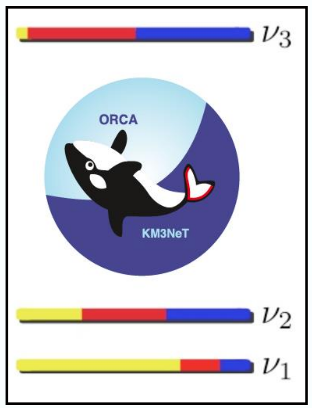
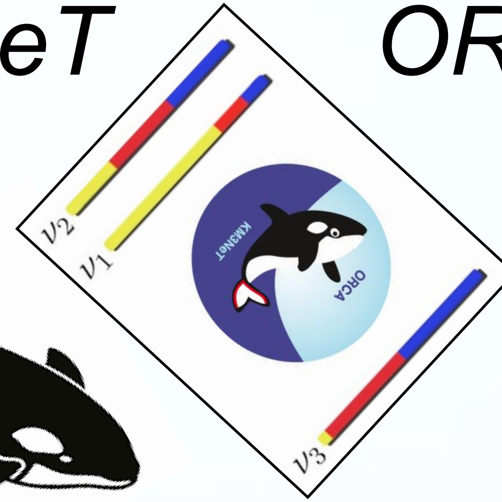
Measuring the neutrino mass ordering and more…with KM3NeT ORCA





The 13th International Symposium on Cosmology and Particle Astrophysics

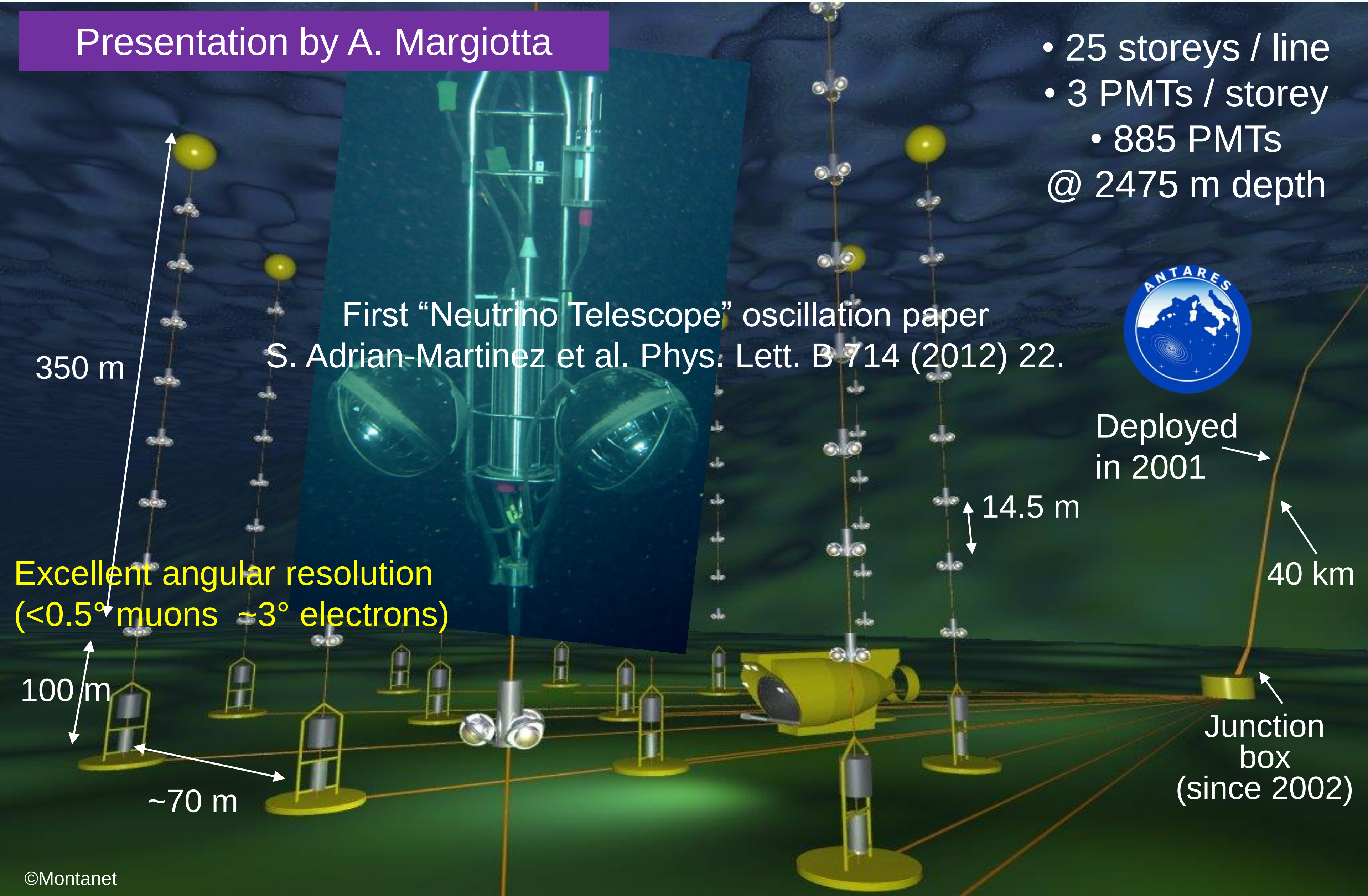
Antoine Kouchner

University Paris Diderot- AstroParticle and Cosmology

for the KM3NeT Collaboration

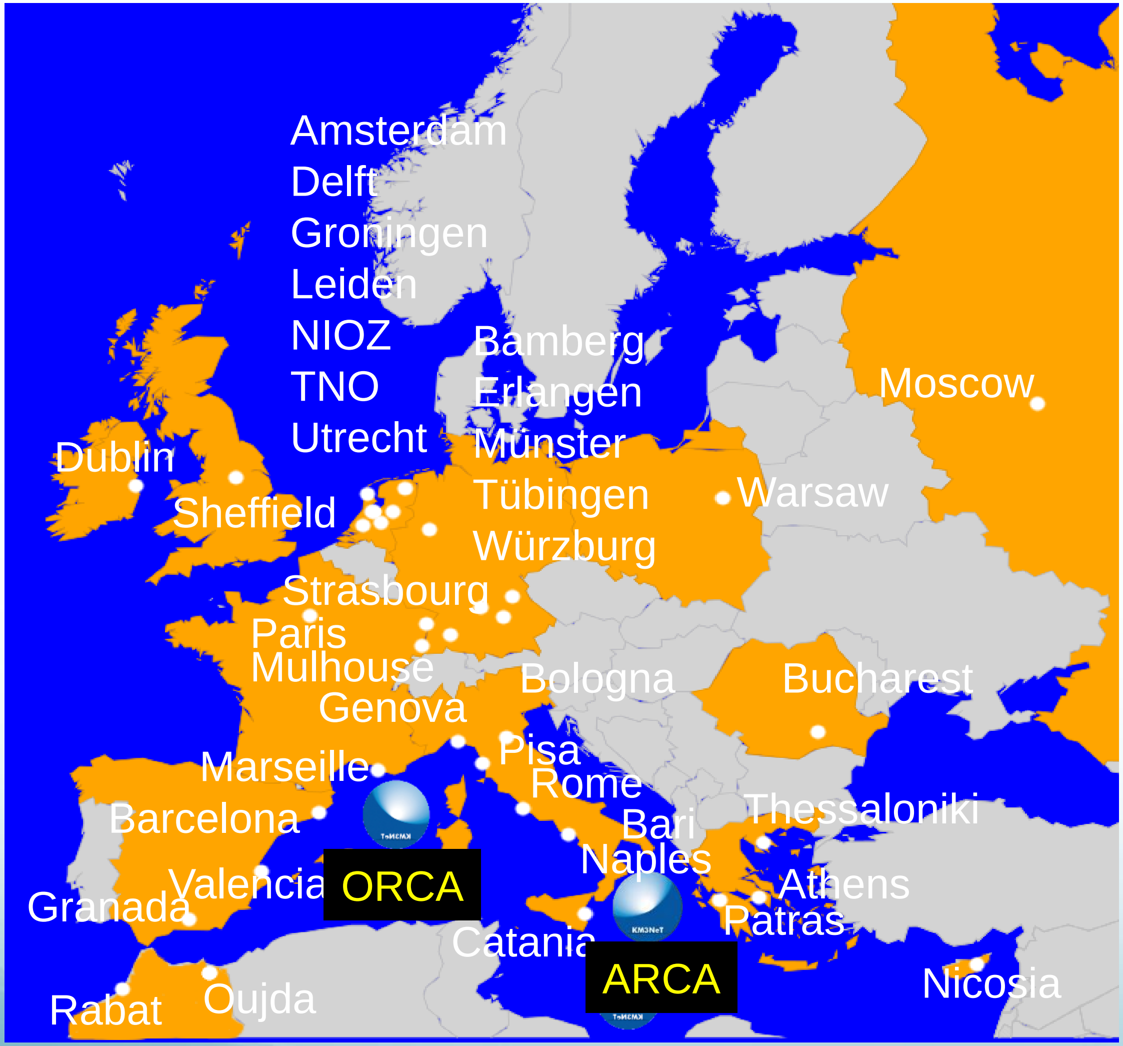
Sydney, Australia **November 28, 2016**

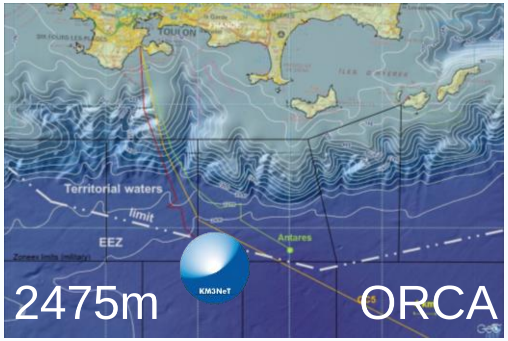
ANTARES: world 1st deep-sea NT

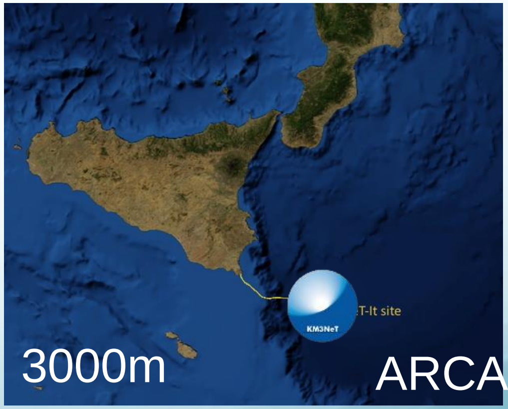


KM3NeT: Next generation Med. NT

KM3NeT is a distributed research infrastructure with <u>2 main physics topics</u>:

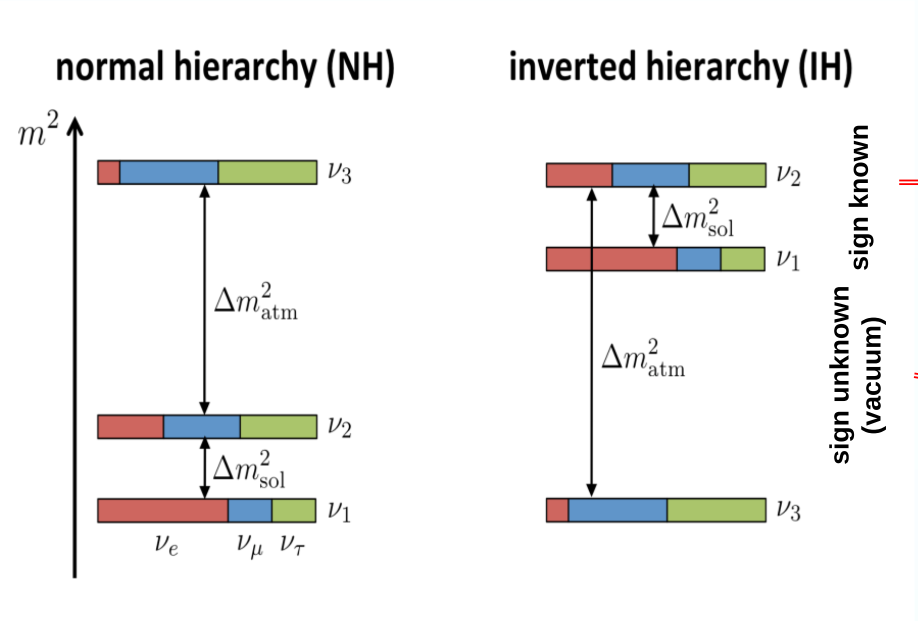






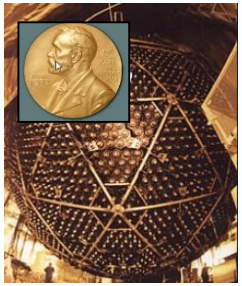
Single Collaboration, Single Technology

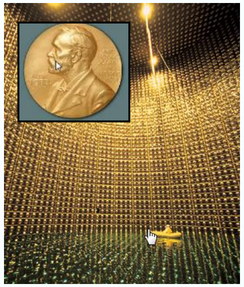
Neutrino Mass Ordering

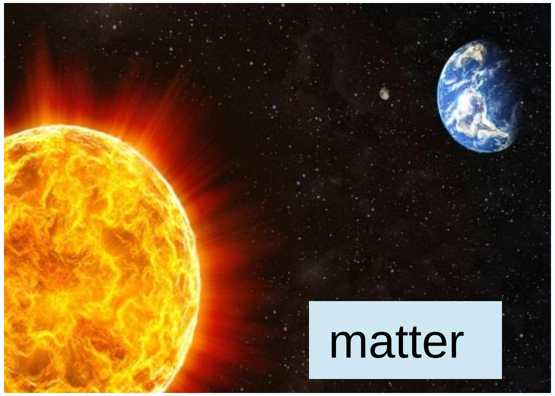


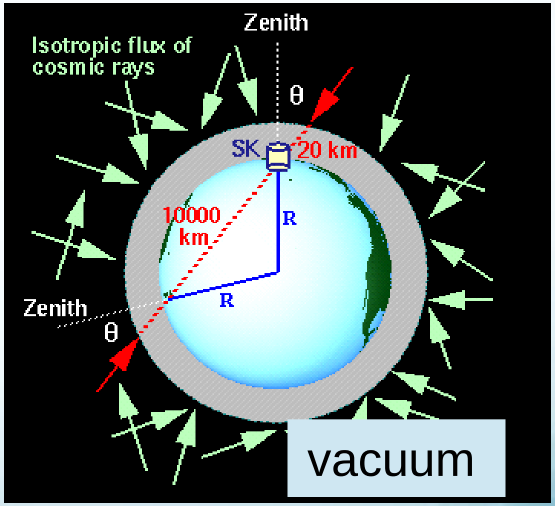
sign known

sign unknown (vacuum)







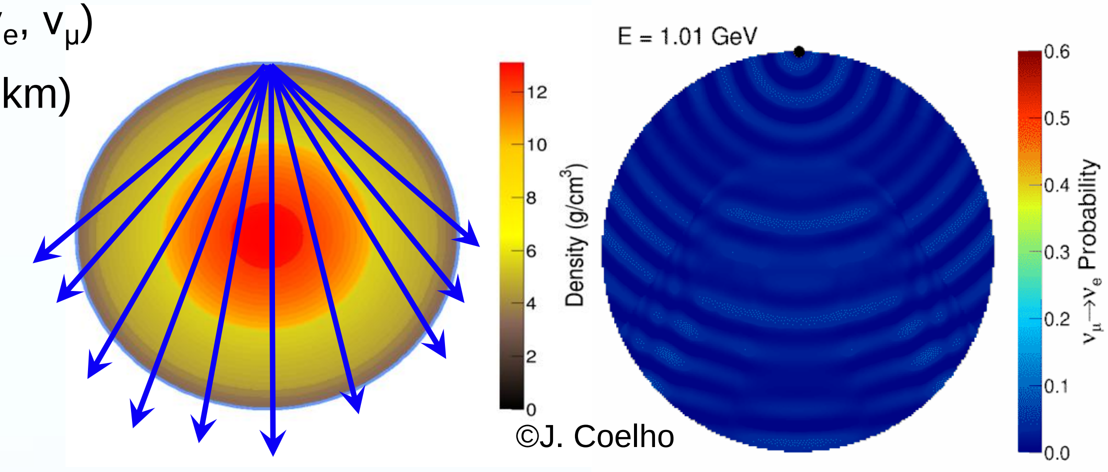


- Ordering important for theory, cosmology, 0νββ
- Measurement needed: Like Super-K

  But now resolve matter-effects in Earth

Measuring NMO with Atmospheric Neutrinos

- A “free beam” of known composition (ν_e, ν_μ)
- Wide range of baselines (50 → 12800 km) and energies (GeV → PeV)



- Oscillation affected by Matter (hierarchy-dependent):

  maximum difference IH □ NH at θ=130° (7645 km) and E_ν = 7 GeV

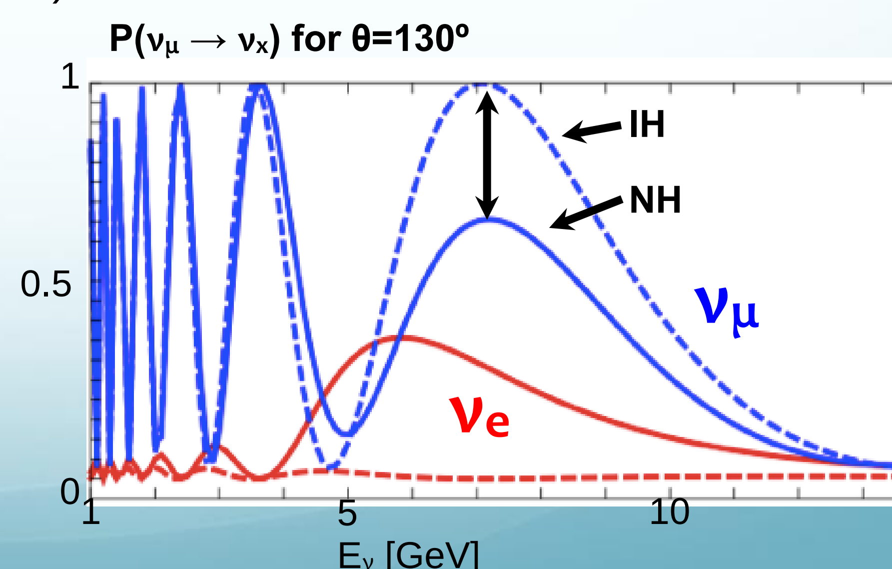
- Opposite effect on anti-neutrinos: IH (v) ≈ NH(anti-v)
  But differences in flux and cross-section:

  $\Phi_{atm}(v) \approx 1.3 \times \Phi_{atm}(\text{anti-}v)$

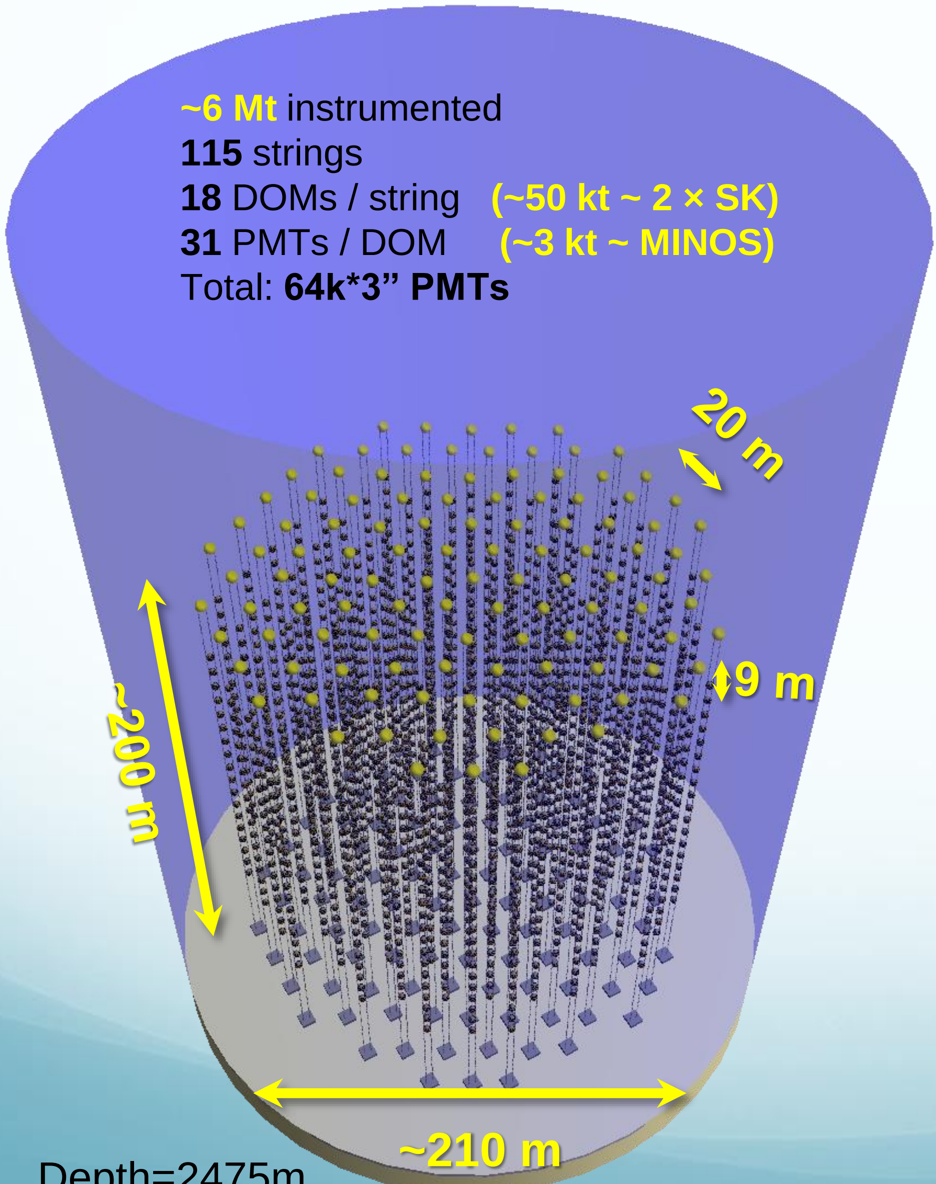
  $\sigma(v) \approx 2\sigma(\text{anti-}v)$ at low energies

- Measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos, identify and count muon and electron channel events

- Careful treatment of systematics mandatory



The ORCA detector



Depth=2475m

Digital Optical Module

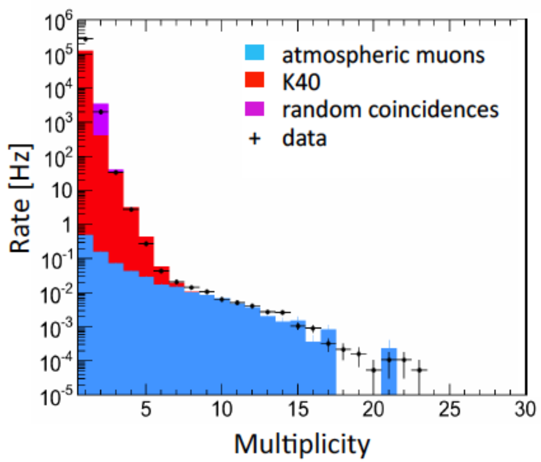
Optical background (mainly ^{40}K):
10kHz/PMT & 500Hz coincidence

- 31 x 3" PMTs
- Uniform angular coverage
- Directional information
- Digital photon counting
- Wide angle of view
- Background rejection
- All data to shore

KM3NeT first Detection Units

- ✓ Optical Module at Antares site, April 2013 (2500 m)

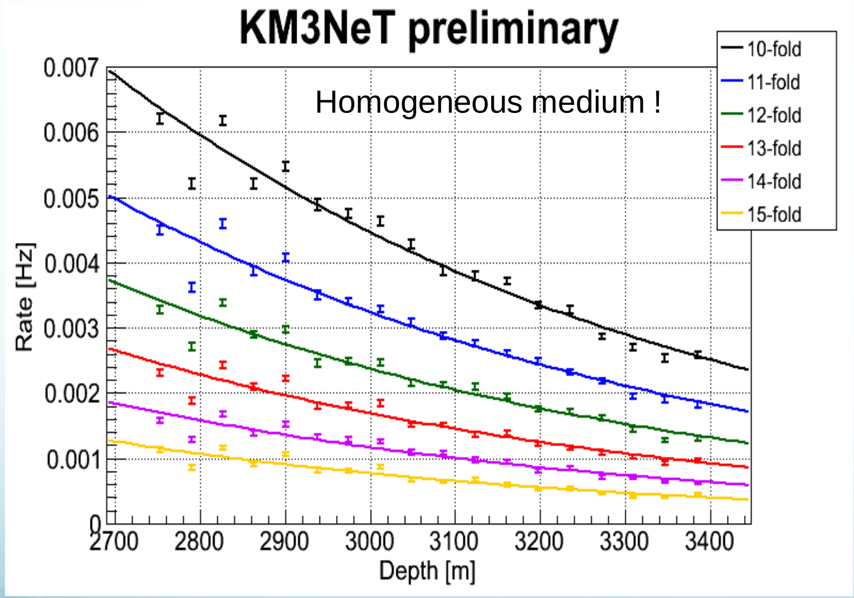
  Muons from a single DOM ! 📖 Eur. Phys. J. C (2014) 74:3056

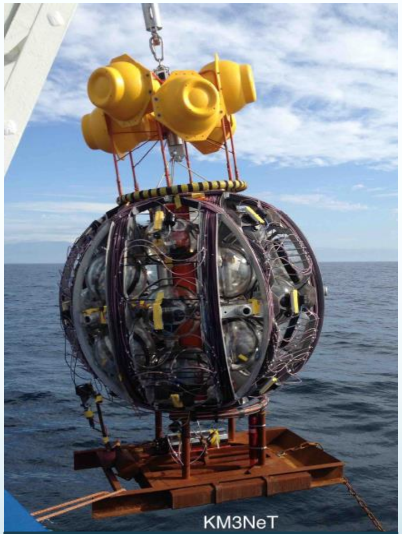


- ✓ Mini string (3 DOMs) at ARCA site, May 2014 (3500 m)

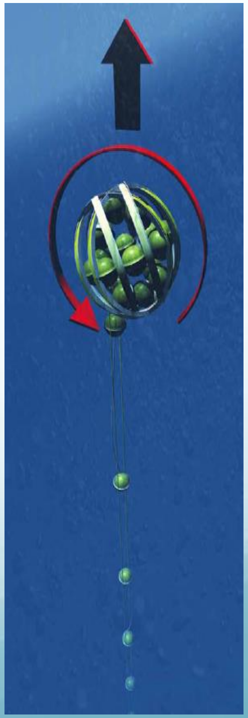
  Track reconstruction 📖 Eur. Phys. J. C (2016) 76:54 -- Cover

- ✓ First full Detection Unit at ARCA site, Dec 2015





rapid deployment
autonomous unfurling
recoverable



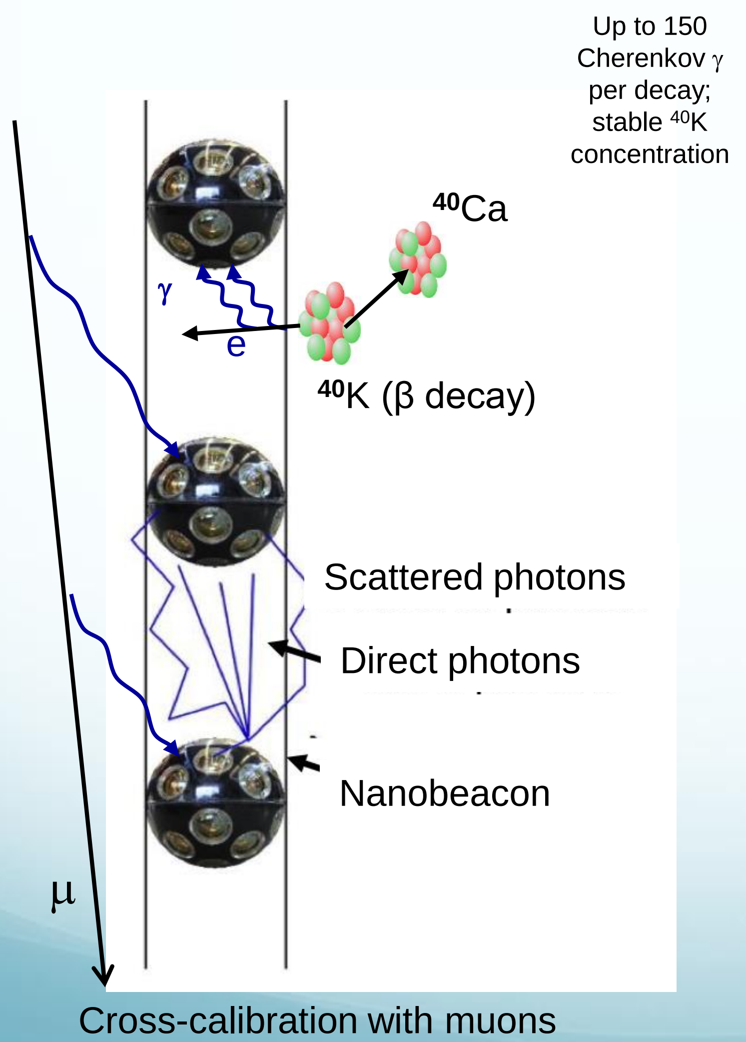
Watch https://www.youtube.com/watch?v=tR8jwgG6uzk

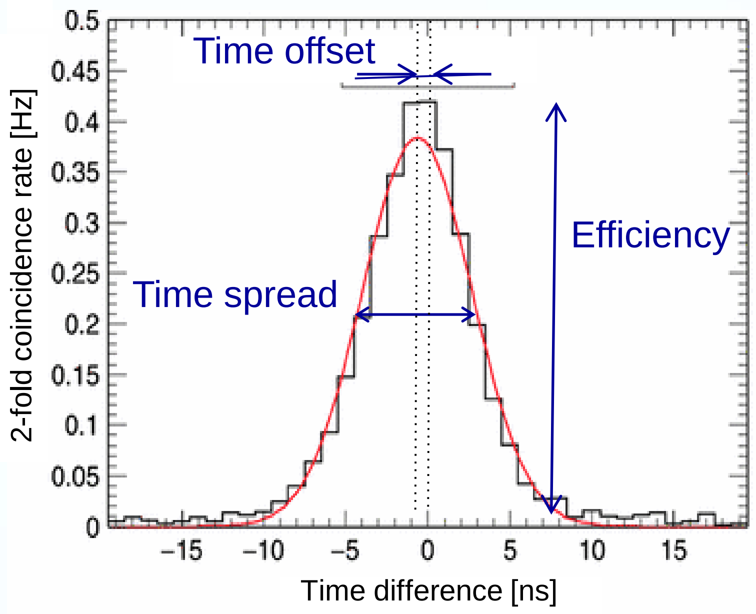
- ✓ One more line in operation since May 2016

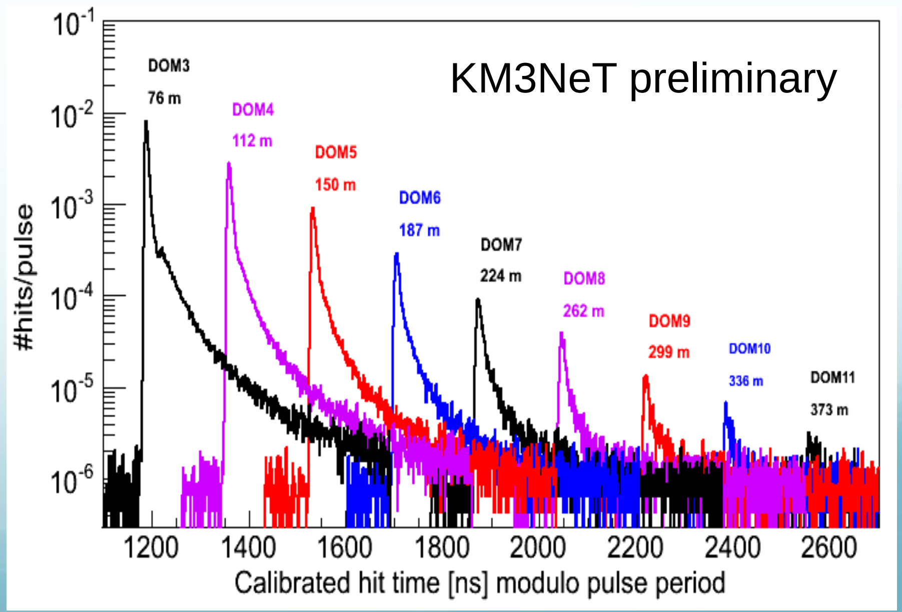
  Another one recovered for inspection

  Multi-line data taking ongoing…

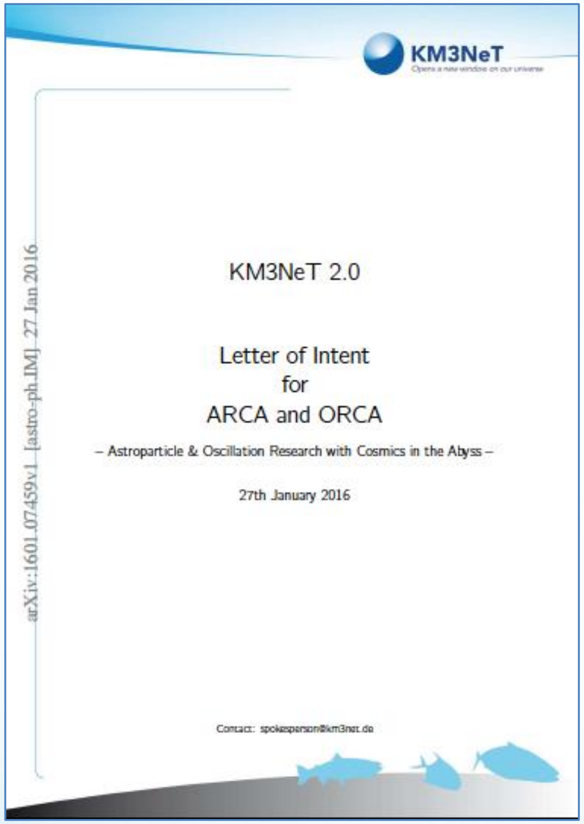
Fast calibration procedures







Detector's simulations


arXiv:1601.07459v1 [astro-ph.IM] 27 Jan 2016

KM3NeT
Opens a new window on our universe

KM3NeT 2.0

Letter of Intent
for
ARCA and ORCA

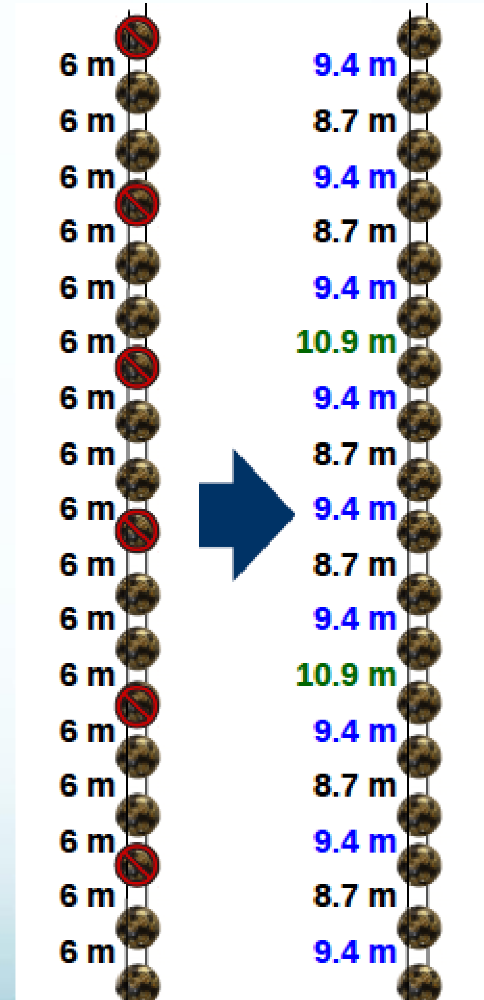
– Astroparticle & Oscillation Research with Cosmics in the Abyss –

27th January 2016

Contact: spokesperson@km3net.de

J. Phys. G 43 (2016) 084001

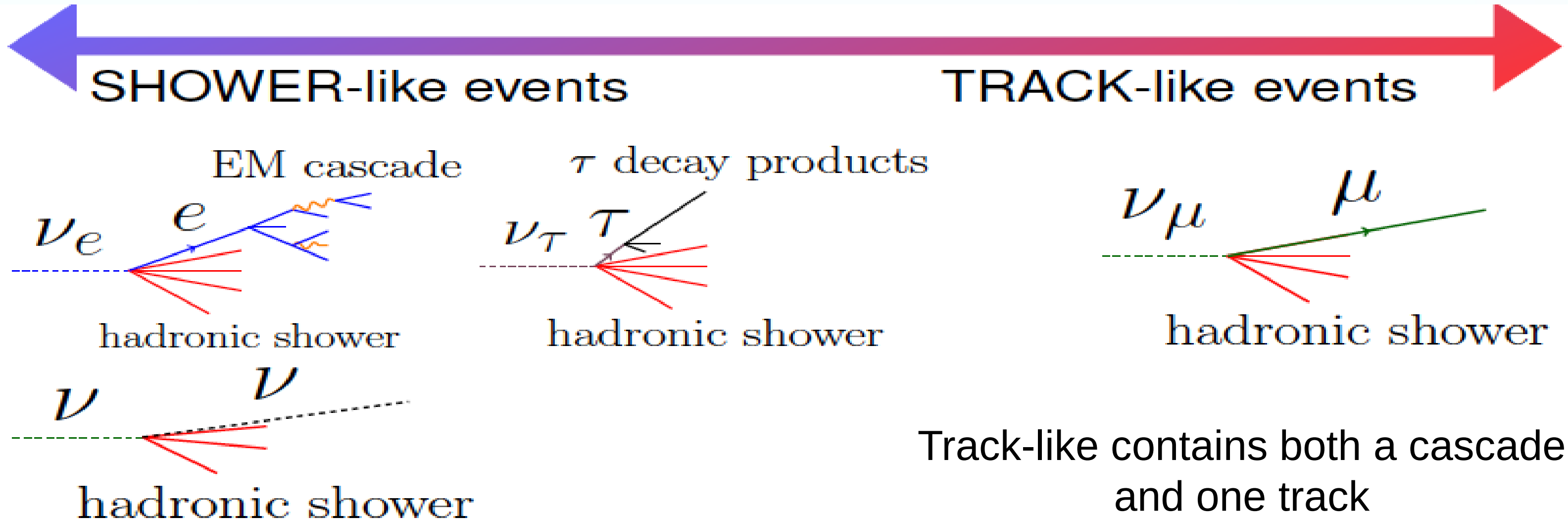
Performances based on temporary detector layout



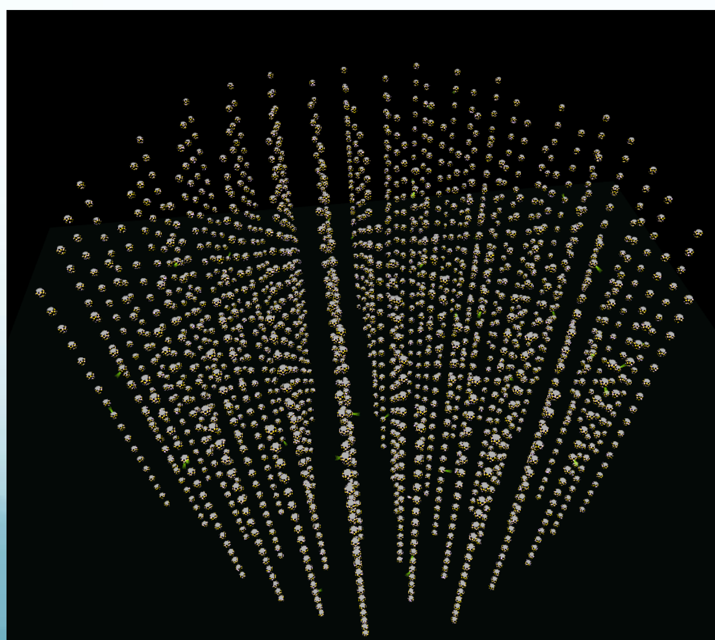
New set of simulations started
+ reconstruction + PID + background rejections
New results expected in a few months
[No significant change expected]

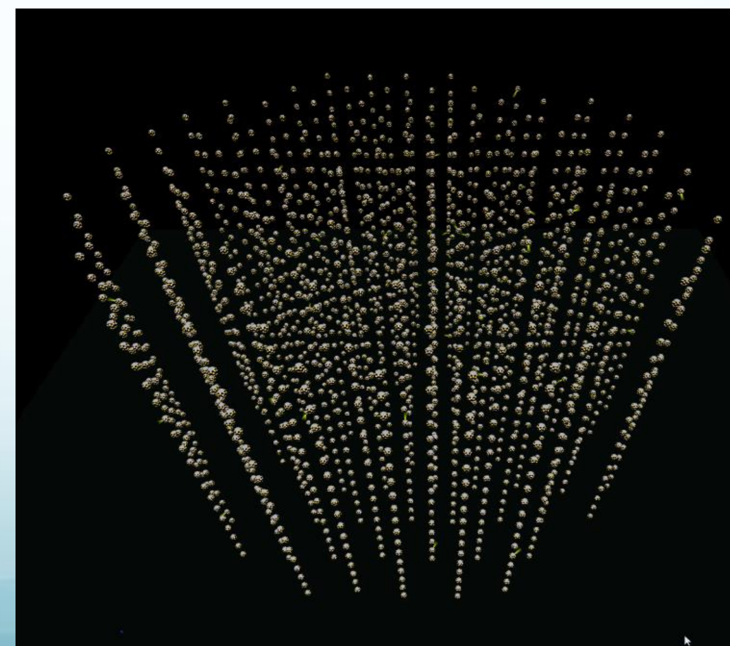
Technical constraints accounted

Event topologies



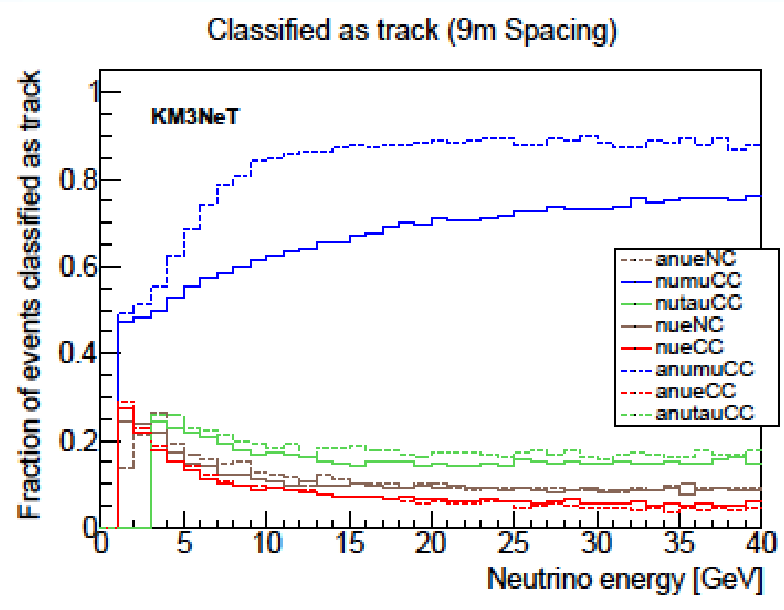
Track-like contains both a cascade and one track

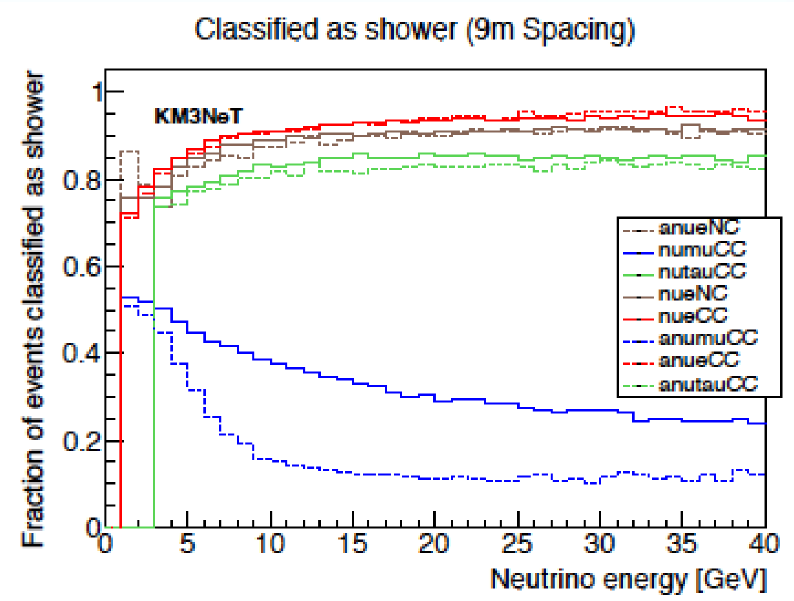




Shower-Track Identification

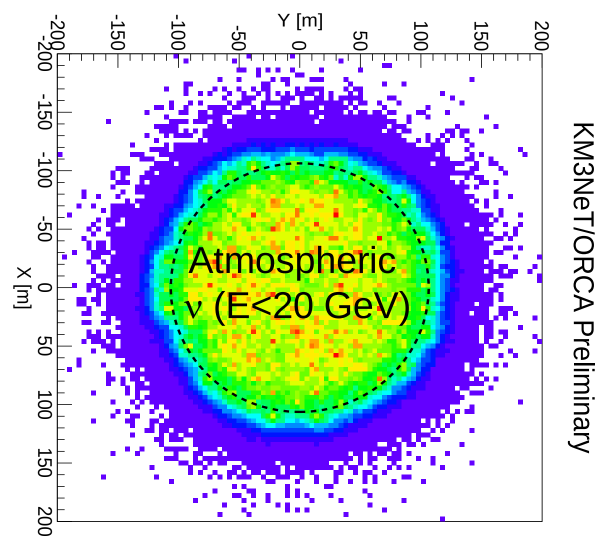
Discrimination of tracks, showers and atmospheric muons via RDF

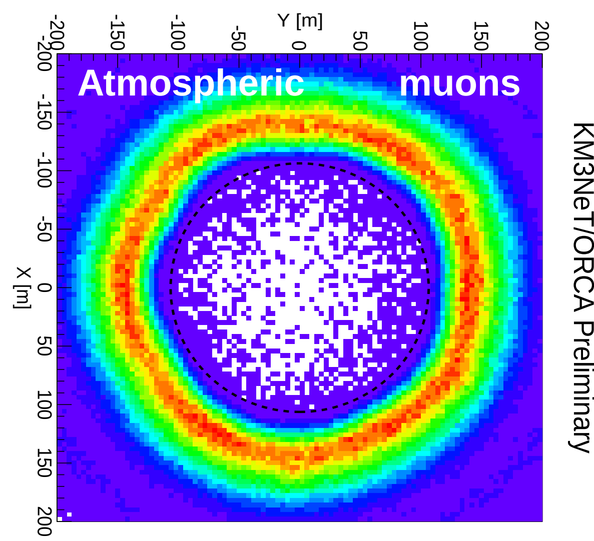




At 10 GeV:

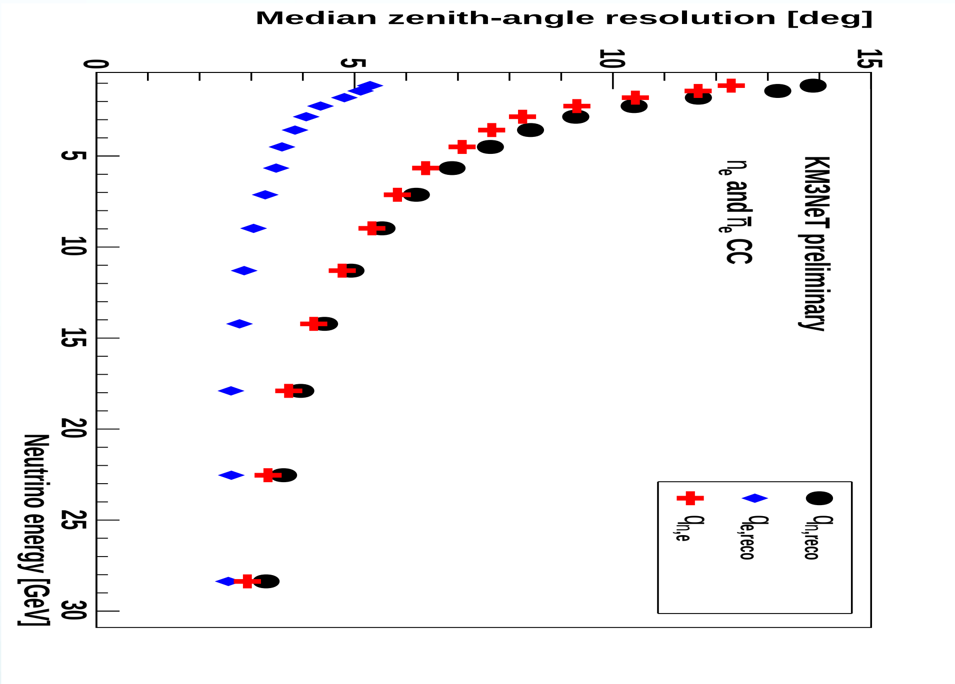
- 90% correct ID of ν_e^{CC}
- 70% correct ID of ν_μ^{CC}



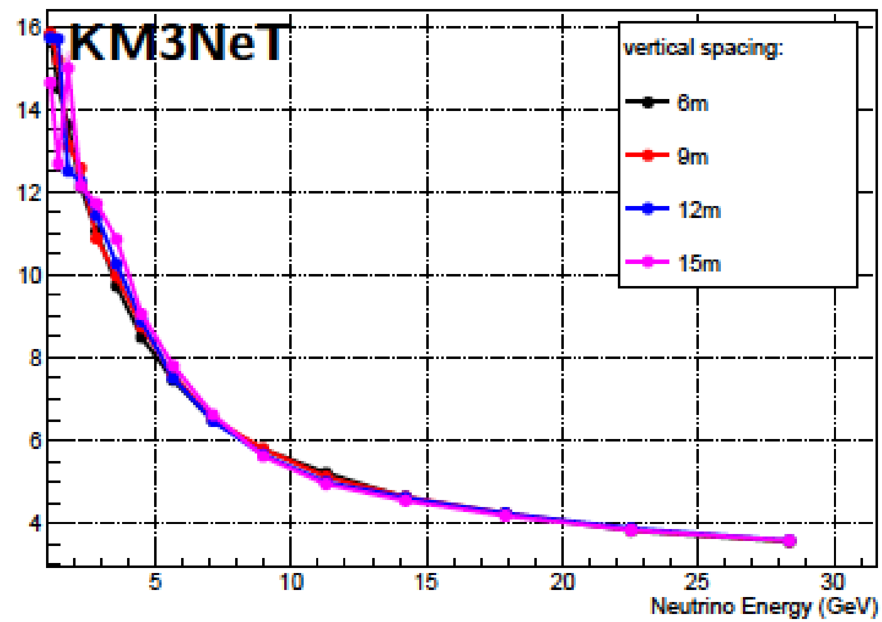


Zenith angle resolution

Shower



Track



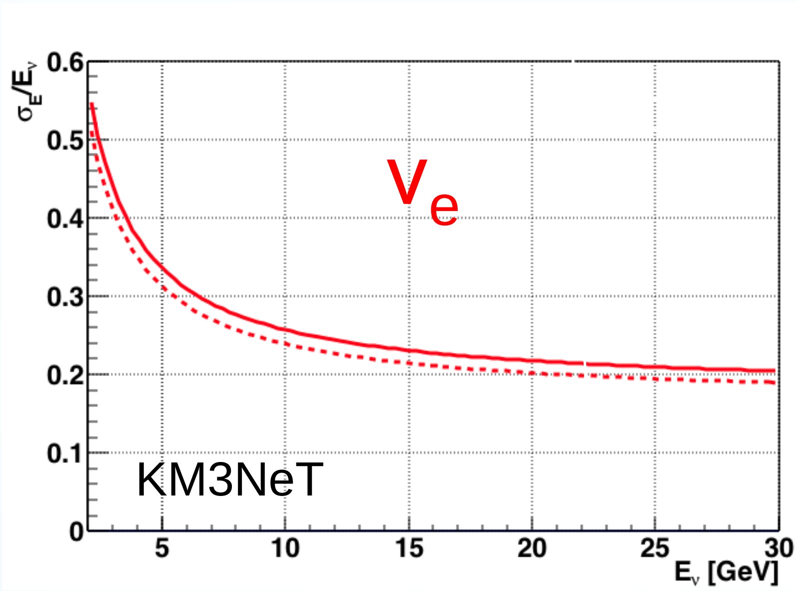
7°(5°) for 5(10) GeV for both channels

Dominated by kinematic smearing

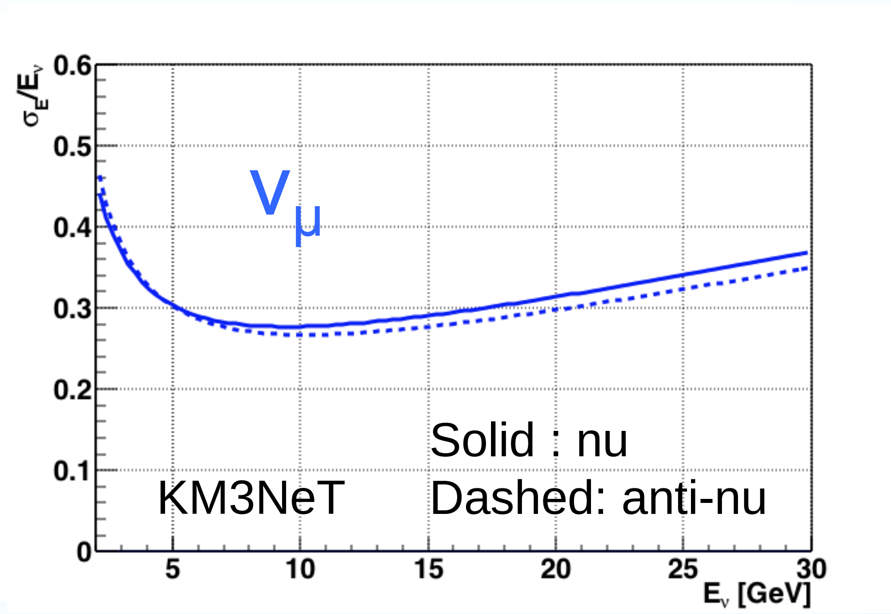
Largely independent of vertical spacing

Energy resolution

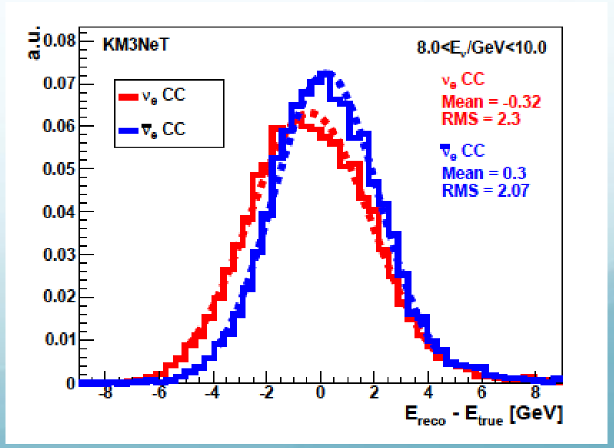
Shower



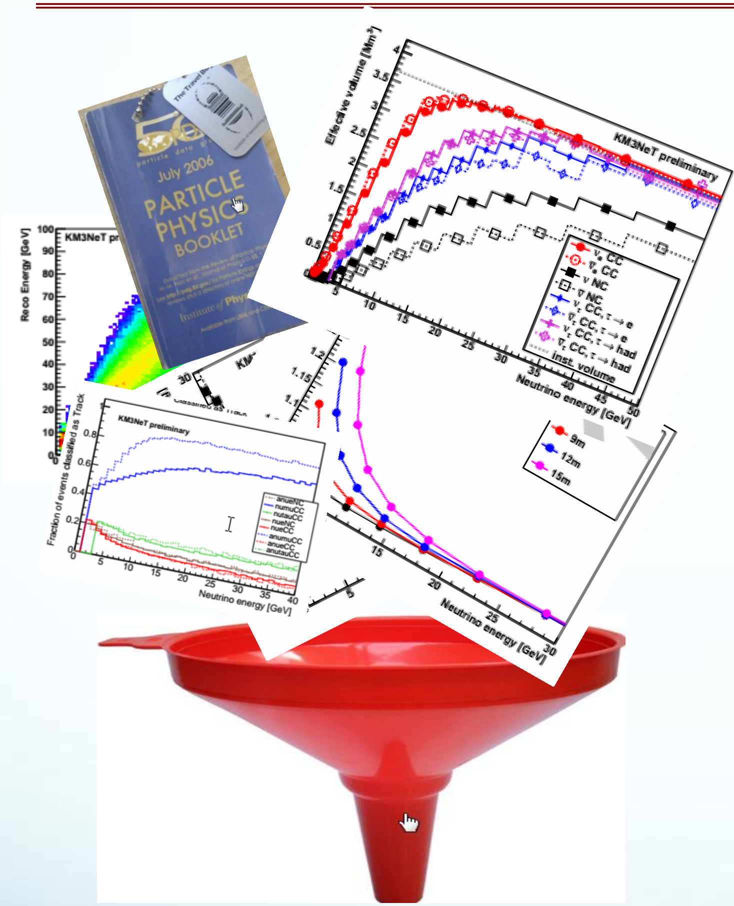
Track

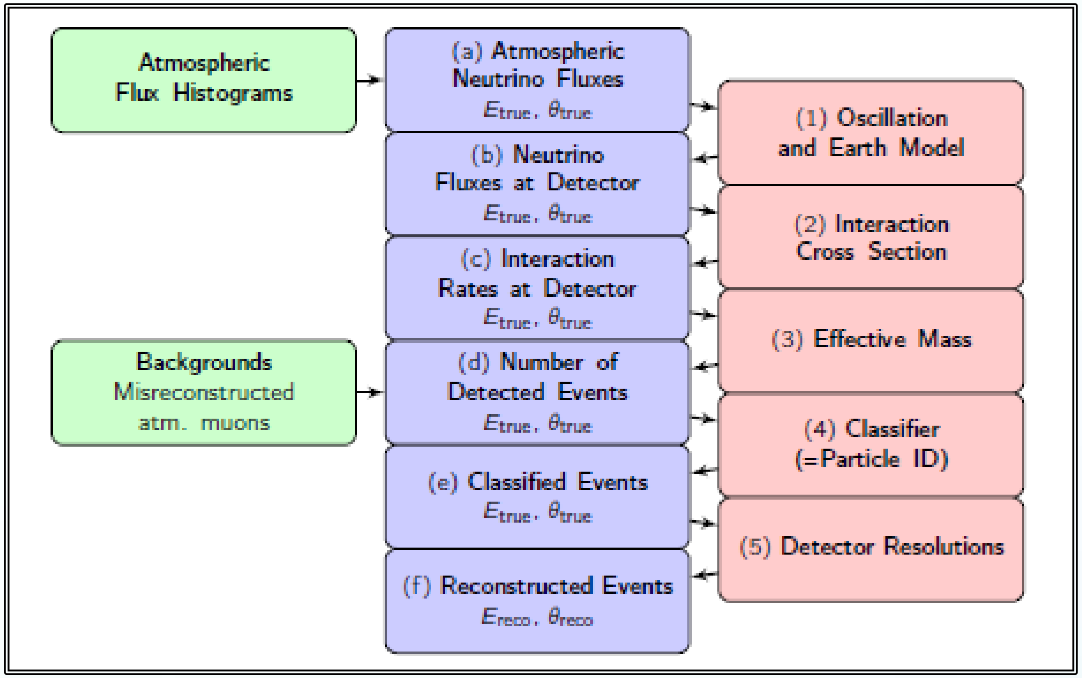


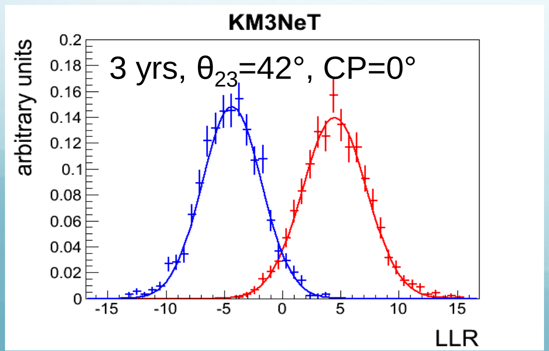
- Energy resolution better than 30% in relevant range
- Close to Gaussian



Mass Ordering Analysis





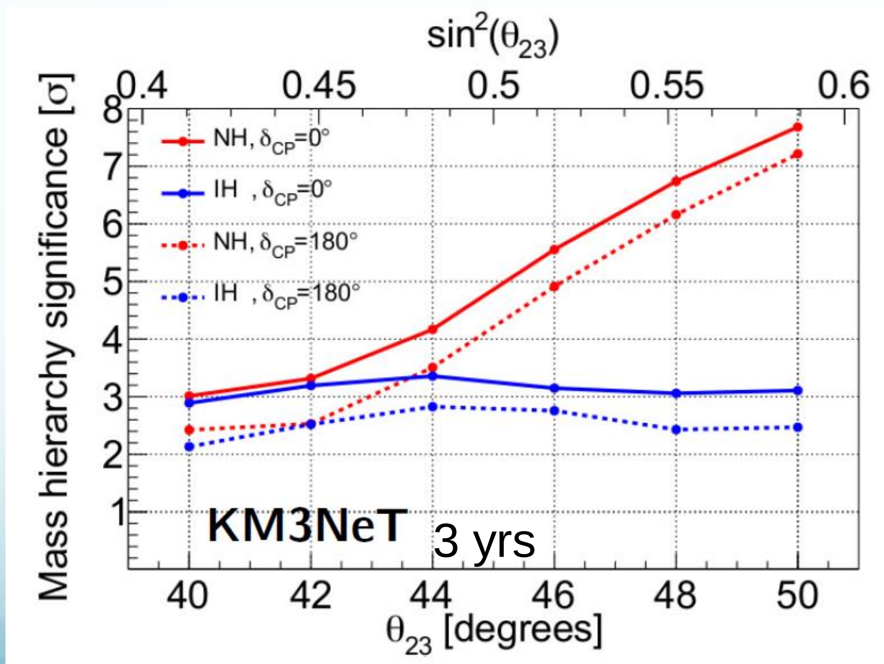


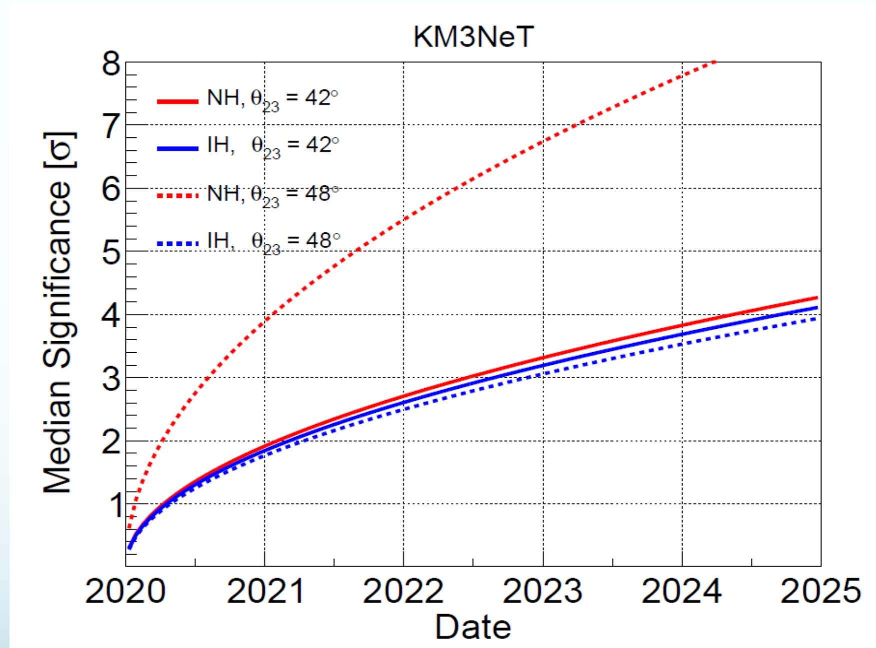
- Pick random values for oscillation parameters and other systematics
- Generate pseudo-experiments for N0, I0 cases
- Find best-fit likelihoods L_{NO}, L_{IO} for the NO, IO cases (maximising w.r.t. 9 free parameters)
- Calculate the log-likelihood ratio log (L_{NO}/L_{IO})

Sensitivity to Mass Ordering

Systematics

parameter	*true value distr.*	*initial value distr.*	*treatment*	*prior*
overall flux factor	1	$\mu = 1, \sigma = 0.1$	fitted	yes
NC scaling	1	$\mu = 1, \sigma = 0.05$	fitted	yes
$\nu/\bar{\nu}$ skew	0	$\mu = 0, \sigma = 0.03$	fitted	yes
μ/e skew	0	$\mu = 0, \sigma = 0.05$	fitted	yes
energy slope	0	$\mu = 0, \sigma = 0.05$	fitted	yes





Worst case 3σ in 4 years

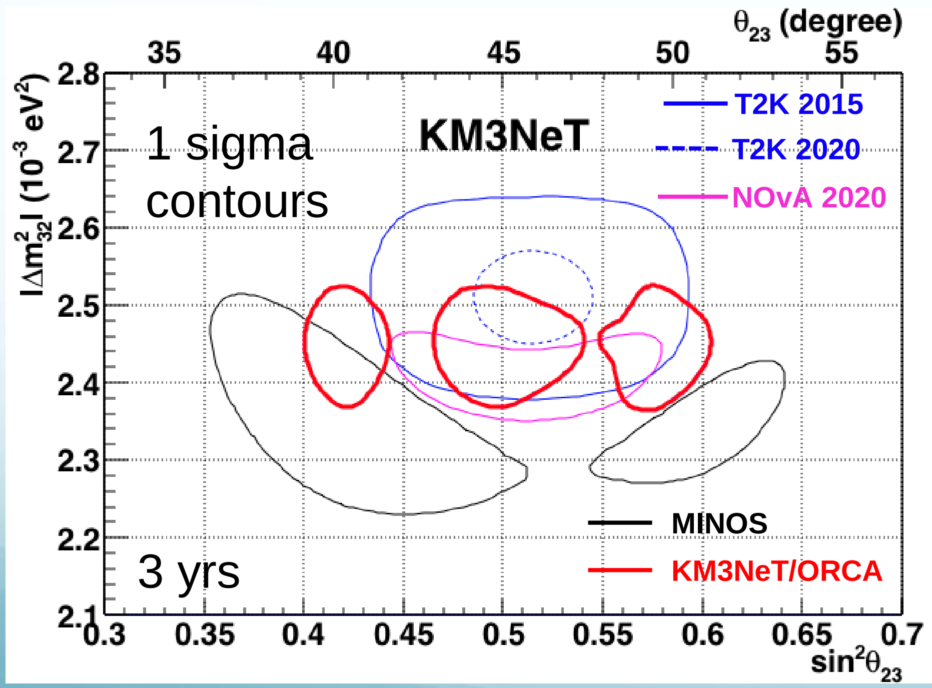
Combination of **NO and upper octant of θ_{23} -- > 5σ in 3 years**

δ_{cp} small but non-negligible ~0.5σ impact on sensitivity

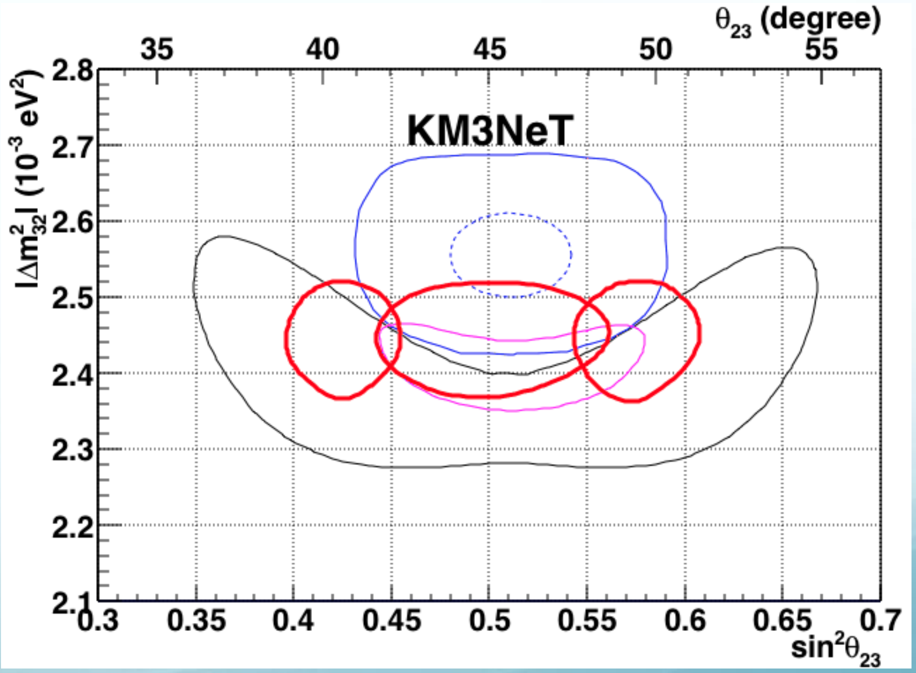
Measurement of Δm^2_{32} and $\sin^2\theta_{23}$

- High statistics and excellent resolution → Measure Δm^2_{32} and $\sin^2\theta_{23}$
- Competitive with NOvA and T2K projected sensitivity in 2020
- Achieve 2-3% precision in Δm^2_{32} and 4-10% in $\sin^2\theta_{23}$

Normal Hierarchy

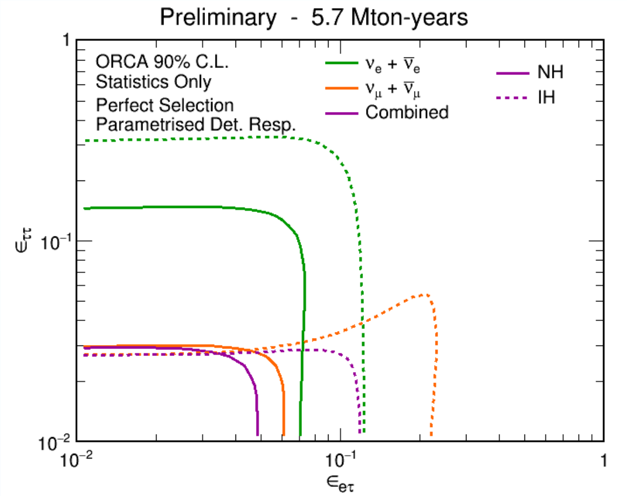


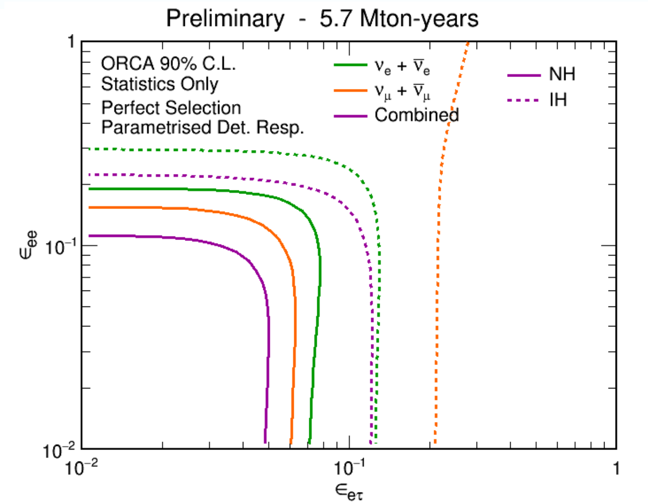
Inverted Hierarchy



Non Standard Interactions/Sterile

Non-Standard Interactions

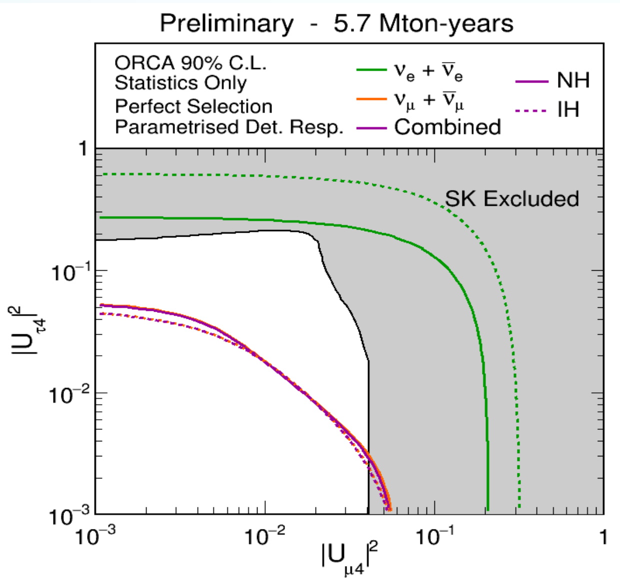


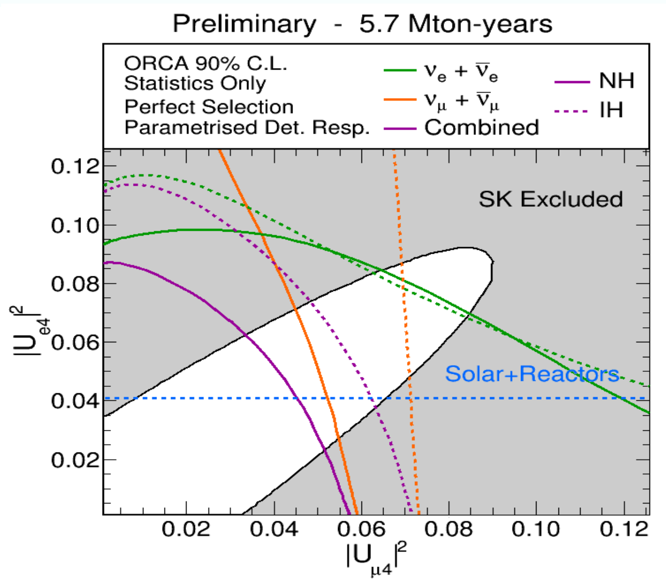


With 1 year of data, ORCA sensitive to NSI effects more than an order of magnitude smaller than current limits.

(perfect selection)

Sterile Neutrinos



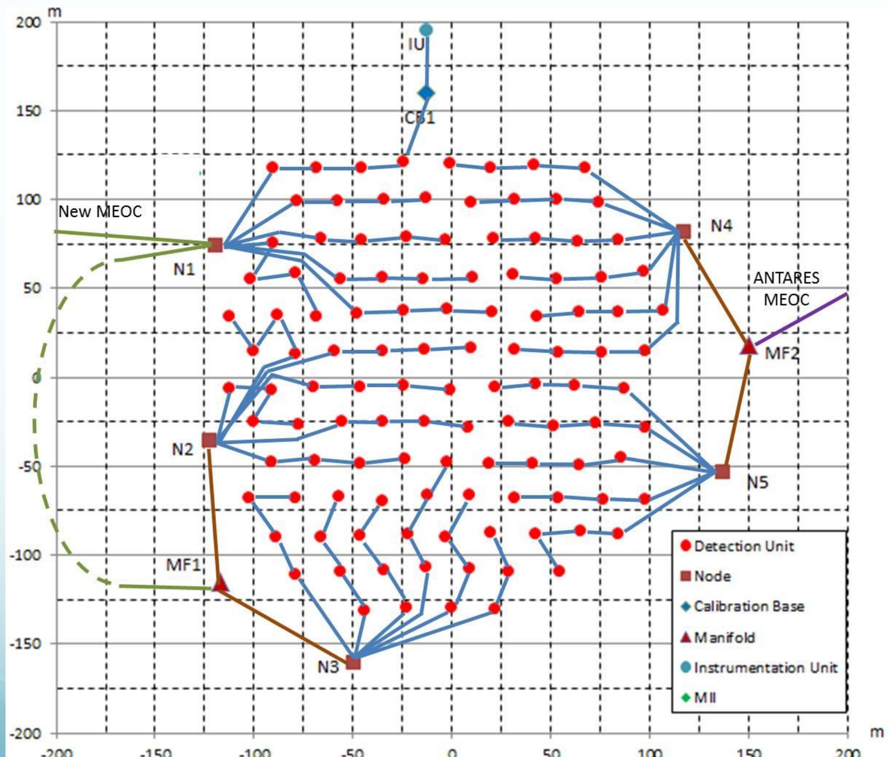


With 1 year of data, ORCA sensitive to $|U_{\tau4}|^2$ values 5x smaller than current limits set by Super-Kamiokande.

ORCA Construction in Progress

Phase 1: 7 string array at KM3NeT-France site to demonstrate technology/detection methods in the GeV range

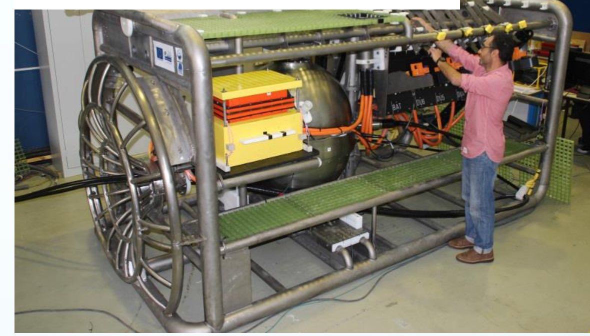
Phase 2: deploy 1 building block (115 strings)



Possibility to redirect the ANTARES cable to ORCA

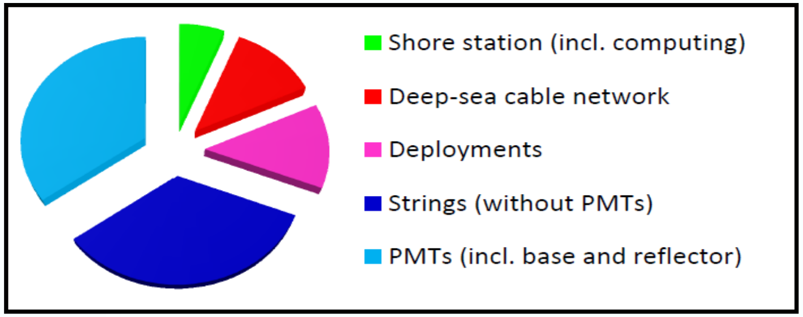
Main cable: Dec 2015

1st node: Sept 2016



1st ORCA string ready

ORCA Funding and Schedule

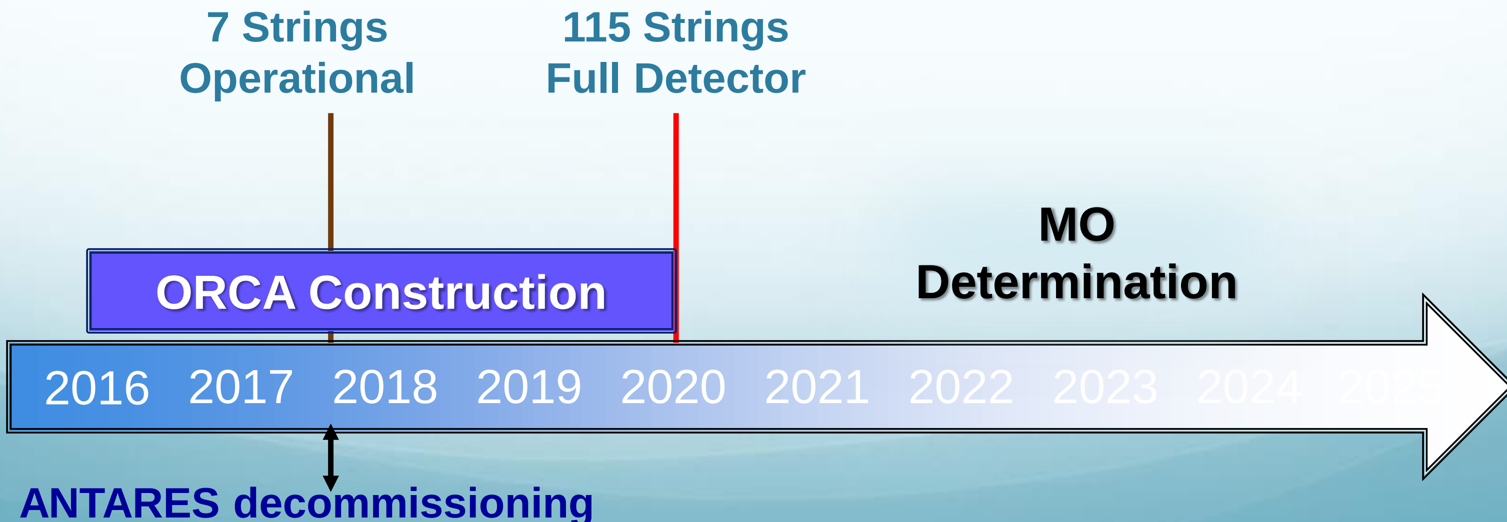


Total ORCA cost ≈ 45 M€

📖 Read our Letter of Intent
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

Phase 1: 7 strings – 11 M€

Phase 2: 115 strings – funding requests ongoing

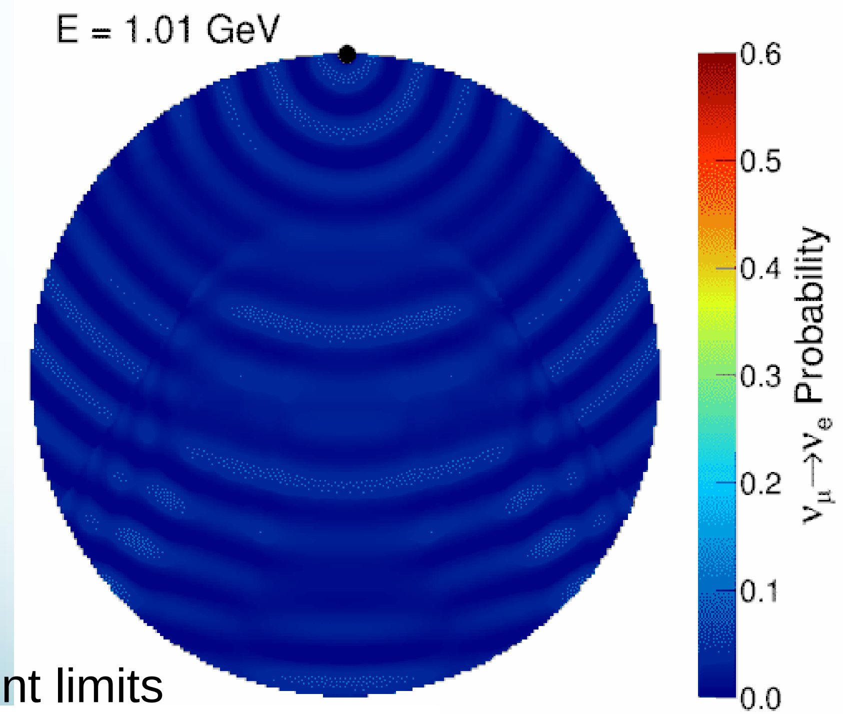


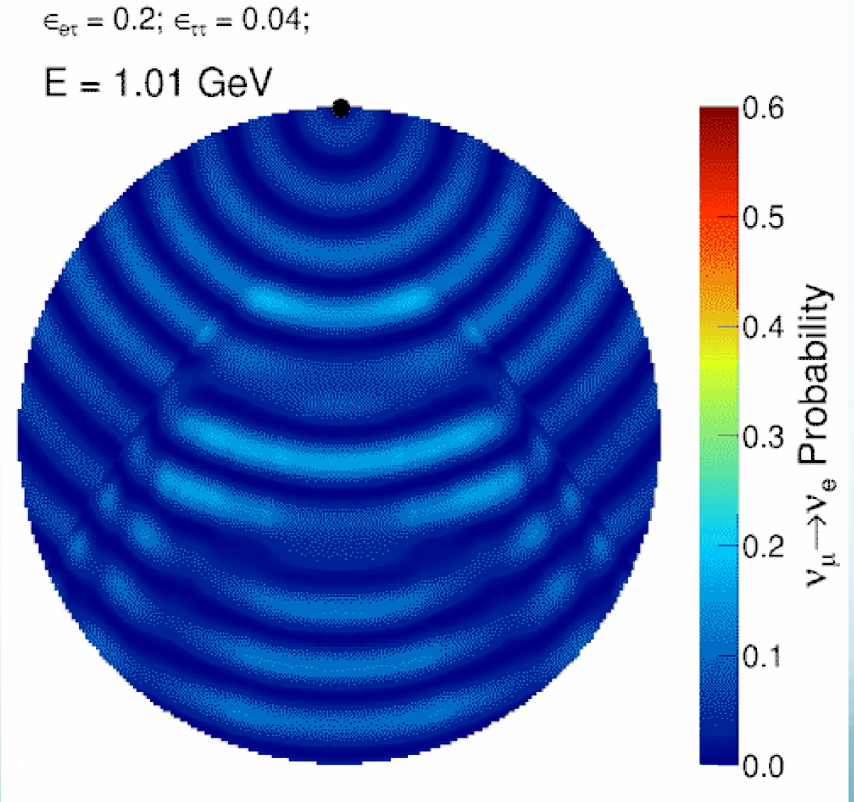
Thank you!

New collaborators are welcome to join the endeavour !

Non Standard Interactions

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$





$\epsilon_{e\tau} = 0.2$; $\epsilon_{\tau\tau} = 0.04$;

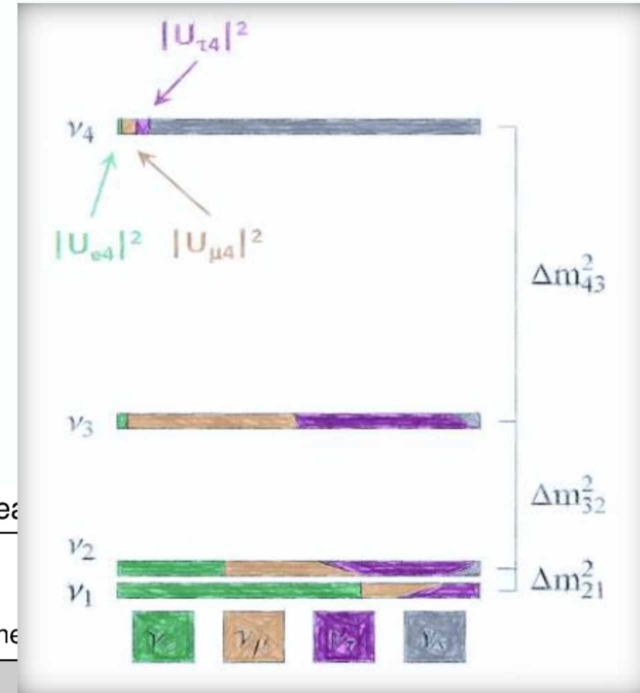
Current limits

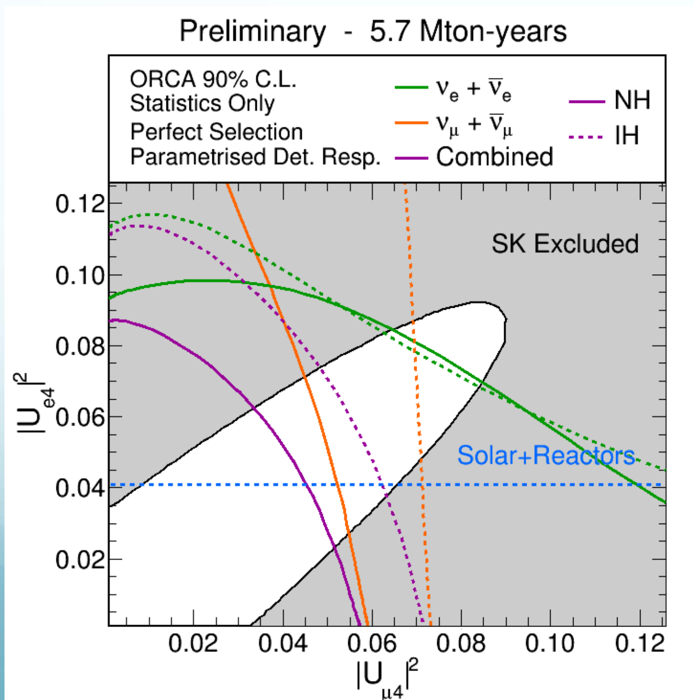
$$\begin{pmatrix}|\varepsilon_{ee}| < 4.2 & |\varepsilon_{e\mu}| < 0.33 & |\varepsilon_{e\tau}| < 3.0\\ & |\varepsilon_{\mu\mu}| < 0.068 & |\varepsilon_{\mu\tau}| < 0.33\\ & & |\varepsilon_{\tau\tau}| < 21\end{pmatrix}$$

Rept. Prog. Phys. 76, 044201 (2013)

Sterile neutrinos

- the dominant effect of adding a eV scale sterile neutrino would be the suppression of ν_μ to ν_τ oscillation at ~20 GeV.
- ORCA sensitive to $|U_{\tau 4}|^2$ values 5 x smaller than current limits set by Super-Kamiokande





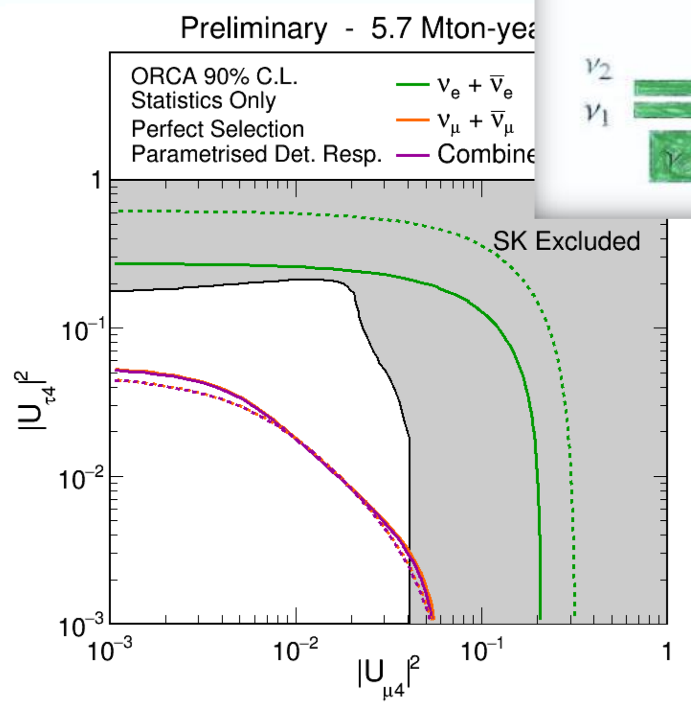


Table 14. Default parameter settings used for the LLR analysis. Where μ and σ are given, they refer to a Gaussian distribution.

Parameter	True value distr.	Initial value distr.	Treatment	Prior
θ_{23} (°)	{40, 42, ..., 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

Note. The † indicates that the initial values for θ_{23} are generated in a special way: a total of seven initial values is tried. They are $x + i \times 5°$, where x is the randomly drawn value and $i \in [-3, -2, \ldots, 3]$.

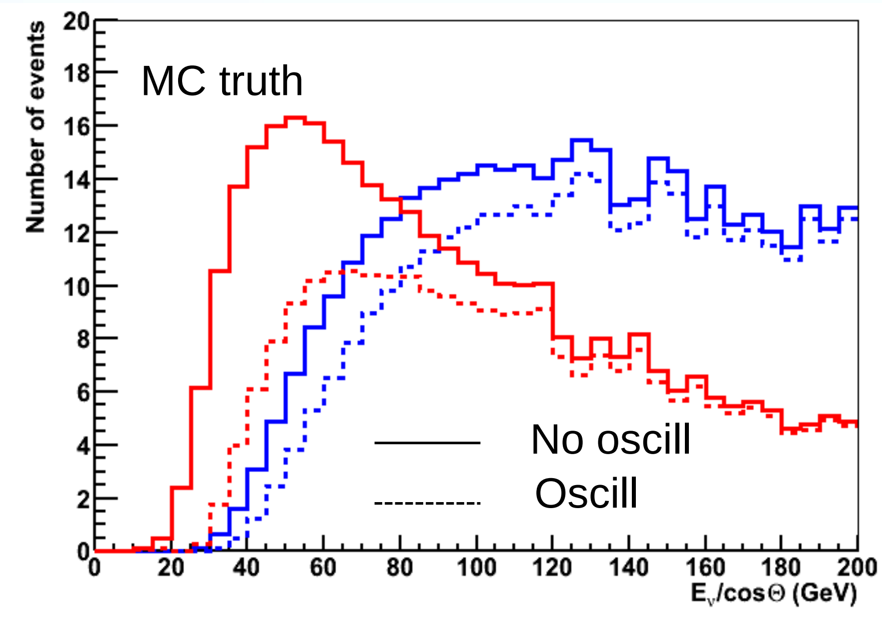
First achievements on neutrino oscillation

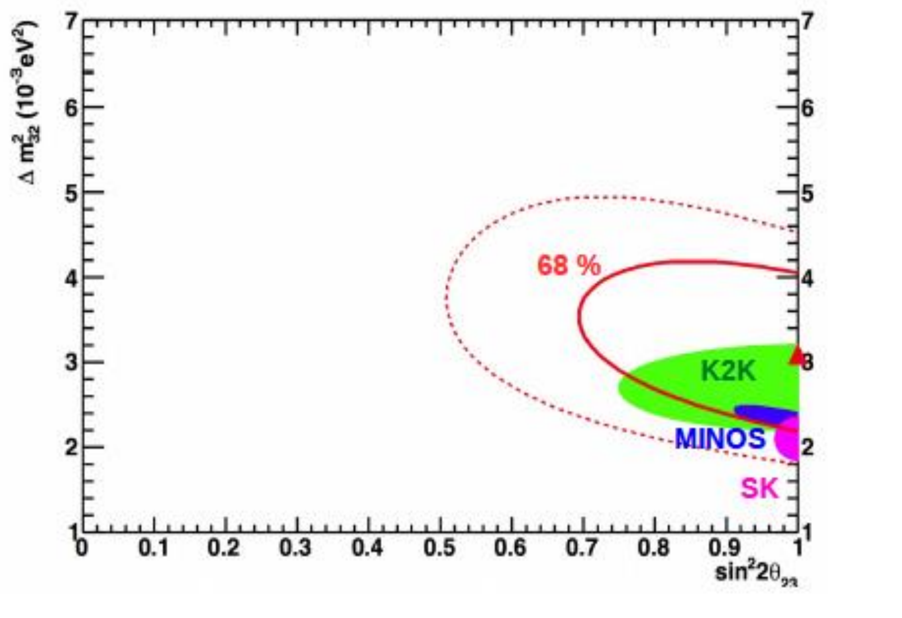
2-flavor approximation analysis with 2008-2010 data

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{16200\ \Delta m^2_{32} \cos\Theta}{E_\nu}\right)$$

Oscillations maximal at 24 GeV for vertical neutrinos (muon range~120m)

Larger effect on low energy (single lines) than higher energy events (multi-lines)



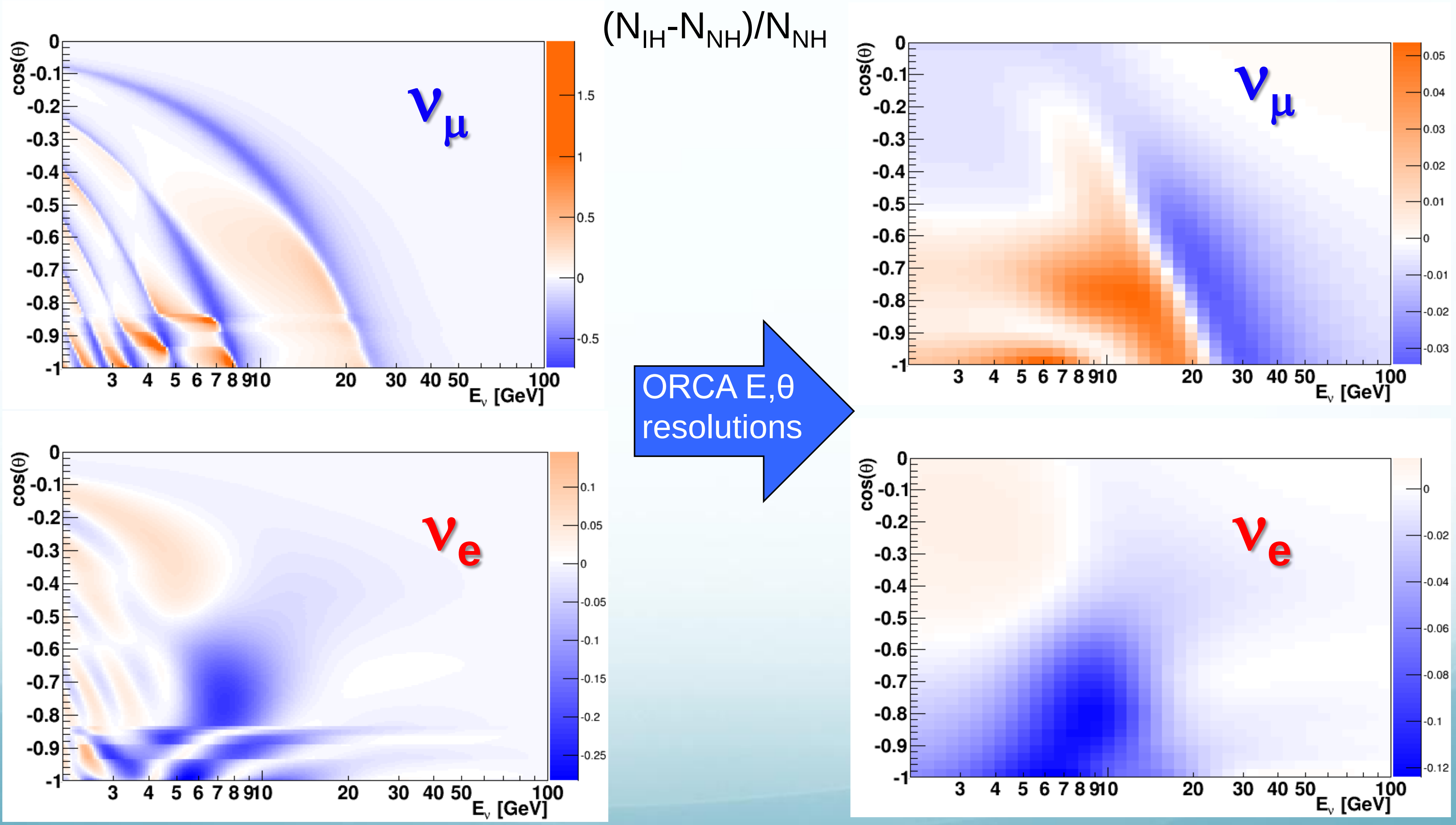


📖 S. Adrian-Martinez et al. Phys. Lett. B 714 (2012) 22.

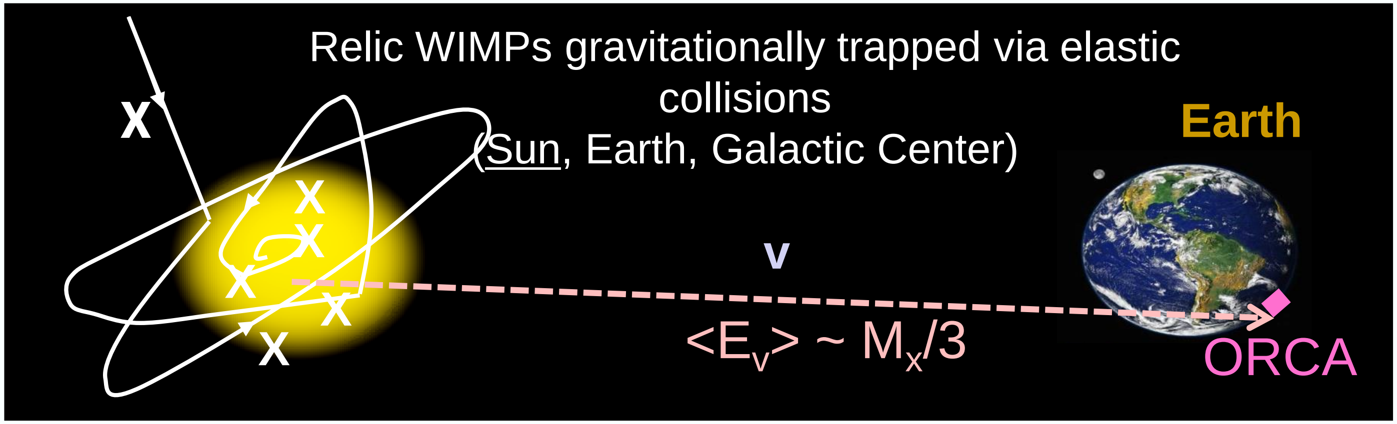
Muon versus Electron channels

Both muon- and electron-channels contribute to net hierarchy asymmetry

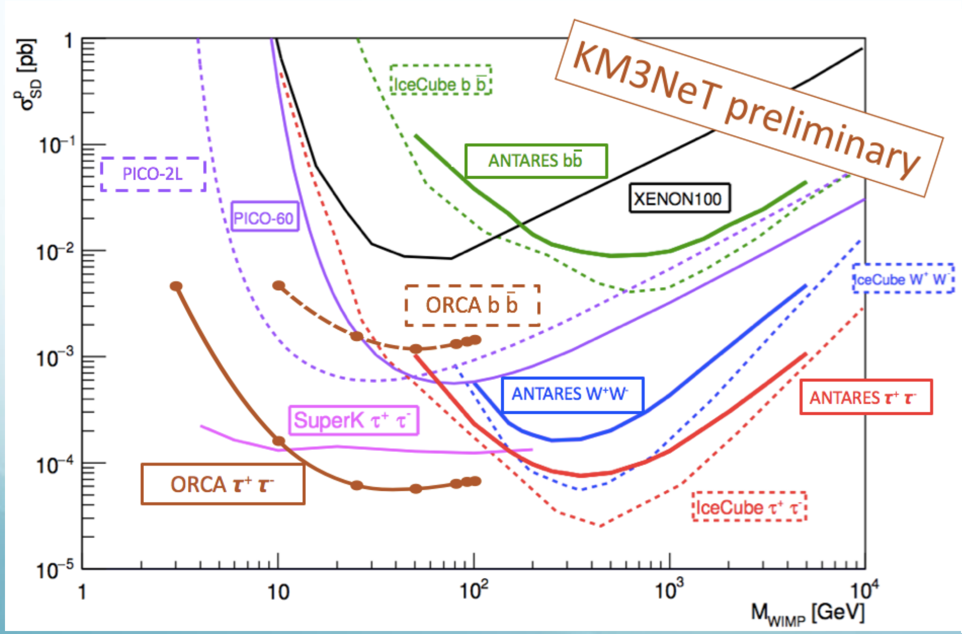
electron channel more robust against detector resolution effects:



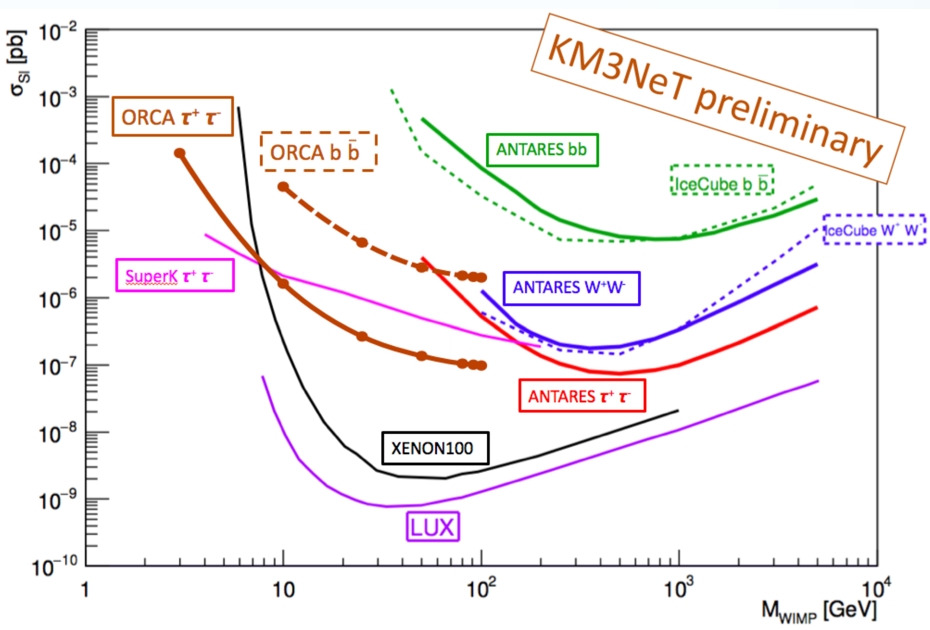
Indirect Detection of Dark Matter



Spin Dependent



Spin Independent



ORCA 3 years – tracks + showers