Семинар НИИЯФ МГУ
19 декабря 2017

Глубоководный детектор нейтрино KM3NeT-ORCA и его возможности по изучению осцилляций атмосферных и ускорительных нейтрино

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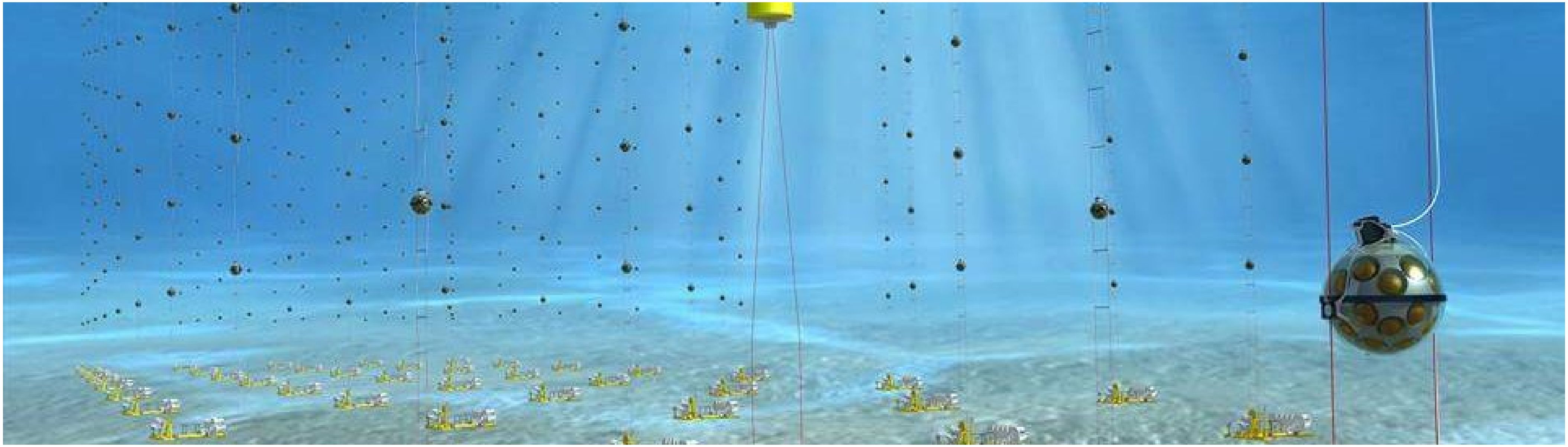
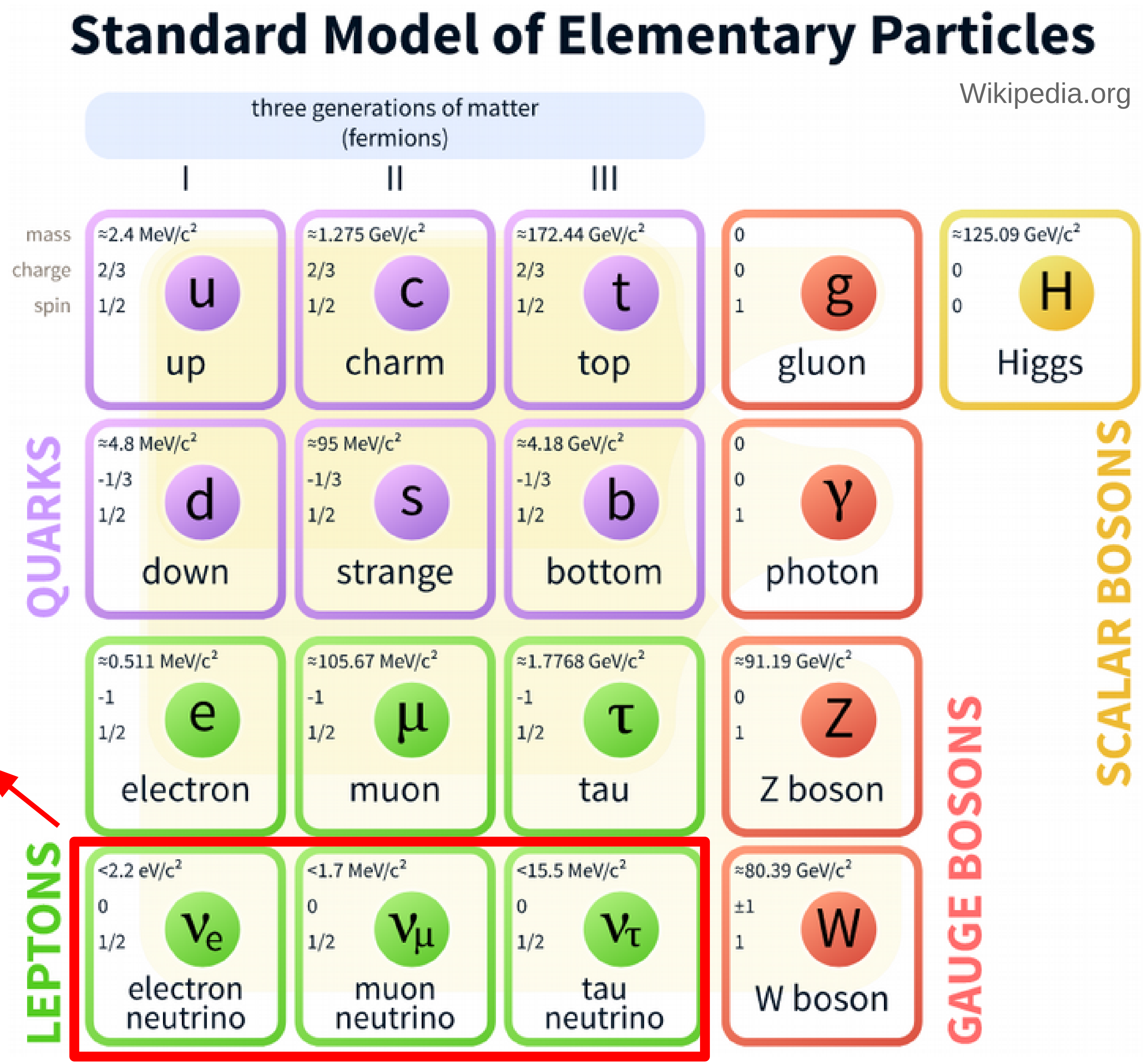


План доклада

1. Краткое введение в актуальные проблемы нейтринной физики
2. KM3NeT/ORCA с атмосферными нейтрино
3. Научный потенциал нейтринного пучка из Протвино

Место нейтрино в стандартной модели



Три аромата нейтрино (учавствуют в слабом взаимодействии)

Три массовых состояния (не тождественны ароматам)

Массы до сих пор не измерены

Что уже известно и еще не известно

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Global fit – Normal hierarchy

$\Delta m^2_{21} = 7.50^{+0.19}_{-0.17} \times 10^{-5}\mathrm{eV}^2$

$\Delta m^2_{31} = 2.457^{+0.047}_{-0.047} \times 10^{-3}\mathrm{eV}^2$

$\theta_{12} = 33.48^{+0.78}_{-0.75}(^\circ)$

$\theta_{23} = 42.3^{+3.0}_{-1.6}(^\circ)$

$\theta_{13} = 8.50^{+0.20}_{-0.21}(^\circ)$

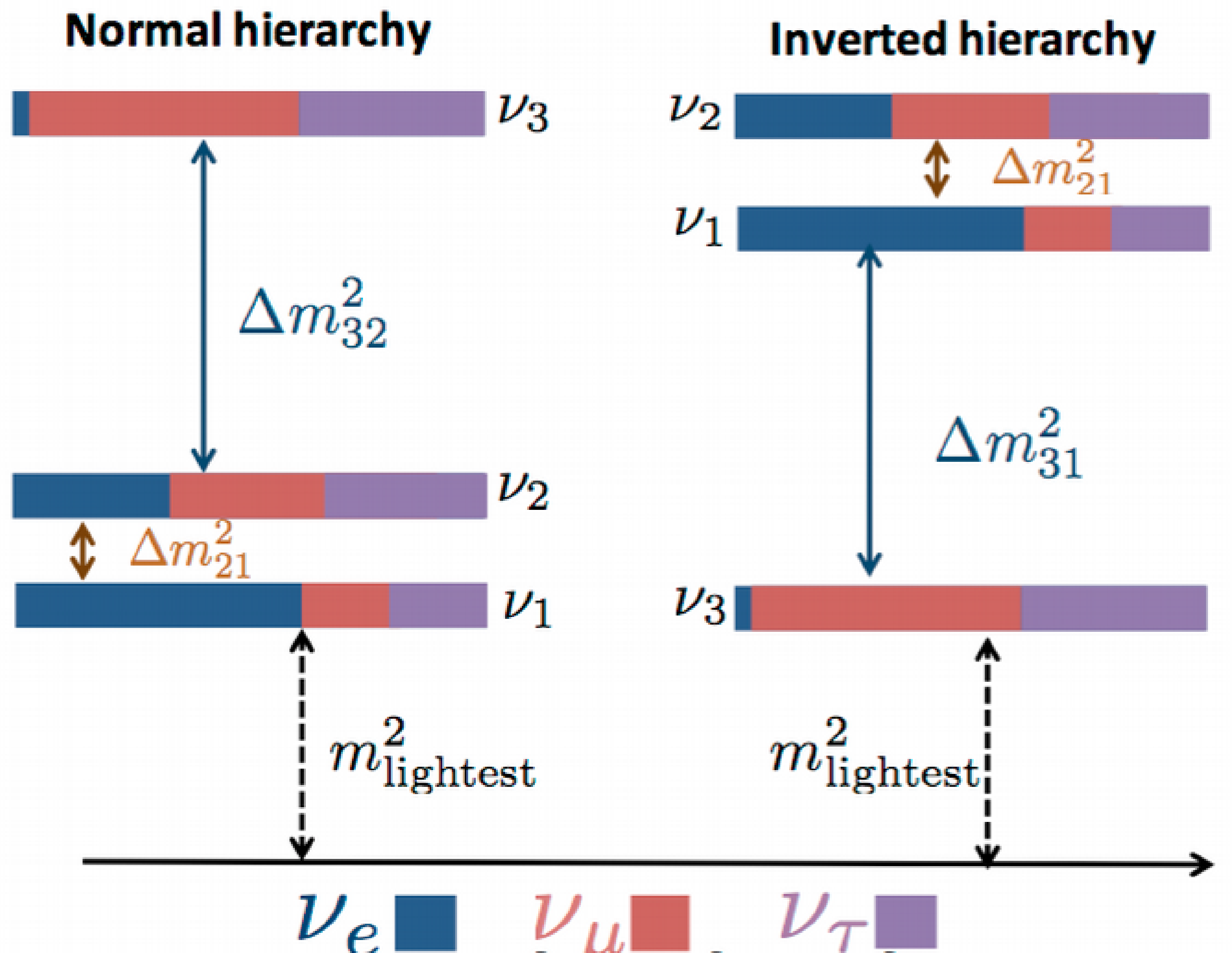
$\mathrm{sign}(\Delta m^2_{32}) = ?$

θ_{23} is maximal ?

$\delta_{CP} = ?$

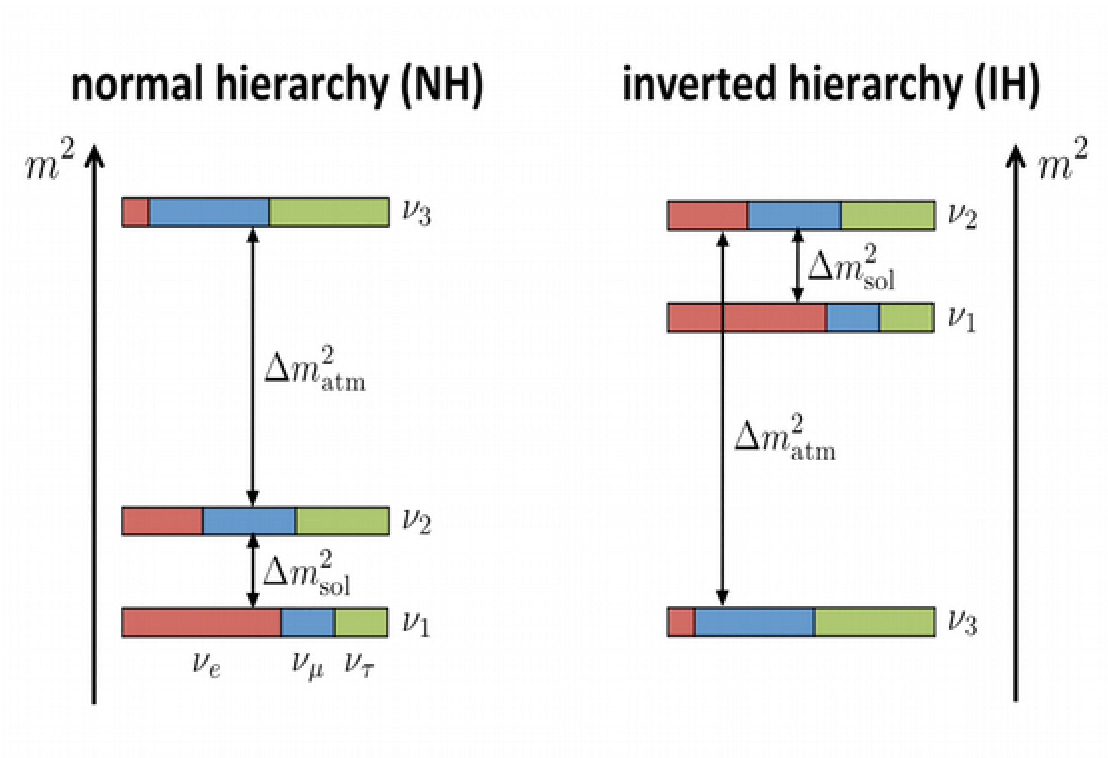
$m_{\mathrm{lightest}} = ?$

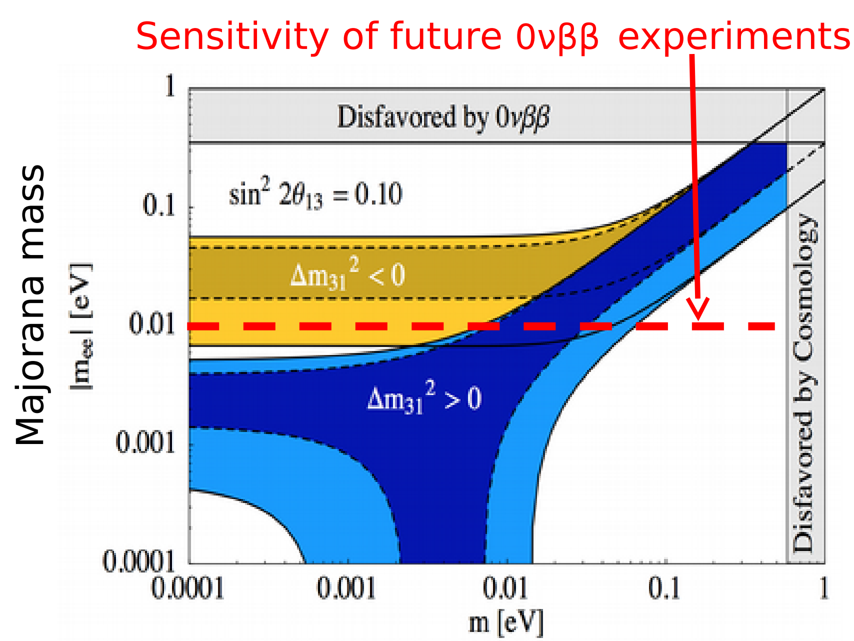
Gonzalez-Garcia *et al.*, arXiv:1512.06856



$$\Delta m^2_{ij} = m^2_{\nu_i} - m^2_{\nu_j}$$

Why mass hierarchy is important





Walter Winter Neutrino 2014

- Important discriminator for theory models
- Helps measuring the CP phase
- Absolute mass scale
- Sensitivity of 0νββ experiments
- Core-Collapse Supernovae Physics

MSW effect

The ν_e component can indeed undergo charged-current (CC) elastic scattering interactions with the electrons in matter and consequently acquire an effective potential:

$$A = \pm\sqrt{2} G_F N_e$$

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

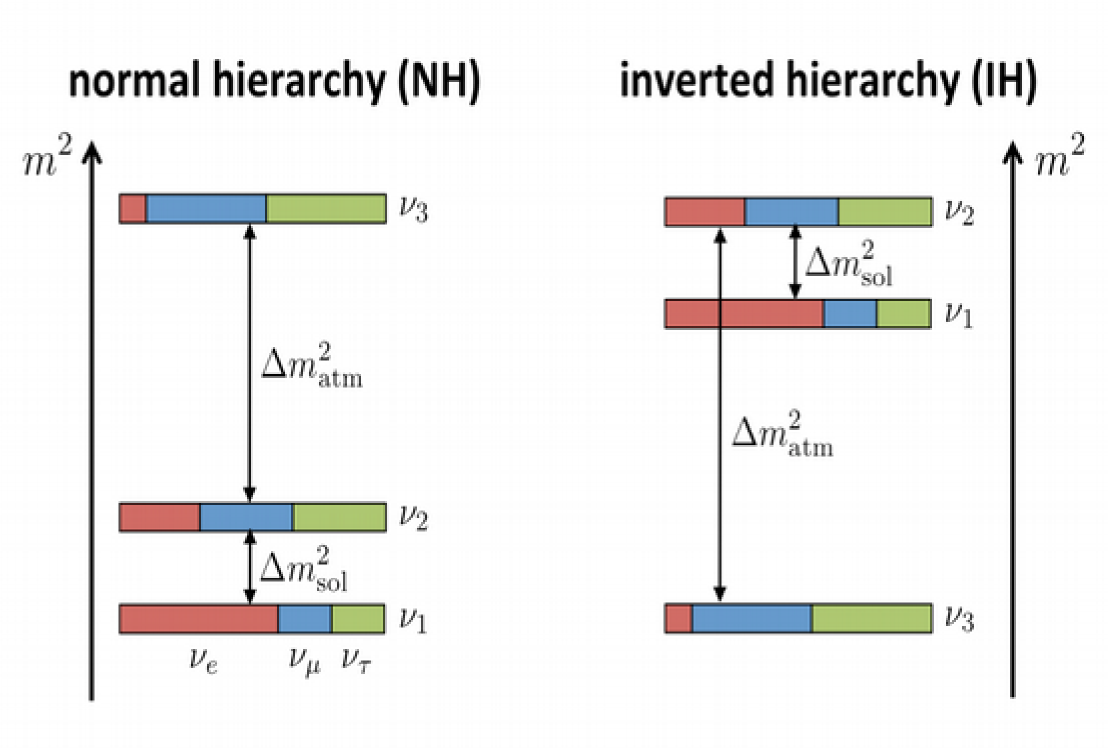
$$\sin^2 2\theta^m_{13} \equiv \sin^2 2\theta_{13} \left(\frac{\Delta m^2_{31}}{\Delta^m m^2}\right)^2$$

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

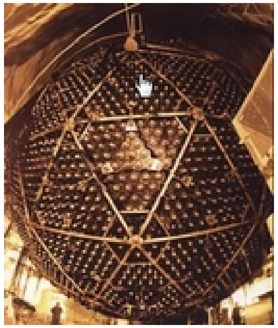
$$E_{\text{res}} \equiv \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2}\, G_F N_e} \simeq 7\,\mathrm{GeV} \left(\frac{4.5\,\mathrm{g/cm^3}}{\rho}\right) \left(\frac{\Delta m^2_{31}}{2.4 \times 10^{-3}\,\mathrm{eV}^2}\right) \cos 2\theta_{13}$$

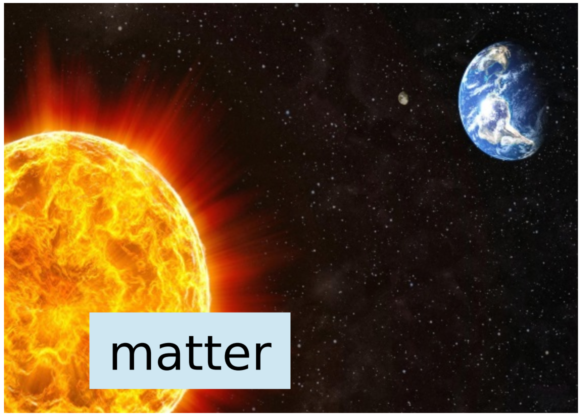
Resonance occurs for neutrinos in the case of NH and for antineutrinos in case of IH

Neutrino mass hierarchy (ordering)

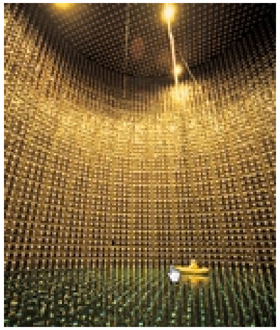


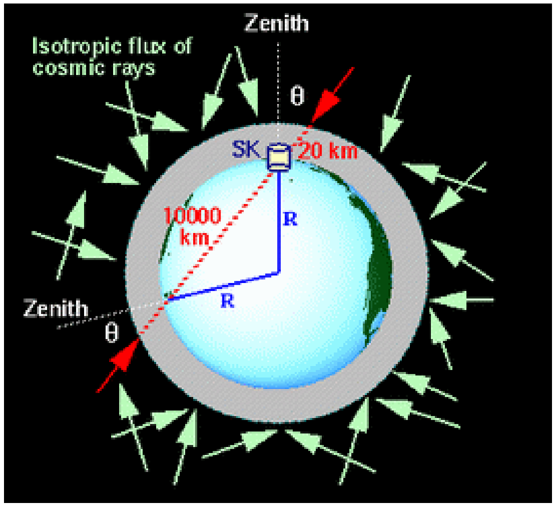
Δm^2_{solar} : sign known





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





In vacuum, sign of Δm^2 has no effect on oscillations.

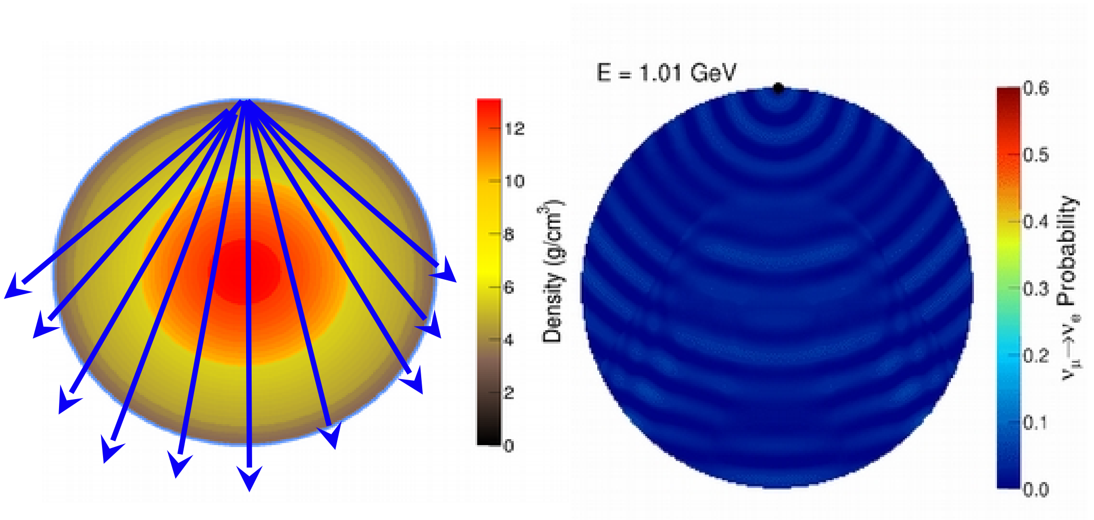
In matter, it controls the polarity of the MSW effect (a.k.a. the matter effect)

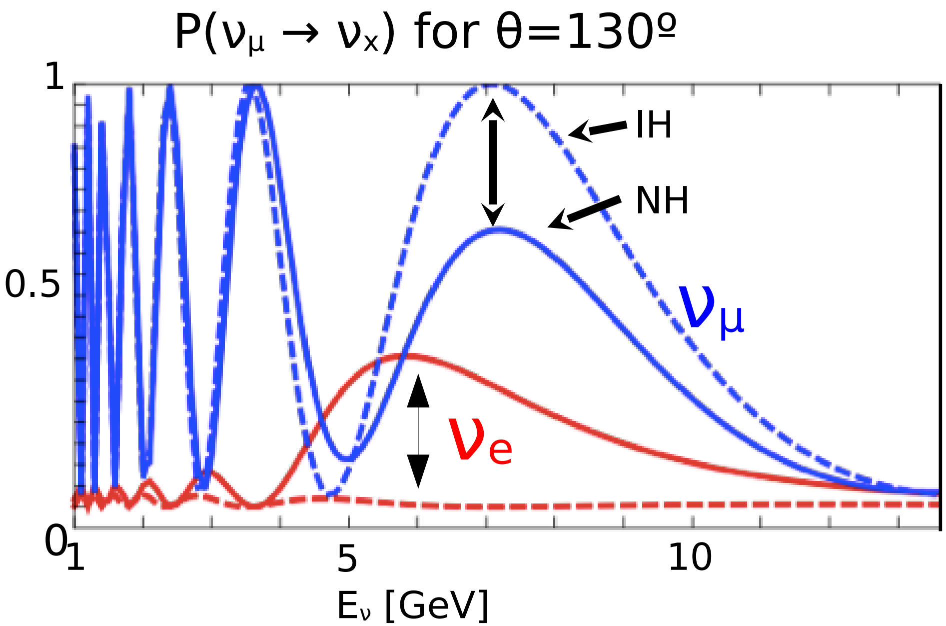
Mass hierarchy with atmospheric neutrino

- 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:

  Φatm(ν) ≈ 1.3 x Φatm(anti-ν)

  σ(ν) ≈ 2σ(anti-ν) at low energies





Нарушение CP симметрии

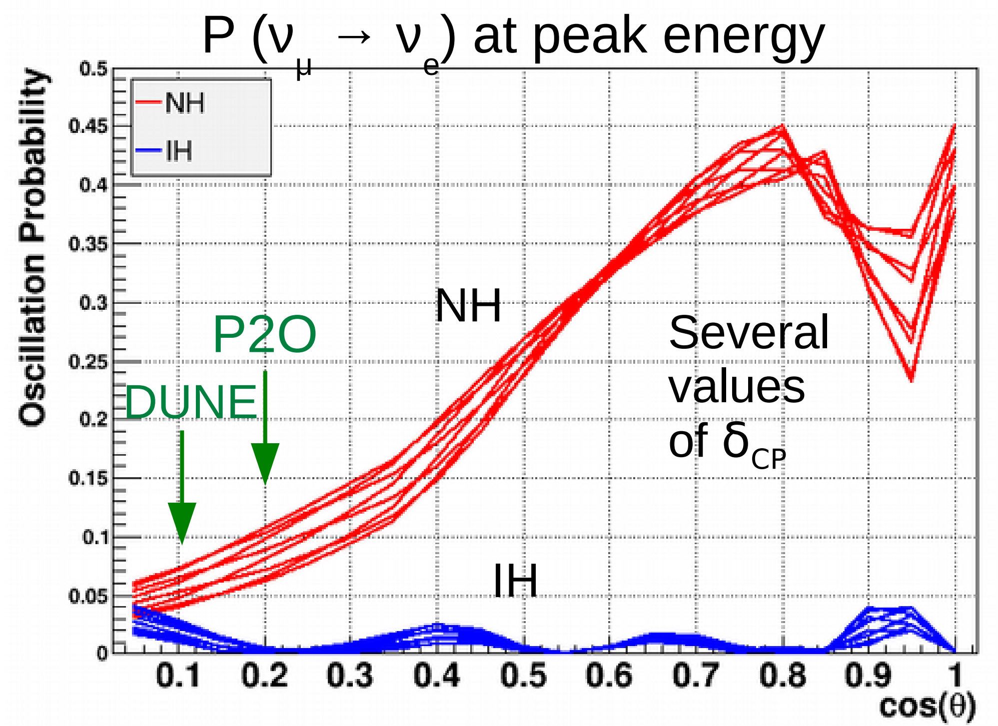
Possible source of matter-antimatter assymetry in the Universe

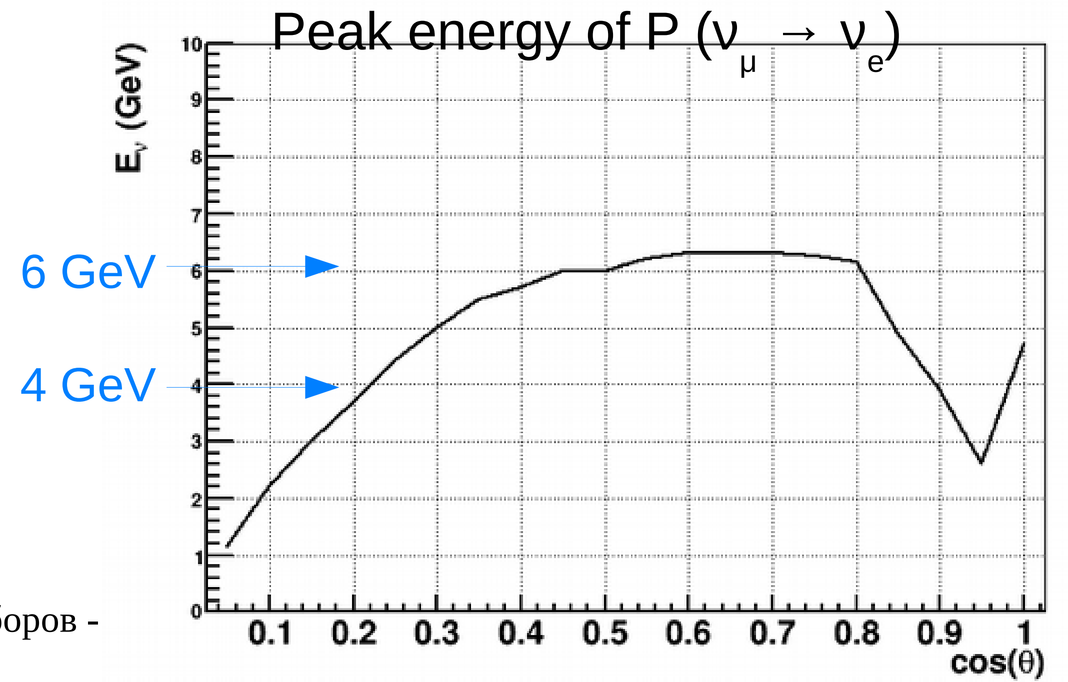
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Similar to CP phase in quark mixing (CKM matrix; Nobel prize 1980)

Mass hierarchy and CP phase effects

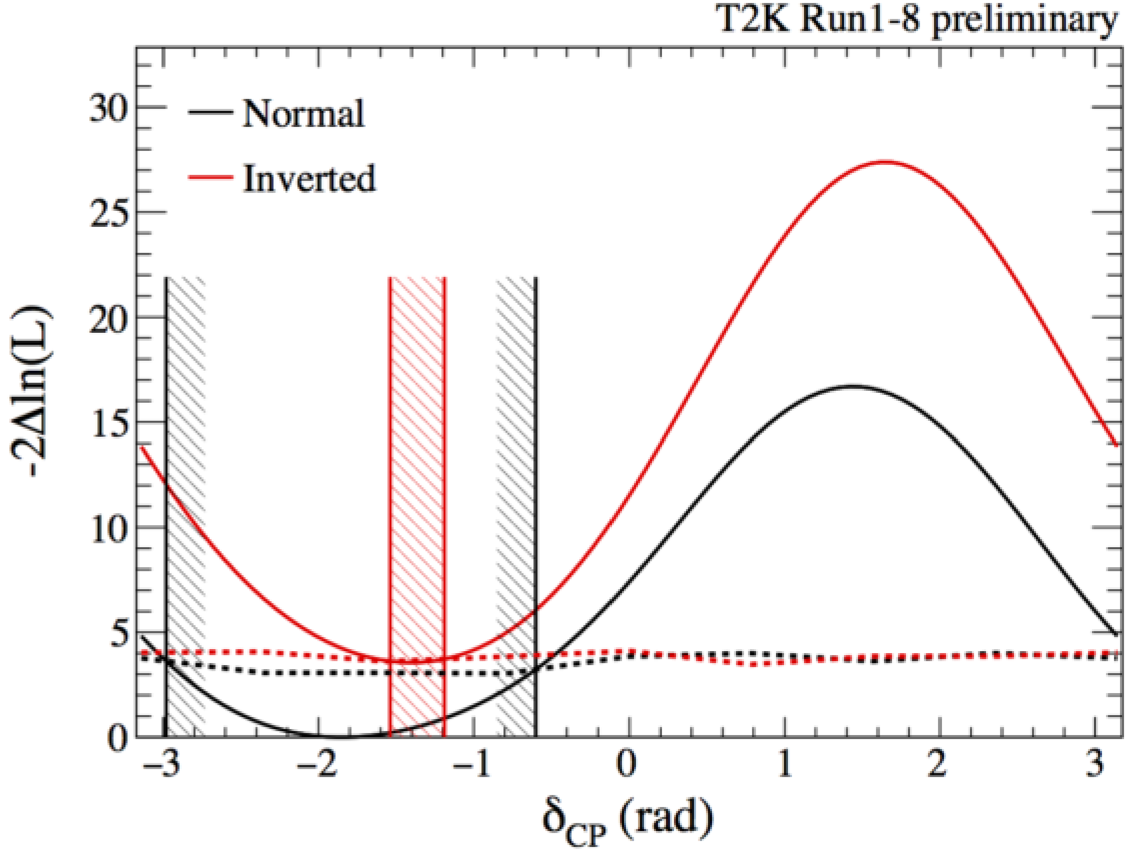
- Optimal baseline to measure mass hierarchy with beam neutrinos is between 2000 km and 4000 km
- Degeneracy between MH and δ_{CP} for L < 1000 km
- Peak energy follows initially first oscillation maximum at E = 25 GeV * cosθ
- levels off at mantle resonance energy (~ 6 GeV)





CP violation: T2K Recent result

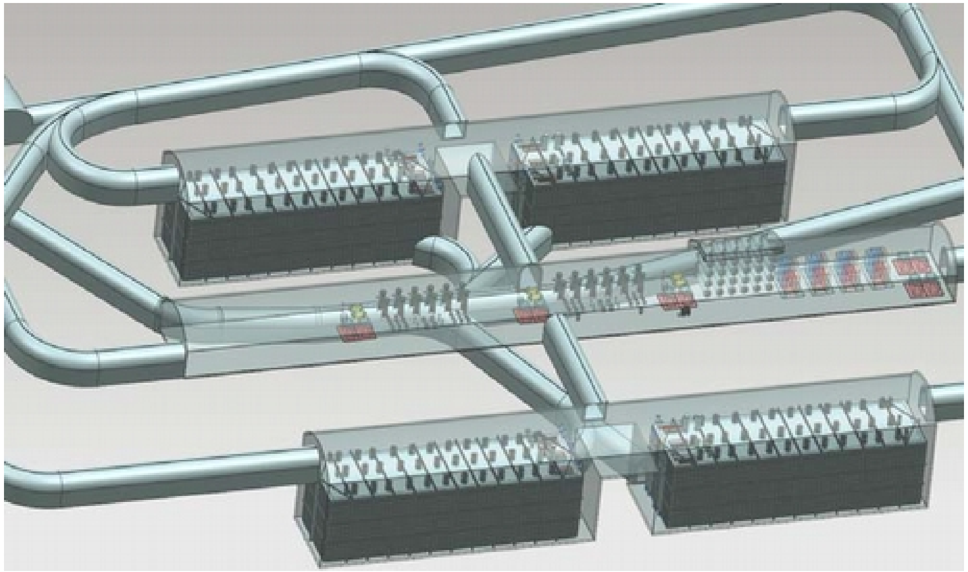
- First measurement of CP violation in the lepton sector
- 89 ν_e CC events + 7 ν_e CC (22kt)
- Preferred range of CP phase : [-171; -34 deg] (95% CL; normal hierarchy)

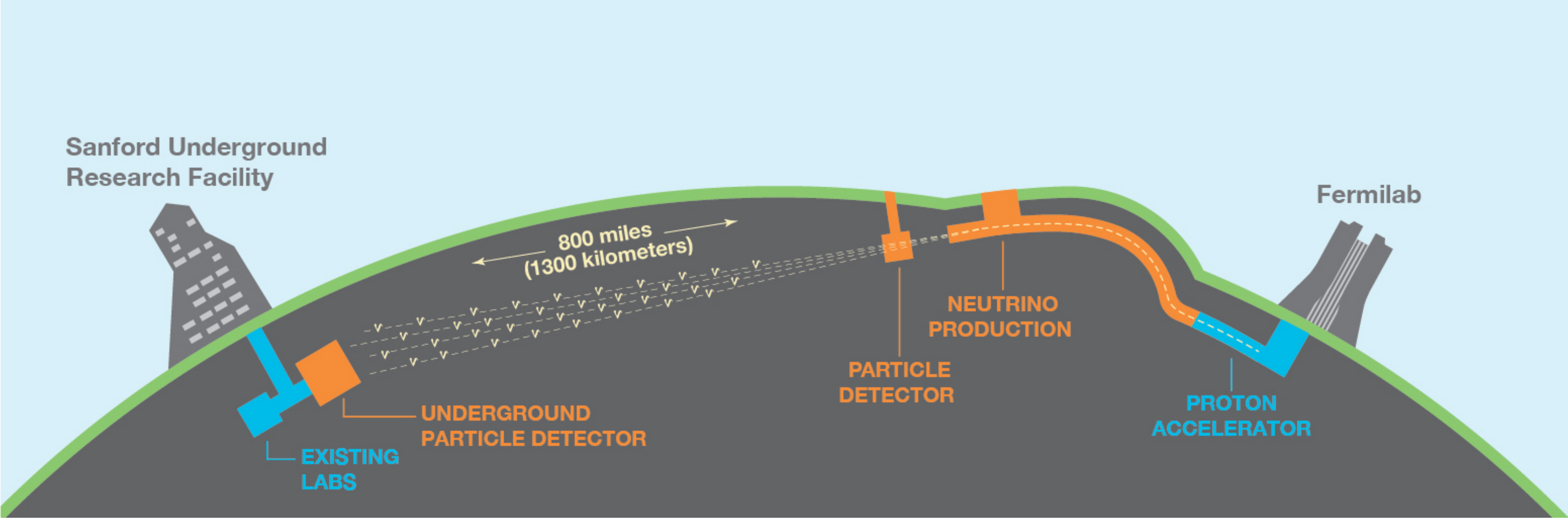


- 10x statistics planned for 2026

DUNE

- 40 kt LAr TPC + 1.2 MW beam (on-axis)
- 1300 km baseline
- Sensitivity to mass hierarchy and CP violation
- First data expected ~ 2024-2028





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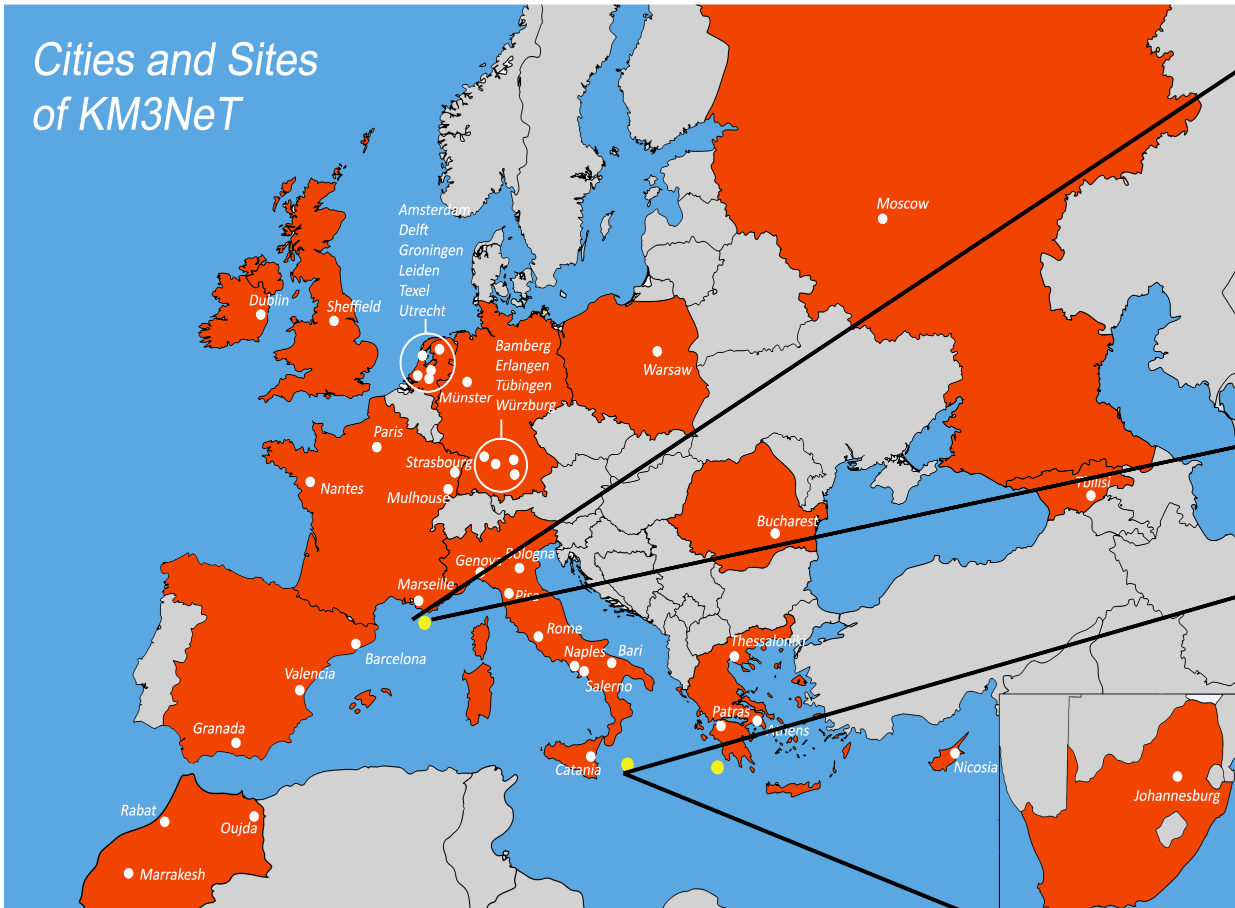
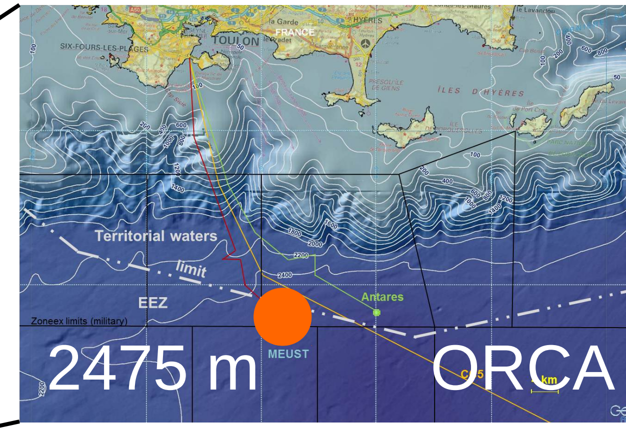
KM3NeT sites and participating countries

A distributed research infrastructure at two sites





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

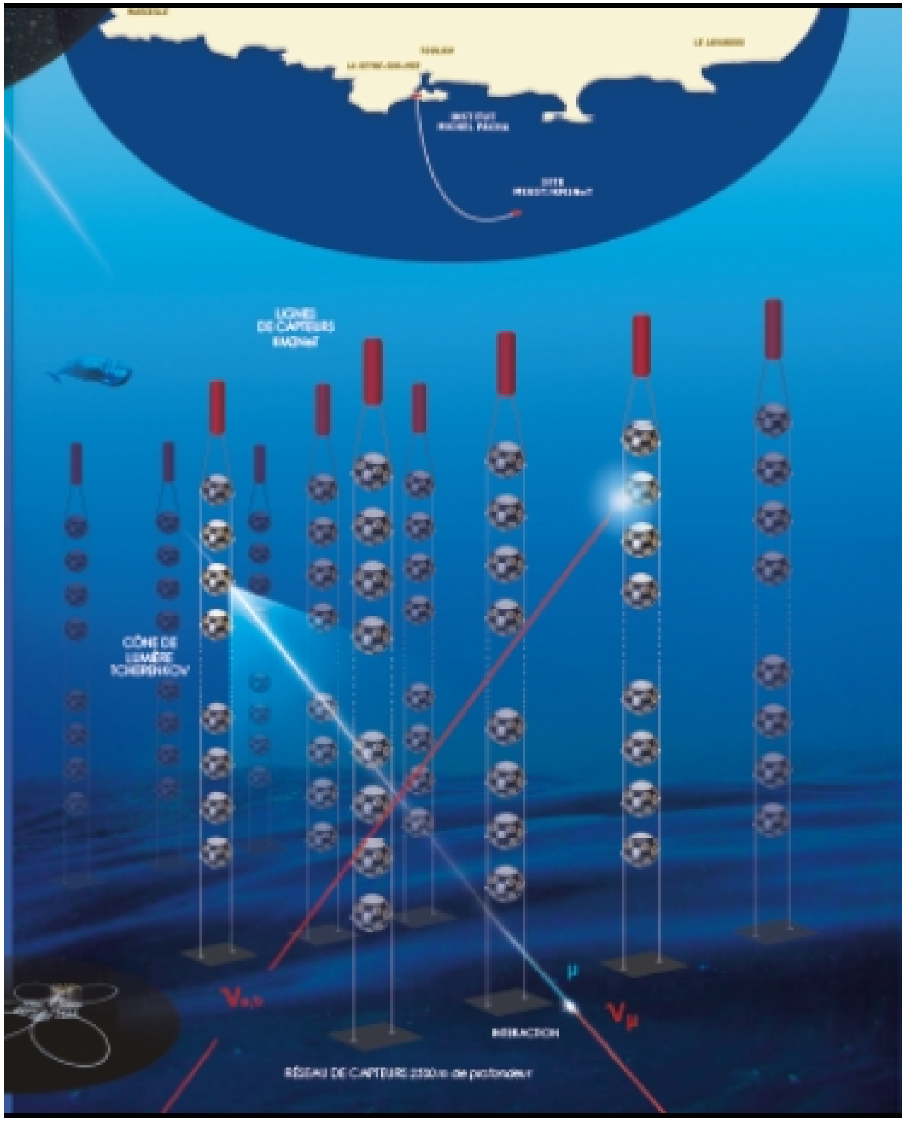
Astroparticle **R**esearch
with **C**osmics In the **A**byss

* KM3NeT = **km³ N**eutrino **T**elescope

Single Collaboration, Single Technology

KM3NeT technology

Sea water serves as target material and Cherenkov radiator

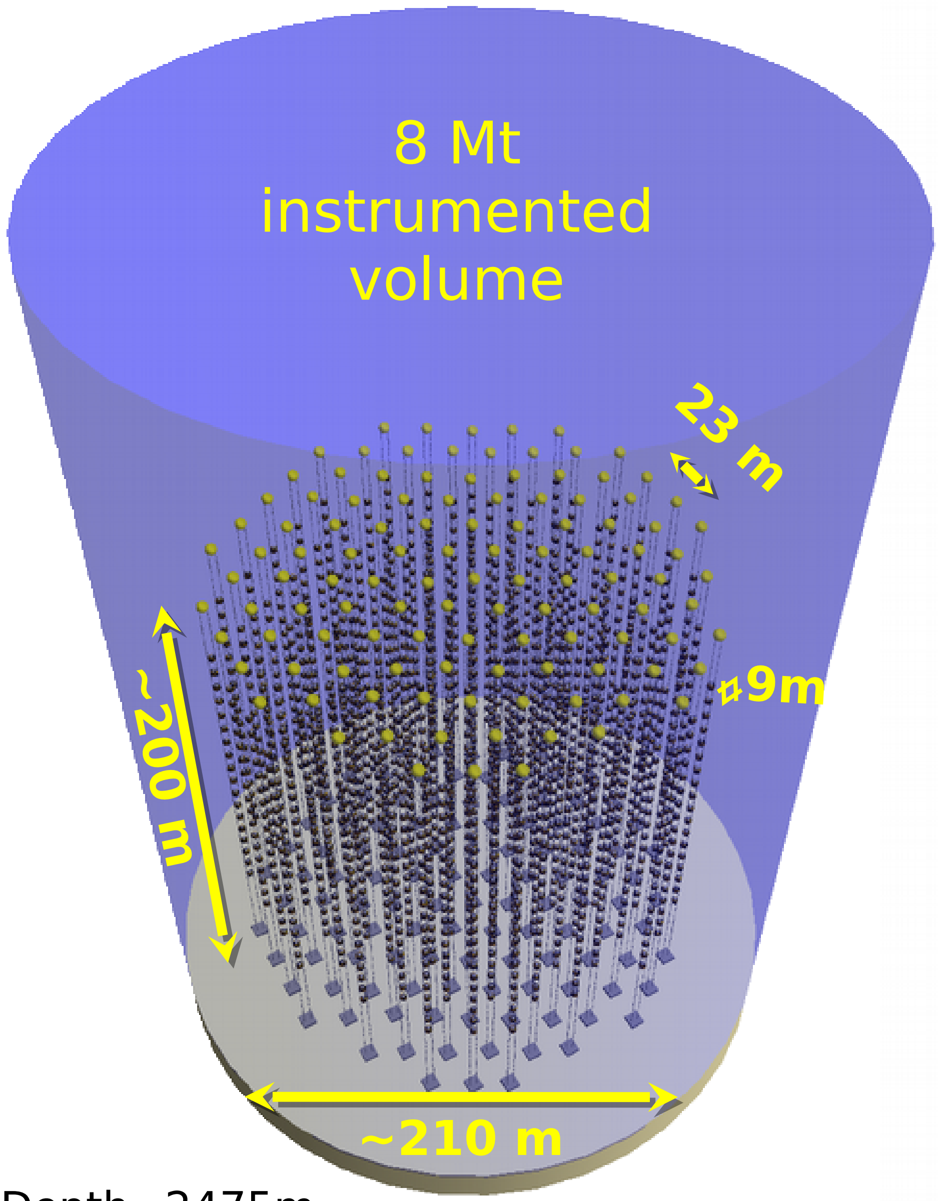


Digital Optical Module (DOM)

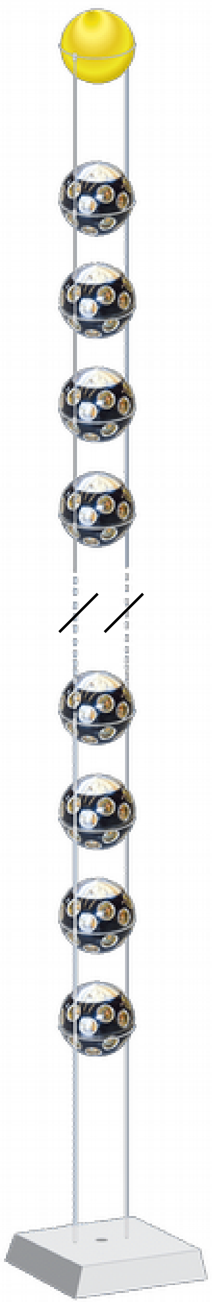
31 3-inch PMTs in 17” glass sphere

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

KM3NeT - ORCA



Depth=2475m



115 strings
18 DOMs / string
31 PMTs / DOM
Total: **64 000 PMTs (3”)**
(2070 DOMs)

Vertical spacing: 9 m
Horizontal spacing: 23 m

Light absorption length ~ 60 m

Volume of water viewed
by one DOM ~ 3 kt

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

Key mission: determine
neutrino mass hierarchy

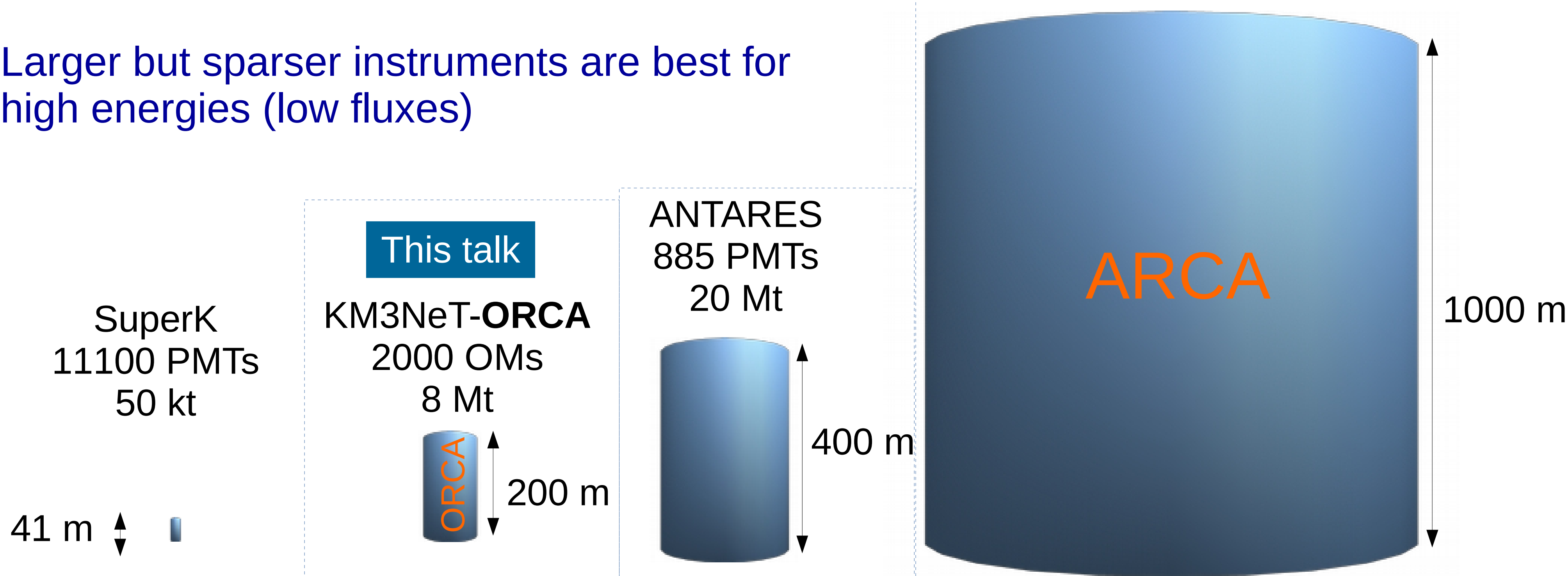
Instrumented volume

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

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

This talk

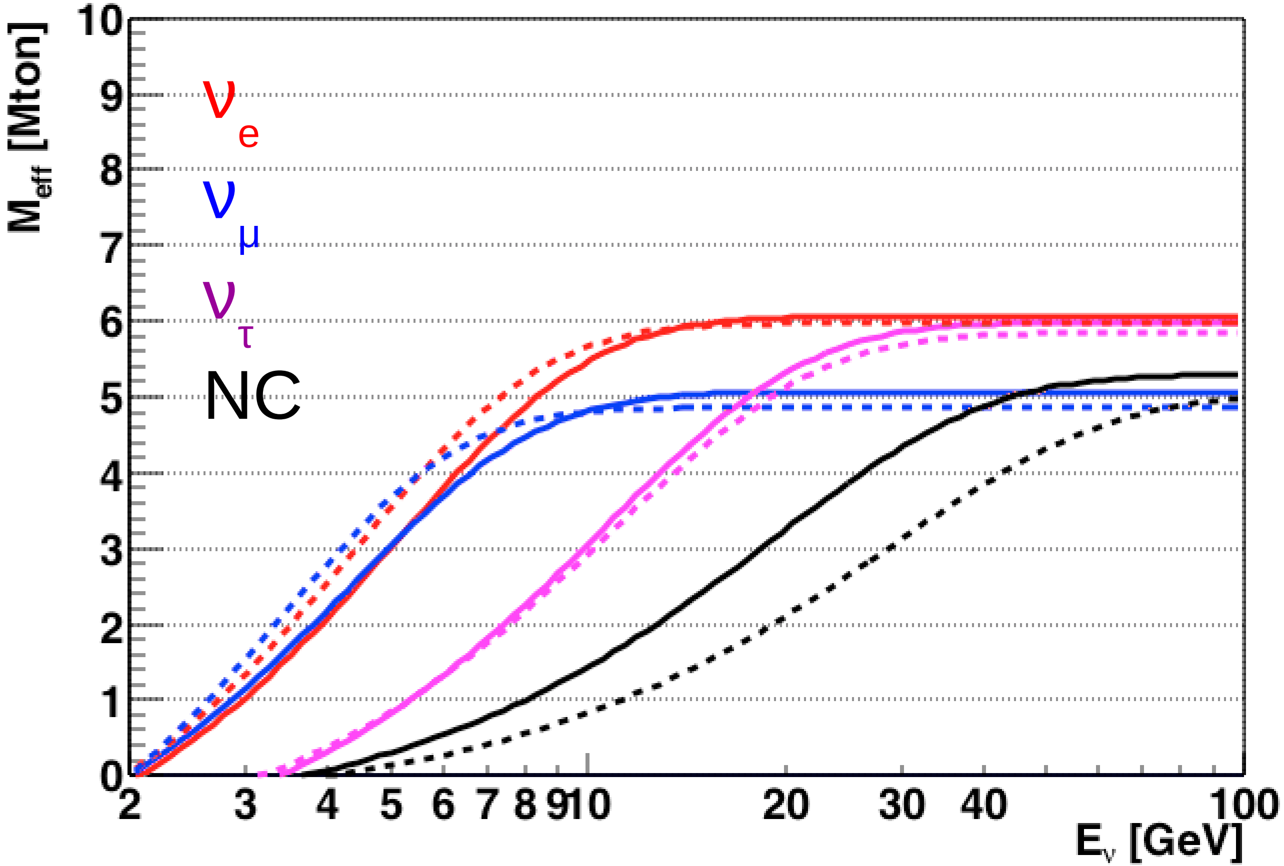
SuperK	KM3NeT-**ORCA**	ANTARES	KM3NeT-**ARCA**
11100 PMTs	2000 OMs	885 PMTs	4000 OMs (128 000 PMTs)
50 kt	8 Mt	20 Mt	1 Gt
MeV - GeV	E > 3 GeV	E > 20 GeV	E > 100 GeV
Solar & atm. ν	atm. ν	astrophysical and atm. ν	astrophysical ν
operating for 20 yr	under construction	operating for 10 yr	under construction



IceCube & Baikal-GVD have similar size

Effective mass

After triggering, atmospheric muon rejection and containment cuts



Atmospheric neutrino events/yr:

ν_e CC: 17,300

ν_μ CC: 24,800

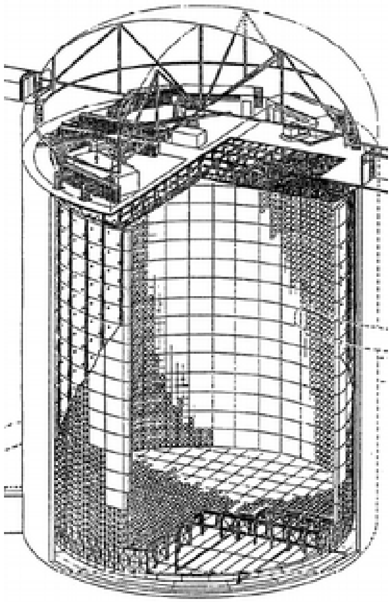
ν_τ CC:3,100

NC: 5,300

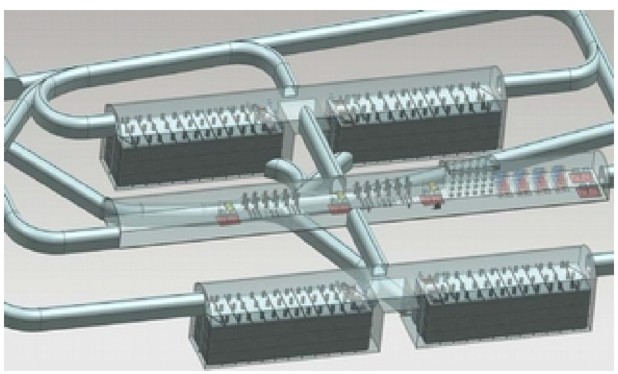
- Energy threshold determined by DOM spacing
- 1 Mton @ 3 GeV
- 6 Mton @ 10 GeV

Effective mass

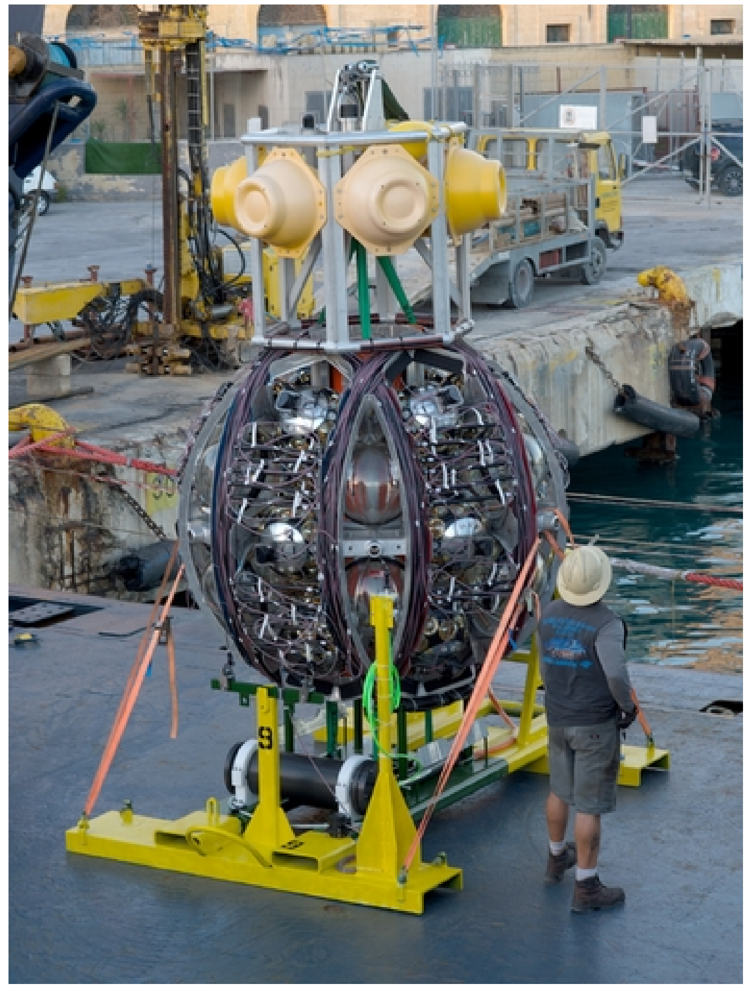
SuperK: 50 kt



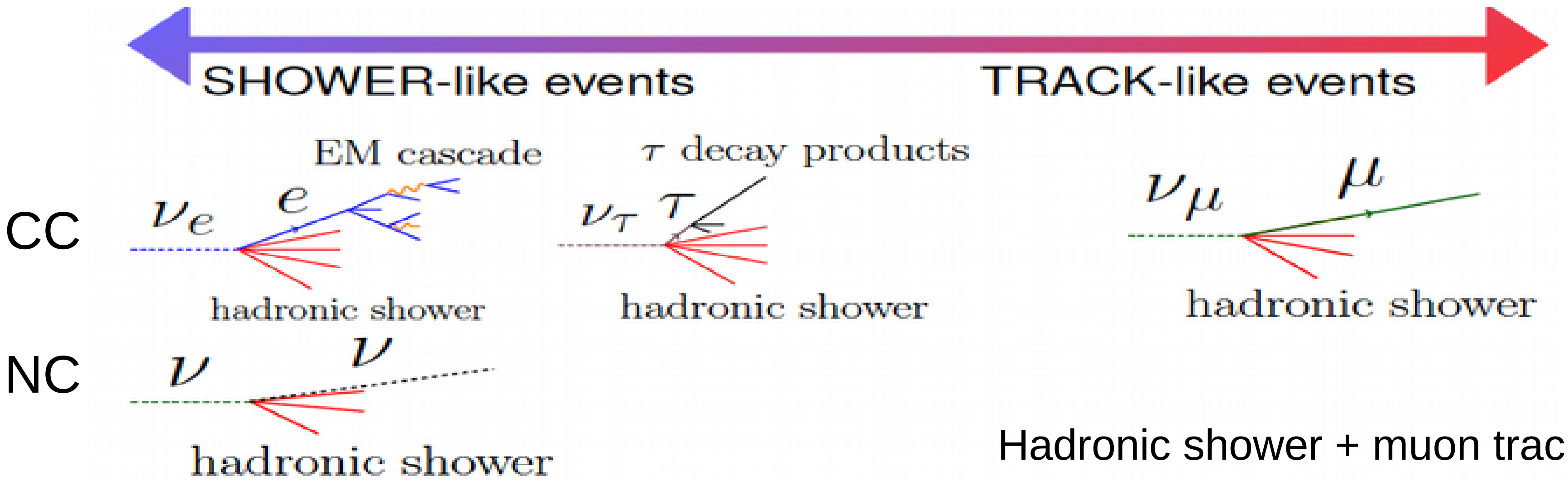
DUNE: 40 kt



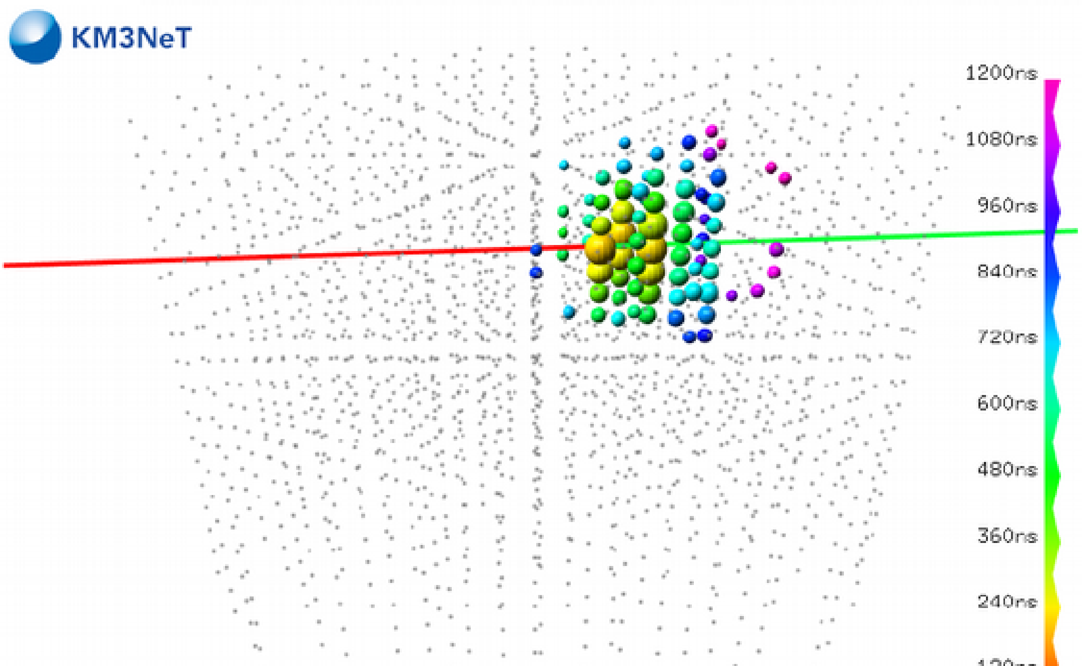
One ORCA line
~ 30 kt @ 5 GeV
~ 60 kt @ 10 GeV



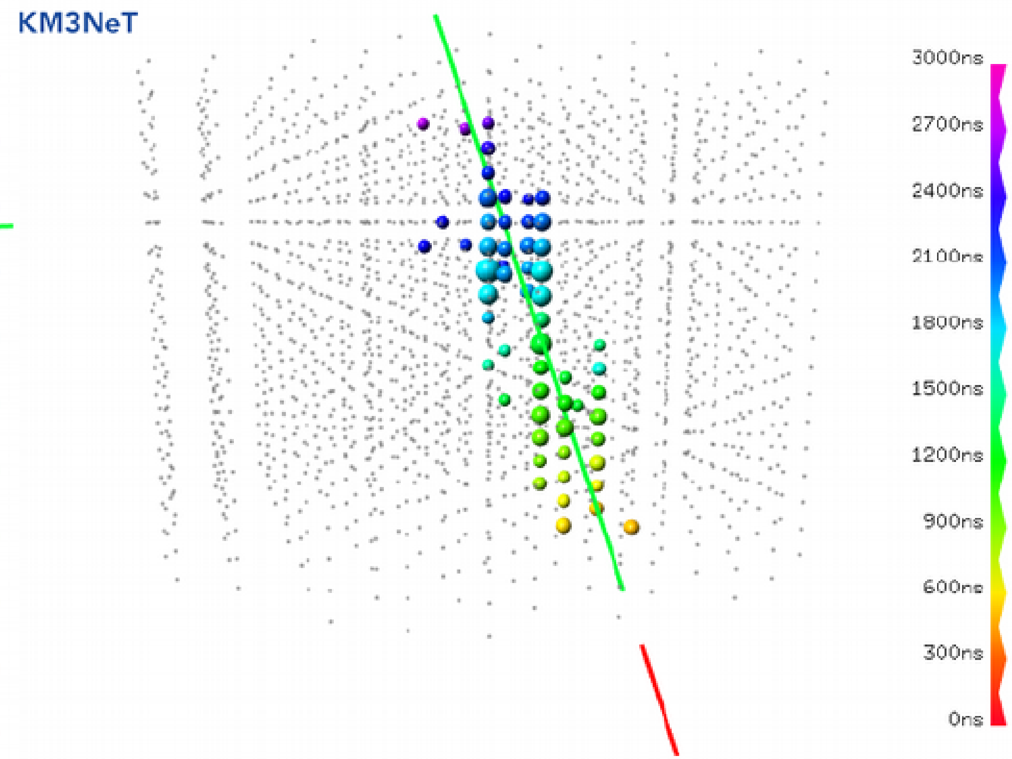
Particle ID



Hadronic shower + muon track

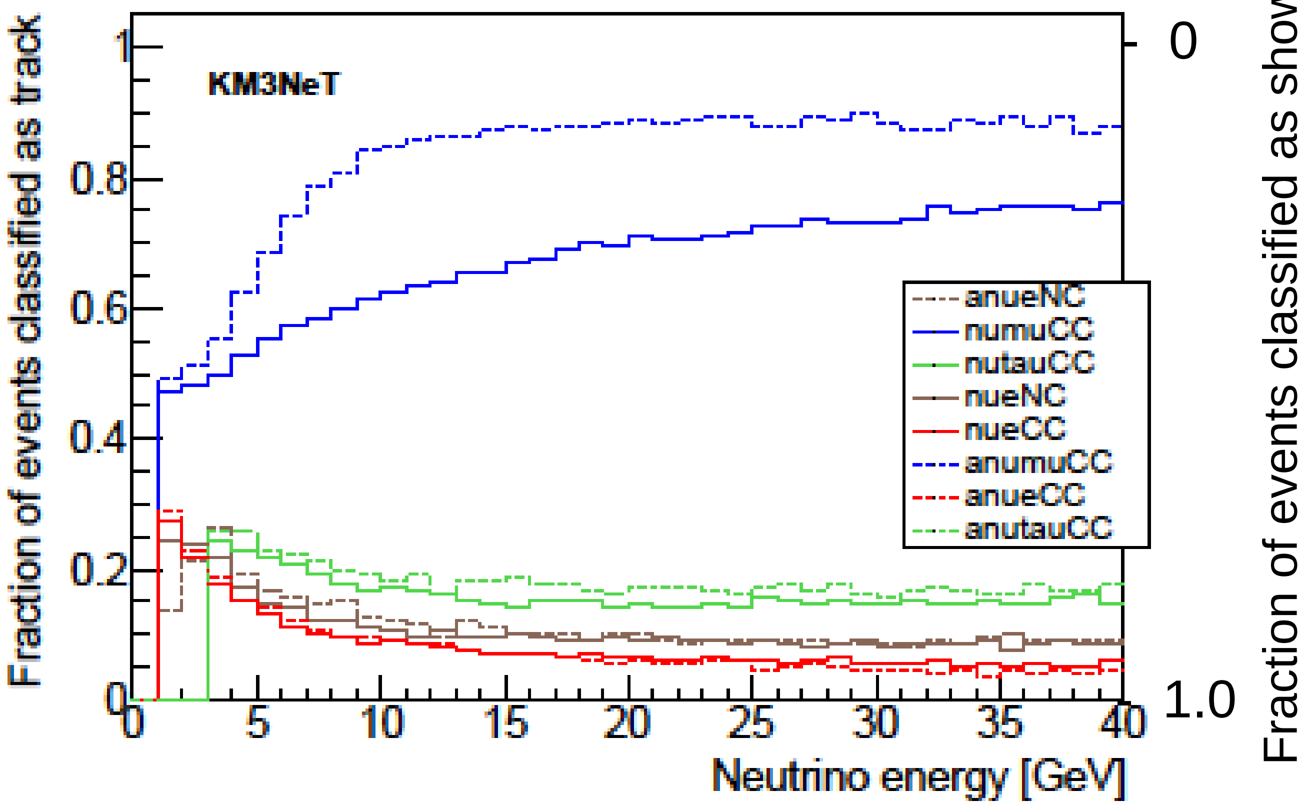


ARCA simulated event (ORCA similar)



Particle ID performance

Track / Shower event classification

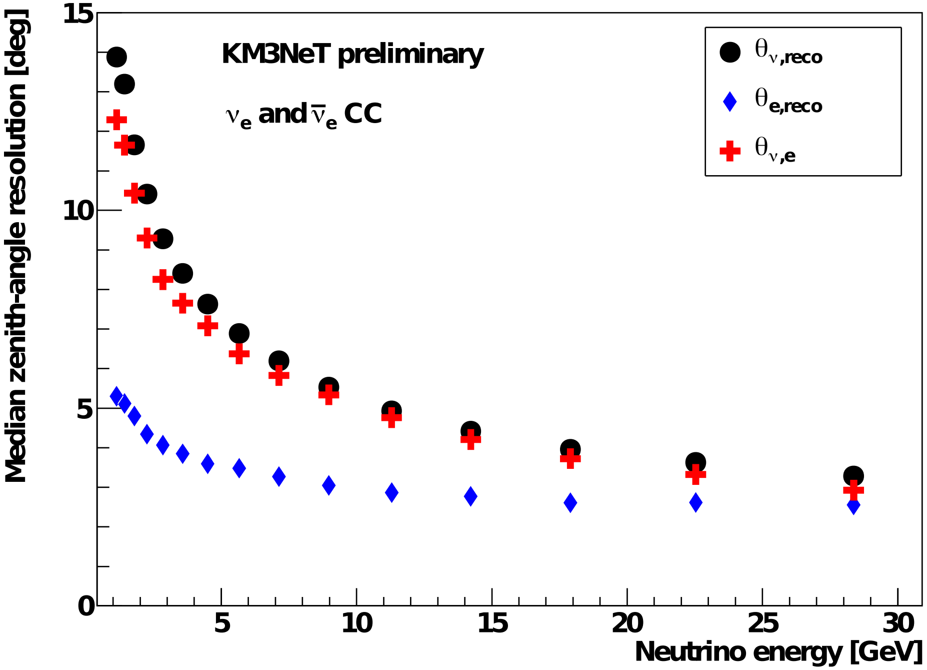


At 10 GeV:

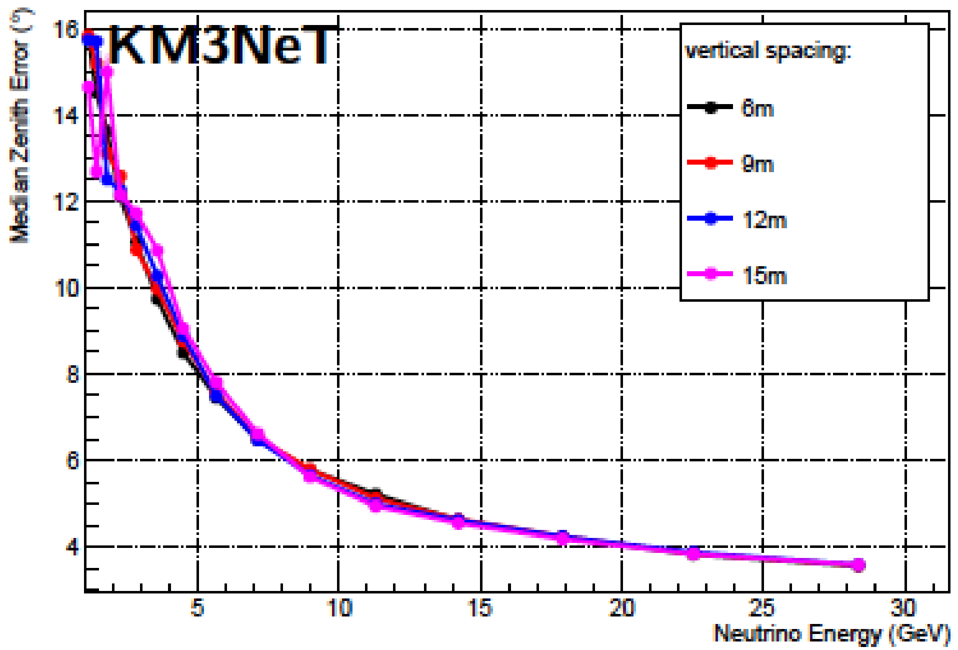
- 90% correct ID of n_e^{CC}
- 70% correct ID of n_m^{CC}

Zenith angle resolution

Showers



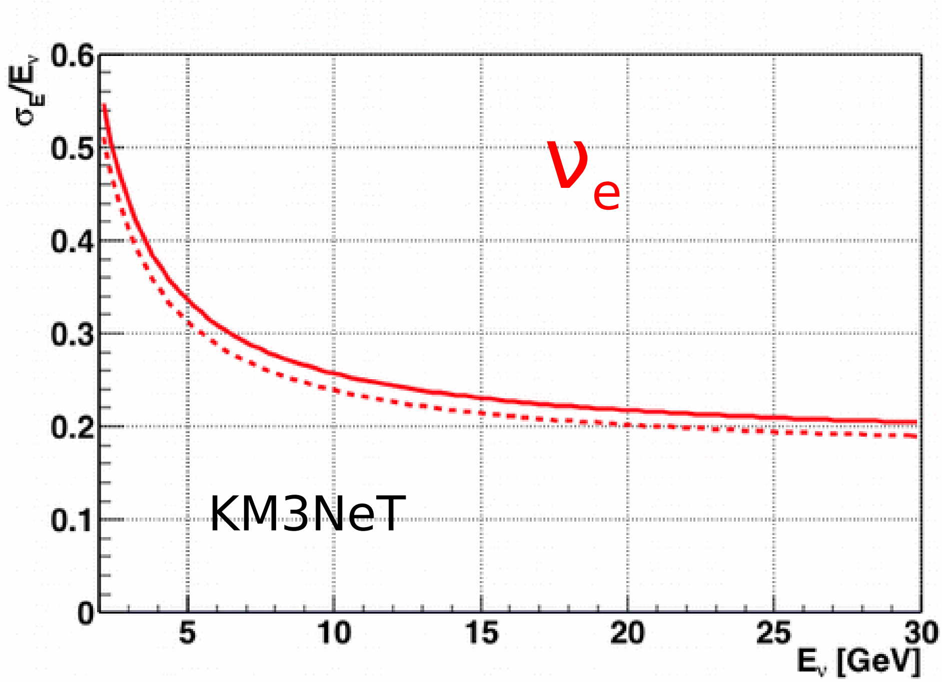
Tracks

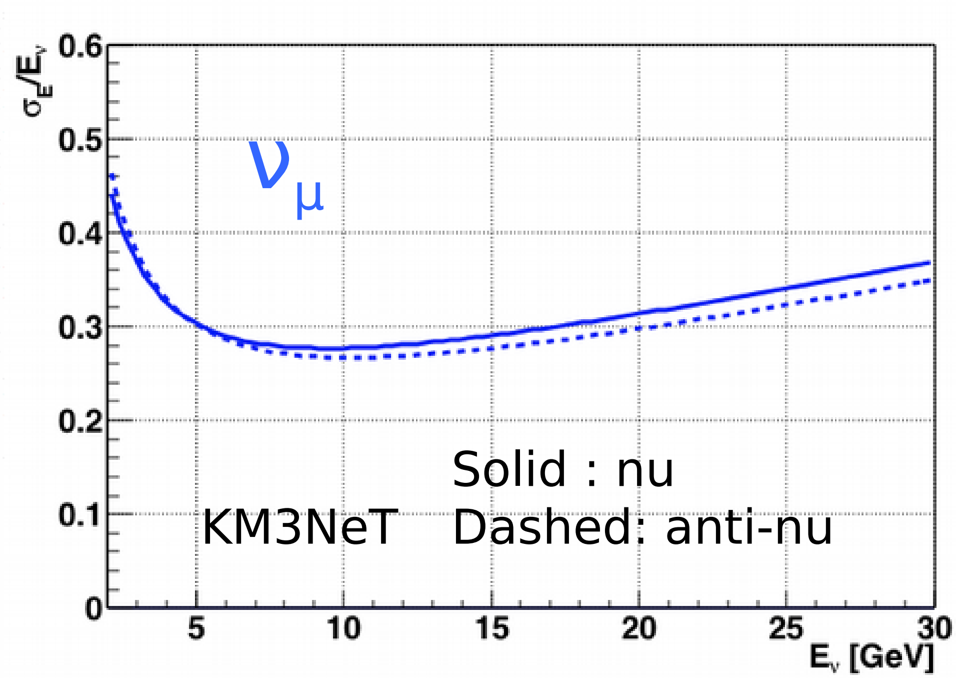


~ 5° error on zenith for 10 GeV neutrinos for both track and shower channels

Limited by interaction kinematics (neutrino – lepton angle)

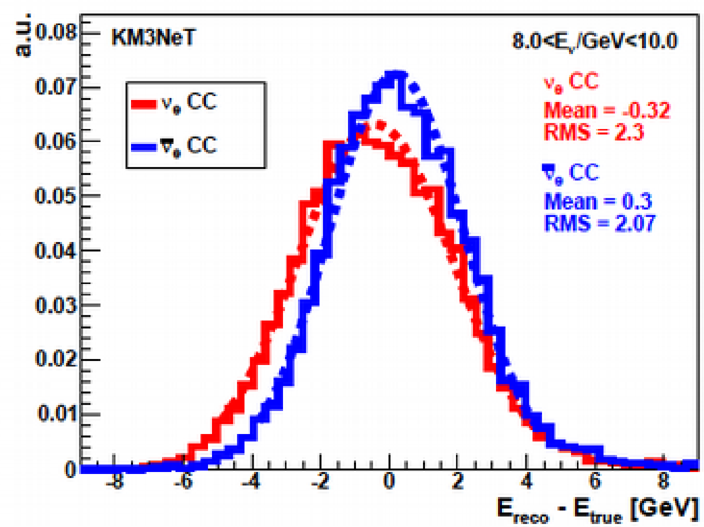
Energy resolution





Energy resolution better than 30% in relevant range

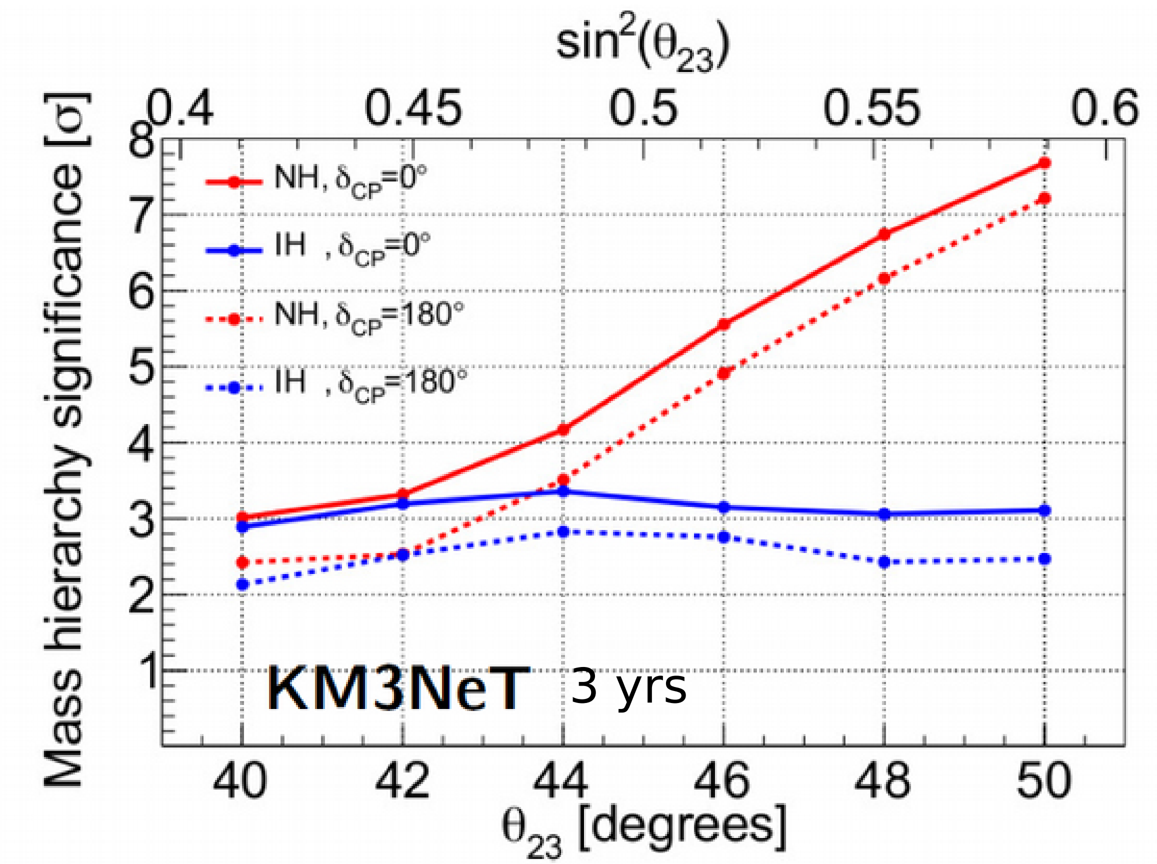
Distribution close to Gaussian



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 theta23)

Recent T2K result on theta23:

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

(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

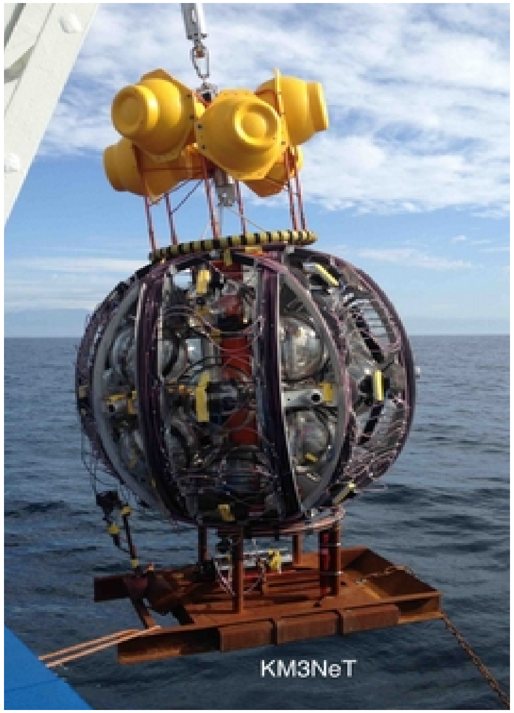
Construction status: sea infrastructure

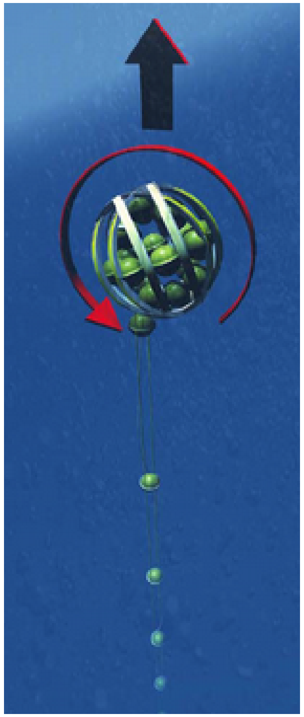
Main electro-optical cable deployed
December 2014

Node1 (Junction Box) deployed
April 2015

KM3NeT detection unit at a test facility

Deployment Scheme





Shown is deployment of ARCA line (ORCA similar)

First ORCA line deployd Sep 2017

Watch:

https://youtu.be/7HKHW0hLxt4

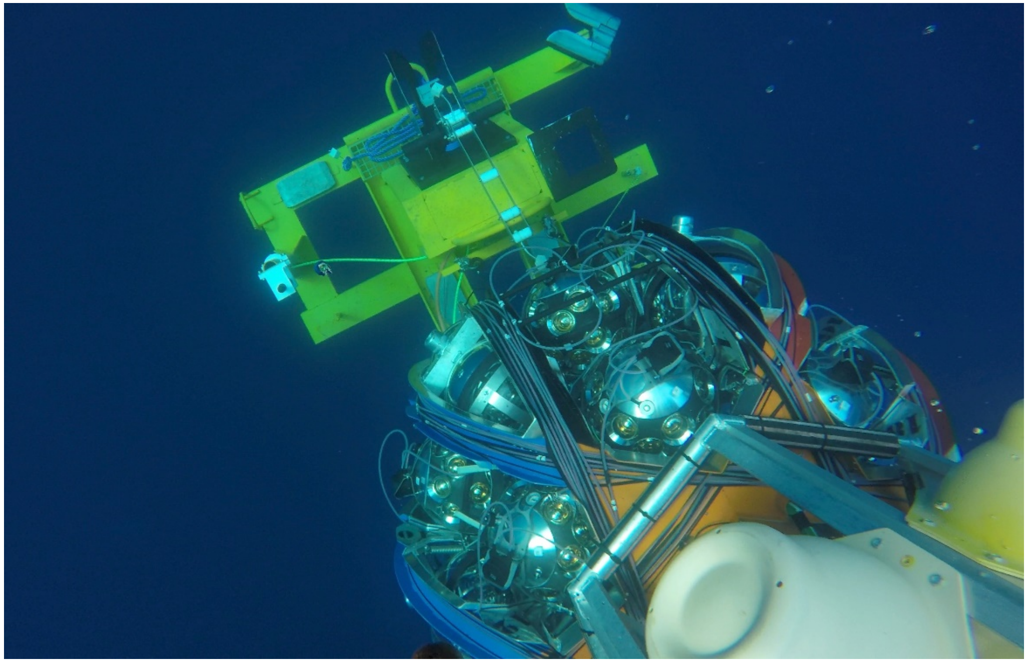
https://youtu.be/g2Y0KD3kdXs

https://youtu.be/xTj4lLMv1Fw

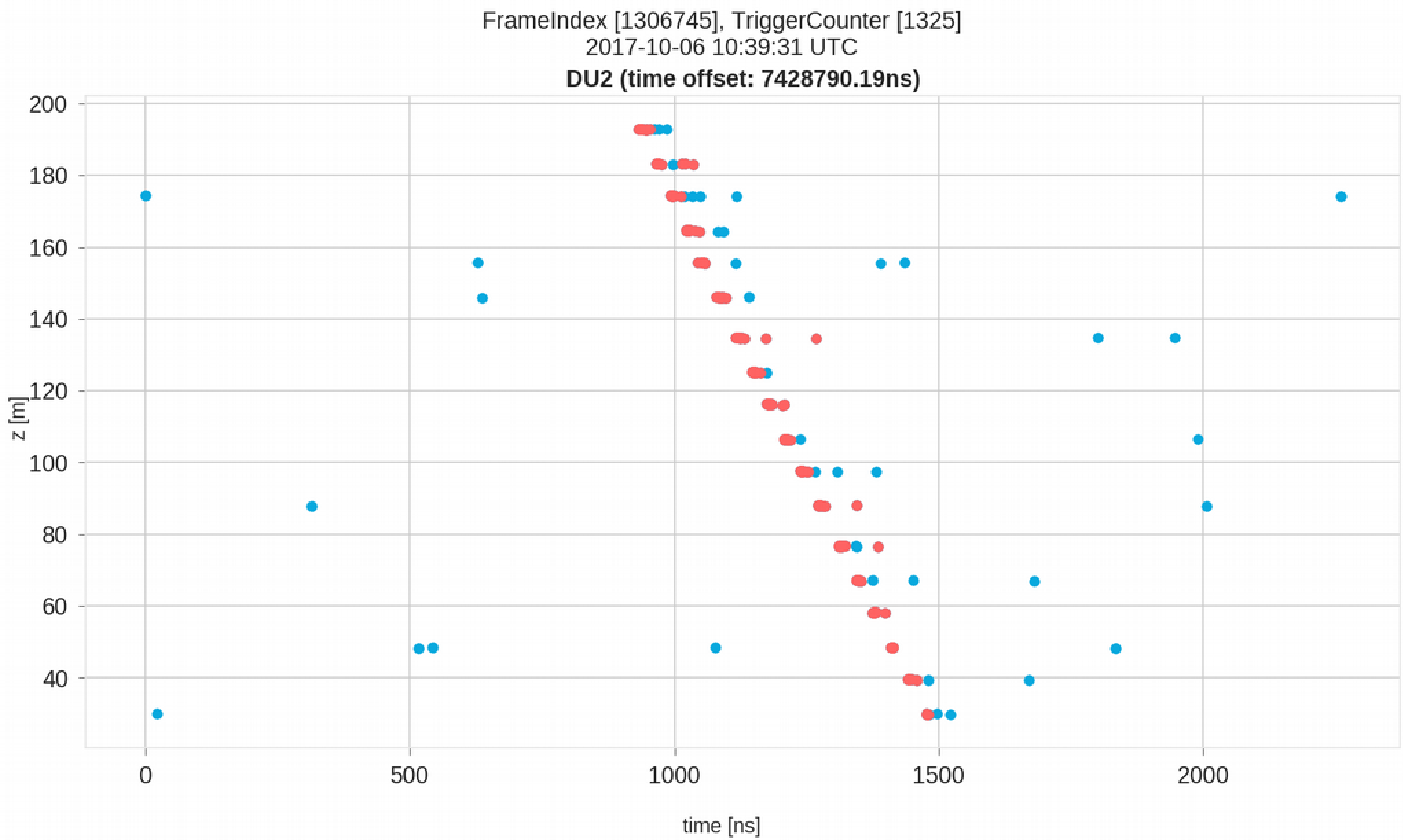
https://youtu.be/XFPCfCoTfUg

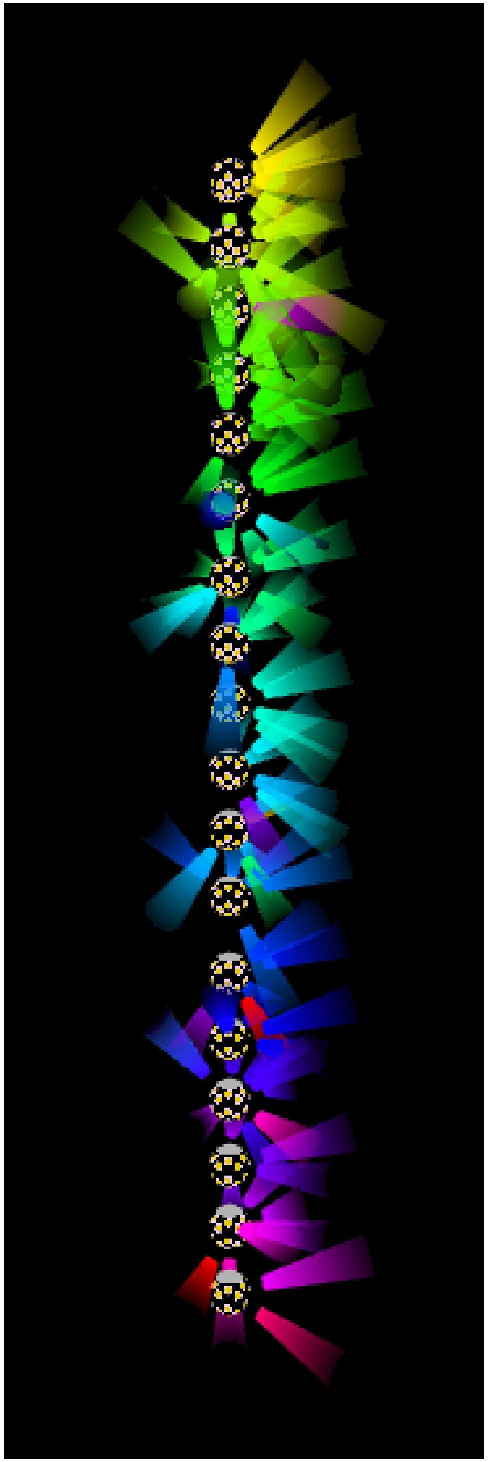
First ORCA DU

- 22/9/2017 : First DU successfully deployed and connected

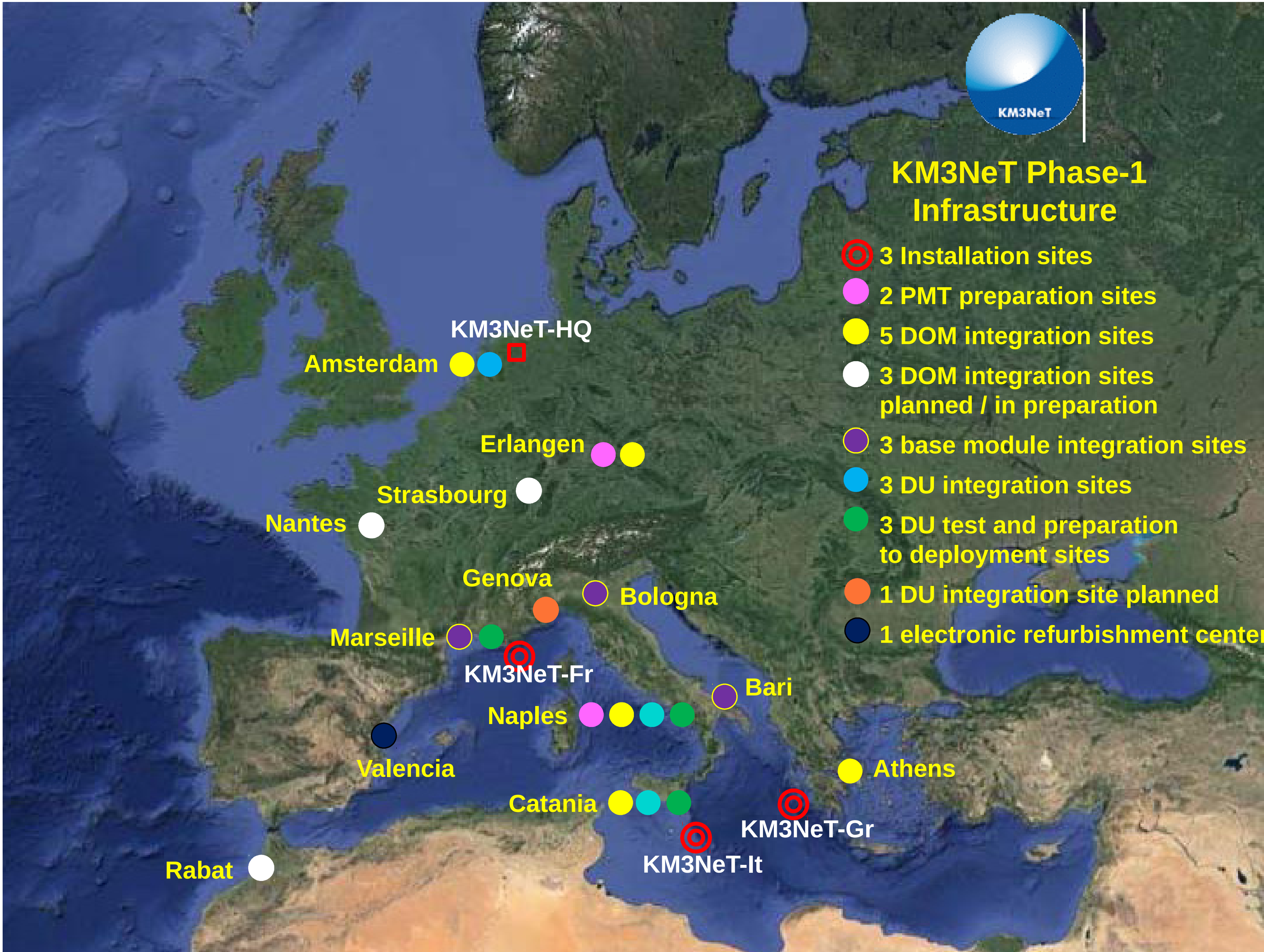


Example atmospheric muon





Another example


KM3NeT Phase-1 Infrastructure
3 Installation sites
2 PMT preparation sites
5 DOM integration sites
3 DOM integration sites planned / in preparation
3 base module integration sites
3 DU integration sites
3 DU test and preparation to deployment sites
1 DU integration site planned
1 electronic refurbishment center
KM3NeT-HQ
Amsterdam
Erlangen
Strasbourg
Nantes
Genova
Bologna
Marseille
KM3NeT-Fr
Bari
Naples
Valencia
Athens
Catania
KM3NeT-Gr
KM3NeT-It
Rabat

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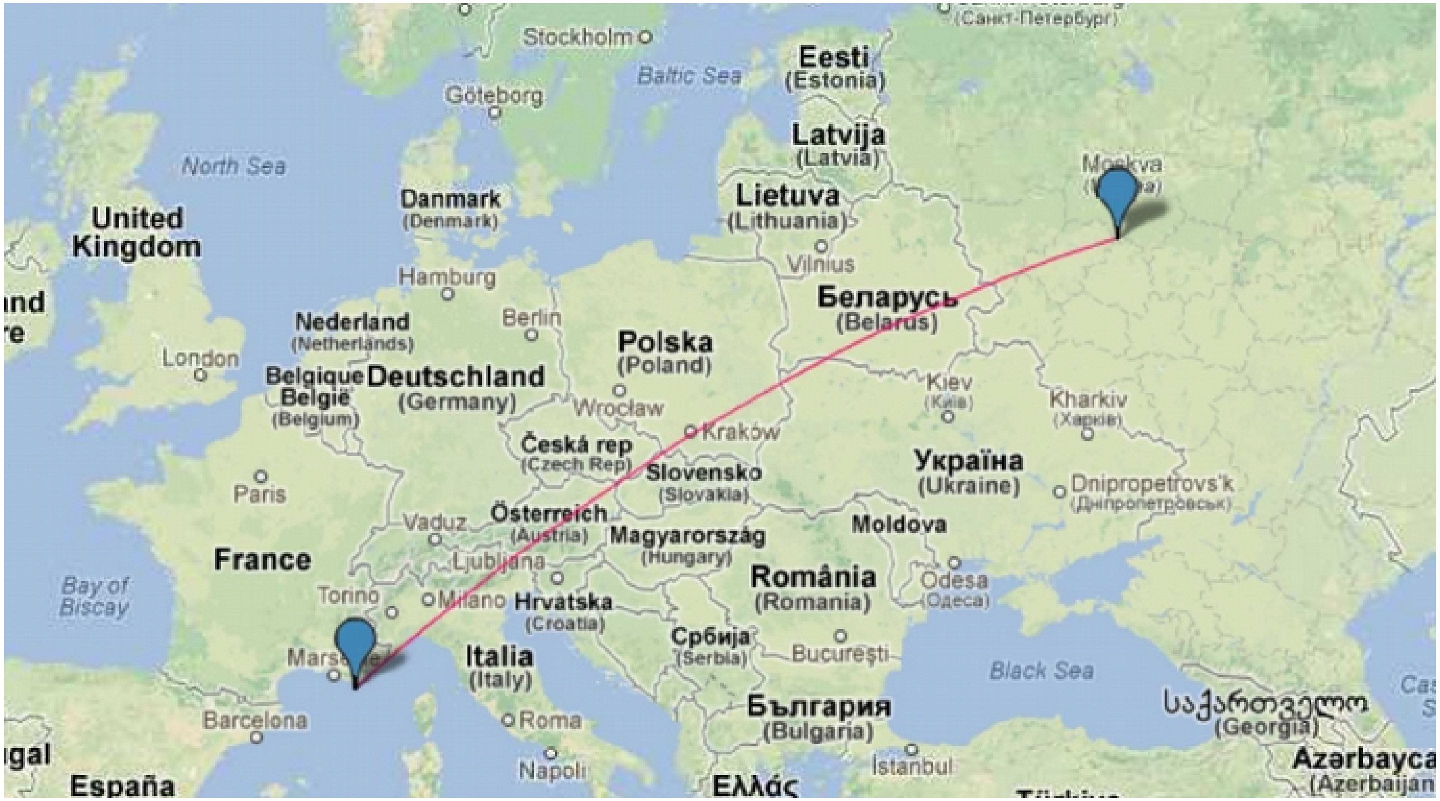
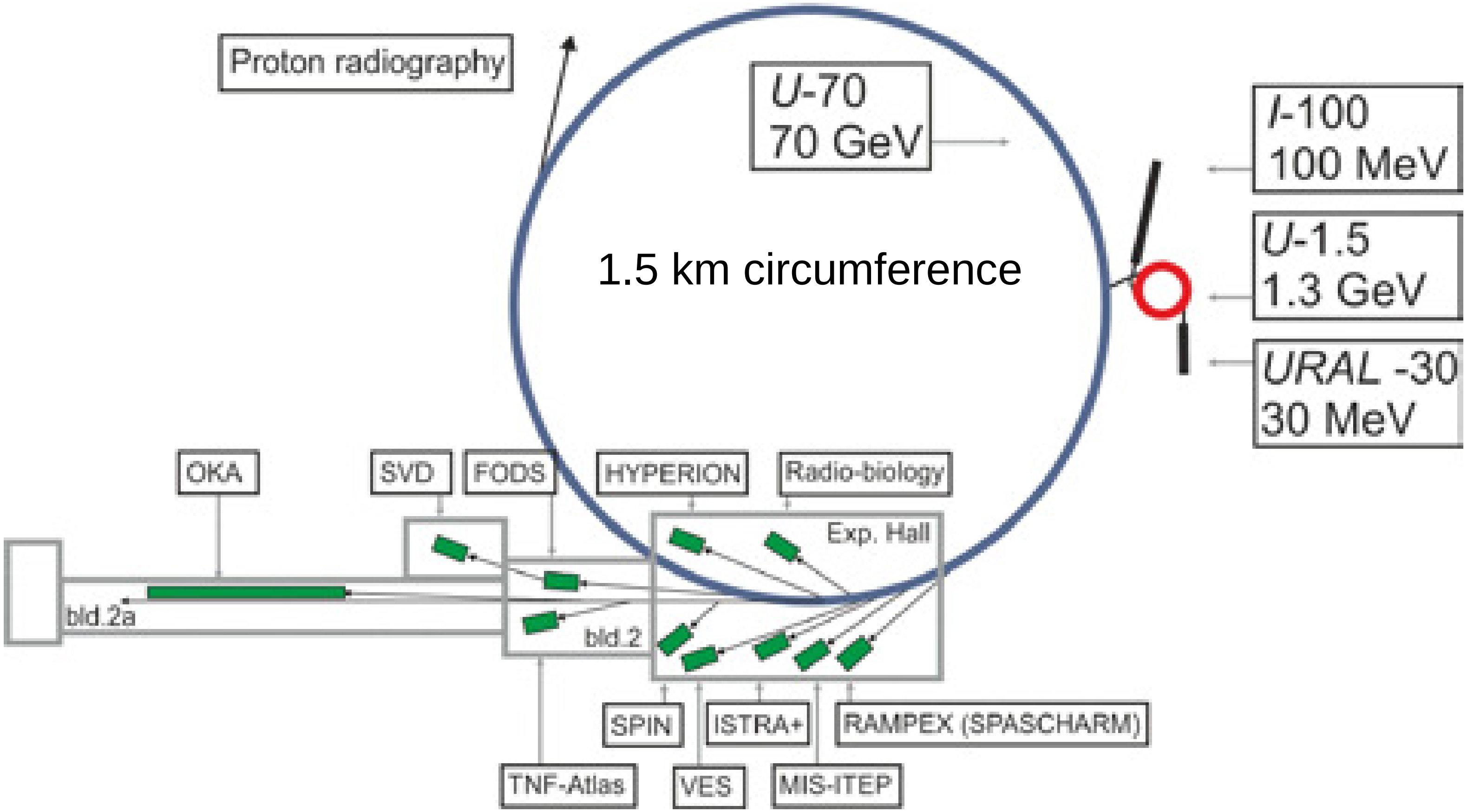
P2O : Protvino to ORCA

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



J. Brunner, arXiv:1304.6230; Adv. High En. Phys., 2013, Art. 782538,
http://dx.doi.org/10.1155/2013/782538,
D. Zaborov et al., Lomonosov conference, Moscow, August 2017

Protvino accelerator complex
(100 km South of Moscow)



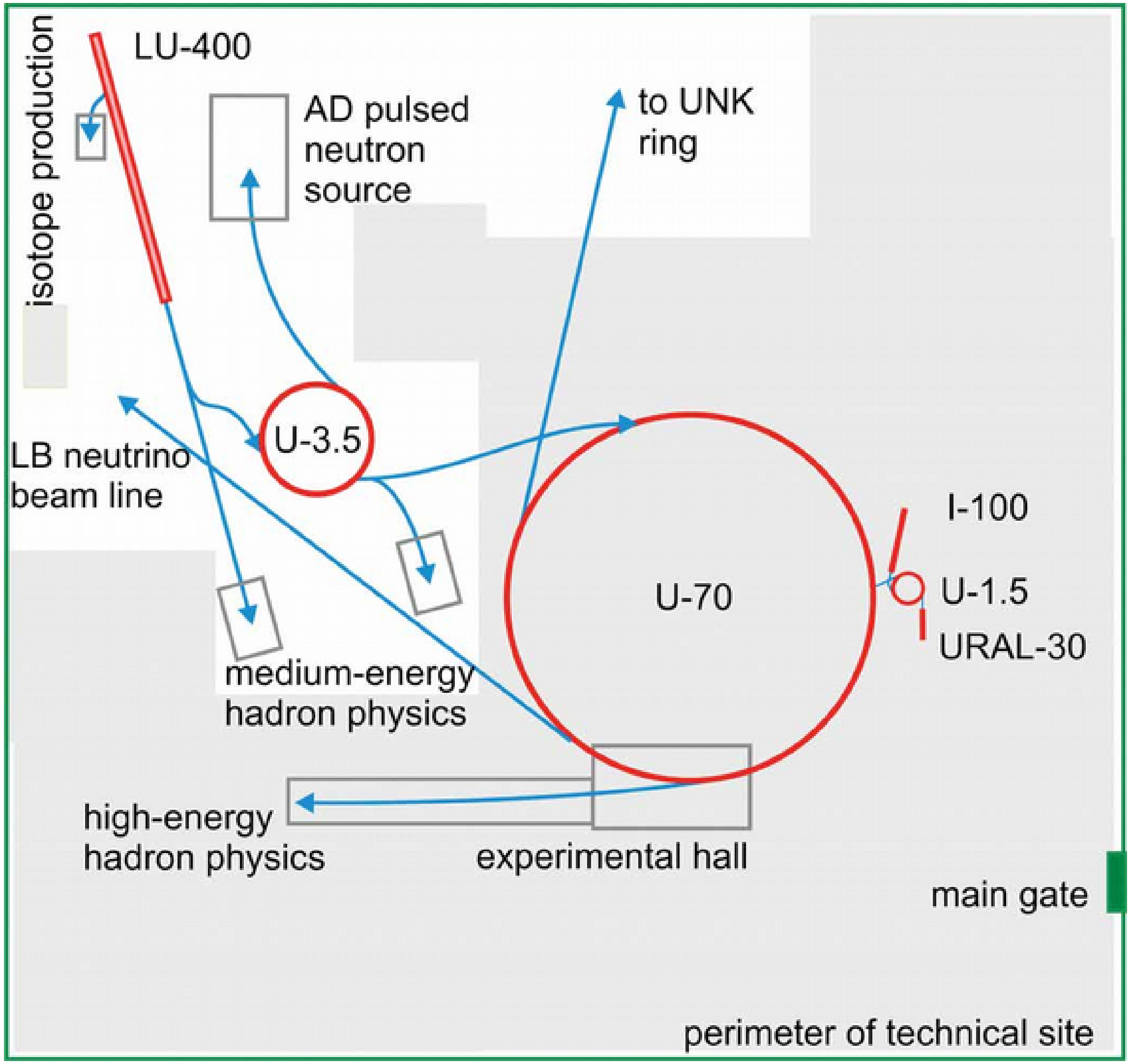
1-turn fast extraction:
5 μs spill every 9 s

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

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

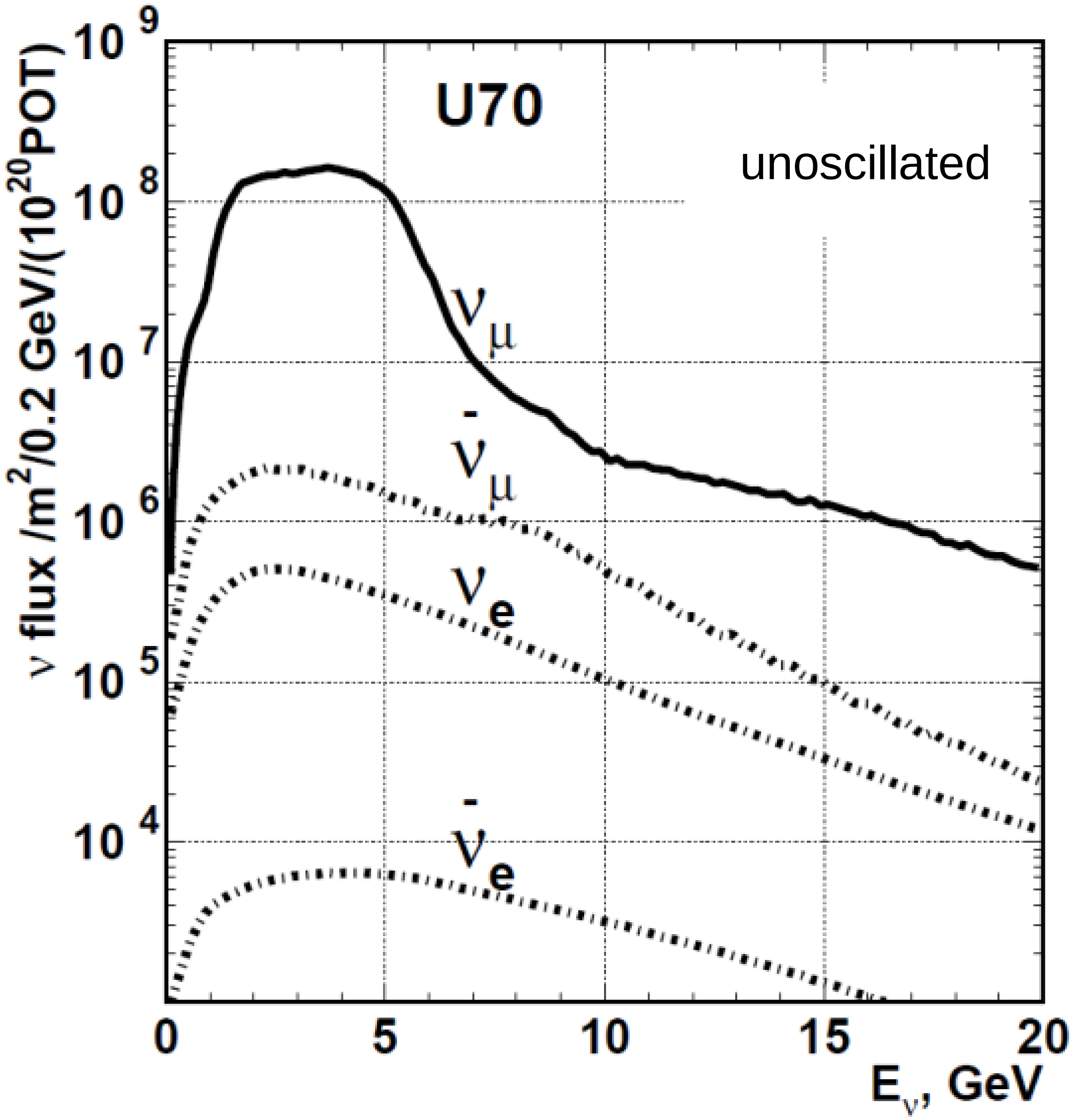
The OMEGA project proposal

- New high intensity linac and booster synchrotron (3.5 GeV), 1.1 MW proton beam
- High-intensity spallation neutron source (similar to J-PARC in Japan and SNS in USA)
- 450 kW power at 70 GeV using existing U-70 synchrotron
- A long baseline neutrino beam



N.E. Tyurin et al, Facility for intense hadron beams (letter of intent), News and Problems of Fundamental Physics 2 (9), 2010, http://exwww.ihep.su/ihep/journal/IHEP-2-2010.pdf

Simulated Neutrino Beam



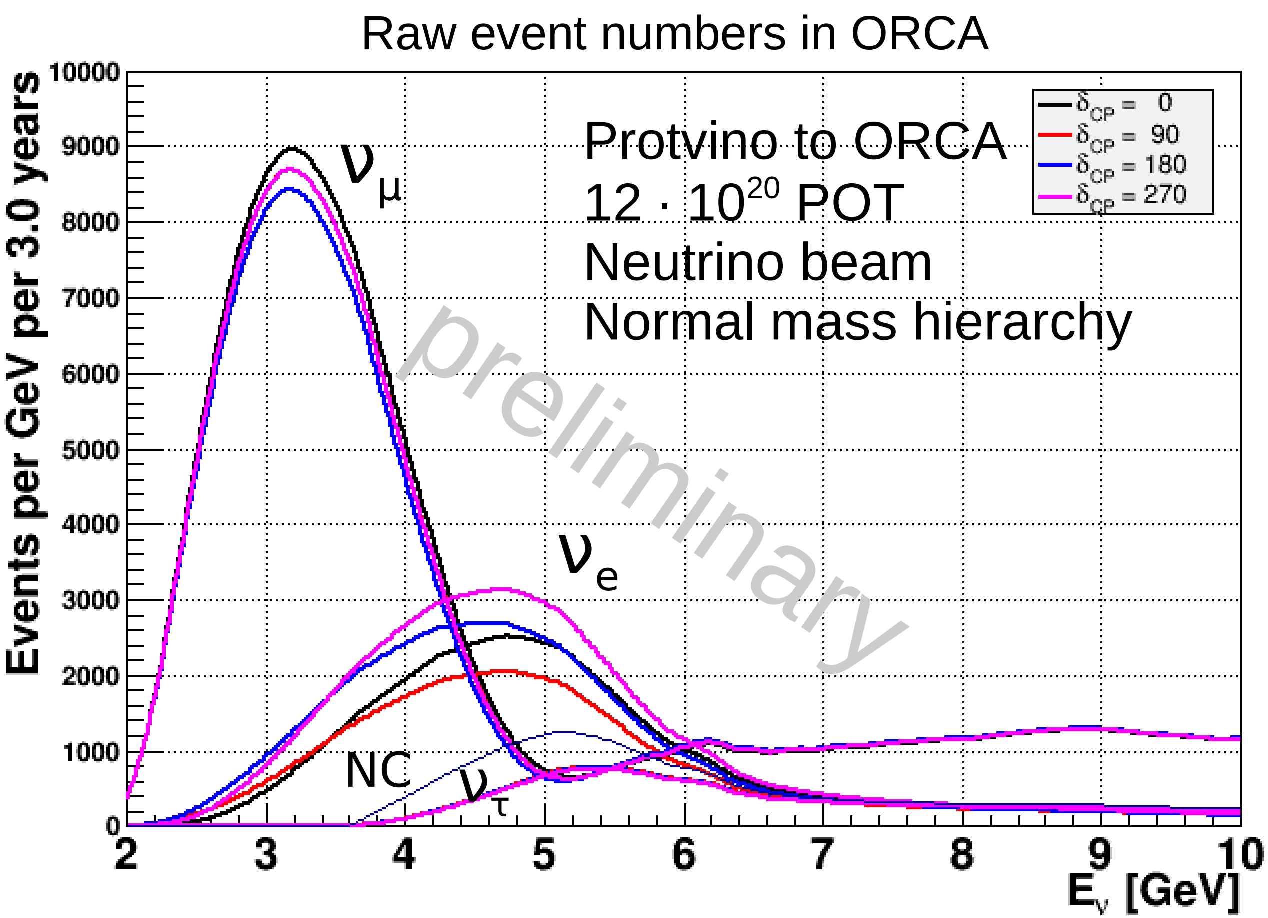
Beam spectra from *V. Garkusha, F. Novoskoltsev & A. Sokolov, Study of Neutrino Oscillations with the U-70 Accelerator Complex, IHEP Preprint 2015-5* – beam optimized for Protvino-Gran Sasso (on-axis)

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

3 yr * 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 / 3 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)

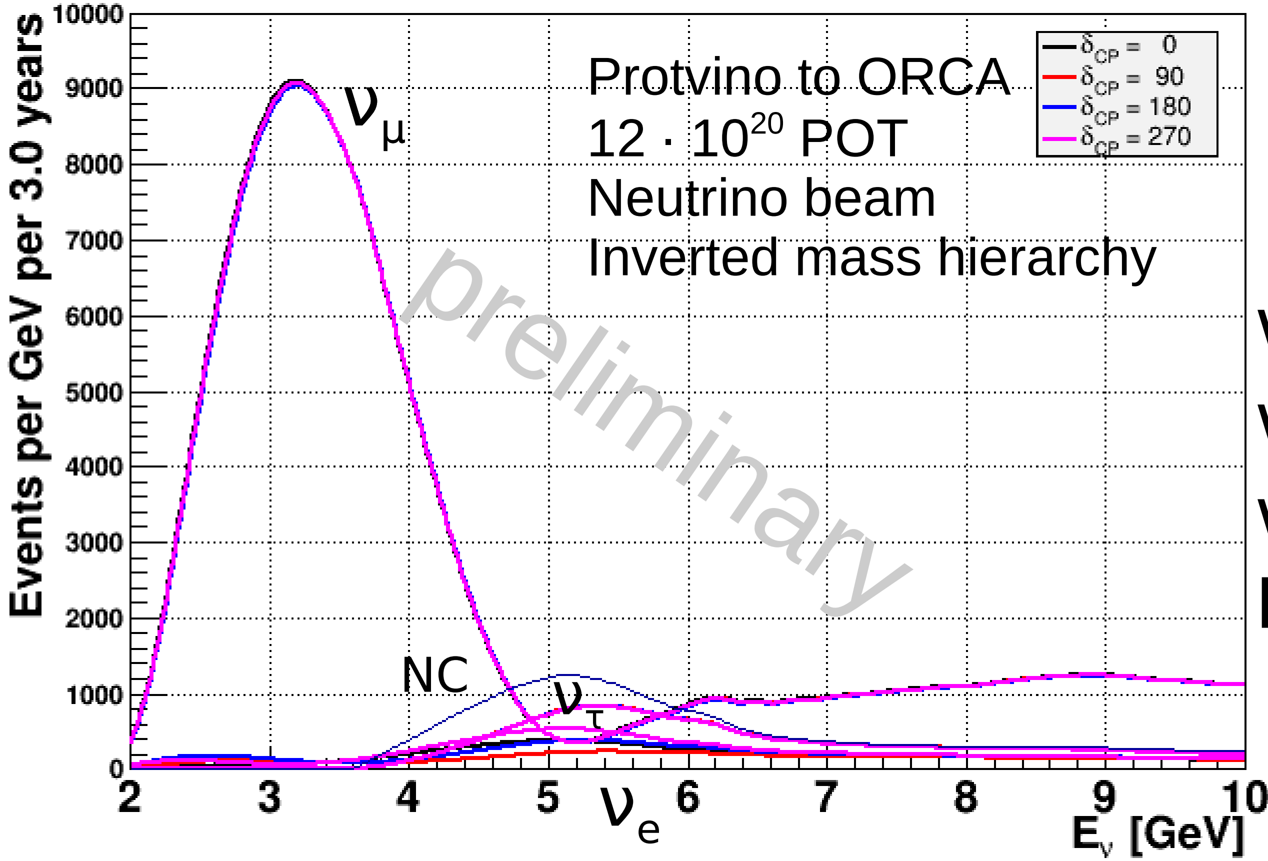
$\nu_\mu \rightarrow \nu_e$ transitions are enhanced by the MSW effect, resonance energy 3.8 GeV

Expected neutrino rates in ORCA

inverted mass hierarchy

Raw event numbers in ORCA

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

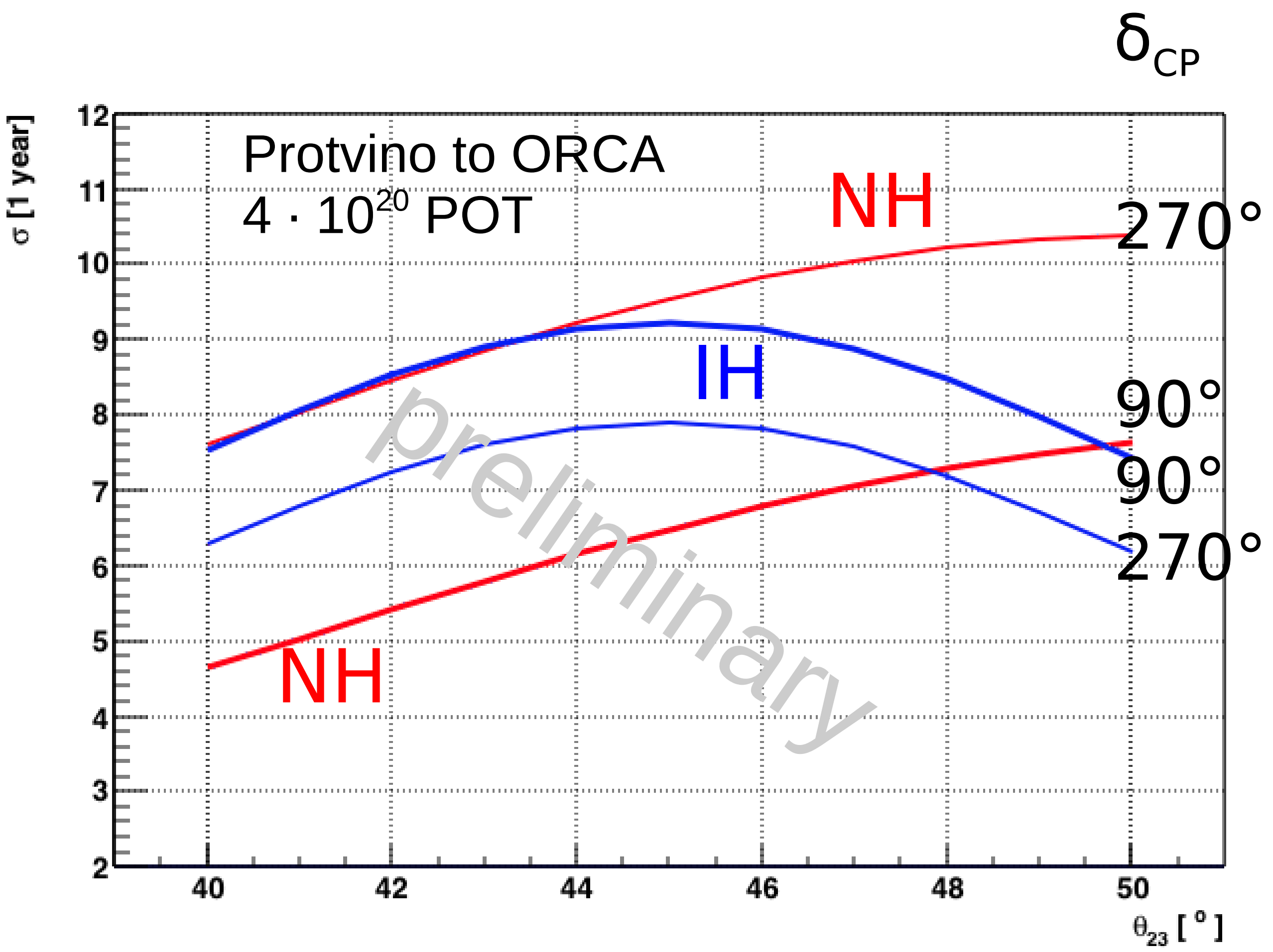
- Combined fit of nuisance and oscillation parameters
- No neutrino/anti-neutrino skew
- No spectral index skew
- No energy scale shift

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

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 / $\bar{\nu}$	1	fix	fix

* Only used for CP fits, not for NMH

Sensitivity to mass hierarchy

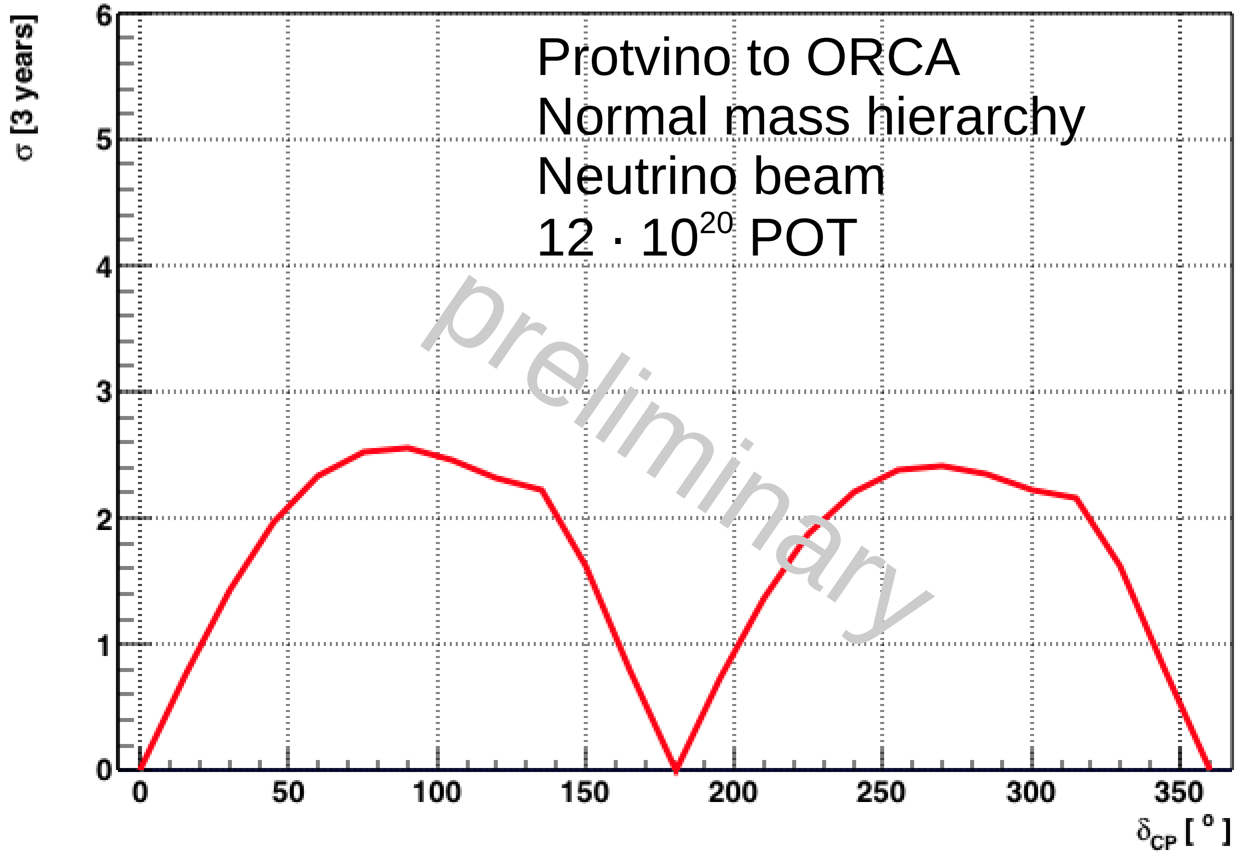


> 5 sigma after 1 year of 450 kW beam

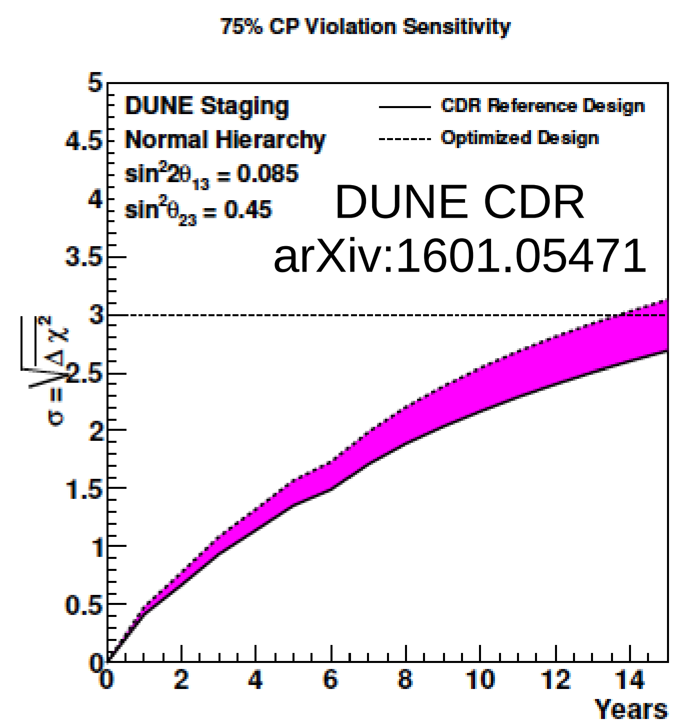
(or 5 years of 100 kW beam)

Sensitivity to CP violation

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

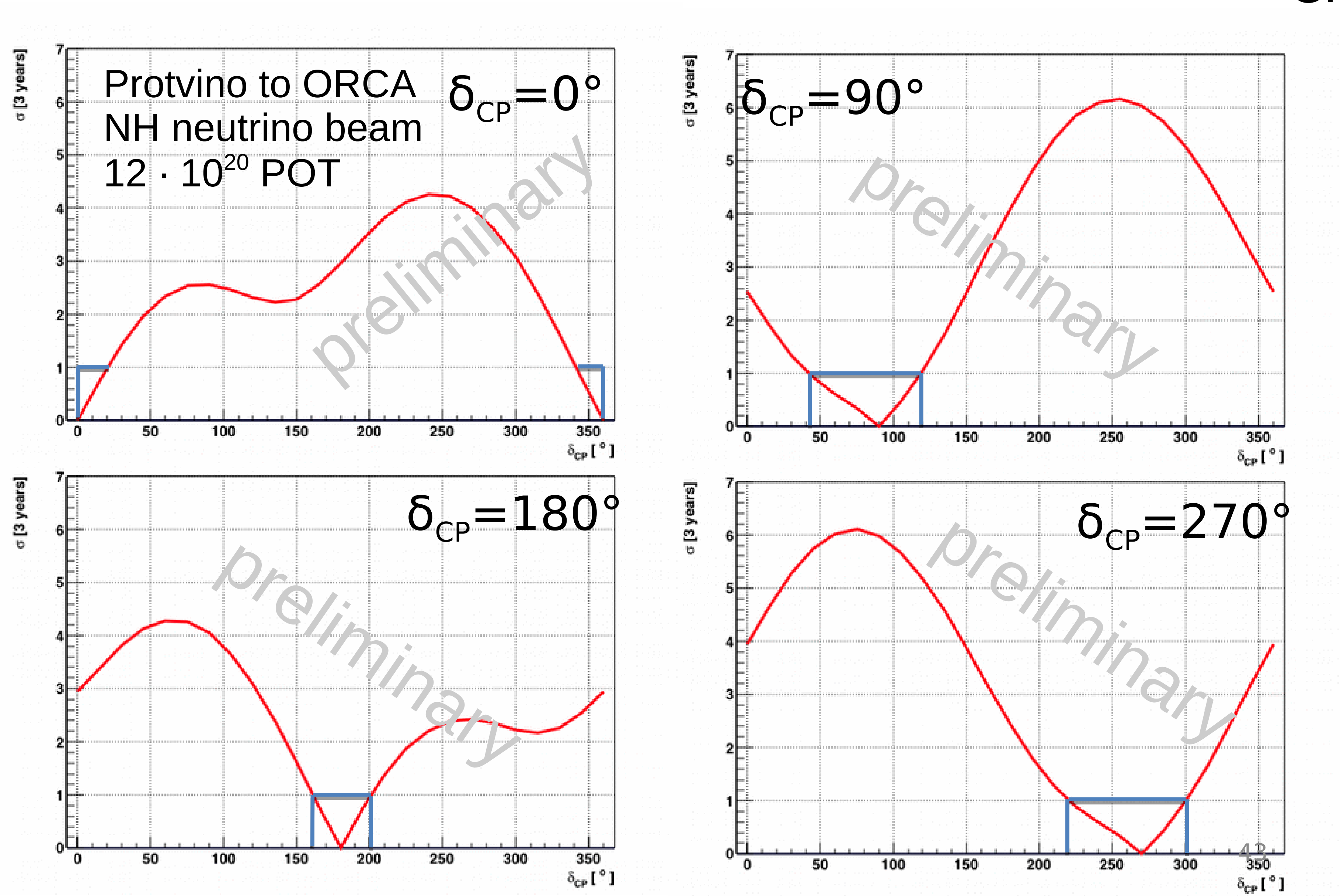


Competitive with DUNE!

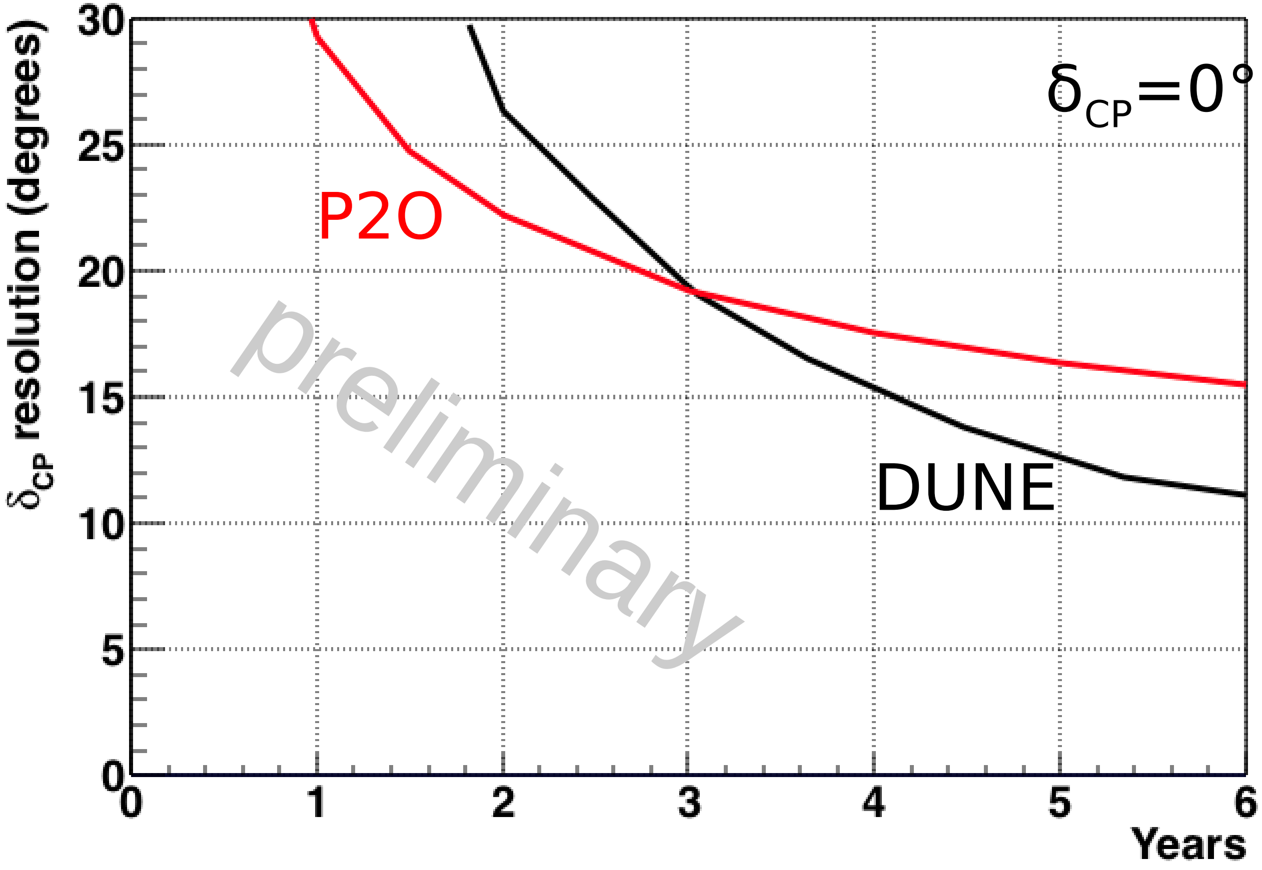


~ 2.5 sigma after 3 years of 450 kW beam

Simulated measurement of δ_{CP}

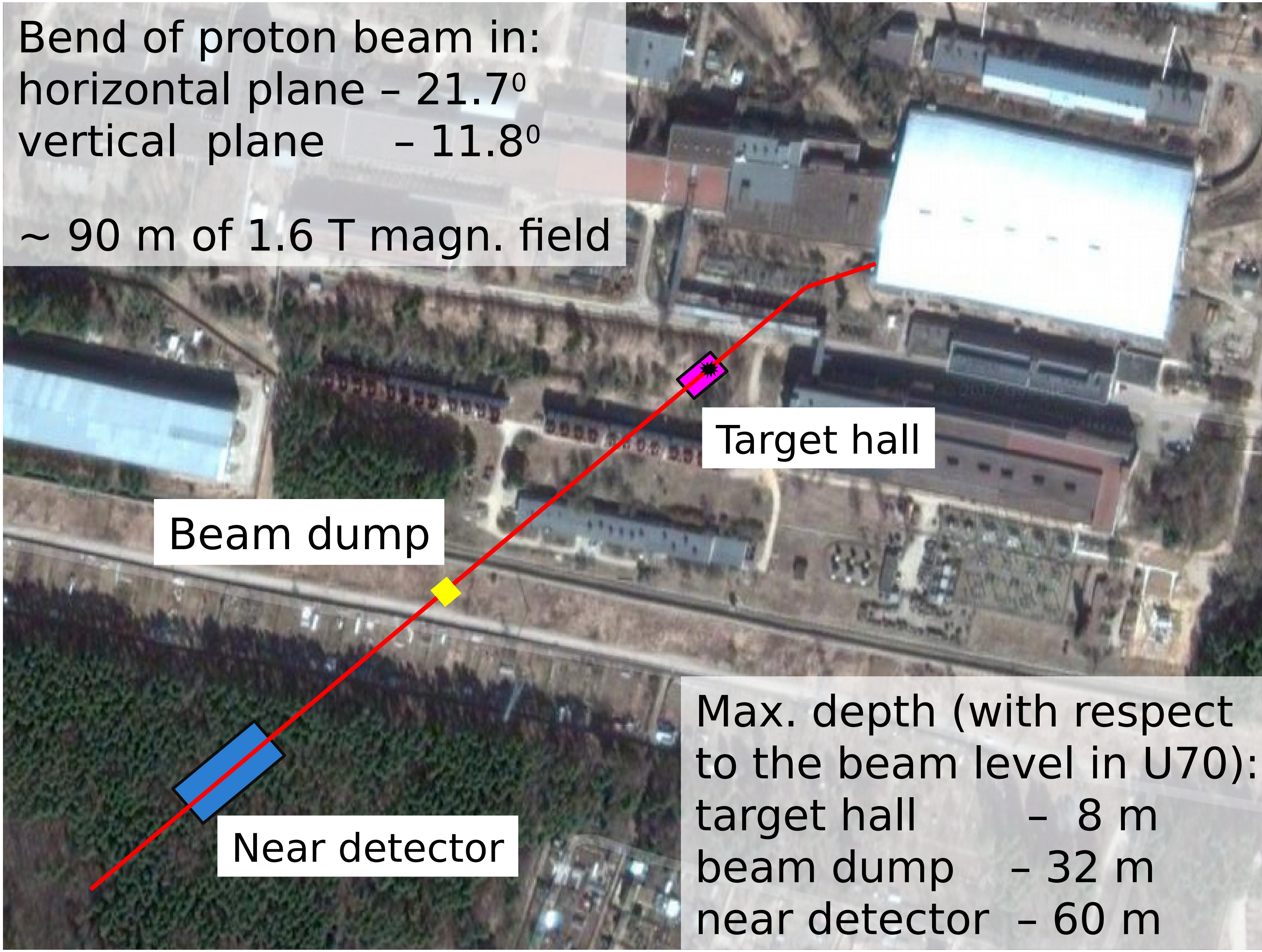


Measurement accuracy of δ_{CP}



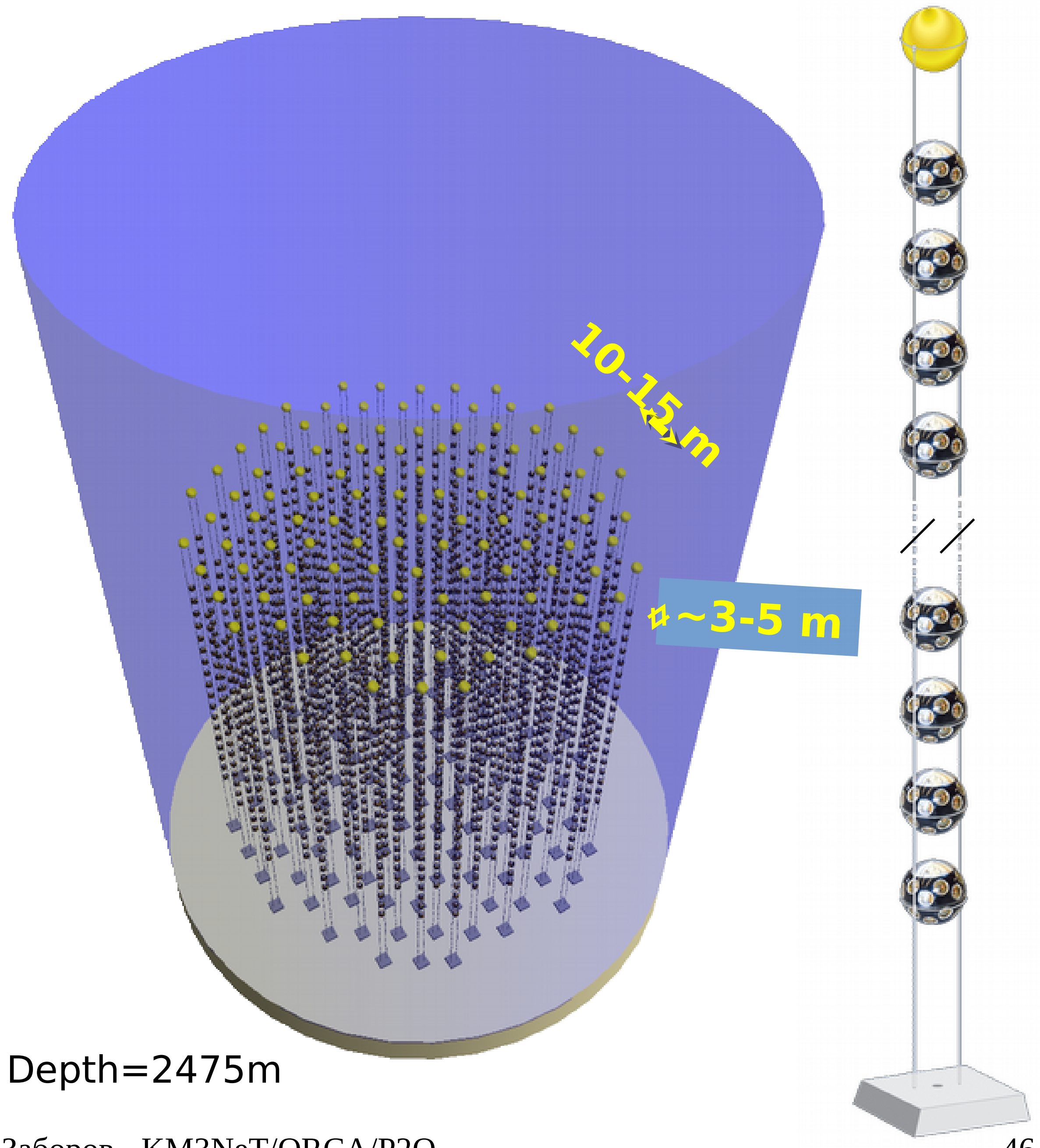
NB: this study uses preliminary estimates of systematic uncertainties

Possible location of the neutrino beam line



SuperORCA proposal

- Key features:
  - 2x-3x denser than ORCA
  - Energy threshold ~ 1 GeV
  - Improved Particle ID
- Key mission: study CP violation using atmospheric and/or beam neutrino
- Moderate intensity (~ 50-100 kW) beam from Protvino could be sufficient (?)



Summary

- KM3NeT/ORCA aims at determining the neutrino mass hierarchy after 3 years of operation
- Construction of ORCA has started and should take 4 years to complete
- Directing a neutrino beam from Protvino to ORCA is of high scientific interest
  - Measurement of the CP-violating phase δ (competitive with DUNE, T2HK)
  - Determination of the neutrino mass hierarchy with a high significance (and well controlled systematic uncertainties)
  - Complementary to ORCA and competitive with DUNE

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/

Last word

~ 4 kt neutrino detector

(E = 10 GeV)

Thank you for your attention

(backup slides follow)

From ANTARES to KM3NeT: Optical Module

ANTARES storey

Optical module is a glass sphere with one 10” PMT

storey =
3 optical modules
+ electronics container
+ titanium frame

KM3NeT storey:

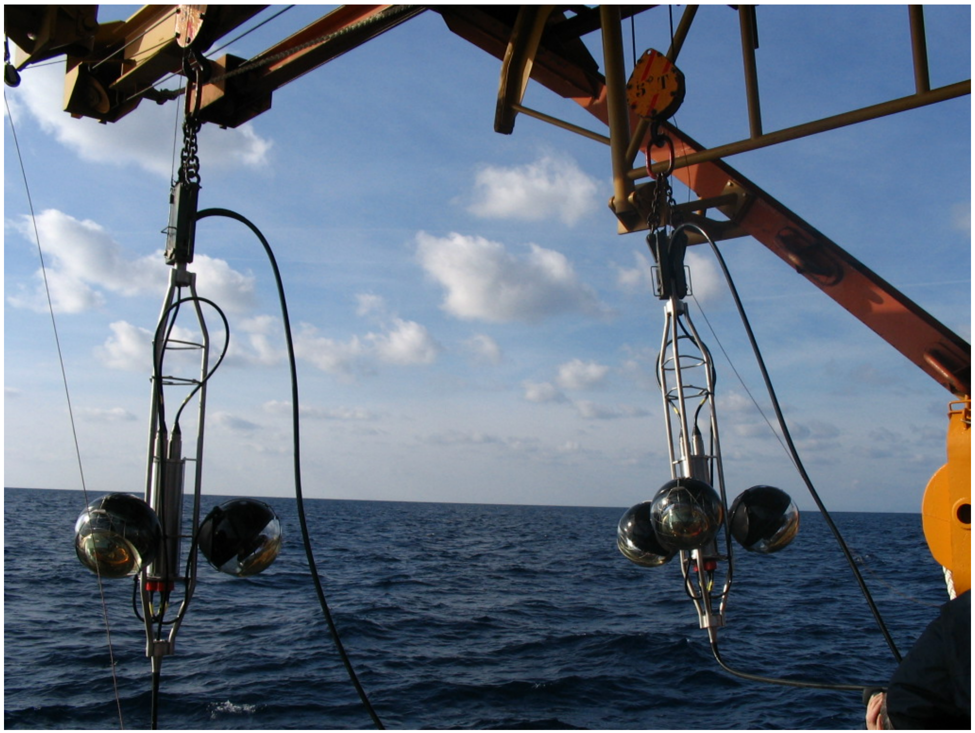
31 x 3” PMTs
+ electronics
in a single glass sphere

Sensitivity ~ 2x - 3x ANTARES OM

Compact structure minimizes bio-luminescence (stimulated by drag)

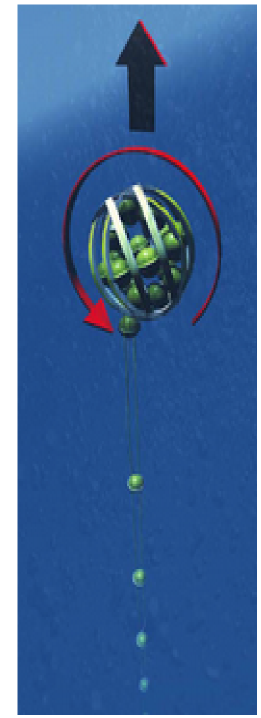
from ANTARES to KM3NeT: deployment method

ANTARES



- Storeys are put in water one-by-one
- The ship can only take one “line” at a time

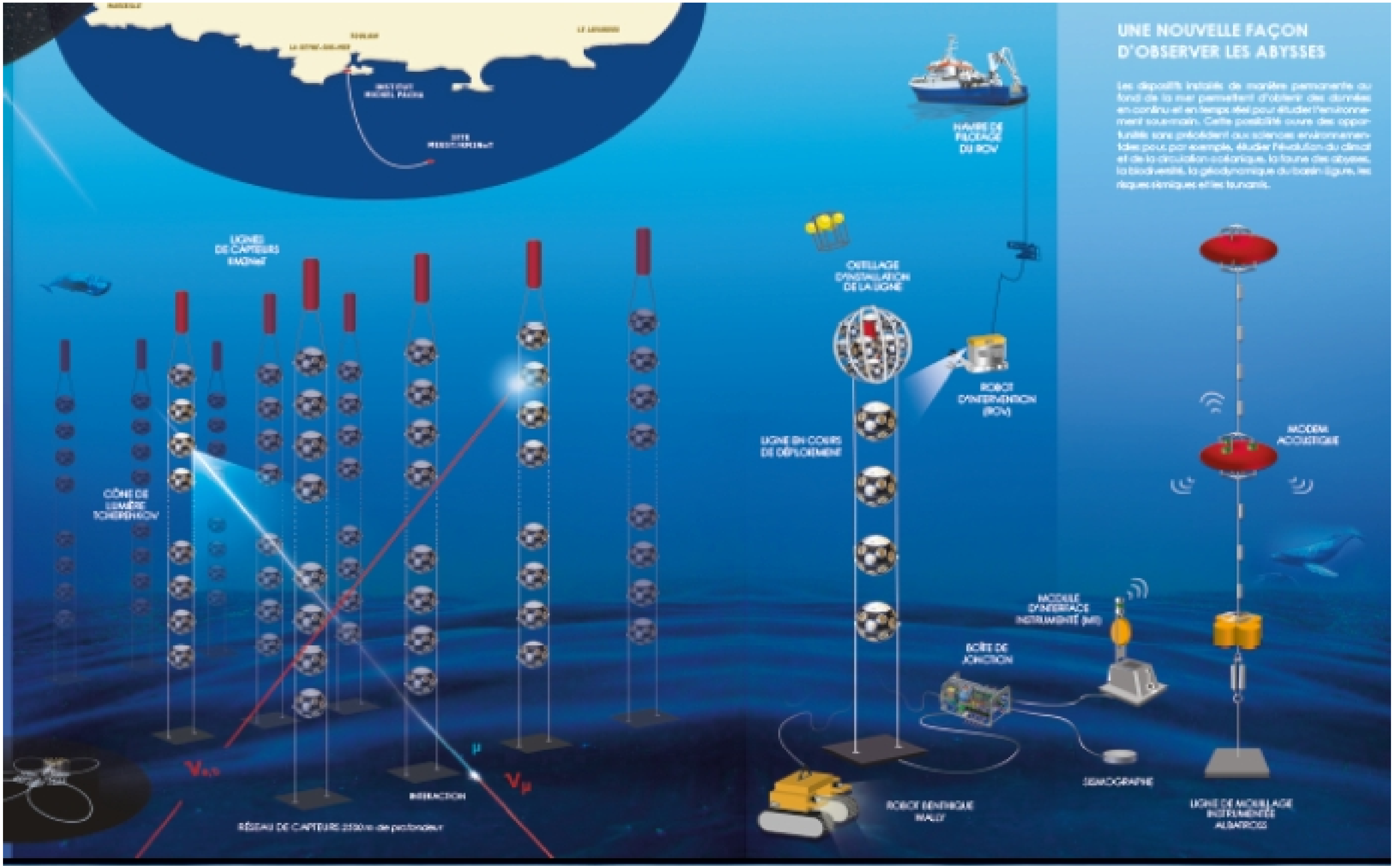
KM3NeT



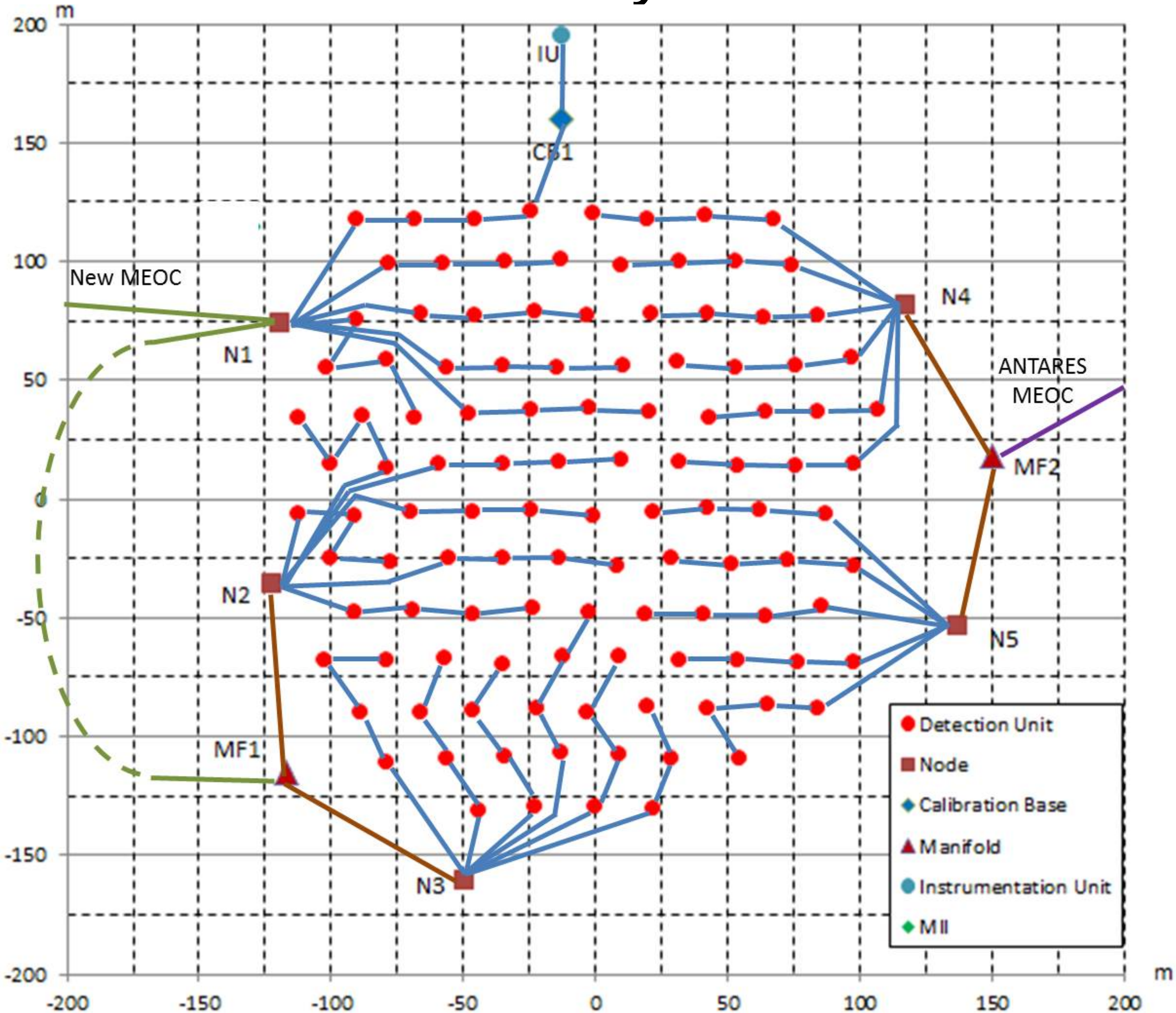
Watch https://www.youtube.com/watch?v=tR8jwgG6uzk

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

Artist’s view of KM3NeT



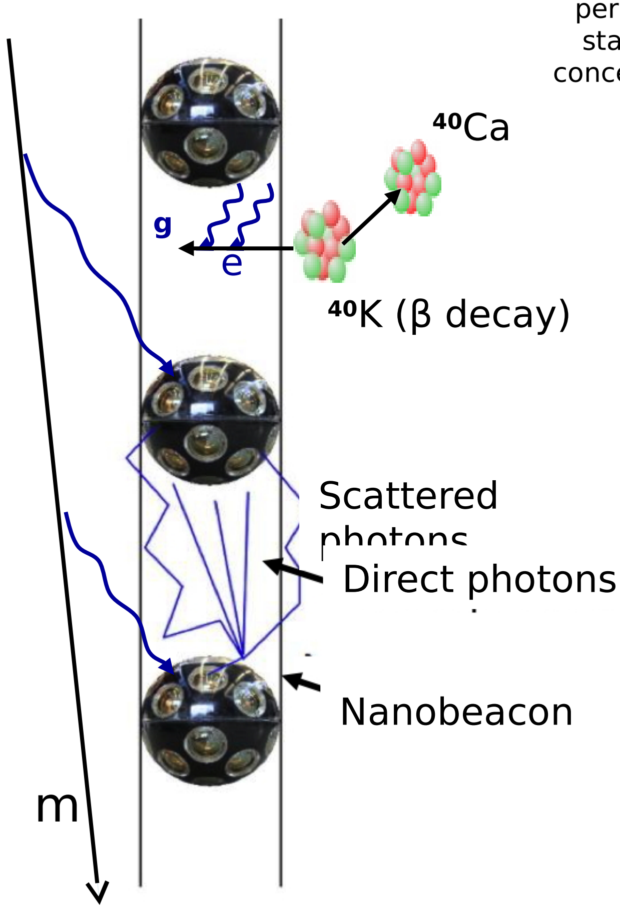
ORCA layout


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

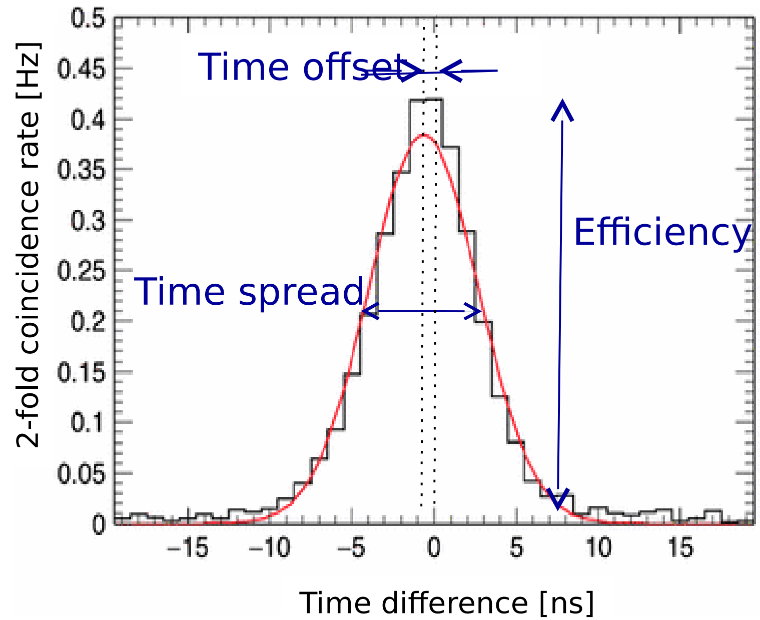
Calibration procedures

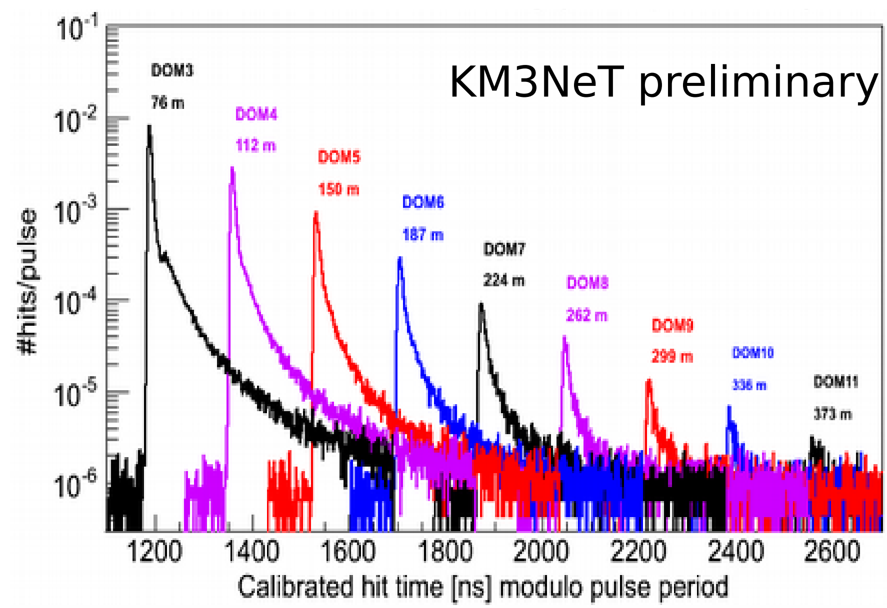
K. Melis PoS (ICRC2017) 1059

Up to 150 Cherenkov g per decay; stable ^{40}K concentration



Cross-calibration with muons

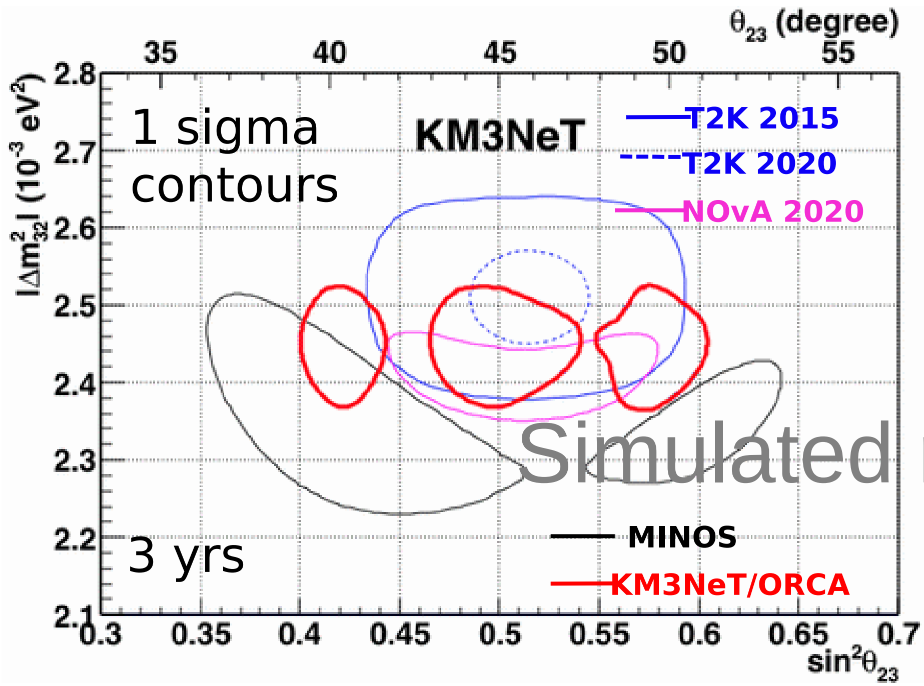




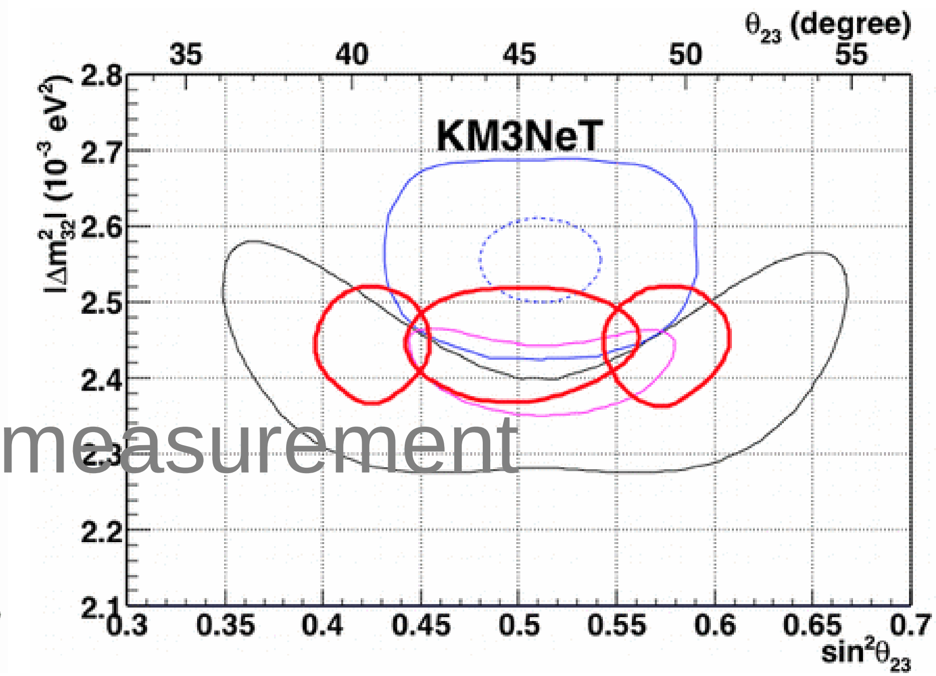
Sensitivity to Δm^2_{32} and $\sin^2\theta_{23}$

- 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

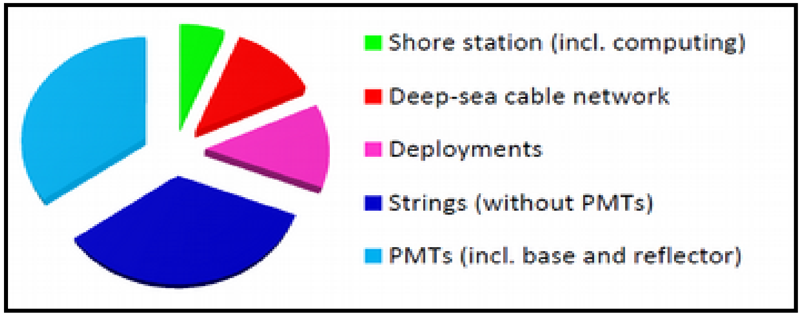


Inverted hierarchy



Simulated measurement

ORCA schedule and funding



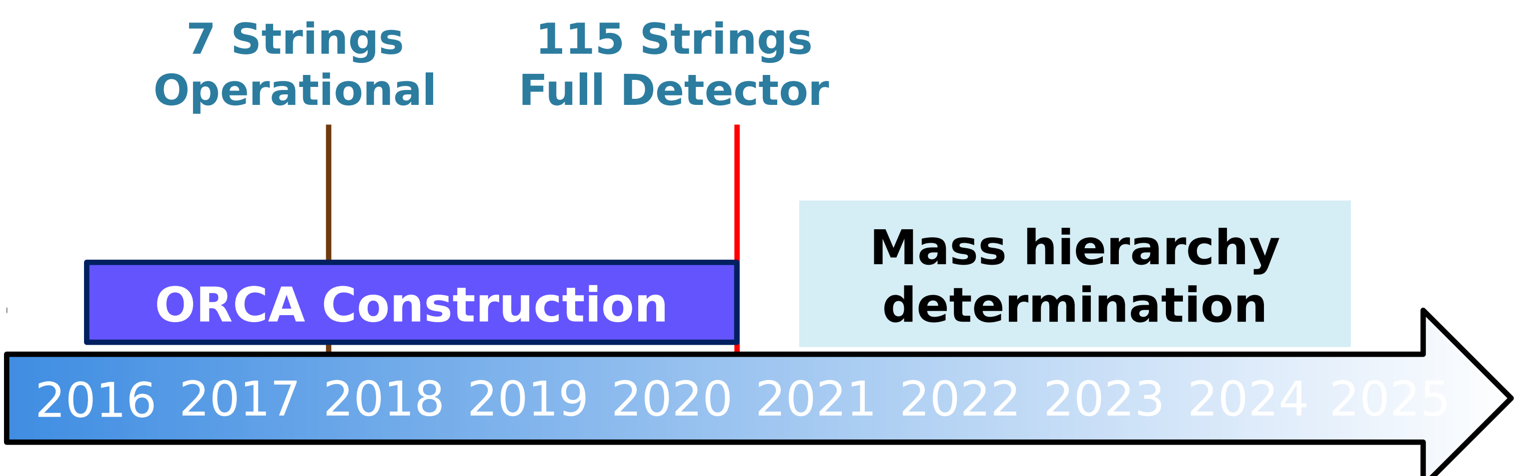
Total ORCA cost ≈ 45 M€

Phase 1: 7 strings – 11 M€

Phase 2: 115 strings – fund requests ongoing

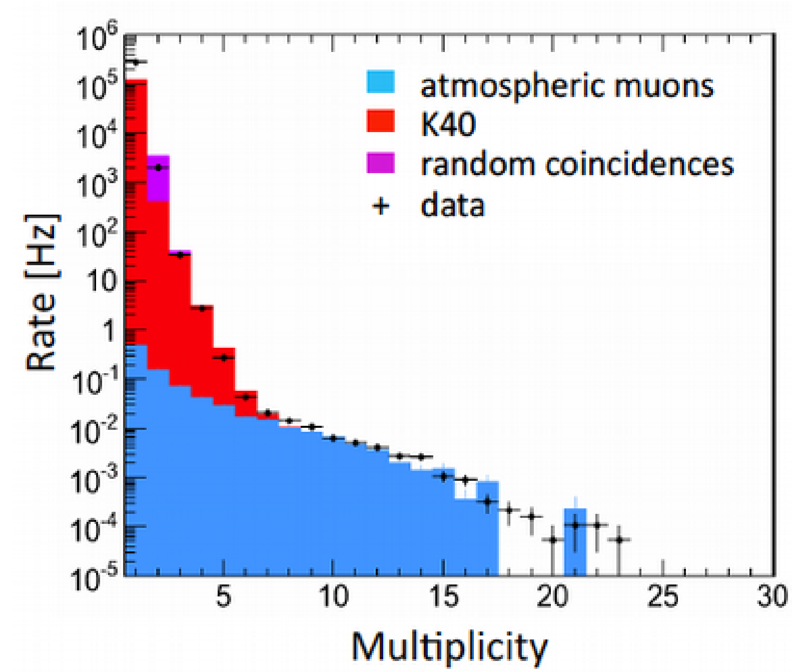
Outlook

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

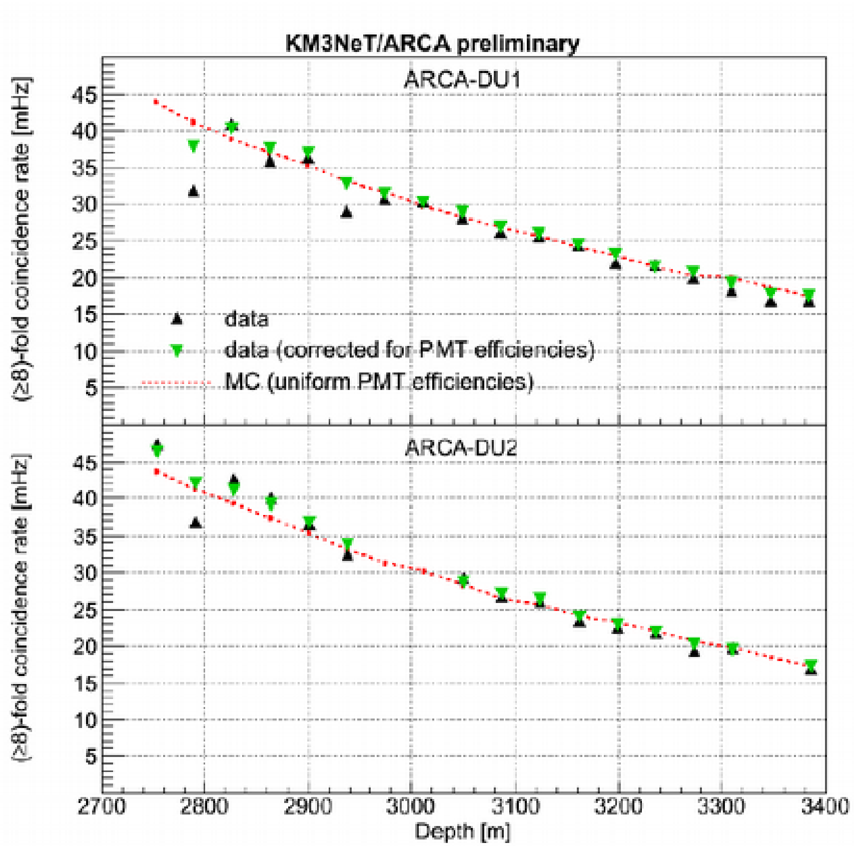


KM3NeT/ARCA first detection lines

- Optical Module at Antares site, April 2013 (2500 m)
  - Muons from a single DOM, Eur. Phys. J. C (2014) 74:3056
- Mini string (3 DOMs) at ARCA site, May 2014 (3500 m)
  - Track reconstruction, Eur. Phys. J. C (2016) 76:54 -- Cover
- First full Detection Unit at ARCA site, Dec 2015
- One more line in operation in May 2016



M. Jongen PoS (ICRC2017) 1018

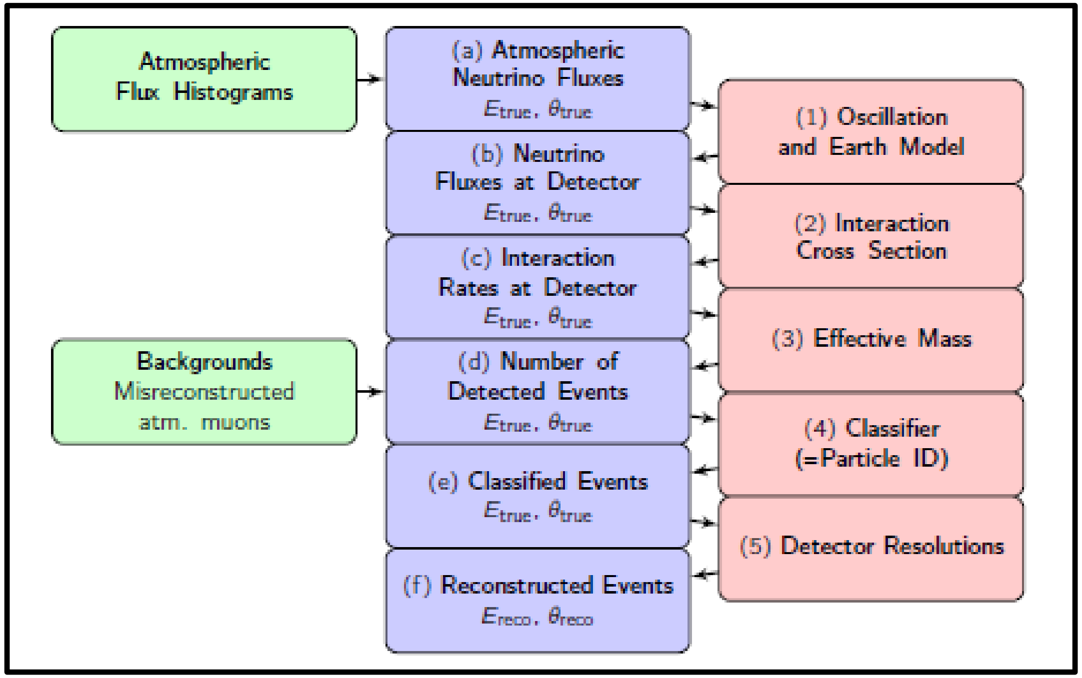


Rejection of atmospheric muons

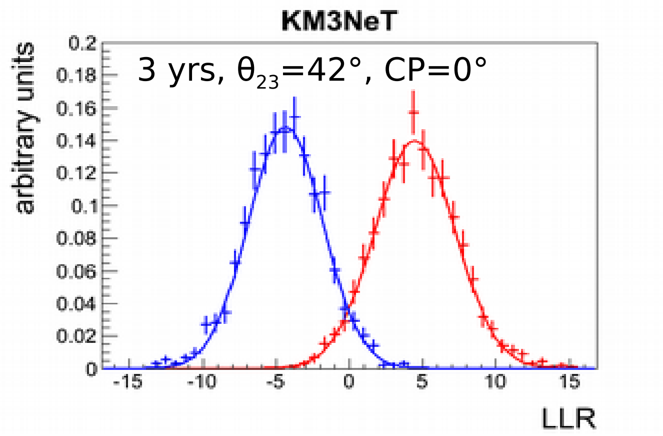
Atmospheric
n (E<20 GeV)

Atmospheric muons

Mass hierarchy measurement technicalities

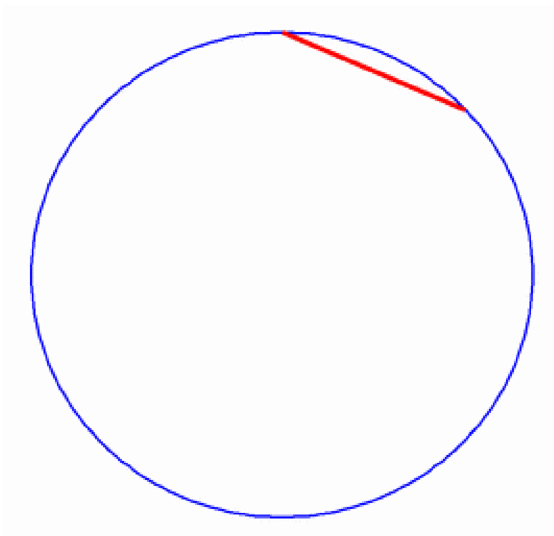


(simulated measurement)

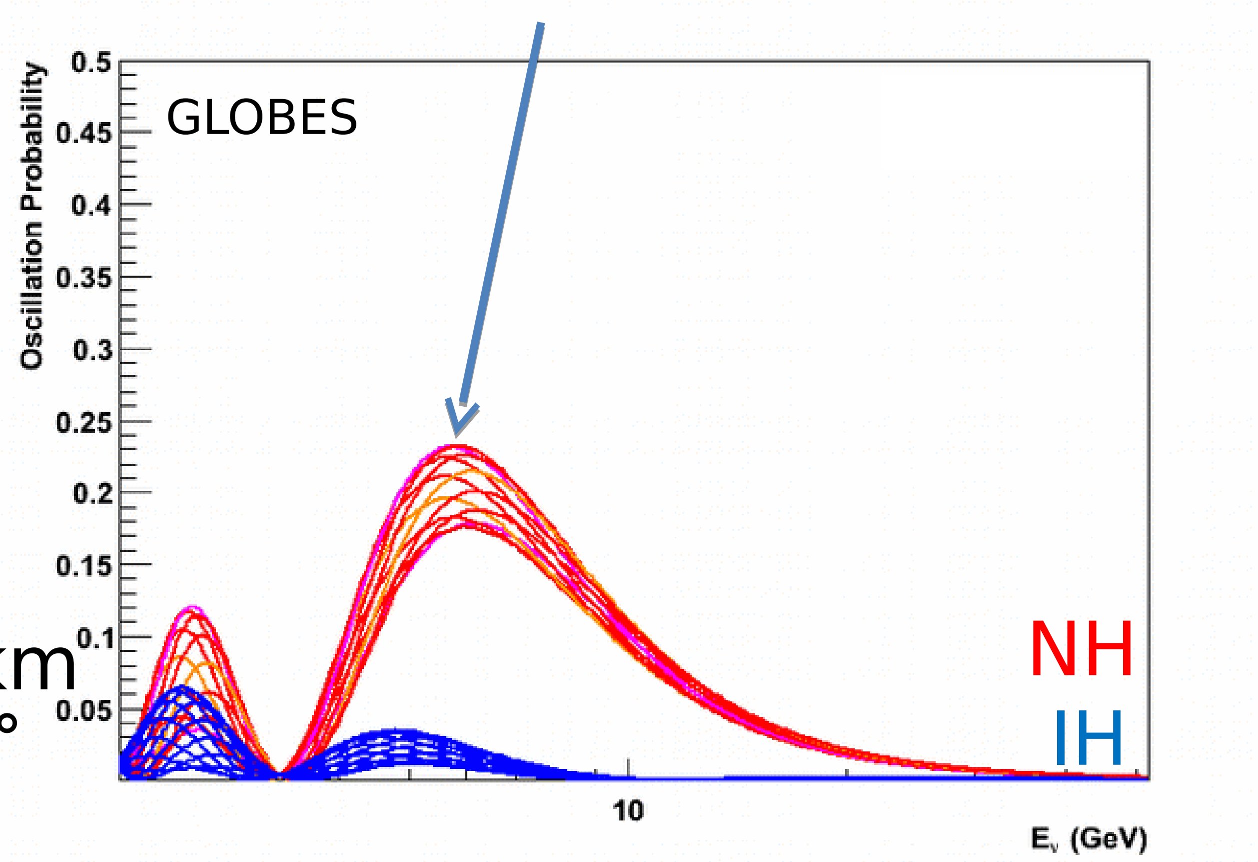


- Pick random values for oscillation parameters and other systematics
- Generate pseudo-experiments for N0, I0 cases
- Find best-fit likelihoods L_{NO}, L_{IO} for the NO, IO cases (maximising w.r.t. 9 free parameters)
- Calculate the log-likelihood ratio log (L_{NO}/L_{IO})

Peak energy example



P ($\nu_\mu \rightarrow \nu_e$) peak energy



cos θ = 0.4
Baseline = 5097 km
Inclination = 23.6°