The KM3NeT Project and Collider Neutrinos

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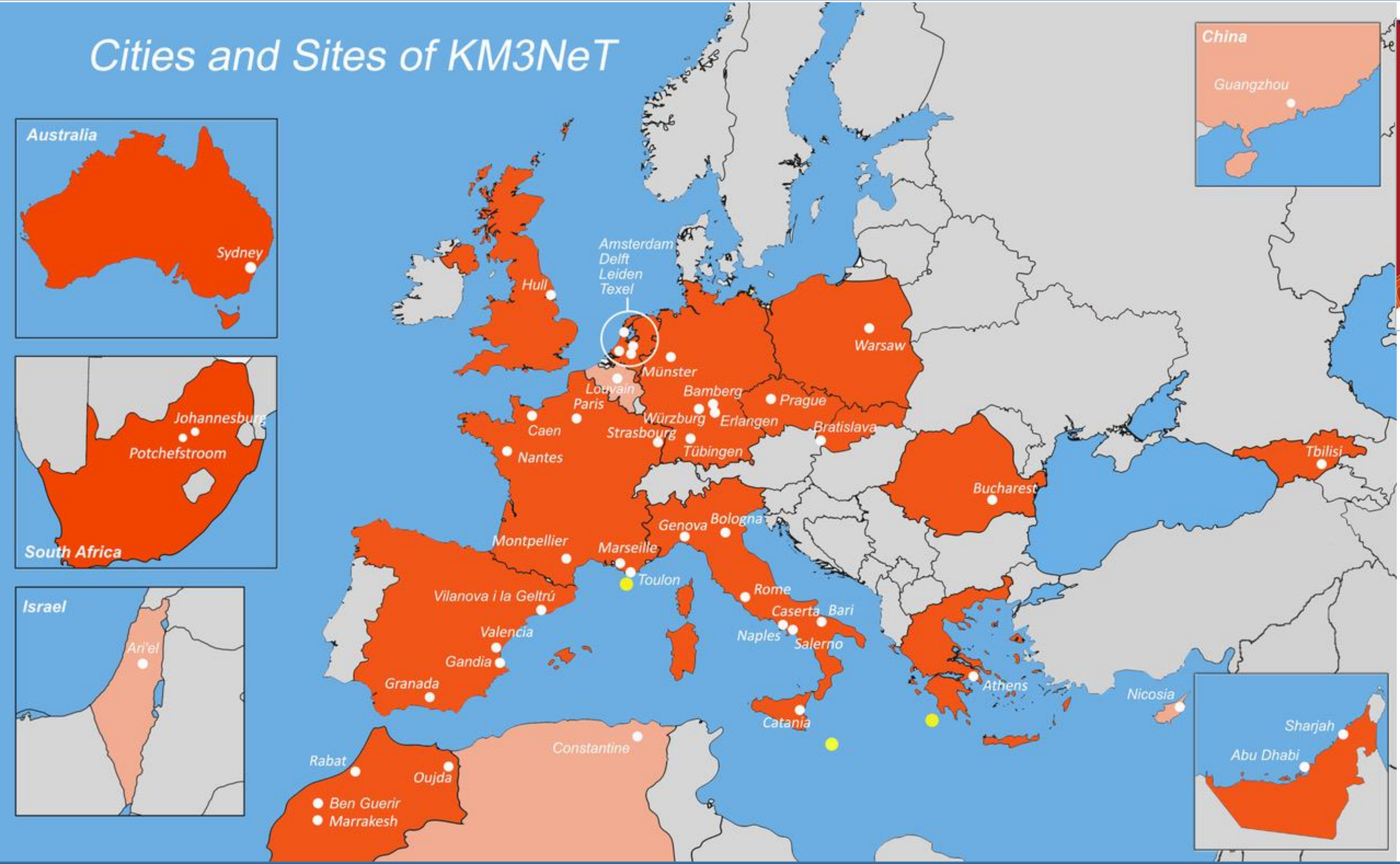
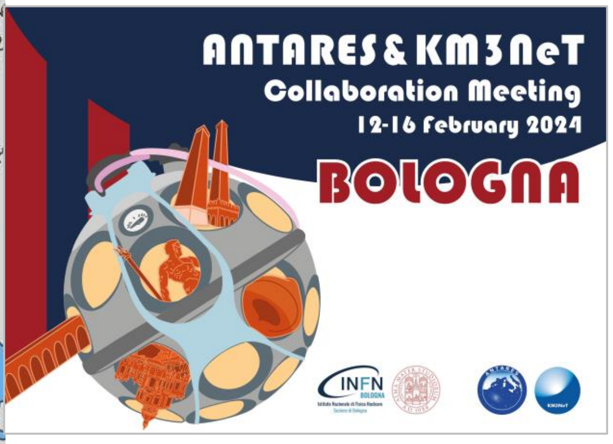
IJCLab, Orsay

27 February 2024

FR-22-13708

The KM3NeT Collaboration





New members:

Drexel University
Philadelphia, US
Naoko Kurahashi Neilson

Universidade Federal
de Alfenas, Brasil
Cássius A. Miquelede Melo

Content

- ❖ Introduction: Neutrinos and Cherenkov detectors
- ❖ Neutrino astronomy: from idea to Neutrino Telescopes (from DUMAND to IceCube and ANTARES)
- ❖ The KM3NeT Mediterranean distributed neutrino Telescopes(s) (ORCA and ARCA)
- ❖ Accelerator neutrinos and the first detection of Collider Neutrinos (The FASER and SND@LHC experiments)
- ❖ Collider neutrinos in KM3NeT?

History of Neutrino

Invention of a new particle

Neutrinos in Nature –
Interdisciplinary aspects

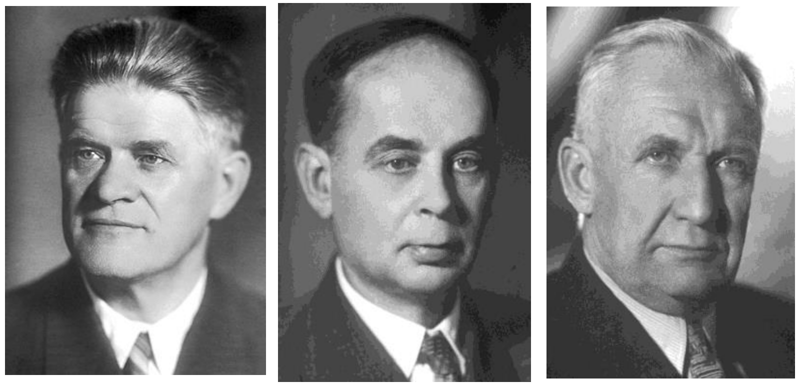
Man-made sources of neutrinos

Quantum mechanics at work:
oscillations & particle physics

Neutrinos and
fundamental particle physics

Messengers of the Universe
and role in other disciplines

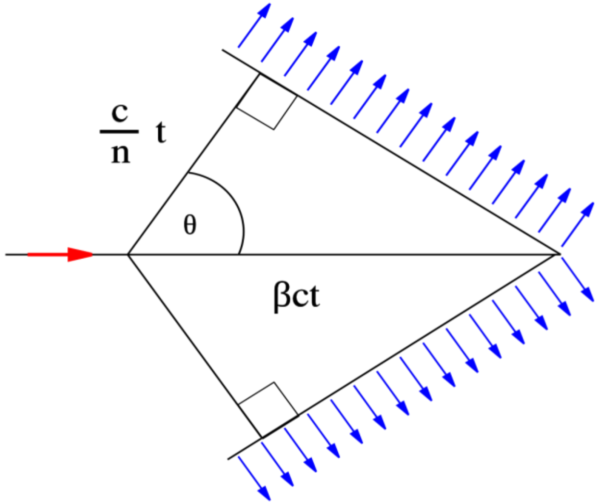
Cherenkov Radiation



P. Cherenkov (1904-1990),
I. Frank (1908-1990), I.Tamm(1895-1971)

1958

- ❖ Was discovered by Pavel Cherenkov 1934 (PhD student of N. Vavilov)
- ❖ Charged particle induced radiation, when $\beta_c > \frac{1}{n}$
- ❖ Interpretation of "Cherenkov effect": I. Frank and I. Tamm (1937)



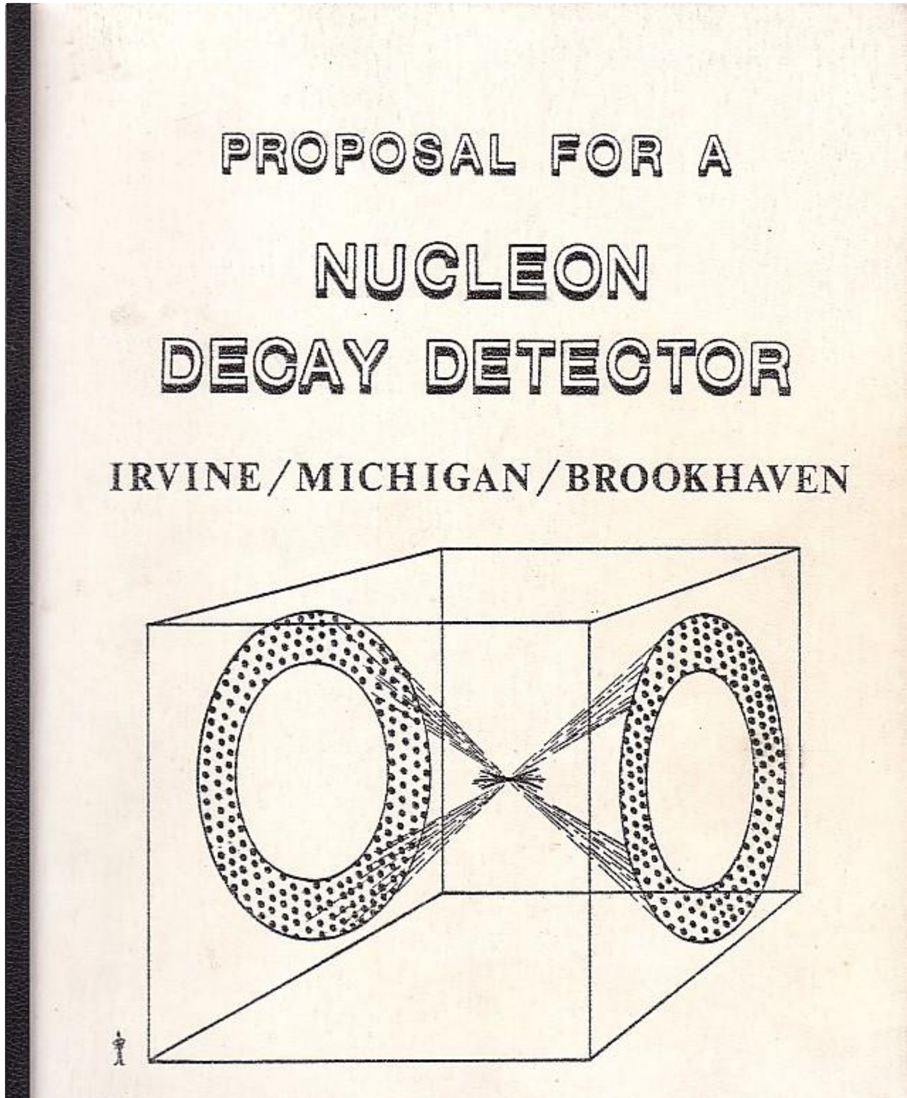
For n=1.33, $\beta_c > 0.76$

Electron kinetic energy > 0.26 MeV

Muon kinetic energy > 55 MeV

Cherenjov angle Θ_c 42^o

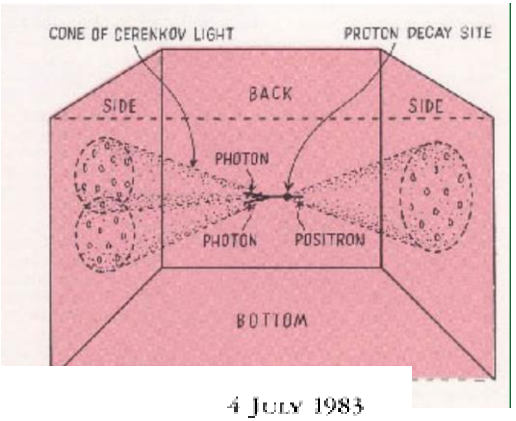
Cherenkov Detectors for Proton Decay



May 1979: sent to US DOE

Prediction from GUT models:

$$p \rightarrow \pi^o e^+$$
$$\pi^o \rightarrow \gamma\,\gamma$$



VOLUME 51, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1983

Search for Proton Decay into $e^+\pi^0$

R. M. Bionta, G. Blewitt, C. B. Bratton, B. G. Cortez,[a] S. Errede, G. W. Forster,[a] W. Gajewski, M. Goldhaber, J. Greenberg, T. J. Haines, T. W. Jones, D. Kielczewska,[b] W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, P. V. Ramana Murthy,[c] H. S. Park, F. Reines, J. Schultz, E. Shumard, D. Sinclair, D. W. Smith,[d] H. W. Sobel, J. L. Stone, L. R. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

The University of California at Irvine, Irvine, California 92717, and The University of Michigan, Ann Arbor, Michigan 48109, and Brookhaven National Laboratory, Upton, New York 11973, and California Institute of Technology, Pasadena, California 91125, and Cleveland State University, Cleveland, Ohio 44115, and The University of Hawaii, Honolulu, Hawaii 96822, and University College, London WC1E 6BT, United Kingdom

(Received 13 April 1983)

Observations were made 1570 meters of water equivalent underground with an 8000-metric-ton water Cherenkov detector. During a live time of 80 d no events consistent with the decay $p\rightarrow e^+\pi^0$ were found in a fiducial mass of 3300 metric tons. It is concluded that the limit on the lifetime for bound plus free protons divided by the $e^+\pi^0$ branching ratio is $\tau/B > 6.5\times10^{31}$ yr; for free protons the limit is $\tau/B > 1.9\times10^{31}$ yr (90% confidence). Observed cosmic-ray muons and neutrinos are compatible with expectations.

PACS numbers: 13.30.Eg, 11.30.Ly, 14.20.Dh

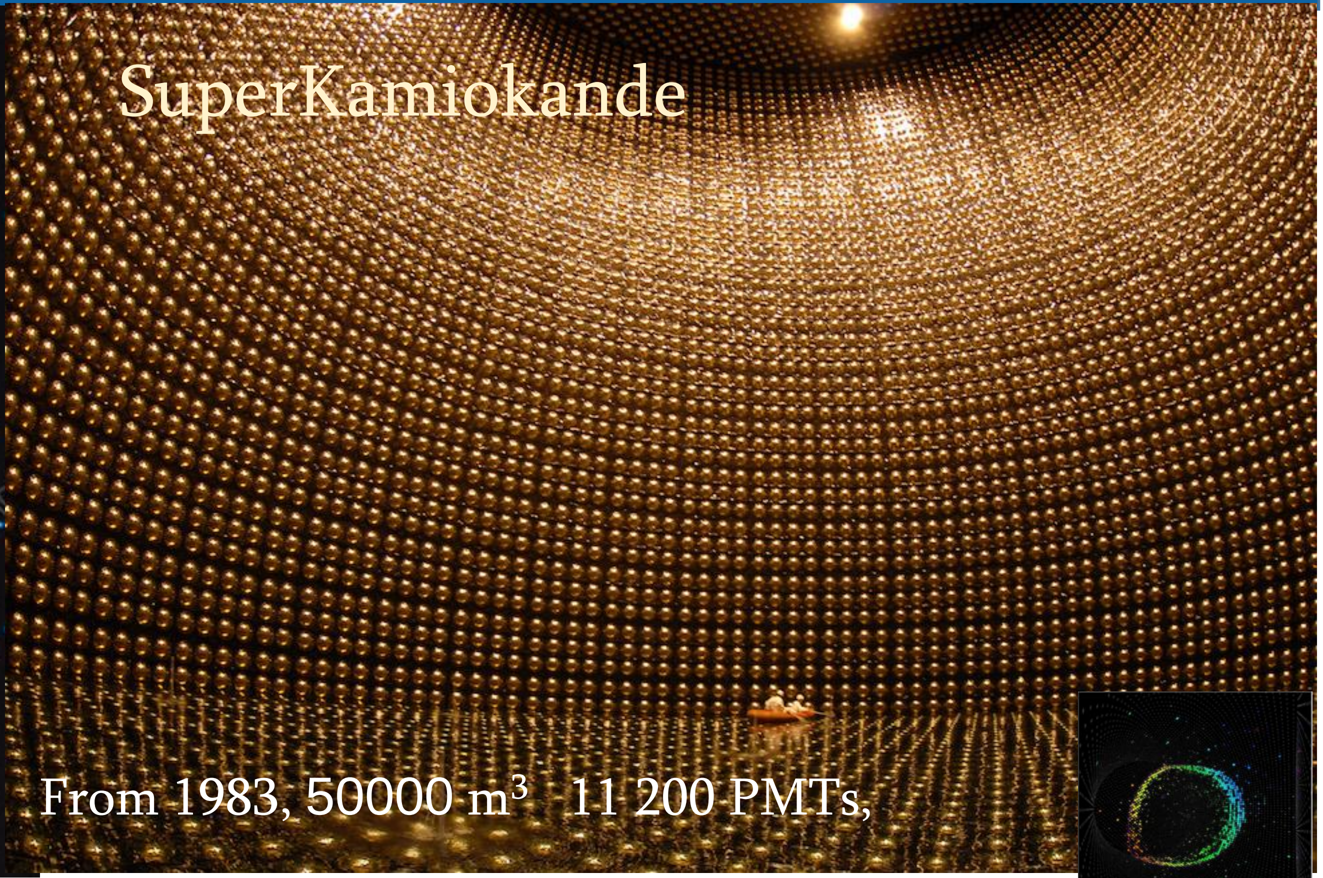
Current limit: $\tau_p > 1.67\times10^{34}$ y

Cherenkov Detectors: IMB and Kamiokande

IMB

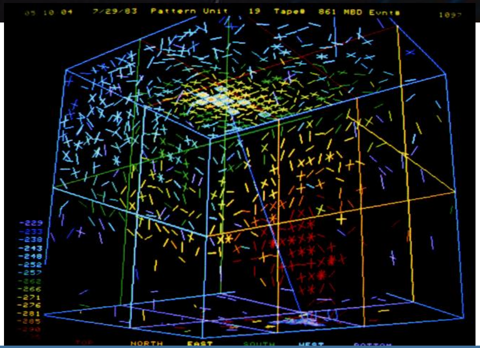
1981-1991, 17×17.5×23 m^3 2048 PMTs,

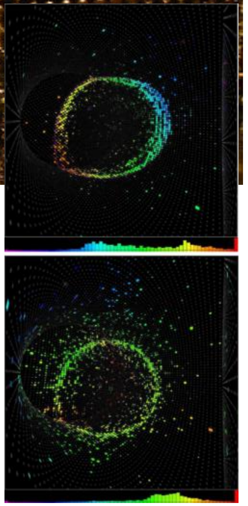
https://public.websites.umich.edu/~jcv/imb/imbp3.html



SuperKamiokande

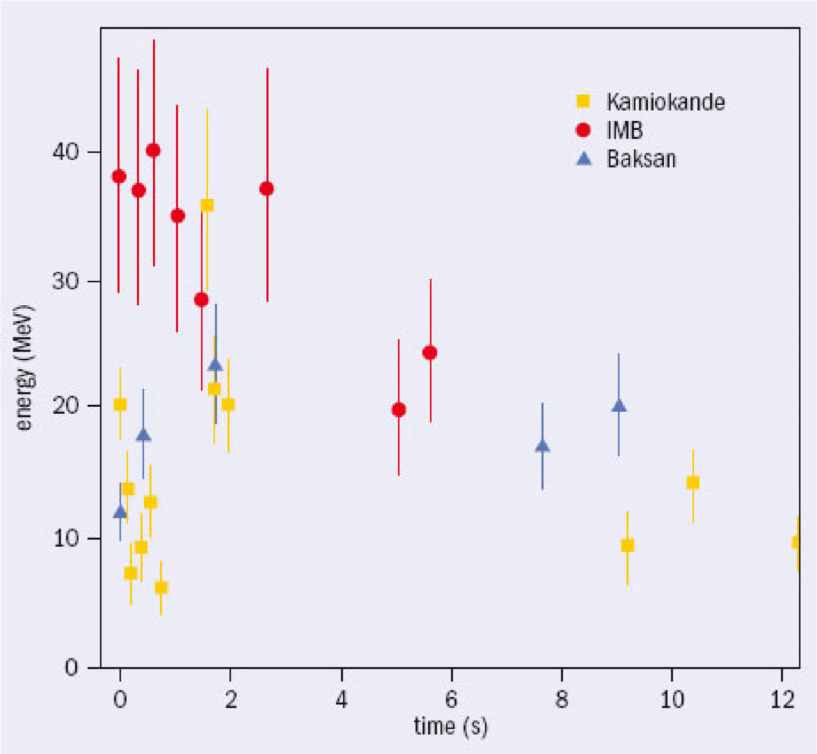
From 1983, 50000 m^3 11 200 PMTs,

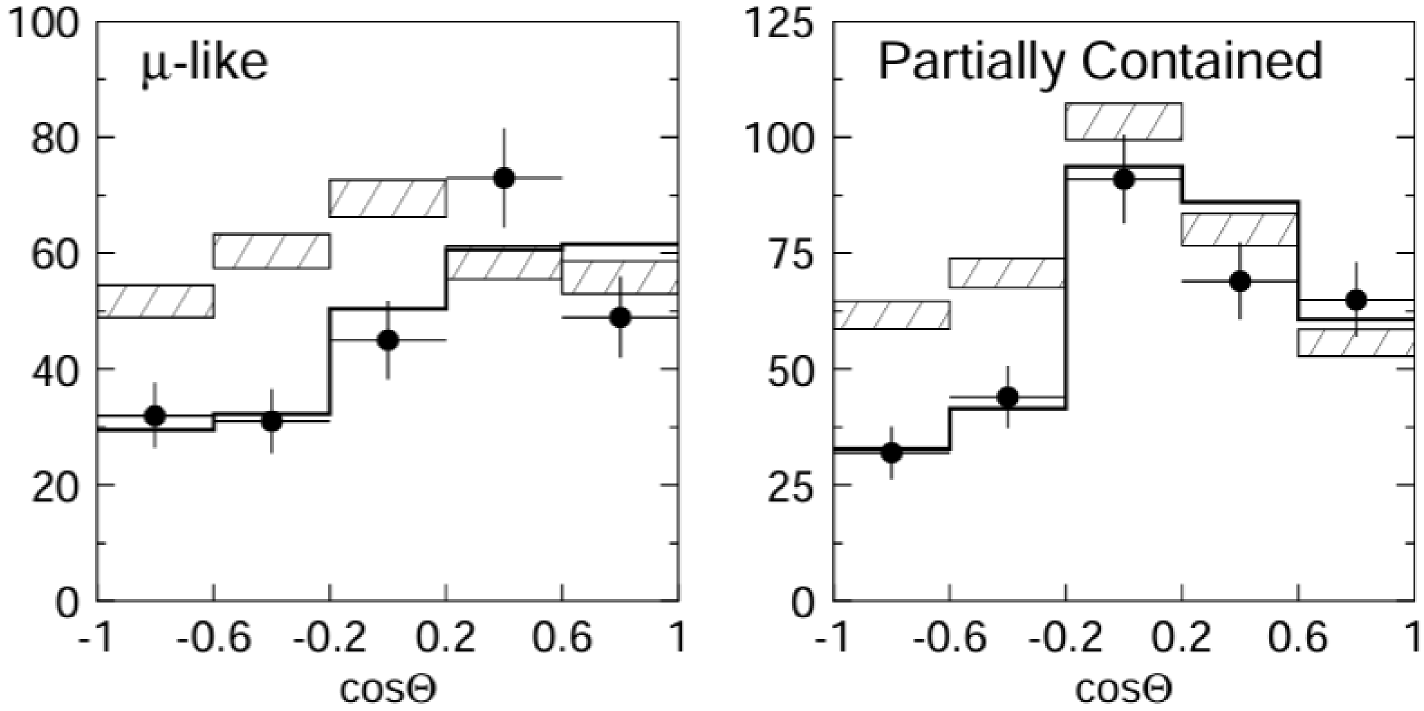




- ❖ Large volumes (a few kton) of ultra-pure water surrounded by photo-sensors
- ❖ Relativistic charged particles are identified by the pattern of PMT signals.
- ❖ Detection of neutrino interaction from about 10 MeV (solar, atmospheric and SN-ν)

Kamiokande: SN1987A and Neutrino Oscillations





The Super-Kamiokande Collaboration, Phys.Rev.Lett. 81 (1998) 1562-1567
Evidence for oscillation of atmospheric neutrinos

Masatoshi Koshiba (1926-2020)

Pioneering contributions to astrophysics in particular for the detection of cosmic neutrinos. (with R. Devis Jr and R. Giacconi)

2002

2013

Takaaki Kajita (with Arthur V. McDonald)

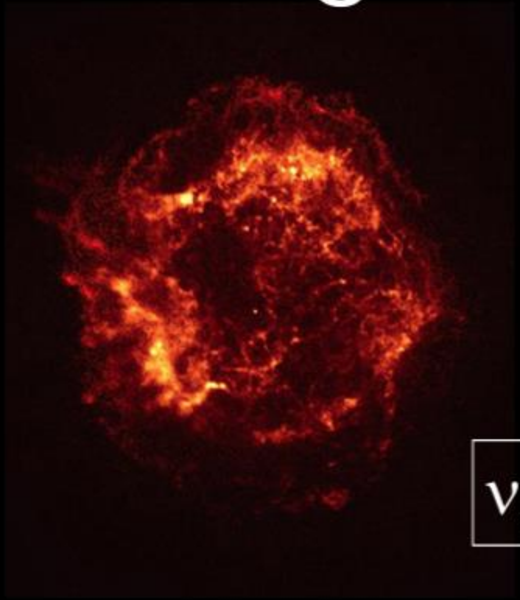
"for the discovery of neutrino oscillations which shows that neutrinos have mass

High Energy Cosmic Neutrino Detection

$$p + \text{target} \to \pi^+ + \ldots..$$

$$\to \mu^+ + \nu_\mu$$

$$\to e^+ + \nu_e + \bar{\nu}_\mu$$

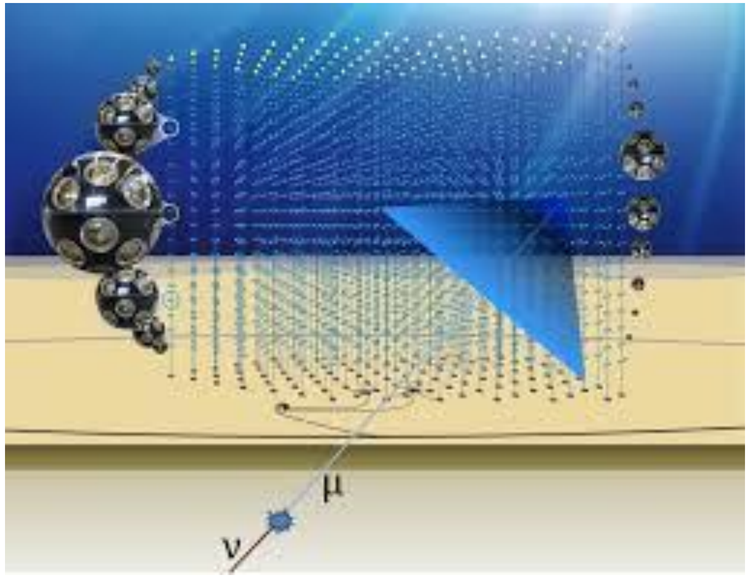


$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

Only from the 1990s on: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

Moisey Markov
1908-1994

Kenneth Greisen
1918-2007



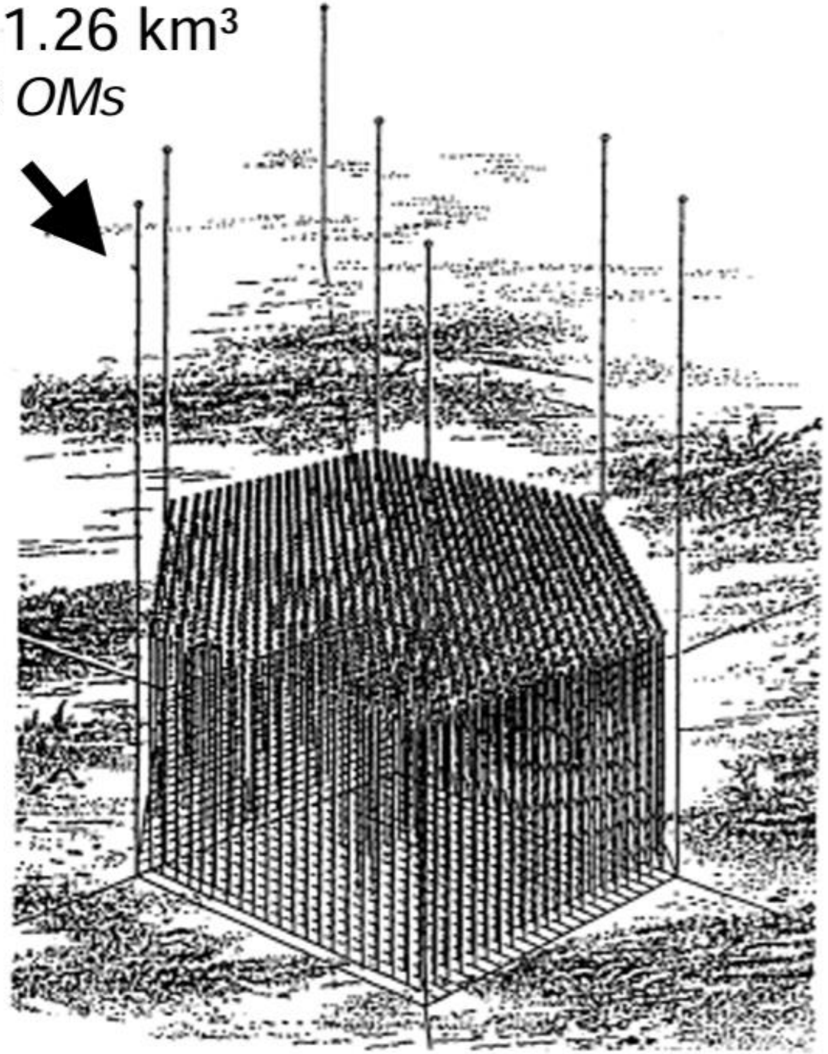
Cherenkov Detectors for High Energy Neutrino

- 1960: method proposed
- 1973 : first steps toward DUMAND
- 1993/96: first neutrinos underwater /in ice (Baikal/AMANDA)
- 2008: first deep sea detector - ANTARES
- 2010: first cubic kilometer detector - IceCube
- 2013: detection of a diffuse extraterrestrial flux of neutrinos
- > 2014: alert/multimessenger program of ANTARES and IceCube
- 2018: evidence of a first individual transient source

DUMAND (Deep Underwater Muon And Neutrino Detector)

1978: 1.26 km³

22,698 OMs



The funding of this project was canceled in 1996 by DOE.

Baikal

Baikal/GVD

AMANDA

IceCube

ANTARES

NESTOR

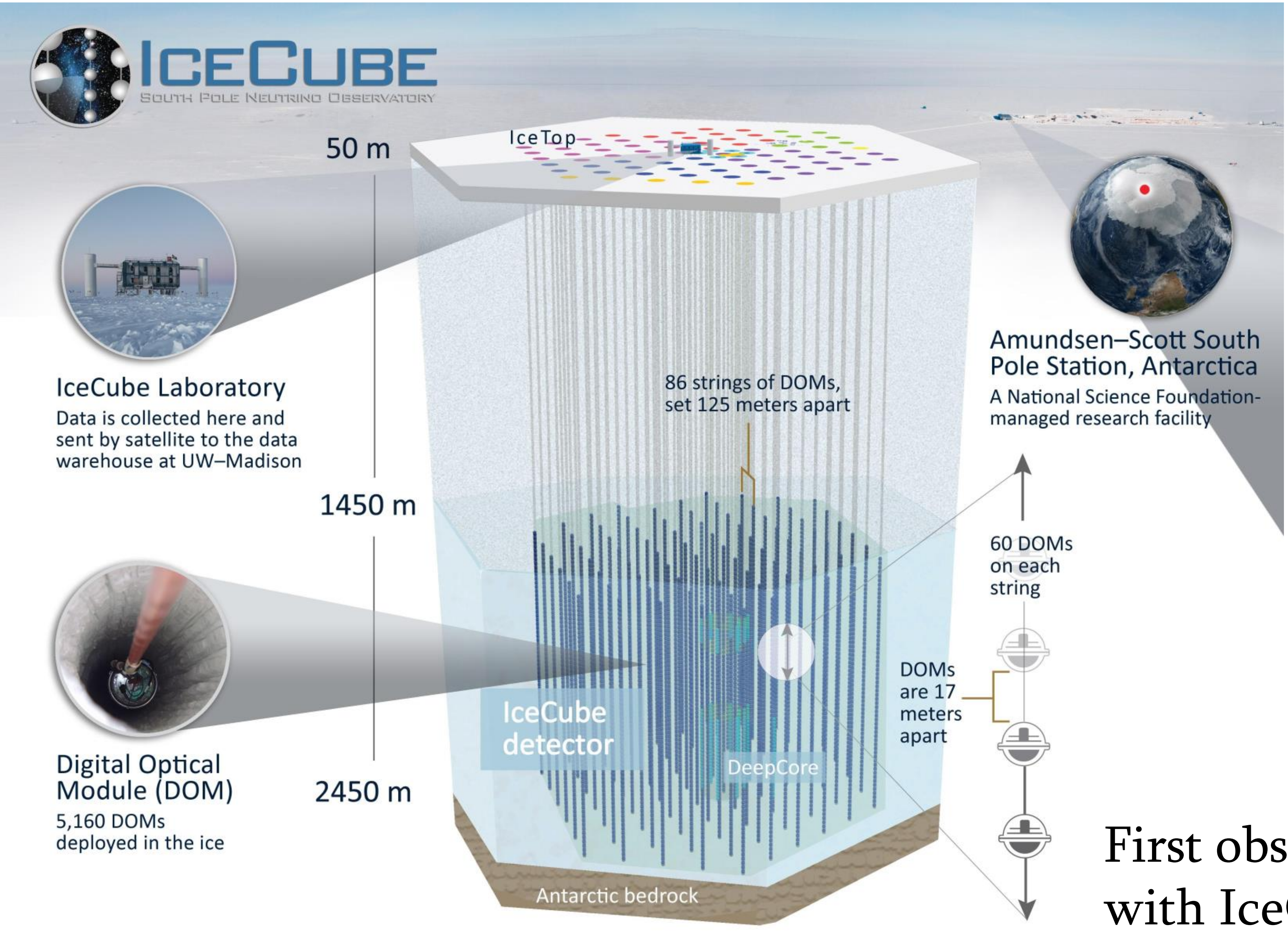
NEMO

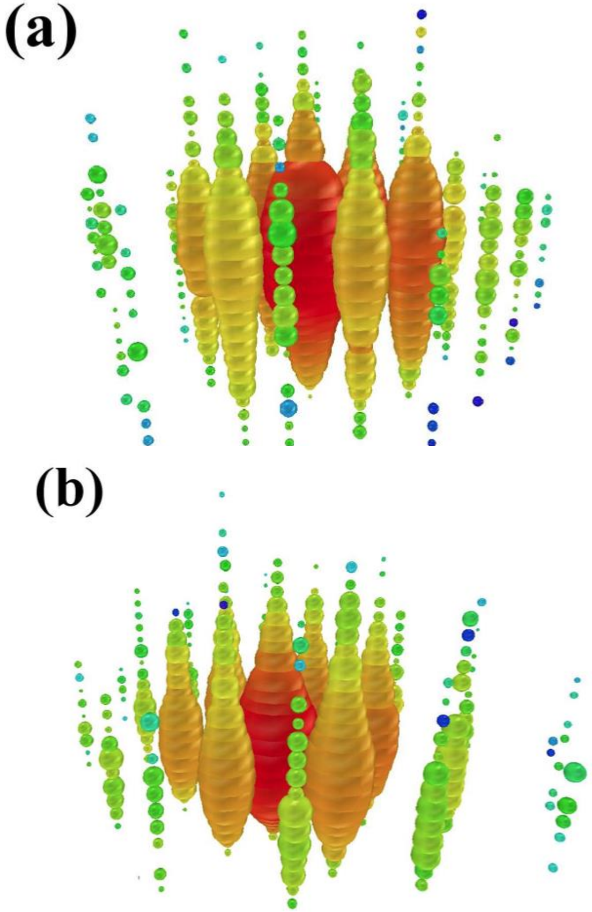
KM3NeT

P-ONE

TRIDENT

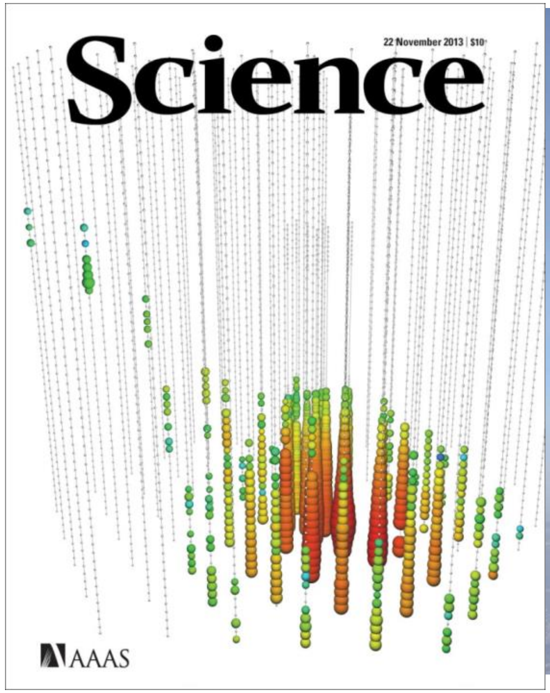
IceCube: First km^3-size (Gton) Neutrino Telescope

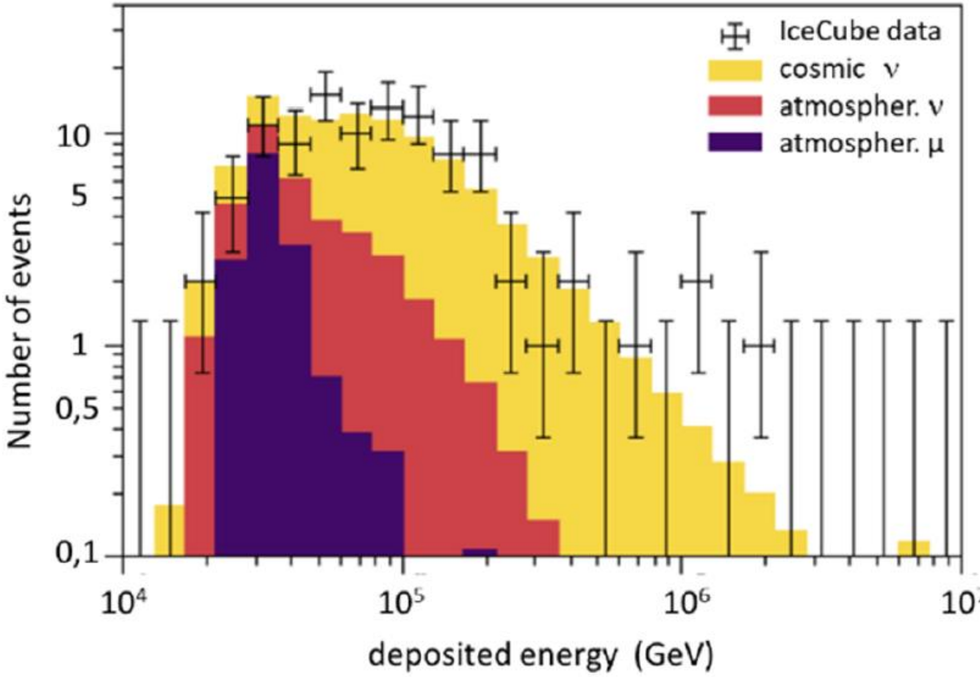




First observation of PeV-energy neutrinos with IceCube, *PRL.* 111 (2013) 021103

IceCube: Breakthrough of the Year 2013





“28 events, have flavors, directions, and energies inconsistent with those expected from the atmospheric muon and neutrino backgrounds. The purely atmospheric origin of these events is rejected at 4σ level”.

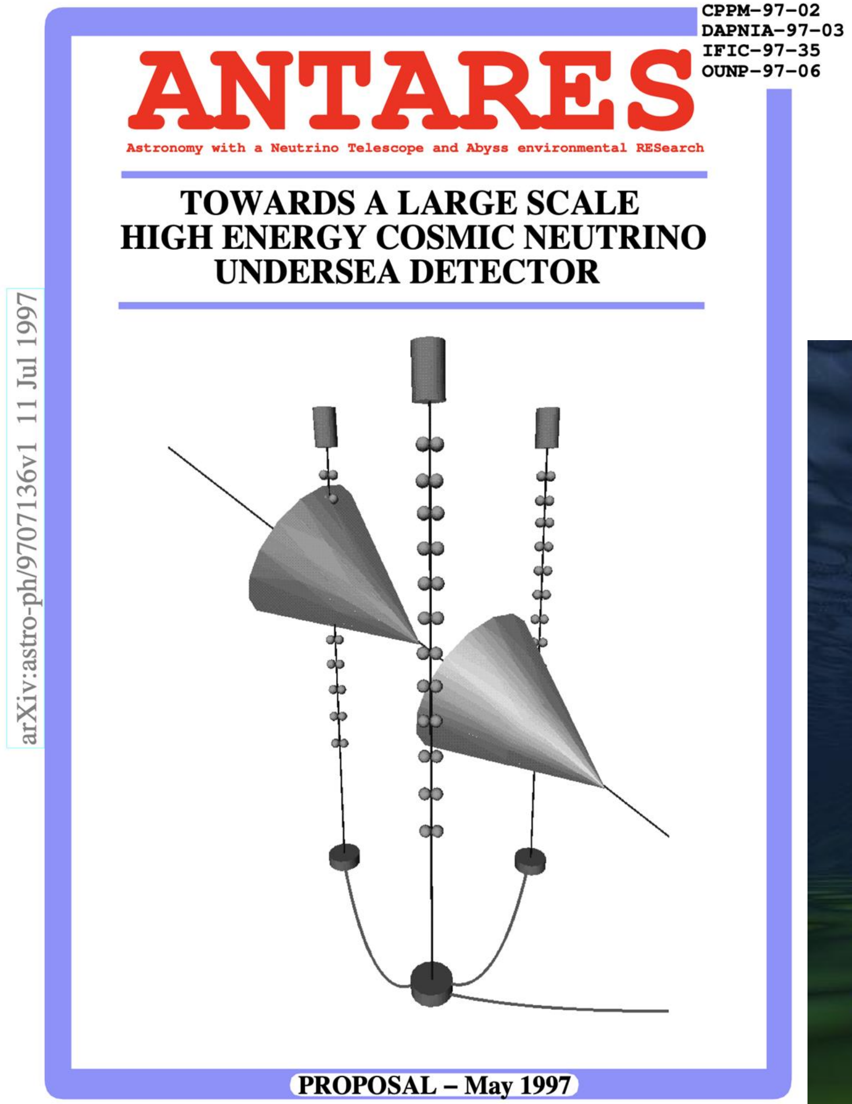
IceCube Collaboration, Science 42 (2013) 1242856, Evidence for High-Energy Extra-terrestrial Neutrinos at the Ice Cube Detector

IceCube Discoveries

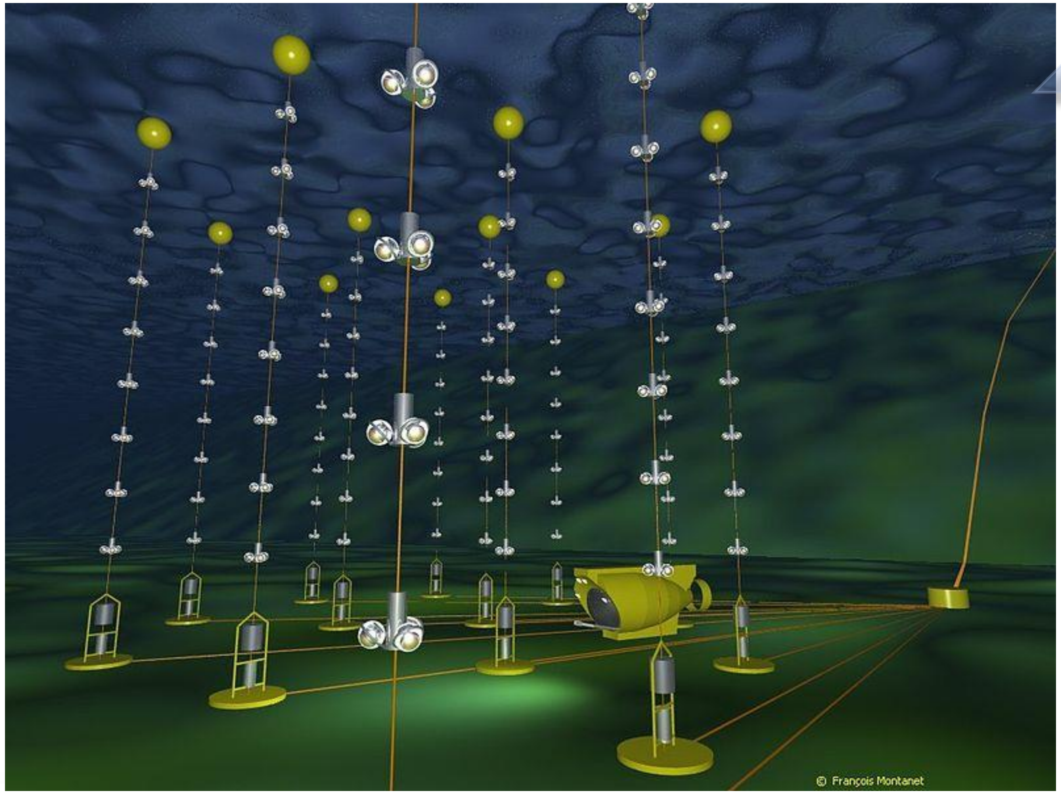
IceCube Collaboration:

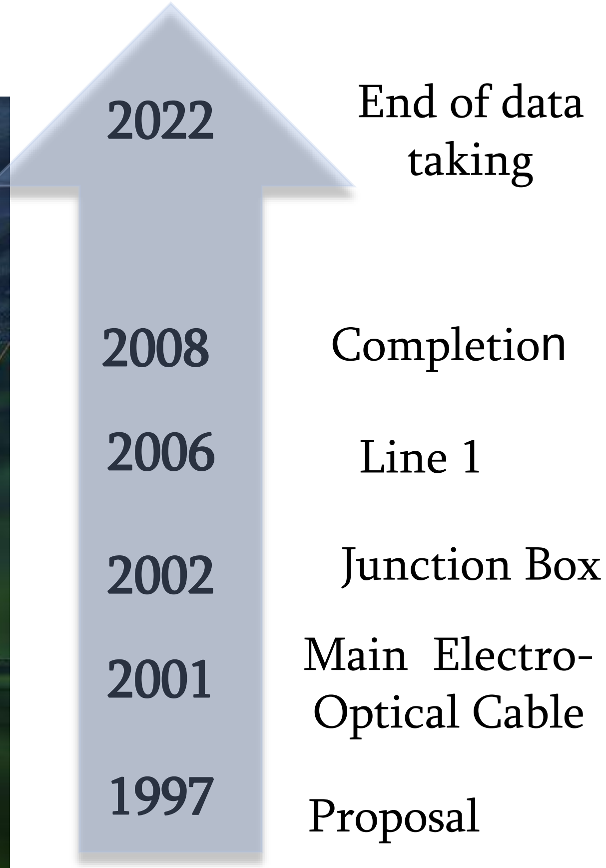
- ✓ First observation of PeV-energy neutrinos with IceCube, *Phys.Rev.Lett.* 111 (2013) 021103
- ✓ Evidence for High-Energy Extraterrestrial Neutrinos at the Ice Cube Detector, Science 42 (2013) 1242856
- ✓ Detection of a particle shower at the Glashow resonance with IceCube, Nature 591(2021) ,220
- ✓ Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922 Aalert, *Science* 361 (2018) 6398, 147
- ✓ Observation of high-energy neutrinos from the Galactic plane, *Science* 380 (2023) 6652

ANTARES: the First Undersea Neutrino Telescope

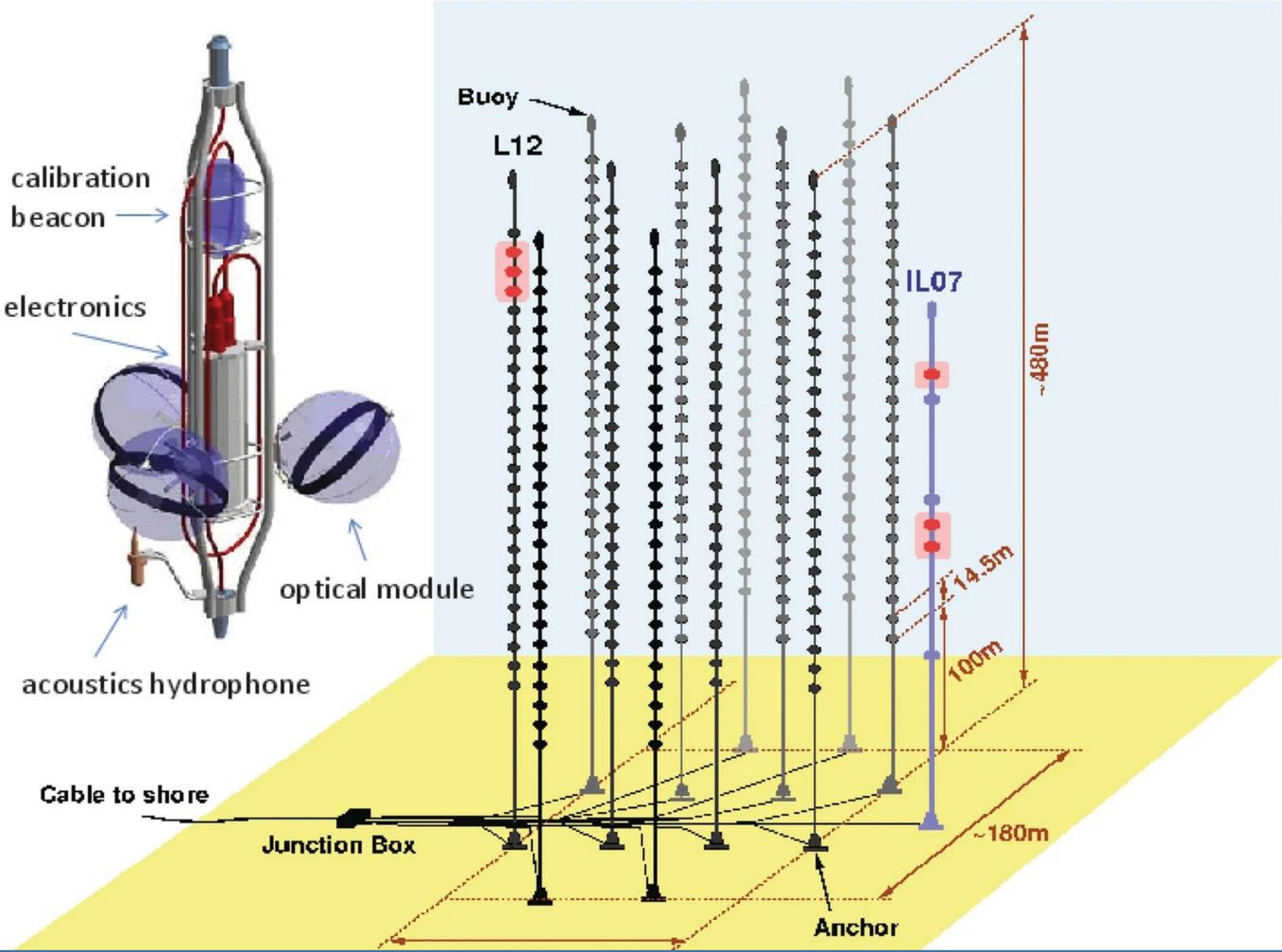


- ❖ "We propose to explore the possibility of a km-scale detector to be installed in a deep site in the Mediterranean Sea"
- ❖ "We will test the sea engineering part of a detector including test deployments close to the Toulon coast."



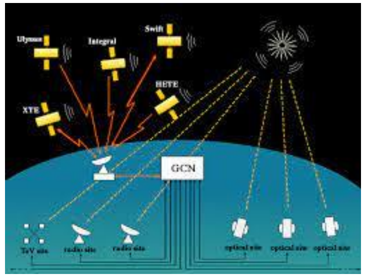


ANTARES: the First Undersea Neutrino Telescope

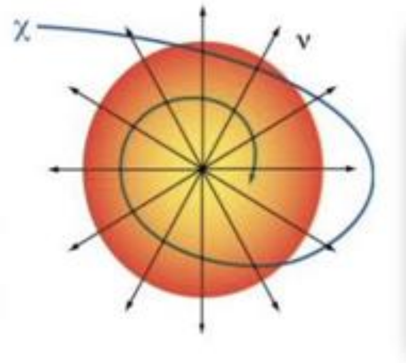


ANTARES: Astronomy and Physics with Neutrinos

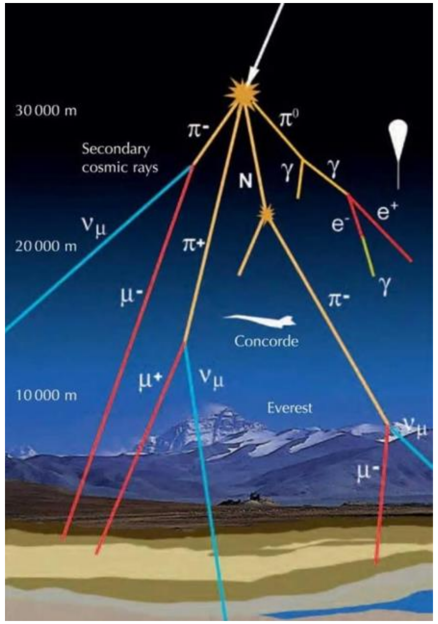
Search for cosmic-ν:
Point sources of cosmic-ν
Diffuse flux of cosmic-ν



Multi-Messenger searches:
GRB alerts from GCN
CCSN neutrino flux (SNEWS)



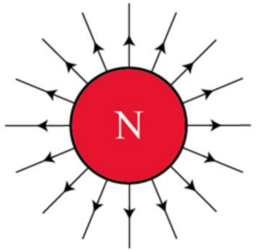
Search for Dark Matter
(annihilation into ν):
from Sun, GC, . . .



E-spectrum of atm-ν

Oscillations of atm-ν

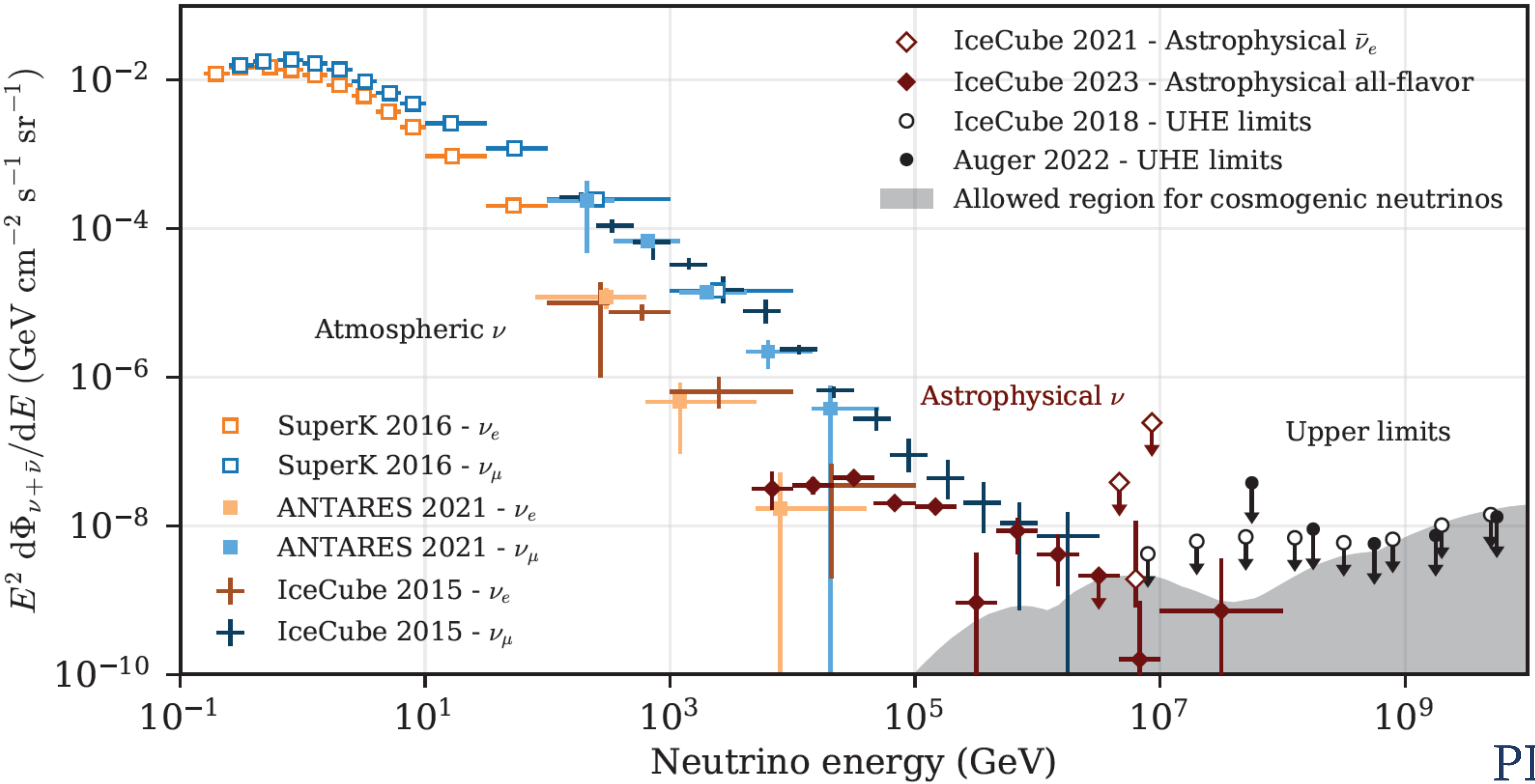
Flux of atm-μ



Search for exotic particles:
Monopoles, nuclearites, . . .

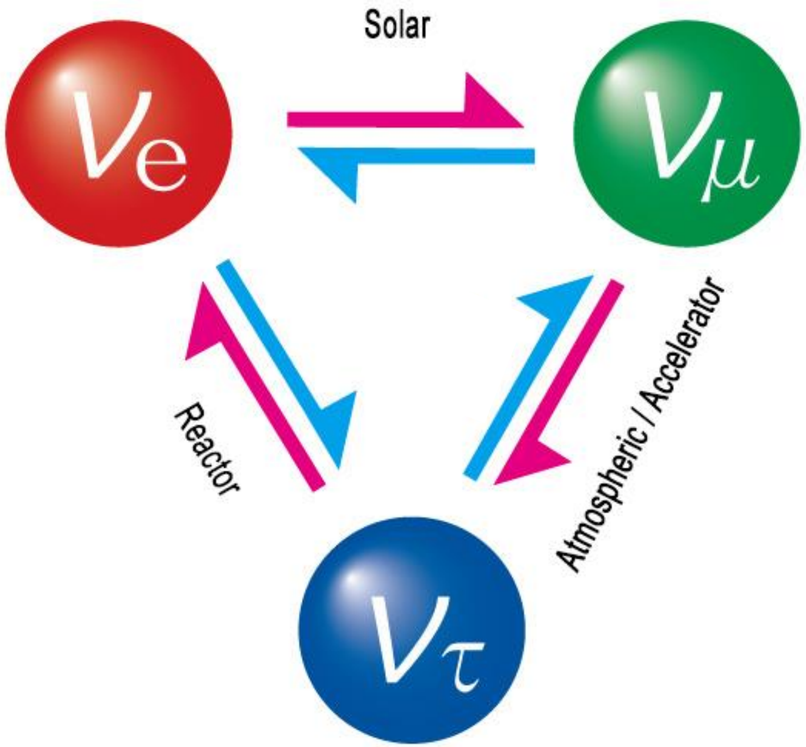
ANTARES calibration: geometry, timing, PMT signals

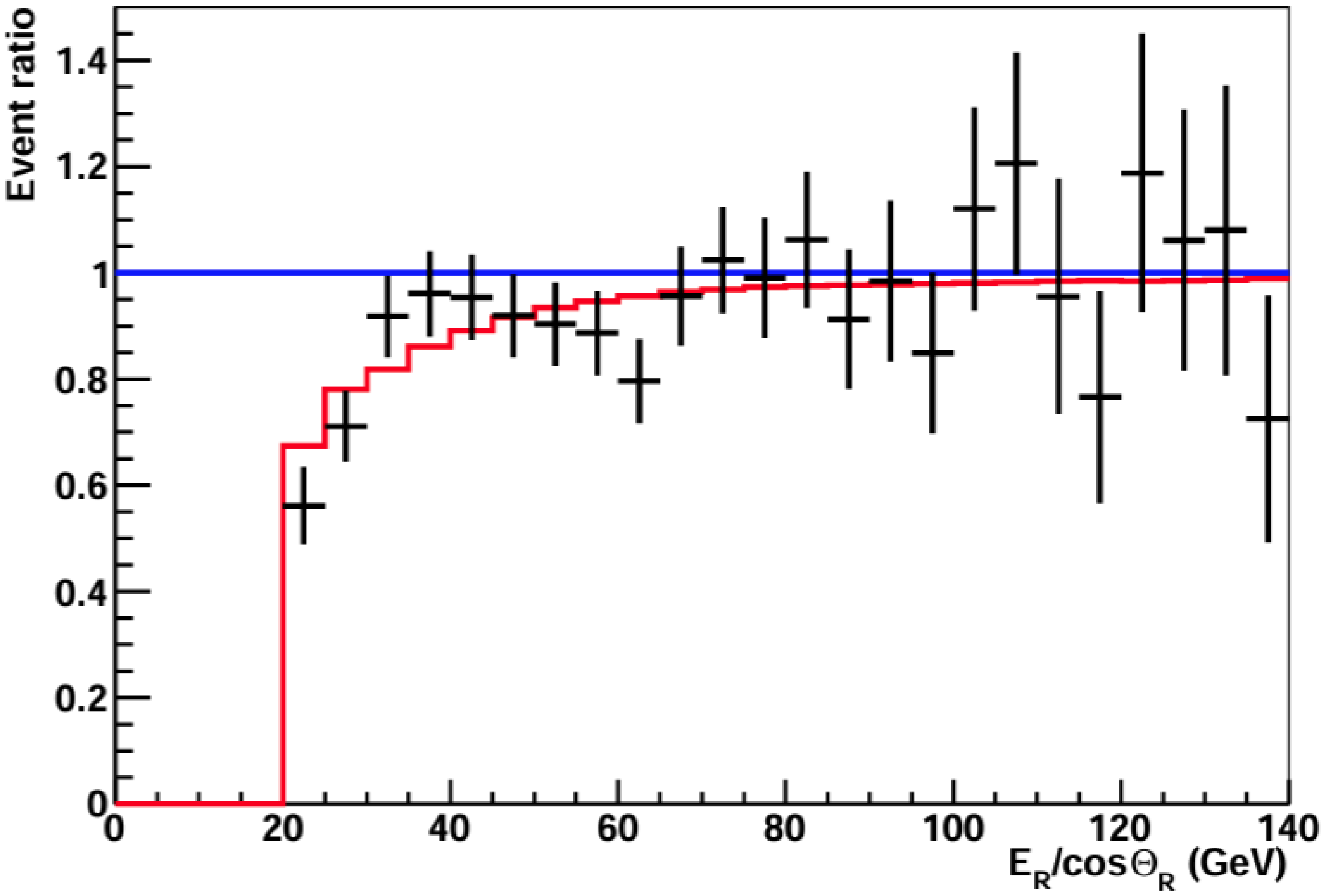
Energy Spectra of Neutrinos



PDG, 2023

ANTARES: Measurement of Neutrino Oscillations

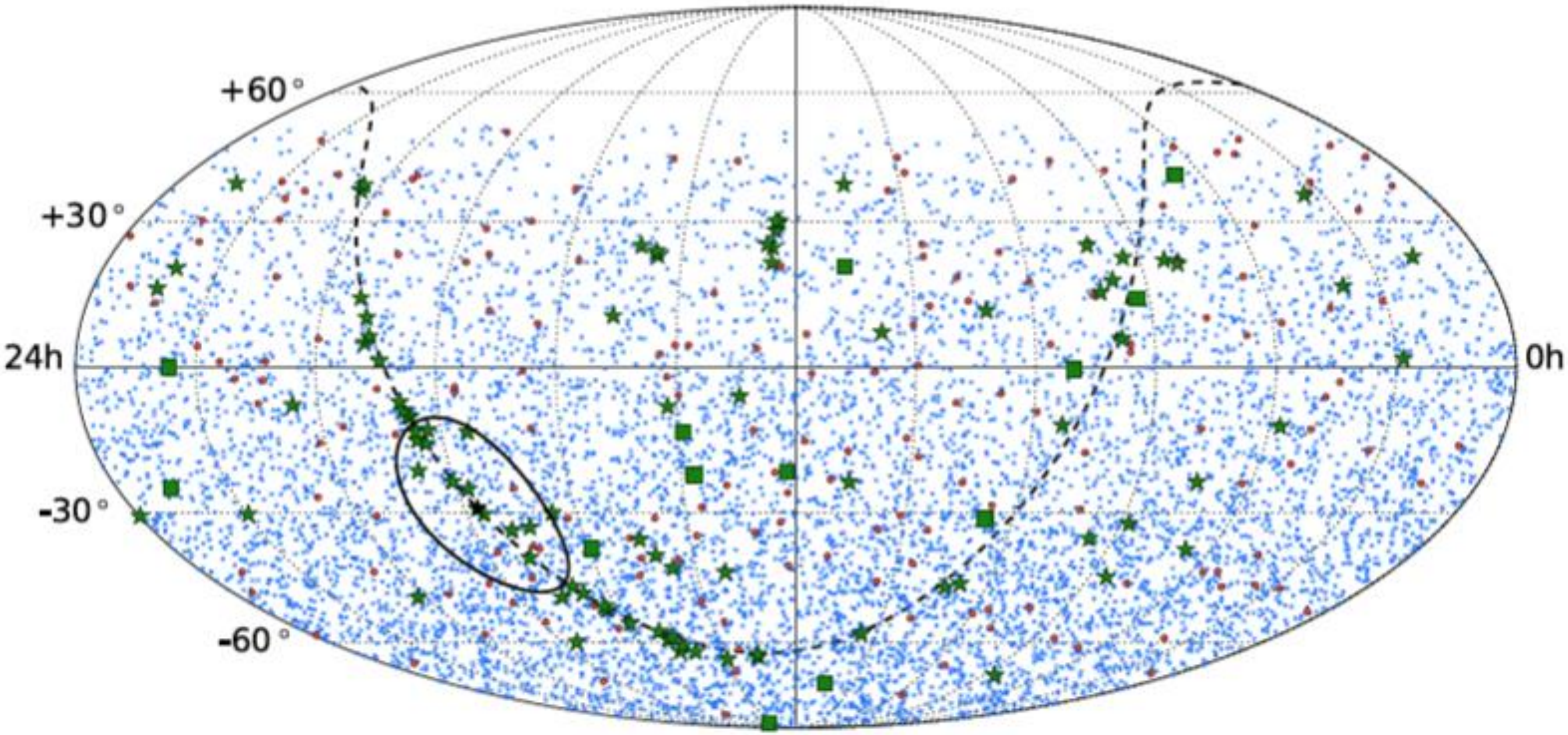




Phys.Lett.B 714 (2012) 224-230

Measurement of Atmospheric Neutrino Oscillations with the ANTARES Neutrino Telescope

ANTARES: Search for Neutrino Sources



ANTARES sky map with 7622 tracks (blue crosses) and 180 showers (red circles). Green stars: location of the 106 candidate neutrino sources.

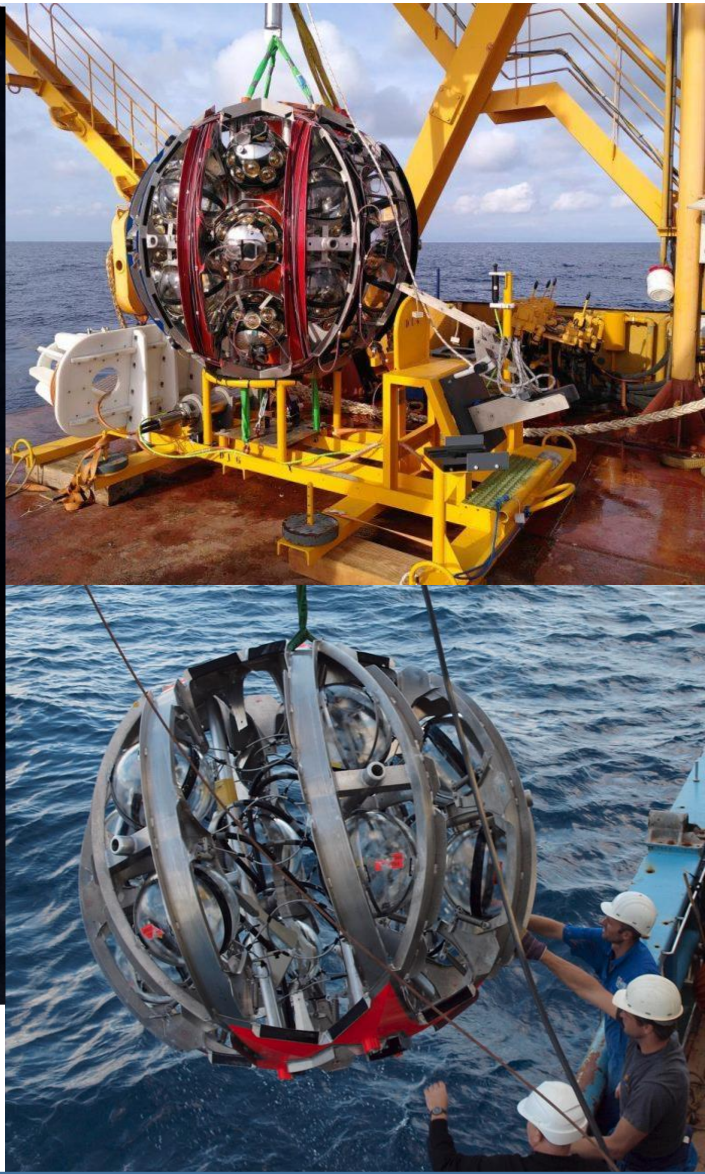
Green squares indicate the location of the 13 tracks from the IceCube high-energy sample events.

First all-flavour Neutrino Point-like Source Search with the ANTARES Neutrino Telescope
Phys.Rev.D 96 (2017) 8, 082001

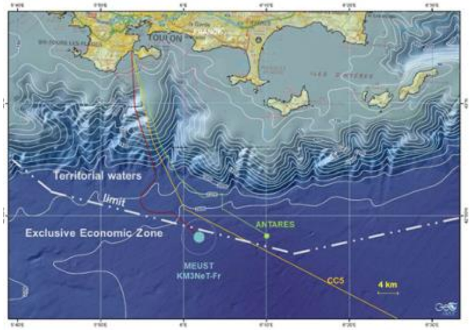
Thank You ANTARES, Welcome KM3NeT!

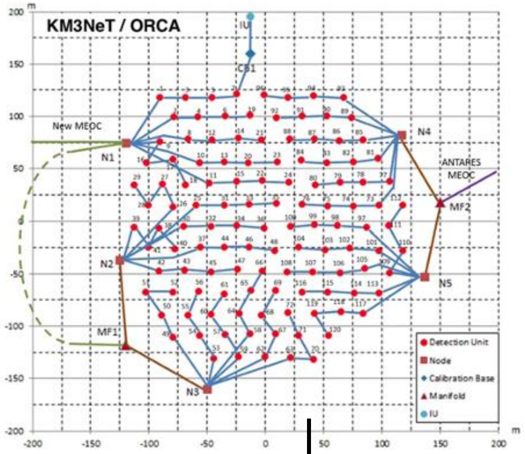
June 2022, Recovery of ANTARES lines

KM3NeT DOM and LOM



KM3NeT: Mediterranean Deep-Sea Research Infrastructure





KM3NeT/ORCA

Oscillation **R**esearch with **C**osmics in the **Abyss**

Study of neutrino oscillations and mass ordering

ORCA: will 1 detector block of 115 DU (about 10 Mton)

TeV PeV

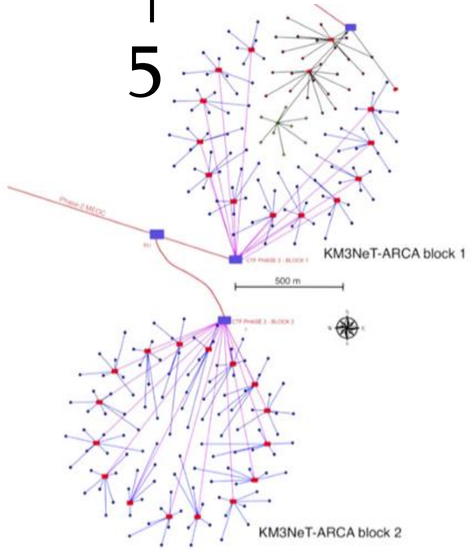
0 1 2 3 5 6

KM3NeT/ARCA

Astroparticle **R**esearch with **C**osmics in the **Abyss**

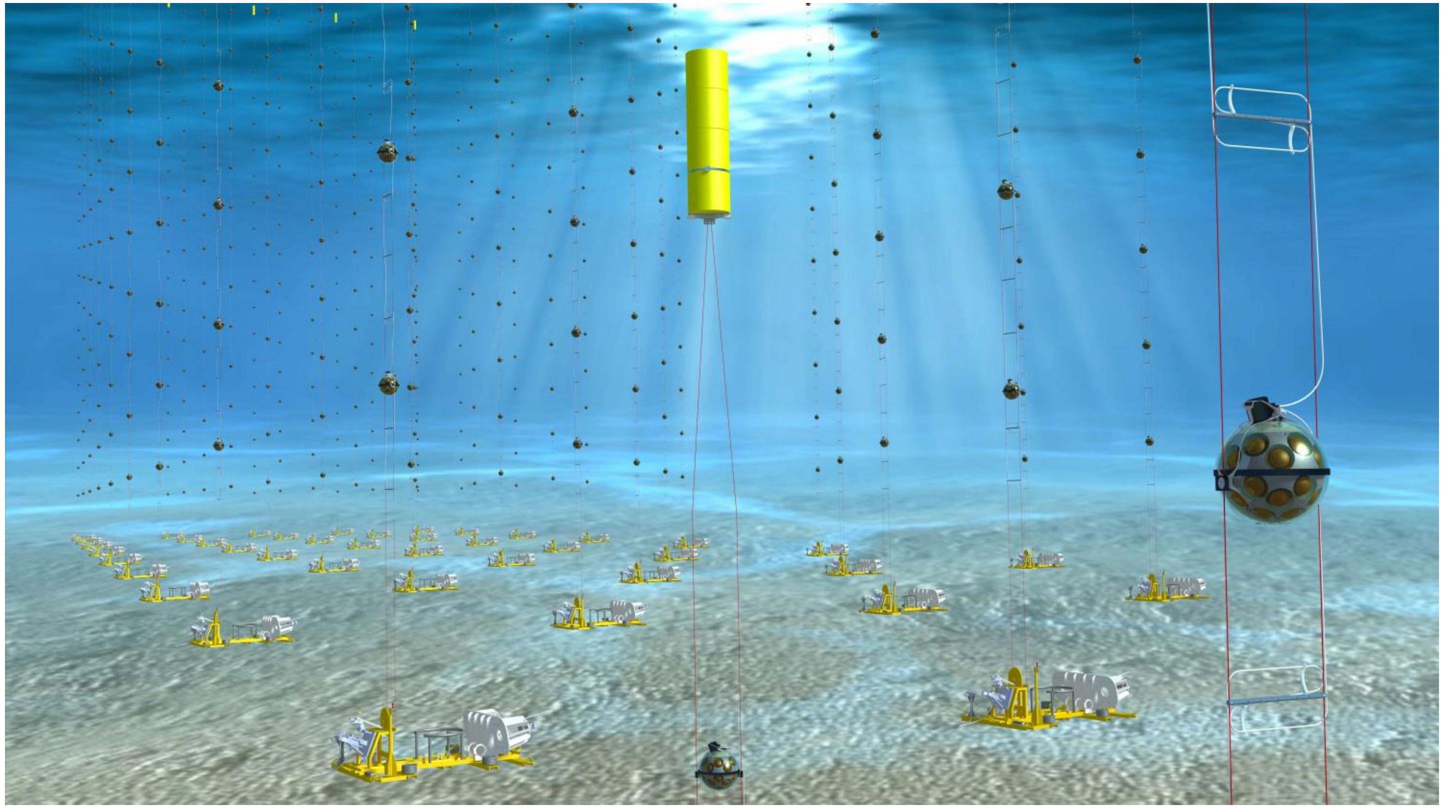
About 100 km off-shore of Portopalo di Capo Passero

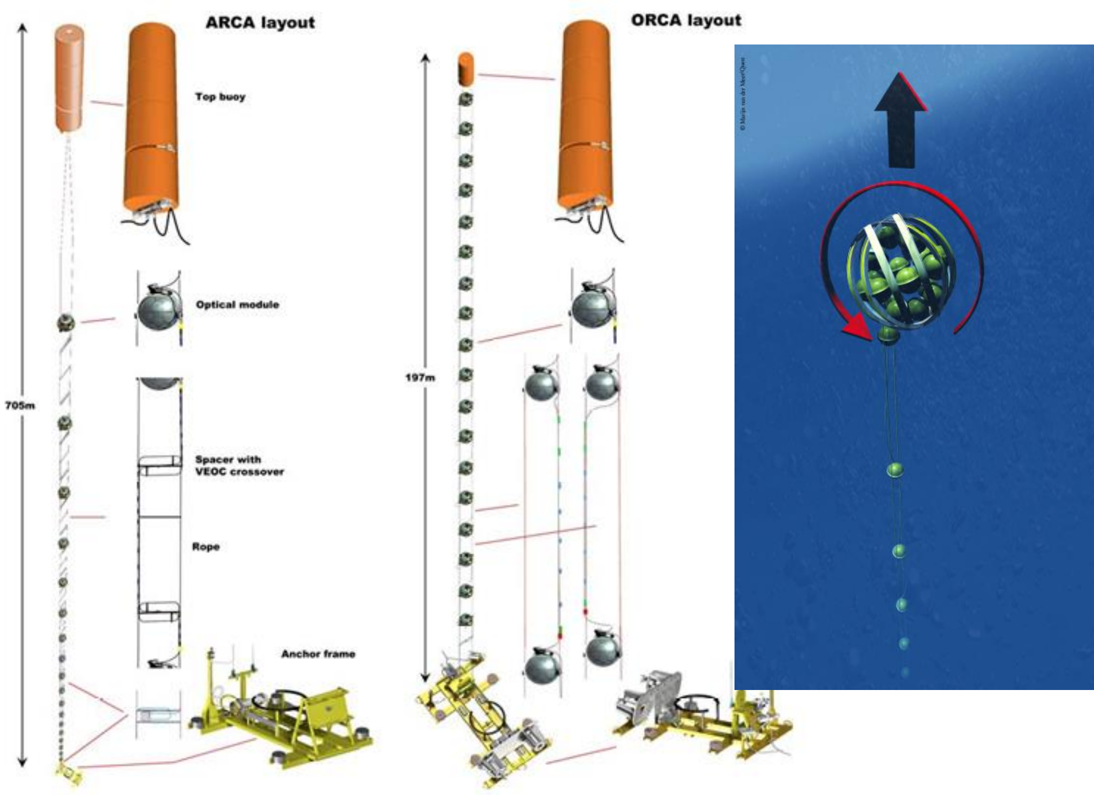
ARCA: 2 detector blocks of 115 DU (about 1 Gton)



KM3NeT Collaboration, Letter of intent for KM3NeT 2.0, *J. Phys.G* 43 (2016) 8, 084001

KM3NeT: ARCA and ORCA Detection Units



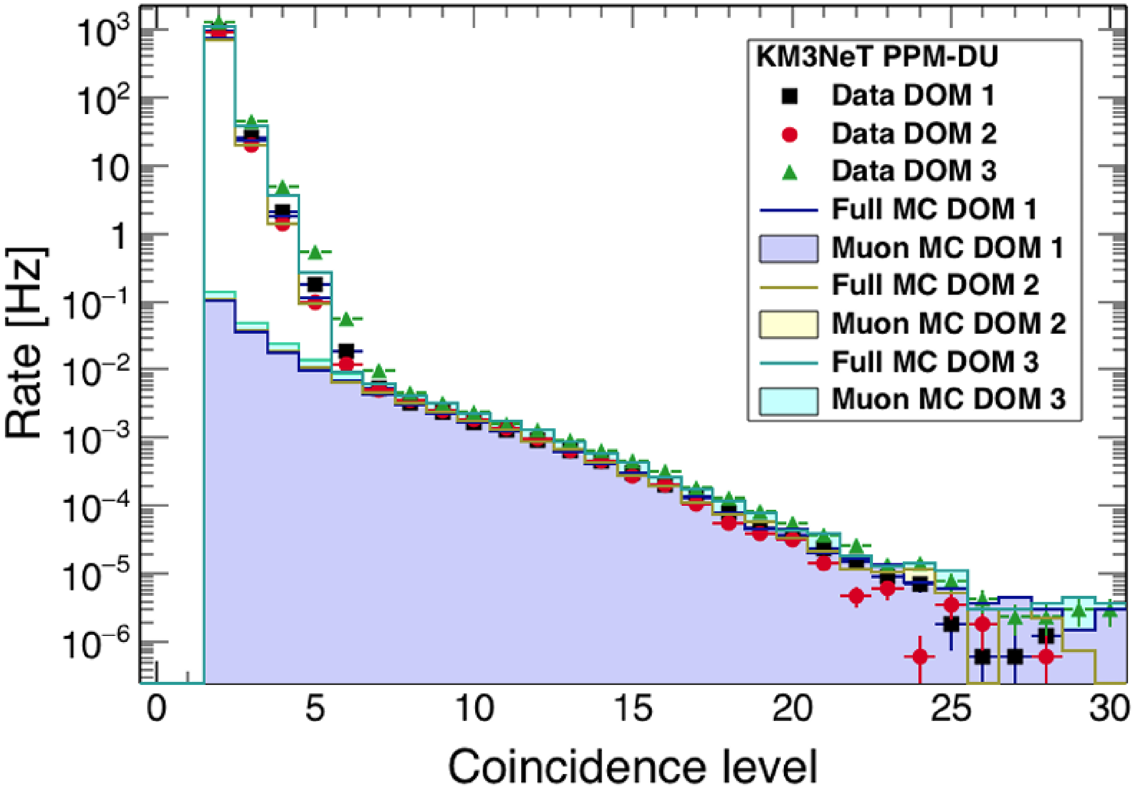


Detector	Depth	Horizontal spacing	Vertical spacing	Detection unit	Volume
ARCA	3500 m	90 m	36 m	2 x 115	1 km^3
ORCA	2500 m	20 m	9 m	115	~0.005 km^3

KM3NeT Collaboration, *JINST* 15 (2020) 11, P11027
Deep-sea deployment of the KM3NeT neutrino telescope detection units by self-unrolling

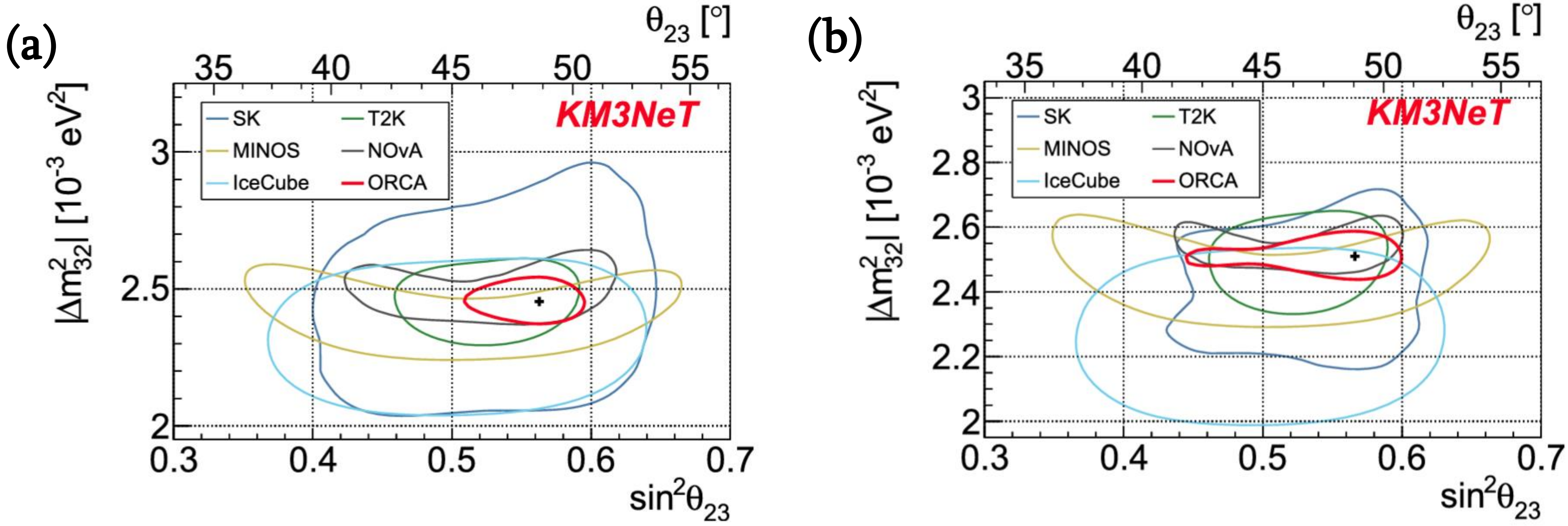
KM3NeT DOM

KM3NeT multi-PMT DOM: 31 PMTs (3") - a single 0.44m diameter glass sphere.



KM3NeT Collaboration, JINT 7 (2022) 07, P07038 The KM3NeT multi-PMT optical module

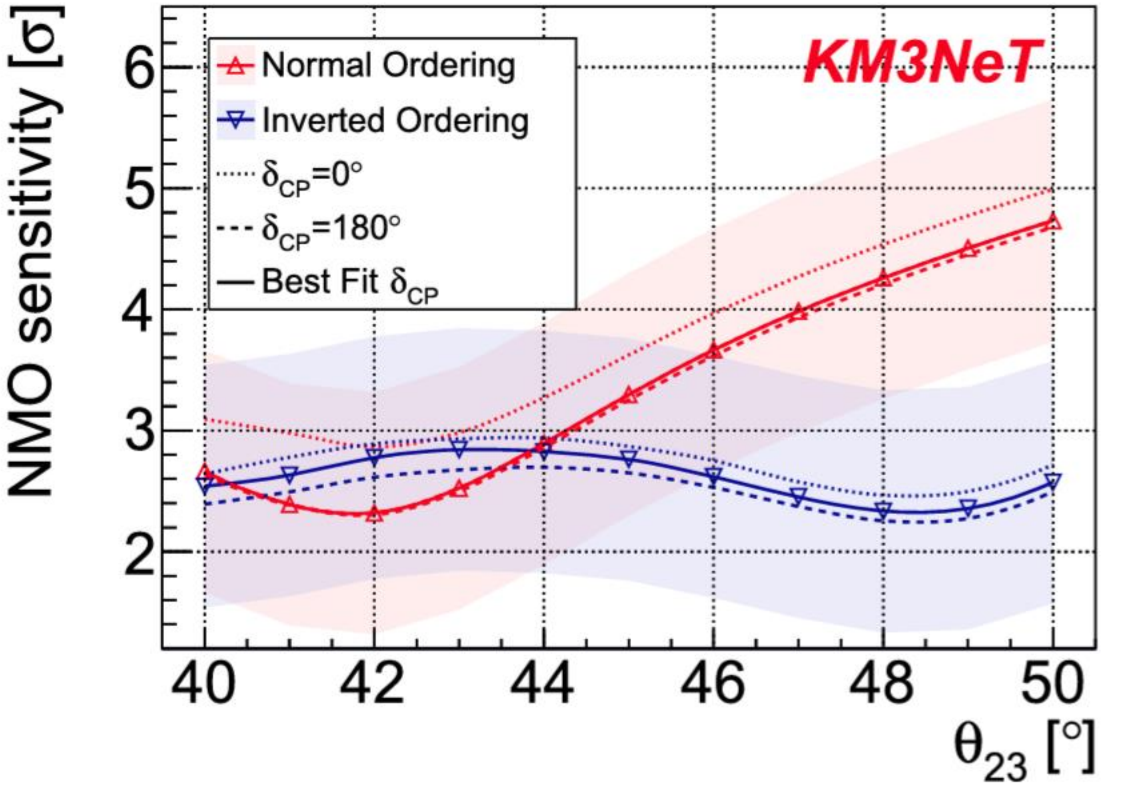
KM3NeT/ORCA: Oscillations

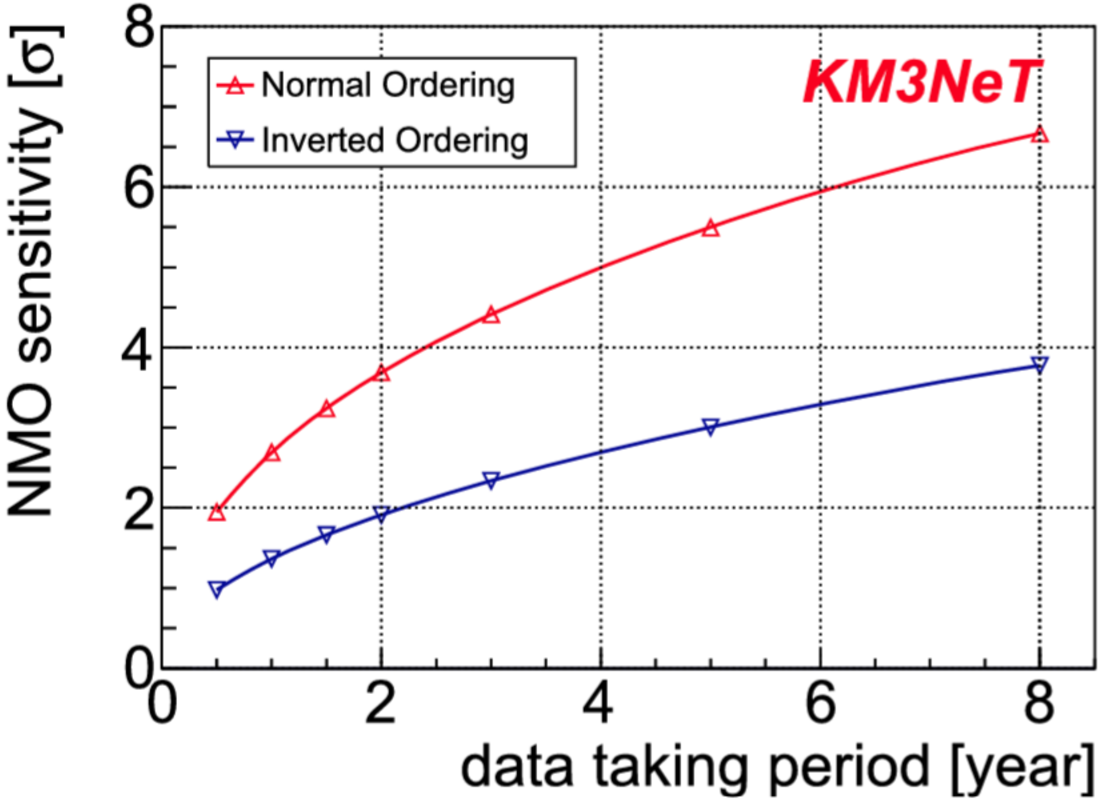


Expected measurement precision of Δm^2_{32} and θ_{23} for both NO (a) and IO(b) after 3y of data taking at 90% confidence level(red) overlaid with results from other experiments.

*EPJ C*82 (2022) 1,26, Determining the neutrino mass ordering and oscillation parameters with KM3NeT/ORCA

KM3NeT/ORCA: Sensitivity to NMO

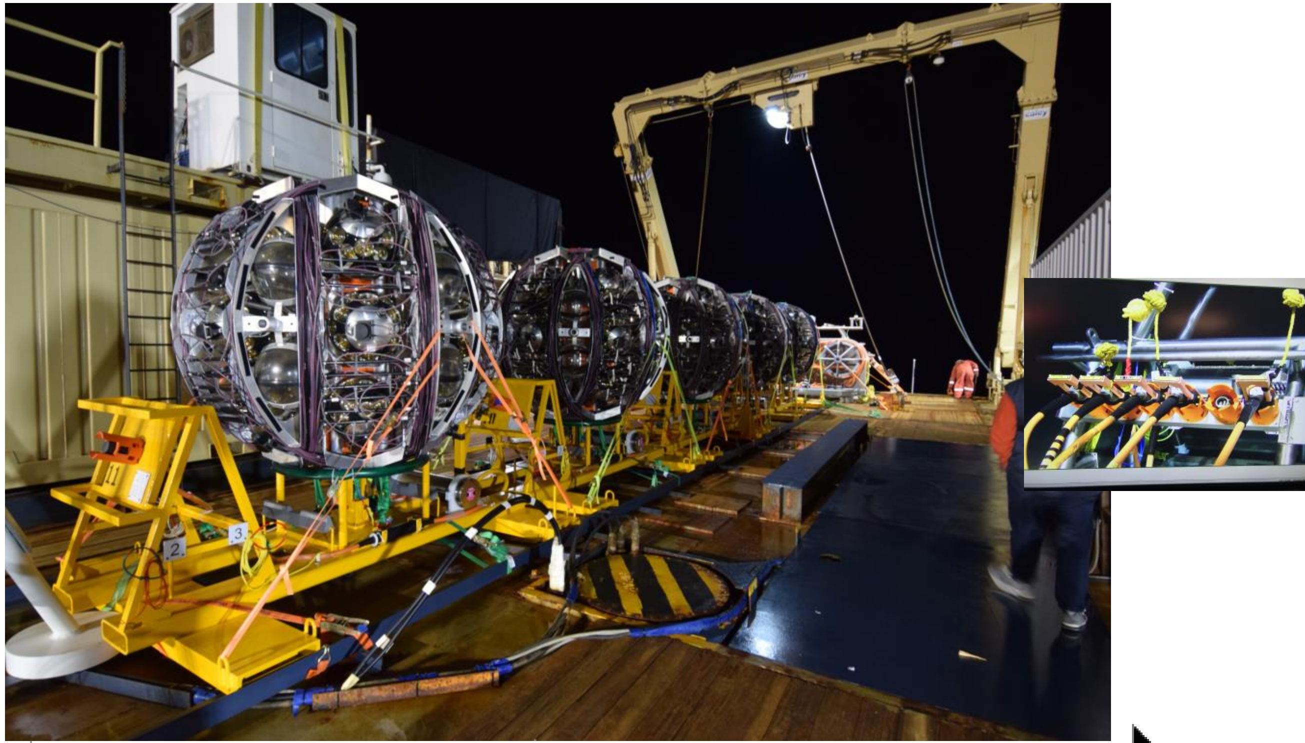




Sensitivity to NMO after 3 years of data taking, as a function of the true θ_{23} value, for both NO.
The colored shaded areas represent the sensitivity that 68% of the experiment realization would yield, according to the Asimov approach. Sensitivity to NMO as a function of data taking time for NO and IO.

*EPJ C*82 (2022) 1,26, Determining the neutrino mass ordering and oscillation parameters with KM3NeT/ORCA

KM3NeT Current Status



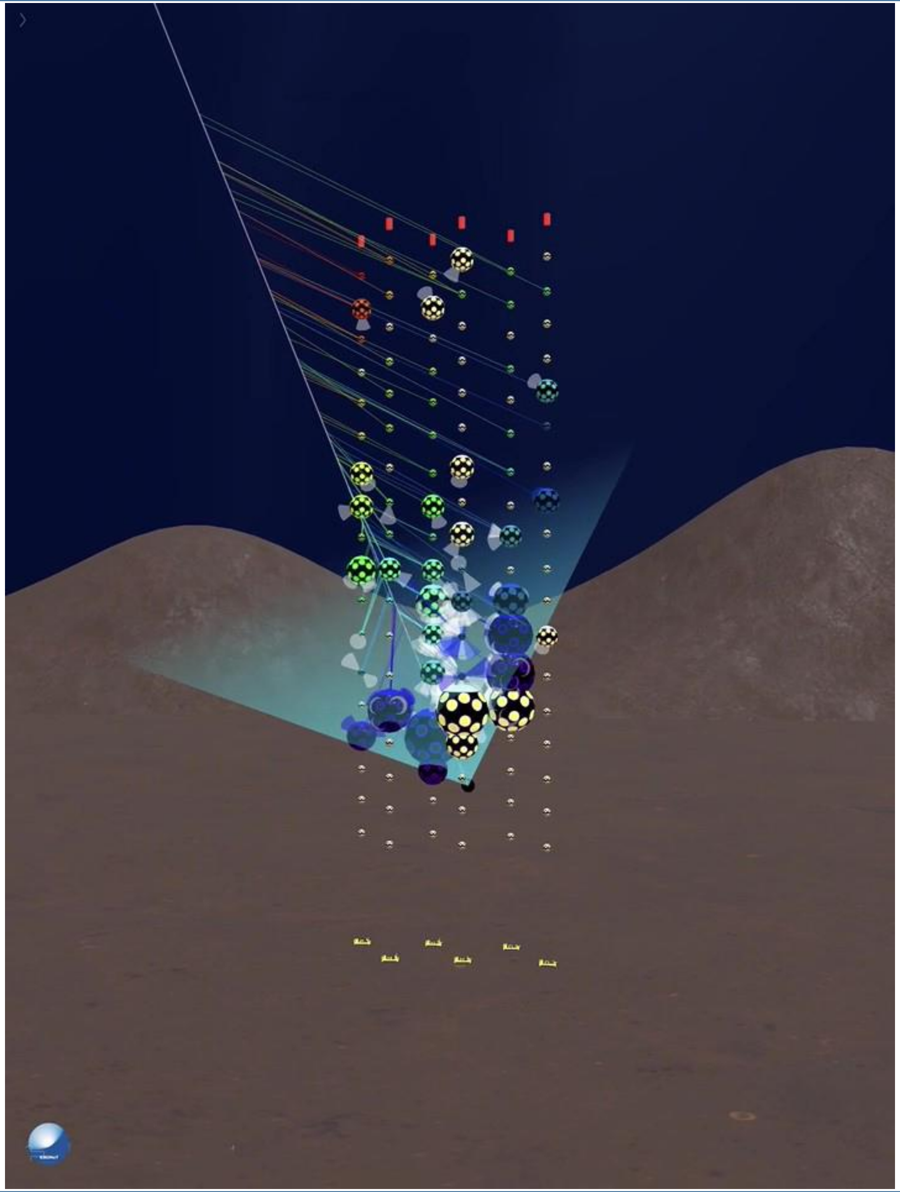
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

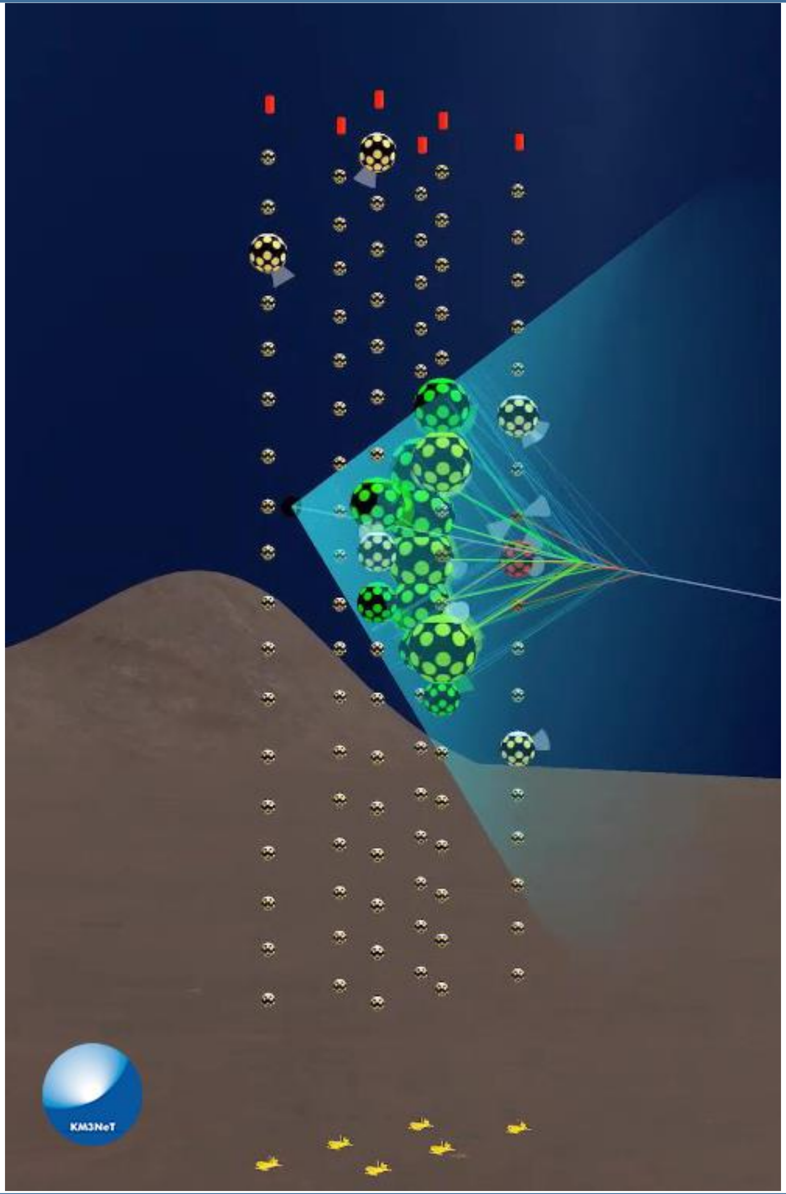
ORCA6:
01/2020-11/2021

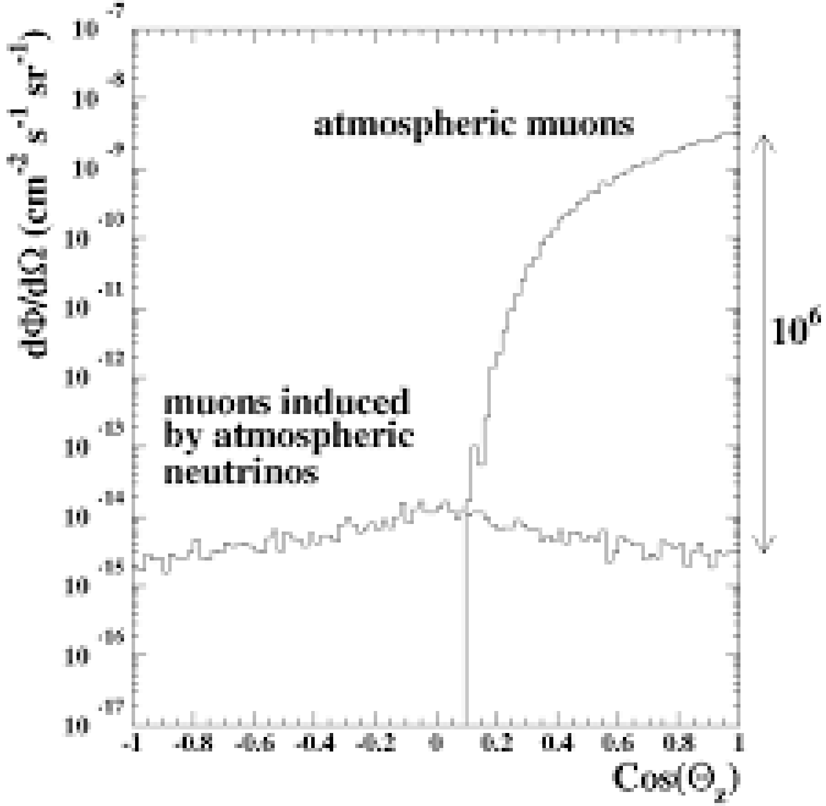
Data taking with
ORCA18 and
ARCA 29

ORCA ARCA
completions

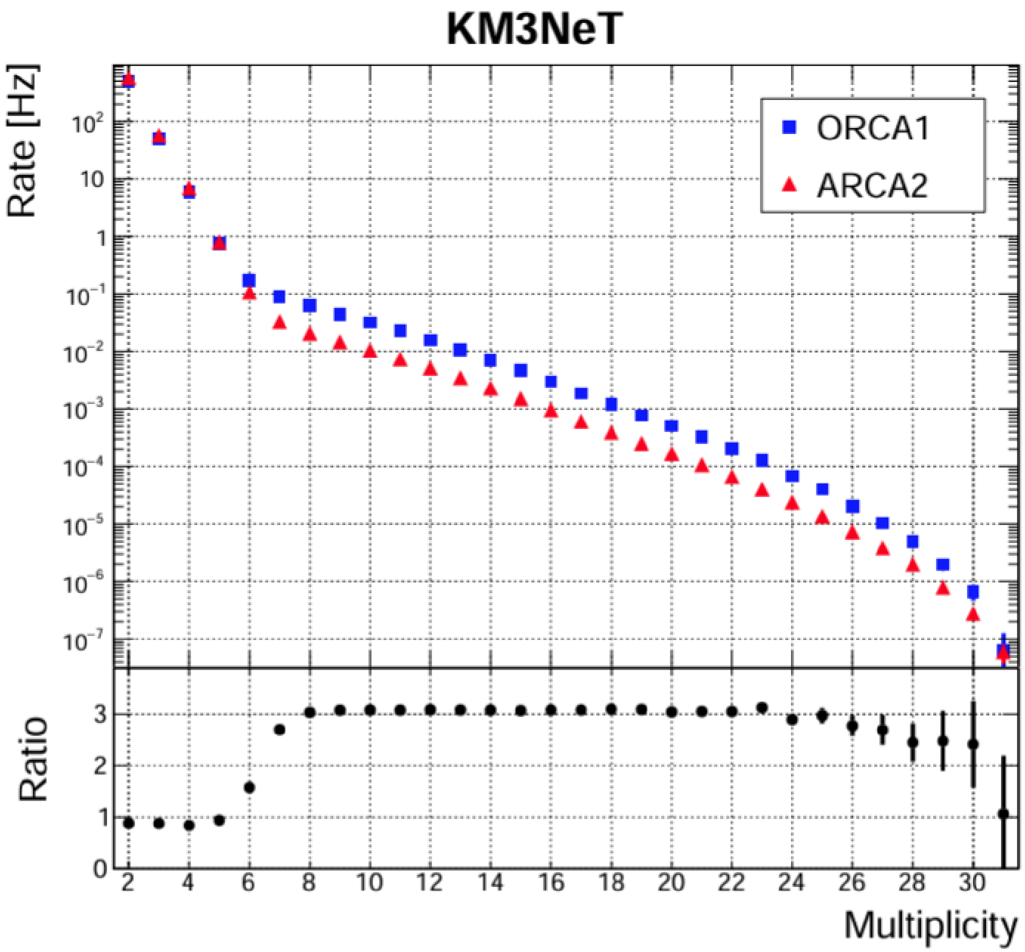
KM3NeT: Muon and Neutrino Events

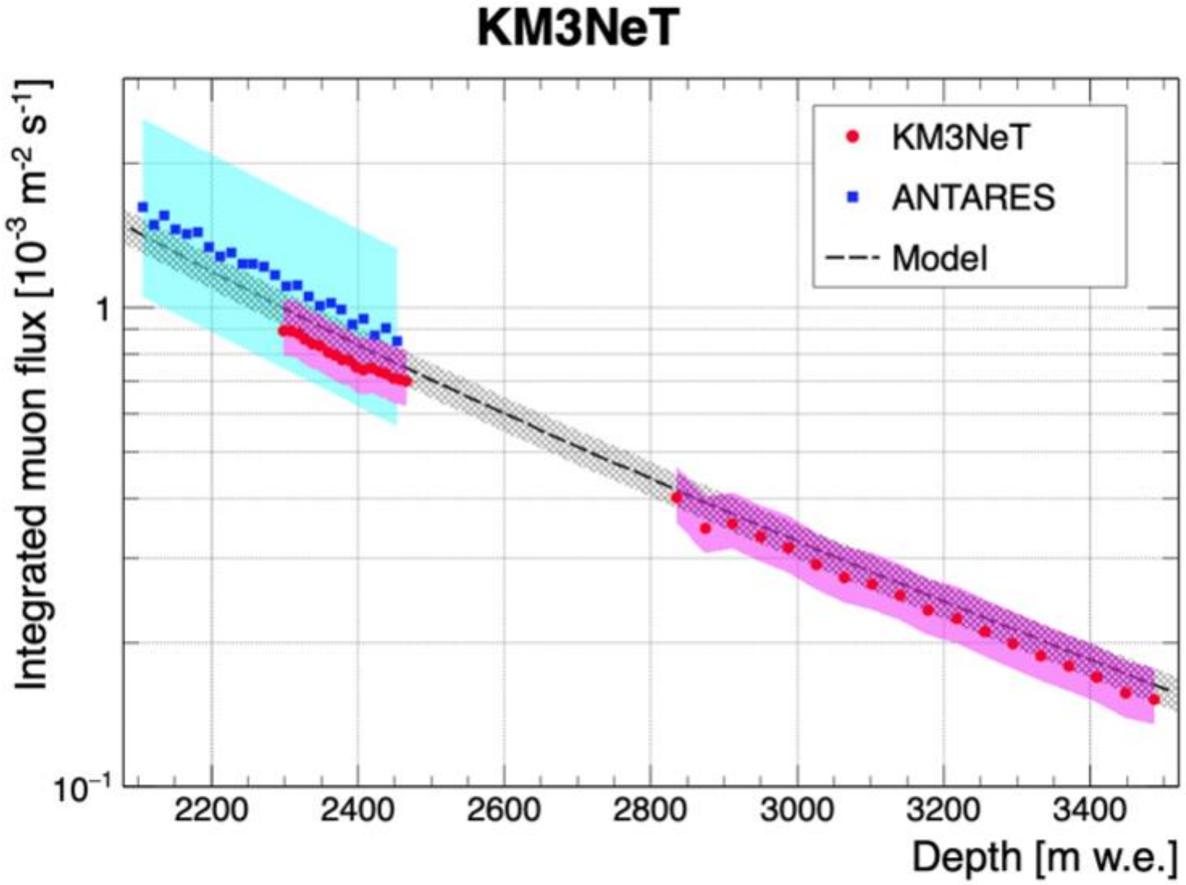






KM3NeT: Muon Flux on Sea Water Depth

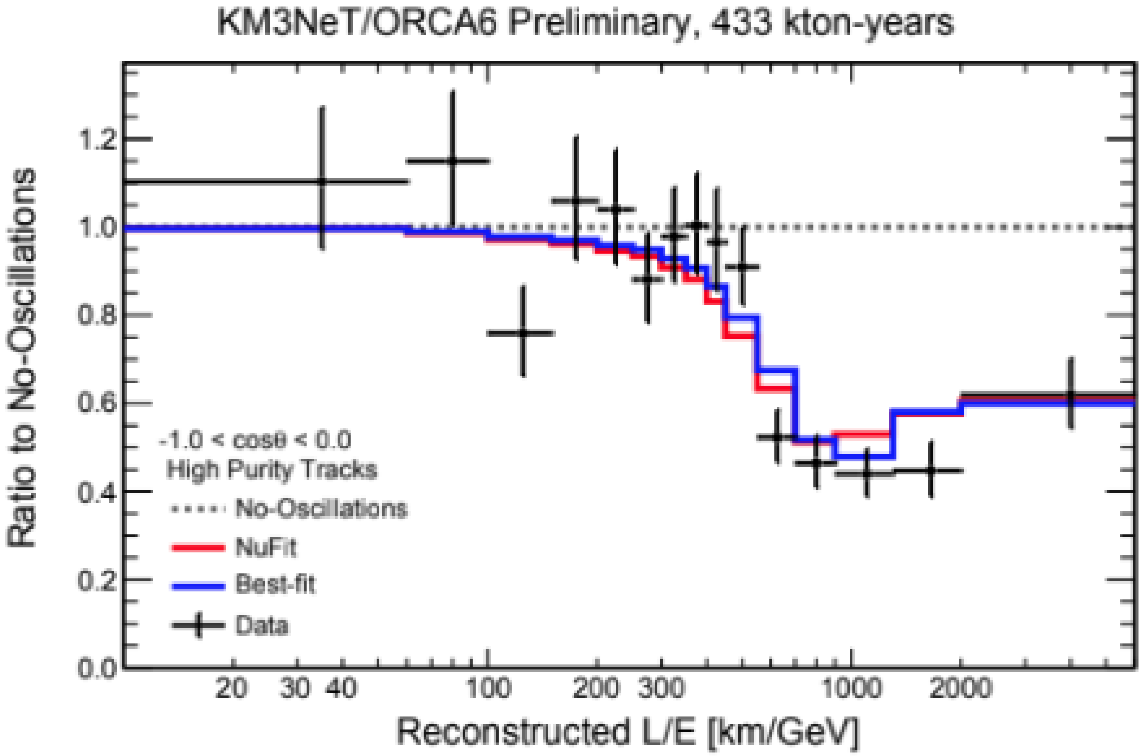




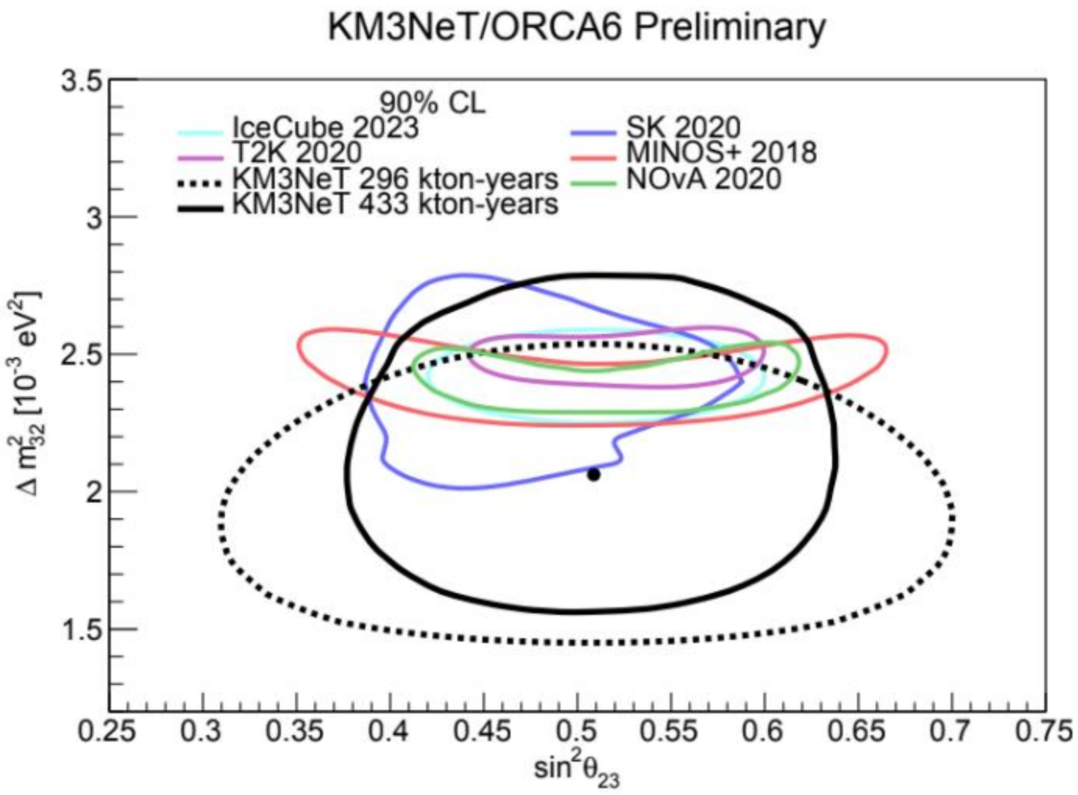
- *Eur.Phys.J.C* 80 (2020) 2, 99, Dependence of atmospheric muon flux on seawater depth measured with the first KM3NeT detection units: The KM3NeT Collaboration

Neutrino Oscillations with ORCA 6

ICRC2023: Measuring atmospheric neutrino oscillations with KM3NeT/ORCA6 (V.Carretero.KM3NeT@ICRC2023)



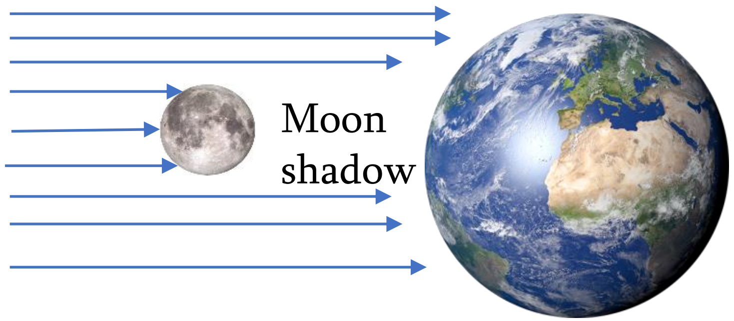
Rati (No/Oscillations) as a function of the reconstructed path length over reconstructed neutrino energy, L/E.



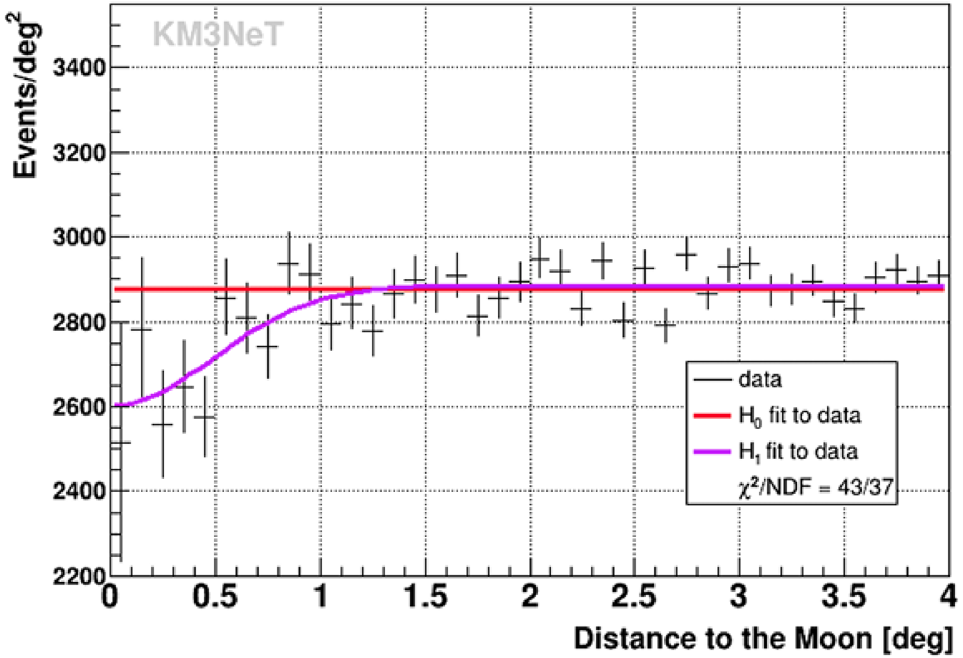
Contour at 90% CL of ORCA6 for the oscillation parameters compared with other experiments.

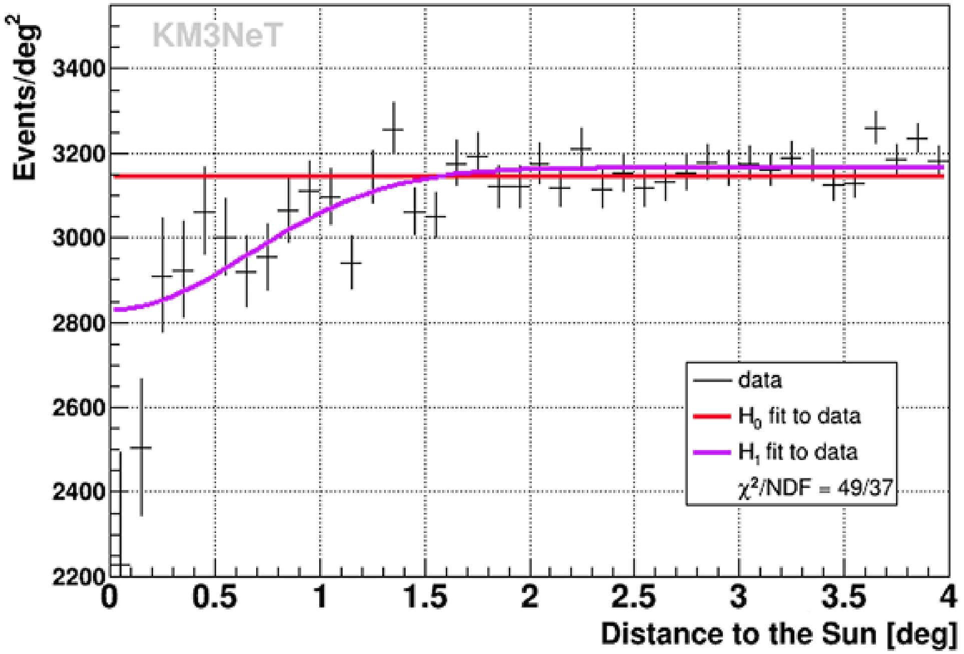
Best-fit: $\sin^2\theta_{23} = 0.51^{+0.06}_{-0.07}$ and $\Delta m^2_{31} = 2.14^{+0.36}_{-0.25} \cdot 10^{-3}\mathrm{eV}^2$

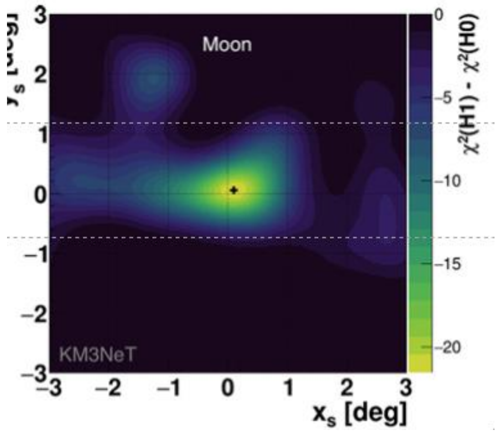
KM3NeT/ORCA6: Moon and Sun Shadow

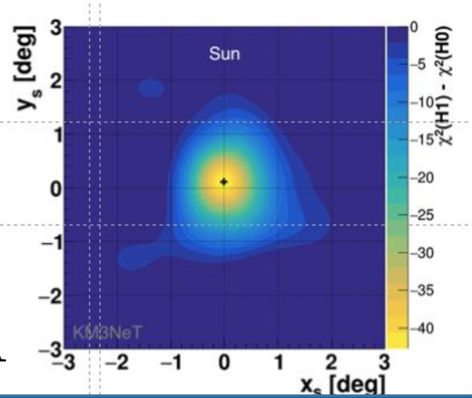


The shadows induced by the Moon and the Sun were detected at their nominal position with a statistical significance of 4.2σ and 6.2σ, and an angular resolution of σ_{res}=0.49◦ and σ_{res}=0.66◦, respectively, consistent with the prediction of 0.53◦ from simulations.



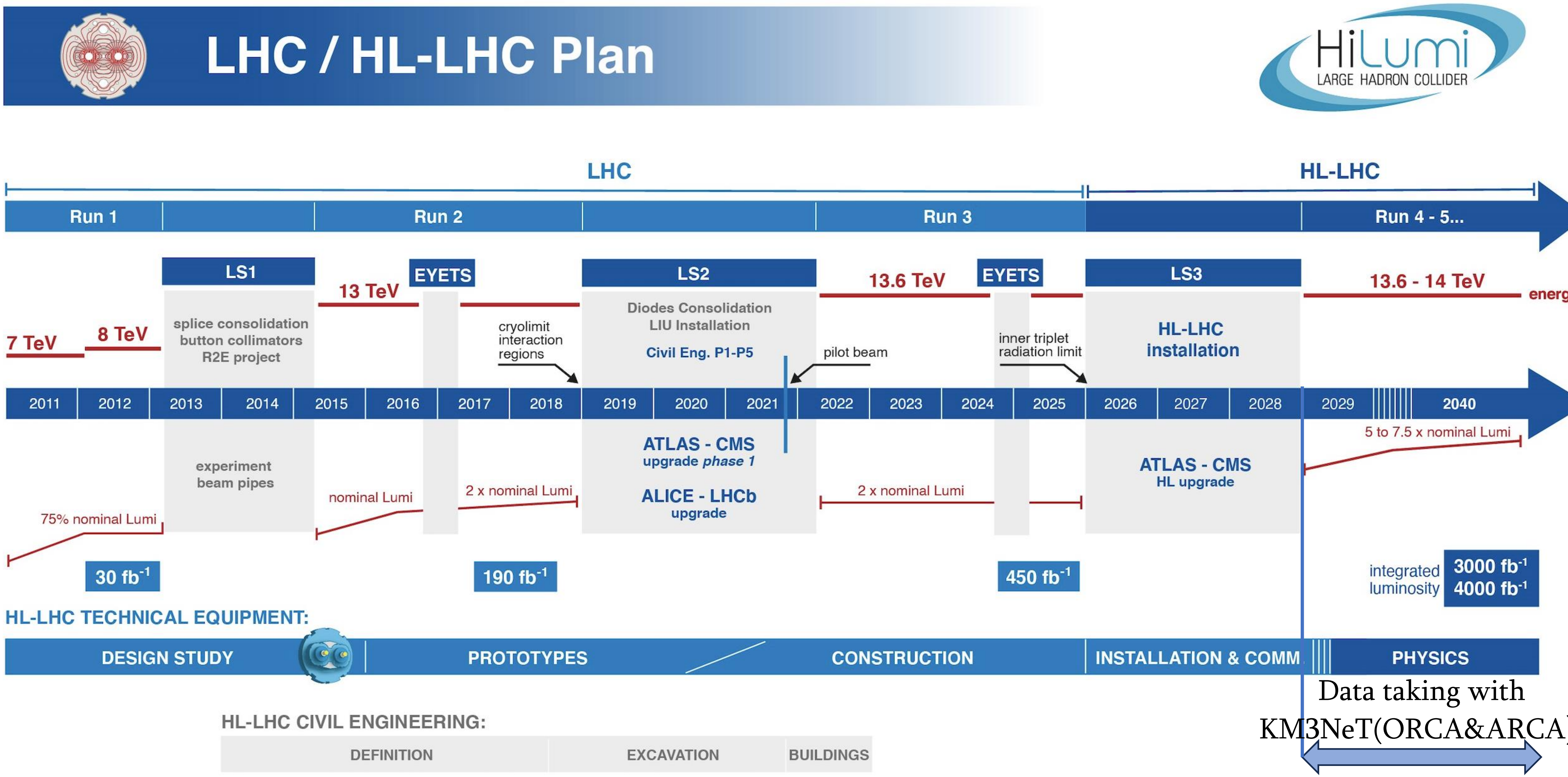






KM3NeT Collaboration, *Eur.Phys.J.C* 83 (2023) 4, 344
First observation of the cosmic ray shadow of the Moon and the Sun with KM3NeT/ORCA

LHC / HL-LHC Plan



Weak Decays: Source of High-energy Neutrinos

Weak decays of hadrons, leptons, and W and Z bosons:

$\pi^{\pm} \to \mu^{\pm} \nu_{\mu}$ 100%

$K^{\pm} \to \mu^{\pm} \nu_{\mu}$ 64%

$K^{\pm} \to \pi^{o} e^{\pm} \nu_{e}$ 5.1%

$K^{\pm} \to \pi^{o} \mu^{\pm} \nu_{\mu}$ 3.4%

Charmed particles:

$D^{\pm} \to \mu^{\pm} X$ 17.6±3.2 %

$D^{\pm} \to e^{\pm} X$ 16.07±0.30 %

$D^{\pm} \to e^{\pm} X$ 16.07±0.30 %

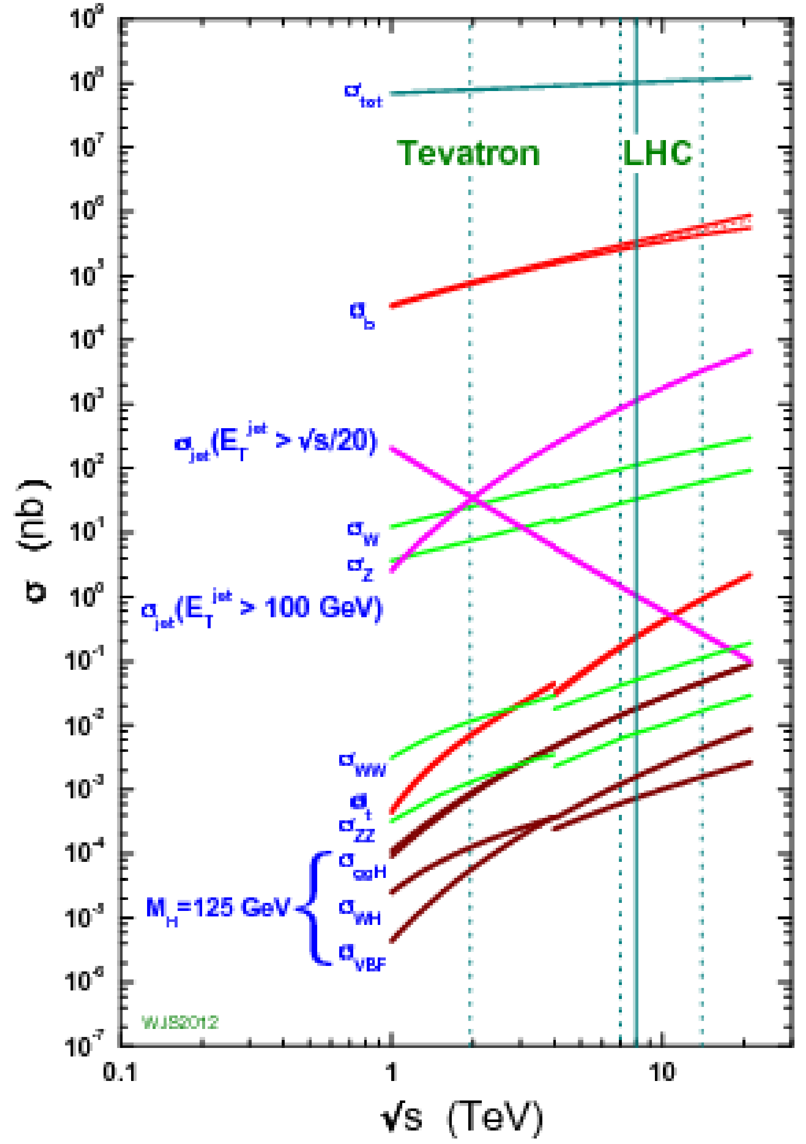
Leptons:

$\mu \to e \, \nu_{\mu} \nu_{e}$

$\tau \to e \, \nu_{\mu} \nu_{e}$

W and Z bosons:

$W \to l\nu$



Accelerator Neutrinos

Leon Lederman (1922-2018),
M. Schwartz (1932-2006),
J. Steinberger (1921-2020)

1988

$\pi^{\pm} \rightarrow \mu^{\pm}\, \nu$

~~$\nu + n \rightarrow p + e^-$~~

~~$\bar{\nu} + p \rightarrow n + e^+$~~

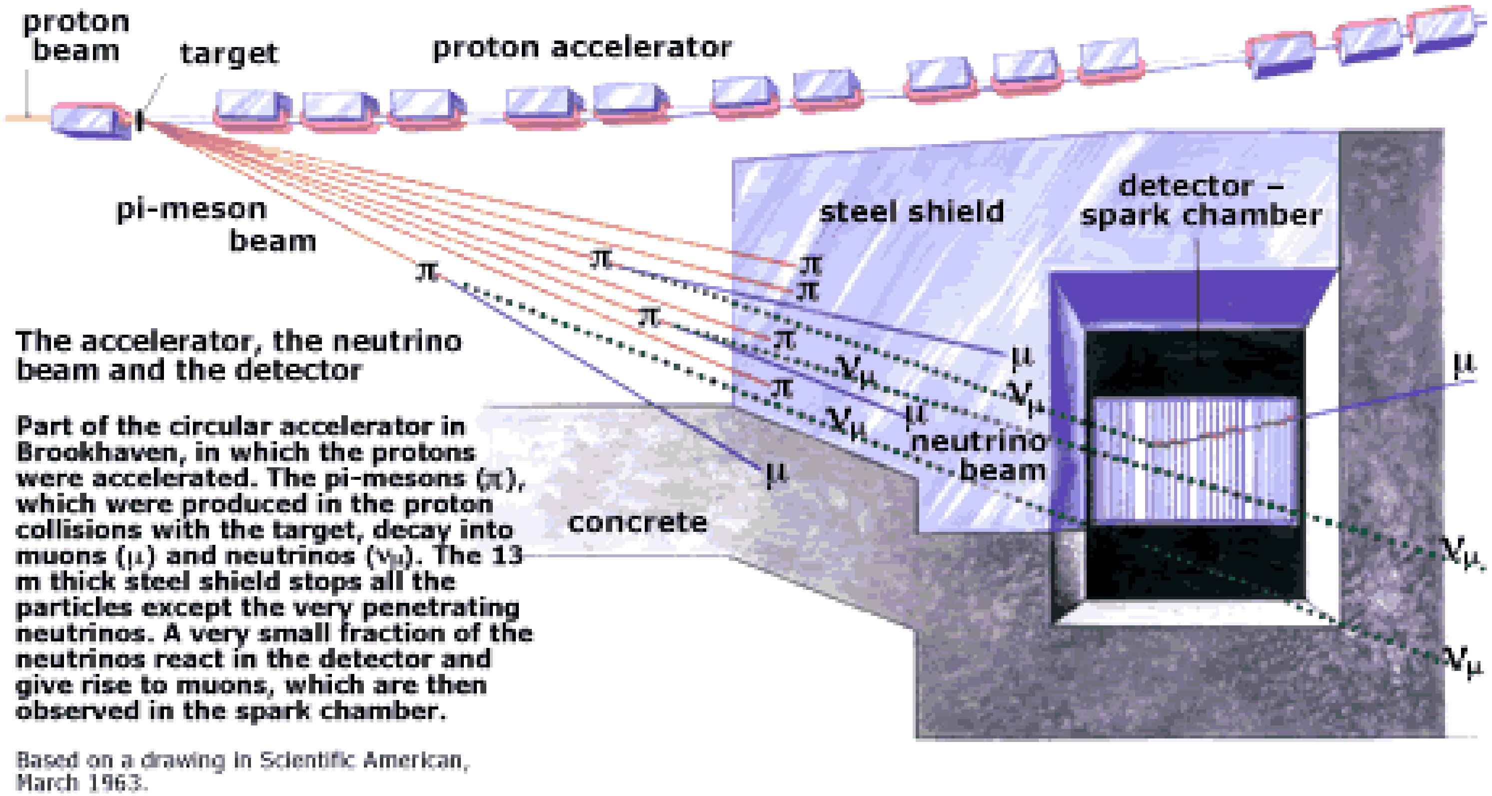
$\nu + n \rightarrow p + \mu^-$

$\bar{\nu} + p \rightarrow n + \mu^+$

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

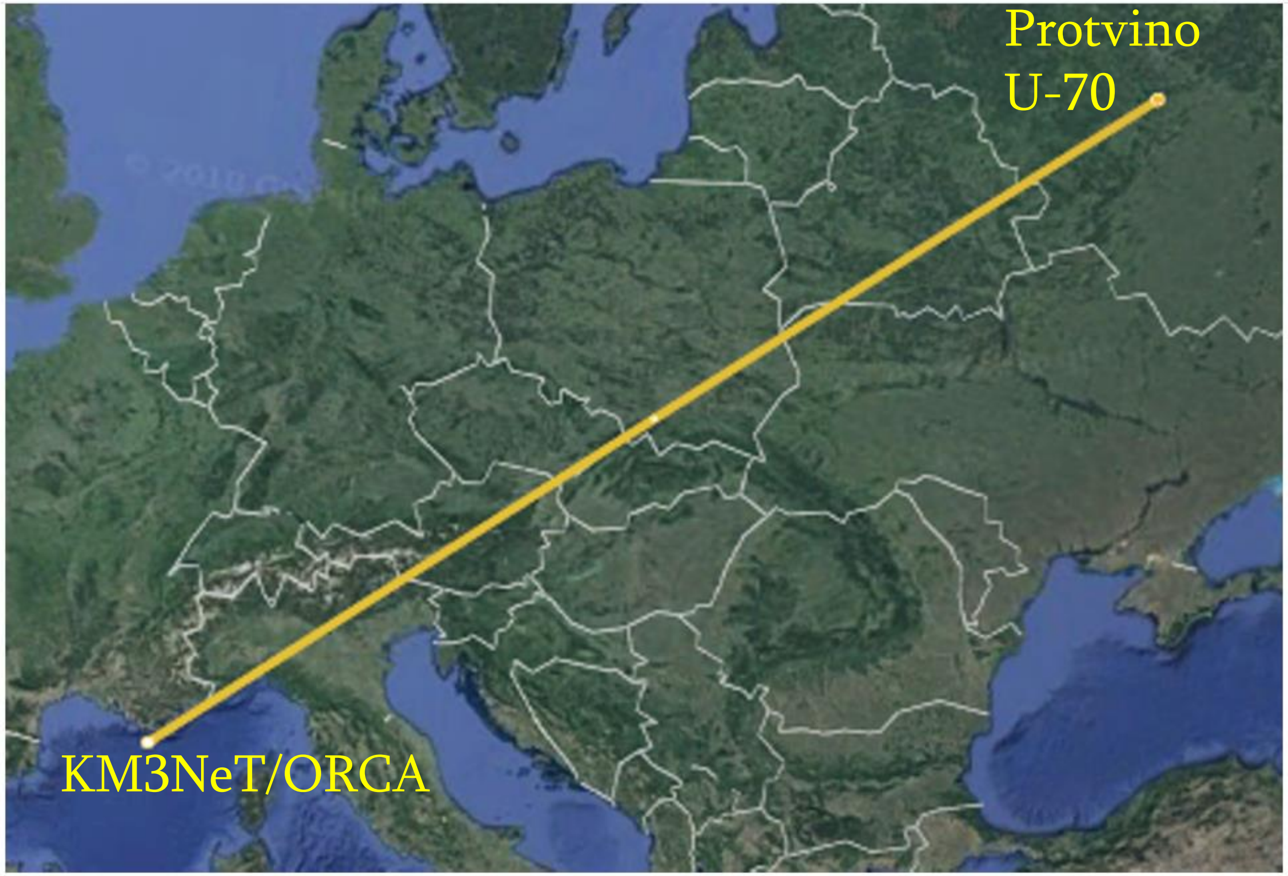
G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

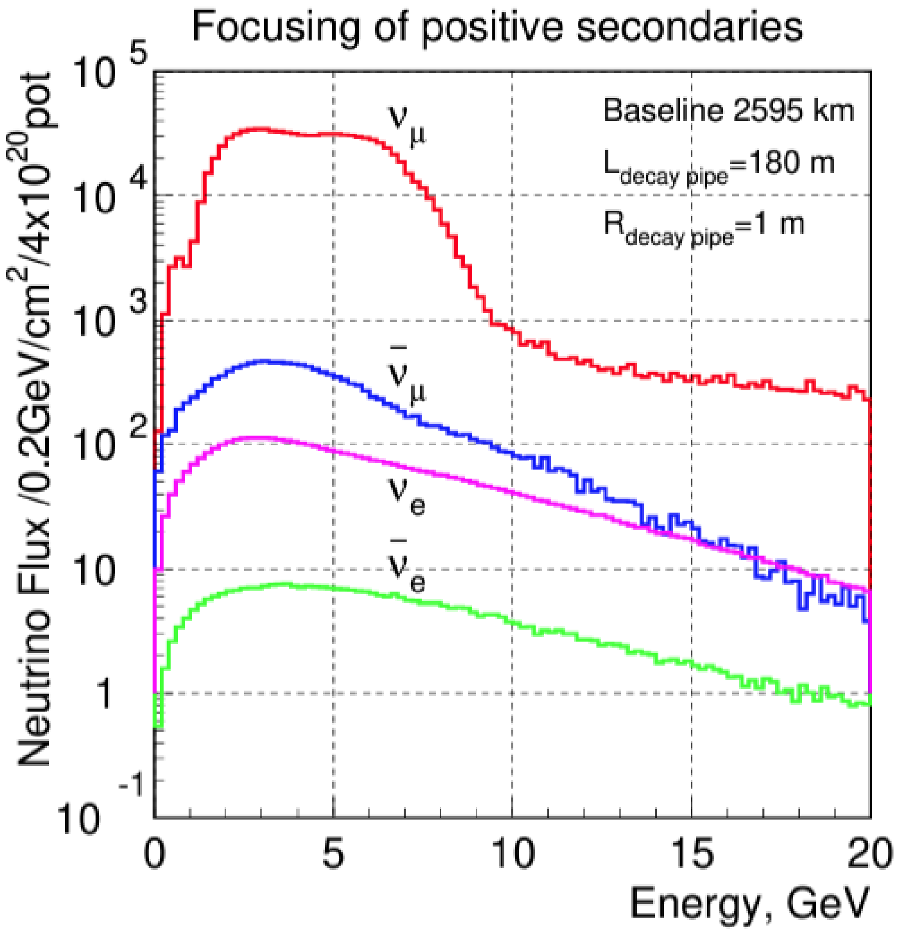
Phys. Rev. Lett. ***9(1962)***, *36*



LoI: Neutrino Beam from Protvino to KM3NeT/ORCA (P2O)

A.V. Akindinov et al., Eur. Phys. J. C (2019) 79 [arXiv, 1902.06083]

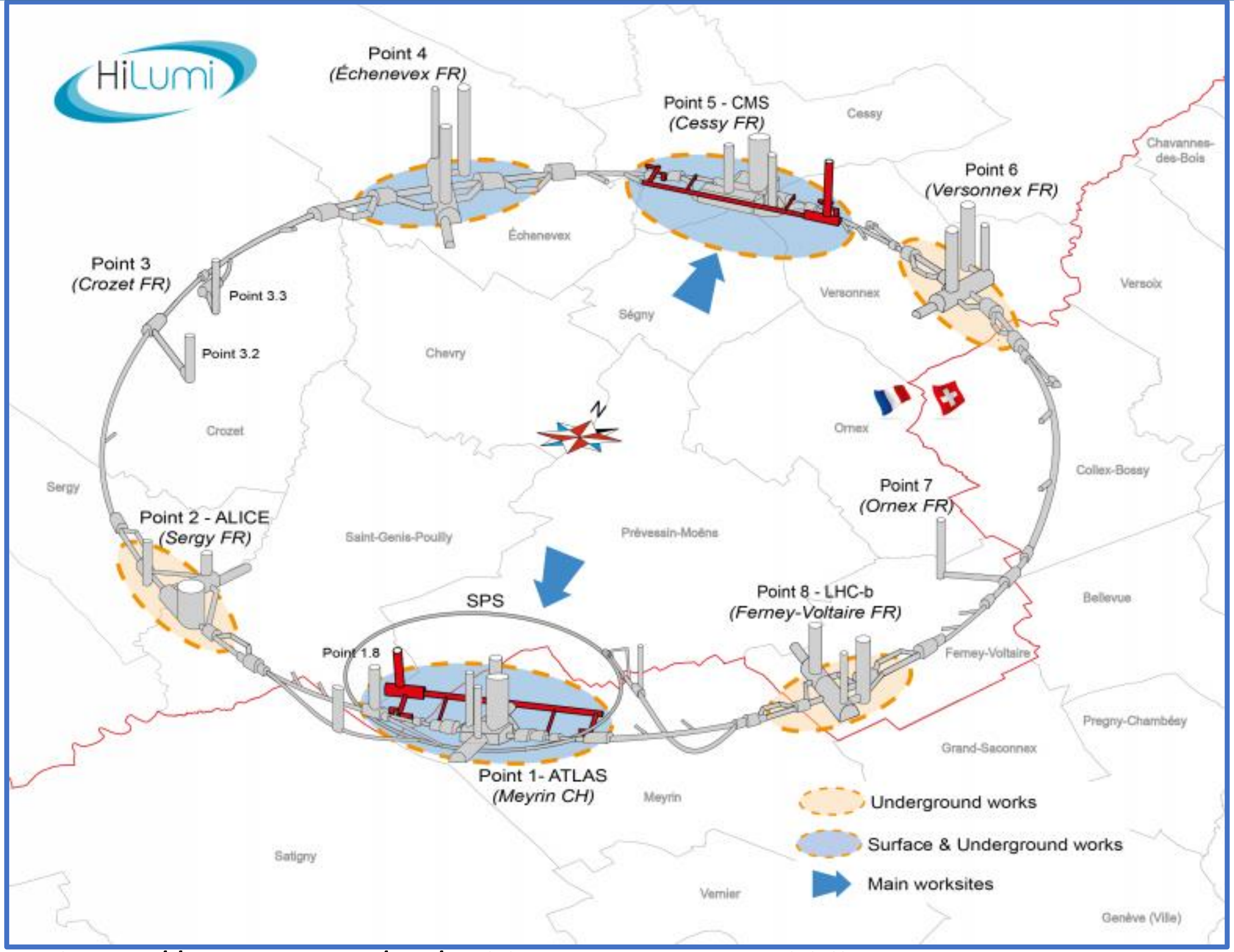




Path (≈2595 km) to be traveled by the neutrino beam from Protvino to KM3NeT/IECA/ORCA. The deepest point is 135 km below sea level, in the upper mantle.

NMO in a few years with modest beam Intensity of 90 kW

Large Hadron Collider



https://voisins.cern/en/public-presentations-hl-lhc-project

Particle production at LHC:

$pp \; at \sqrt{s} \; = 14$ TeV

IP1 (ATLAS) and IP5(CMS)

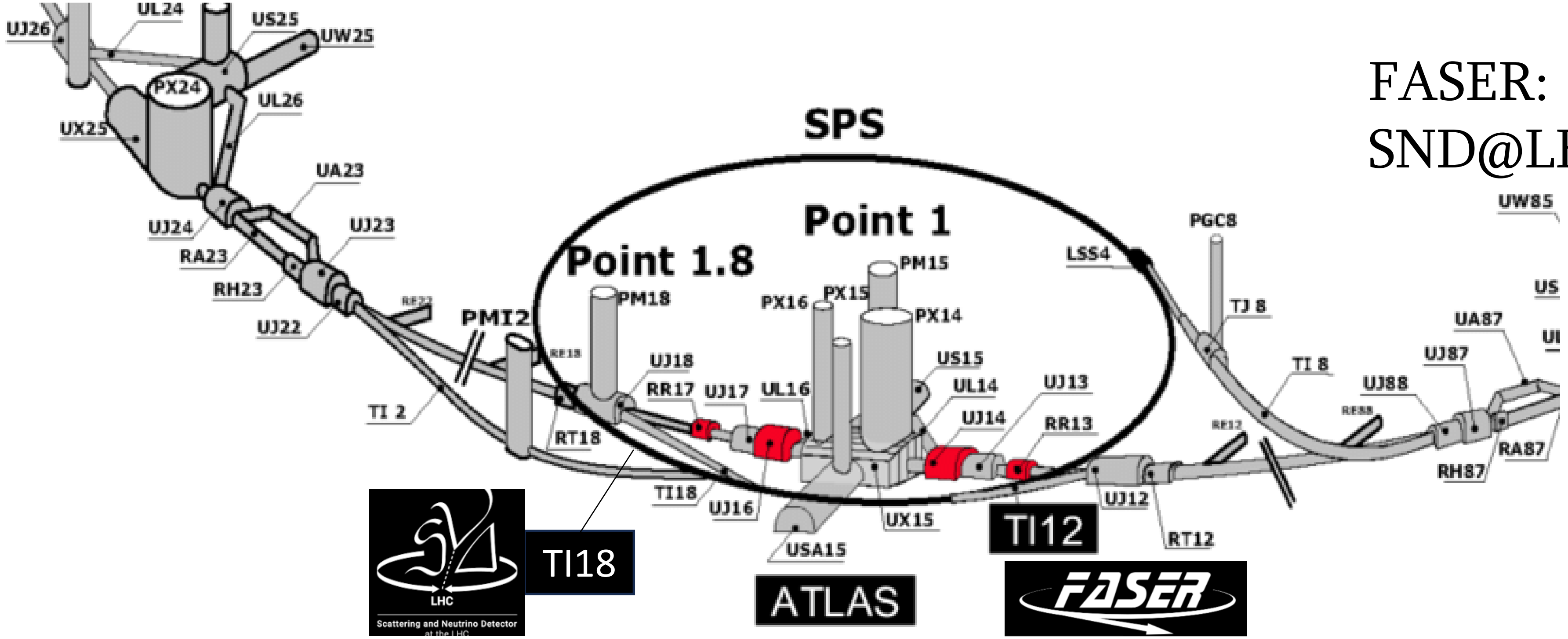
IP8(LHCb) and IP2(ALOCE)

$pA \; at \sqrt{s} \; = 114$ GeV

Beam-gas interaction in beam-pipe

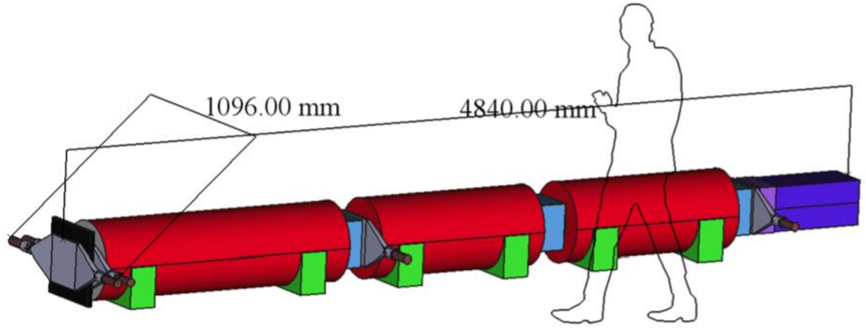
Beam-dump of proton beam on carbon absorber

FASER and SND@LHC



FASER: faser.web.cern.ch
SND@LHC: snd-lhc.web.cern.ch

FASER detector. scintillators, magnets. tracking, preshower and calorimeter
(cost is 1–1.5 M CHF_



FASER LoI, 1811.10243

FASER (ForwArd SeaRch **ExpeRiment) at the LHC**

arXiv:2207.11427 The FASER Collaboration, The FASER Detector

SND@LHC: Scattering and Neutrino Detector at the LHC

arXiv:2210.02784 The SND@LHC Collaboration, SND@LHC: The Scattering and Neutrino Detector at the LHC

Estimation of the LHC Neutrino Fluxes

- ✓ A. De Rujula, E. Fernandez and J.J. Gomez-Cadenas, Nucl Phys. B405(1993), 80
  Neutrino fluxes at future hadron colliders

- ✓ HyangKyu Park, JHEP (2011) The estimation of neutrino fluxes produced by proton-proton collisions at ps = 14 TeV of the LHC [arXiv: 1110.1971]

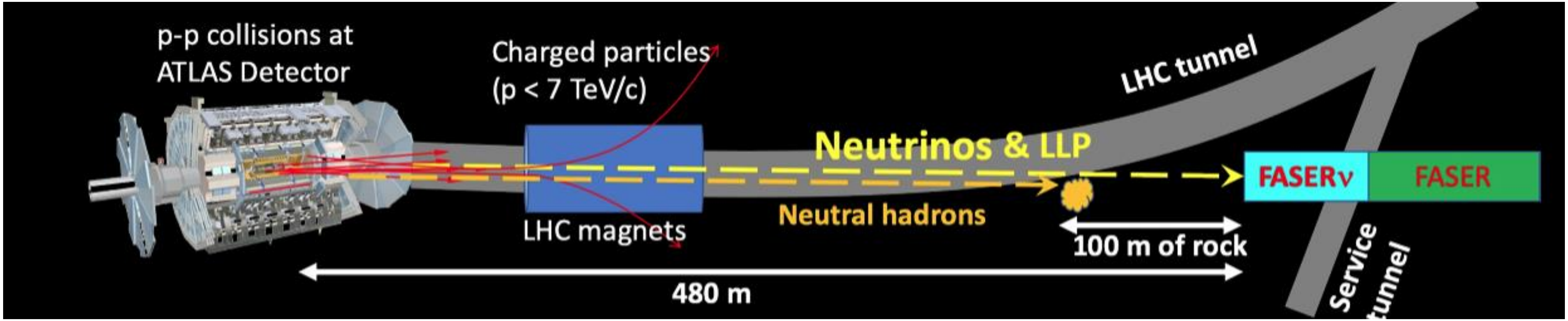
- ✓ N. Beni et al., J Phys. G46 (2019), 115008, Physics potential of an experiment using LHC neutrinos, [arXiv: 1903.06564]

- ✓ F.Klingand, L.J.Nevay, Phys.Rev.D104 (2021),113008, Forward neutrino fluxes at the LHC

- ✓ R.Shanidze, NIM A567 (2006), 483-485, Neutrinos from LHC and the Mediterranean very large neutrino telescope (KM3NeT)

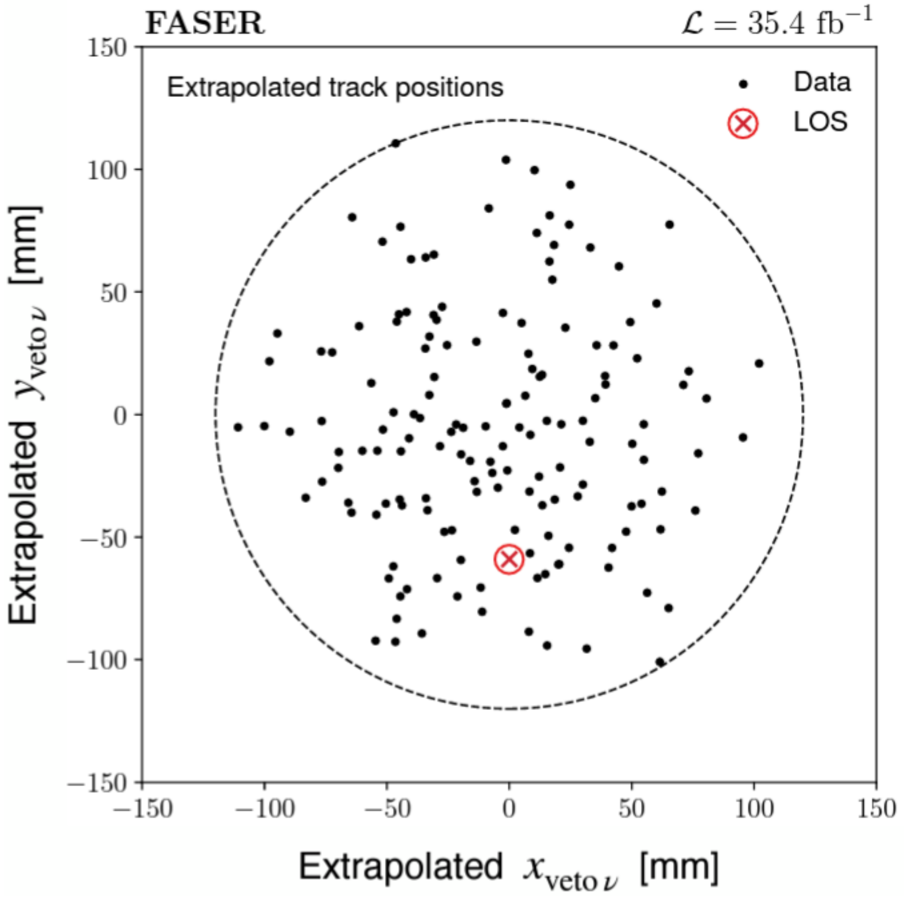
FASER Experiment

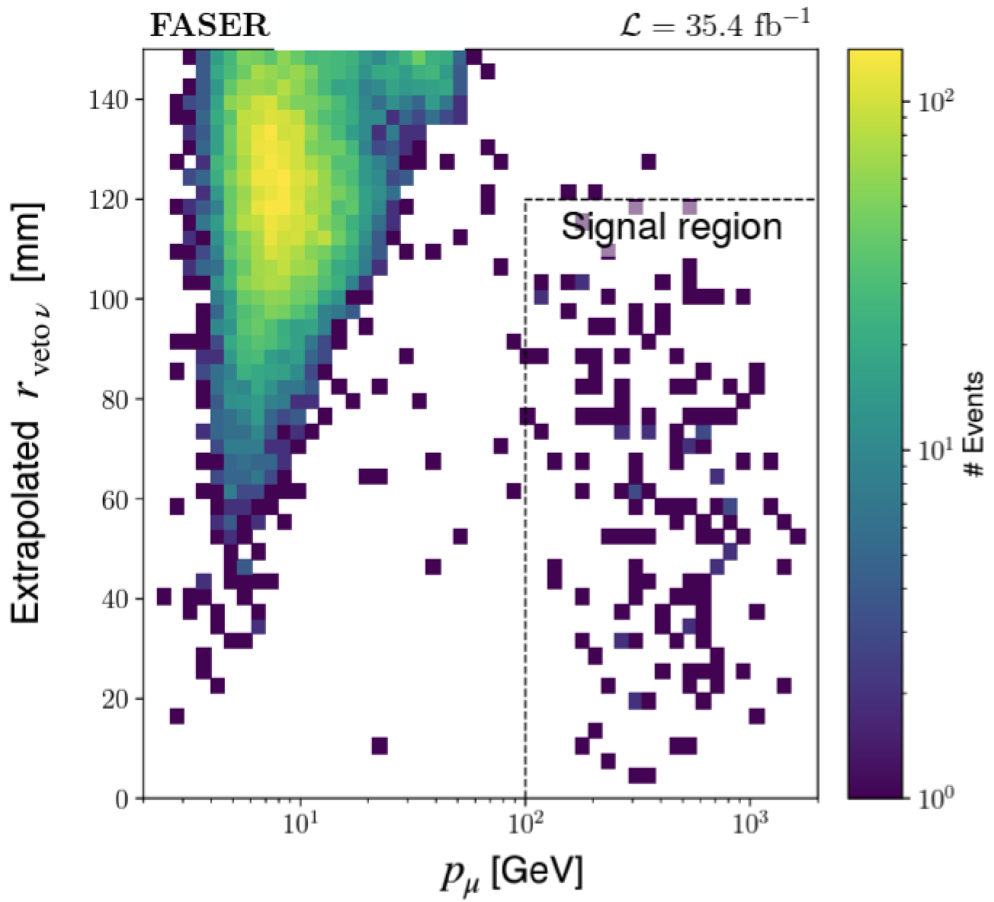
✓ FASER Collaboration, Letter of Intent for FASER: **F**orw**A**rd **S**earch **E**xpe**R**iment at the LHC, arXiv: 1811.10243 (CERN-LHCC-2018-030, LHCC-I-032)



Dedicated to searching for light, extremely weakly-interacting particles at CERN's LHC. Such particles may be produced in the very forward direction of the LHC's high-energy collisions and then decay to visible particles inside the FASER detector. FASER also includes a sub-detector, FASERν, designed to detect neutrinos produced in the LHC collisions and to study their properties.

First Direct Observation of Collider Neutrino

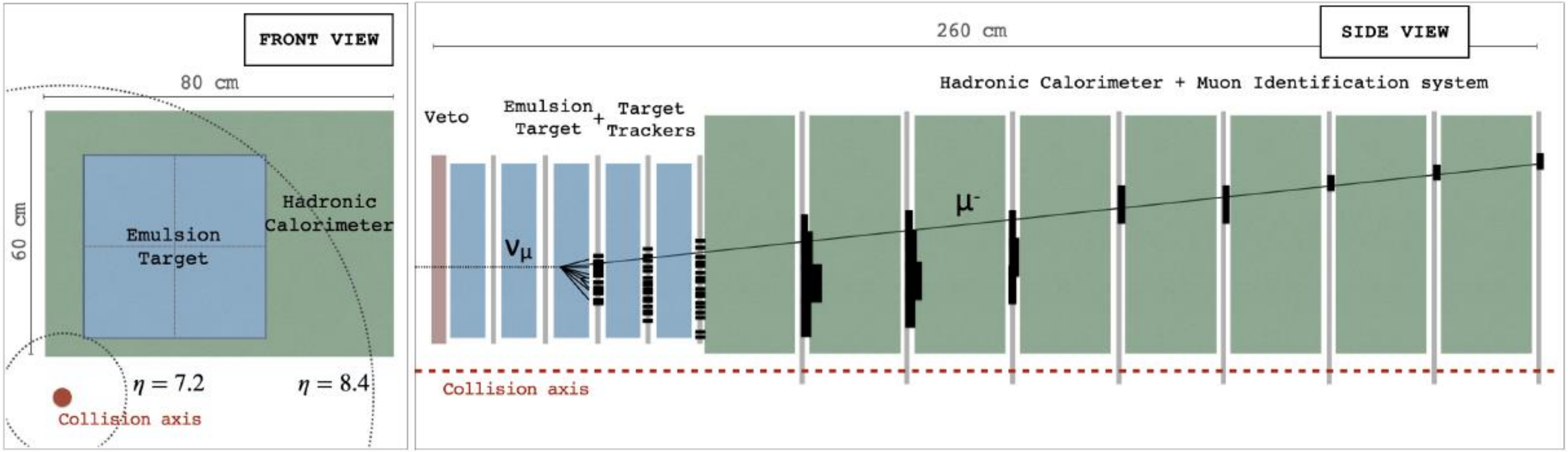




153 (+12–13) neutrino candidate events from 13.6TeV pp collision, 35.4 fb^{-1} The candidates are required to have a track propagating through the entire length of the FASER detector. ν_μ-CC events, with E>200 GeV are 16 σ above the background-only hypothesis.

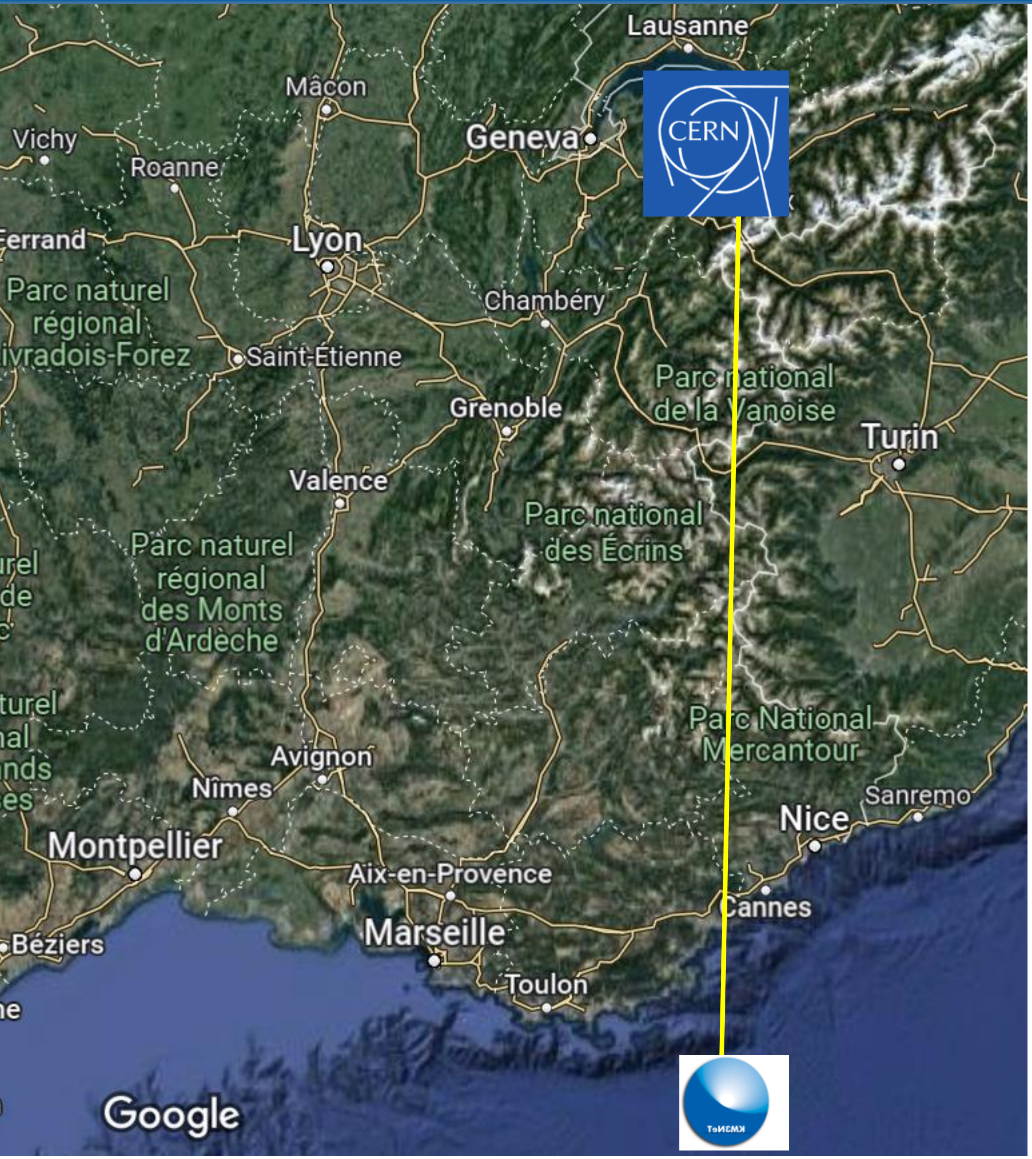
SND@LHC Experiment

Collaboration with180 members from 23 institutes in 13 countries and CERN.



SND@LHC is a compact and stand-alone experiment to perform measurements with neutrinos produced at the LHC in a hitherto unexplored pseudo-rapidity region of $7.2 < \eta < 8.4$, complementary to all the other experiments at the LHC.

LHC KM3NeT/ORCA



CERN (46.2330° N, 6.0557° E)

KM3NeT/ORCA (42°48’ N, 6°02’ E)
(42.8° N, 6.0333° E)

CERN experiments:

ATLAS (46.235° N, 6.053° E)

CMS (46.3098° N, 6.0764° E)

LHCb (46.2412° N, 6.0969° E)

Distances:

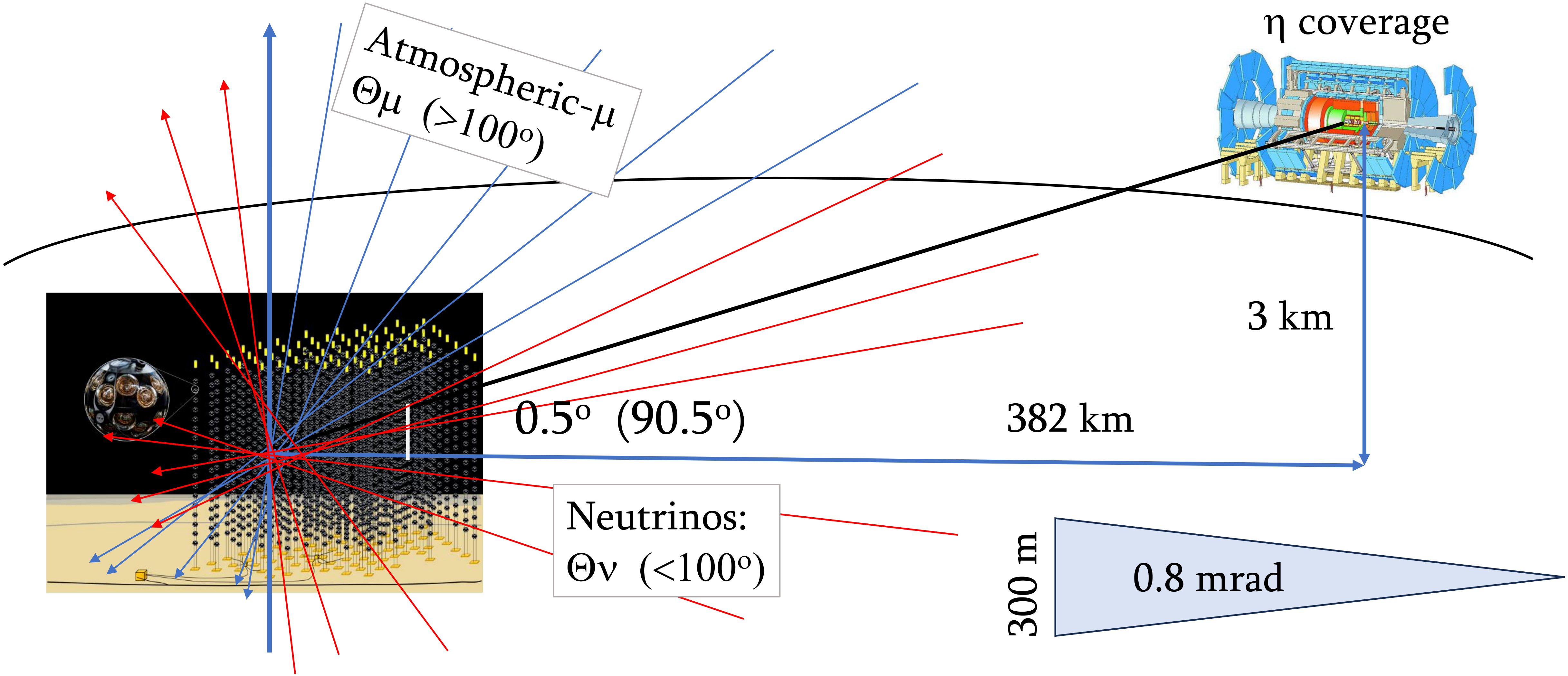
ATLAS - KM3NeT/ORCA: 382 km

CMS - KM3NeT/ORCA: 390 km

KM3NeT/ORCA

LHC to KM3NeT/ORCA

Expected ν-angle at KM3NeT/ORCA:



Summary and Outlook

- KM3NeT is a Mediterranean research infrastructure with 2 Cherenkov neutrino detectors: ORCA and ARCA, with a main aim to measure neutrino oscillations, determine NMO and detect cosmic neutrino fluxes and sources.

- KM3NeT detectors are currently taking data with about 15% of the final configuration(s). KM3NeT will be completed for 2028-2029.

- From 2029 HL-LHC will copiously produce neutrinos of all flavors with E<7 TeV

- neutrinos and "exotics" from HL-LHC could enhance the physics potential/program of KM3NeT/ORCA.

- Work in progress: calculation of kinematical parameters of LHC to ORCA project and expected neutrino rates

Merci beaucoup

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