Measuring the neutrino mass hierarchy with KM3NeT/ORCA

Jannik Hofestädt on behalf of the KM3NeT Collaboration
15th TAUP Conference
Sudbury, Canada, 27/07/2017

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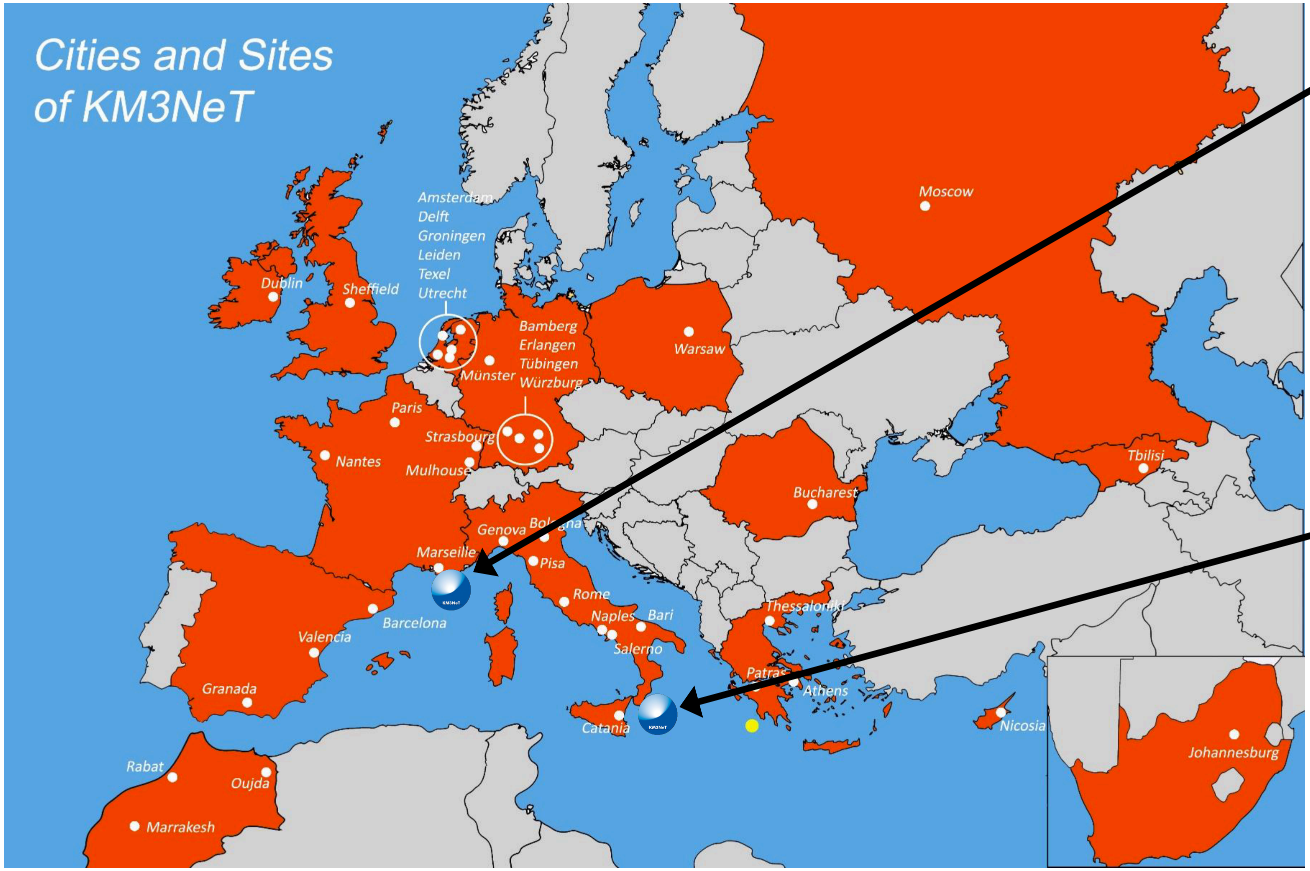
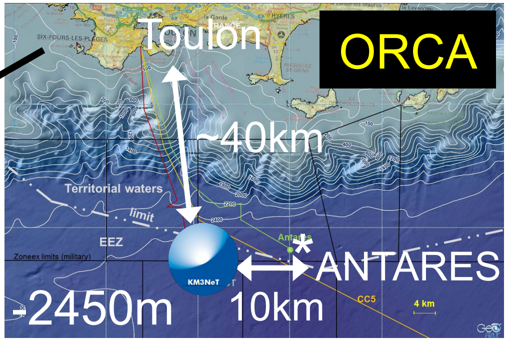
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

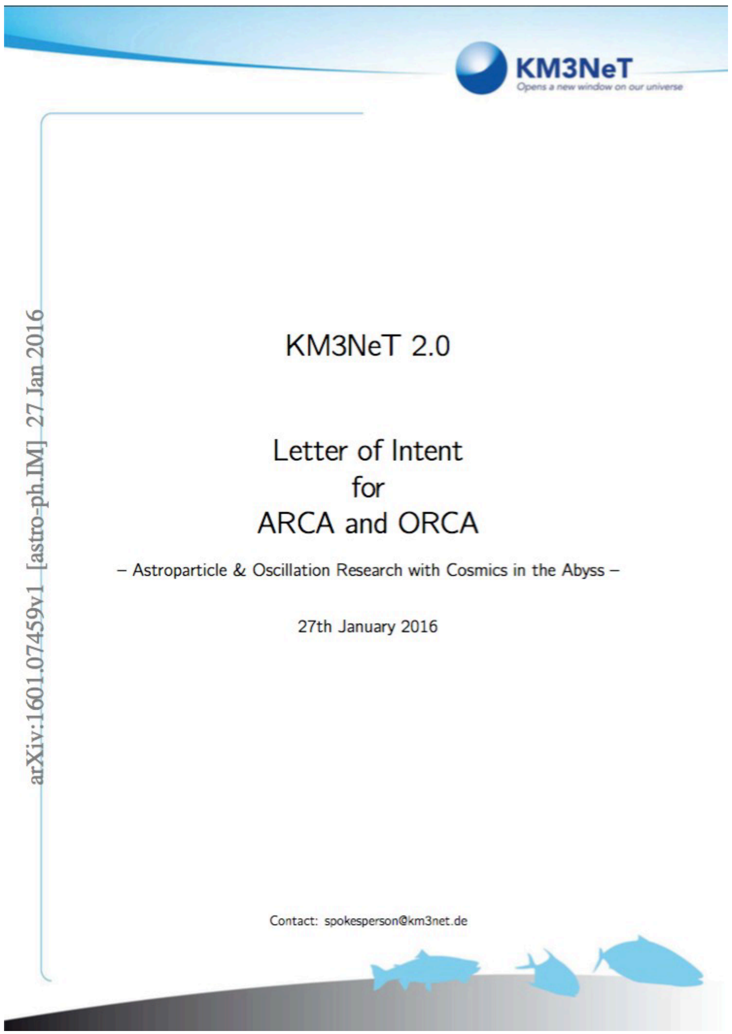
KM3NeT





Single collaboration - single technology

KM3NeT ARCA & ORCA: Objectives


KM3NeT
Opens a new window on our universe

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

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. G43 (2016) no.8, 084001

- **O**scillation **R**esearch with **C**osmics in the **A**byss (**ORCA**)
  → dense detector optimised for few-GeV atmospheric neutrinos
  → determine neutrino mass hierarchy

- **A**stroparticle **R**esearch with **C**osmics in the **A**byss (**ARCA**)
  → sparse detector optimised for TeV-PeV cosmic neutrinos
  → discover high-energy neutrino sources

☞ talk by P. Sapienza

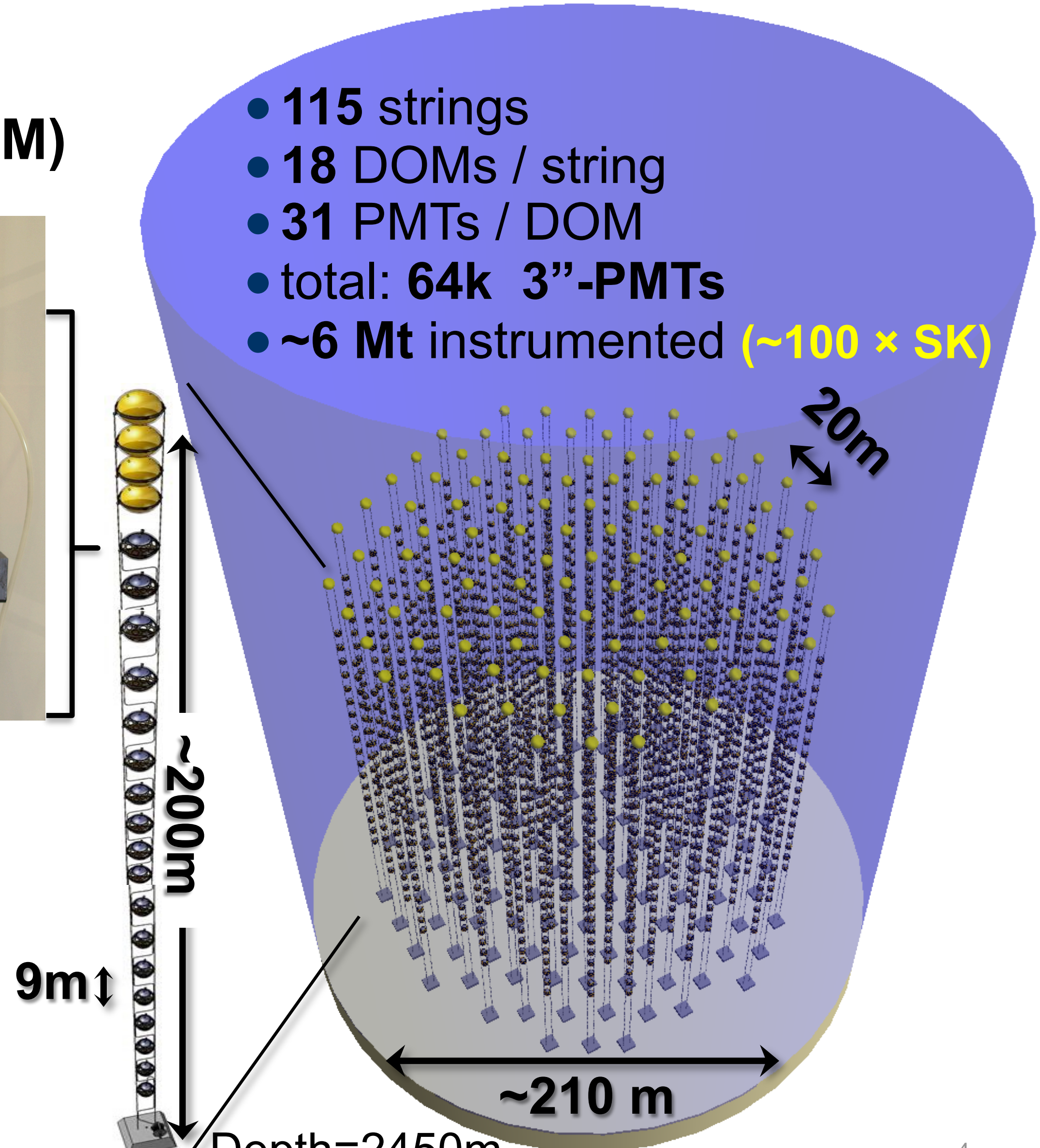
KM3NeT/ORCA Detector

Digital Optical Module (DOM)

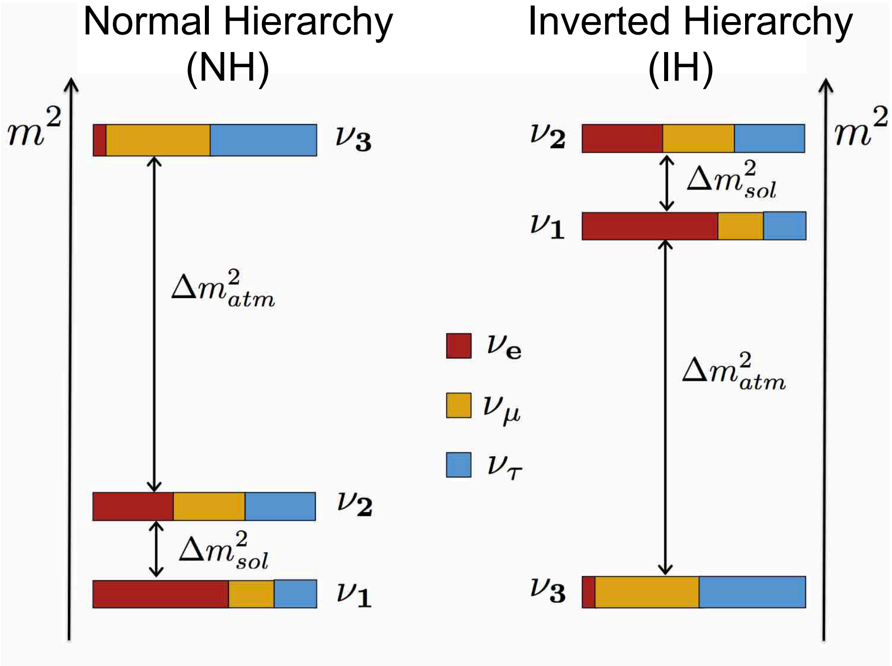
31 x 3”-PMTs
(19↓, 12↑)

- Uniform angular coverage
- Directional information
- Single photon counting

- **115** strings
- **18** DOMs / string
- **31** PMTs / DOM
- total: **64k 3”-PMTs**
- **~6 Mt** instrumented **(~100 × SK)**

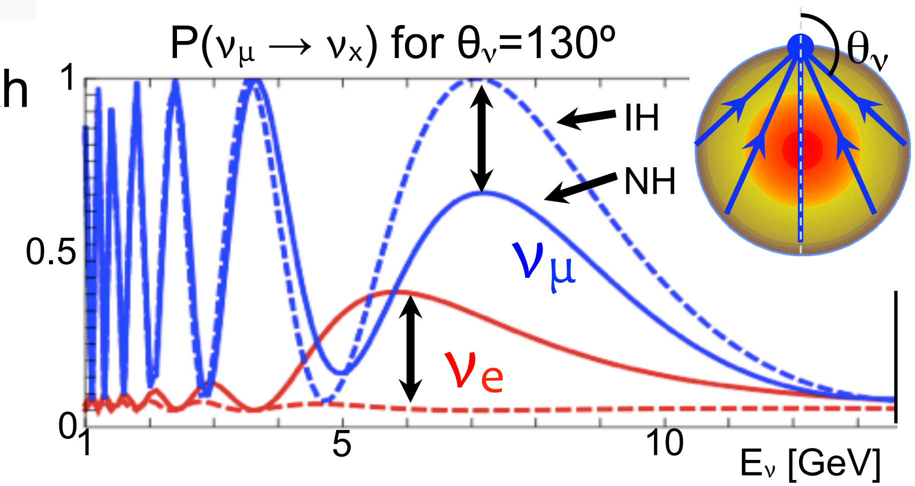


Neutrino Mass Hierarchy (Ordering)



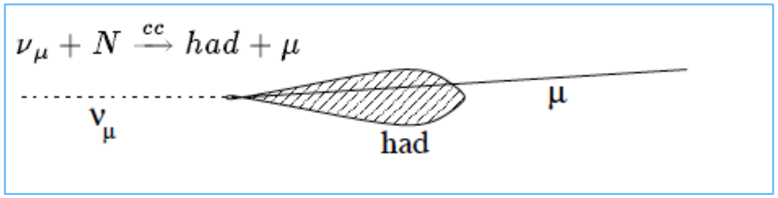
- Knowledge on mass hierarchy important for:
  - theory and cosmology
  - design and interpret other experiments (δ_{CP}, $0\nu\beta\beta$, …)

- Oscillation pattern distorted by Earth matter effects: IH ↔ NH difference
- Approach:
  measure E_ν and θ_ν of upgoing few-GeV atmospheric neutrinos, identify and count ν_μ and ν_e events

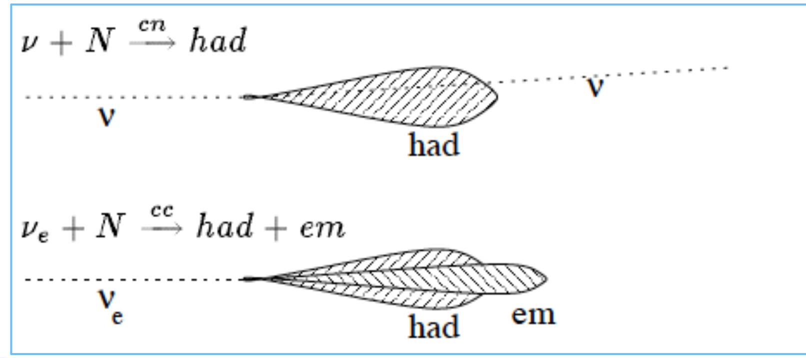


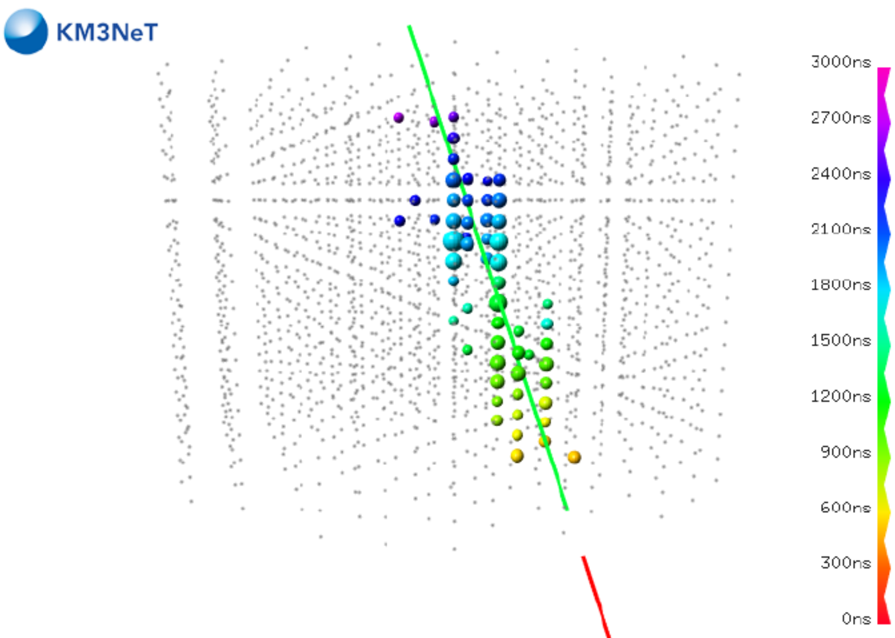
Event Topologies

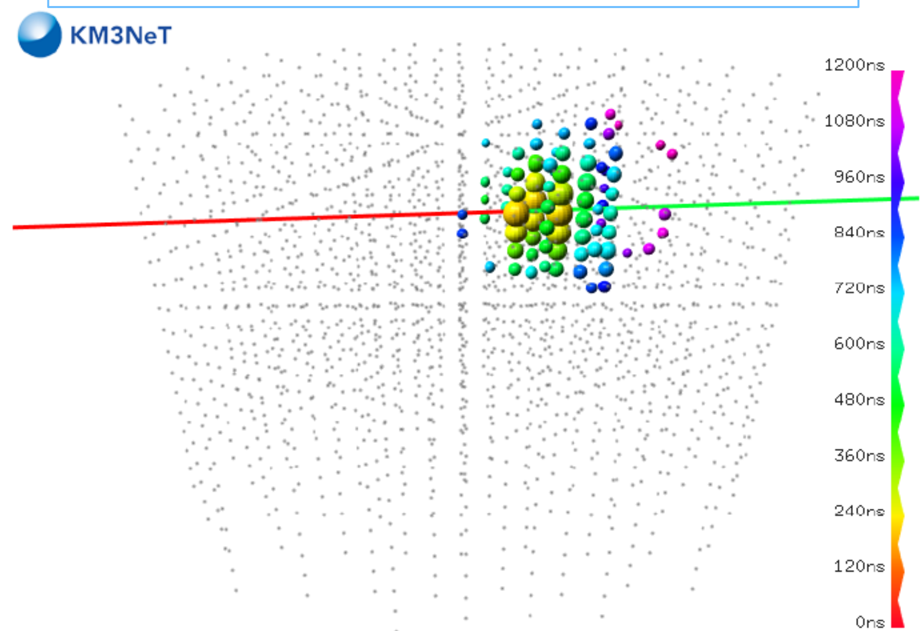
Track-like: ν_μ^{CC}, ν_τ^{CC} ($\tau\to\mu$)



Shower-like: ν_e^{CC}, ν^{NC}, ν_τ^{CC} ($\tau\to$ ~~μ~~)







ARCA simulation, TeV neutrino energies

ORCA Detector Performance

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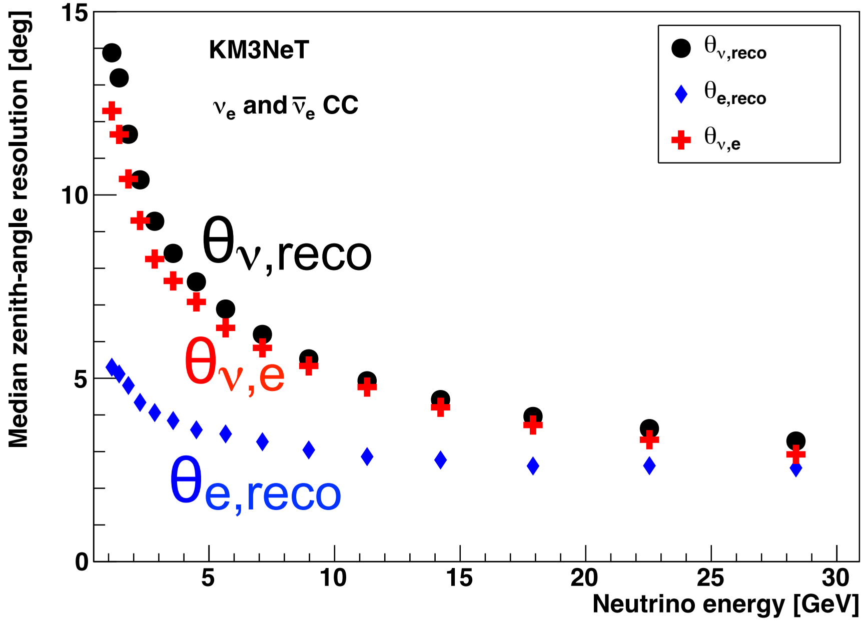
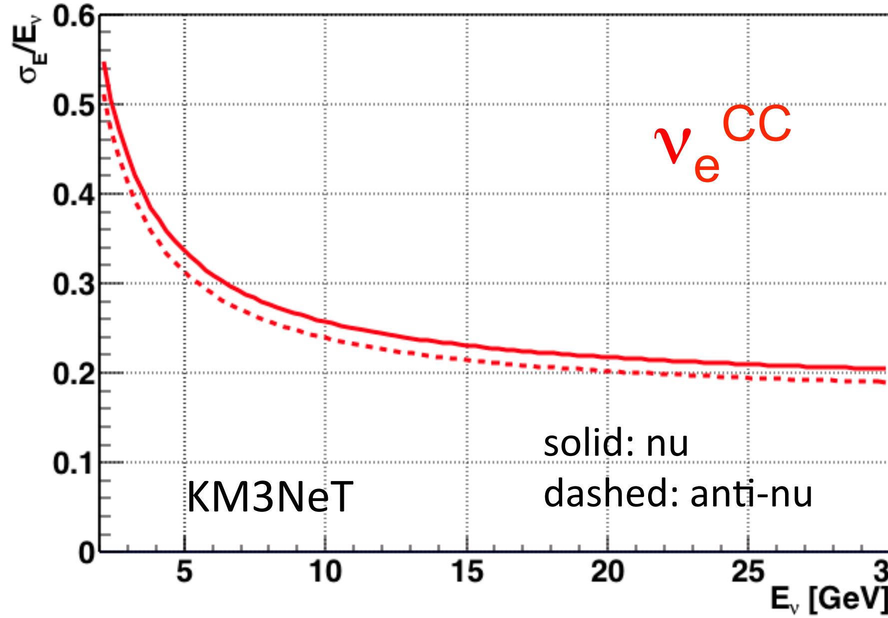
Illustration plots show shower channel (similar for track channel)





Zenith-angle resolution: 5° @10GeV
(dominated by ν-lepton kinematics)

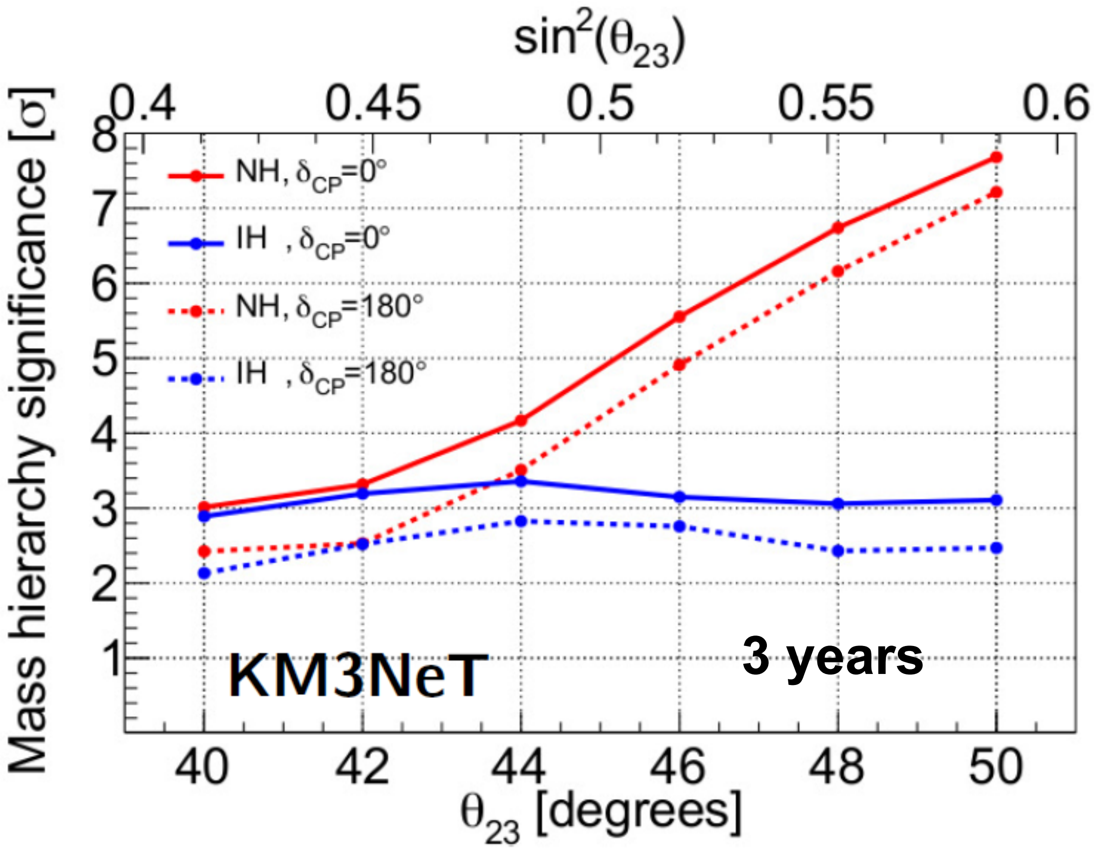
Energy resolution: 25% @10GeV
(dominated by light yield fluctuations)

Event classification:
90% (70%) correct classified
ν_eCC (ν_μCC) @10GeV

~50k events/yr:
ν_eCC: 17,300
ν_μCC: 24,800
ν_τCC: 3,100
NC: 5,300

Sensitivity to Mass Hierarchy

- Method: log-likelihood ratio test, including systematics
- **3σ median significance after 3-4 years**
- Best case (NH, θ_{23} upper octant): >5σ after 3 years
- Value of δ_{CP} has small but non-negligible impact on sensitivity



Sensitivity to $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$

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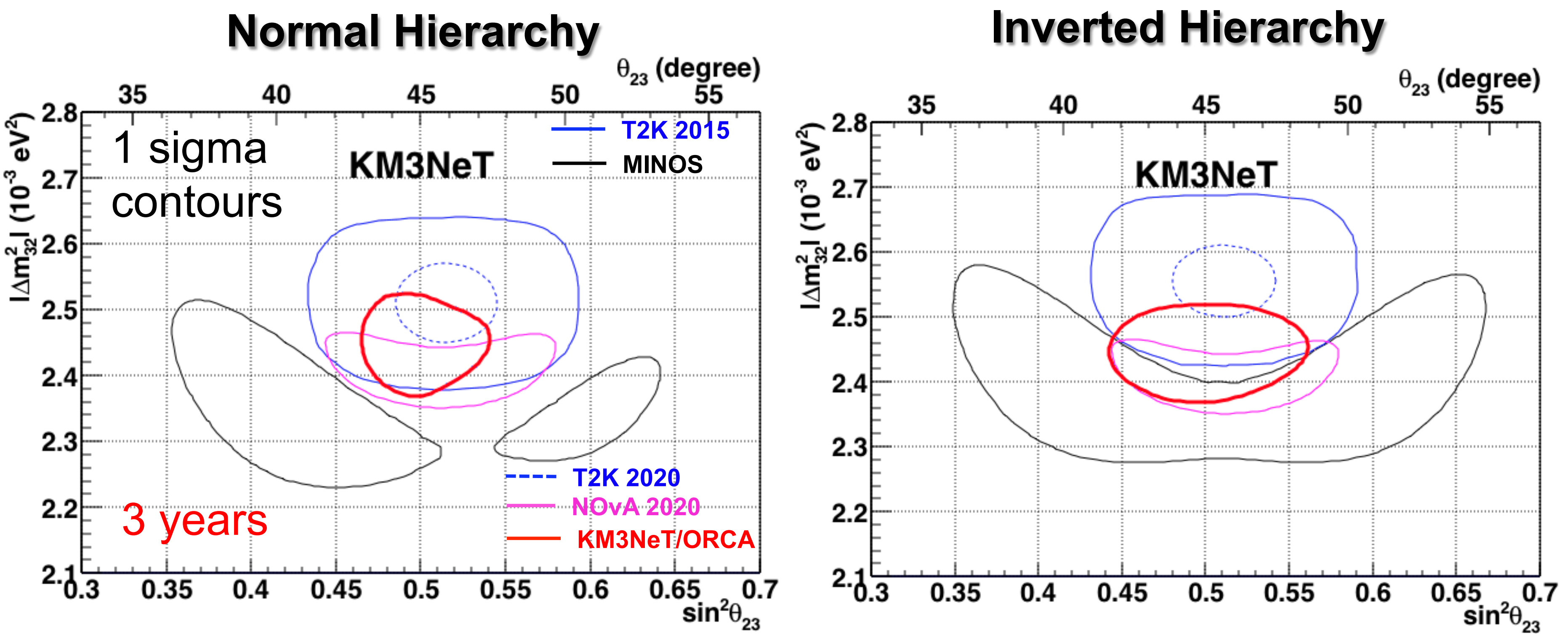
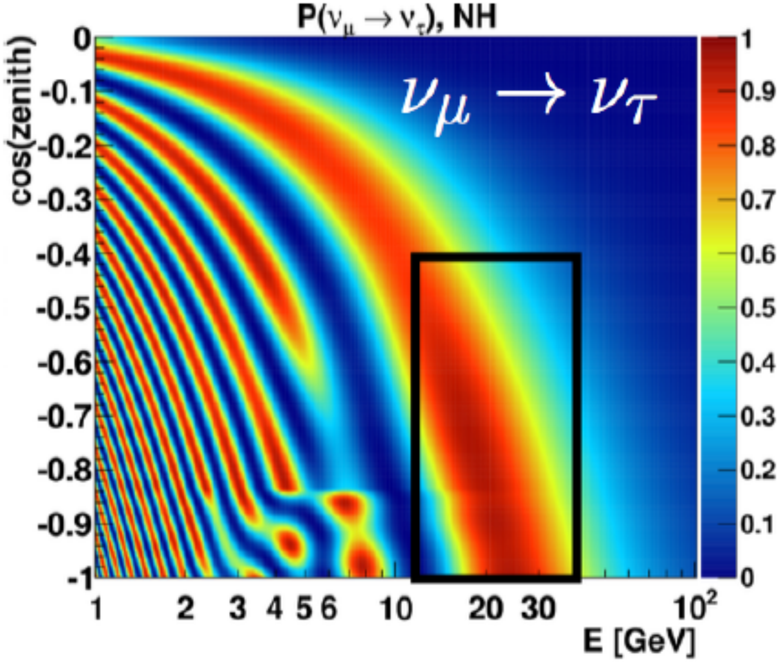
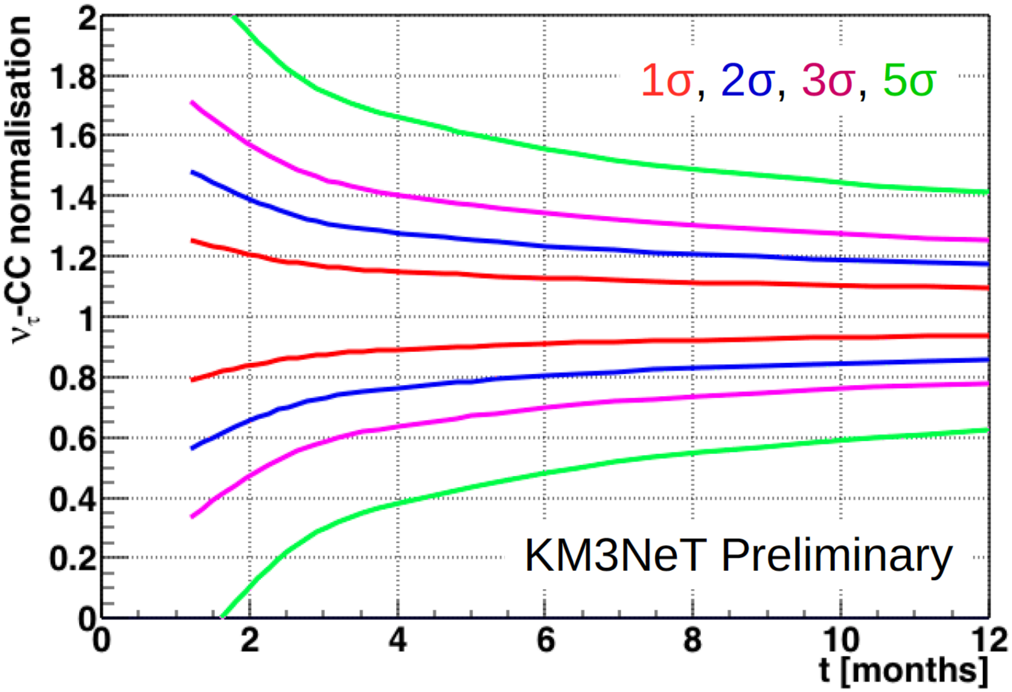
- Achieve 2-3% precision in $|\Delta m^2_{32}|$ and 4-10% in $\sin^2\theta_{23}$
- Competitive with NOvA and T2K projected sensitivity in 2020



Tau Neutrino Appearance

- ν_τ appearance tests unitarity of 3ν-mixing matrix
- ~3k ν_τ^{CC} events / year with full ORCA
- Rate constrained to ~10% after 1year
- Early physics result





← unitarity

← no appearance

☞ PoS (ICRC2017) 1025

Additional ORCA Science Topics

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- Sterile neutrinos & non-standard interactions
- Earth tomography and composition
- Supernovae monitoring
- Indirect search for Dark Matter

Presented at ICRC2017:
☞ PoS (ICRC2017) 1027
☞ PoS (ICRC2017) 1020
☞ PoS (ICRC2017) 1142

- Low-energy (GeV-TeV) neutrino astrophysics

- Earth and Sea science
  → oceanography, bioluminescence, bioacoustics, seismology

- Possible future options to measure δ_{CP}:
  - neutrino beam from Protvino (Russia) 🕮 Brunner, arXiv:1304.6230
  - ~5x denser detector with atm. neutrinos 🕮 Razzaque & Smirnov, JHEP05(2015)139

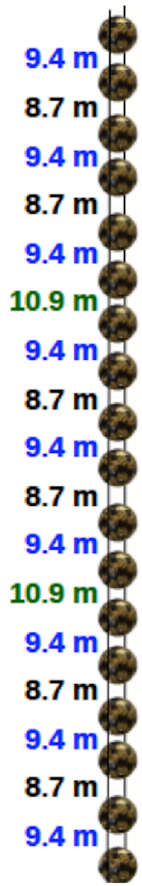
Updated Detector Simulations

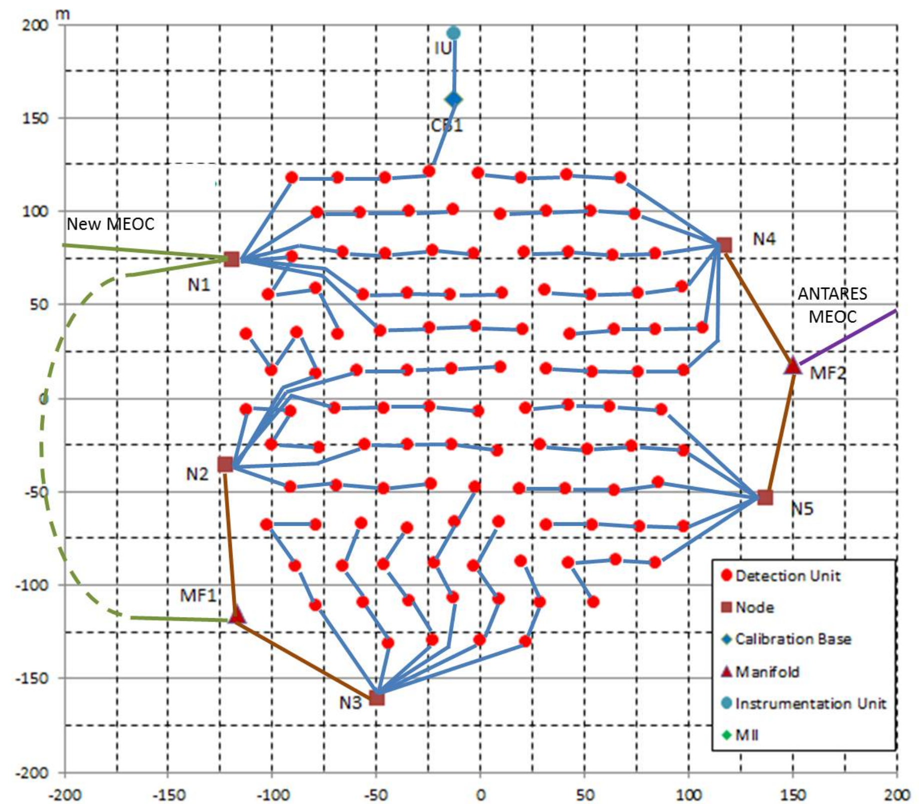
Progress since Letter of Intent (LoI):

- Significant improvements in trigger / reconstruction
- New detector layout (accounts for technical constrains):

  - realistic sequence of spacing between DOMs along string
  - 20m → 23m spacing between strings

From **5.7 Mton**
to **~8 Mton**



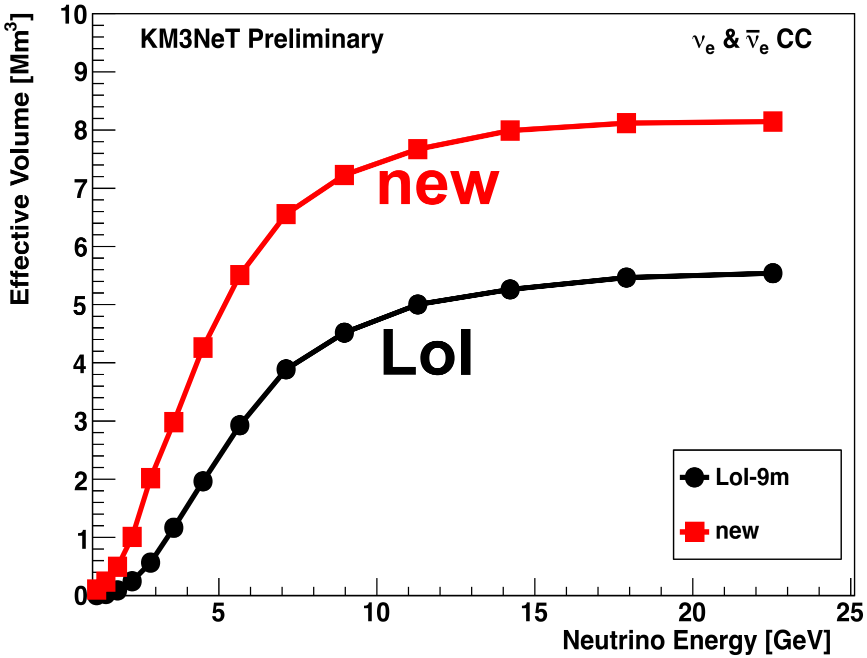


Seafloor network

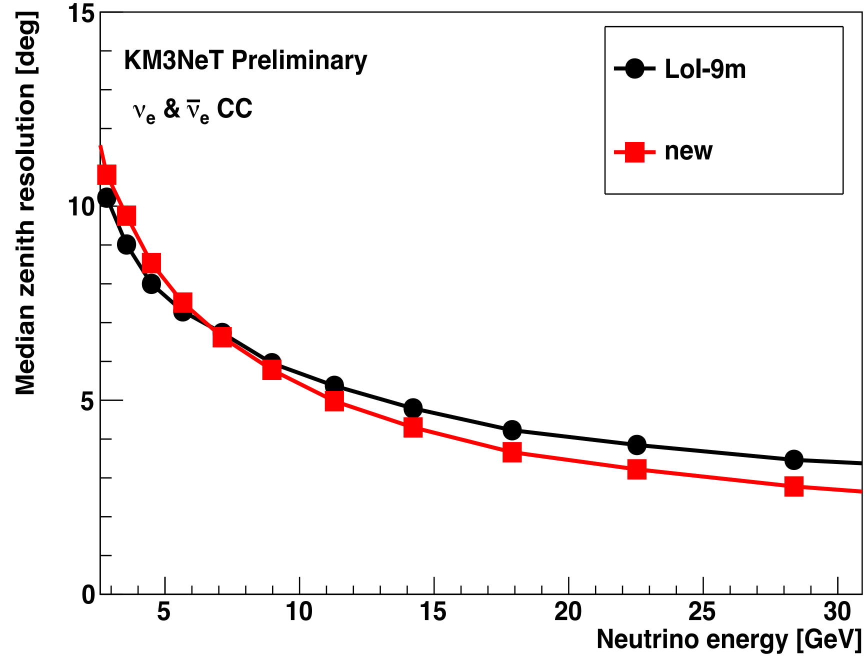
Improvements in Detector Performance

- Improved trigger and reconstruction algorithms allow for fainter events

Effective volume



Direction resolution



- Compared to LoI: 20% faster turn-on and 40% higher plateau of effective volume with similar reconstruction resolutions, despite sparser detector

→ Expect increase in sensitivity on NMH and oscillation parameters, but robust estimate requires full simulation chain (ongoing)

ORCA Timeline

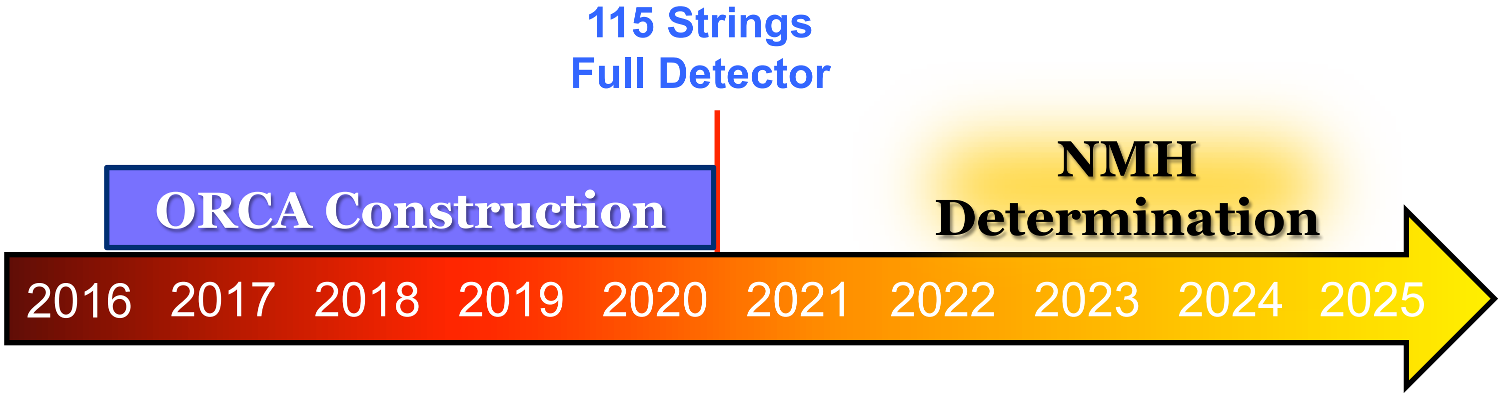
- Phase 1: few-string demonstrator

  Today: 2 strings nearly ready for deployment (scheduled Sept.)

- Phase 2:

  Full detector with 115 strings

  Completion: mid 2020



Summary and Outlook

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- ORCA: underwater Cherenkov detector optimised for few-GeV atmospheric neutrinos to determine neutrino mass hierarchy

- First 2 ORCA strings will be deployed in September

- With ORCA, 3σ NMH sensitivity in 3-4 years feasible, competitive measurements of $|\Delta m^2_{32}|$ & $\sin^2\theta_{23}$ and rich additional science program

- Recent improvements in trigger & reconstruction
  → **Stay tuned for sensitivity update!**

Thank you for your attention !

DFG Deutsche Forschungsgemeinschaft

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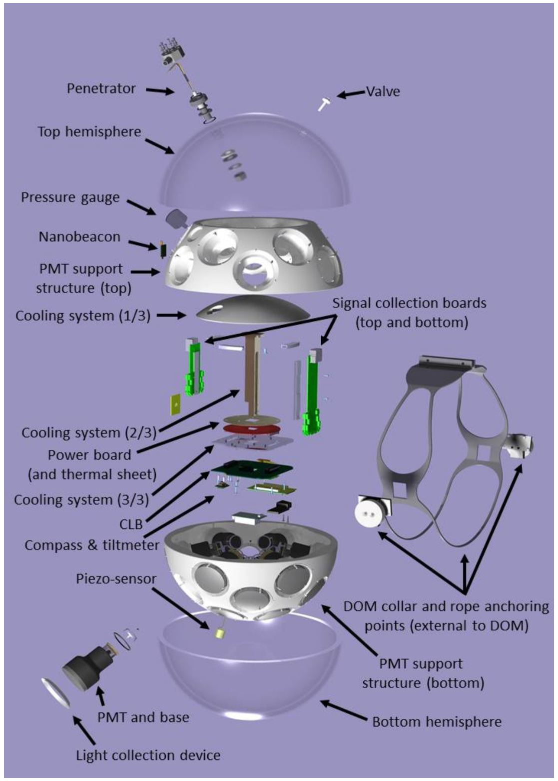
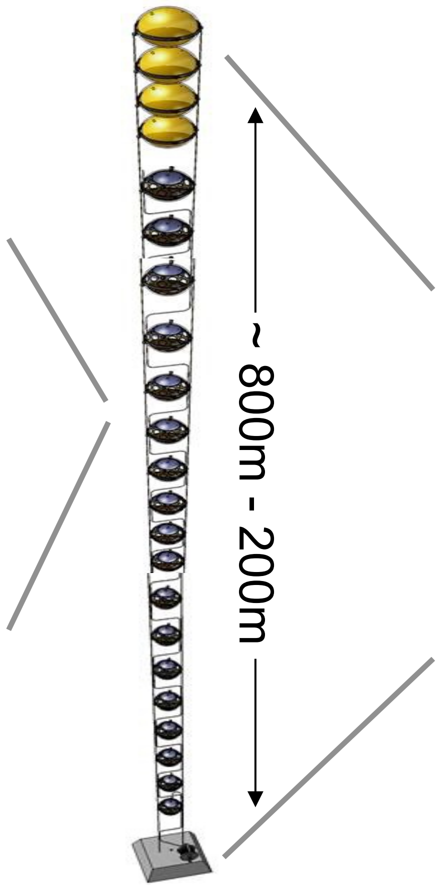
KM3NeT Technology

Digital Optical Module



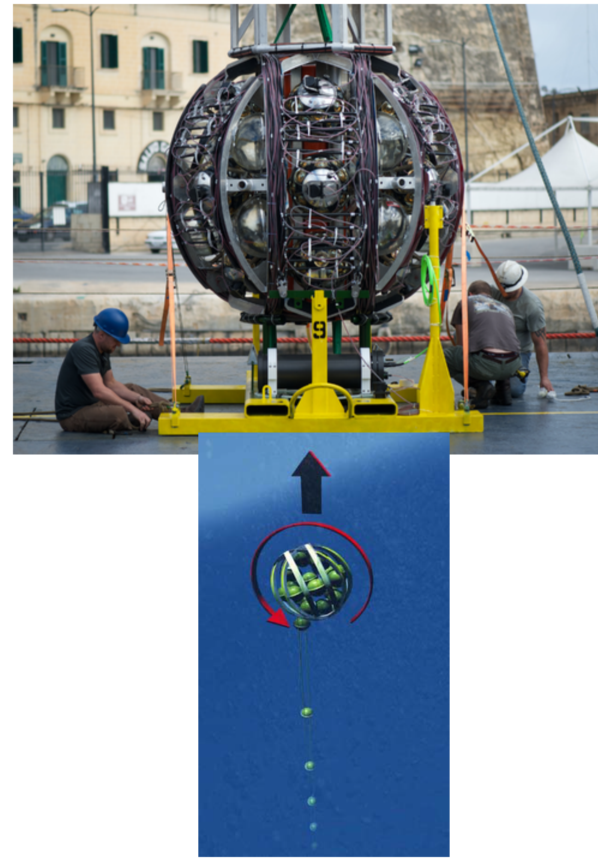
- All data to shore
- Gbit/s on optical fibre
- Hybrid White Rabbit
- LED flasher & acoustic piezo
- Tiltmeter/compass

String



- 2 dyneema ropes
- Oil filled PVC tube
- Low drag
- Low cost

Deployment Vehicle

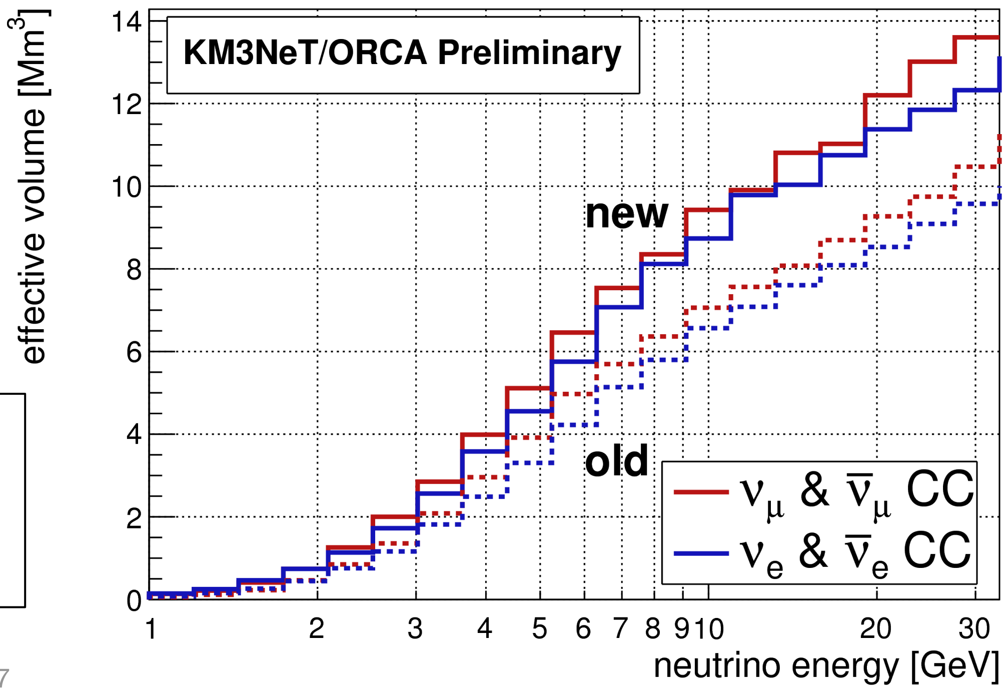


- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reuseable

Improvements in Trigger

- Addition of new trigger:
  - before: cluster of 3-4 causally connected L1 hits (≥2-fold coincidence on same DOM)
  - now: one L1 plus causally-connected hits in vicinity (do not have to be coincidences)
- Keep bandwidth requirements: trigger rate from pure-noise smaller than irreducible trigger rate from atmospheric muons (~50Hz)

Increase of effective volume also at low energies despite sparser detector



Mass Hierarchy Sensitivity Analysis

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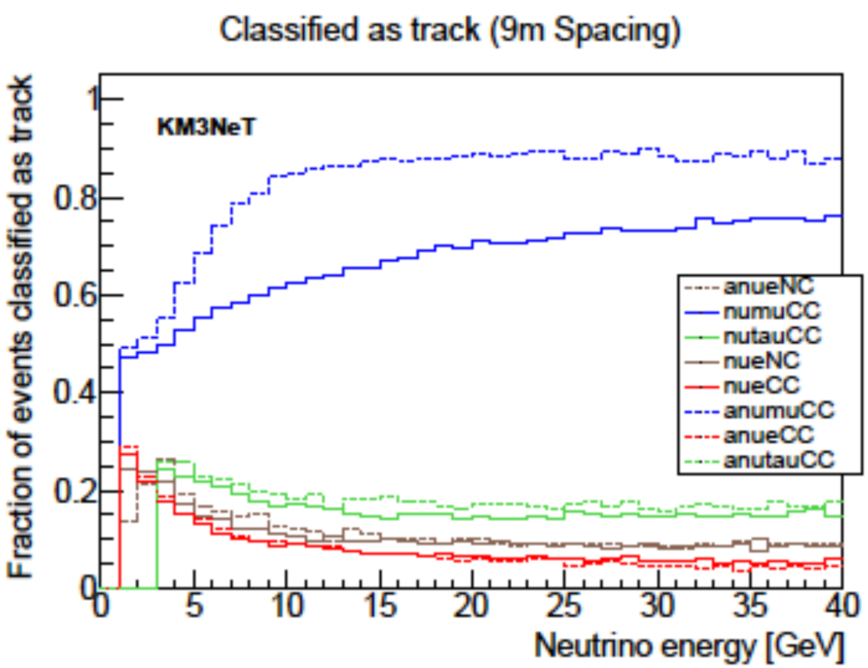
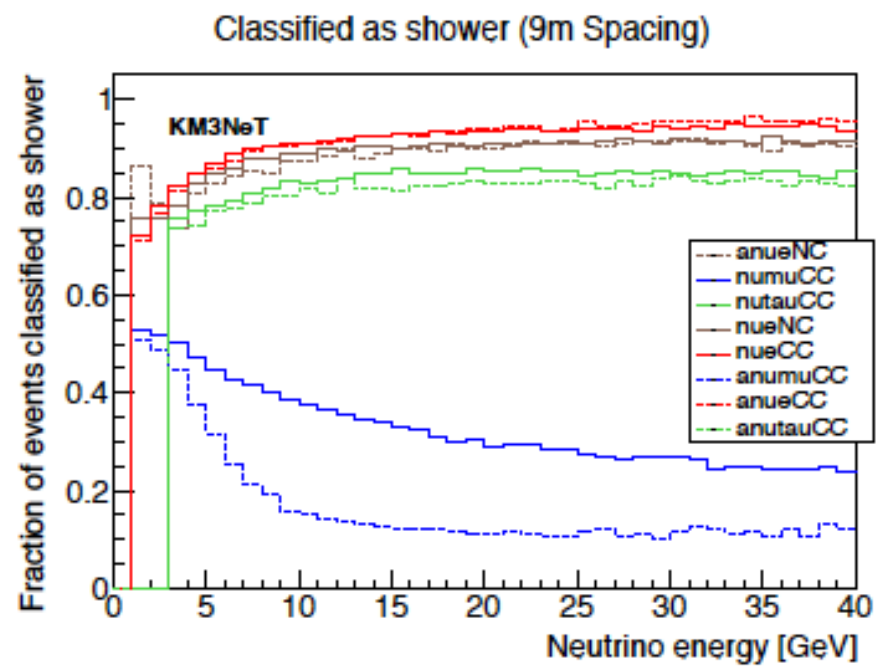
- Based on pseudo-experiments
- Combined fit of neutrino mass hierarchy, oscillation parameters and other nuisance parameters
- Sensitivity from log-likelihood ratio (L_{NH}/L_{IH})

	parameter	*true value distr.*	*initial value distr.*	*treatment*	*prior*
nu parameters	θ_{23} [°]	$\{40, 42, \ldots, 50\}$	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
systematics	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

Shower / Track Identification

- Discrimination of track-like and shower-like events via Random Decision Forest

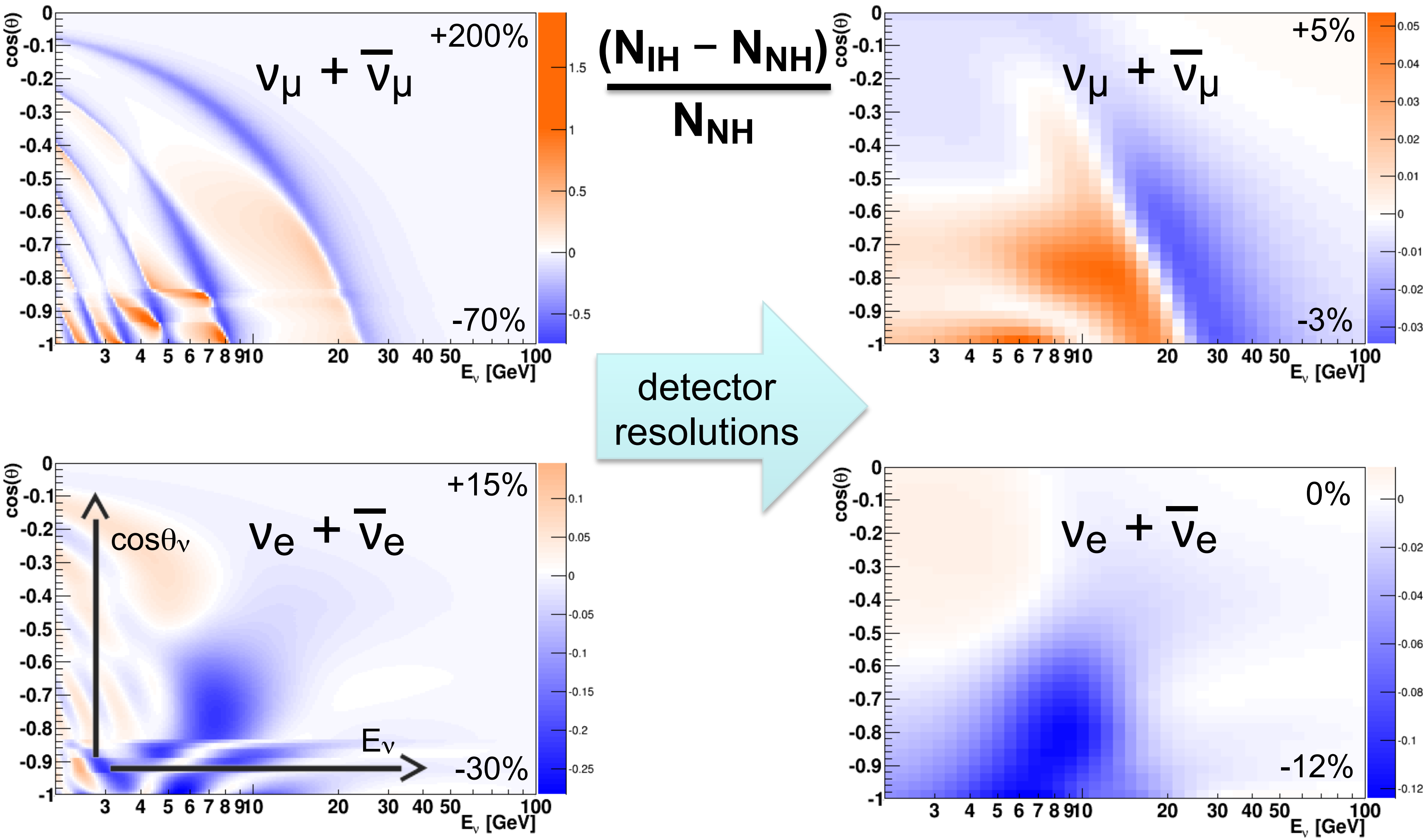




At 10 GeV:

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

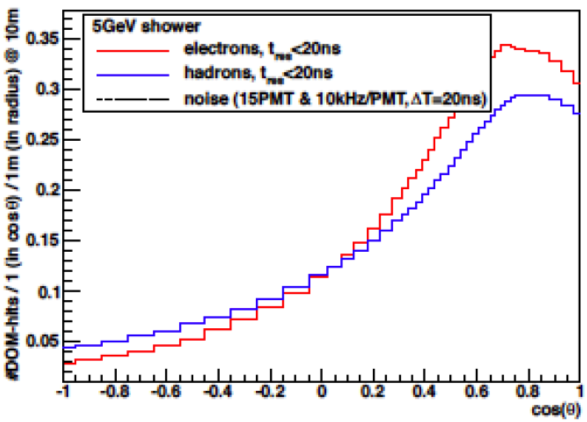
Signature for Neutrino Mass Hierarchy



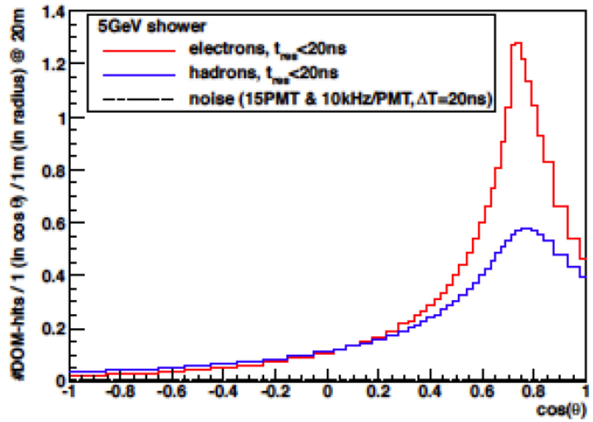
Both $\overset{(-)}{\nu}_e$ & $\overset{(-)}{\nu}_\mu$ channel contribute; largest NH-IH asymmetry from 5-12GeV $\overset{(-)}{\nu}_e$

Signal over Background

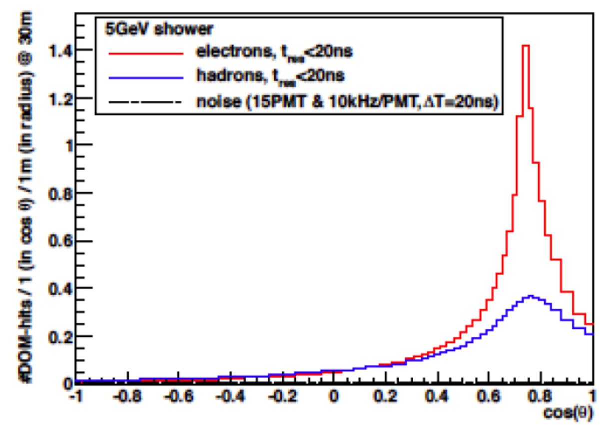
J. Hofestädt, PhD thesis (2017)



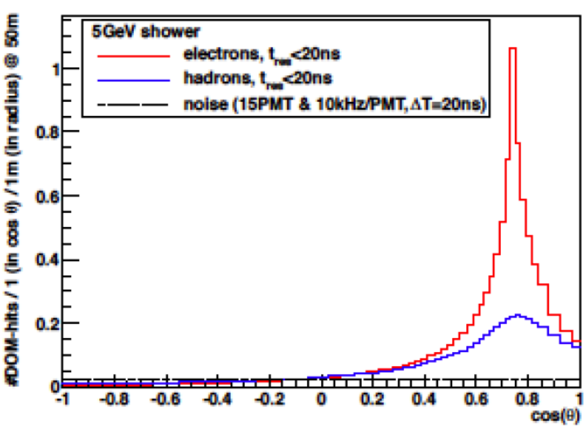
(a) 10 m



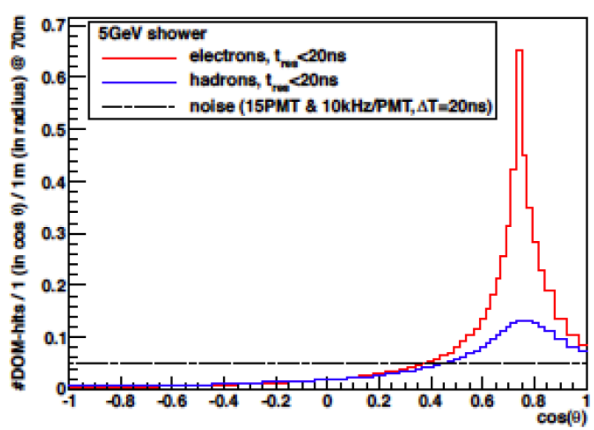
(b) 20 m



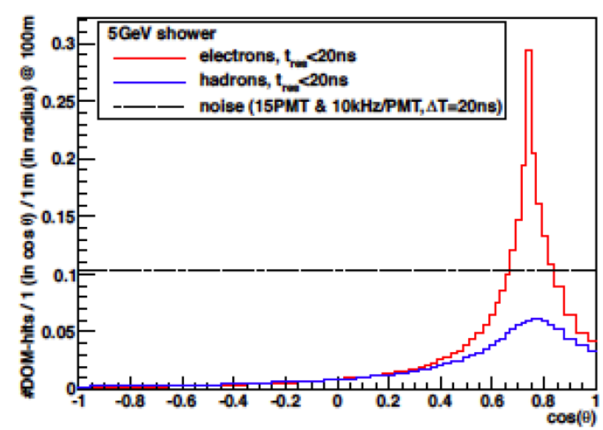
(c) 30 m



(d) 50 m

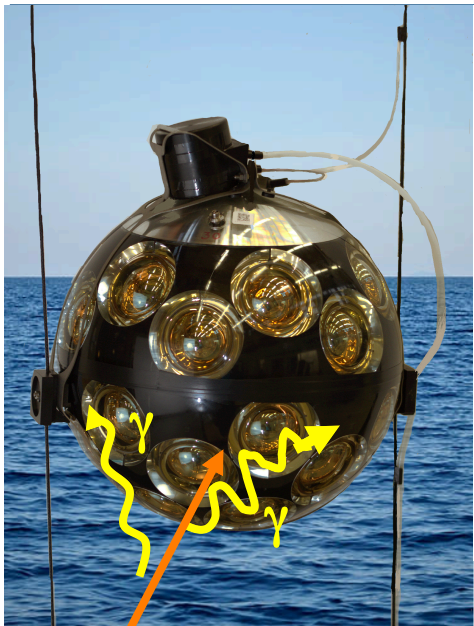


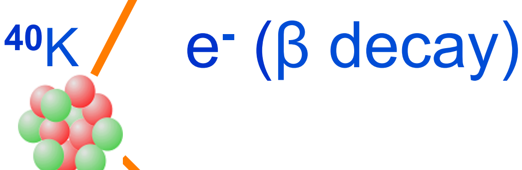
(e) 70 m

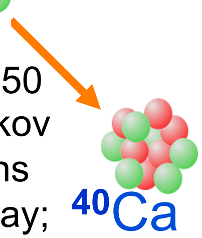


(f) 100 m

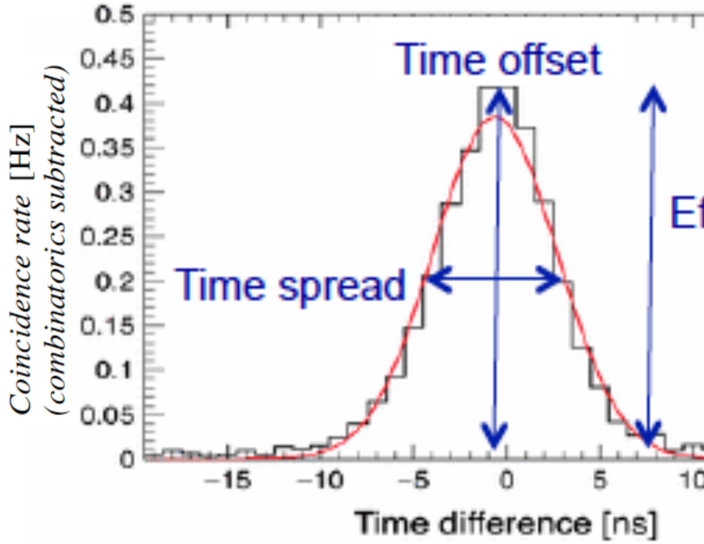
K40: Inter-PMT Calibration

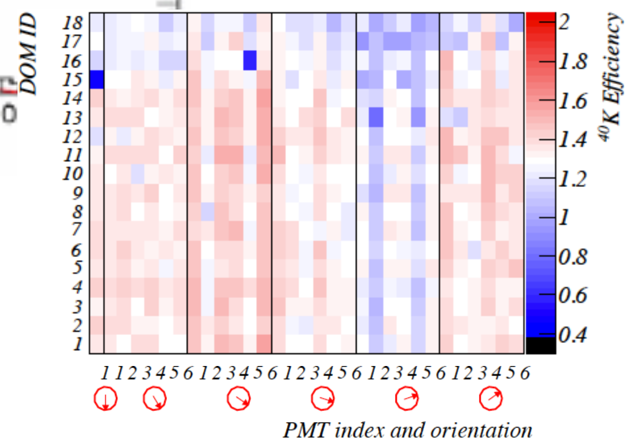


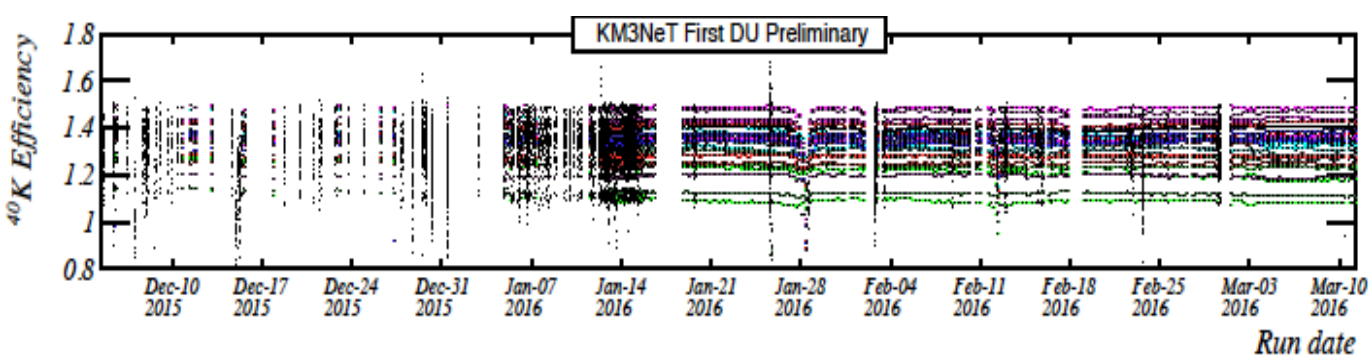




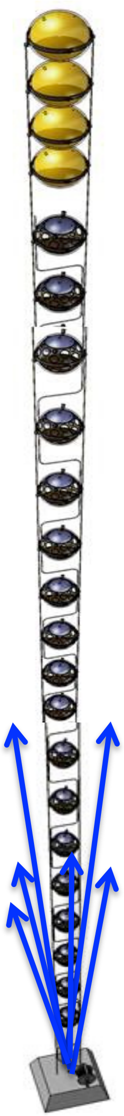
Up to 150 Cherenkov photons per decay; stable ^{40}K concentration

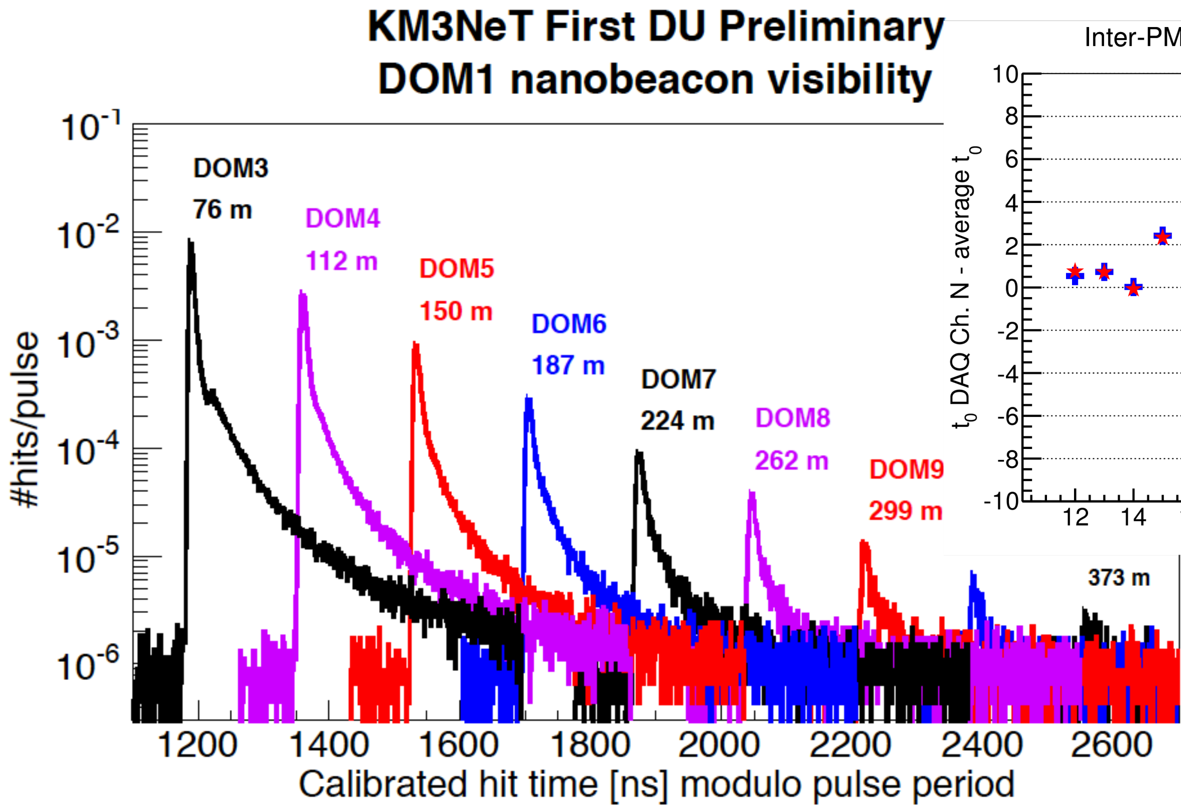


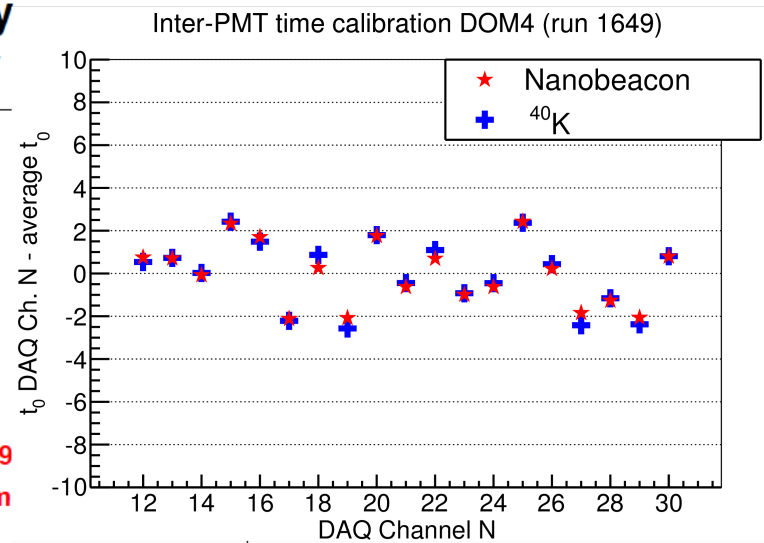




Nanobeacon: Inter-DOM Calibration

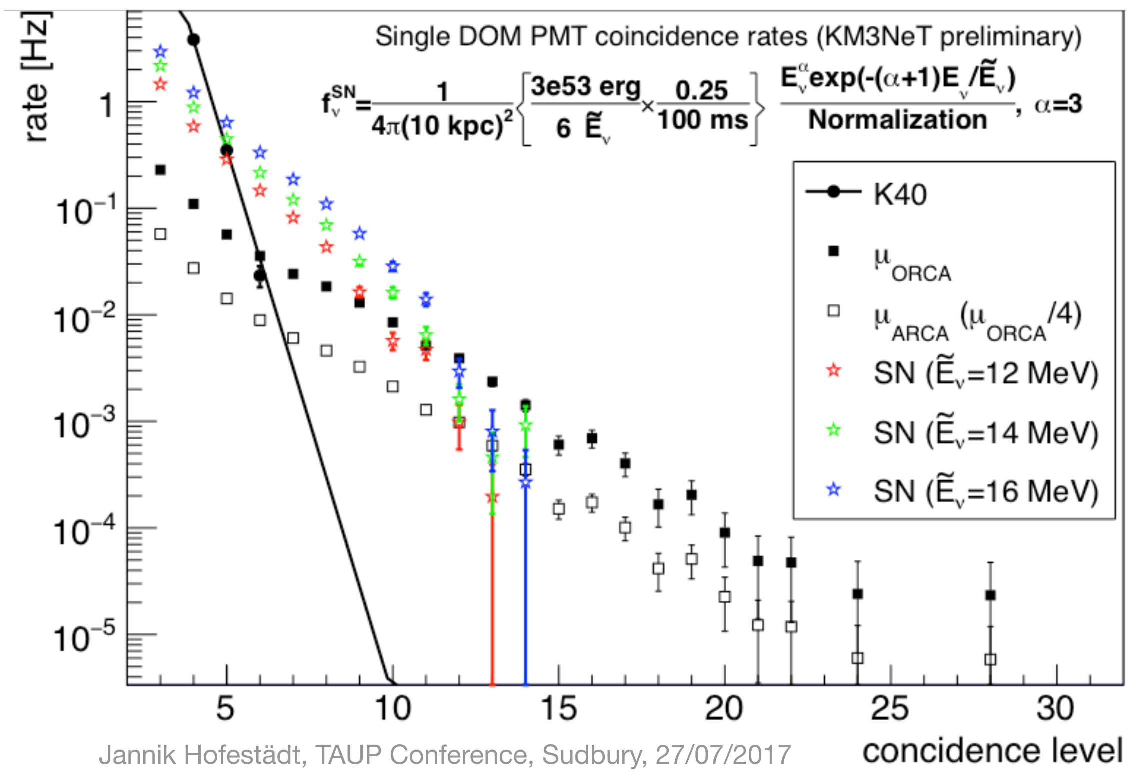






KM3NeT Supernovae Sensitivity

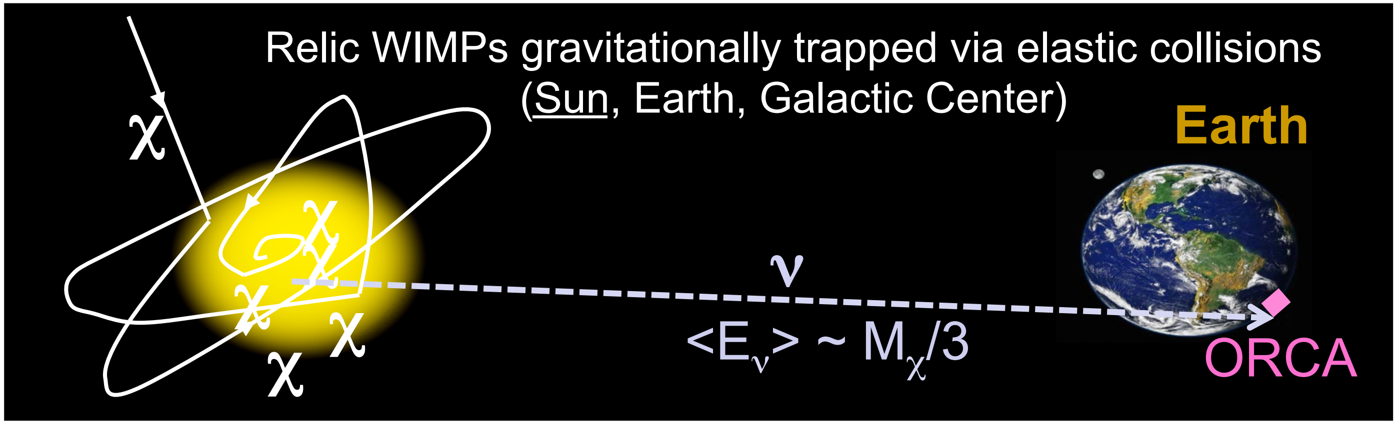
- Simulation (SN1987A-like): 10 kpc, 3 10^{53} erg, 1/6 in $\bar{\nu}_e$, 25% in the first 100 ms
- Spectra: $f = E_\nu^\alpha e^{-(\alpha+1)E_\nu/\tilde{E}_\nu}$, α=3, $\tilde{E}_{\bar{\nu}_e}$= 12, 14 & 16 MeV
- Supernova coincidence distribution is harder than ^{40}K but softer than muons
- Best sensitivity for PMT coincidence level greater than 6



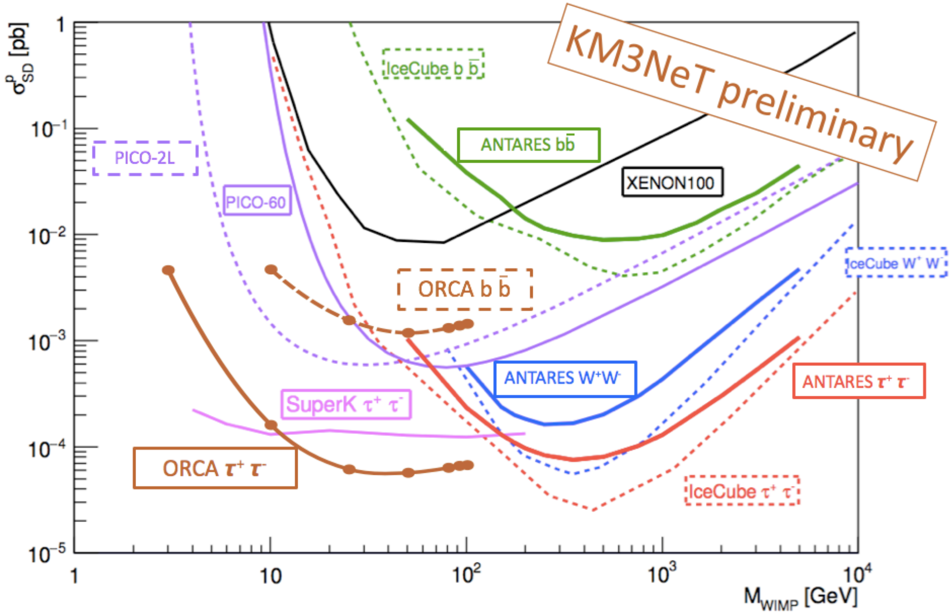
$\tilde{E}_{\bar{\nu}_e}$ MeV	N_{ev} per block	$D_{5\sigma}$ (kpc) ARCA	$D_{5\sigma}$ (kpc) ORCA
12	60	23	16
14	100	29	19
16	150	37	24

>80% of all Galactic SN with a single building block

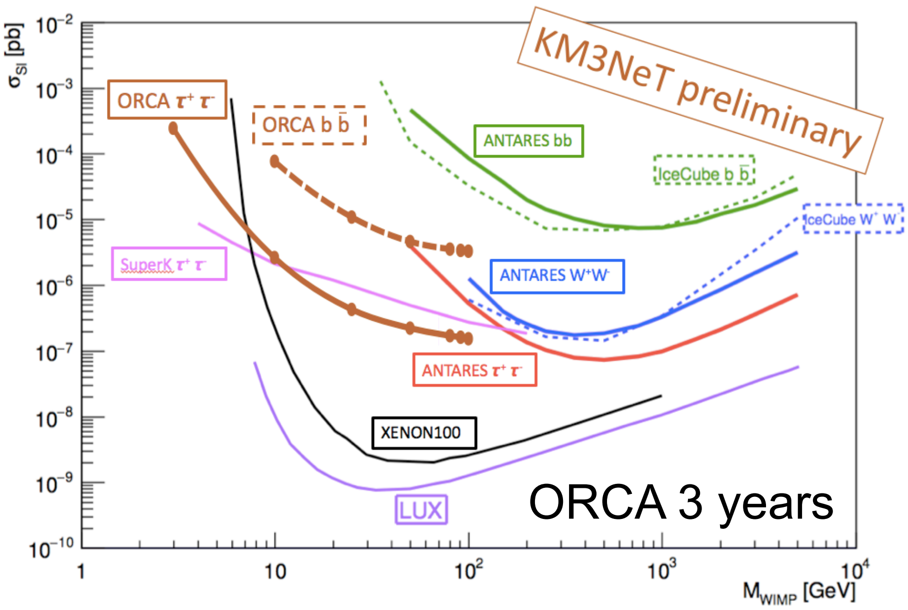
Indirect Detection of Dark Matter



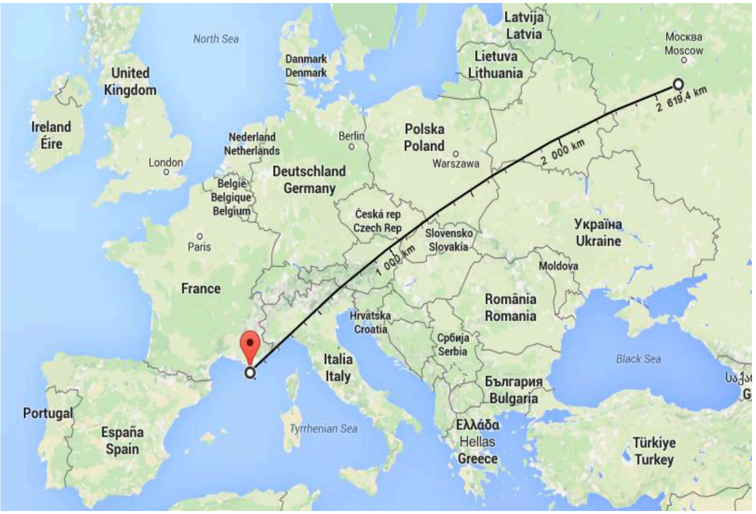
Spin Dependent



Spin Independent



P2O: Protvino to ORCA



- U70 proton accelerator in Protvino
  $E = 70$ GeV
- Proposed intensity upgrade
  P = **450 kW**
  - Up to **4.10^{20} POT / year**
- ν_e appearance at **L = 2600 km**
- Target energy range : **3-8 GeV**
- Optimal baseline for separating NMH from δ_{CP}