KM3NeT/ORCA

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Rencontres de Blois 2017

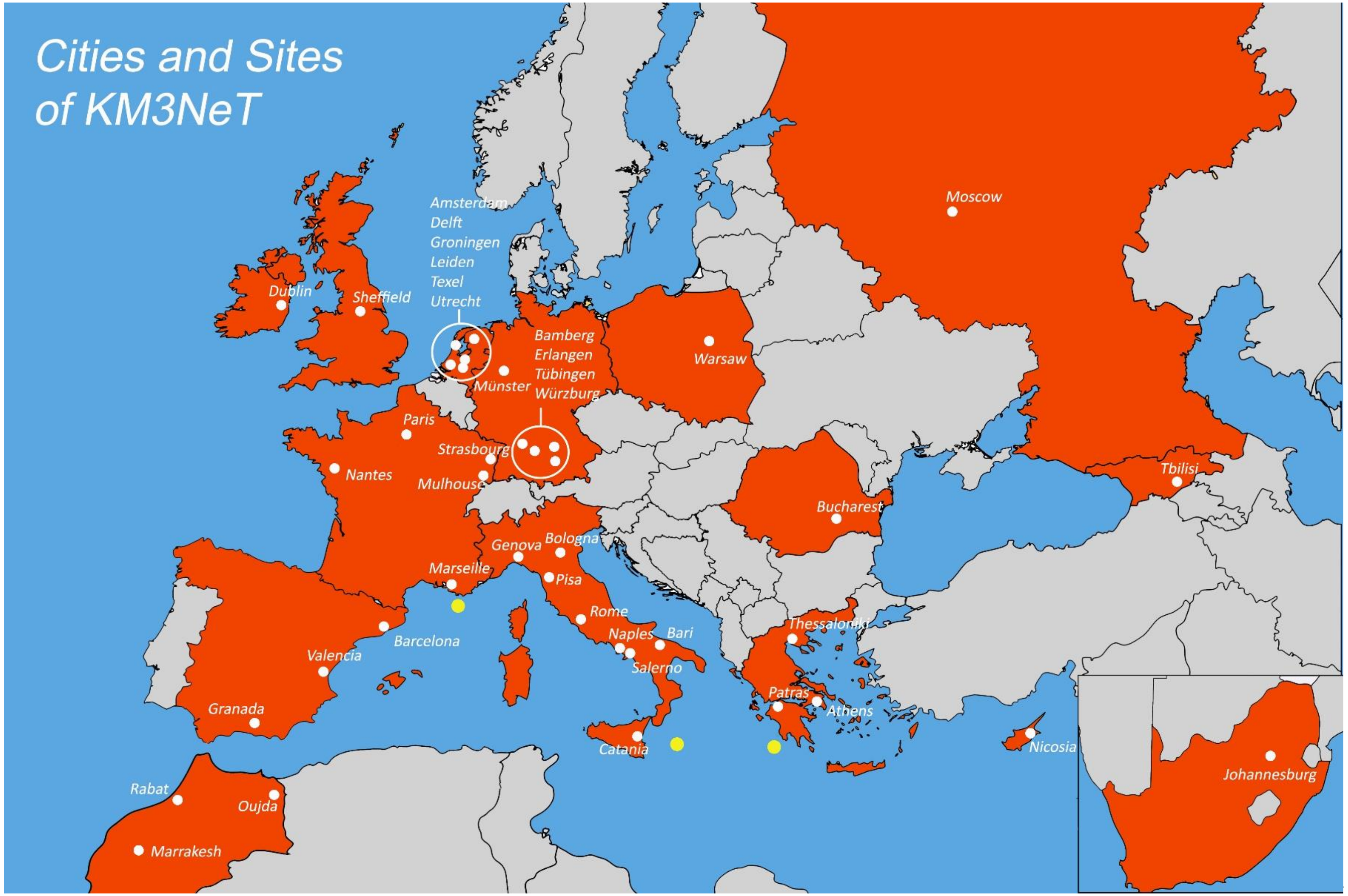
KM3NeT Collaboration

KM3NeT
Opens a new window on our universe

14 Countries
44 Institutes
240 Scientists

Sites :

KM3NeT – FR
KM3NeT – IT
KM3NeT - GR



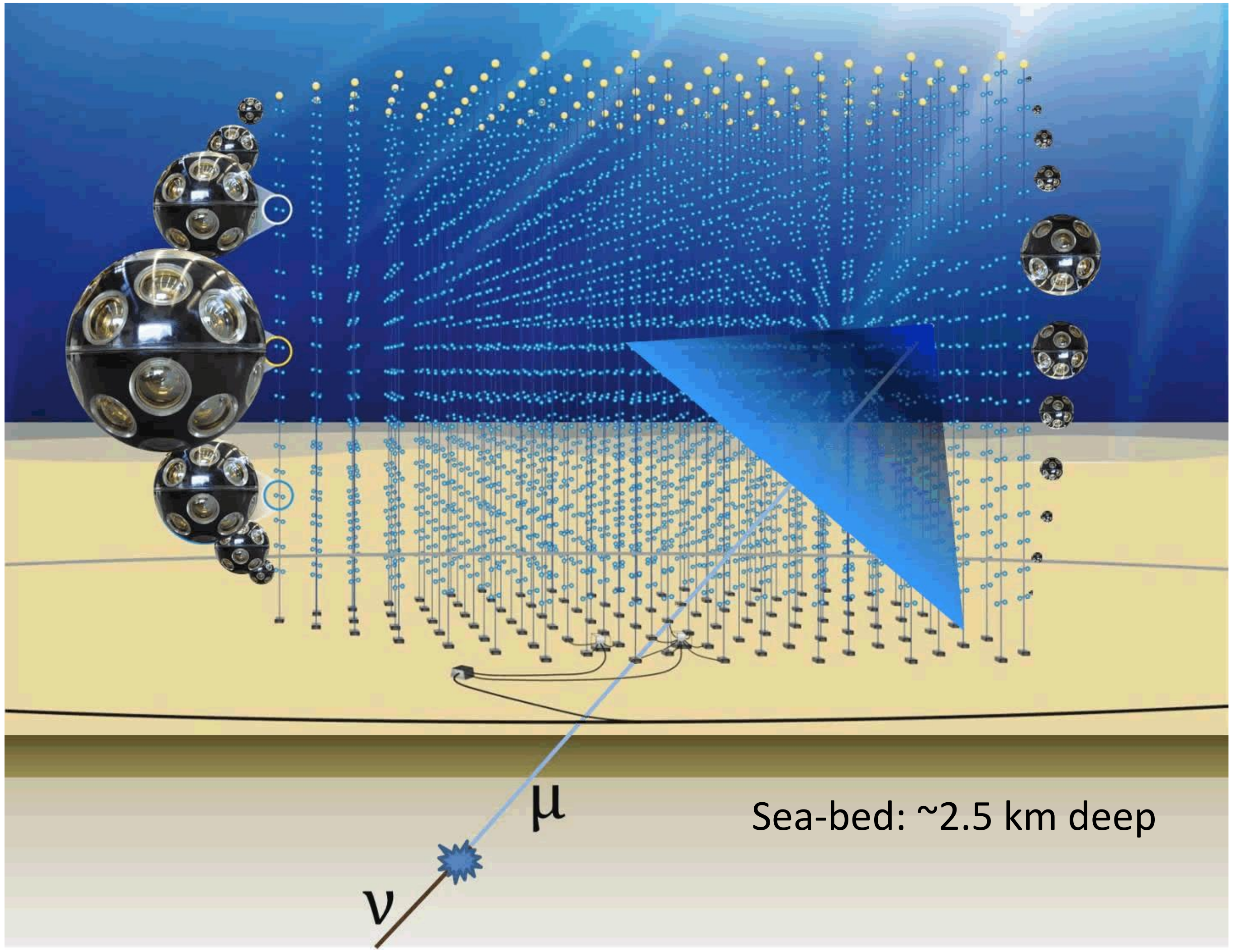
Large Volume Neutrino Telescopes

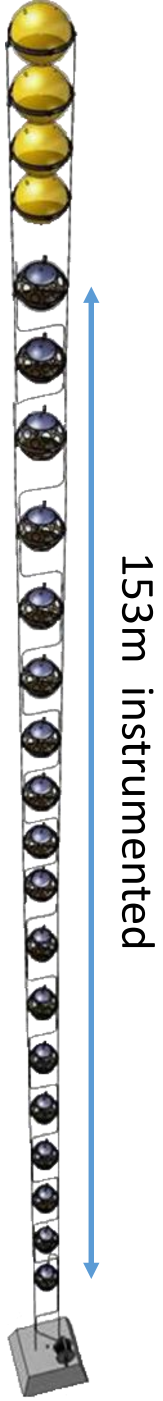
Cherenkov light from the charged products of neutrino interactions in sea-water are detected by a sparse array of photo-multiplier tubes

Two *general* event types:

Tracks - Charged current (CC) υ_μ interaction

Showers - Neutral current υ interaction
- υ_e CC electromagnetic shower
- Vertex of CC interaction
- τ decay shower





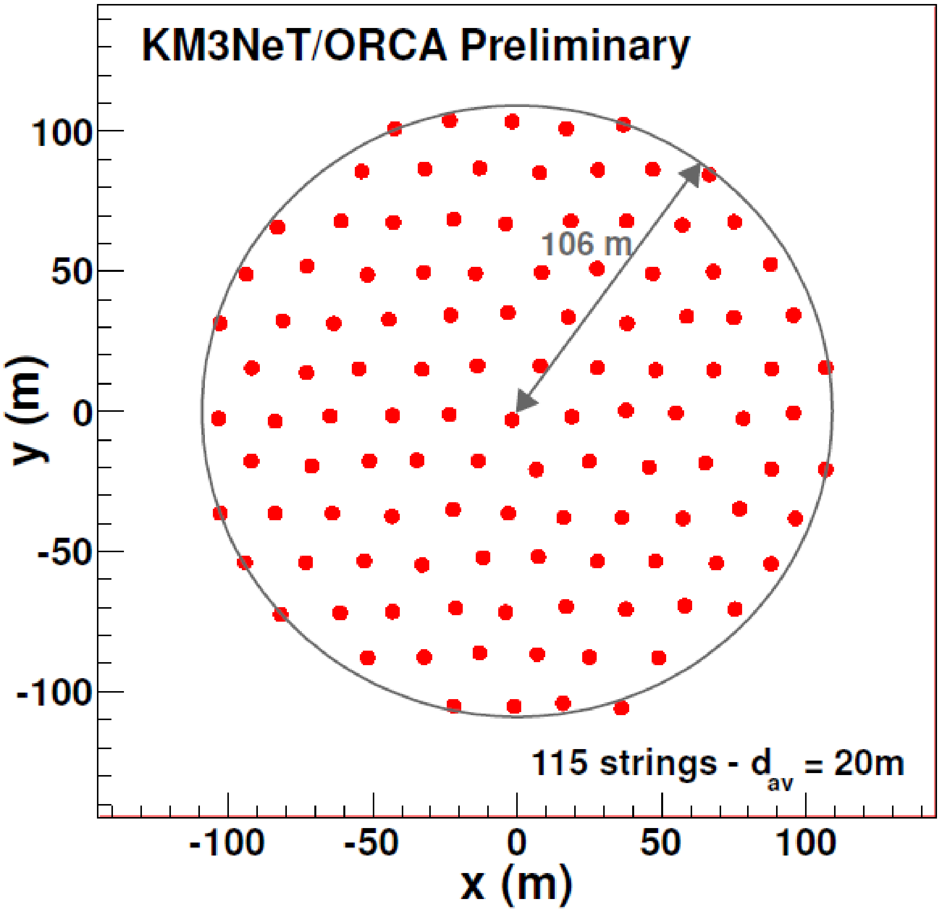
KM3NeT Design (ORCA)

Detection Units:

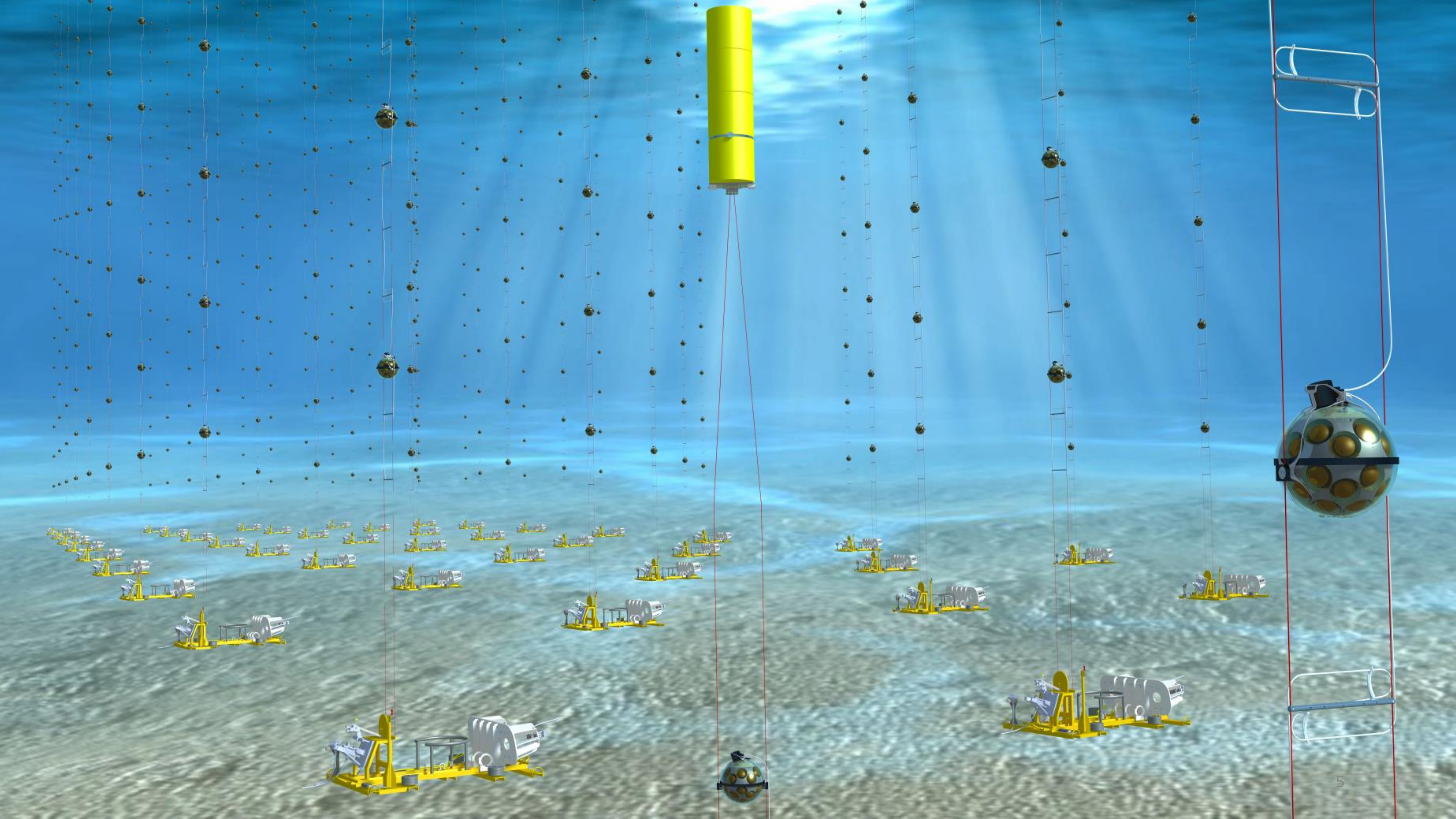
18 optical modules per detection unit
9m between optical modules
Lowest optical module 40m above seabed
Two Dyneema® ropes
Backbone: 2 copper conductors; 18 fibres (+spares)
Break out of cable at each optical module
Base module with DWDM at anchor
Cable for connection to seafloor network
Cost saving design

Infrastructure:

Building block of 115 strings
Sea-bed infrastructure
(facility for long term high-bandwidth connection for sea-science, biology etc.)
Optical data transmission
All-data-to-shore
Filtering/Trigger on-shore in computer farm



(´ORCA´ layout)



KM3NeT Digital Optical Module (DOM)

Segmented cathode area: 31 x 3” PMTs

➢ Directional Sensitivity

➢ Photon Counting

Light concentrator ring

Cathode area: ~ 3 x 10-inch PMT

➢ Less overhead

Custom low-power HV bases

LED, piezo, compass and tiltmeter inside

PMT Time-over-Threshold measurements

FPGA readout

PMT Features:

➢Timing	≤2ns (RMS)
➢QE	≥25-30%
➢Collection efficiency	≥90%
➢Photon counting purity	100% (by hits, ≤7)
➢Price/cm2	≤10” PMT

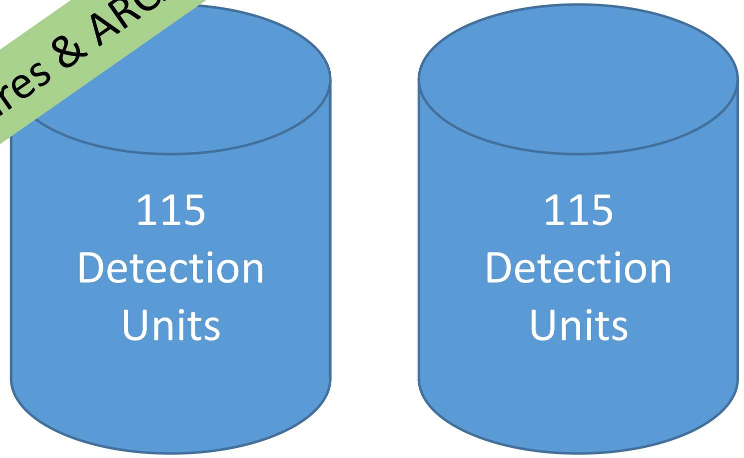
ARCA & ORCA

High Energy Neutrino Astronomy:

ARCA: Astroparticle Research with Cosmics in the Abyss

Large Detector: ~1 km^3 total
Sparse: 36 m vertical spacing, 100 m horizontal
TeV-PeV Energies
Astrophysical Neutrinos

See talk by S. Navas on Antares & ARCA

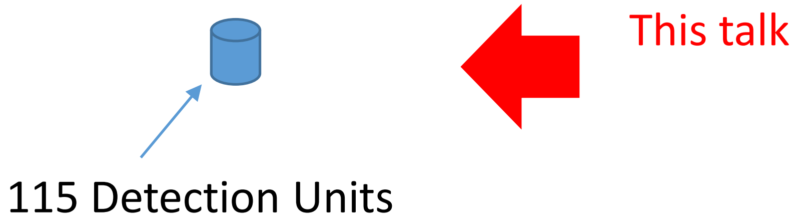


Same technology & layout, dimensions scaled ↕

Neutrino Physics:

ORCA: Oscillations Research with Cosmics in the Abyss

´Smaller´ detector: 5.7 Mton
Dense : 9m vertical spacing, 20m horizontal
GeV energies
Atmospheric neutrinos



Current Status & Future

- KM3NeT Phase-1:
  - Fully funded
  - 24 ARCA Detection Units
  - 6 ORCA Detection Units
  - Under Construction

2 ARCA lines deployed

2 ORCA lines to be deployed !

- KM3NeT 2.0 :
  - ARCA: 2 x 115 Detection Units by 2020 (1 block almost funded)
  - ORCA : 115 Detection Units by 2020 (half block funded)
  - ESFRI Roadmap

KM3NeT 2.0 Letter of Intent

J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

… and beyond : phase-3 (6 blocks), super ORCA ??

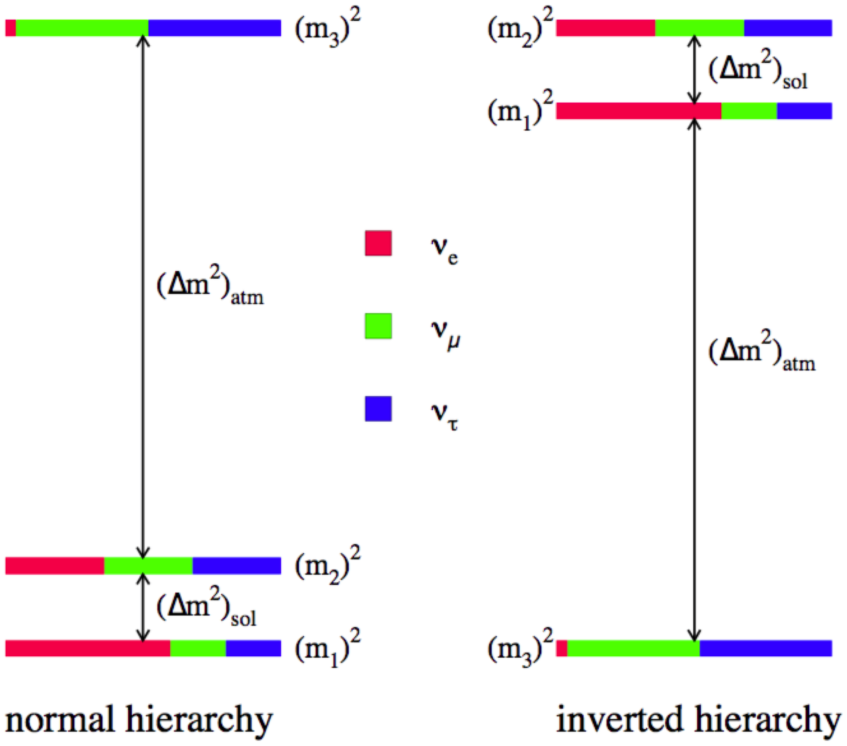
ORCA Goal: Neutrino Mass Hierachy

Neutrinos can change flavour during propagation as the mass eigenstates are not their flavour eigenstates

Neutrino flavour oscillations are described by the PMNS matrix:

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

and two mass squared differences



Only the size (not the sign) of the large mass squared difference ΔM^2 is known. This allows for two orderings of the neutrino mass eigenstates

Neutrino Mass Hierarchy (NMH)

Also: CP violating phase δ_{CP} unknown and octant of θ_{23}

Determining the NMH with atmospheric υ´s

In vacuum, neutrino oscillations are unaffected by the mass ordering. E.g:

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

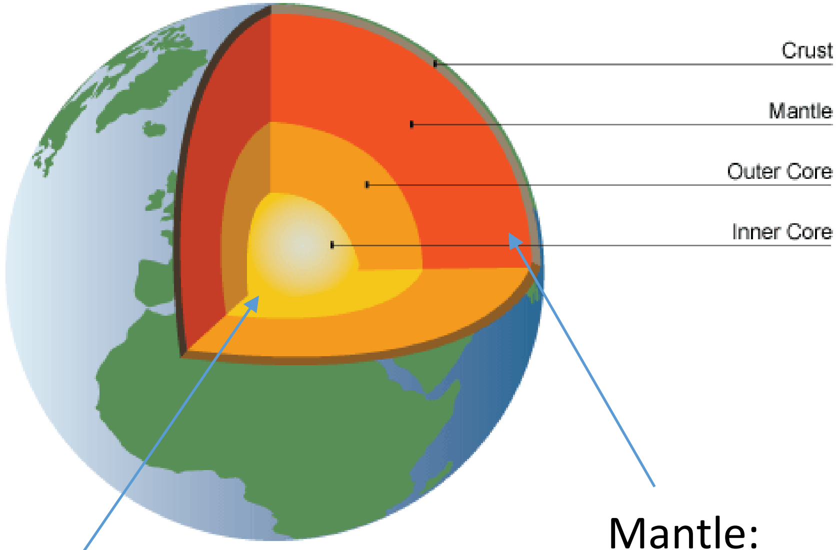
$$P_{3\nu}(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\,\sin^2\theta_{23}\,(1-\cos^2\theta_{13}\,\sin^2\theta_{23})\,\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

In matter $\nu_e(\bar{\nu}_e)$acquires effective potential $A = \pm\sqrt{2}G_f N_e$ through charged current elastic interactions with electrons. And oscillations probabilities are modified.

This affects phase and amplitude of oscillations and is strongest at resonance energy:

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

Density profile of the path through the Earth depends on zenith angle



Core: $E_{res} \approx 3GeV$

Mantle: $E_{res} \approx 7GeV$

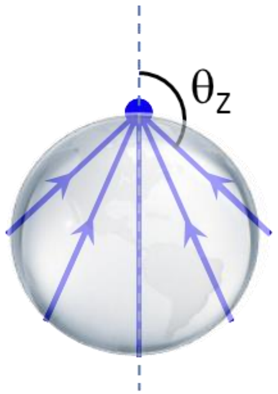
See: Akhmedov, E.K., Razzaque, S. & Smirnov, A.Y. J. High Energ. Phys. (2013) 2013: 82.

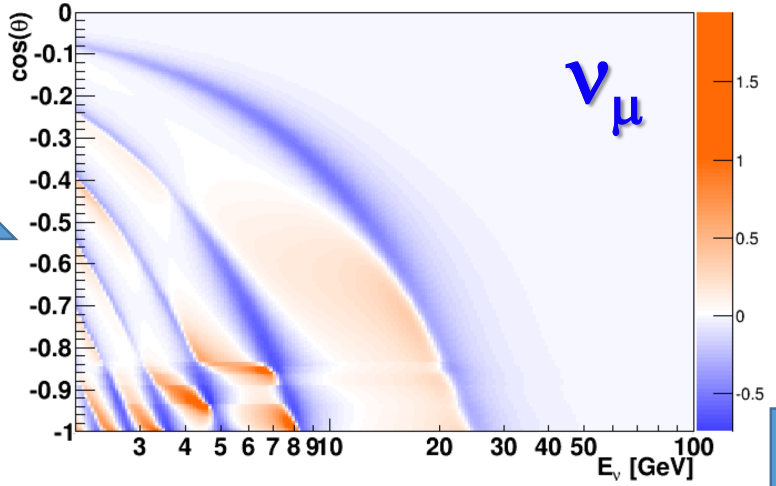
Measure atmospheric neutrino flux as function of energy and zenith angle!

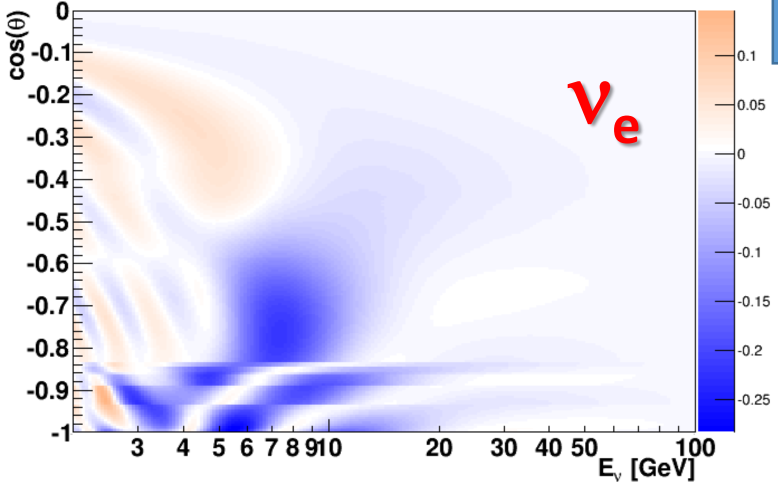
Determining the NMH with atmospheric υ´s

Relative difference in event numbers between normal and inverted hierarchy $(N_{IH}-N_{NH})/N_{NH}$

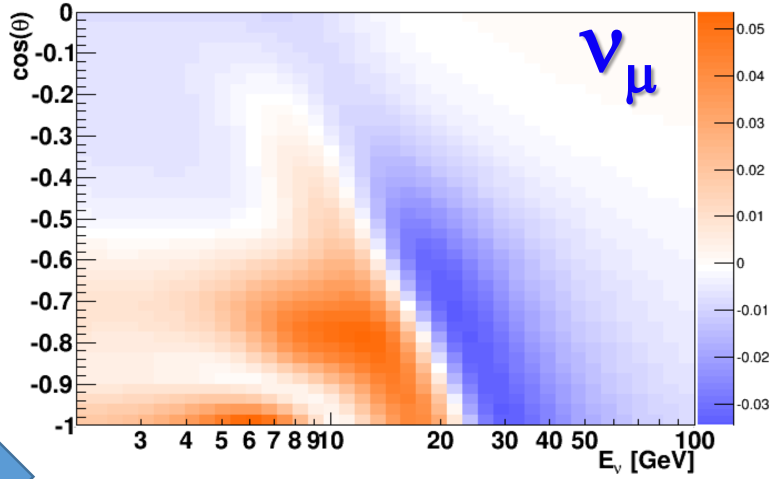
Zenith angle
corresponds with different distance and density profile !

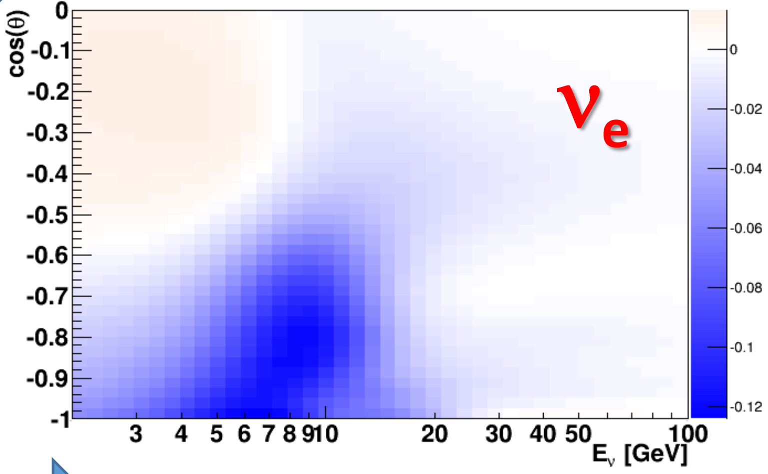






Resolutions

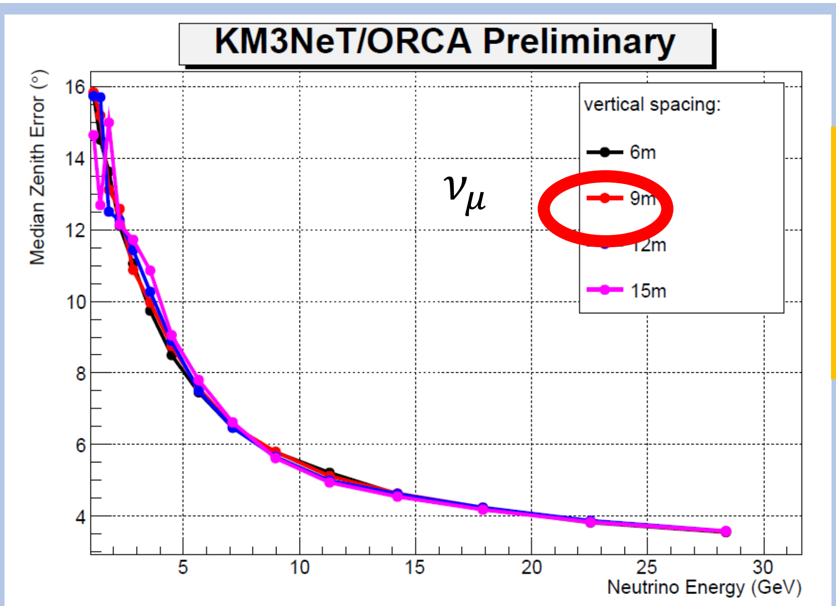




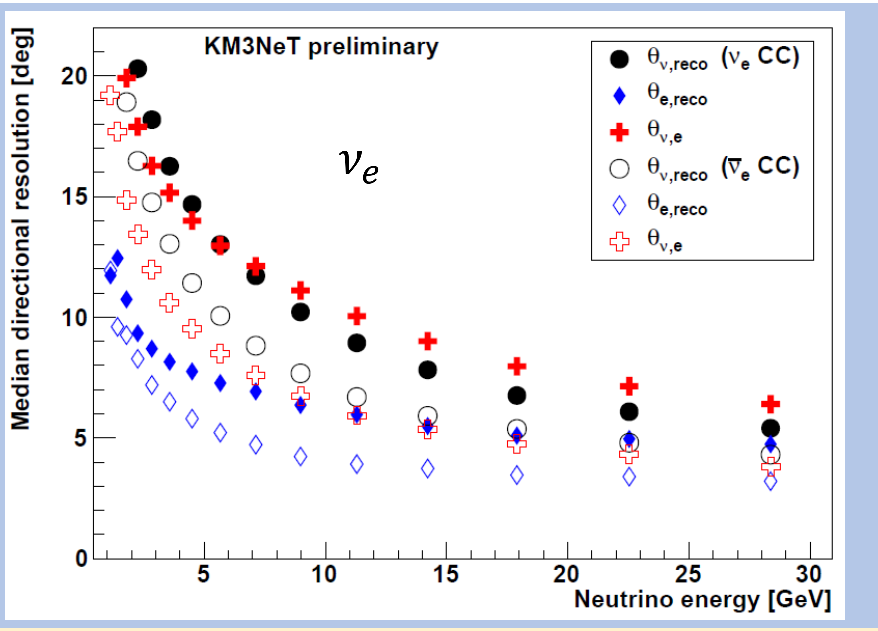
Neutrino Energy

Resolutions

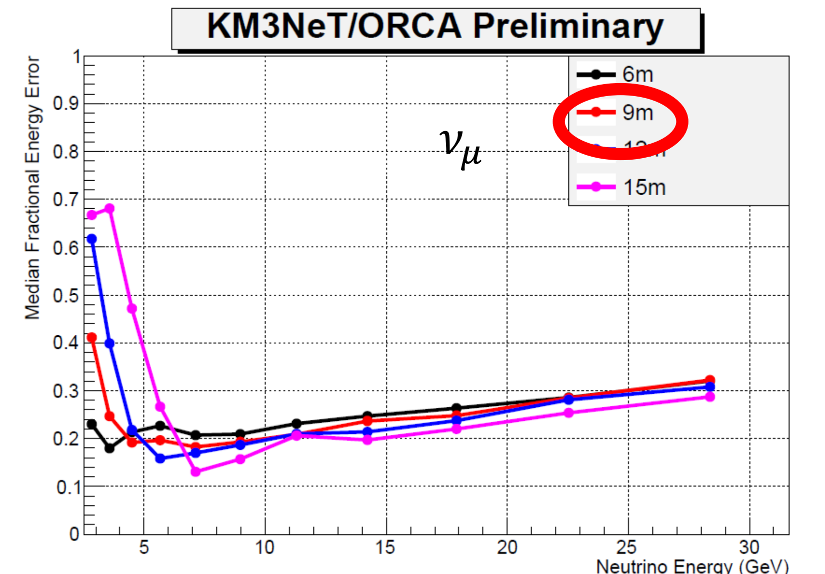
Direction

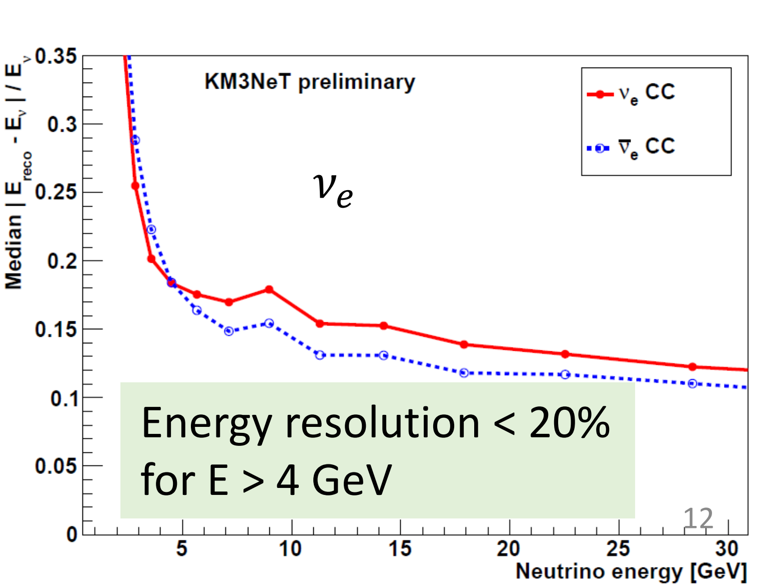


At relevant energies, neutrino/lepton scattering angle dominates



Energy





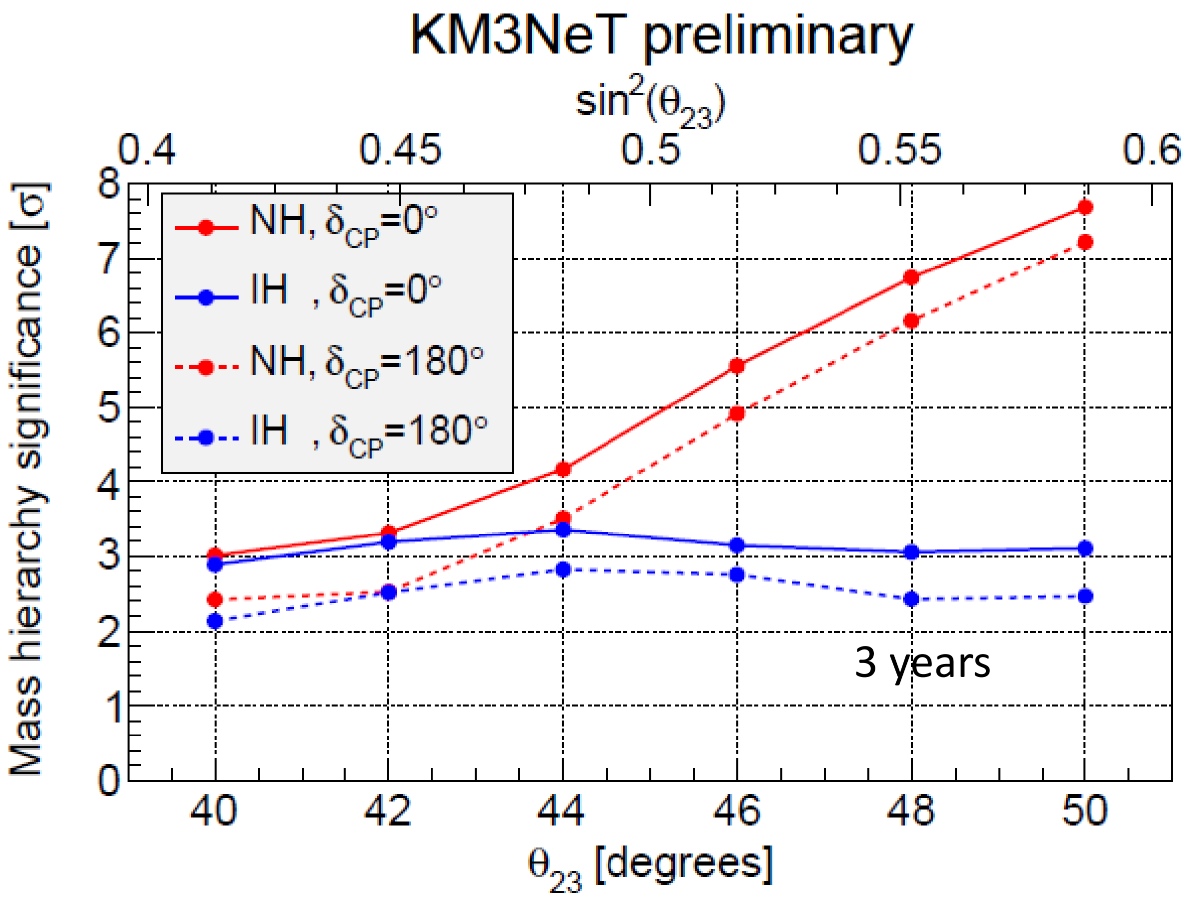
Energy resolution < 20% for E > 4 GeV

Sensitivity for Neutrino mass ordering

Sensitivity to distinguish between normal and inverted hierarchy:

3 σ in 3 years (median sensitivity)

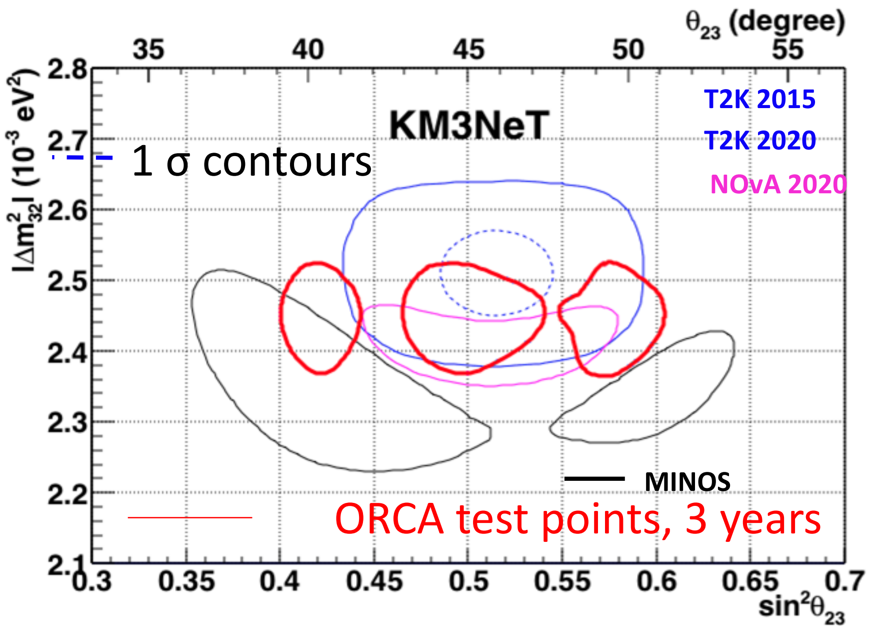
Normal hierarchy + upper octant θ_{23} gives more sensitivity (5 σ in 3 years)



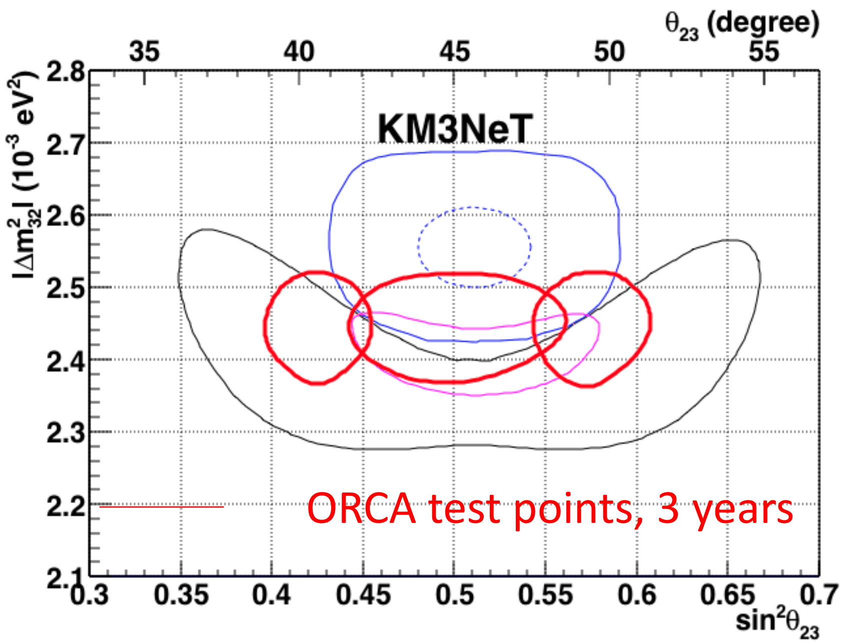
New (improved!) results underway !!

Δm^2_{32} and $sin^2\theta_{23}$

Normal Hierarchy



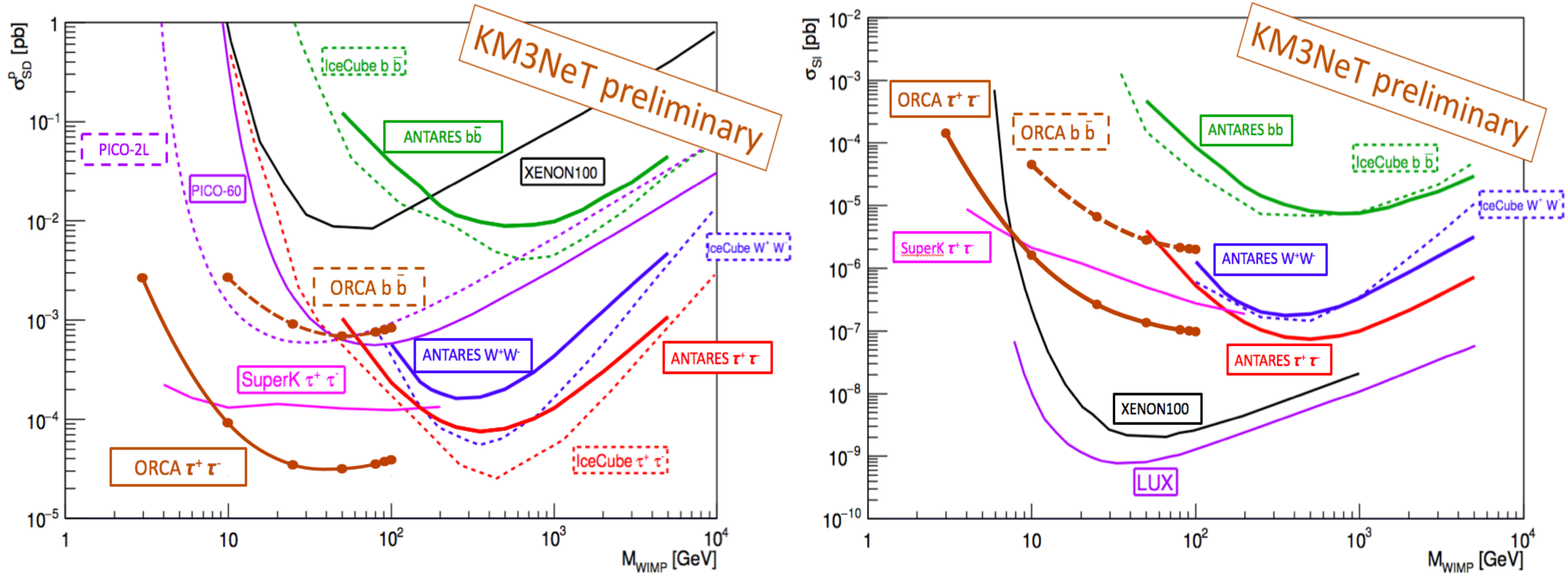
Inverted Hierarchy



Competitive measurements of Δm^2_{32} (2-3%) and $sin^2\theta_{23}$ (4-10 %)

Indirect Dark Matter detection

Gravitationally trapped relic WIMPs (Sun, Galactic center) annihilate and resulting products are measured.



3 years, tracks and showers

Supernova detection

~10 MeV supernova neutrinos can not be resolved individually

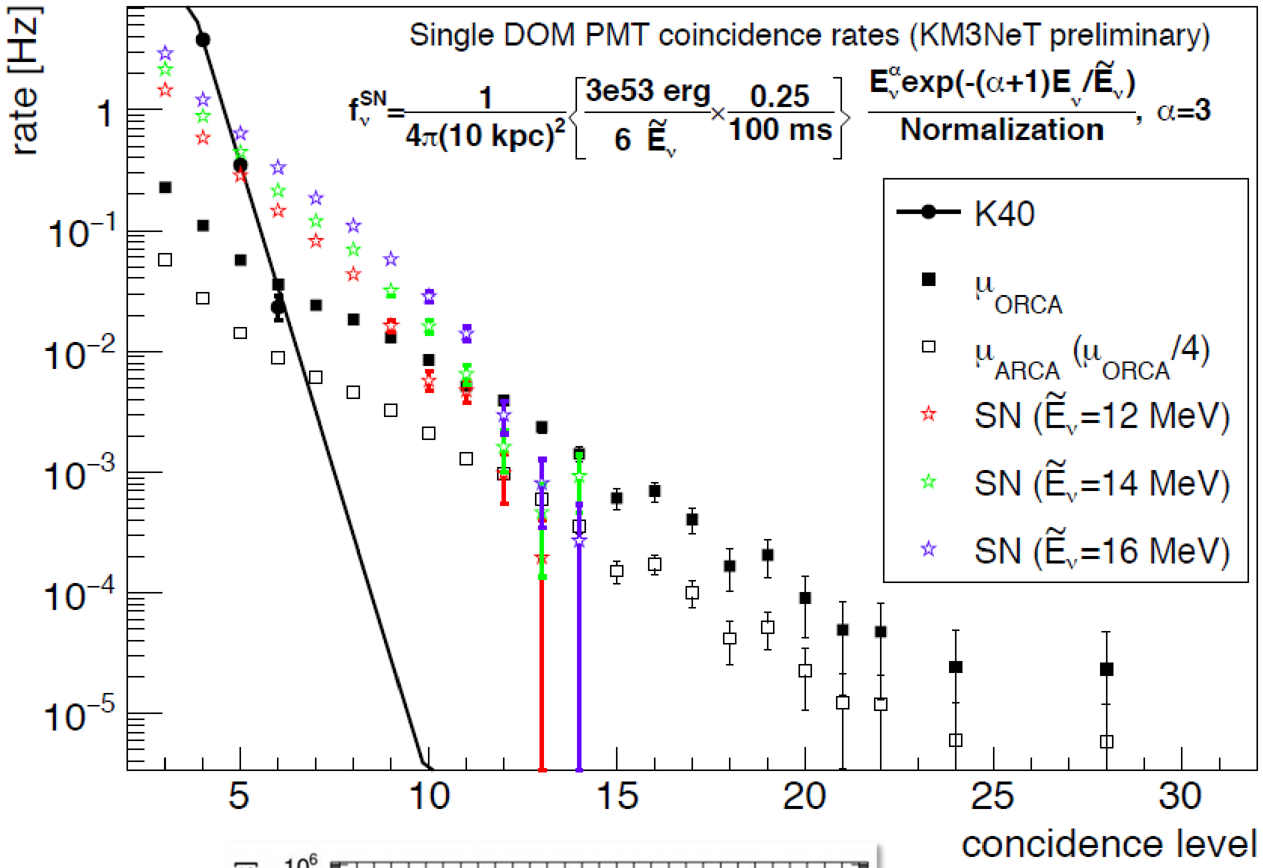
Detection of Galactic supernovae by enhanced collective coincidence rates between PMTs in DOMs

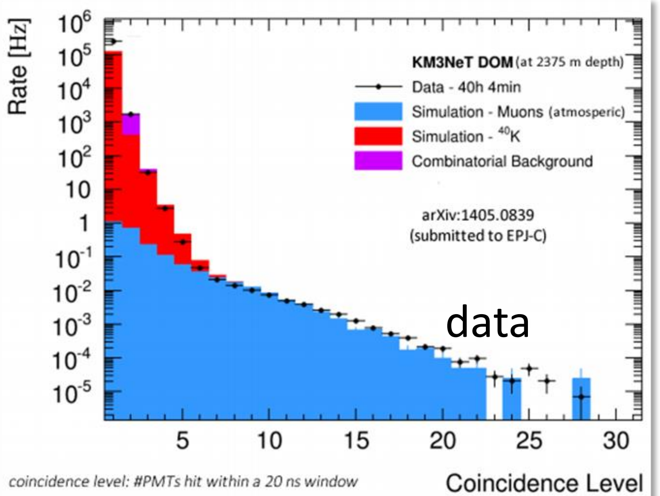
SN1987A - like supernova at 10 kpc, $3 \cdot 10^{53}$ erg, $\bar{\nu}_e$ component (1/6) with 25% in first 100 ms

At >= 6 coincidences per DOM, SN signal exceeds background.

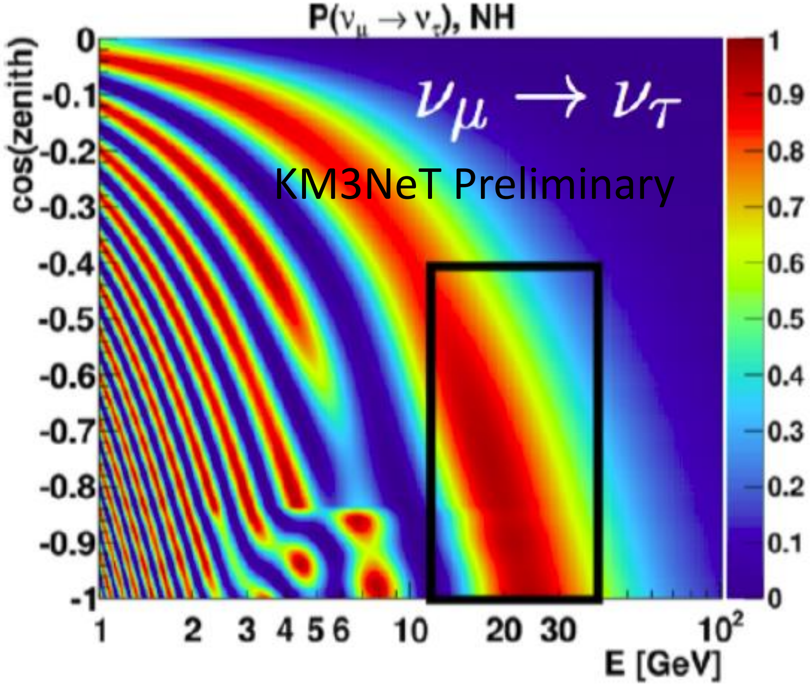
ORCA: 5 σ discovery distance 16 (24) kpc at $\langle E_\nu \rangle$ = 12 (16) MeV (ARCA: up to 37 kpc)

(Note: neutrino fluxes from SN are influenced by mass-hierarchy!)





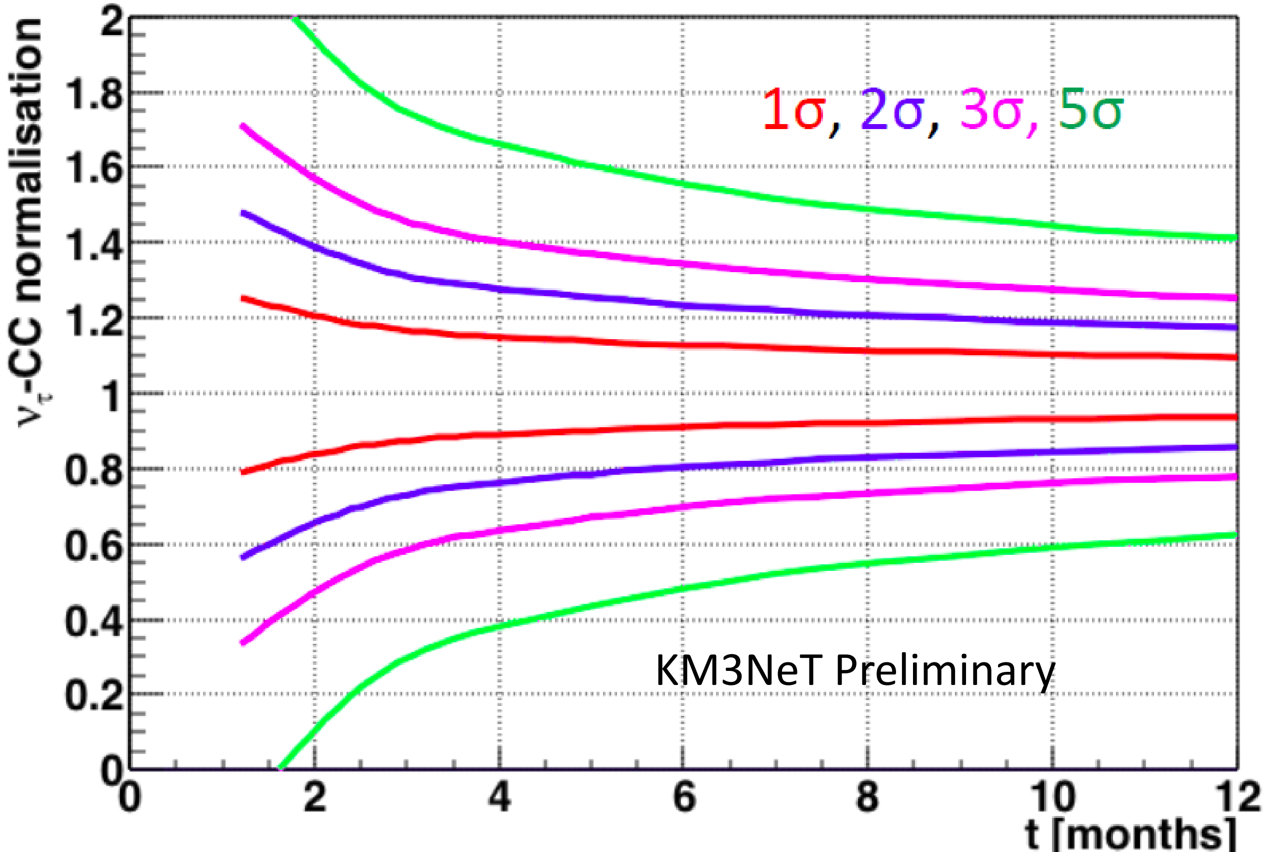
τ appearance



Early physics result

3k tau events/year

Rate constrained to 10% in one year

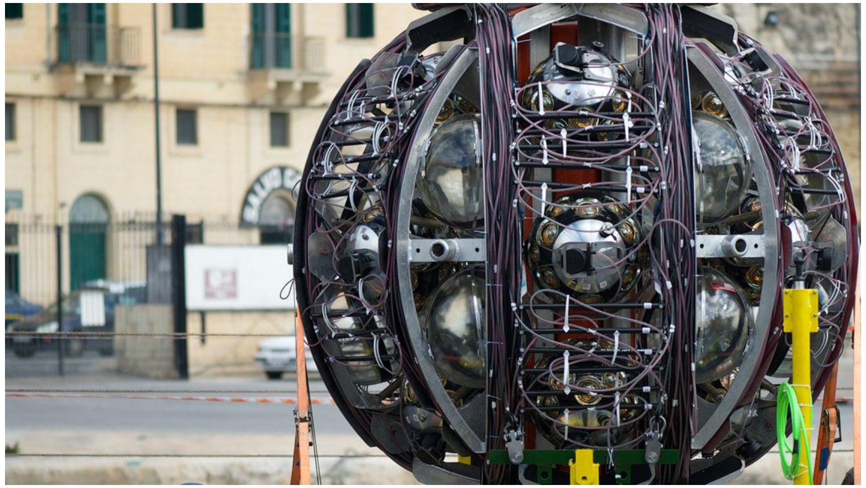


Other ORCA Physics Topics

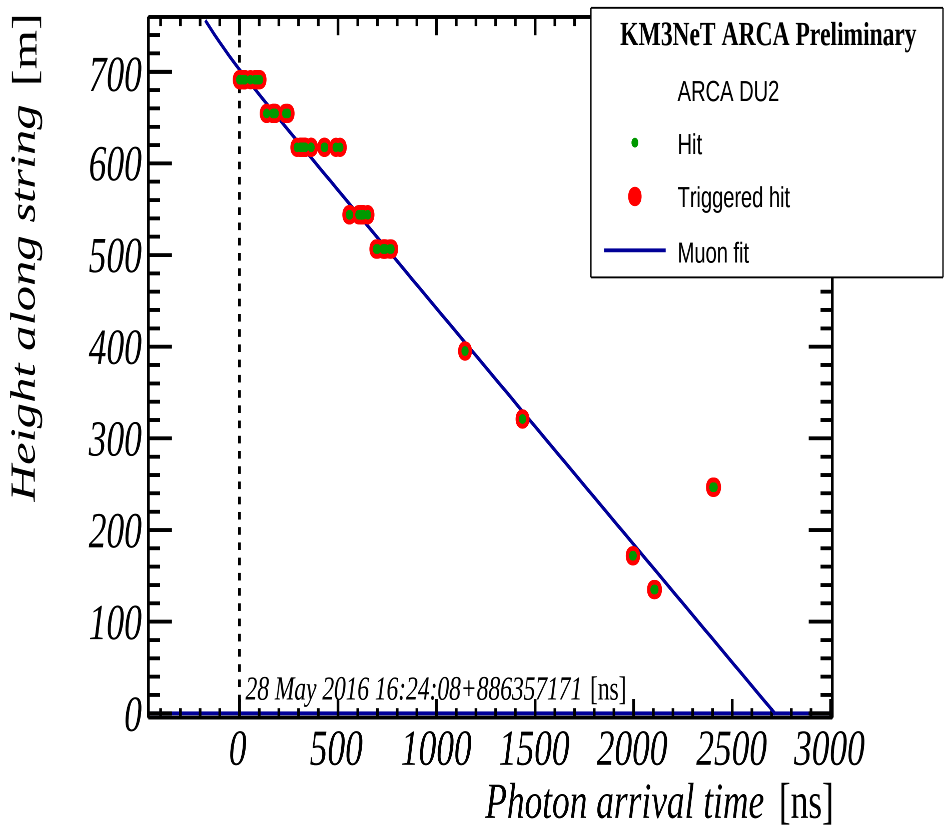
- Non-Standard interactions and Sterile Neutrinos
    - J. Coelho, Neutrino 2016, P 2.026
- Neutrino Beam from Protvino to ORCA
    - CP & NMH
    - J. Brunner, AHEP, Volume 2013 (2013), Article ID 782538
- Low Energy Neutrino Astrophysics
    - J. Becker Tjus, arXiv: 1405.0471
- Earth Tomography and Composition
    - S. Bourret, Procs. Neutrino 2016, arXiv:1702.03723
- Earth and Sea Sciences

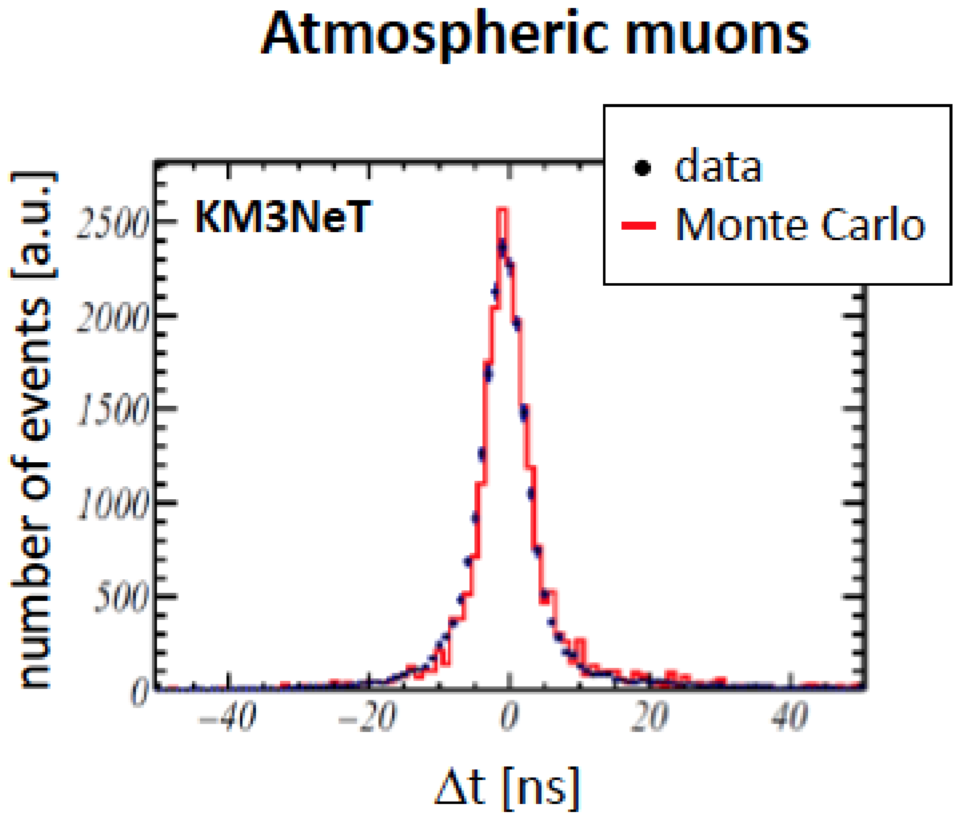
First (ARCA) lines and prototypes

- In-situ prototypes 2013 (1 DOM) & 2015 (3 DOMs)
- Two ARCA lines deployed in December 2015 and May 2016
- Identical technology, except for vertical and horizontal spacing
  - Calibration procedures and systematic studies relevant for ORCA



Selected result: Atmospheric muons





Residual between predicted and measured photon arrival time

Summary

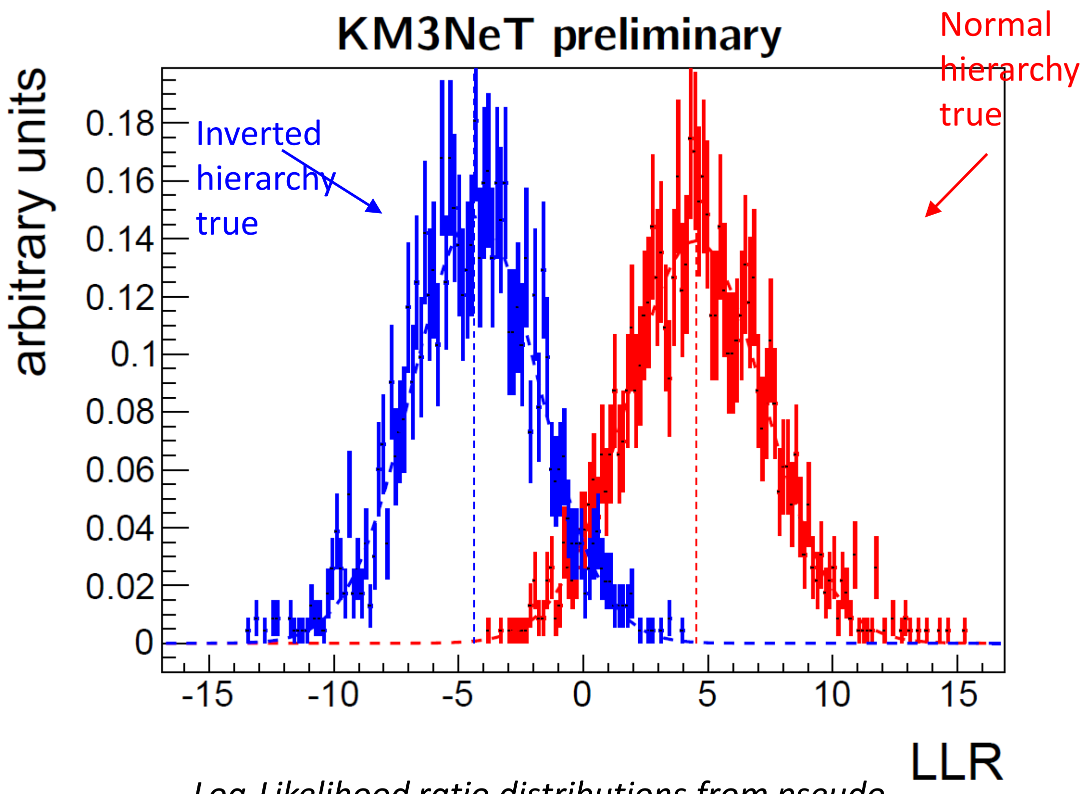
- ORCA can measure the neutrino mass hierarchy within a few years of operation (3 sigma in 3 years)
  - And, competitive measurement of other oscillation parameters
- Many other physics opportunities
  - Sterile neutrinos/Non-standard interactions
  - Dark Matter
  - Supernovae
  - Beam options explored (CP?)
- ORCA Phase 1 with 6 detection units being constructed
  - ORCA phase 2 with 115 detection units is partially funded
- Data from ARCA lines validate understanding of detector and simulations

Backup

Sensitivity study

- Generate many pseudo-experiments
  - A set of ´true´ values for oscillation parameters and systematics
  - Both normal and inverted hierarchy
  - Calculate oscillation probabilites
  - Apply resolutions, particle ID etc. (determined from simulations)
- Determine likelihood for both NH and IH cases
  - Maximize w.r.t. free parameters
- Calculate log-likelihood ratio L_{IH}/L_{NH}
- Calculate median sensitivity for hypothesis and time

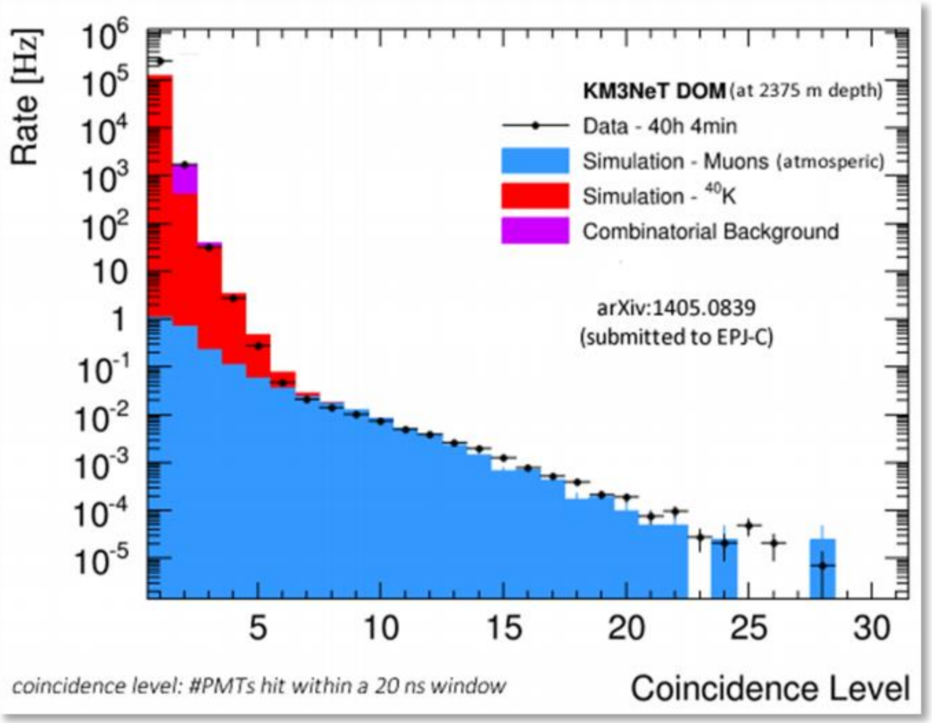
A simpler approach based on Asimov-sets yields similar results

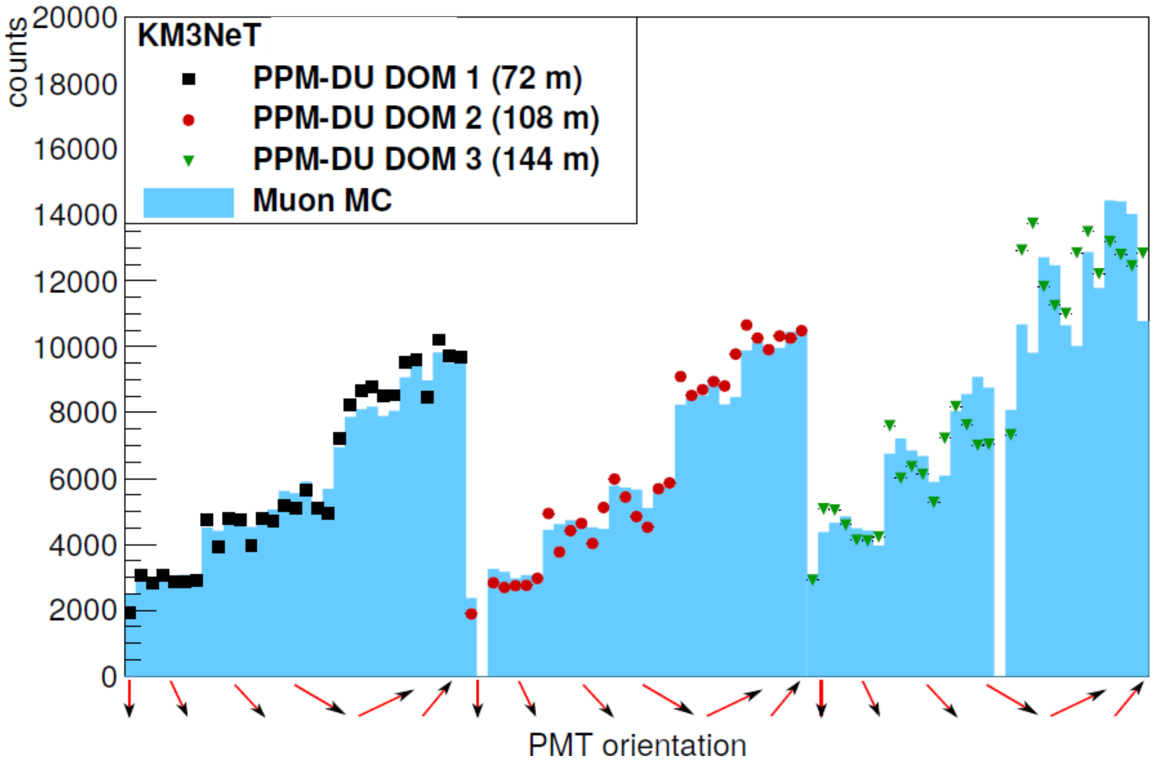


Log-Likelihood ratio distributions from pseudo-experiments

parameter	*true value distr.*	*initial value distr.*	*treatment*	*prior*
θ_{23} [°]	$\{40, 42, \dots, 50\}$	uniform over [35, 55] †	fitted	no
θ_{13} [°]	8.42	$\mu = 8.42$, $\sigma = 0.26$	fitted	yes
θ_{12} [°]	34	$\mu = 34$, $\sigma = 1$	nuisance	N/A
ΔM^2 [10^{-3} eV^2]	$\mu = 2.4$, $\sigma = 0.05$	$\mu = 2.4$, $\sigma = 0.05$	fitted	no
Δm^2 [10^{-5} eV^2]	7.6	$\mu = 7.6$, $\sigma = 0.2$	nuisance	N/A
δ_{CP} [°]	0	uniform over [0, 360]	fitted	no
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

Photon counting and direction





Photon counting

(muons cause higher multiplicity coincidences)

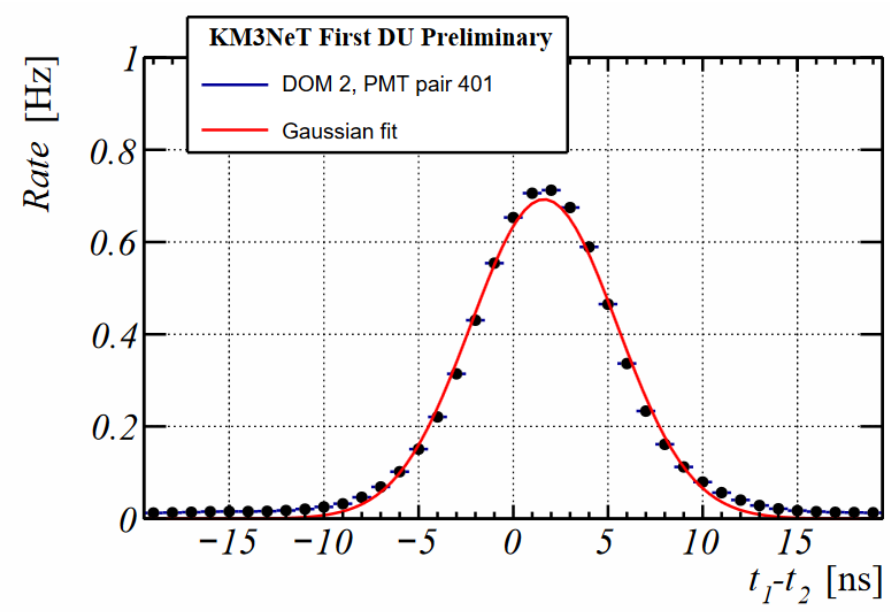
Directional sensitivity

(photons from muons come from above)

(data in these plots is from prototypes PPM-DOM (*Eur. Phys. J. C (2014) 74:3056*) and PPM-DU (*Eur.Phys.J. C76 (2016) no.2, 54*)

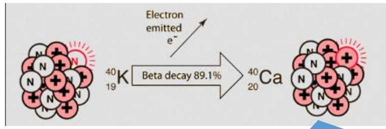
K40 time calibration

Time difference distribution between two PMTs in a DOM

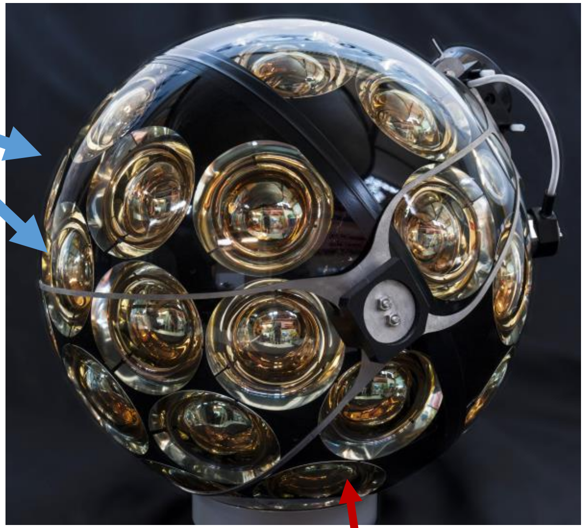


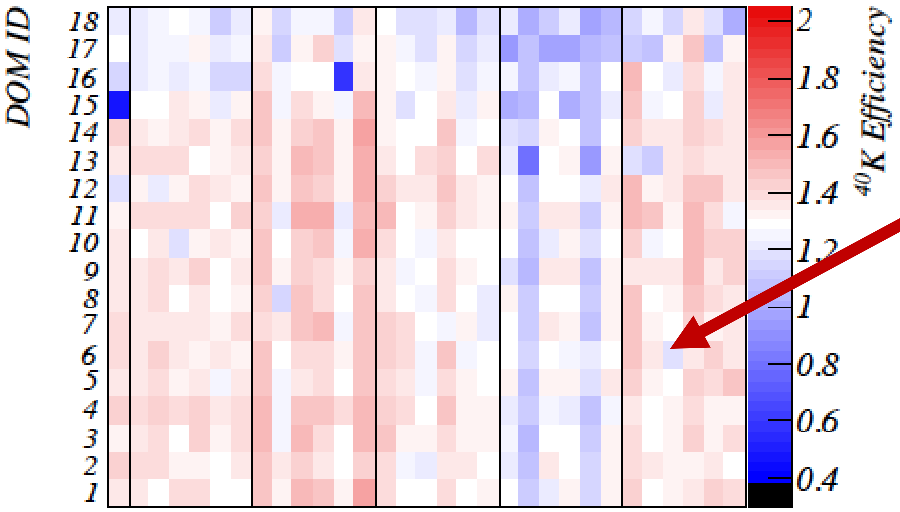
Time offset between the two PMTs

Information from k40 decay :
- time offset
- efficiency
- time spread



Photons from individual decays on different PMTs





PMT in DOM

Structure modifies efficiency of individual PMTs

Particle Identification