Neutrino Oscillations with Atmospheric Neutrinos

European Neutrino Town Meeting

Jürgen Brunner

22/10/18

ANTARES

ORCA KM3NeT

PRECISION ICECUBE NEXT GENERATION UPGRADE

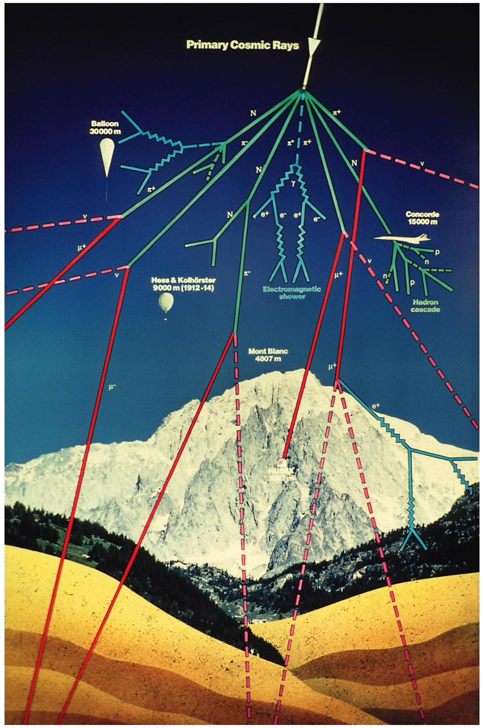
ICECUBE

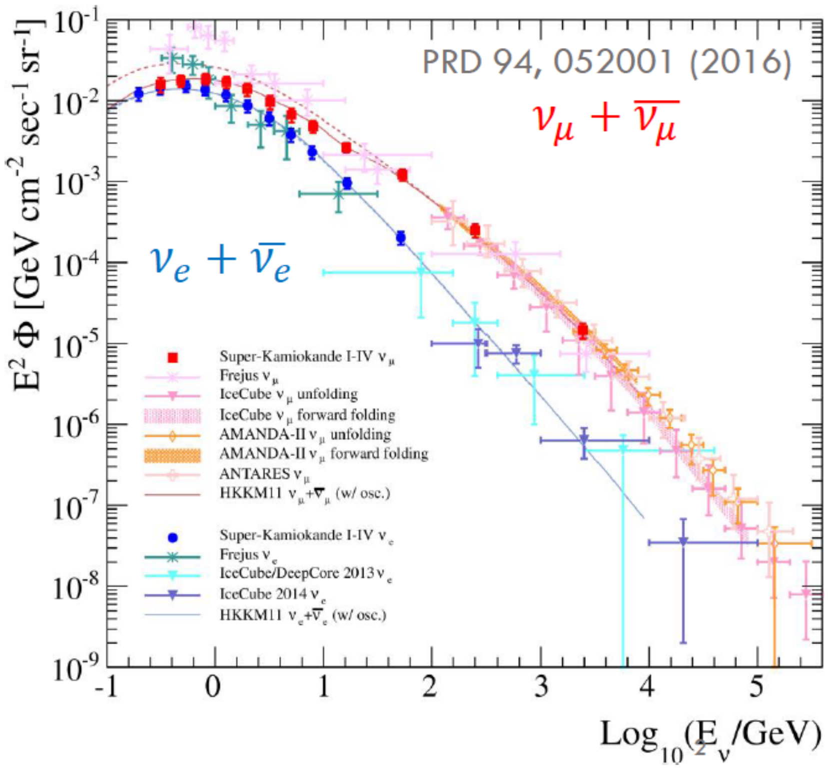
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

Aix*Marseille université

Atmospheric Neutrino Flux

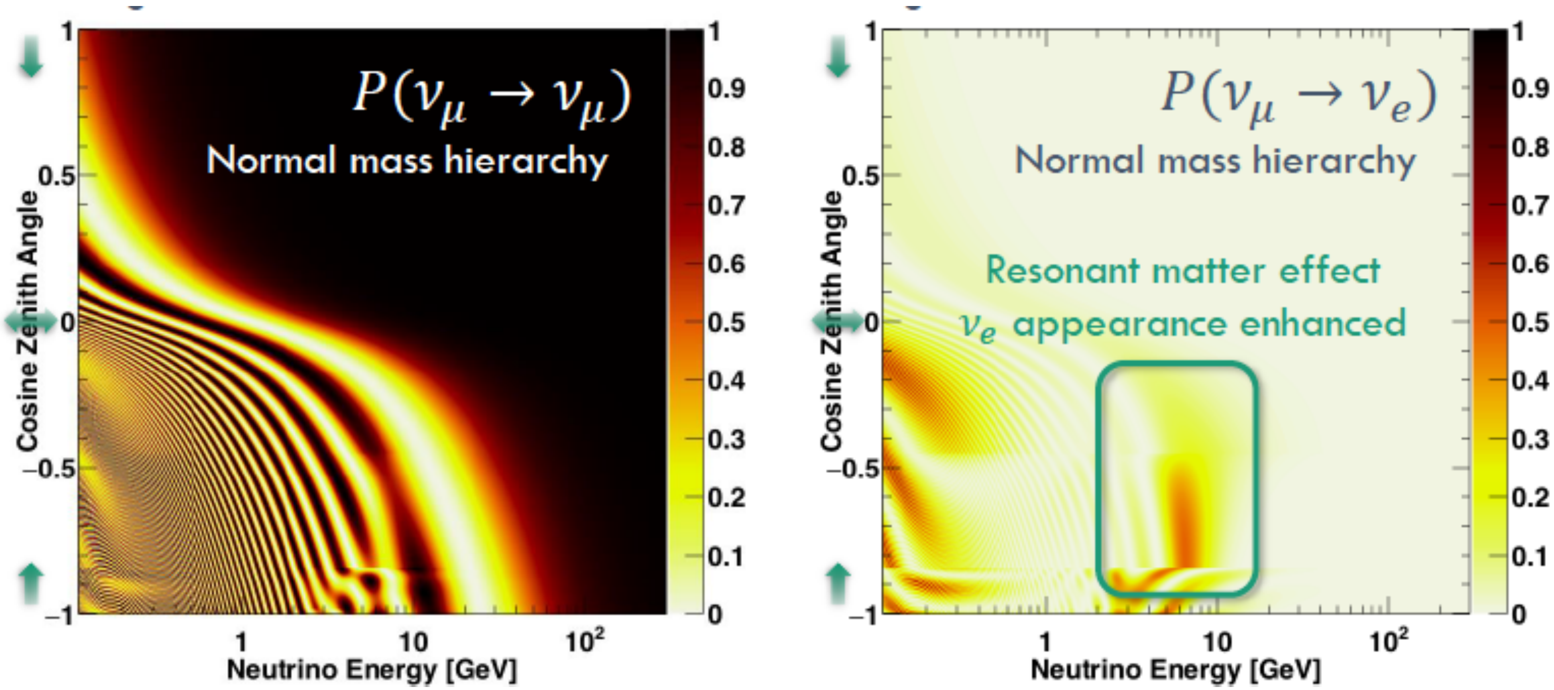
- Measured over more than 5 orders of magnitude
- Major contributions from SuperK, IceCube, Antares



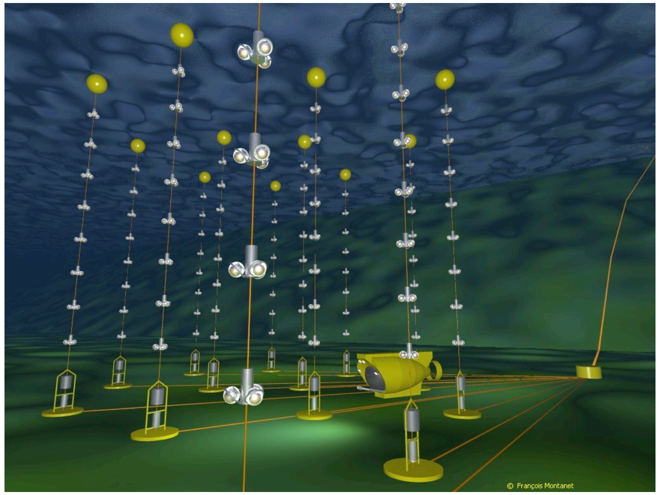


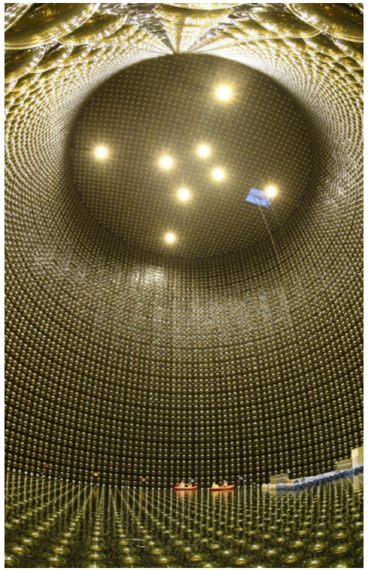
Oscillations with atmospheric ν

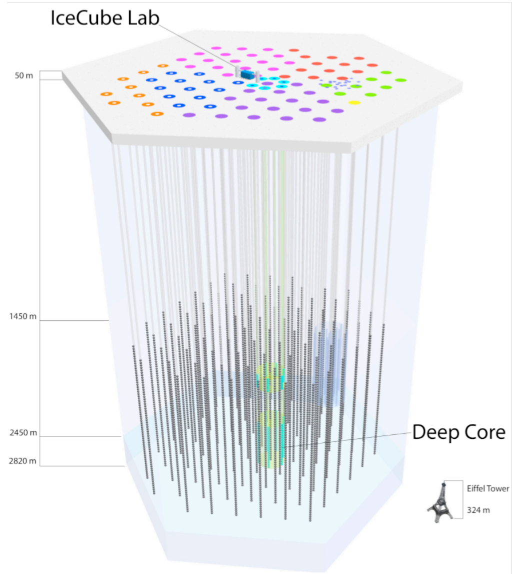
- Δm^2_{32} , θ_{23}
- Tau neutrino appearance
- Exotics (sterile ν , NSI)
- Neutrino Mass Ordering



Current Projects







ANTARES

Complete in 2008

~12 Mtons

SuperKamiokande

Complete in 1996, SK-IV : 2009

22 ktons

IceCube

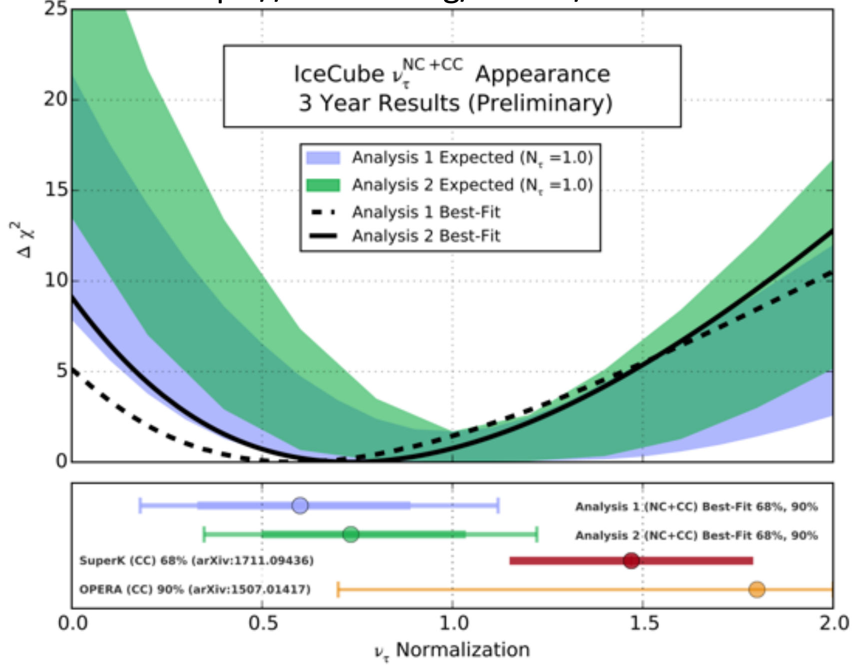
Complete in 2010

1Gton

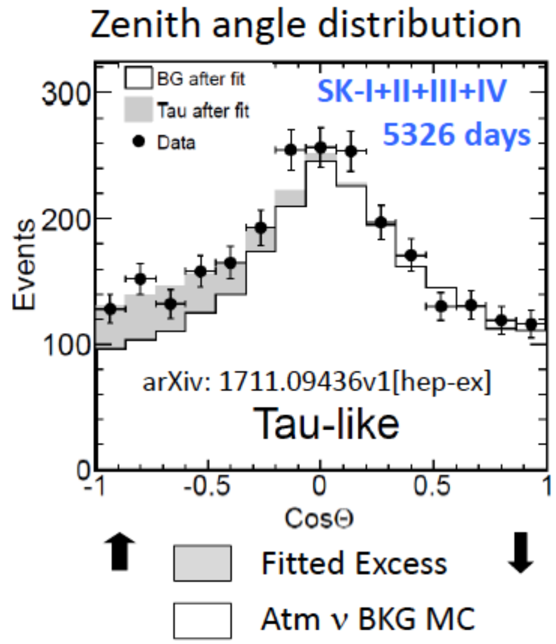
ν_τ appearance

IC/DeepCore

https://zenodo.org/record/1304920



SuperK



0.33 Mton year
338 ± 73 ν_τ events
4.6σ rejection of no-tau-appearance

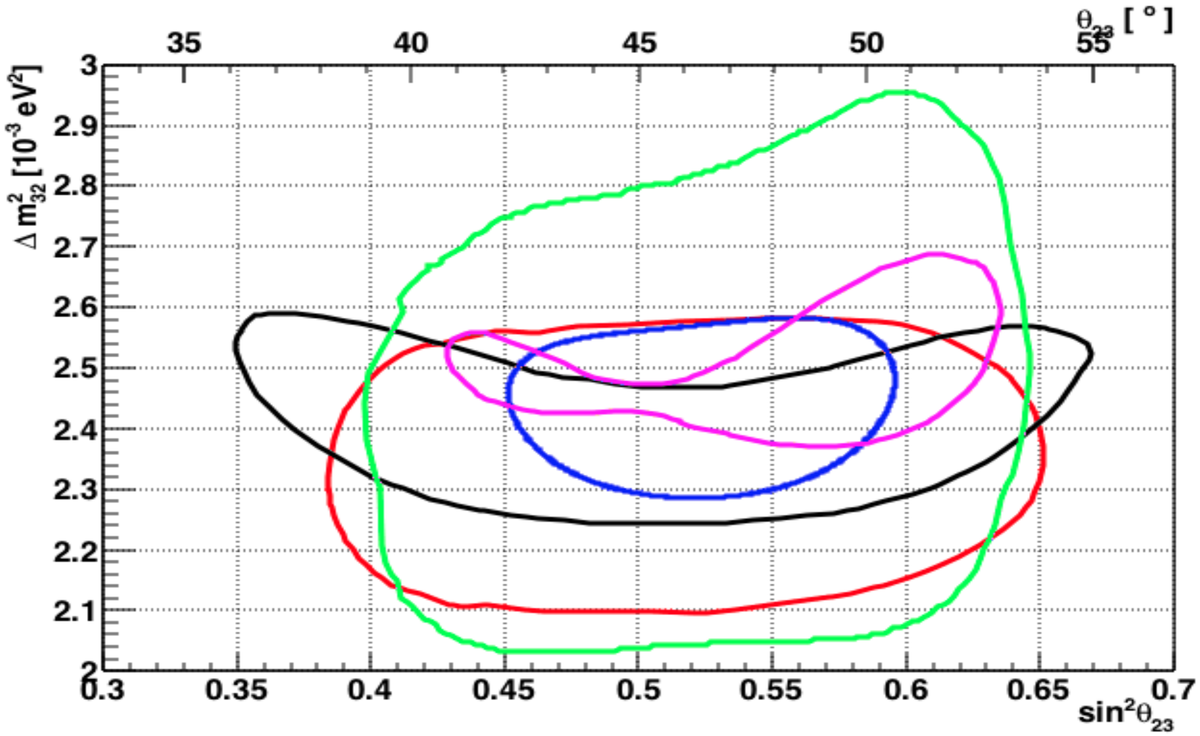
- Errors still rather large
- Compatible with 3 flavour oscillations & ν_τ cross section

Measurement of Δm^2_{32} , θ_{23}

- Recent updates at Nu 2018
- Atmospheric results competitive with accelerators

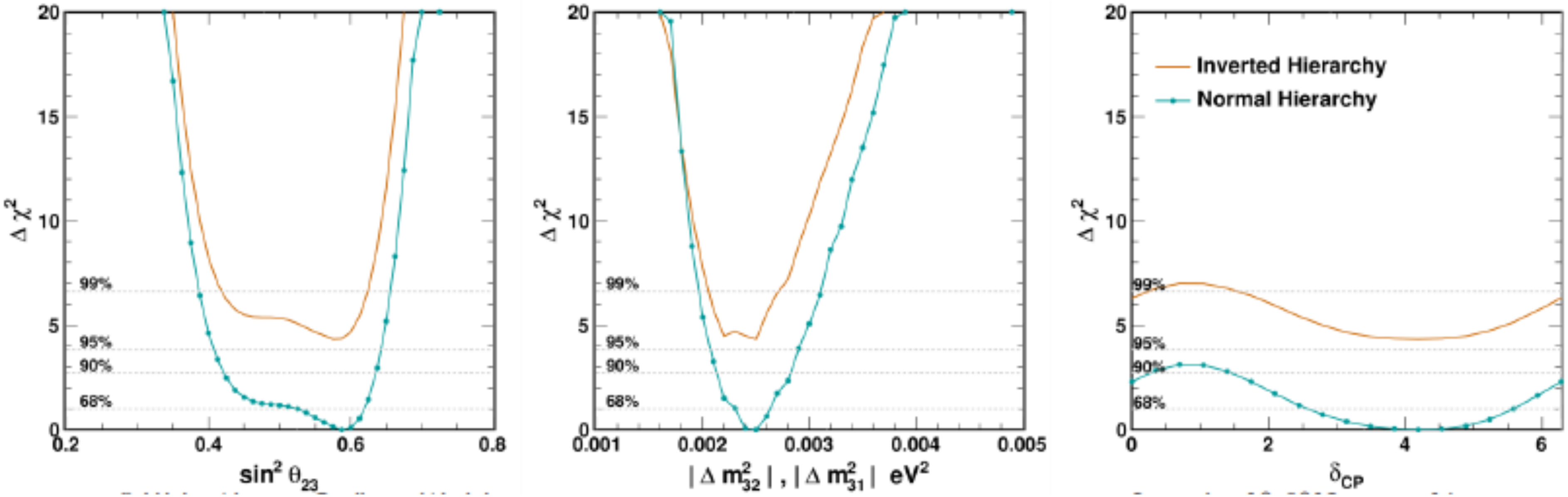
SuperK 2018
IC/DC 2017

MINOS 2018
NOvA 2018
T2K 2018



Neutrino Mass Hierarchy - SuperKamiokande

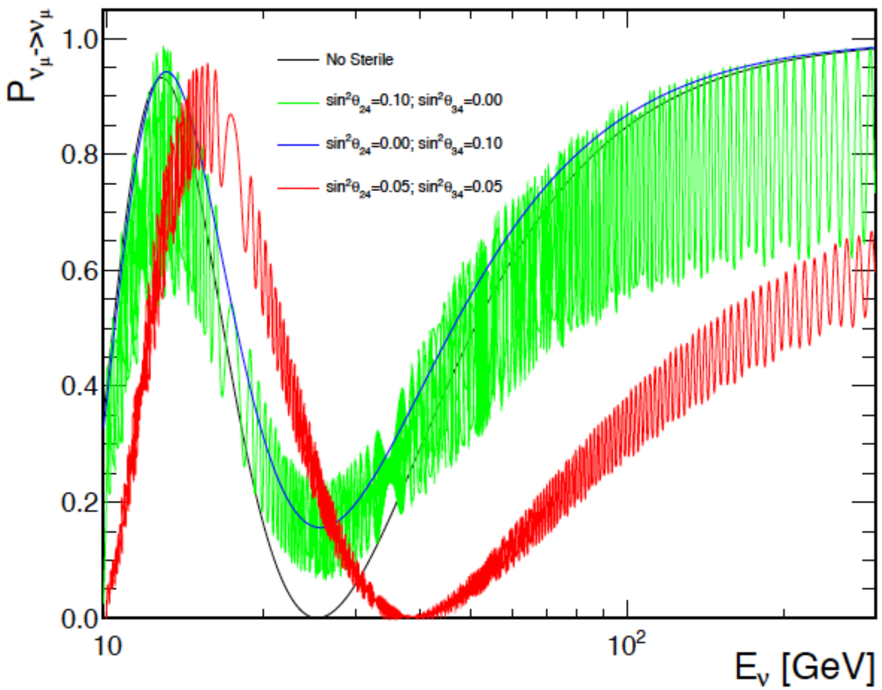
- Neutrino / Antineutrino separation based on neutron capture (20% efficiency on H)
- NH prefered by ~2σ

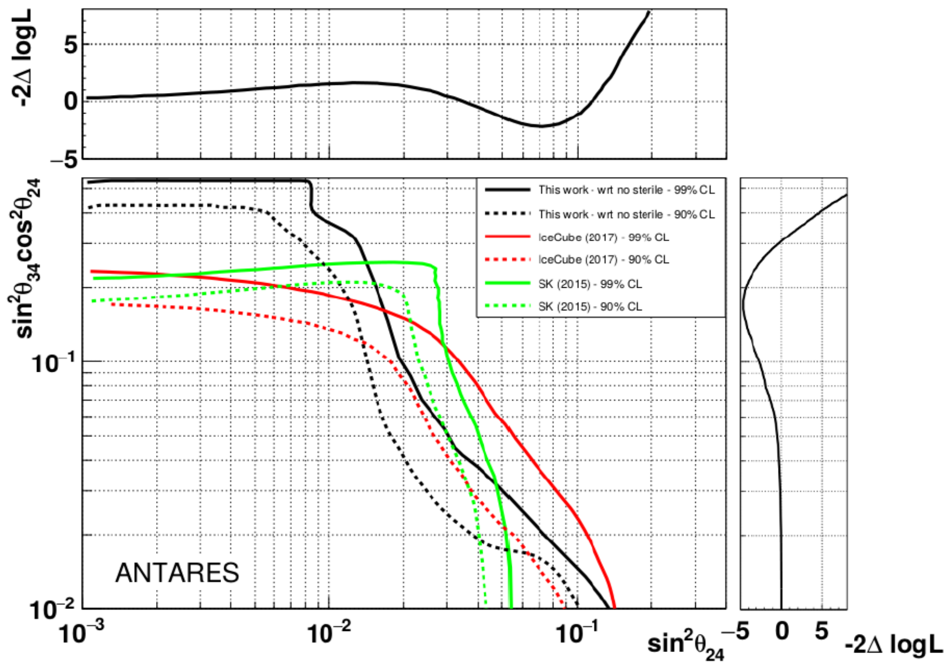


C. Vileva NOW 2018

ANTARES 2018 : sterile neutrinos 3+1 model

- 10 years of data 2007-2016
- Antares improves limits from IC & SuperK
- 1-dim limits 90% C.L. $|U_{\mu 4}|^2 < 0.14$ and $|U_{\tau 4}|^2 < 0.36$

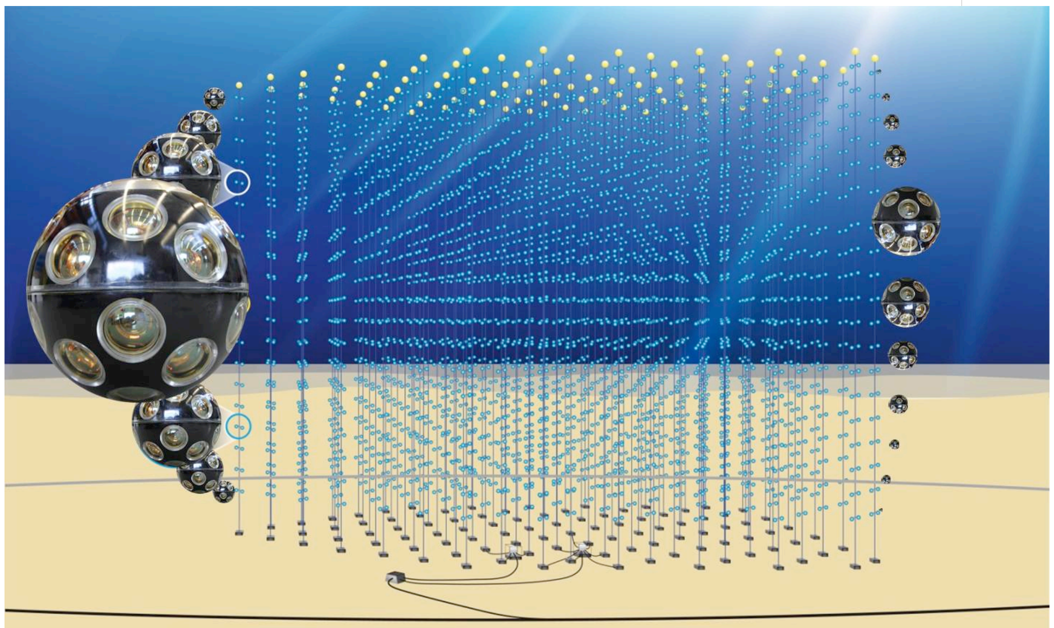


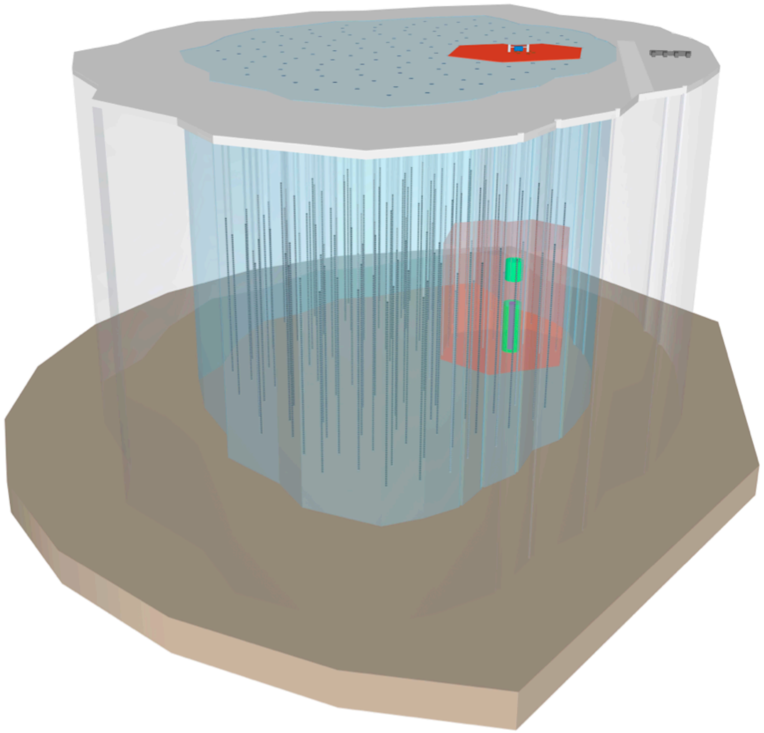


Future Projects

- Enhanced physics potential

KM3NeT

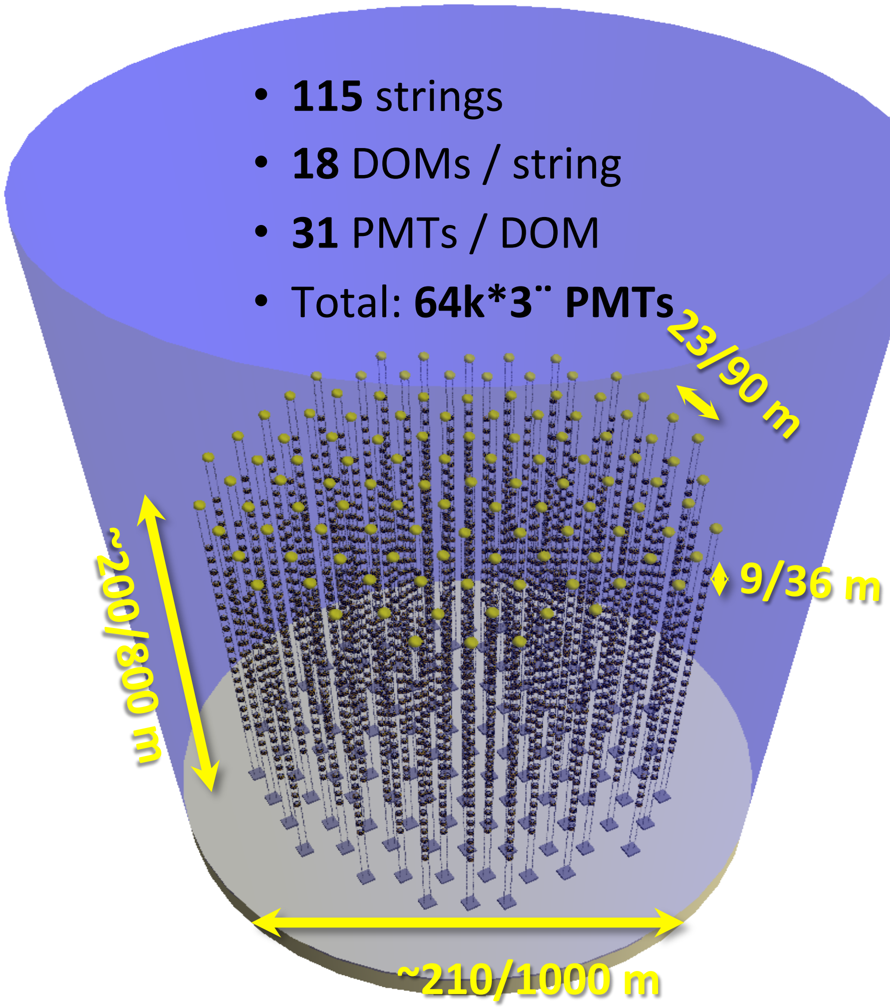


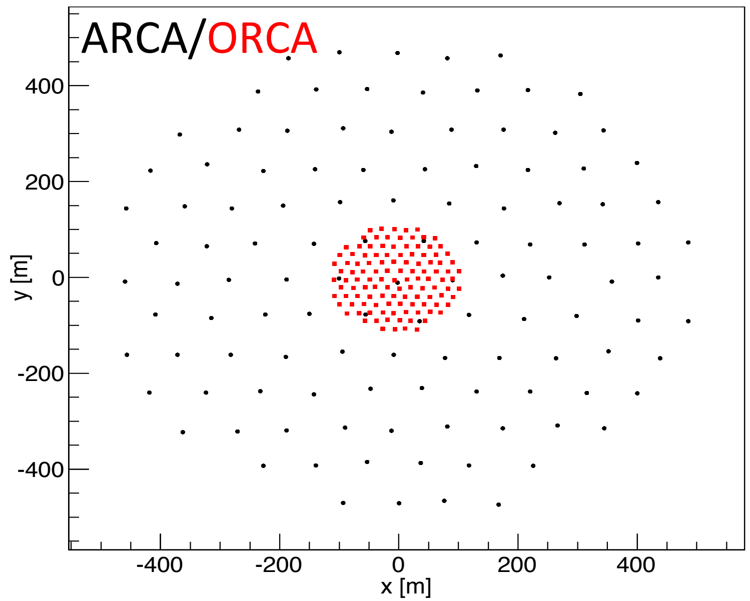


IceCube Gen2

KM3NeT Building Block

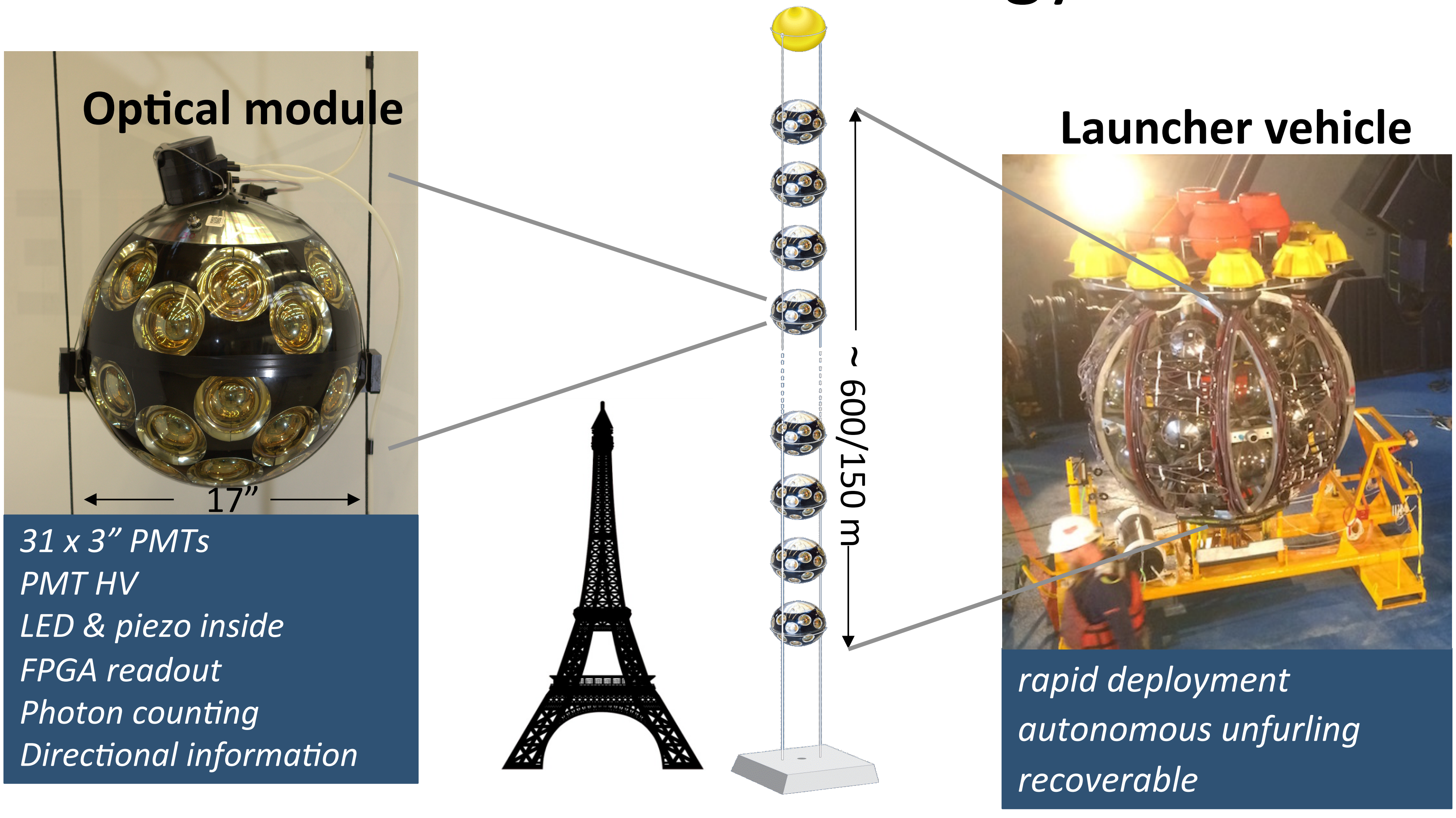
- **115** strings
- **18** DOMs / string
- **31** PMTs / DOM
- Total: **64k*3¨ PMTs**





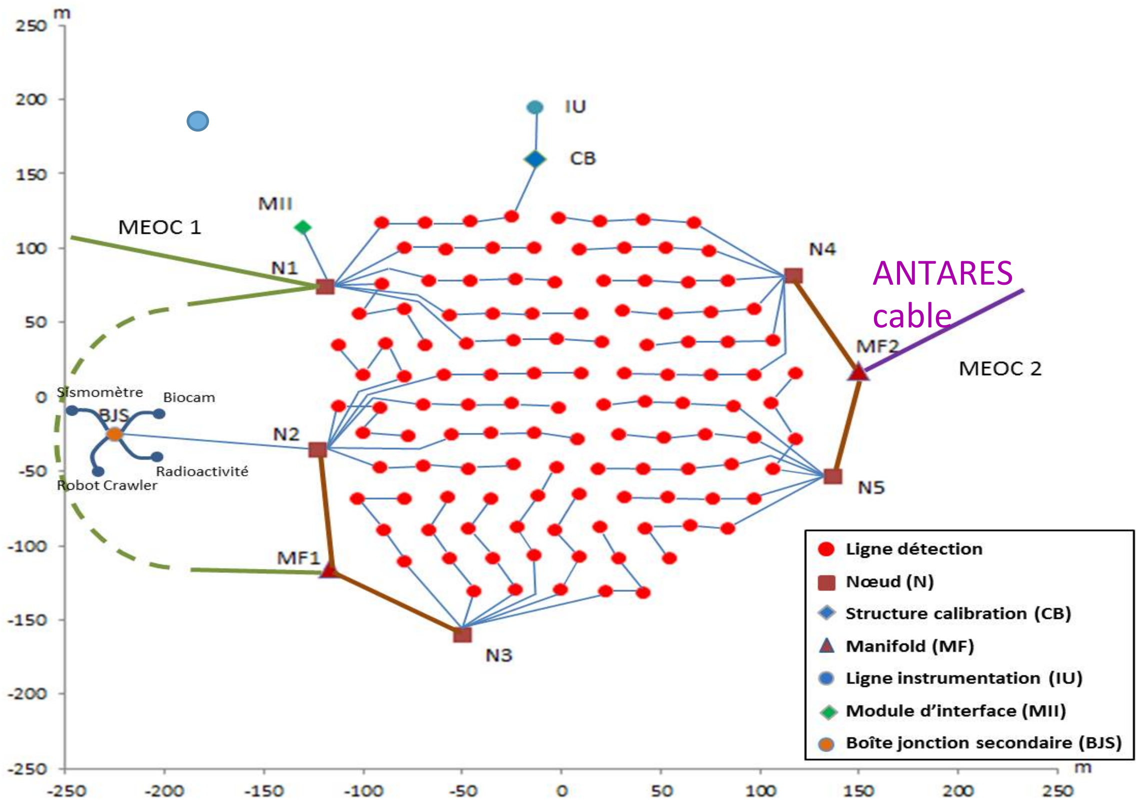
	ORCA	ARCA
String spacing	23 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	8 Mton	0.5*2 Gton

KM3NeT Technology



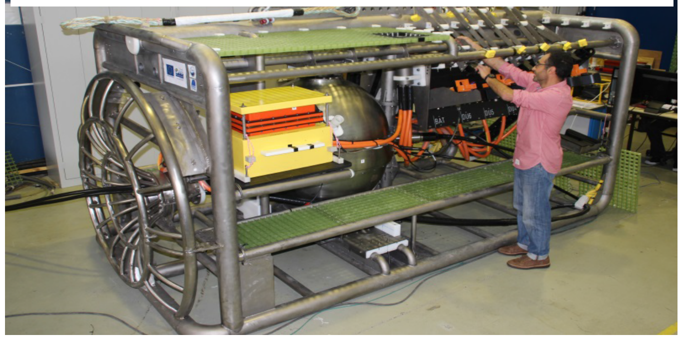
KM3NeT/ORCA Status

Construction started
First data arrived in 2017



Main Cable, 2015

Junction Box, Sept 2016



First ORCA string: Sep 2017

First neutrino analysis

82 days of data taking with first ORCA line

cos(theta) > 0 [0.5]

----

observed : 13 [10]

atm. muon: 1 [0]

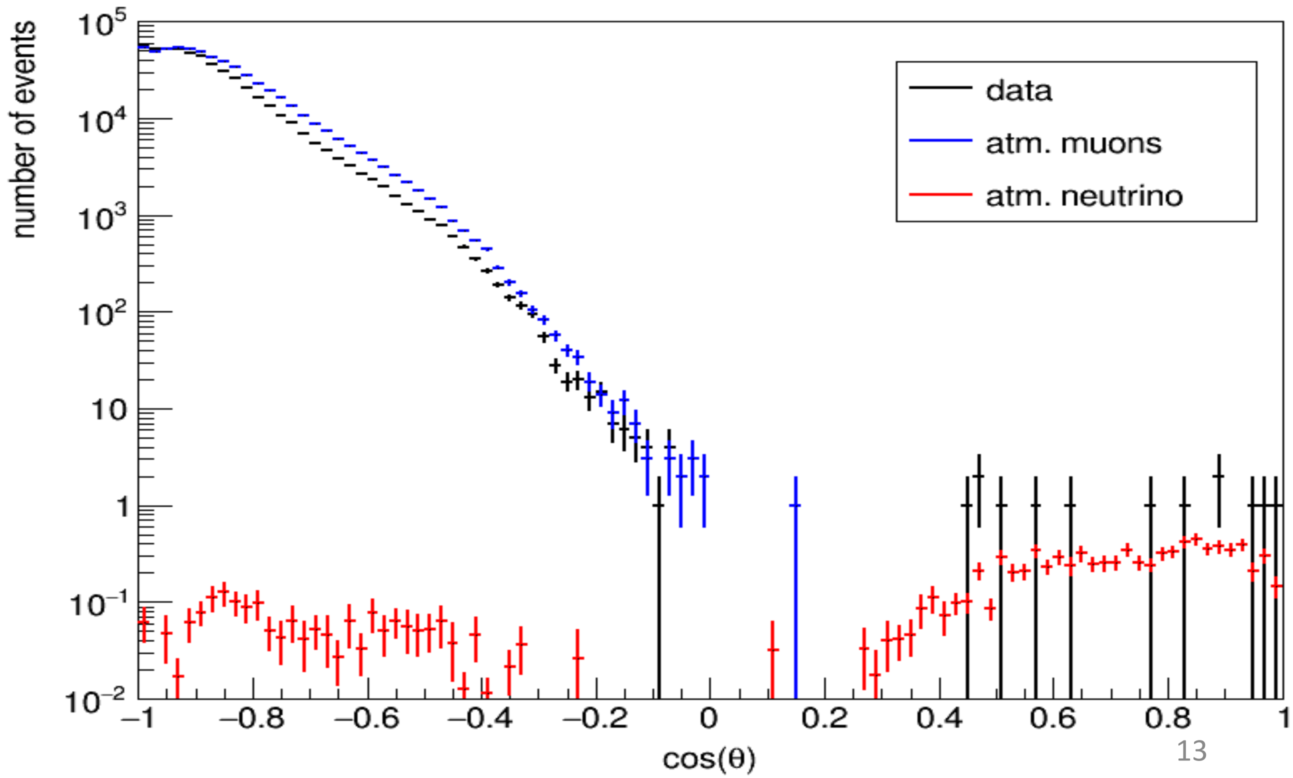
neutrino : 8.33 [7.36]

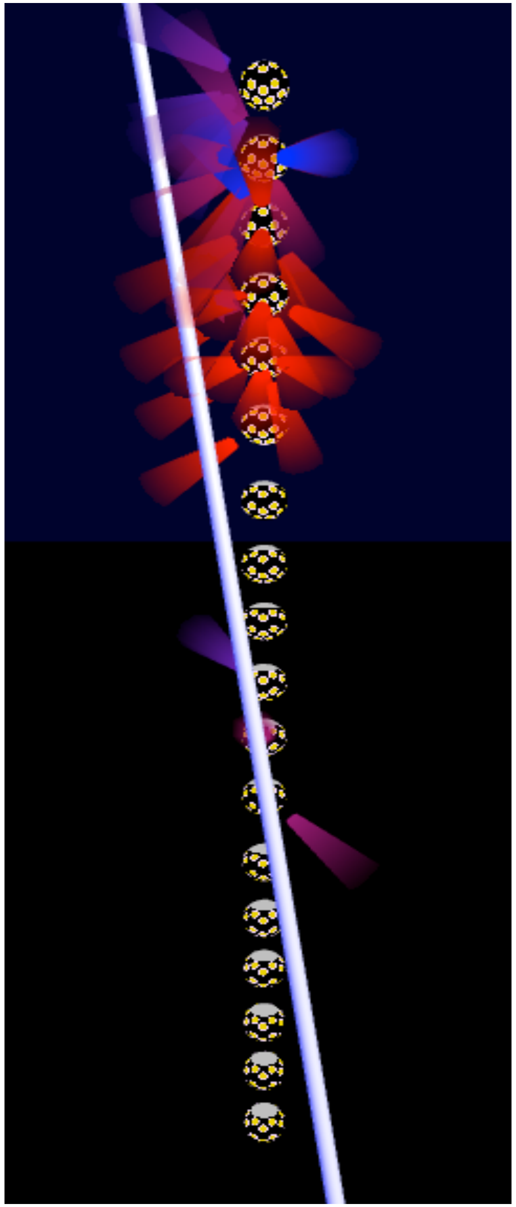
ν_μ : 5.44 [4.89]

ν_e : 1.36 [1.17]

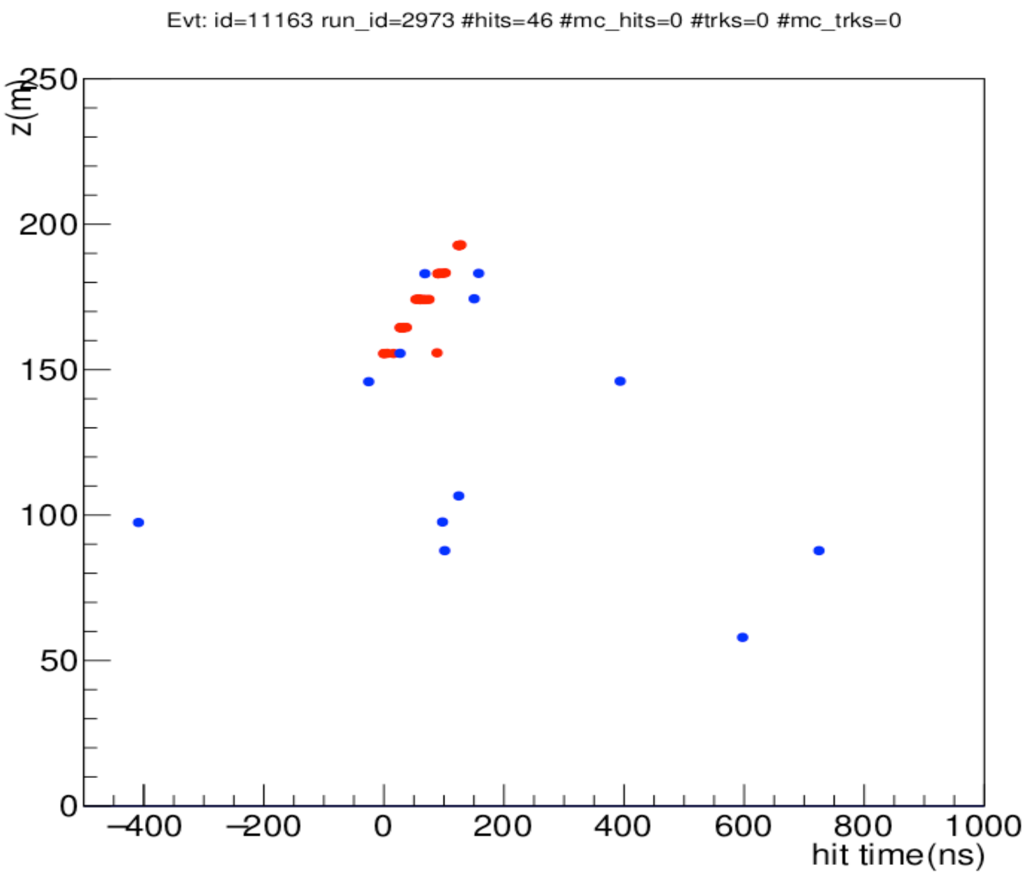
ν_τ : 0.96 [0.83]

ν_{NC} : 0.57 [0.47]





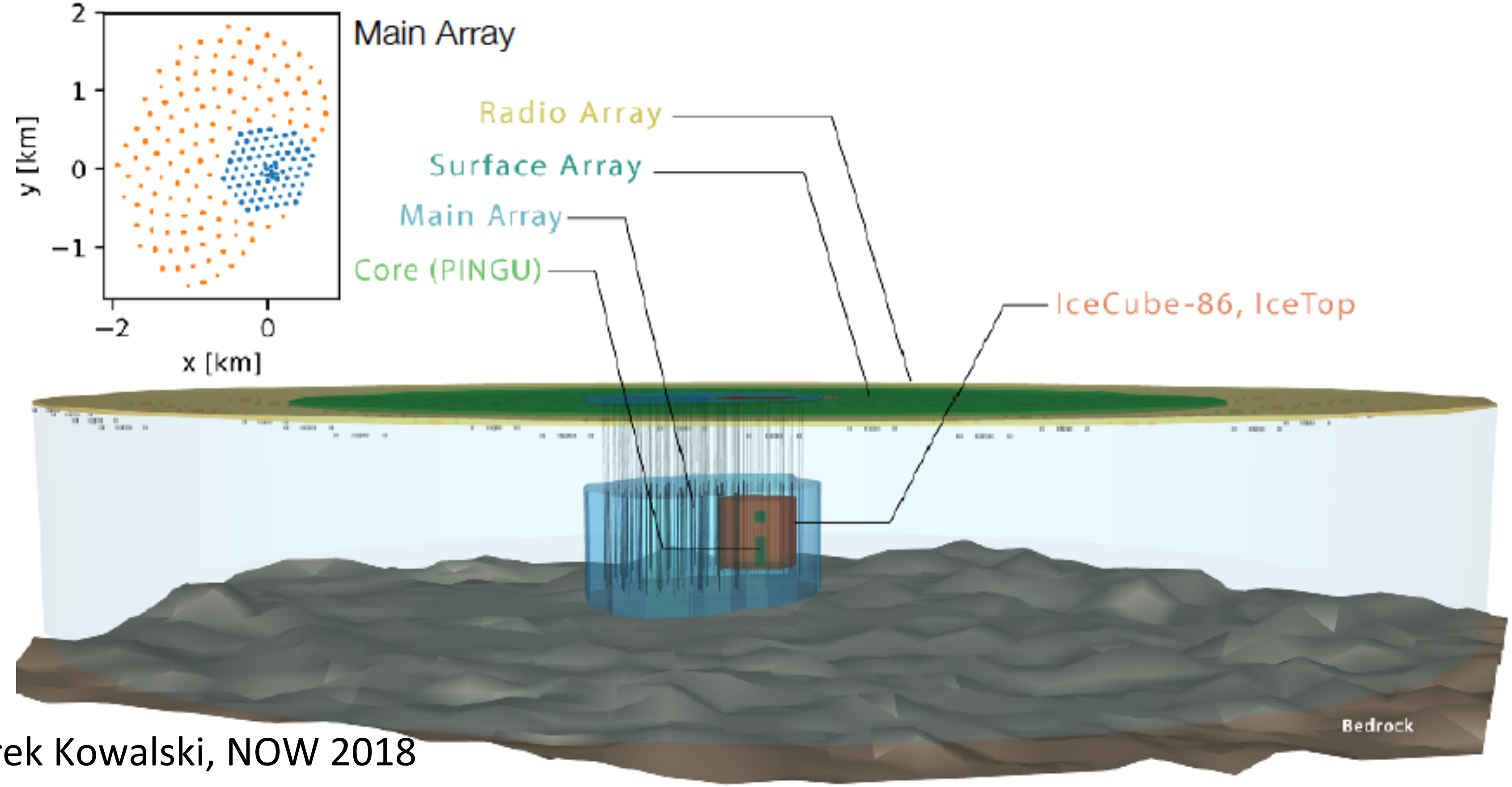
Selected Neutrino Candidate



Estimated energy 5-10 GeV

IceCube-Gen2 Facility

A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

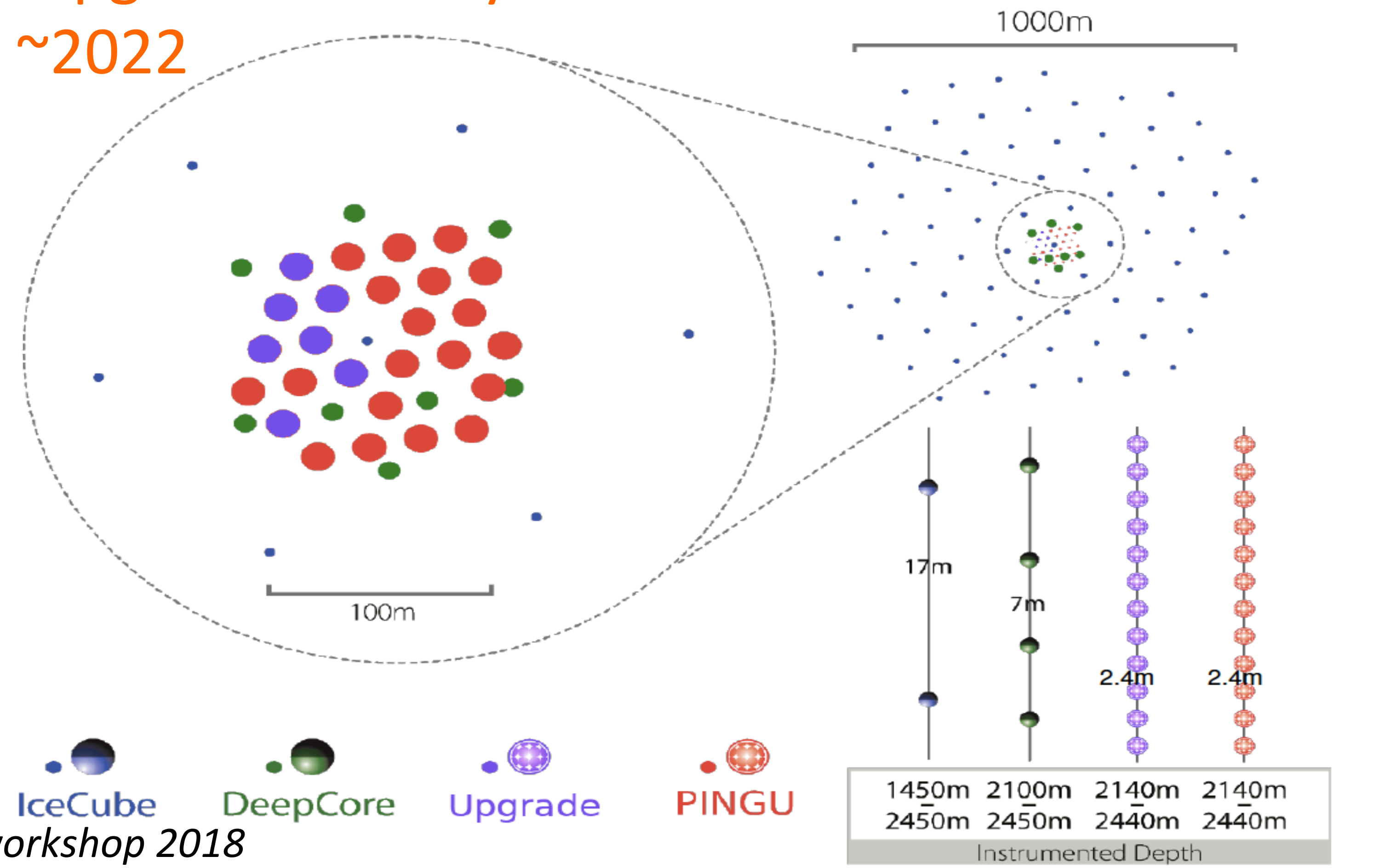


Marek Kowalski, NOW 2018

Low Energy Upgrade & PINGU

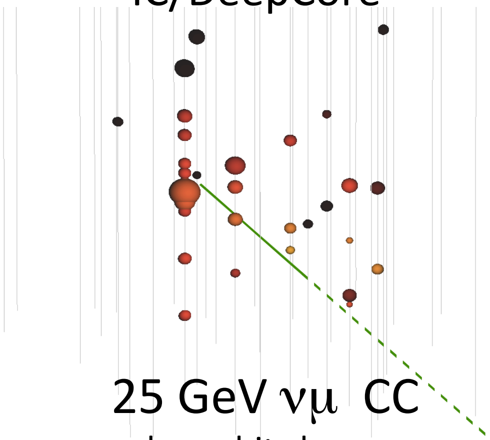
7 strings for upgrade recently financed

Installation ~2022



J. Hignight, PANE workshop 2018

IC/DeepCore

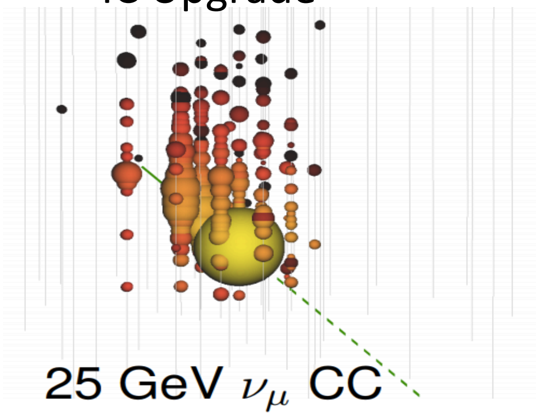


25 GeV $\nu\mu$ CC

color -> hit charge

size -> hit charge

IC Upgrade

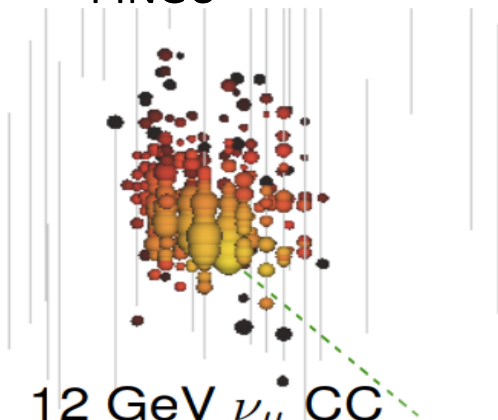


25 GeV ν_μ CC

color $\rightarrow$ hit time

size $\rightarrow$ hit charge

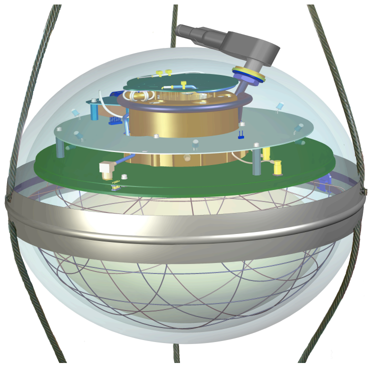
PINGU



12 GeV ν_μ CC

color $\rightarrow$ hit time

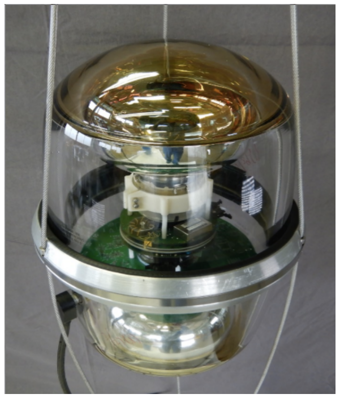
size $\rightarrow$ hit charge



10 “ PMTs

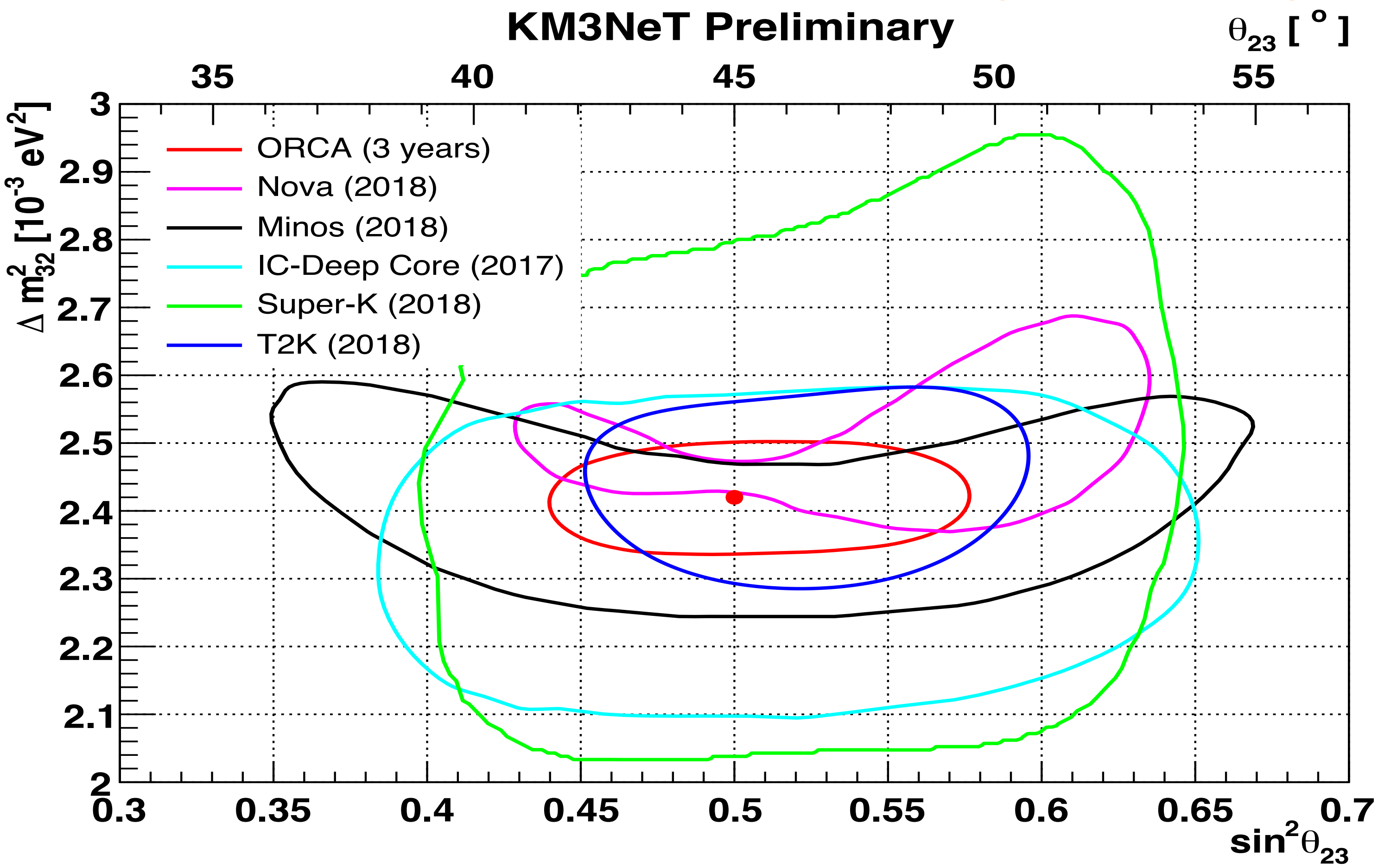
New detector module designs

24 x 3” PMTs



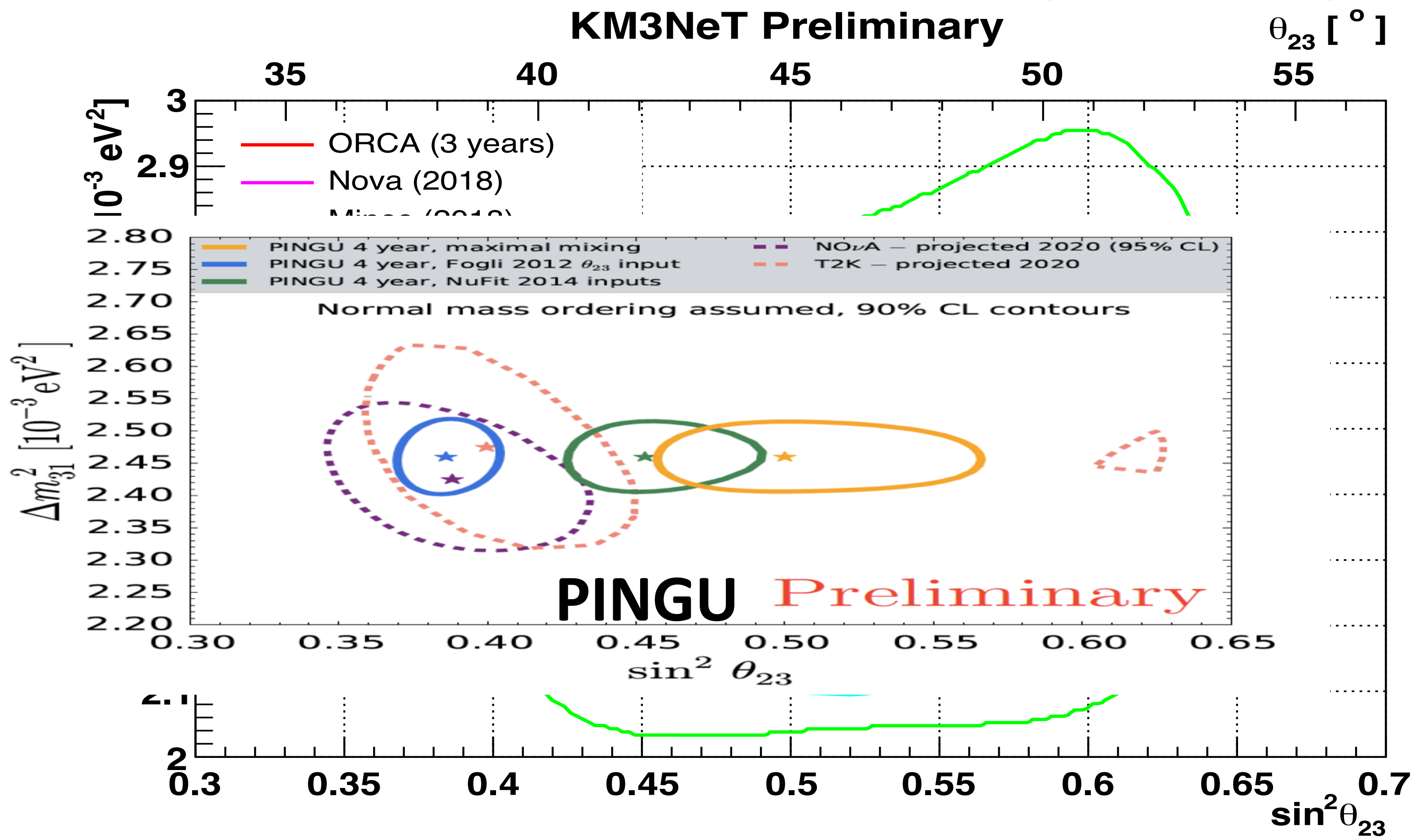
2 x 8” PMTs

Measurement of Δm^2_{32} , θ_{23}



ORCA - 3 years full detector

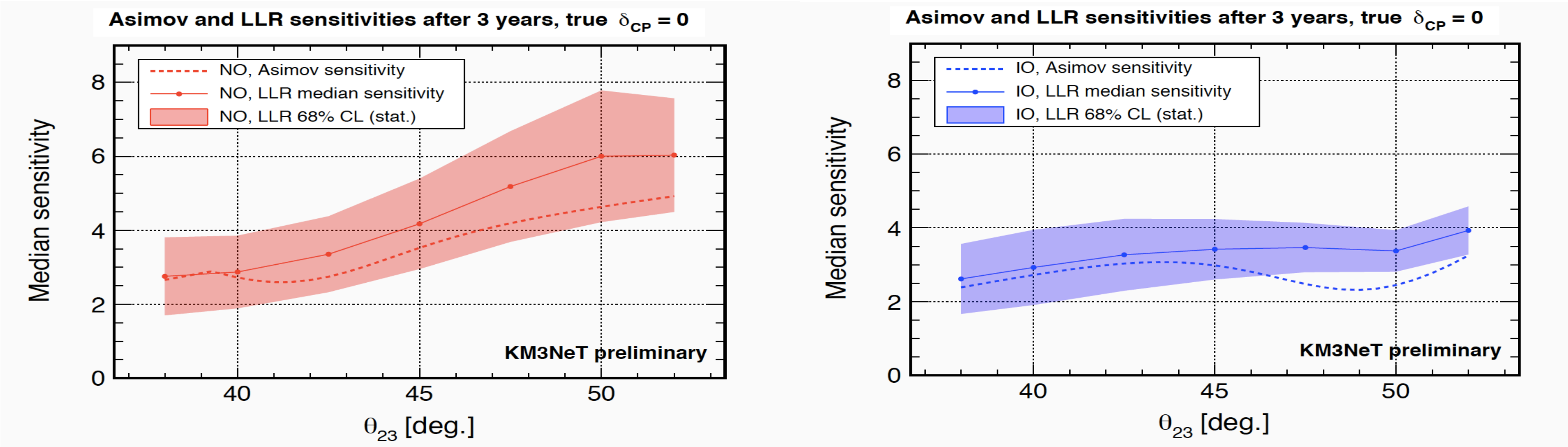
Measurement of Δm^2_{32} , θ_{23}



PINGU - 4 years full detector

NMH sensitivities as function of θ_{23}

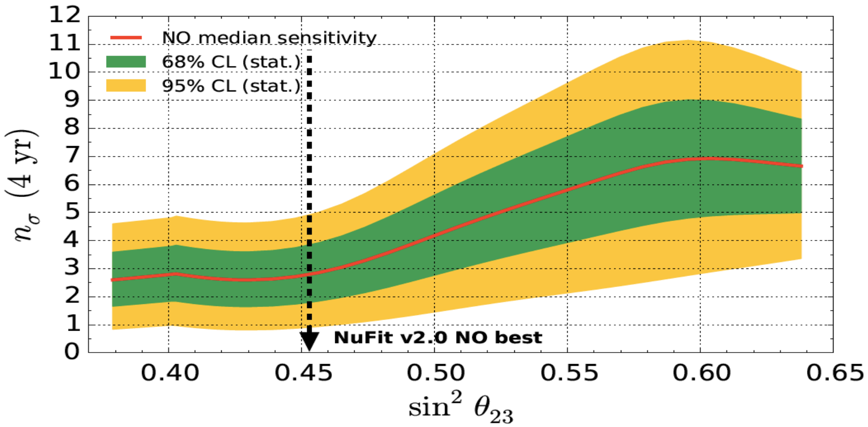
KM3NeT/ORCA

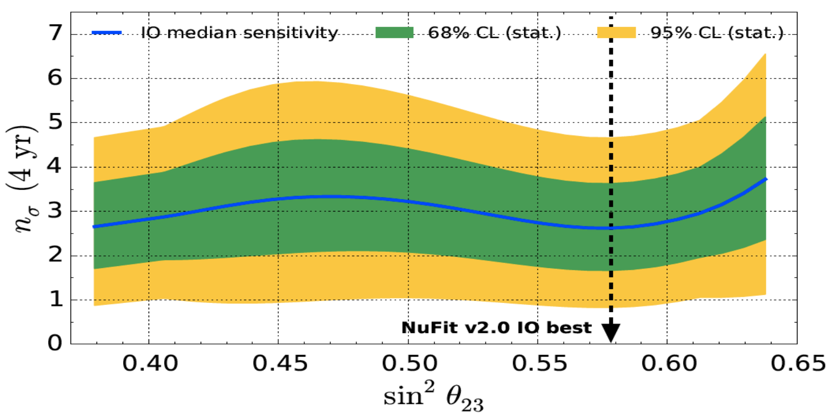


Fit in 2 'flavour' bins (track/shower)
Improvements expected with
-- using inelasticity binning
-- using more flavour bins

NMH sensitivities as function of θ_{23}

PINGU

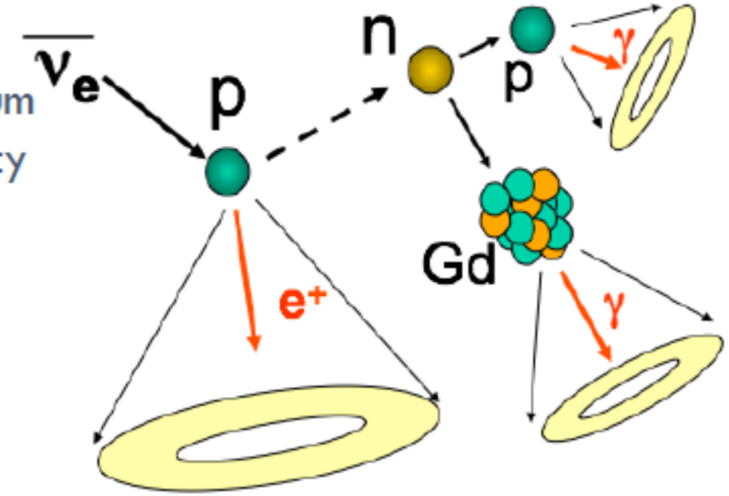




Fit in 2 ‘flavour’ bins (track/shower)
Improvements expected with
-- using inelasticity binning
-- using more flavour bins

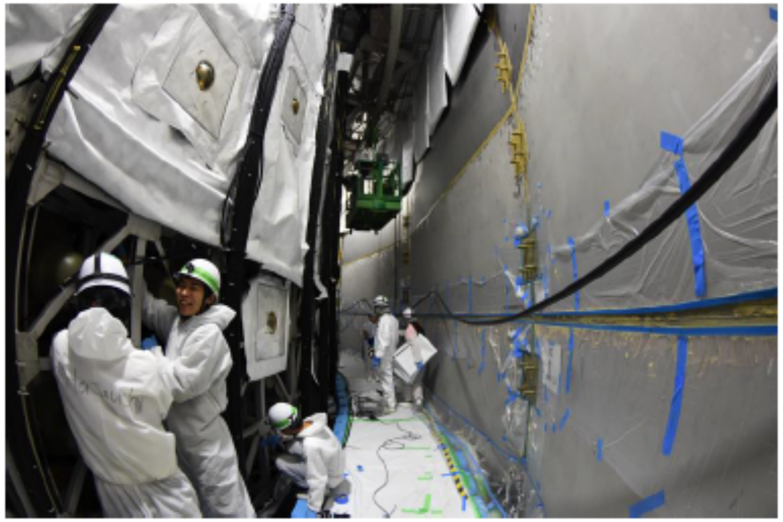
GADOLINIUM UPGRADE

SuperKamiokande



- Loading the Super-K water with gadolinium will increase the neutron tagging efficiency to 90%
- Detector is currently undergoing refurbishment work necessary for gadolinium loading

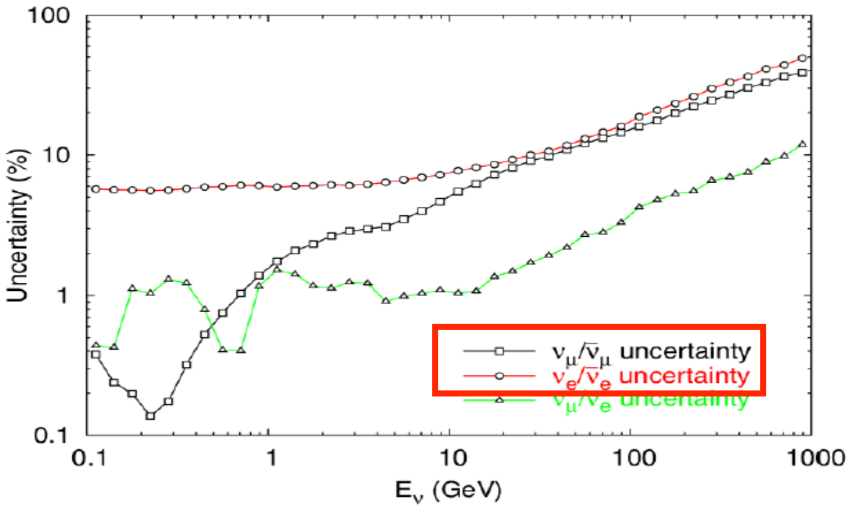
C. Vileva NOW 2018

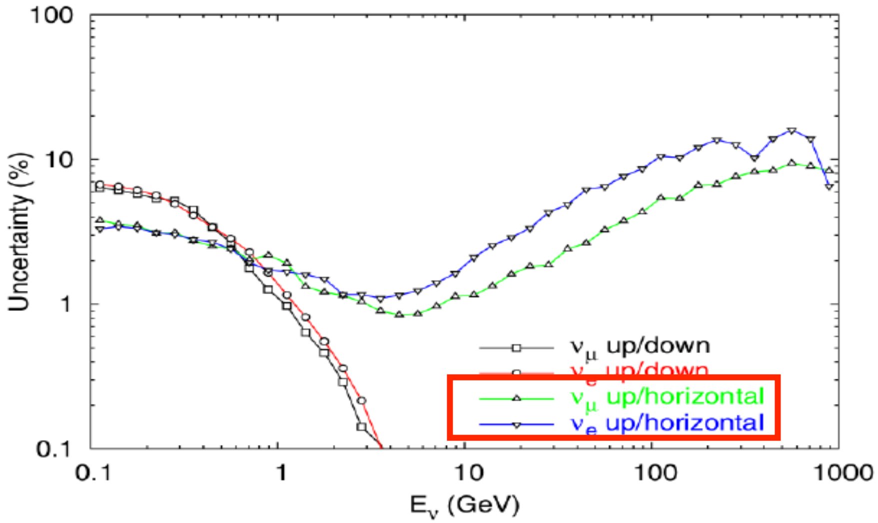


Neutrino flux systematics

- Shown results impacted by neutrino flux systematics
- Strongest effects from skews, not normalisation
- Neutrino/anti-neutrino ratio and up/horizontal ratio

Improvement from forward hadron production ratio : π^+/π^-, K^+/K^-, π/K ?

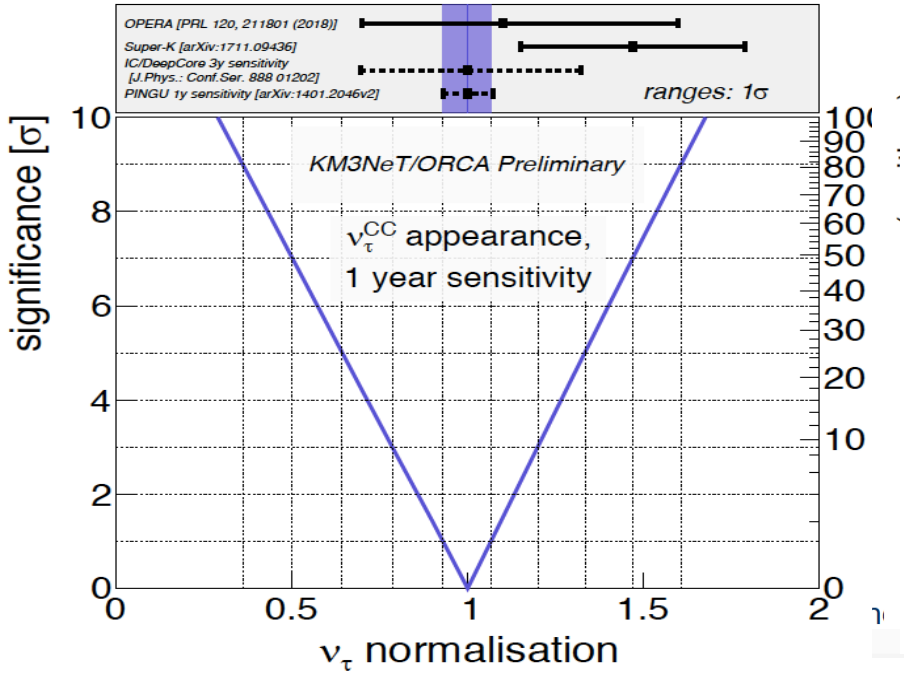




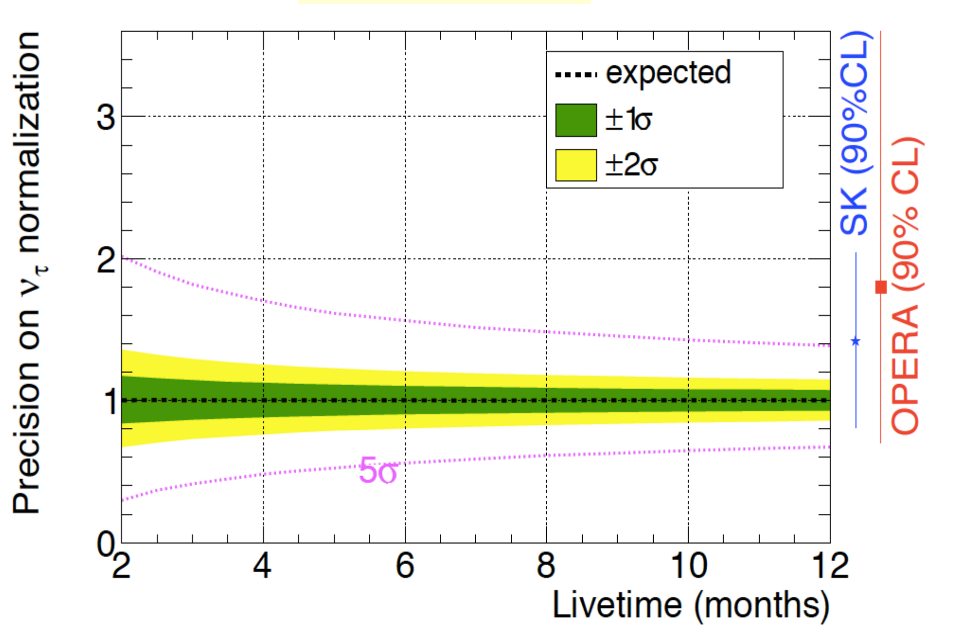
G. D. Barr et al., Phys. Rev. D 74 (2006) 094009.

ν_τ appearance – early physics

KM3NeT/ORCA



PINGU

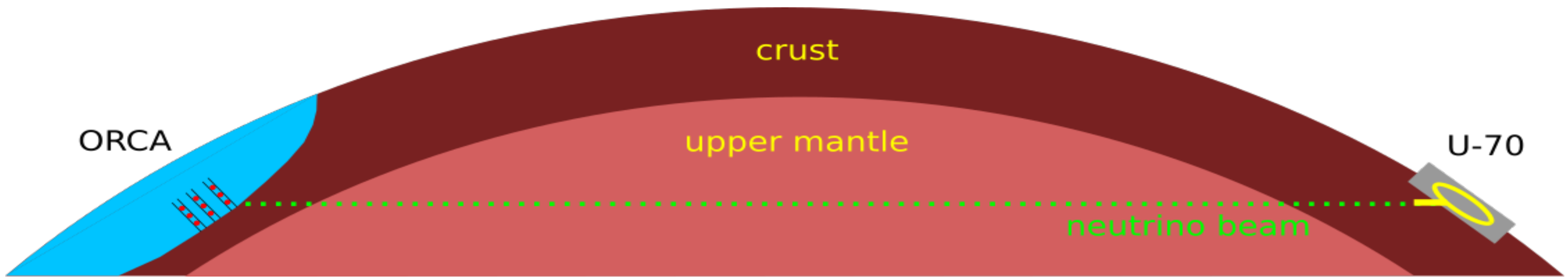


- Event rate normalisation constrained (3σ) within 20% after 1 year

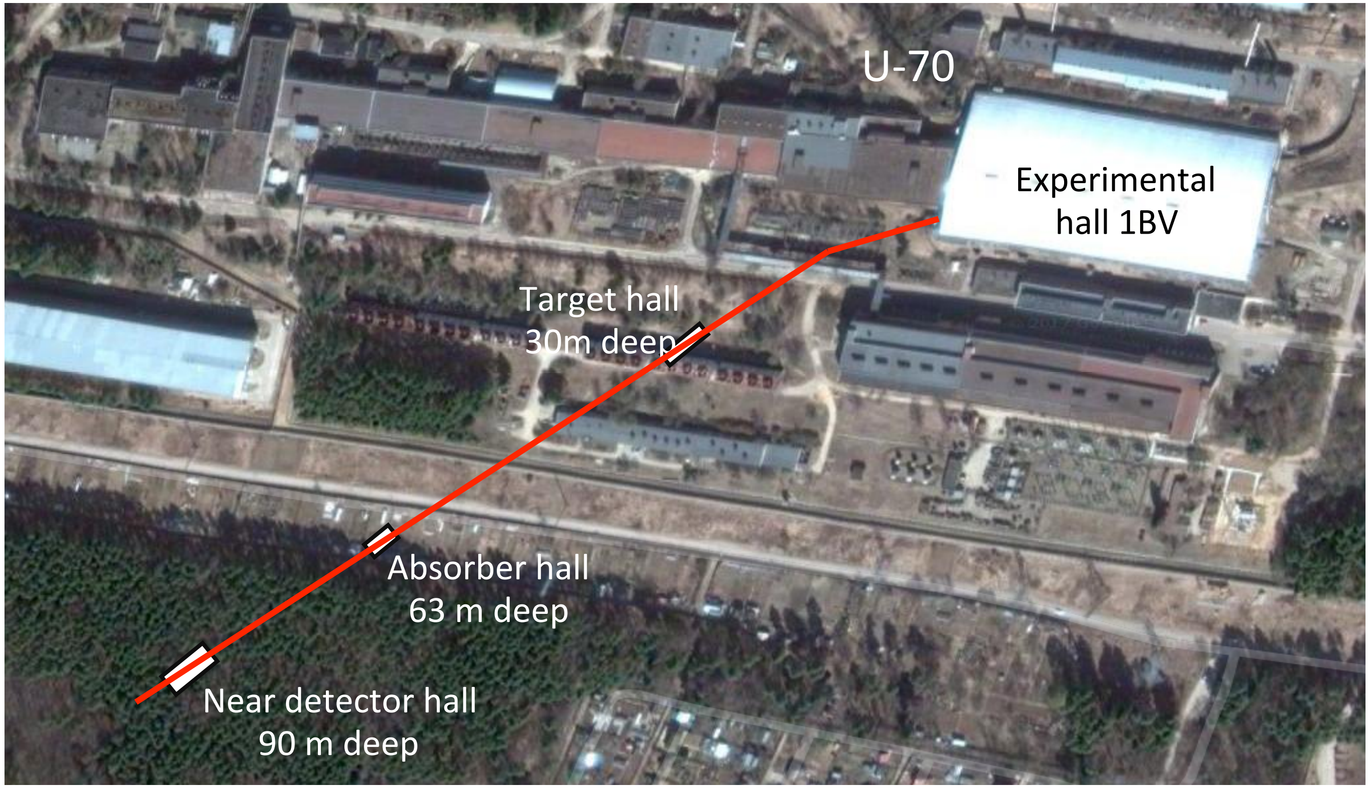
Needs precise knowledge of ν_τ cross sections → SHIP ?

Protvino to ORCA – key numbers

- Baseline 2590 km
- beam inclination : 11.7˚ (cosθ = 0.2)
- Deepest point at 134 km
- Upper mantle : density 3.4 g/cm^3 , Z/A = 0.4956



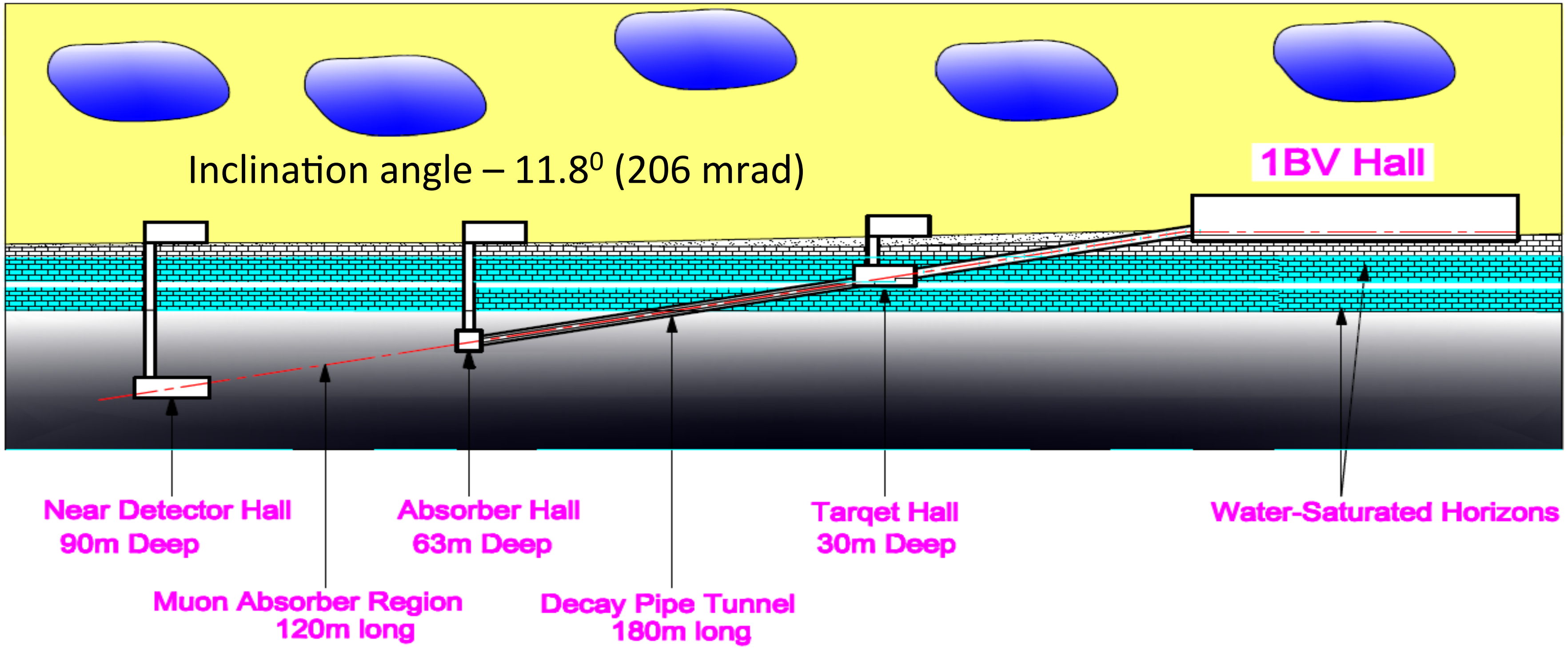
Neutrino Beam Layout



Proton beam bend:
in horizontal plane – appr. 22^0
in vertical plane – 11.8^0

A. Zaitsev, IHEP

Elevation View of Neutrino Beam

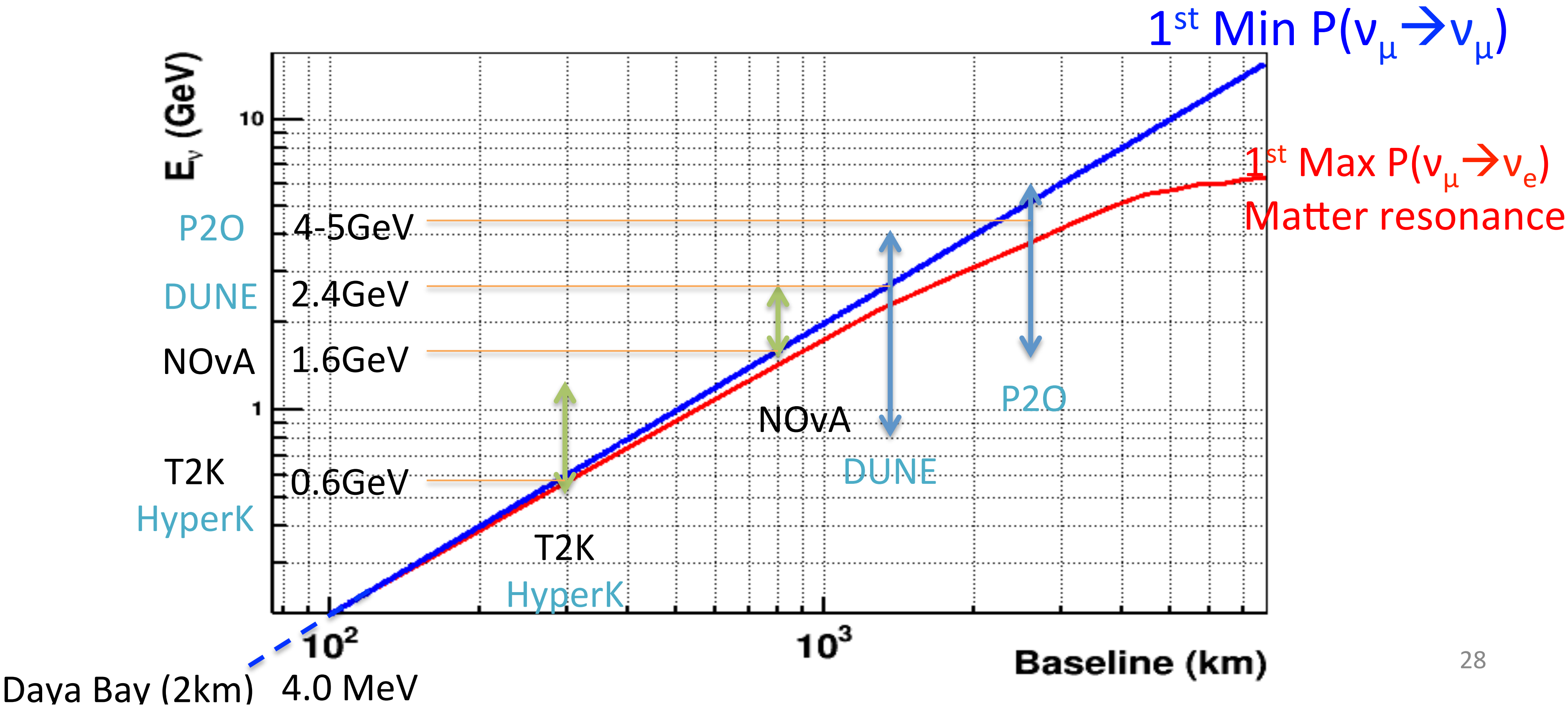


Target hall – 9×12×24 m (W×H×L)
Absorber hall – 6×12×12 m (W×H×L)
Near Detector hall – 9×12×36 m (W×H×L)

A. Zaitsev, IHEP

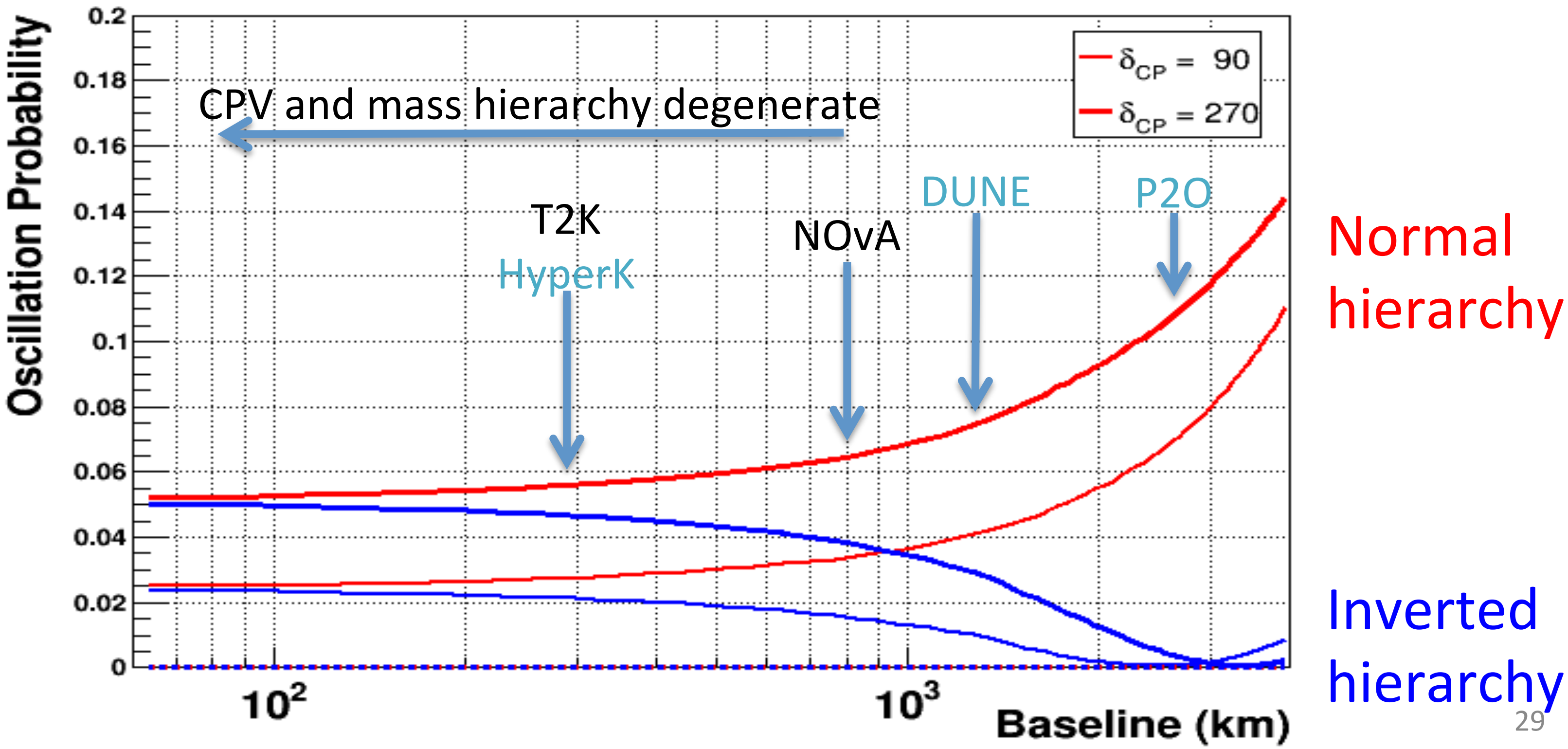
Comparison of LBL Projects

- Energy versus baseline

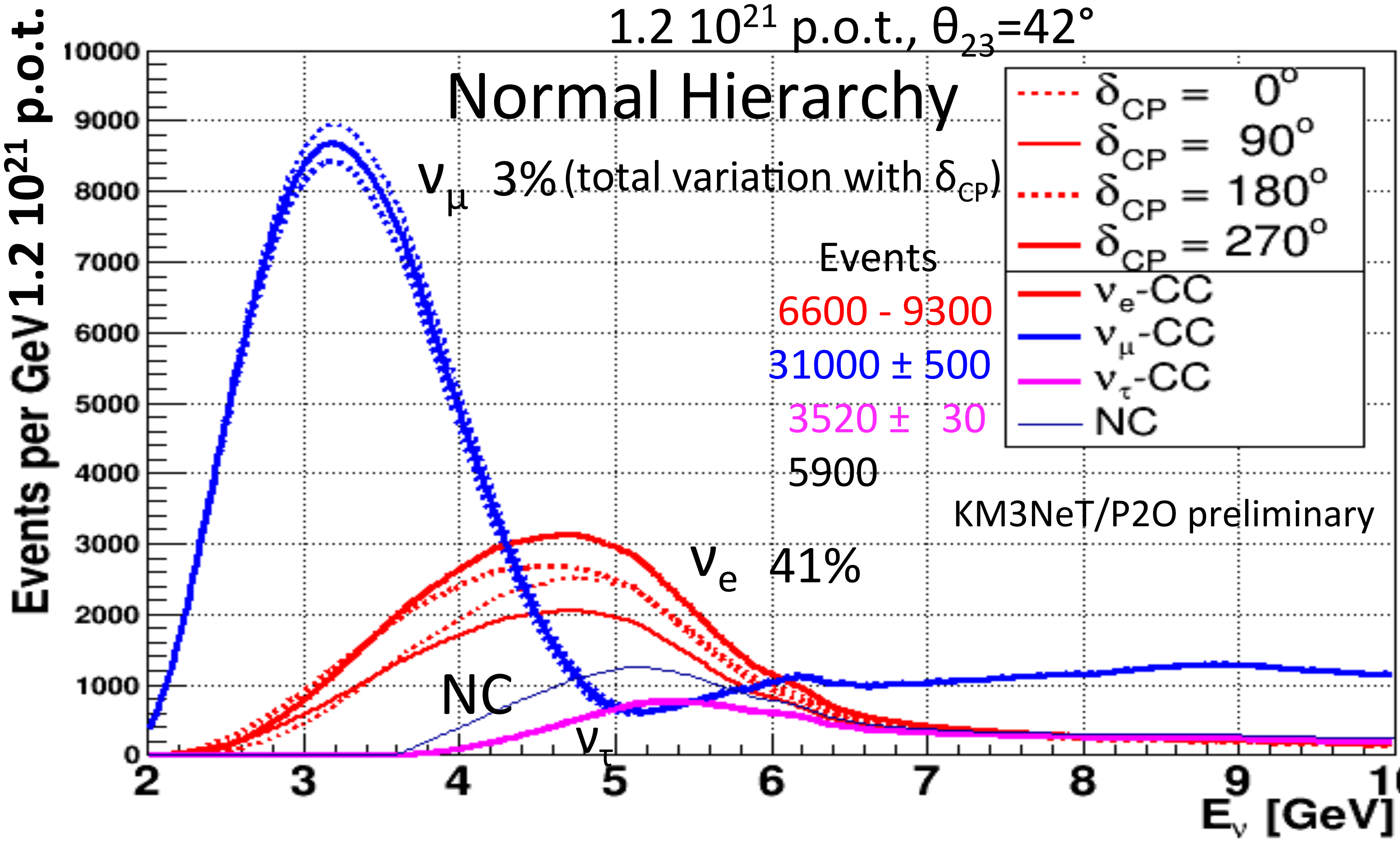


Comparison of LBL Projects

- Main Signal : Appearance of ν_e : $P(\nu_\mu \rightarrow \nu_e)$



Event numbers – Neutrino Beam



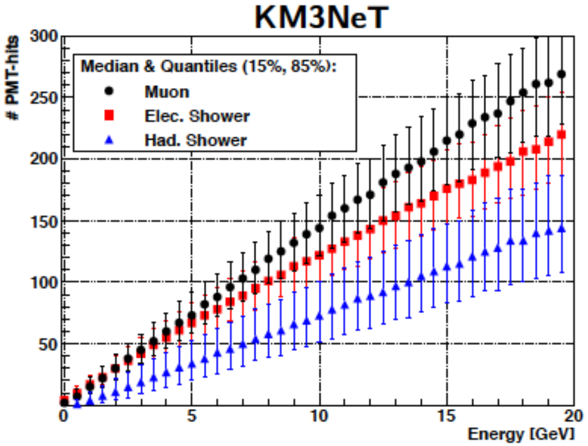
Phased approach

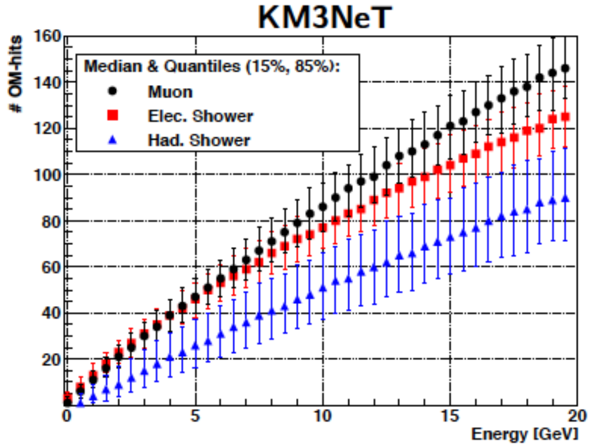
- Phase 1
  - ORCA : 1 building block (~2022)
  - 115 detection units, performance as in LoI
  - Accelerator : moderate intensity upgrade 15 kW → 75kW
  - 7 10^{19} protons on target per year
- Phase 2
  - Densified ORCA (~5x more photocathode area)
    - Example : 10x denser but half as big
  - Particle ID via Cherenkov ring fuzziness becomes possible
  - Accelerator : 450 kW
  - 1.2 10^{21} protons on target in 3 years

Photon detection in (dense) ORCA

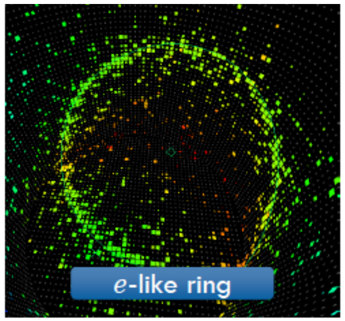
- 150 (muon), 130 (e/m), 70 (hadron) PMTs hit per GeV
- 90 (muon), 80 (e/m), 50 (hadron) Optical modules hit per GeV

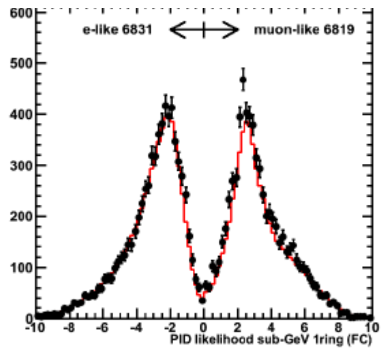
ORCA

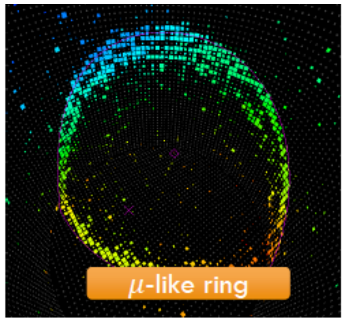




SuperK

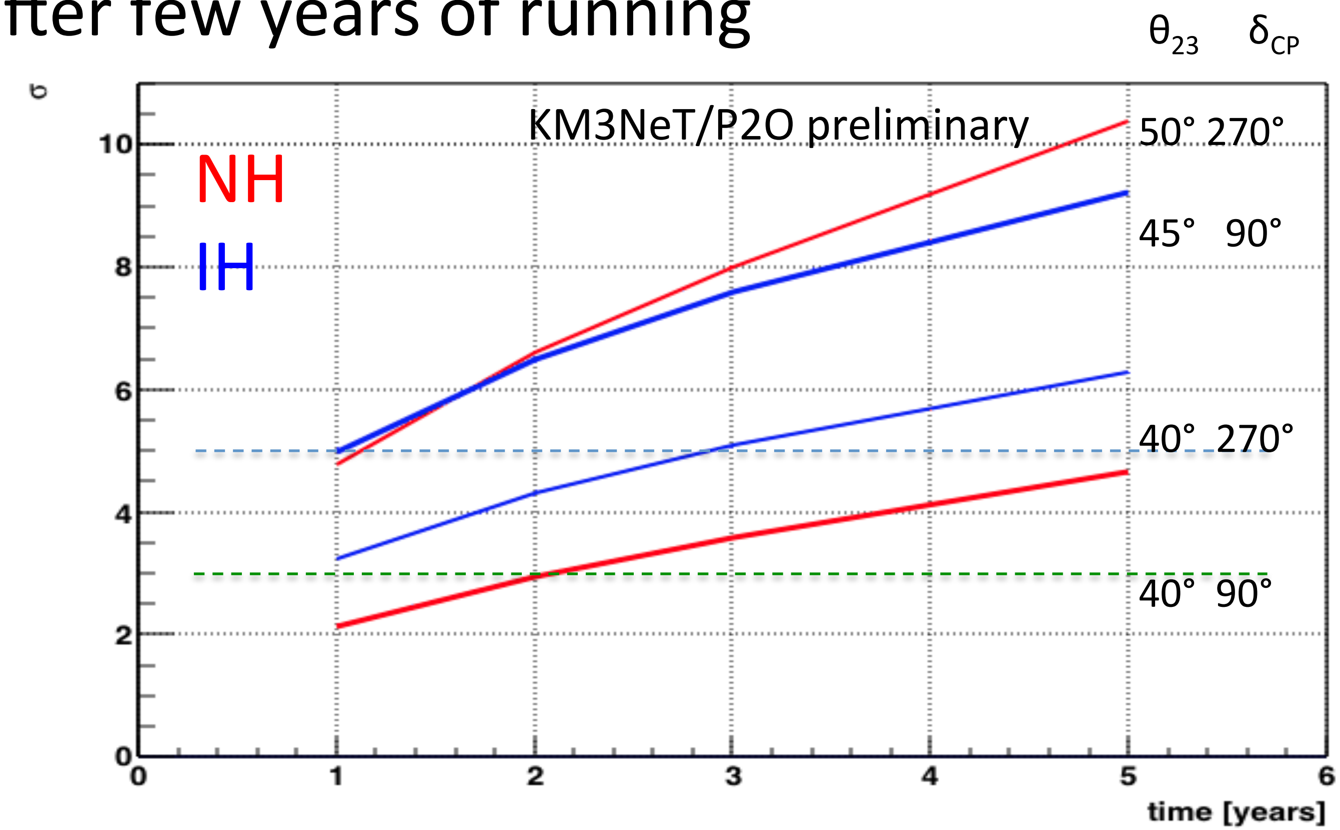






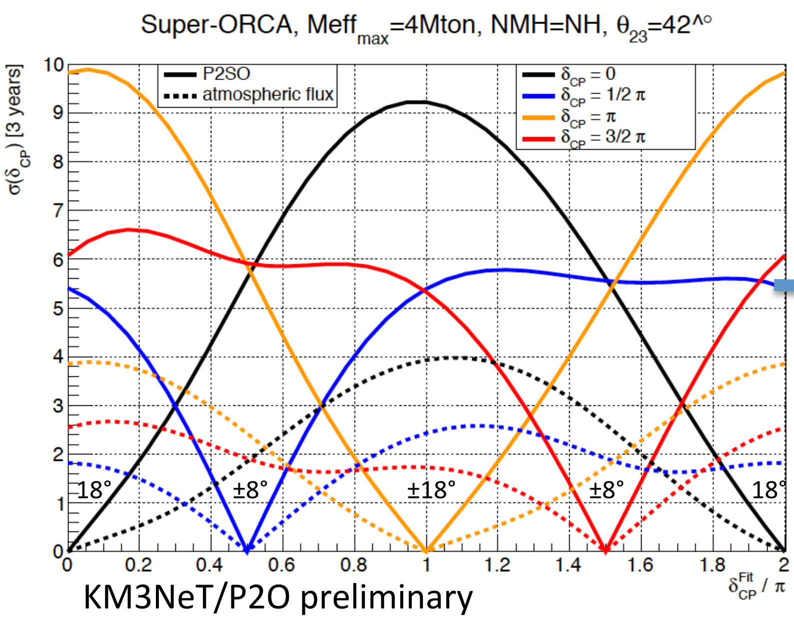
NMH - beam intensity 75kW

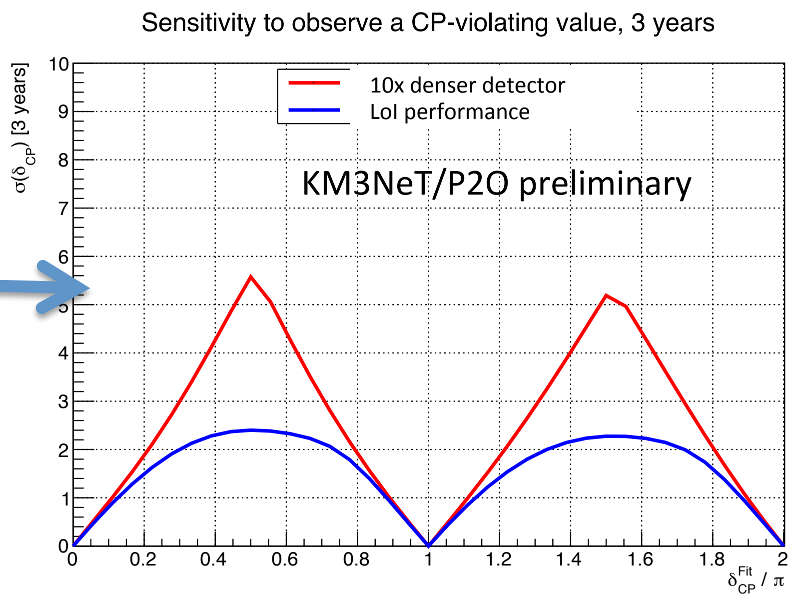
- Evolution with time – decisive NMH determination after few years of running



CP measurement

- 450 kW, 3 years, 10x denser ORCA → setup also used to study CP-violation with atmospheric ν (dashed lines)
- Fuzziness of Cherenkov rings for e/μ separation



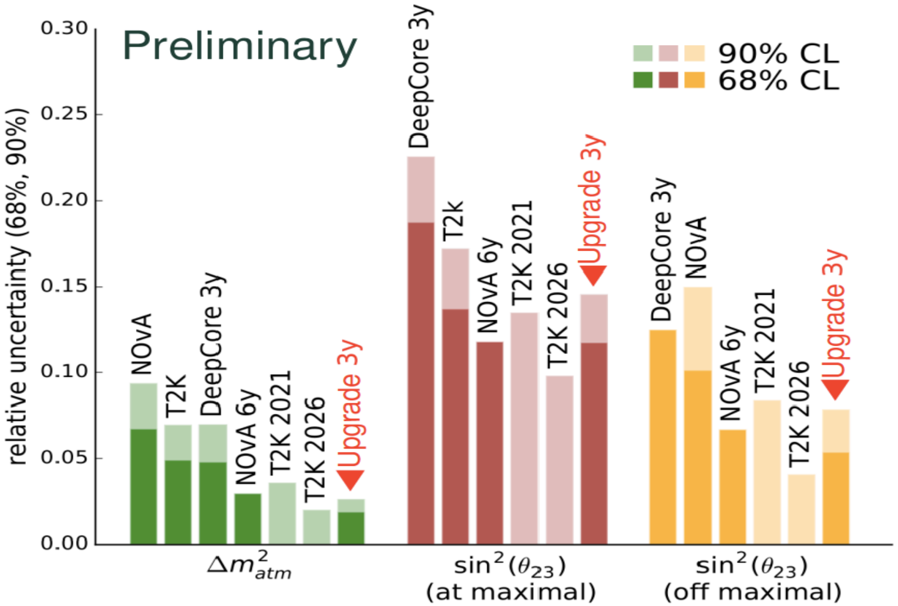


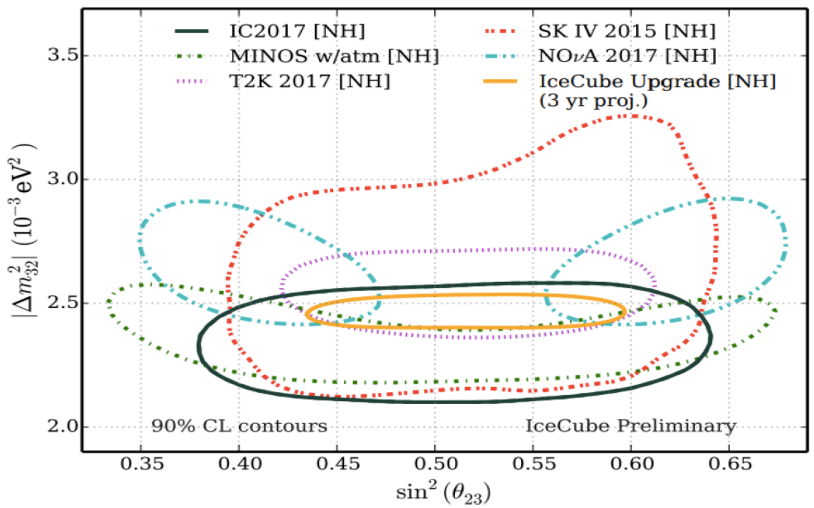
10.5281/zenodo.1292936

Summary

- Diverse & interesting physics program with atmospheric ν @ future neutrino telescopes
- Hadron experiments @ CERN might help reducing flux/x-sec systematics
- Construction underway for KM3NeT detector
- IceCube (7str.) upgrade financed, IceCube-Gen2 planned
- 3rd generation LBL experiment being explored using intense neutrino source at Protvino + dense version of KM3NeT/ORCA

backup

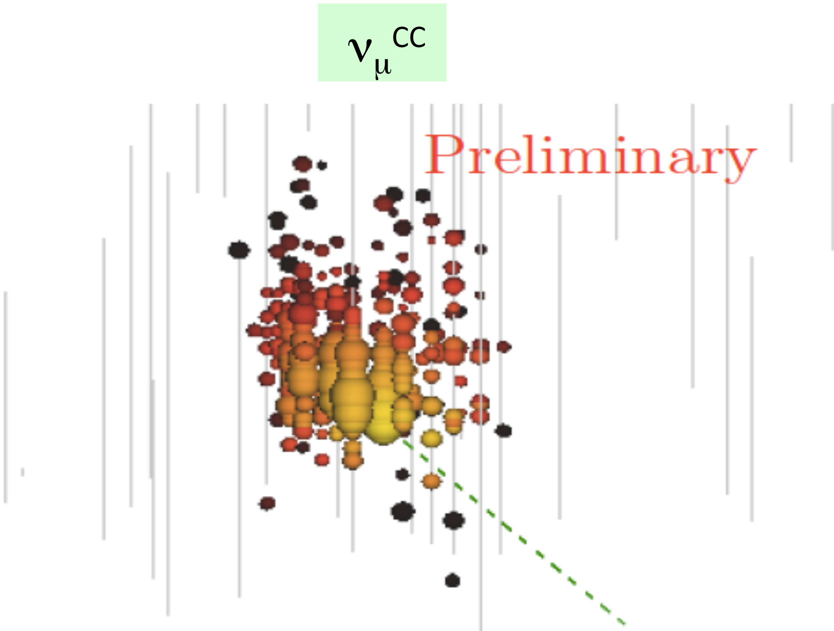

Preliminary
90% CL
68% CL
relative uncertainty (68%, 90%)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
NOvA
T2K
DeepCore 3y
NOvA 6y
T2K 2021
T2K 2026
Upgrade 3y
T2k
NOvA
Δm^2_{atm}
$\sin^2(\theta_{23})$ (at maximal)
$\sin^2(\theta_{23})$ (off maximal)

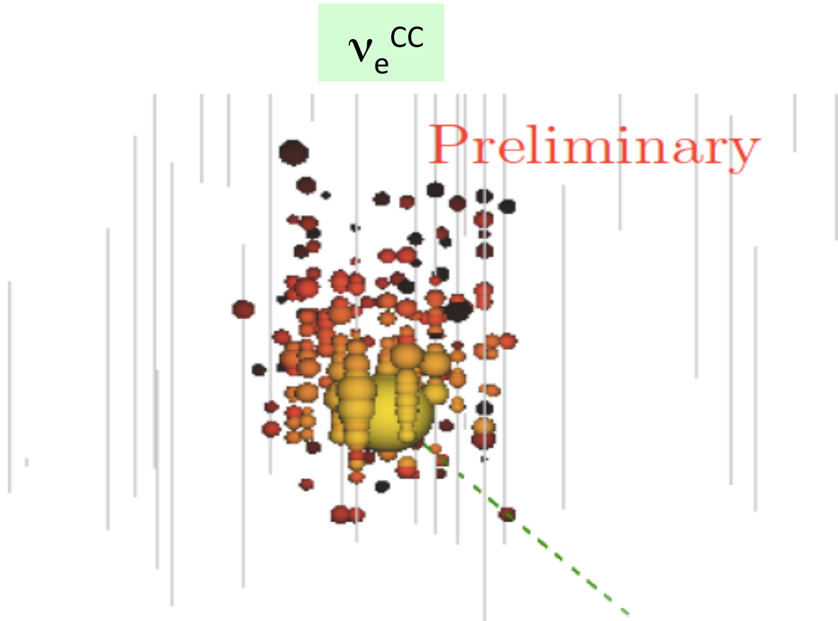

IC2017 [NH]
MINOS w/atm [NH]
T2K 2017 [NH]
SK IV 2015 [NH]
NOνA 2017 [NH]
IceCube Upgrade [NH] (3 yr proj.)
90% CL contours
IceCube Preliminary
$|\Delta m^2_{32}|$ $(10^{-3}\mathrm{eV}^2)$
$\sin^2(\theta_{23})$
2.0
2.5
3.0
3.5
0.35
0.40
0.45
0.50
0.55
0.60
0.65

Deployment First Line 22/09/2017

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

Flavour Identification

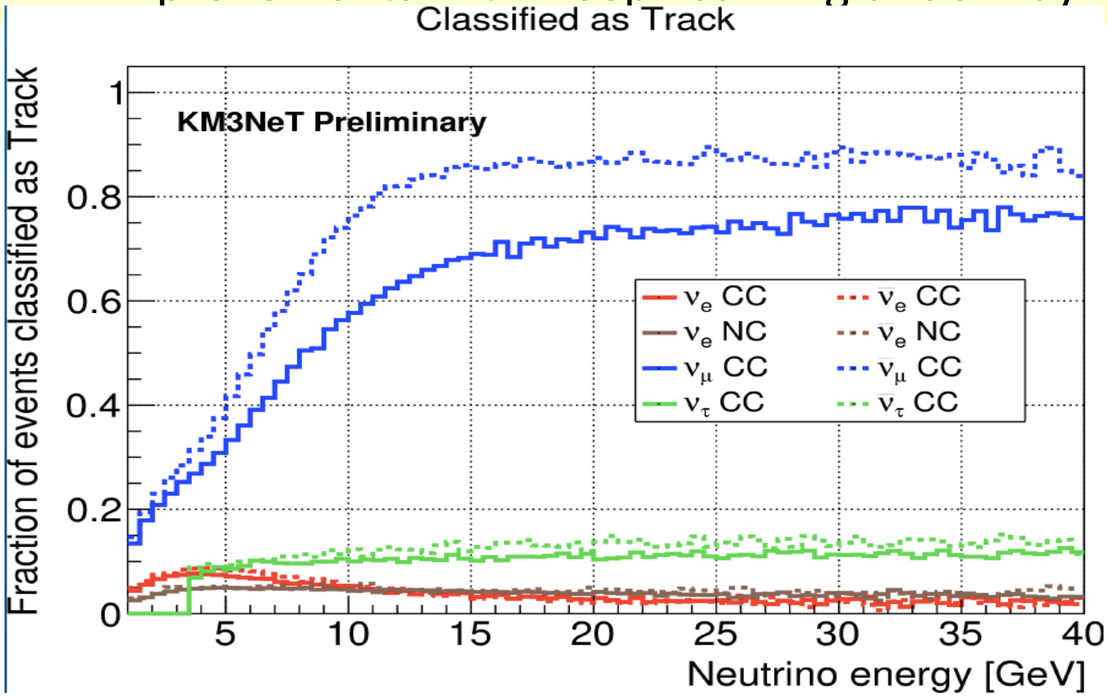




PINGU simulation: 12 GeV neutrino with 10 GeV lepton
Critical problem : use advanced IT technology

Flavour Identification

- Discrimination of track-like (ν_μ^{CC}) and cascade-like (ν^{NC}, $\nu_{e/\tau}^{CC}$) events
- **KM3NeT:**
  - Classification uses "Random Decision Forest"
  - Better than 80% above 10 GeV for all channels but ν_μ^{CC}
  - Improvements with Deep Learning underway

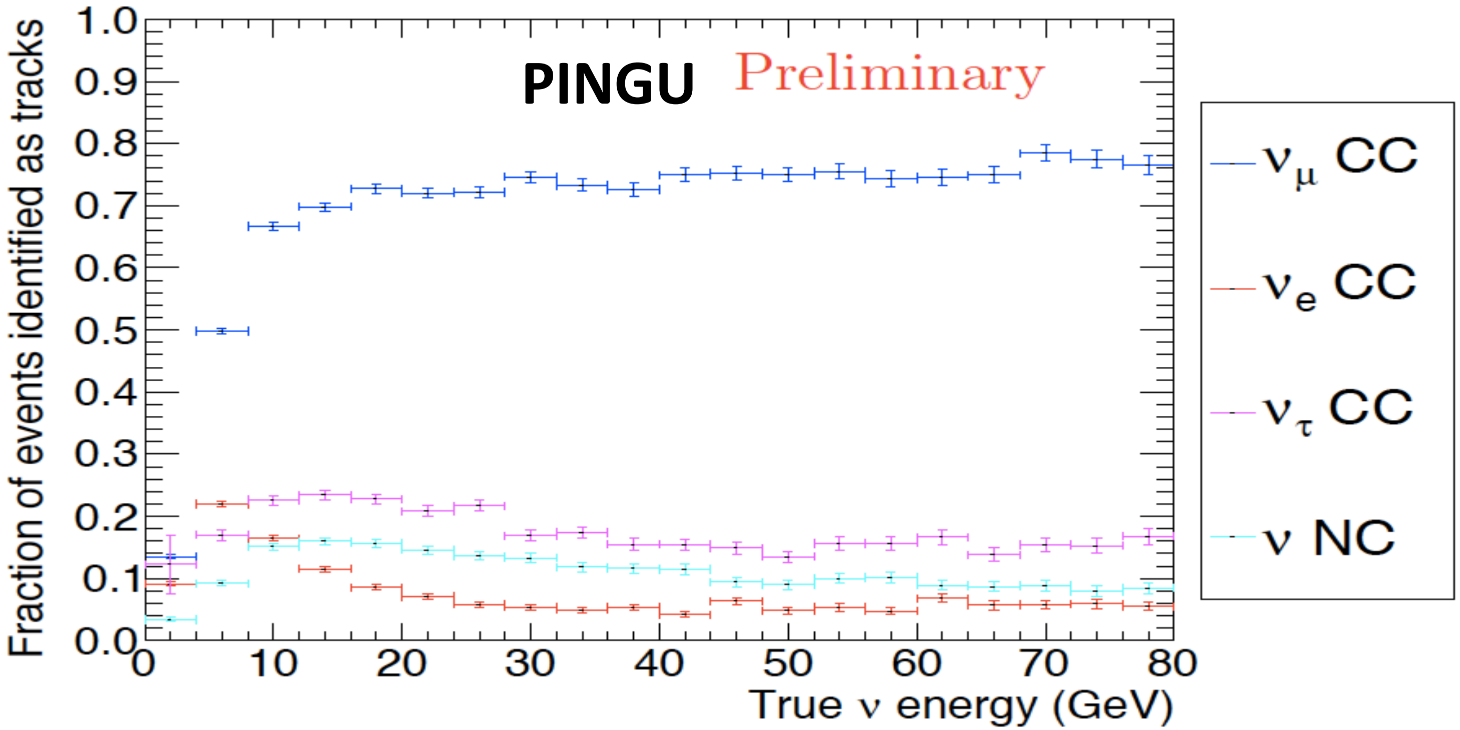


<- $\bar{\nu}_\mu$CC
<- ν_μCC
<- ν_τCC
<- ν_eCC, NC

Difference due to different inelasticities

Flavour Identification

- Discrimination of track-like (ν_μ^{CC}) and cascade-like (ν^{NC}, $\nu_{e/\tau}^{CC}$) events
- **PINGU:**
  - Classification uses multilayer perceptron (MLP) neural net



Reconstructed events

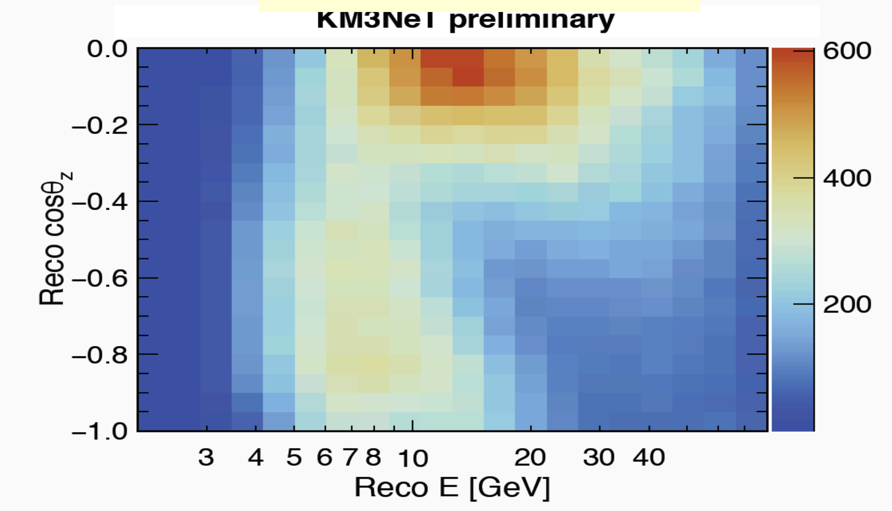
KM3NeT/ORCA

channel	events/y	channel	events/y
$\bar{\nu}_e$CC	14700	$\bar{\nu}_\tau$ CC	2900
ν_e CC	5700	ν_τ CC	1300
$\bar{\nu}_\mu$ CC	21300	$\bar{\nu}$ NC	5300
ν_μ CC	9900	ν NC	1500

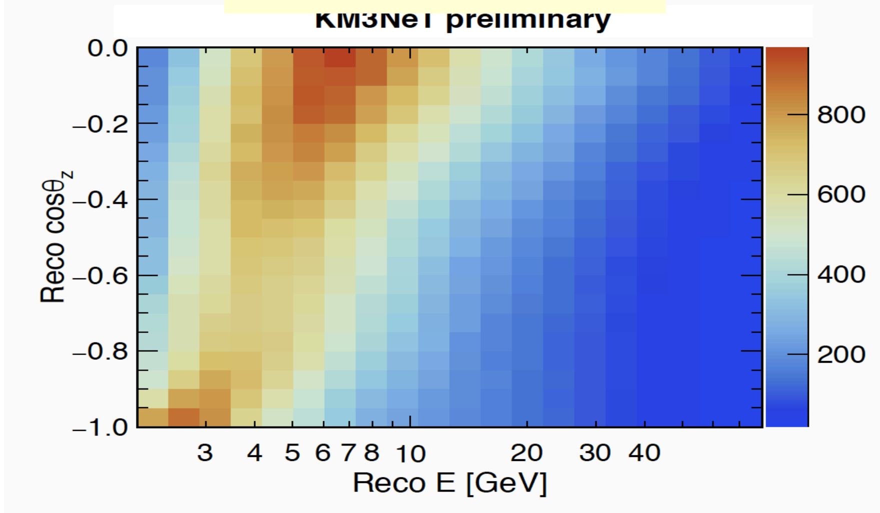
PINGU

Interaction type	Events per year
$\nu_\tau + \overline{\nu}_\tau$ CC	2,800
$\nu_\mu + \overline{\nu}_\mu$ CC	32,600
$\nu_e + \overline{\nu}_e$ CC	25,400
$\nu + \overline{\nu}$ NC	7,400

Classified as Track

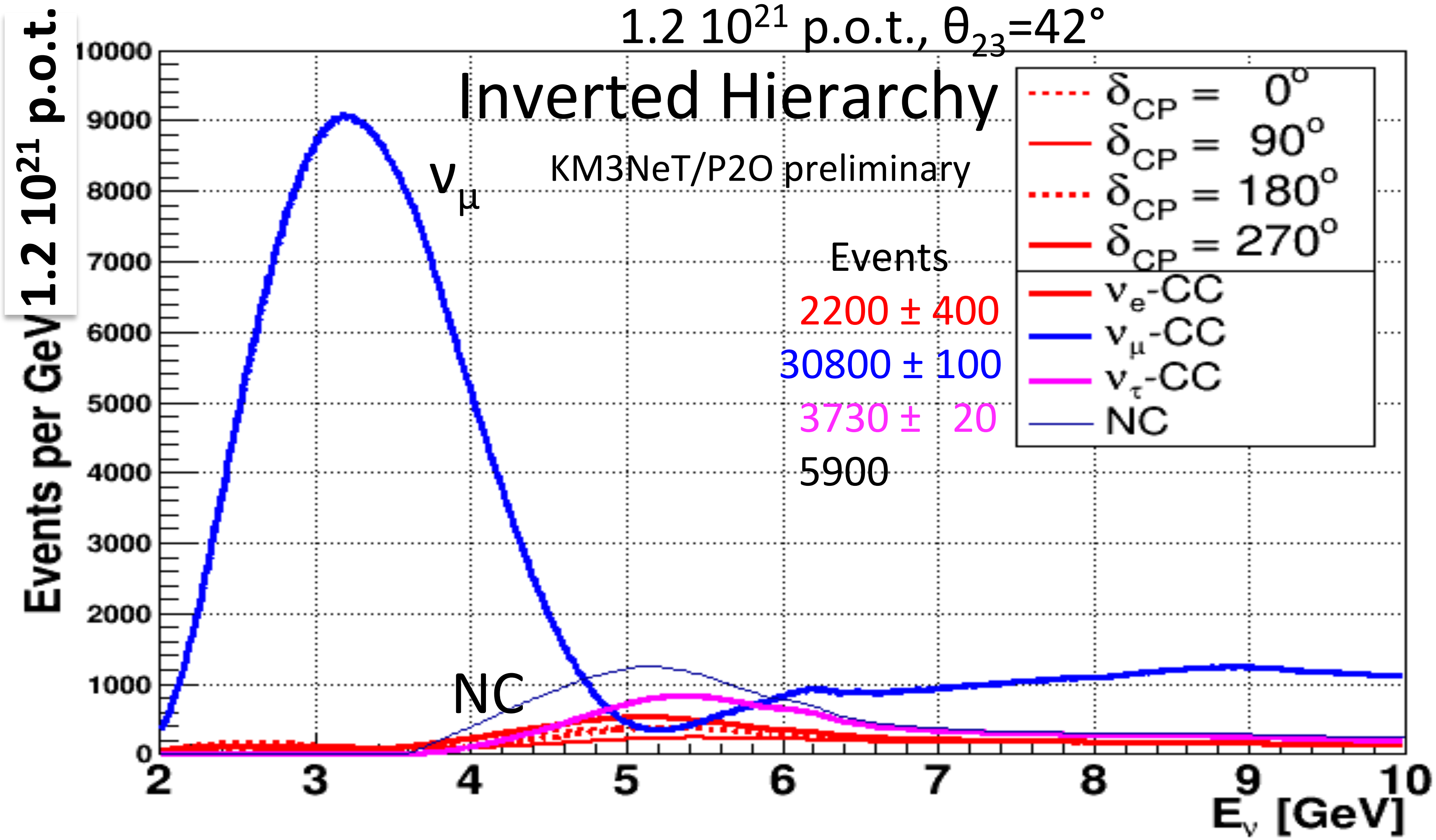


Classified as Shower

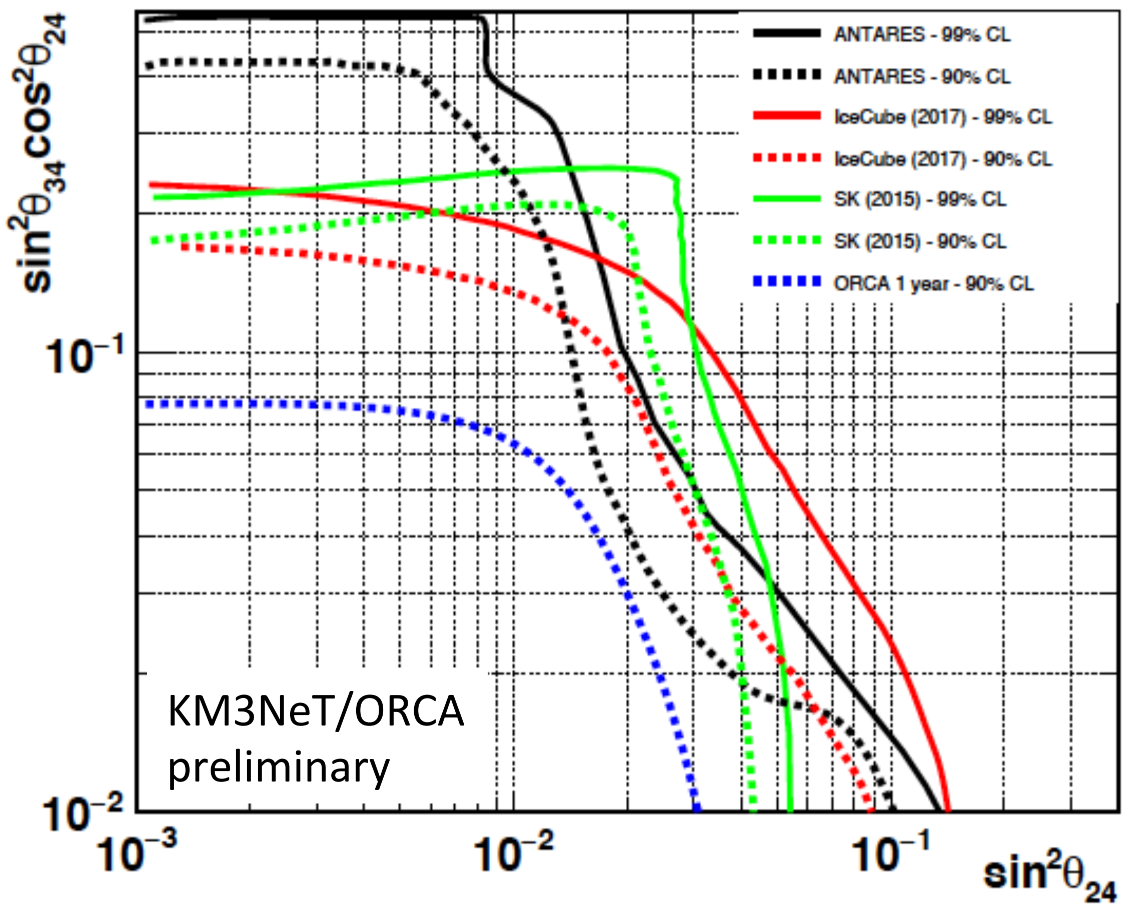


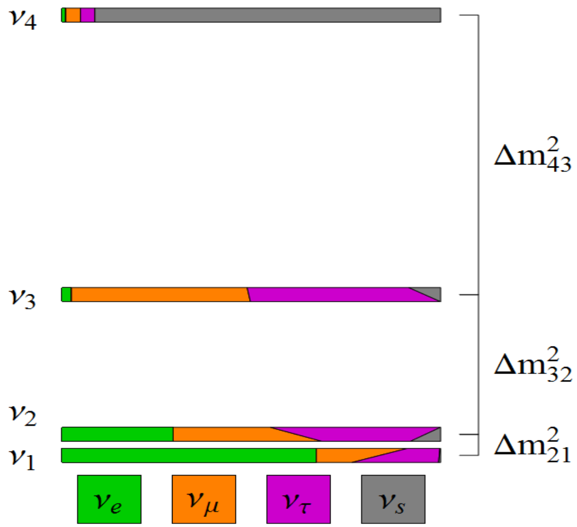
Event distribution for 3 years

Event numbers – Neutrino Beam



Sterile neutrinos – early physics





Significant improvement after one year

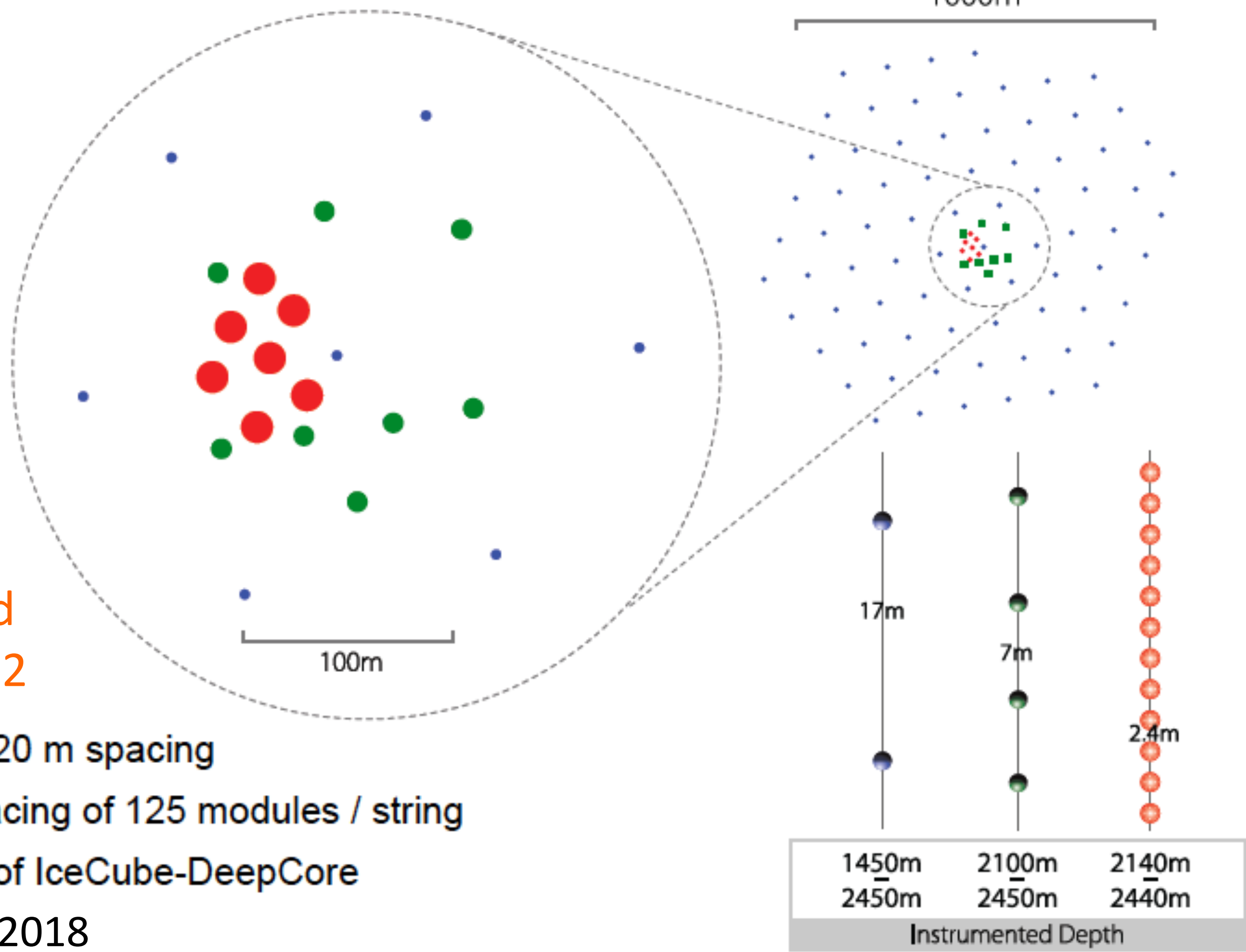
The IceCube Upgrade

The next step in precision astroparticle physics with IceCube

IceCube

DeepCore

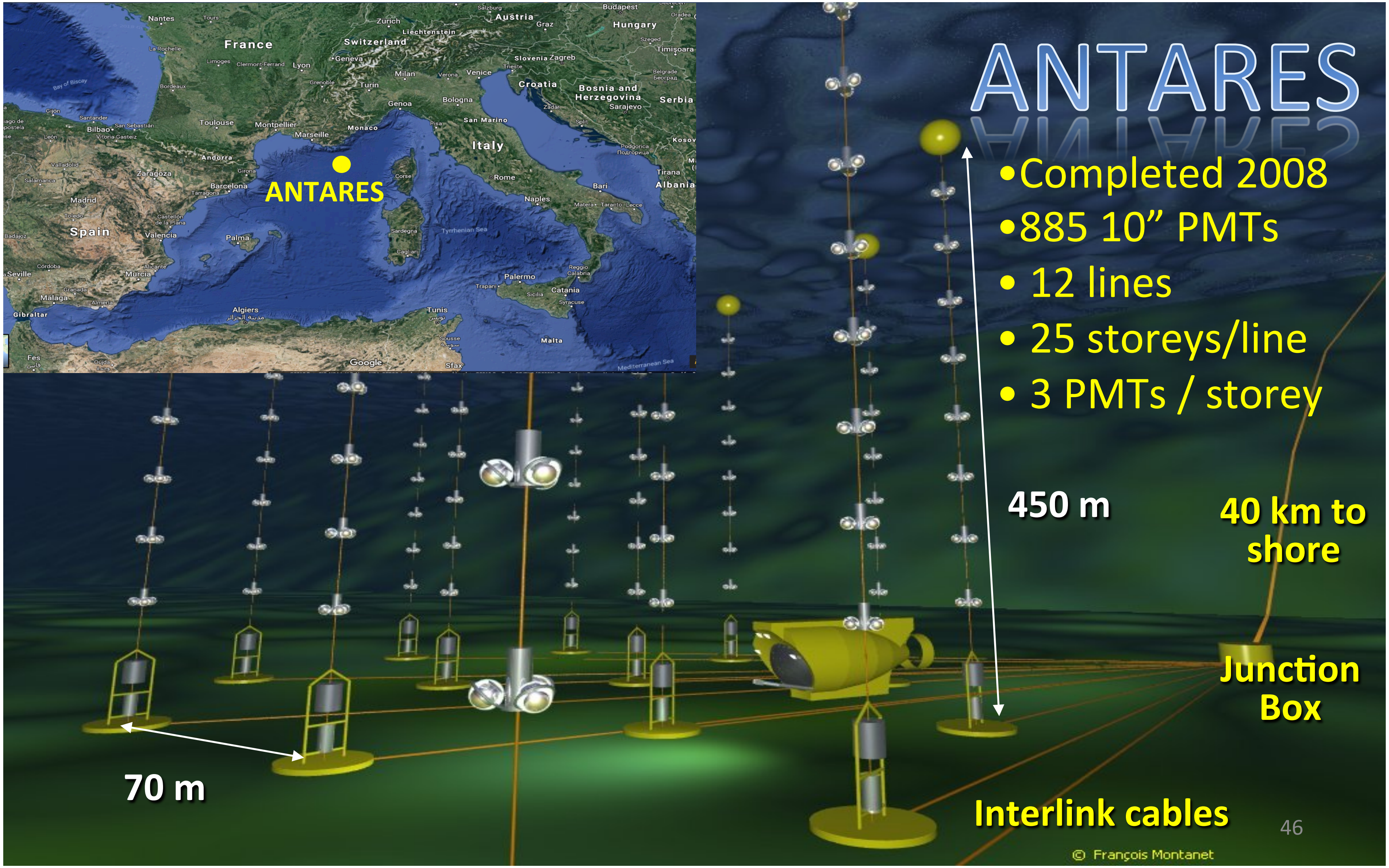
IC Upgrade



recently financed
Installation ~2022

- 7 strings with ~20 m spacing
- 2 m vertical spacing of 125 modules / string
- Located inside of IceCube-DeepCore

Marek Kowalski, NOW 2018


ANTARES
•Completed 2008
•885 10” PMTs
• 12 lines
• 25 storeys/line
• 3 PMTs / storey
ANTARES
France
Switzerland
Austria
Hungary
Croatia
Bosnia and Herzegovina
Serbia
Italy
Spain
Albania
Marseille
Monaco
Rome
Naples
Madrid
Barcelona
Valencia
Palermo
Tunis
Algiers
Malta
Gibraltar
Google
450 m
40 km to shore
Junction Box
70 m
Interlink cables
46
© François Montanet

THE ICECUBE NEUTRINO OBSERVATORY

Deployed in the deep glacial ice at the South Pole

5160 PMTs

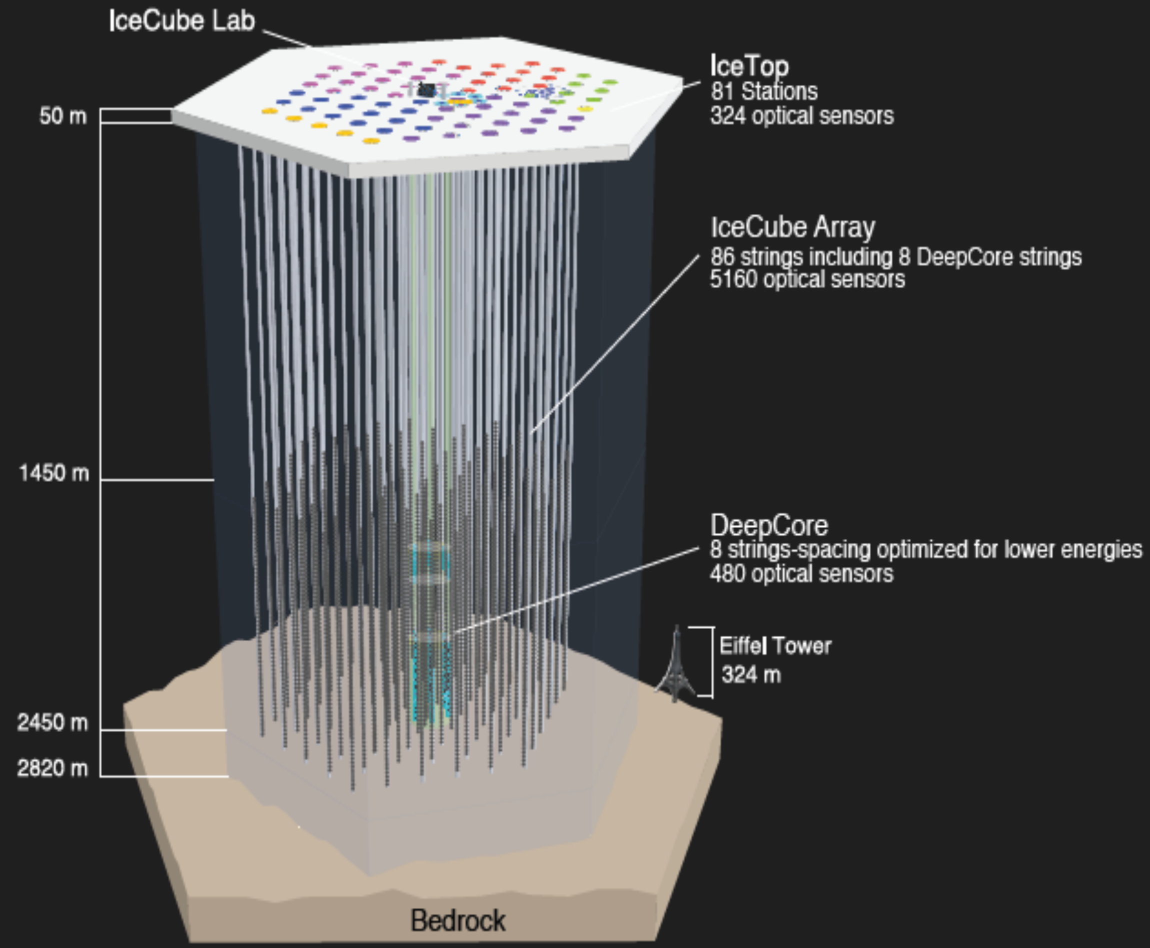
1 km³ volume

86 strings

17 m vertical spacing

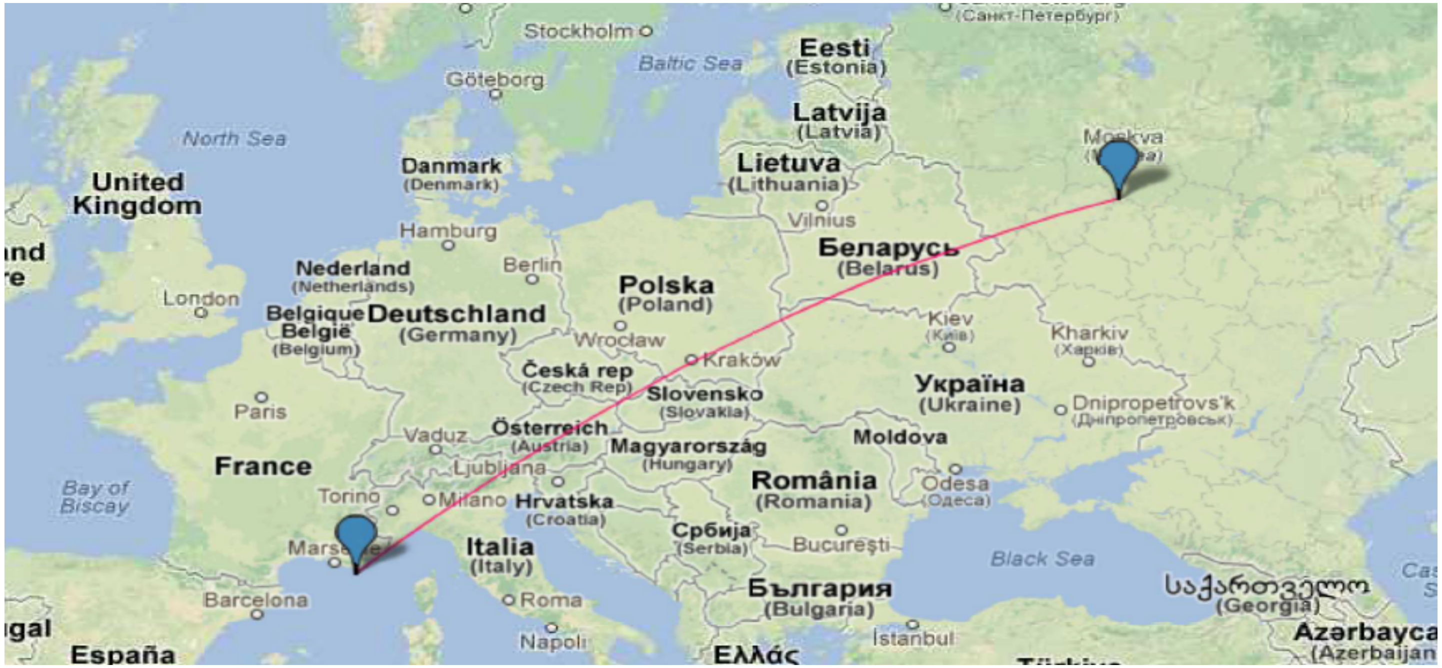
125 m string spacing

Completed **2010**



Protvino to ORCA – key numbers

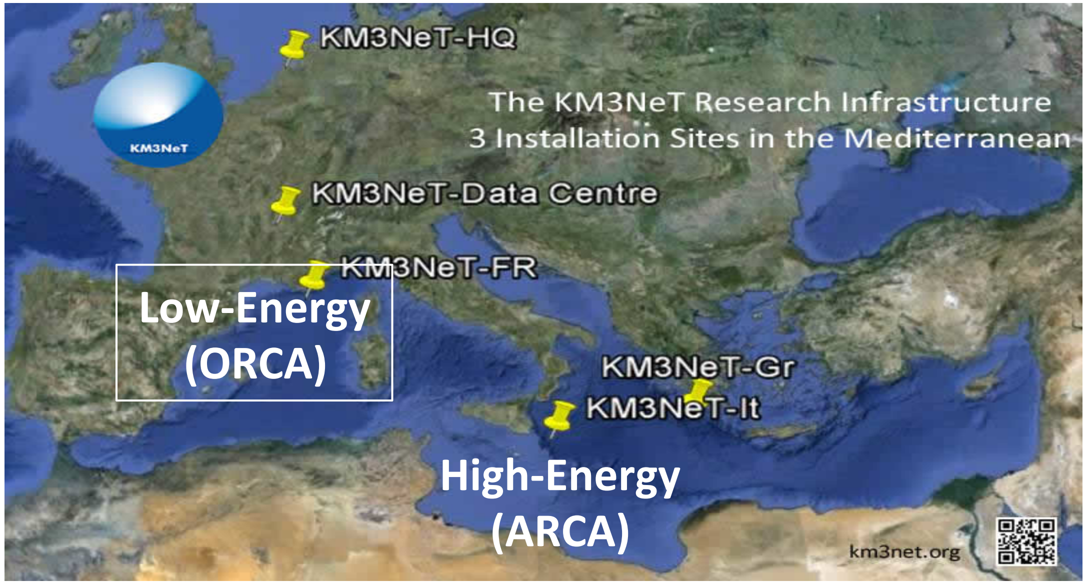
- Baseline 2590 km
- First oscillation maximum 5.1 GeV
- Matter resonance maximum 3.8 GeV



KM3NeT

KM3NeT is a research infrastructure with 2 main physics topics:

- The origin of cosmic neutrinos (high energy)
- Measurement of fundamental neutrino properties (low energy)
- Deep Sea Observatory (Oceanography, bioacoustics, bioluminescence, seismology)



ARCA- Astroparticle Research with Cosmics in the Abyss

ORCA- Oscillation Research with Cosmics in the Abyss

Prompt neutrino flux

- So far only upper limits

IceCube upgoing muons

Astrophysical ν fitted together with prompt atmospheric model