KM3NeT:

A neutrino detector in the Mediterranean deep-sea

DAAN VAN EIJK

On behalf of the KM3NeT Collaboration,

NPC Neutrino Seminar at Fermilab, November 16, 2017

INTRODUCTION

- Current position: postdoctoral fellow at UW Madison/ WIPAC
  - IceCube, CHIPS
- Former position: postdoc at Nikhef Amsterdam
  - KM3NeT
    - Optical Module integration coordinator

OUTLINE

- KM3NeT Introduction
- Neutrino Detection and Event Topologies
- KM3NeT Physics
- KM3NeT Detector and Construction
- KM3NeT First Results, Current Status and Outlook

KM3NET MOTIVATION

- km^3 Ne(utrino) T(elescope)
- Northern Hemisphere counterpart of existing IceCube detector at South Pole
- Independent confirmation of astrophysical high-energy neutrino flux as discovered by IceCube
- Point source studies with unprecedented angular resolution
  - Larger scattering length in water compared to ice
- Low energy atmospheric neutrinos: oscillation studies
- Sea science infrastructure

6 year HESE data

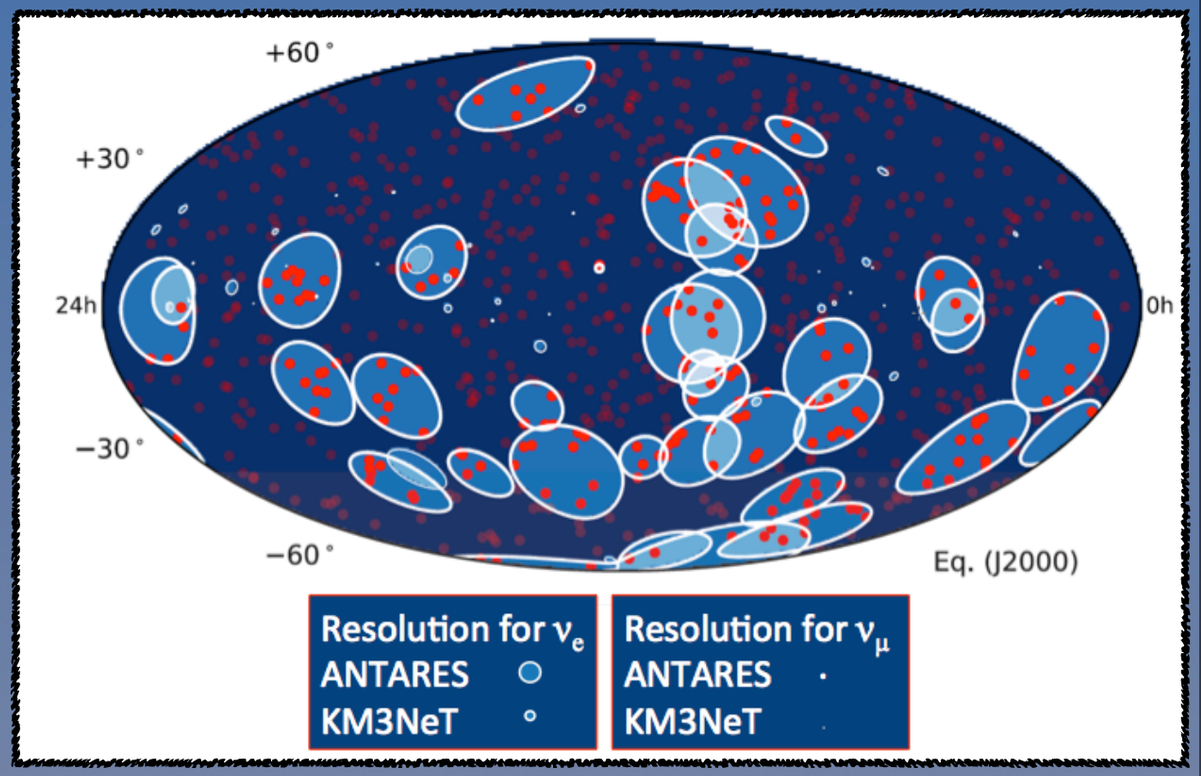
E > 60 TeV

$\Theta < 20^\circ$

Points : Fermi data

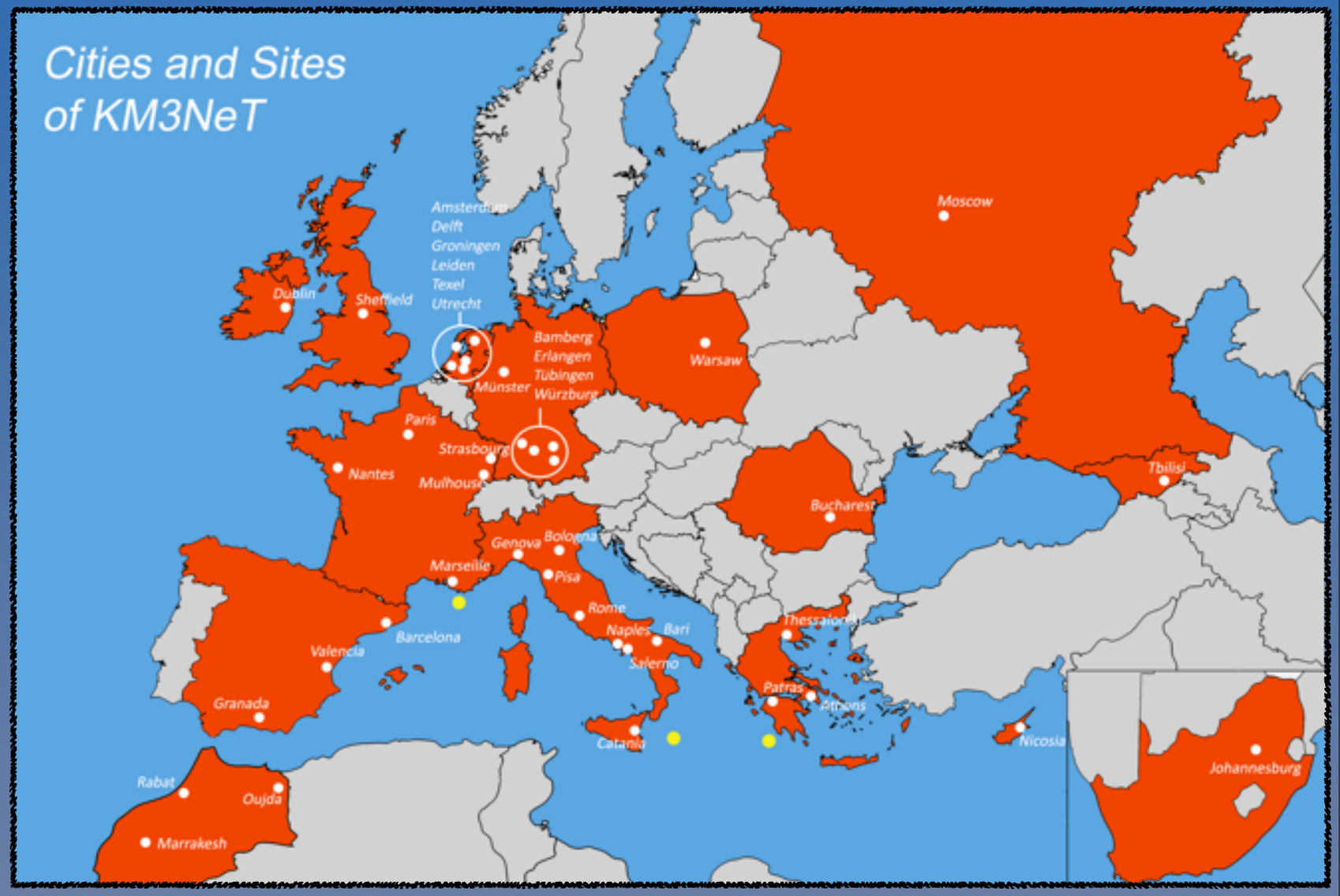
Courtesy: A. Heijboer and

E. Resconi, ICRC 2017

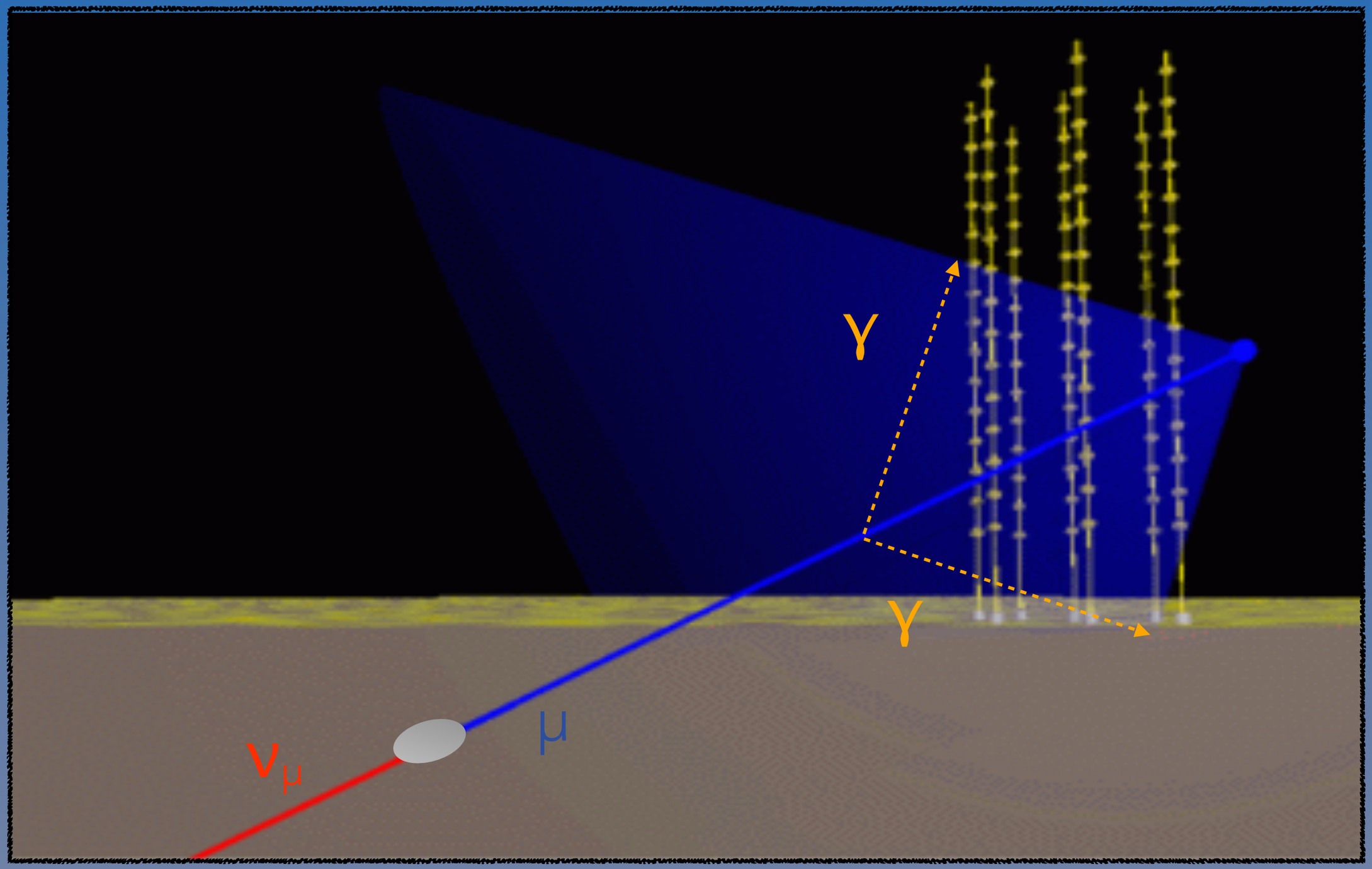


KM3NET COLLABORATION

- 13 countries
- 51 institutes
- ≧ 220 scientists



NEUTRINO DETECTION



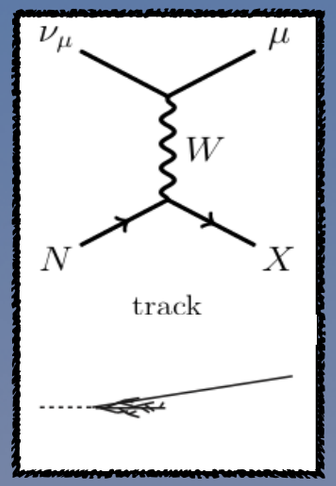
EVENT TOPOLOGIES

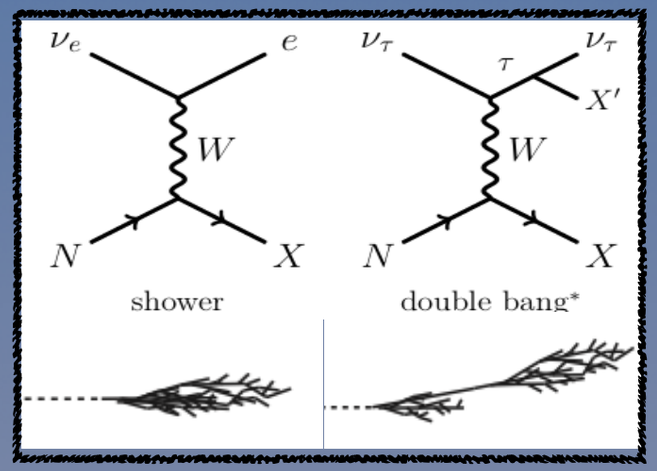
Tracks

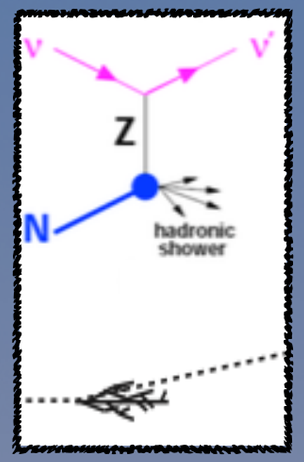
- $\nu_\mu \rightarrow \mu$ charged current (CC) interaction
- Good angular resolution
- Poor energy resolution

Cascades/showers

- $\nu_\tau \rightarrow \tau$ and $\nu_e \rightarrow e$ charged current (CC) interactions
- Neutral current (NC) interactions of all neutrino flavors
- Poor angular resolution
- Good energy resolution







KM3NET PHYSICS

ORCA

(Oscillation Research with Cosmics in the Abyss)

- GeV (low-energy) atmospheric neutrinos

ARCA

(Astrophysics with Cosmics in the Abyss)

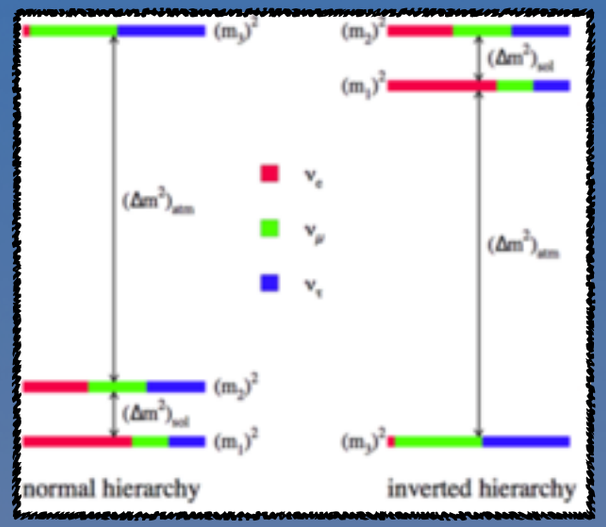
- TeV-PeV (high-energy) astrophysical neutrinos

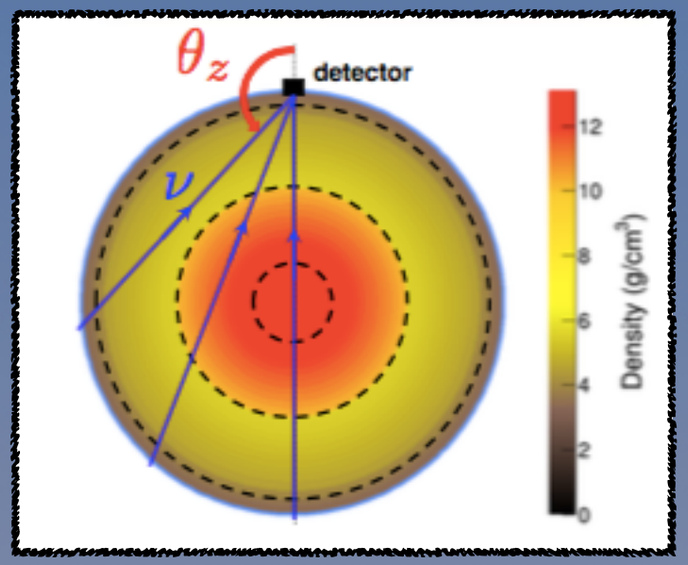
Same DOM and DU technology, only detector layout dimensions are scaled!

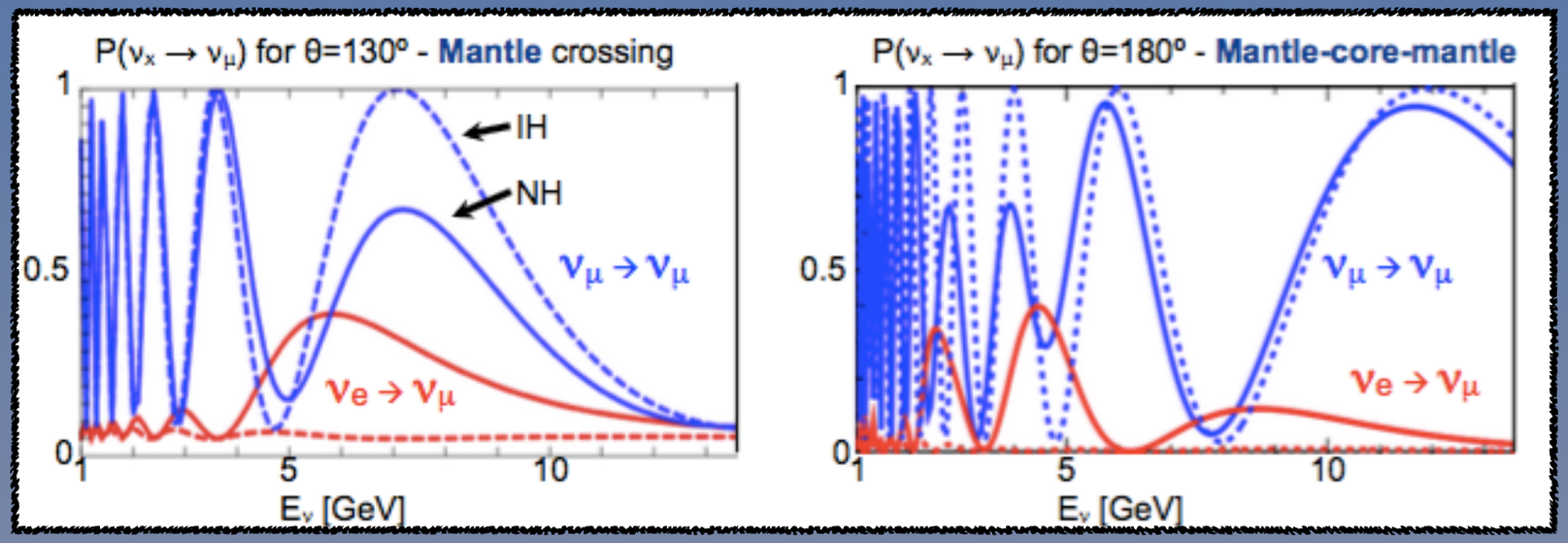
ORCA

Measurement of neutrino oscillation parameters and determination of the neutrino mass hierarchy (NMH):

- In matter, ν_e/anti-ν_e acquires effective potential through CC elastic interactions with electrons, resulting in modified oscillation probabilities

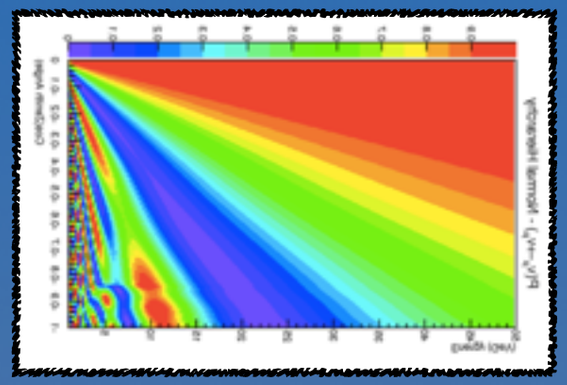


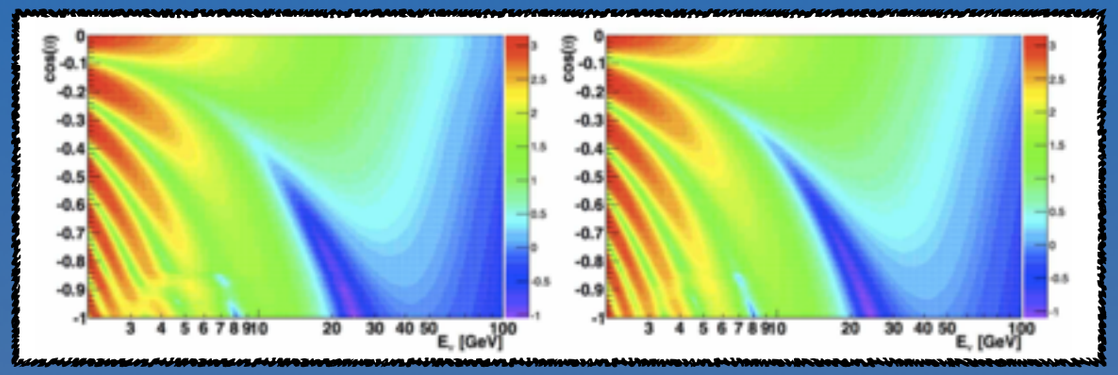


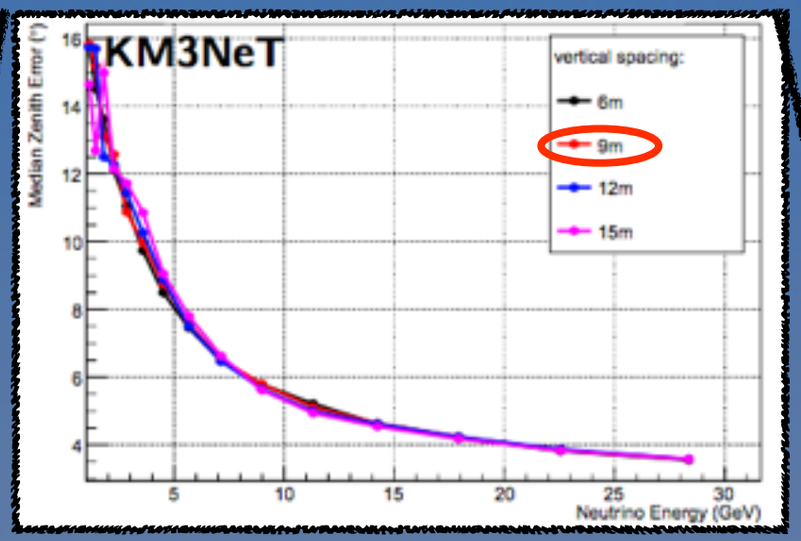


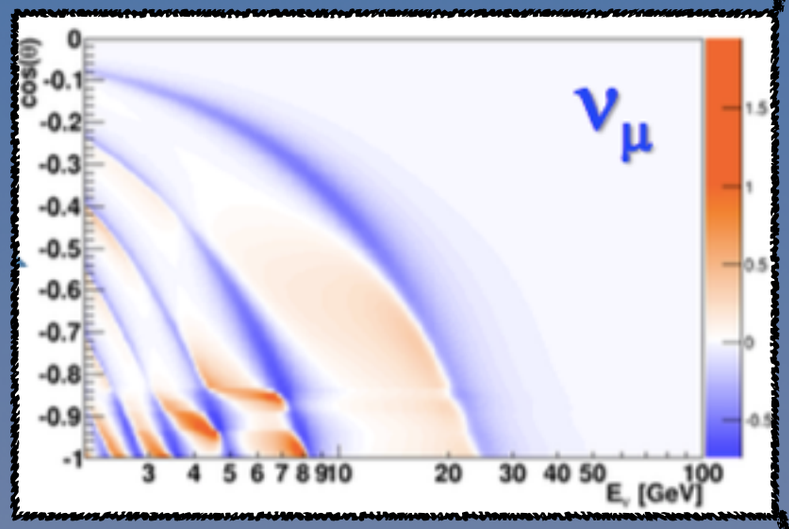
ORCA NMH ANALYSIS

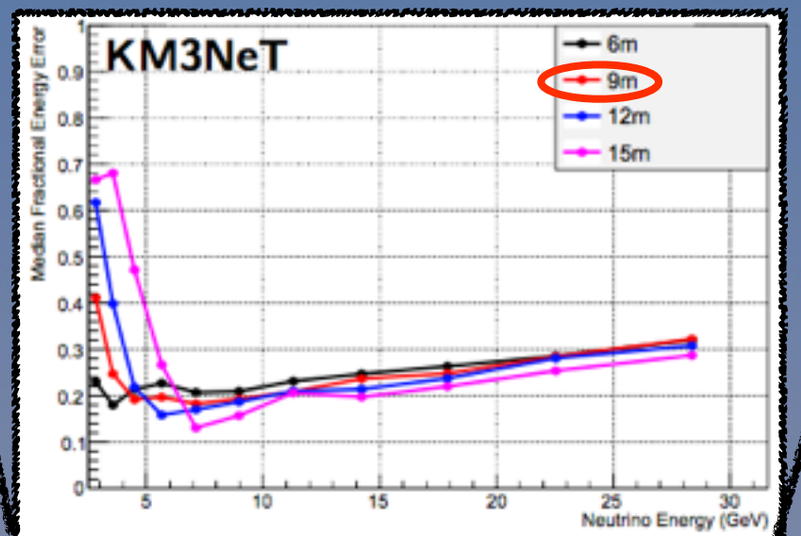
Oscillograms of $(N_{IH}-N_{NH})/N_{NH}$ give the relative difference in event numbers between NH and IH

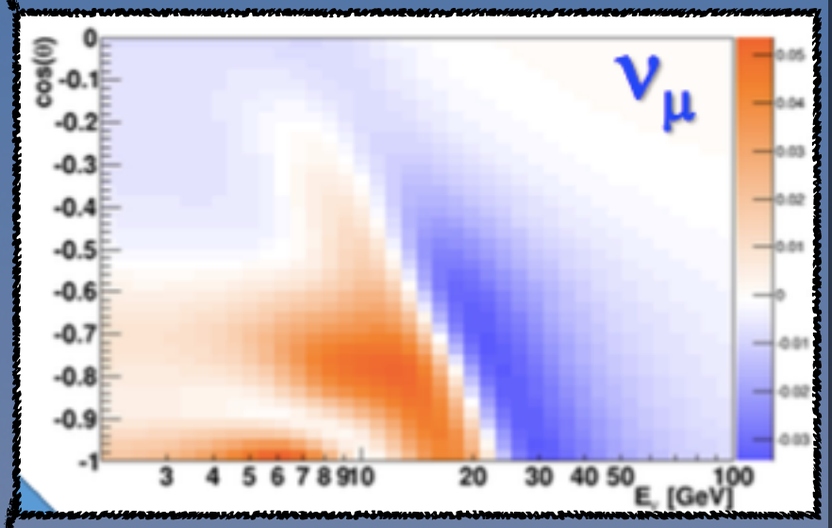






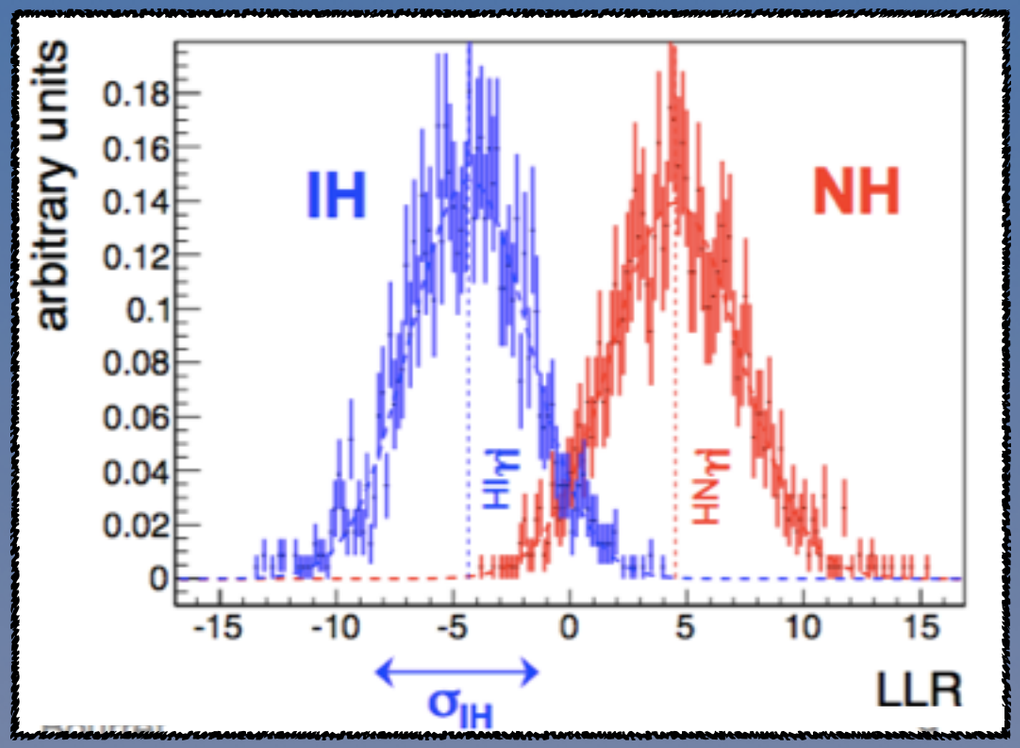


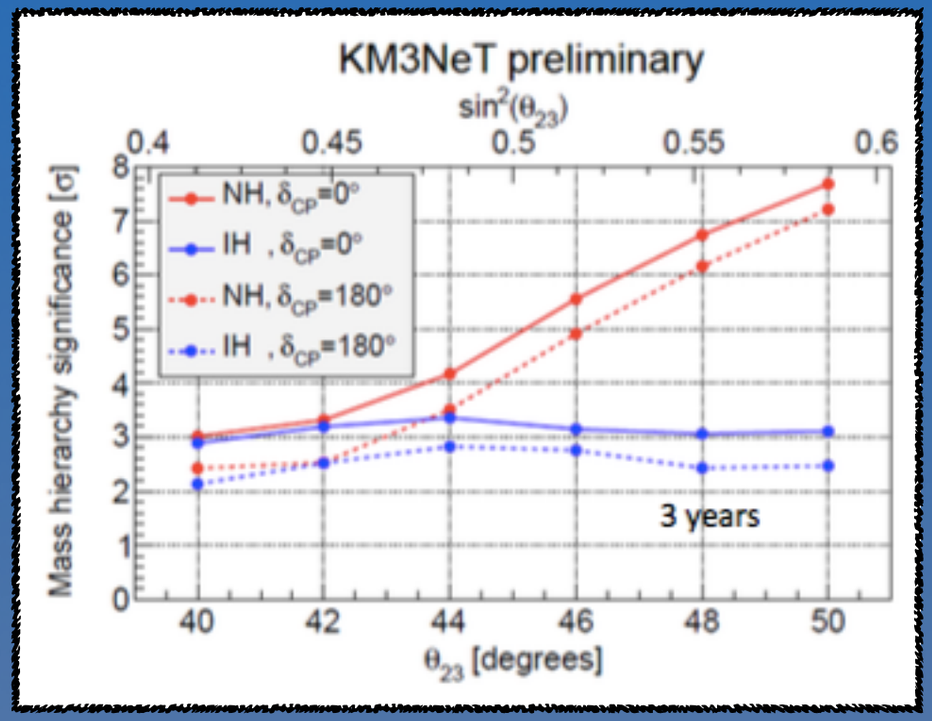




ORCA NMH SENSITIVITY STUDY

- Pick true physics and nuisance parameters
- Generate two sets of many pseudo-experiments for both NH and IH
- For both sets, calculate LLR = $\log(\mathscr{L}_{NH}/\mathscr{L}_{IH})$, where $\mathscr{L}_{NH}$ and $\mathscr{L}_{IH}$ are the best-fit likelihoods under the NH and IH assumption, respectively
- Fit LLR distributions with Gaussians
- Median significance or sensitivity $S = (\mu_{NH} - \mu_{IH})/(\sigma_{IH})$, gives the probability of observing median LLR of wrong hierarchy

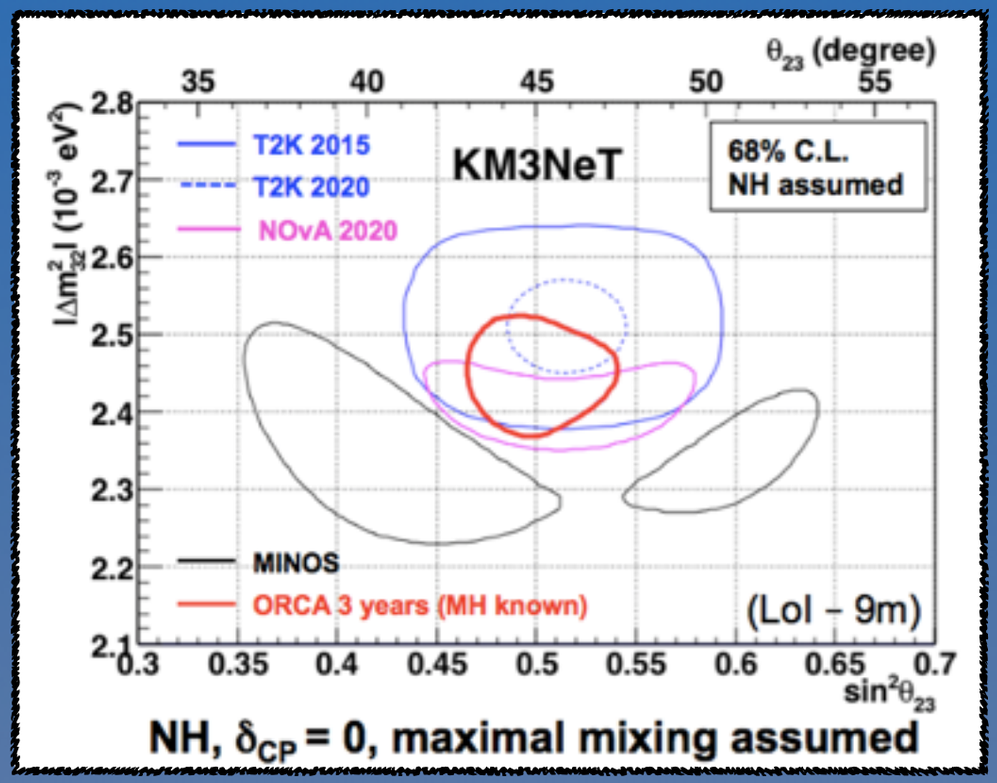




- Sensitivity to distinguish between normal and inverted hierarchy: 3 sigma in three years
- Normal hierarchy and upper octant for θ_{23} gives more sensitivity (5 sigma in three years)

ORCA NEUTRINO OSCILLATION PARAMETERS

- Achieve 2-3% precision in Δm^2_{32} and 4-10% in $\sin^2\theta_{23}$ after 3 years
  - Competitive with LBL experiments projected sensitivities in 2020
- Early determination of the θ_{23} octant is feasible

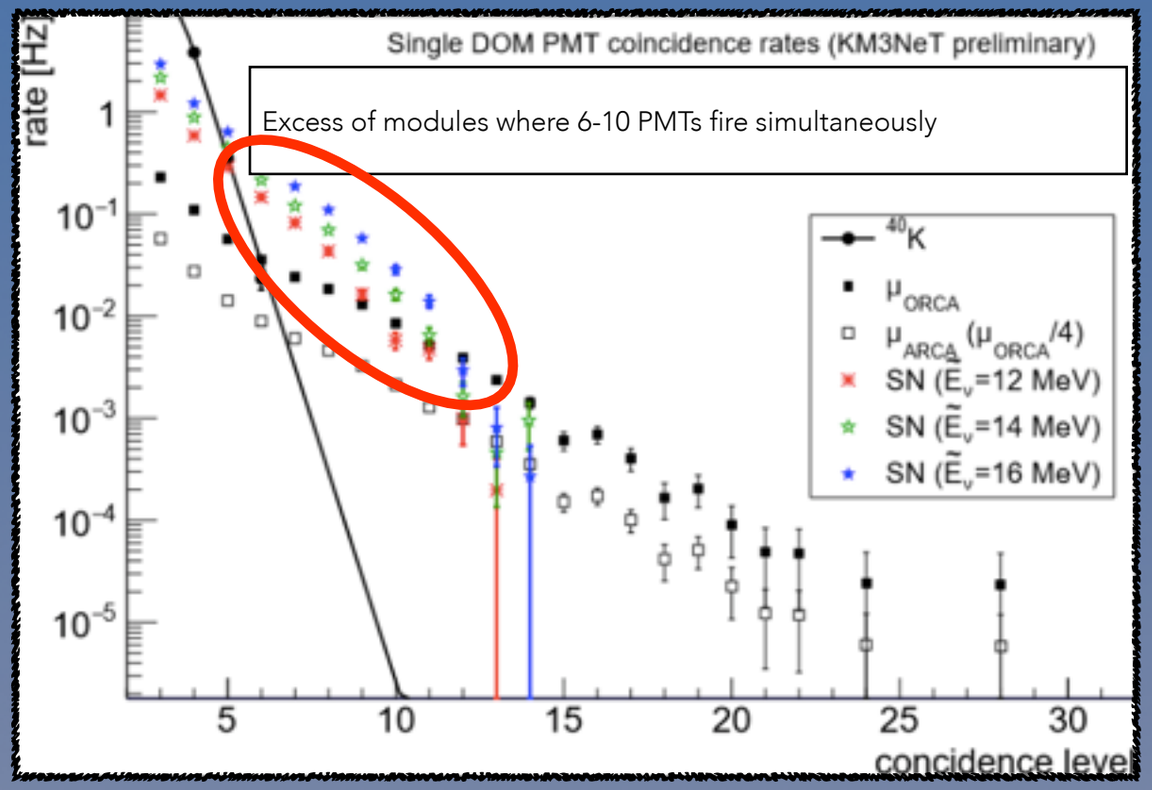


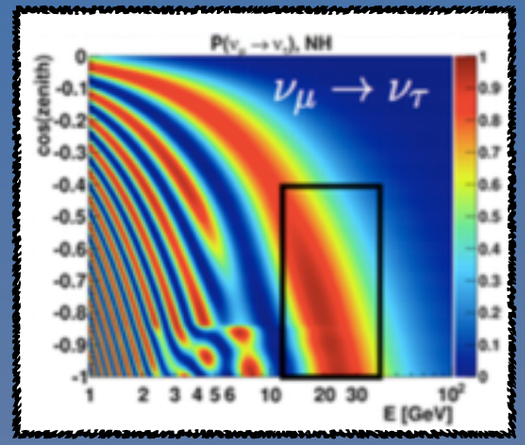
- θ_{12}, θ_{13} and δm^2 fixed
- Energy scale uncertainty added (no impact on NMH sensitivity)

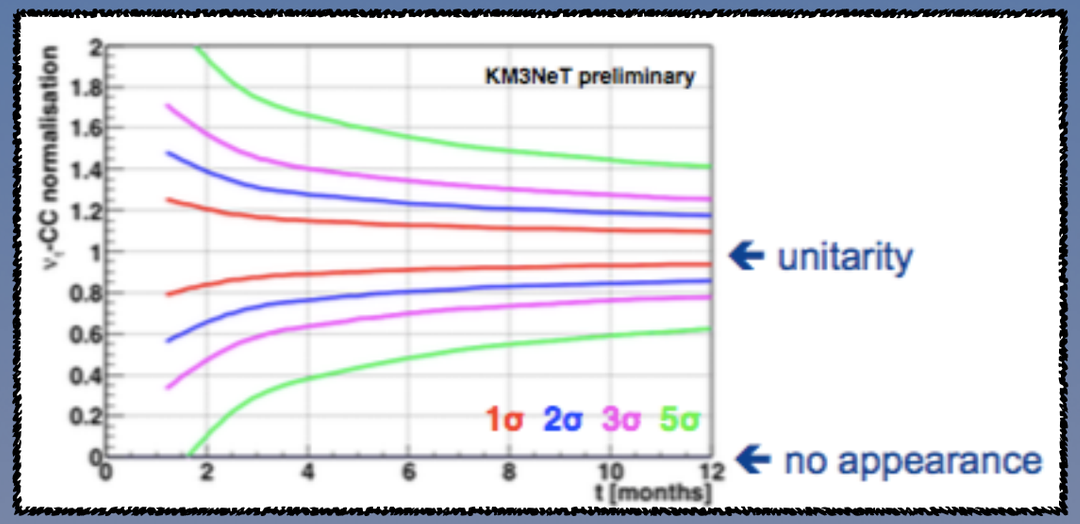
SUPERNOVAS AND TAU NEUTRINOS

- Supernova detection:
  - ~10 MeV neutrinos
  - Enhanced collective coincidence rate between PMTs in DOMs
    - At ≧ 6 coincidences per DOM, SN signal exceeds background

- Tau appearance/normalization:
  - ν_τ appearance tests PMNS unitarity and BSM theories
  - ~ 3k ν_τ CC events/year with full ORCA
  - Rate constrained within ~10% in 1 year

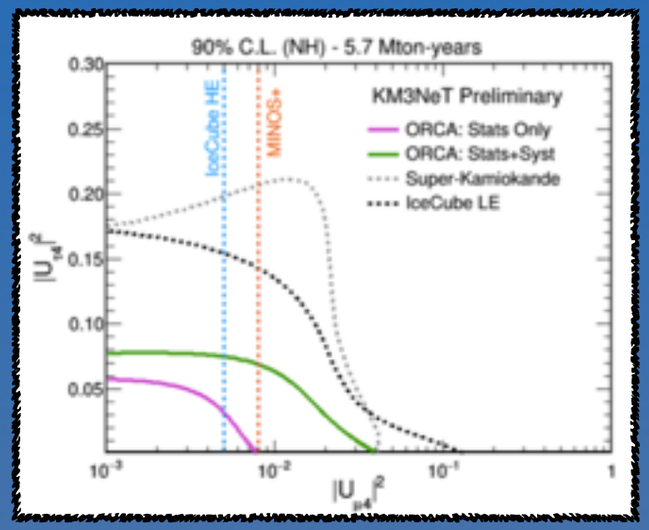


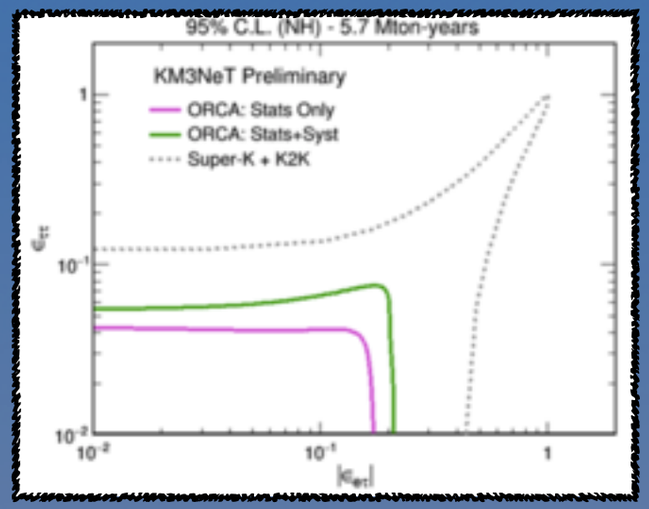


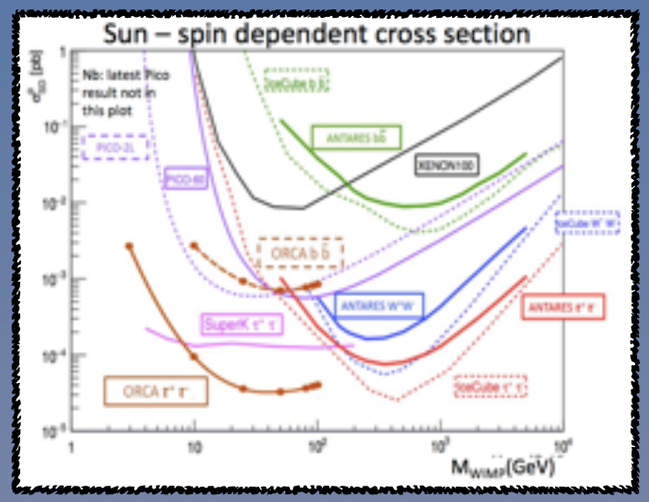


OTHER ORCA SCIENCE

- Sterile neutrinos and NSI
- Indirect dark matter detection
- Neutrino beam from Protvino (Russia) to ORCA
- Earth tomography and composition
- Earth and Sea sciences







INTERMEZZO: ICECUBE

HESE: High-energy starting events

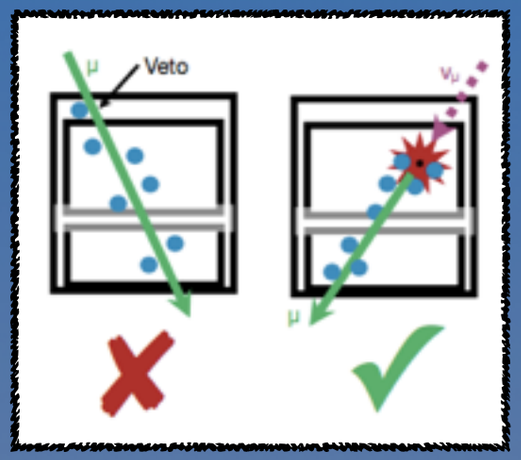
Observed flux :

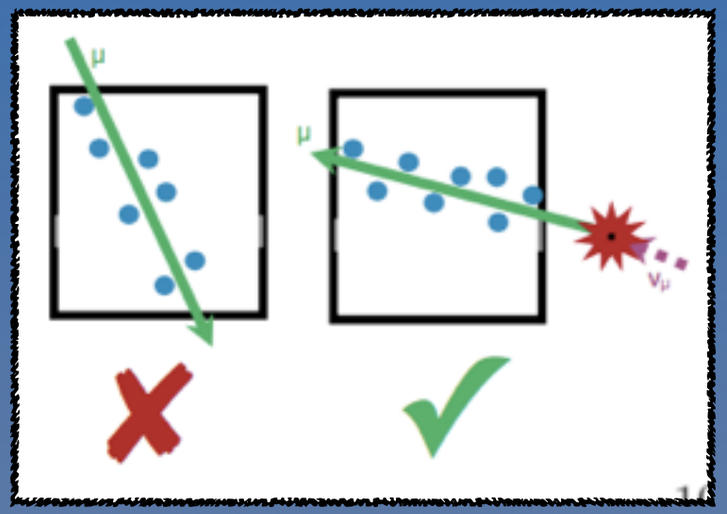
6.7×10^{-18} GeV^{-1} cm^{-2} sr^{-1} s^{-1} (E/100 TeV)$^{-2.50}$

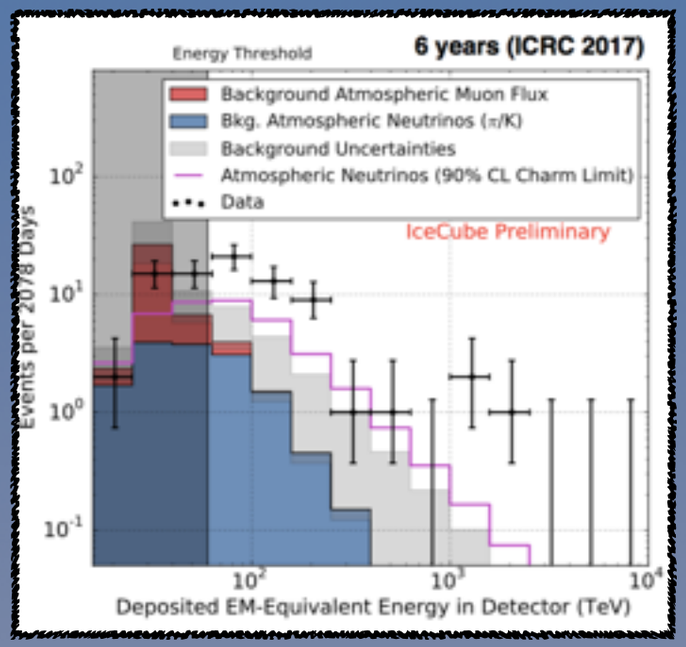
Earth through-going muons:

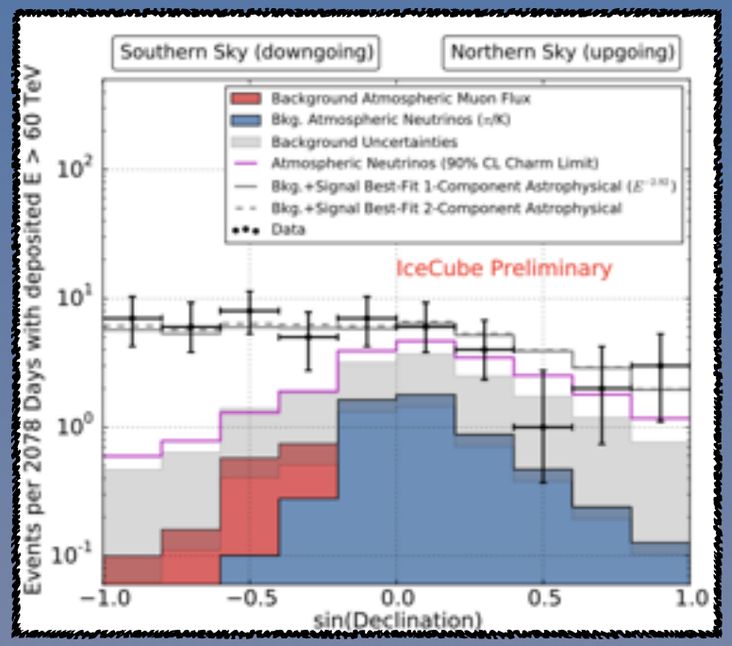
Observed flux:

0.90×10^{-18} GeV^{-1} cm^{-2} sr^{-1} s^{-1} (E/100 TeV)$^{-2.13}$





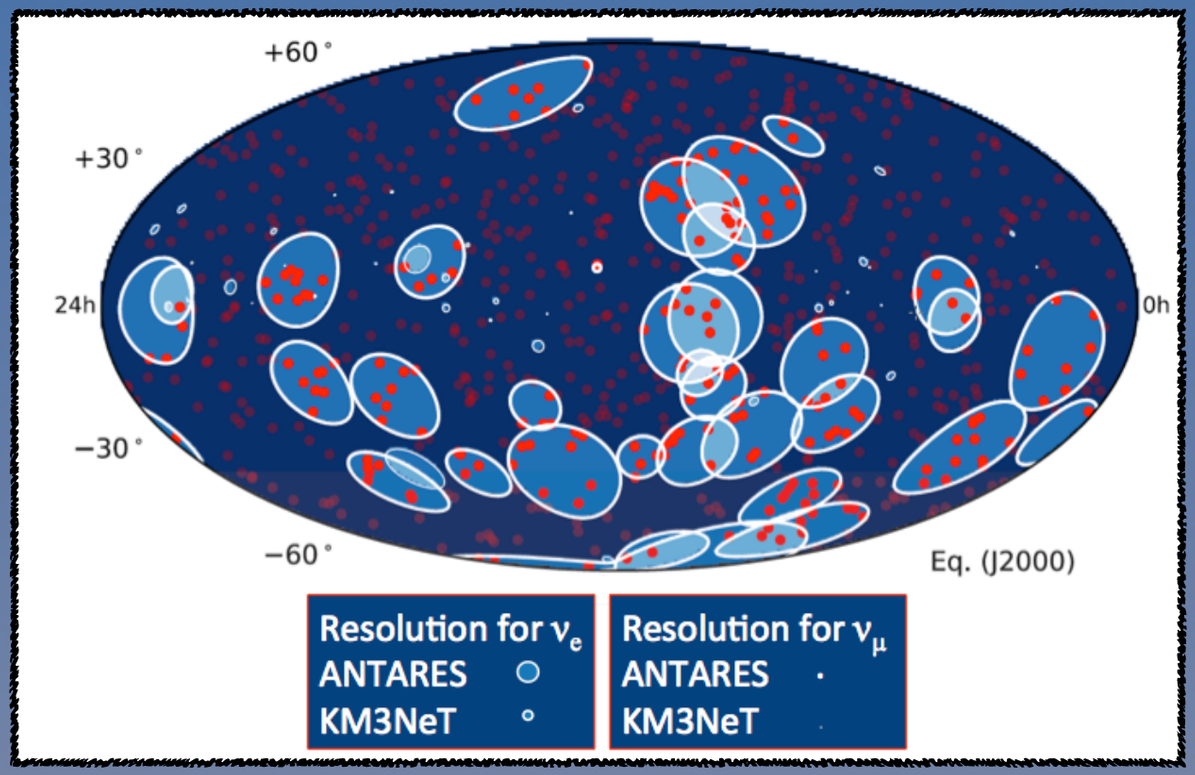




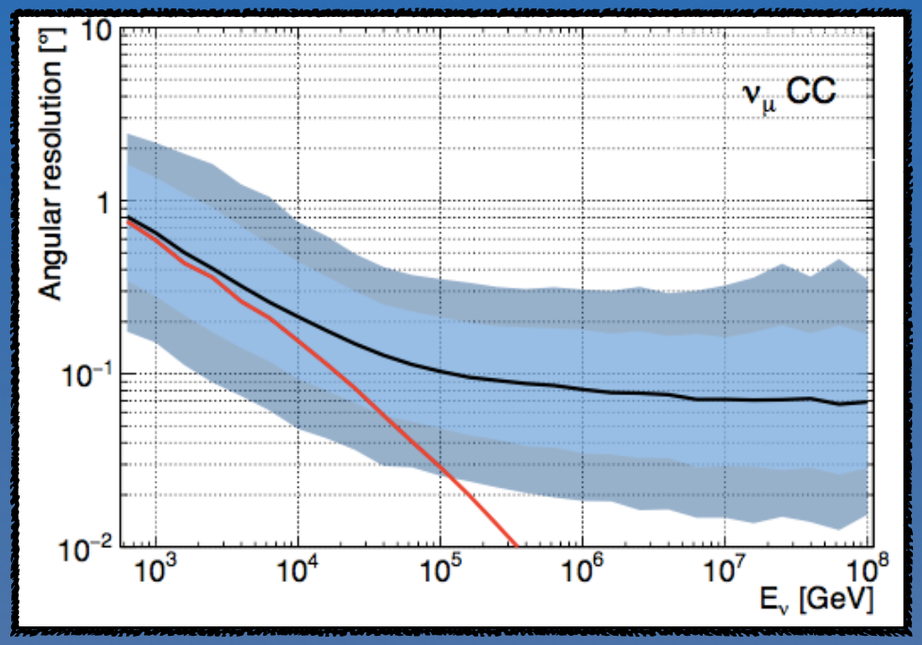
ARCA

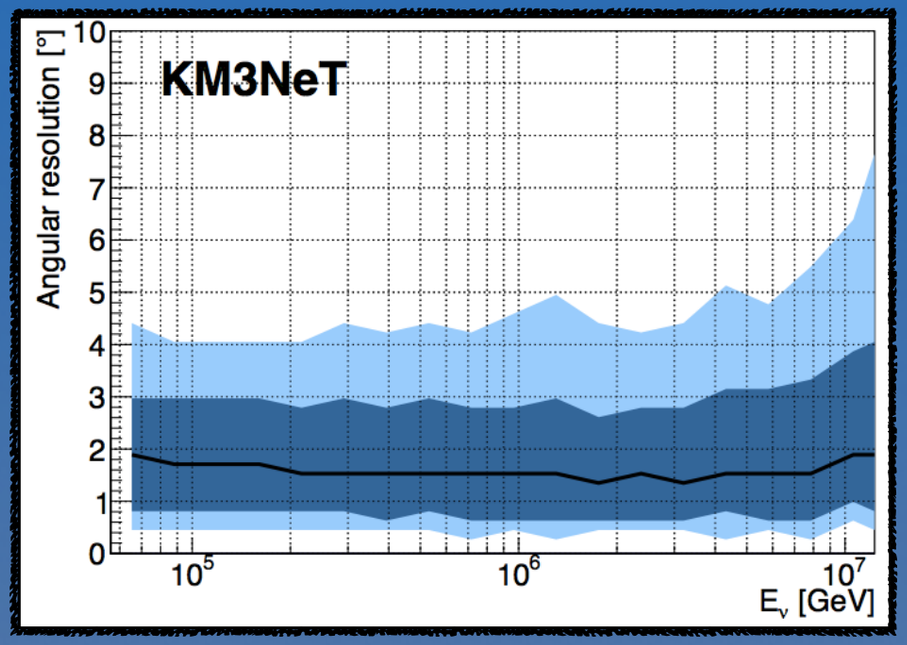
Independent confirmation of astrophysical high-energy neutrino flux as discovered by IceCube with different methodology, improved resolution and a complementary field of view

Most galactic sources in Southern sky → ideal for KM3NeT



ARCA RESOLUTIONS





Upgoing tracks (ν_μ CC):

Angular resolution < 0.2° for E_ν > 10 TeV

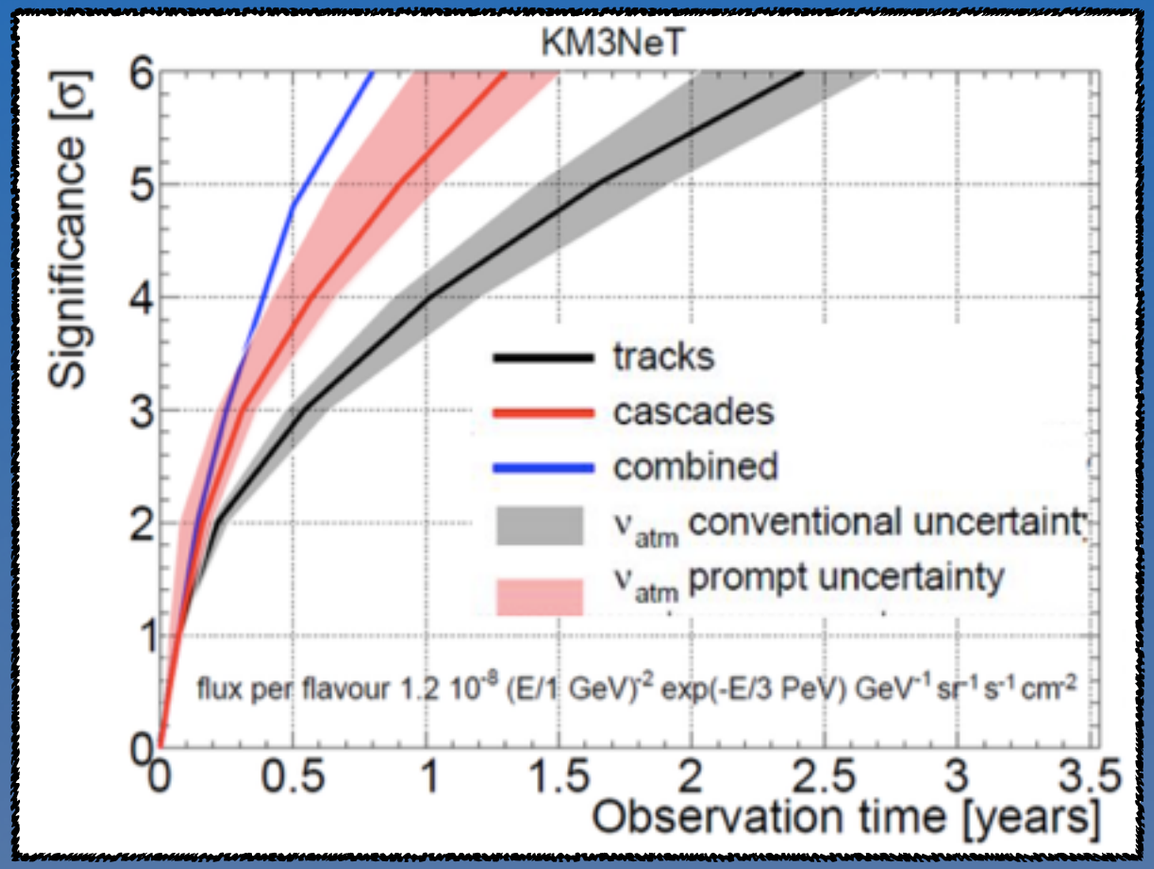
Energy resolution < 0.3 in $\log_{10}(E_{reco}/E_\nu)$

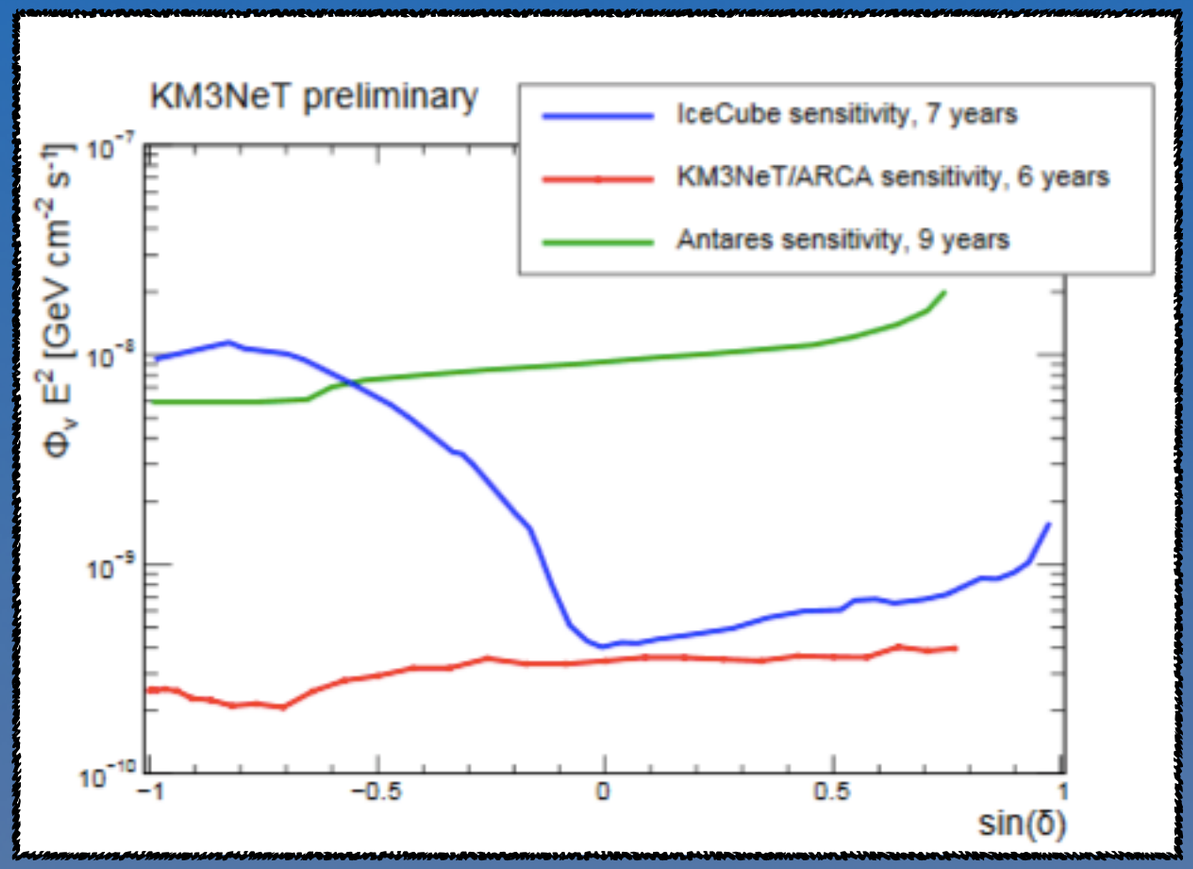
Cascades (NC, $\nu_{e,\tau}$ CC):

Angular resolution < 1.5°

Energy resolution for ν_e: ~5%

ARCA SENSITIVITY



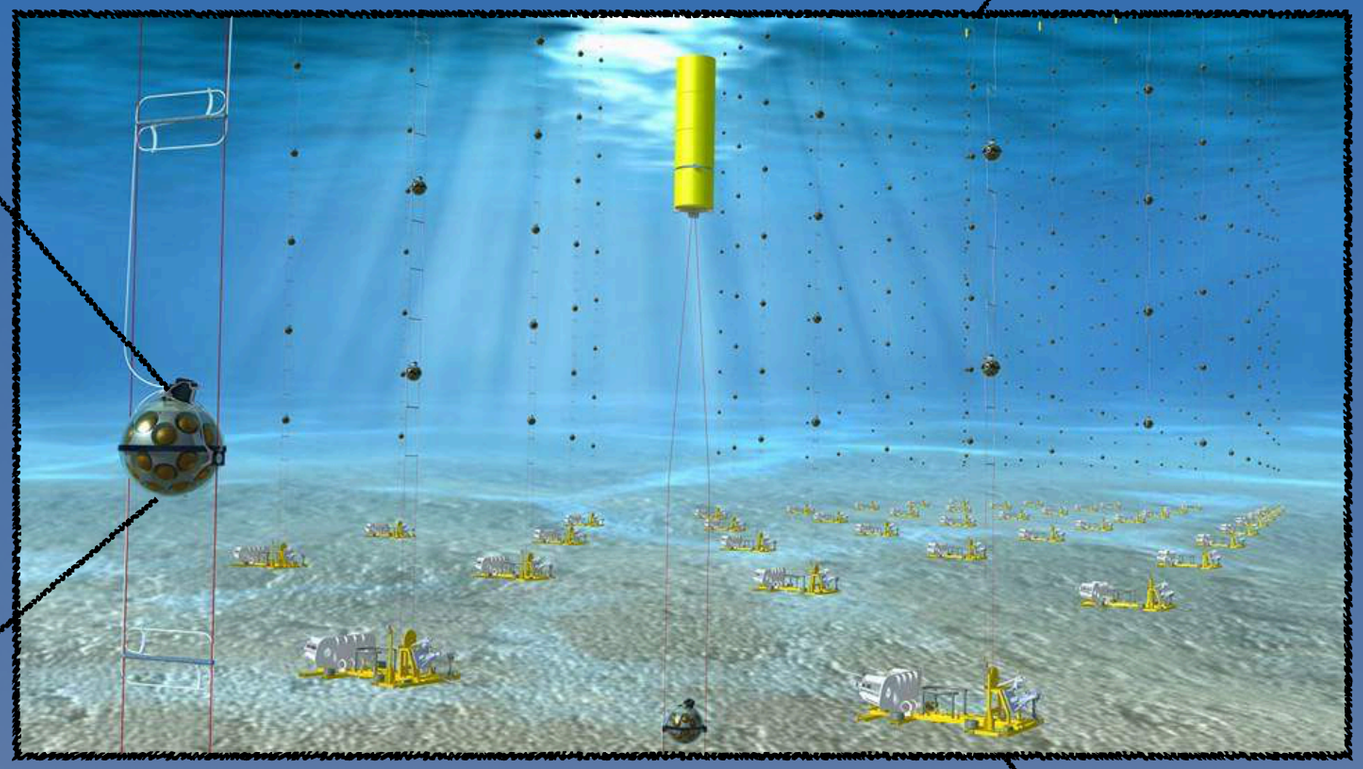


After that: targeted point source studies, extended sources such as Galactic plane, diffuse flux determination, flavor composition, astrophysical oscillations, multi-messenger astronomy (i.e. coincidence with gravitational waves), …

KM3NET DETECTOR

Digital Optical Module (DOM)

Detector Unit (DU)



KM3NET SITES

ORCA

- 30 km off French Coast
- Depth ~2.5 km

ARCA

- 100 km off Italian (Sicilian) Coast
- Depth ~3.5 km

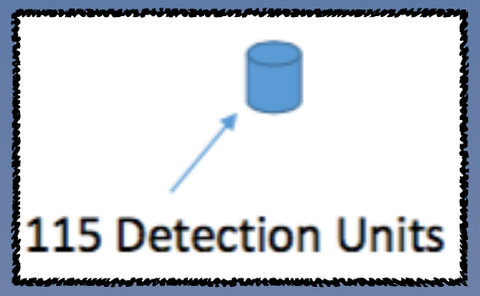
KM3NET DETECTOR LAYOUT

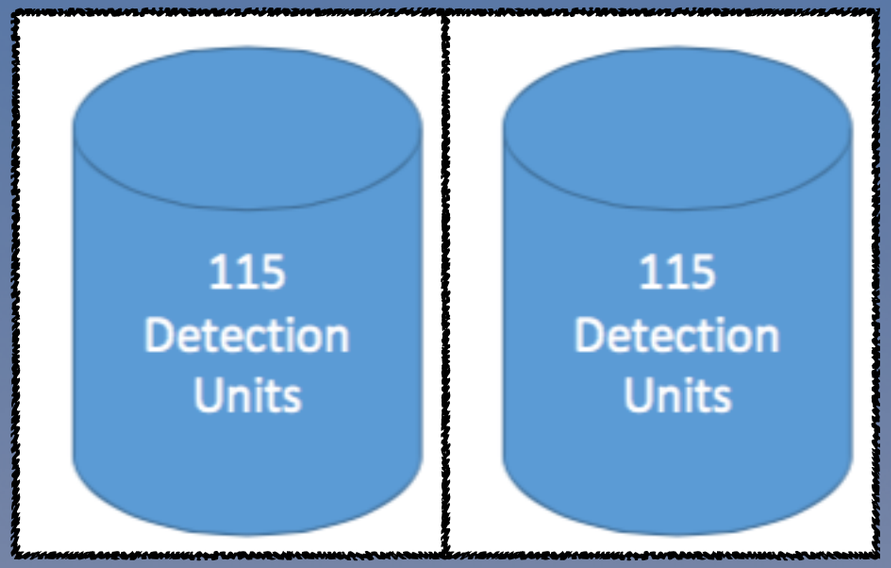
ORCA

- Horizontal DU spacing: ~20 m
- Vertical DOM spacing: 9 m
- 115 DUs
- 5.7 Mton detector

ARCA

- Horizontal DU spacing: ~100 m
- Vertical DOM spacing: 36 m
- 2 x 115 DUs
- ~1 km^3





KM3NET PMT'S

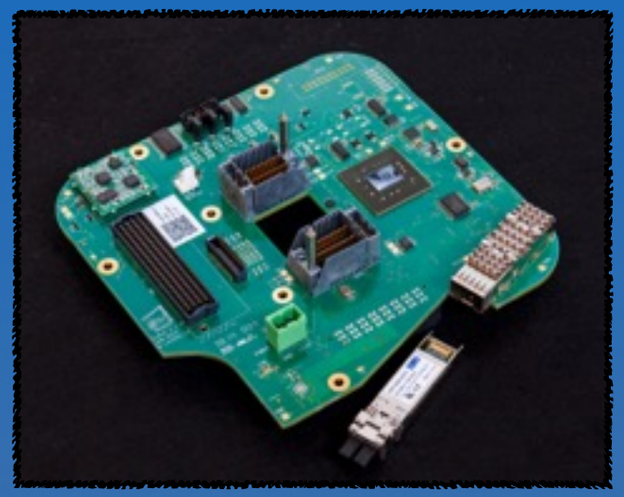
- 80 mm Hamamatsu R12199-02
- Timing ≦ 2 ns RMS
- QE ≧ 25-30%
- HV for gain of $3*10^6$: 900-1300V
- Dark count (15°C, 0.3 pe threshold): 1.5 kHz
- TTS: 4.5 ns FWHM
- Price/cm^2 <= 10"PMT
- Low-power Cockcroft-Walton base provides negative HV to cathode

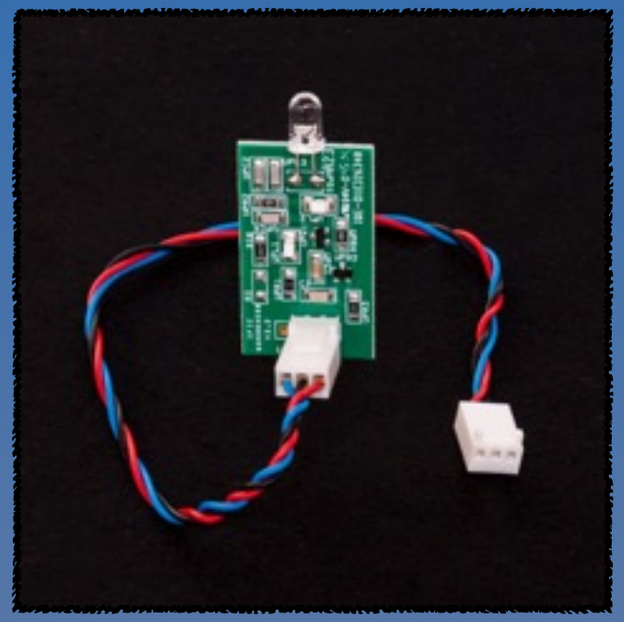
KM3NET DOM (1)

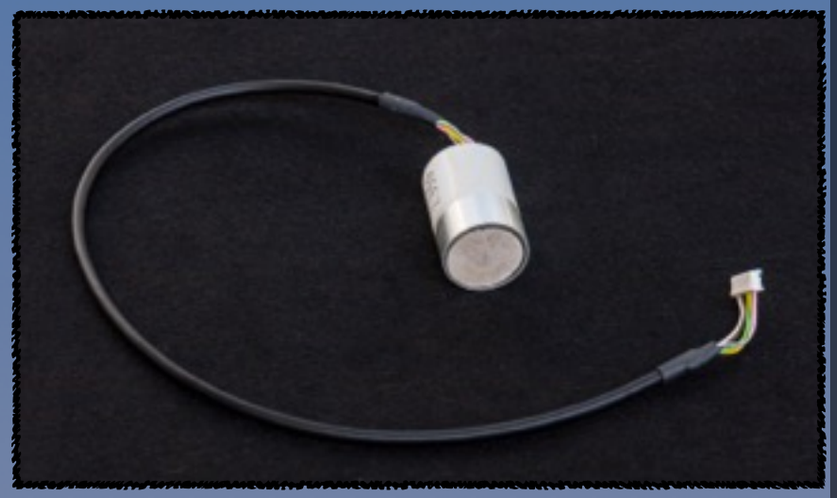
- Novel multi-PMT design:
  - 31 PMTs/DOM
  - Directional sensitivity
  - Suppress uncorrelated photon background from PMT coincidences
  - Photon counting
- Total cathode area = 3 x 10" PMT
- LED, piezo, compass, tilt meter

KM3NET DOM (2)

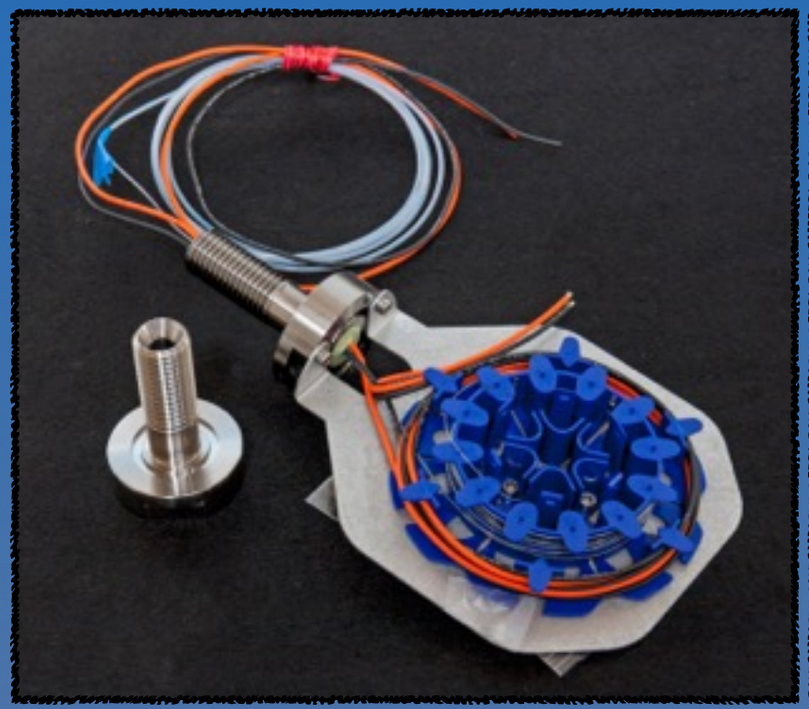
- Read out only PMT time-over-threshold (ToT)
  - No online triggering: all data to shore
- LED for intra-DOM calibration
- Piezo for acoustic positioning
- Compass, tilt meter for DOM orientation

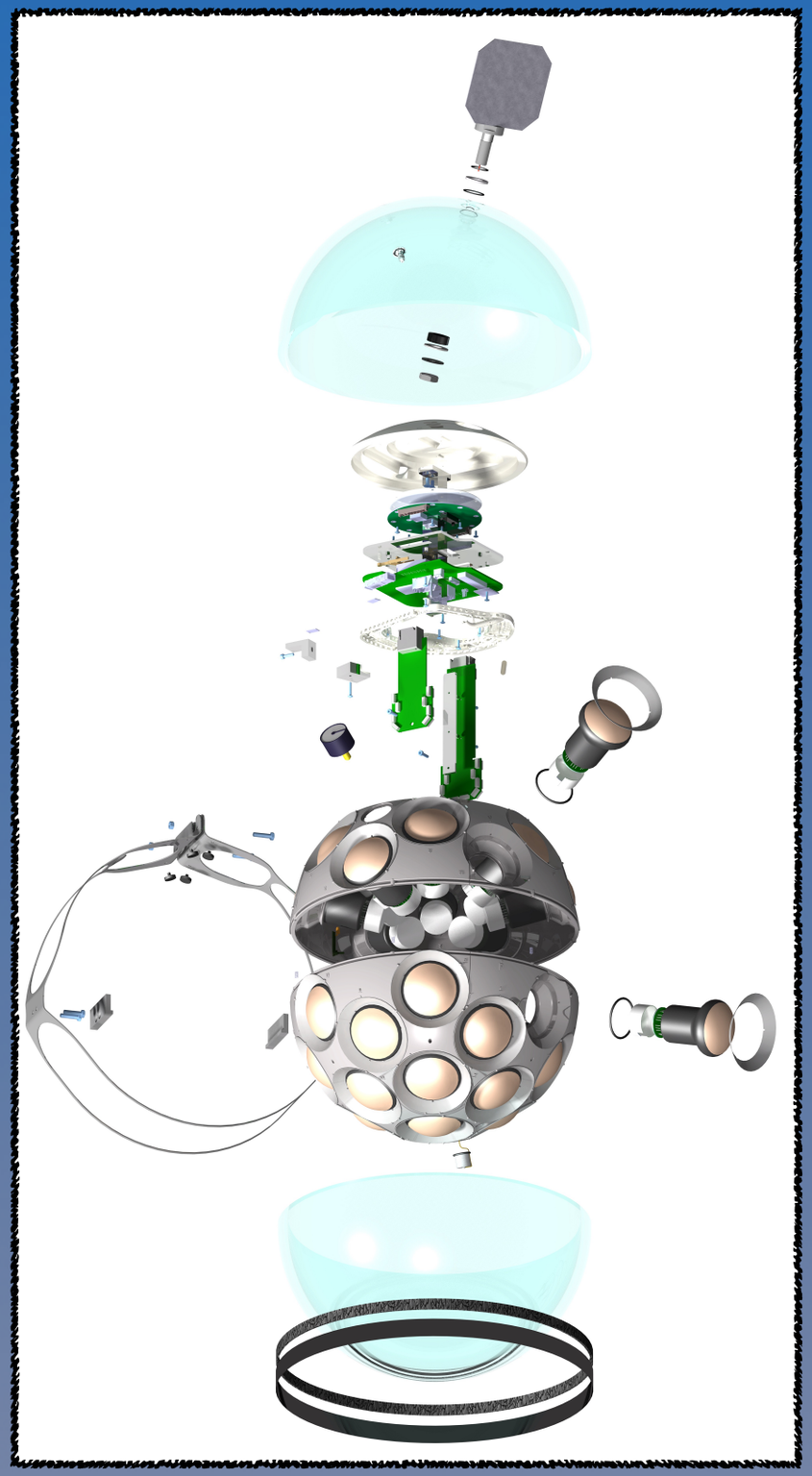






KM3NET DOM (3)



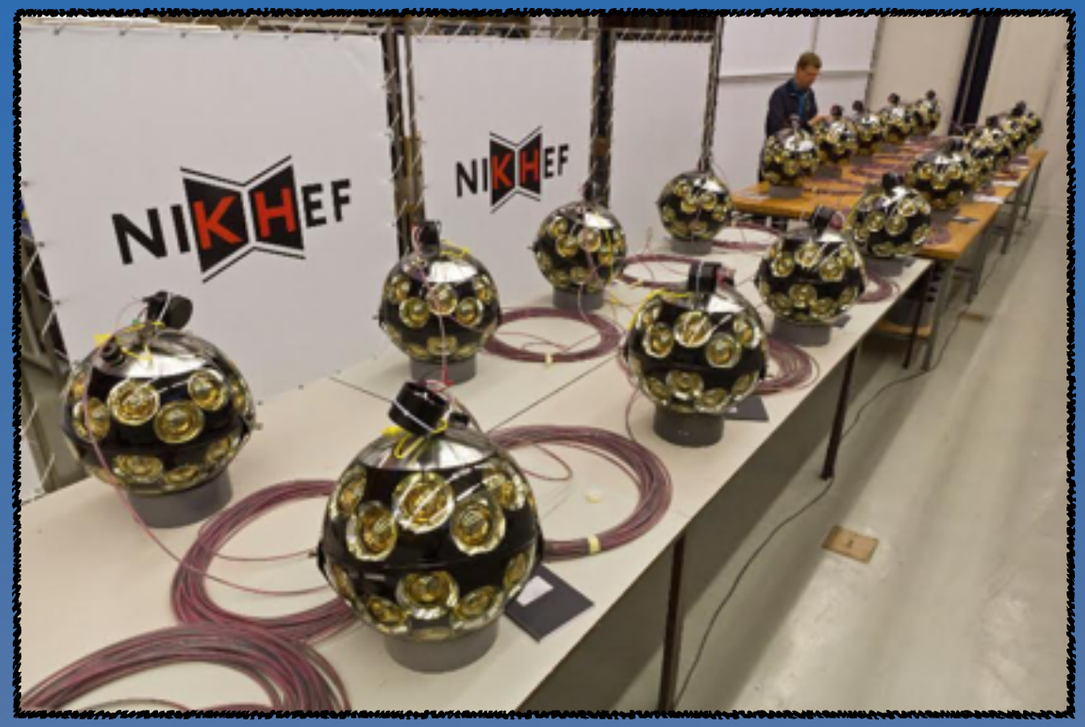


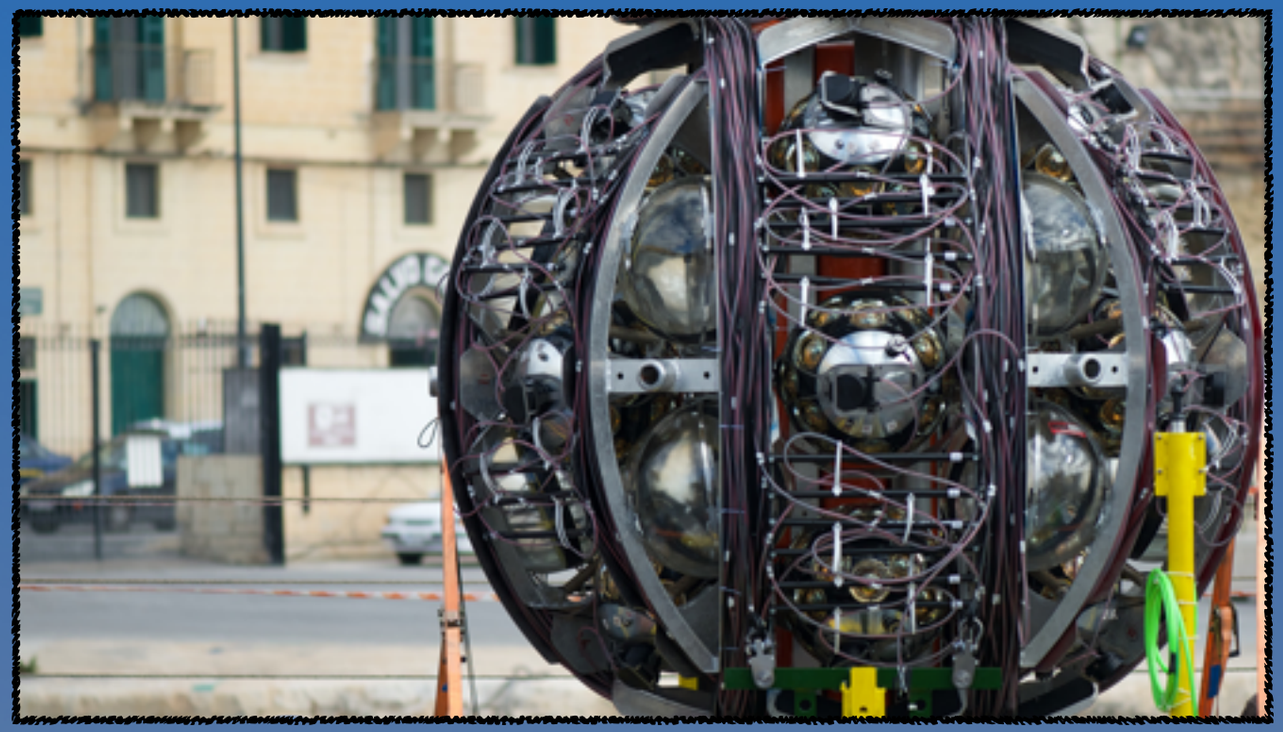
KM3NET DU

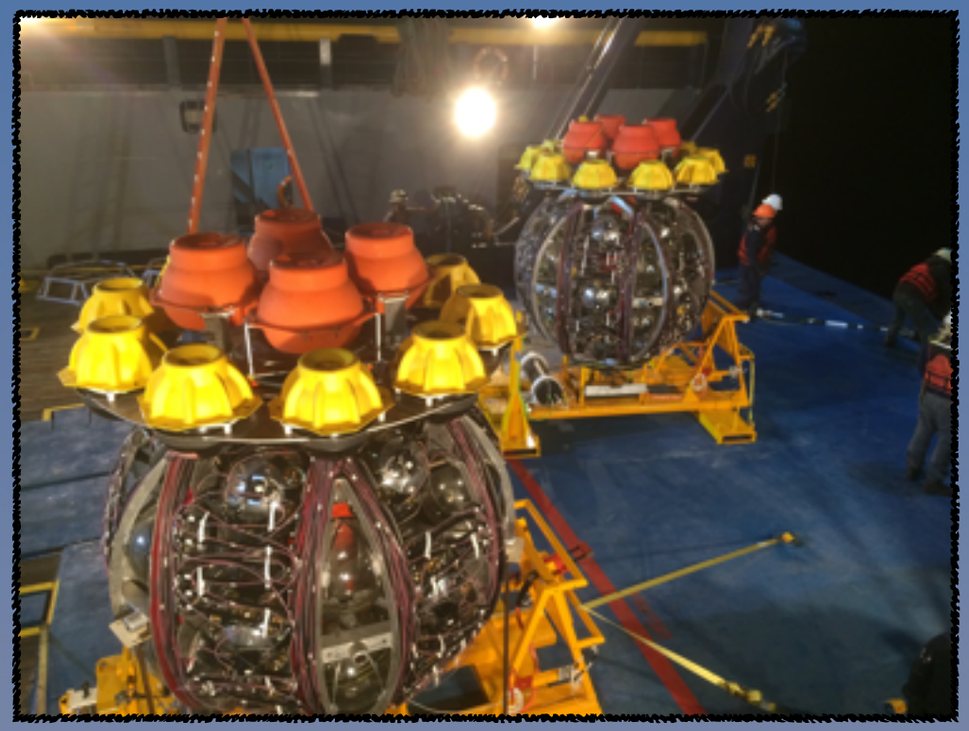
Not to scale!!!

- 18 DOMs/DU
- Anchor on sea bottom, buoy on top of DU keeps it upright
- Two Dyneema® ropes to connect DOMs mechanically
- Backbone cable : 2 copper conductors and 24 optical fibres (6 spares)
  - Break-out of 1 fiber and power at every DOM
- Base module with wavelength multiplexer at anchor
- Cable from anchor for connection to seafloor network

KM3NET CONSTRUCTION: DEPLOYMENT

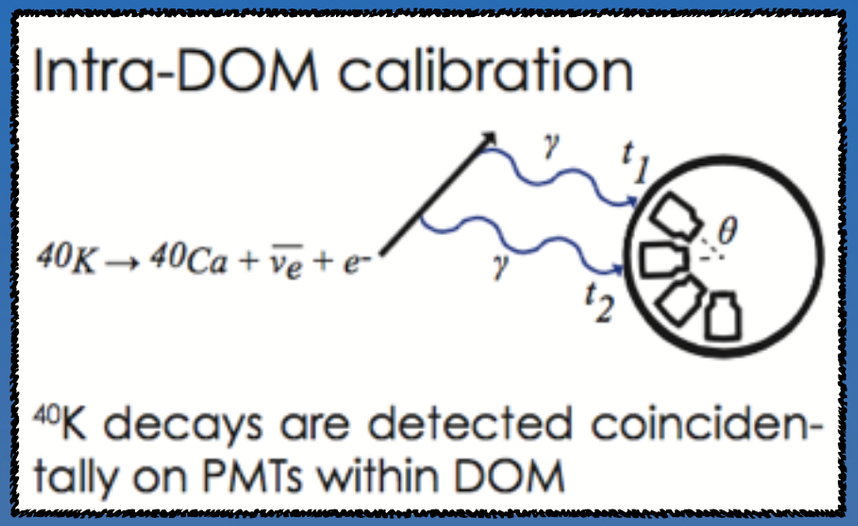


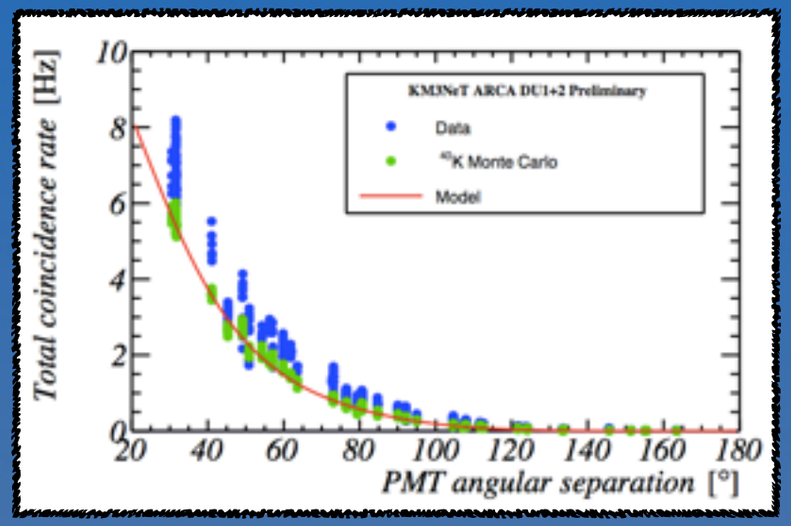


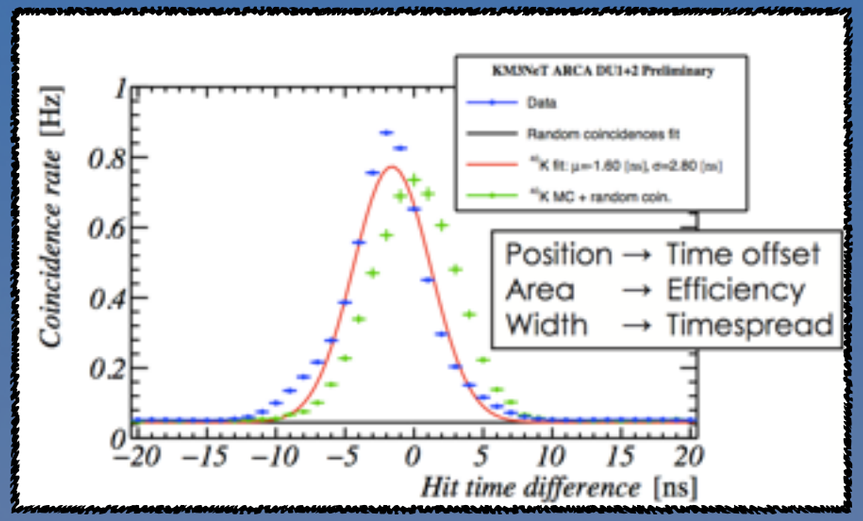


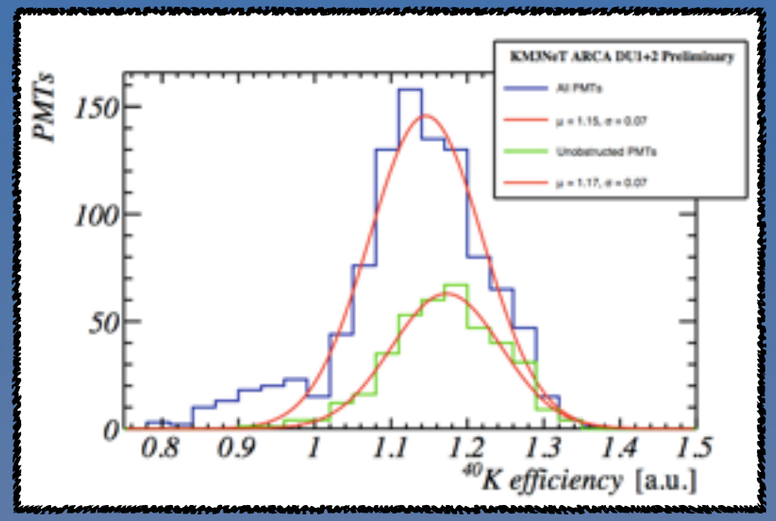
ORCA deployment movie:
www.youtube.com/watch?v=omLFKdCKbYk

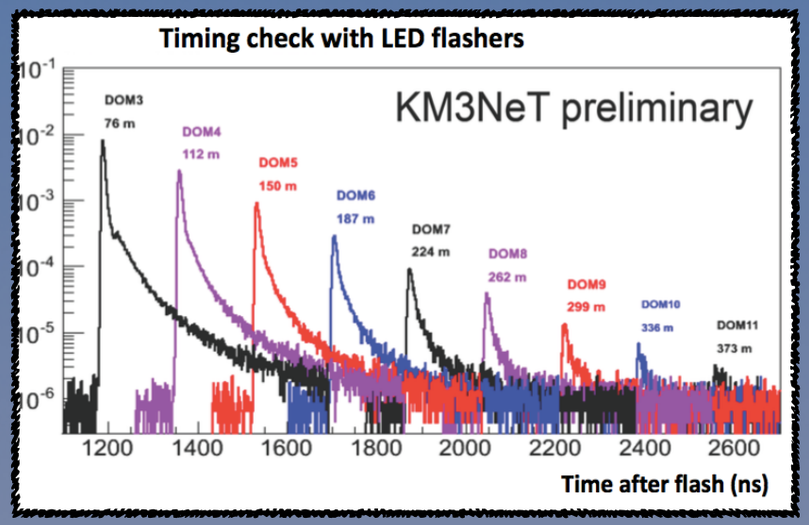
KM3NET FIRST RESULTS (1)

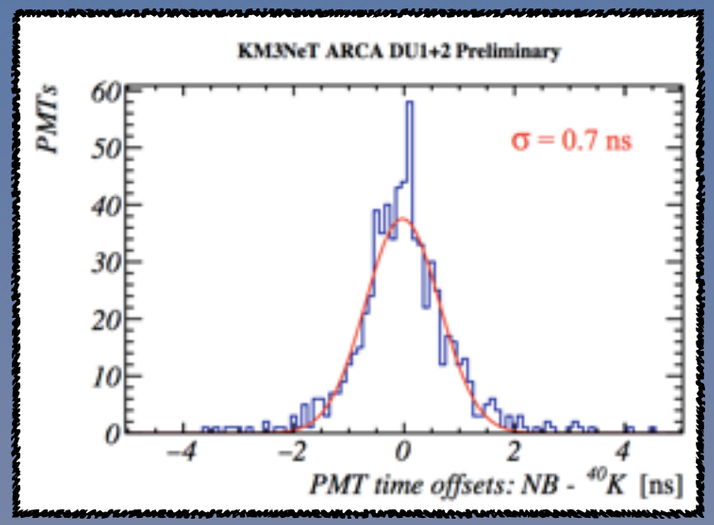




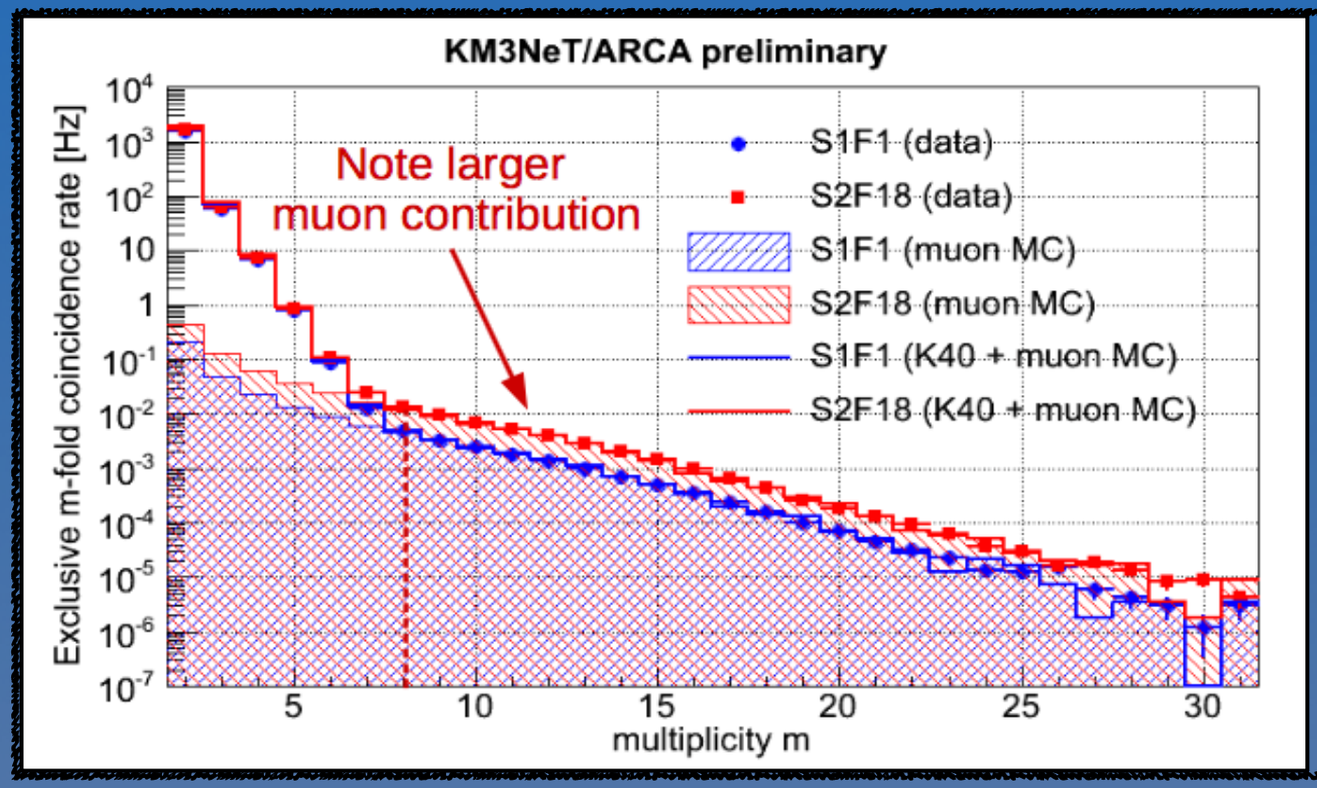


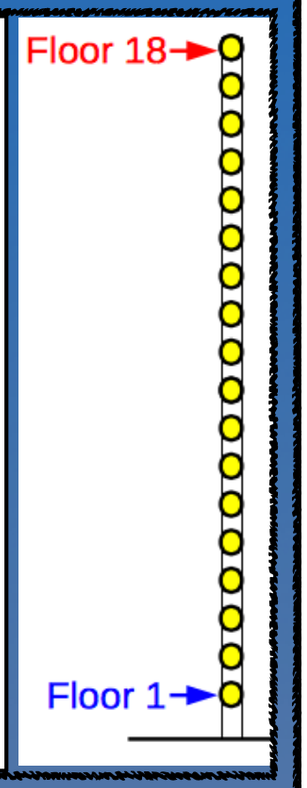


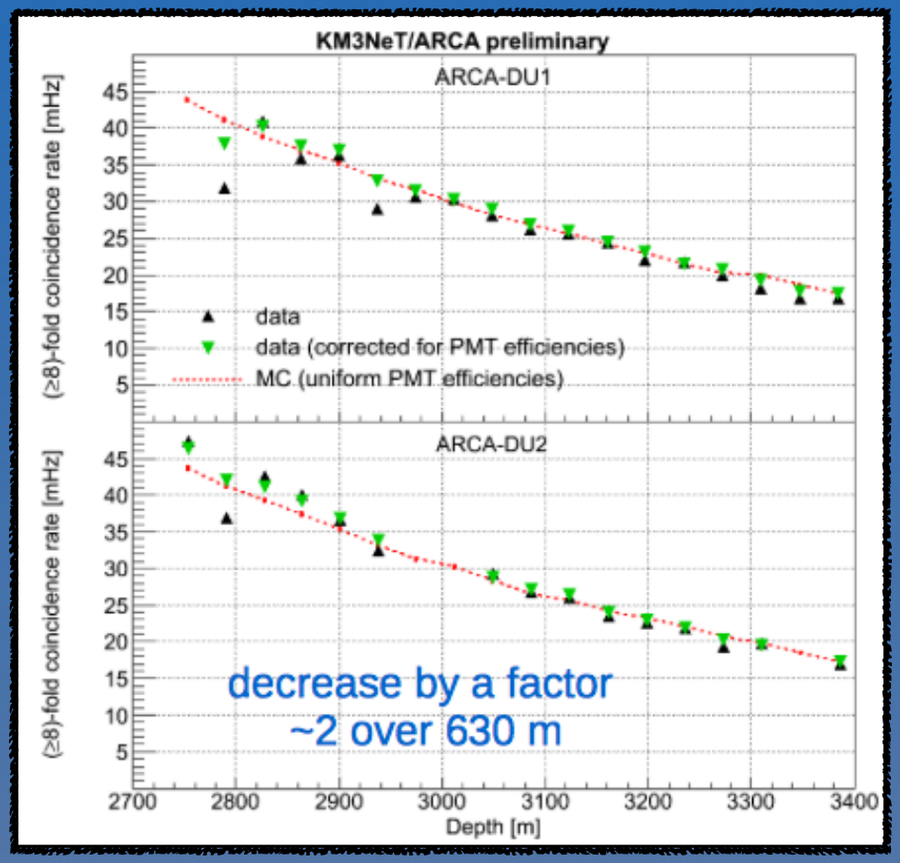




KM3NET FIRST RESULTS (2)







- Depth dependence of high-multiplicity rates measured with ARCA-DU1 and ARCA-DU2
- Excellent data/MC agreement
- In-situ measured PMT efficiencies improve data/MC agreement

KM3NET FUNDING

- KM3NeT Phase-1 fully funded and under construction:
  - 24 ARCA DUs
  - 6 ORCA DUs
- KM3NeT 2.0:
  - ARCA: 2 x 115 DUs by 2020 (1 block almost funded)
  - ORCA: 115 DUs by 2020 (half block funded)
  - On ESFRI roadmap (European Strategy Forum on Research Infrastructures)

KM3NET STATUS AND OUTLOOK

- One ORCA DU and two ARCA DUs have been taking data since their deployment
- Redesign of Italian sea floor network underway
- DOM and DU integration ongoing:
  - Additional 40 ORCA DUs by end of 2018
  - Additional 30 ARCA DUs by end of 2018
- Next DUs to be deployed will be of ORCA type

CONCLUSIONS

- KM3NeT is a next-generation neutrino telescope currently under construction in the Mediterranean deep-sea
- Novel multi-PMT concept implemented in optical modules
- Improved resolution due to water properties and detector technology, complementary field of view with respect to existing IceCube detector at South Pole
- ARCA:
  - Independent confirmation of IceCube high-energy astrophysical neutrino flux:
    - 5 sigma within one year after detector completion
  - More than order of magnitude improvement in Southern Hemisphere point source sensitivity
- ORCA:
  - Neutrino oscillation studies
  - Determination of NMH: three sigma in three years after detector completion
  - Better sensitivity possible depending on NMH and θ_{23} octant

BACKUP

BACKUP

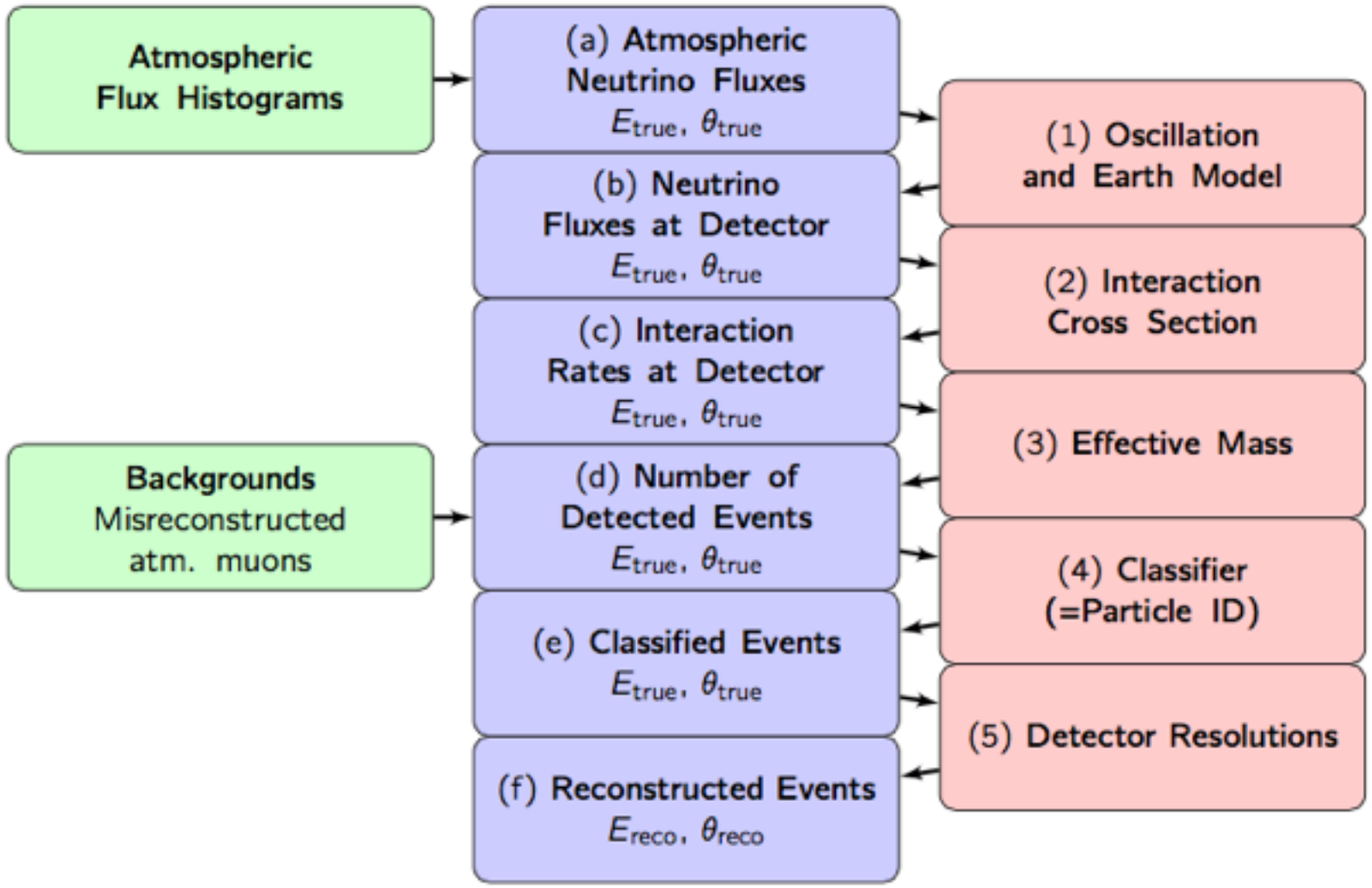
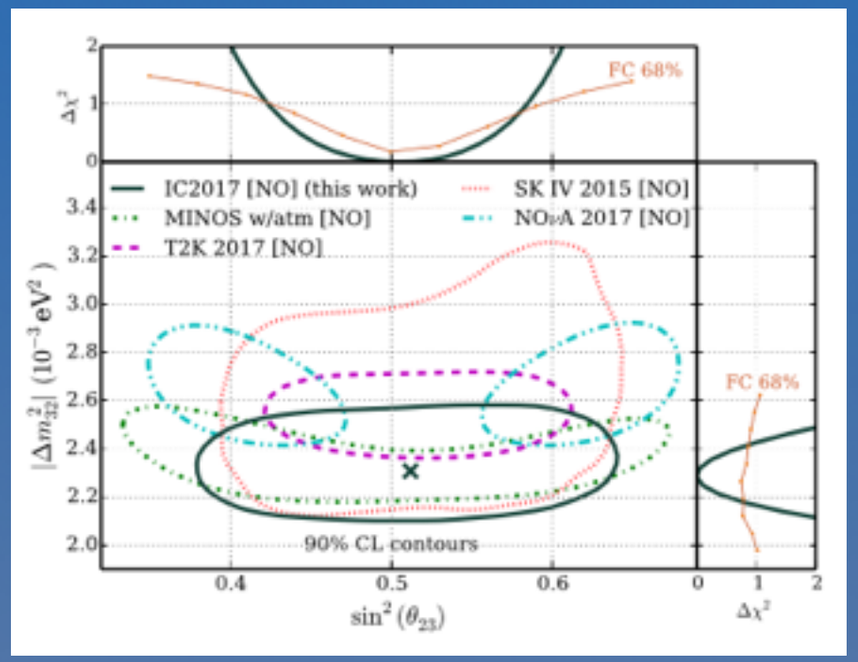


Figure 101: A flowchart showing the different steps in the computation chain. The blue blocks show the intermediate results consisting of sets of histograms as a function of the two variables written below the title. The red blocks describe the steps to go from one intermediate result to the next. The green blocks describe additional inputs that do not use the result from the previous step.



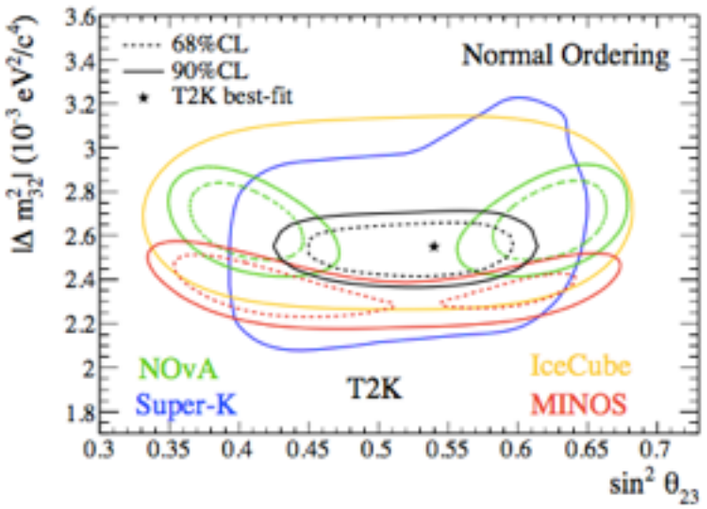


FIG. 40. Allowed region at 90% confidence level for oscillation parameters $\sin^2\theta_{23}$ and Δm^2_{32} using T2K data with the reactor constraint ($\sin^2(2\theta_{13}) = 0.085 \pm 0.005$). The normal mass ordering is assumed and the T2K results are compared with NOνA [86], MINOS [87], Super-K [88], and IceCube [89].

- From IceCube 2017 numu disappearance
- From T2K update article

indicated by the step function. The discovery potential shows a strong variation with declination. In the up-going region ($\delta \geq -5°$), atmospheric muon background is efficiently removed and a large effective area with good angular resolution is achieved above TeV energies, compare Fig. 1 and Fig. 2. This yields a discovery potential reaching from TeV to EeV energies at the horizon ($\delta = 0°$, blue). For vertically up-going events ($\delta = 60°$, red), neutrinos at energies above 100 TeV begin to be absorbed in the Earth, hence reducing the discovery potential compared to the horizon.

In the down-going region (southern sky, $\delta < -5°$), large backgrounds of atmospheric muons result in a higher energy threshold of ~ 100 TeV. Moreover, muon bundles imitate single muons at very high energies resulting in a high energy background. This diminishes the performance compared to the northern sky. At

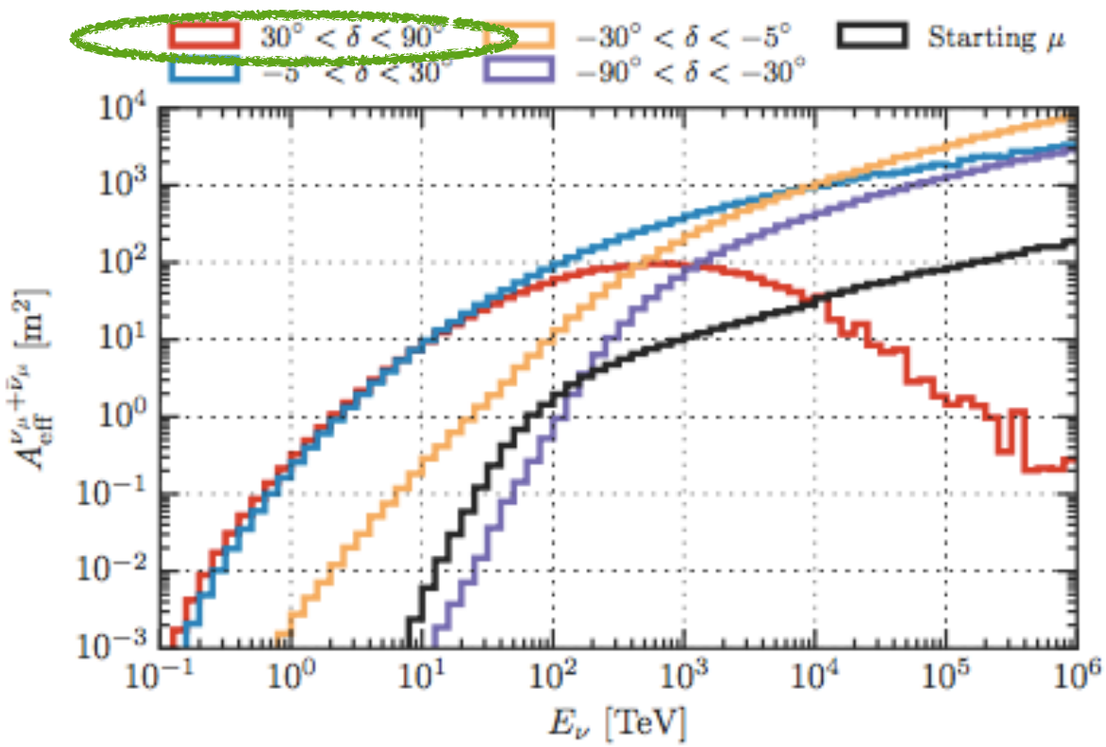


Figure 1. IceCube effective area as defined in Eq. 1 versus neutrino energy for a flux of $\nu_\mu + \bar{\nu}_\mu$ calculated using simulation of neutrino events for the selection of IC86 (seasons 2012-2015) described in Section 2.2. The effective area for through-going muons is averaged over the solid angle in the declination range (δ) indicated in the legend. Additionally, the effective area for starting tracks in the southern sky ($\delta < -5°$) is shown in black (cf. Section 2.3).

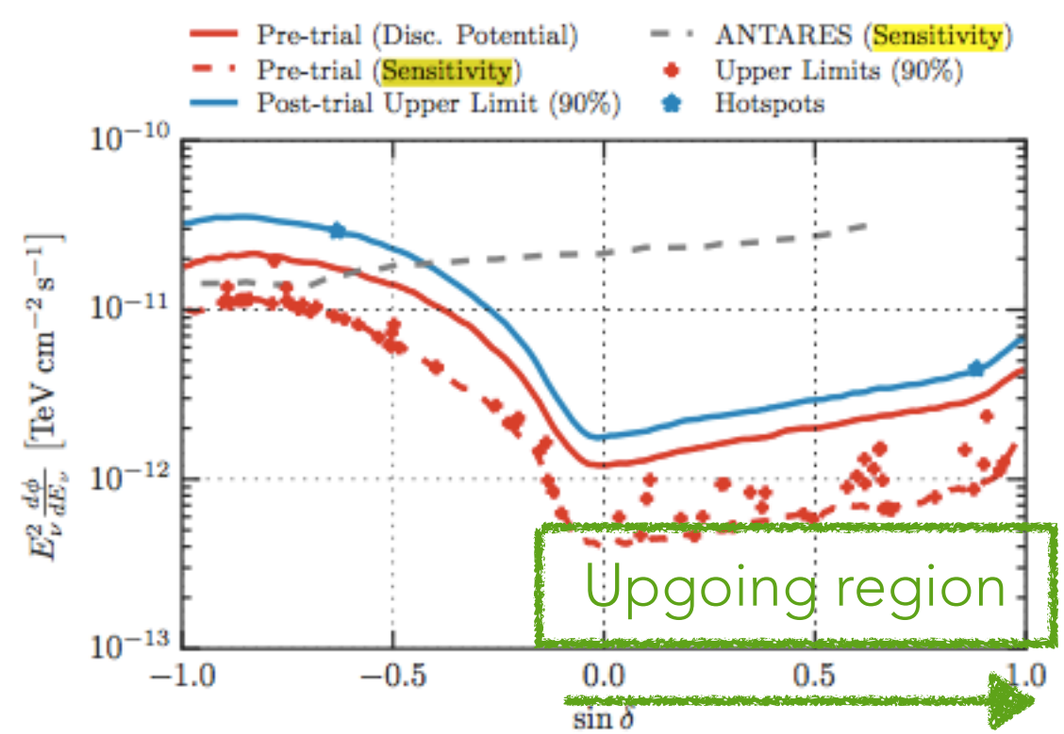


Figure 8. Discovery potential (5σ, solid red) and sensitivity (dashed red) for a $\nu_\mu + \bar{\nu}_\mu$ unbroken $E_\nu^2 d\phi/dE_\nu$ flux shown against declination δ. The gray line shows the results of (Adrian-Martinez et al. 2014) in the south. Upper limits of source candidates in Tab. 2 and Tab. 3 are depicted by red crosses. The blue line represents the upper limit for the observed most significant spots in each half of the sky for all declinations, the actual declination position of the spots is indicated by a star.