NUFACT 2018 - 20th International Workshop on Neutrinos from Accelerators
Blacksburg, VA
August 12-18, 2018

Neutrino physics with KM3NeT / ORCA

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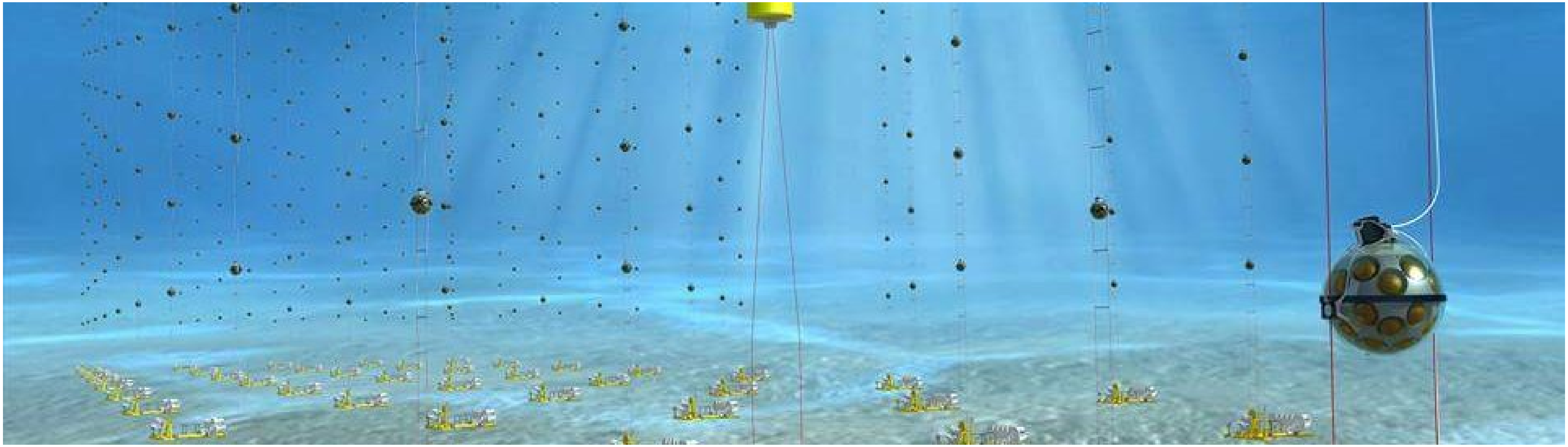
(Aix Marseille Univ. / CPPM, Marseille, France)

on behalf of the KM3NeT collaboration

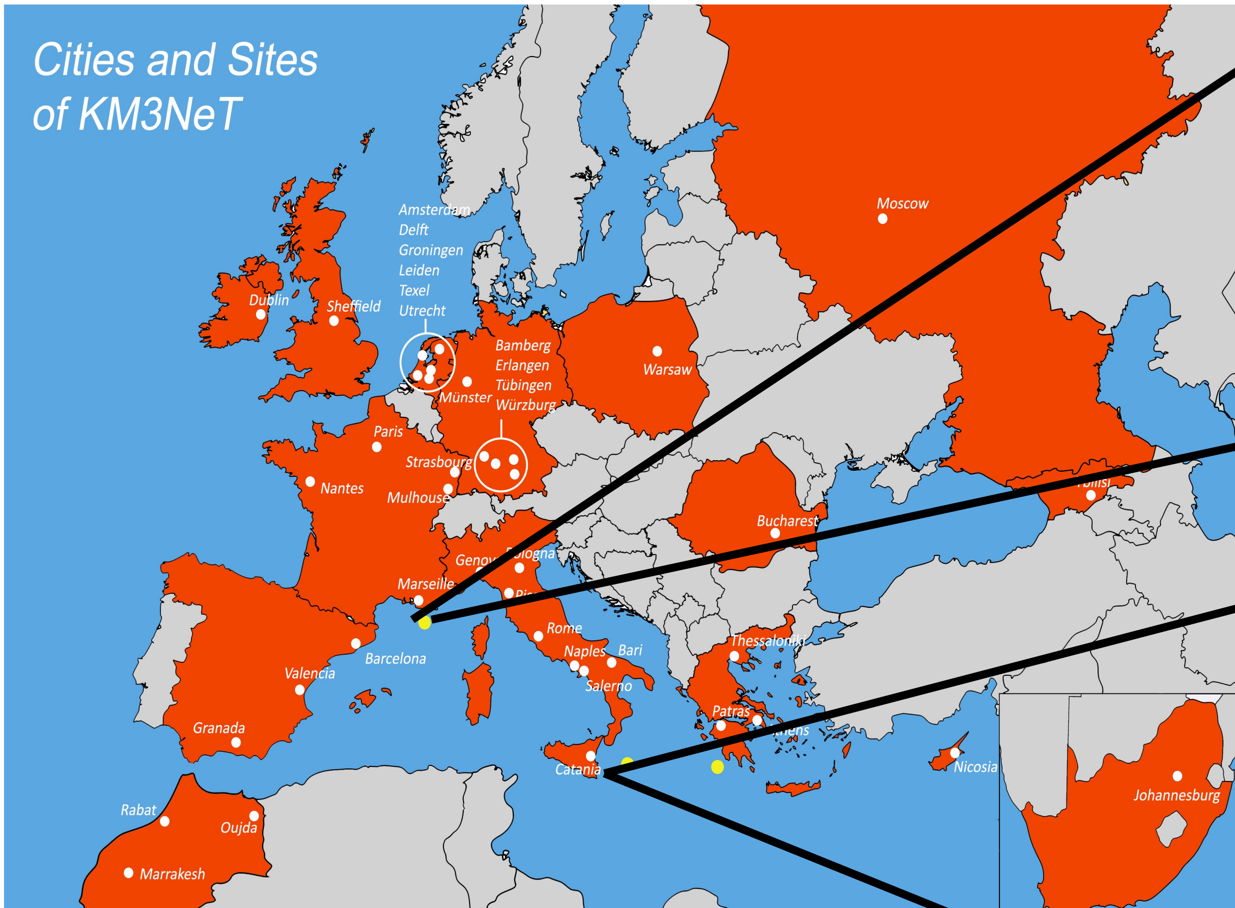


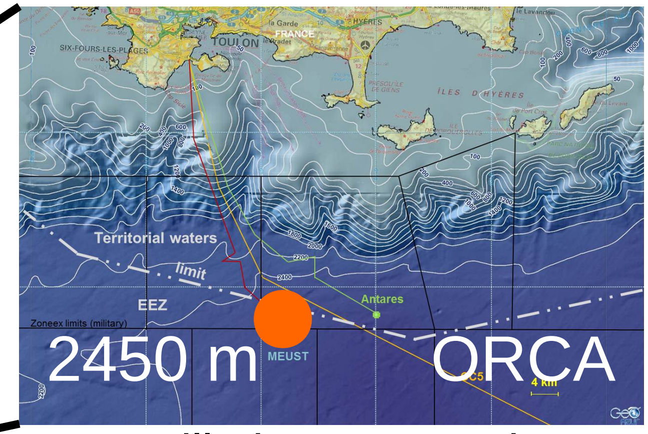
Outline

- ORCA detector
- ORCA science
- Current status
- Prospects for a neutrino beam from Protvino to ORCA

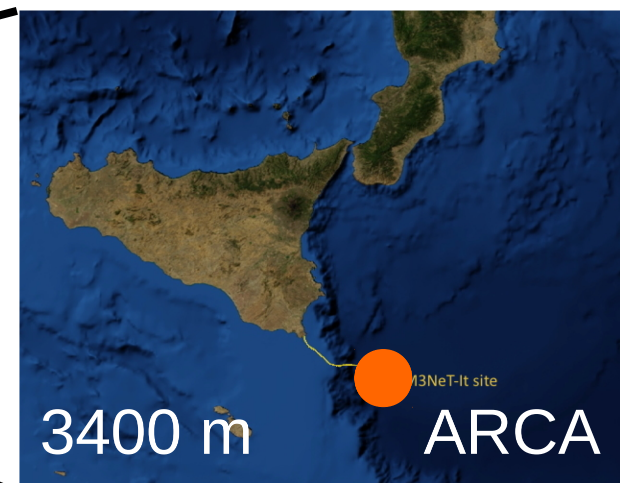
KM3NeT sites and participating countries

A distributed research infrastructure at two sites





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

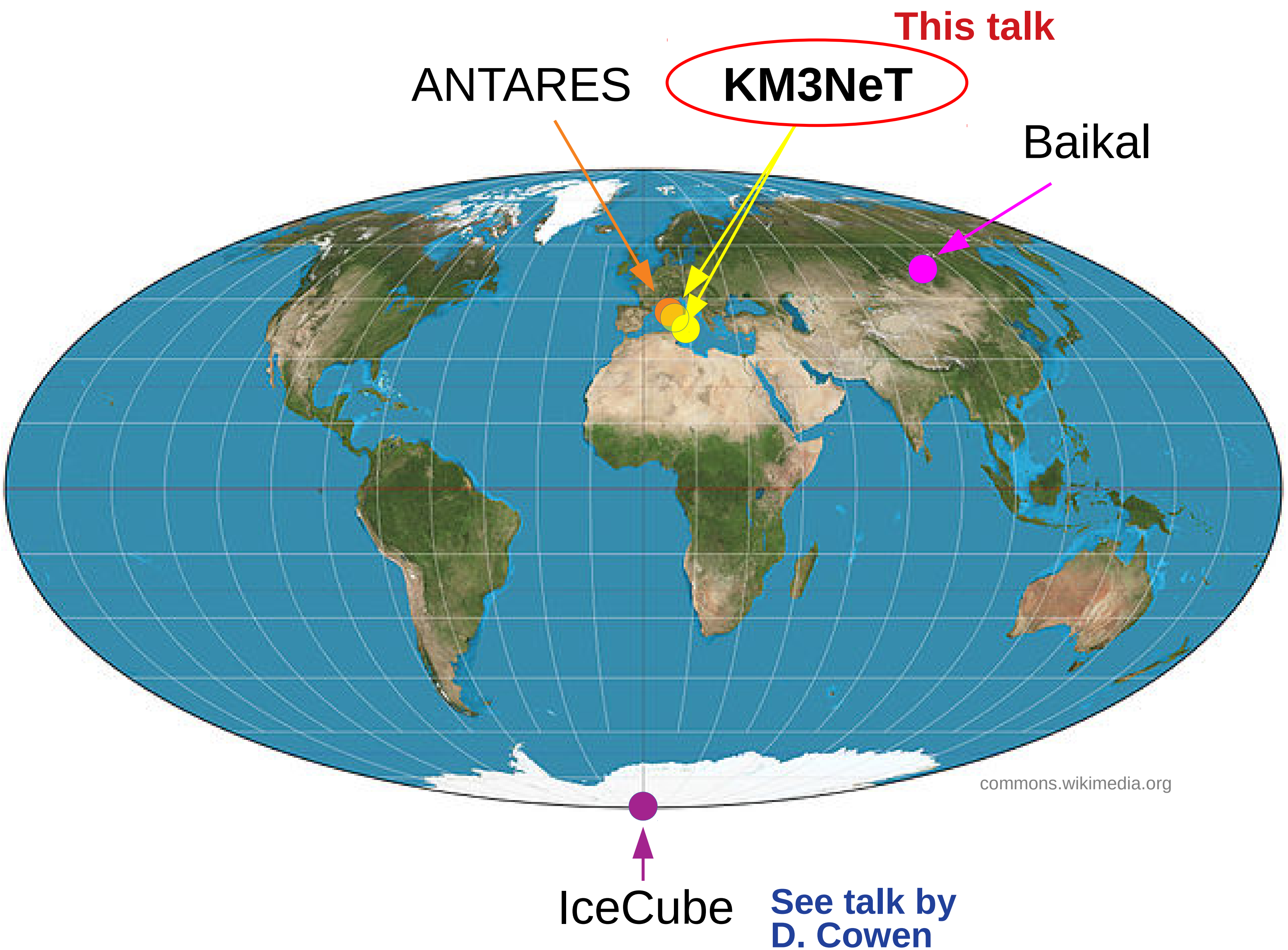


Astroparticle **R**esearch with **C**osmics In the **A**byss

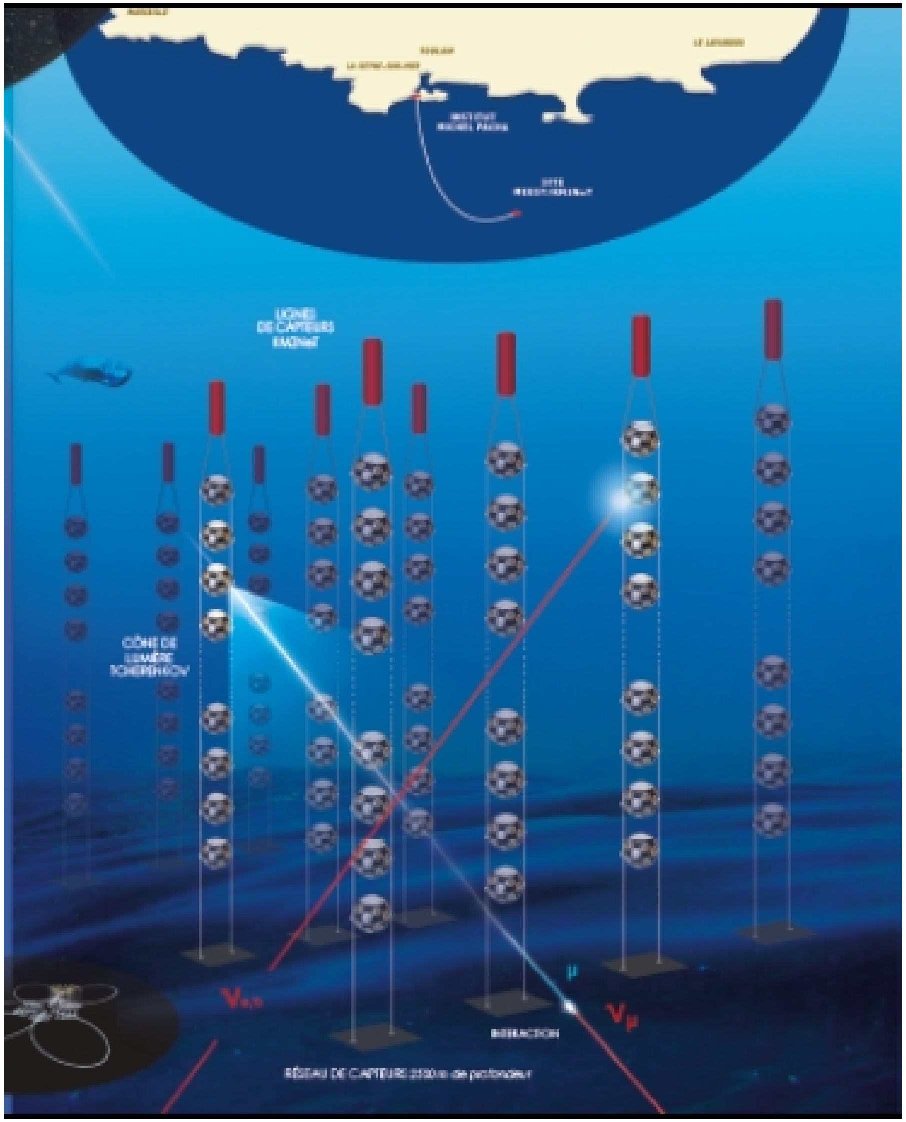
* KM3NeT = **km^3 N**eutrino **T**elescope

Single Collaboration, Single Technology

Neutrino telescopes around the world



Neutrino detection principle



Sea water
=
target material for
ν interactions
+
Cherenkov radiator

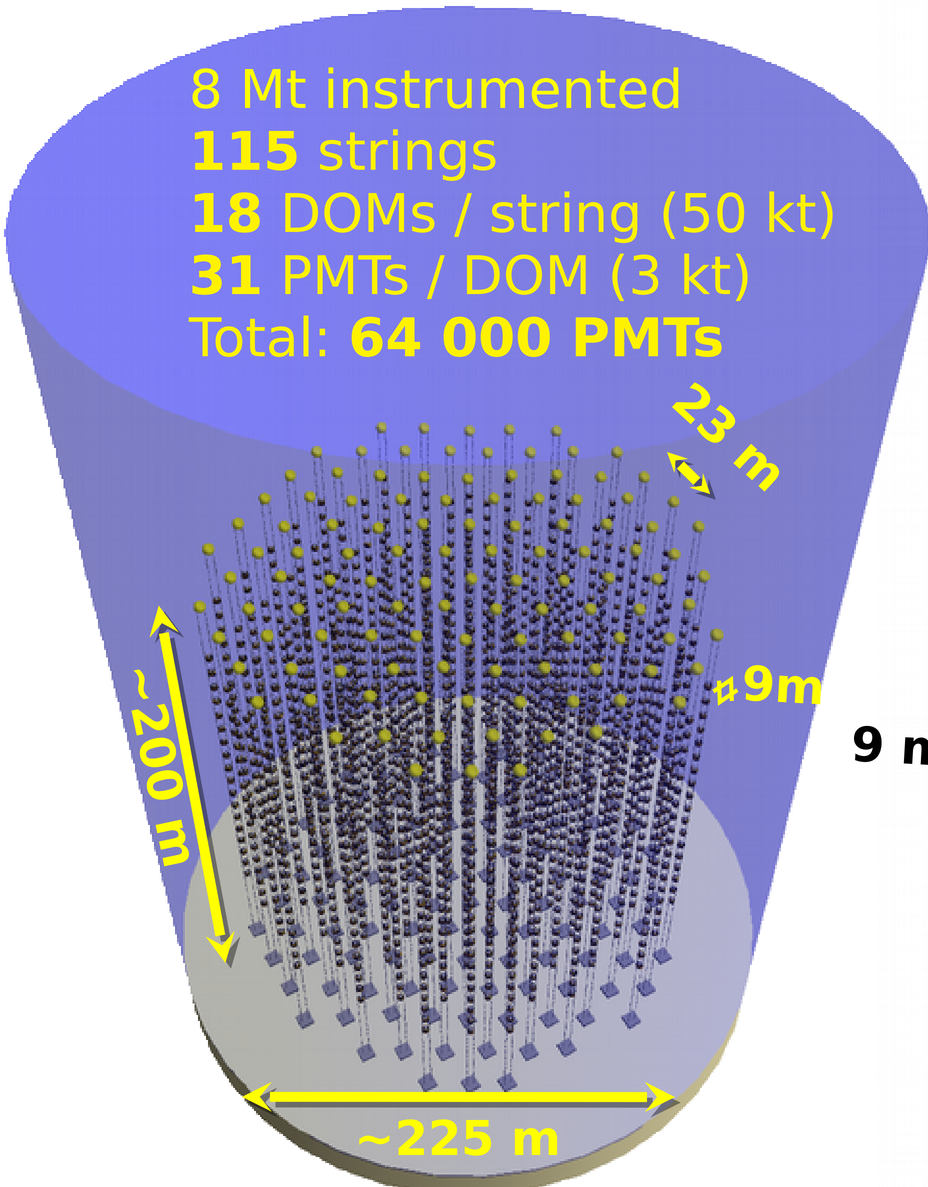
Mediterranean deep-sea water

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

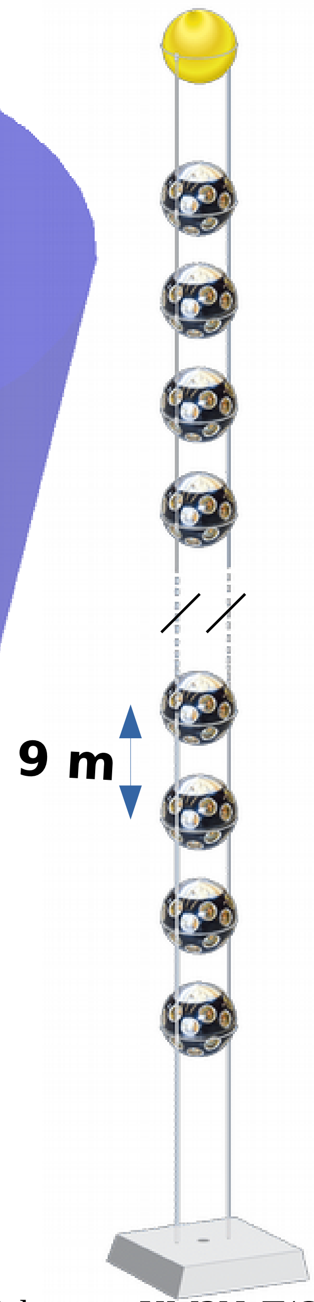
Light **scattering** length: ~ **260 m**

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

KM3NeT - ORCA



Depth=2450 m



Digital Optical Module

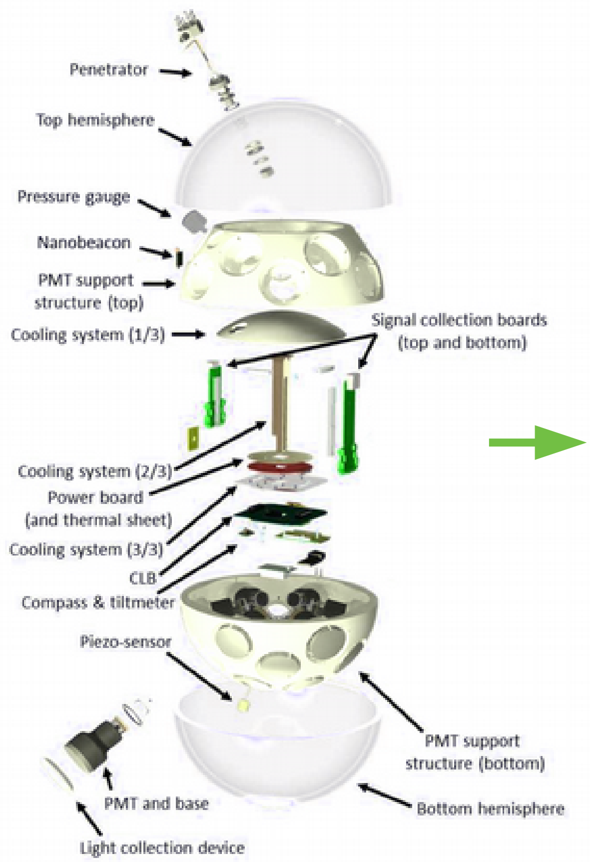
- 31 x 3” PMTs
- PMT HV
- LED & piezo
- FPGA readout
- DWDM

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

photocathode area similar to a 17” PMT

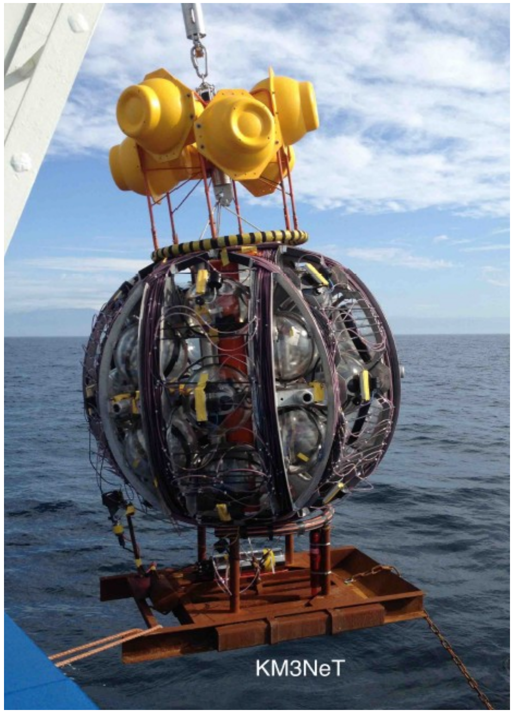
Optical background (mainly ^{40}K): 5-10 kHz/PMT

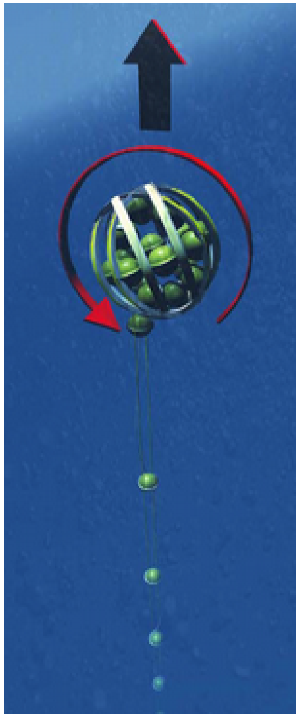
Assembly and deployment



DOM

DU





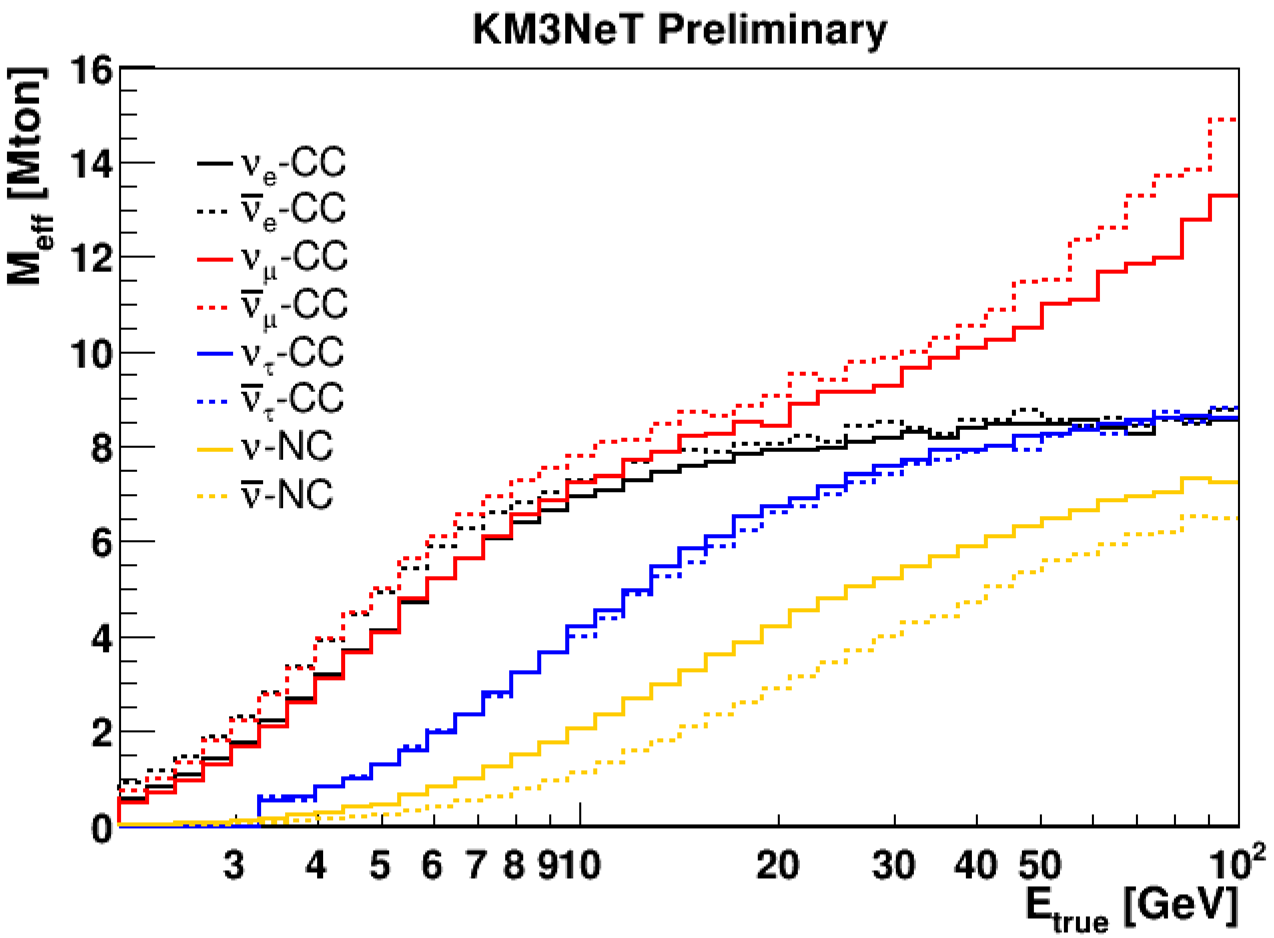
Watch https://www.youtube.com/watch?v=tR8jwgG6uzk

https://youtu.be/7HKHW0hLxt4
https://youtu.be/g2Y0KD3kdXs
https://youtu.be/xTj4lLMv1Fw
https://youtu.be/XFPCfCoTfUg

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

ORCA effective mass

After triggering, atmospheric muon rejection and containment cuts



Atmospheric neutrino events / year:

ν_e CC: 14 700

$\bar{\nu}_e$ CC: 5 700

ν_μ CC: 21 300

$\bar{\nu}_\mu$ CC: 9 900

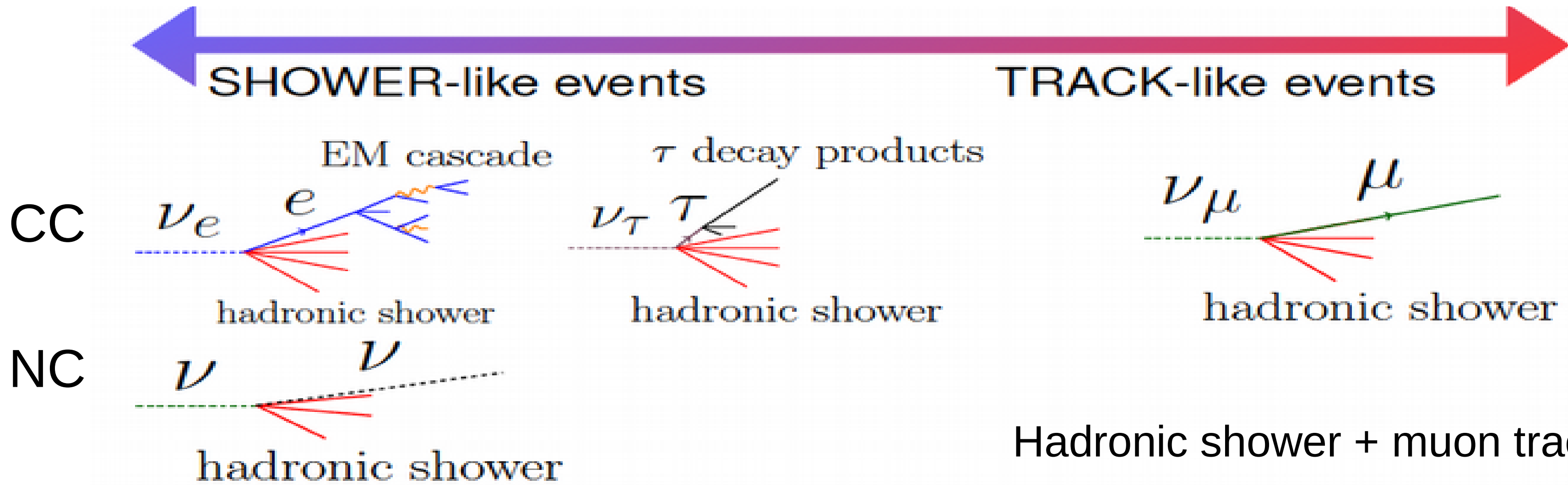
ν_τ CC: 2 900

$\bar{\nu}_\tau$ CC: 1 300

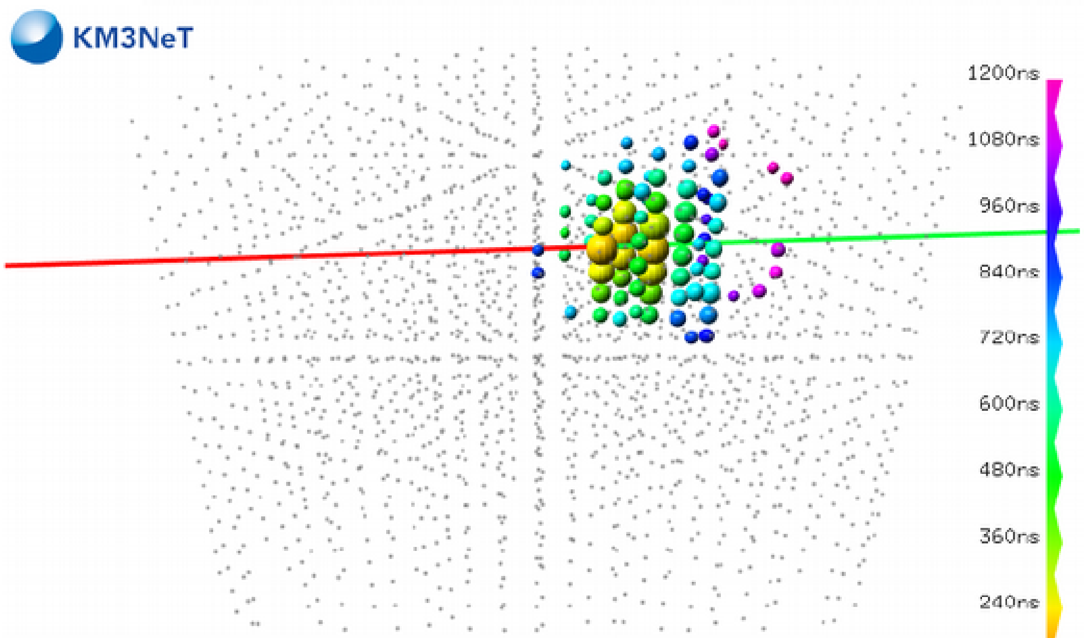
NC: 6 800

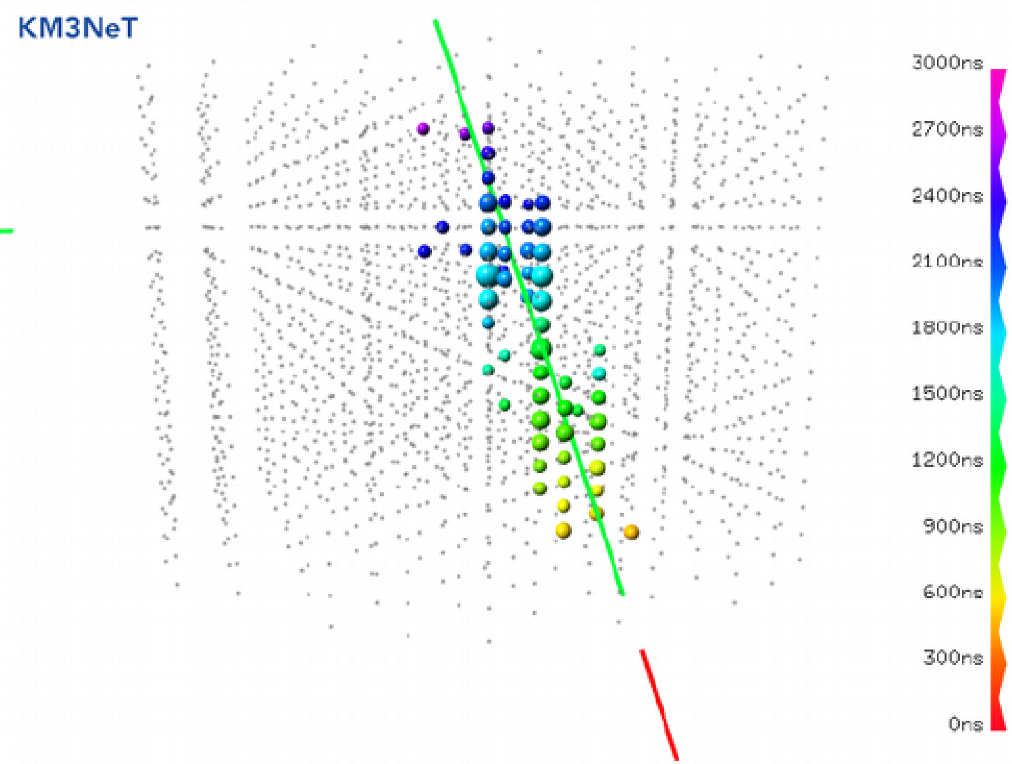
- Effective volume reaches instrumented volume at ~ 10 GeV
- 50% effective at 5 GeV

Particle ID



Hadronic shower + muon track

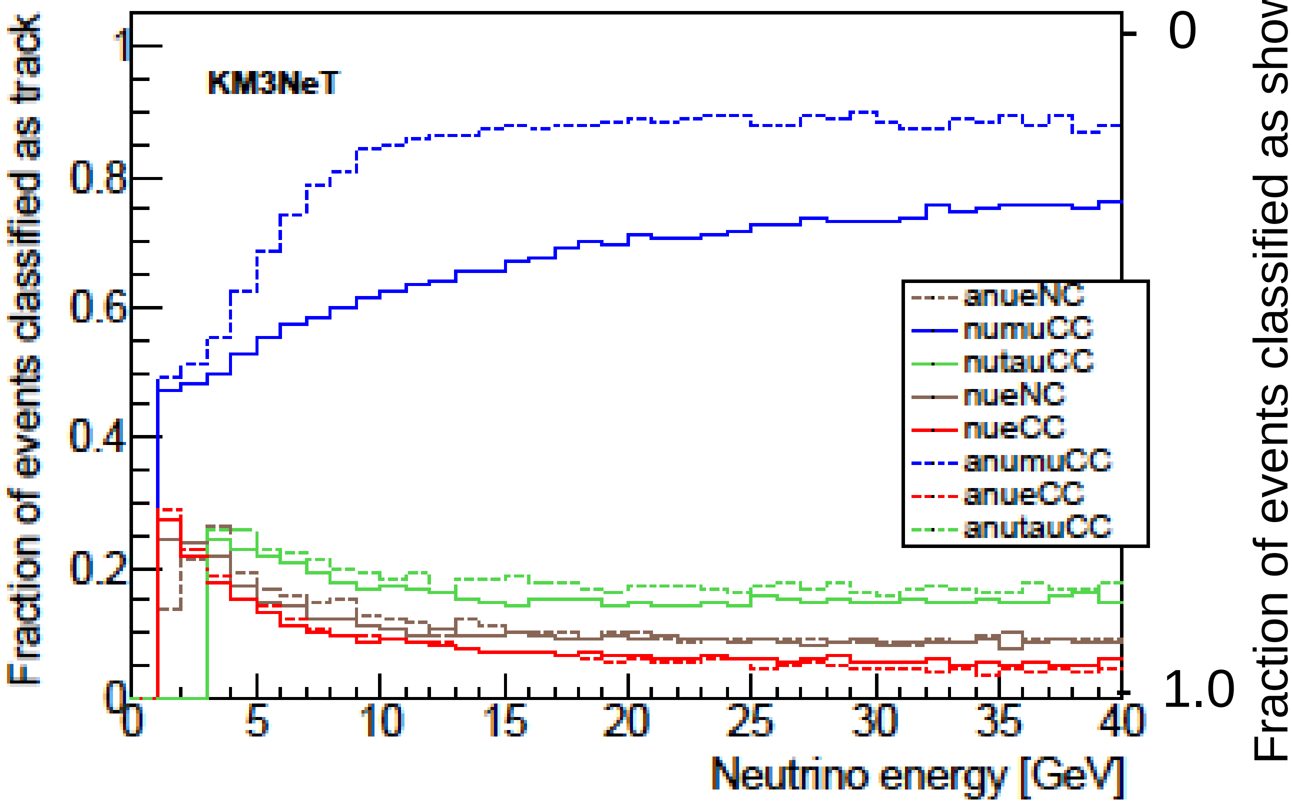




ARCA simulated events

Particle ID performance

Track / Shower event classification



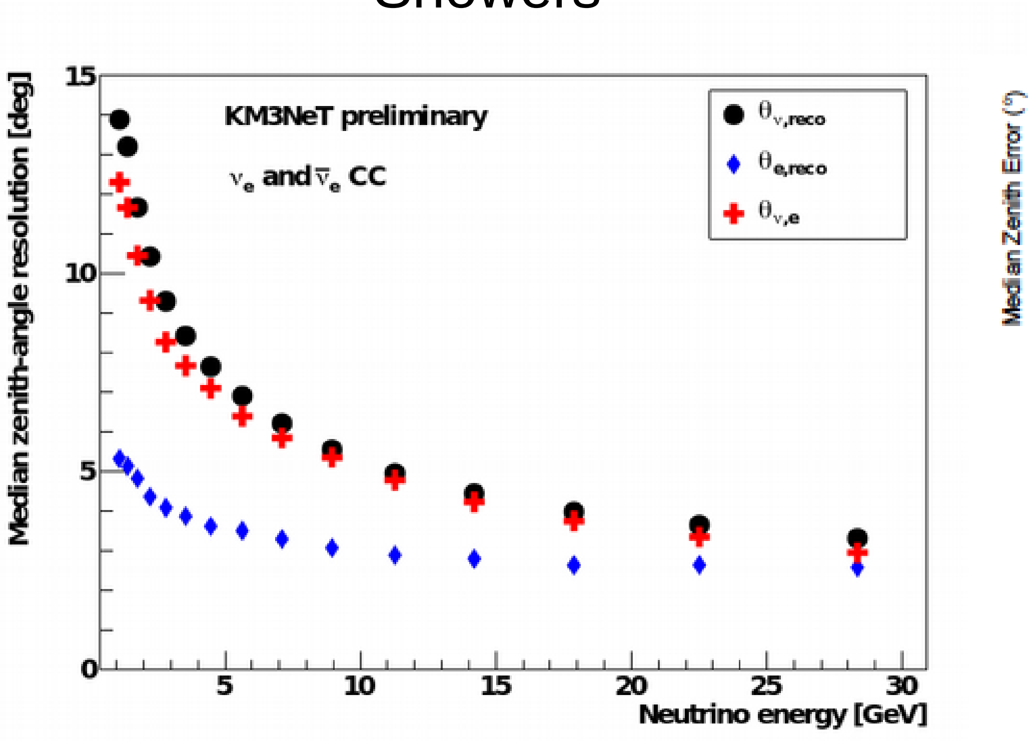
At 10 GeV:

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

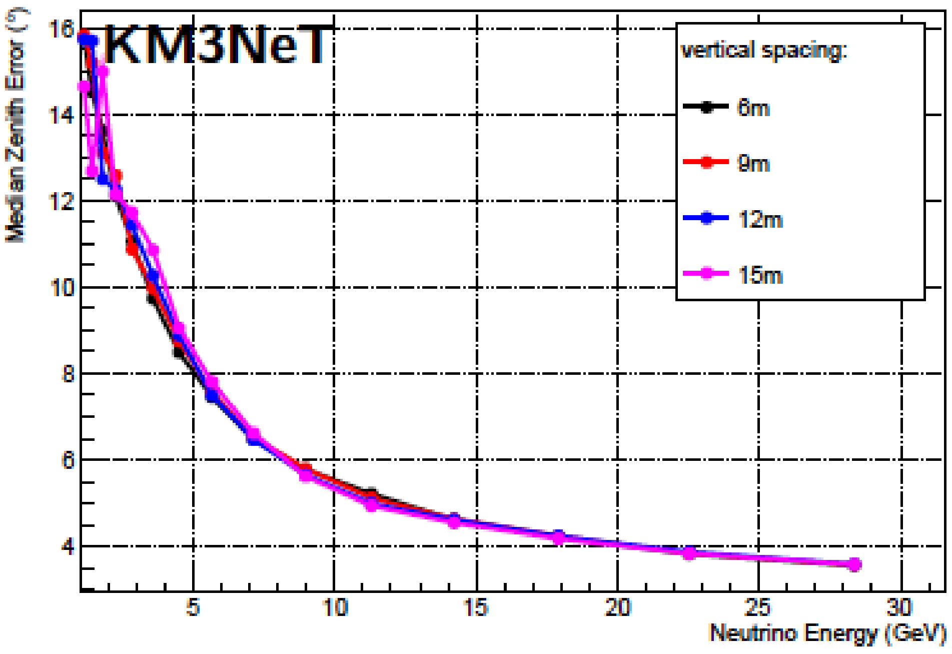
Improvements in progress, e.g. using Deep Learning (see T. Eberl et al. @ Neutrino 2018)

Zenith angle resolution

Showers



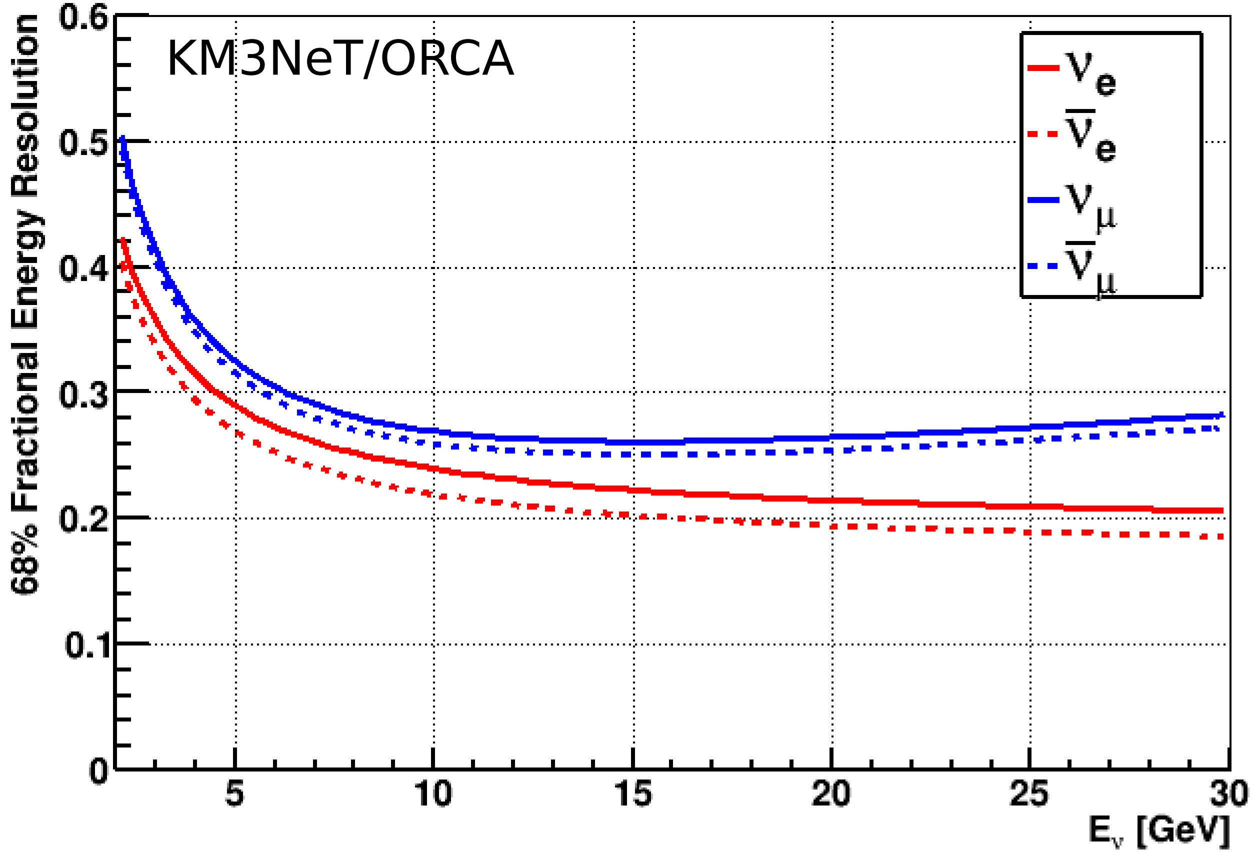
Tracks



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

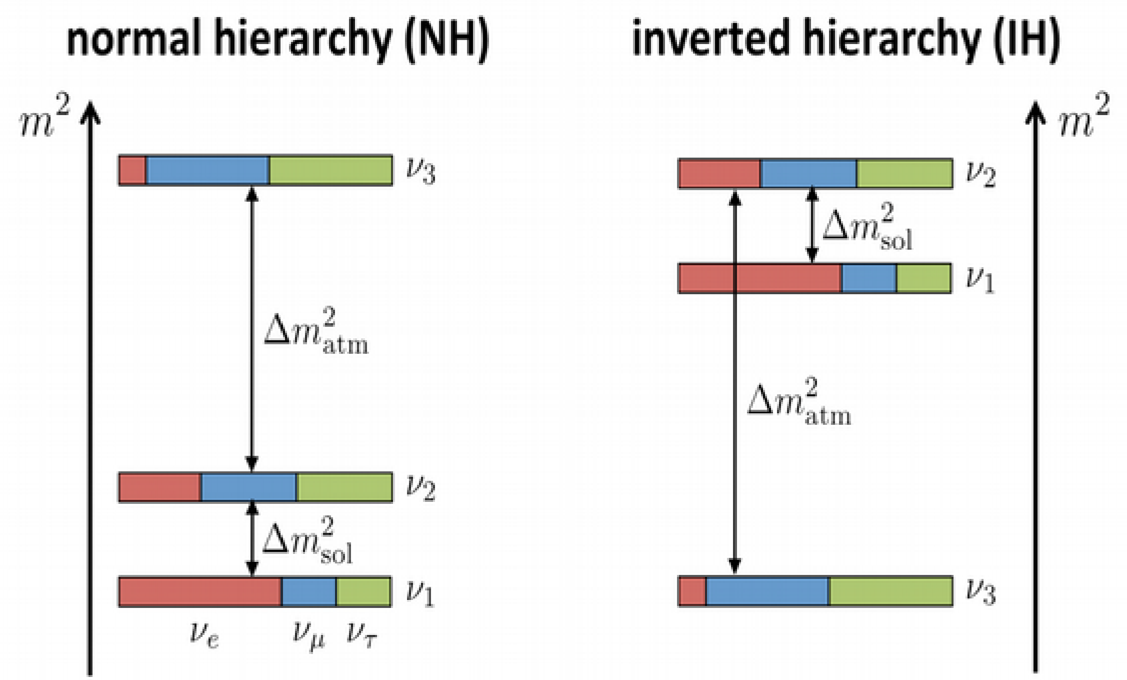
Limited by interaction kinematics (neutrino – lepton angle)

Energy resolution



Energy resolution ~ 25 – 30%

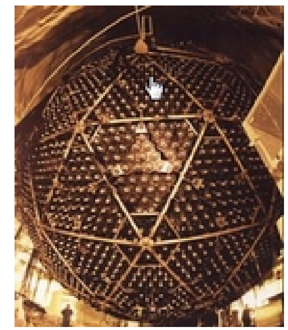
Neutrino mass hierarchy (ordering)

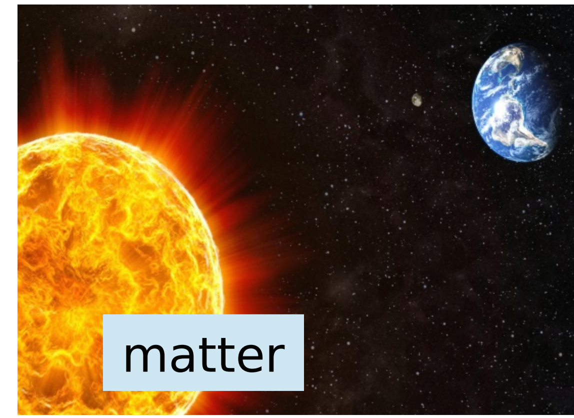


Why mass hierarchy is important:

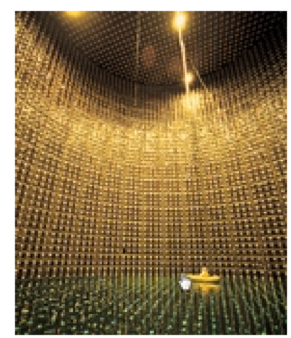
- Prime discriminator for theory models
- Helps measuring the CP phase
- Sensitivity of 0νββ experiments
- Absolute mass scale
- Dirac vs Majorana
- Origin of neutrino mass and flavour
- Core-collapse supernovae physics

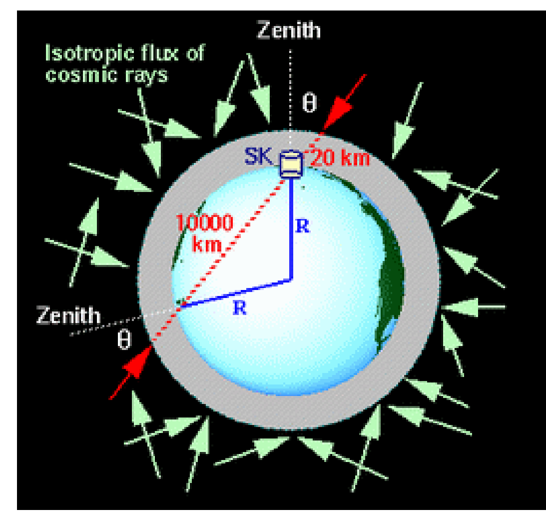
$\Delta m^2_{\rm solar}$: sign known





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



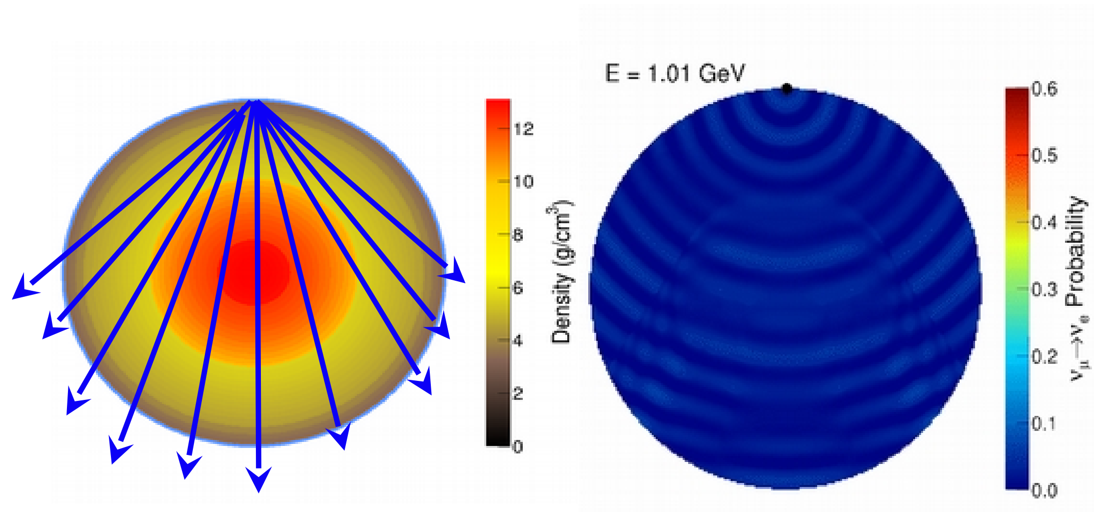


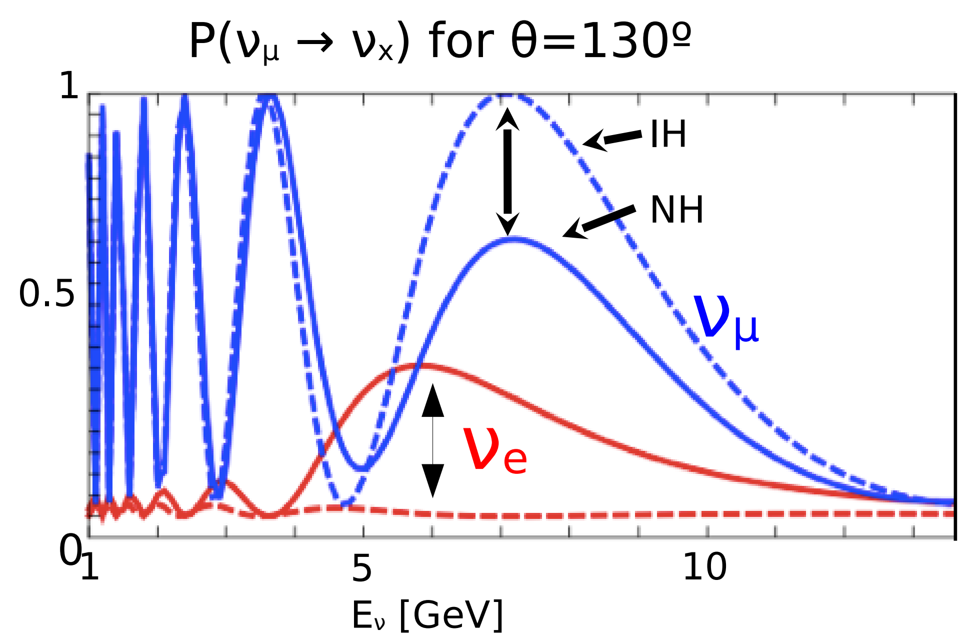
Mass hierarchy with atmospheric neutrinos

- Known composition (νe, νμ)
- Wide range of baselines (20 - 12800 km) and energies (100 MeV – 100 TeV)
- Oscillation affected by matter (mass hierarchy-dependent): maximum difference IH / NH at θ=130° (7645 km) and Eν = 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 sensitivity to Mass Hierarchy

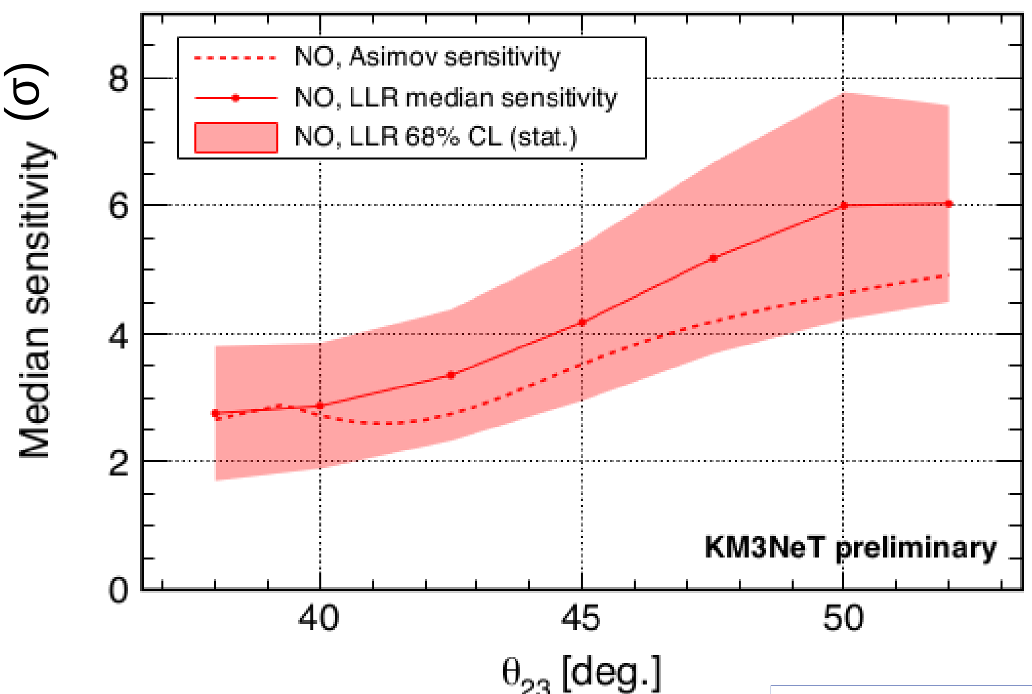
osc. parameters

param.	*treatment*	*true value*	*prior*
ΔM^2	fitted	$2.48\ 10^{-3}\ eV^2$	free
Δm^2_{21}	fix	$7.53\ 10^{-5}\ eV^2$	–
θ_{13}	fitted	8.42°	0.26
θ_{12}	fix	33.4°	–
θ_{23}	fitted	38° – 52°	free
δ_{CP}	fitted	0 – 2 π	free

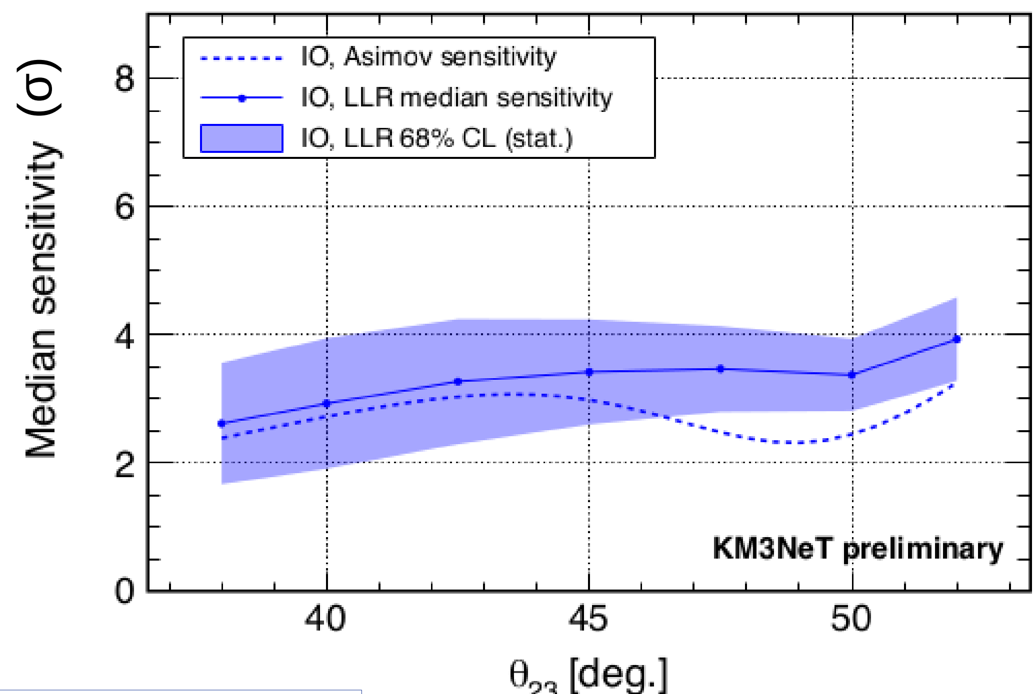
Systematics

Parameter	*treatment*	*true value*	*prior*
Flux spectral tilt	fitted	0	free
$\nu/\bar{\nu}$ skew	fitted	0	0.03
Track normalization	fitted	1	free
Cascade normalization	fitted	1	free
NC events normalization	fitted	1	0.1

ORCA sensitivity after 3 yr (NH, δ_{CP}=0)

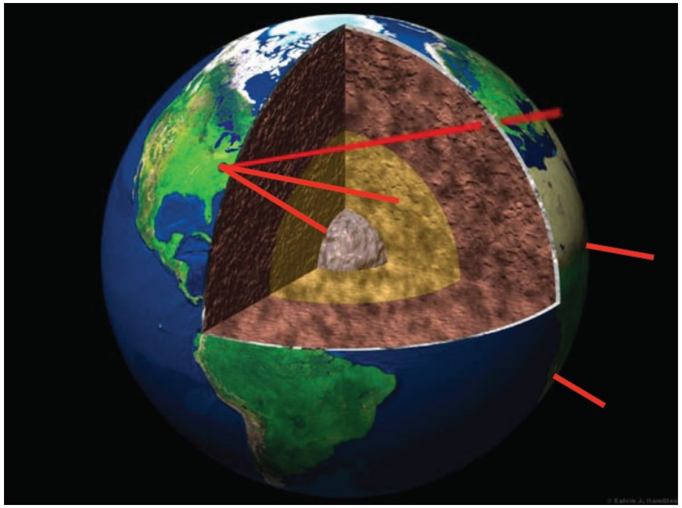


ORCA sensitivity after 3 yr (IH, δ_{CP}=0)



S. Bourret & L. Quinn, et al,
@ Neutrino 2018

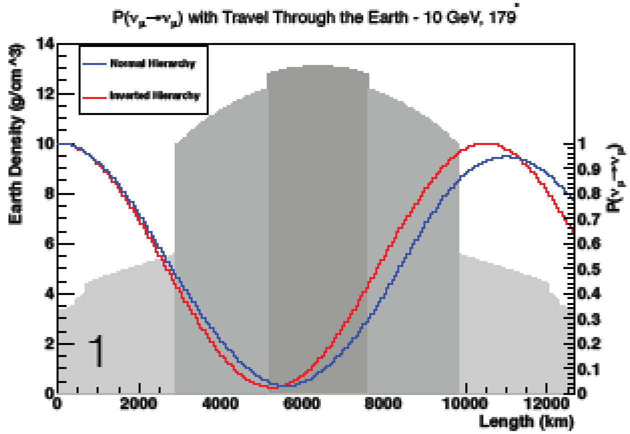
Sensitivity to Earth electron density profile

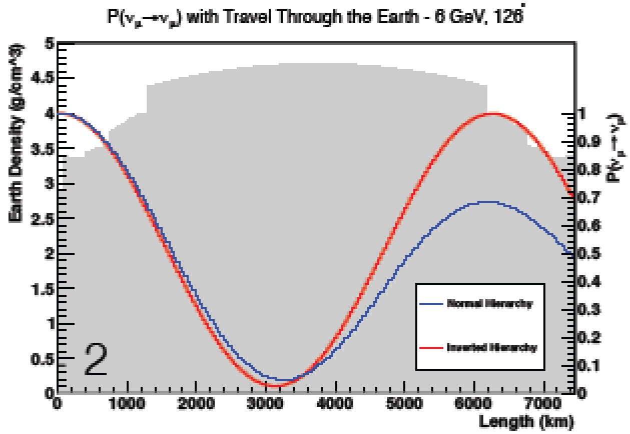


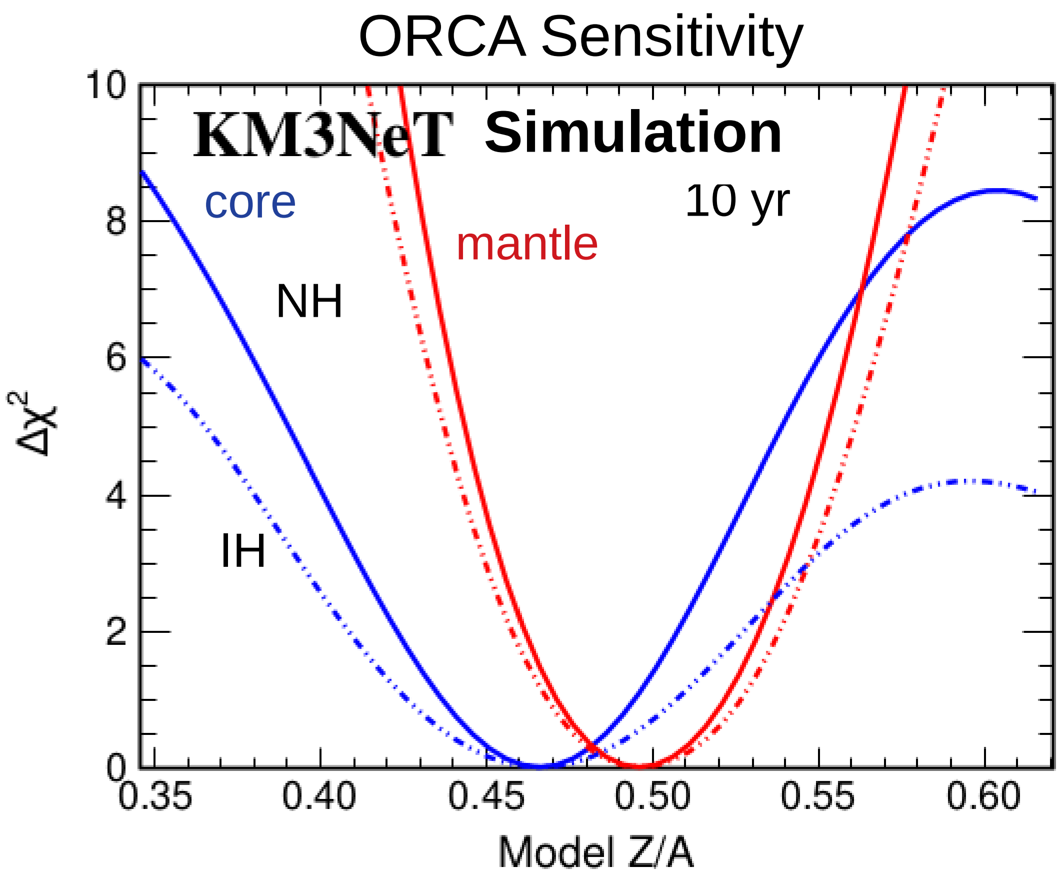
Earth density 4-13 g/cm³

Relevant: $E_\nu \sim 3\text{–}10$ GeV

ORCA 10 yr:
5-6% precision for mantle
6-9% precision for core







7% wt Hydrogen content in core (Z/A ~ 0.53) could be excluded at 90% C.L.

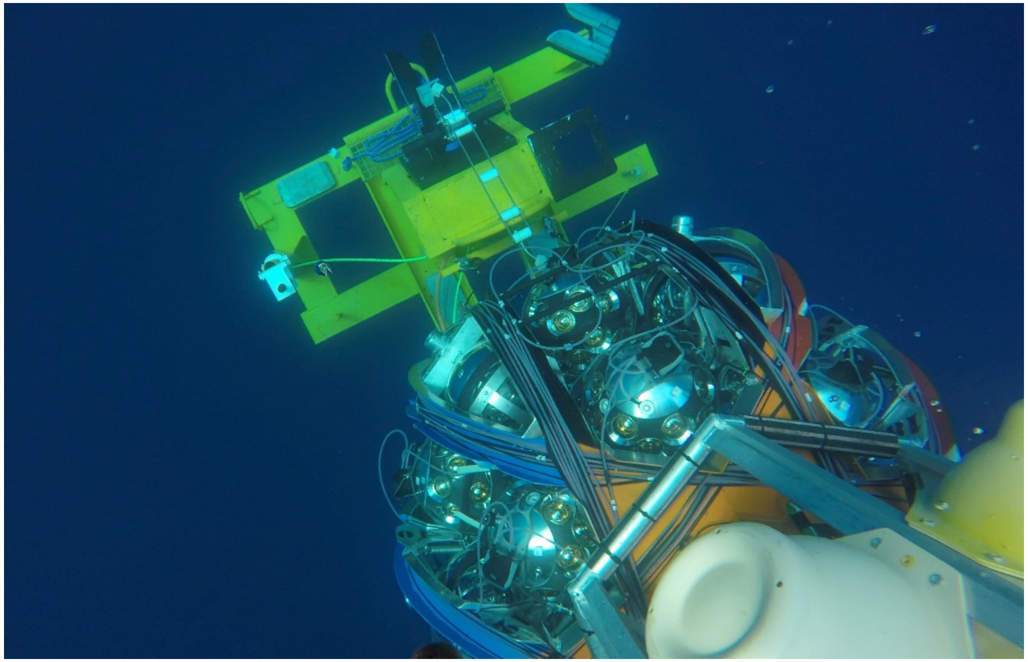
S. Bourret, J. Coelho, V. Van Elewyck, et al., Neutrino oscillation tomography of the Earth with KM3NeT-ORCA, ICRC 2017

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
- Tau neutrino appearance and unitarity
- Indirect search for Dark Matter
- Low energy (GeV-TeV) neutrino astrophysics
- Supernova monitoring
- …

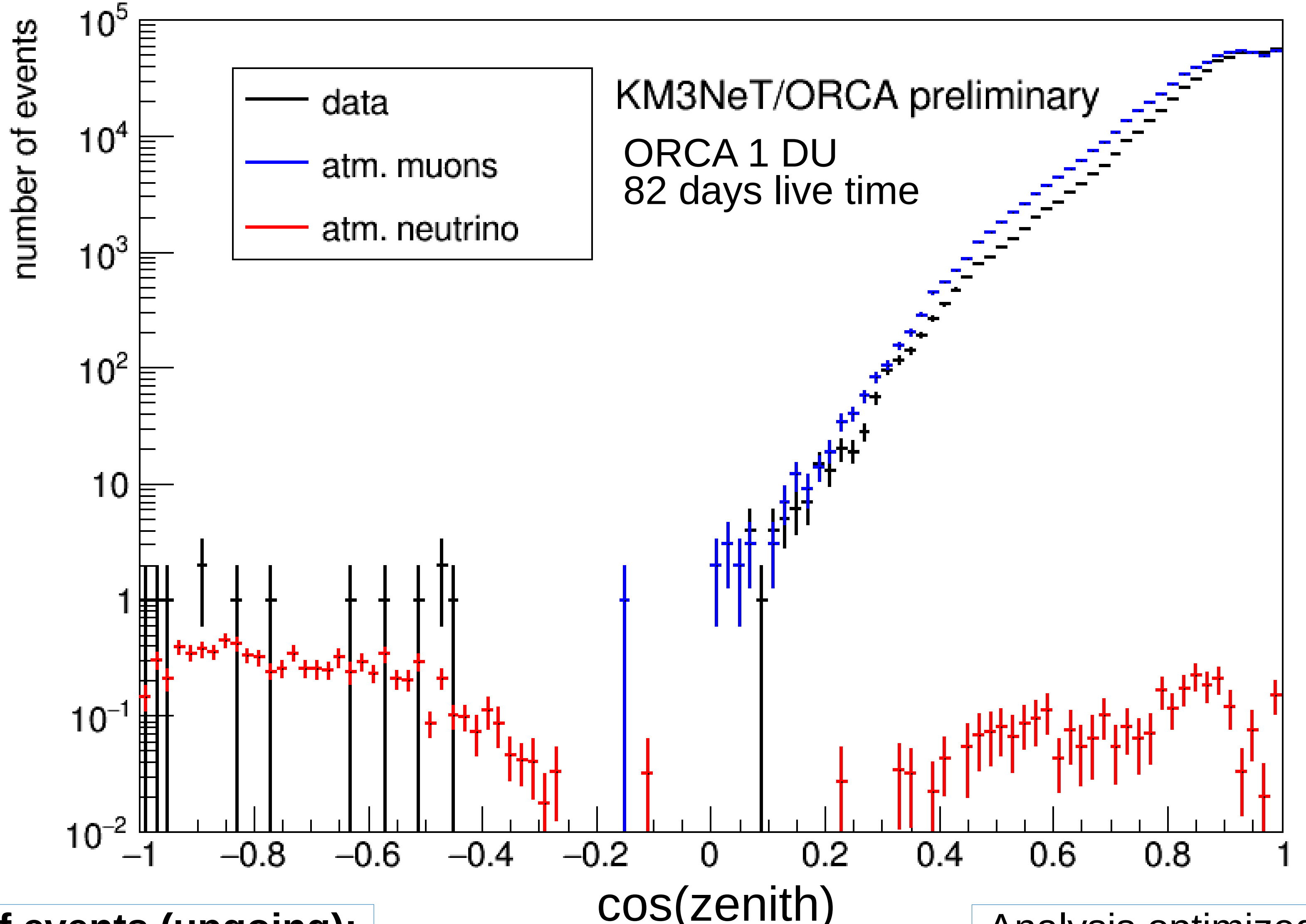
First ORCA detection unit

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



First results from first ORCA Detection Unit

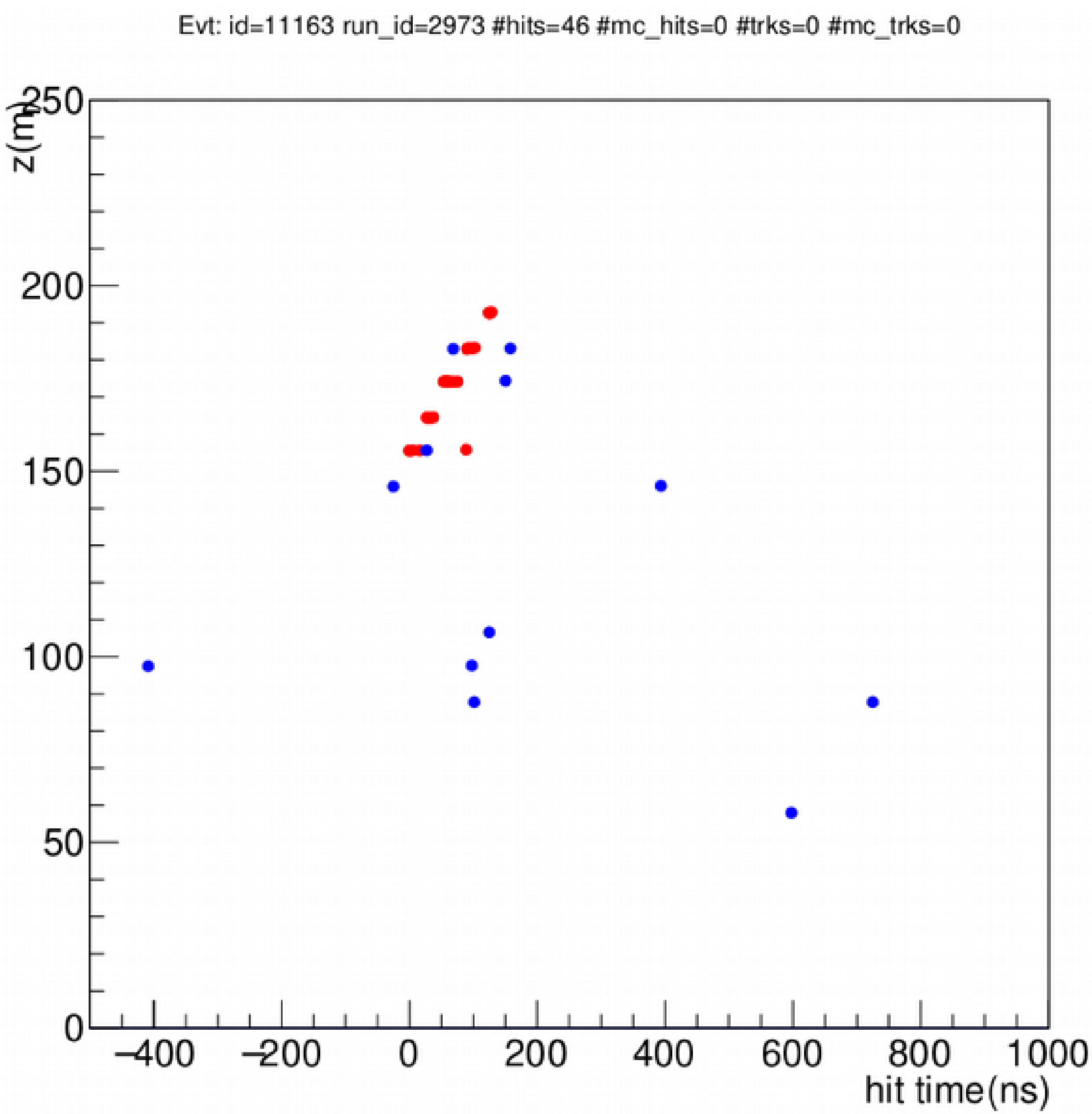
deployed in September 2017

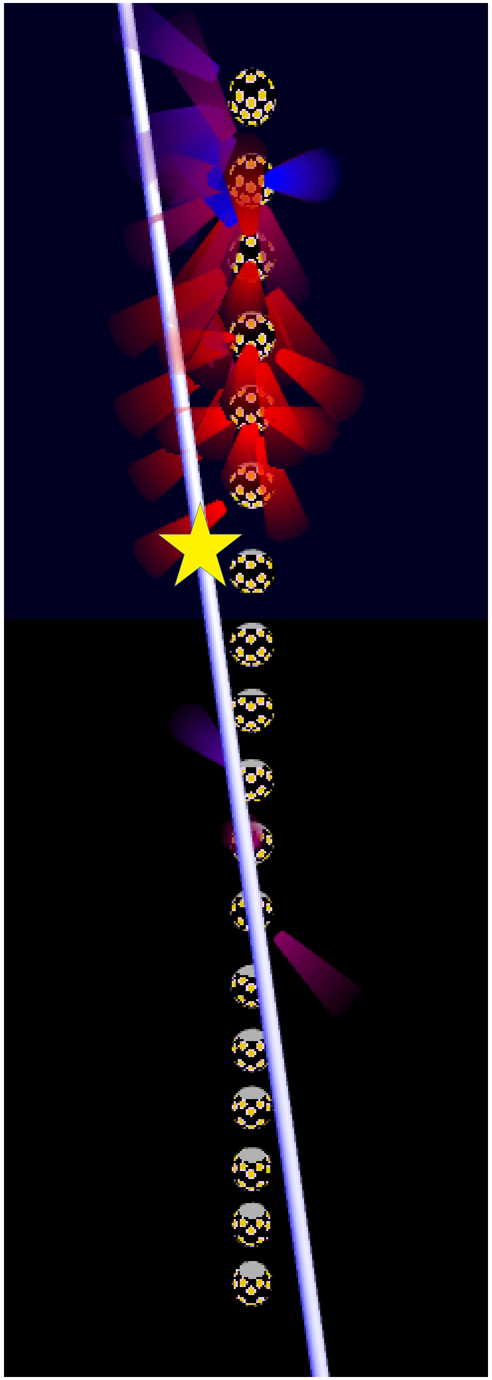


Number of events (upgoing):
MC atm neutrinos : 8.33
MC atm. muons : ~ 1
observed : 13

Analysis optimized for vertical upgoing tracks (horizontal tracks suppressed)

A neutrino candidate from ORCA



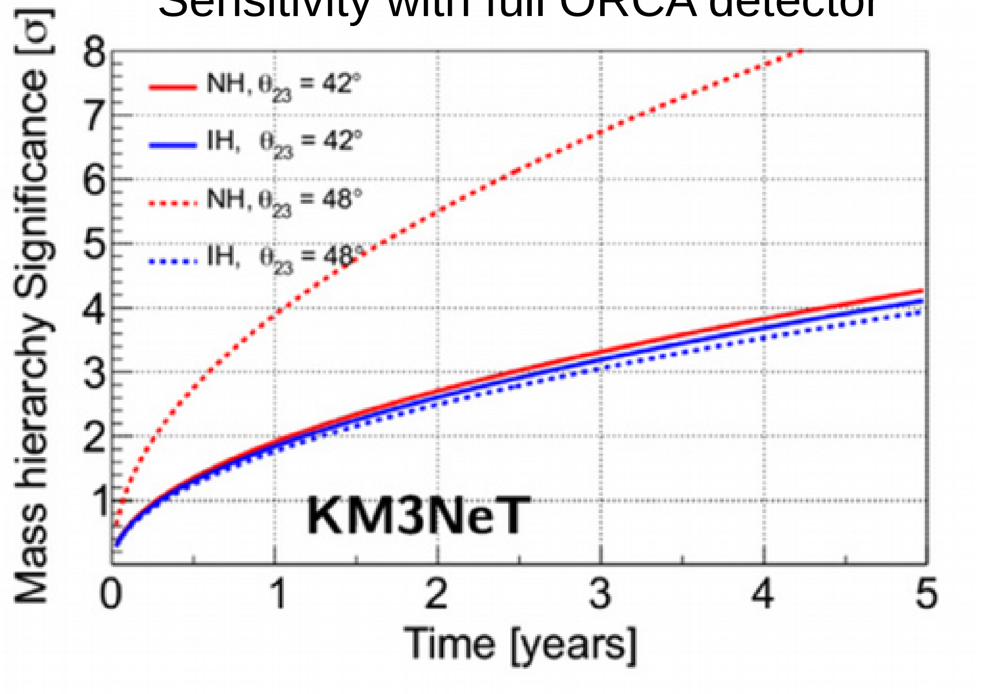


Energy ~ 10 GeV

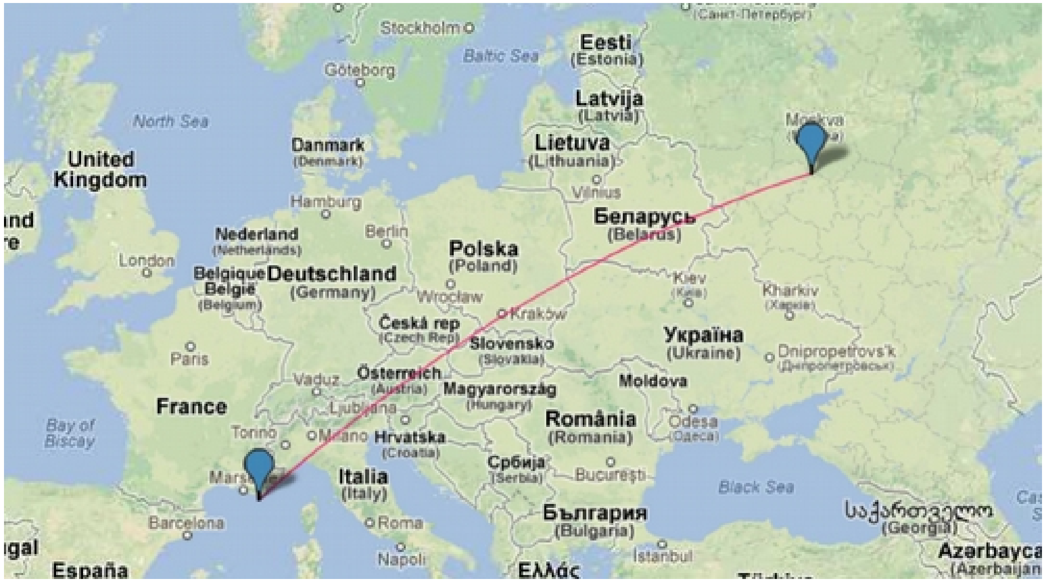
Current status and plans

- Problem with cable to shore, replacement in Sep 2018
- DOM and DU assembly proceeds according to normal schedule, deployment after cable repair
- 5 DUs being prepared for deployment later this year
- Full detector in 4 yr

Sensitivity with full ORCA detector

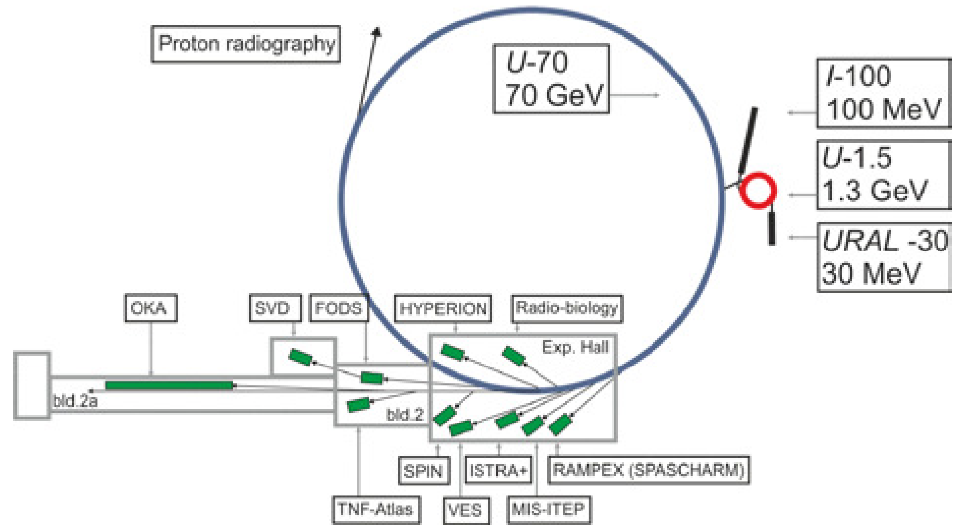


P2O : Protvino to ORCA



- 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

Protvino accelerator complex



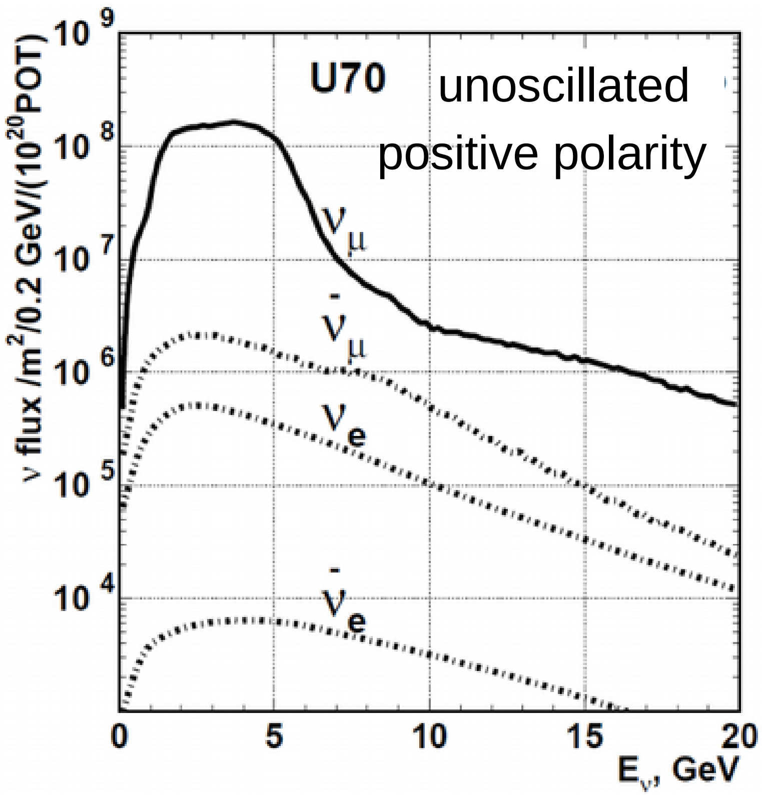
Current operation:

- Protons up to **70 GeV**
- **15 kW** beam power
- 5 μs spill every 9 s

Upgradable up to 90 – 450 kW

arXiv:1304.6230 / Adv. High En. Phys. (2013) 782538 http://dx.doi.org/10.1155/2013/782538;
arXiv:1803.08017
J. Brunner et al., Neutrino 2018

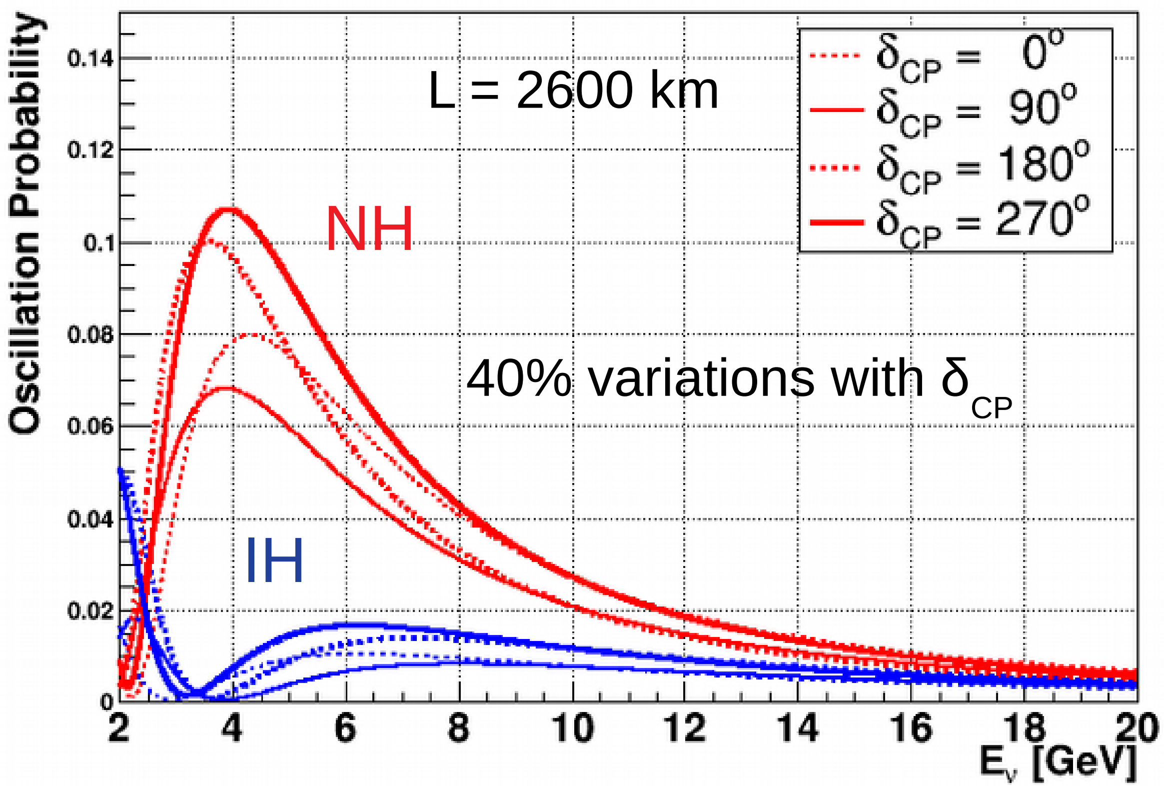
Simulated neutrino beam and oscillations



On-axis 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

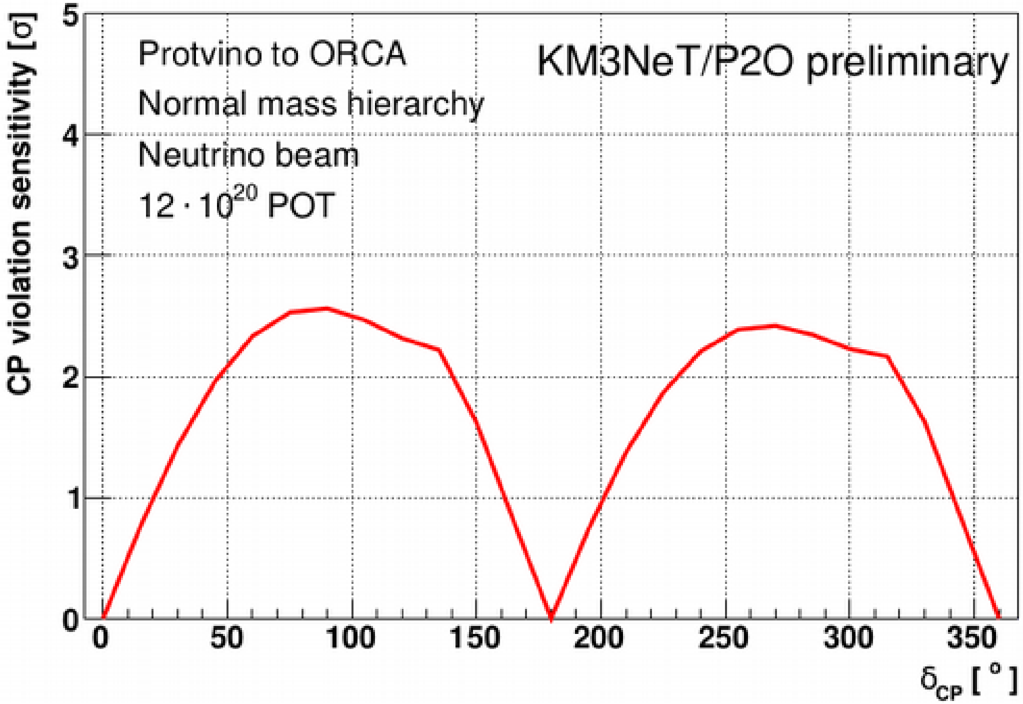
$P(\nu_\mu \rightarrow \nu_e)$

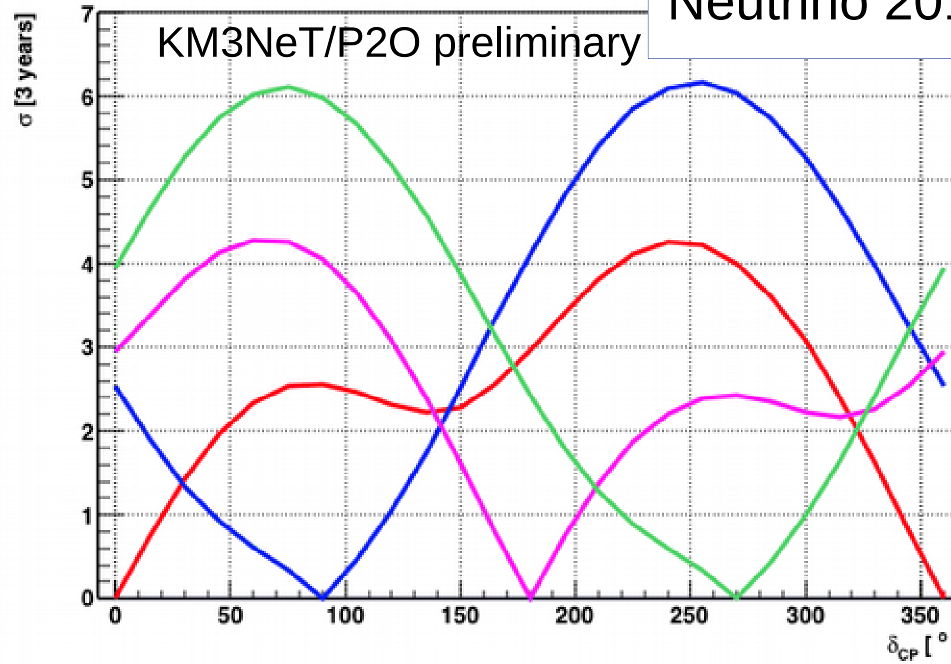


Beam polarity chosen depending on neutrino mass hierarchy

P2O sensitivity to CP violation

J. Brunner et al, Neutrino 2018





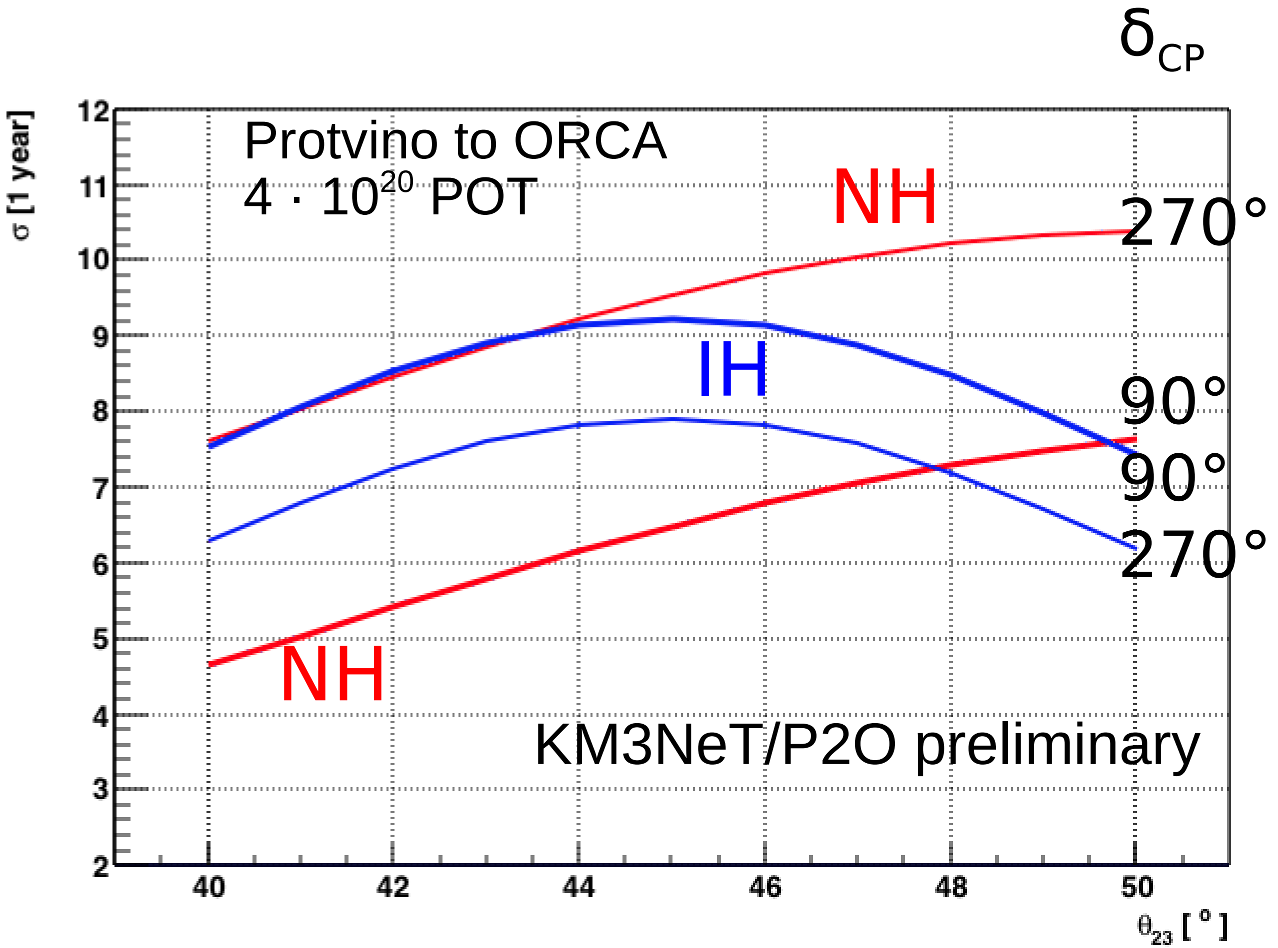
2.5 sigma after 3 years of 450 kW beam
or 15 years of 90 kW beam

δ_{CP} precision
~ 20° - 40° after 3 yr

50% phase space covered with 2σ
and 75% with 1σ after 3 yr

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

P2O sensitivity to mass hierarchy



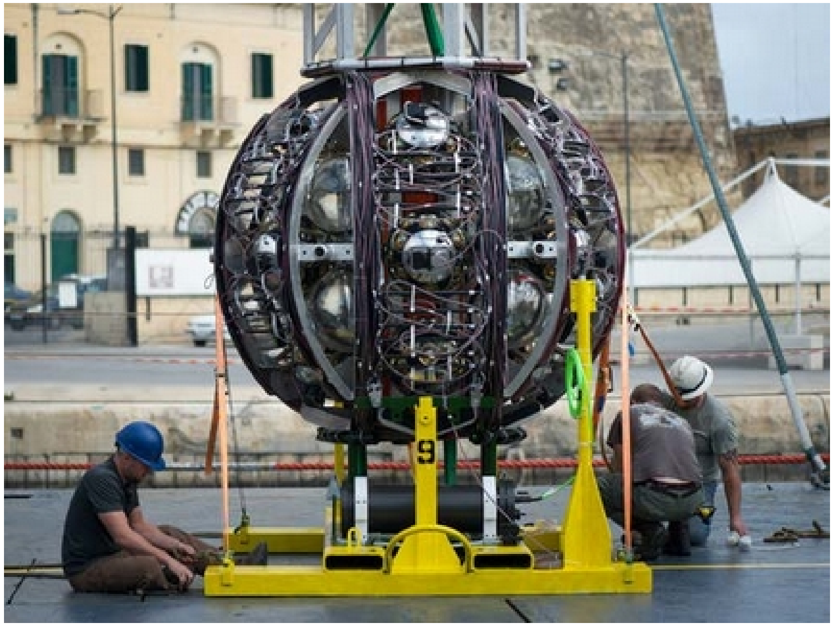
> 5 sigma after 1 year of 450 kW beam
(or 5 years of 100 kW beam)

Summary

- Using atmospheric neutrinos, KM3NeT-ORCA aims at determining the neutrino mass hierarchy with a 3 σ significance after 3 years of operation
- Construction in progress, first neutrinos already detected
- A neutrino beam (~ 100 – 500 kW) from Protvino to ORCA could provide a competitive sensitivity to leptonic CP violation and mass hierarchy (4 GeV matter resonance)

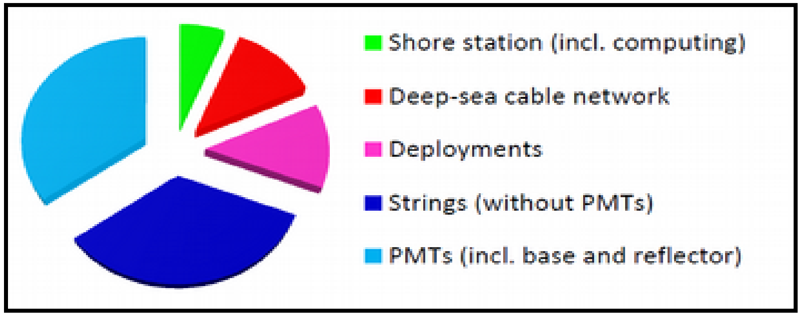
Learn more about KM3NeT

- 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



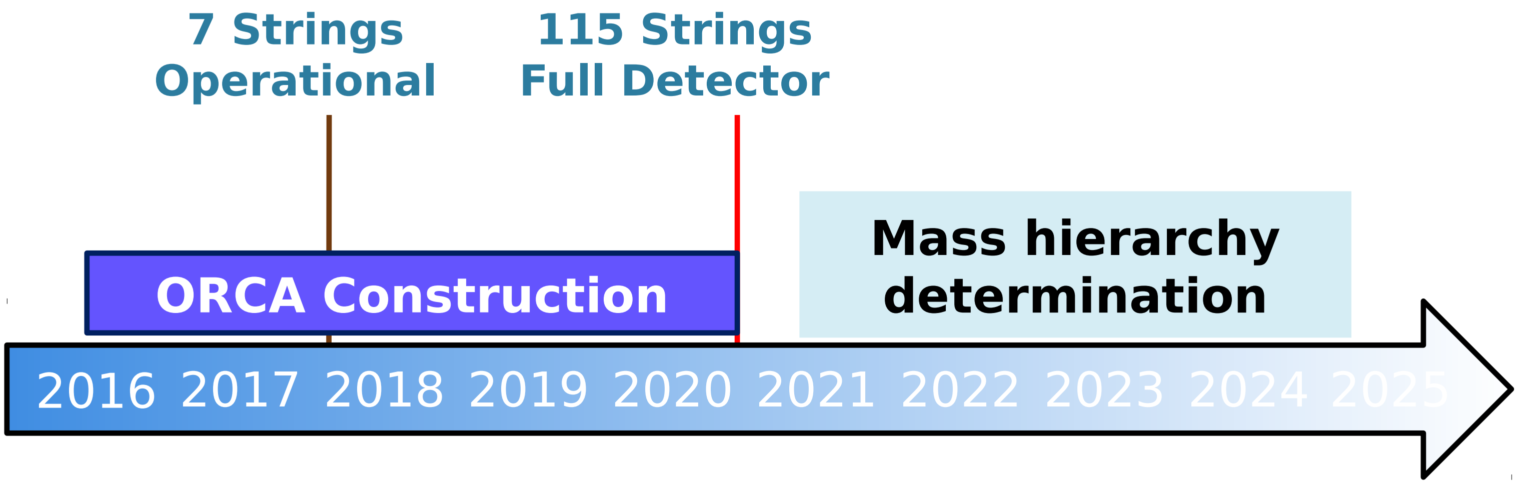
Total ORCA cost ≈ 45 M€

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



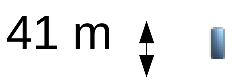
Instrumented volume comparison

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

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

IceCube & Baikal-GVD have similar size

SuperK
11100 PMTs
50 kt

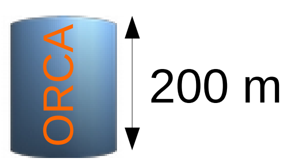


MeV - GeV

Solar & atm. ν

operating for 20 yr

KM3NeT-**ORCA**
2000 OMs
(64000 PMTs)
8 Mt

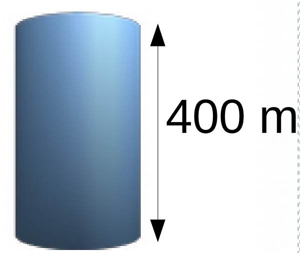


E > 3 GeV

atm. ν

under construction

ANTARES
885 PMTs
15 Mt



E > 20 GeV

astrophysical and atm. ν

operating for 10 yr

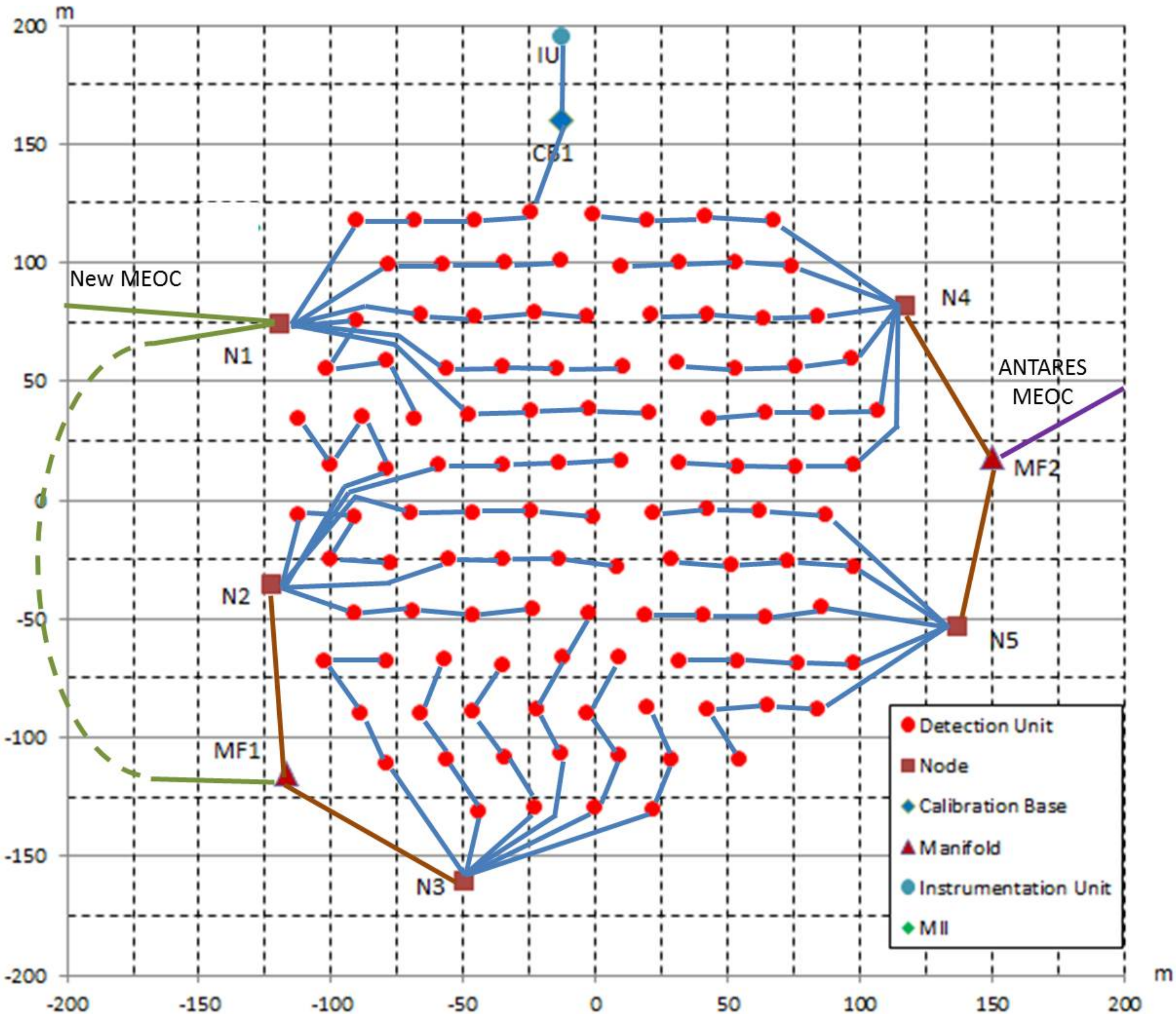
KM3NeT-**ARCA**
4000 OMs (128 000 PMTs)
1 Gt

E > 100 GeV

astrophysical ν

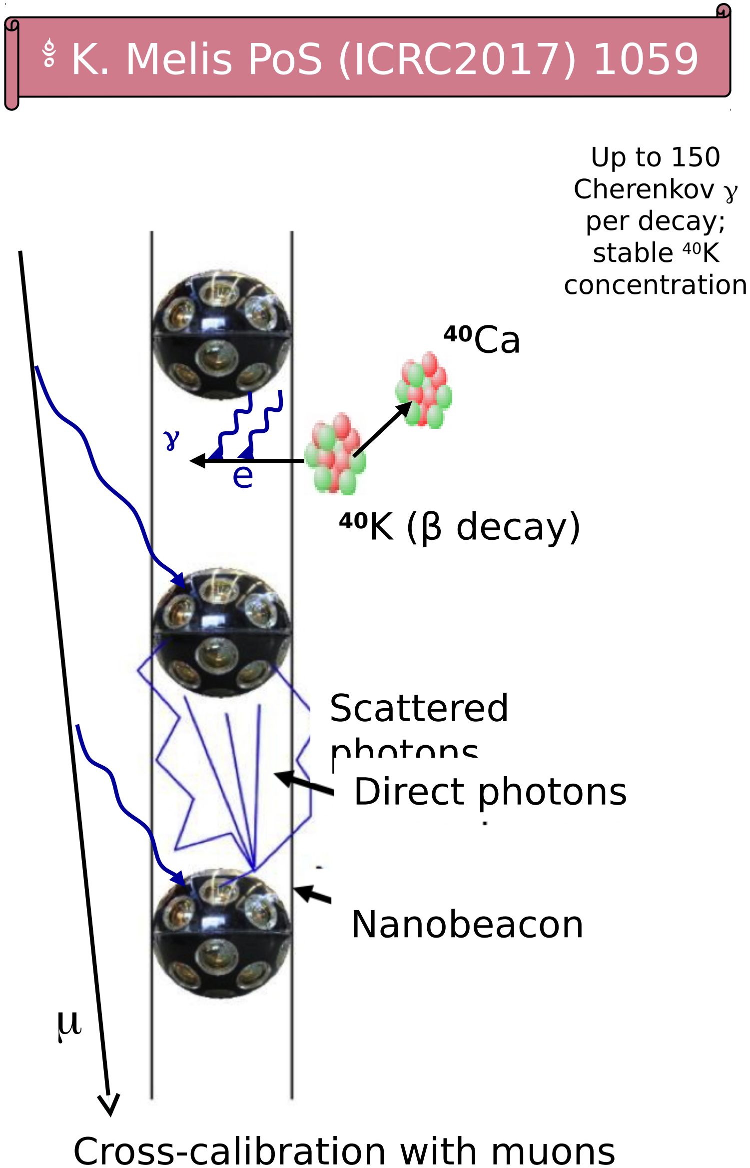
under construction

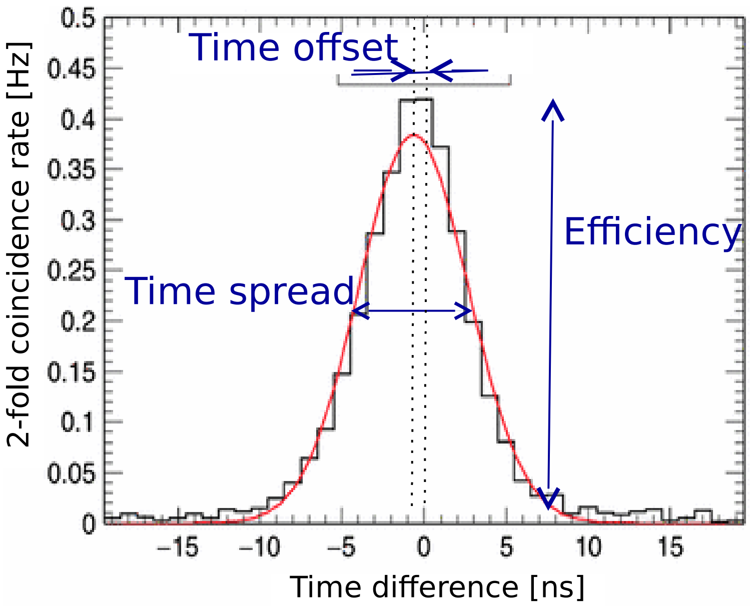
ORCA layout

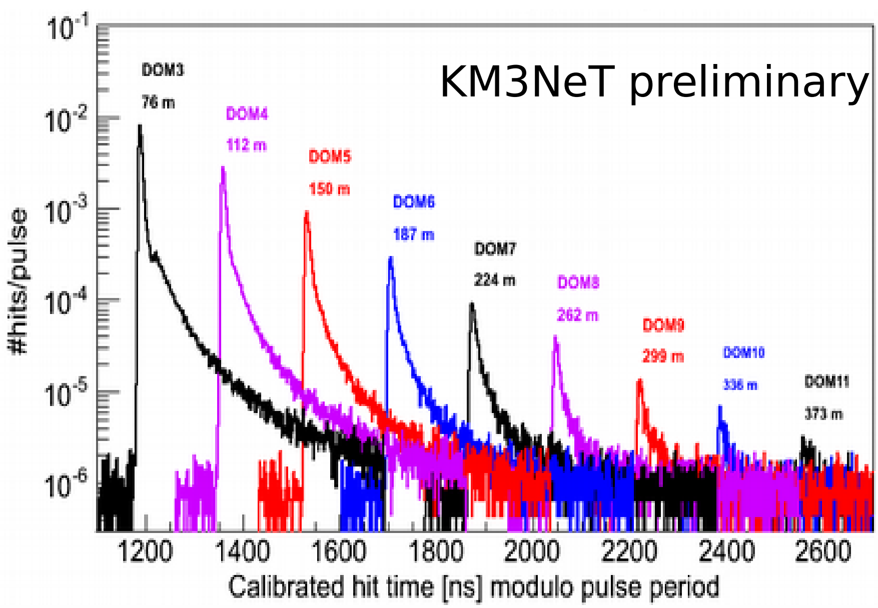


m
200
150
100
50
0
-50
-100
-150
-200
-200
-150
-100
-50
0
50
100
150
200
m
IU
CB1
New MEOC
N1
N2
N3
N4
N5
MF1
MF2
ANTARES
MEOC
Detection Unit
Node
Calibration Base
Manifold
Instrumentation Unit
MII

Calibration procedures



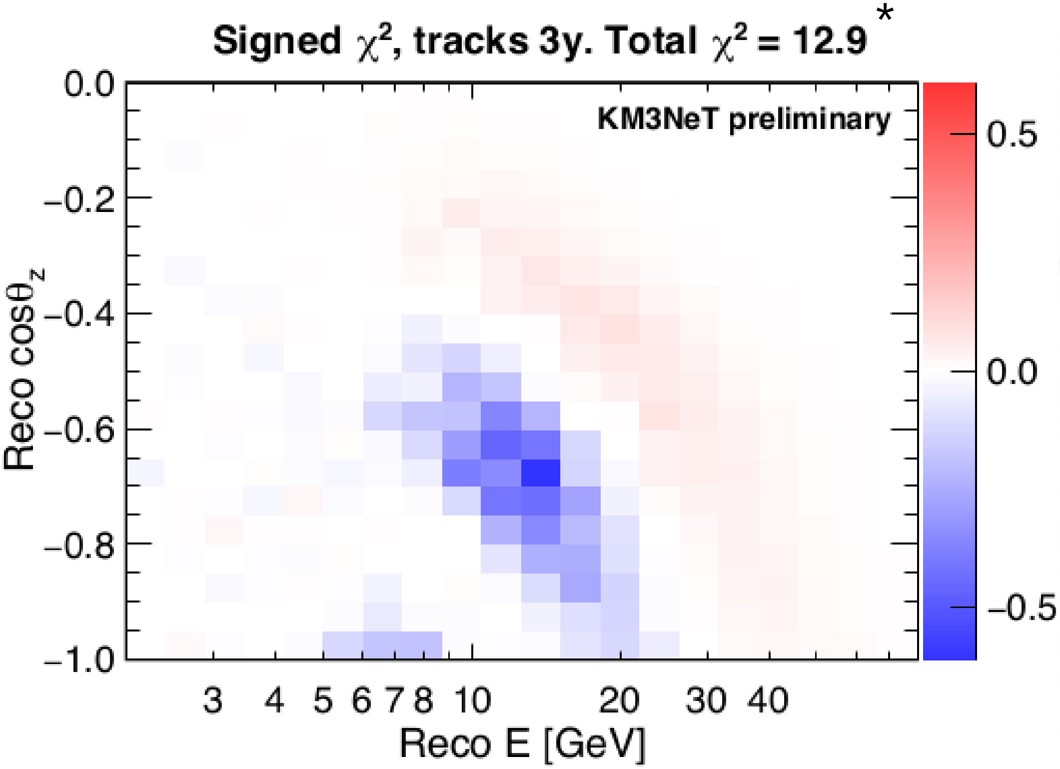




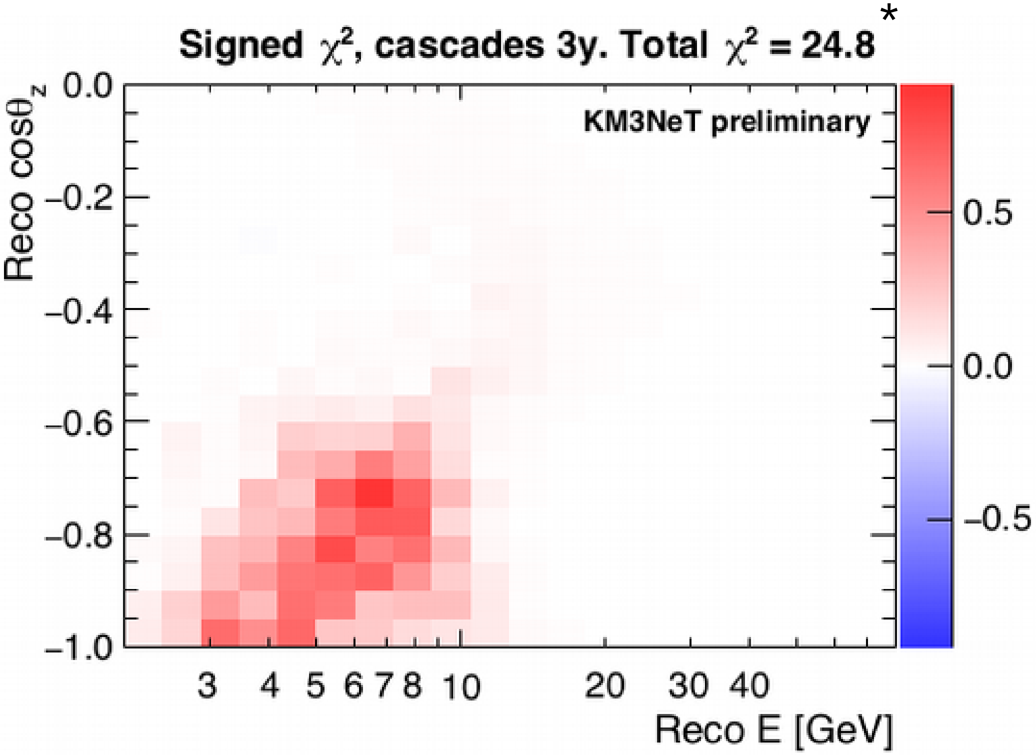
Mass hierarchy measurement technicalities

$$\chi^2 = (N_{NO} - N_{IO})\,|N_{NO} - N_{IO}|\,/\,N_{NO}$$

Track channel



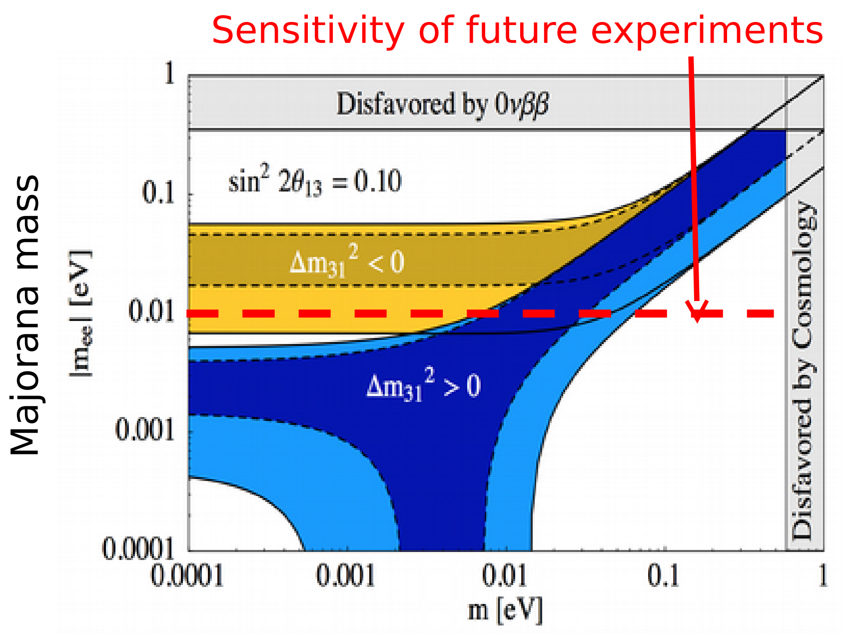
Cascade channel



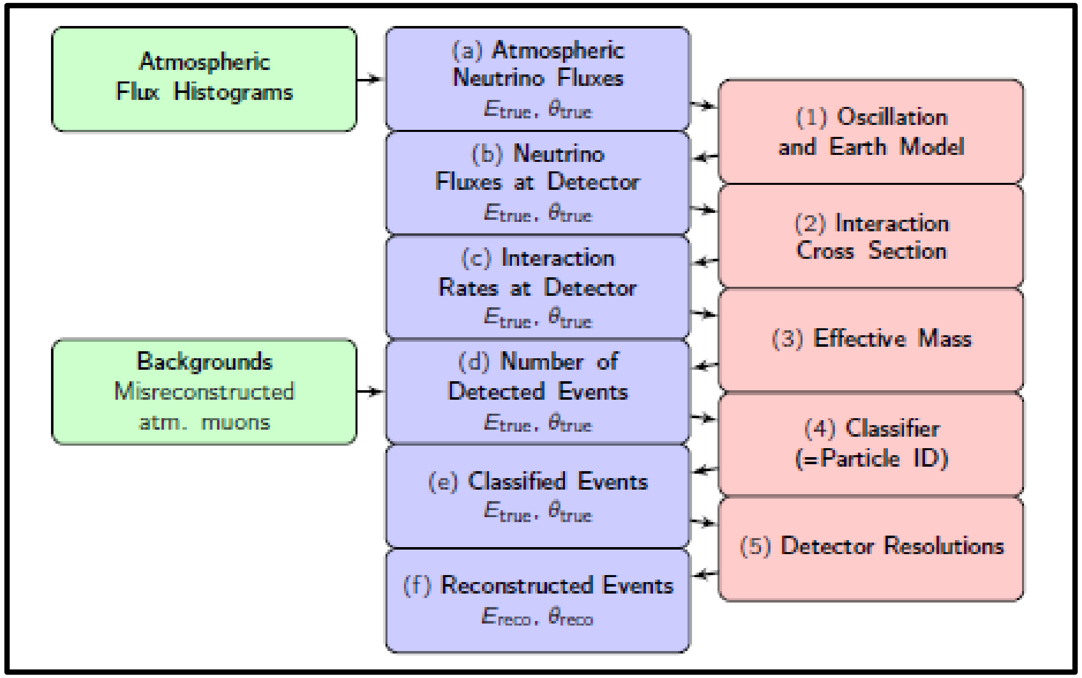
S. Bourret & L. Quinn @ Neutrino 2018 (Heidelberg)

* purely statistical χ^2 values (not including systematics and oscillation parameter priors)

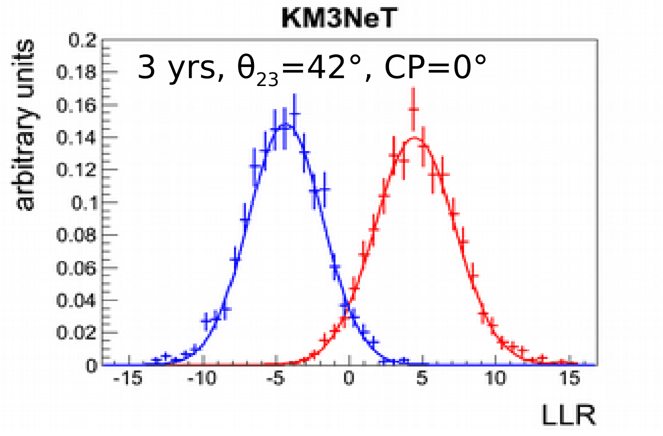
Why mass hierarchy is important



Mass hierarchy measurement technicalities

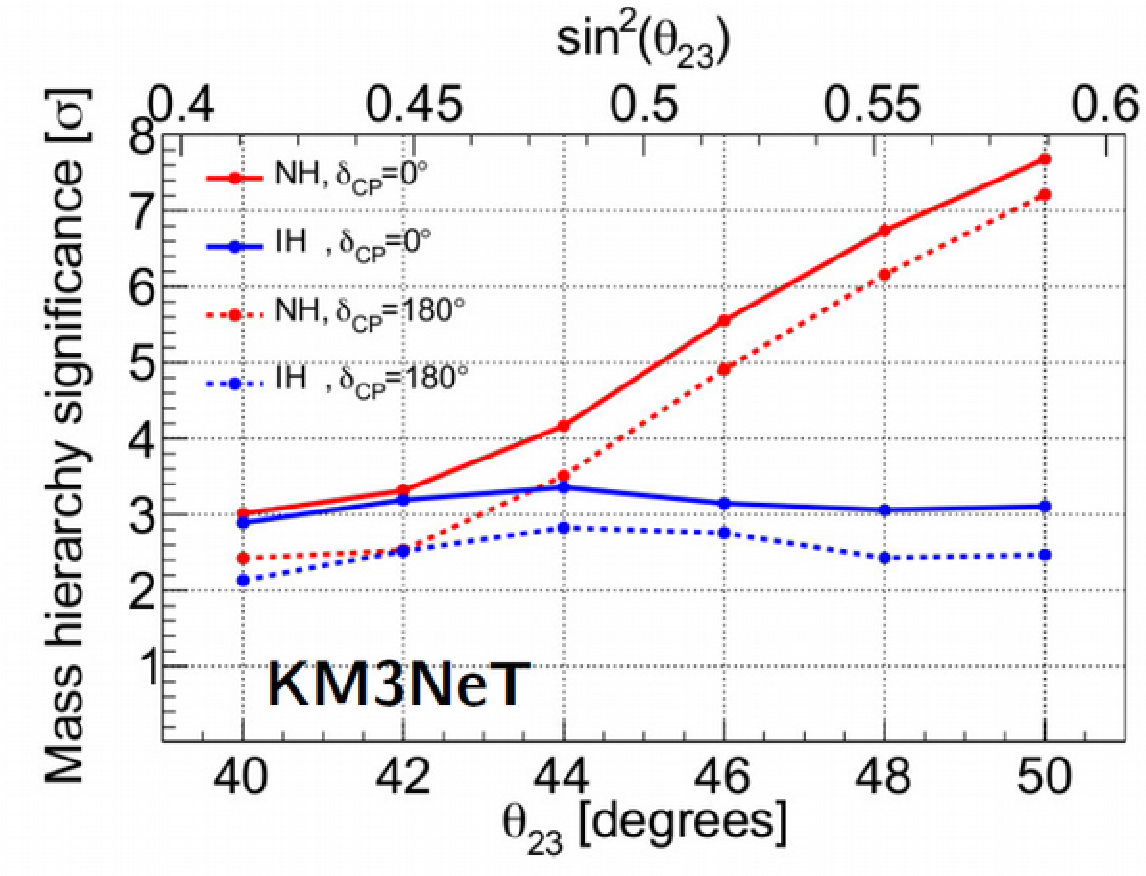


(simulated measurement)



- 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})

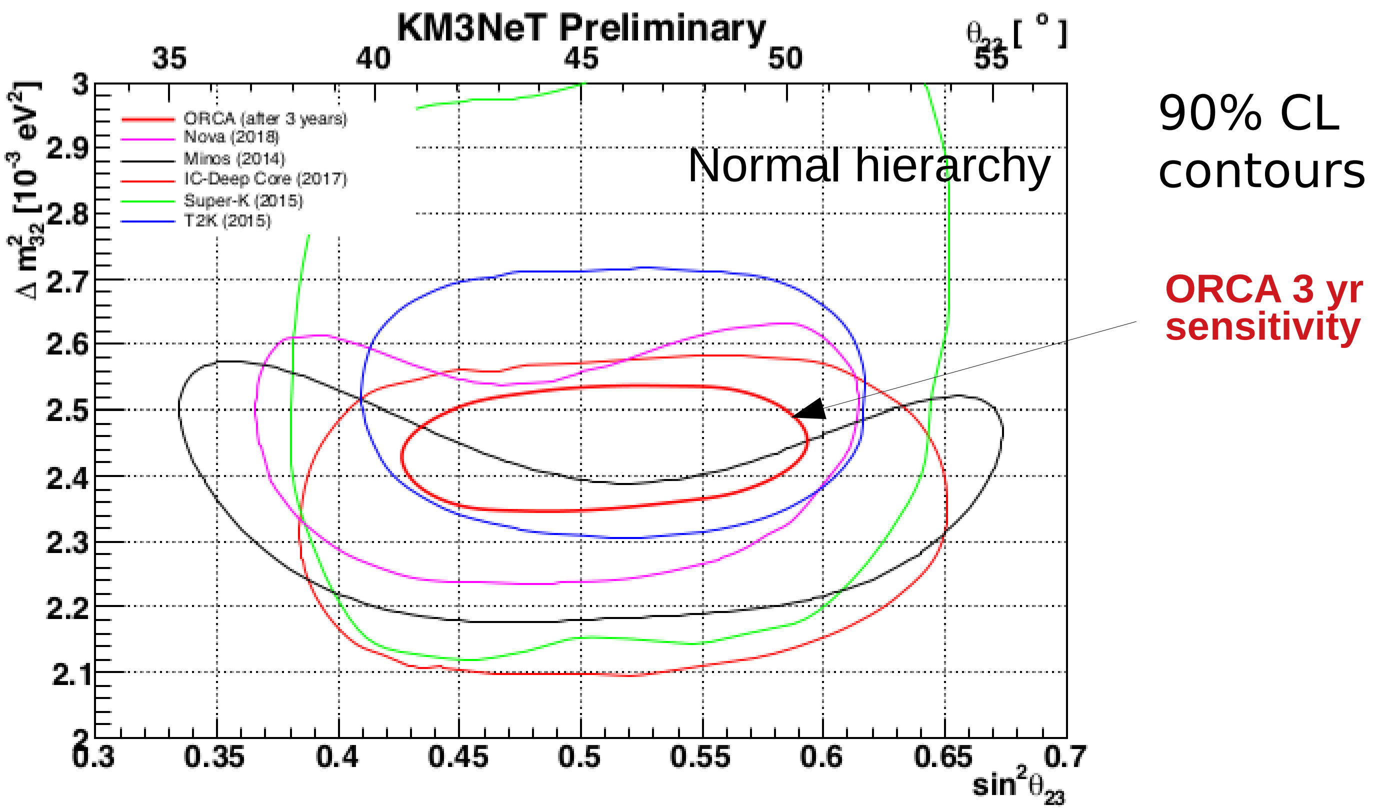
ORCA sensitivity to mass hierarchy (old)



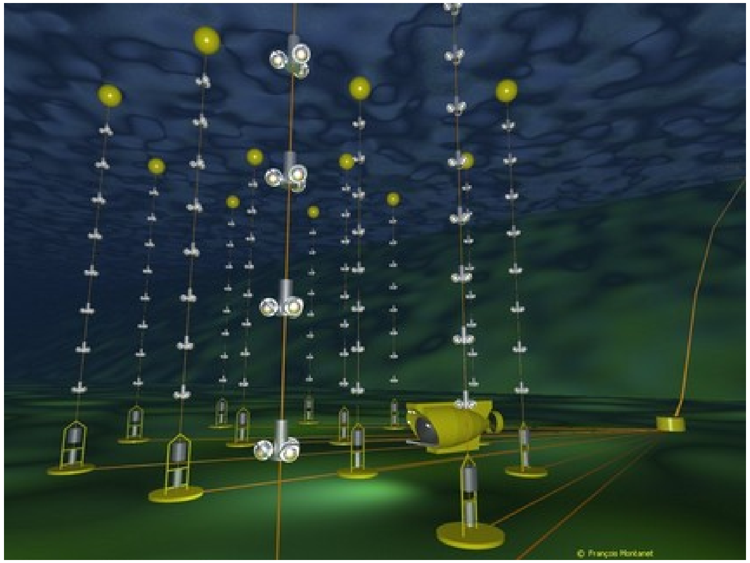
ORCA sensitivity to Δm^2_{32} and $\sin^2\theta_{23}$

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

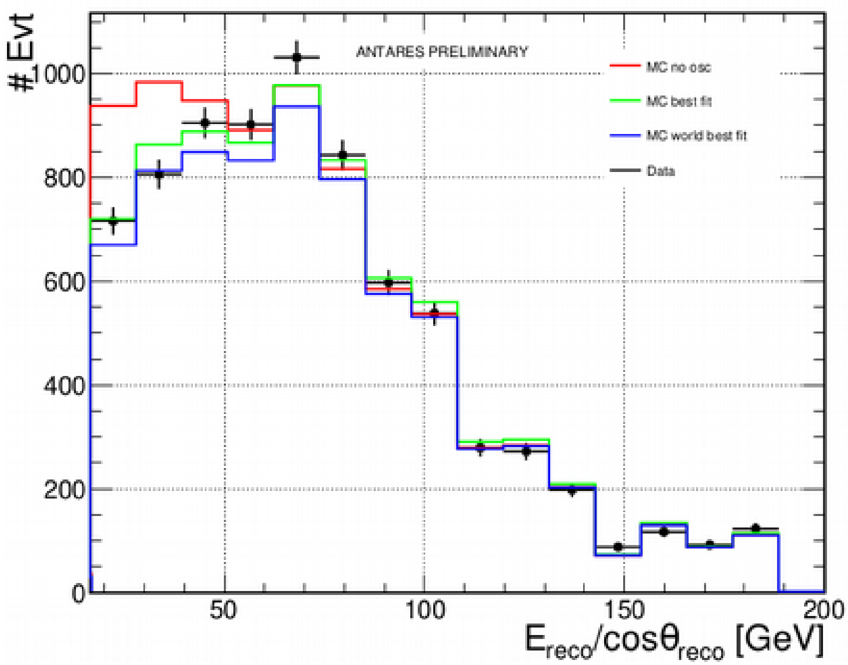
S. Bourret & L. Quinn
Neutrino 2018 (Heidelberg)

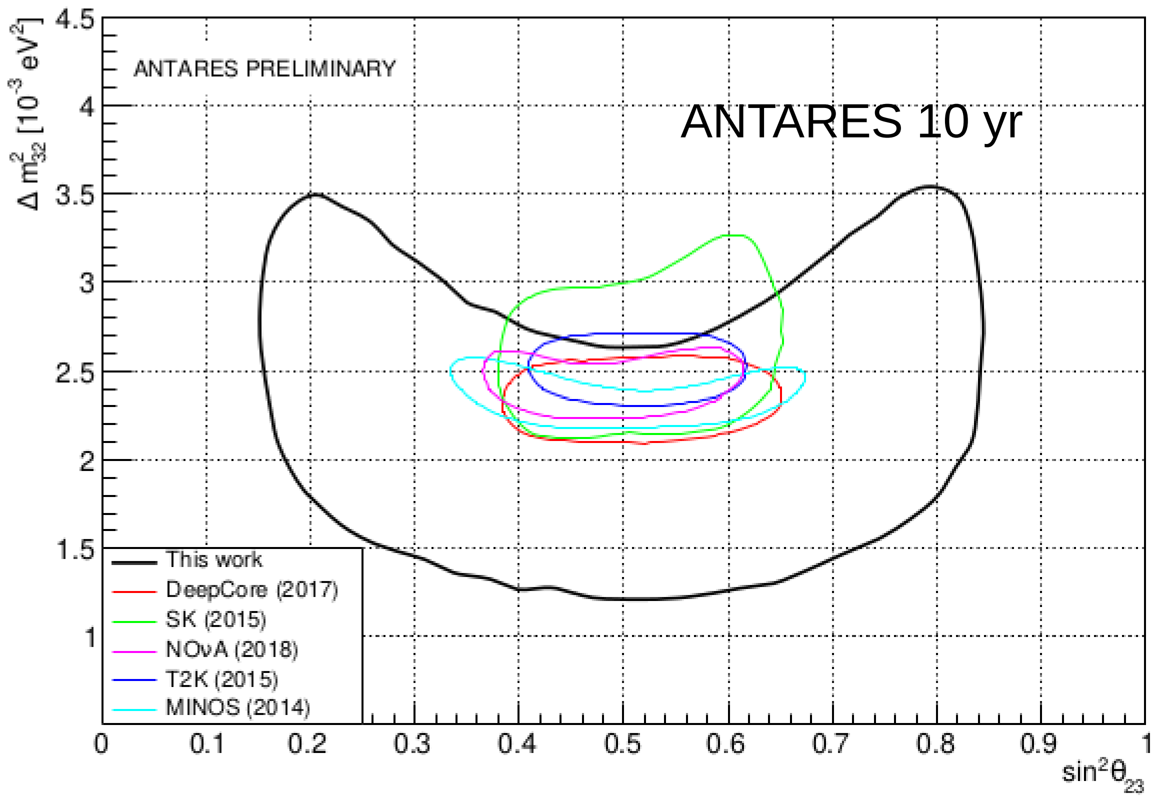


ANTARES oscillation result 2018



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

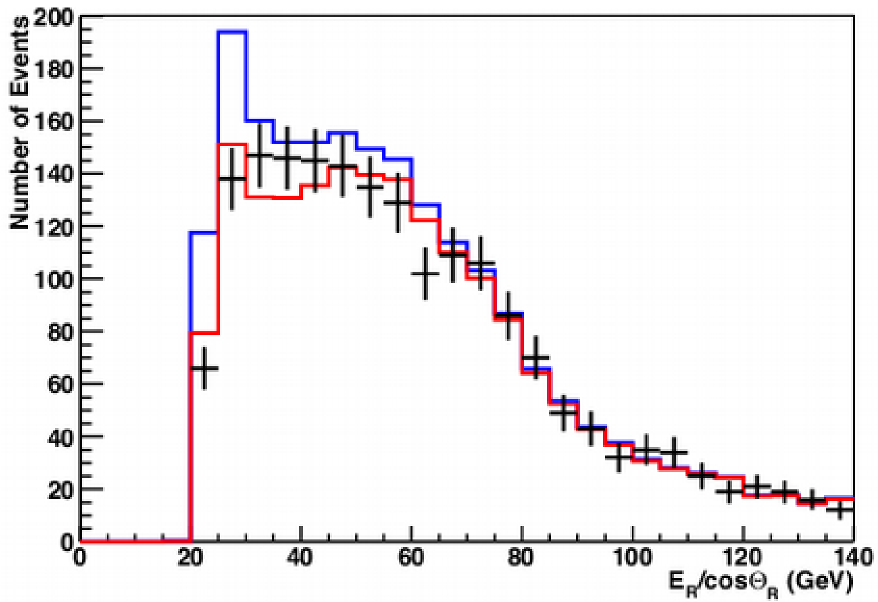


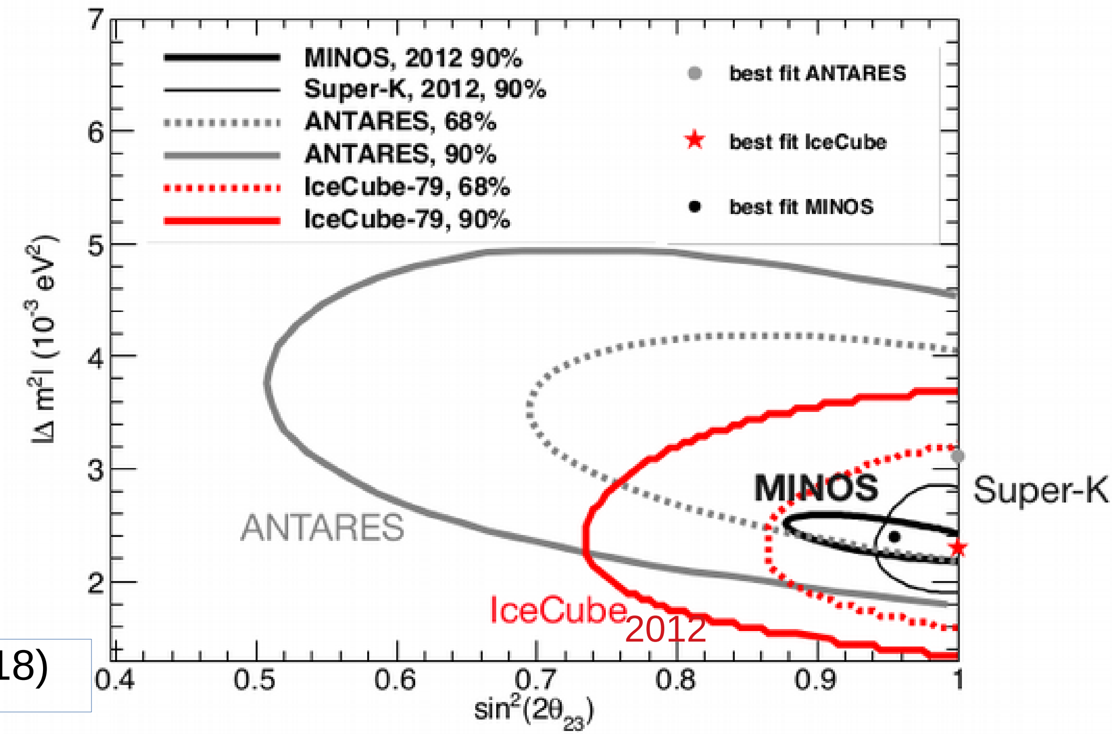


I. Salvadori, Neutrino 2018

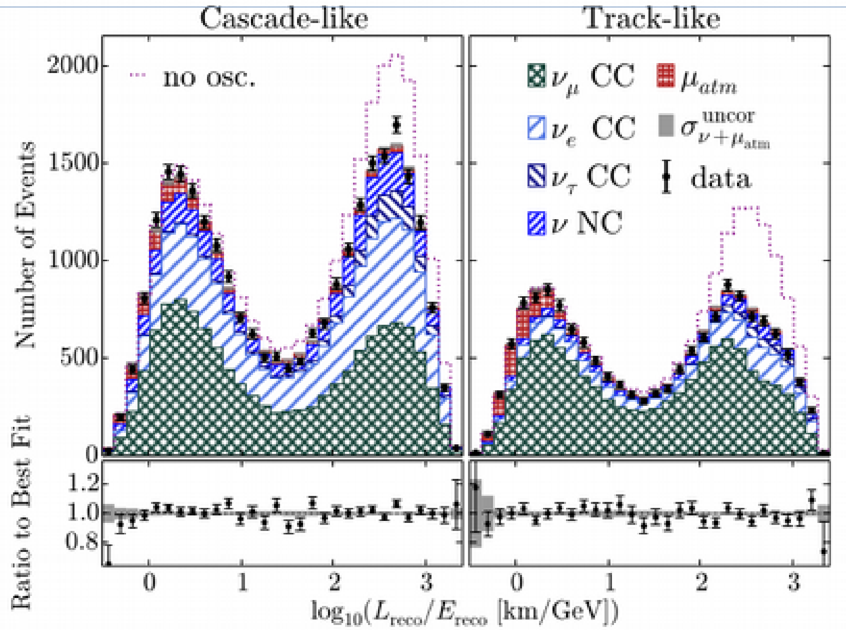
Oscillations with neutrino telescopes

S. Adrián-Martinez et al. (ANTARES), Phys. Lett. B714 (2012)





M. Aartsen et al. (IceCube), Phys. Rev. Let. 120 (2018)

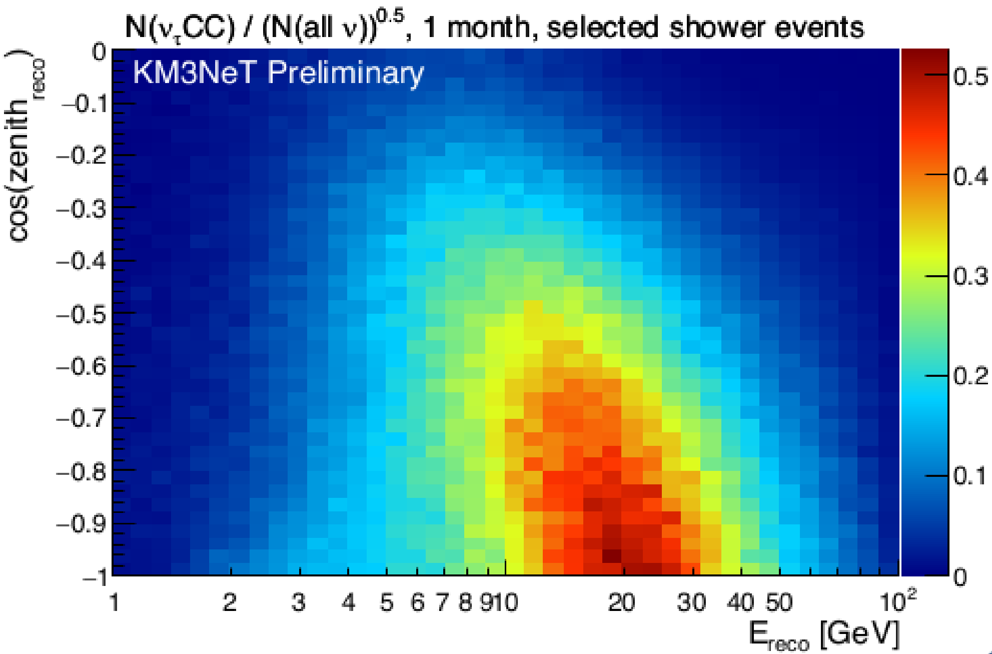


Muon neutrino disappearance observed by both ANTAREs and IceCube/deepCore

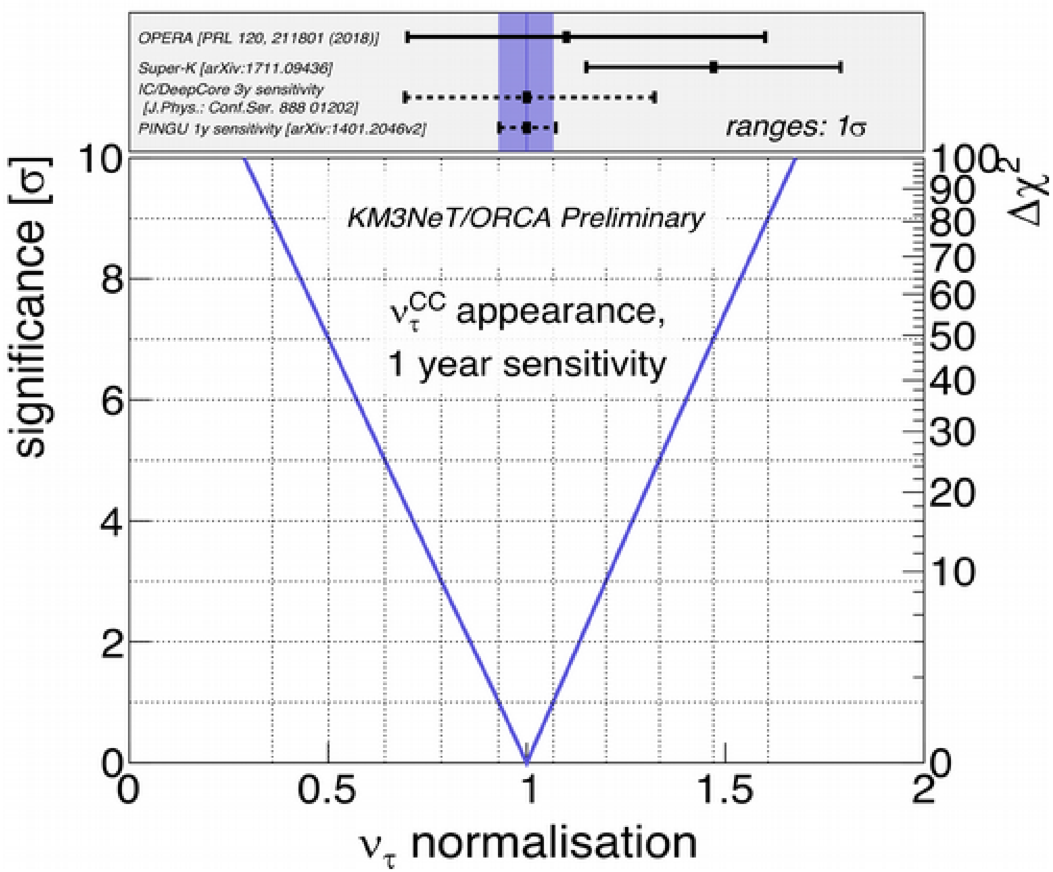
→ Atmospheric oscillation parameters

Tau neutrino appearance and unitarity

Tau appearance significance map



Most of the tau neutrino appearance signal is expected at 10 – 30 GeV reconstructed neutrino energy and with up-going direction

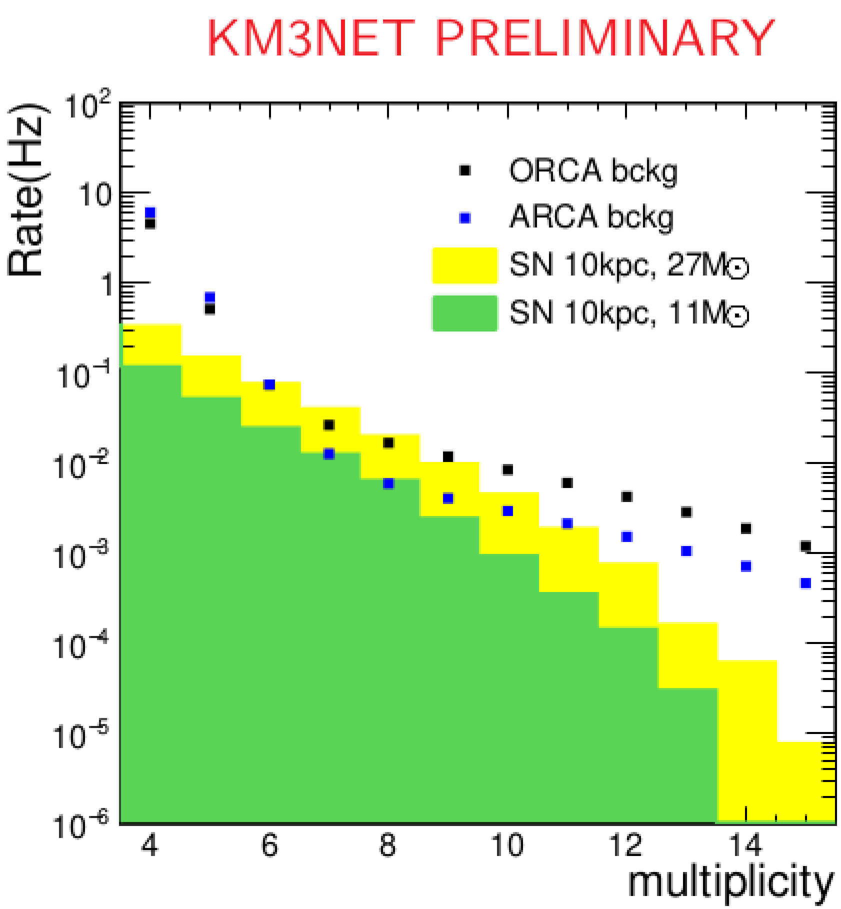


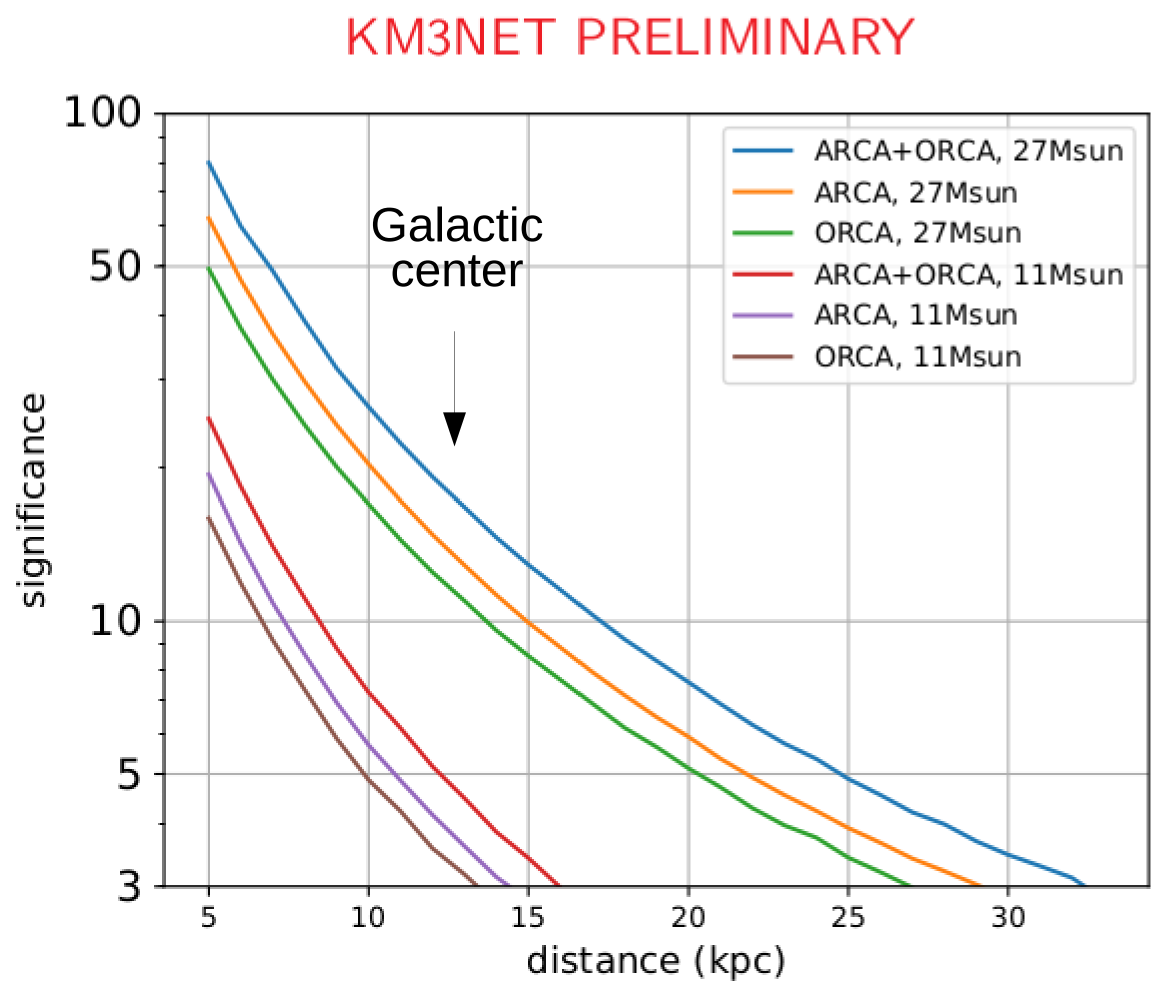
Highly competitive sensitivity

T. Eberl et al., Neutrino 2018

Sensitivity to galactic supernova

Looking for a sudden increase in count rates

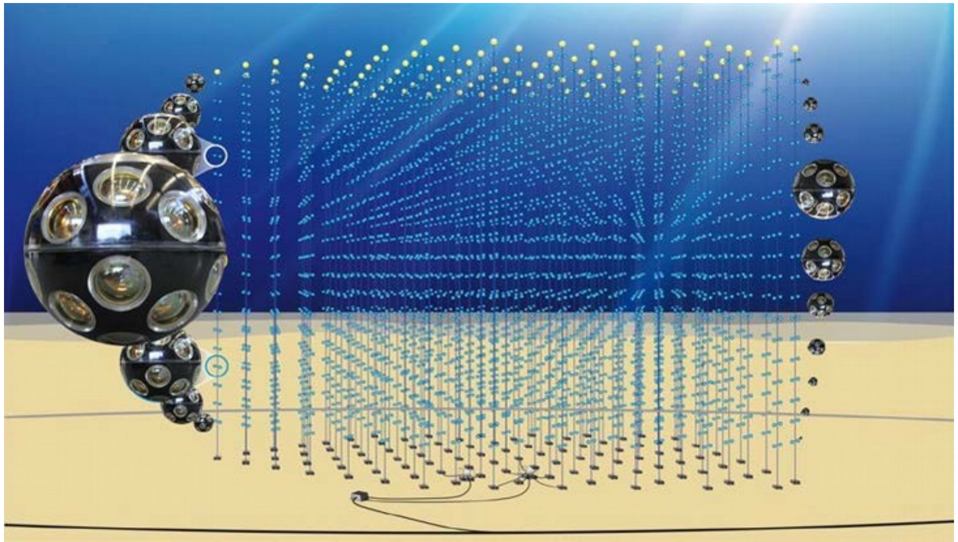




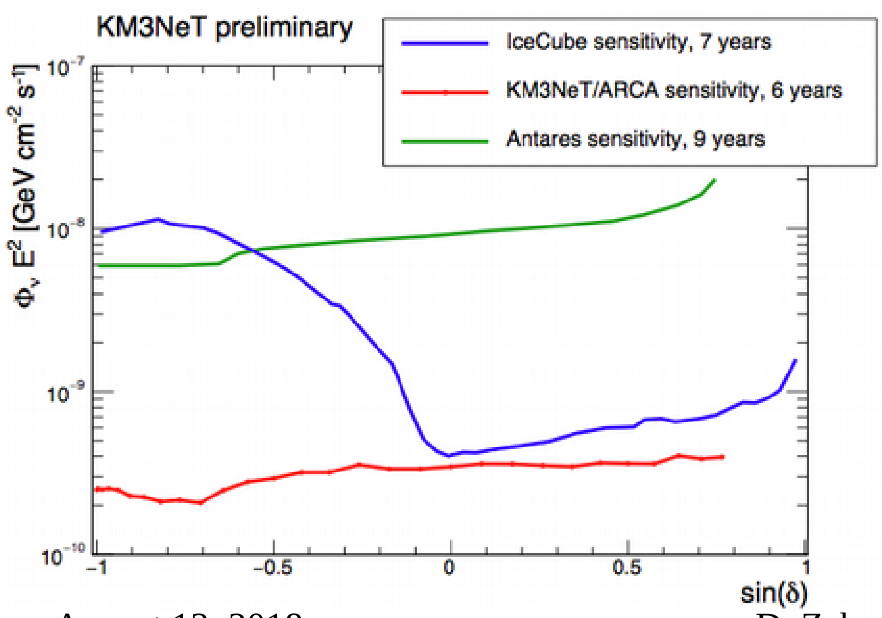
5 σ detection possible in case of SN explosion in our Galaxy

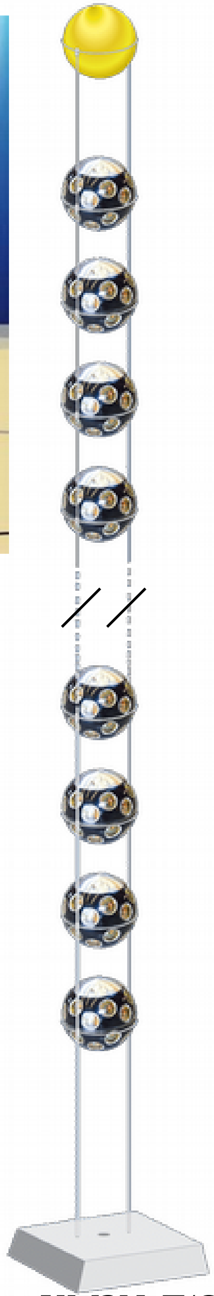
M. Lincetto, M. Colomer et al., Neutrino 2018

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

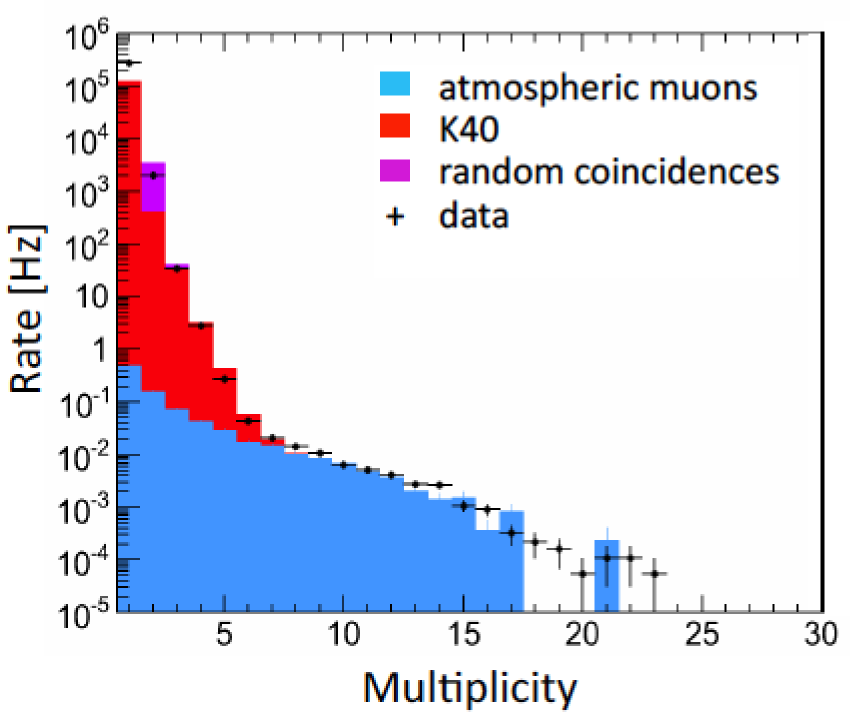
Angular resolution ~ 0.2 deg
(tracks, E > 10 TeV)

Energy resolution up to 5%
(cascades)

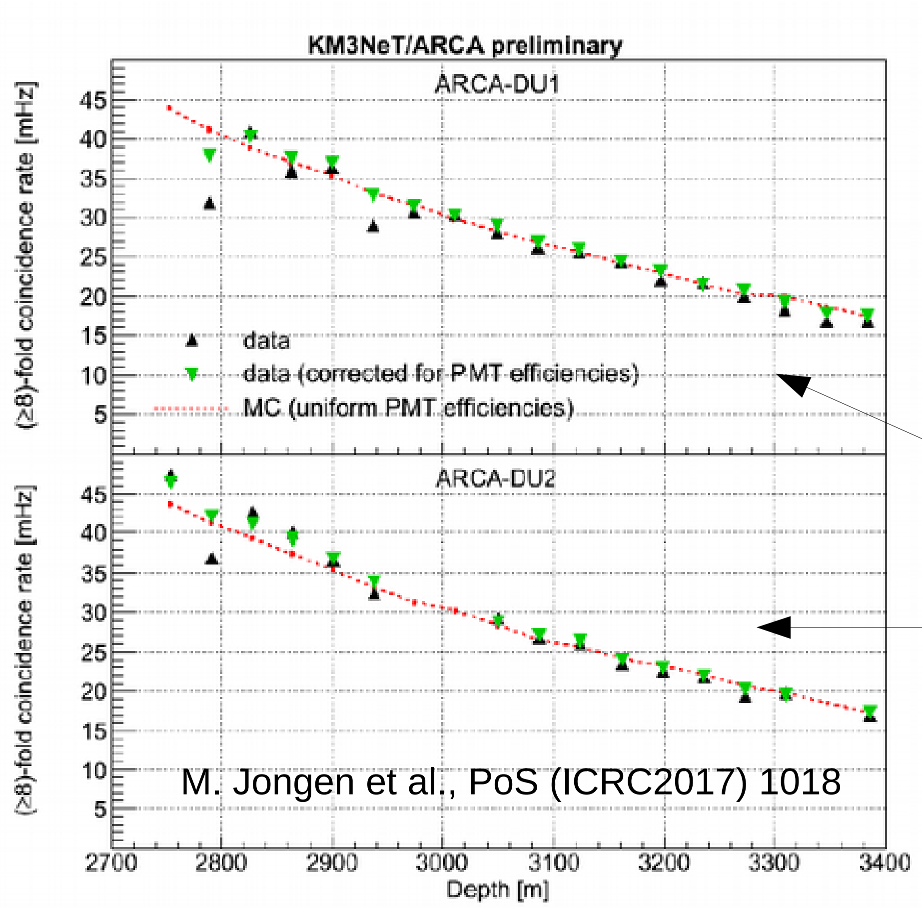
Sensitivity similar to IceCube,
but covering both sky hemispheres

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)

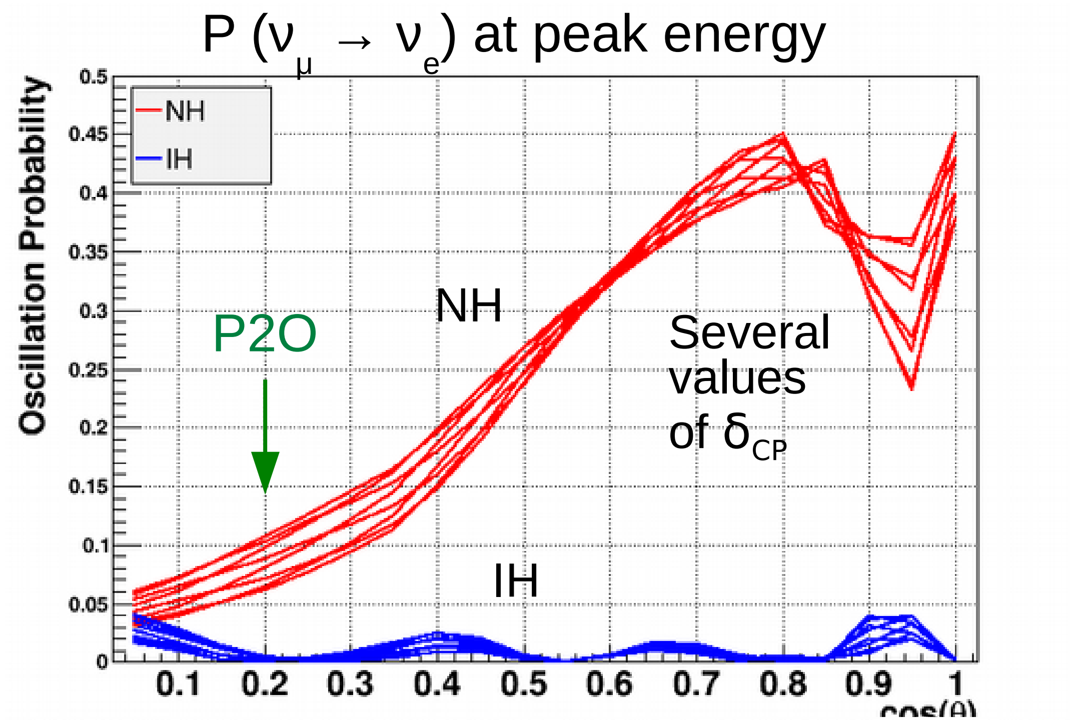


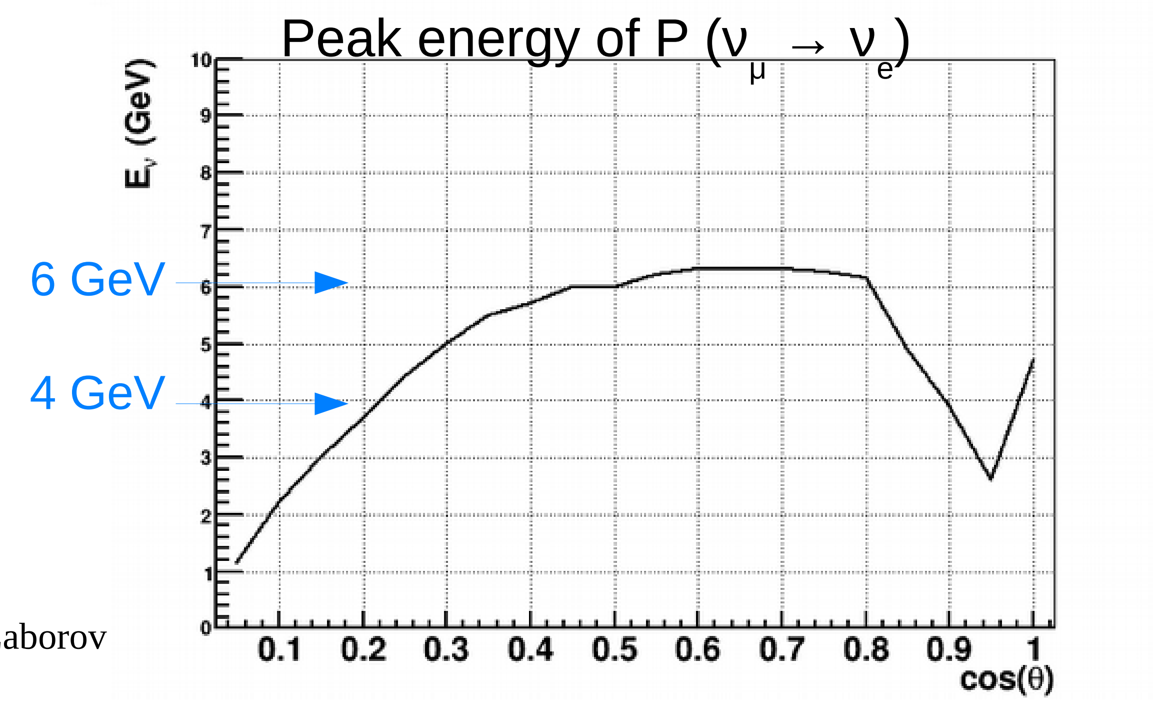
- First full Detection Unit at ARCA site, Dec 2015
- One more DU added in May 2016

depth

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 * $\cos\theta$
- levels off at mantle resonance energy (~ 6 GeV)

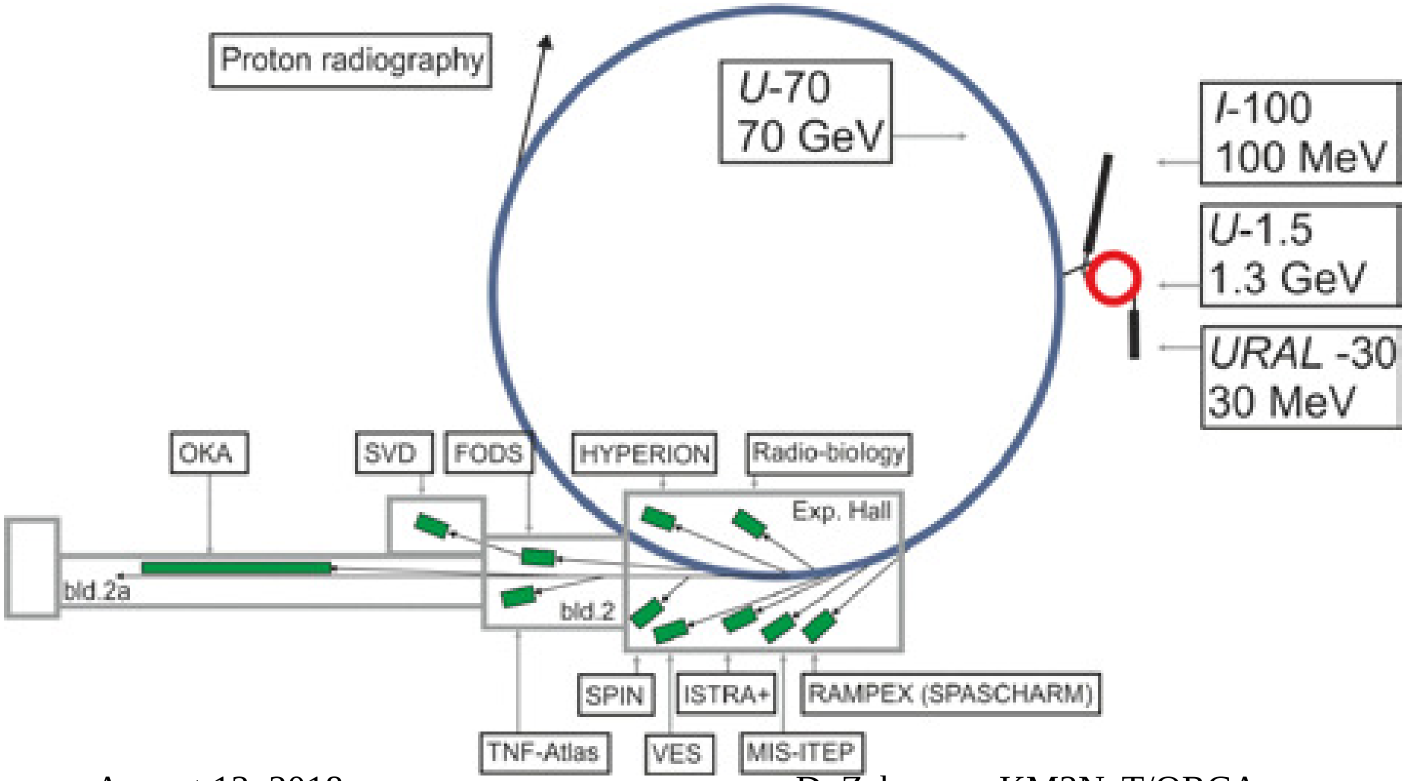




Protvino accelerator complex
(100 km South of Moscow)

U-70 accelerator constructed in 1967

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

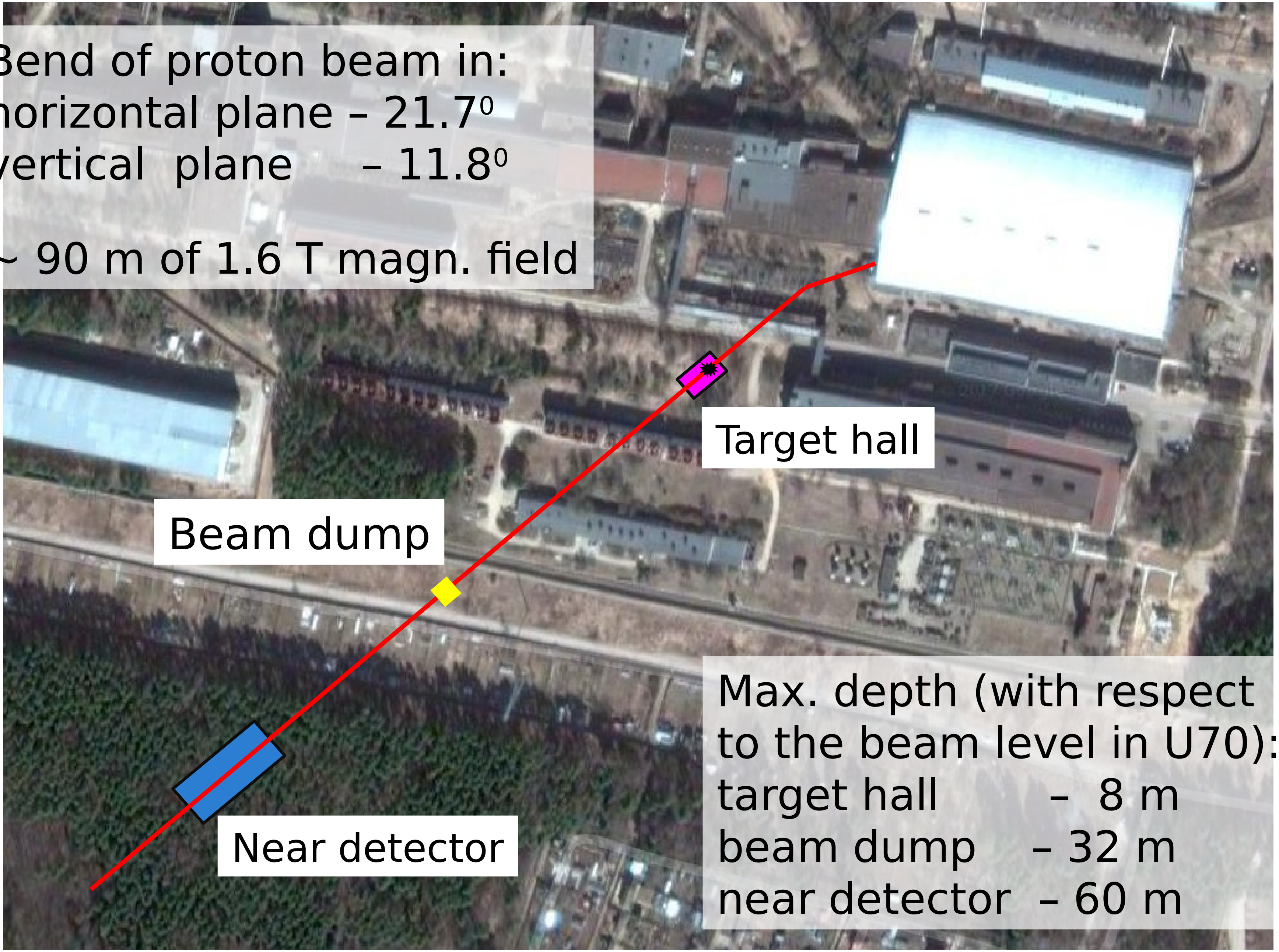


Current operation:

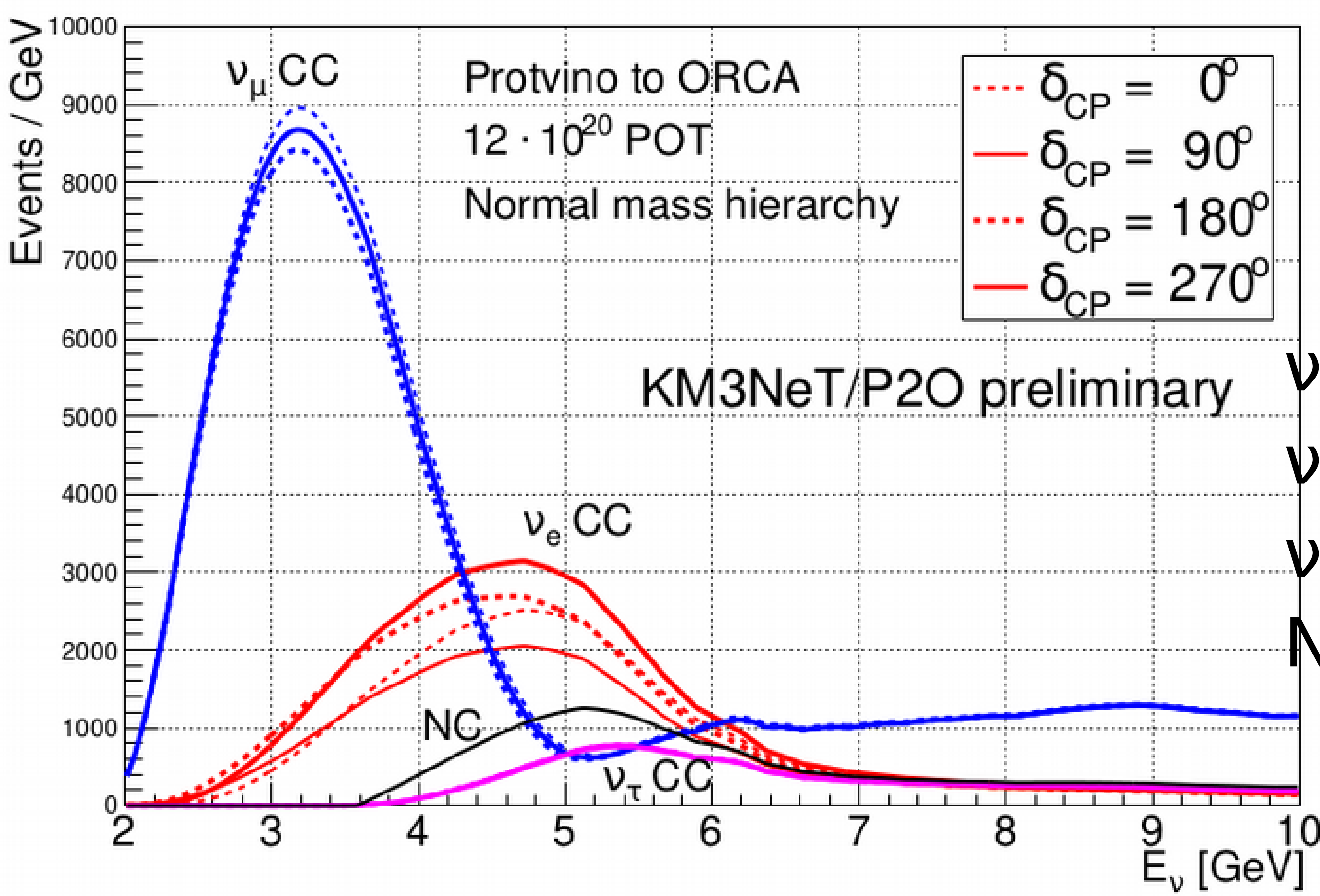
- Protons up to **70 GeV**
- **15 kW** beam power
- 5 μs spill every 9 s

Upgradable up to 90 – 450 kW

Possible location of the neutrino beam line



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)

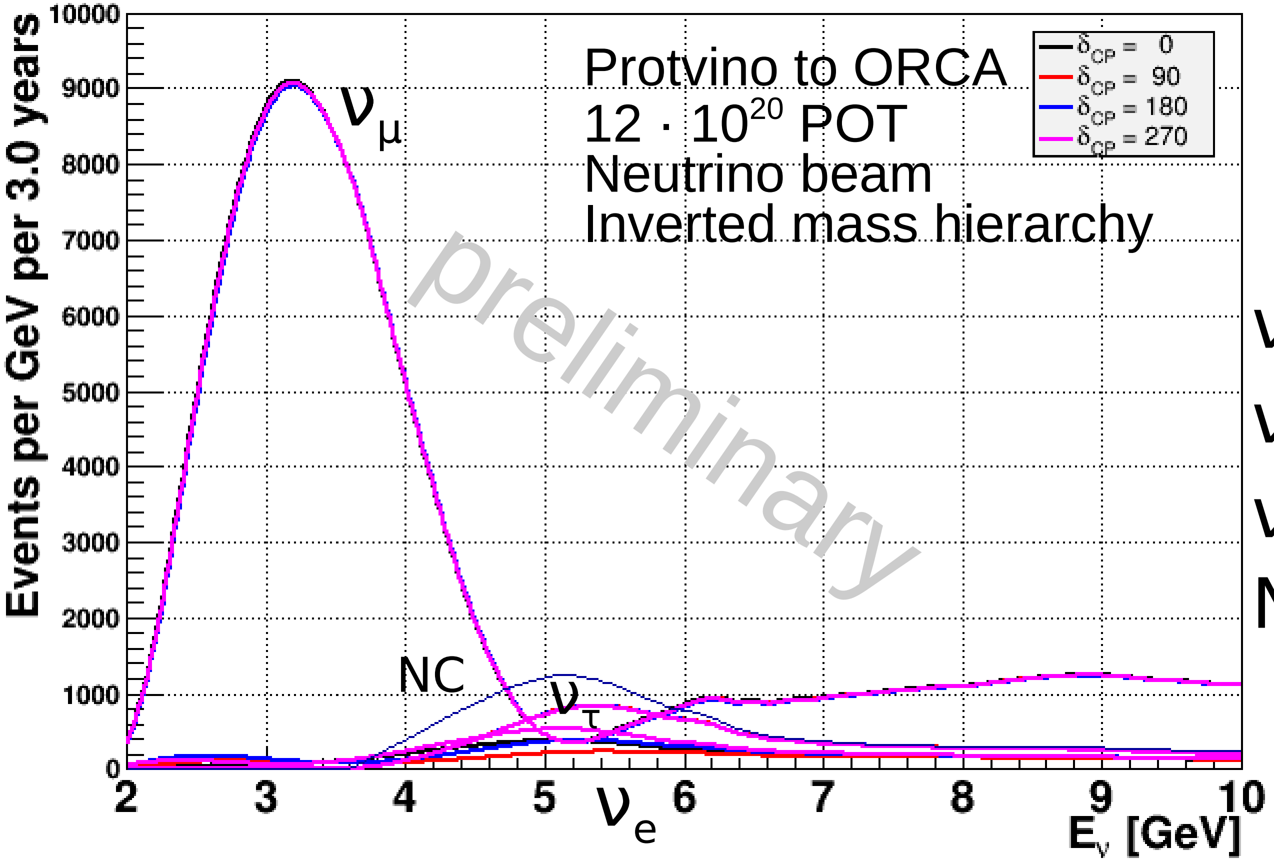
$\nu_\mu \rightarrow \nu_e$ transitions are enhanced by the MSW effect, resonance energy 3.8 GeV

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 of simulated data

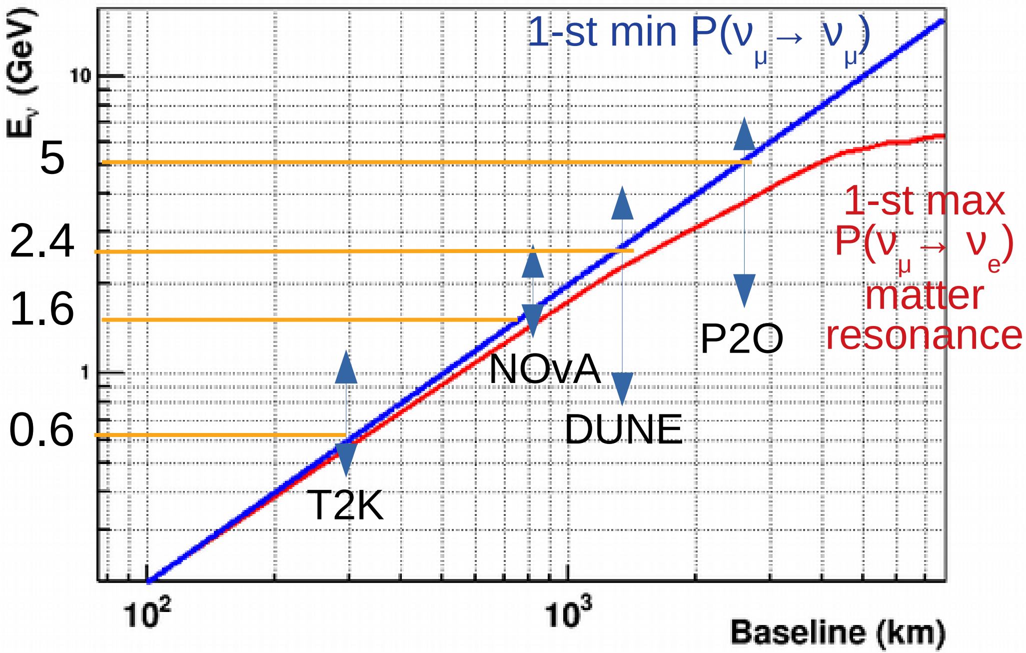
- Combined fit of nuisance and oscillation parameters
- No neutrino/anti-neutrino skew
- No spectral index skew
- No energy scale shift

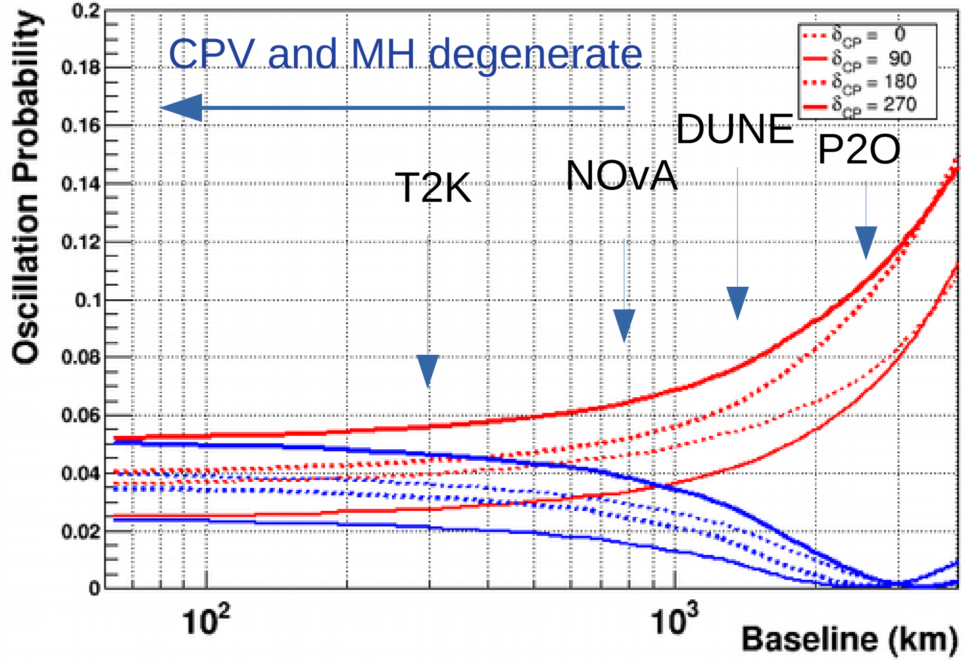
Parameter	True value	Prior	Start value
θ_{12}	33.4°	fix	fix
Δm^2 [eV²]	7.53 10^{-5}	fix	fix
θ_{13}	8.42°	0.15°	8.42°
θ_{23}	41.5°	1.3°	41.5°
ΔM^2 [eV²]	2.44 10^{-3}	0.06	2.44 10^{-3}
δ_{CP}	many	no	many

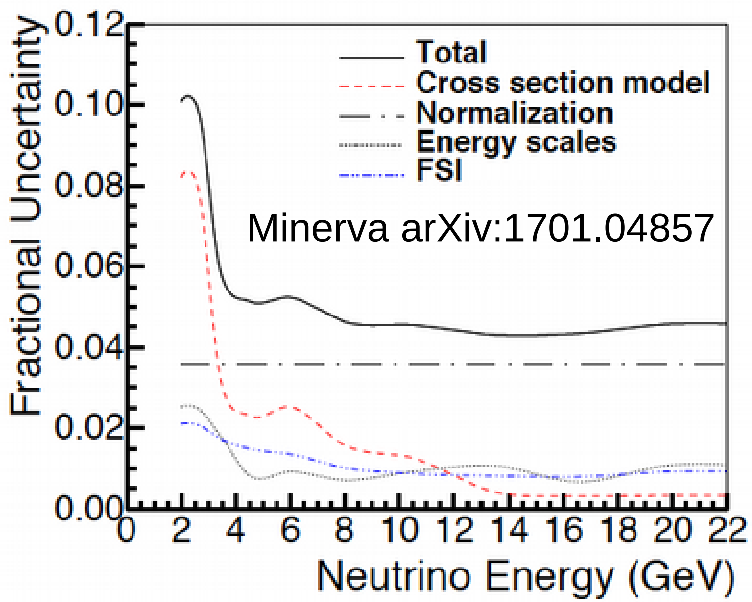
* Only used for CP fits, not for NMH

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

Comparison with other LBL projects



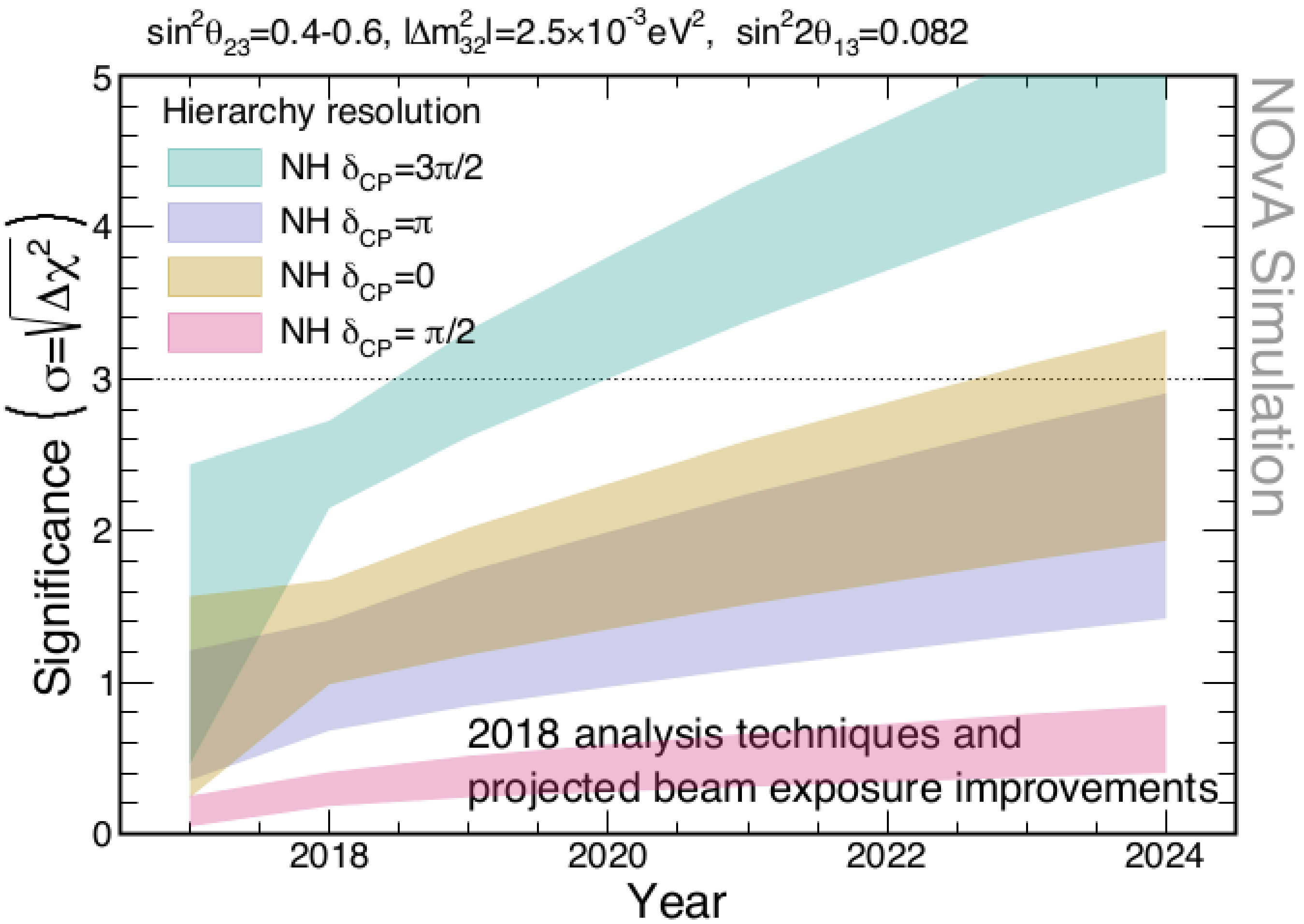




- Longest baseline
- Highest energy
- No degeneracy CPV MH
- Largest value of $P(\nu_\mu \rightarrow \nu_e)$
- Smallest neutrino cross section uncertainties

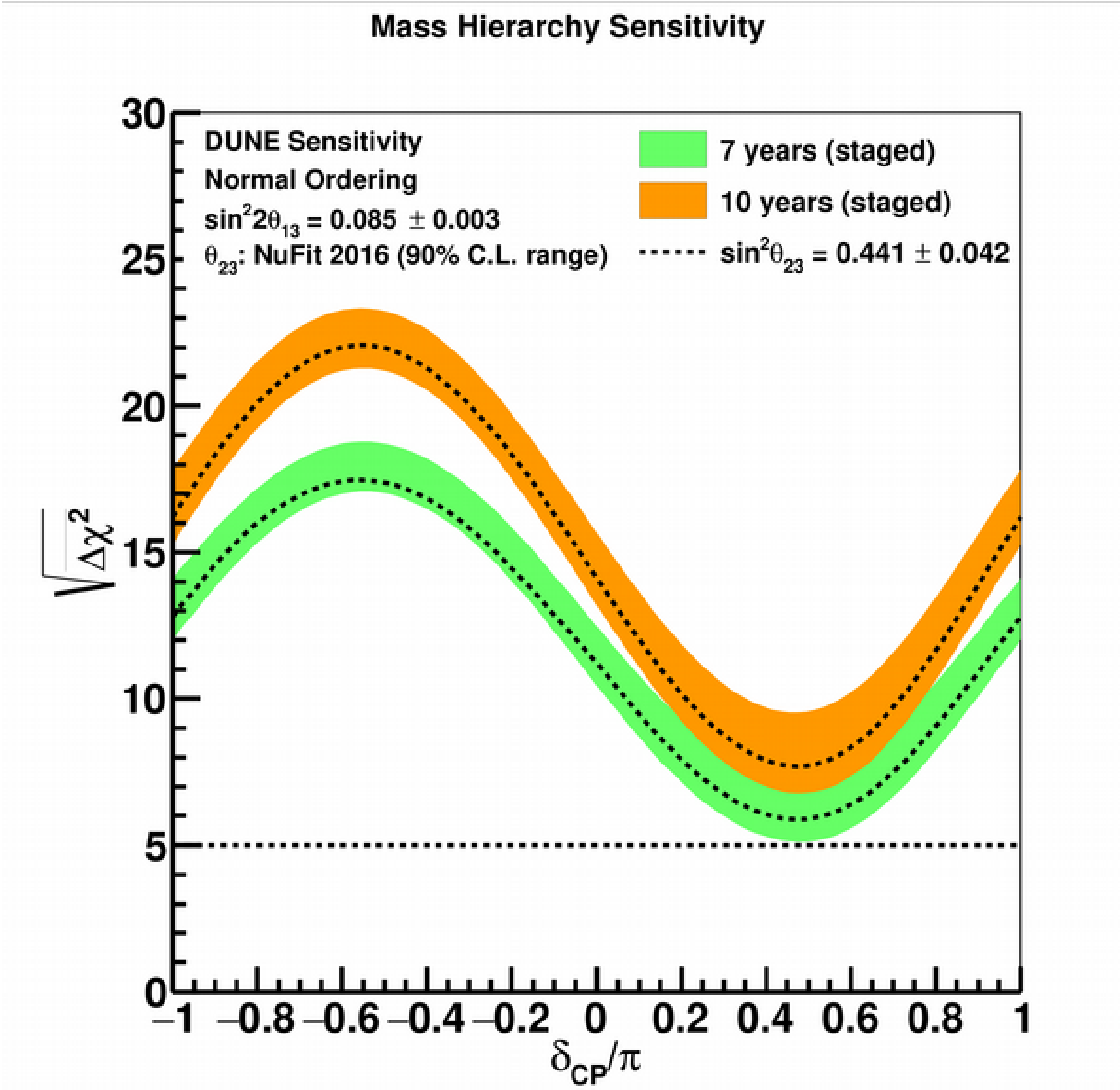
J. Brunner et al,
Neutrino 2018

NovA sensitivity to mass hierarchy



M. Sanchez, Neutrino 2018

DUNE sensitivity to Mass Hierarchy



> 5 sigma after 7 years

DUNE sensitivity to CP violation

Beam and detector staging assumptions are included:
- Start with 20 kt, increasing to 40 kt
- 80 GeV primary protons @ 1.07 MW, increasing to 2.14 MW