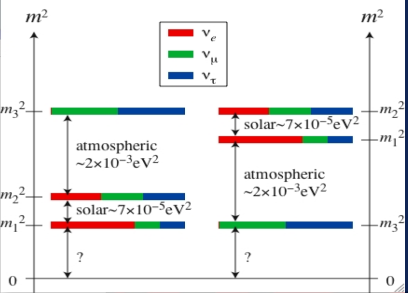
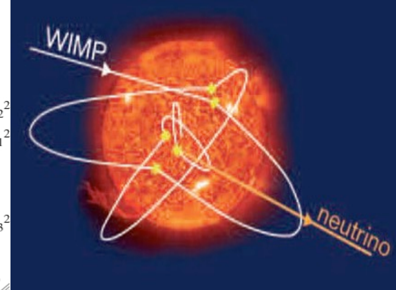




KM3NeT

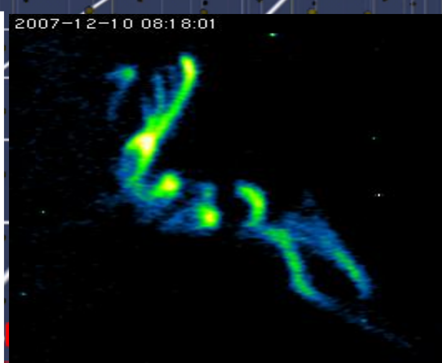
KM3NeT: Astroparticle and Oscillation Research in the Abyss

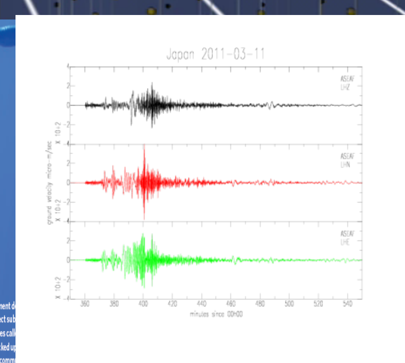
IceCube Particle Astrophysics Symposium

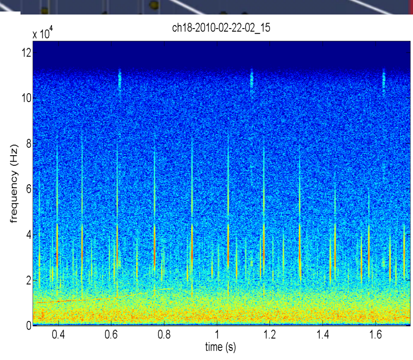
9/5/17

Paschal Coyle
Centre de Physique des Particules de Marseille

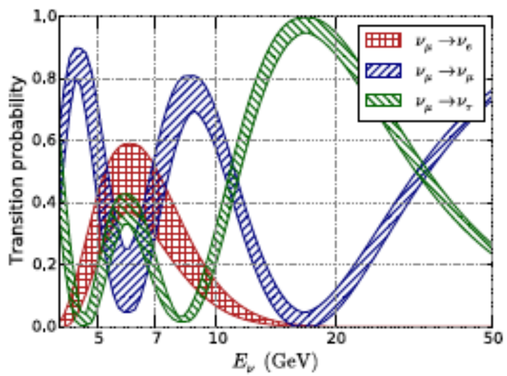
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

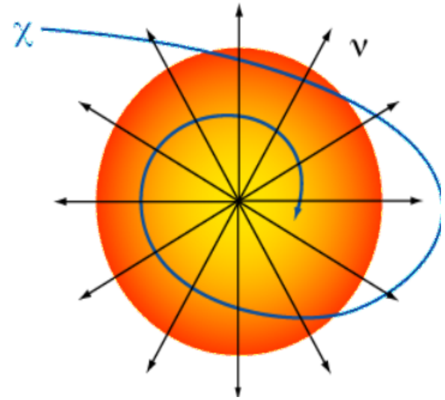


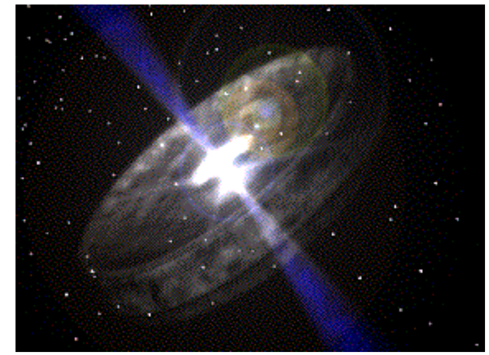





Neutrino telescopes: science scope







Low Energy	Medium Energy	High Energy
MeV < E_ν < 100 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV

ν Oscillations
ν Mass hierarchy
Supernova

Dark matter search
Monopoles, nuclearites,…

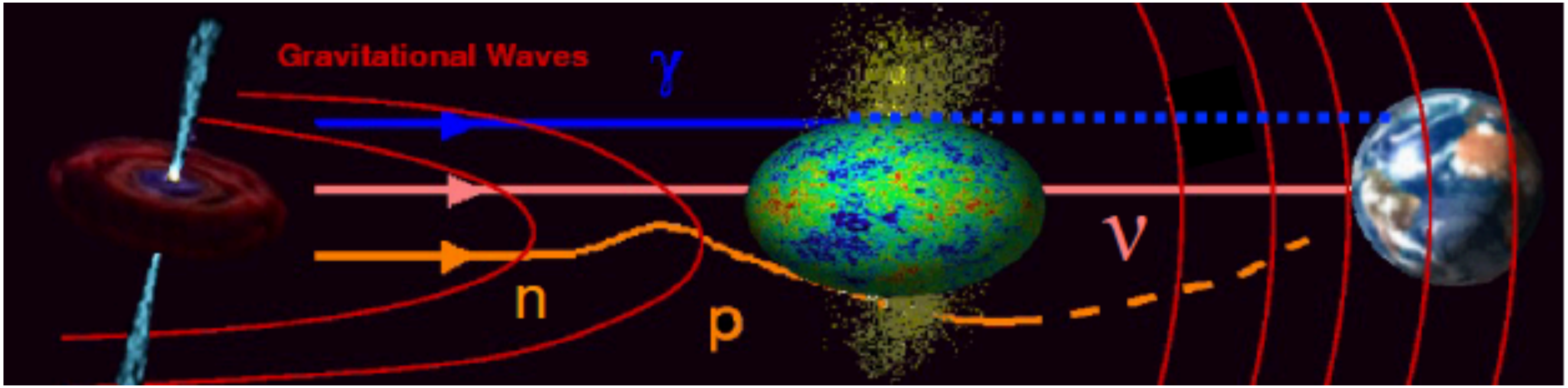
ν from extra-terrestrial sources

Origin and production mechanism of HE CR

KM3NeT-ORCA — ANTARES — KM3NeT-ARCA

+ oceanography, biology, seismology,…

Neutrinos: cosmic messengers



Neutrinos: neutral, stable, weakly interacting

not absorbed by background light/CMB ➔ access to full energy range
not absorbed by matter ➔ access to dense environments
not deviated by magnetic fields ➔ astronomy over cosmological distances

'Smoking gun' signature for hadronic processes

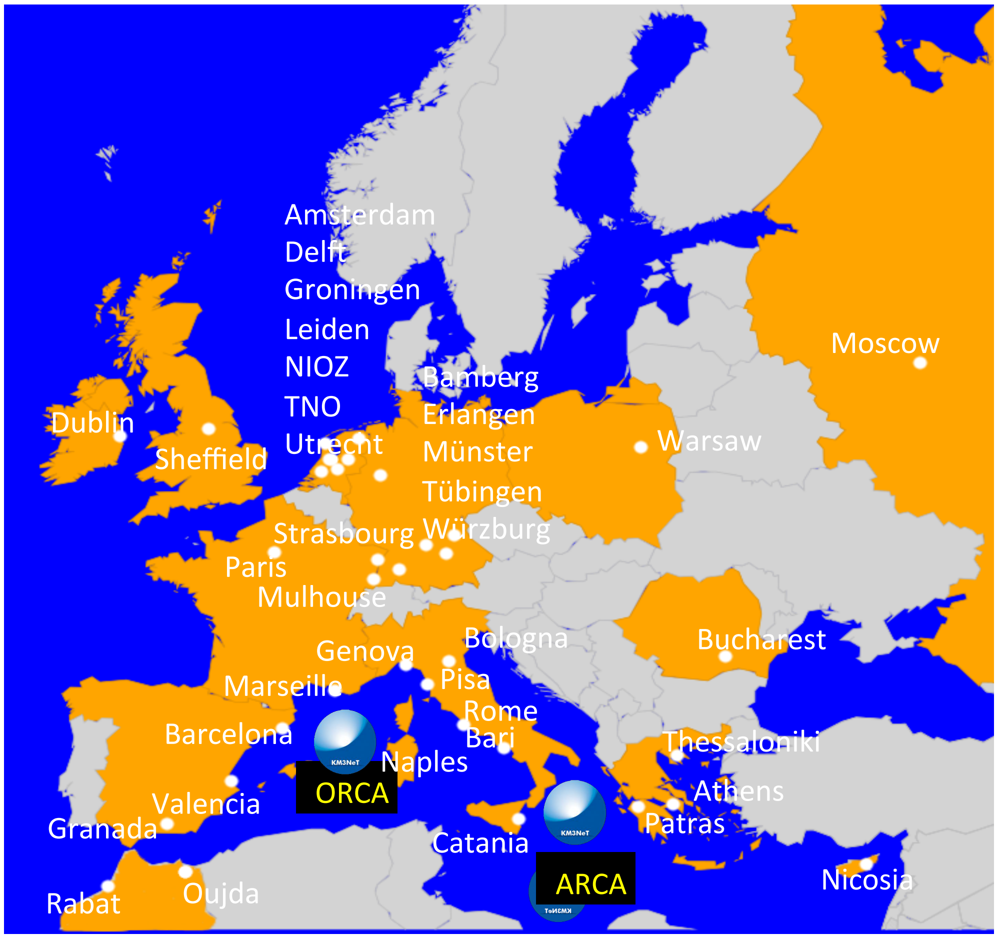
Correlated in time/direction with electromagnetic and gravitational waves

KM3NeT/IceCube: complementary fields of view

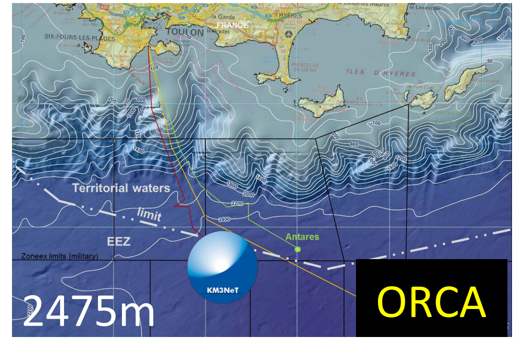
KM3NeT

Multi-site, deep-sea infrastructure

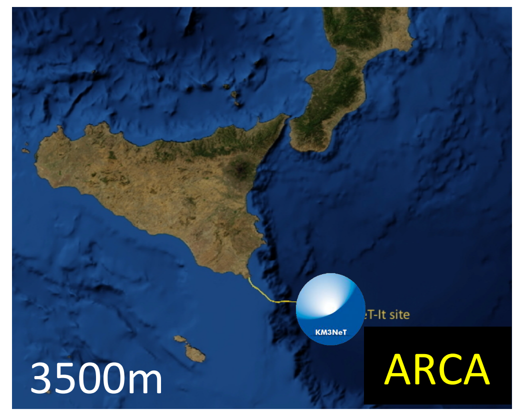
Single collaboration, Single technology



+Nantes, Johannesburg, Marrakech, Tbilisi



Oscillation **R**esearch with **C**osmics In the **A**byss

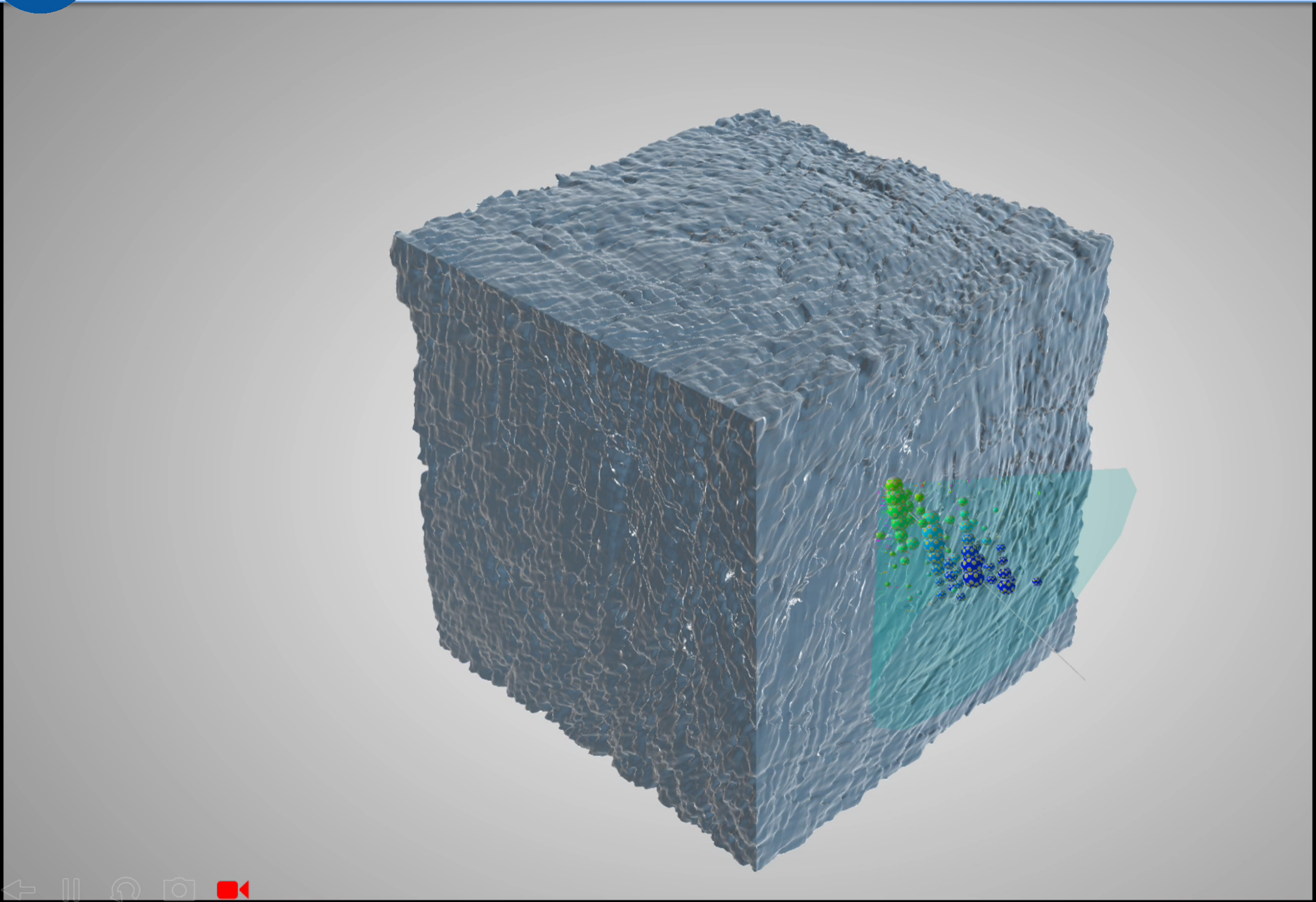


Astroparticle **R**esearch with **C**osmics In the **A**byss

Potential 3rd site: Pylos, Greece

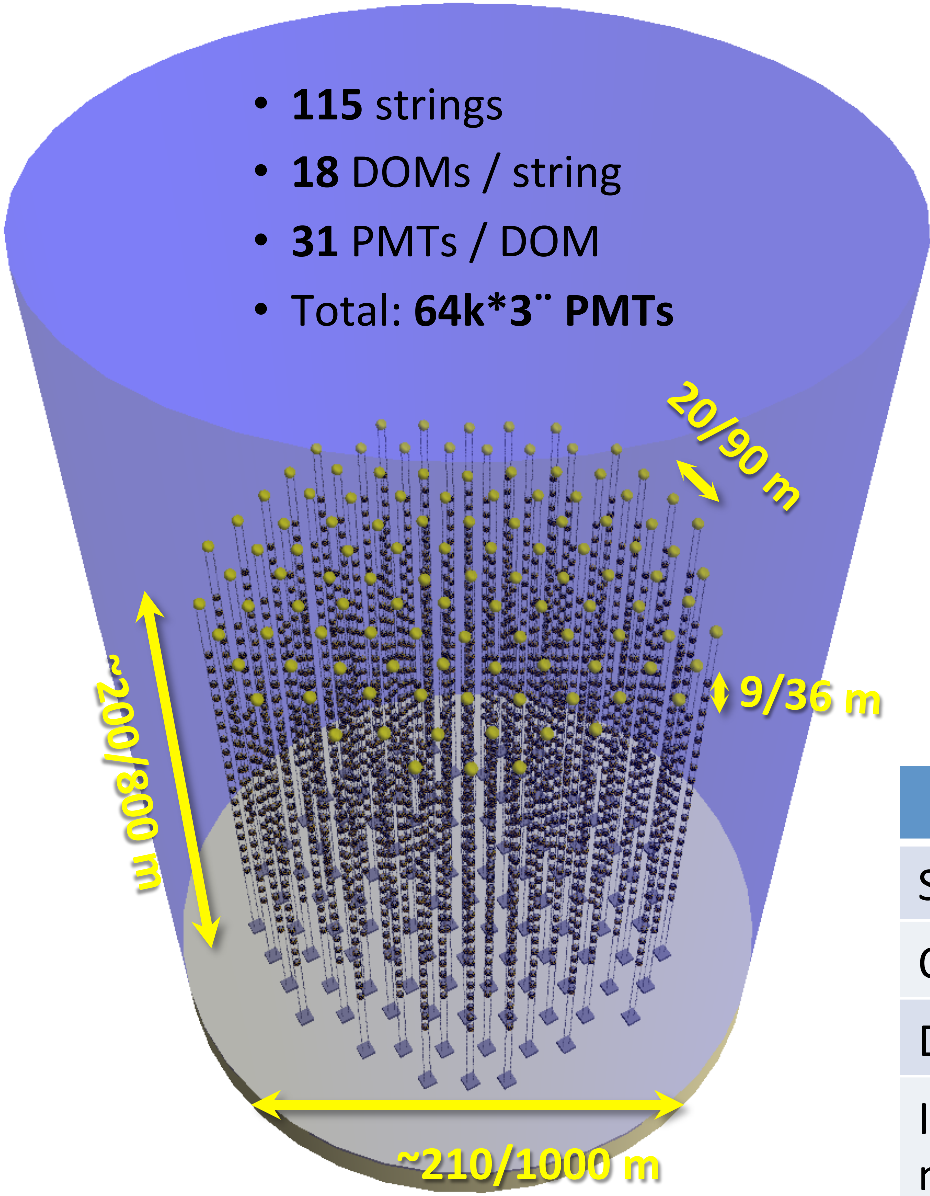
Connection nodes of european multidisciplinary seafloor & water column observatory emso

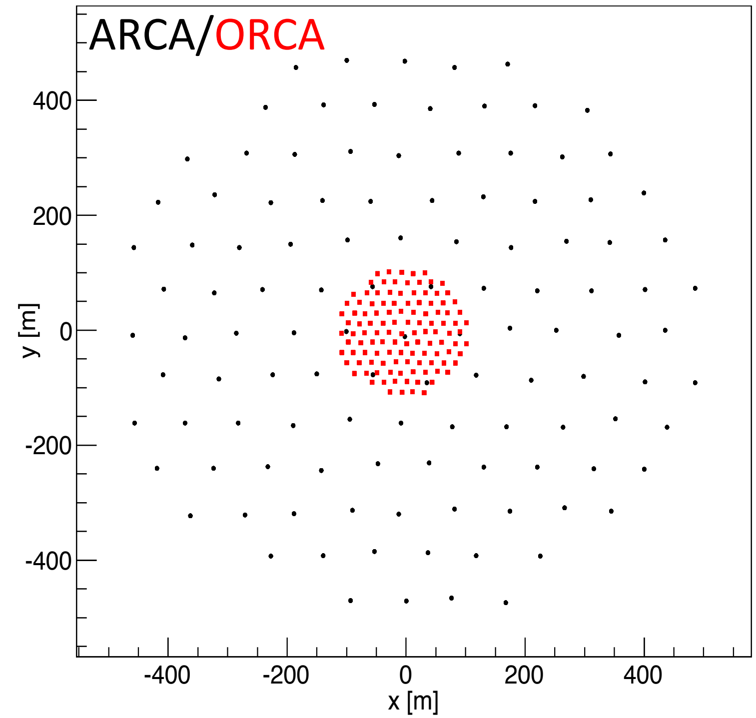
Instrument km^3 of Seawater



KM3NeT Building Block

- **115** strings
- **18** DOMs / string
- **31** PMTs / DOM
- Total: **64k*3¨ PMTs**





	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	5.7 Mton	0.6*2 Gton

KM3NeT Phased Implementation

Phase	Blocks	Science	Funding Status
1	0.1	Proof of feasibility and first science results (7 ORCA strings/ 24 ARCA strings)	Fully funded
2.0	2 *ARCA*	Study of neutrino signal reported by IceCube All flavor neutrino astronomy	1 block almost funded
	1 *ORCA*	Neutrino mass hierarchy	Half block funded
3	1+6	Neutrino astronomy including Galactic sources Neutrino properties	Not yet

KM3NeT 2.0: ESFRI Roadmap 2016

KM3NeT selected for the 2016 ESFRI Roadmap

10 March 2016 – Today, at its launch event at the Royal Netherlands Academy of Arts and Sciences in Amsterdam, the European Strategy Forum for Research Infrastructures (ESFRI) announced that KM3NeT 2.0 is selected for the 2016 ESFRI Roadmap for Research Infrastructures. The ESFRI Roadmap identifies new Research Infrastructures of pan-European interest corresponding to the long-term needs of the European research communities. Its mission is to ensure that scientists in

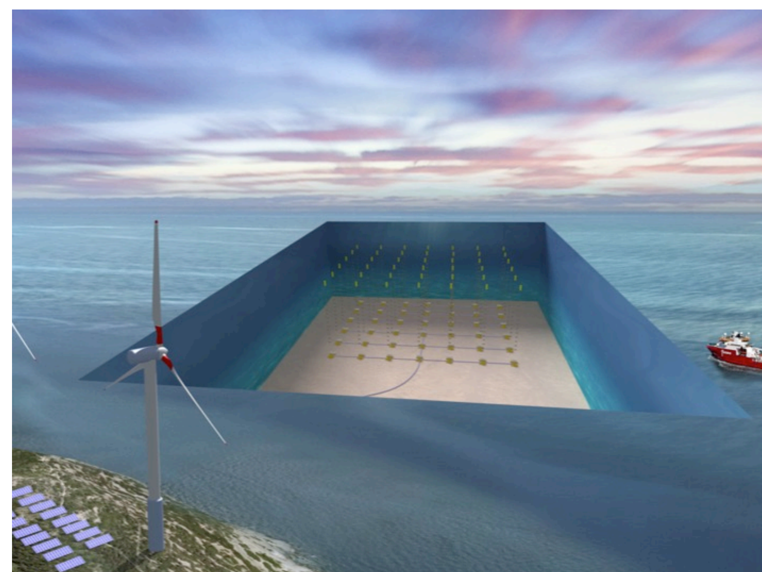
H2020: KM3NeT 2.0

Prepare legal entity (ERIC)

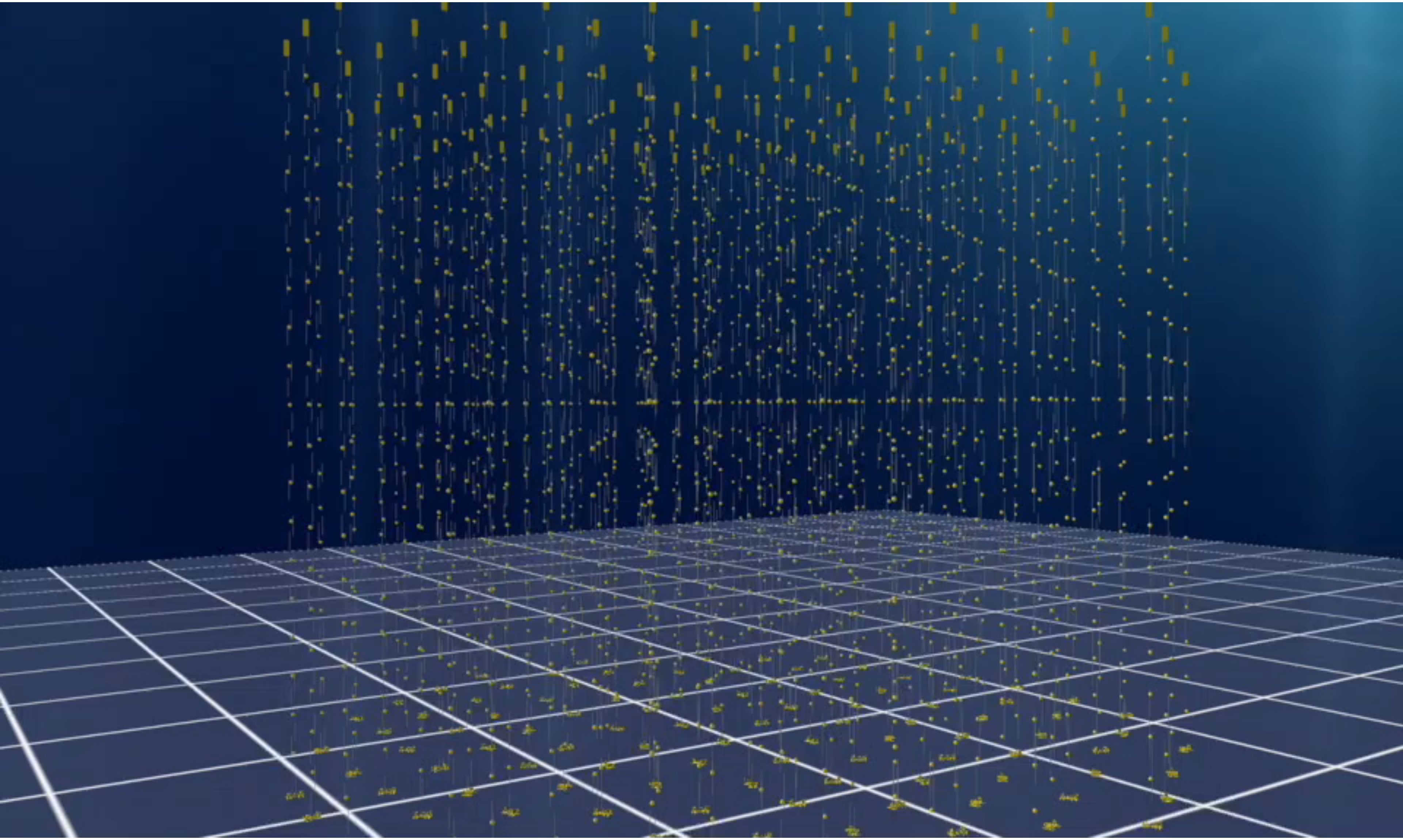
Approved Oct 2016

3.8 M€

Priority on APPEC roadmap



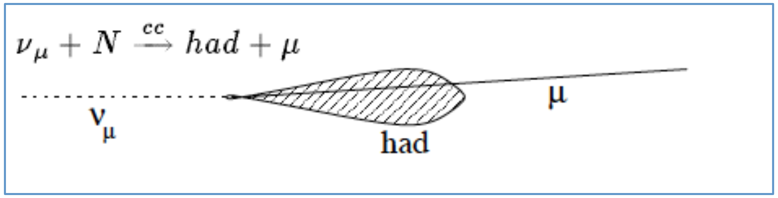
Principle of Detection



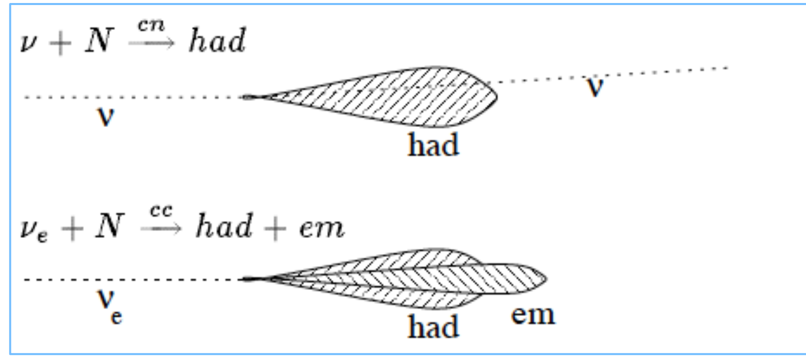
google also: ‘The KM3NeT Virtual Reality Experience’

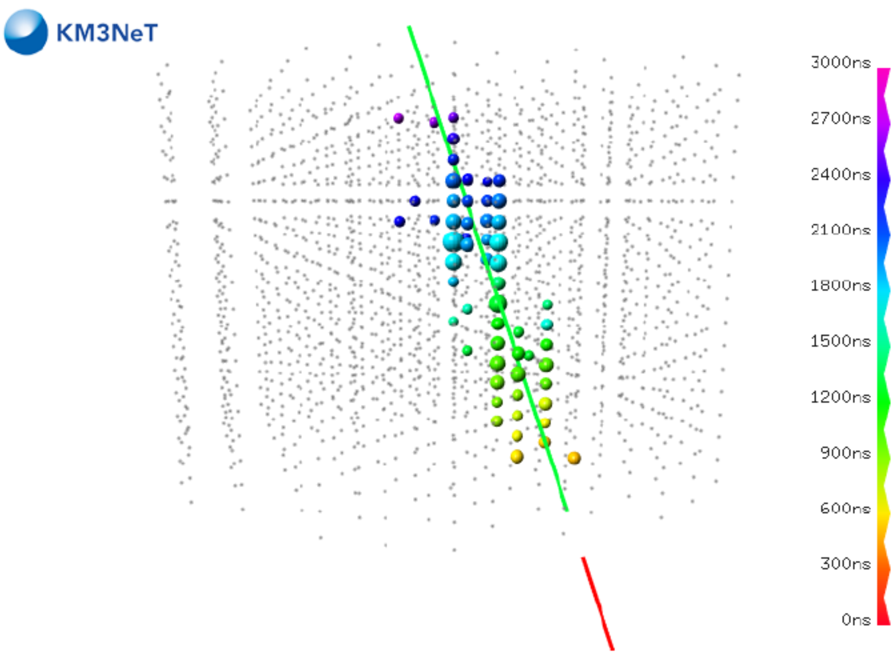
Event Topologies

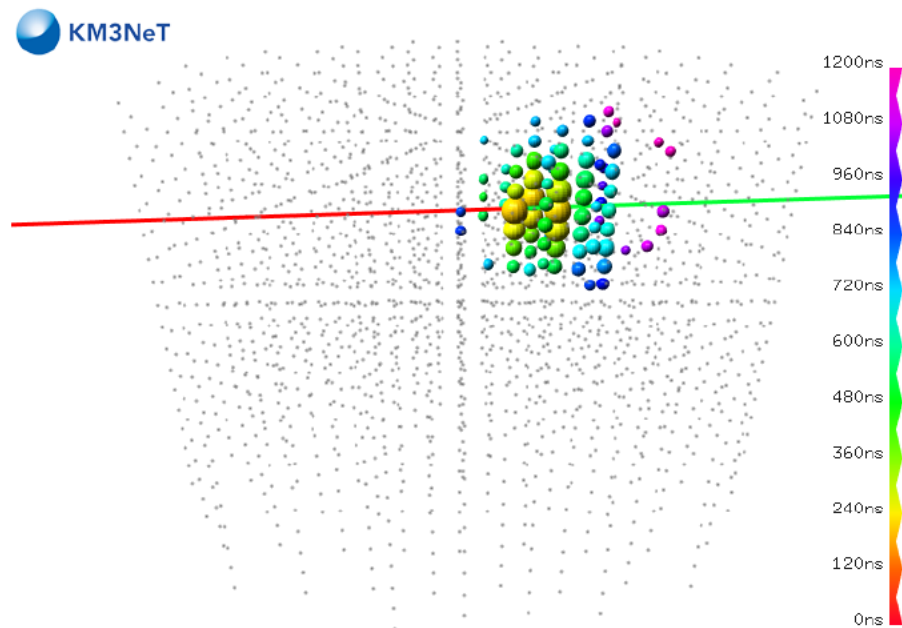
Track-like (ν_μ^{CC})



shower-like (ν^{NC}, ν_e^{CC})

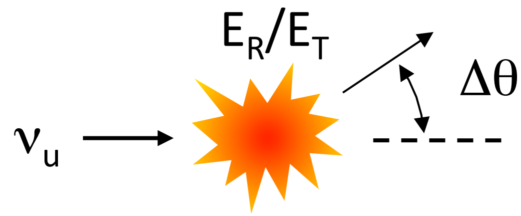




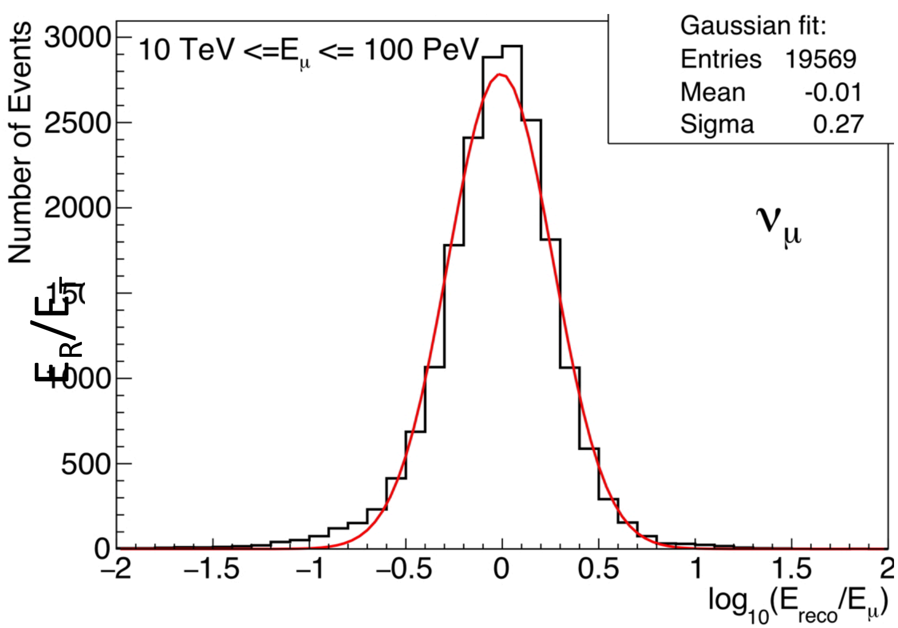


ARCA simulation, TeV neutrino energies

ARCA Track Resolutions

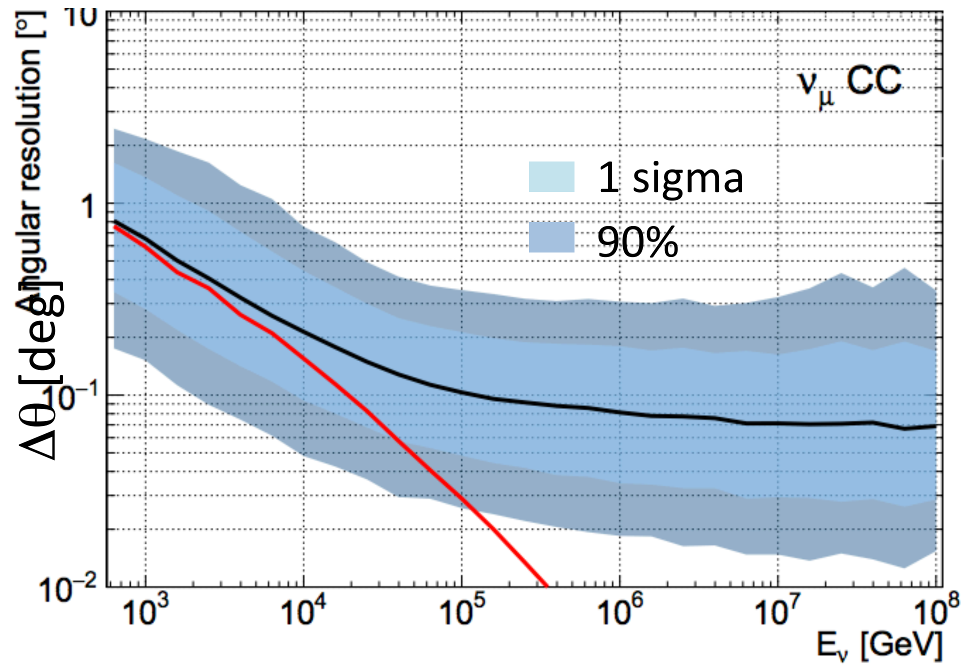


Energy



E_ν [GeV]

Direction

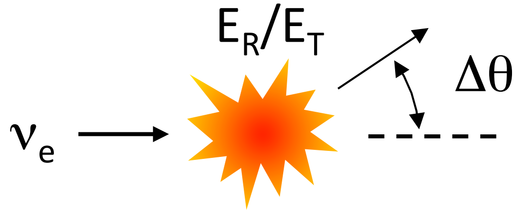


E_ν [GeV]

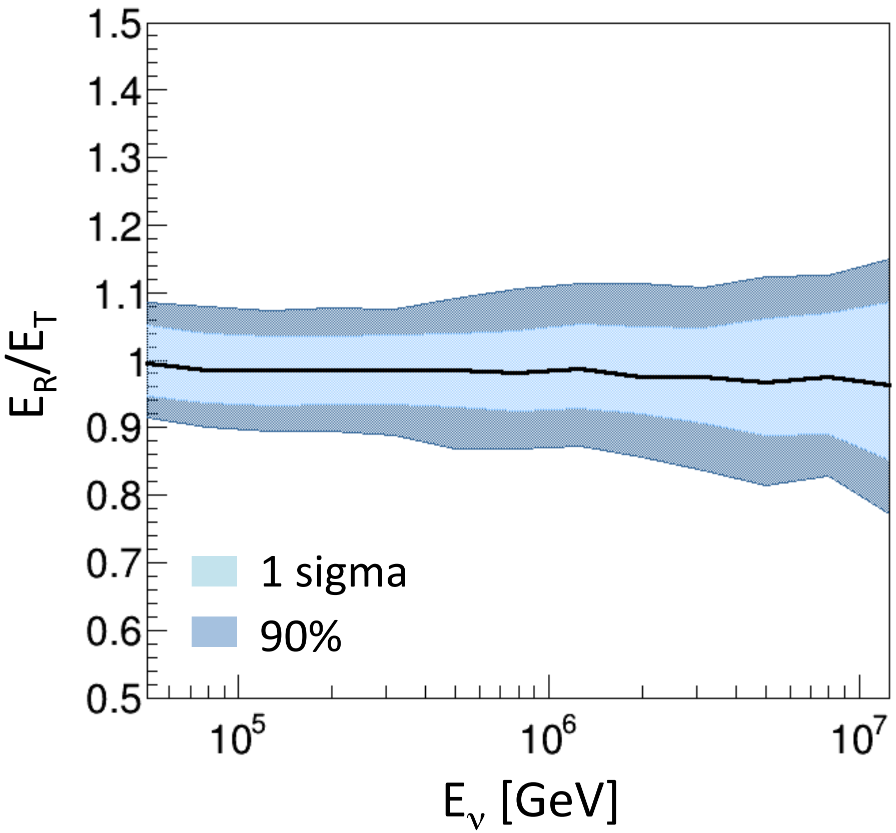
0.3 Log E (E>10 TeV)

<0.1° (E>10 TeV)

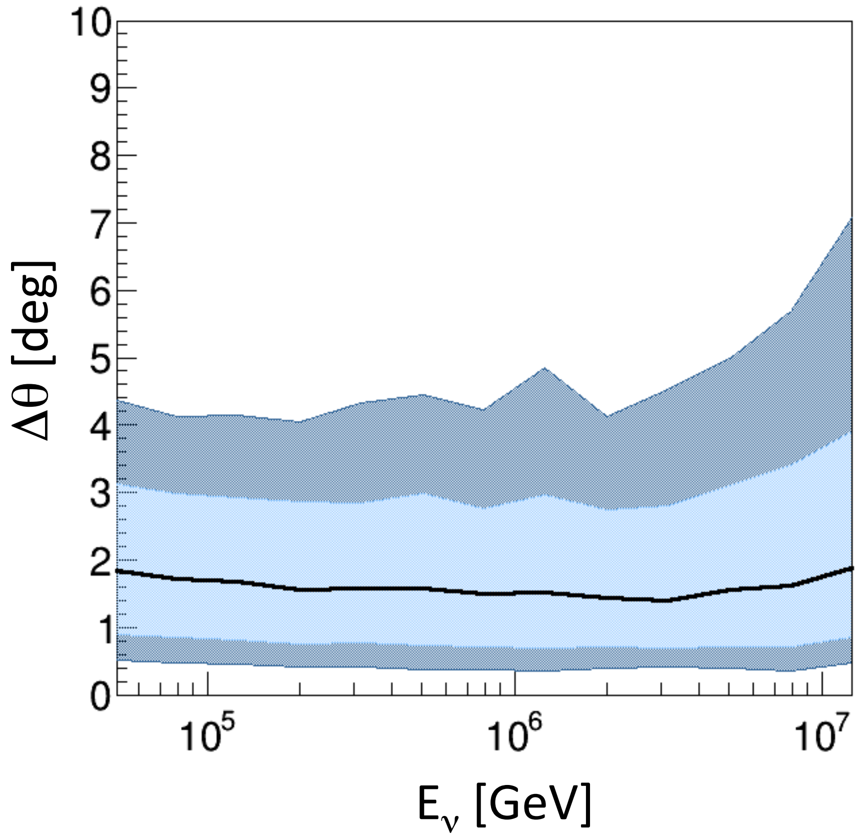
ARCA Cascade Resolutions



Energy



Direction



5%

<2°

ARCA Diffuse Cosmic Neutrinos

Final ANTARES sensitivity ~ IC flux

Track channel

Analysis for up-going events based on maximum likelihood

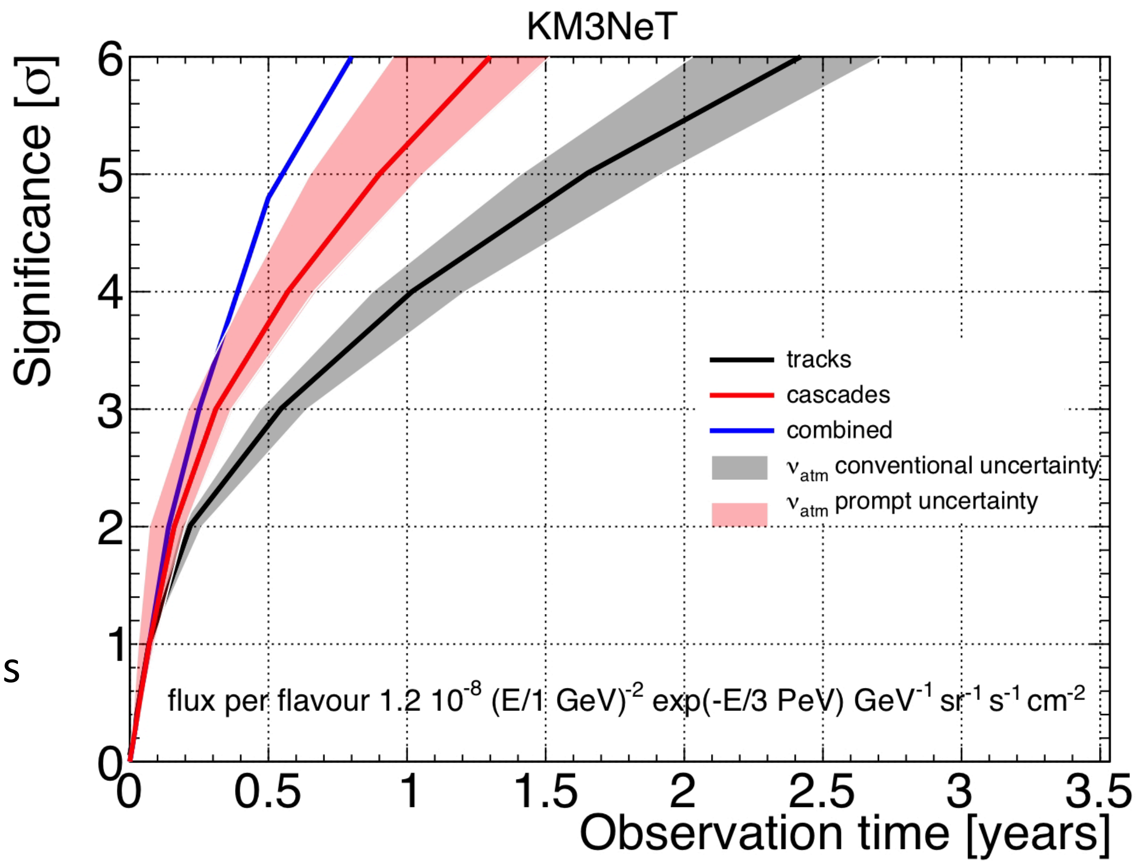
Pre-cuts on θzen >80°,

reconstruction quality parameter and Nhit (proxy for muon energy)

Cascade channel

Containment cut on reconstructed vertex to remove atmospheric muons (excludes upper 100m layer)

Full sky analysis based on BDT and maximum likelihood.

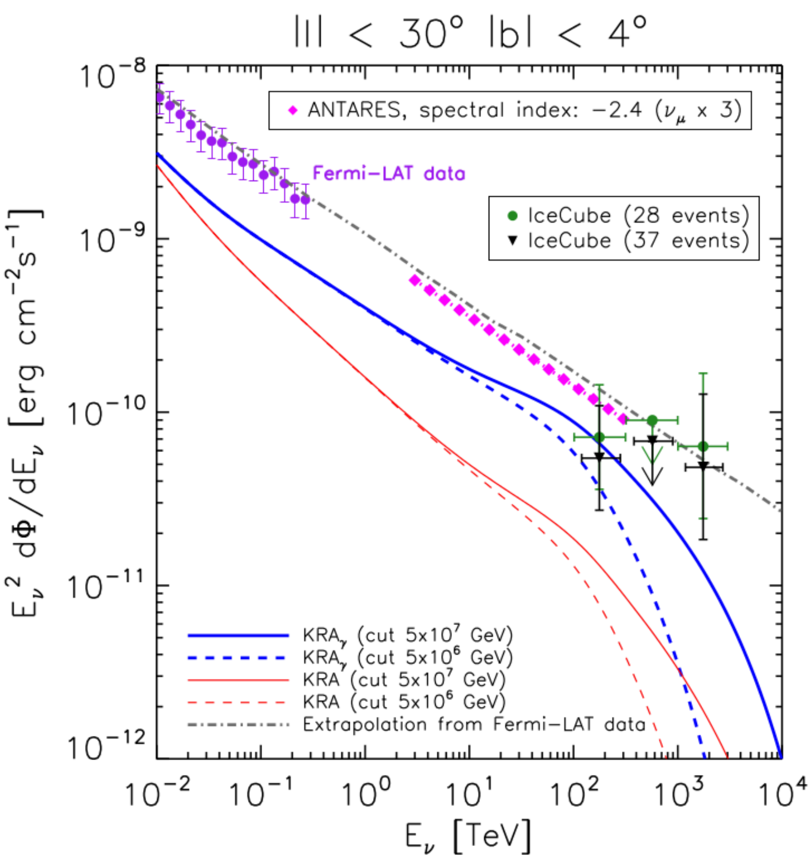


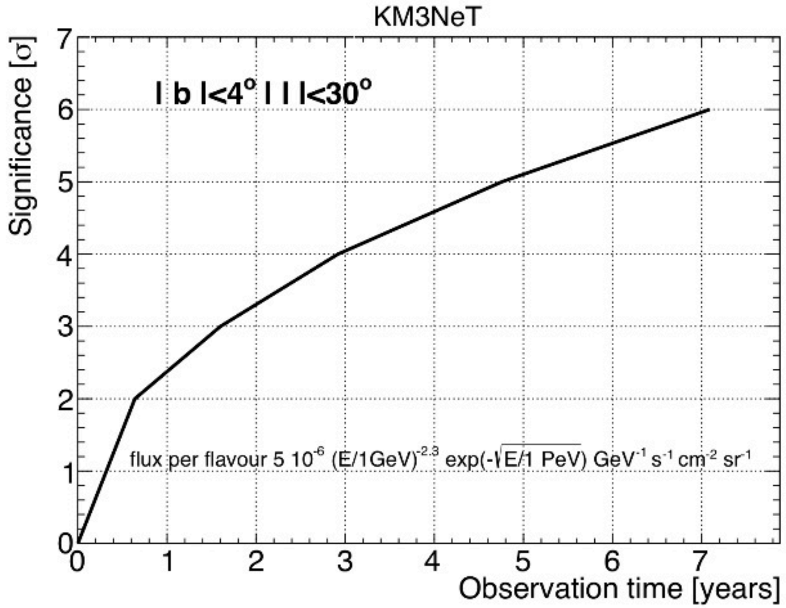
Definitive independent confirmation with KM3NeT 2.0 (5 sigma in 6 months)

ARCA Diffuse Flux from Galactic Plane

ARCA sensitivity to a flux from a region of the Galactic Plane near the Galactic Center

Neutrino flux estimate based on a radially-dependent cosmic-ray transport properties

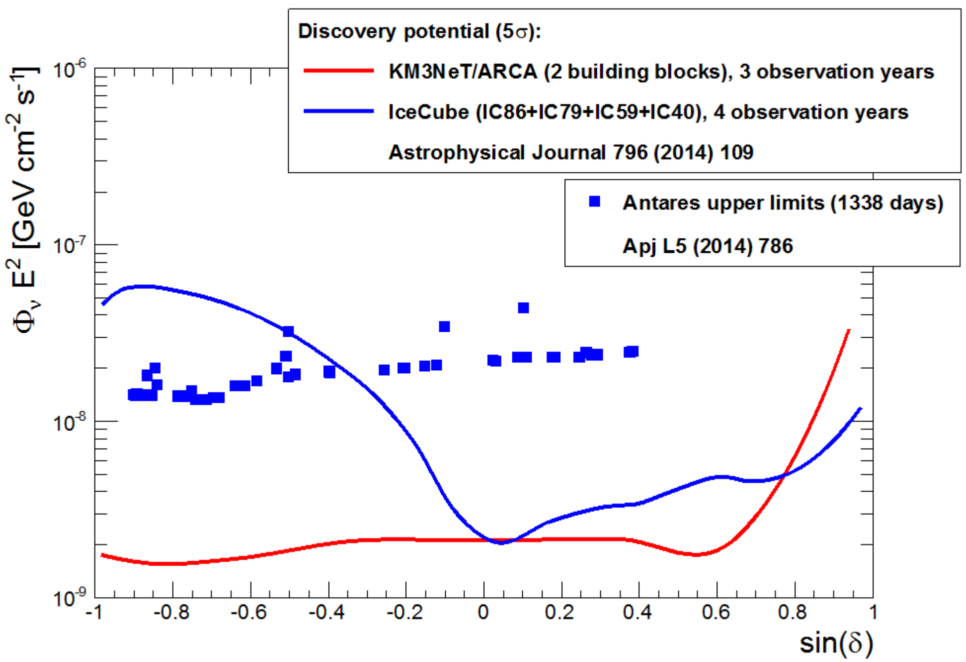


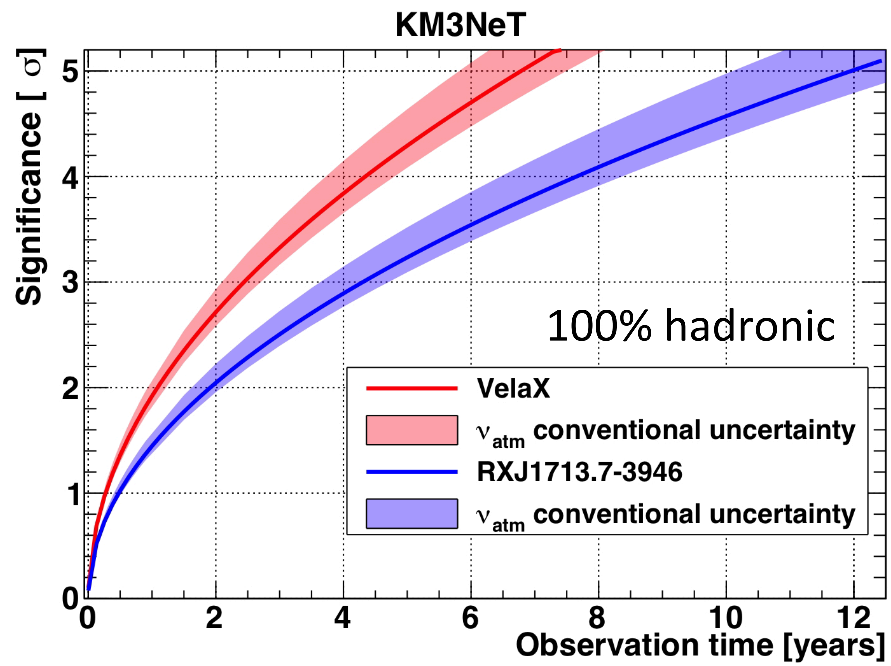


Discovery at 5σ significance (50% probability) in about 5 years

ARCA Point Sources

- Unprecedented angular resolution
- Multi-flavour astronomy
- Significant discovery potential for extragalactic sources
- Galactic sources in reach





The neutrino mass hierarchy

- Prime discriminator for theory models
- Origin of neutrino mass and flavour
- Help measuring the CP phase
- Nature (Dirac vs Majorana)
- Core-Collapse Supernovae Physics

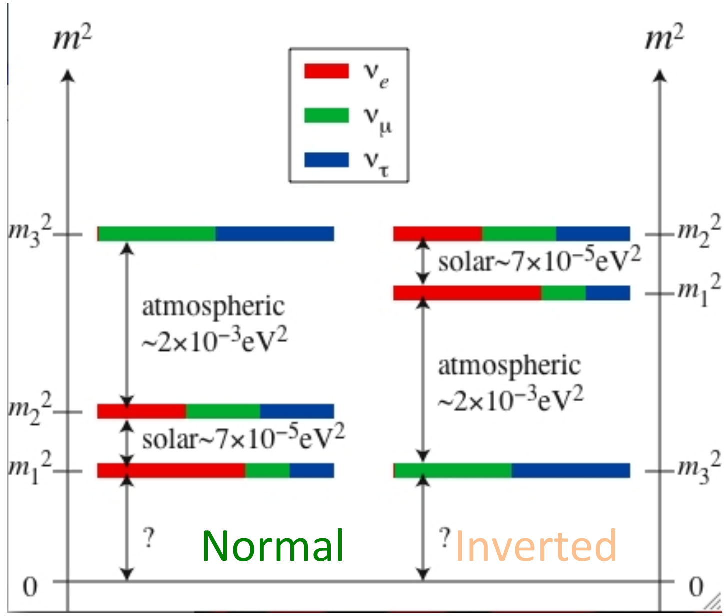
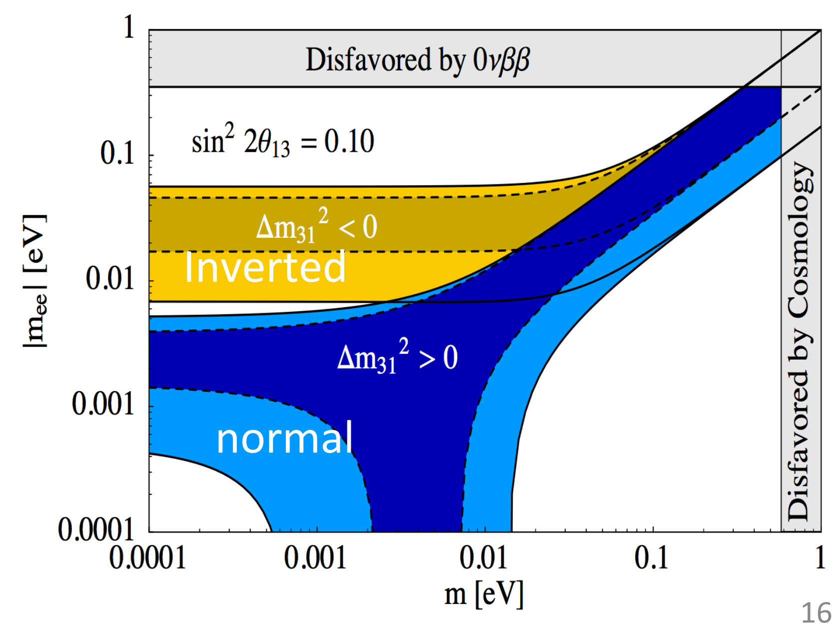


TABLE I: Mixing Angles for Models with Lepton Flavor Symmetry.

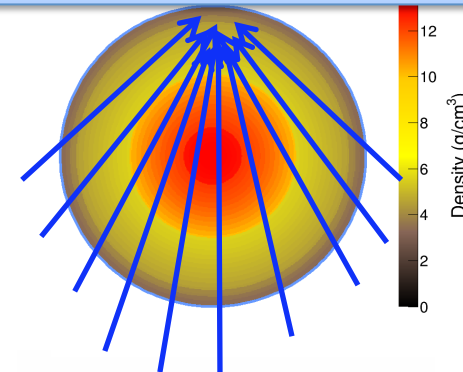
Reference		Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
Anarchy Model:					
dGM	[18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:					
BM	[35]	Inverted			0.00029
BCM	[36]	Inverted			0.00063
GMN1	[37]	Inverted		≥ 0.52	≤ 0.01
GL	[38]	Inverted			0
PR	[39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:					
CFM	[40]	Normal			0.00006 - 0.001
HLM	[41]	Normal	1.0	0.43	0.0044
		Normal	1.0	0.44	0.0034
KMM	[42]	Inverted	1.0		0.000012
MN	[43]	Normal			0.0024
MNY	[44]	Normal			0.000004 - 0.000036
MPR	[45]	Normal			0.006 - 0.01
RS	[46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
		Normal	$\theta_{23} \leq 45°$		0
TY	[47]	Inverted	0.93	0.43	0.0025
T	[48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:					
ABGMP	[49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL	[50]	Normal			0.006 - 0.04
Ma	[51]	Normal	1.0	0.45	0
SO(3) Models:					
M	[52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:					
CPP	[53]	Normal			0.007 - 0.008
		Inverted			≥ 0.00005
		Inverted			≥ 0.032
WY	[54]	Either			0.0006 - 0.003
		Either			0.002 - 0.02
		Either			0.02 - 0.15

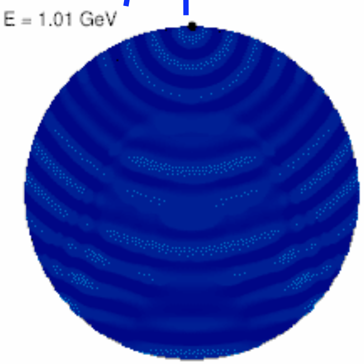


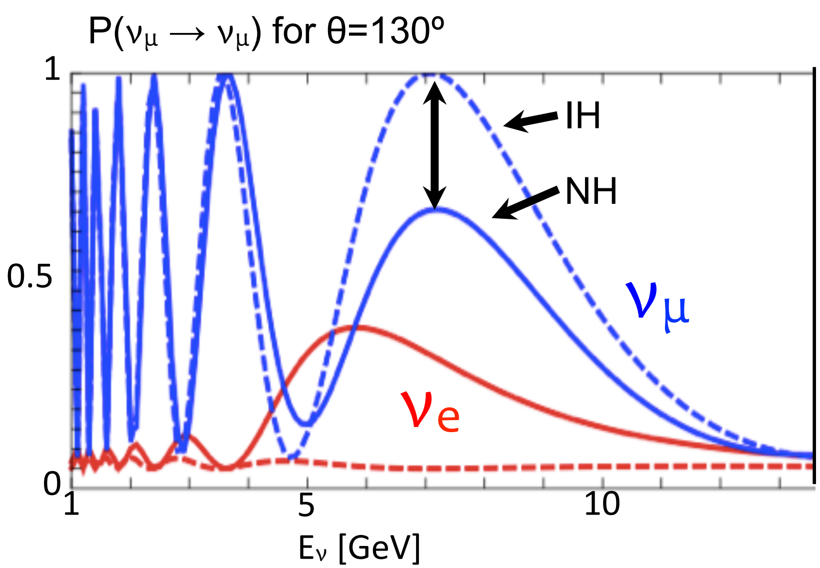
Walter Winter Neutrino 2014

Measuring NMH with Atmospheric Neutrinos

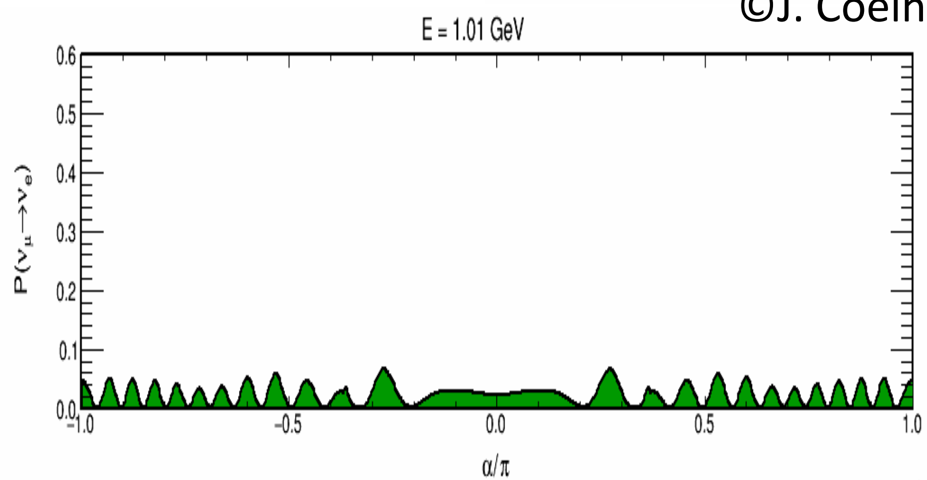
- A ¨free beam¨ of known composition (ν_e, ν_μ)
- Wide range of baselines and energies
- Oscillation pattern distorted by Earth matter effects maximum difference IH ↔ NH for resonance in Earth mantle: θ=130° (7645 km) and E_ν = 7 GeV



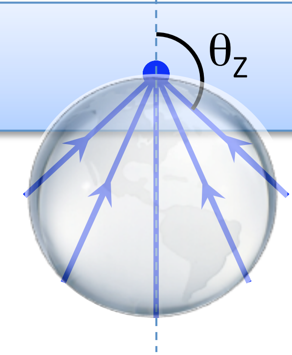




©J. Coelho

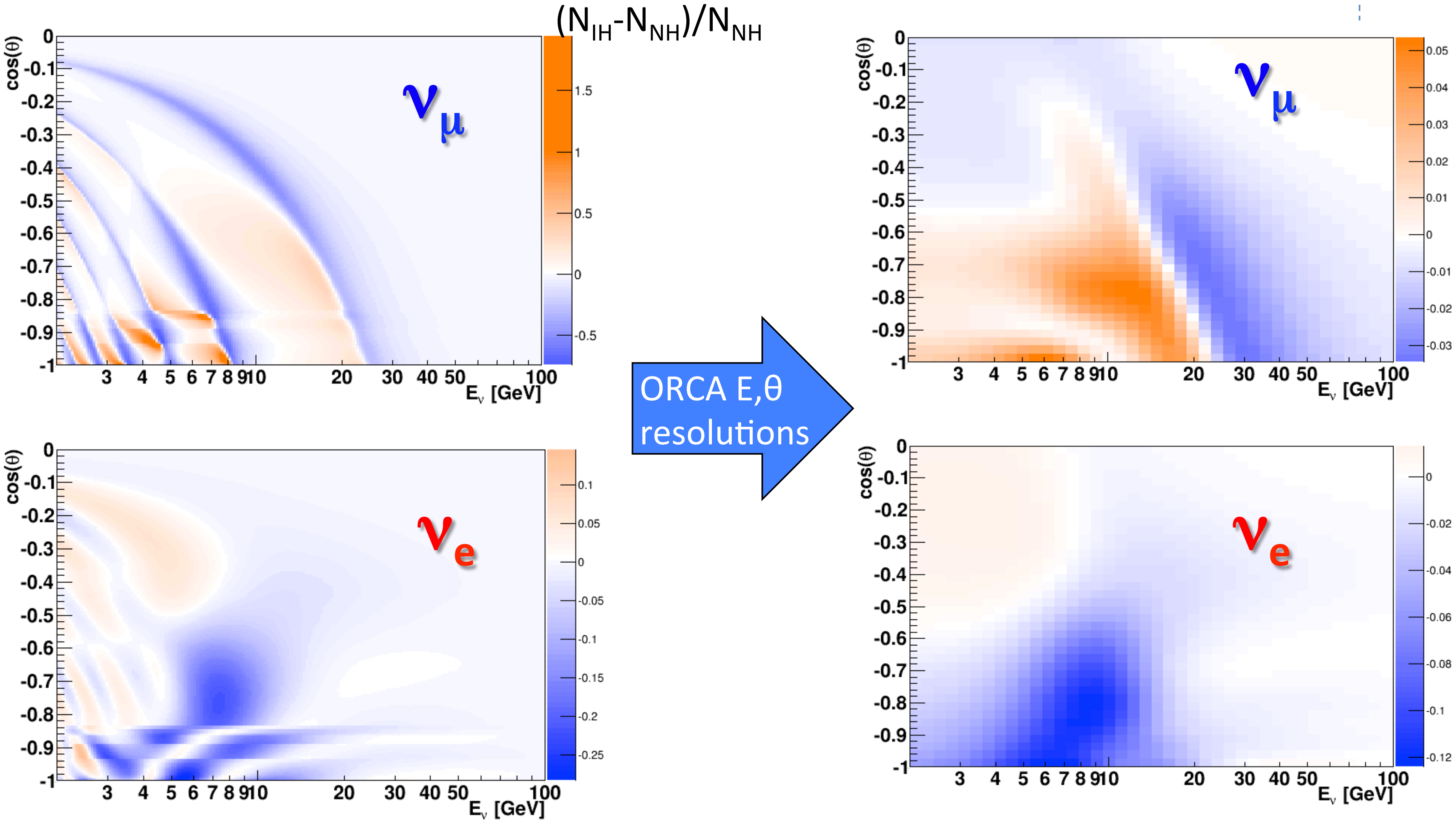


ORCA NMH Experimental Signature



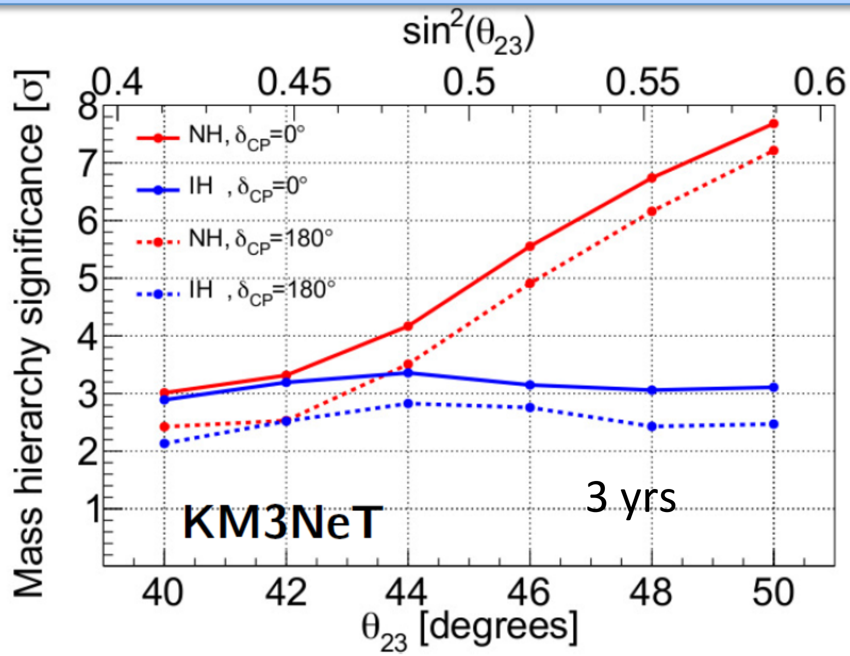
Both muon- and electron-channels contribute to hierarchy asymmetry

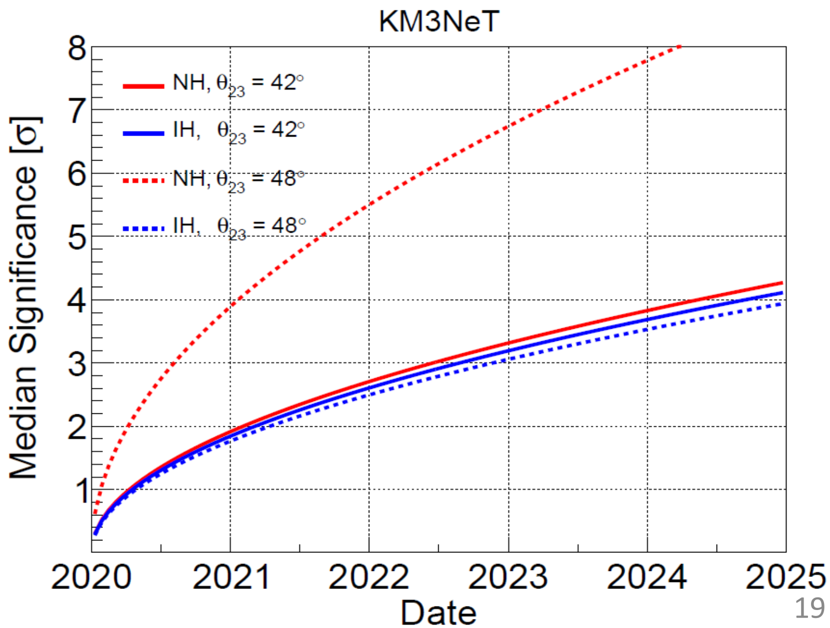
Electron channel more robust against detector resolution effects



ORCA Sensitivity to Mass Hierarchy

- ~3σ MH sensitivity in 3 years
- For IH, sensitivity is essentially independent of θ_{23}
- The combination of NH and upper octant of θ_{23} gives significantly improved sensitivity (>5σ in 3 years)
- The value of δ_{cp} has small but non-negligible impact on sensitivity

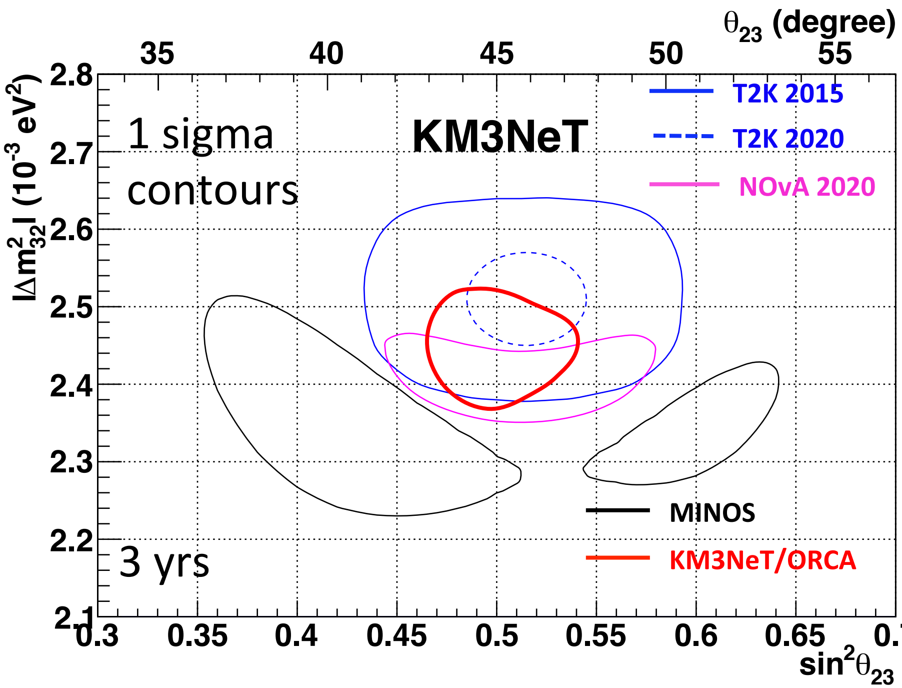




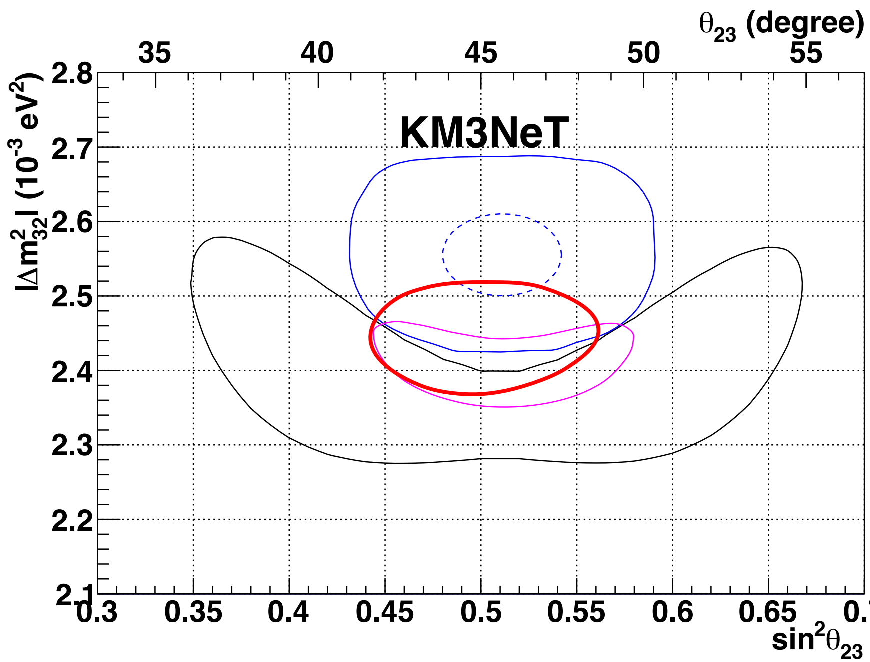
ORCA Measurement of Δm^2_{32} and $\sin^2\theta_{23}$

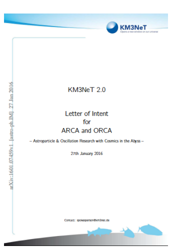
- Achieve 2-3% precision in Δm^2_{32} and 4-10% in $\sin^2\theta_{23}$
- Competitive with NOvA and T2K projected sensitivity in 2020

Normal Hierarchy



Inverted Hierarchy



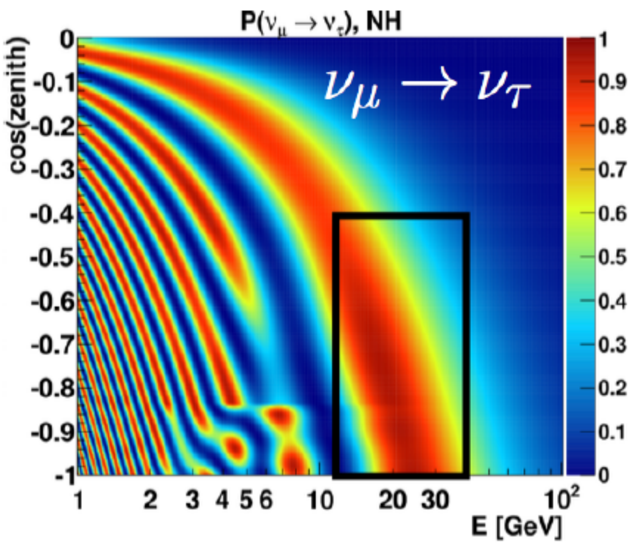


KM3NeT 2.0: Letter of Intent

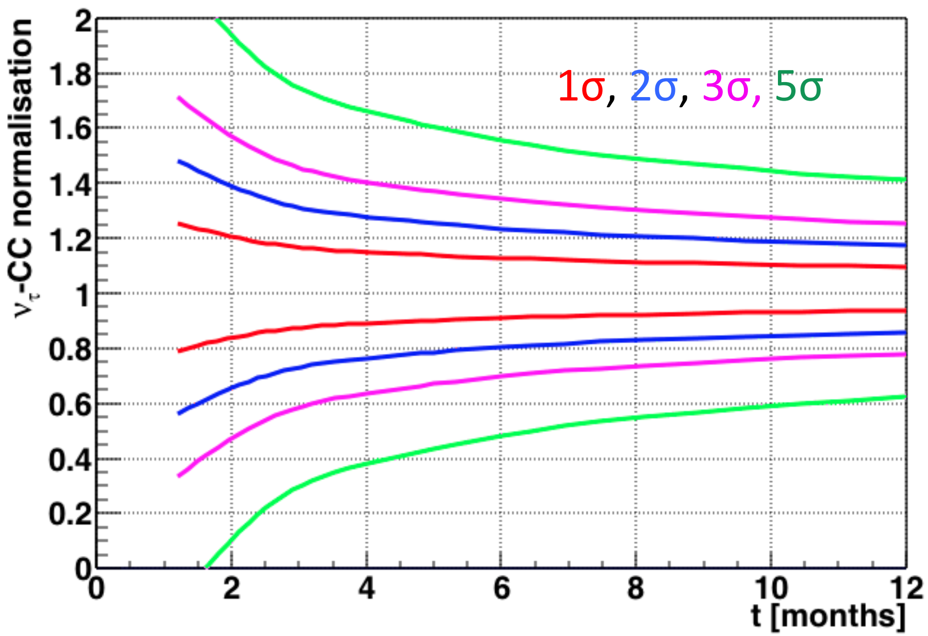
http://dx.doi.org/10.1088/0954-3899/43/8/084001

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

ORCA Tau Neutrino Appearance

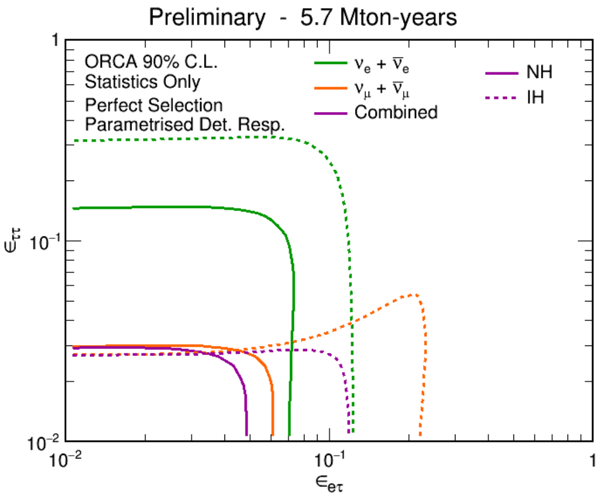


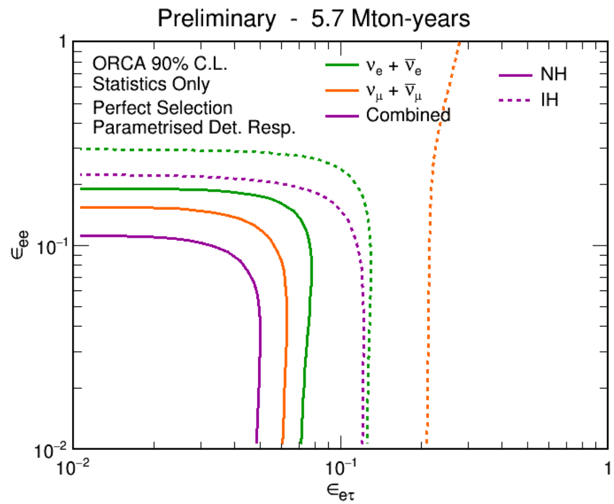
- ν_τ appearance tests PMNS unitarity and BSM theories
- ≈3k ν_τ CC events/year with full ORCA
- Rate constrained within ≈10% in 1 year
- Early physics result



ORCA Non Standard Interactions/Sterile

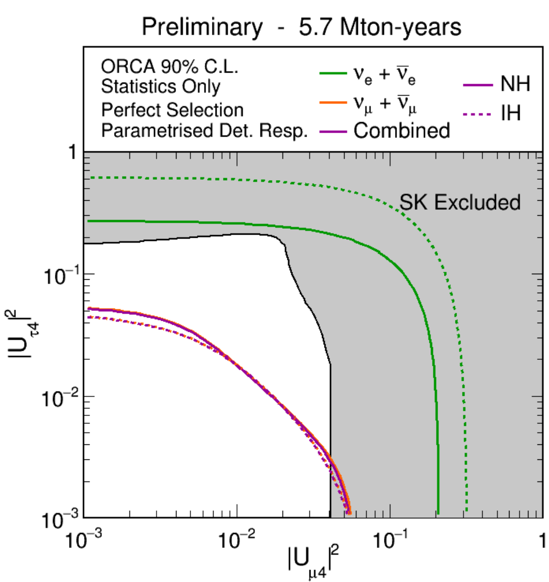
Non-Standard Interactions

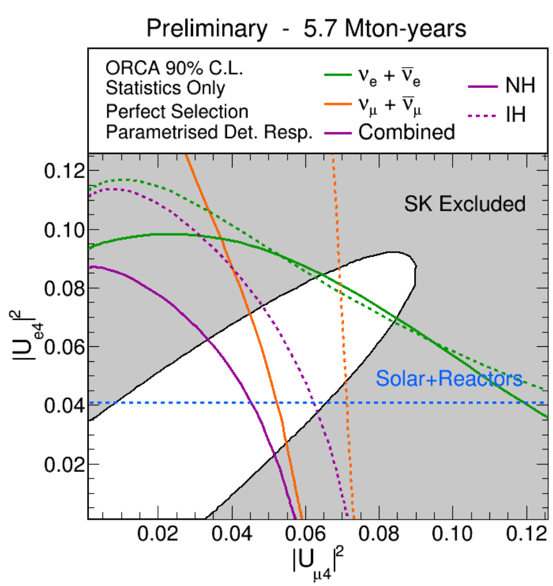




With 1 year of data, ORCA sensitive to NSI effects more than an order of magnitude smaller than current limits.

Sterile Neutrinos

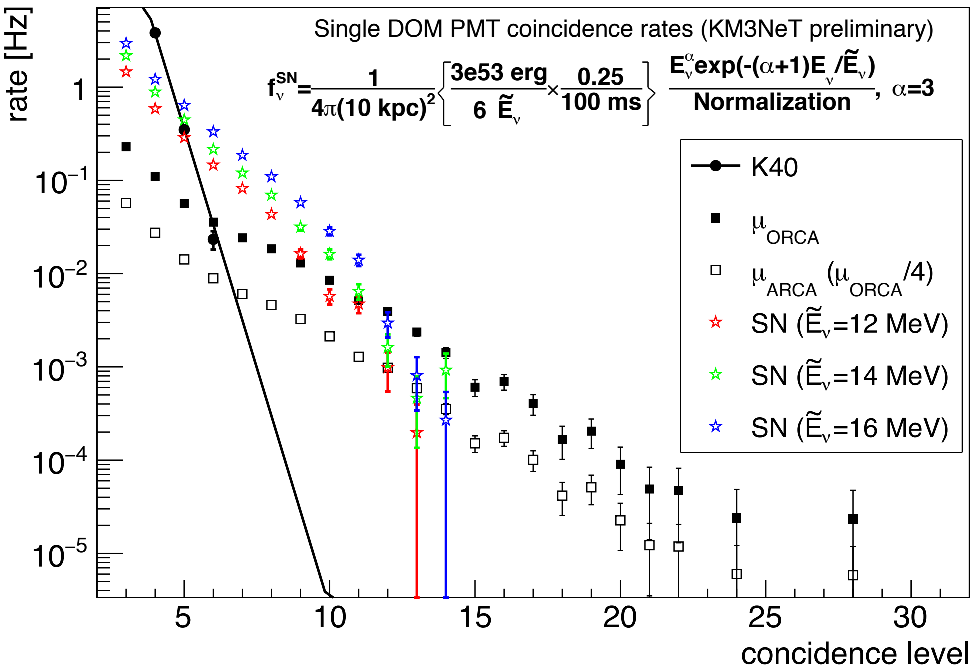




With 1 year of data, ORCA sensitive to $|U_{\tau4}|^2$ values 5x smaller than current limits set by Super-Kamiokande.

KM3NeT Supernova Sensitivity

- Simulation (SN1987A-like): 10 kpc, 3e53 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



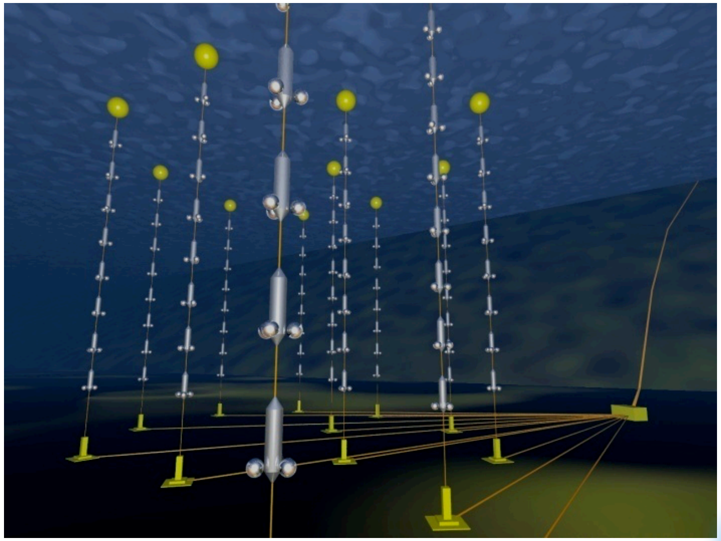
$\tilde{E}_{\bar{\nu}_e}$ MeV	N_{ev} per block	$D_{5\sigma}$ (kpc) ARCA	$D_{5\sigma}$ (kpc) ORCA
12	60	23	16
14	100	29	19
16	150	37	24

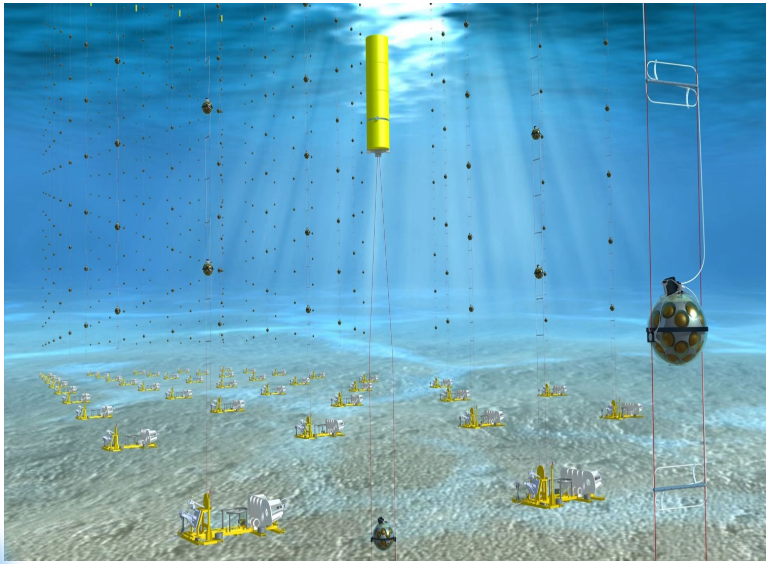
>80% of all Galactic SN with a single building block

ANTARES -> KM3NeT 2.0

12 lines, 900 OMs

3 Building Blocks (3*115 lines, ~3*2000 OMs)

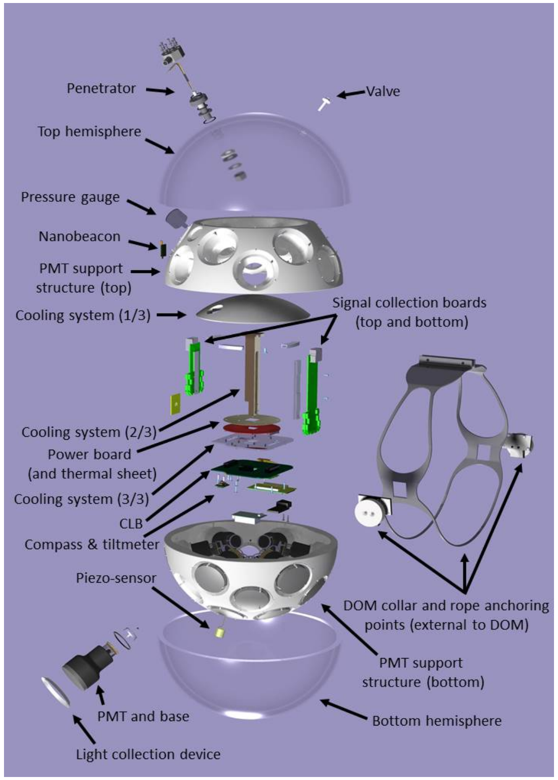




– 31 x 3” PMTs
– Uniform angular coverage
– Directional information
– Digital photon counting
– Reduced ageing

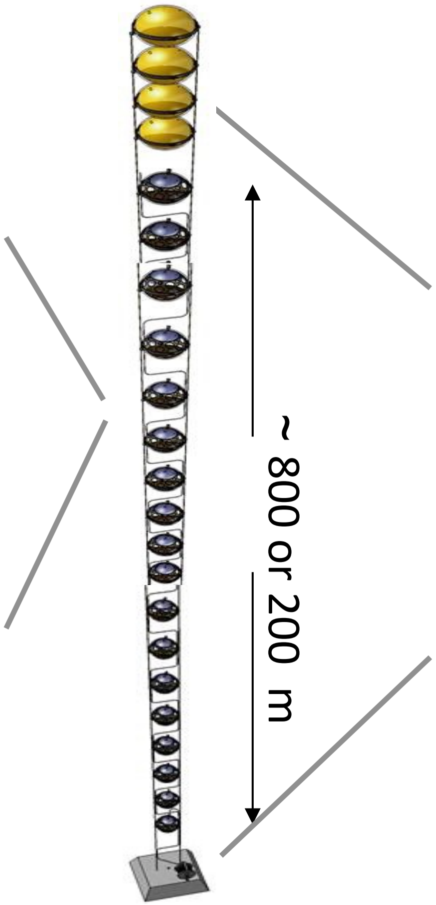
KM3NeT Technology

Digital Optical Module



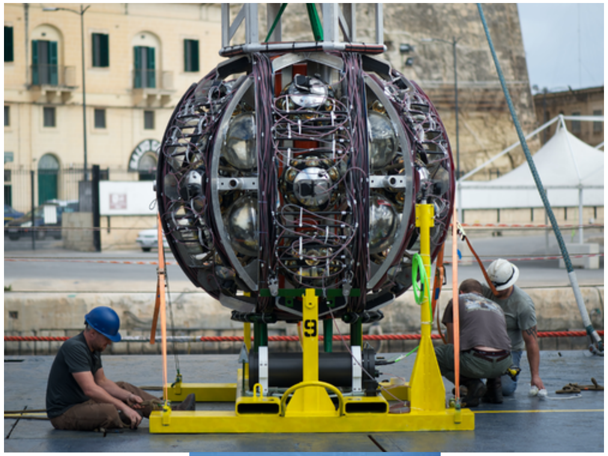
- All data to shore
- Gbit/s on optical fibre
- Hybrid White Rabbit
- LED flasher & acoustic piezo
- Tiltmeter/compass

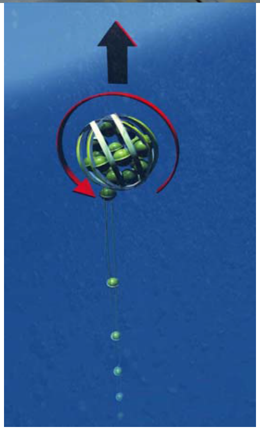
String



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

Deployment Vehicle



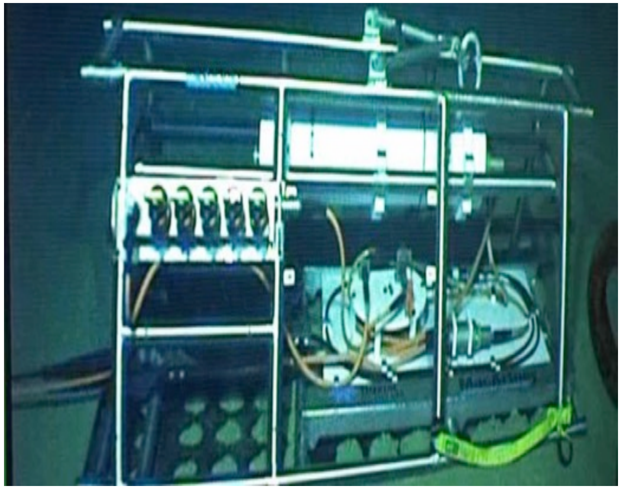


- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reuseable

Test of String Deployment

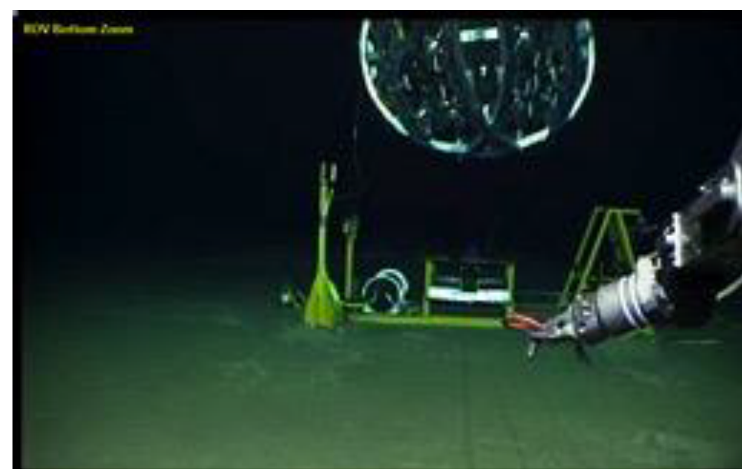
KM3NeT First Strings

1) First string connected at Capo Passero, Dec 2015



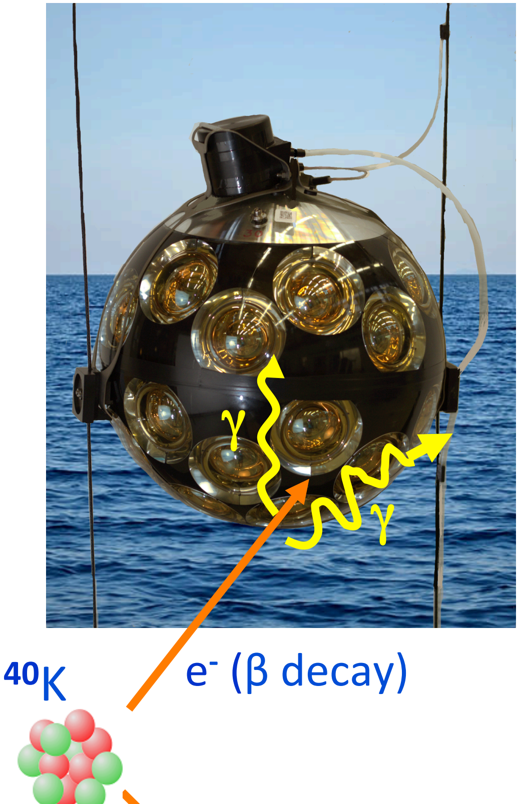
2) Two more strings at Capo Passero, May 2016

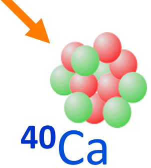




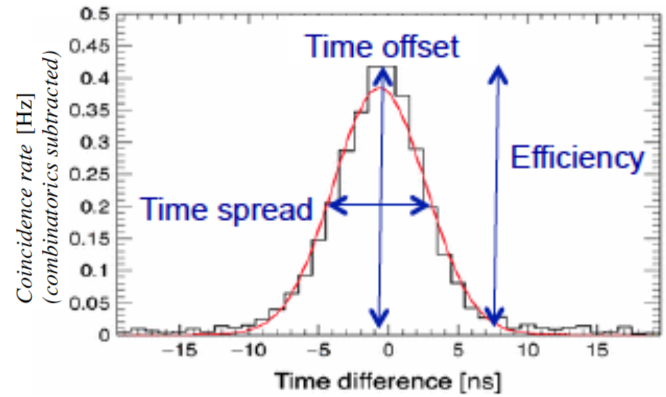
3rd string non-operational immediately after deployment -> recovered

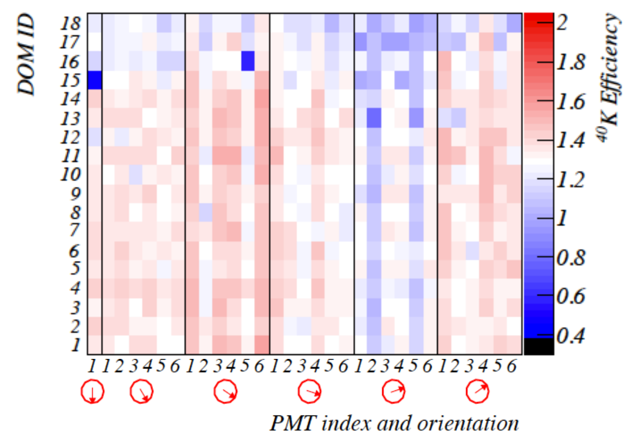
^{40}K: Inter-PMT Calibration

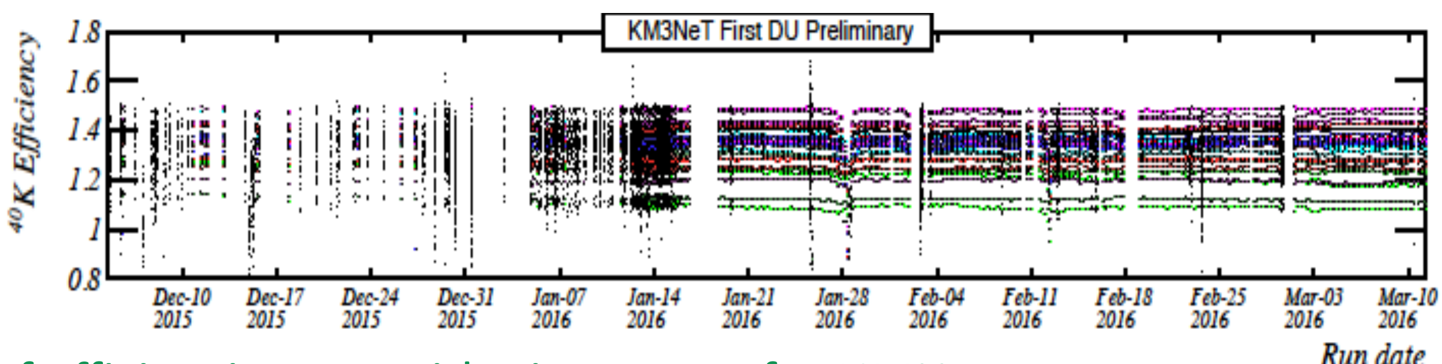




Up to 150 Cherenkov photons per decay; stable ^{40}K concentration

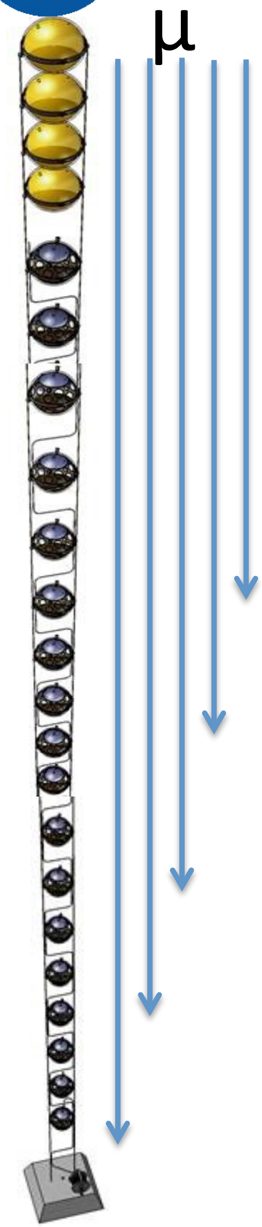


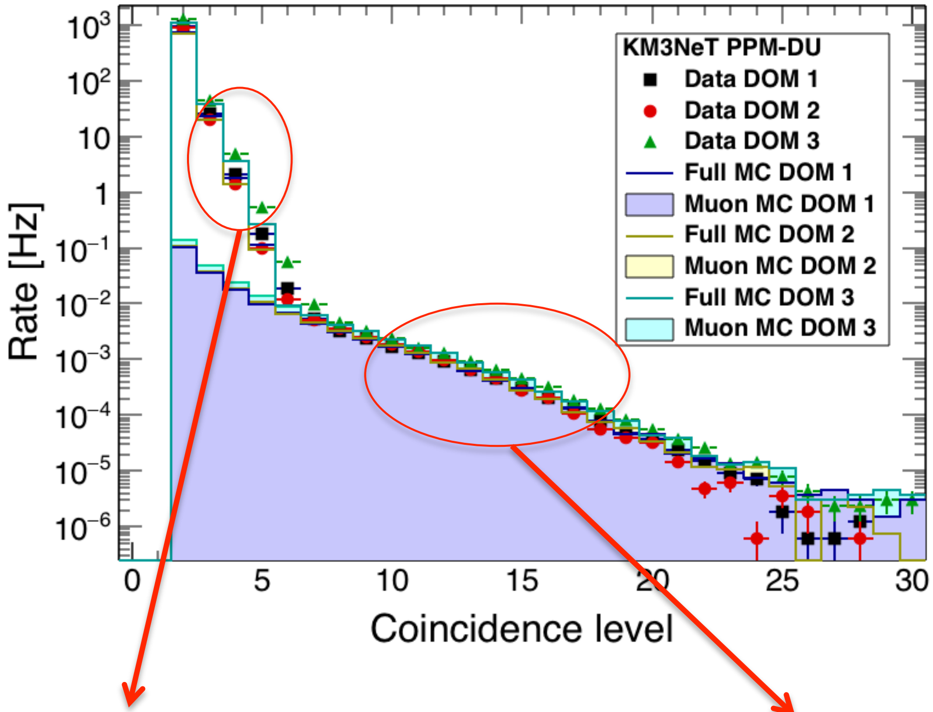


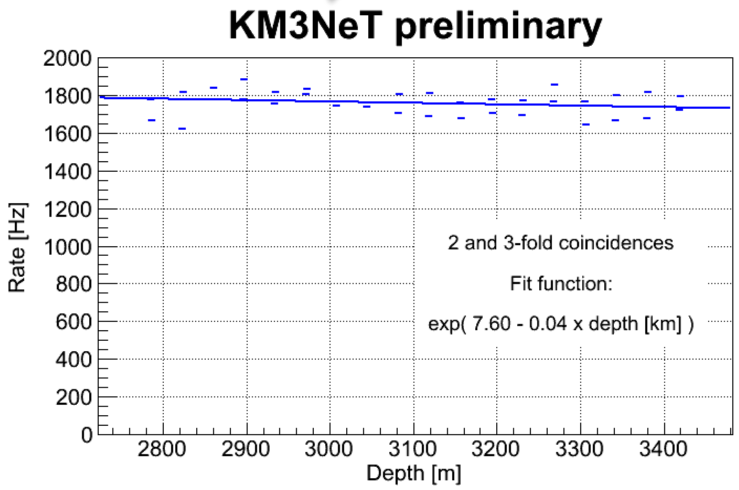


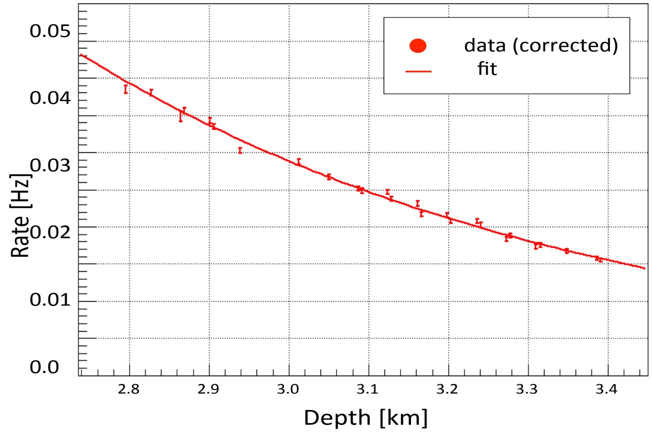
Knowledge of efficiencies vs zenith - important for NMH measurement

Muon Depth Dependence

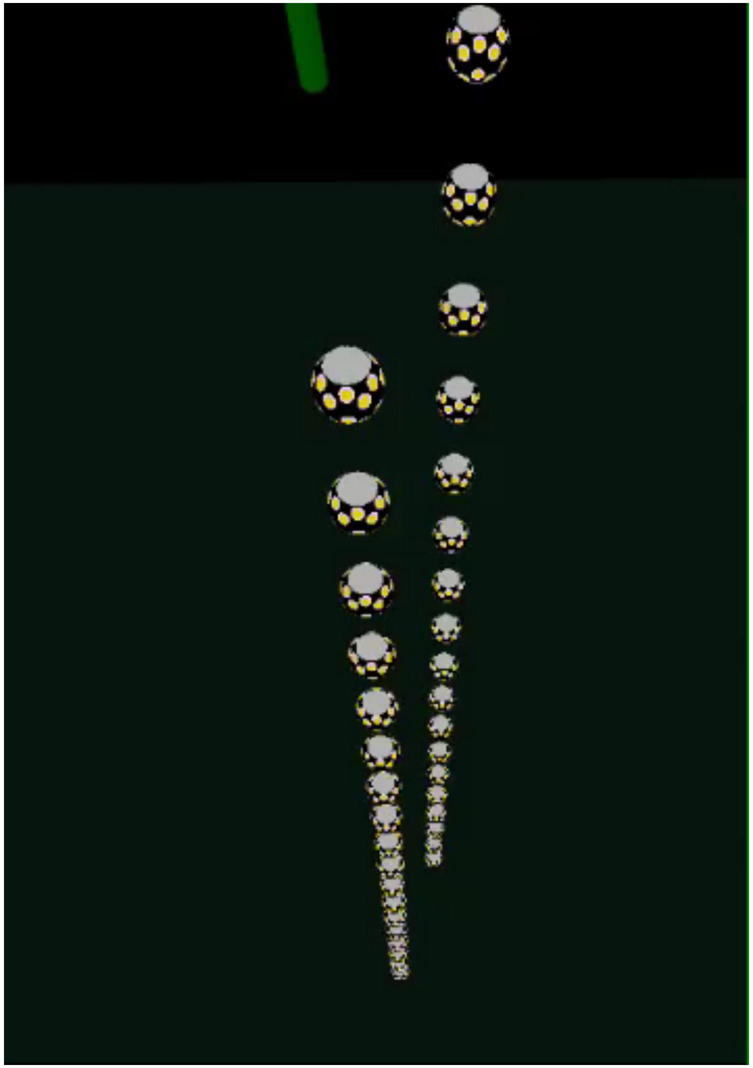


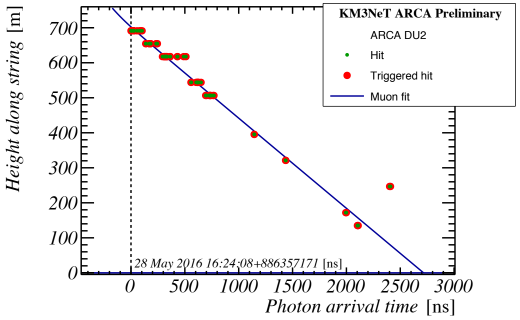


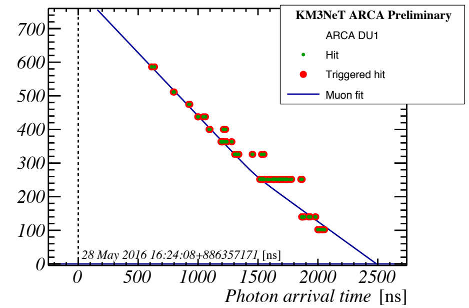




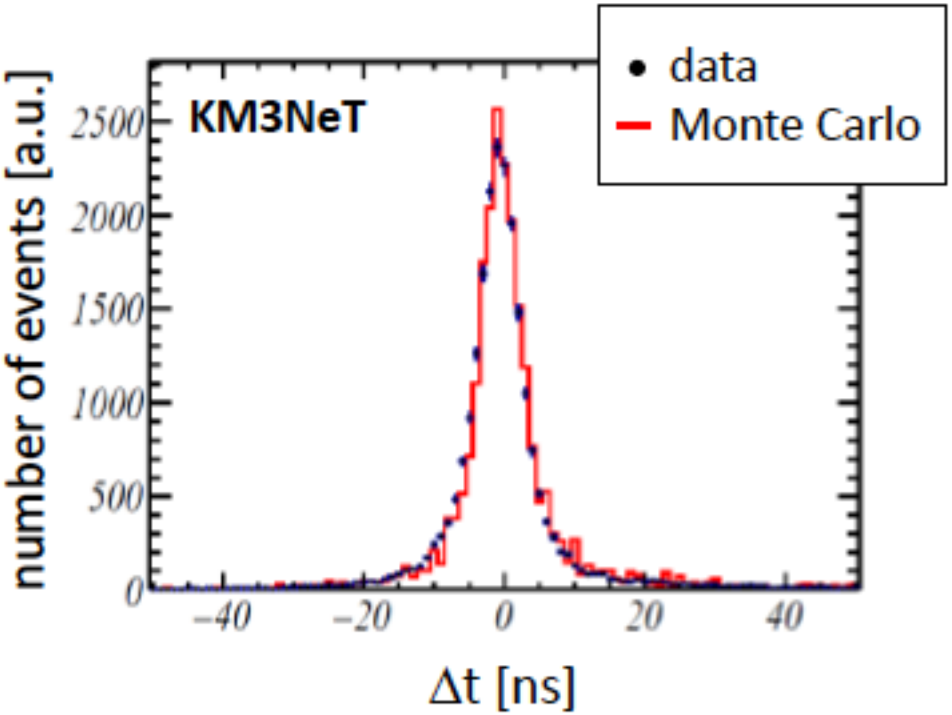
ARCA Atmospheric Muons



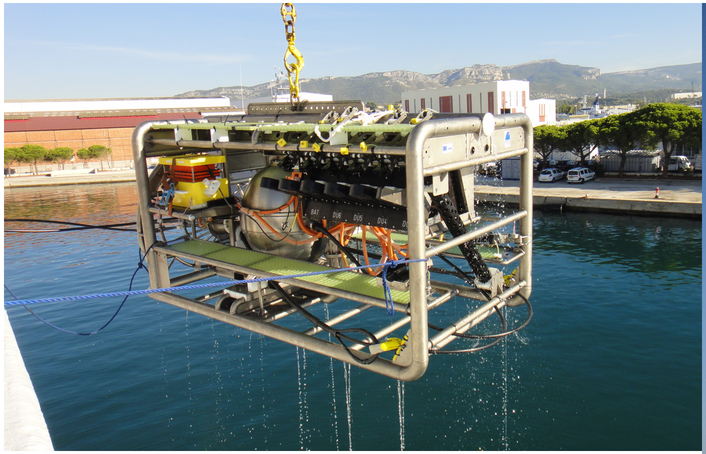


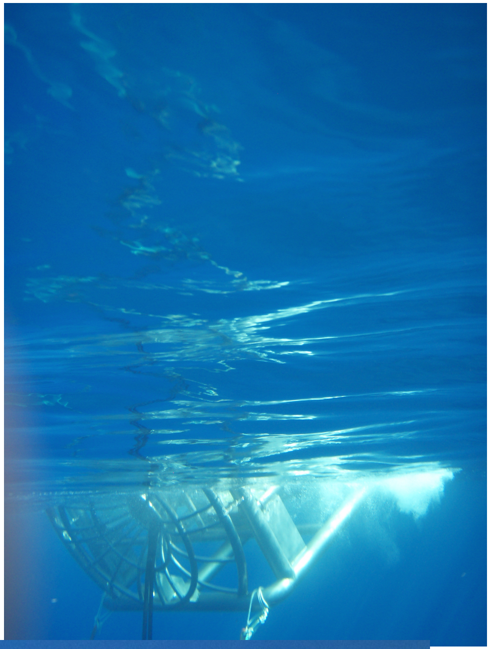
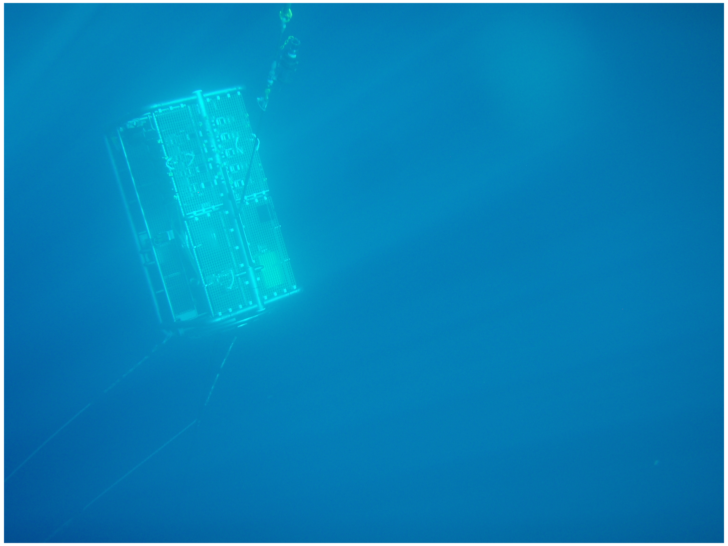
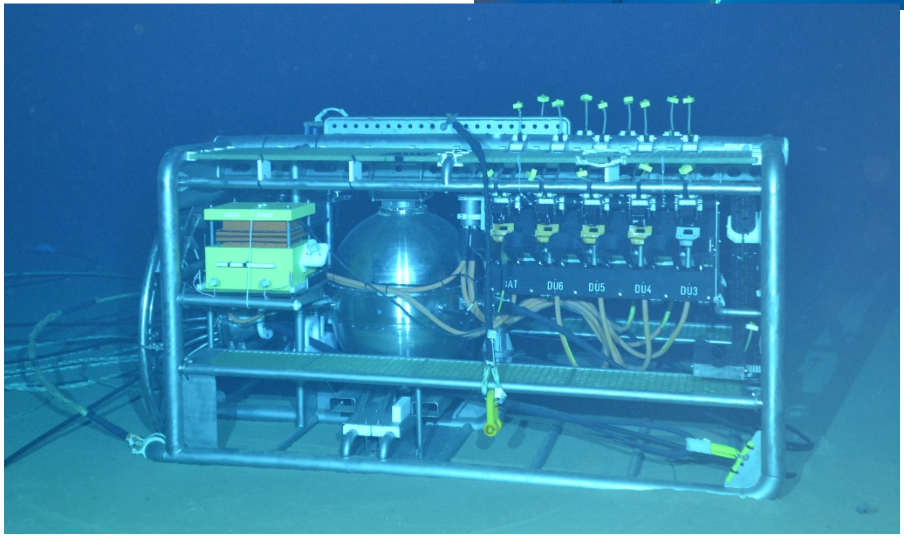


Atmospheric muons



ORCA Junction Box Re-deployment (29 Sept 2016)



Operational, but fault developed in deep sea cable

Timeline

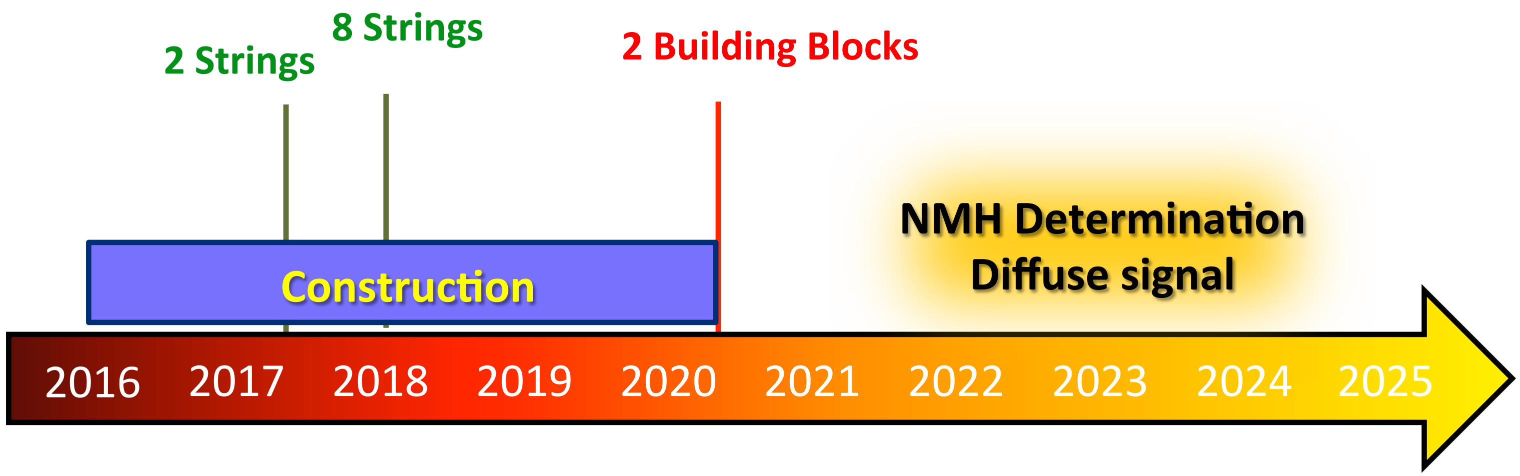
May 2017: Repair of KM3NeT-Fr deep sea cable

July 2017: Deploy two ORCA strings

Spring/Summer 2017: Production Readiness Reviews

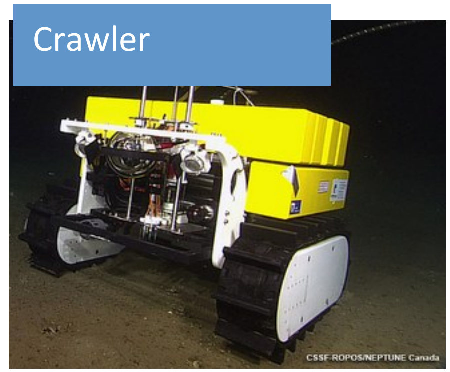
End 2017: Four ORCA strings + Four ARCA strings

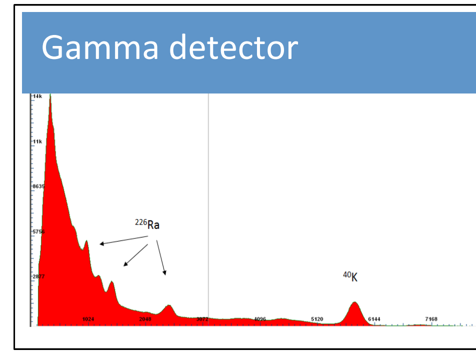
2020: Two full Building Blocks (115*2 strings)

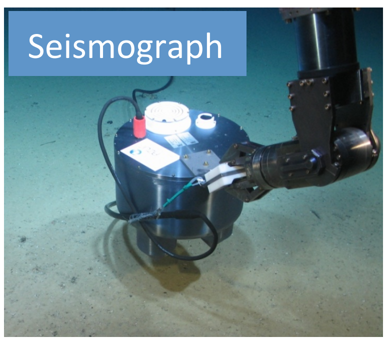


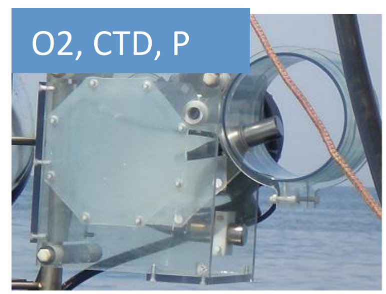
ANTARES/KM3NeT: Earth and Sea Sciences

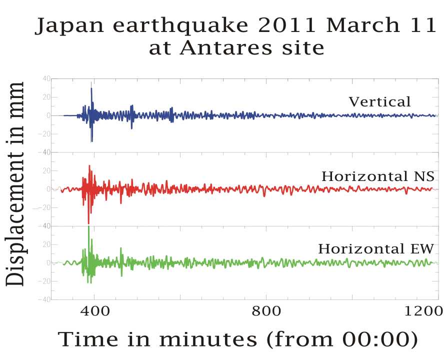
- Real-time
- Continuous
- High frequency
- High power
- Multiple sensors

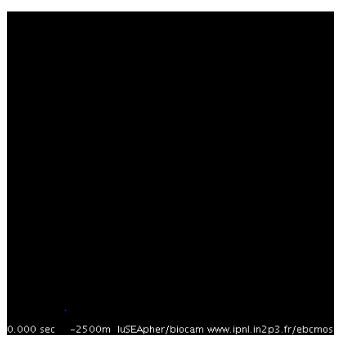


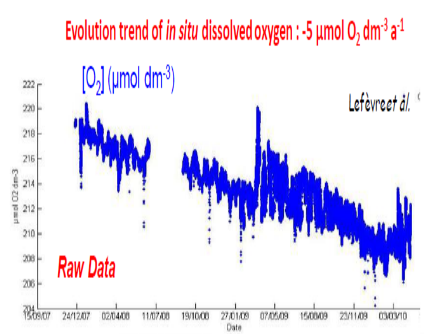


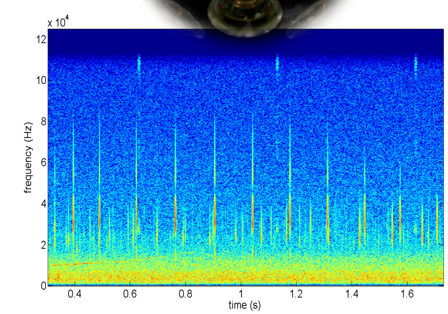




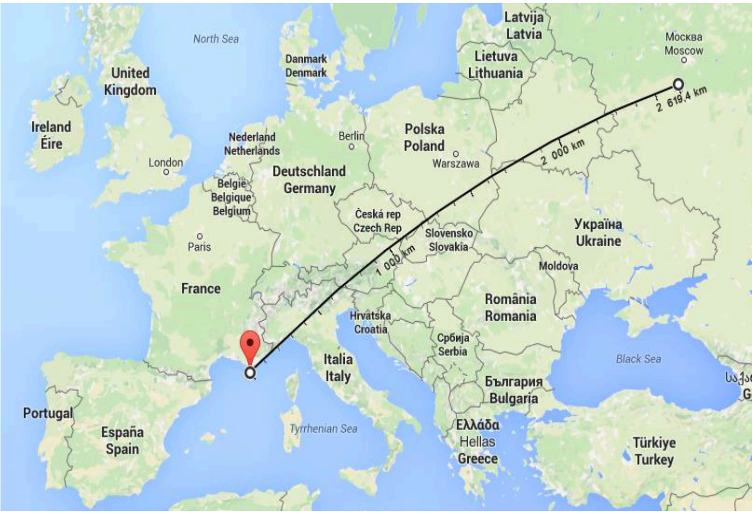






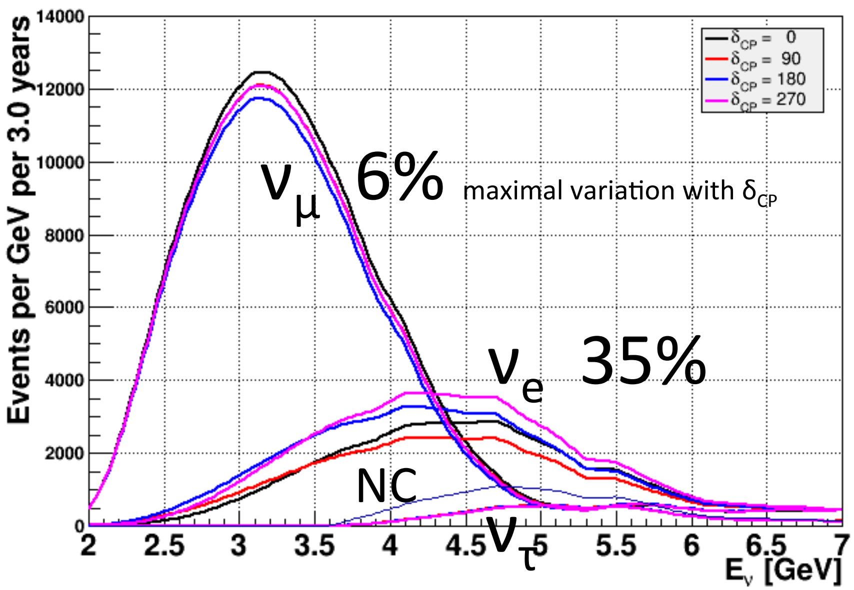


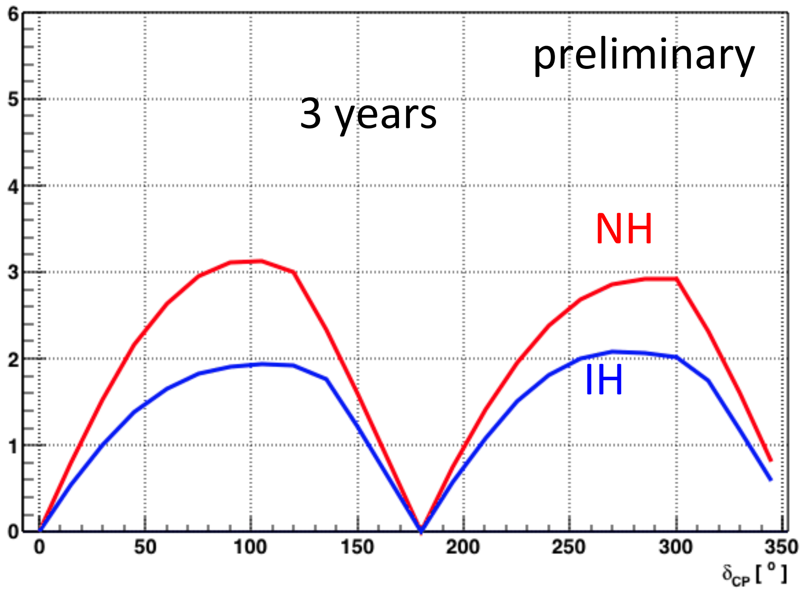
P2O: Protvino to ORCA



- U70 accelerator in Protvino (near Moscow), 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}





Summary and Perspectives

KM3NeT: phased construction of a next-generation neutrino telescope

Developed novel and performant multi-PMT technology
interest from IC-Gen2, CHIPs, NuPrism, HyperK, JUNO,…

ARCA-high energy:

- unprecedented angular resolution/multi-flavour astronomy
- investigation of diffuse flux and point-like sources

ORCA-low energy:

- NMH at 3 sigma level in 3 years (IH, NH/first octant)
  Much quicker if NH/second octant
- Competitive measurements of Δm^2_{32} and $\sin^2\theta_{23}$, tau appearance, sterile neutrinos, NSI, DM, tomography,…

Synergy with Earth and Sea sciences

CP Violation?:

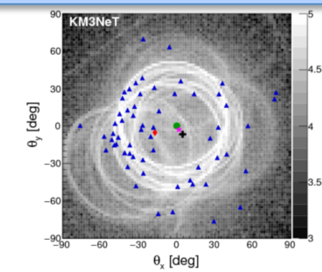
- P2O: Protvino beam to ORCA
- Super ORCA: denser array with threshold ~1 GeV

New collaborators very welcome

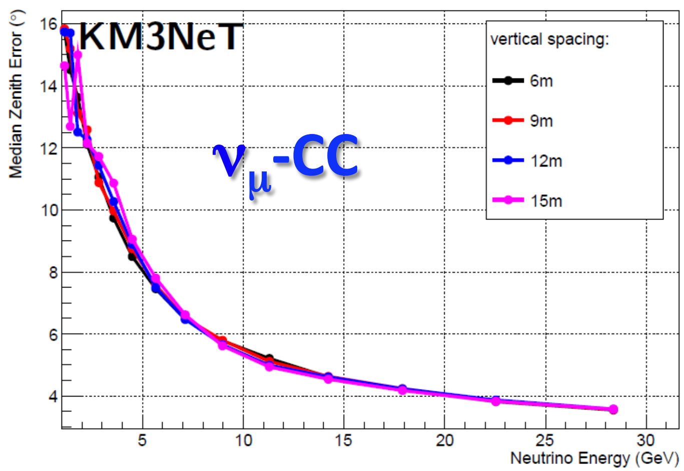
BACKUPS

ORCA Reconstruction Performance

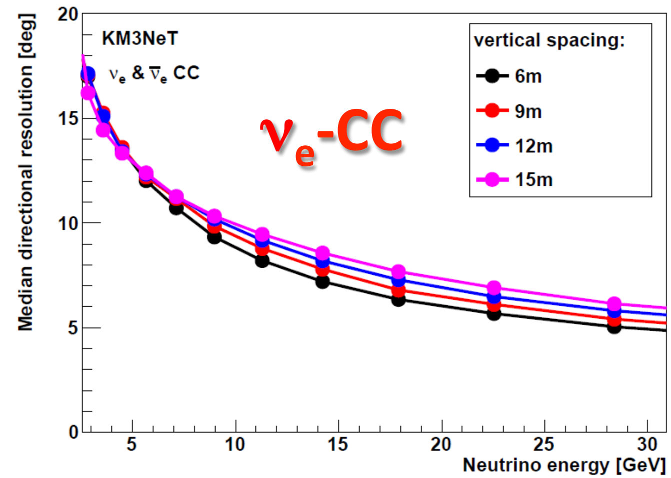
- Angular resolution: Better than 10 degrees at relevant energies
- Energy resolution: ~25% (Close to limit arXiv:1612.05621)



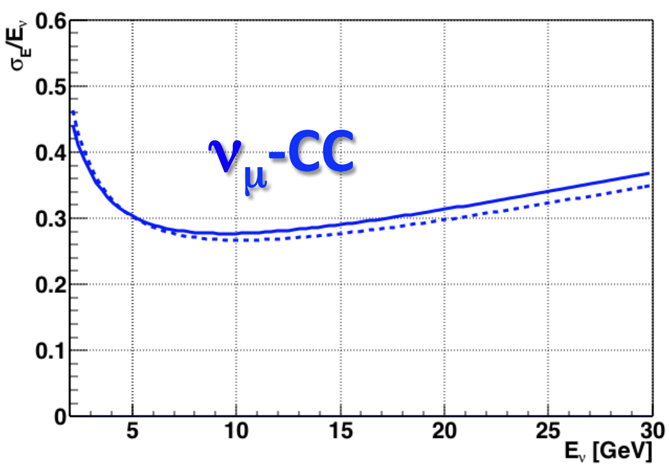
θ Res.



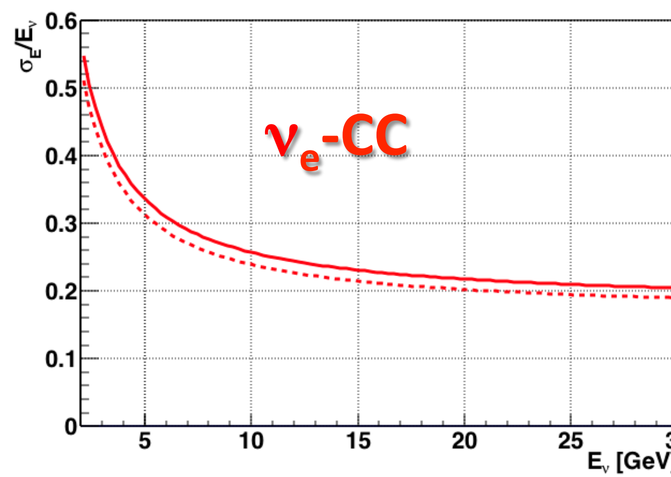
θ Res.



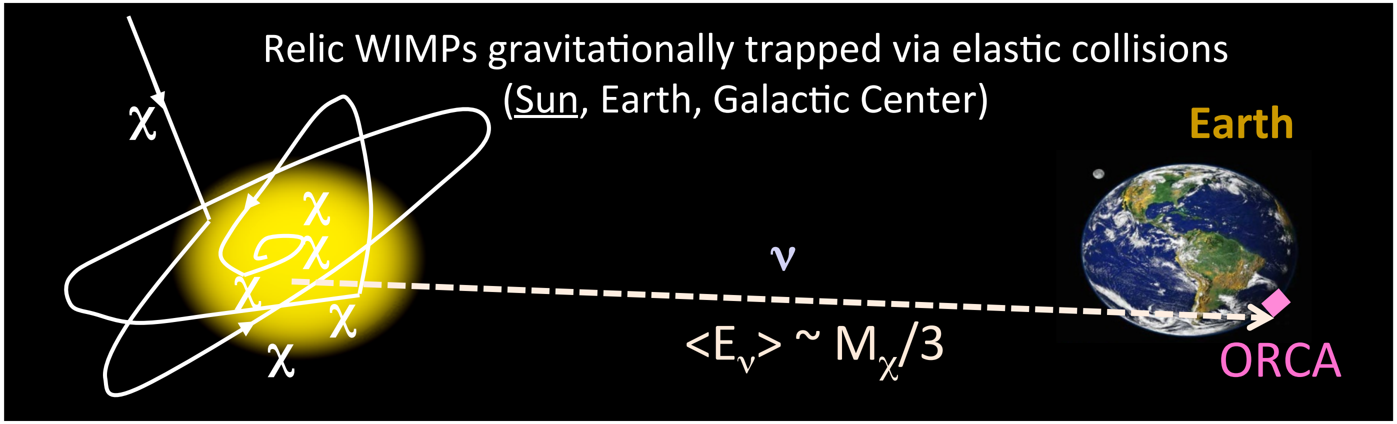
E Res.



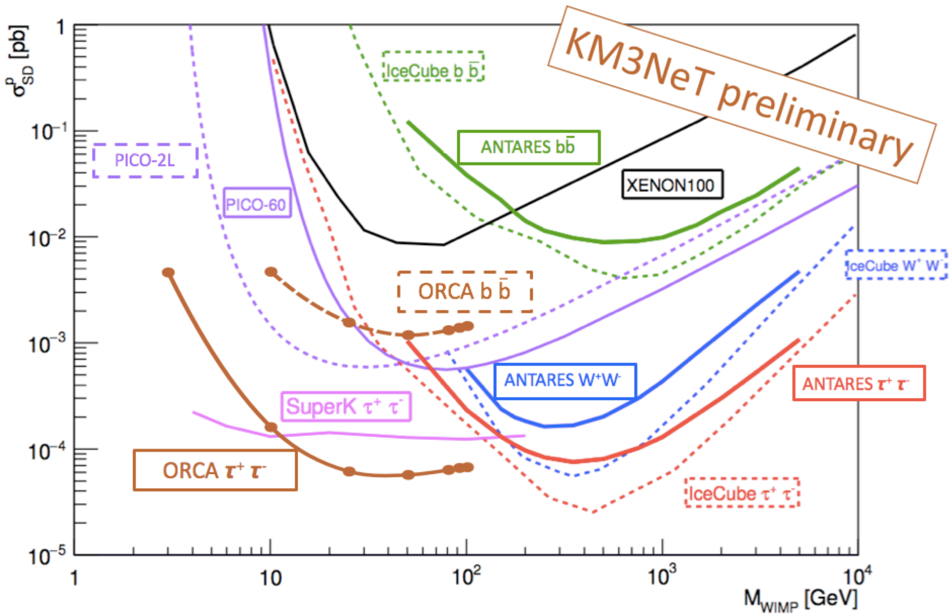
E Res.



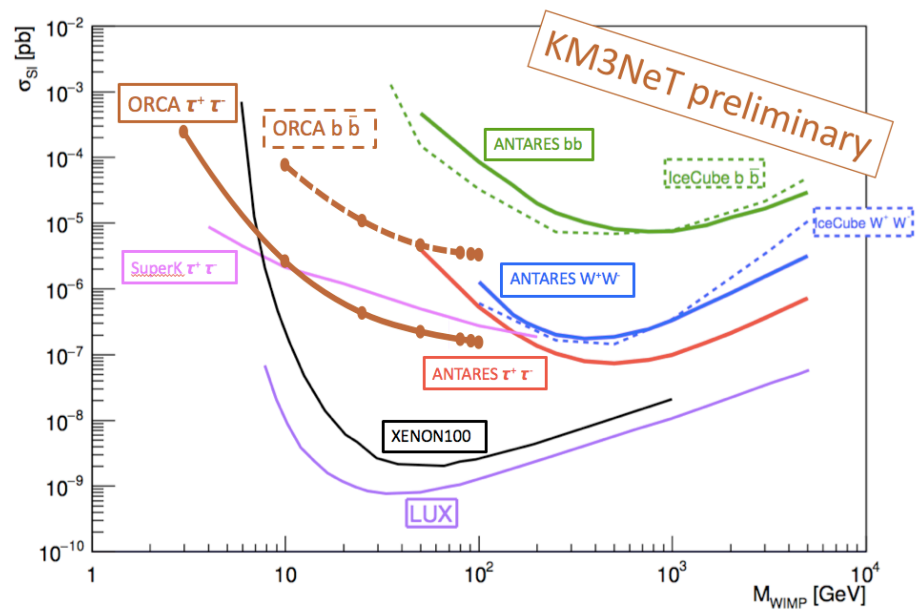
Indirect Detection of Dark Matter



Spin Dependent



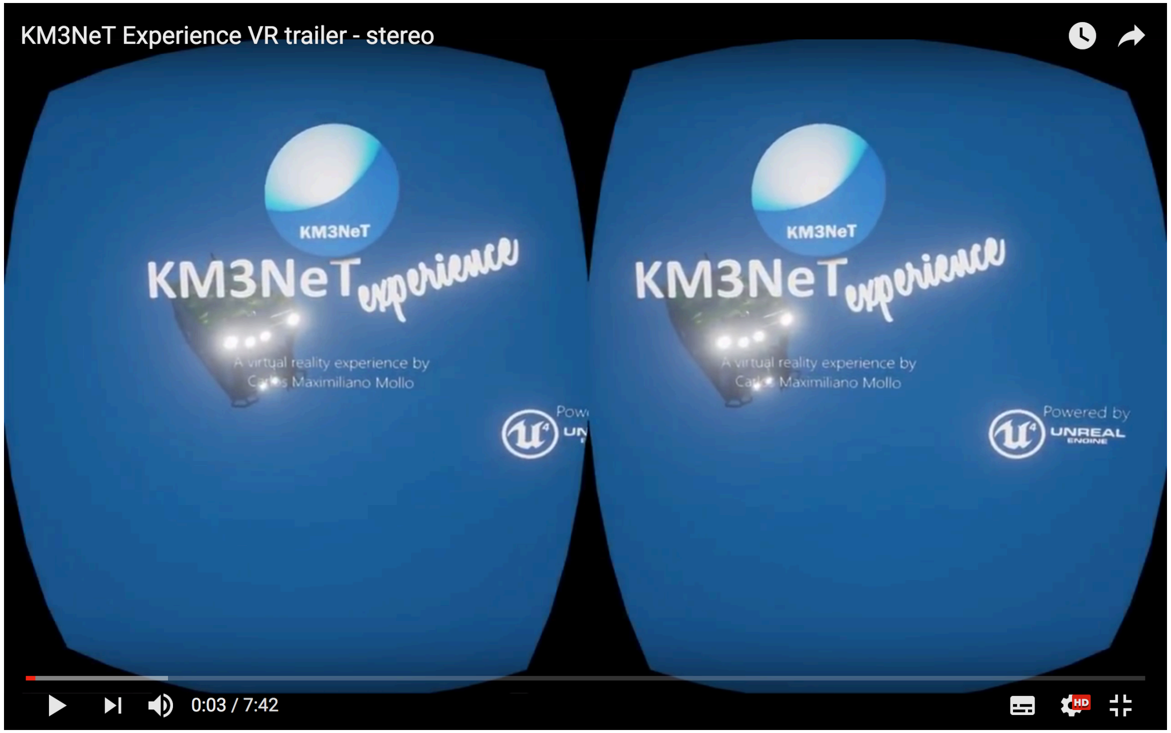
Spin Independent



ORCA 3 years - tracks+showers

Thank you!

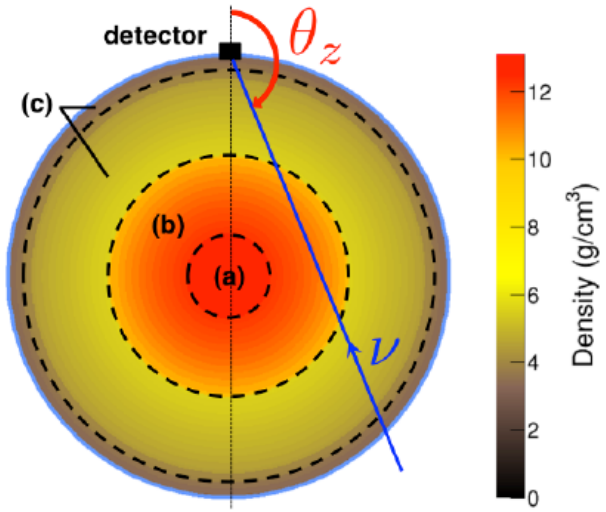
“We know nothing in reality,
for truth lies in the abyss”
ĐÊMOCRITUS OF ABDÊRA,
fragment 117, 420BC



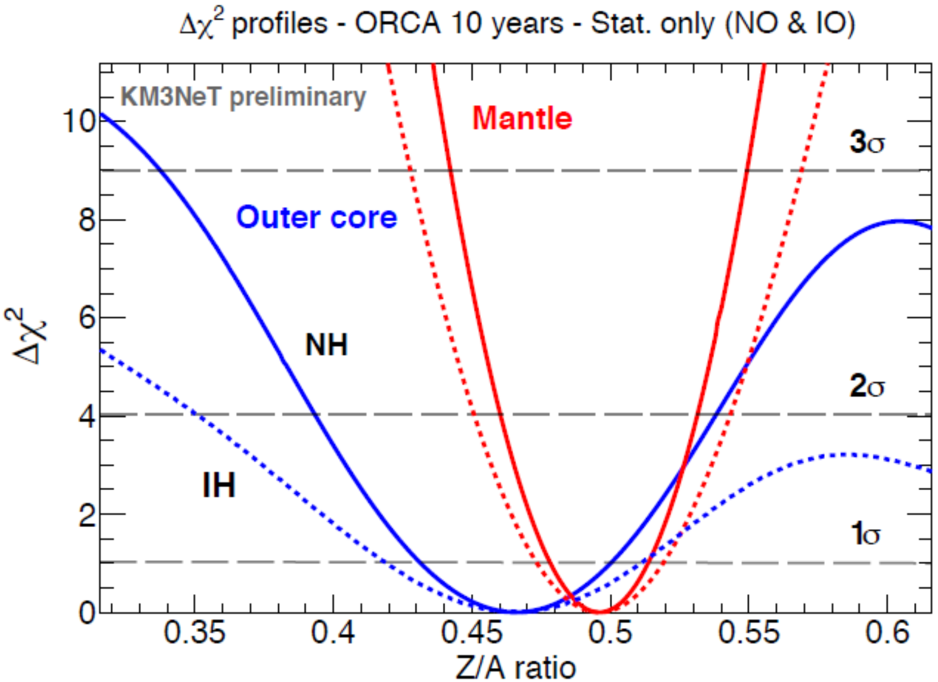
https://www.youtube.com/watch?v=Bcqpa4YbxCk

Earth Tomography

- ORCA is sensitive to the electron density N_e while geophysics measure ρ_m
- 1σ stat. uncertainty after 10 years for NH:
  - ~ 4% in the whole mantle (c)
  - ~ 7% in the whole outer core (b)



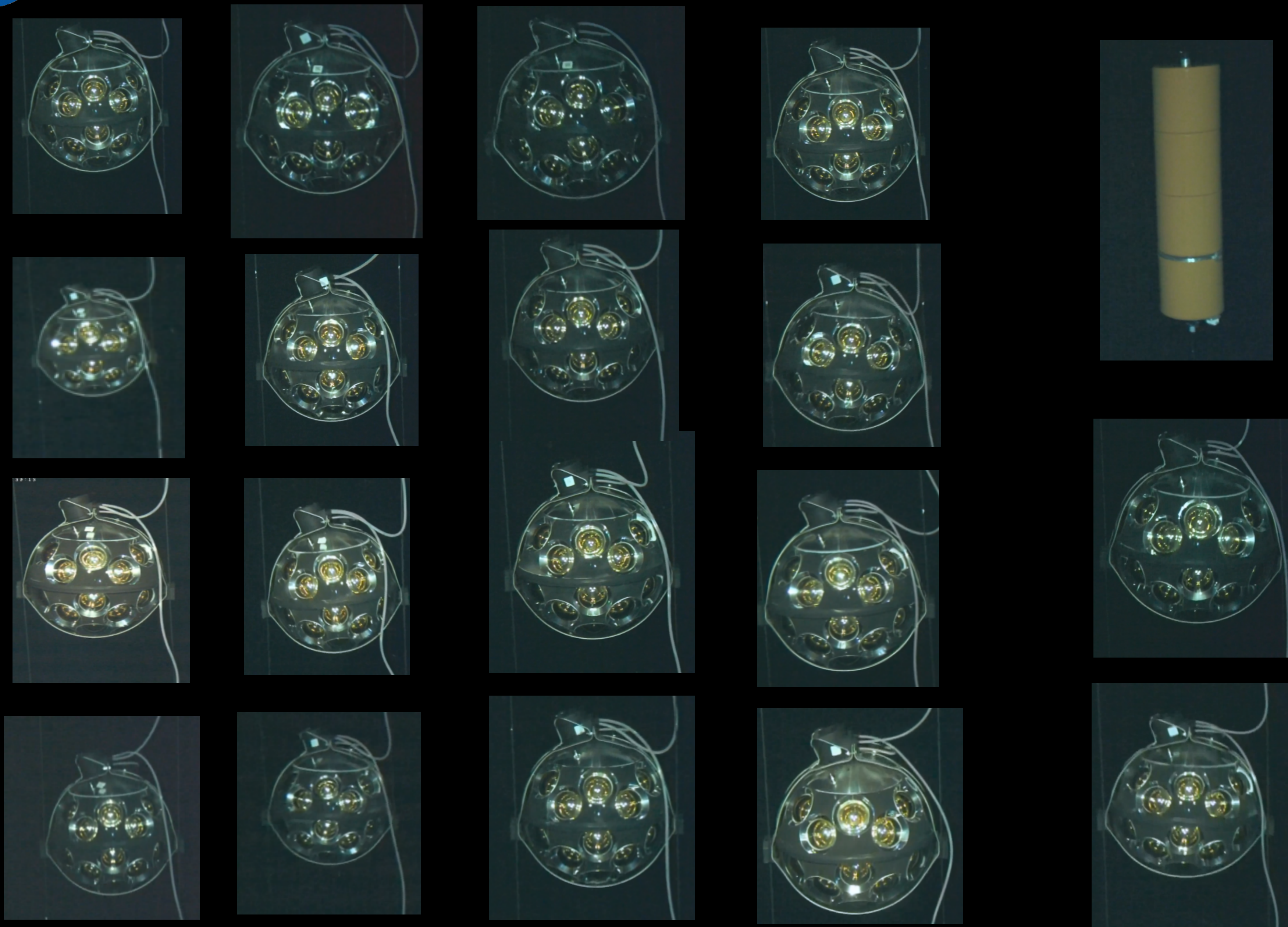
$$\frac{N_e}{\rho_m} \propto \sum_i w_i \frac{Z_i}{A_i}$$



S Bourret et al (KM3NeT) 2016
J. Phys.: Conf. Ser. [Neutrino2016]

- PREM model basis for ρ_m
- uniform Z/A rescaling in layer
- Monte Carlo response & PID
- statistical uncertainty only

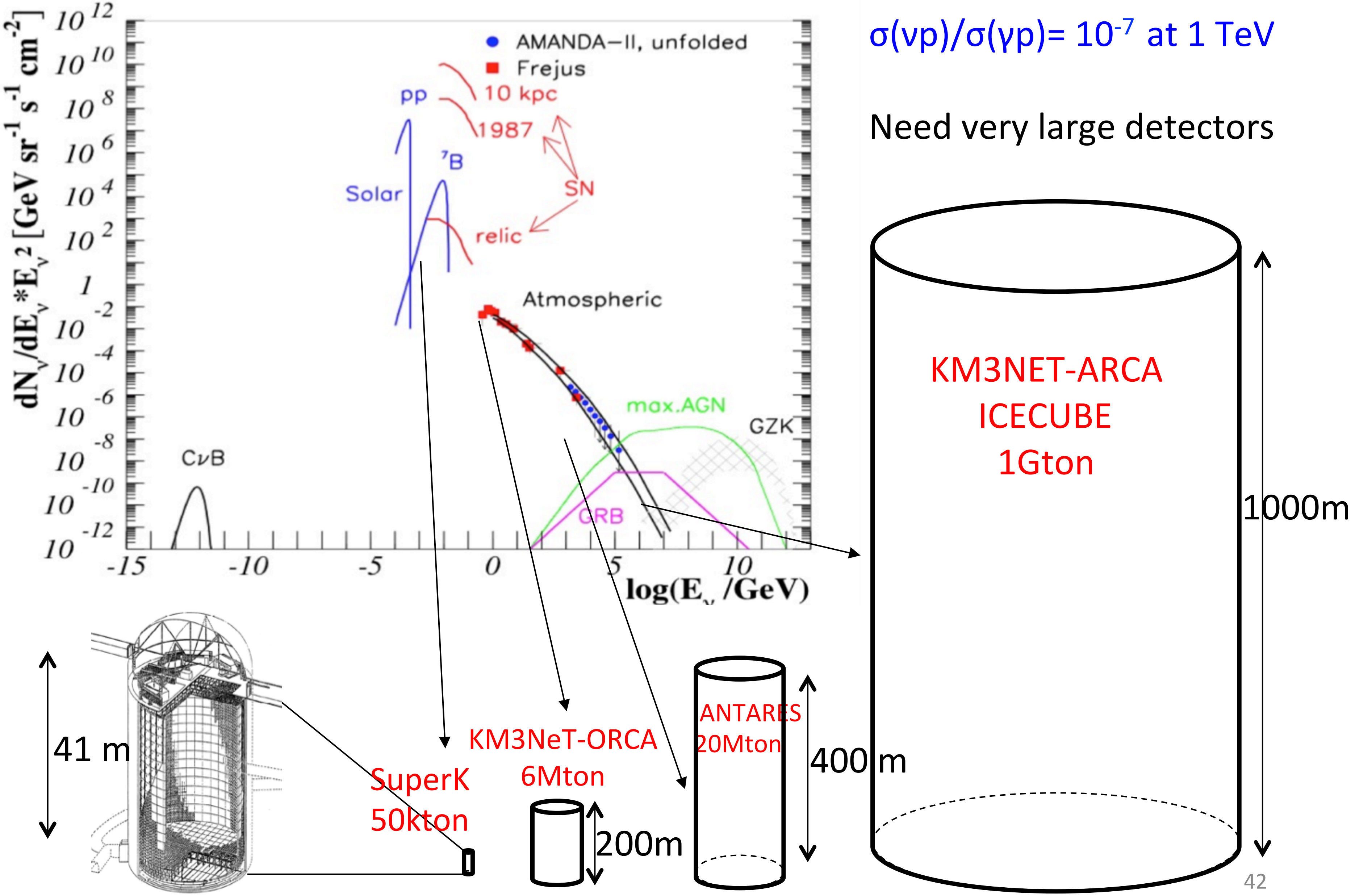
The first KM3NeT String (in-situ)



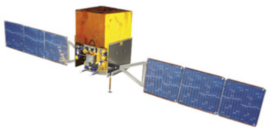
Neutrinos Fluxes From MeV to PeV

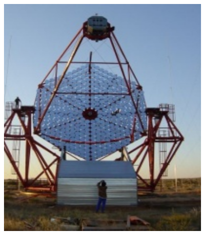
σ(νp)/σ(γp)= 10^{-7} at 1 TeV

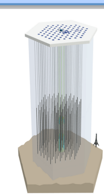
Need very large detectors

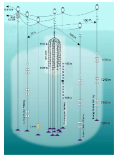


Multi-Messenger/Multi-flavour Astronomy







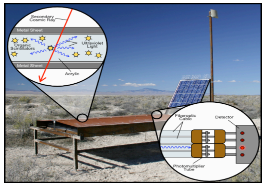


neutrinos
IceCube, GVD, SNEWS

GeV-TeV γ-rays
Fermi, HESS, HAWC, CTA

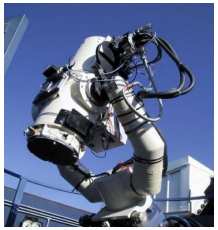
UHECR
Auger, TA

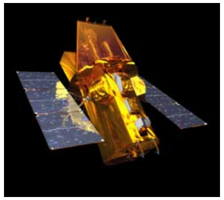
only spatial coincidence



ANTARES, KM3NET

Receive alerts
Generate alerts





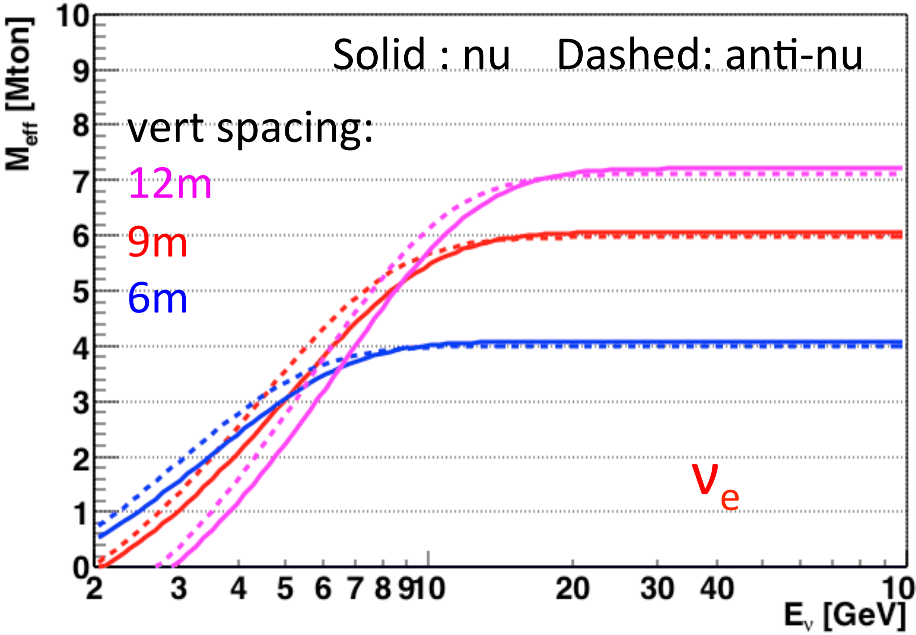
Radio/Optic /X-ray
TAROT, MASTER, Swift, SVOM, MWA

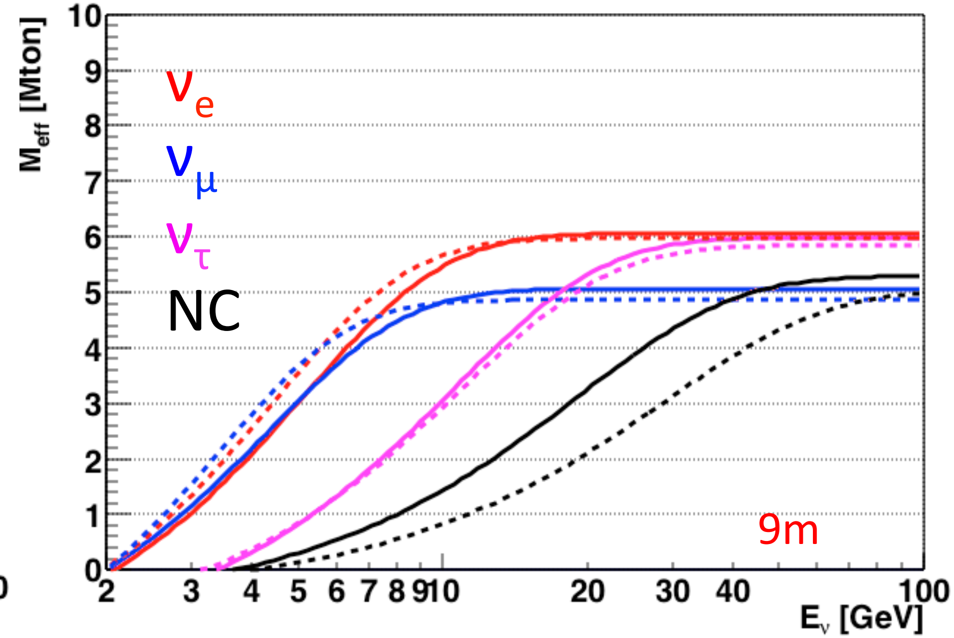
Gravitational Waves
VIRGO, LIGO

- Space/time correlation reduced background (improved sensitivity)
- Track and shower topologies
- Rapid (few secs) real-time alerts for interesting neutrino events
- Event-by-event identification of neutrino origin

Effective Mass

After triggering, atmospheric muon rejection and containment cuts:



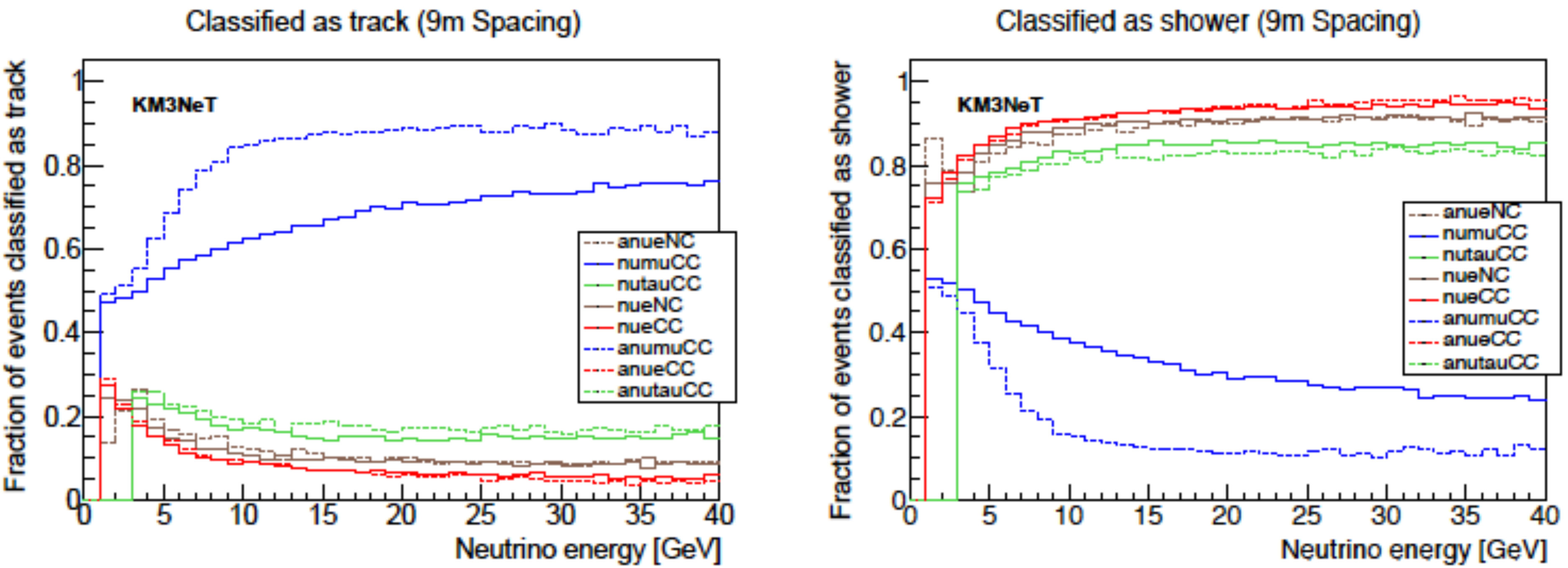


- Energy threshold determined by DOM spacing
- 9m vertical spacing -> 6 Mton@10 GeV
  - 50% Efficiency at 5 GeV
  - Instrumented volume reached at ~10 GeV
- Lower efficiency for neutral current

Events/yr:
ν_eCC: 17,300
ν_μCC: 24,800
ν_τCC: 3,100
NC: 5,300

Shower/Track Identification

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



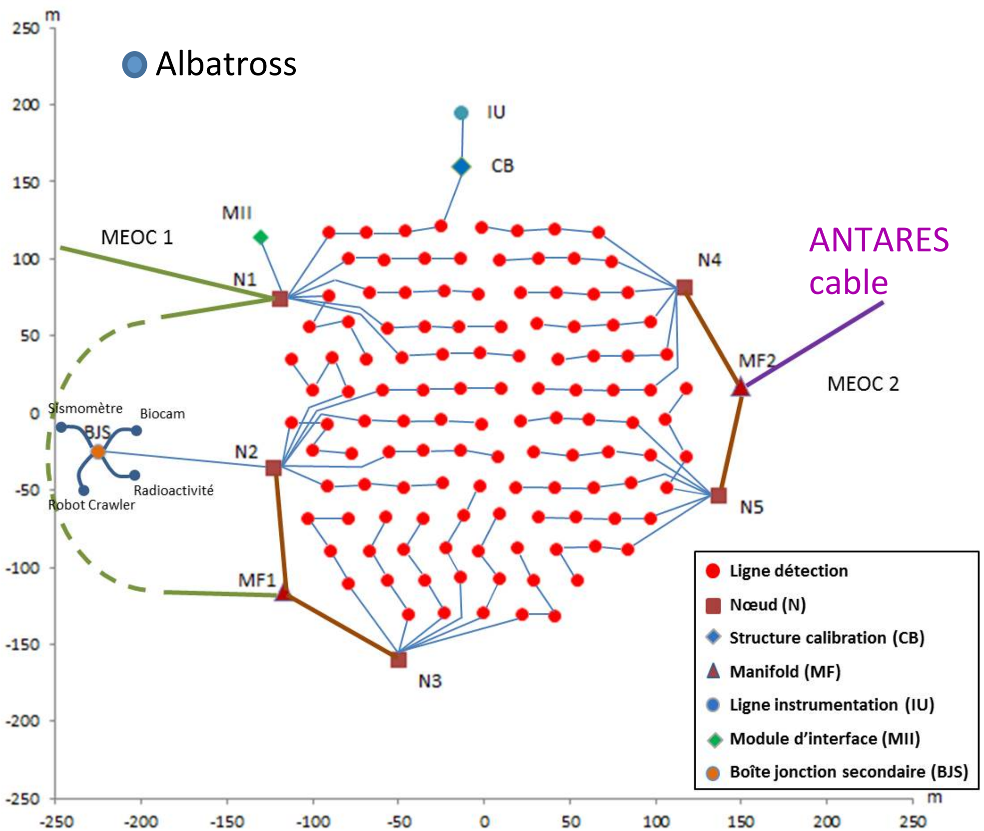
At 10 GeV:

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

ORCA Status

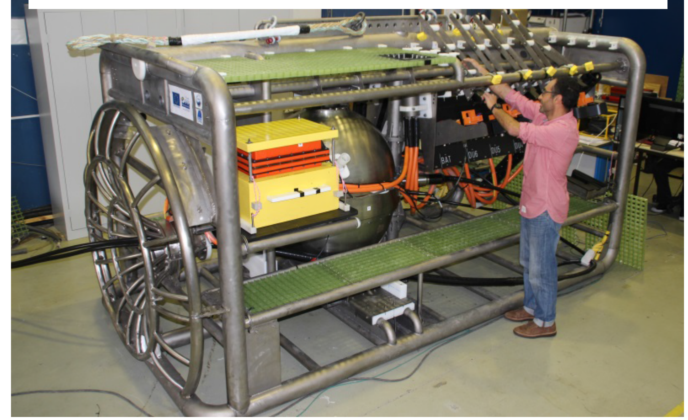
Phase 1: 7 string array at KM3NeT-France site to demonstrate technology/detection methods in the GeV range

Phase 2: Deploy 1 building block (115 strings)

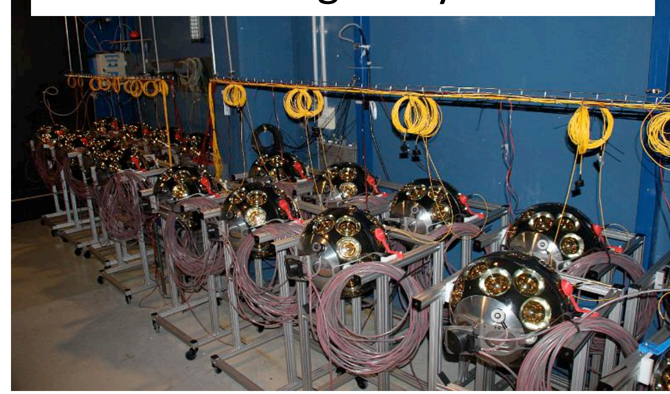


MEOC: Dec 2015

1st node: May 2015, Sept 2016

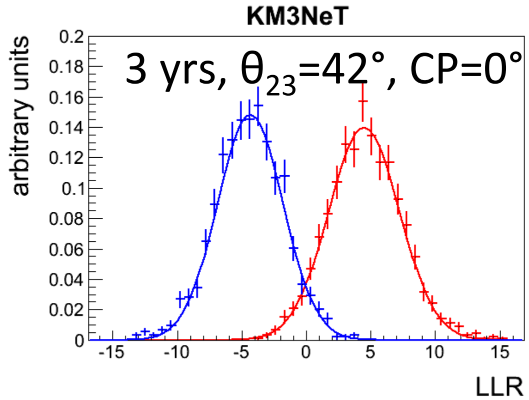


2 ORCA strings: July 2017



Sensitivity Studies (Pseudo Expts)

- Pick set of true values for oscillation parameters and other systematics
- Generate pseudo-experiments for NH, IH cases
- Find best-fit likelihoods L_{NH}, L_{IH} for the NH, IH cases (maximising w.r.t. 8/9 free parameters)
- Calculate the log-likelihood ratio log (L_{NH}/L_{IH})



	parameter	true value distr.	initial value distr.	treatment	prior
nu parameters	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
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

Sensitivity Studies (Asimov)

Various systematic effects taken into account:

- Oscillation parameters
  - Δm^2, θ_{12} fixed;
  - θ_{13} fitted within its error
  - ΔM^2, θ_{23}, δ_{CP} → Fitted unconstrained

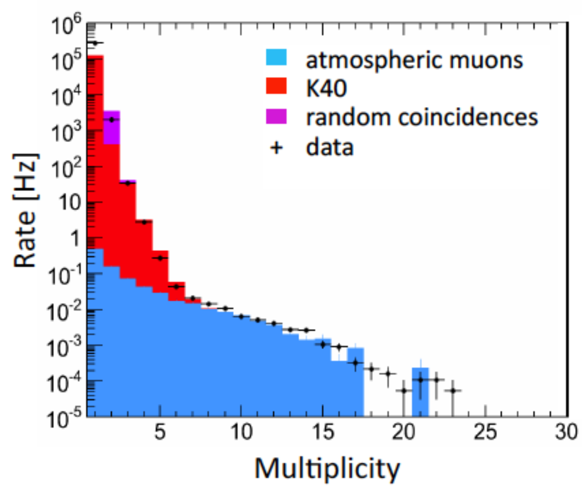
- Flux, cross section, detector related

	(average fluctuation w.r.t. nominal)
Overall normalisation	(2.0%)
ν/anti-ν ratio	(4.0%)
e/μ ratio	(1.2%)
NC scaling	(11.0%)
Energy slope	(0.5%)
Energy scale	

→Fitted unconstrained

KM3NeT Prototypes

1) Optical Module deployed at Antares, April 2013 (2500 m)



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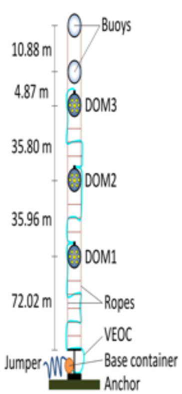
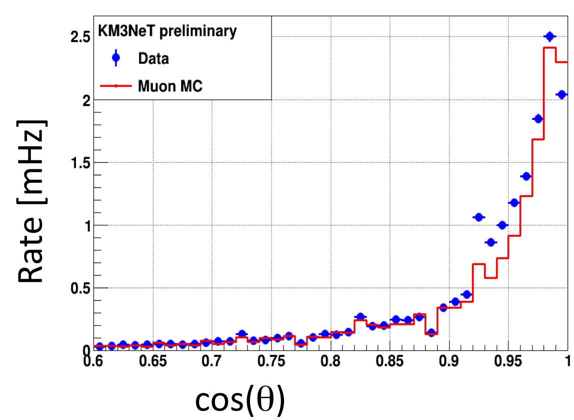
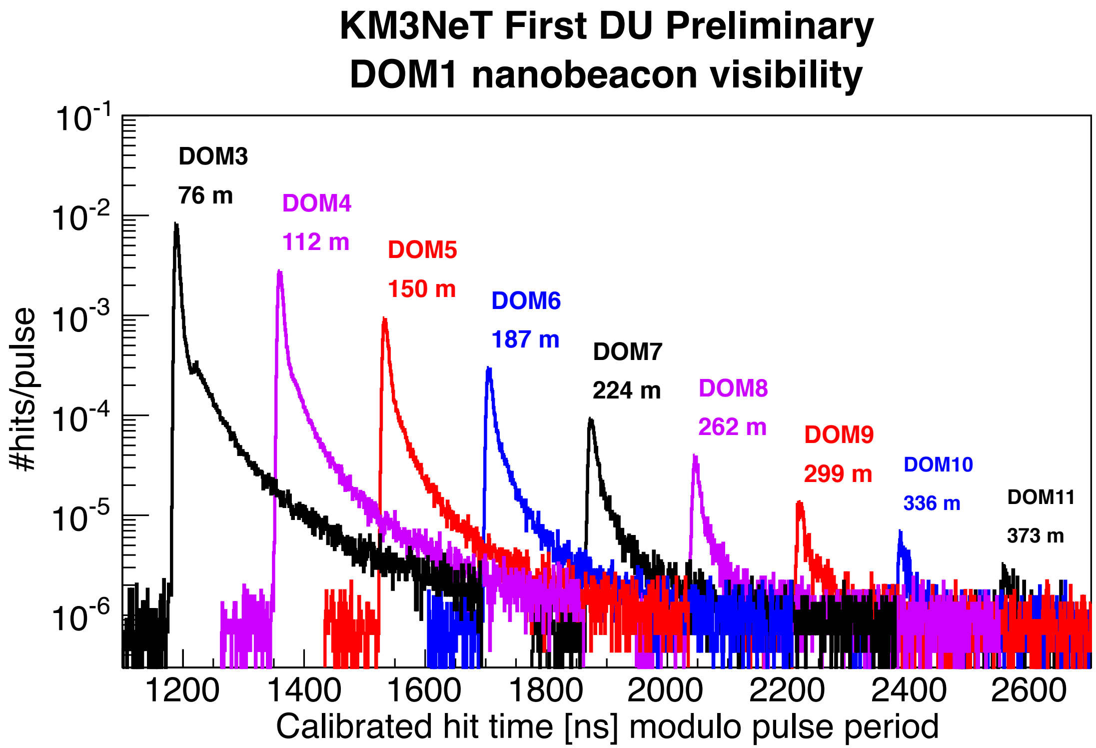
2) Mini string deployed at Capo Passero, May 2014 (3500 m)

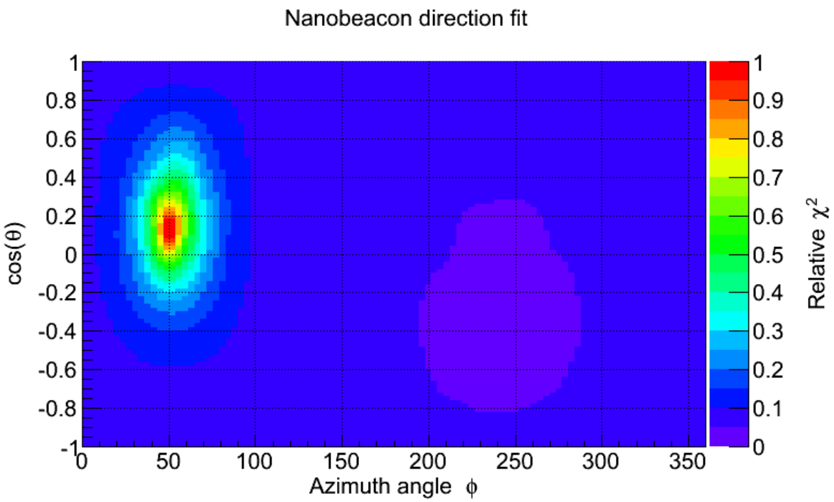


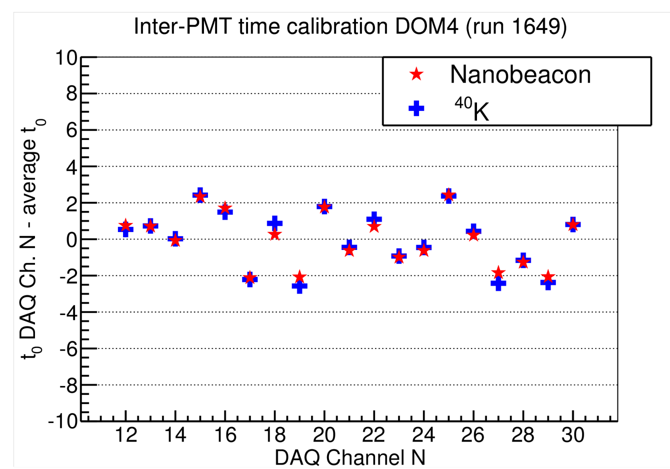


Eur. Phys. J. C (2016) 76: 54

Nanobeacon: Inter-DOM Calibration

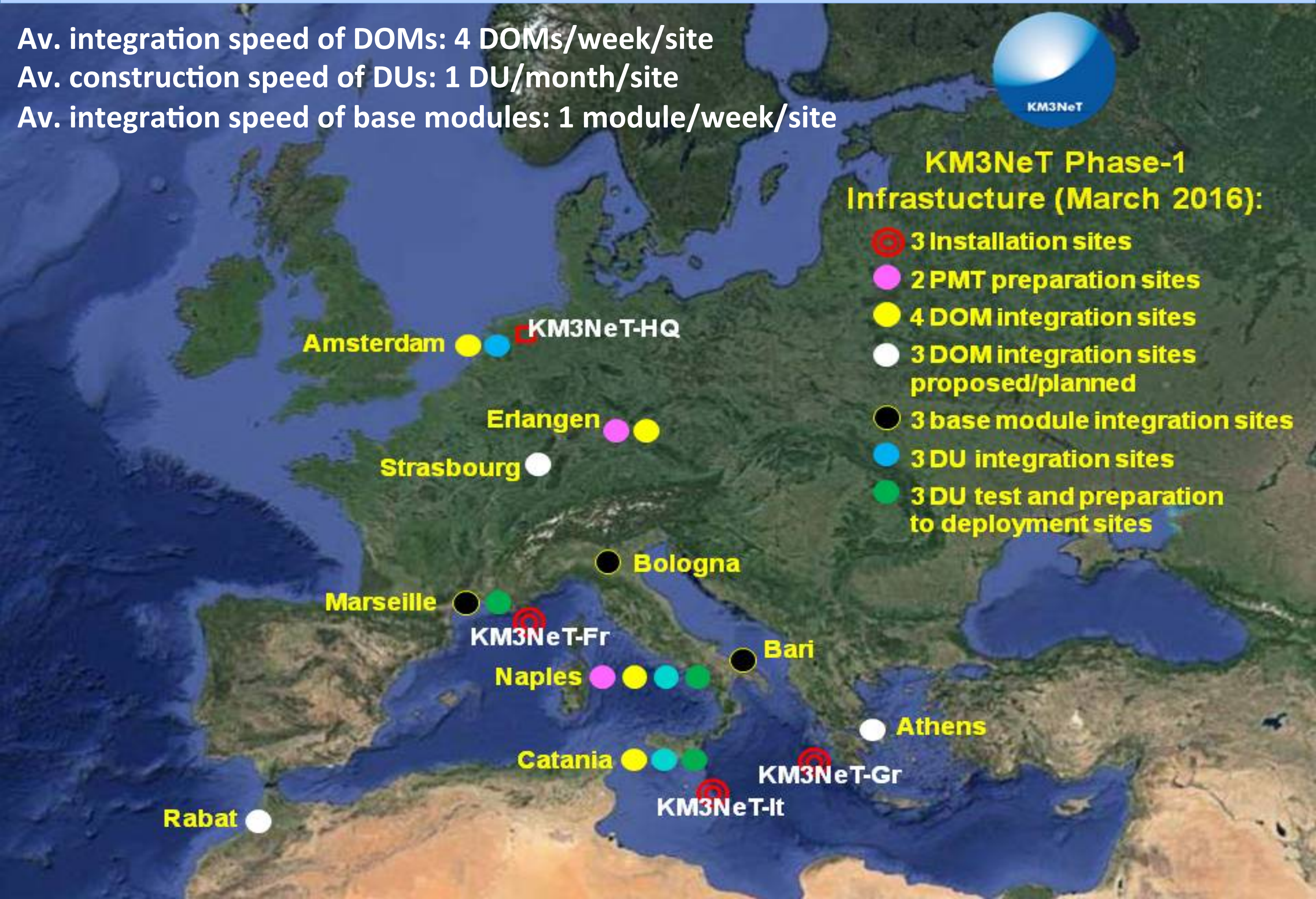






KM3NeT Integration Sites

Av. integration speed of DOMs: 4 DOMs/week/site
Av. construction speed of DUs: 1 DU/month/site
Av. integration speed of base modules: 1 module/week/site



ORCA/PINGU: Neutrino Mass Hierarchy Determination

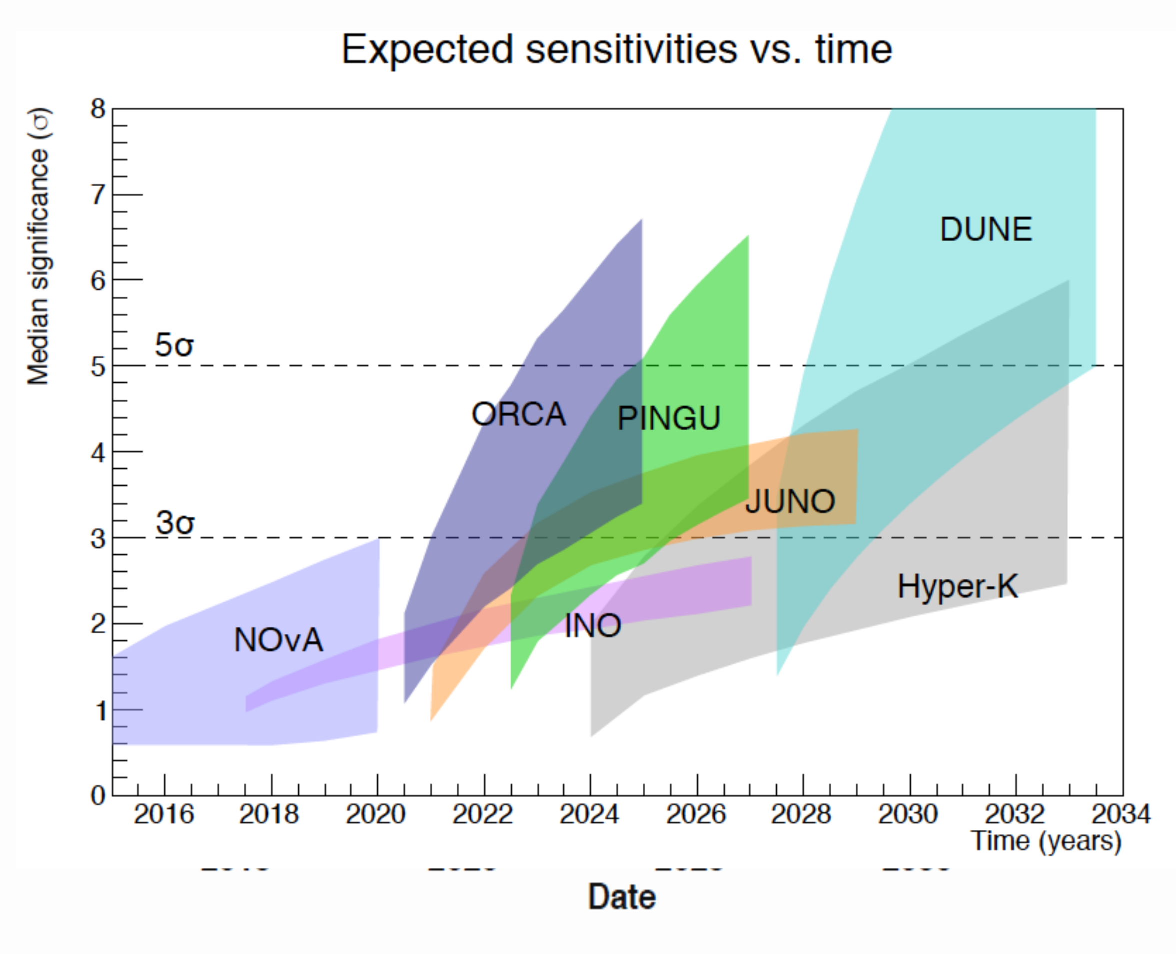
3 sigma determination of neutrino mass hierarchy in 3/4 years

Widths indicate main uncertainty
- LBNE/NOVA: δcp, θ_{23}
- JUNO: σE (3.0-3.5%)
- ORCA/PINGU/INO: θ_{23}

Other projections assume worst case parameters (1st oct)

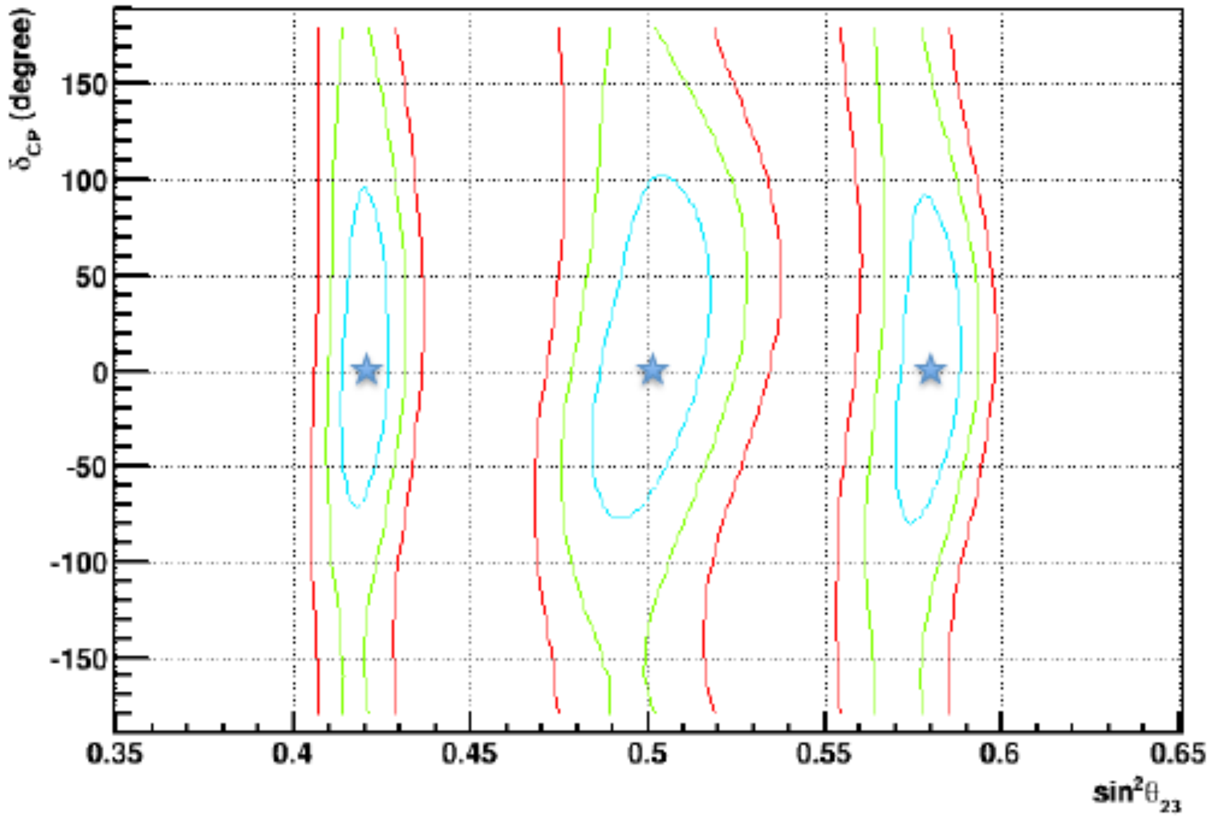
ORCA timeline, assumes start construction 2017 for 3 years

LBNE from LBNE-doc-8087-V10
PINGU from MANTS 2015
Others Blennow



Sensitivity to CP phase ?

6 years, no systematics
NH true, δCP=0, three test points, 1/2/3 sigma



Comparison with other projects

- ORCA
- Per year ν_μ CC : 24,800 & ν_e CC : 17,300

- NOVA (2x 1.8 10^{21} p.o.t.)
  - per year ~70 ν_μ and 15-25 ν_e (less with anti-nu)
  - 6 years running planned (shared nu/anti-nu)
- T2K (7.8 10^{21} p.o.t.)
  - Until 2020 : 1400 ν_μ and 240 ν_e
- DUNE (34kt)
  - Per year 150 ν_e