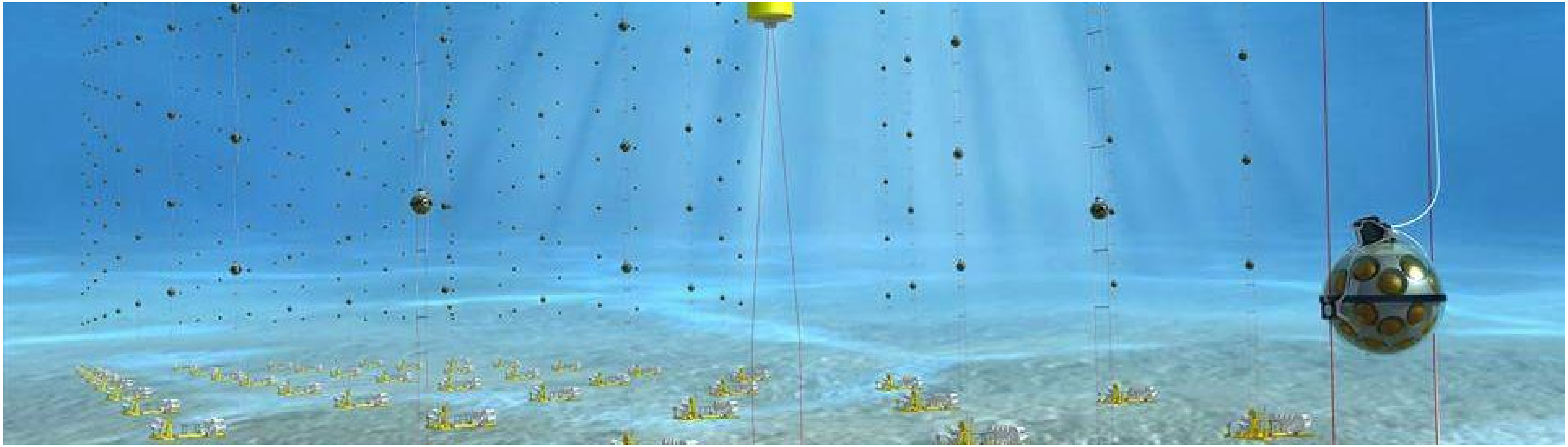
XXth International Seminar on High Energy Physics “Quarks-2018”
Valday, Russia
May 27 – June 2, 2017

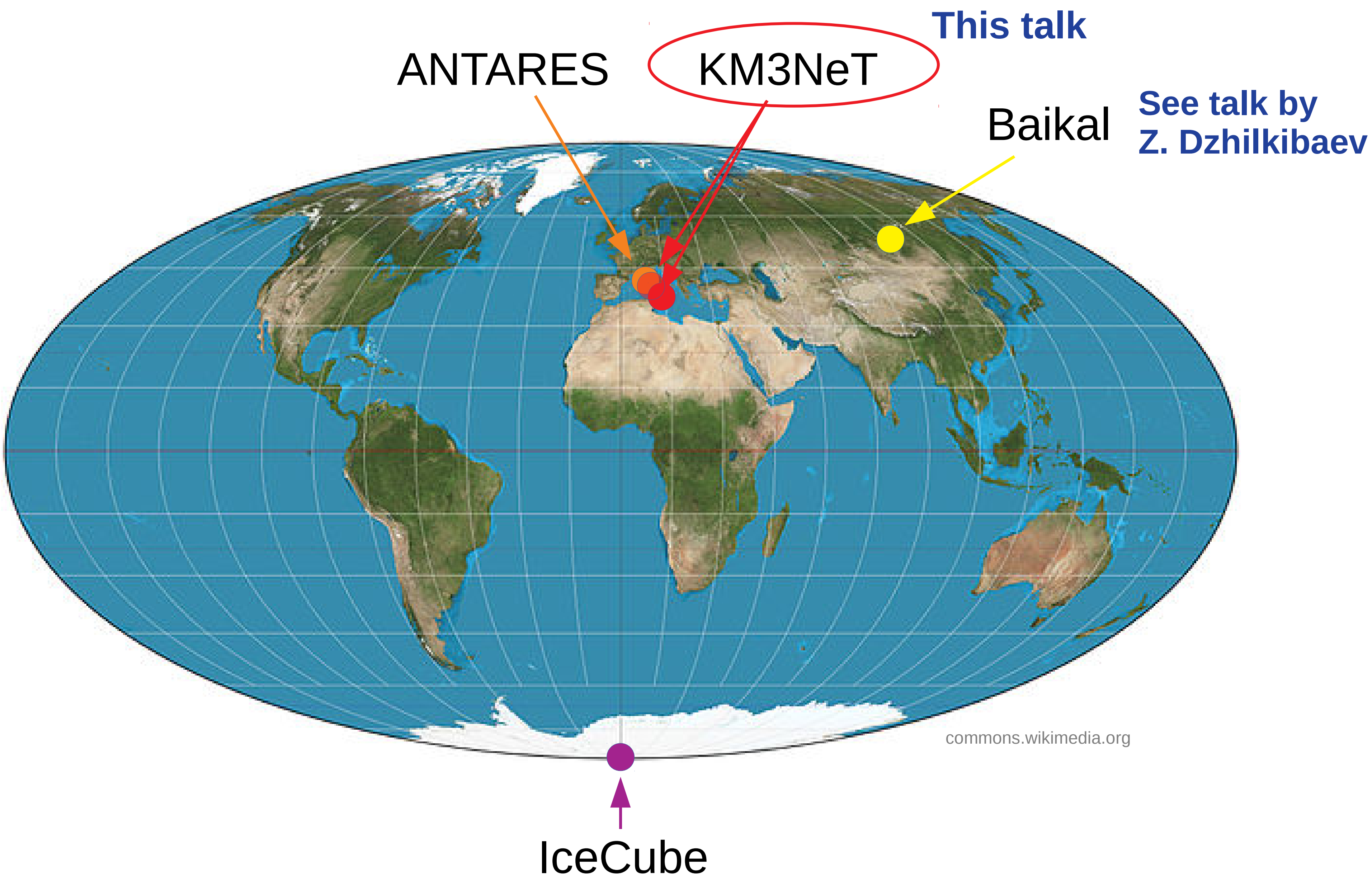
KM3NeT : neutrino oscillation and astroparticle research in the Mediterranean sea

Dmitry Zaborov
(CPPM / Aix-Marseille Univ., Marseille, France)
on behalf the KM3NeT collaboration

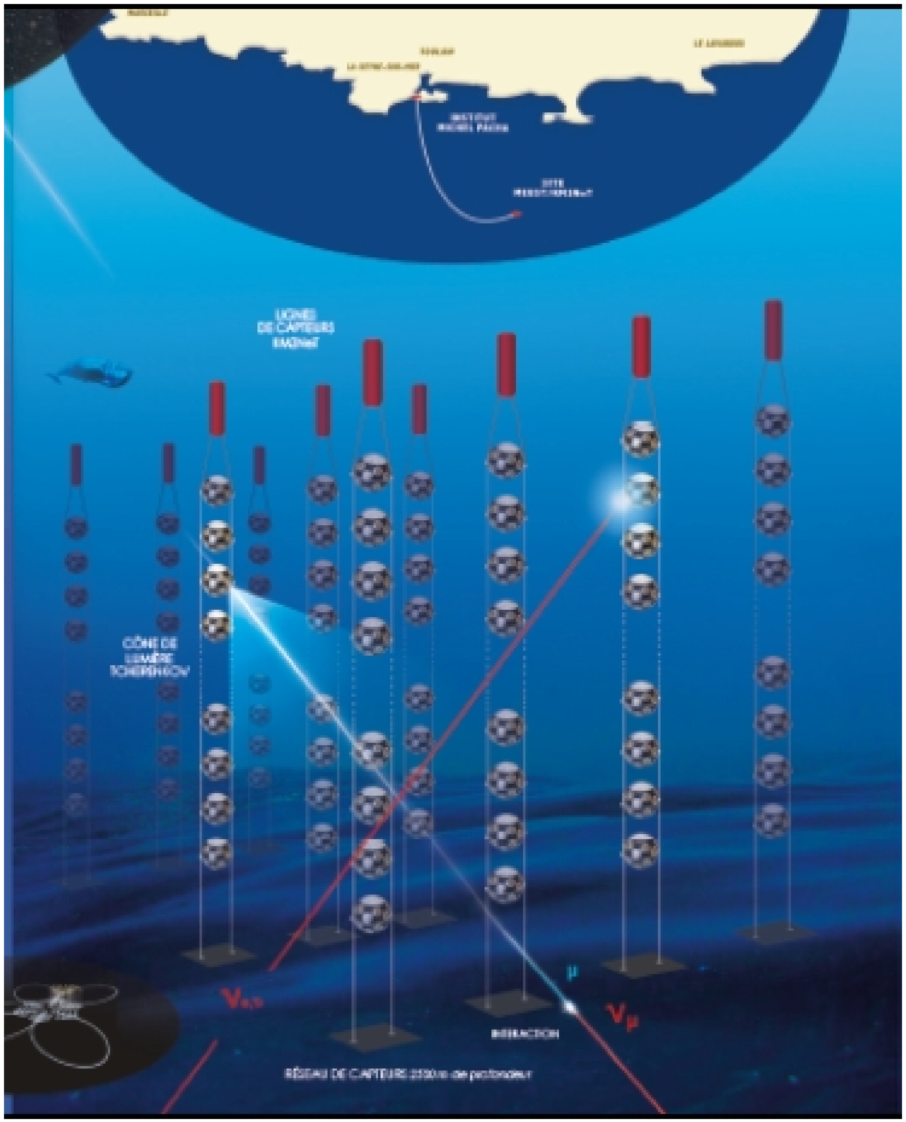


Contents

Neutrino telescopes around the world



Neutrino detection principle



Sea water
=
target material for
ν interactions
+
Cherenkov radiator

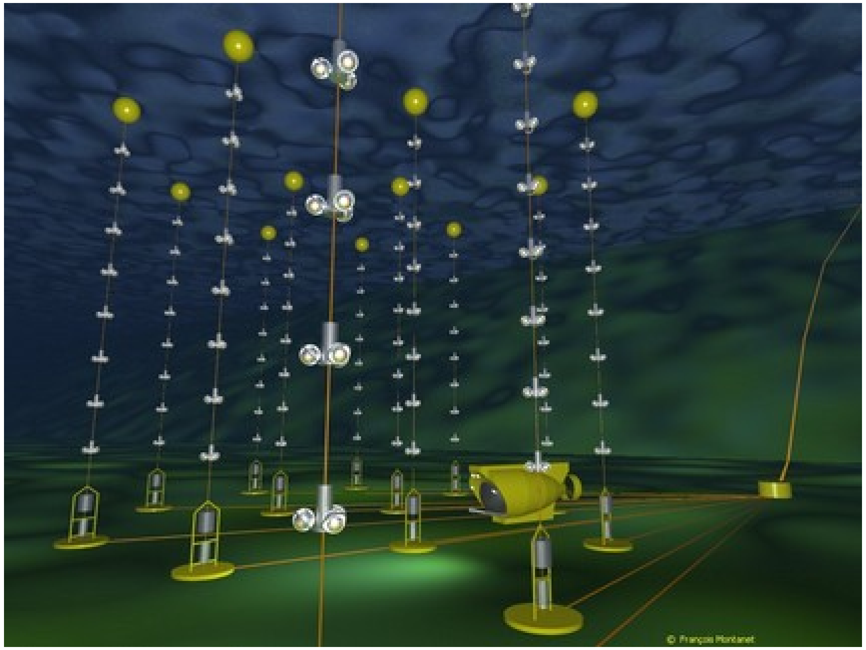
Mediterranean deep-sea water

Light **absorption** length: ≈ **60 m**

Light **scattering** length: ~ **260 m**

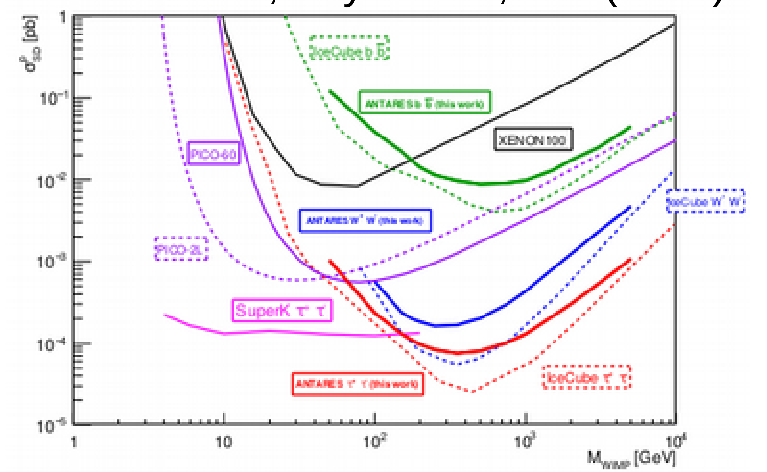
[Astropart. Phys. 23 (2005) 131-155]

ANTARES

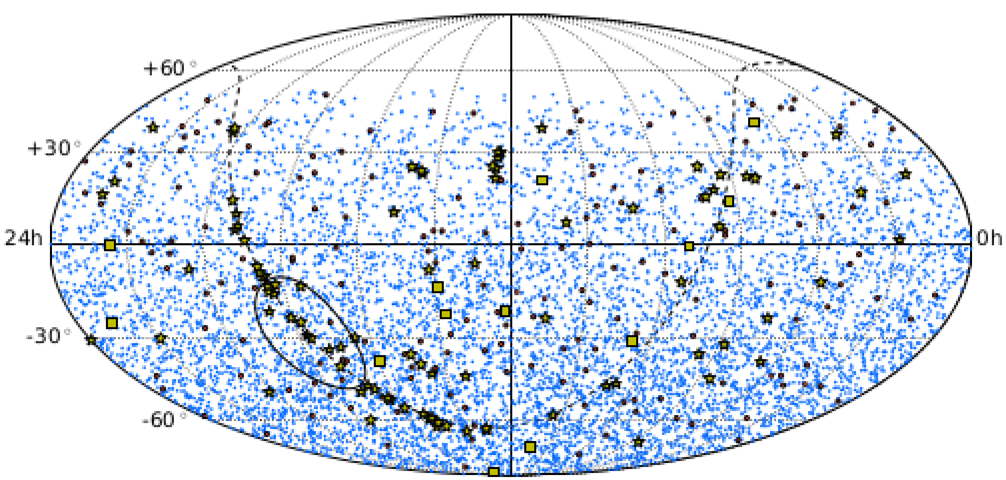


875 optical modules on 12 strings
Completed in 2008
Operating for **10 yr** now

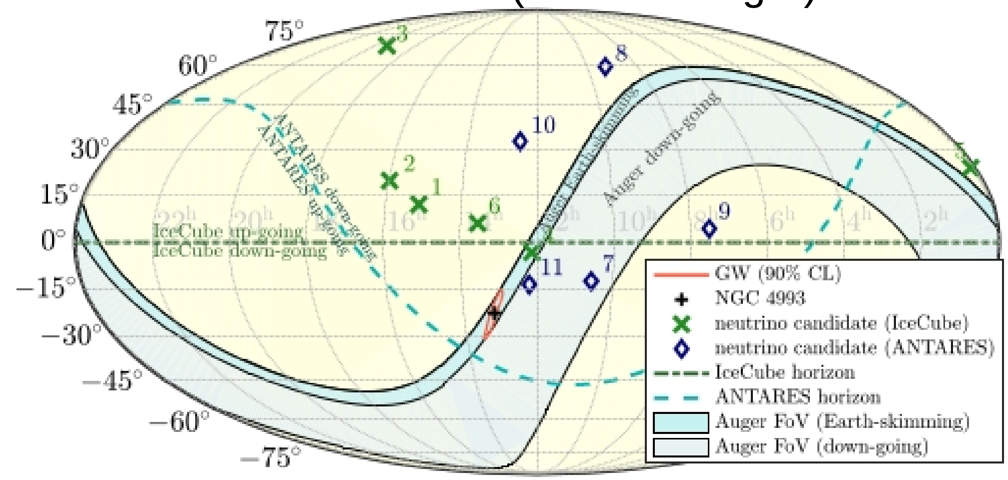
Dark matter limits, Phys.Let.B, 759 (2016) 69



All-flavour neutrino search, Phys. Rev. D 96, 082001 (2017)



GW 171807 (NS-NS merger)

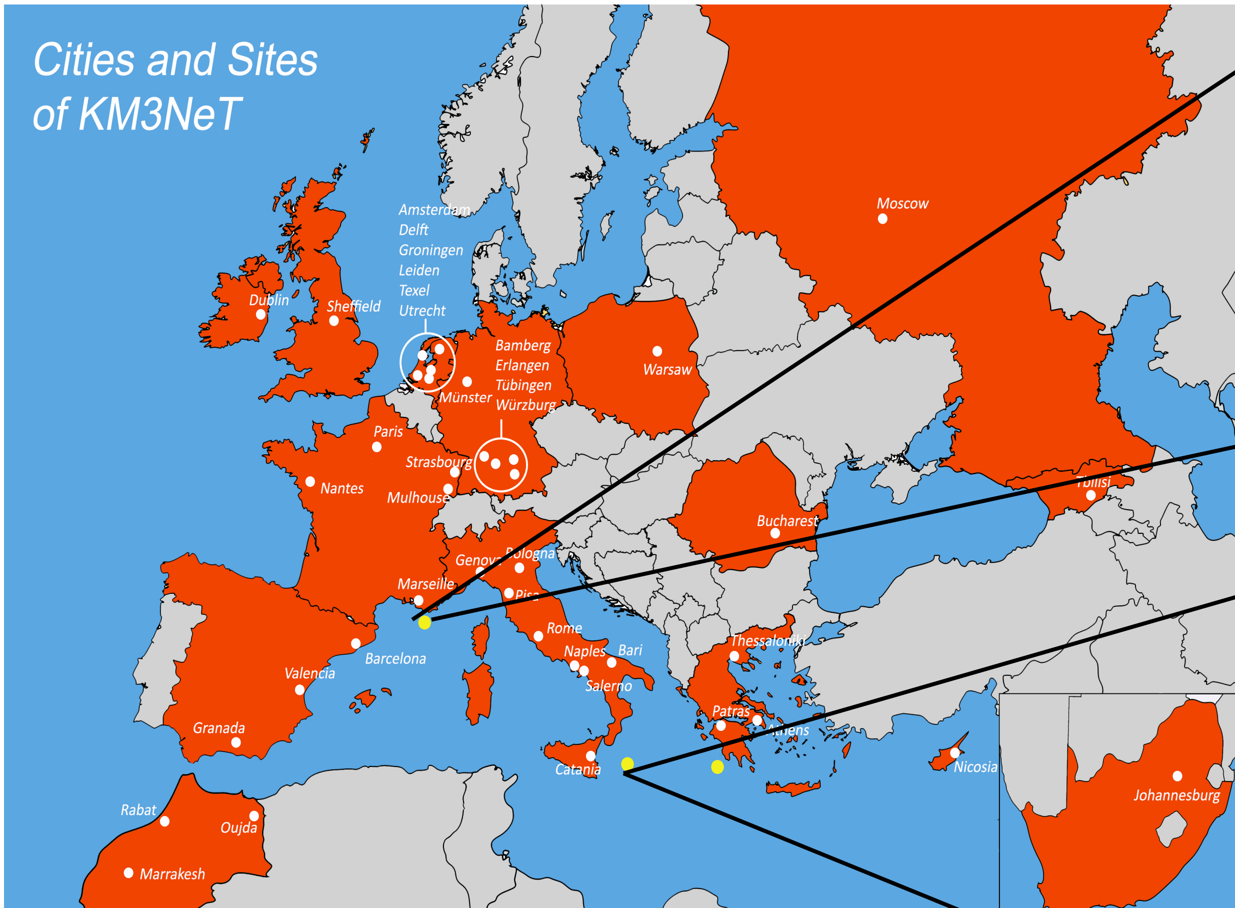


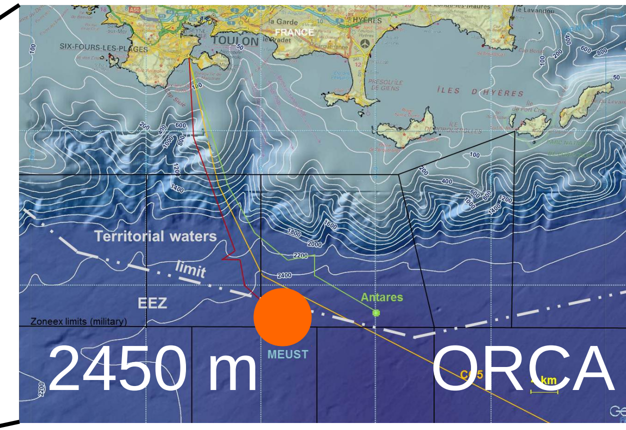
ApJL 850 (2017) L35

... and many other results

KM3NeT sites and participating countries

A distributed research infrastructure at two sites





Oscillation **R**esearch
with **C**osmics In the **A**byss

Astroparticle **R**esearch
with **C**osmics In the **A**byss

* KM3NeT = **km**^{3} **N**eutrino **T**elescope

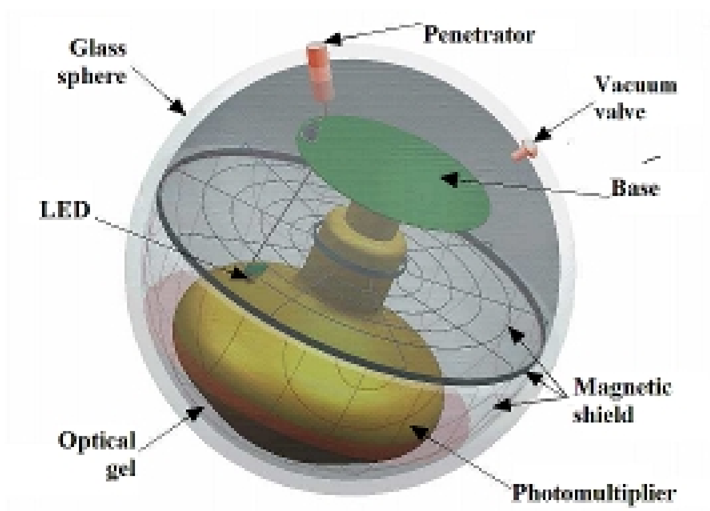
Single Collaboration, Single Technology

From ANTARES to KM3NeT: Optical Module

ANTARES Optical Module (OM)

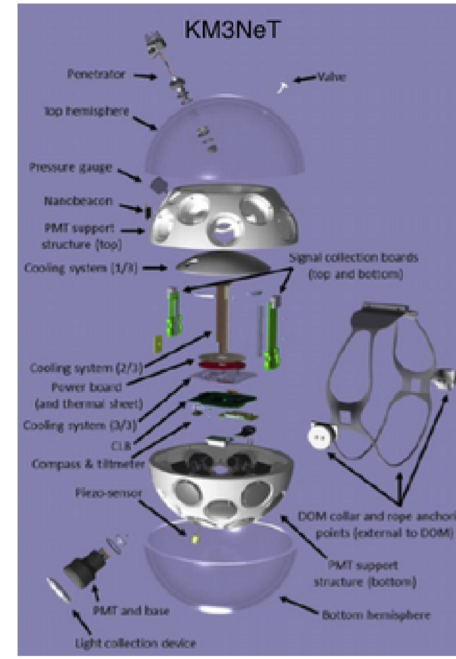
- 10” PMT
- HV base
- LED

⟵ 17” ⟶



KM3NeT Digital Optical Module (DOM)

⟵ 17” ⟶



- 31 x 3” PMTs
- PMT HV
- LED & piezo
- FPGA readout
- White Rabbit
- DWDM

photocathode area similar to a 17” PMT

- ✔ Uniform angular coverage
- ✔ Directional information
- ✔ Digital photon counting
- ✔ All data to shore

From ANTARES to KM3NeT: detector storey

ANTARES storey

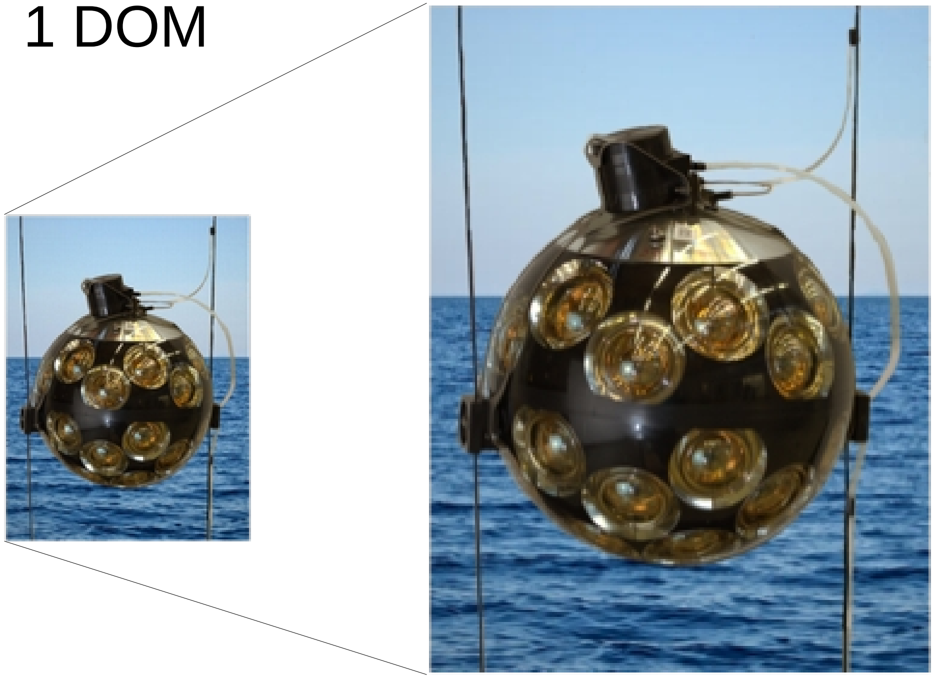
3 OMs

electronics container (Ti)

frame (Ti)

KM3NeT storey

1 DOM



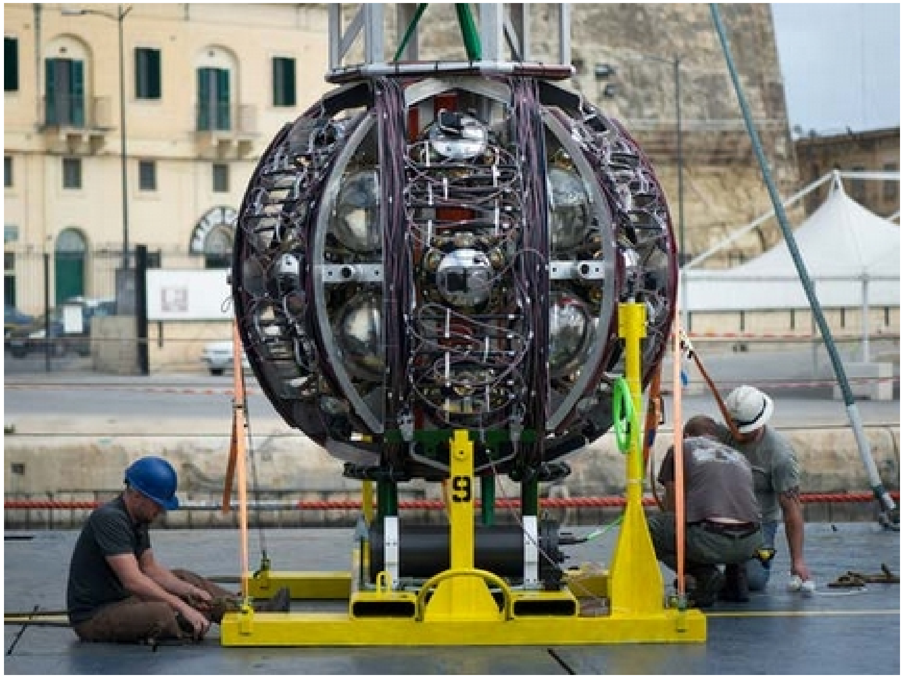
Sensitivity ~ 2x - 3x ANTARES OM

Compact structure minimizes bio-luminescence (stimulated by drag)

From ANTARES to KM3NeT: detector string

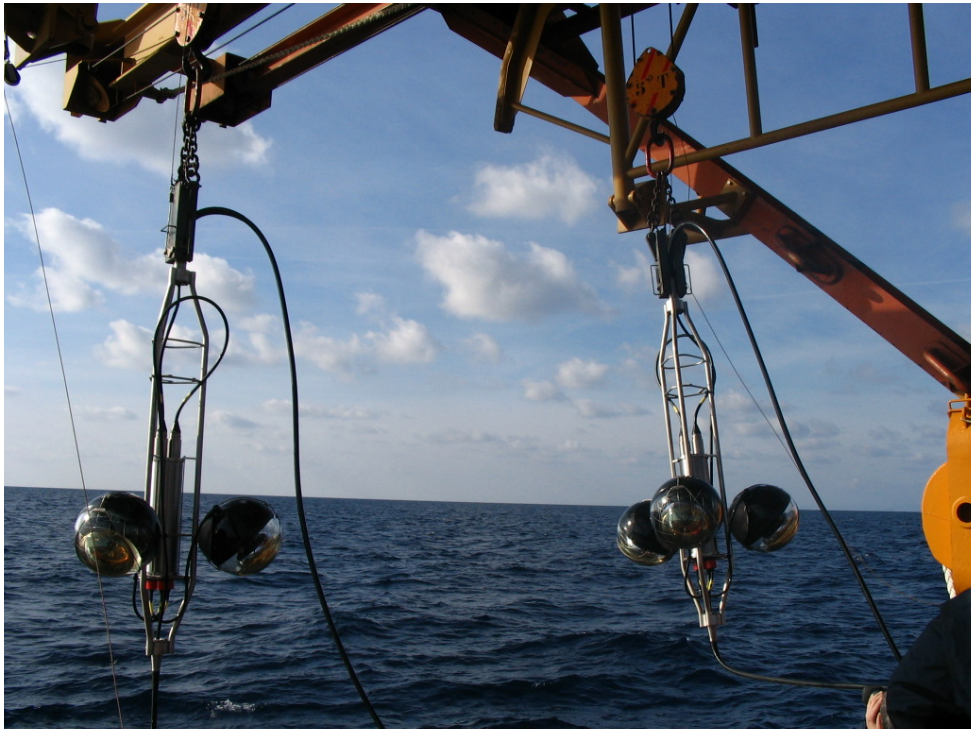
ANTARES string

KM3NeT Detection Unit
(DU, string)

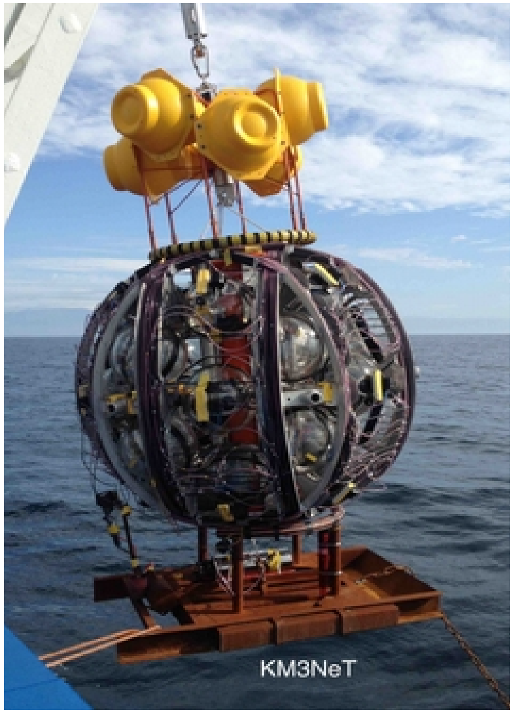


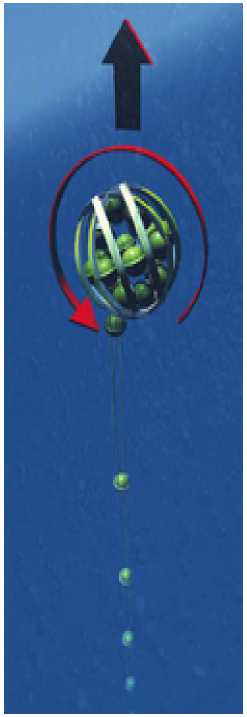
From ANTARES to KM3NeT: deployment method

ANTARES



KM3NeT

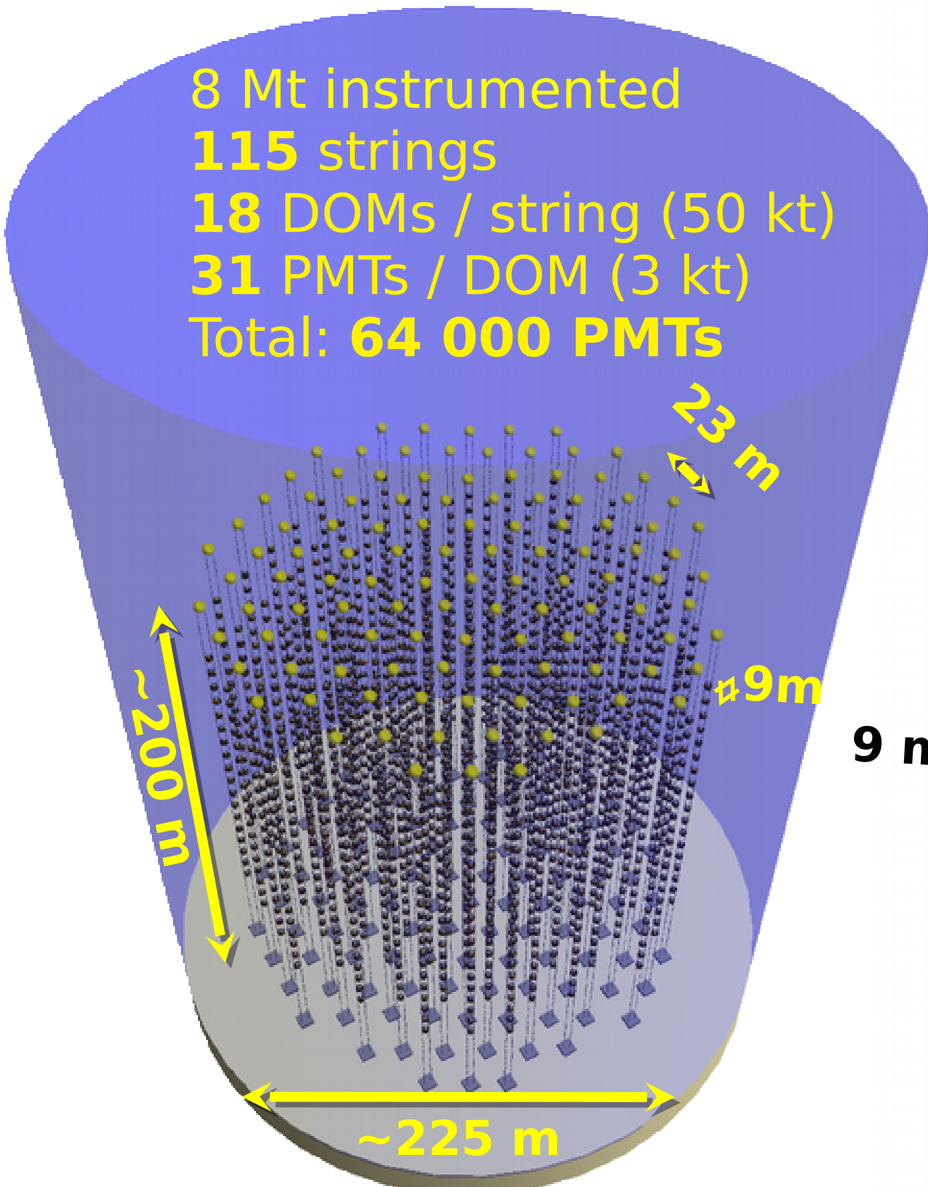




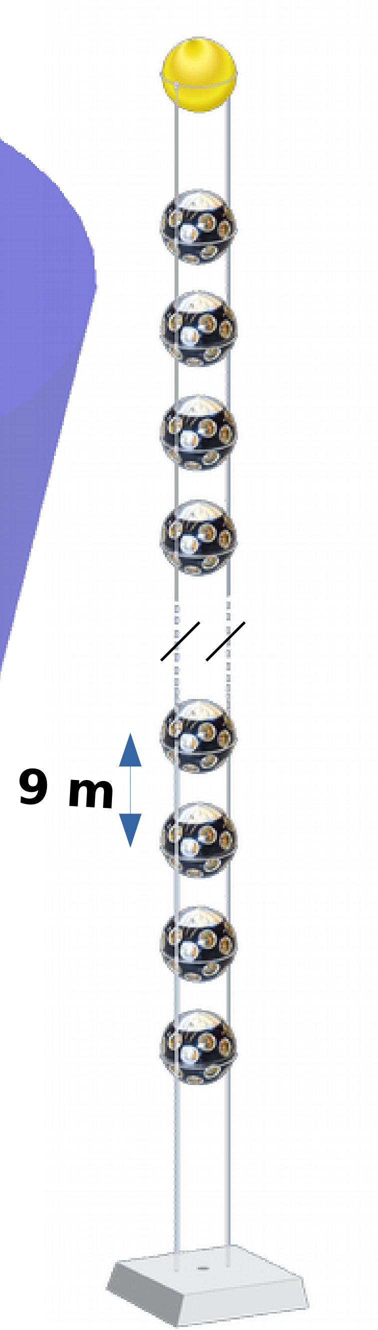
Watch https://www.youtube.com/watch?v=tR8jwgG6uzk

- Rapid deployment
- Autonomous unfurling
- Multiple DUs can be deployed in one sea operation

KM3NeT - ORCA



Depth=2450 m



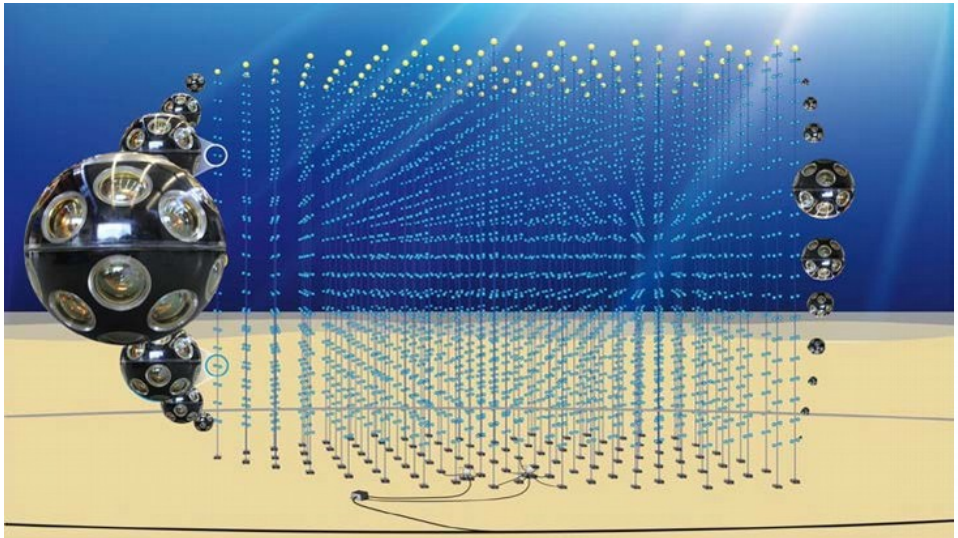
Digital Optical Module

← 17” →

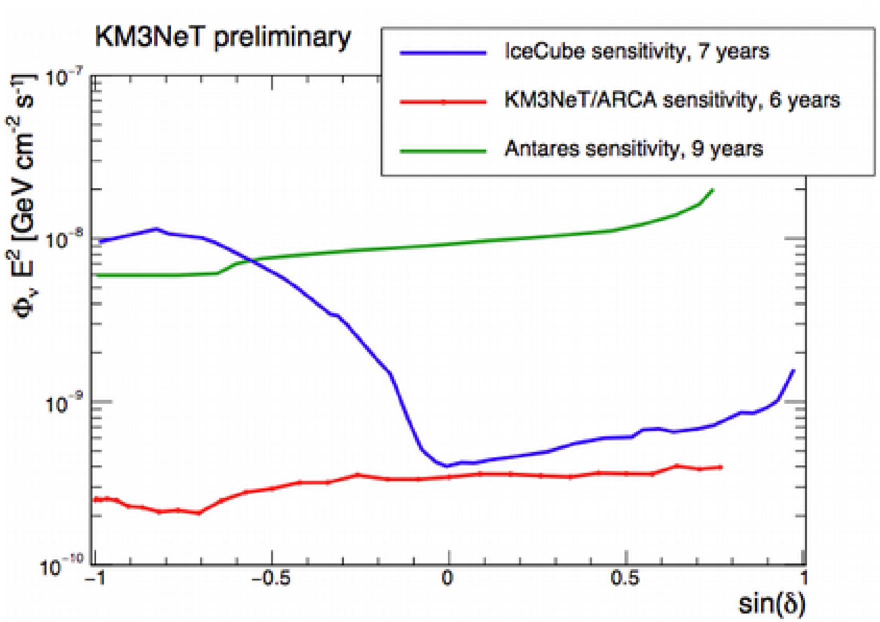
Key mission: determine neutrino mass hierarchy

Optical background (mainly ^{40}K): 10 kHz/PMT

KM3NeT - ARCA



Volume : 1 Gt



2 x 115 strings
18 DOMs / string
31 PMTs / DOM
Total: **128 000 PMTs (3”)**

Vertical spacing: 36 m
Horizontal spacing: 90 m

Mission: neutrino astronomy

Angular resolution ~ 0.2 deg
(tracks, E > 10 TeV)

Energy resolution up to 5%
(cascades)

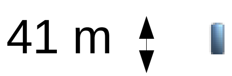
Sensitivity similar to IceCube,
but covering both sky hemispheres

Instrumented volume

Smaller but denser instruments are best for low energies (low amount of light)

Larger but sparser instruments are best for high energies (low fluxes)

SuperK
11100 PMTs
50 kt

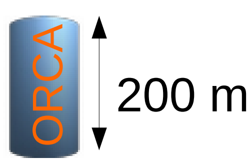


MeV - GeV

Solar & atm. ν

operating for 20 yr

KM3NeT-**ORCA**
2000 OMs
8 Mt

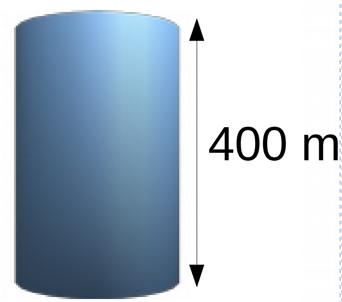


E > 3 GeV

atm. ν

under construction

ANTARES
885 PMTs
20 Mt



E > 20 GeV

astrophysical and atm. ν

operating for 10 yr

KM3NeT-**ARCA**
4000 OMs (128 000 PMTs)
1 Gt

E > 100 GeV

astrophysical ν

under construction

IceCube & Baikal-GVD have similar size

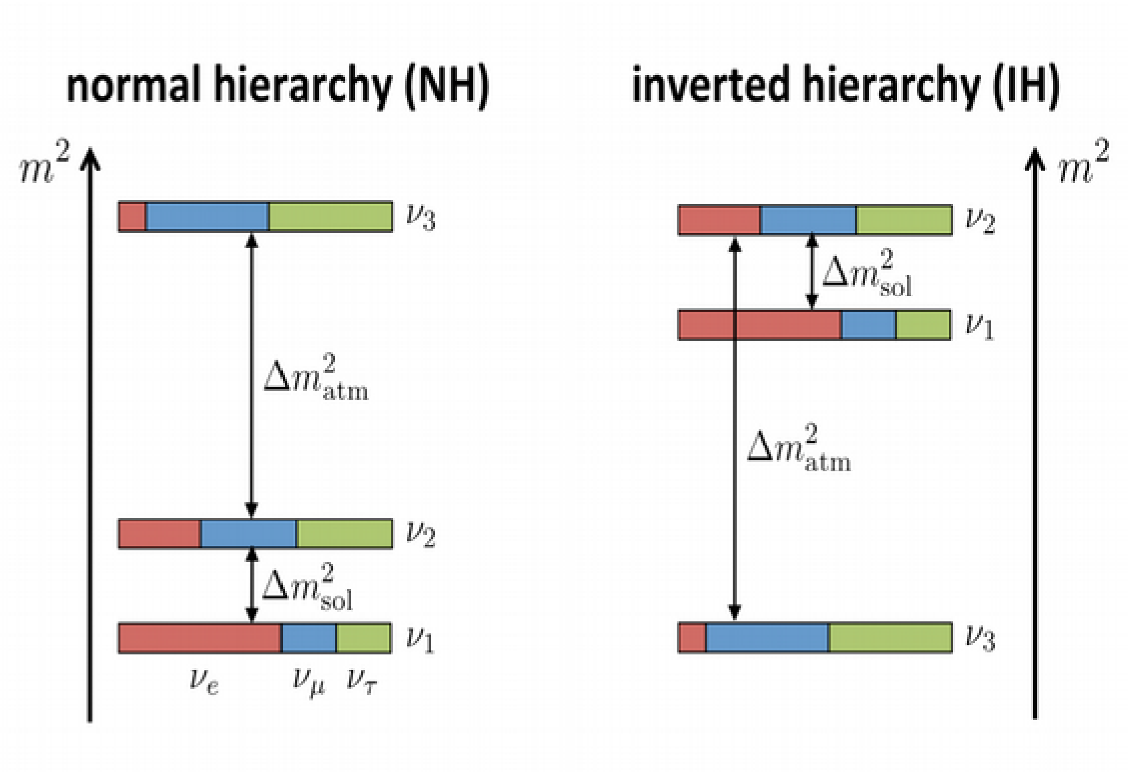
1) Introduction to KM3NeT

2) KM3NeT / ORCA

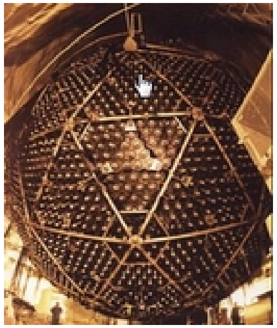
3) Current status

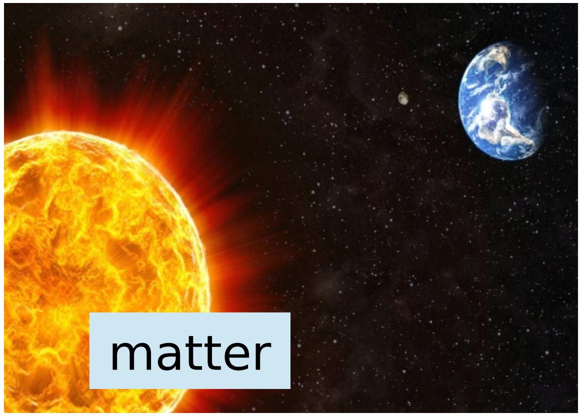
4) Potential of a neutrino beam from Protvino to ORCA

Neutrino mass hierarchy (ordering)

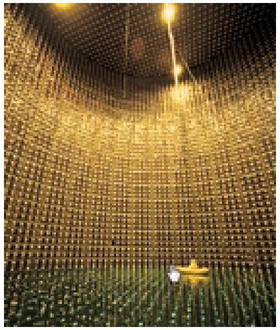


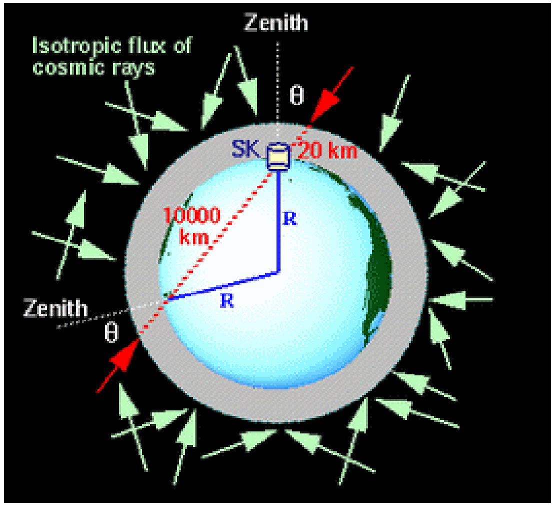
Δm^2_{solar} : sign known





$\Delta m^2_{atmospheric}$: sign unknown





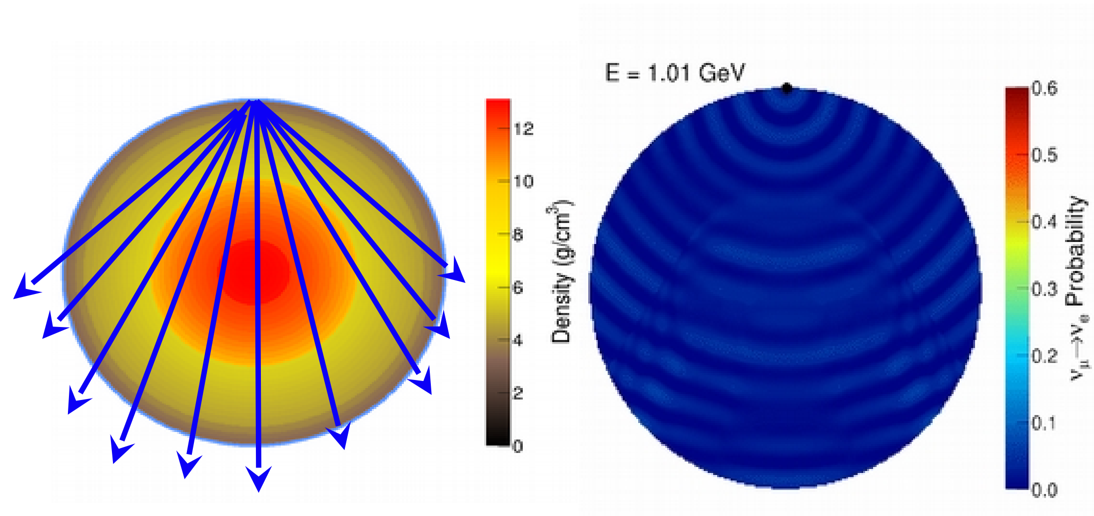
Important for theory, 0νββ, ...

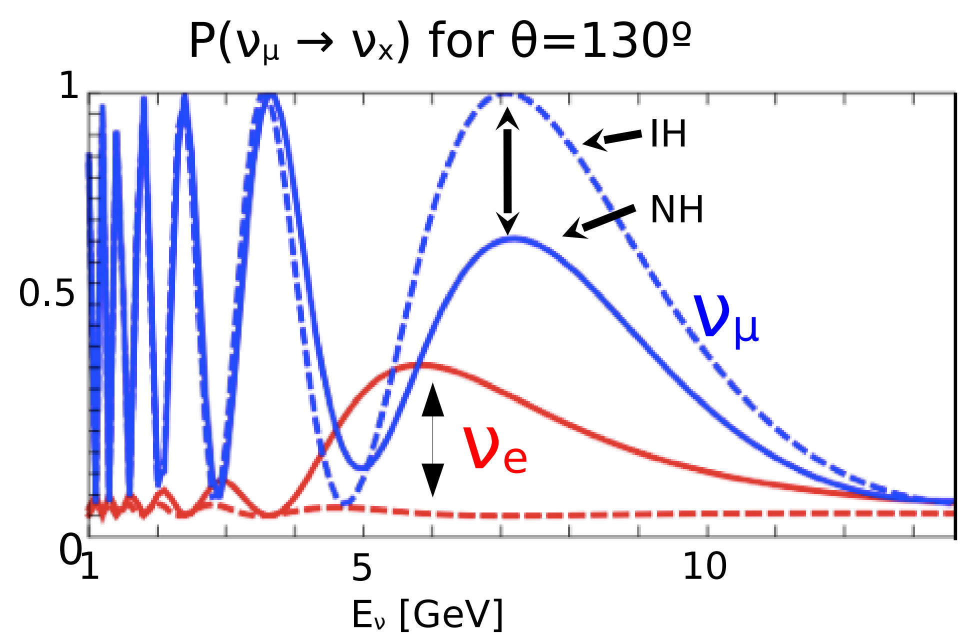
Mass hierarchy with atmospheric neutrino

- Known composition (ν_e, ν_μ)
- Wide range of baselines (50 - 12800 km) and energies (GeV - PeV)
- Oscillation affected by matter (mass hierarchy-dependent): maximum difference IH / NH at θ=130° (7645 km) and E_ν = 7 GeV
- Opposite effect on anti-neutrinos: IH (ν) ≈ NH(anti-ν) but differences in flux and cross-section:

  $\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\text{anti-}\nu)$

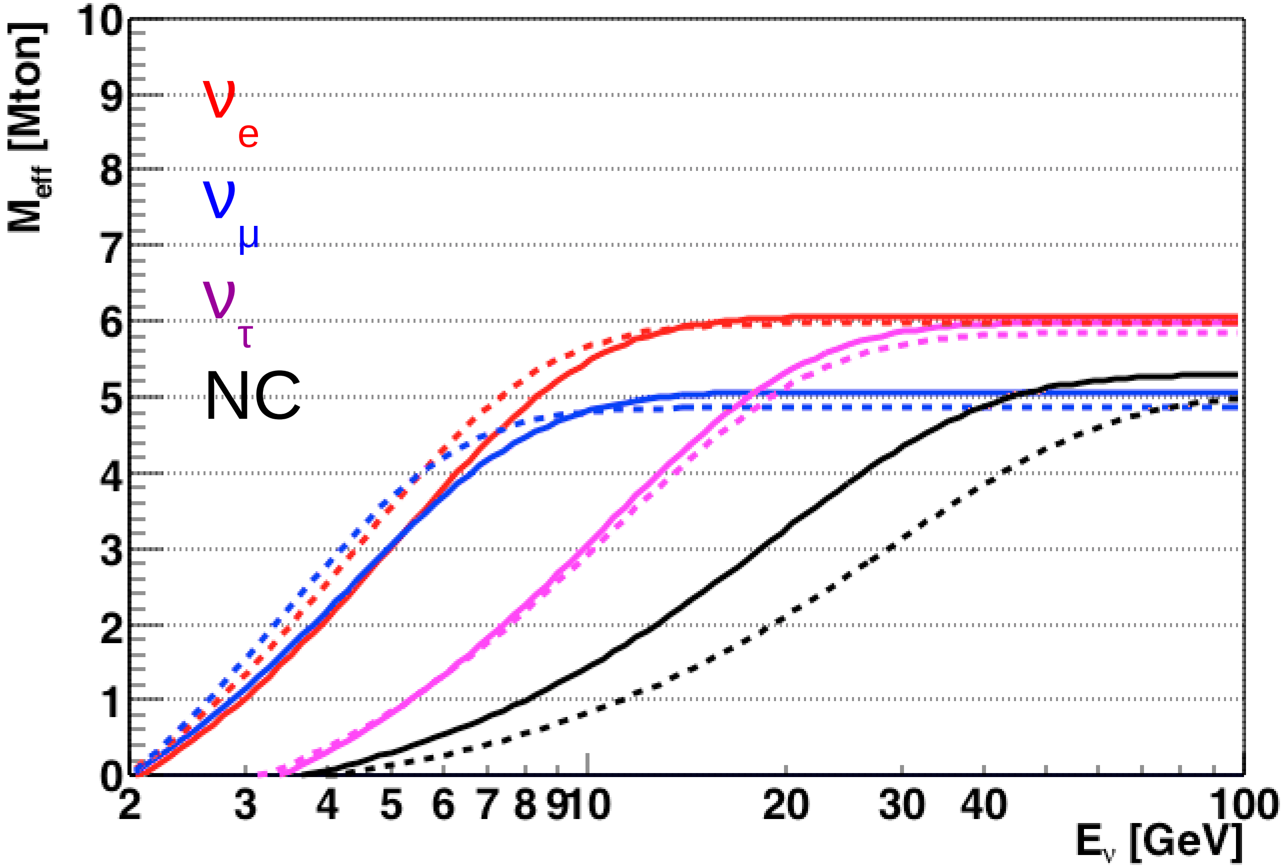
  $\sigma(\nu) \approx 2\sigma(\text{anti-}\nu)$ at low energies





ORCA effective mass

After triggering, atmospheric muon rejection and containment cuts



Events/yr:

ν_e CC: 17,300

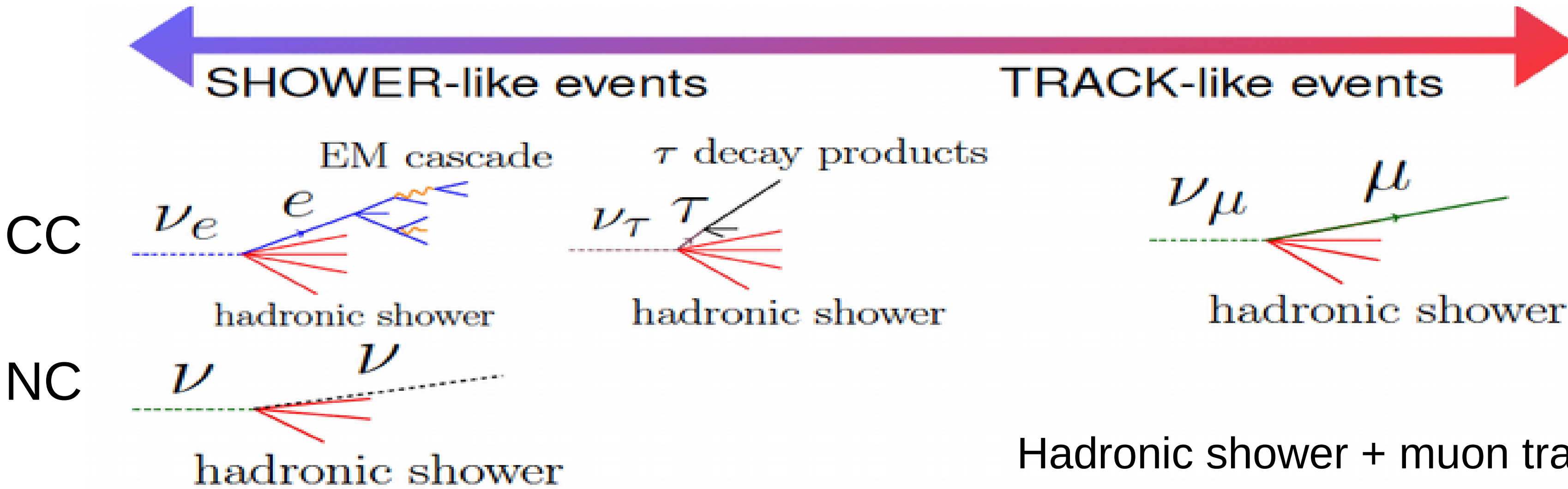
ν_μ CC: 24,800

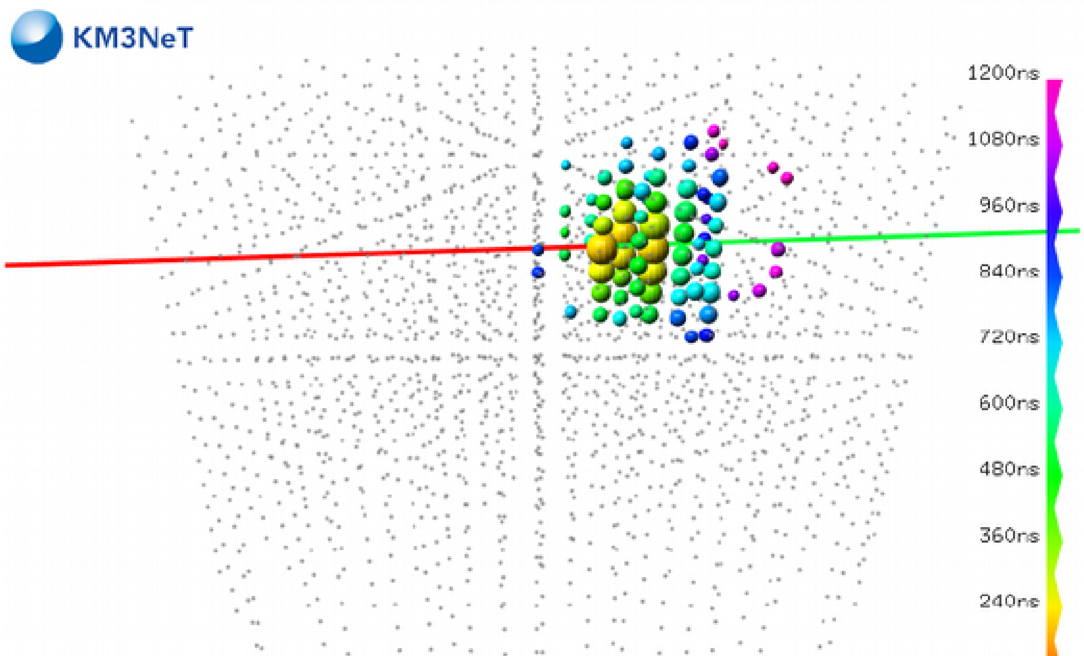
ν_τ CC:3,100

NC: 5,300

- Energy threshold determined by DOM spacing
- 1 Mton @ 3 GeV
- 6 Mton @ 10 GeV

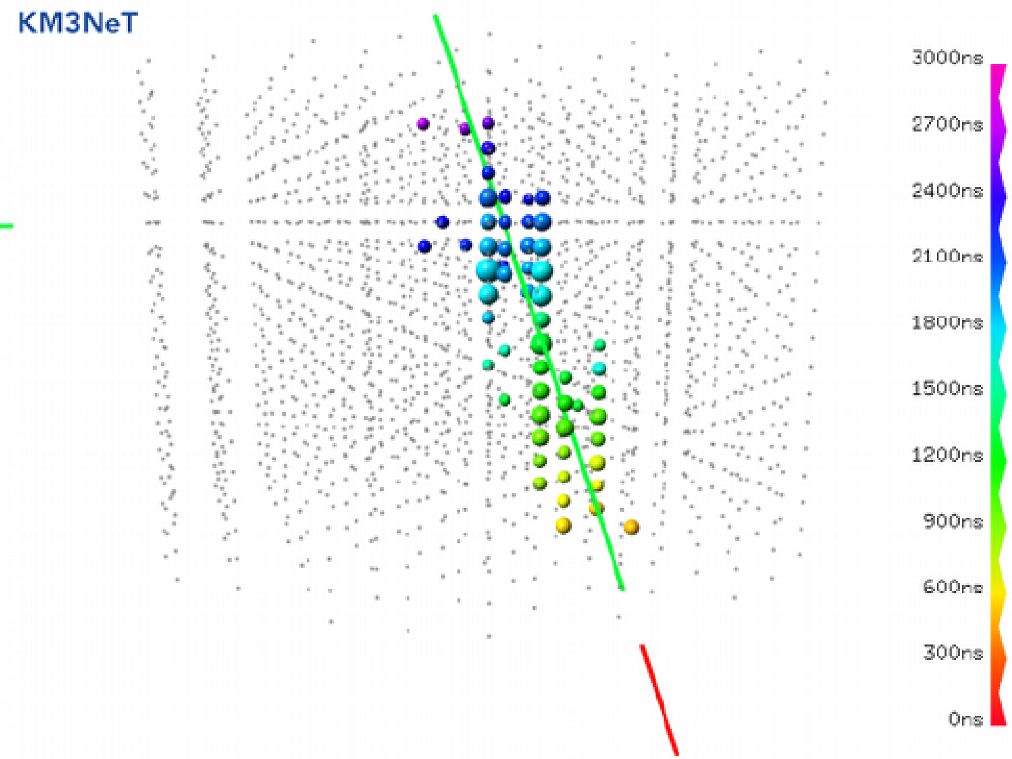
Particle ID





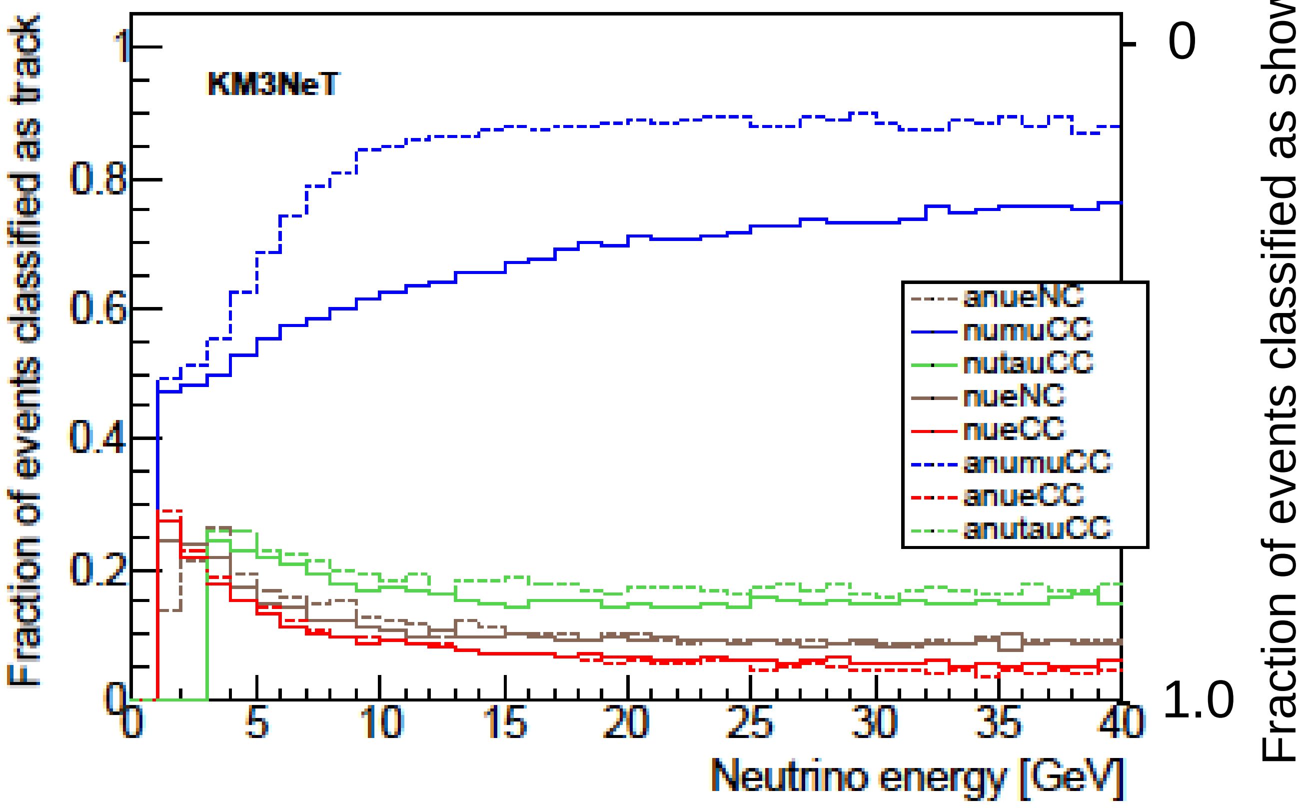
ARCA simulated event (ORCA similar)

Hadronic shower + muon track



Particle ID performance

Track / Shower event classification

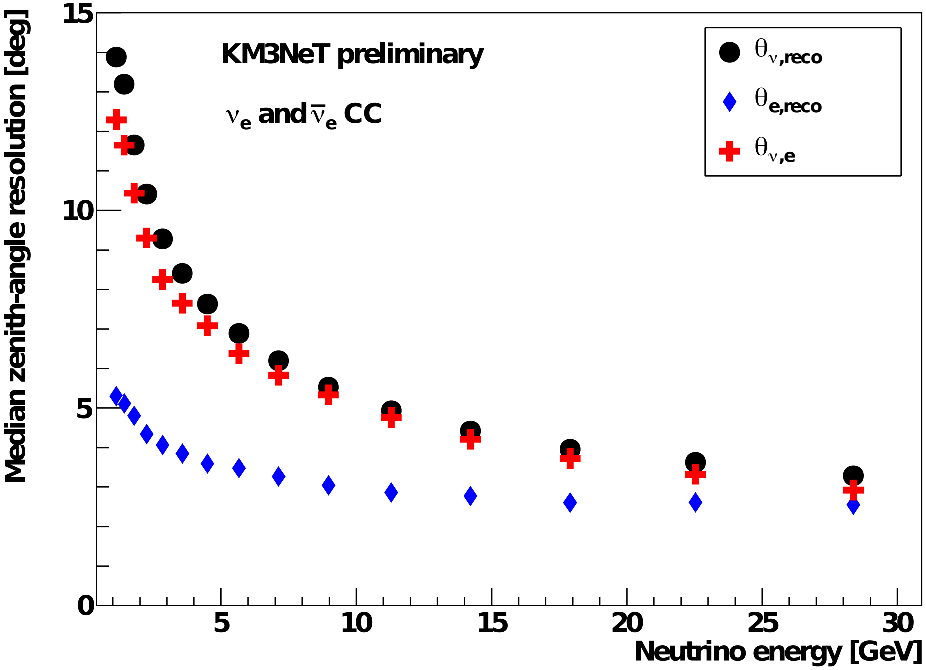


At 10 GeV:

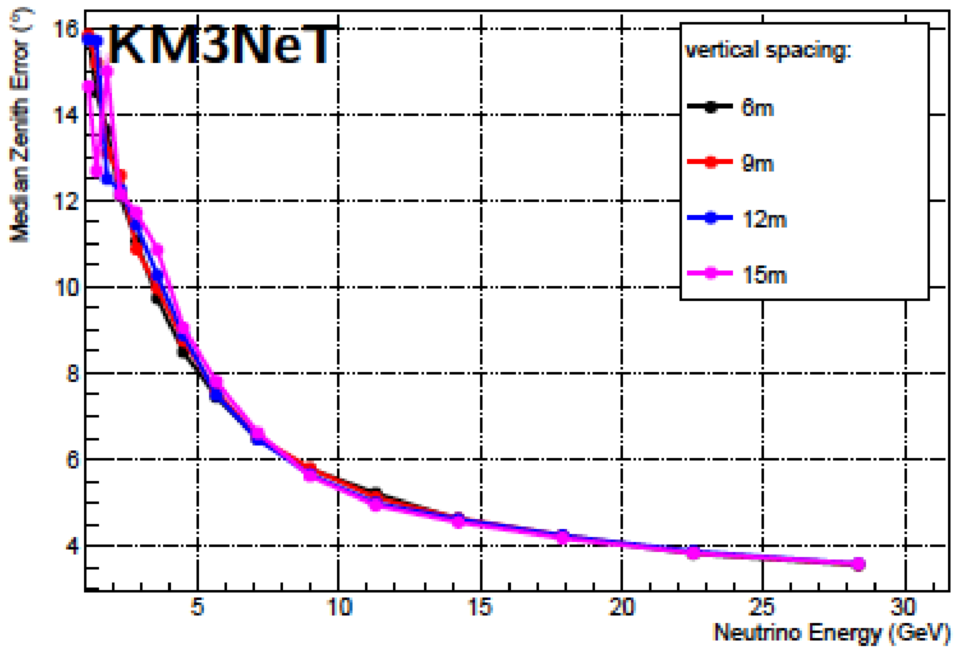
- 90% correct ID of ν_e^{CC}
- 70% correct ID of ν_μ^{CC}

Zenith angle resolution

Showers



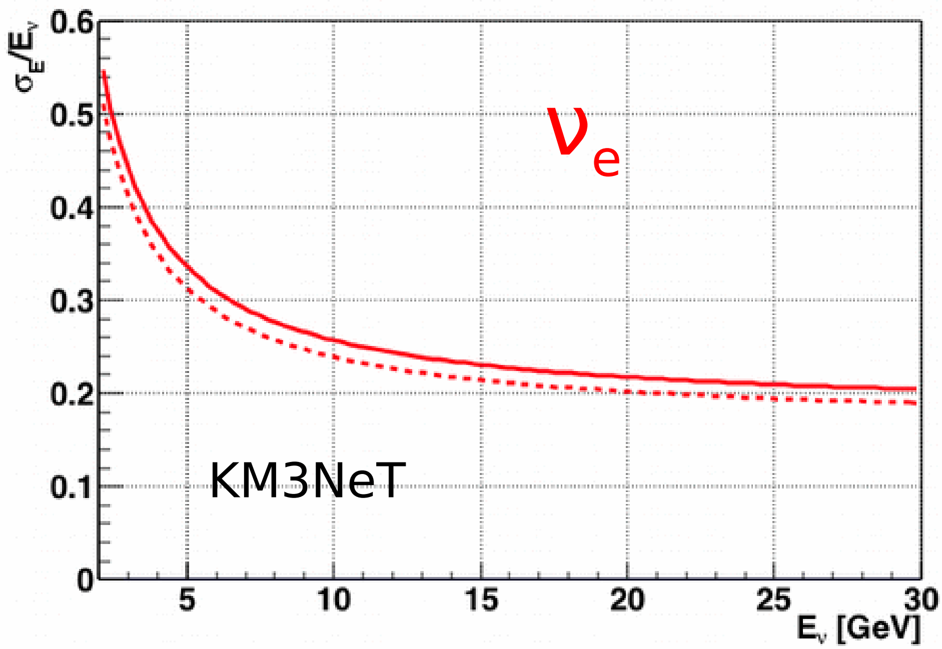
Tracks

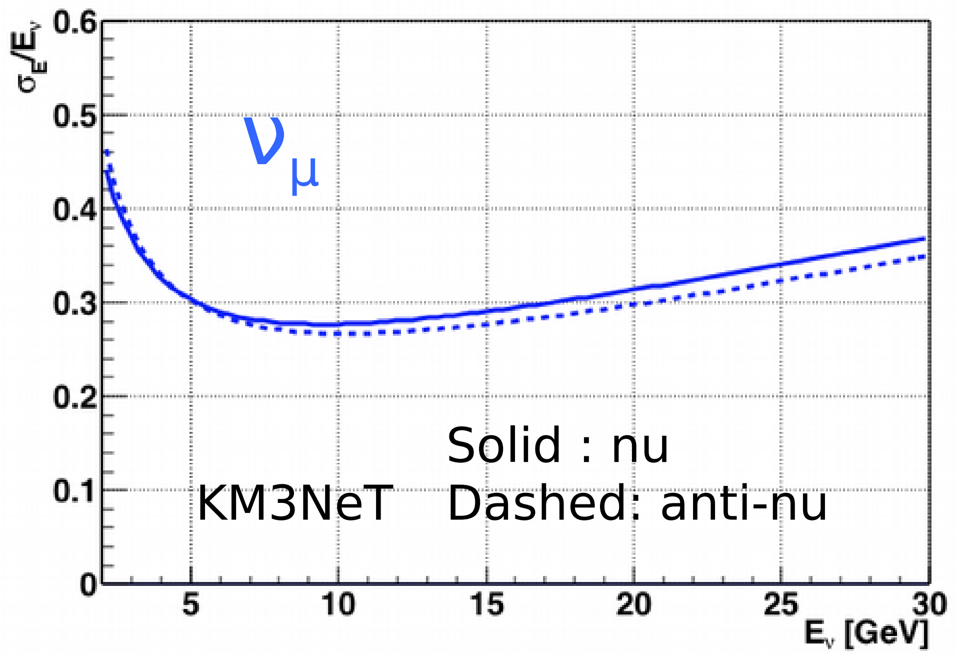


~ 5° error on zenith for 10 GeV neutrinos for both track and shower channels

Limited by interaction kinematics (neutrino – lepton angle)

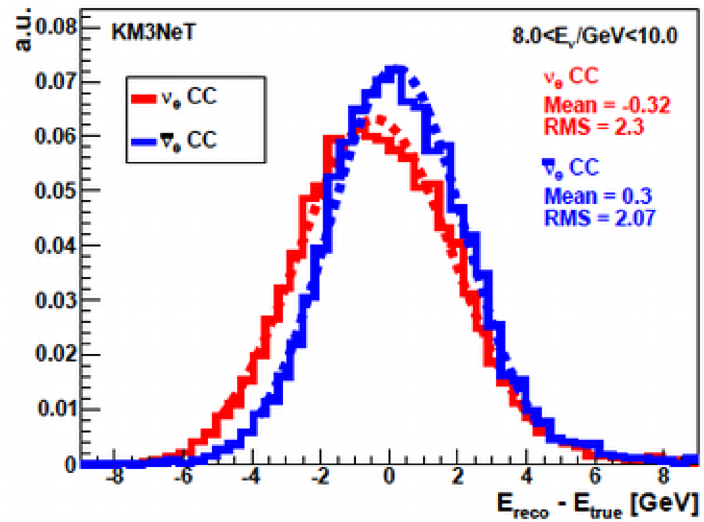
Energy resolution





Energy resolution better than 30% in relevant range

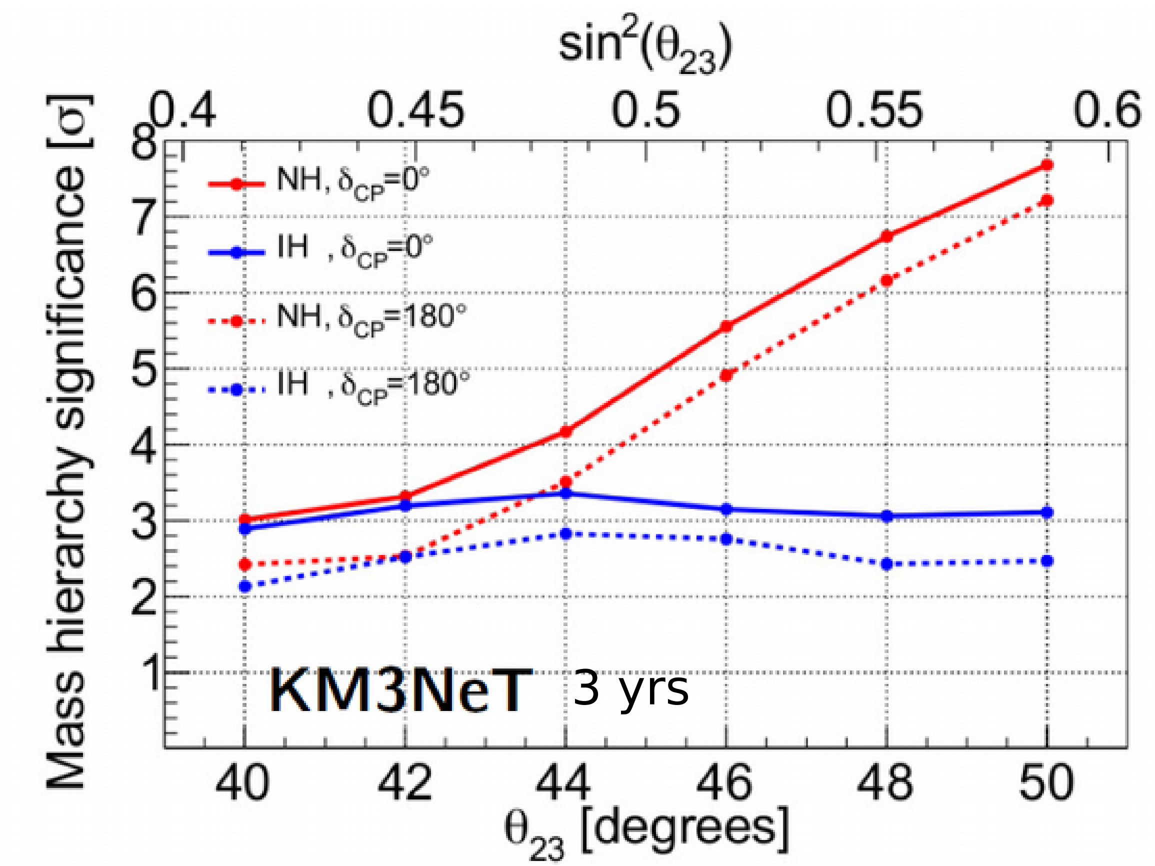
Distribution close to Gaussian



Sensitivity to Mass Ordering

Systematics

parameter	true value distr.	initial value distr.	treatment	prior
overall flux factor	1	$\mu = 1, \sigma = 0.1$	fitted	yes
NC scaling	1	$\mu = 1, \sigma = 0.05$	fitted	yes
$\nu/\bar{\nu}$ skew	0	$\mu = 0, \sigma = 0.03$	fitted	yes
μ/e skew	0	$\mu = 0, \sigma = 0.05$	fitted	yes
energy slope	0	$\mu = 0, \sigma = 0.05$	fitted	yes



Worst case: 3 sigma in 4 years

Best case: > 5 sigma in 3 years (NH & upper octant of θ_{23})

Recent T2K result on θ_{23}:

$$\sin^2\theta_{23} = 0.55^{+0.05}_{-0.09}\ (0.55^{+0.05}_{-0.08})$$

(arXiv:1707.01048)

Other ORCA science topics

- Precision measurement of neutrino mixing parameters (2% on Δm^2_{23} and 4-10% on $\sin^2\theta_{23}$)
- Sterile neutrino & non-standard interactions
- Earth tomography and composition
- Supernova monitoring
- Indirect search for Dark Matter
- Low energy (GeV-TeV) neutrino astrophysics

1) Introduction to KM3NeT

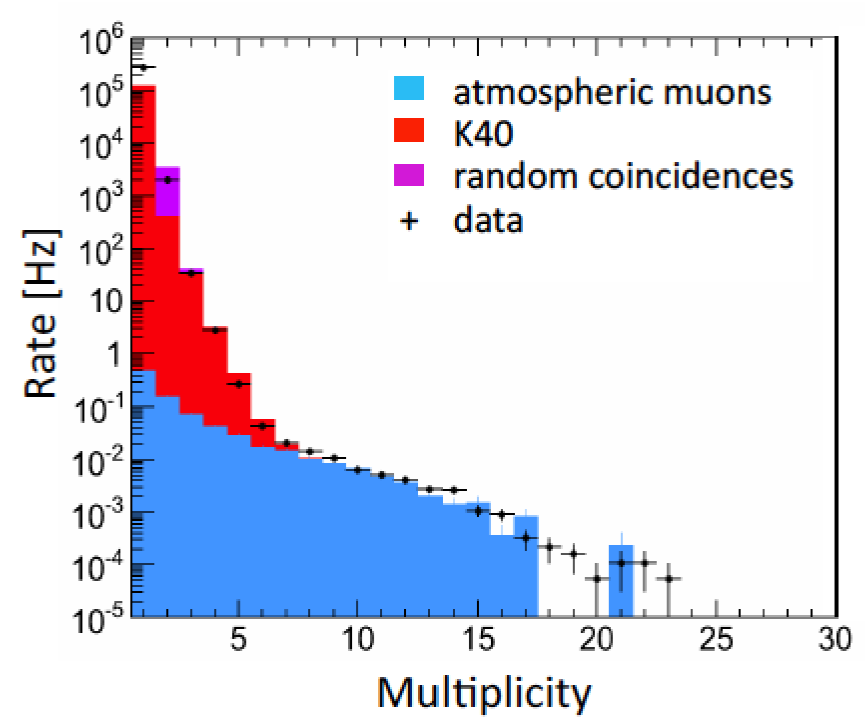
2) KM3NeT / ORCA

3) Current status

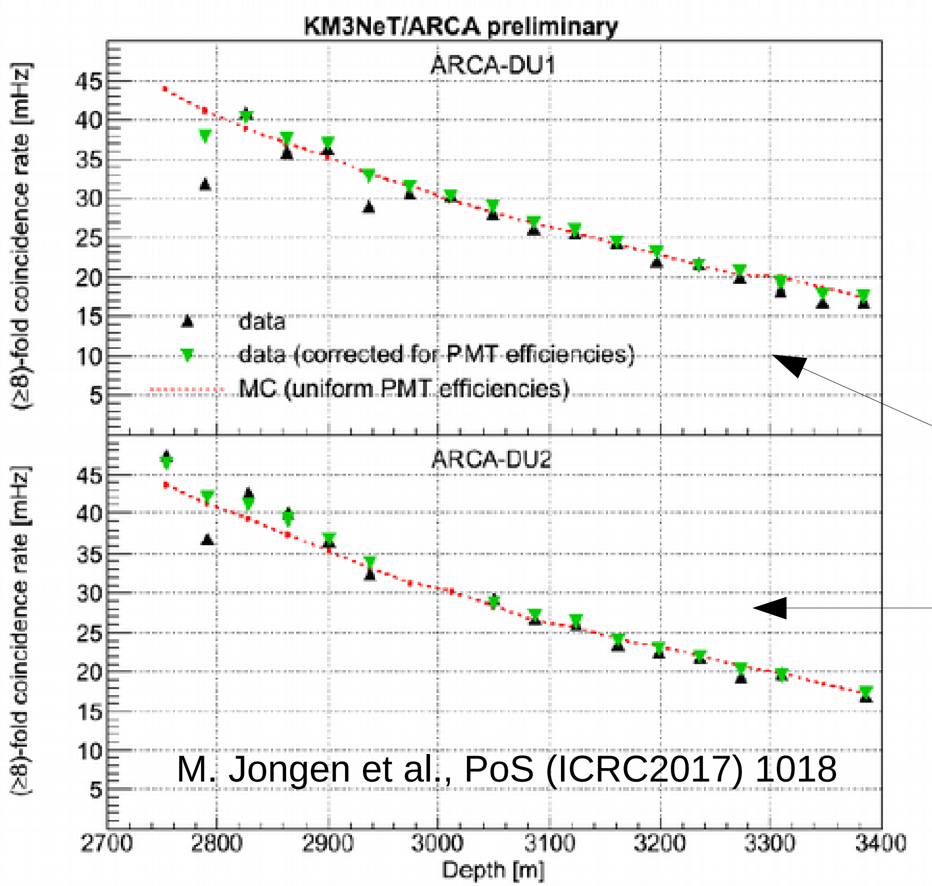
4) Potential of a neutrino beam from Protvino to ORCA

News from first ARCA Detection Units

- Optical Module at Antares site, April 2013
  - Muons from a single DOM,
    Eur. Phys. J. C (2014) 74:3056
- Mini string (3 DOMs) at ARCA site, May 2014
  - Track reconstruction - Eur. Phys. J. C (2016) 76:54 -- Cover



event rate (atmos-pheric muons)

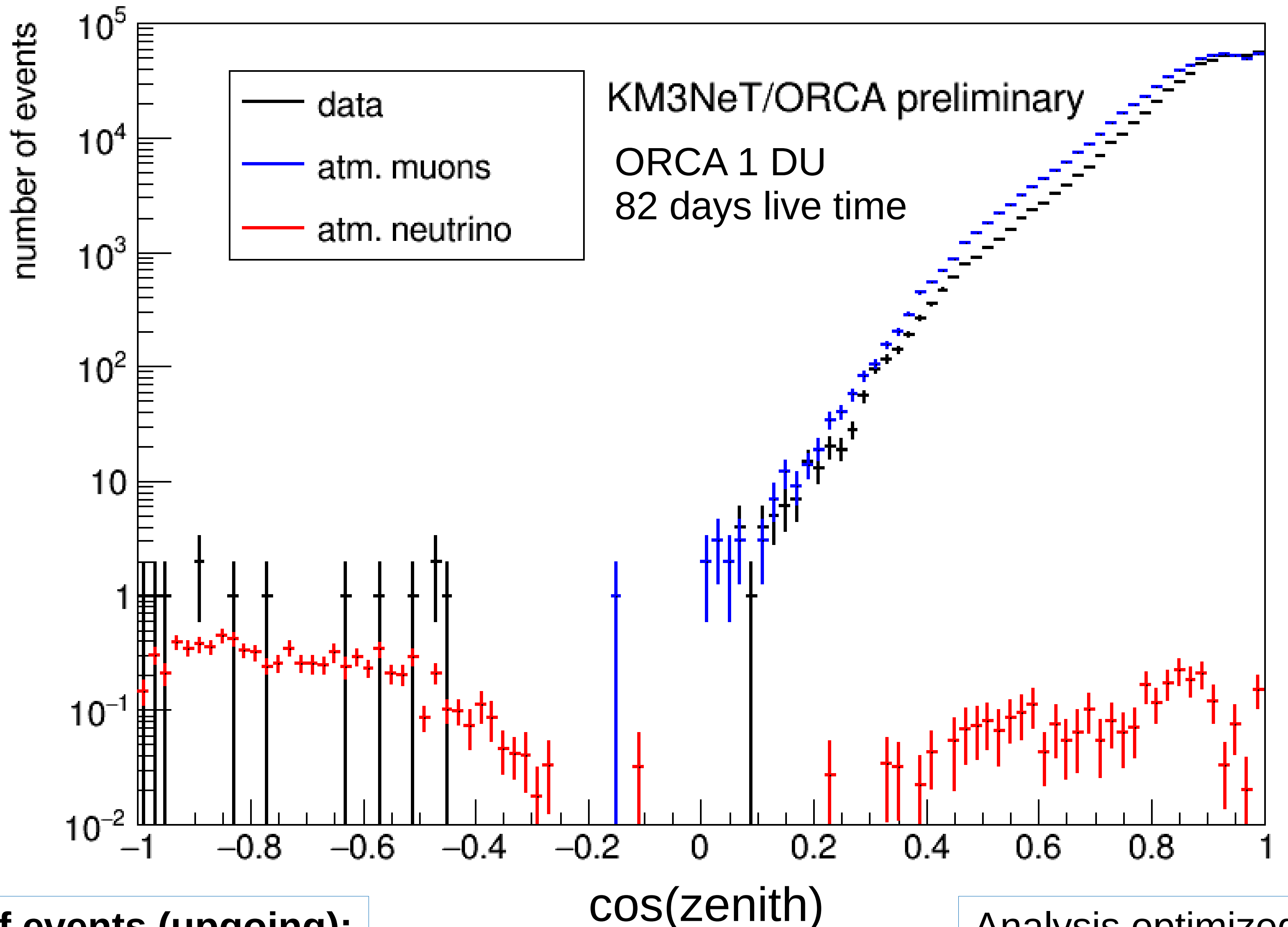


depth

- First full Detection Unit at ARCA site, Dec 2015
- One more DU added in May 2016

News from the first ORCA Detection Unit

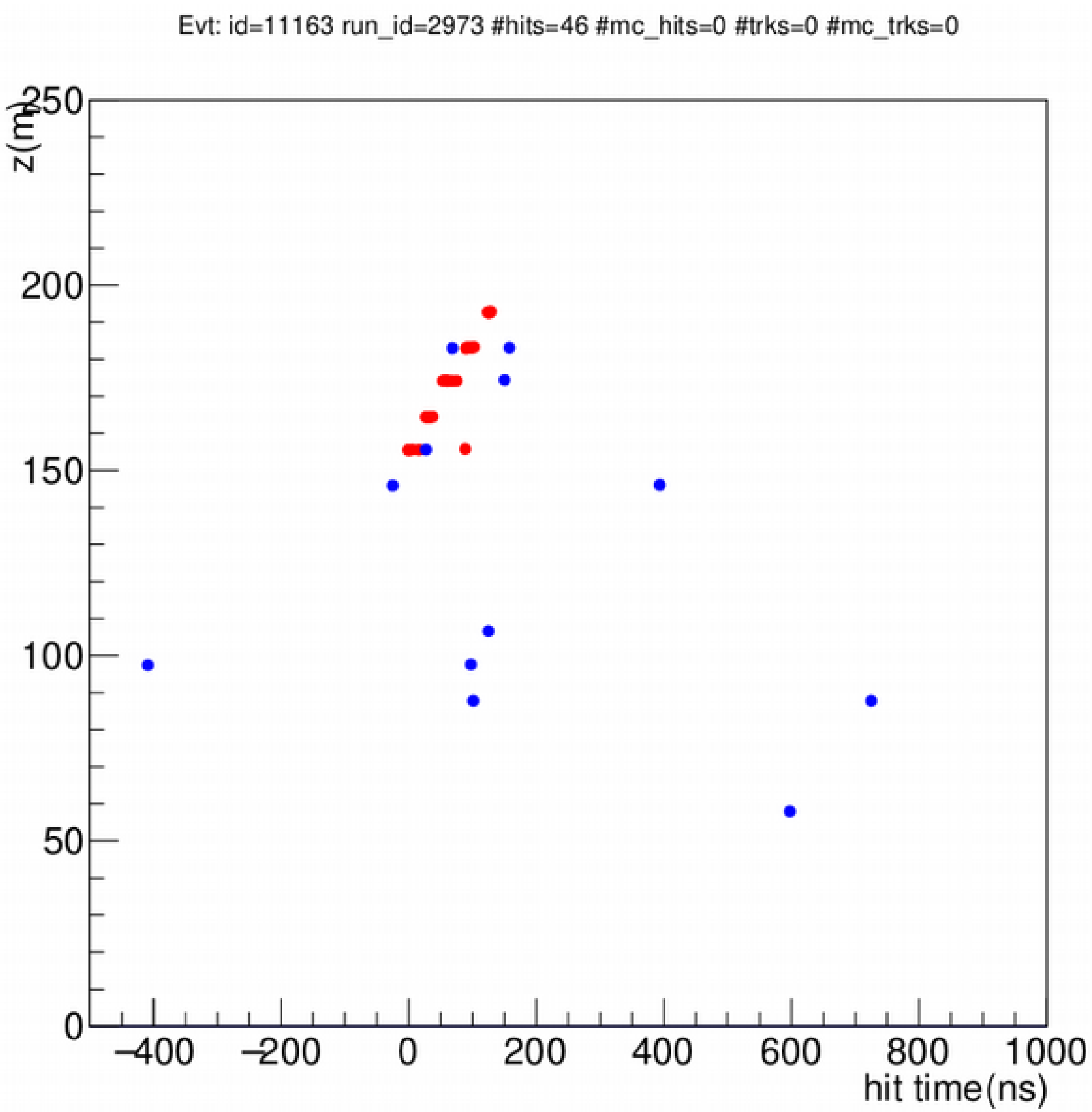
deployed in September 2017

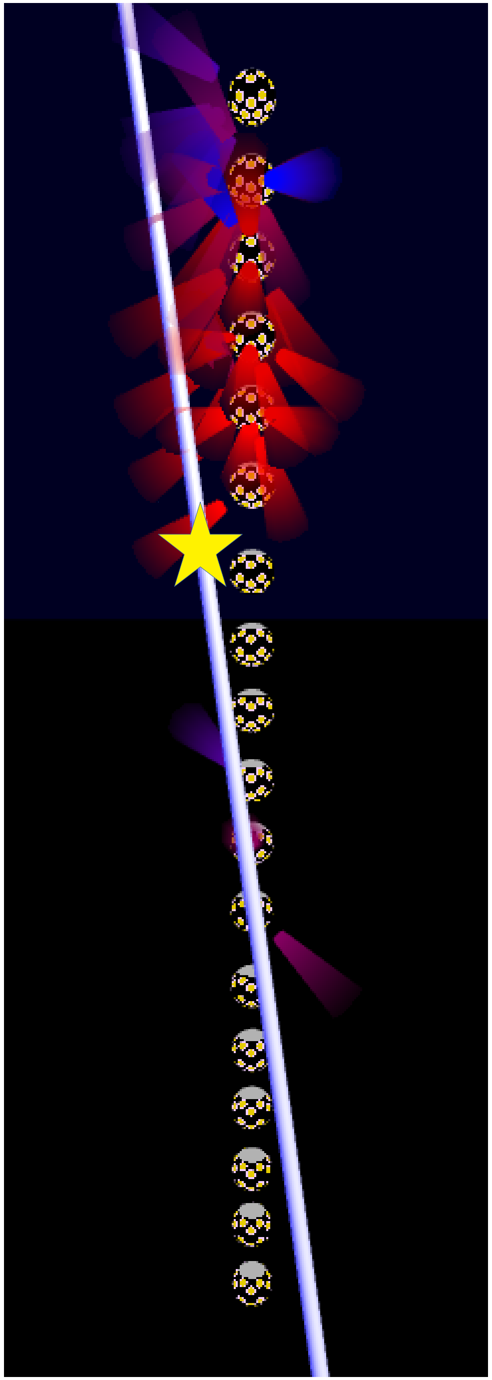


Number of events (upgoing):
MC atm neutrinos : 8.33
MC atm. muons : ~ 1
observed : 13

Analysis optimized for vertical upgoing tracks (horizontal tracks suppressed)

A neutrino candidate from ORCA DU-2





Energy ~ 10 GeV

1) Introduction to KM3NeT

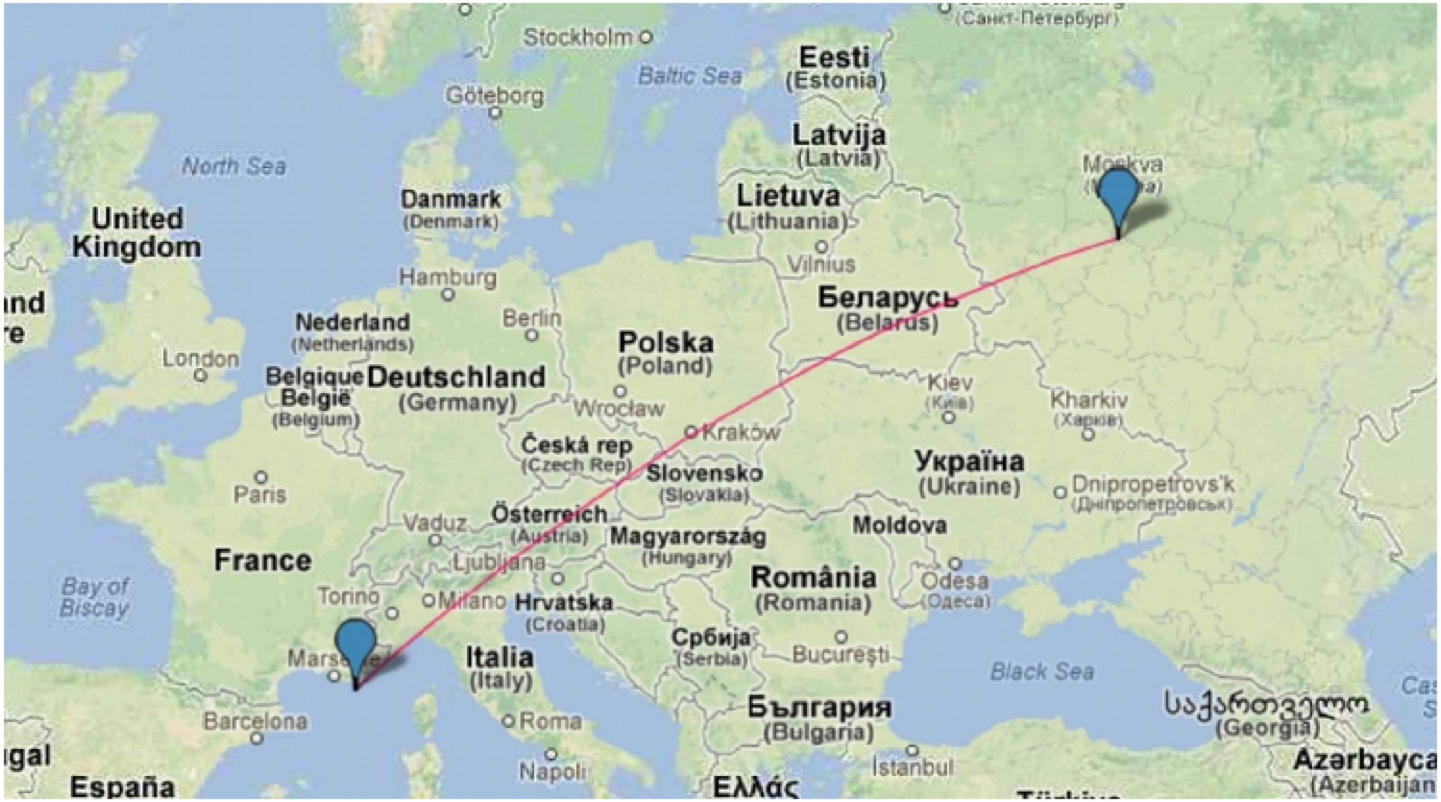
2) KM3NeT / ORCA

3) Current status

4) Potential of a neutrino beam from Protvino to ORCA

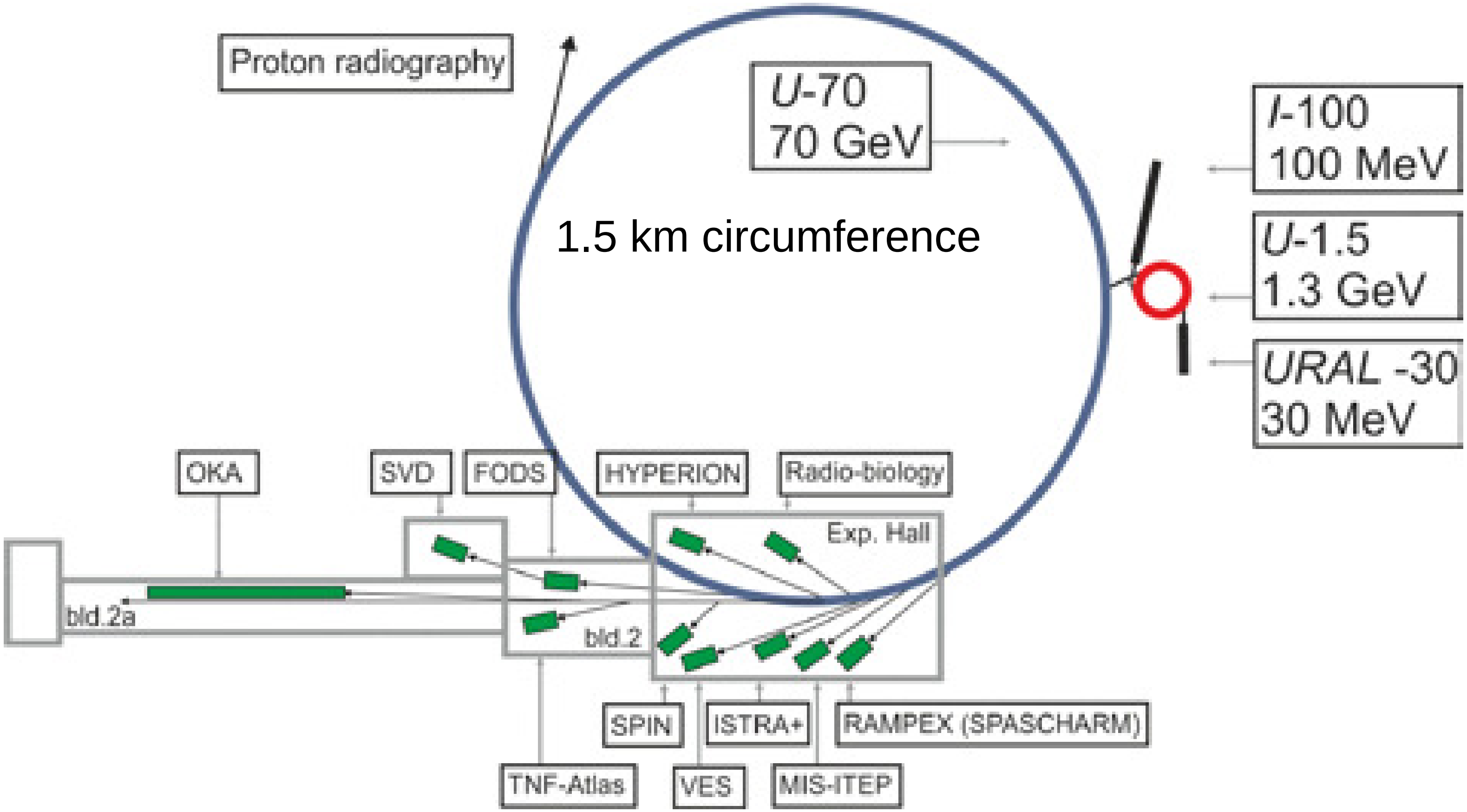
P2O : Protvino to ORCA

- Baseline 2588 km ; beam inclination : 11.7° (cos θ = 0.2)
- Deepest point 134 km : 3.3 g/cm3
- First oscillation maximum 5.1 GeV
- Sensitivity to mass hierarchy and CP violation



arXiv:1304.6230 / Adv. High En. Phys. (2013) 782538 http://dx.doi.org/10.1155/2013/782538
arXiv:1803.08017

Protvino accelerator complex
(100 km South of Moscow)

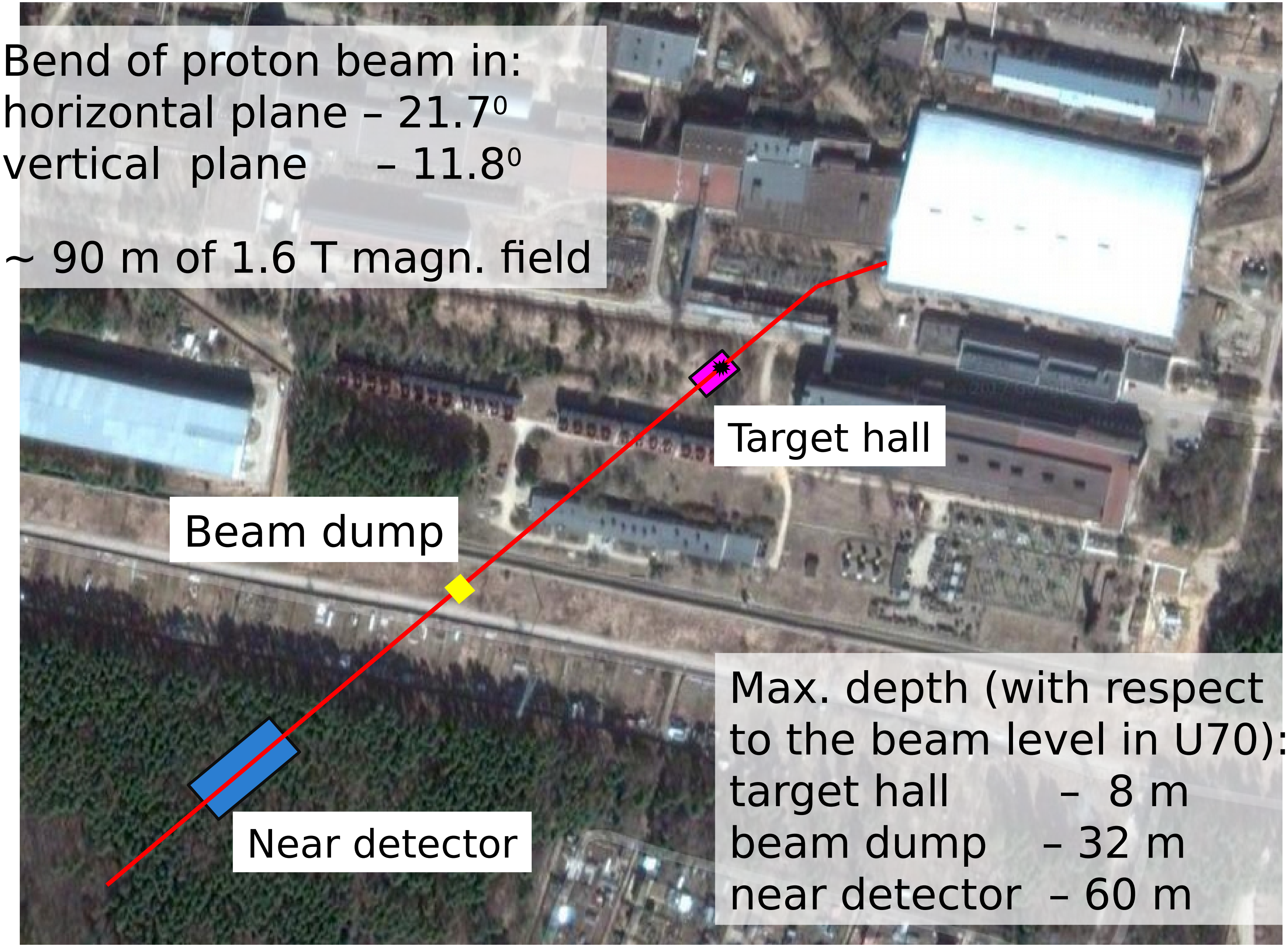


1-turn fast extraction:
5 µs spill every 9 s

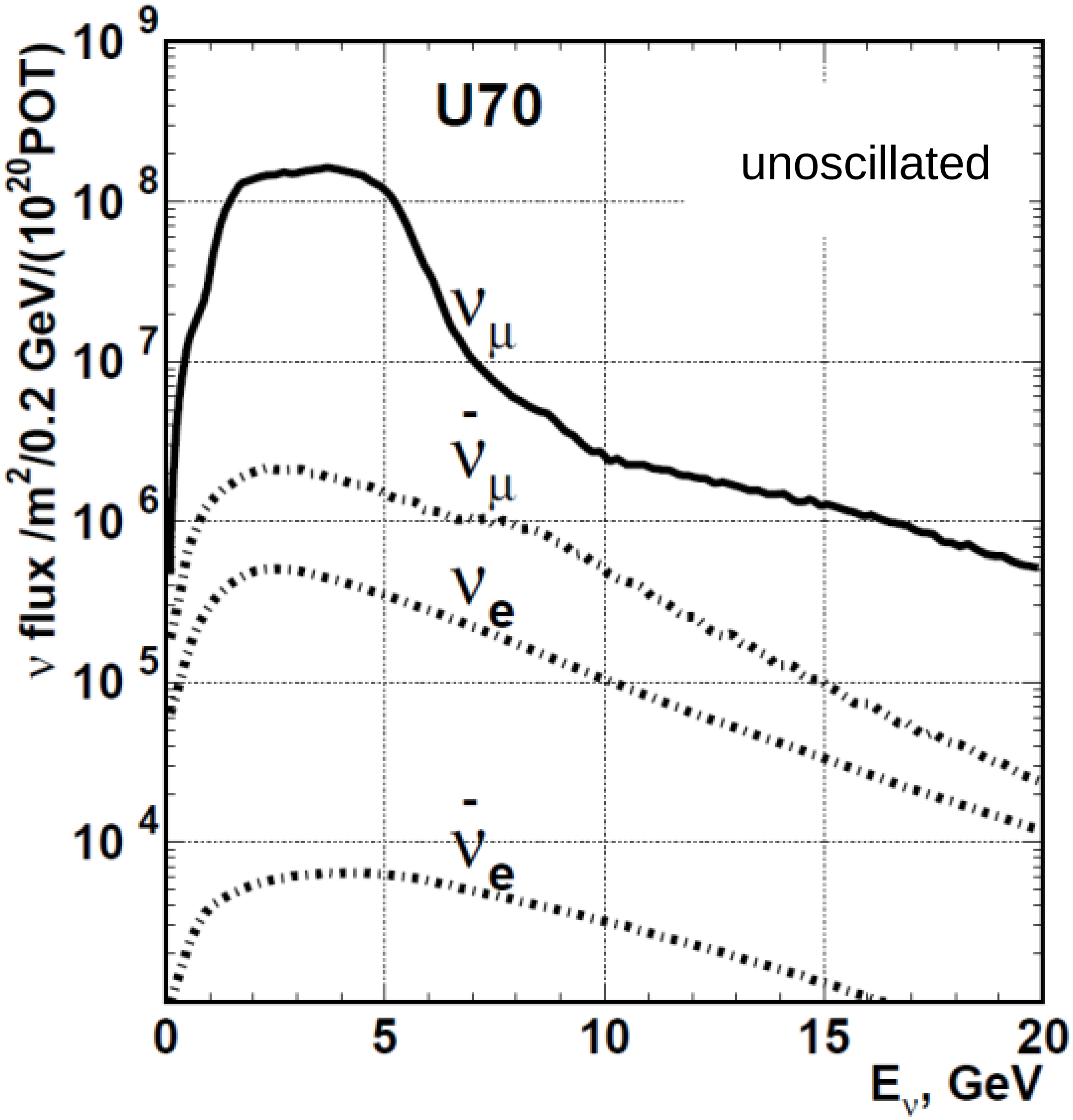
U-70 accelerator constructed in 1967
Now operates at 8 - 15 kW

Operated by NRC «Kurchatov Institute» – Institute for High Energy Physics (IHEP), Protvino

Possible location of the neutrino beam line



Simulated Neutrino Beam



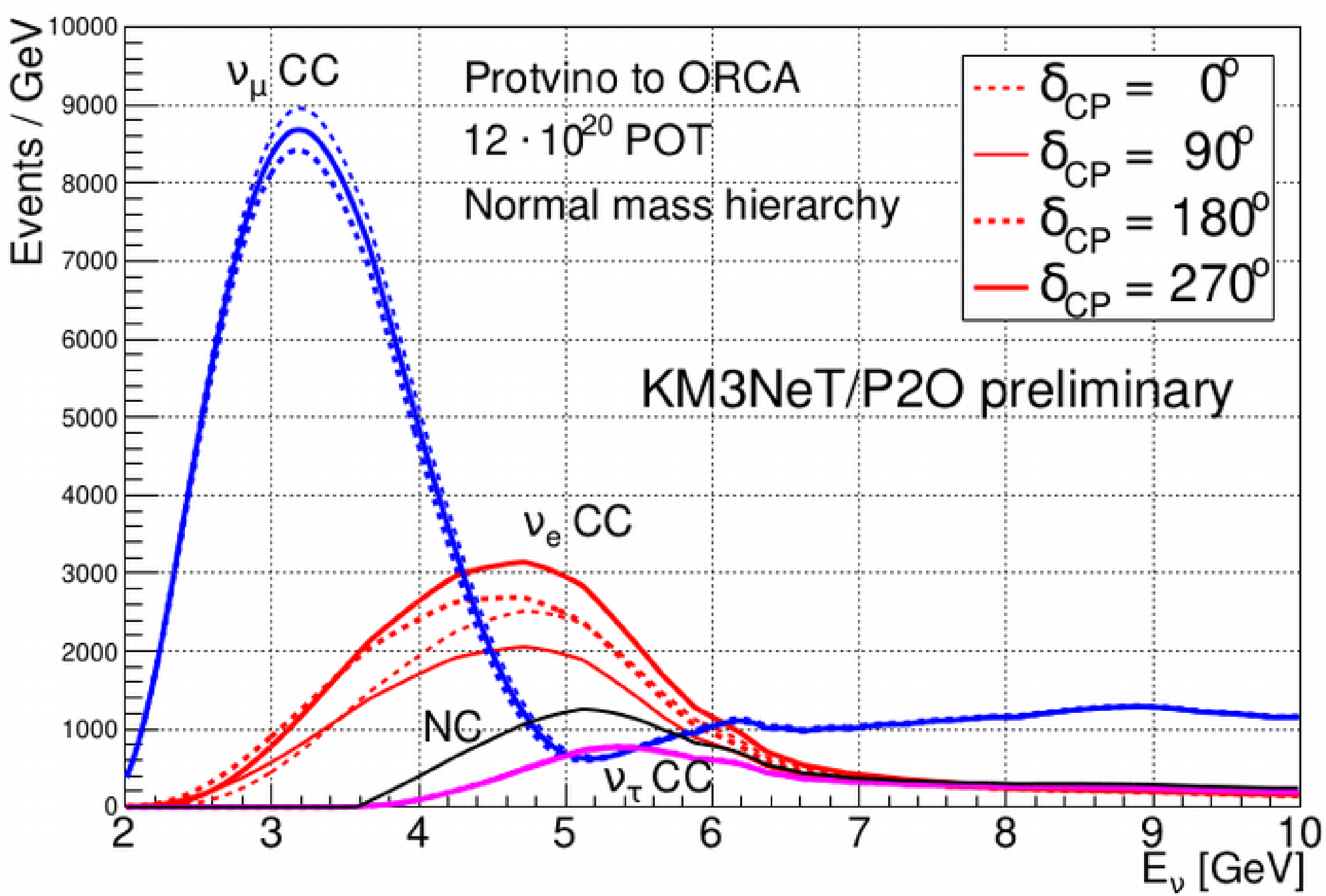
Beam spectra from *V. Garkusha, F. Novoskoltsev & A. Sokolov, Study of Neutrino Oscillations with the U-70 Accelerator Complex, IHEP Preprint 2015-5* – beam optimized for Protvino-Gran Sasso (on-axis)

Focus π+ (Neutrino beam)

Beam power : 450 kW,
4 * 10^{20} p.o.t. per year

(for reference:
Fermilab-Nova beam is 700 kW)

Expected neutrino rates in ORCA
normal mass hierarchy



Calculations with GloBES

After 3 yr of 450 kW beam:

ν_μ CC: ~ 30000 events

ν_e CC: ~ 8000 events

ν_τ CC: ~ 3500 events

NC: ~ 6000 events

For comparison:
DUNE: ~ 250 ν_e events / yr

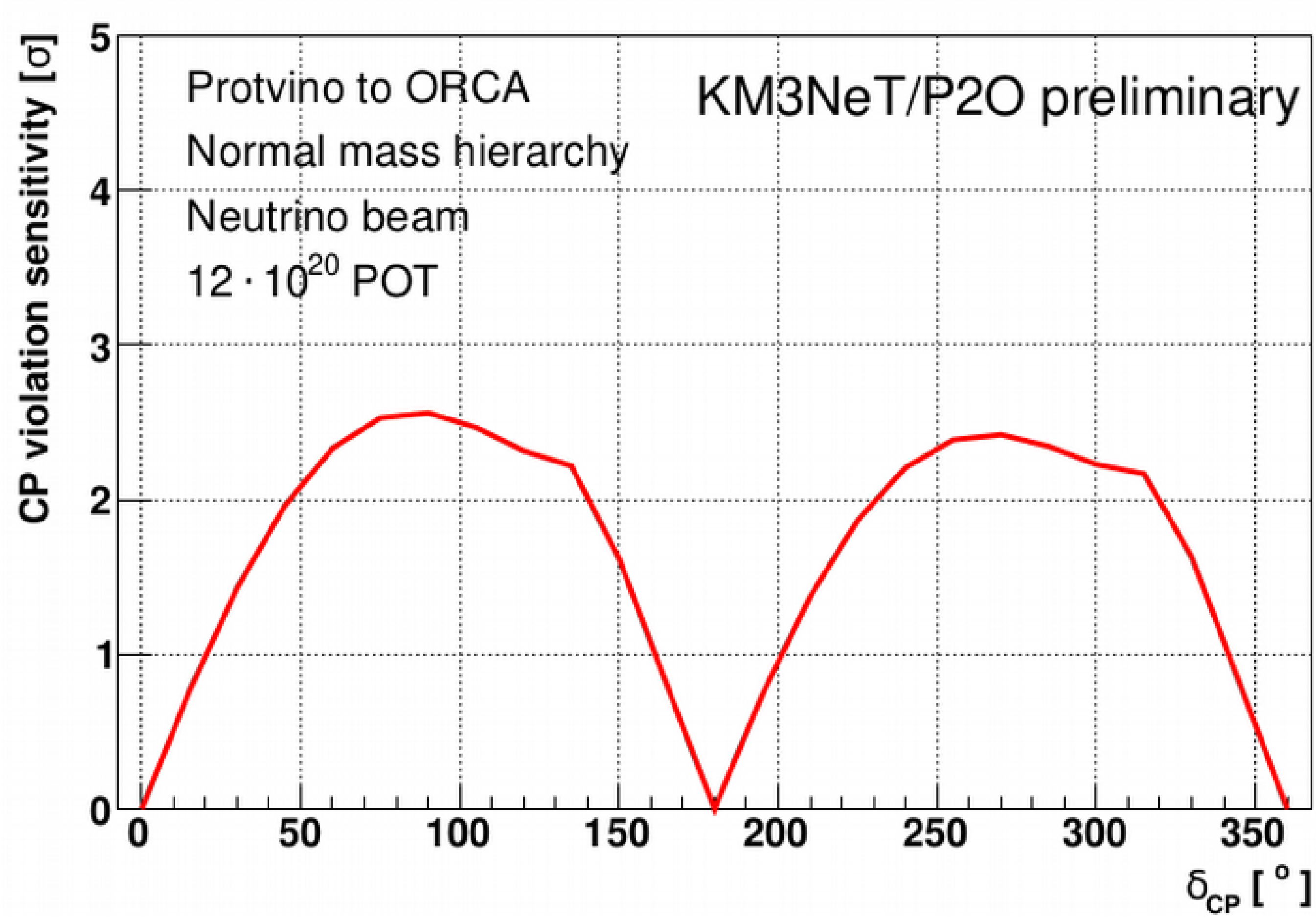
Vacuum oscillation maximum at E = 5.1 GeV

Most ν_μ convert to ν_τ which remains largely invisible (CC reaction suppressed by τ mass)

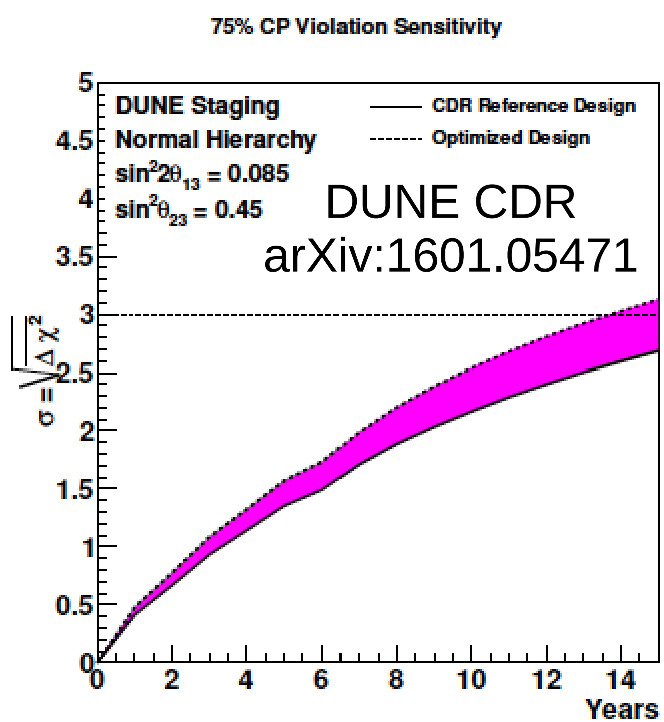
$\nu_\mu \rightarrow \nu_e$ transitions are enhanced by the MSW effect, resonance energy 3.8 GeV

Sensitivity to CP violation

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

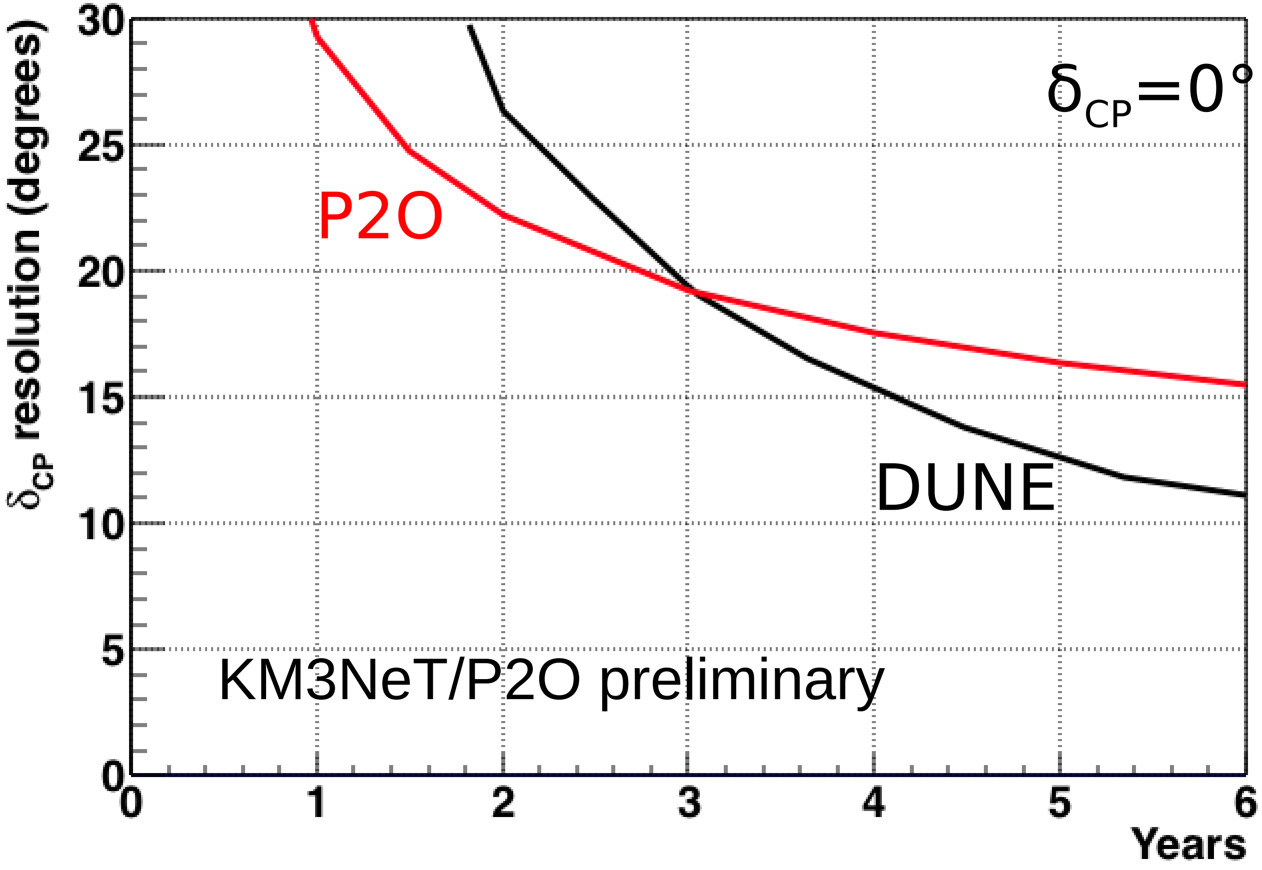


Competitive with DUNE!



2.5 sigma after 3 years of 450 kW beam
or 15 years of 90 kW beam

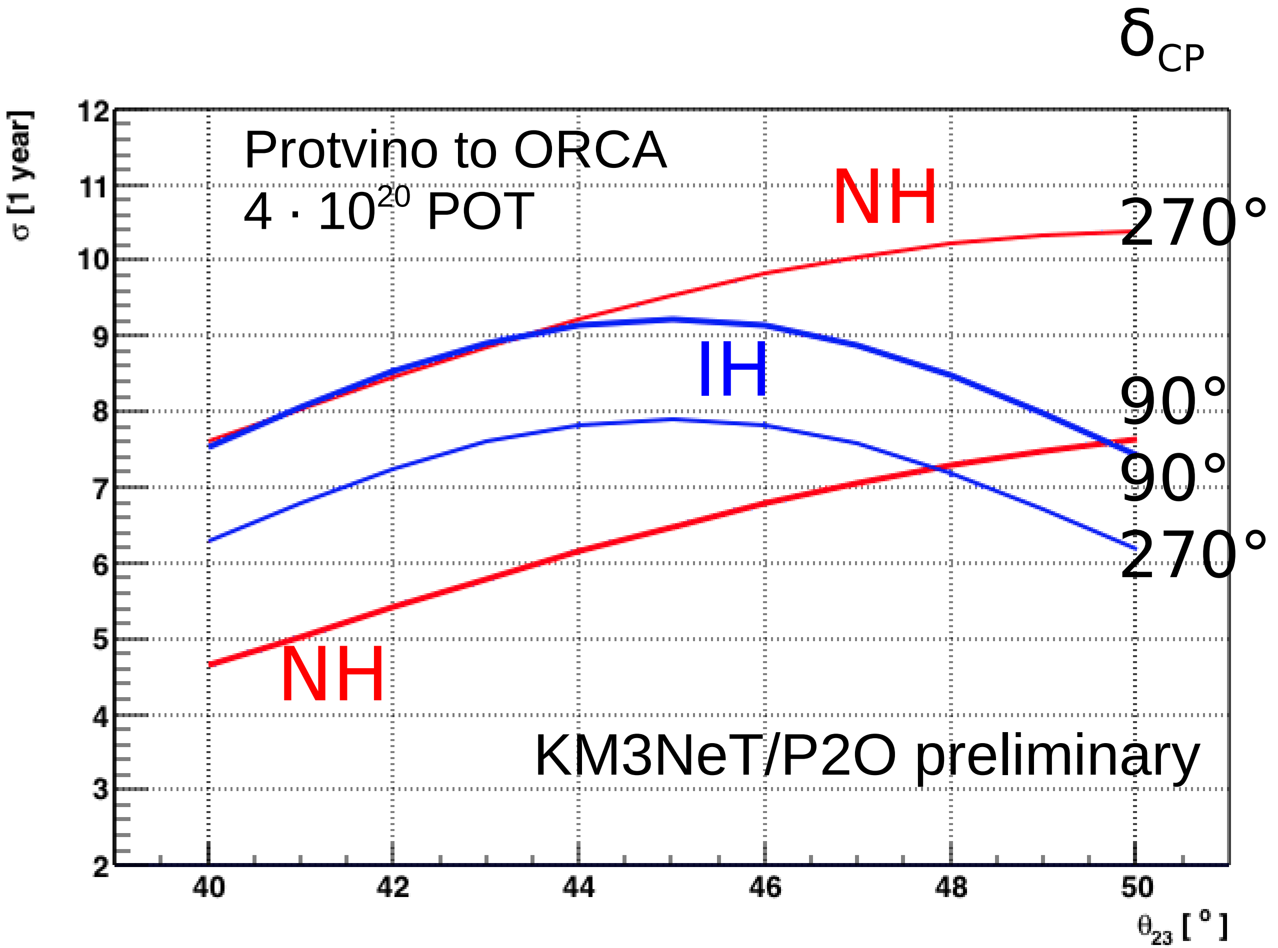
Measurement accuracy of δ_{CP}



450 kW beam

NB: this study uses preliminary estimates of systematic uncertainties

P2O sensitivity to mass hierarchy



> 5 sigma after 1 year of 450 kW beam

(or 5 years of 100 kW beam)

Summary

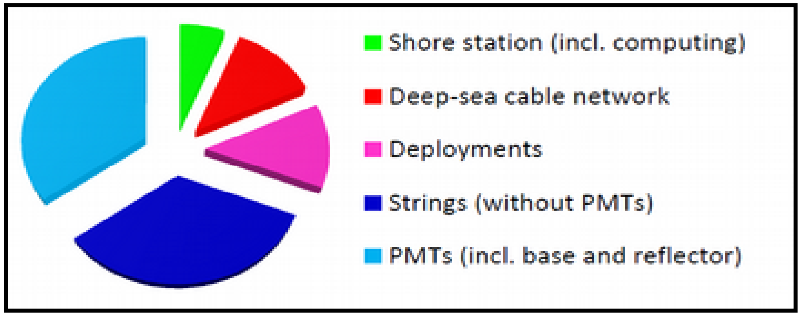
- KM3NeT-ARCA will explore the high energy neutrino sky with an unprecedented sensitivity
- KM3NeT-ORCA aims at determining the neutrino mass hierarchy after 3 years of operation
- Both ORCA and ARCA are now under construction
- A neutrino beam from Protvino to ORCA is a promising venue to study leptonic CP violation (competitive with DUNE, T2HK)

Learn more about KM3NeT

- S. Adrián-Martínez et al., **Letter of Intent** for KM3NeT 2.0, Journal of Physics G: Nuclear and Particle Physics, 43 (8), 084001, 2016 – arXiv:1601.07459
- http://www.km3net.org/

Backup slides

ORCA schedule and funding



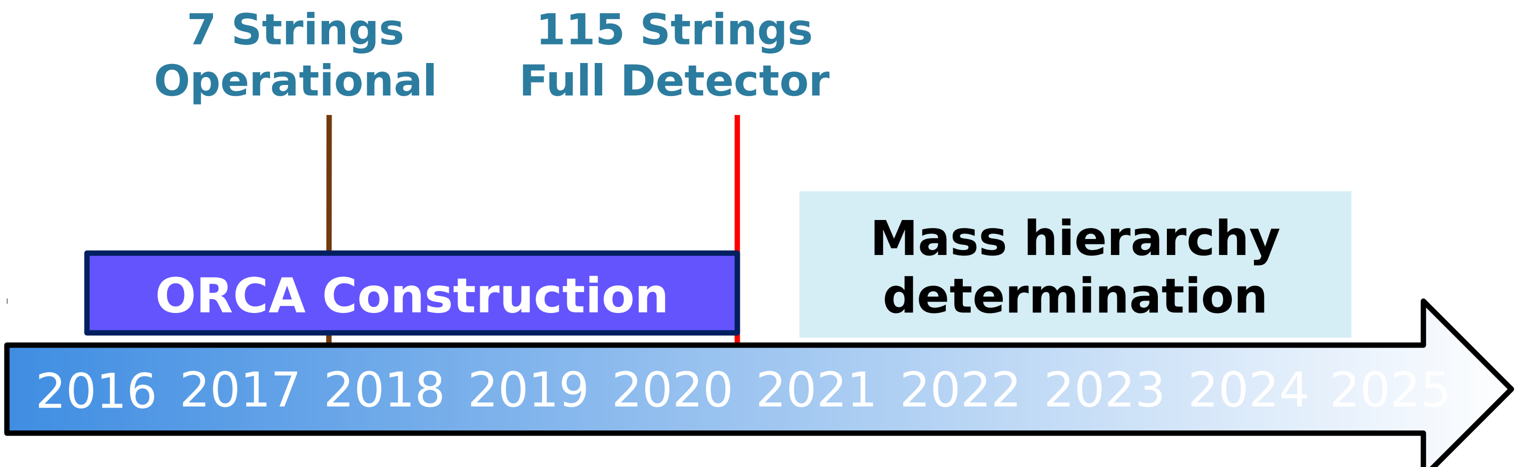
Total ORCA cost ≈ 45 M€

Phase 1: 7 strings – 11 M€

Phase 2: 115 strings – fund requests ongoing

Outlook

ORCA will determine the NMO in 3 years with at least 3σ significance

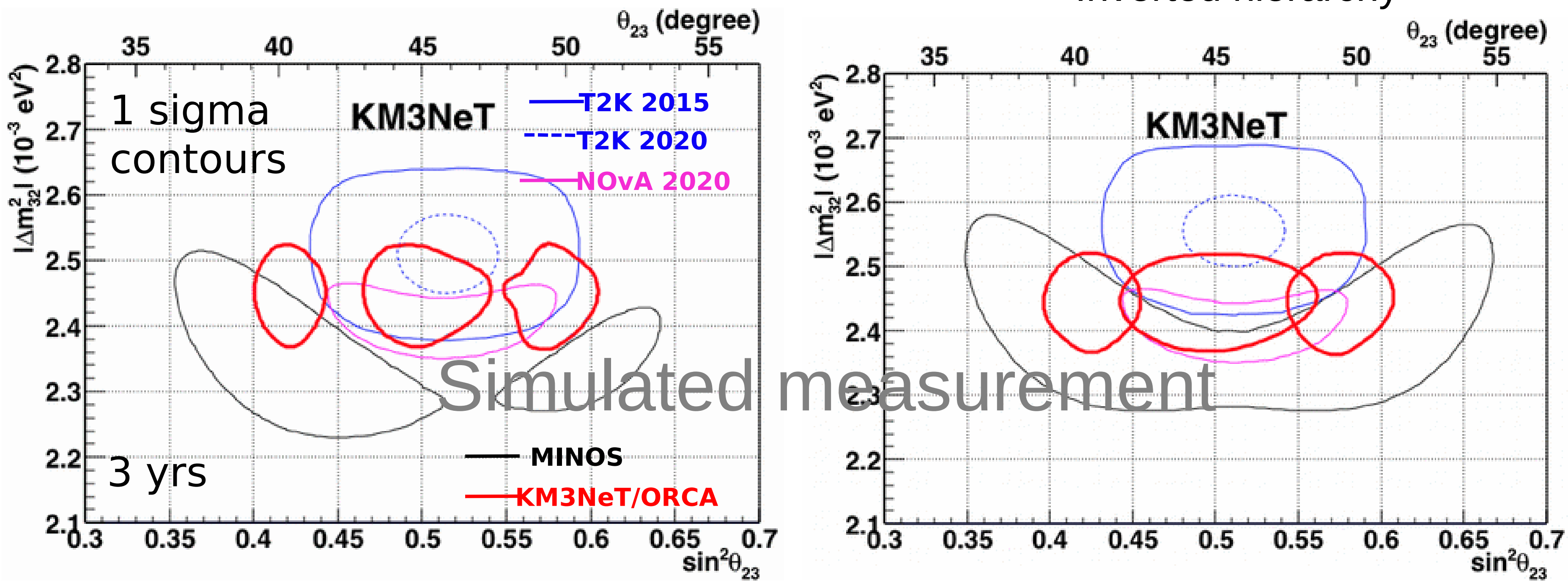


ORCA sensitivity to Δm^2_{32} and $\sin^2\theta_{23}$

- High statistics and excellent resolution → Measure Δm^2_{32} and $\sin^2\theta_{23}$
- Competitive with NOvA and T2K projected sensitivity in 2020
- Expect 2-3% precision in Δm^2_{32} and 4-10% in $\sin^2\theta_{23}$

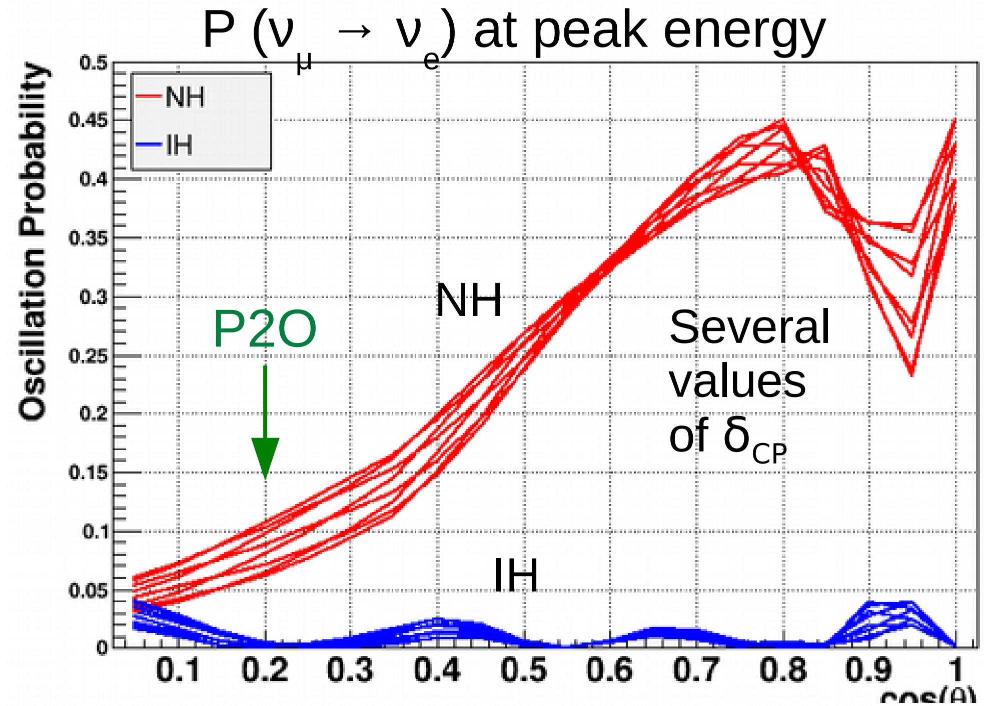
Normal hierarchy

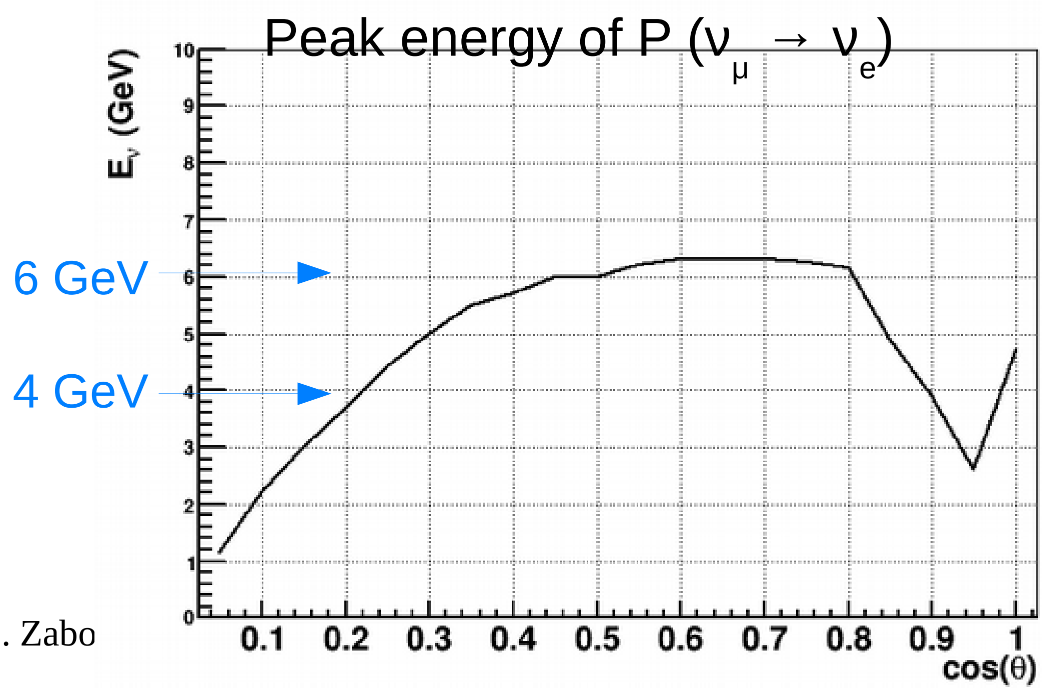
Inverted hierarchy



Optimal baseline

- Optimal baseline to measure mass hierarchy with beam neutrinos is between 2000 km and 4000 km
- Degeneracy between MH and δ_{CP} for L < 1000 km
- Peak energy follows initially first oscillation maximum at E = 25 GeV * cosθ
- levels off at mantle resonance energy (~ 6 GeV)

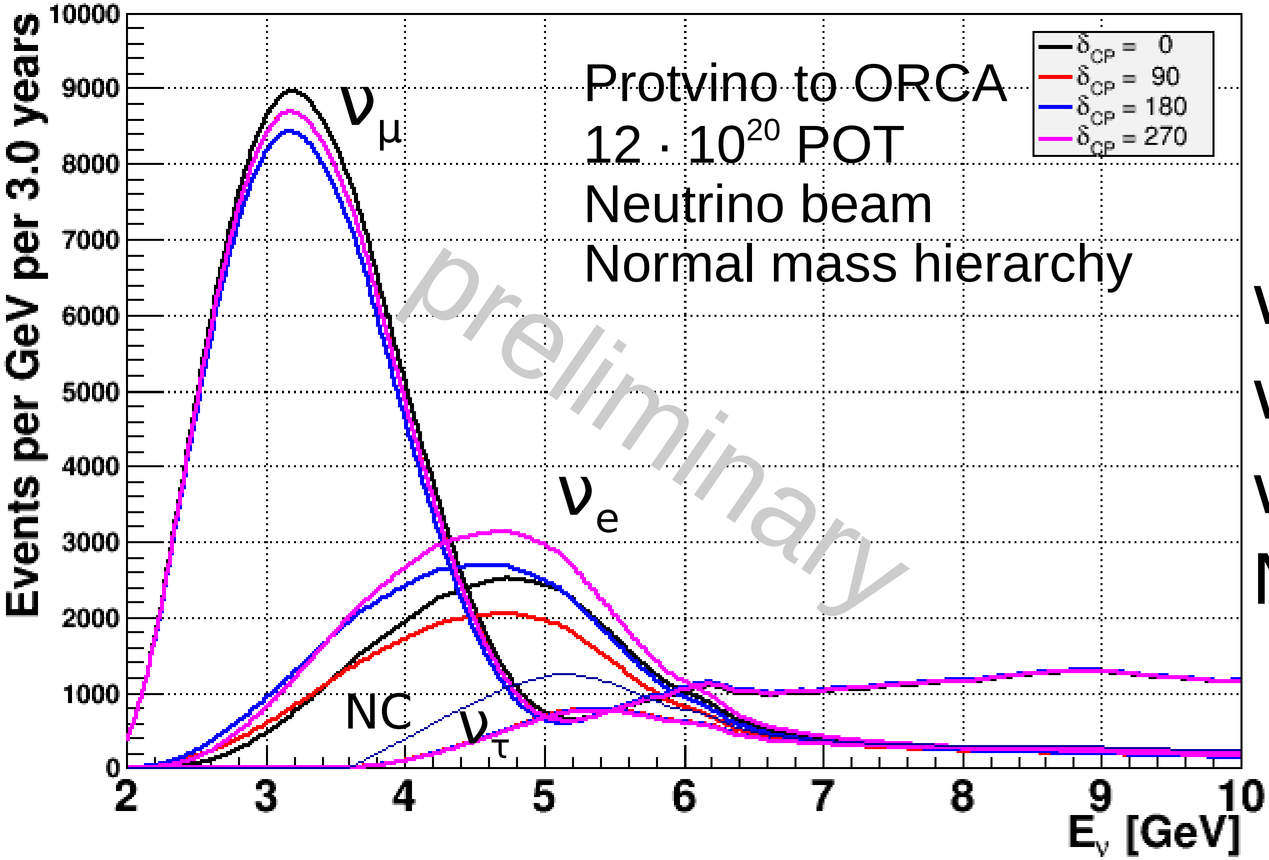




Expected neutrino rates in ORCA

normal mass hierarchy

Raw event numbers in ORCA



Calculations with GloBES

After 3 years of 450 kW beam:

ν_μ CC: ~ 30000 events

ν_e CC: ~ 8000 events

ν_τ CC: ~ 3500 events

NC: ~ 6000 events

For comparison:

DUNE: ~ 900 ν_e events / yr

Vacuum oscillation maximum at E = 5.1 GeV

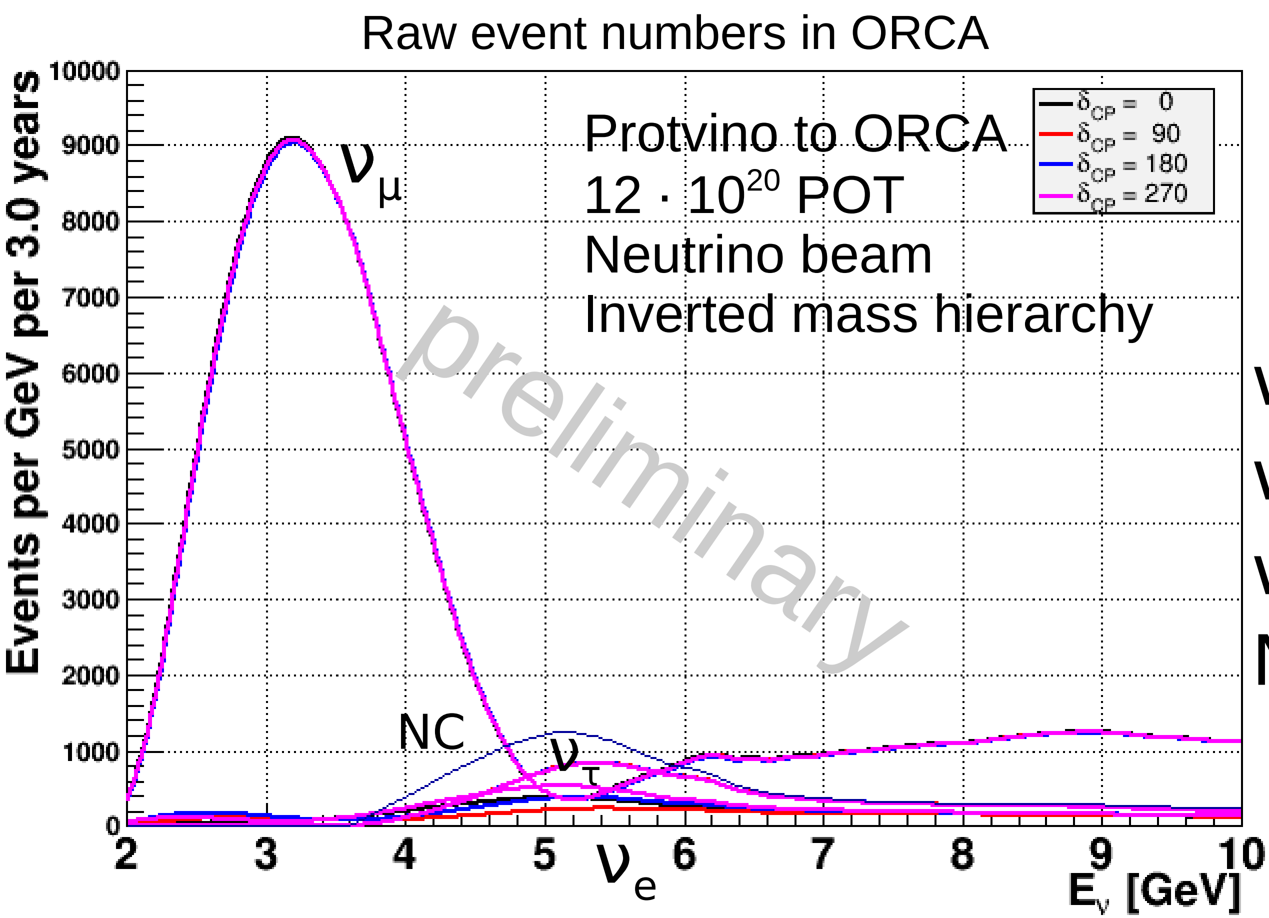
Most ν_μ convert to ν_τ which remains largely invisible (CC reaction suppressed by τ mass)

$\nu_\mu \rightarrow \nu_e$ transitions are enhanced by the MSW effect, resonance energy 3.8 GeV

Expected neutrino rates in ORCA

inverted mass hierarchy

Calculations with GloBES



ν_μ CC: ~ 30000 events

ν_e CC: ~ 2000 events

ν_τ CC: ~ 3700 events

NC: ~ 6000 events

$\nu_\mu \rightarrow \nu_e$ transitions suppressed by the MSW effect

If inverted mass hierarchy is true, switch to anti-neutrino beam (for CPV studies)

Multi-Parameter fit of simulated data

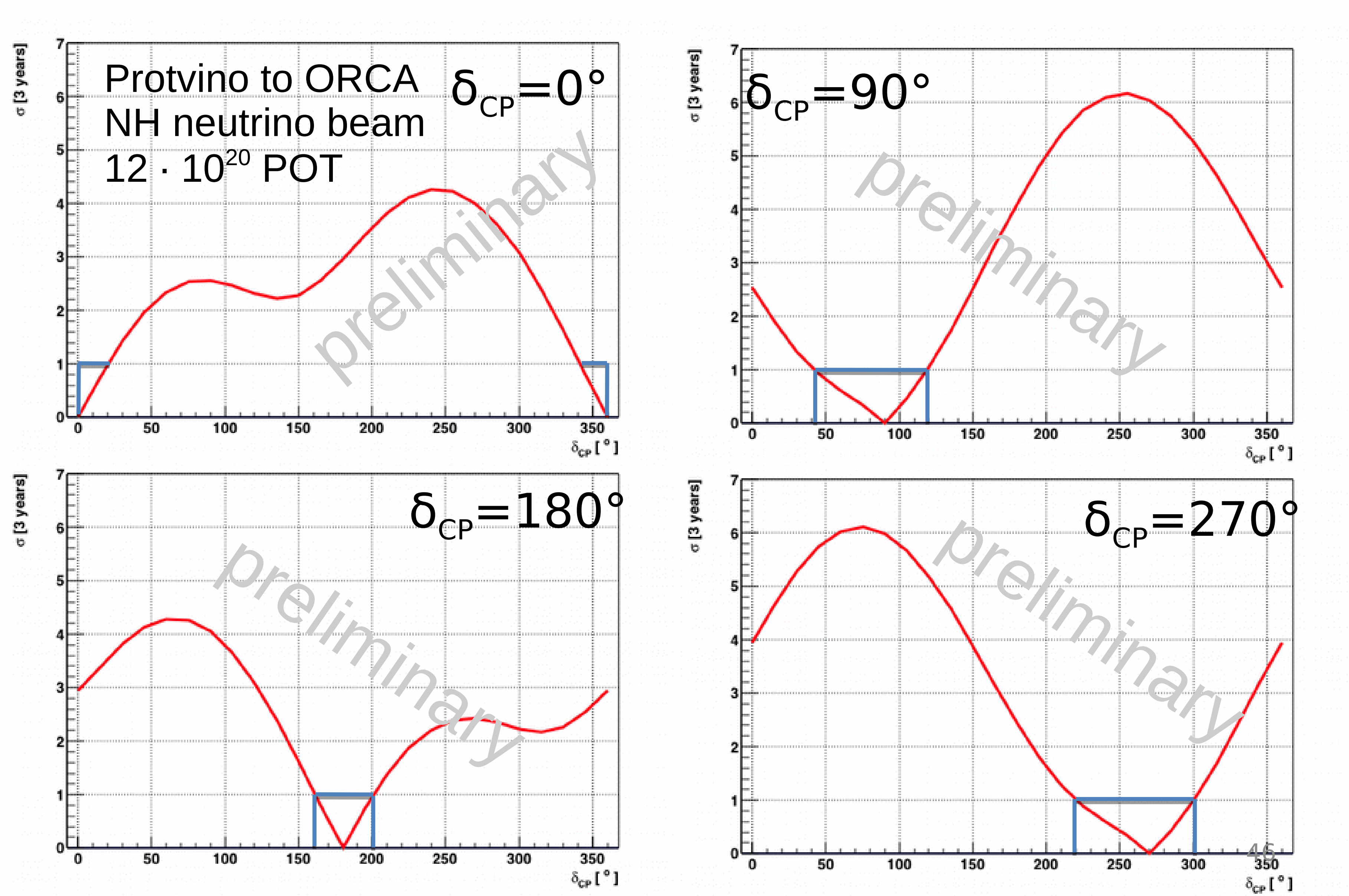
- Combined fit of nuisance and oscillation parameters
- No neutrino/anti-neutrino skew
- No spectral index skew
- No energy scale shift

Parameter	True value	Prior	Start value
θ_{12}	33.4°	fix	fix
Δm^2 [eV^2]	7.53 10^{-5}	fix	fix
θ_{13}	8.42°	0.15°	8.42°
θ_{23}	41.5°	1.3°	41.5°
ΔM^2 [eV^2]	2.44 10^{-3}	0.06	2.44 10^{-3}
δ_{CP}	many	no	many

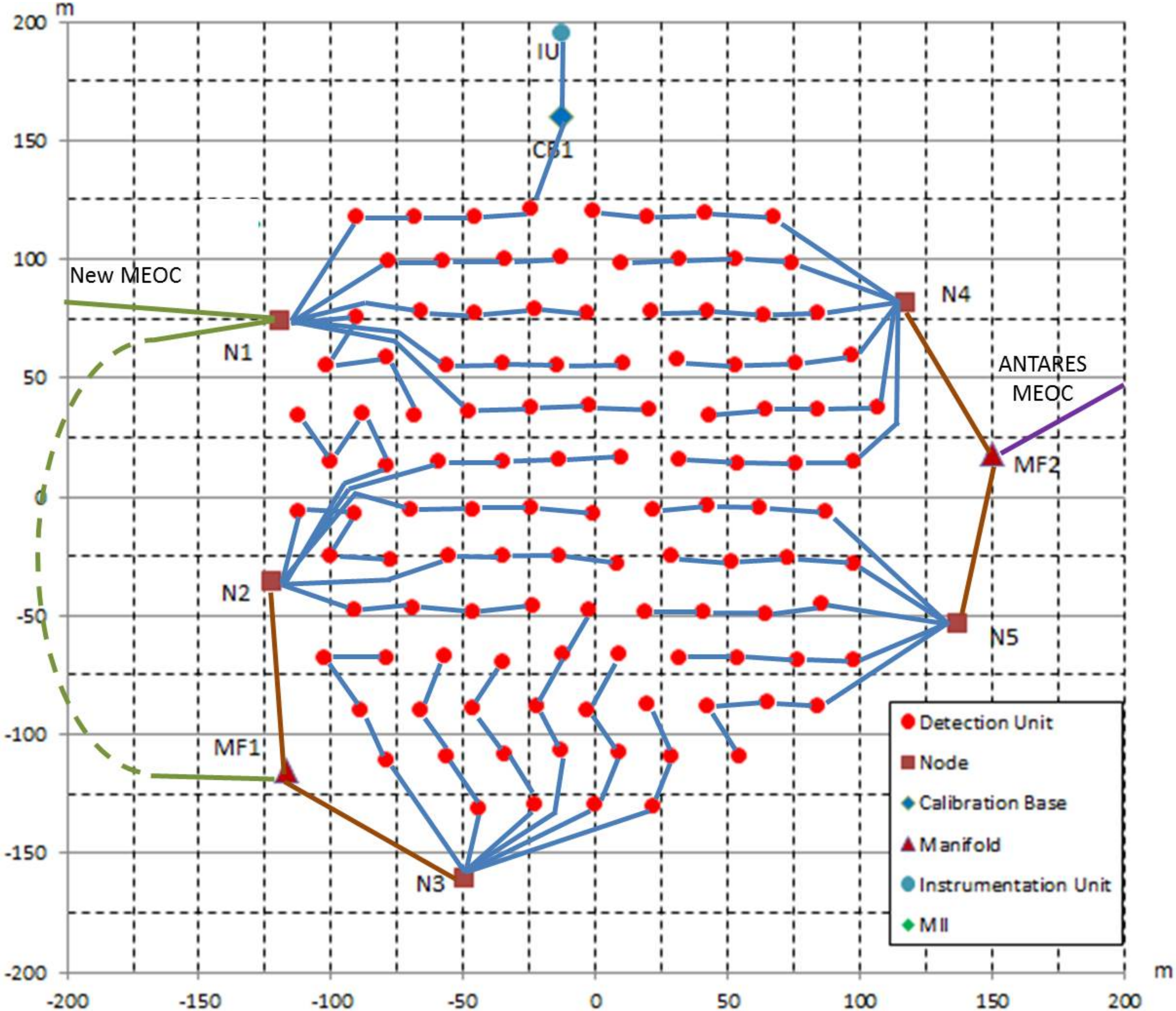
* Only used for CP fits, not for NMH

Parameter	True value	Prior	Start value
Norm ν_e CC	from ν_μ CC	fix	fix
Norm ν_μ CC	1	0.05	1
Norm ν_τ CC	1	0.10	1
Norm NC	1	0.05	1
PID	1	0.10	1
ν / ν	1	fix	fix

Simulated measurement of δ_{CP}



ORCA layout



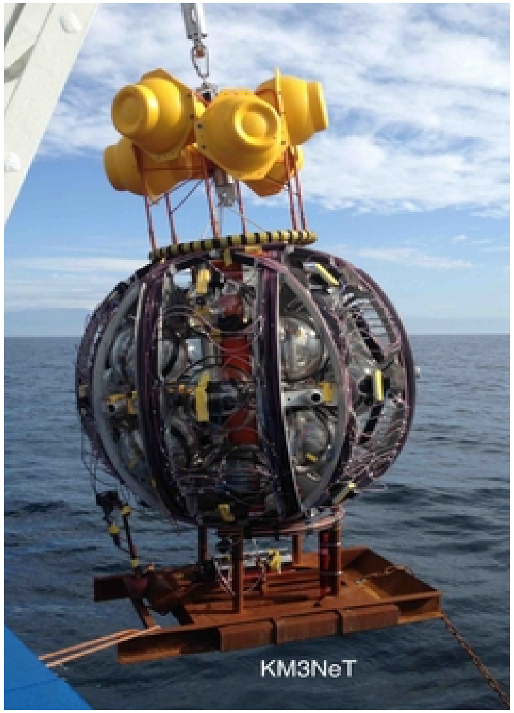
m
200
150
100
50
0
-50
-100
-150
-200
-200
-150
-100
-50
0
50
100
150
200
m
IU
CB1
New MEOC
N1
N2
N3
N4
N5
MF1
MF2
ANTARES
MEOC
Detection Unit
Node
Calibration Base
Manifold
Instrumentation Unit
MII

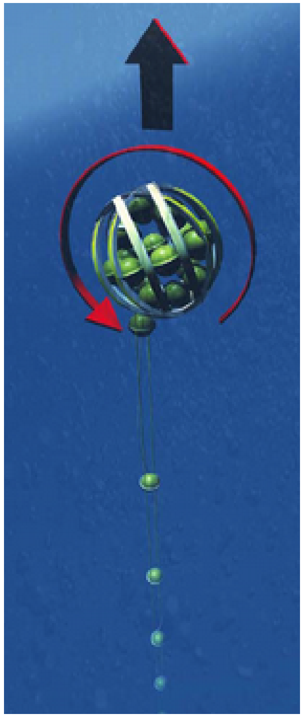
Construction status: sea infrastructure

Main electro-optical cable deployed
December 2014

Node1 (Junction Box) deployed
April 2015

Deployment Scheme





Shown is deployment of an ARCA DU (ORCA similar)

First ORCA DU deployed in September 2017

Watch:

https://youtu.be/7HKHW0hLxt4

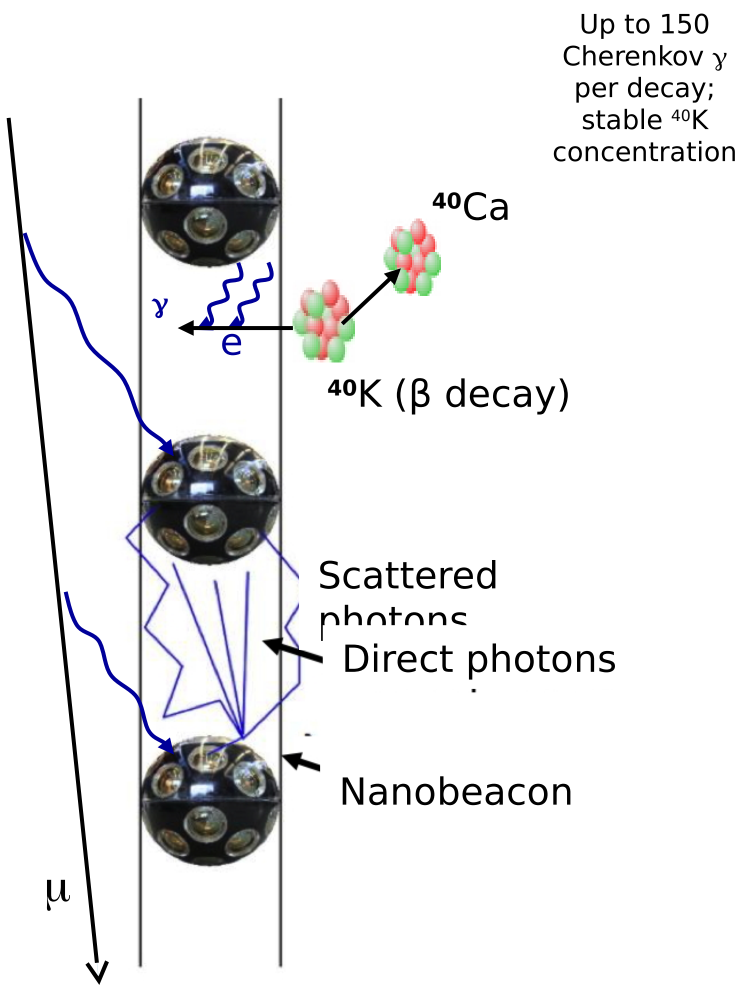
https://youtu.be/g2Y0KD3kdXs

https://youtu.be/xTj4lLMv1Fw

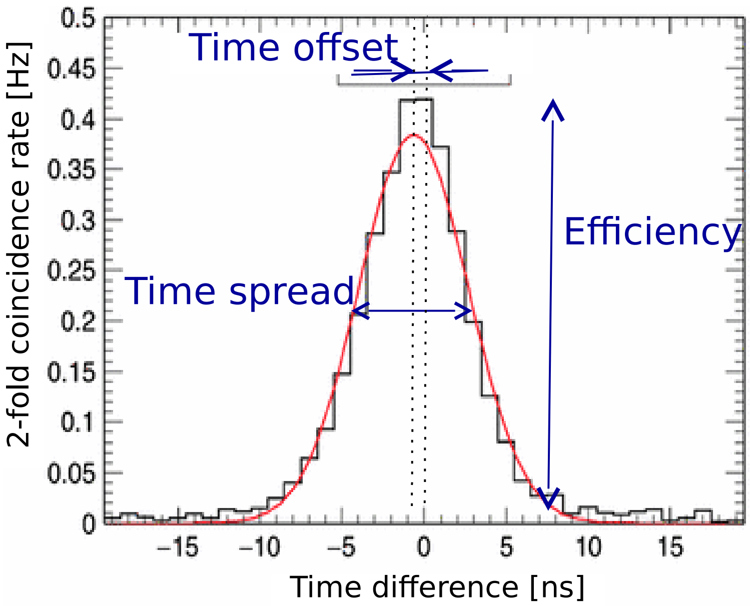
https://youtu.be/XFPCfCoTfUg

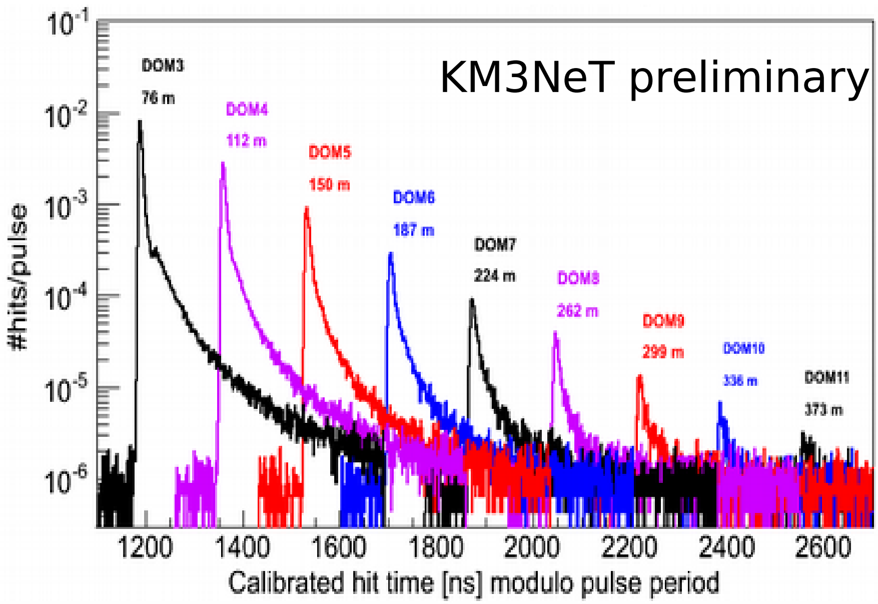
Calibration procedures

K. Melis PoS (ICRC2017) 1059



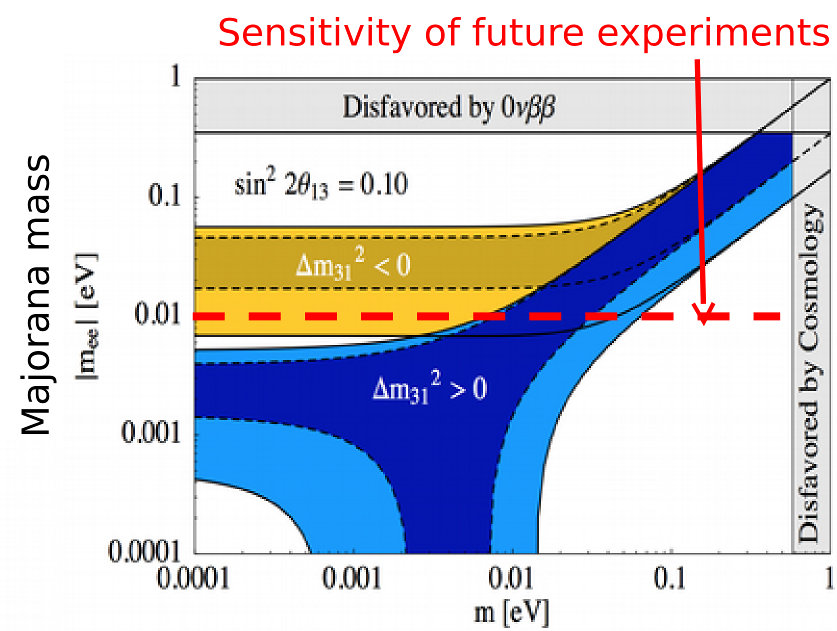
Cross-calibration with muons



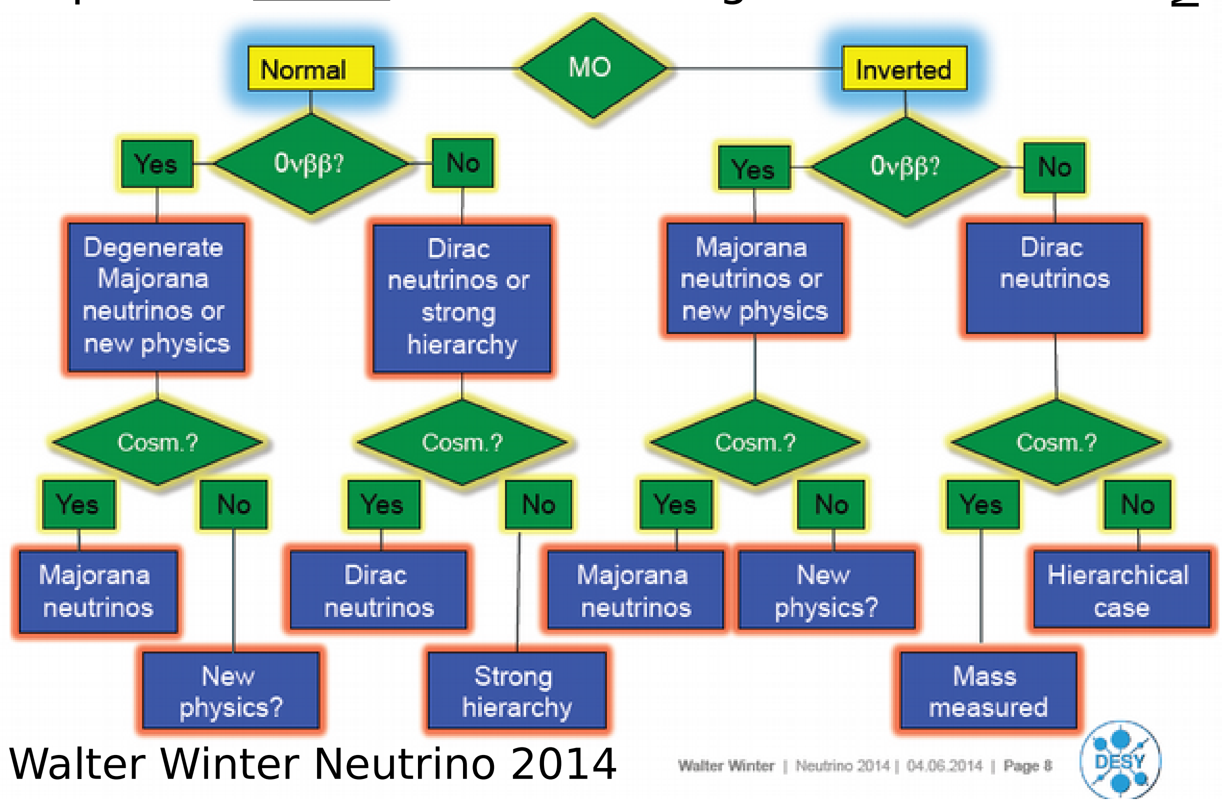


Why mass hierarchy is important

- Prime discriminator for theory models
- Helps measuring the CP phase
- Absolute mass scale
- Nature (Dirac vs Majorana)
- Origin of neutrino mass and flavour
- Core-Collapse Supernovae Physics

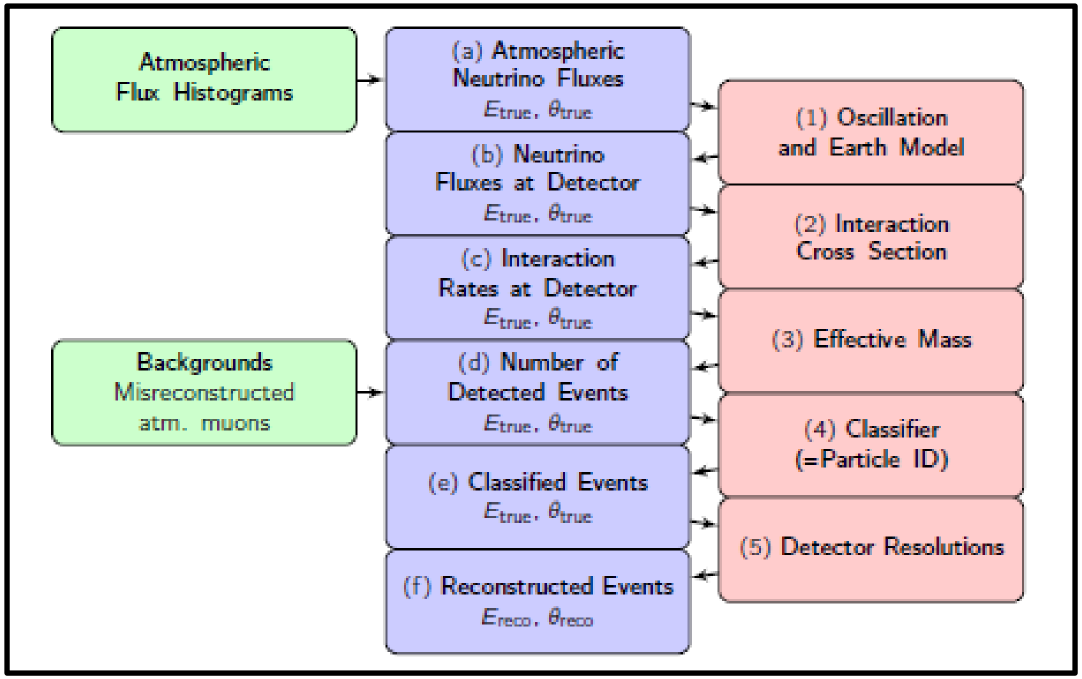


Impact of <u>direct</u> mass ordering measurement

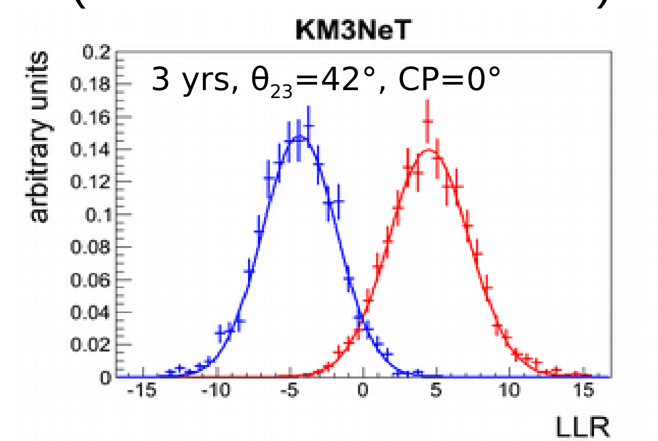


Walter Winter Neutrino 2014

Mass hierarchy measurement technicalities



(simulated measurement)



- Pick random values for oscillation parameters and other systematics
- Generate pseudo-experiments for N0, I0 cases
- Find best-fit likelihoods L_{NO}, L_{IO} for the NO, IO cases (maximising w.r.t. 9 free parameters)
- Calculate the log-likelihood ratio log (L_{NO}/L_{IO})