ORCA - ν Oscillation Research with Cosmics in the Abyss within KM3NeT: a feasibility study

Piera Sapienza

What Next - Neutrino Oscillations

Padua, 1-2 December 2014

Outline

- Introduction
- Aim of the experiment
- Detector design and technology
- Preliminary telescope performances
- Very preliminary results on sensitivity
- Conclusions and perspectives

An update on KM3NeT strategy

- Multi-site experiment
  - High Energy ν astronomy - offshore Capo Passero
  - ORCA Neutrino Mass Hierarchy - offshore Toulon

- KM3NeT Phase 1 -> funded (mainly PON 20.8 M€ + Nikhef)
  - 8 towers + 24 strings to be installed off-shore Capo Passero in 2015-2016
  - 6 strings for ORCA feasibility study off-shore Toulon ->2016

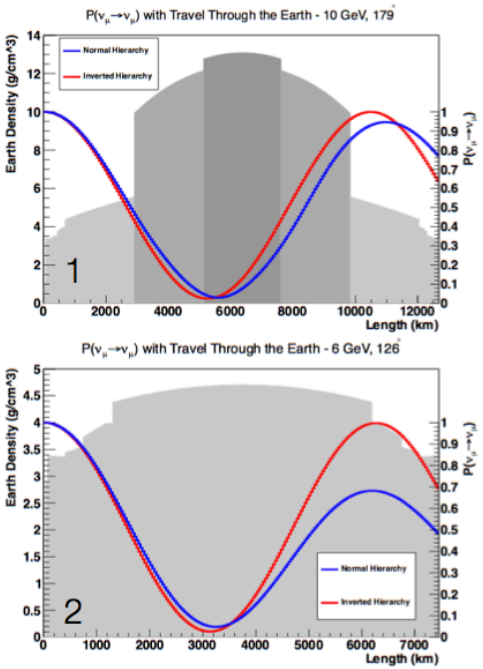
- KM3NeT Phase 1.5 -> not funded, application for a new ESFRI proposal
  - Neutrino Astronomy: two blocks of 115 strings (1-1.6 Gton) LoI to be released in January 2015 see R. Coniglione talk
  - ORCA: one block of 115 strings i.e. about 4 Mton - LoI in preparation to be released at beginning 2015

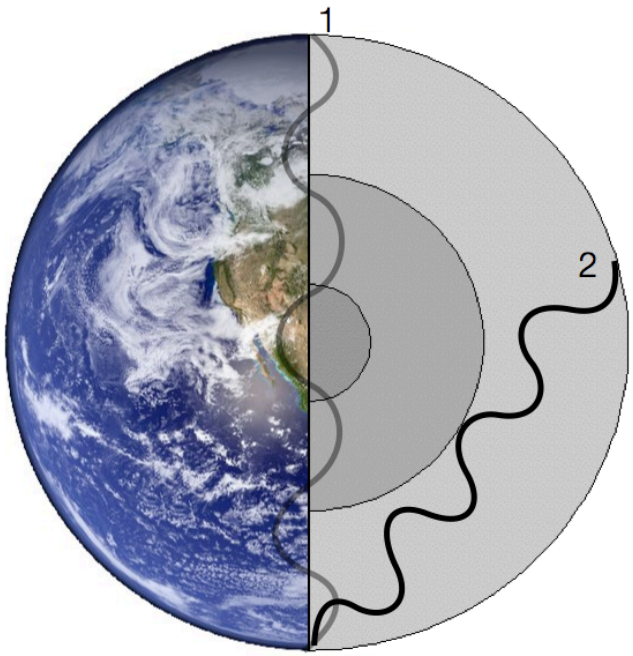
The experimental concept

- Measure of the Neutrino Mass Hierarchy (NMH) with atmospheric neutrinos in a Mton scale ice/deep sea Cherenkov detector at GeV energy
- PINGU in IceCube proposed at Neutrino 2012
- MSW effect on up-going neutrinos passing through Earth modify oscillation pattern allowing to disentangle NMH sign
- Exploit ν_μ, ν_e oscillations in atmospheric up-going events

Measurement of the Neutrino Mass Hierarchy with upgoing atmospheric ν in deep ice/sea

- Broad range of baselines and energies
- Oscillation signal enhanced at resonance energy in matter (about 3 GeV in core, 7 GeV in mantle)





$$P_{e\to\mu} \approx P_{\mu\to e} \approx \sin^2\theta_{23}\sin^2(2\theta_{13}^{\text{eff}})\sin^2\left(\frac{\Delta_{13}^{\text{eff}}L}{2}\right)$$

$$\Delta_{13} = \frac{\Delta m^2_{13}}{2E_\nu} \qquad \sin^2(2\theta_{13}^{\text{eff}}) = \frac{\Delta^2_{13}\sin^2(2\theta_{13})}{\Delta_{13}^{\text{eff}}L}$$

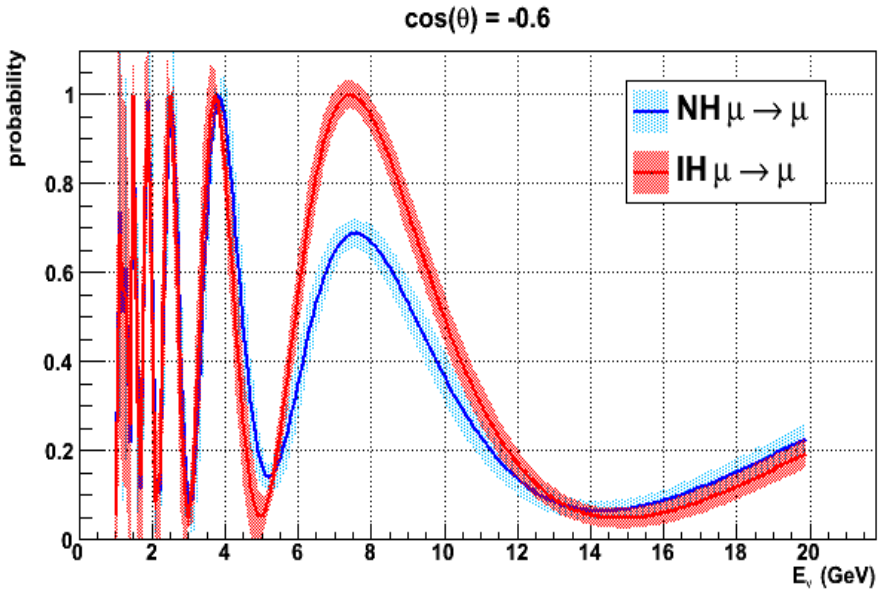
$$\Delta_{13}^{\text{eff}} = \sqrt{[\Delta_{13}\cos(2\theta_{13}) - A]^2 + \Delta^2_{13}\sin^2(2\theta_{13})}$$

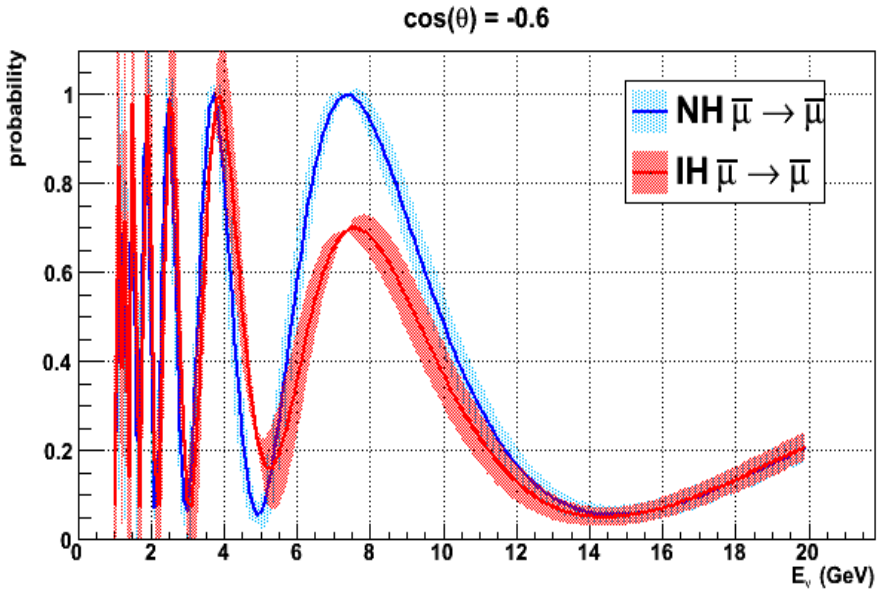
$A = \sqrt{2}G_F N_e$ for ν and $A = -\sqrt{2}G_F N_e$ for $\bar{\nu}$

$$E_\nu^{\text{res}} = \pm\frac{\Delta m^2_{13}\cos(2\theta_{13})}{2\sqrt{2}G_F N_e}$$

ν_μ oscillation probability

L = 7645 m





neutrinos and anti-neutrinos have opposite behaviour and contributions will cancel if summed, but …

- different cross section
- different flux

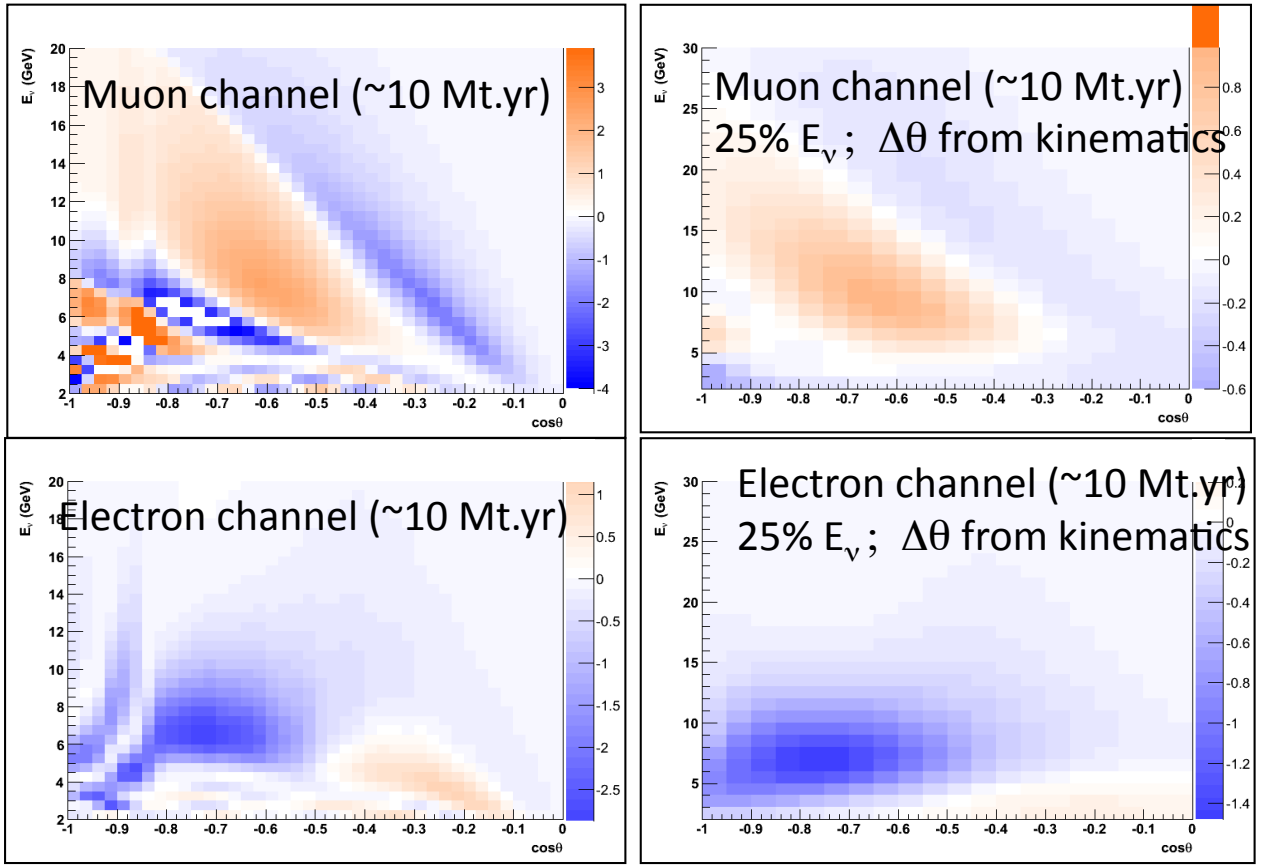
Very challenging experiments

- Relatively low statistics for energy above 2-3 GeV
- Presence of both neutrinos and anti-neutrinos in the atmospheric flux
  - no magnetic field
  - speculation about experimental access to inelasticity in order to disentangle between neutrinos and anti-neutrinos (to be checked…)
- Flavour (mis) identification
- Neutral current vs charge current cascade events
- Smearing of signal over energies and zenith angles due to experimental resolutions
- Uncertainties due to poor knowledge of
  - neutrino cross sections
  - flux and shape of atmospheric neutrino spectra
  - neutrino properties (octant, precisions on parameters, …)
  - Earth properties
  - …

Oscillation pattern and sensitivity in the muon and electron channel

- Sensitivity and detector resolution effects:

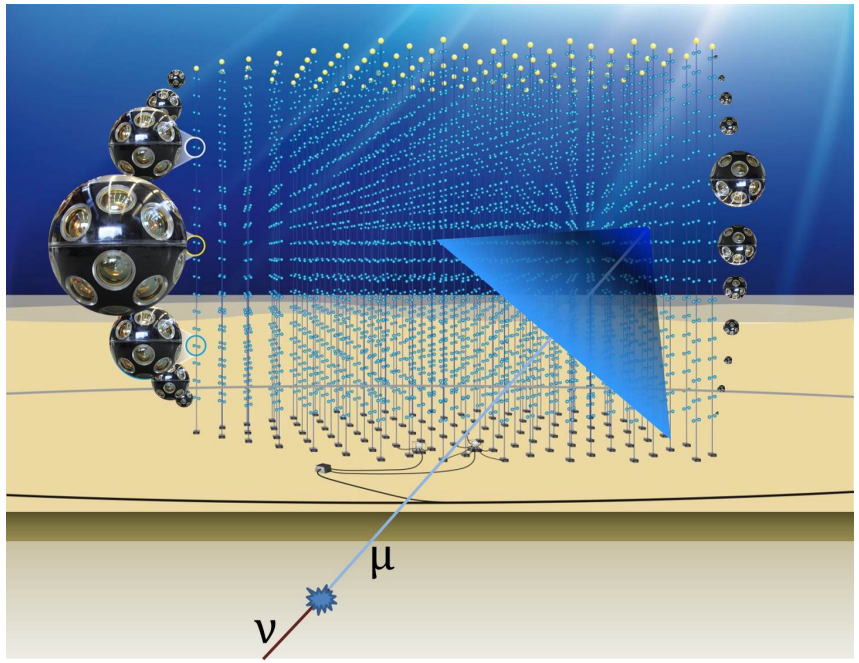
$(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$ $(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$



- Maximum sensitivity between 5 GeV and 10 GeV
- Electron channel more robust

KM3NeT experimental technique and detector design

Detection principle => measure optical Cherenkov radiation produced by energetic charged particle interactions in deep sea water λ_{abs} 50-70m, λ_{scatt} > 100 m



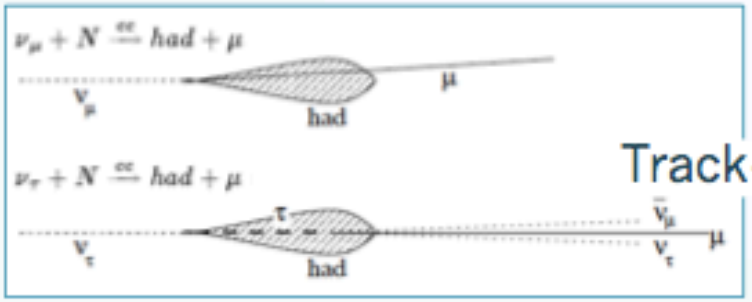
Detection units (DU) – vertical slender string with multi-PMT digital optical modules (DOMs)

Detector made of building blocks with 115 DUs

Seafloor network provide data and power distribution

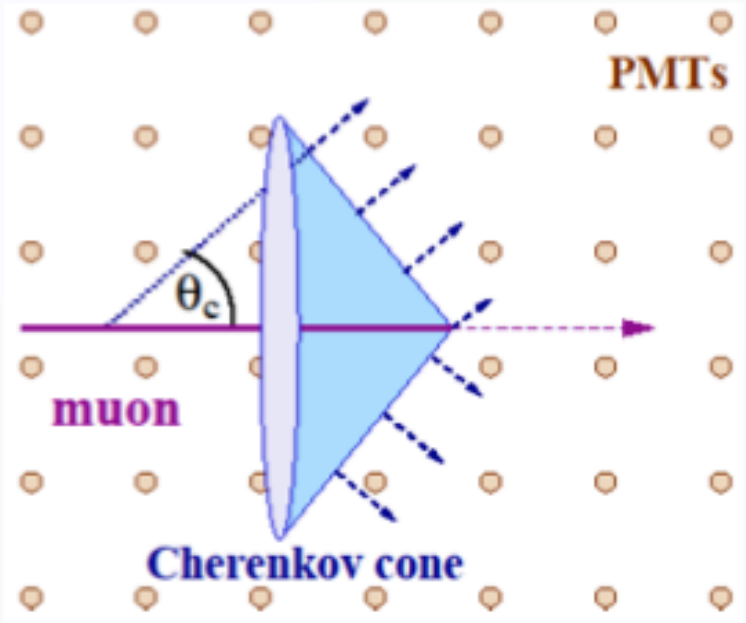
All-data-to-shore concept

Event topologies

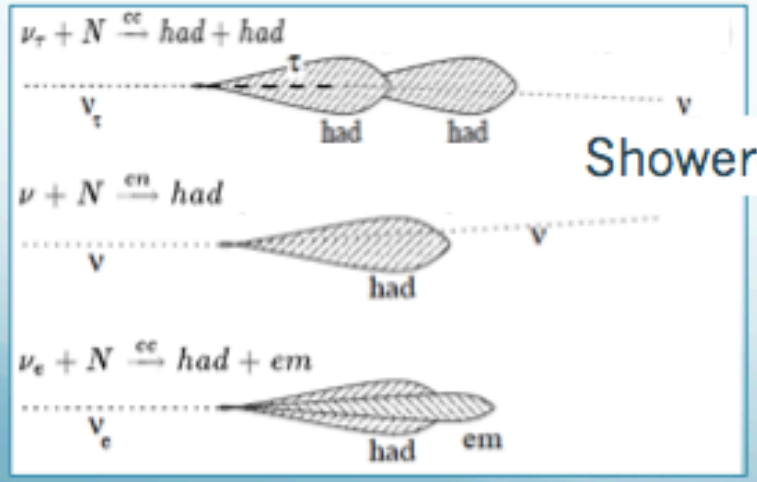


Track-like

Track-like contains both a cascade and one track

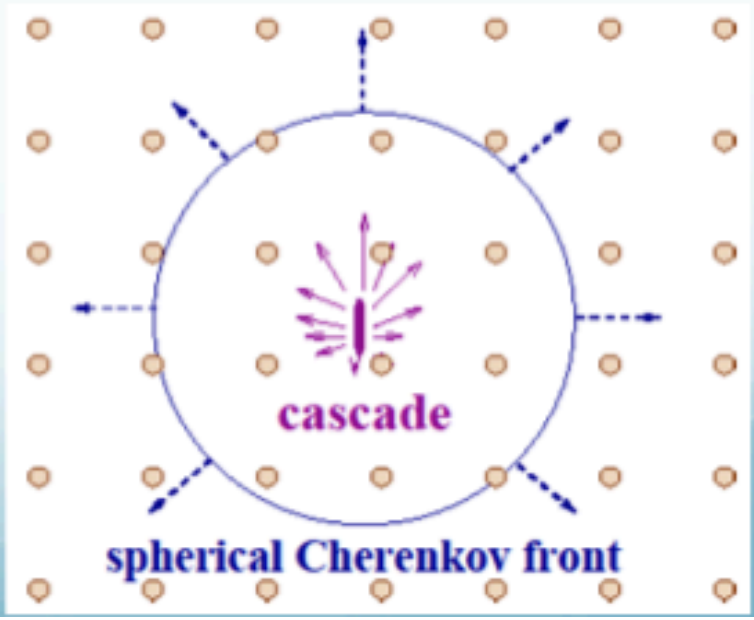


Not to scale



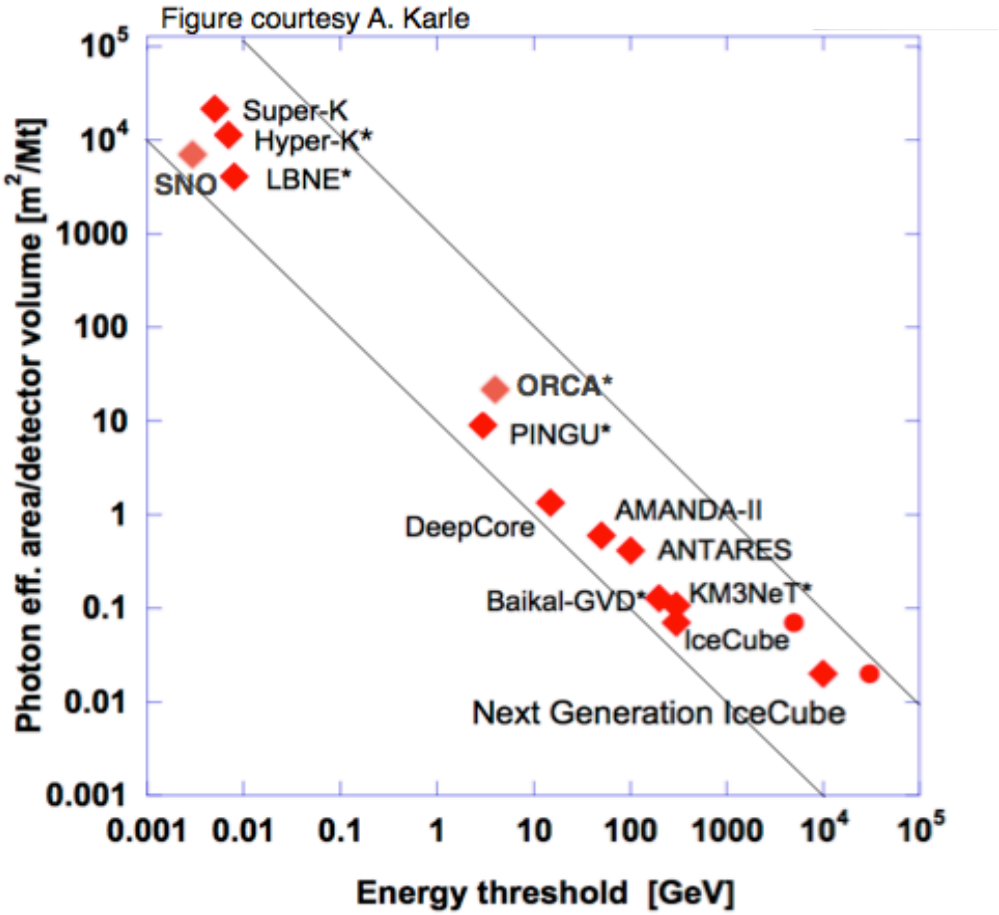
Shower-like

No track is identified



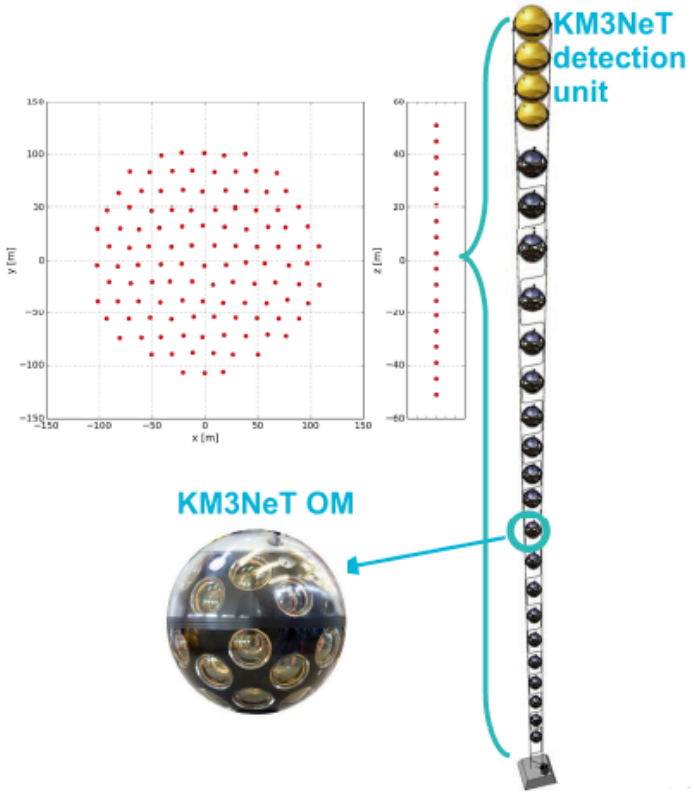
Detector “granularity”

The detection threshold decreases with increasing photocathode area density



ORCA NMH vs KM3NeT HE ν astronomy

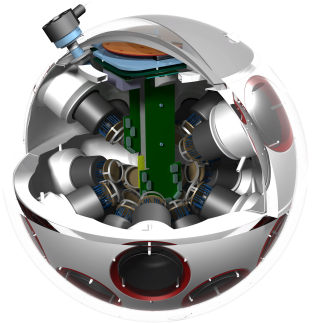
- ORCA is part of the KM3NeT research infrastructure
  - A different detector with same technology
  - From 0.1 TeV to few GeV signals => more compact detector



- 115 detection units, 20 m instead of 90-120 m spacing
- 18 Optical Modules (DOMs) per detection unit
- 6 m instead of 36 m vertical distance between DOMs
- 31 3” PMTs/DOM
- Instrumented volume Mton instead of Gton scale
- Estimated cost 40 M€ (conservative)
- Geometry optimisation study ongoing

KM3NeT Optical Module

- Segmented cathode area 31 x 3”PMTs equivalent to 3 Antares/IceCube OM => optical background rejection, directionality
- Instrumentation inside DOM (LED & piezo, compass and tiltmeter)
- Several providers for PMTs



ETEL D792

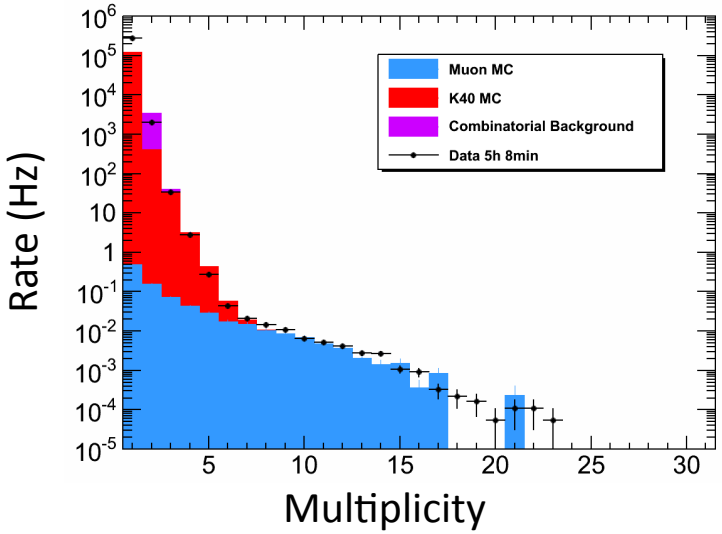
Hamamatsu R12199

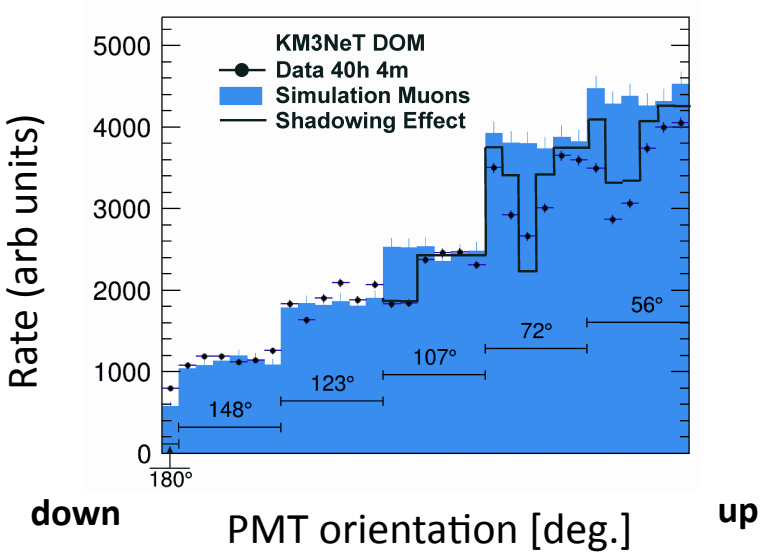
HZC XP53B20

Detector validation: Optical Module Prototype

- KM3Net-Fr @ ANTARES:
  - First DOM prototype
  - Deployed April 2013
  - Operational since then

Article accepted for publication in EPJ
http://arxiv.org/abs/1405.0839





✓ photon counting

✓ directionality

KM3NeT detection unit

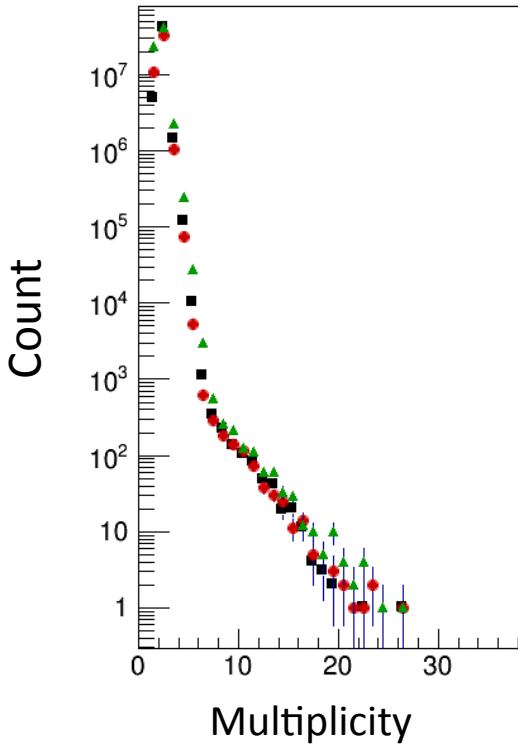
- String with 18 optical full
- Mechanical support made of two dynema ropes
- Backbone: electro-optical cable with 2 copper conductors and 18 fibers + spares
- Break out of cable at each optical module
- Base module with DWDM at anchor
- Jumper for connection to the seafloor network

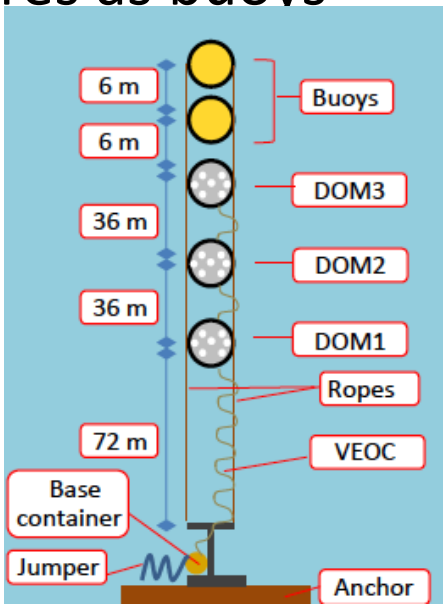
DU - Deployment concept

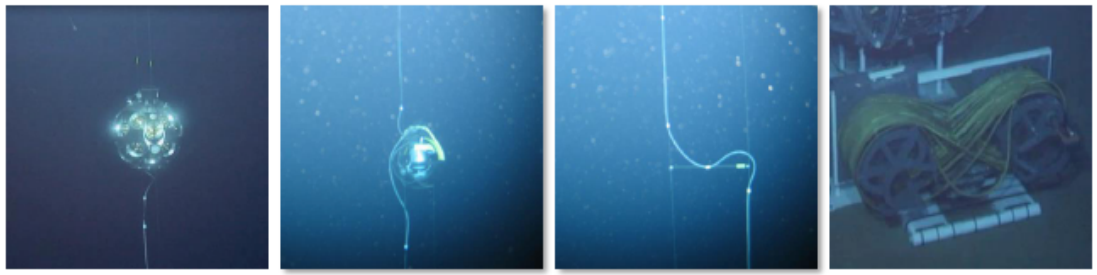
- Deployment of compact structure and unfurling from sea bottom => safe and successful
- Use of the same LOM for ORCA understudy

Detector validation: String Prototype

- KM3Net-It @ Capo Passero 3500 m depth
  - String made of 3 optical modules and two spheres as buoys
  - Deployed and connected May 2014
  - Operational since then





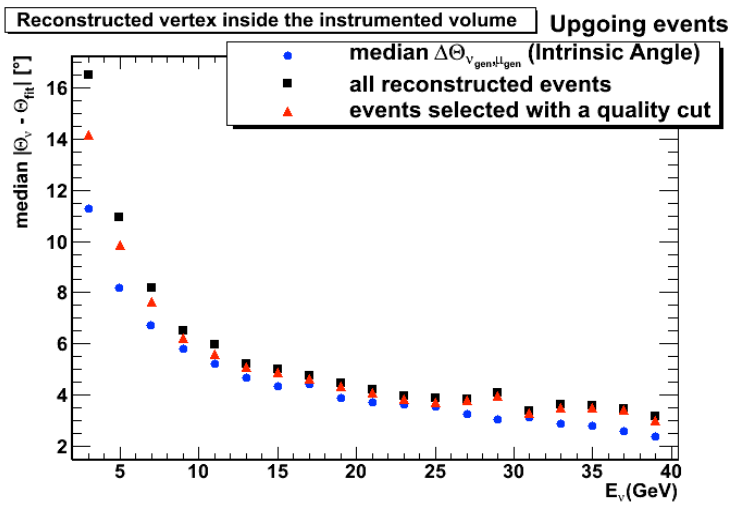


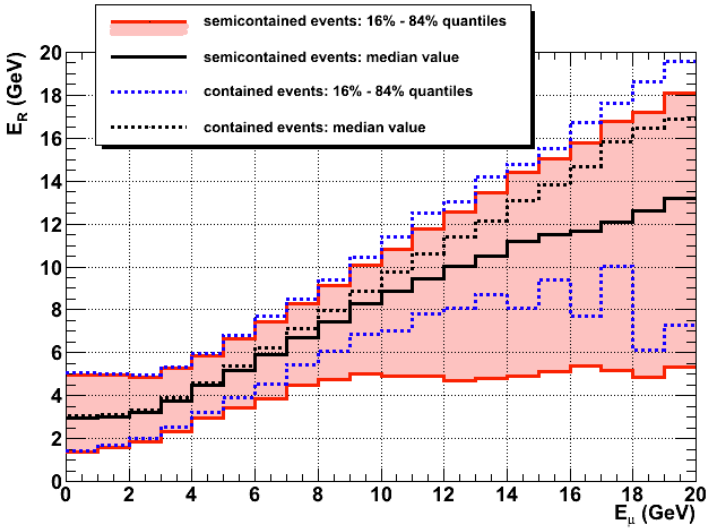
ORCA performances

- Work in progress
- This presentation is based on official results estimated for a reference 50 strings detector scaled for 115
- Sensitivity calculations on final detector ongoing, results (seem promising) will be reported in the ORCA LoI at the beginning of 2015

ORCA resolution: μ channel - preliminary

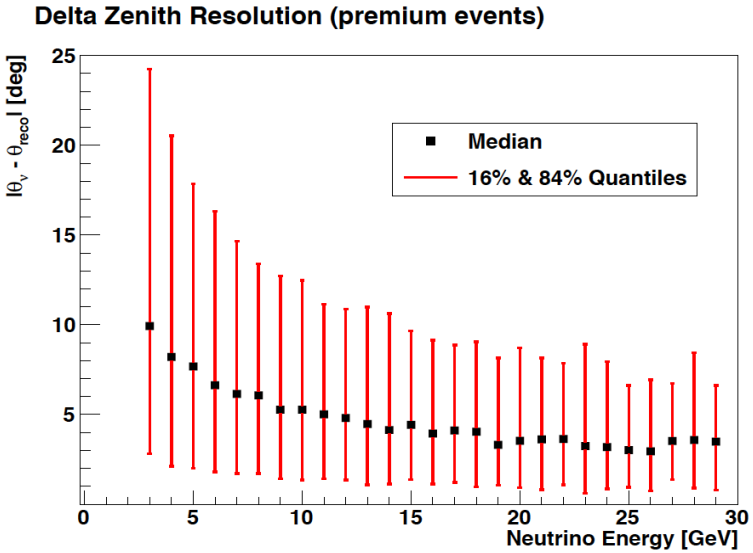
- Results obtained with the “reference detector”: 50 strings, 20 DOM, 20 m spaced, 6 m spacing between DOMs
- Resolutions on ν_μ CC events with $E_\nu > 5$ GeV:
  - Zenith angle resolution: about 5° in the 5-10 GeV energy range
  - Track length as energy estimator, hadronic shower at vertex not included => Energy resolution: better than 35% (expected improvement => around 25%)

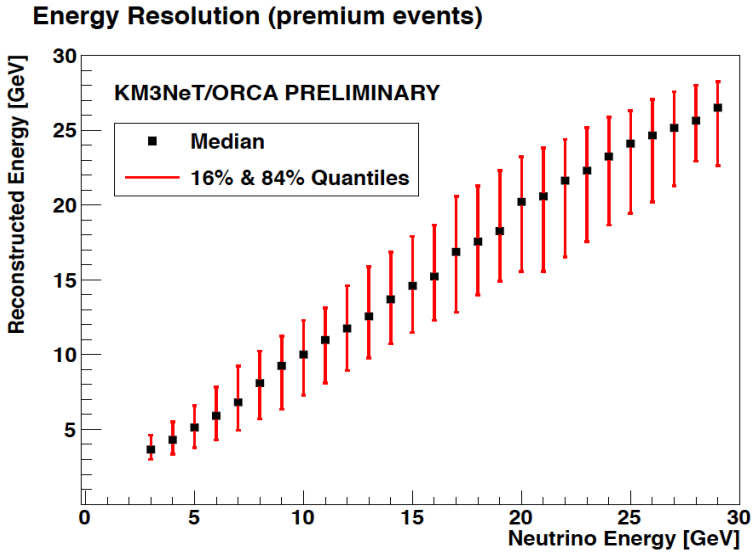




ORCA resolution: e channel - preliminary

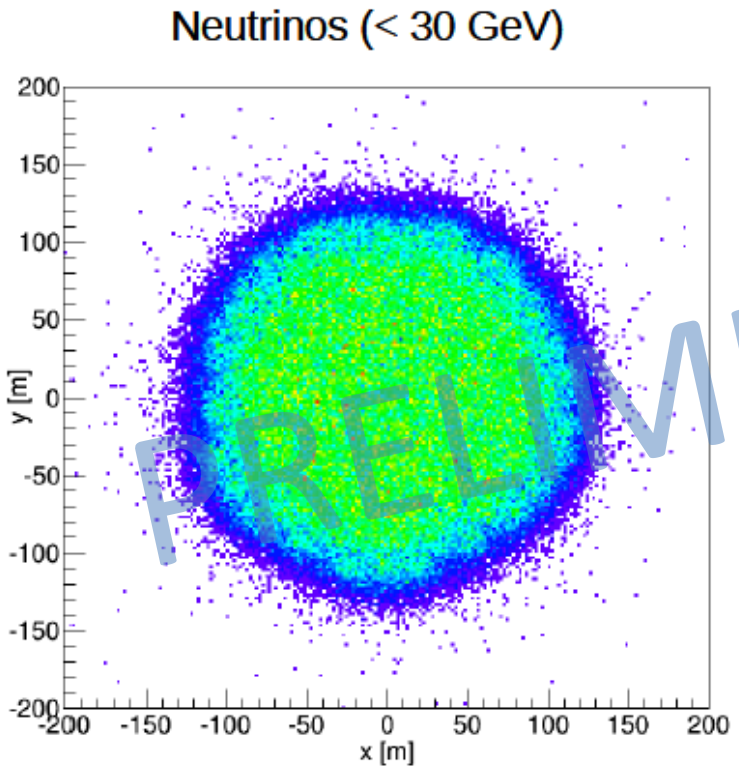
- Results obtained with the reference detector: 50 strings, 20 DOM, 20 m spaced, 6 m spacing between DOMs
- Selection of golden events
- Resolutions on ν_e CC events with $E_\nu > 5$ GeV:
  - Zenith angle resolution: better than 10^o (expected improvement => around 5%)
  - Energy resolution: better than 30% (expected improvement => around 20%)

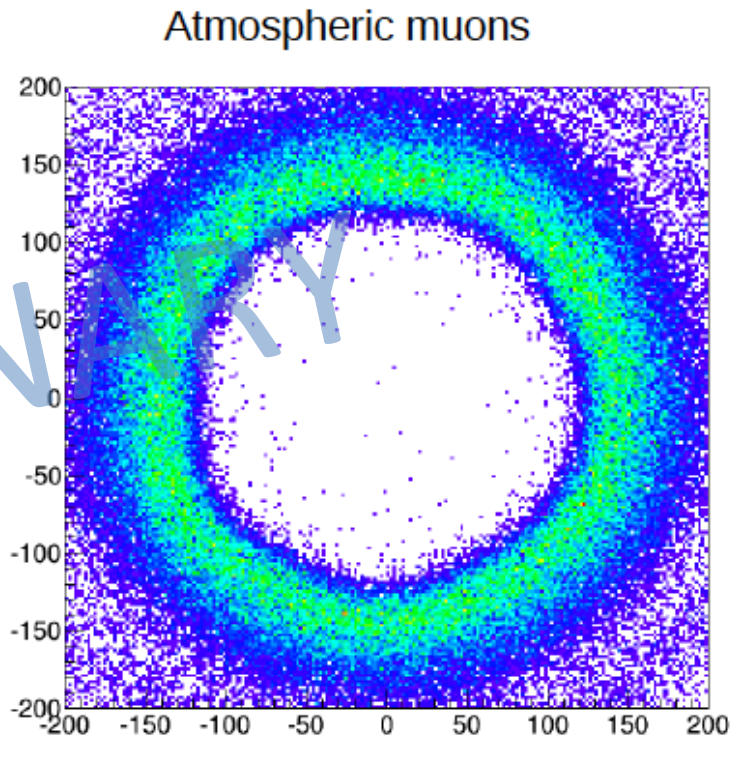




Atmospheric muon rejection

Cut on the reconstructed pseudo-vertex and quality parameters of reconstruction





Boosted Decision Tree

reconstruction quality,
vertex distance to center

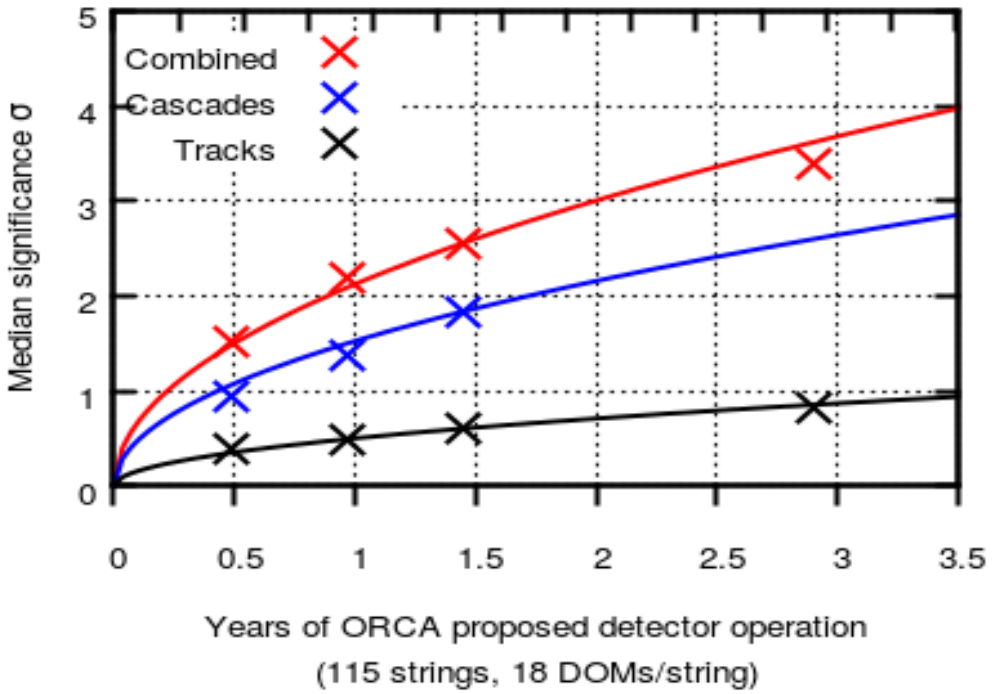
Instrumental veto is not mandatory
(though not impossible)

Few % contamination achievable without strong signal loss

Room for improvement

ORCA Sensitivity - Very Preliminary!!!

- Goal: Neutrino Mass Hierarchy determined at 3σ level after about 3 years of data taking
- Fit on oscillation parameters, 1° octant assumed for θ_{23}
- State of art E-θ resolution included
- Channel misindentification tracks vs cascades included, but not optimal



Current ORCA Sensitivity

Pros & expected improvements

- Full correlations of osc. parameters
  (uncertainties will reduce in future)
- Most influential parameters fitted
- Improvement in the muon channel for energy due to inclusion of hadronic shower and larger detector (50 -> 115 strings)
- Add reconstructed inelasticity (y)
- Try statistical separation of neutrinos from anti-neutrinos
- Geometry optimisation

Cons & expected degradations

The sensitivity study does not yet account for:

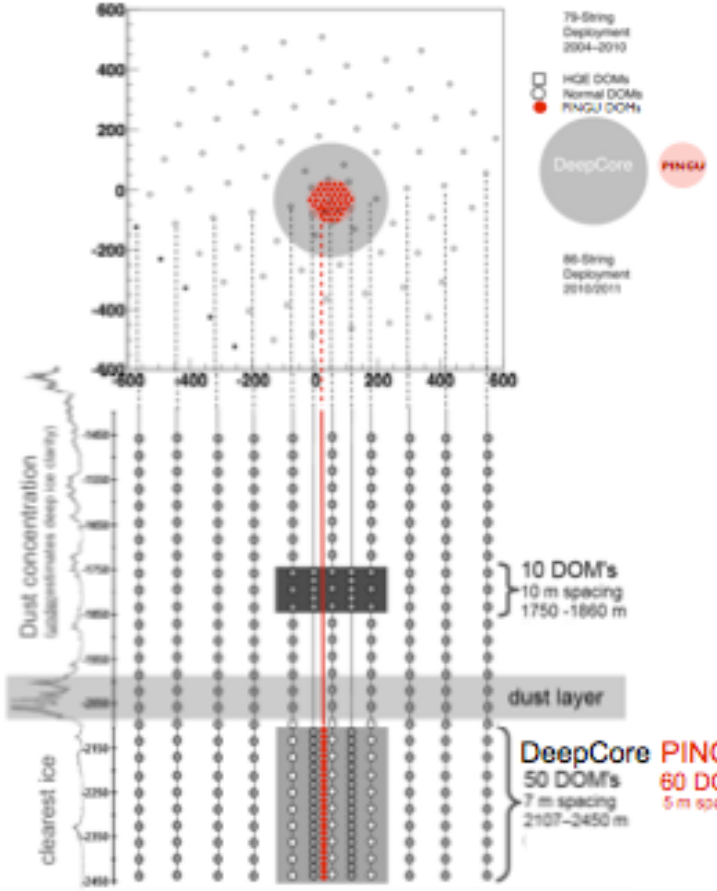
- The overall flux normalization
- Neutral Currents and tau neutrinos
- Atmospheric muon background
- Other systematics
  - Flux polarity uncertainties
  - Flux flavour uncertainties
  - Cross sections
  - Energy scale
  - Exposure
  - Acceptance
  - …

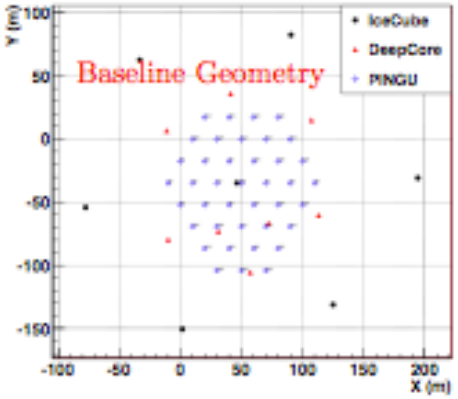
Work in progress

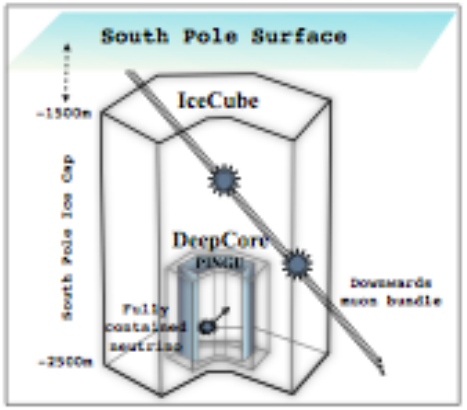
Comparison ORCA-PINGU

- Direct comparison not straight forward, different methods and ingredients
- A very accurate work in progress with a common work in the two collaboration, final results expected soon

PINGU inside IceCube

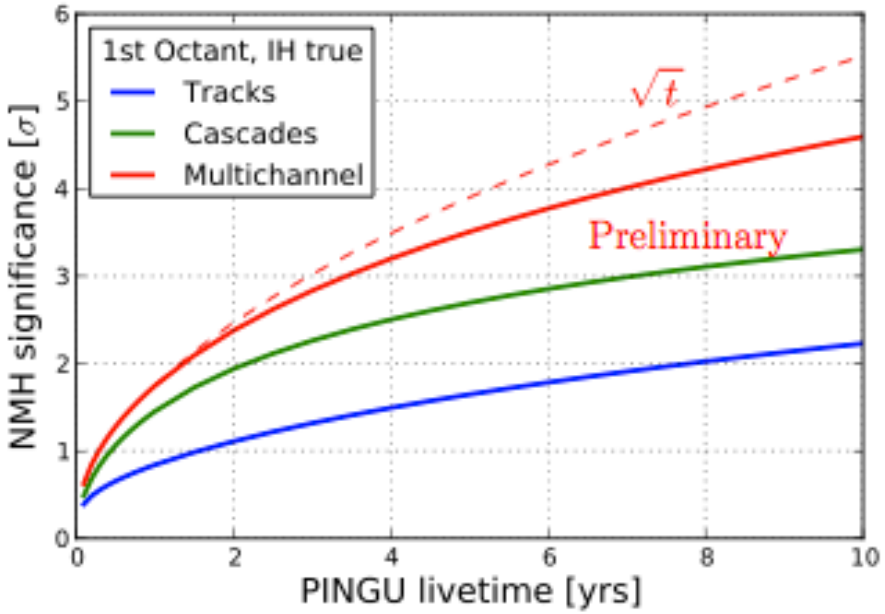






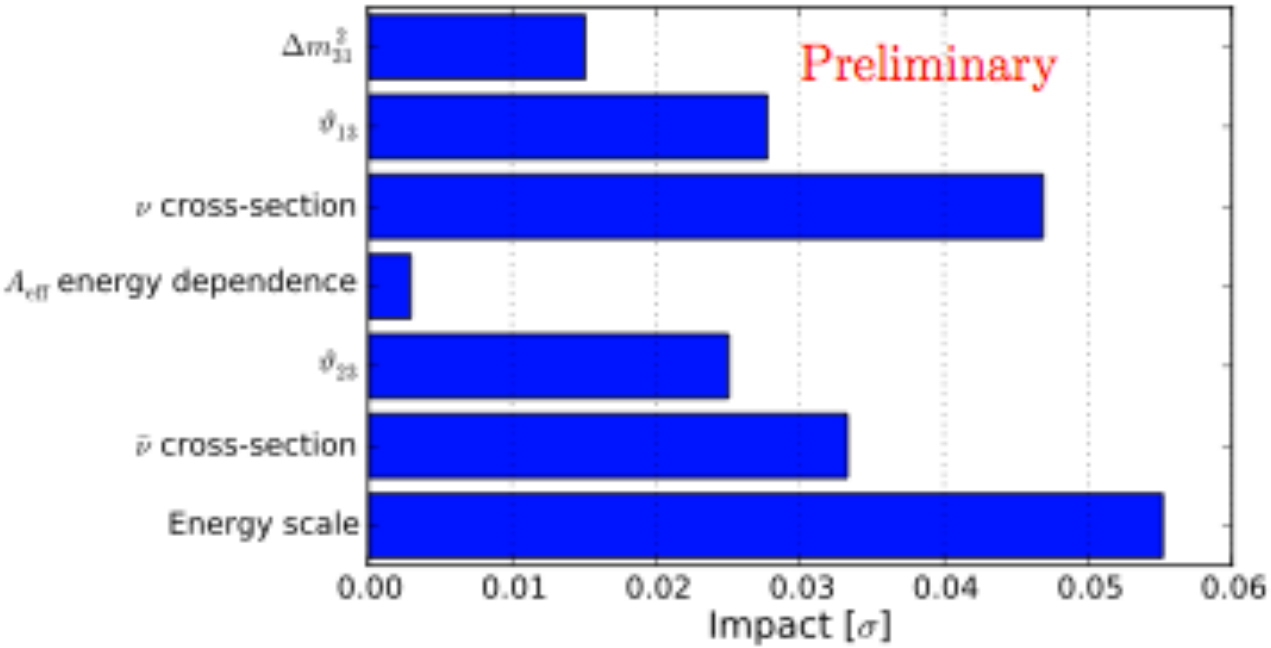
PINGU significance for NMH

- 3σ in less than 4 years



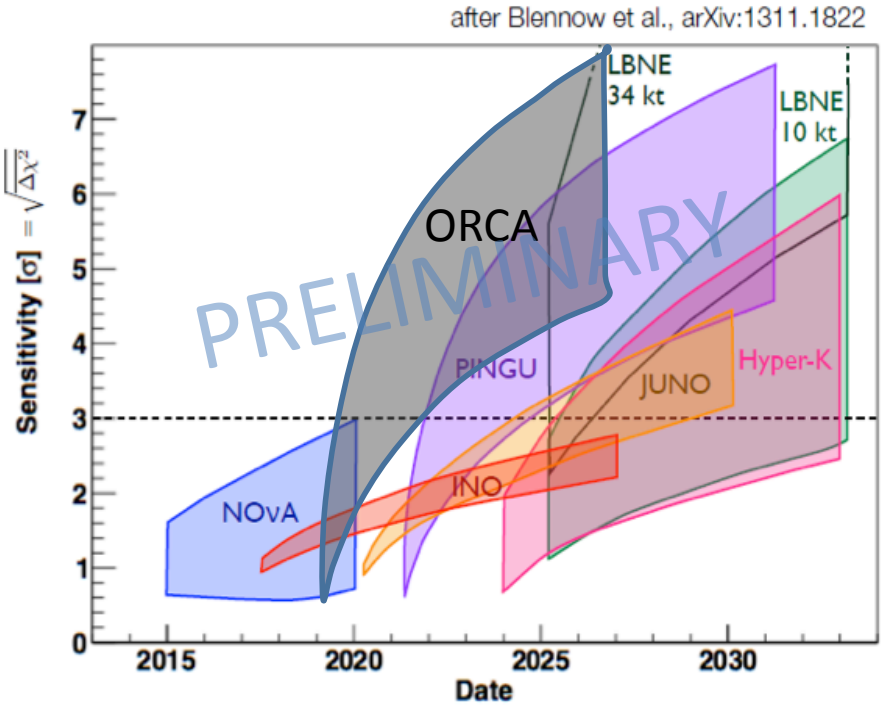
Systematic uncertainties

- Estimates by PINGU collaboration



Sensitivity of NMH experiments

- We wouldn't like to show this plot, but other people do….



Conclusions and perspectives

- ORCA enforces the KM3NeT case extending the physics case to low energy
  - focus on Neutrino Mass Hierarchy, but also Dark Matter, SuperNova neutrinos, etc could be promising even if not investigated yet

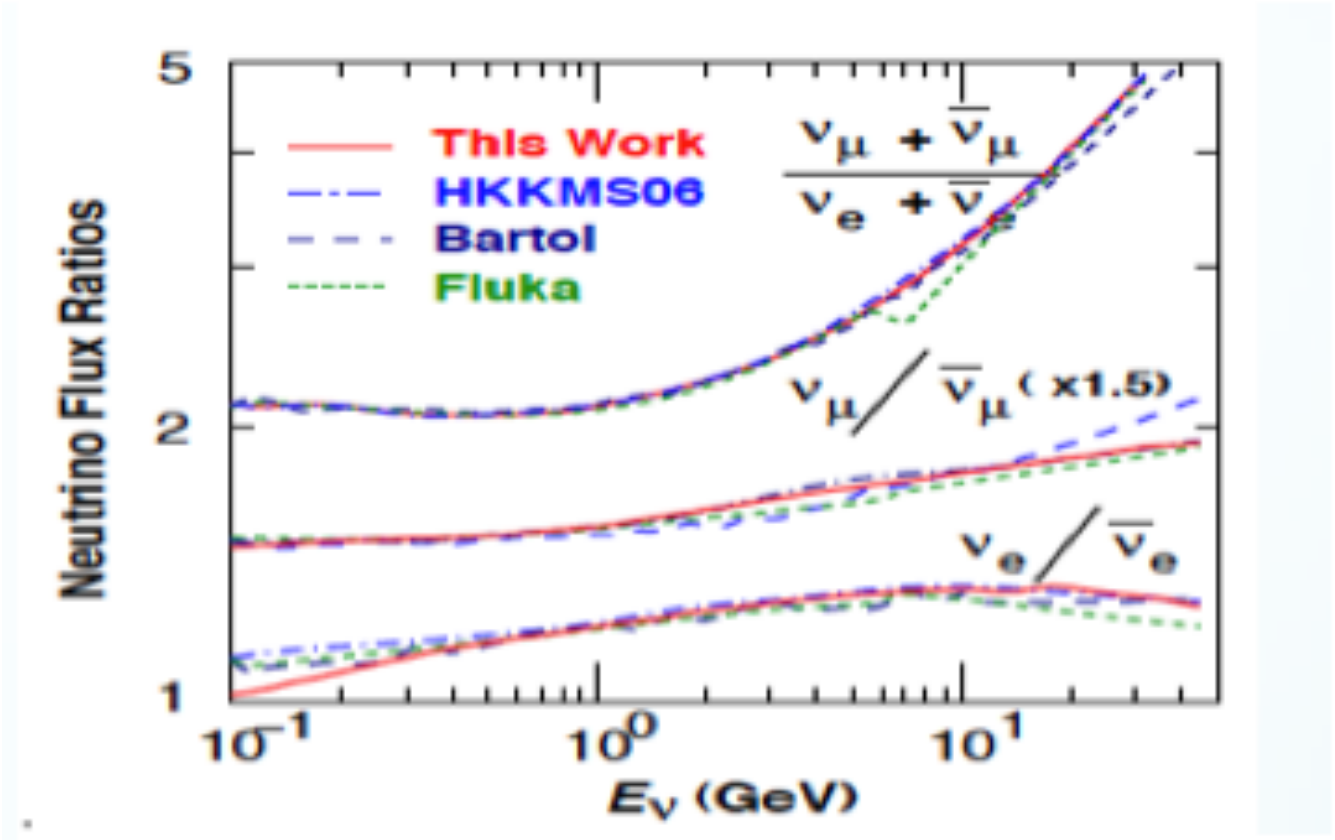
- So far no showstopper identified. ORCA will proceed with a demonstrator array. LoI to be released at beginning 2015

- Demonstrator made of 6 strings to be deployed in Toulon in 2016 allow to validate technology (especially deployment, …) and prove feasibility.

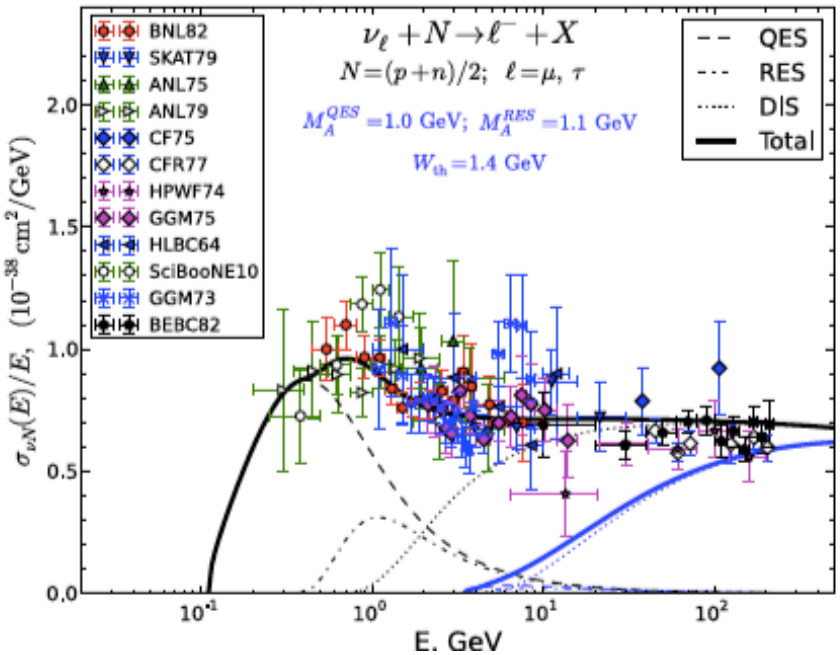
- New ESFRI proposal including Neutrino Astronomy (in Capo Passero) and Neutrino Mass Hierarchy (in Toulon) in preparation

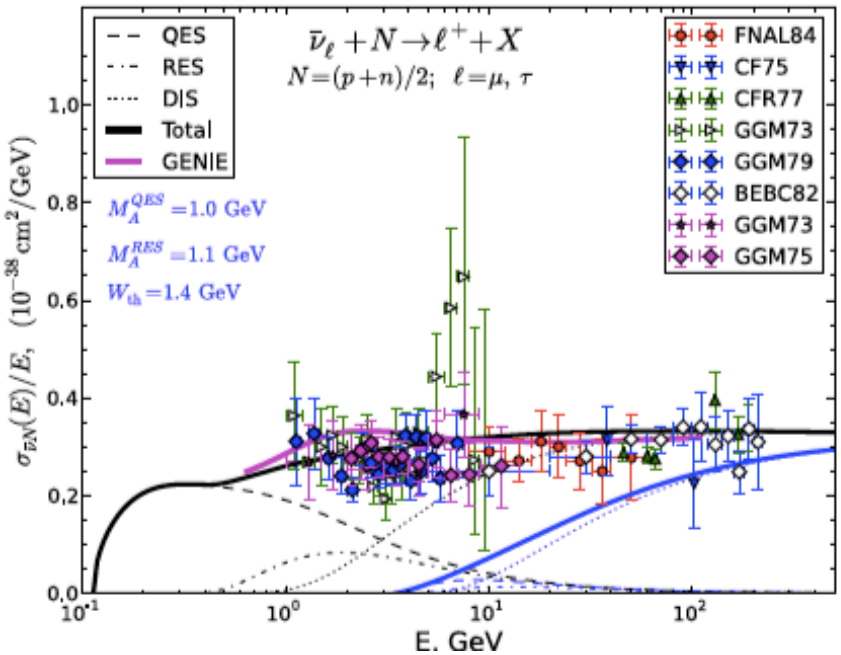
BACK UP

nm ne fluxes


Neutrino Flux Ratios
5
2
1
This Work
HKKMS06
Bartol
Fluka
$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$
$\nu_\mu / \bar{\nu}_\mu$ (x1.5)
$\nu_e / \bar{\nu}_e$
10^{-1}
10^{0}
10^{1}
E_ν (GeV)

neutrino and anti-neutrino cross-section





Sensitivity studies

Global fit approach to the mass hierarchy discrimination:

likelihood ratio test *with nuisance parameters*

(→ deal with degeneracies by fitting)

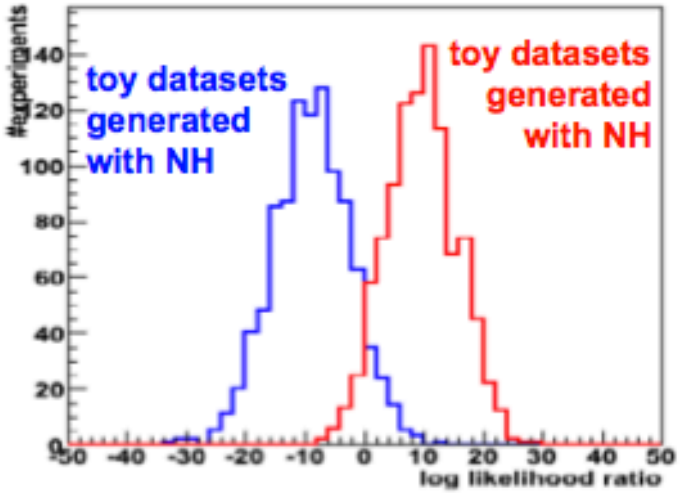
1) fit mixing parameters assuming NH

2) fit mixing parameters assuming IH

3) compute

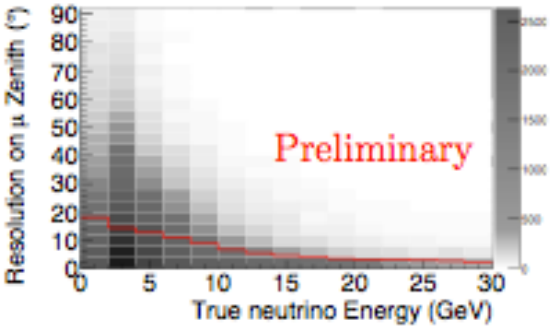
$$\Delta \log(L^{\max}) = \sum_{\text{bins}} \log P(\text{data}|\hat{\theta}^{\text{NH}}, \text{NH}) - \log P(\text{data}|\hat{\theta}^{\text{IH}}, \text{IH})$$

$\hat{\theta}^{\text{H}} =$ maximum-likelihood estimates for the Δm^2's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

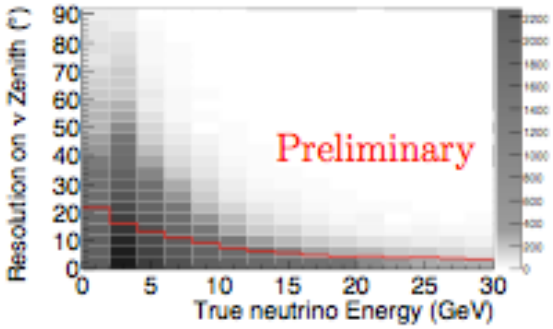


(example shown is for 10 Mt*yr)

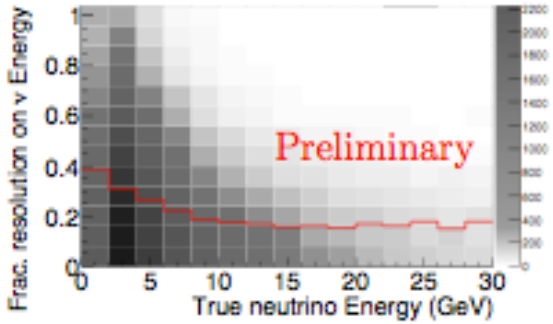
ν_μ



(a) $|\theta_{\mu,\mathrm{true}} - \theta_{\mu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.

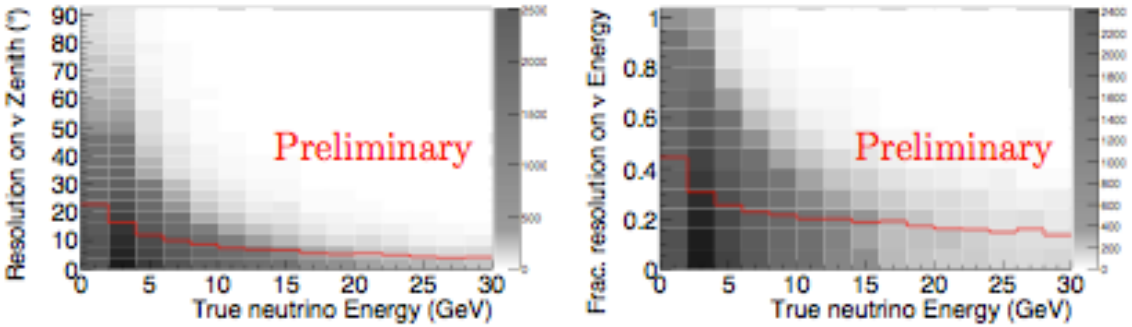


(b) $|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.



(c) $|E_{\nu,\mathrm{reco}} - E_{\nu,\mathrm{true}}|/E_{\nu,\mathrm{true}}$ vs. $E_{\nu,\mathrm{true}}$.

ν_e



(a) $|\theta_{\nu,\text{true}} - \theta_{\nu,\text{reco}}|$ vs. $E_{\nu,\text{true}}$.

(b) $|E_{\nu,\text{reco}} - E_{\nu,\text{true}}|/E_{\nu,\text{true}}$ vs. $E_{\nu,\text{true}}$.

Figure 8: Zenith angle and fractional energy resolutions for ν_e events with reconstructed vertices within the PINGU fiducial volume. The red line indicates the median value in each bin. The gray scale indicates number of simulated events in each bin. The resolutions for ν_τ and NC events are similar.