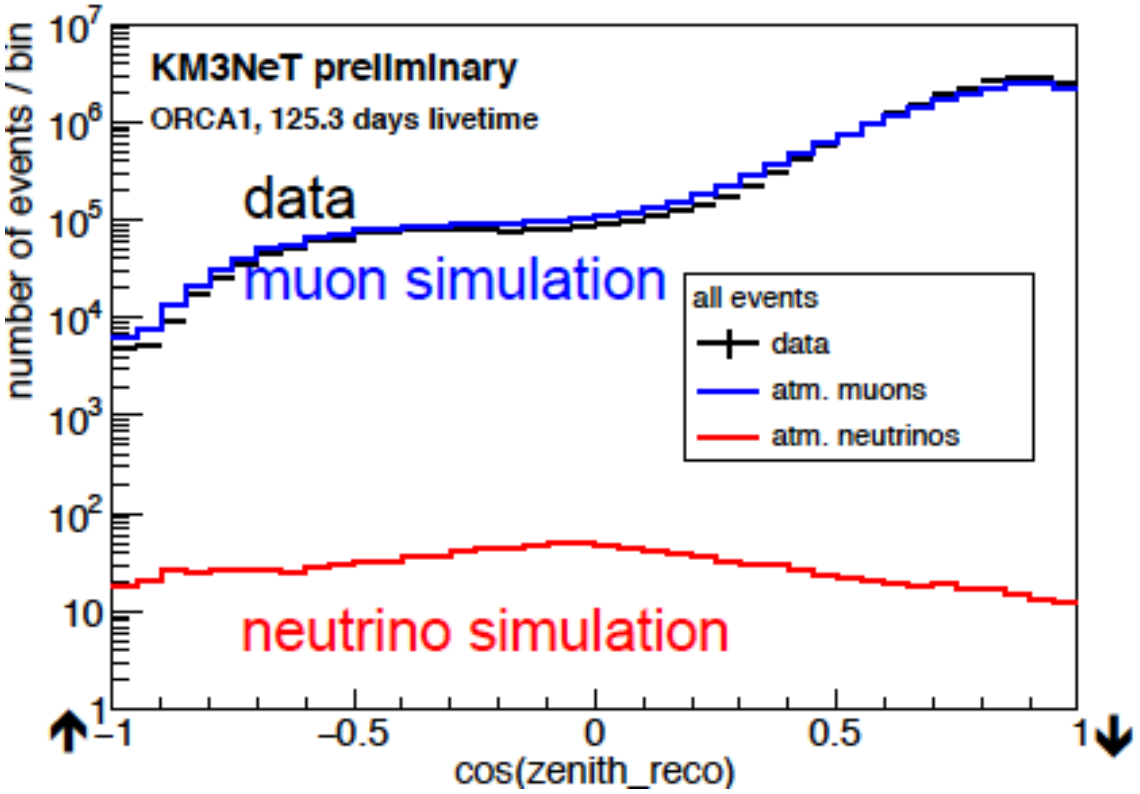
PMT hit multiplicity per DOM

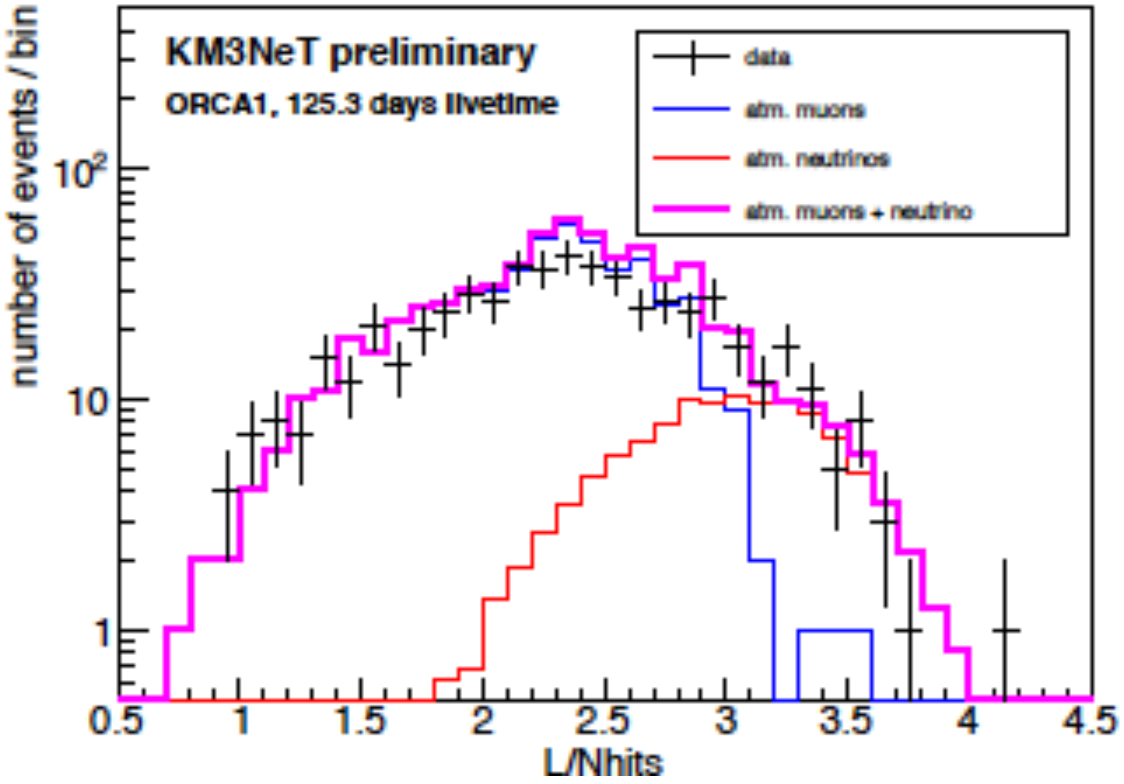


8 or more multiplicity selection



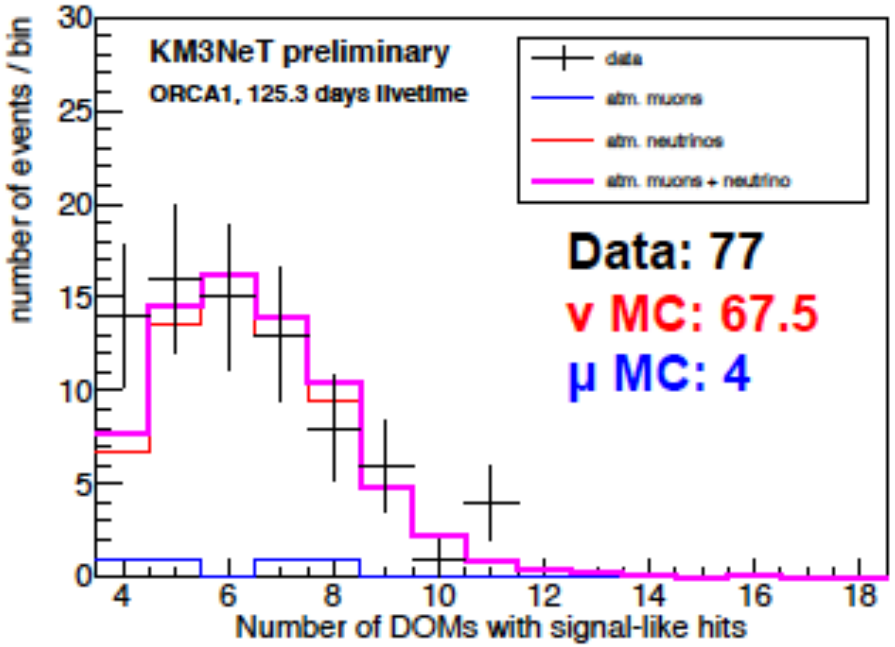
Atmospheric neutrino candidates selection in ORCA

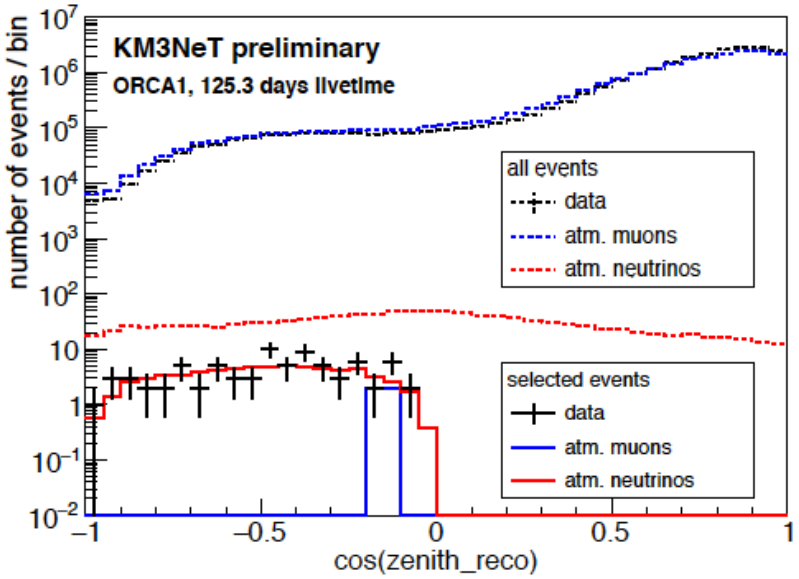


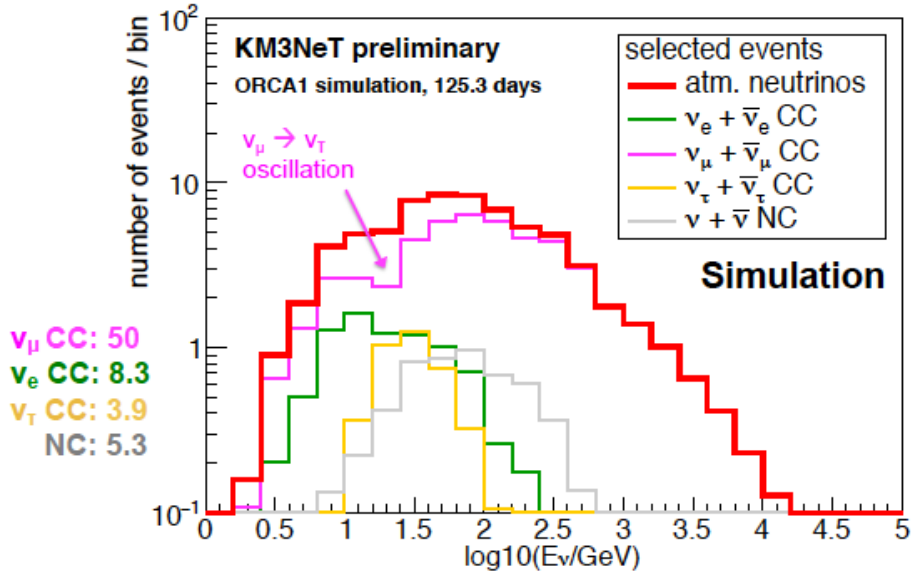


neutrino likelihood

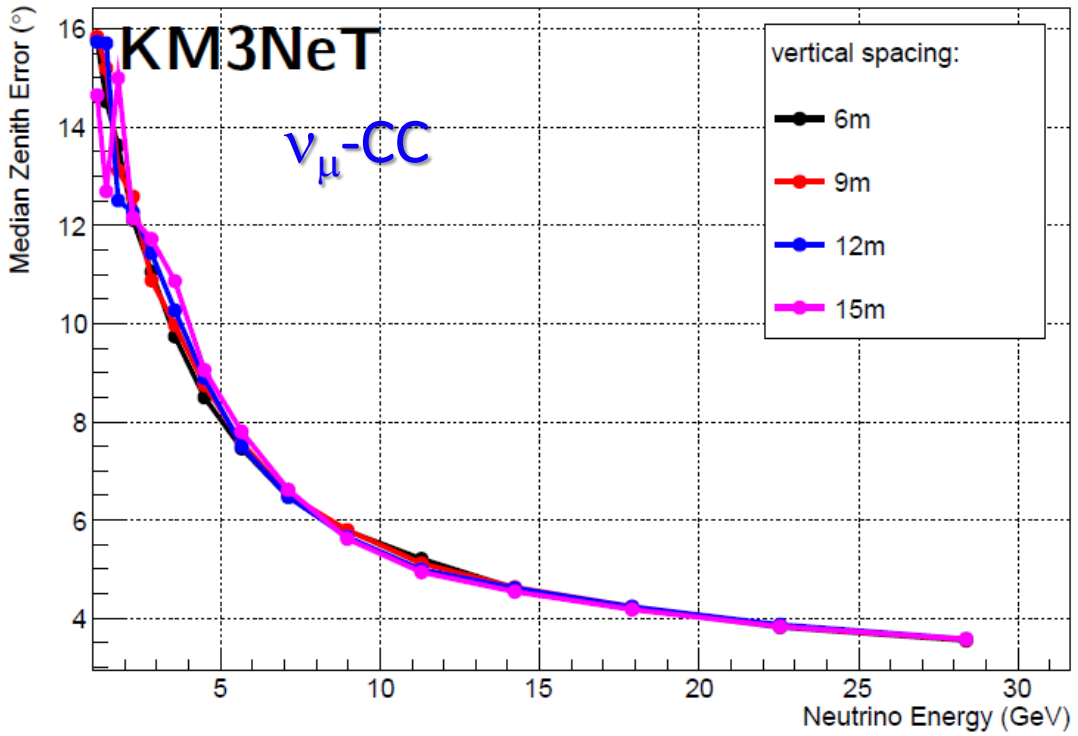
Atmospheric neutrino candidates selection in ORCA



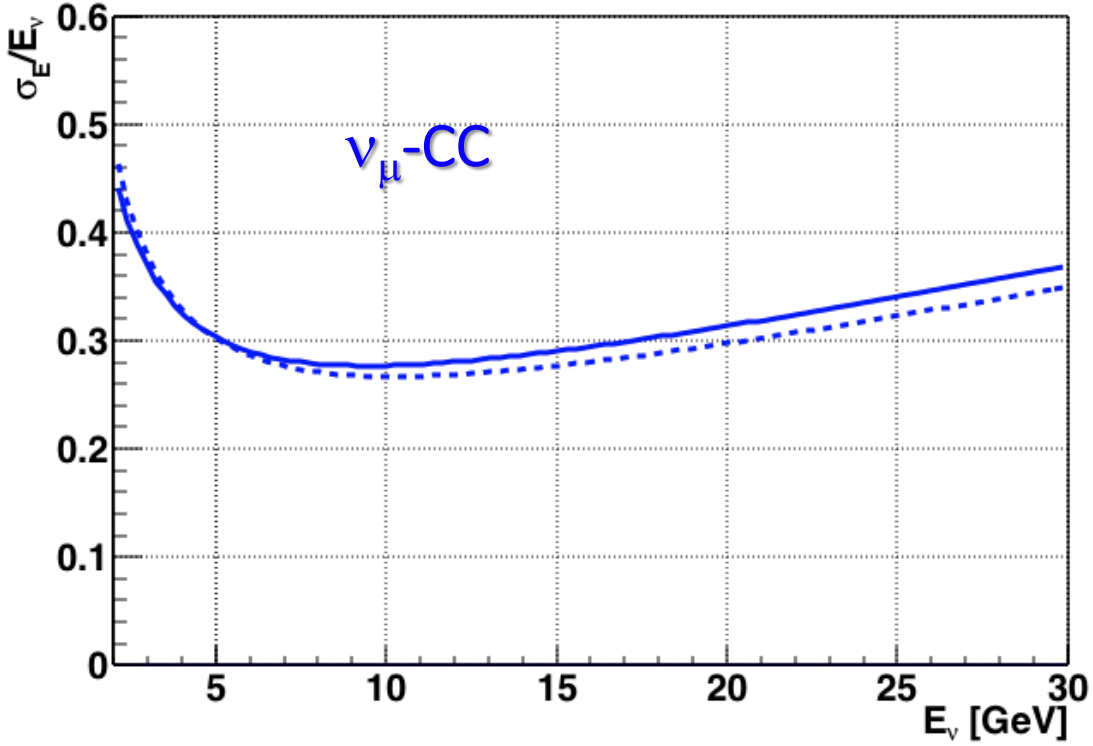




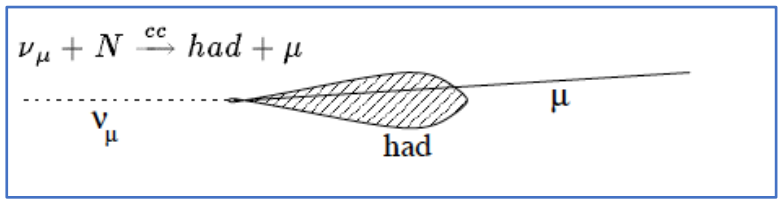
Resolution for track-like events from muon neutrinos



Angular resolution

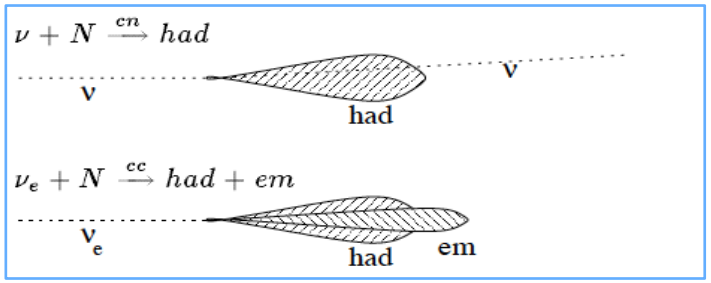


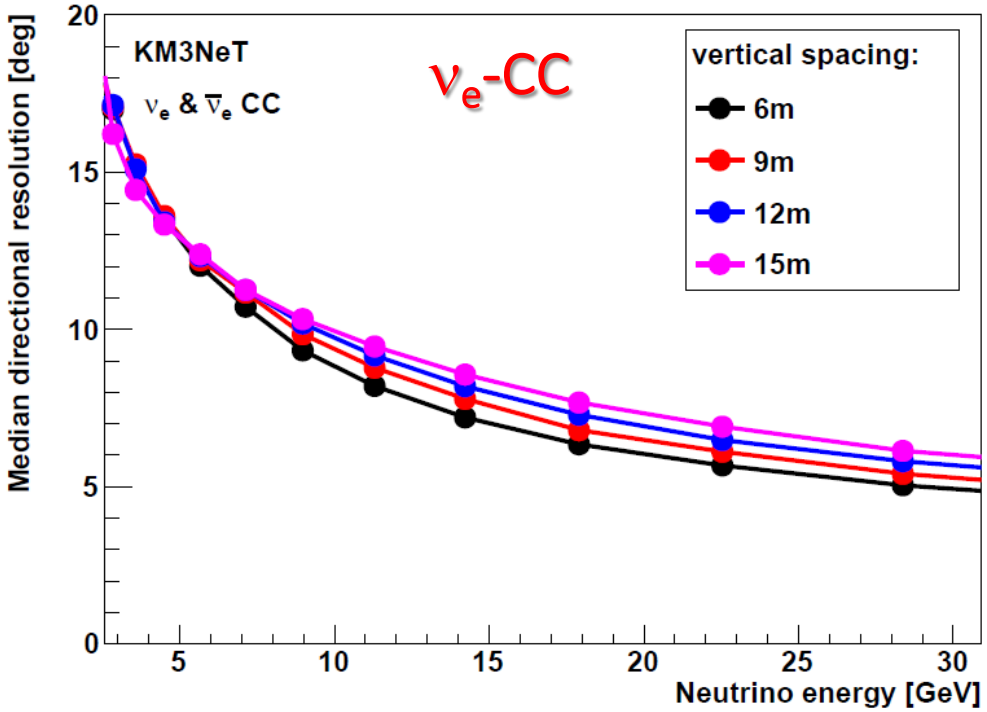
Energy resolution



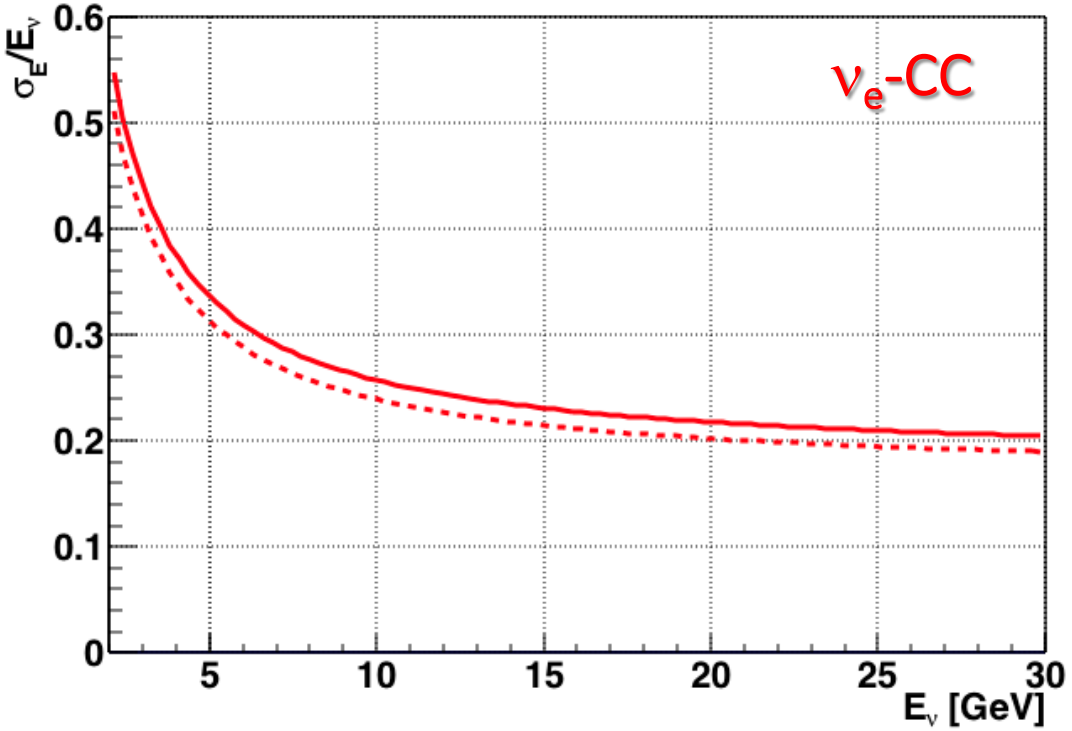
At low neutrino energies, tracks are short

Resolution for shower-like events from electron neutrinos



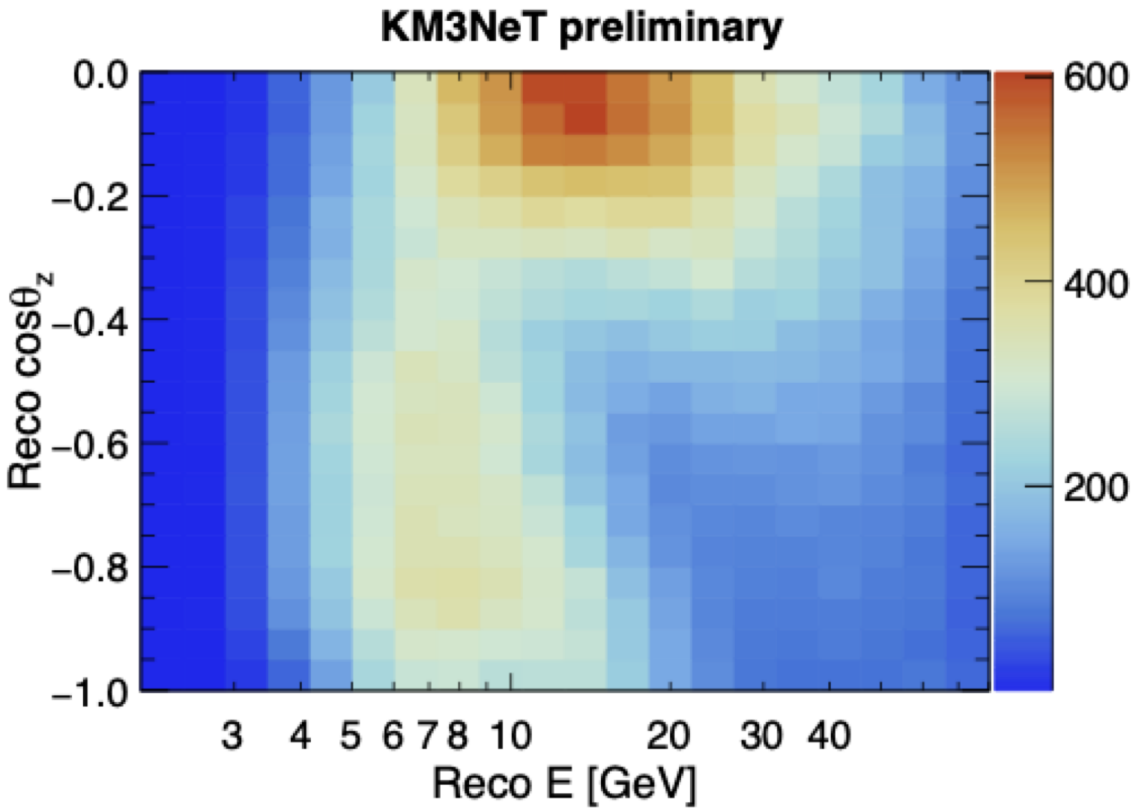


Angular resolution

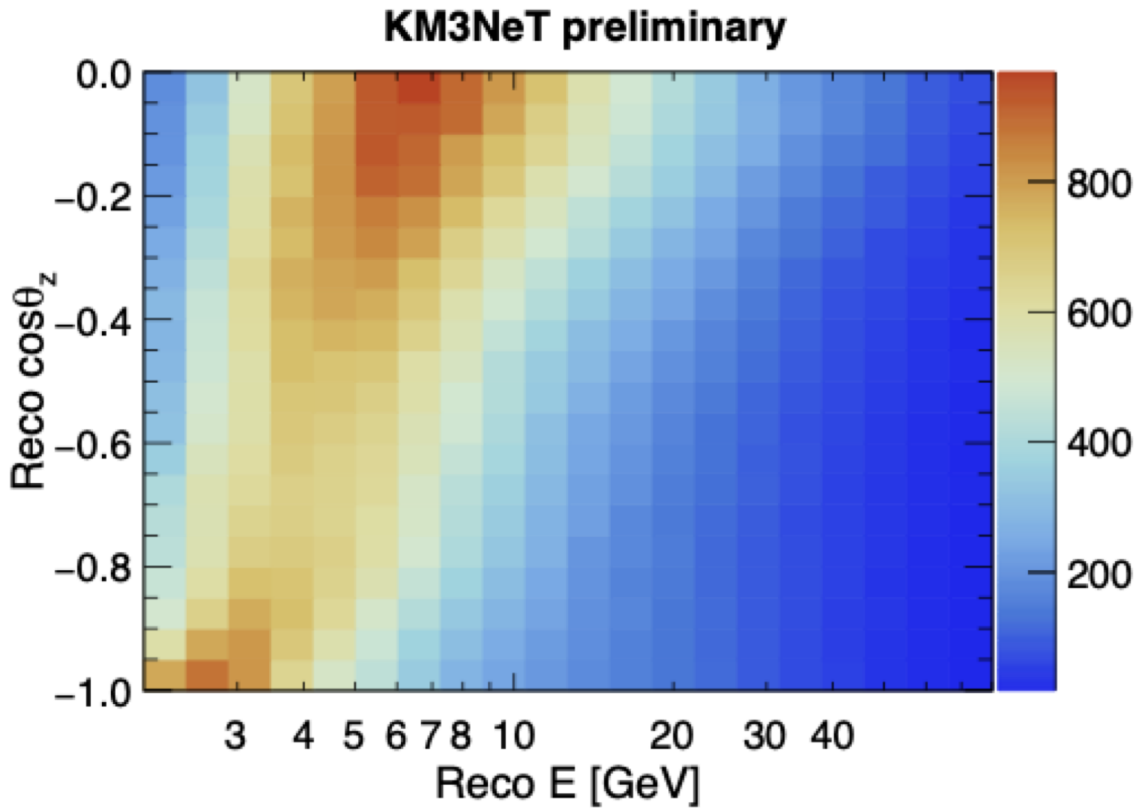


Energy resolution

Simulated event rates for 3-year full ORCA

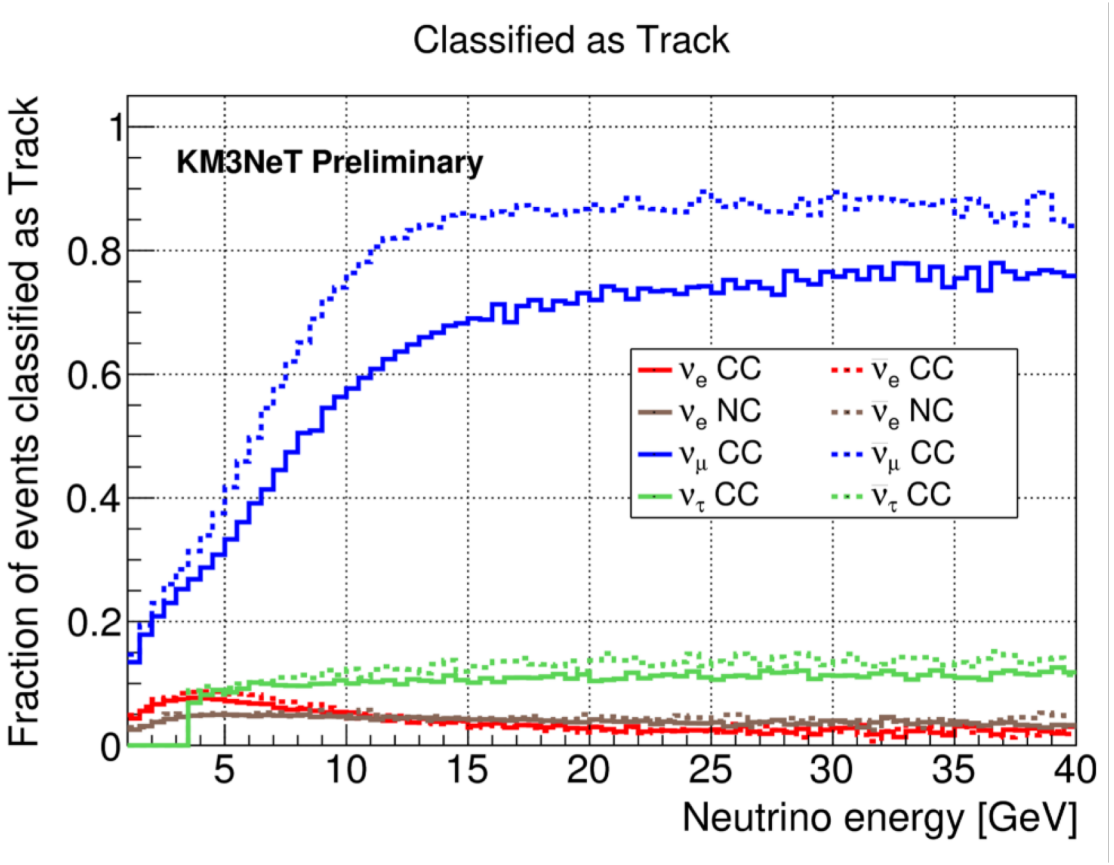


tracks

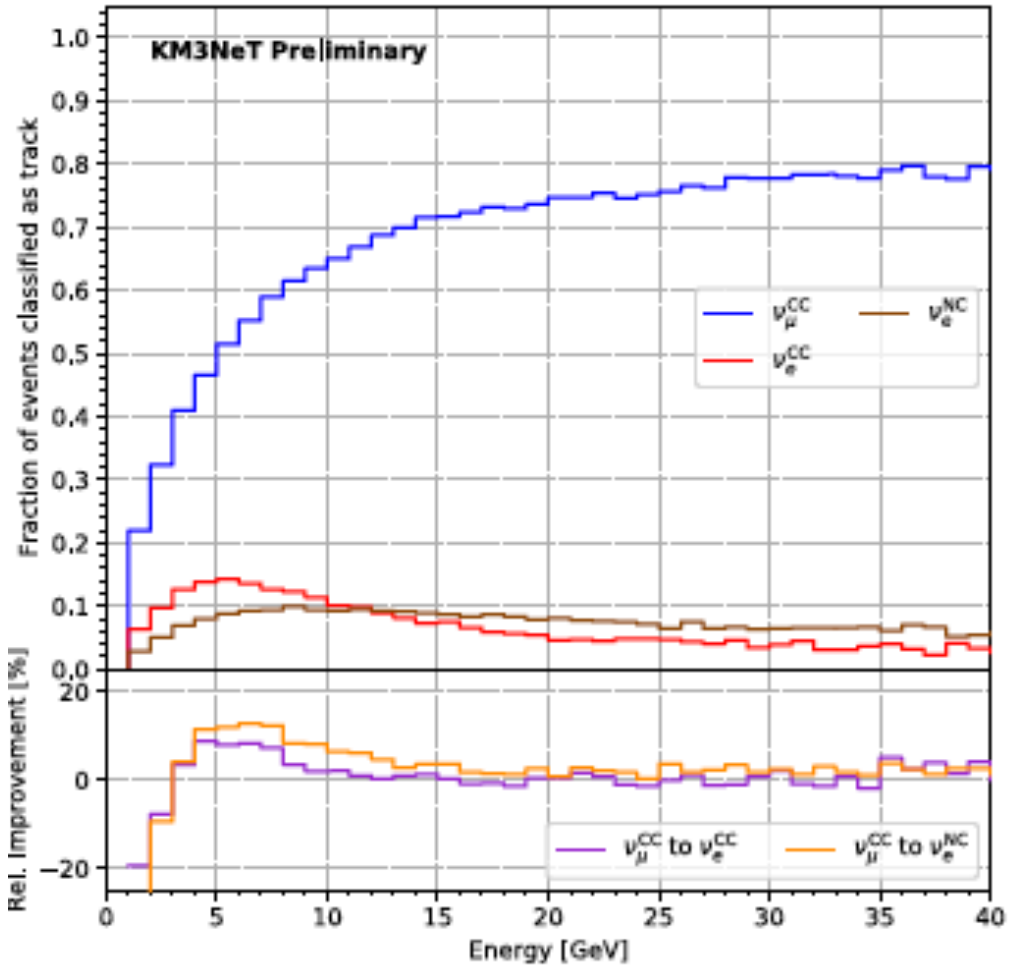


showers

Event classification, machine learning

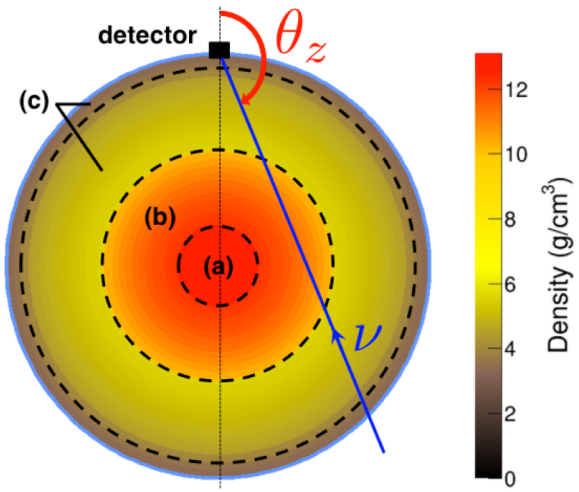


Conventional classifier



Convolutional neutral network

ORCA Oscillation physics



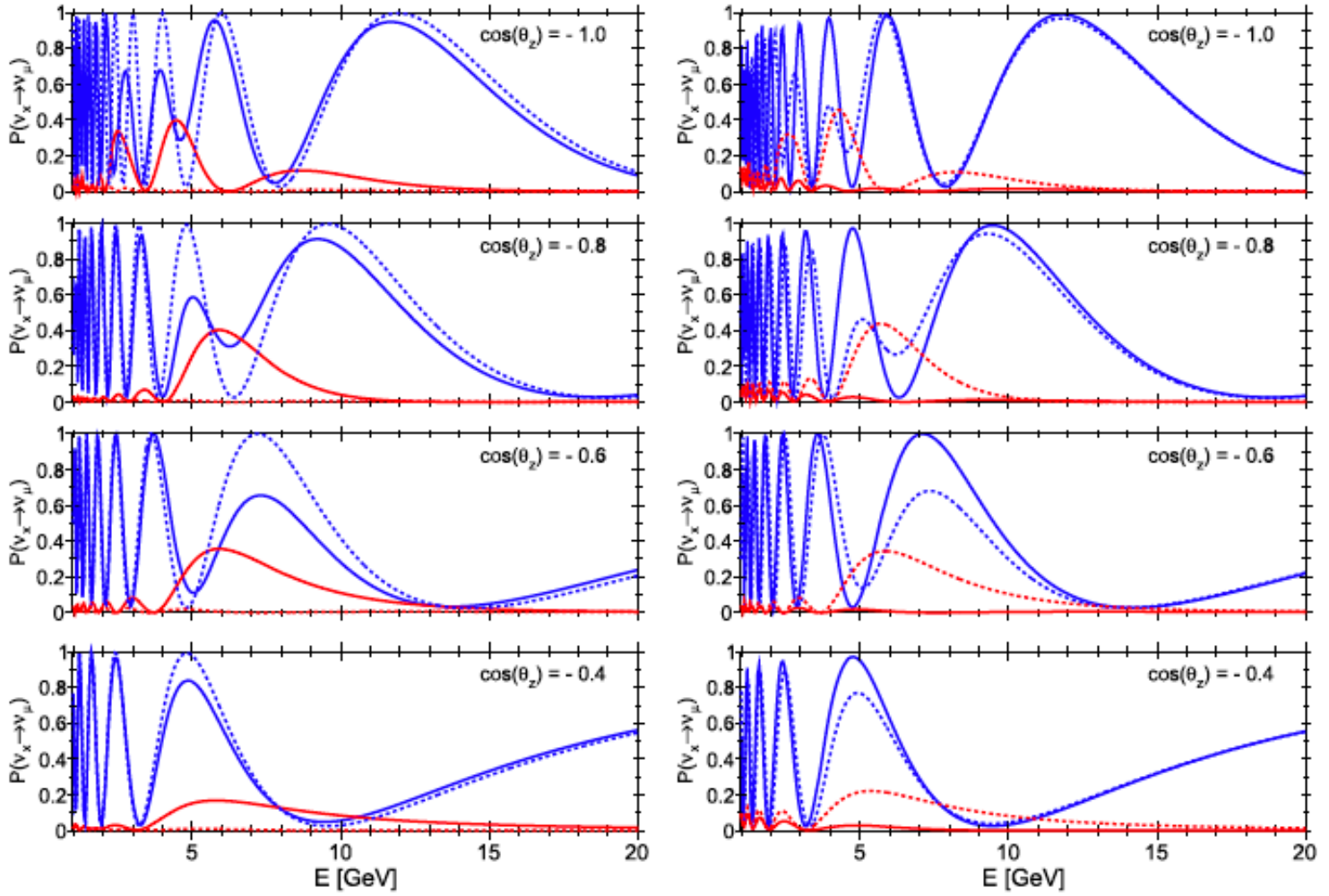
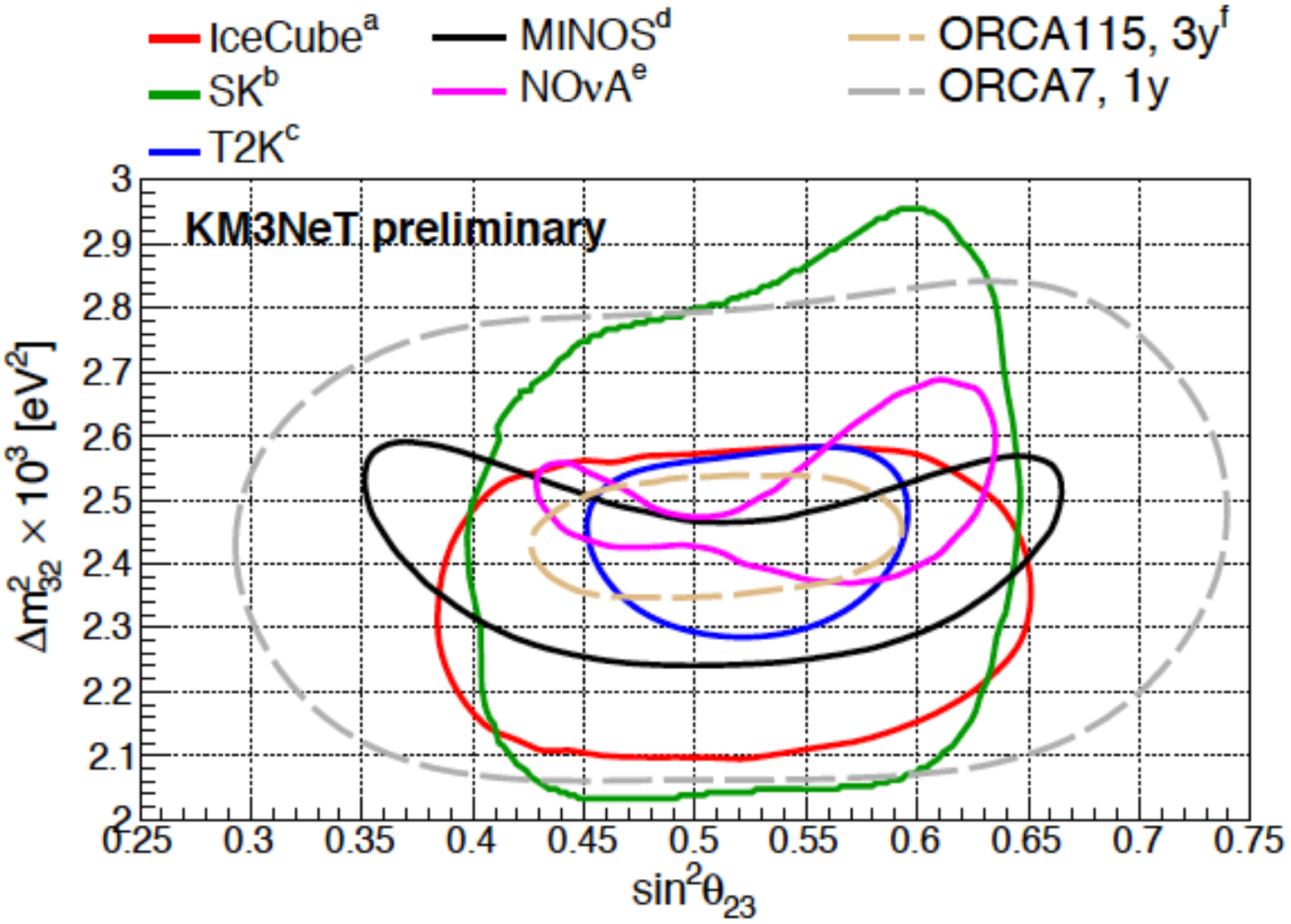
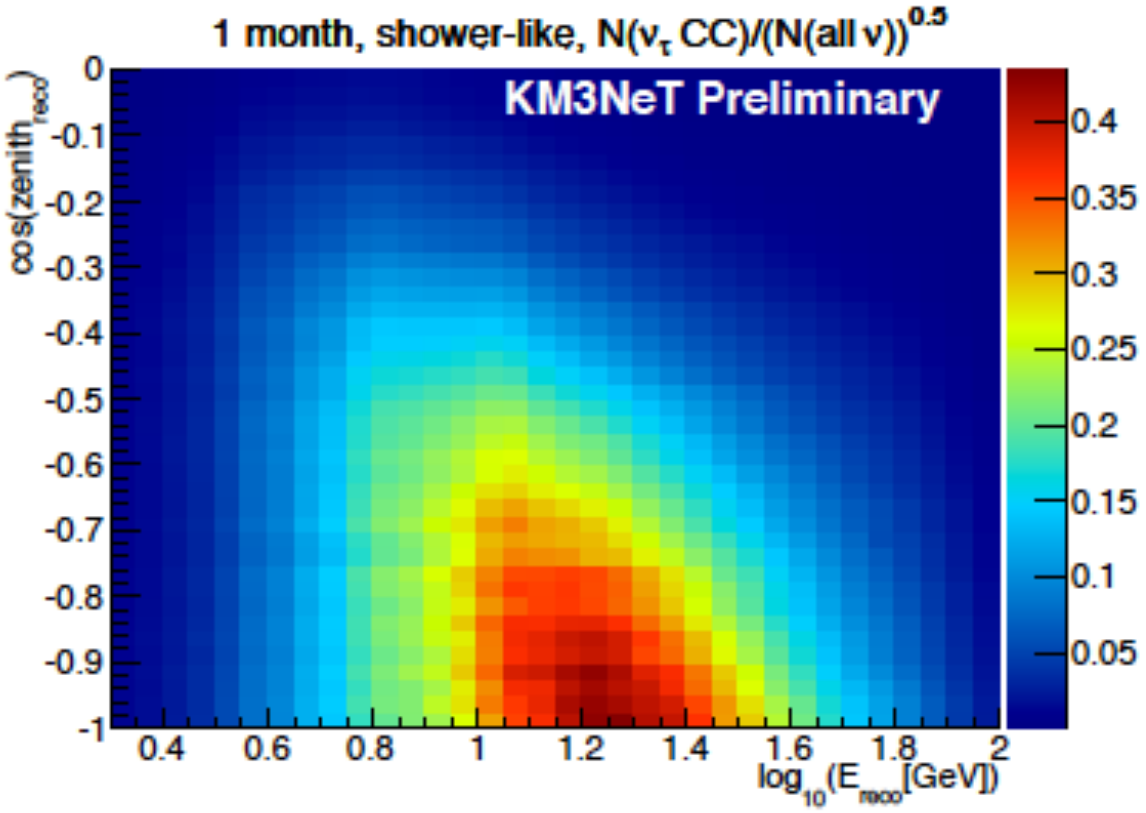


Figure 47. Oscillation probabilities $\nu_\mu \rightarrow \nu_\mu$ (blue lines) and $\nu_e \rightarrow \nu_\mu$ (red lines) as a function of the neutrino energy for several values of the zenith angle (corresponding to different baselines). The solid (dashed) lines are for NH (IH). For neutrinos (left) and for antineutrinos (right).

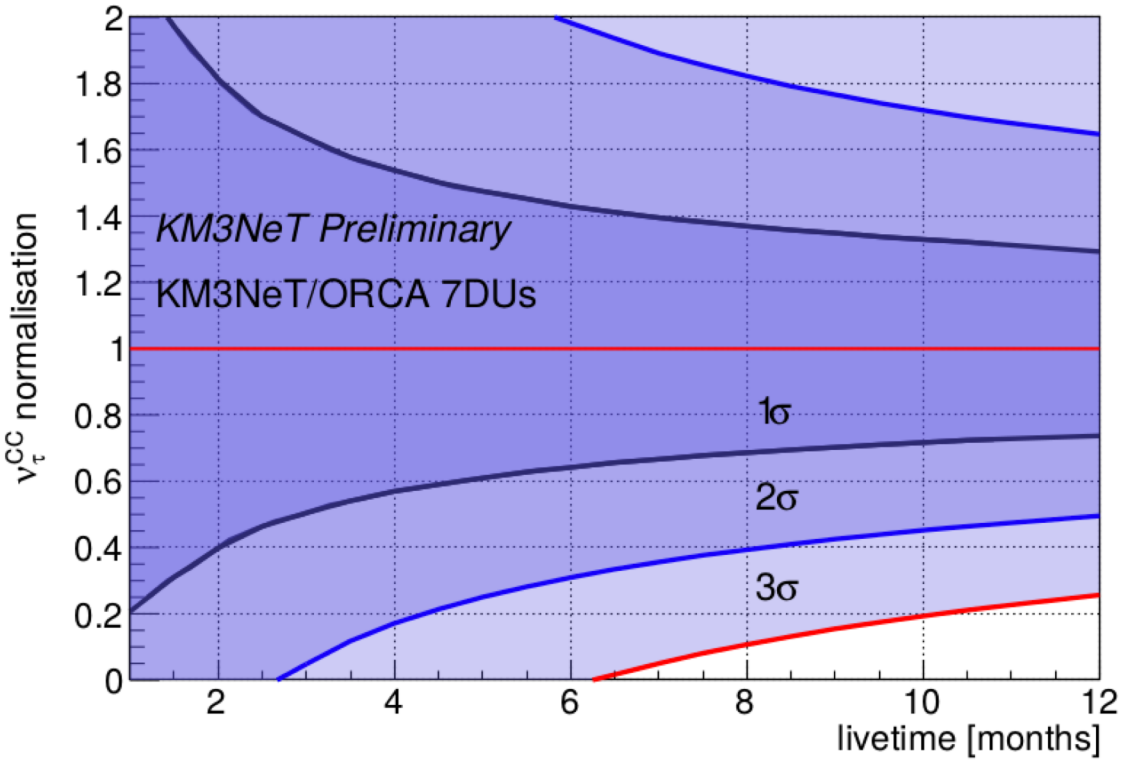
Expectations for oscillation parameter fit



Tau neutrino appearance and normalization

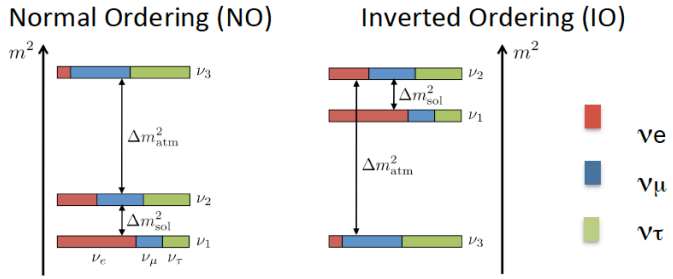


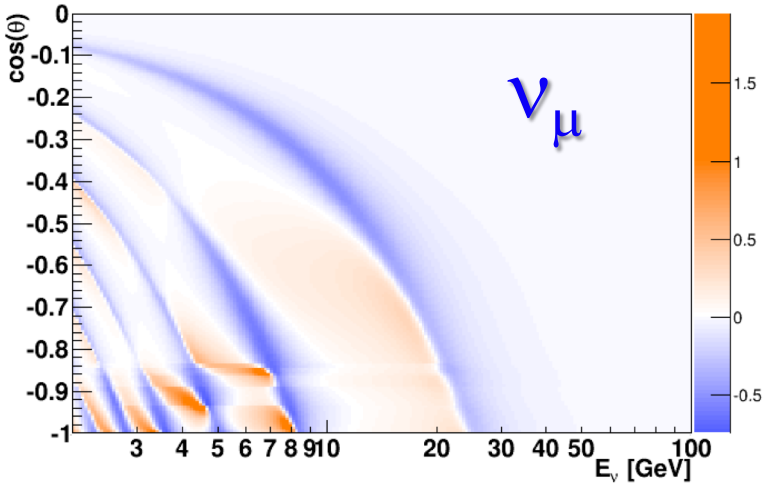
Significance 1 month full ORCA

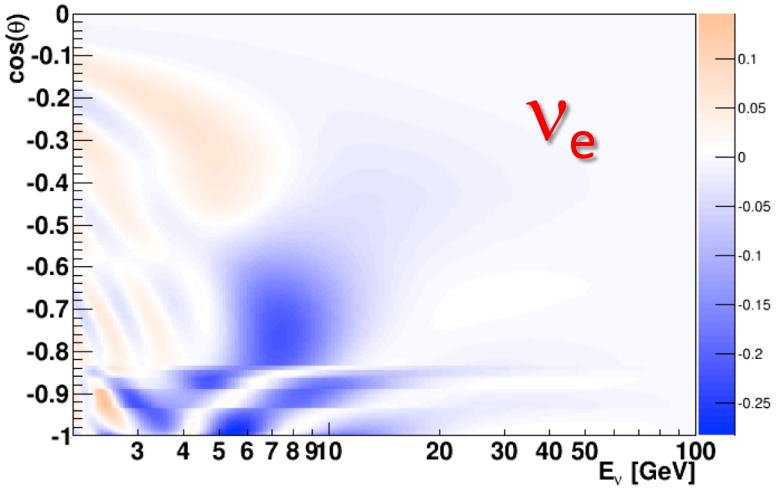


Normalization capability ORCA 7 DUs

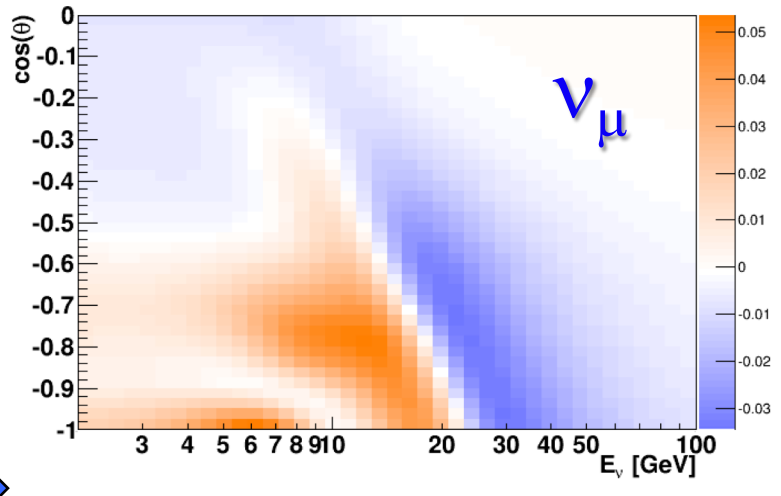
Asymmetry in expectation Normal Ordering / Inverted Ordering: $(N_{IO}-N_{NO})/N_{NO}$

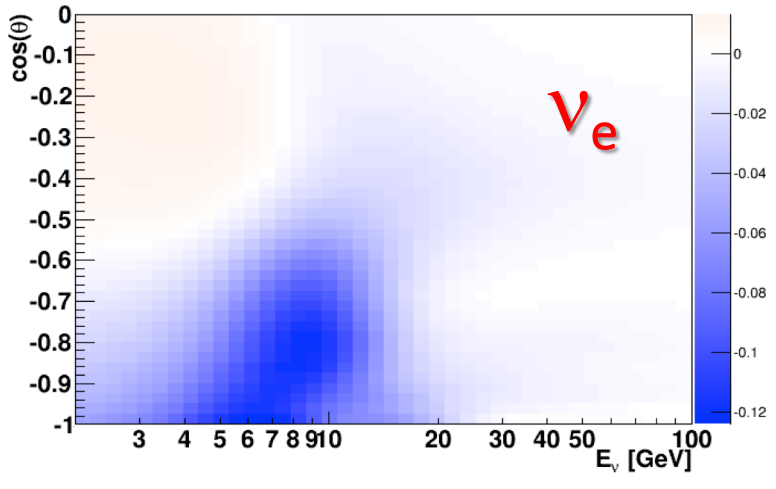




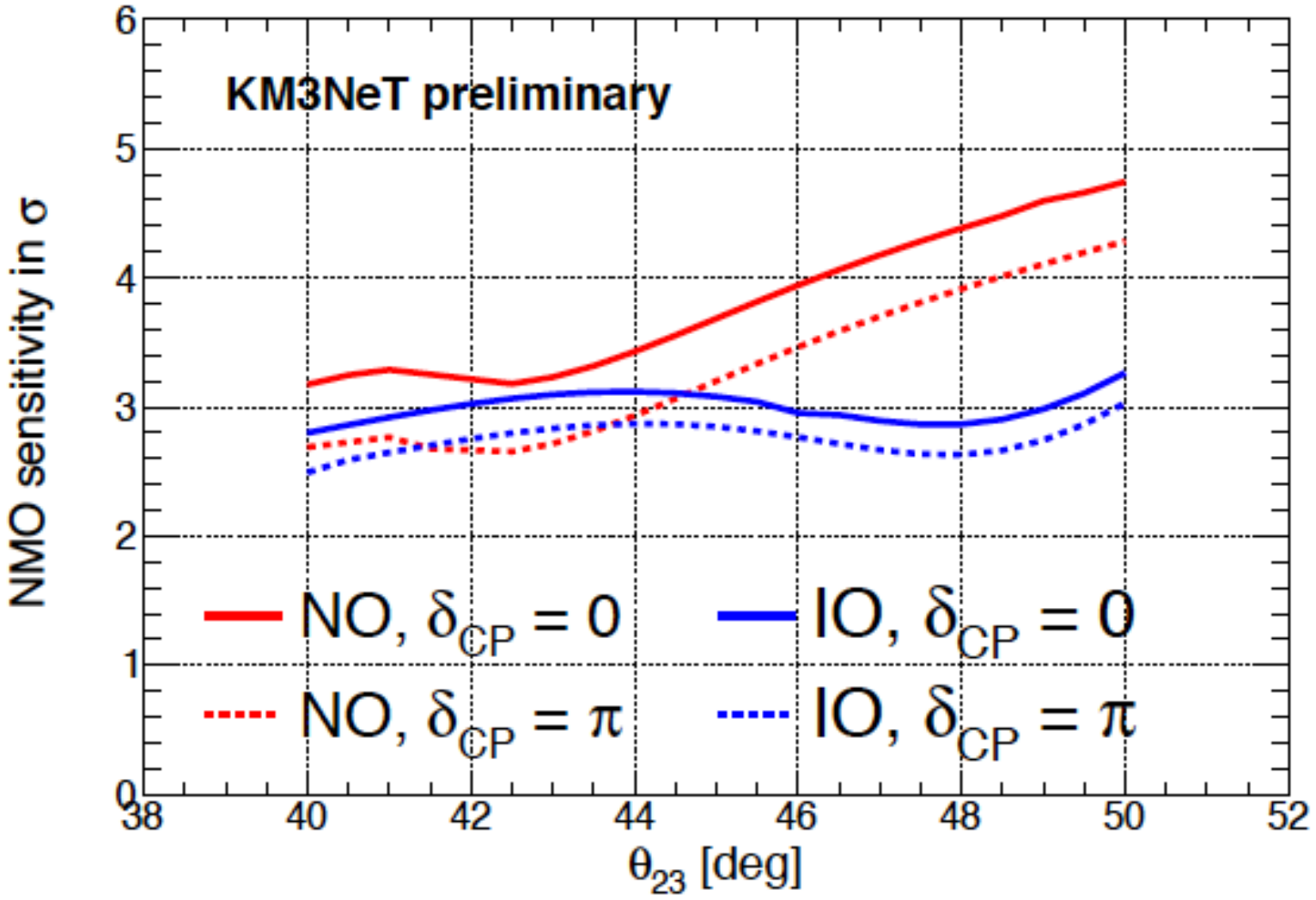


ORCA E,θ resolutions





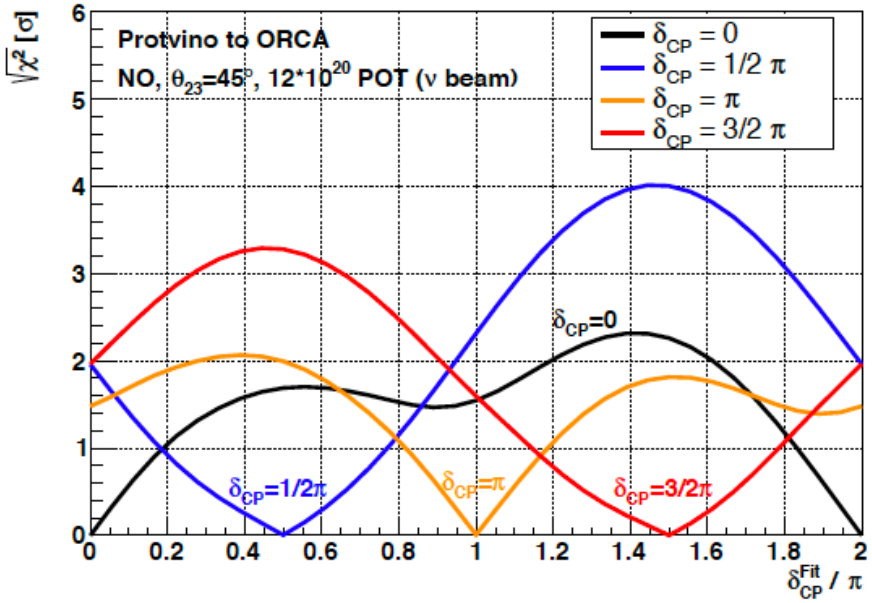
Sensitivity mass ordering full ORCA after 3 years

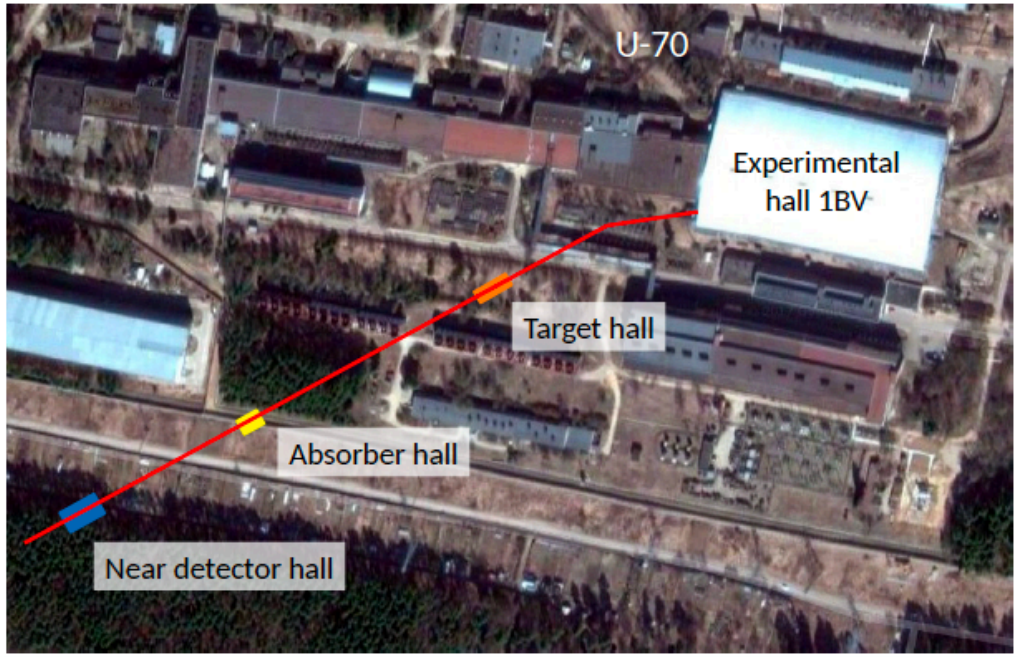


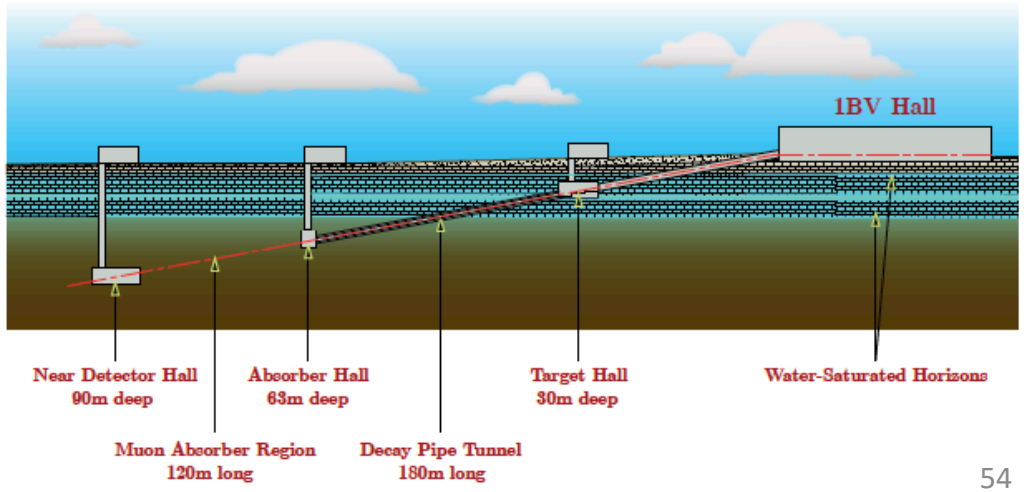
Improvements in pipeline

A neutrino beam from Protvino to ORCA (letter of interest 2019)

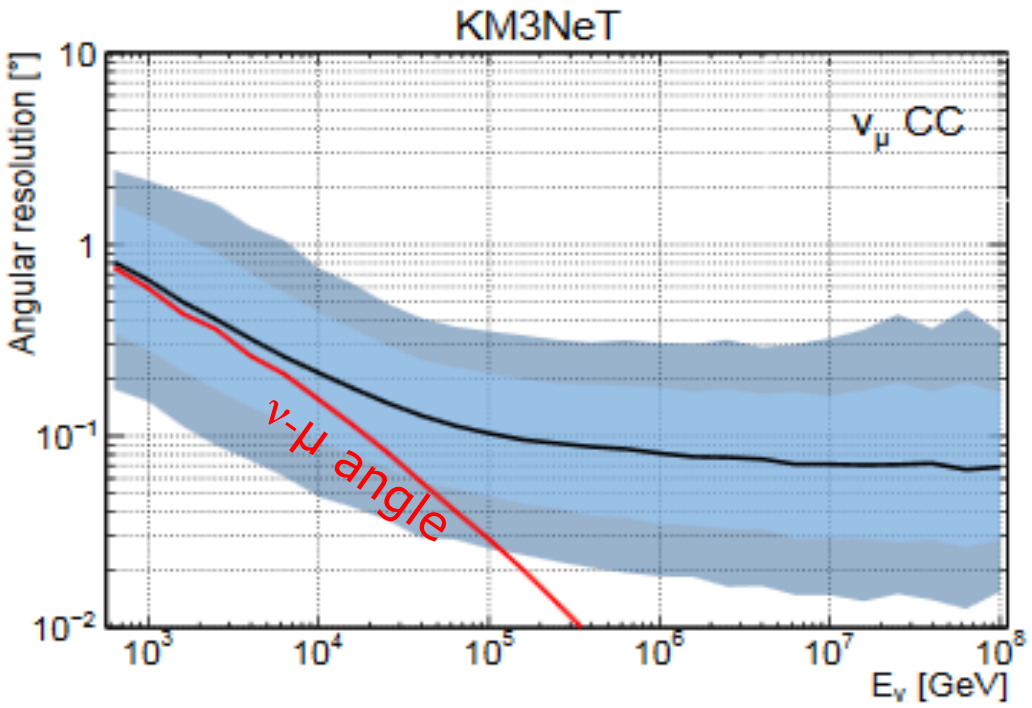
CP-violation: 3 years with 450 kW beam



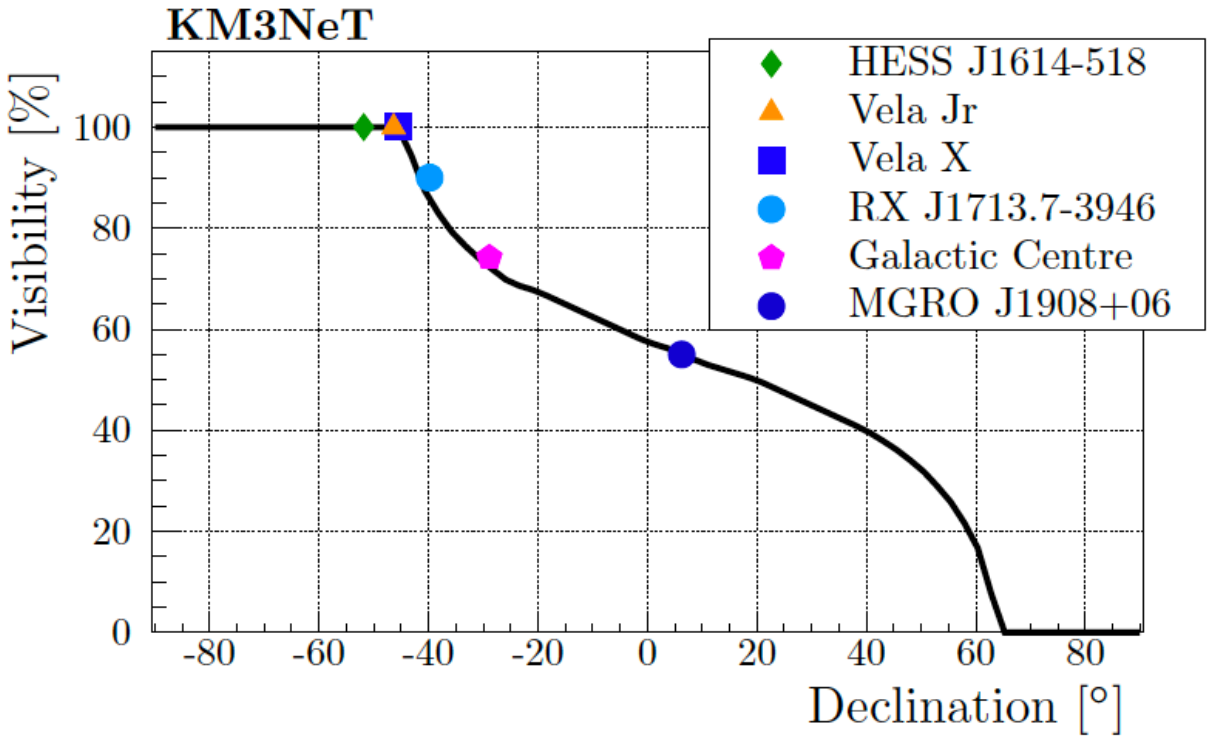




Expectations for ARCA

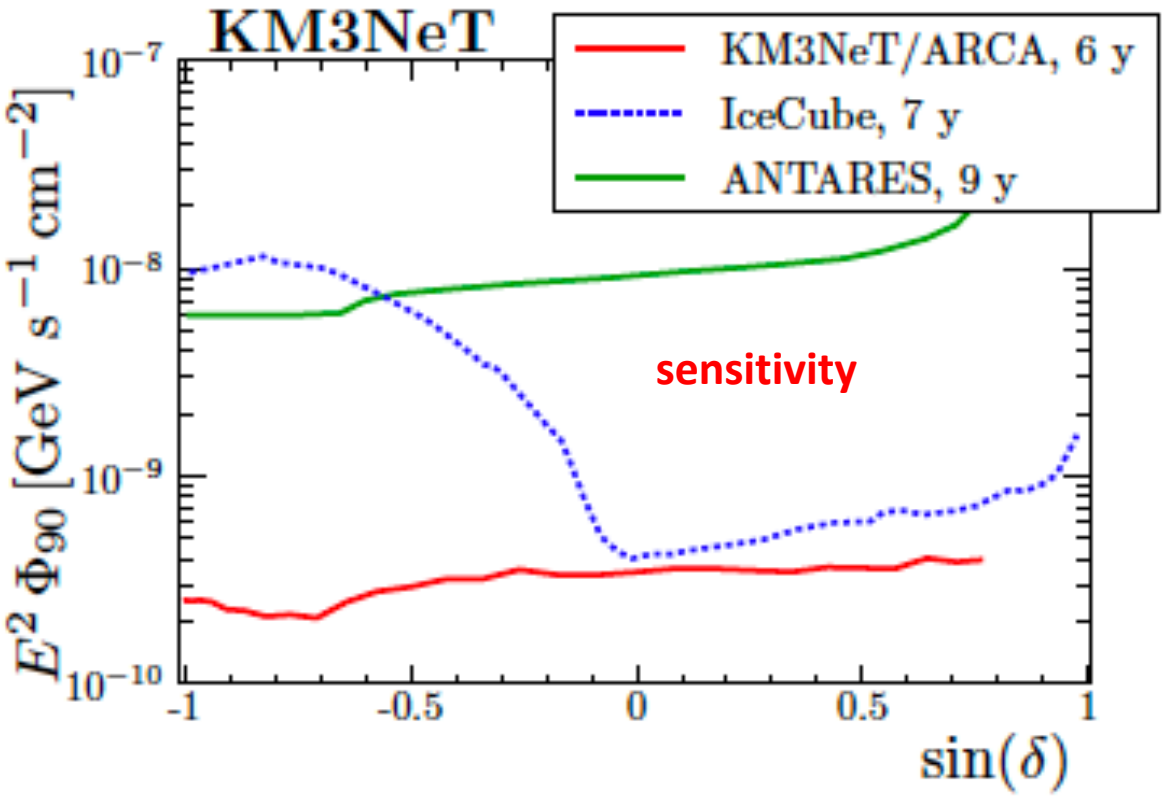


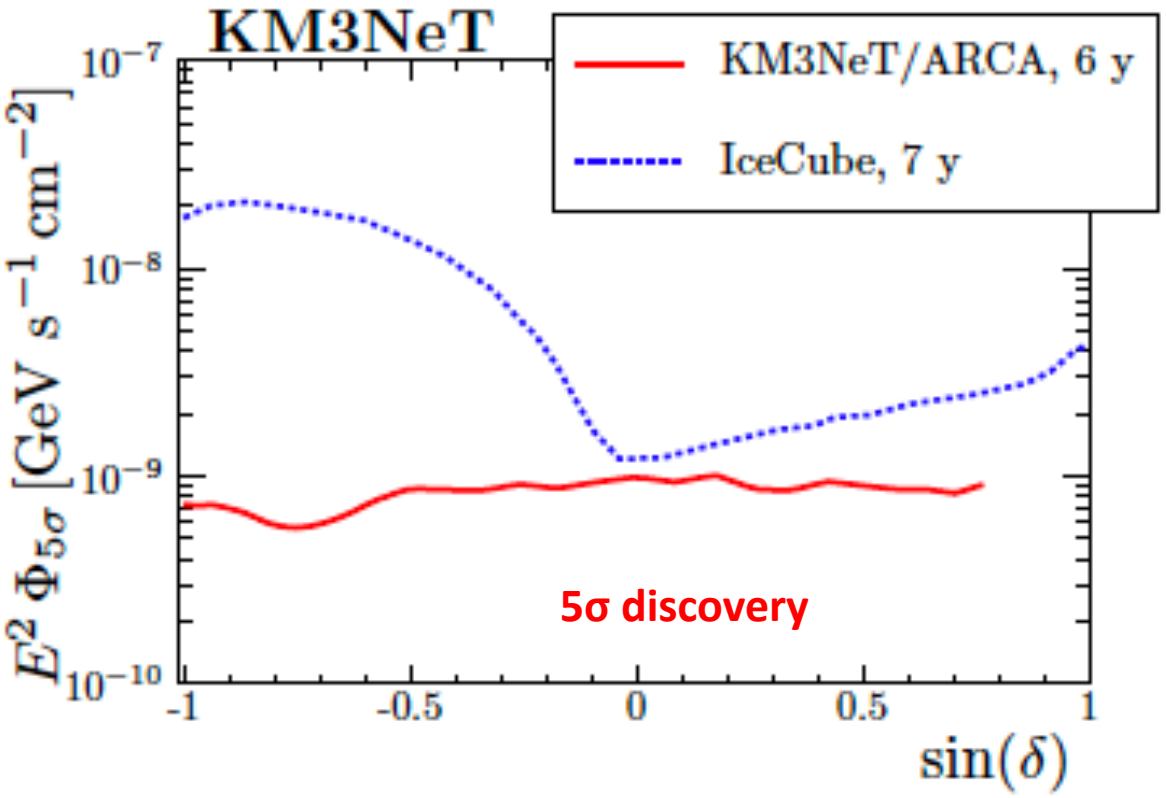
Angular resolution



Visibility of interesting objects

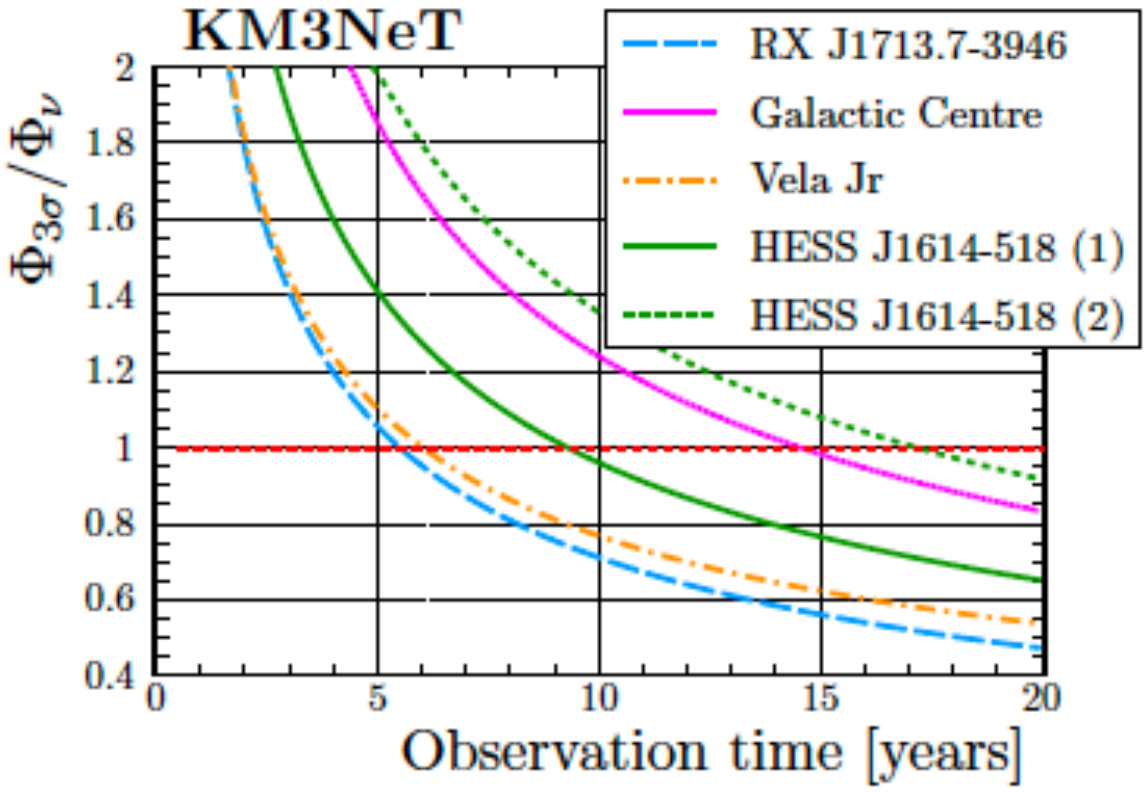
Sensitivity and discovery flux expectations



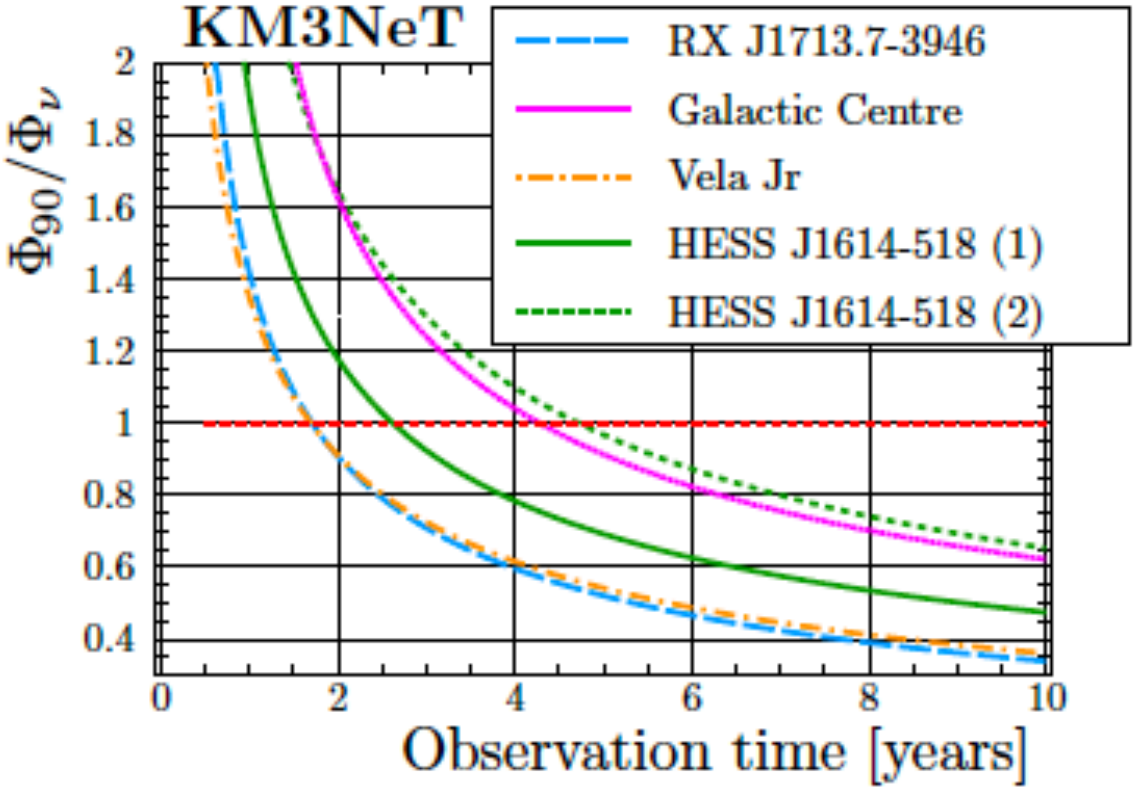


For E^{-2} spectrum

Time needed for discovery or exclusion of expected fluxes for various objects

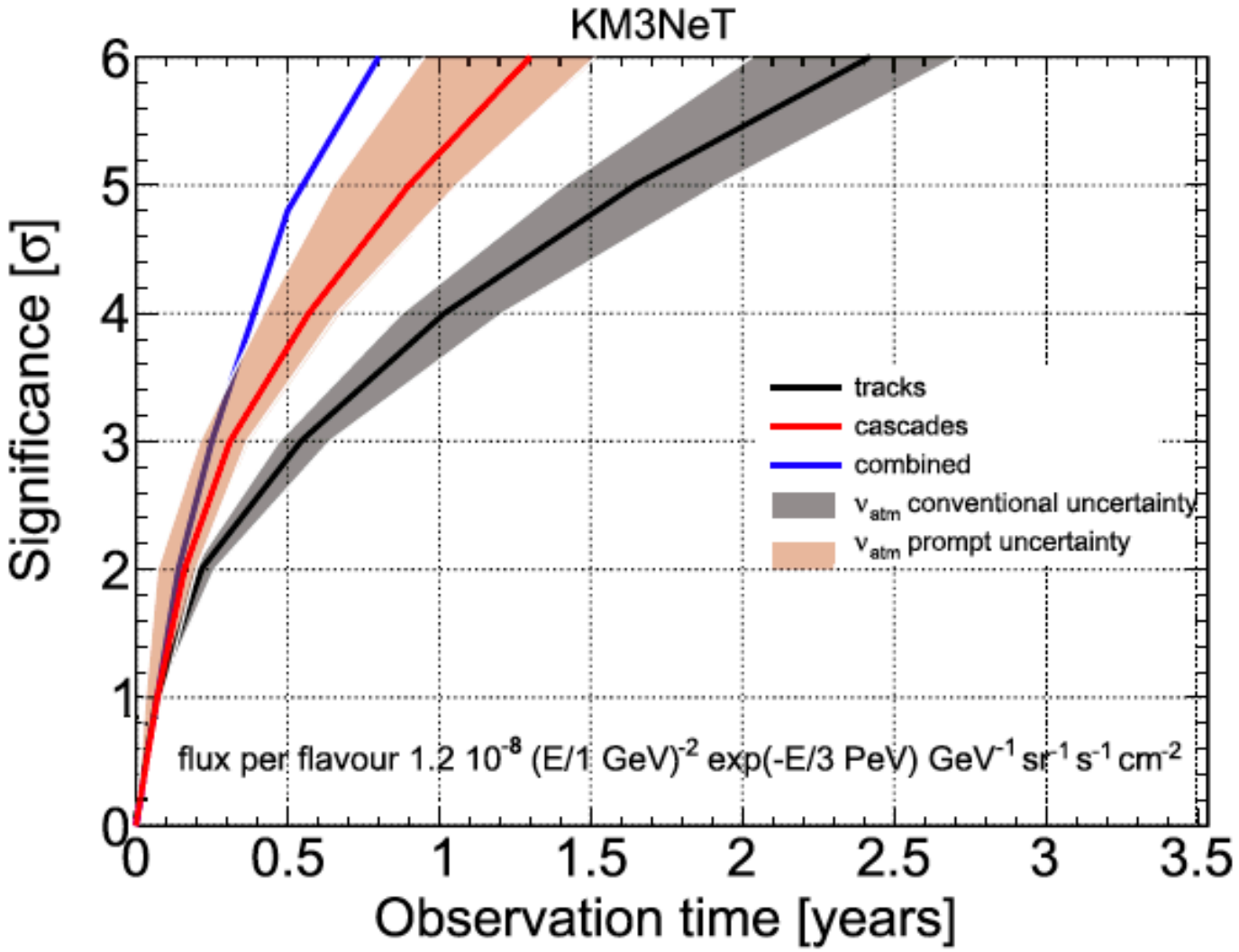


discovery



exclusion

Expected time needed for observation of diffuse cosmic flux



Summary and conclusions

Antares has been a pioneer deep-sea neutrino telescope
After 12 years, time for retirement

Successor KM3NeT is slowly getting off the ground
Data taking ORCA with 4 (soon 6) lines
Data/simulation looks good, first neutrinos seen
On target for oscillation physics soon
ARCA sea-floor network ready for more lines in 2020
DOMs for 25 lines already available, mass-production 2020