IRN Neutrino Meeting
June 11th, 2021

Status, first data and prospects of KM3NeT-ORCA

Juande Zornoza (IFIC, UV-CSIC)

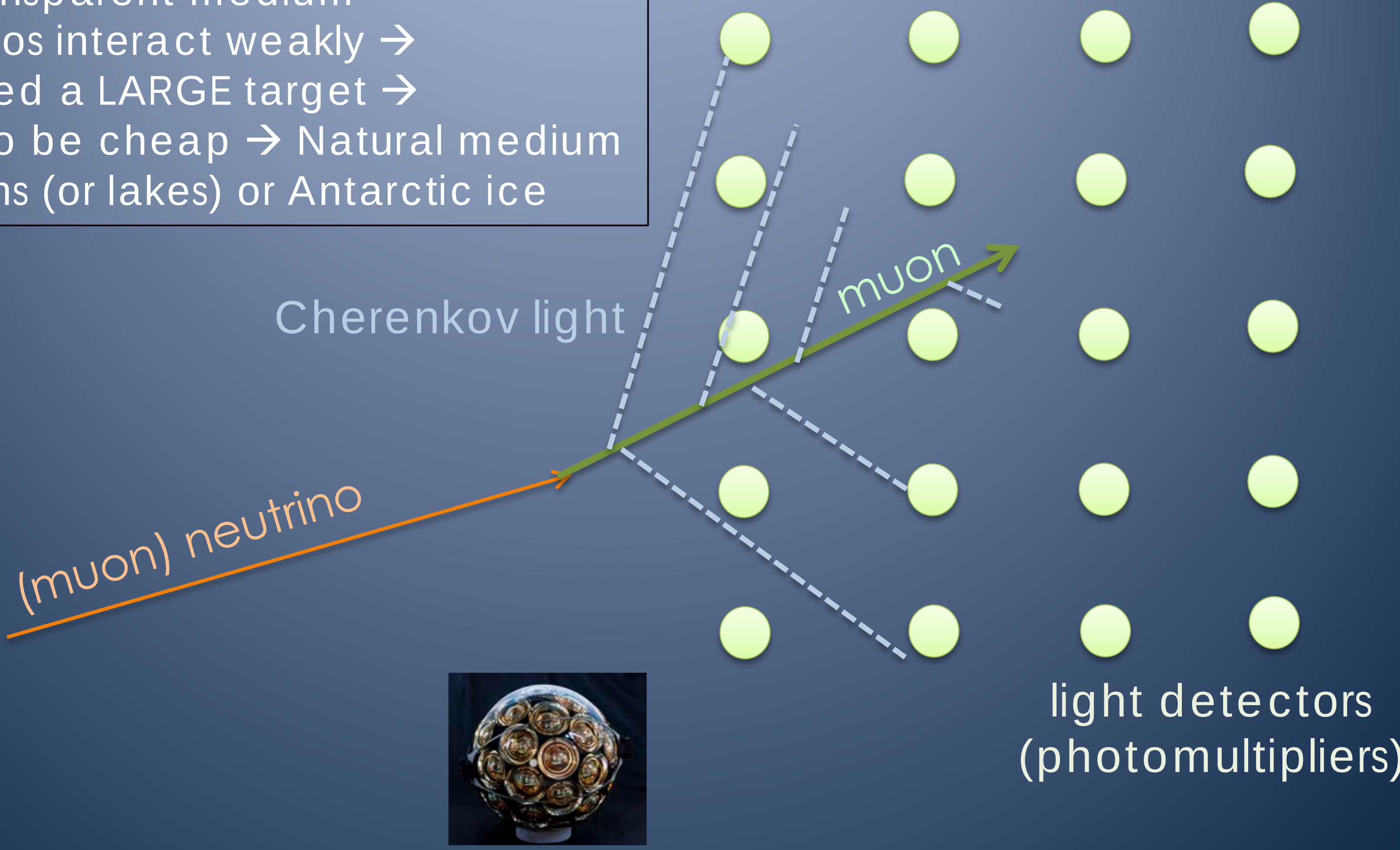
Outline

- Introduction
- KM3NeT-ORCA detector
  - Prospects
  - Status
  - First data and results
- Conclusions

Introduction

Detection Principle

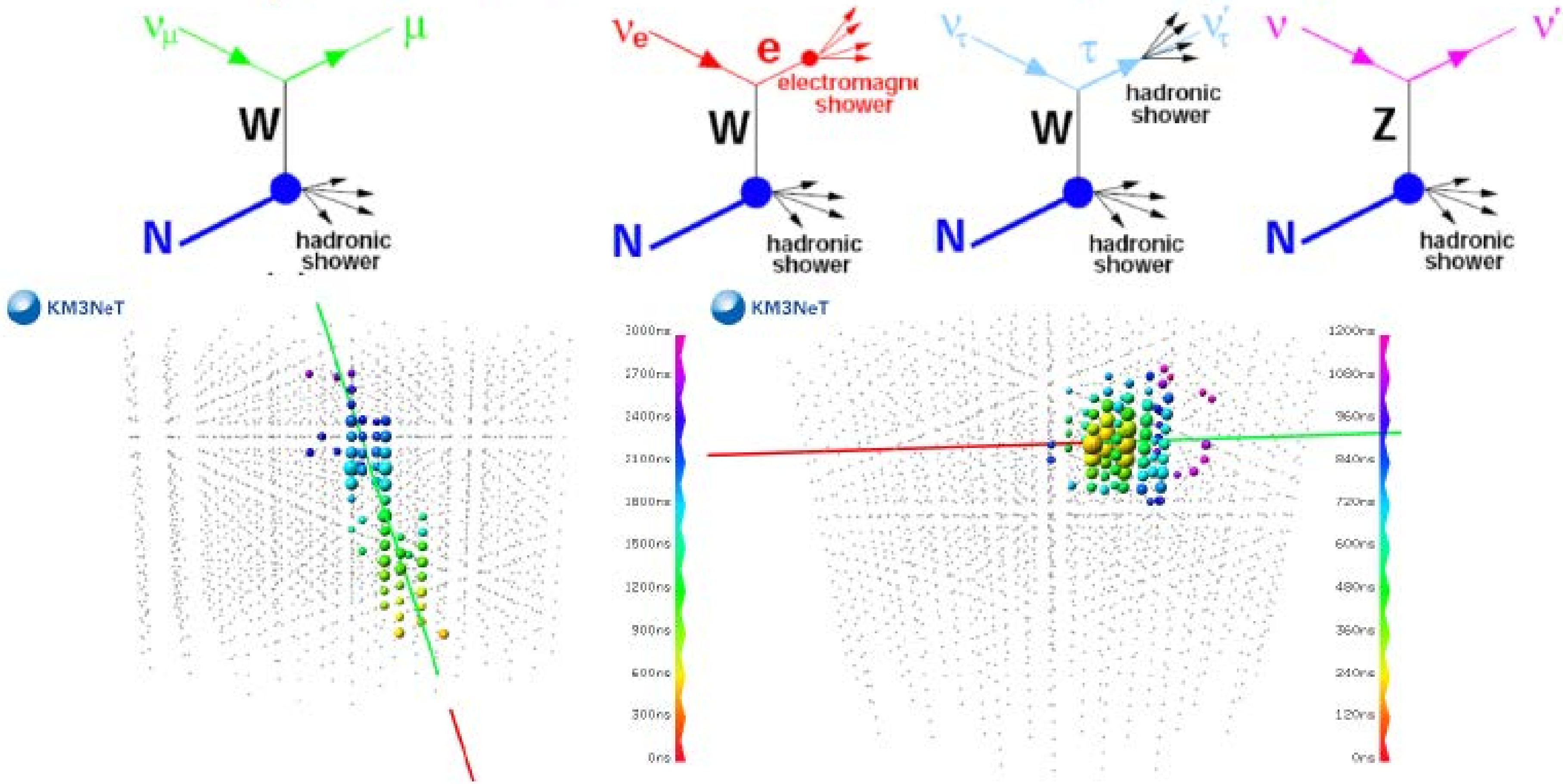
Where to put the detector?
1) In a transparent medium
2) Neutrinos interact weakly →
→ We need a LARGE target →
→ It has to be cheap → Natural medium
→ Oceans (or lakes) or Antarctic ice



Signatures

Tracks: ν_μ^{CC}, ν_τ^{CC} (17%)

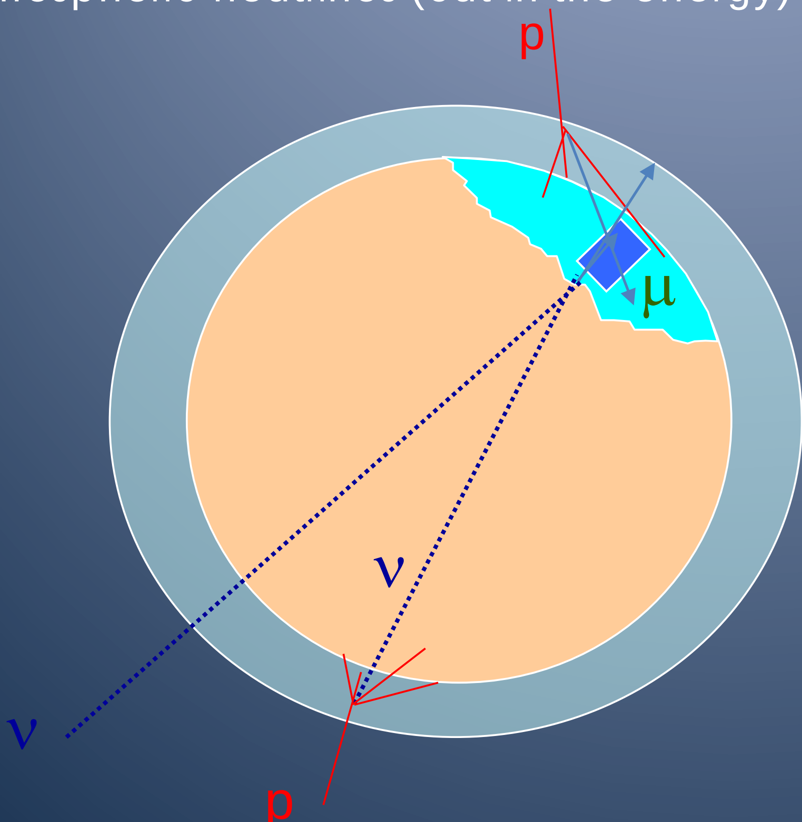
Showers: ν_e^{CC}, ν_τ^{CC}, ν^{NC}

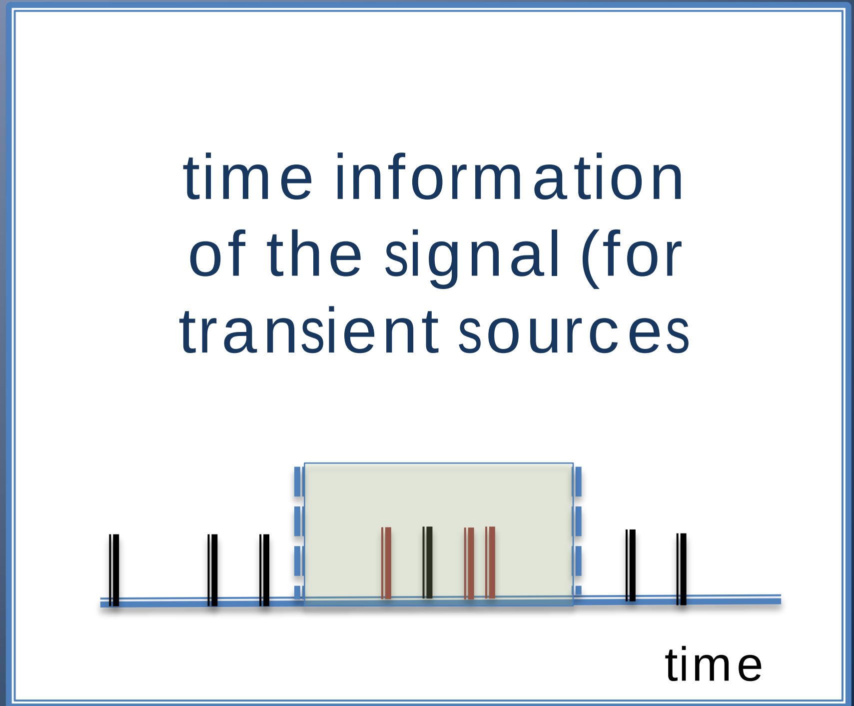


Physical Background (or signal!)

- There are two kinds of background:
  - Muons produced by cosmic rays in the atmosphere (→ detector deep in the sea and selection of up-going events)
  - Atmospheric neutrinos (cut in the energy)

$$p \to \pi^+ (+K^+ \ldots) \to \mu^+ + \nu_\mu$$
$$\mapsto e^+ + \bar{\nu}_\mu + \nu_e$$





Scientific Scope

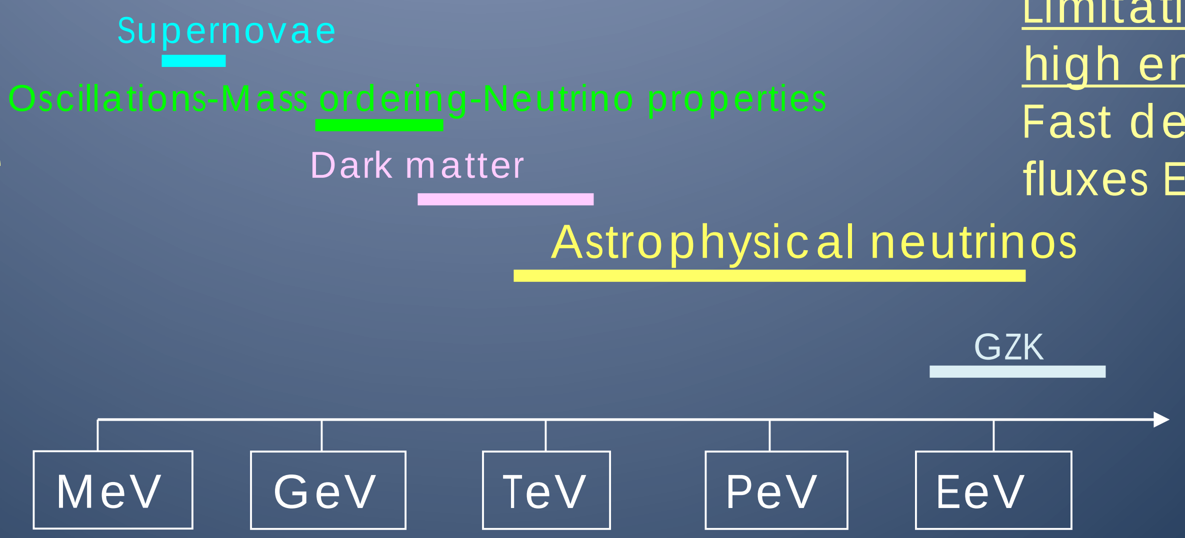
- Origin of cosmic rays
- Hadronic vs. leptonic signatures
- Neutrino mass ordering
- Dark matter

Detector size

Limitation at high energies:
Fast decreasing fluxes E^{-2}, E^{-3}

Limitation at low energies:
-Short muon range
-Low light yield
-^{40}K (in water)

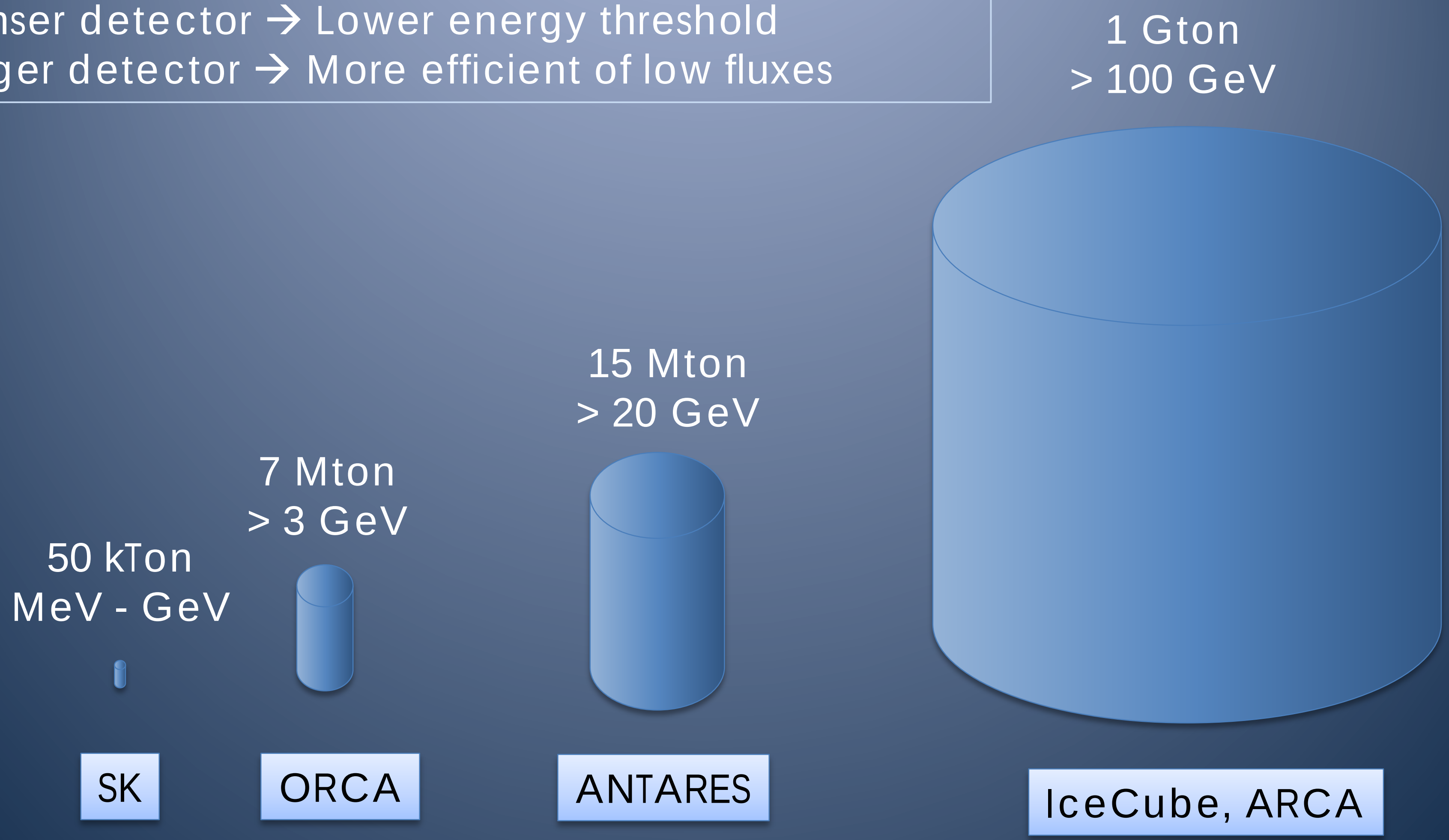
Detector density



Other physics: monopoles, nuclearites, Lorentz invariance, etc...

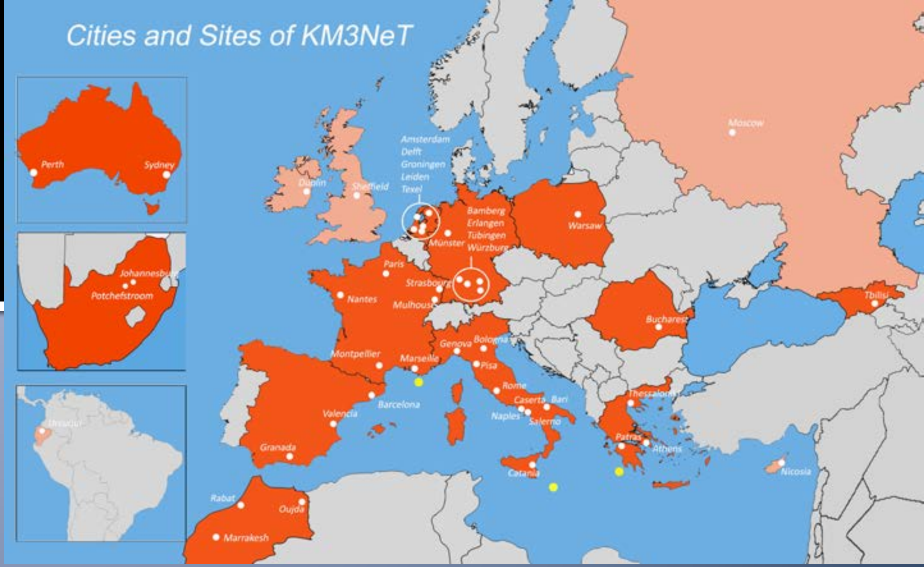
Detector size

Denser detector → Lower energy threshold
Larger detector → More efficient of low fluxes

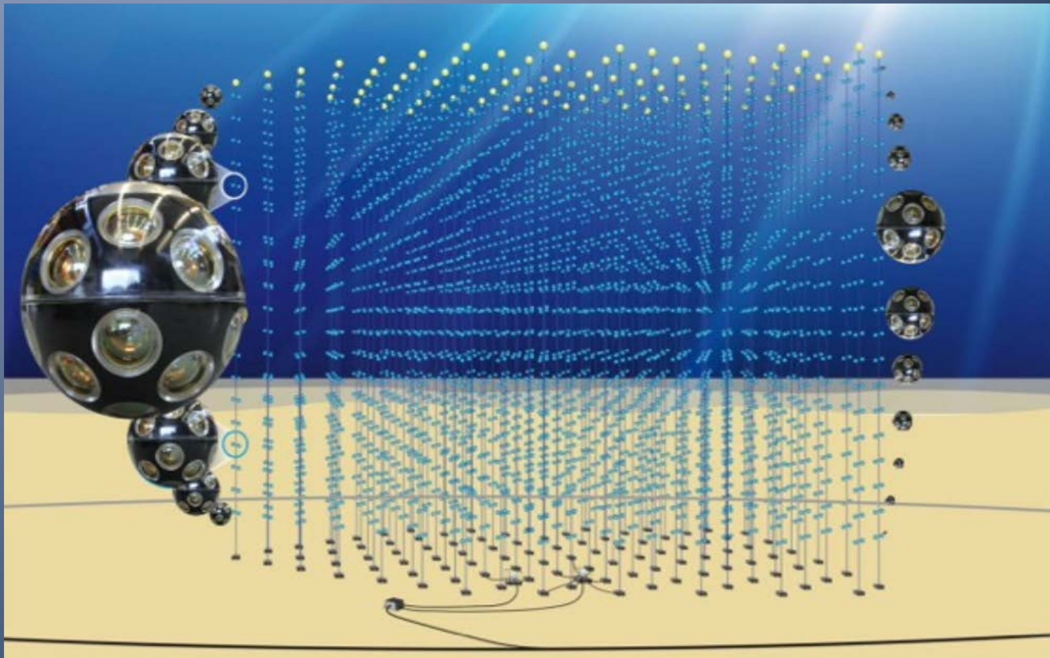


KM3NeT

KM3NeT



- KM3NeT is a common project to construct neutrino telescope in the Mediterranean with an instrumented volume of several cubic kilometers
- It will also be a platform for experiments on sea science, oceanography, geophysics, etc.
- 56 institutes and groups of Astroparticle Physics and Sea Science from 78 countries are involved
- New groups are welcome!



Letter of Intent: J. Phys. G: Nucl. Part. Phys. 43 084001 (2016), arXiv:1601.07459

Phases, status and plans

PHASE 1:

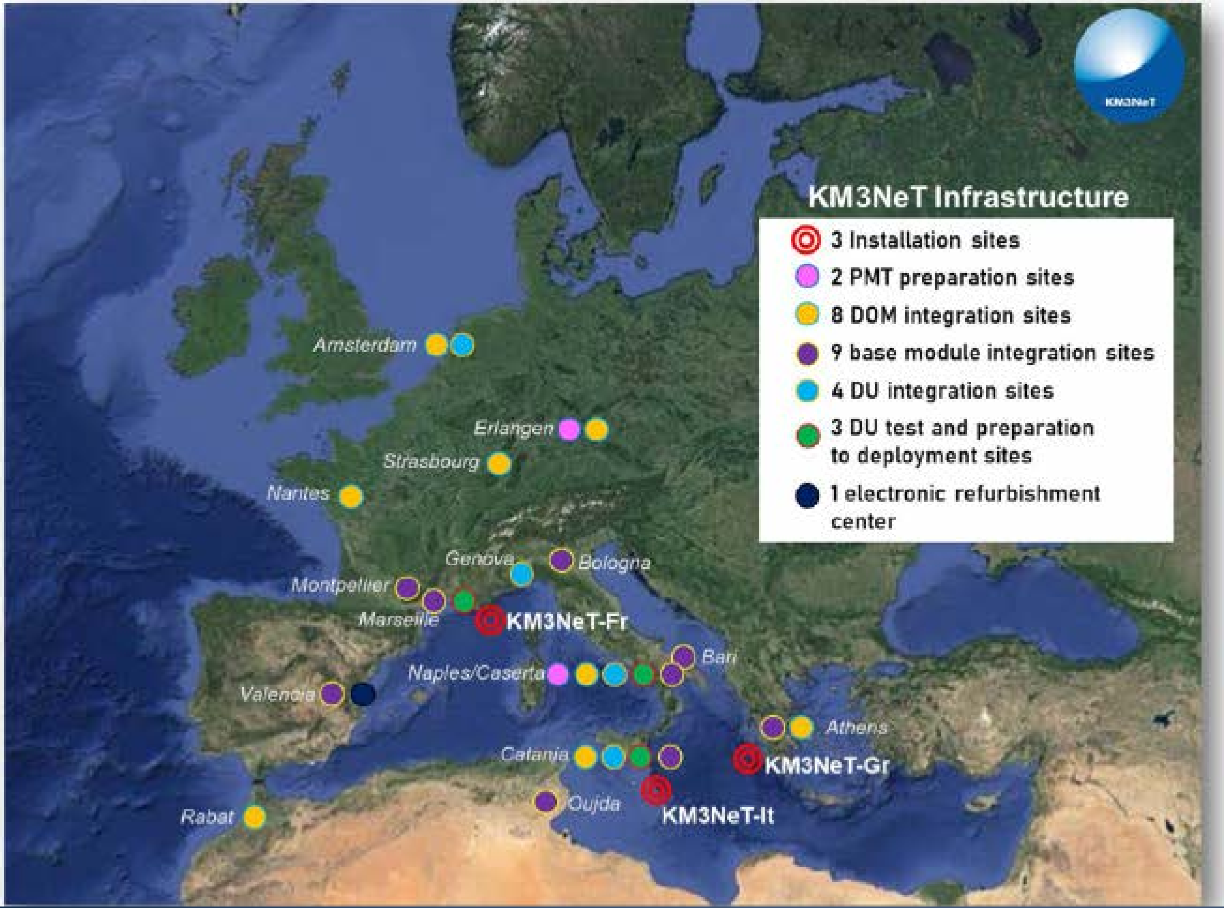
- 30 lines (24 in Italy, 6 in France)
- Proof of feasibility and first science results

Physics starts as soon as a few lines are deployed… =NOW!

<u>ARCA</u>
6 lines installed
11 lines by Fall 2021
23 lines by Spring 2022

<u>ORCA</u>
6 lines installed (+ 4 more in two weeks!)
13 lines by Fall 2021
20 lines by Spring 2022

Detector construction



DOMs:
- 8 integration sites
- 640 DOM produced

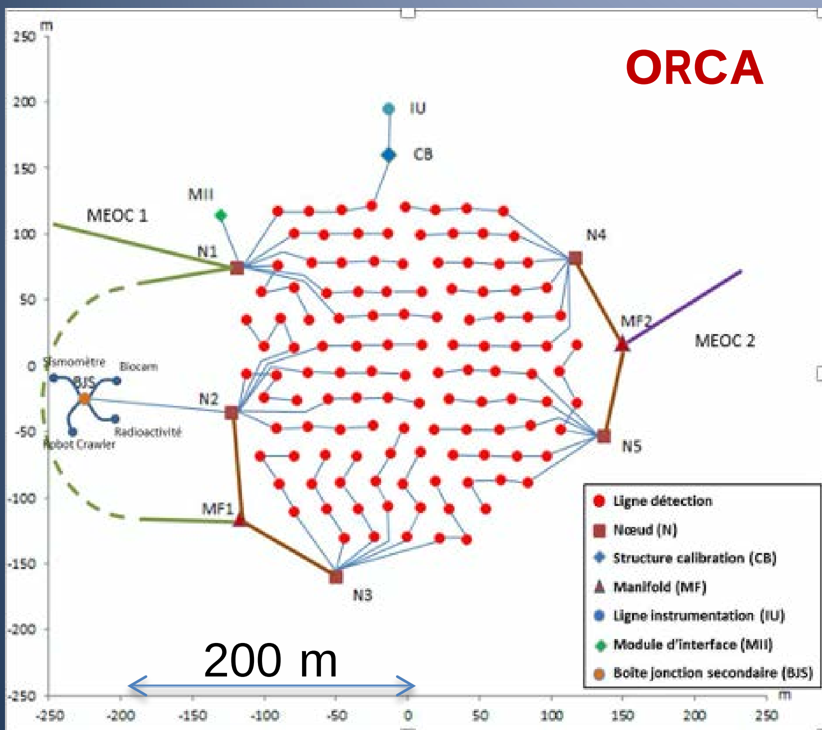
(400 ARCA,240 ORCA)
- 100 currently in progress

BMs:
- 9 integration sites
- 27 BMs produced
- 6 currently in progress

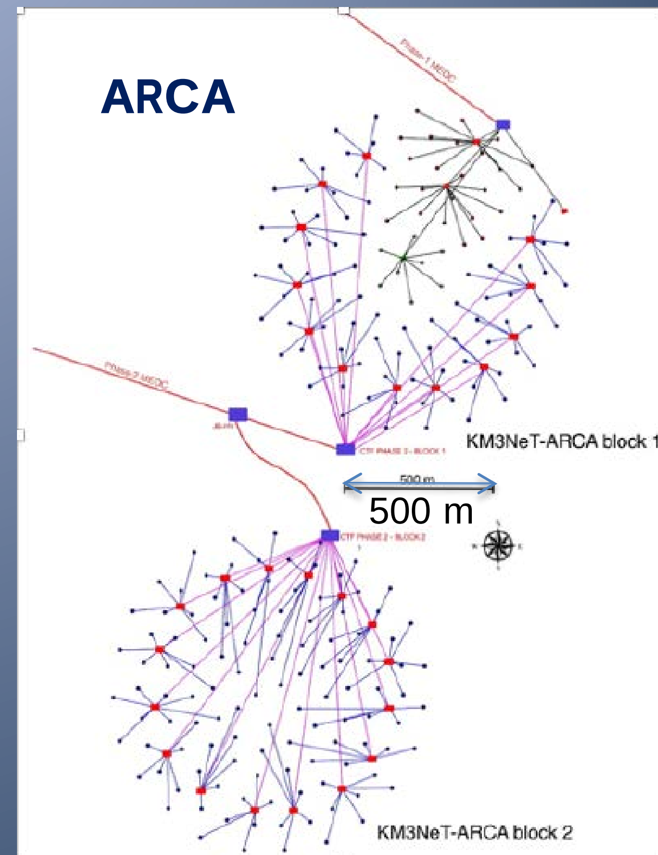
DUs:
- 5 integration sites
- 13 DUs produced
- 8 currently in progress

Total:22 integration sites!
(last year:15)

ORCA and ARCA



1 builing block (115 detection units)
18 DOMs / DU
inter-DU distance: 20 m
inter-DOM distance: 9 m



2 builing blocks (230 detection units)
18 DOMs / DU
inter-DU distance: 90 m
inter-DOM distance: 36 m

Same technology

KM3NeT Optical Modules

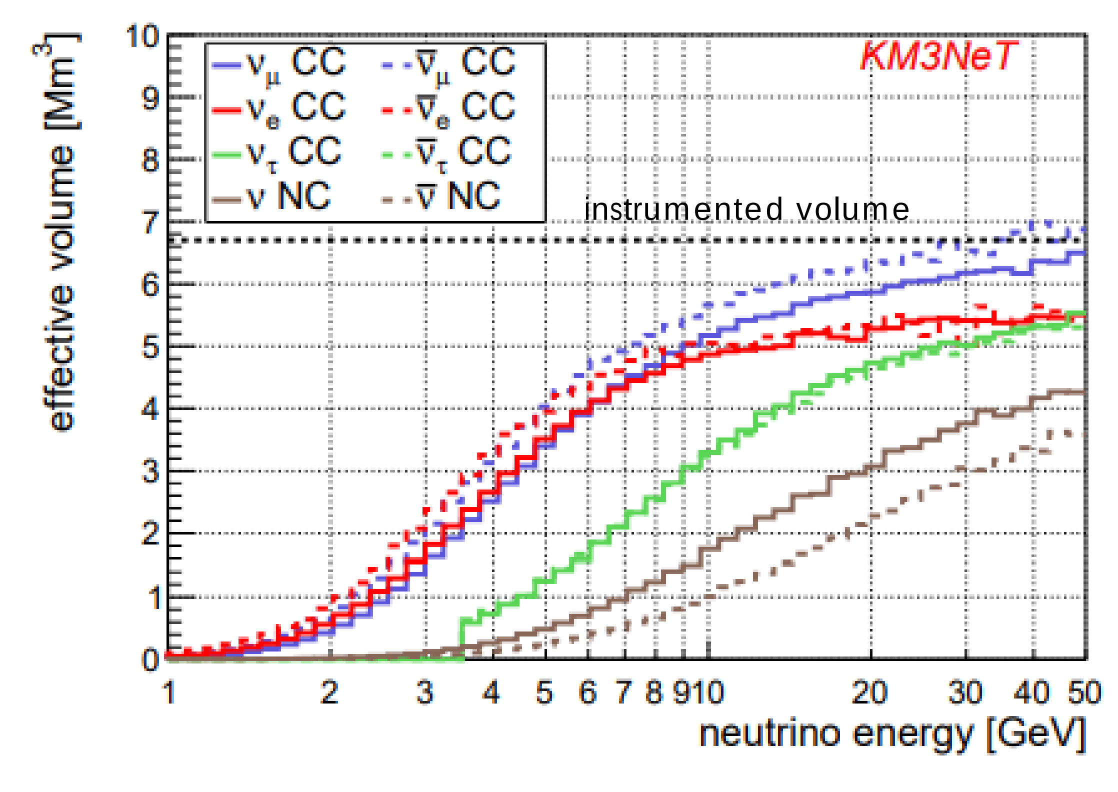
- (Multi-PMT) Optical Module
  - 31 x 3” PMTs
  - diameter: 17’’
  - low power requirements
  - “full” module: no additional electronics vessel needed
  - uniform angular coverage
  - information of the arrival direction of photons
  - better rejection of background

- Detector Units (strings)
  - 18 DOMs, separated vertically by: 6 m (ORCA) or 36 m (ARCA)
  - anchored at sea floor by a dead weight
  - kept vertical by buoys
  - 115 DUs = 1 building block

Prospects

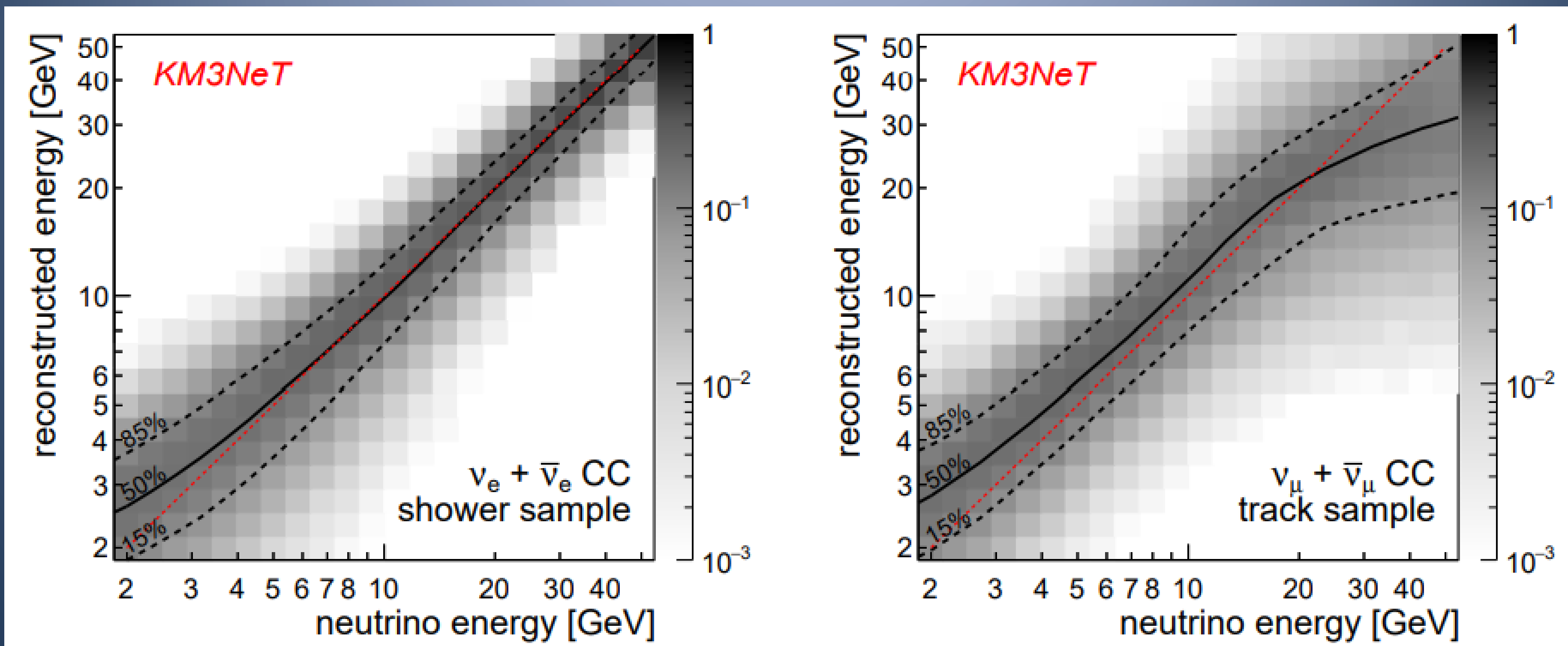
ORCA effective volume

update on performance, recently submitted: arxiv: 2103.09885
-geometry detector updated
-improvement in trigger
-improvement in event reconstruction



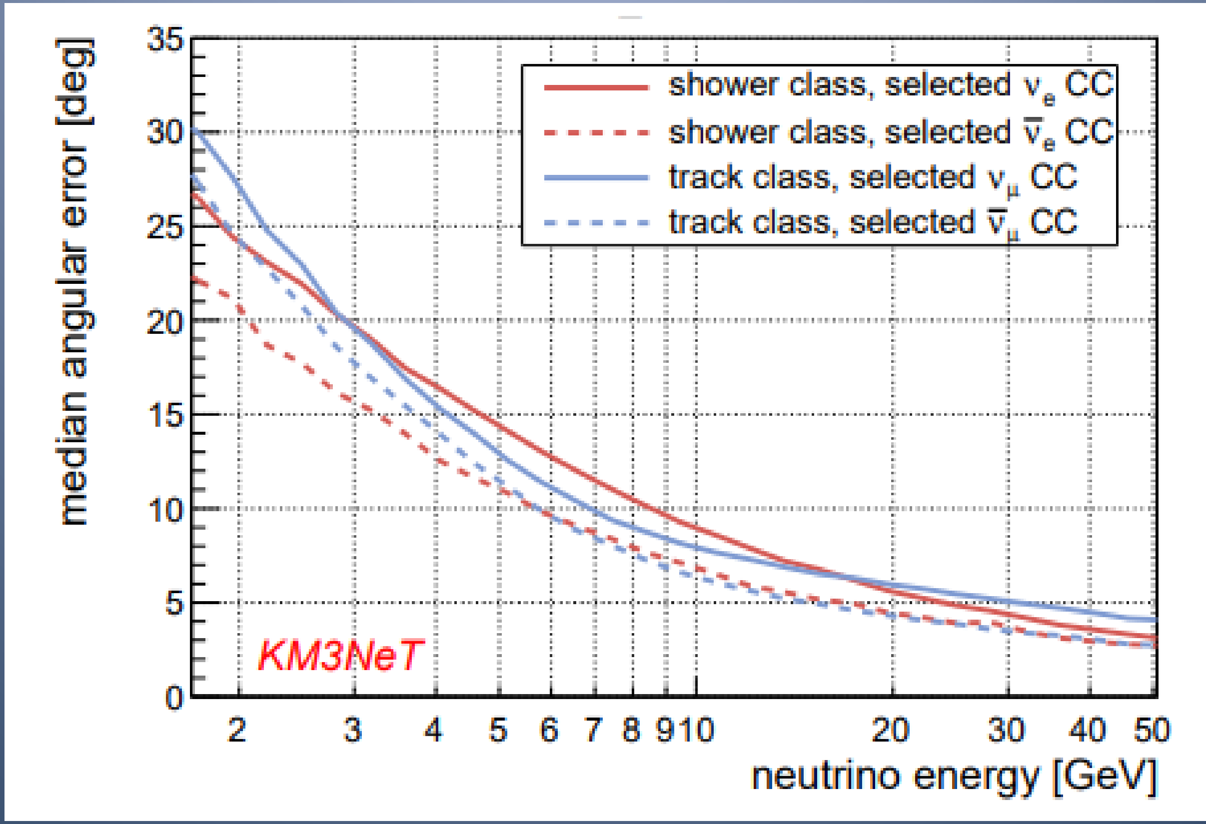
100% eff. at E > 15 GeV
50% eff. at E ~ GeV

ORCA: energy resolution



- $\Delta E/E \sim 25\%$ for ν_e CC events at E=10 GeV (dominated by intrinsic light yield fluctiations in hadronic shower)
- $\Delta E/E \sim 35\%$ for ν_μ CC events (outgoing muon often not fully contained)

ORCA: angular resolution



Neutrino direction resolution dominated by intrinsic ν-lepton scattering kinematics

NMO with atmospheric neutrinos

- In matter, the sign of Δm^2_{13} appears in oscillations

$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta^m_{13}\,\sin^2\left(\frac{\Delta^m m^2_{31}\,L}{4E_\nu}\right),$$

$$\sin^2 2\theta^m_{13} \equiv \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}}{\Delta^m m^2_{31}}\right)^2$$

$$\Delta^m m^2_{31} \equiv \sqrt{(\Delta m^2_{31}\cos 2\theta_{13} - 2\,E_\nu A)^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2},$$

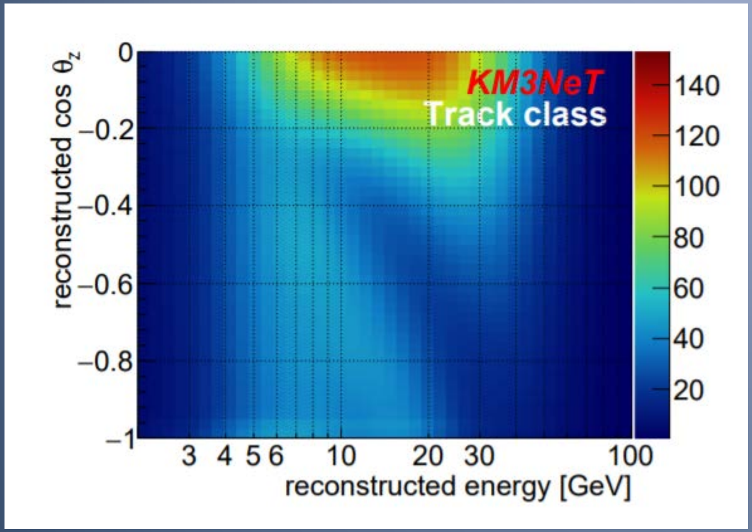
- Normal Ordering → resonance for neutrinos
- Inverted Ordering → resonance for anti-neutrinos

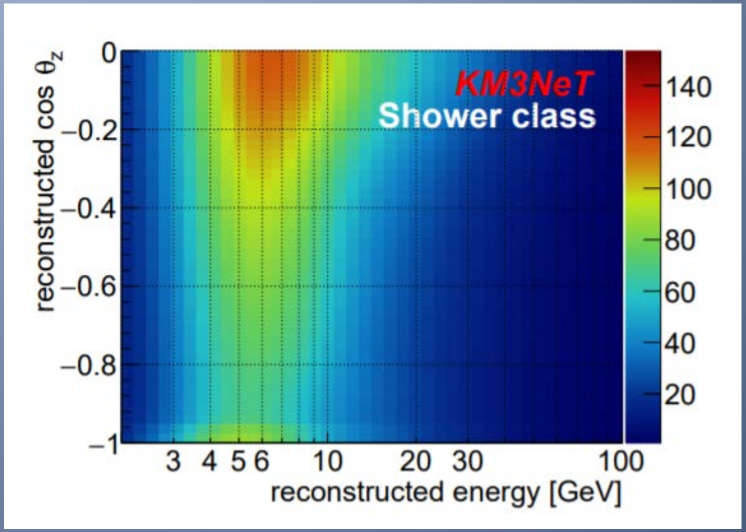
$\sigma_\nu \sim 2\,\sigma_{\text{anti-}\nu}$
$\phi_\nu \sim 1.1\,\phi_{\text{anti-}\nu}$

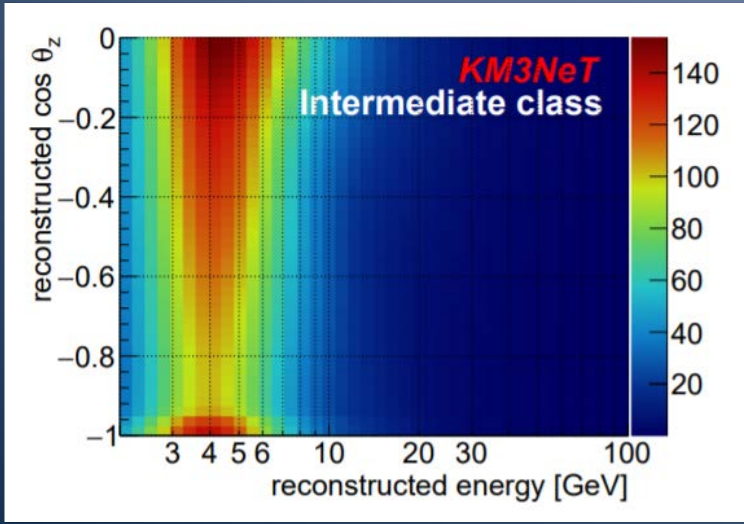
$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}\,G_F\,N_e} \simeq 7\,\text{GeV}\left(\frac{4.5\,\text{g/cm}^3}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times10^{-3}\,\text{eV}^2}\right)\cos 2\theta_{13}$$

E_{res}~7 GeV (mantle)
E_{res}~3 GeV (core)

Oscillograms







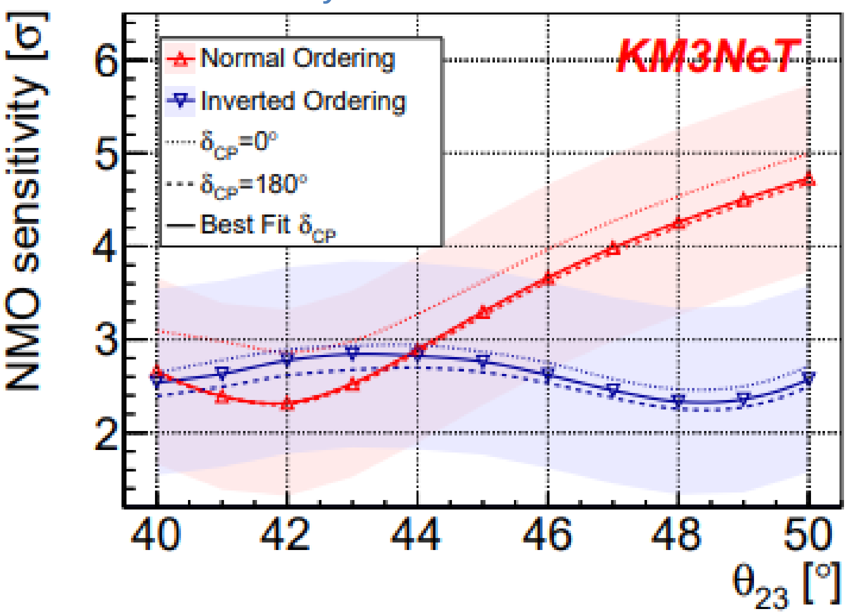
NMO would affect to oscillograms (cos θ - E plots)

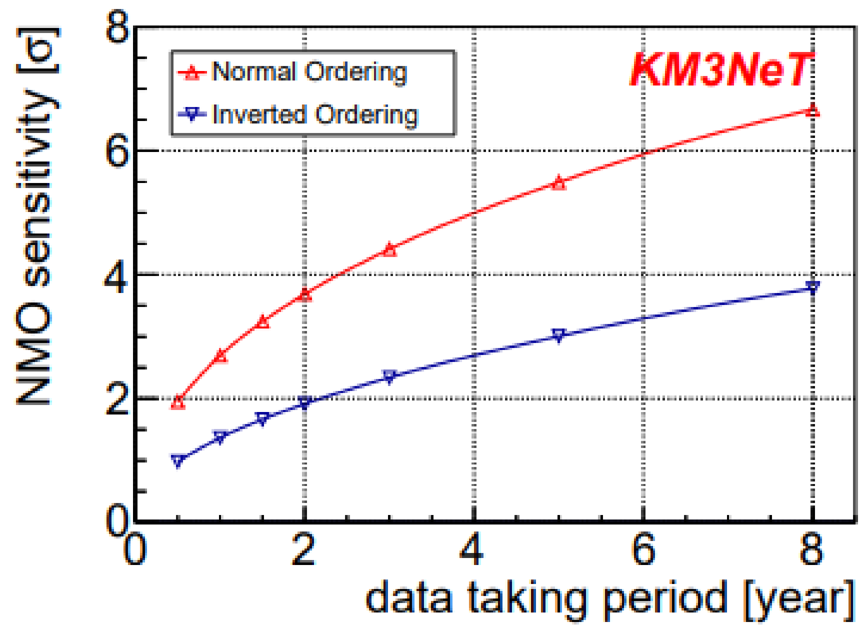
Events are classified in three classes: track-like, shower-like and intermediate

Neutrino Mass Ordering

arxiv: 2103.09885

after three years



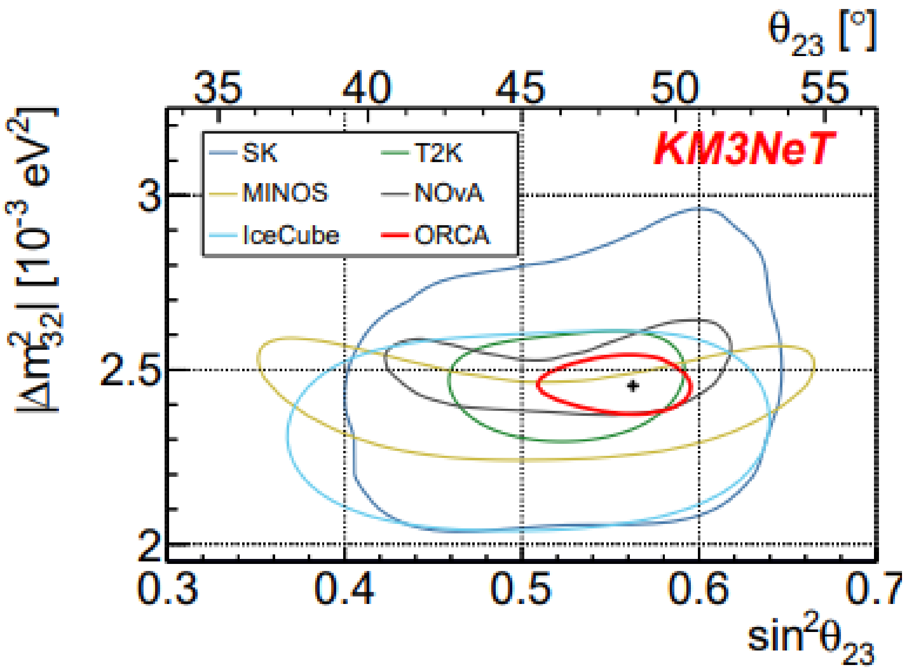


- Assuming current estimates for θ_{23}, NMO sensitivity is to 4.4σ for NO and 2.3σ for IO
- NMO can be determined at 3σ after 1.3 years if NO and after 5.0 years if IO

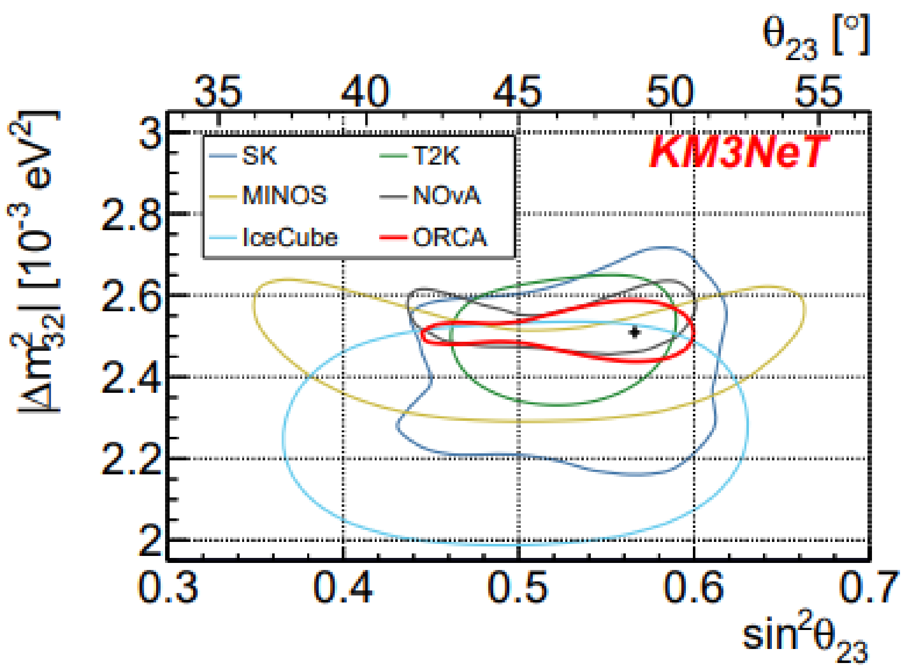
Oscillation parameters

arxiv: 2103.09885

Normal ordering



Inverted ordering



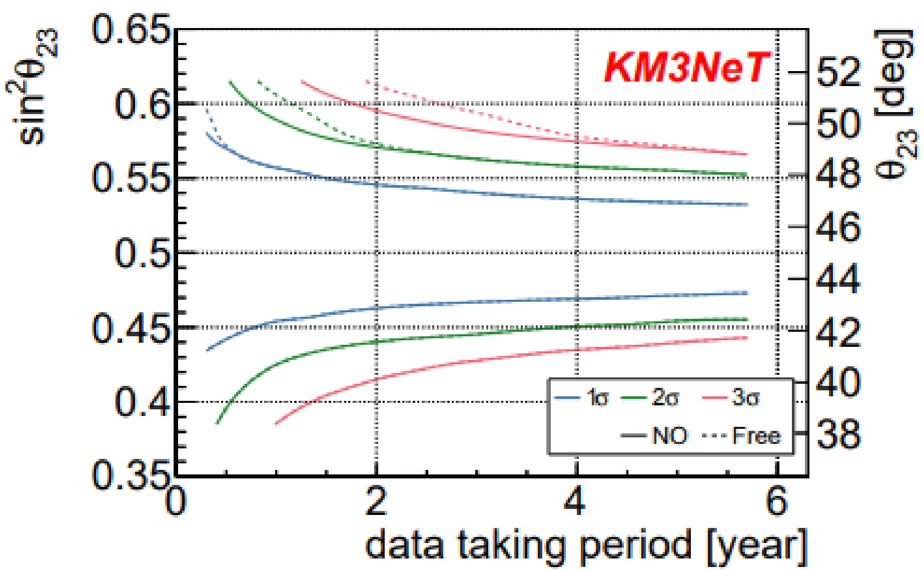
90% confidence level interval for Δm^2_{32} and θ_{23}:

- NO: 85×10^{-6} eV^2 and $(^{+1.9}_{-3.1})°$
- IO: $75 \cdot 10^{-6}$ eV^2 $(^{+2.0}_{-7.0})°$

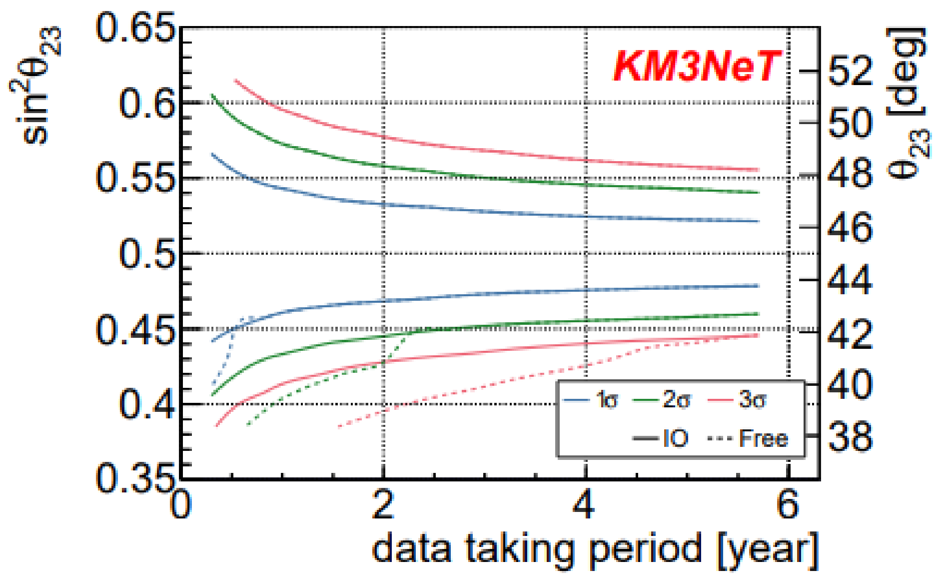
Octant of θ_{23}

arxiv: 2103.09885

Normal ordering



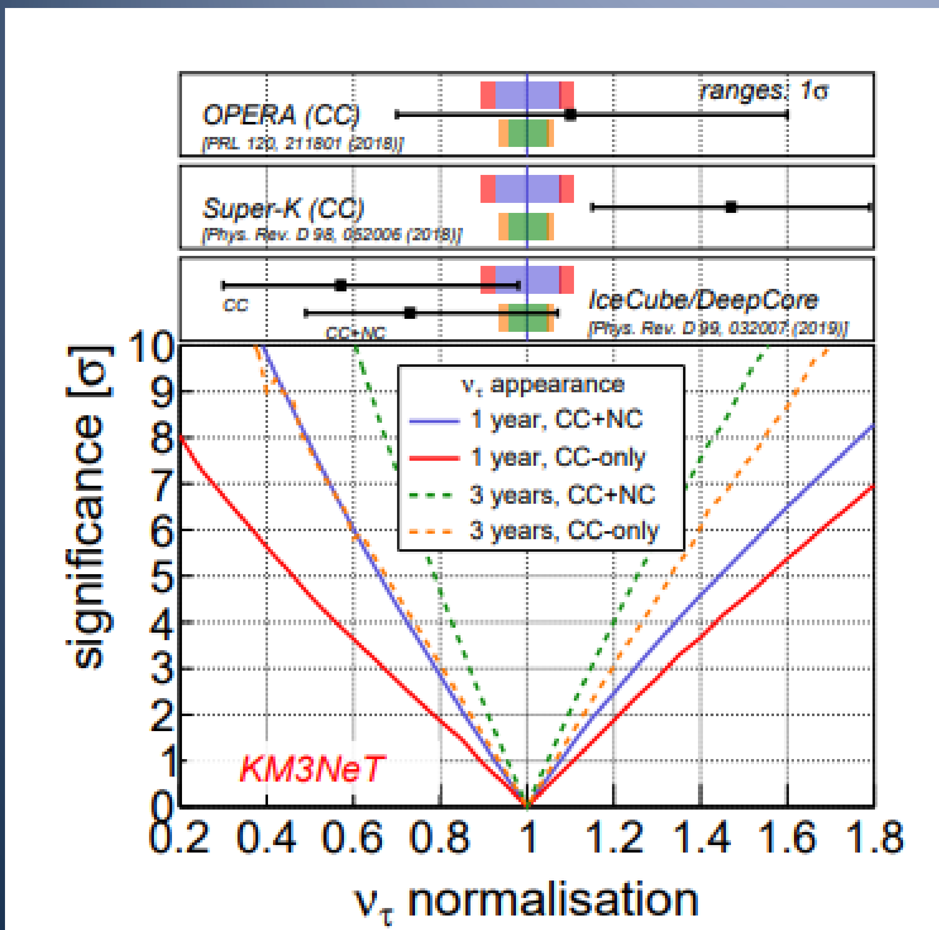
Inverted ordering



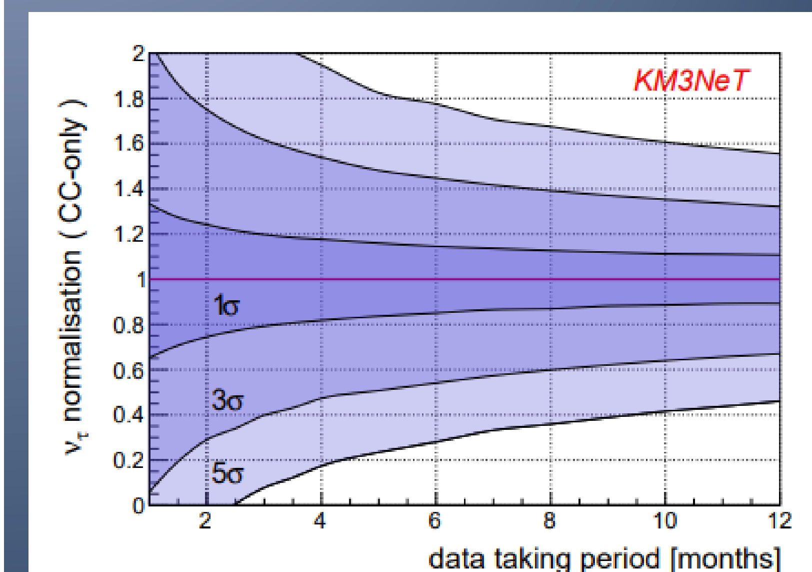
Solid: NMO known
Dashed: NMO not known

Appearance of ν_τ

arxiv: 2103.09885



- ν_τ appearance allows to probe deviatations from unitarity (mainly from the >15 GeV region)
- Deviations from 1 in the normalization factor in the fit would hint to new physics

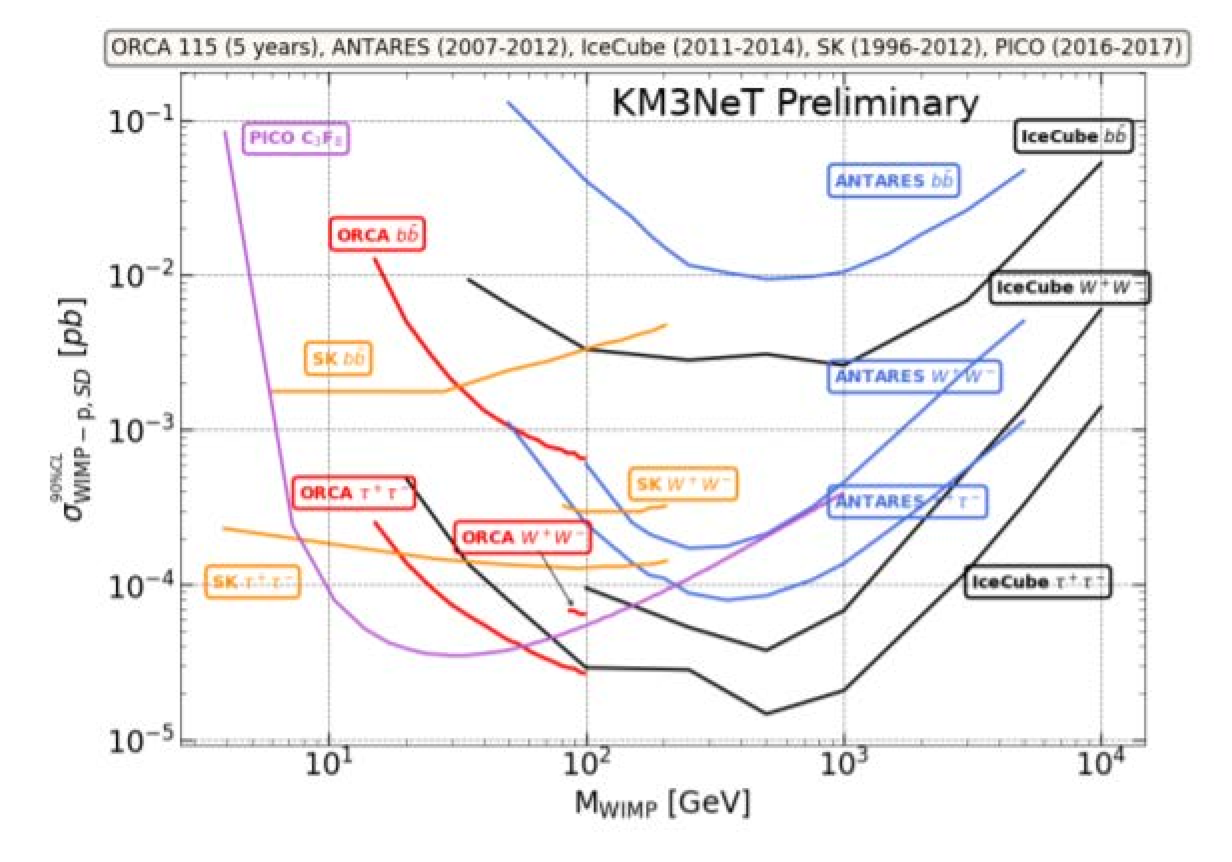


Dark matter: the Sun

- WIMPs (neutralinos, KK particles) are among the most popular explanations for dark matter
- They would accumulate in massive objects like the Sun, the Earth or the Galactic Centre
- The products of such annihilations would yield “high energy” neutrinos, which can be detected by neutrino telescopes

Dark matter: the Sun

PoS(ICRC2019)536



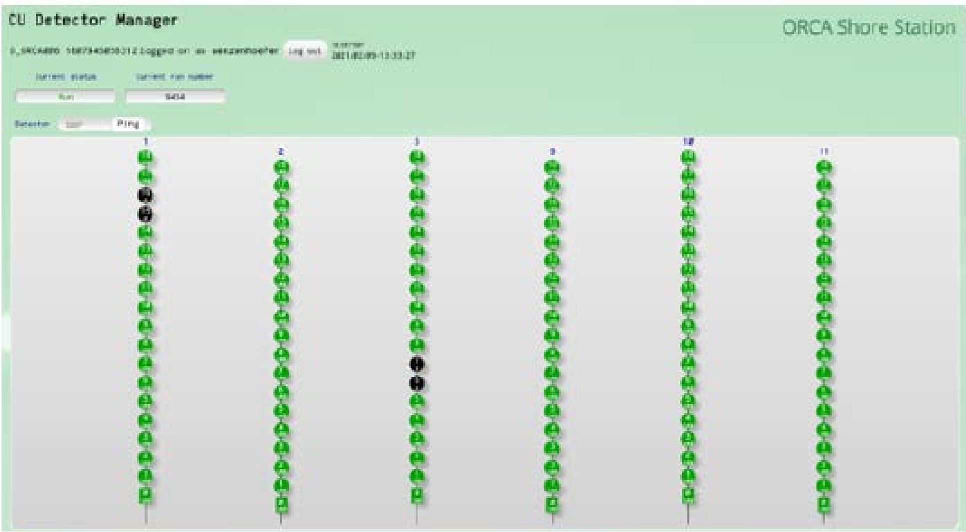
Sun is almost free of astrophysical background (very clean signal)
(With ARCA, very good limits for GC at large WIMP masses)

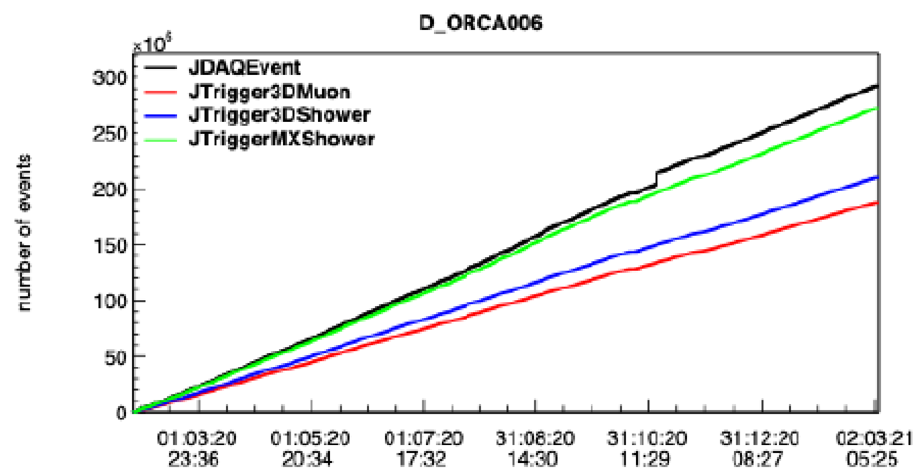
Status and first data





ORCA: data taking



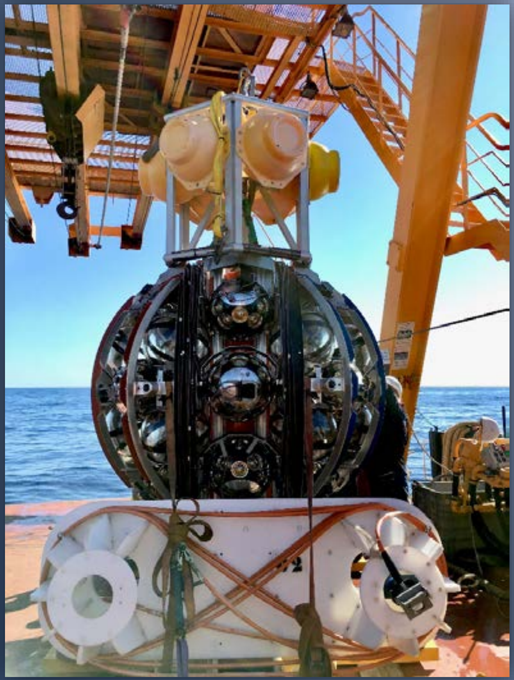


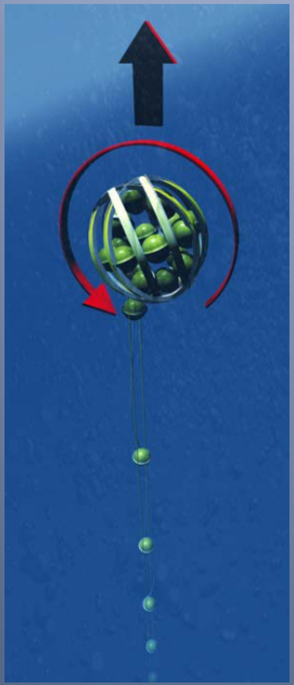
More than one year of data (six lines in operation since February 2020)

High data taking efficiency: ~99%

Second Junction Box installed (room now for 52 lines)

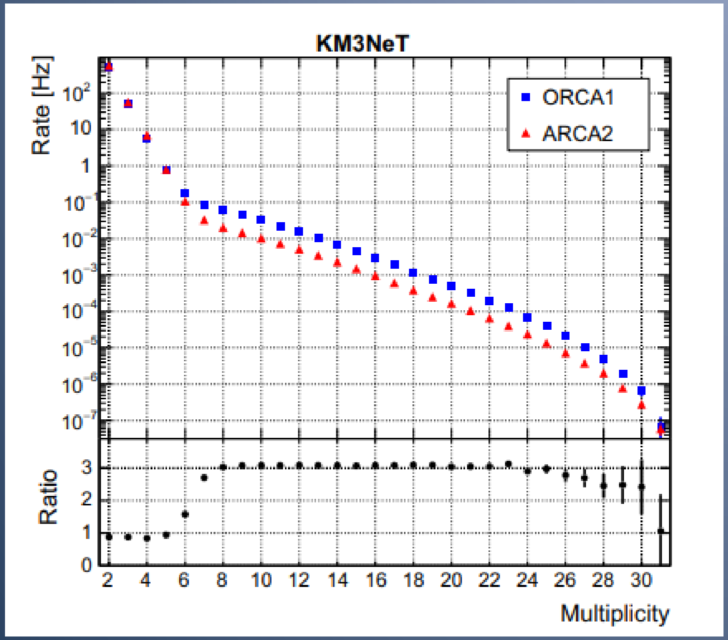
First KM3NeT lines installed and taking data





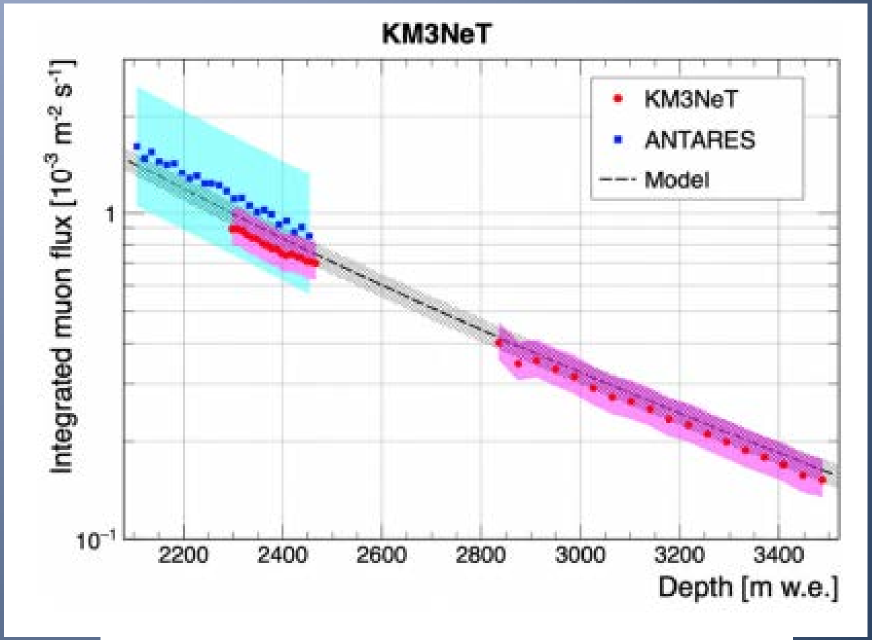
First results (ORCA1 and ARCA2): atmopheric muon flux

Eur. Phys. J. C (2020)



Multiplicity in PMTs in DOMs is dominated by K40 below 6 and by muons above 8 atmospheric

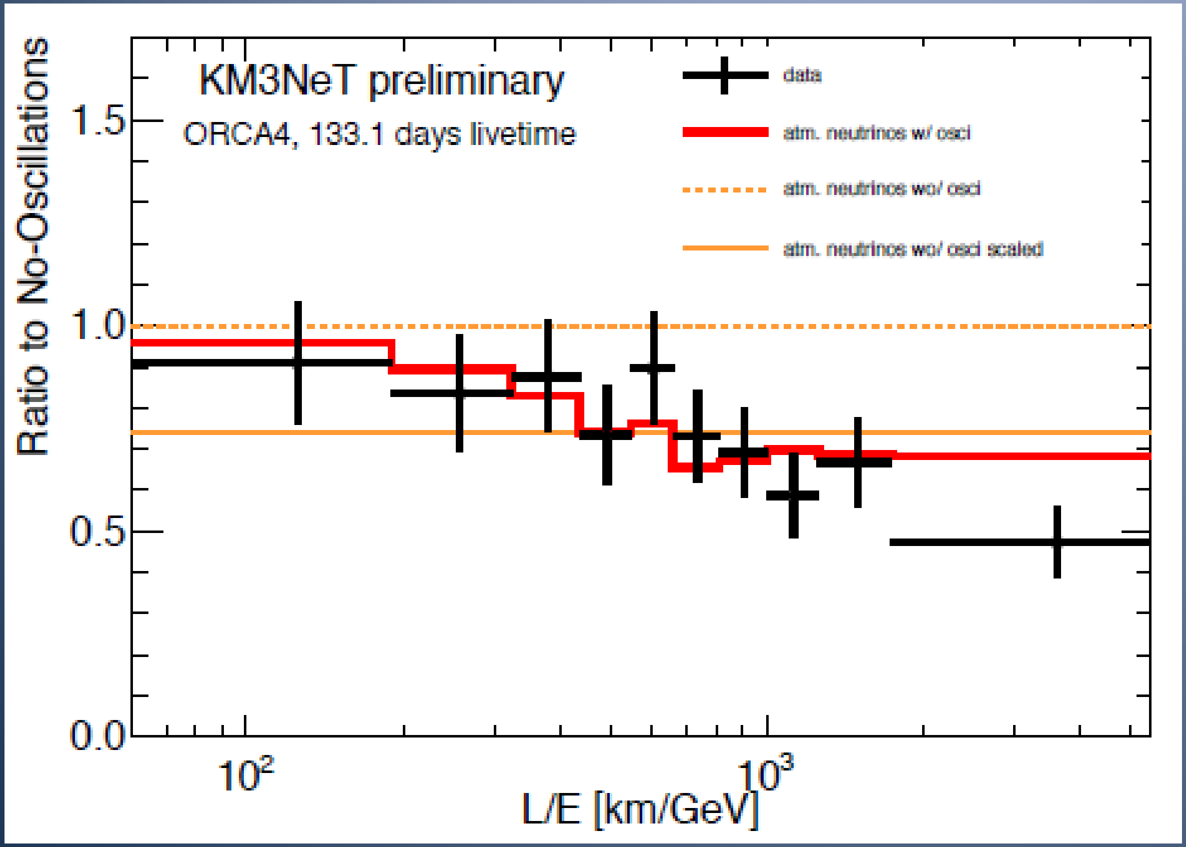
Atmospheric muon flux



$$I_\mu(d) = \frac{I_\mu(d, \theta = 0)}{C(d)} = \frac{A_1 \cdot e^{A_2 \cdot d} + A_3 \cdot e^{A_4 \cdot d}}{B_1 + B_2 \cdot d},$$

$A_1 = 1.31 \times 10^{-5} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, $A_2 = -2.91 \times 10^{-3}\,\mathrm{m}^{-1}$,
$A_3 = 7.31 \times 10^{-7} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, $A_4 = -1.17 \times 10^{-3}\,\mathrm{m}^{-1}$,
$B_1 = 4.16 \times 10^{-1}\,\mathrm{sr}^{-1}$, $B_2 = 1.07 \times 10^{-4} \mathrm{m}^{-1}\,\mathrm{sr}^{-1}$.

First results (ORCA4): oscillations



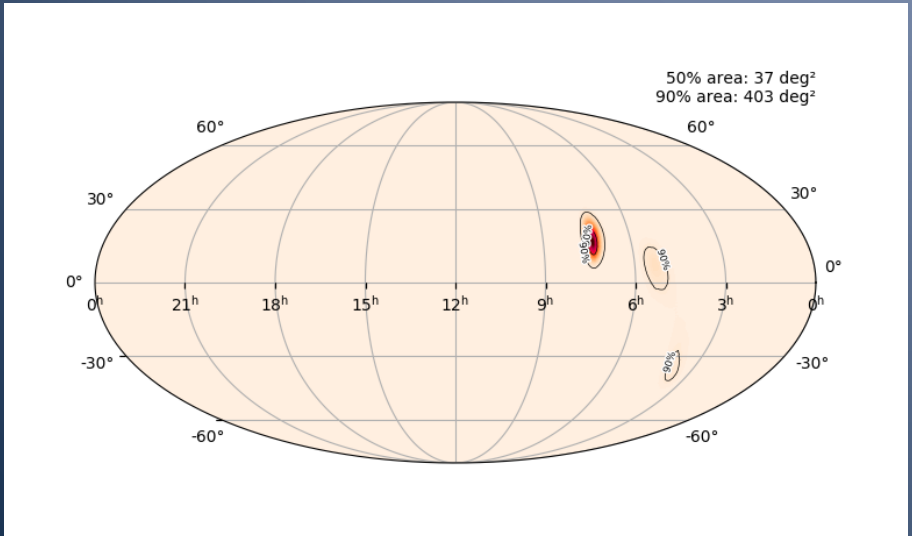
Hint for neutrino oscillation seen: data non compatible with non-oscillation hypothesis at 2.5σ level

Good MC-data agreement

First results (ORCA4): S200114f

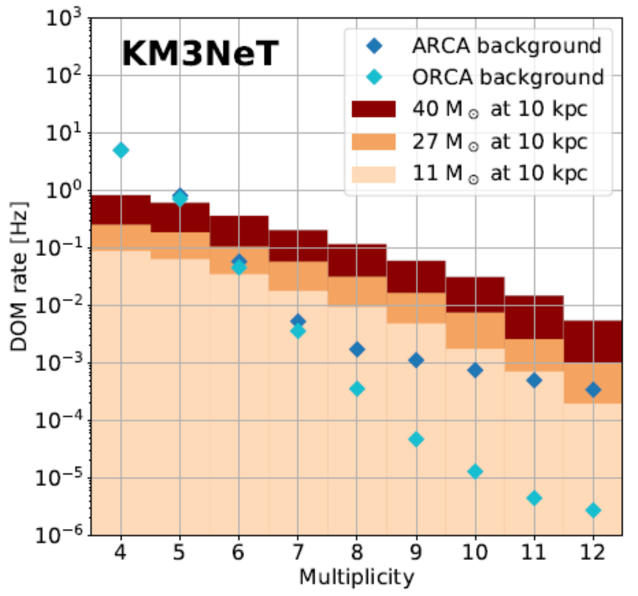
- Event: burst S200114f
- GCN GCN #26734
- Date: November 10th, 2019
- Detector: ORCA4

unmodelled GW trigger
→ CCSN candidate



https://gracedb.ligo.org/superevents/S200114f/view/

Detour: detecting Sne with NTs



Multiplicity = number of PMTs in a DOM detecting a photon in a 10 ns window

Looking for SN neutrinos with neutrino telesopes is <u>challenging</u>, in particular in the sea

Supernova neutrinos are of very low energy (~MeV)

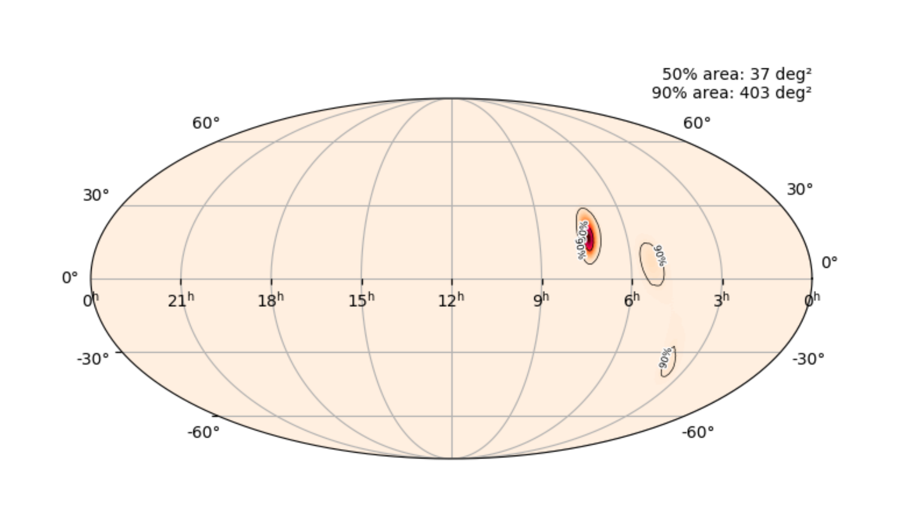
Strategy: look for an overall increase in coincidences in the DOMs

Background: K40, bioluminescence, atmospheric muons

First results (ORCA4): s20014f

- Event: burst S200114f
- GCN GCN #26734
- Date: November 10th, 2019
- Detector: ORCA4

unmodelled GW trigger
→ CCSN candidate



Strategy: search for correlations of MeV neutrinos in 400 ms window after the trigger:

Two events observed
1.4 expected
→ p-value = 40%
(GCN #26751)

https://gracedb.ligo.org/superevents/S200114f/view/

Marta Colomer's PhD thesis,
U. Paris – U. Valencia, 2020

s20014f

- Assuming CCSN Garching flux models, we can derive the expected signal (S_0) and therefore we can constrain parameters in case of non-observation:

$$D^{90\%} = (10\text{kpc}) \times \sqrt{\frac{S_0}{S_{90\%}}}$$

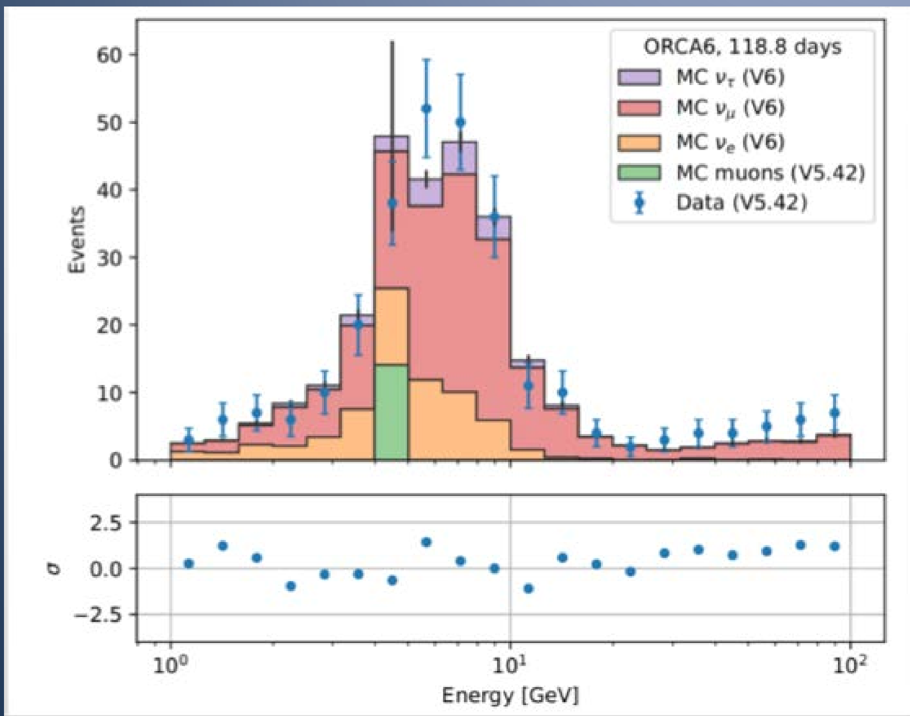
Progenitor	$d_{90\%}$ [kpc] (lower limit)	Galactic coverage
11 $M_\odot$	6.1	10-15%
27 $M_\odot$	11.5	∼65%
40 $M_\odot$	21	∼98%

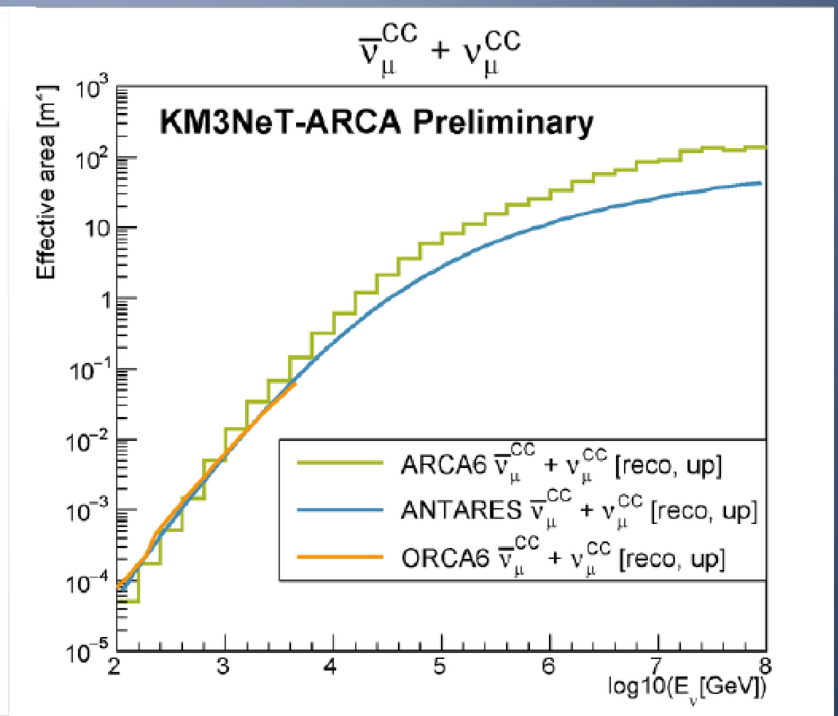
- We can also derive limits in the total energy emitted in neutrinos:

$$E^{tot}{}_{\nu}(90\%) = 2.9\ 10^{53}\ \text{erg}$$

(assuming quasi-thermal distribution with $<E\nu>=15$ MeV, $\alpha=3$, d=10 kpc)

First results (ORCA 6)





Neutrino rate: ~3-4/day

To be increased soon with several more lines!

Summary

- Neutrino telescopes offer a very wide scientific scope: astrophysical sources, neutrino properties, dark matter...
- ANTARES has shown the feasibility of the underwater technique (and provided a rich harvest of scientific results along)
- KM3NeT-ORCA's main goal is NMO, which would be at hand in a few years
- Early physics results on other topics: NSIs, neutrino decay, transients, etc.
- First 12 lines of KM3NeT are successfully taking data
- Interesting times ahead...

Thanks for your attention!