KM3NeT: Astroparticle and Oscillation Research in the Abyss

FCPPL Workshop
31 March 2016

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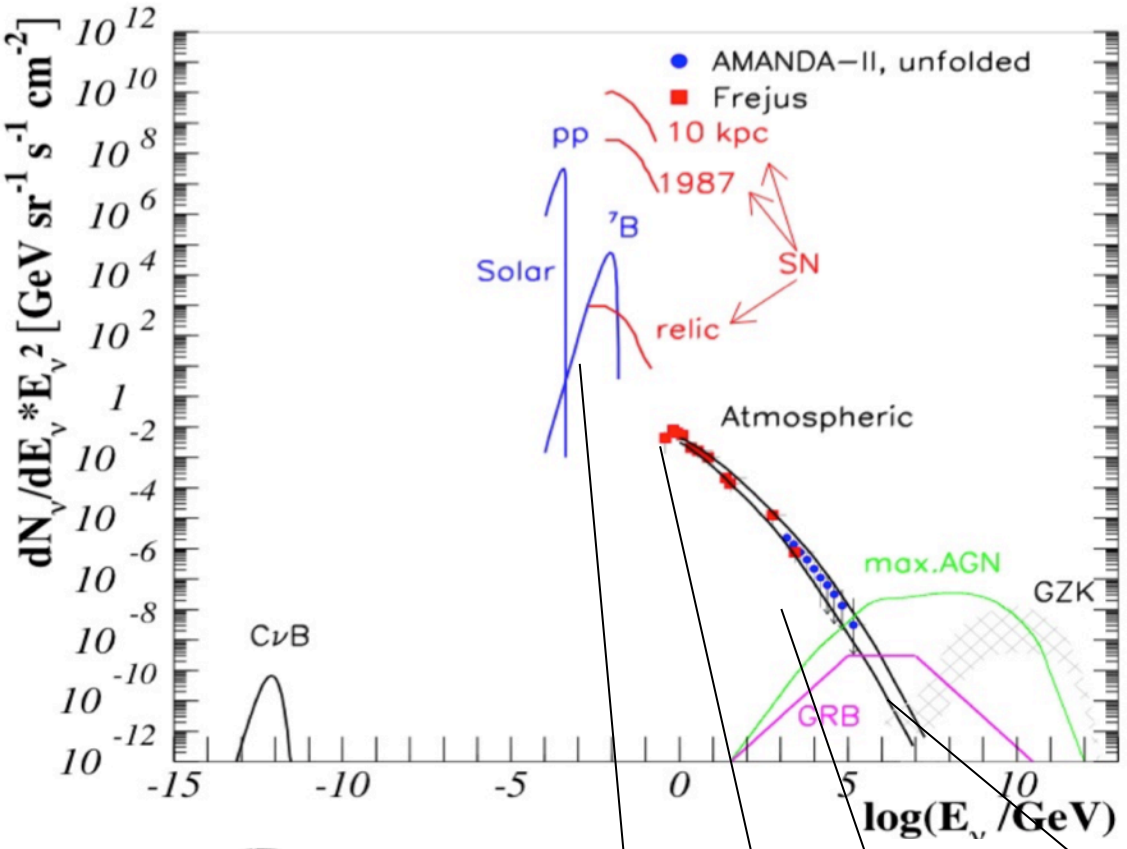
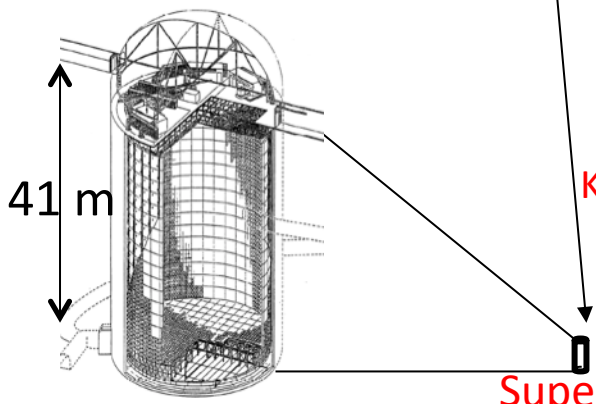
Centre de Physique des Particules de Marseille

Neutrinos From MeV to PeV



Small cross-sections:
Need very large detectors for highest energies



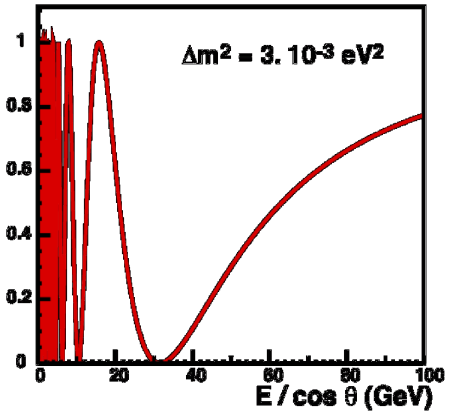
SuperK

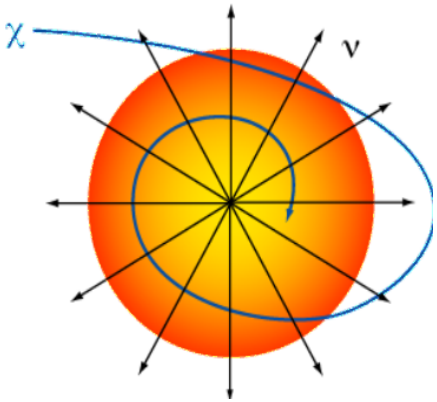
KM3NeT-ORCA
PINGU

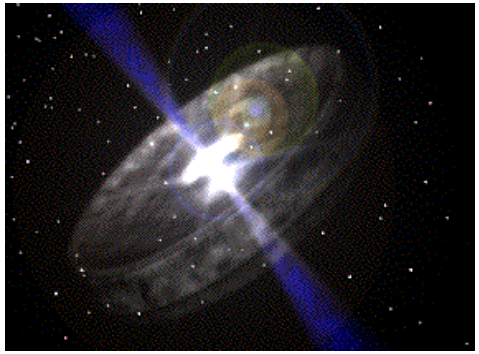
ANTARES

KM3NET-ARCA
ICECUBE

Neutrino telescopes: science scope







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

ν Oscillations
ν Mass hierarchy

Dark matter search

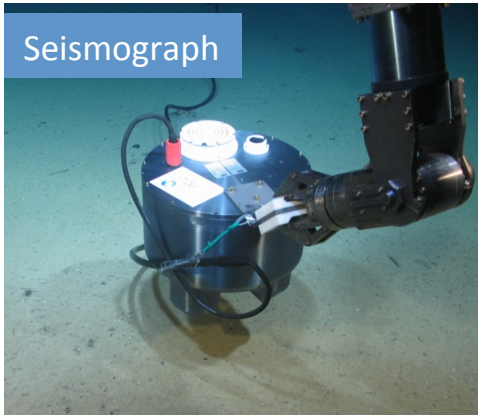
ν from extra-terrestrial sources

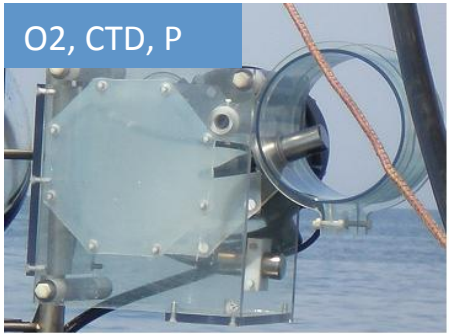
Origin and production mechanism of HE CR

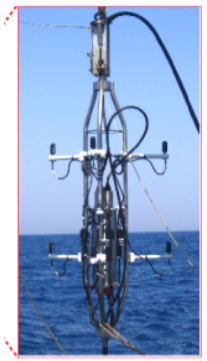
Exotic particle physics
Monopoles, nuclearites,…

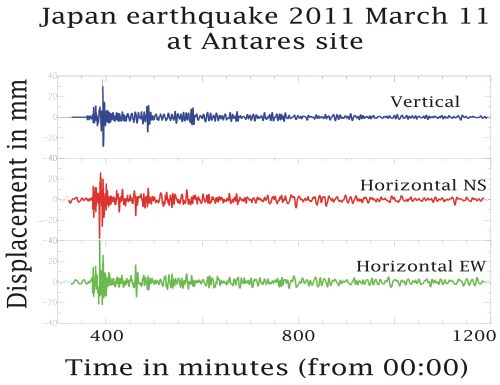
oceanography, biology, seismology,…

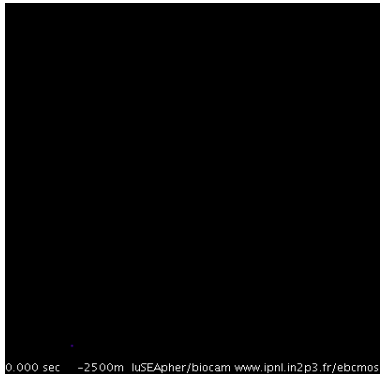
Earth and Sea Sciences (ANTARES)

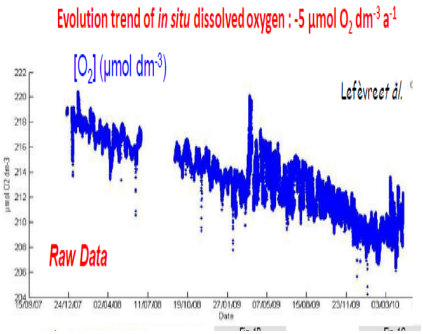


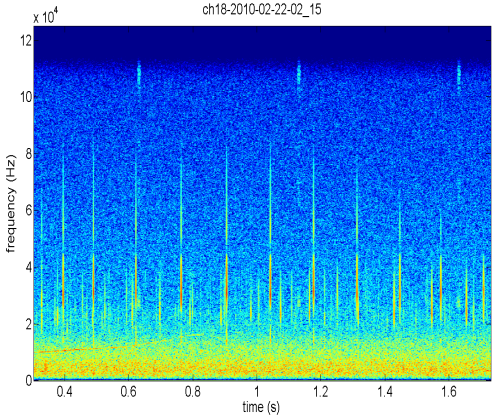


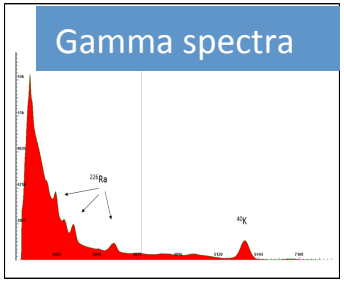












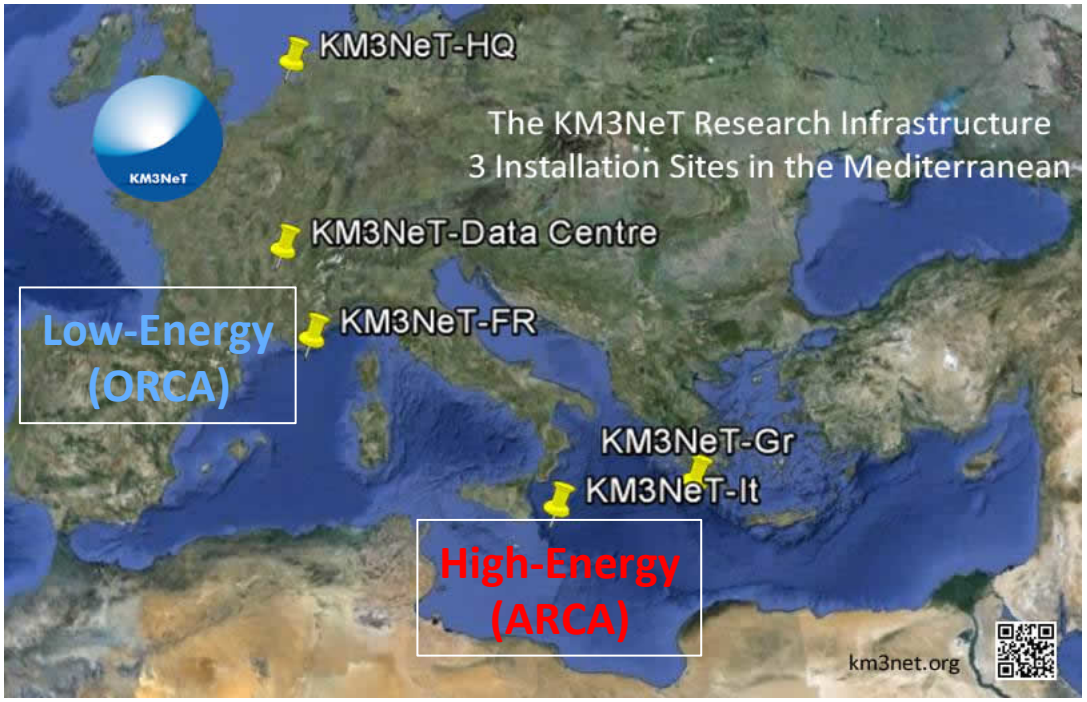
KM3NeT

KM3NeT is a distributed research infrastructure with 3 main science topics:

- The origin of cosmic neutrinos (high energy)
- Measurement of fundamental neutrino properties (low energy)
- Deep Sea Observatory - Oceanography, bioacoustics, bioluminescence, seismology

Single Collaboration

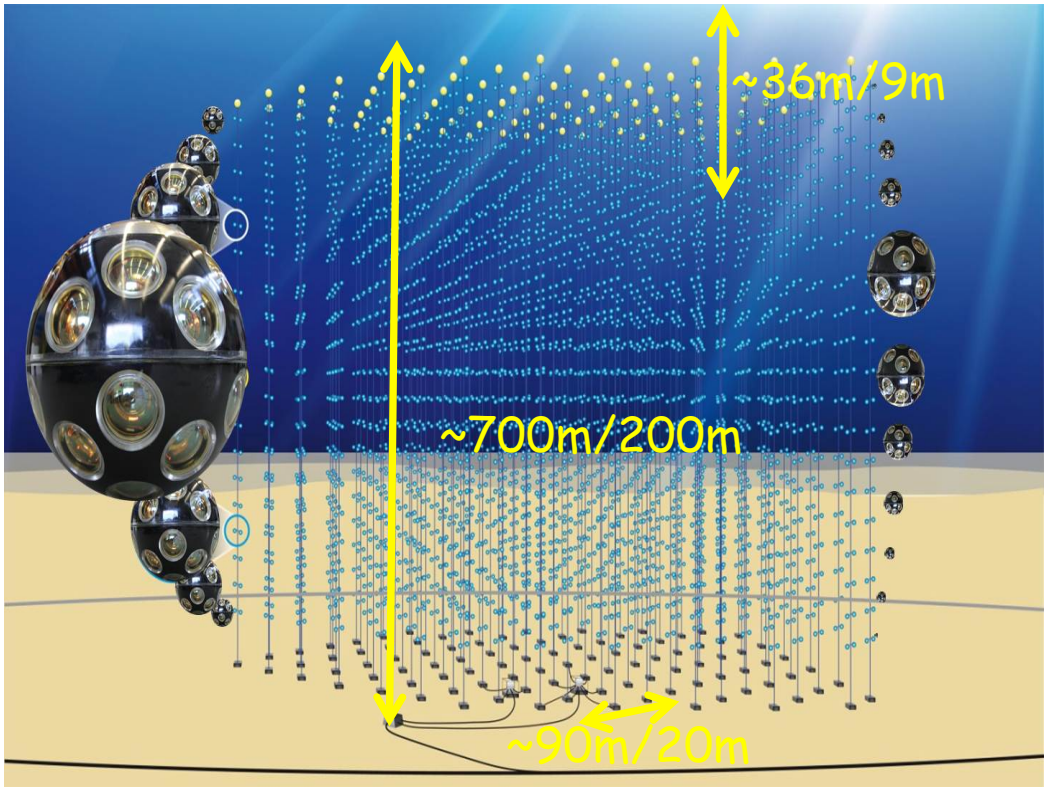
Single Technology

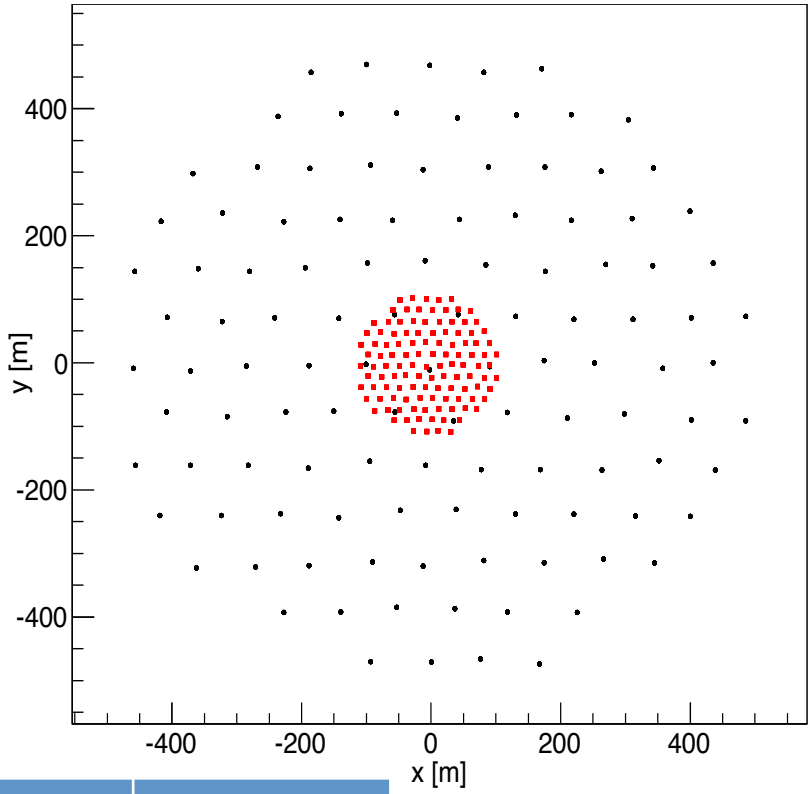


ARCA- Astroparticle Research with Cosmics in the Abyss

ORCA- Oscillation Research with Cosmics in the Abyss

KM3NeT Building Block (115 strings)





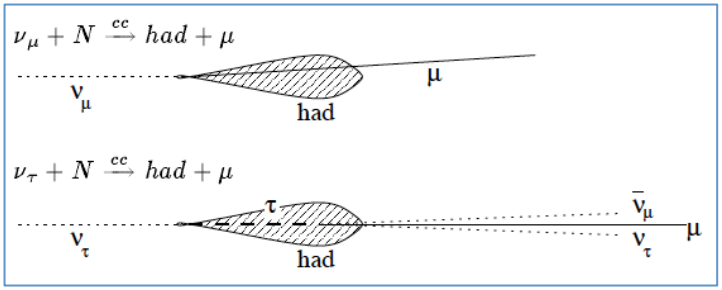
	ARCA	ORCA
Location	Italy	France
String distance (m)	90	20
DOM spacing (m)	36	9
Volume (MTon)	500*2	6.7

Phased Implementation

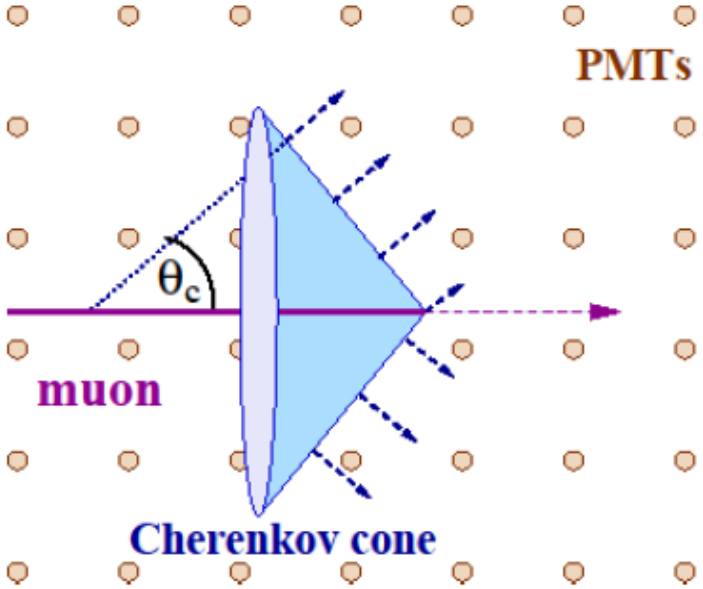
Phase	Blocks	Primary deliverables
1	0.2	Proof of feasibility and first science results (6 ORCA strings/ 24 ARCA strings)
2.0	2 *ARCA*	Study of neutrino signal reported by IceCube; All flavor neutrino astronomy
	1 *ORCA*	Neutrino mass hierarchy
3	1+6	Neutrino astronomy including Galactic sources

Event Topologies

Track-like



Track-like contains both a cascade and one track



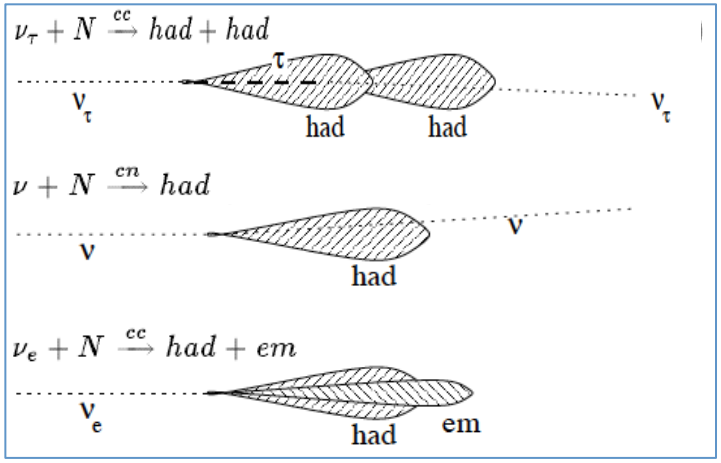
Muon track from CC muon neutrinos

Angular resolution 0.5°/0.1° for ice/water at 100 TeV

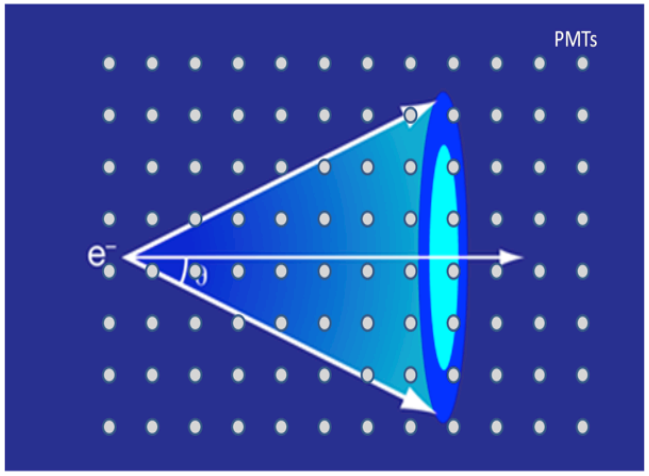
dE/dx resolution factor 2-3

Not to scale

Shower-like



No track is identified



CC electron/tau and NC all flavour

80% of all nu interactions

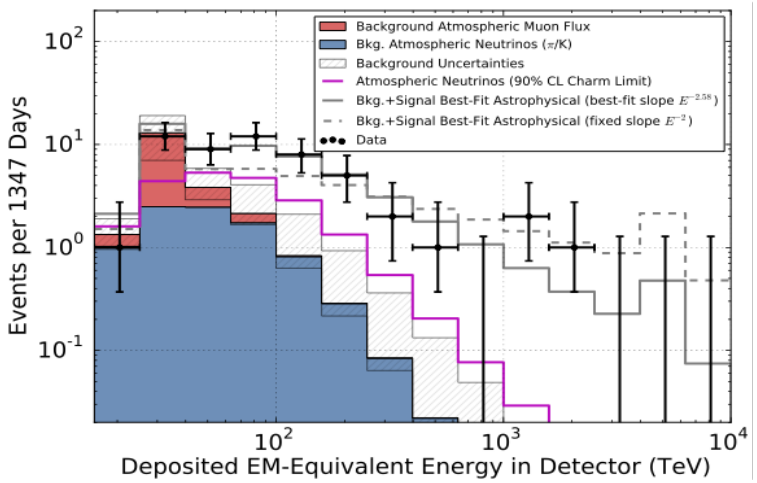
Angular resolution 15°/1° at 100 TeV for ice/water

Energy resolution ~ 10%

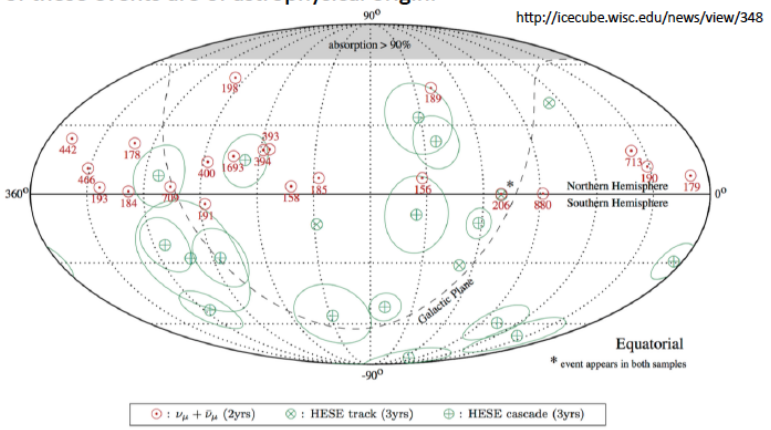
KM3NET: Diffuse Flux

IceCube: 4 year HESE analysis (ICRC 2015)
53 events (5.7 sigma), Ethreshold: 60 TeV

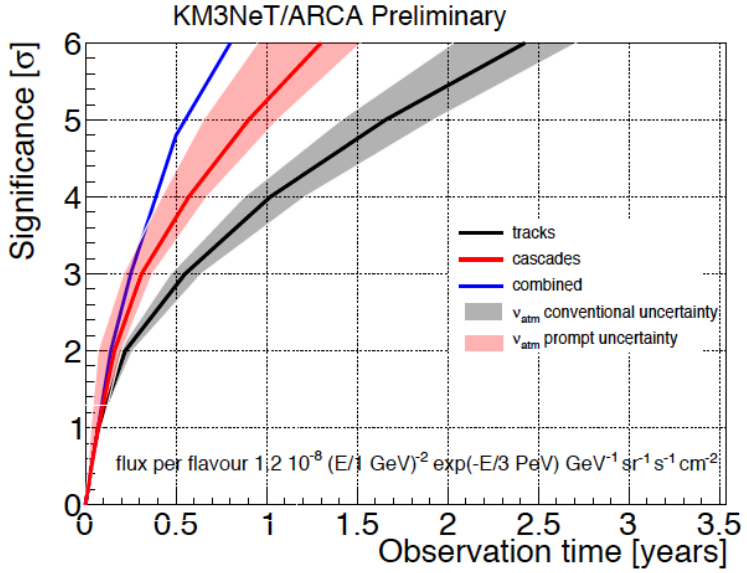
p=2.5% in gal. plane scan
within ± 7.5° gal. latitude



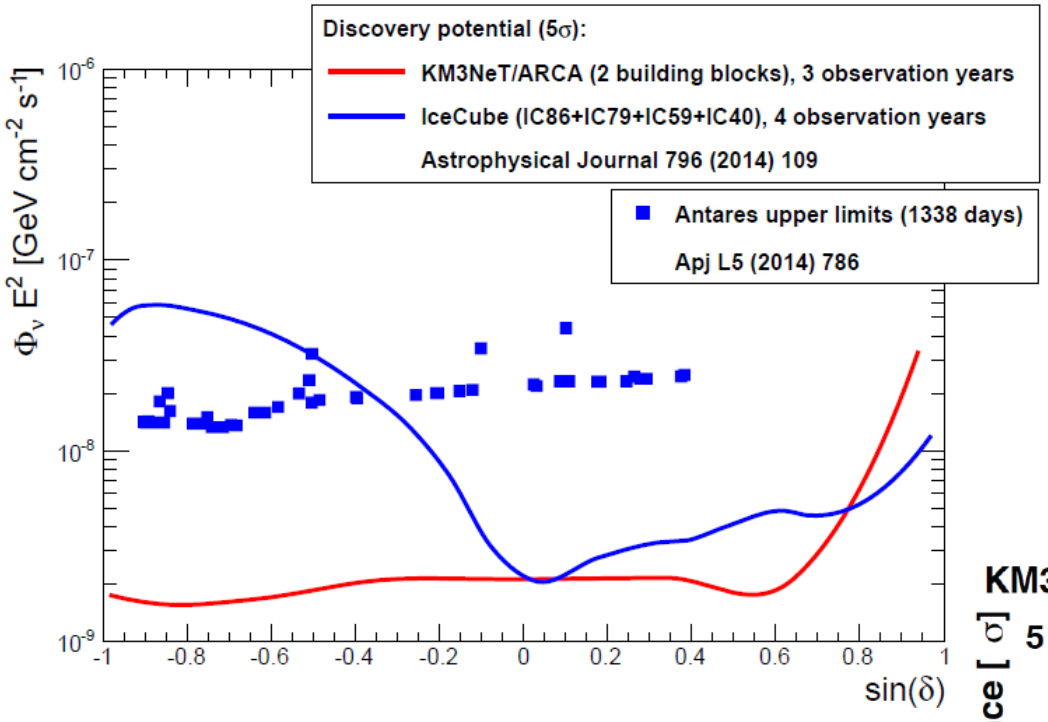
Only highest energy events are shown.
Most of these events are of astrophysical origin.



KM3NeT:
5 sigma in 1/2 year



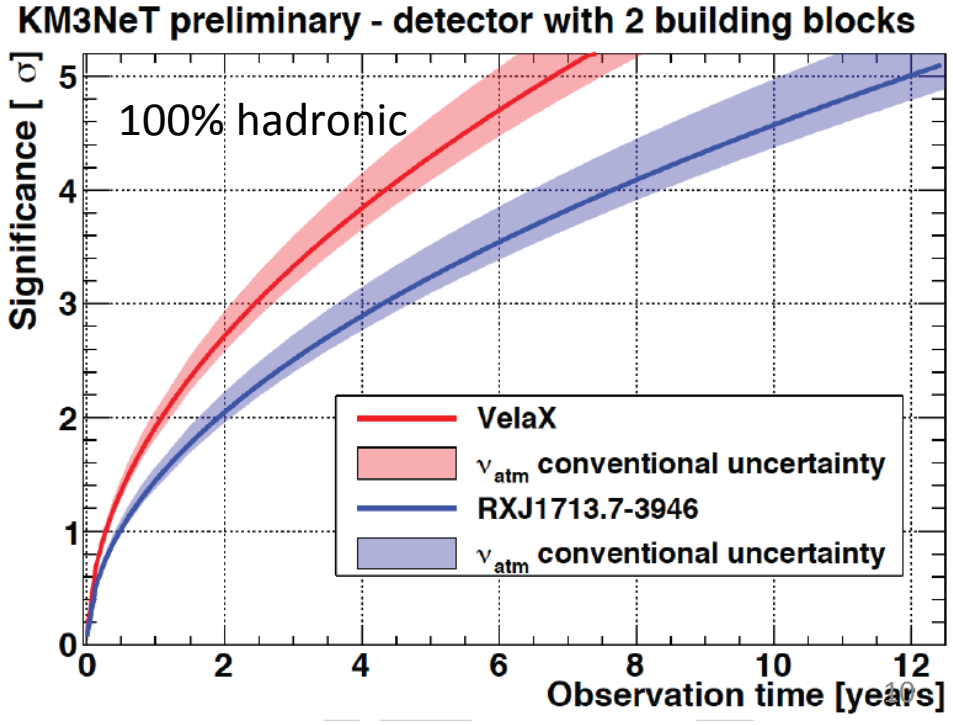
KM3NET: Point Sources



- Significant discovery potential for extragalactic sources
- Galactic sources in reach

	muon	cascade
Angular resolution	0.1° (0.5°)	2° (15°)
Energy resolution	300%	5%

(IceCube performance)



Oscillation of massive neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric θ_A~45°

Reactor θ_{13}~9°

Solar $\theta_\odot$~30°

Majorana

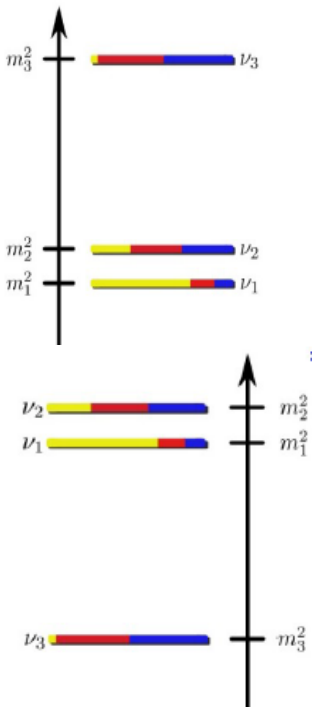
↓

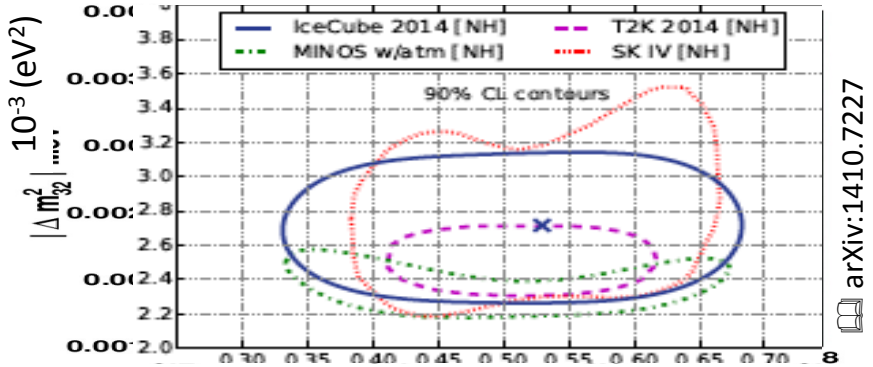
CP violating phase δ_{CP}

$$m_1^2 < m_2^2$$

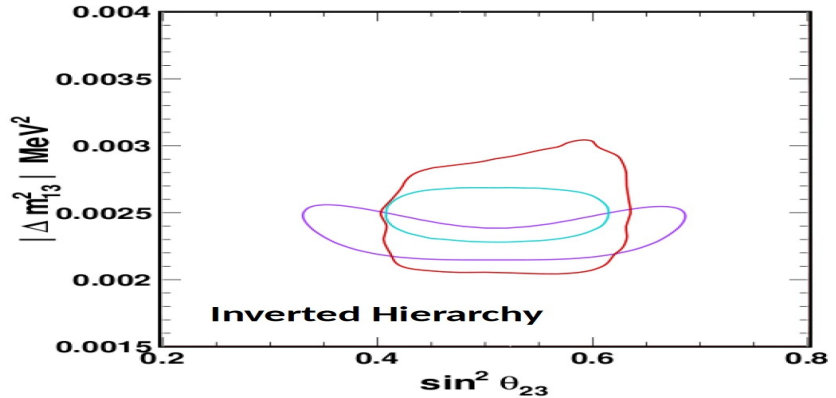
$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

All parameters measured to fair precision except:
<u>mass ordering</u>
octant of θ_{23}
CP phase





arXiv:1410.7227



The neutrino mass hierarchy

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

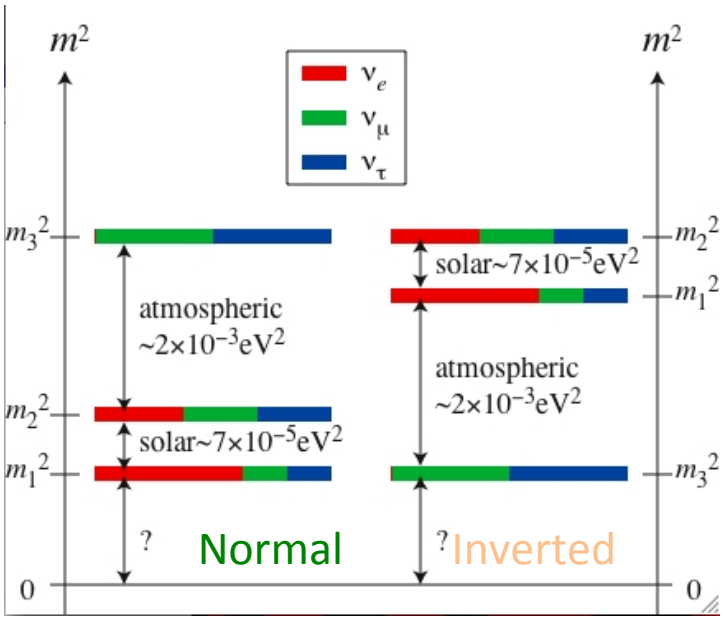
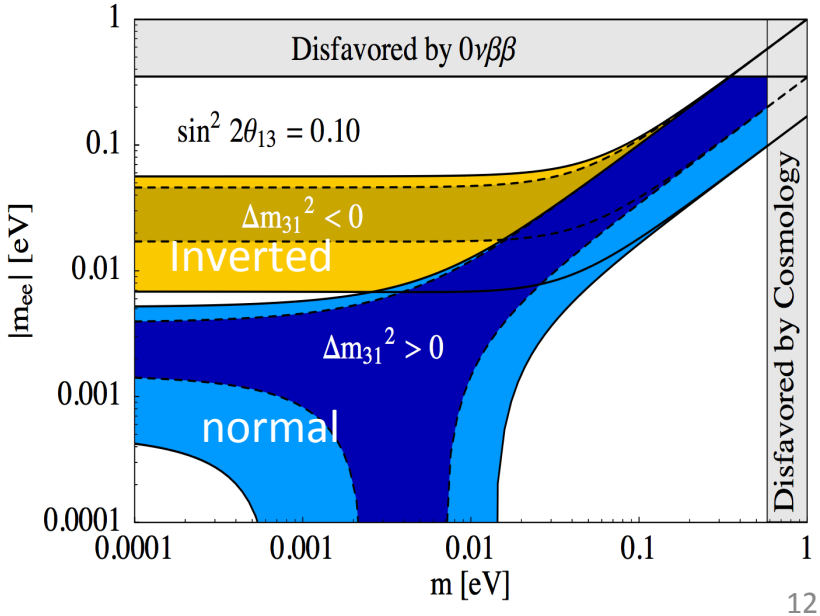
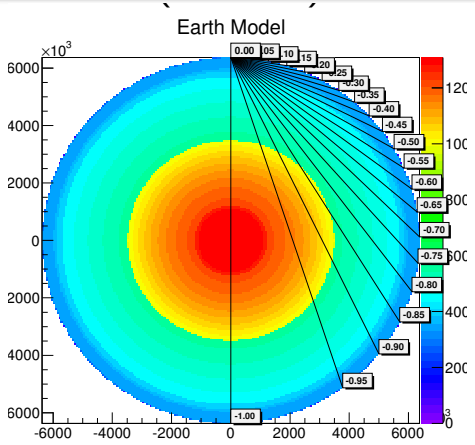


TABLE I: Mixing Angles for Models with Lepton Flavor Symmetry.

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

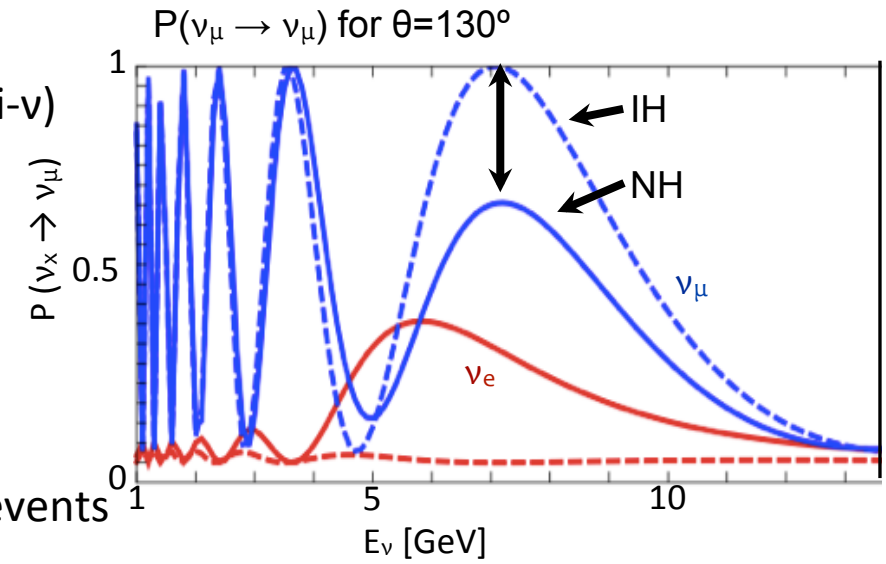


Measuring the neutrino mass hierarchy with atmospheric neutrinos



- a « free beam » of known composition (ν_e, ν_μ)
- wide range of baselines (50 → 12800 km) and energies (GeV → PeV)
- oscillation pattern distorted by Earth matter effects (hierarchy-dependent):

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

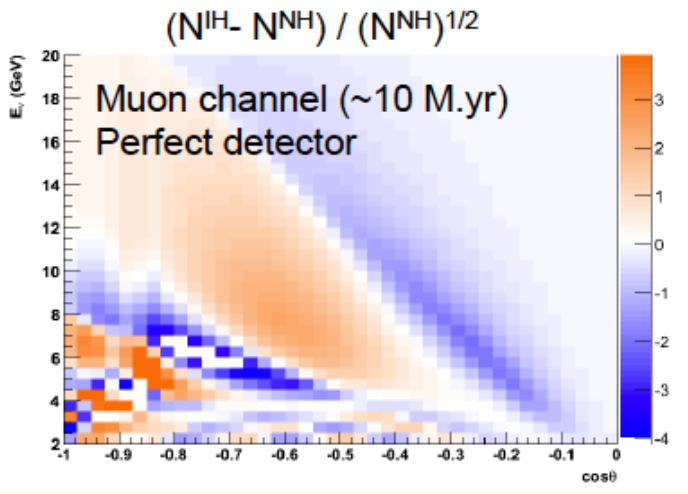


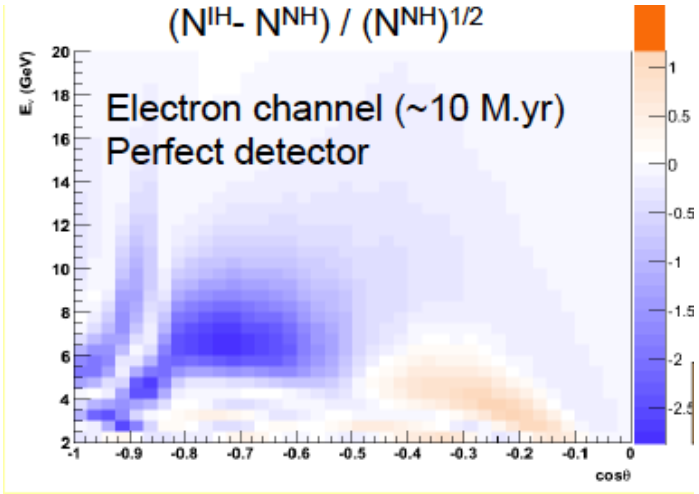
- opposite effect on anti-neutrinos: IH(ν)≈NH(anti-ν)
  BUT differences in flux and cross-section:
  $\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\text{anti-}\nu)$
  $\sigma(\nu) \approx 2\sigma(\text{anti-}\nu)$ at low energies
- measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos, identify and count muon and electron channel events
- feasible now that θ_{13} is measured to be large

📖 Akmedov, Razzaque & Smirnov, JHEP 02 (2013) 082

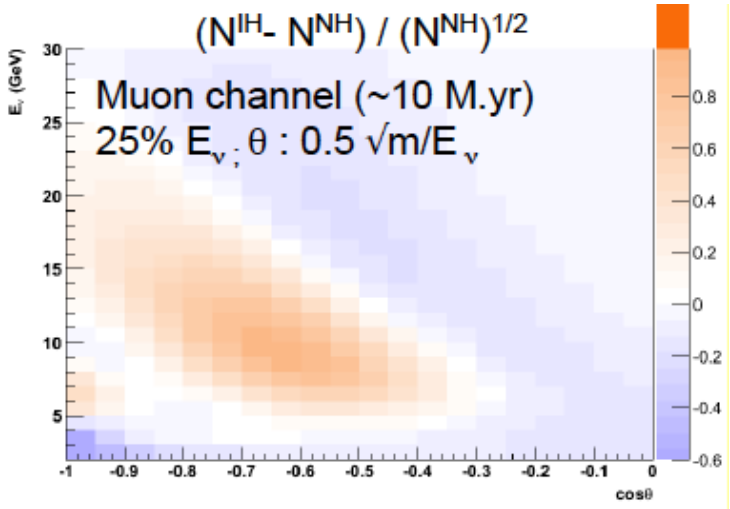
Experimental signature

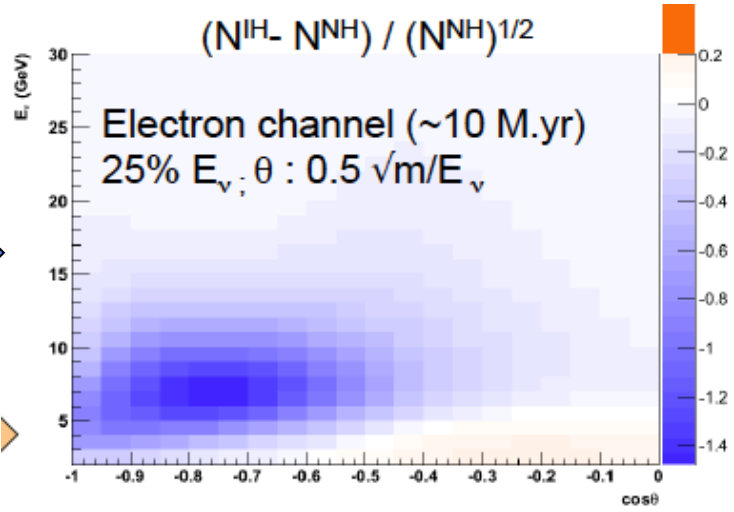
Both muon- and electron-channels contribute to net hierarchy asymmetry
electron channel more robust against detector resolution effects:





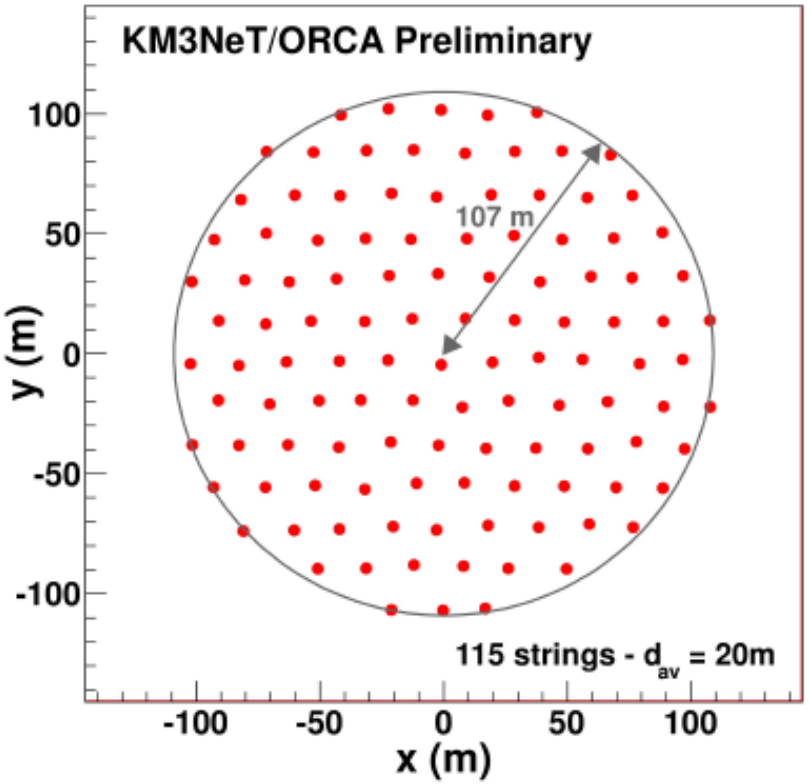
E, θ smearing
(kinematics
+ detector
resolution)



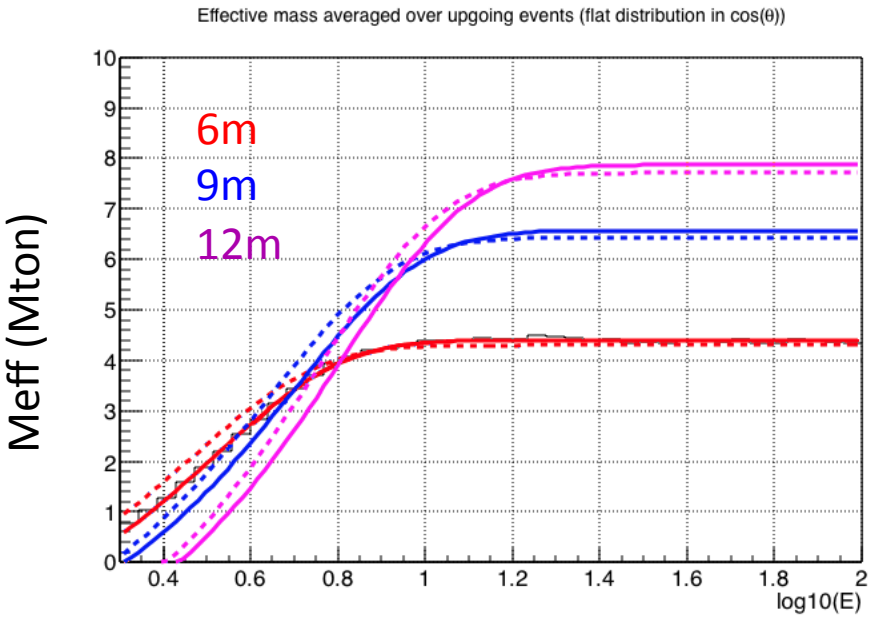


The ORCA benchmark design

115 lines, 20m spaced,
18 DOMs/line 9m spaced

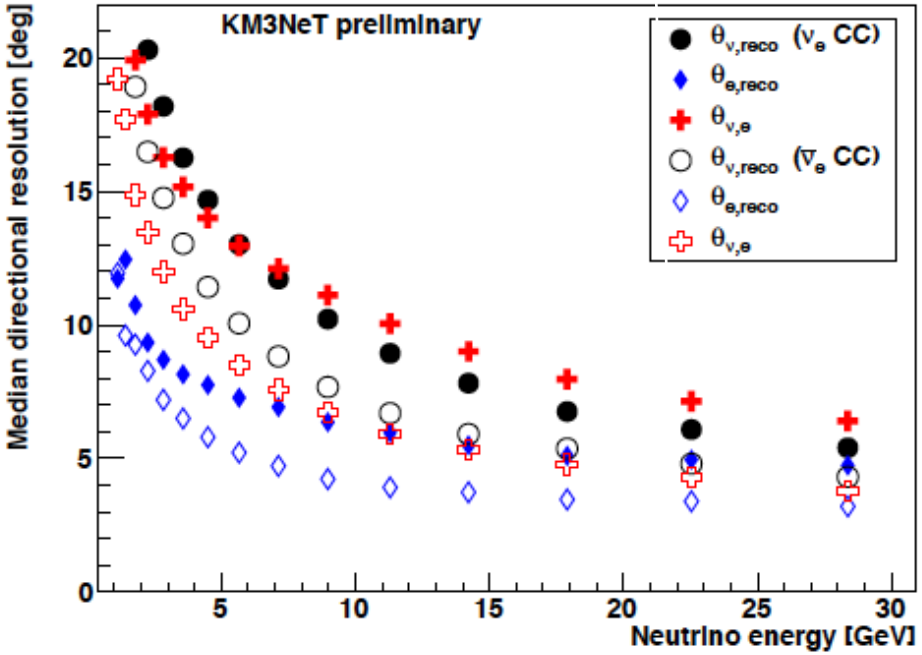


Instrumented volume ~6.5 Mt, 2070 DOM
Optical background:
10kHz/PMT & 500Hz coincidence

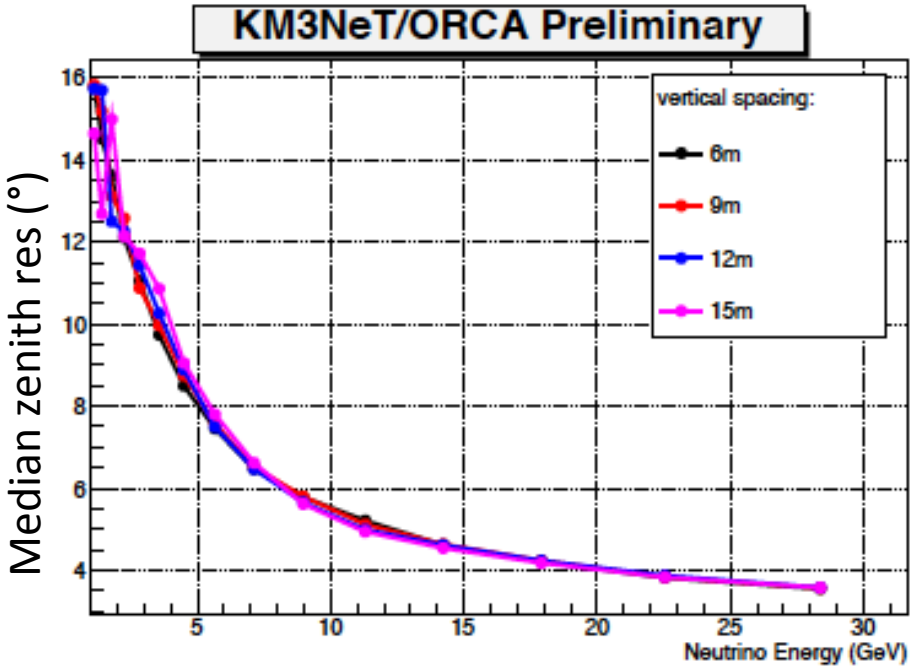


Angular Resolutions

cascade



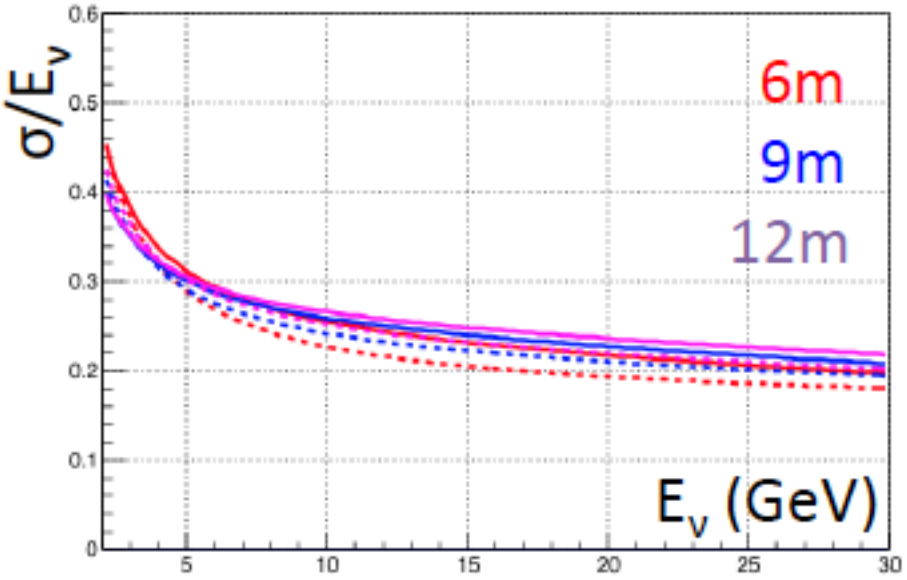
track



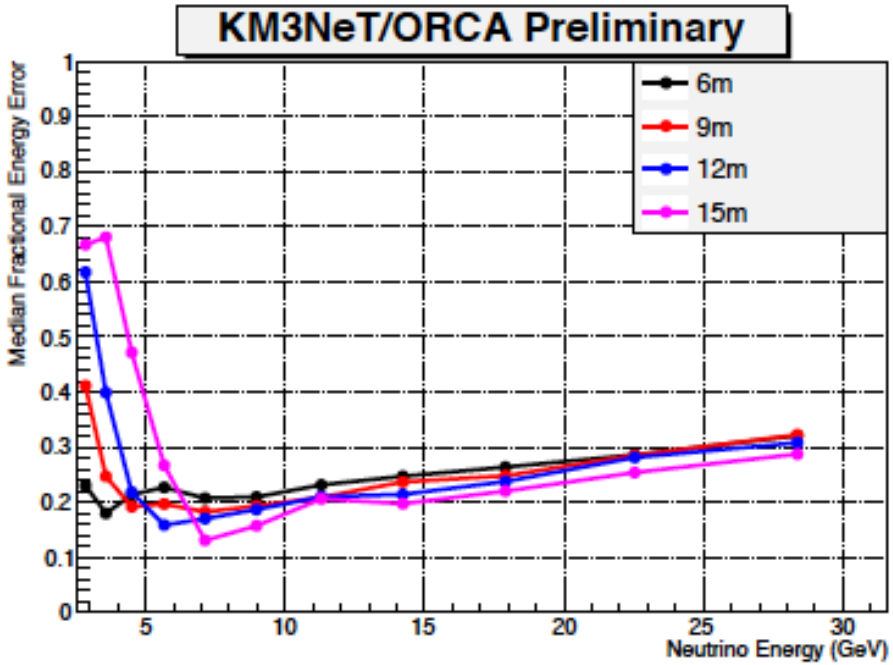
Excellent angular resolution
Dominated by kinematics
Largely independent of vertical spacing

Energy Resolutions

cascade



track



Energy resolution better than 25% in relevant range
– close to Gaussian

Sensitivity Studies

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

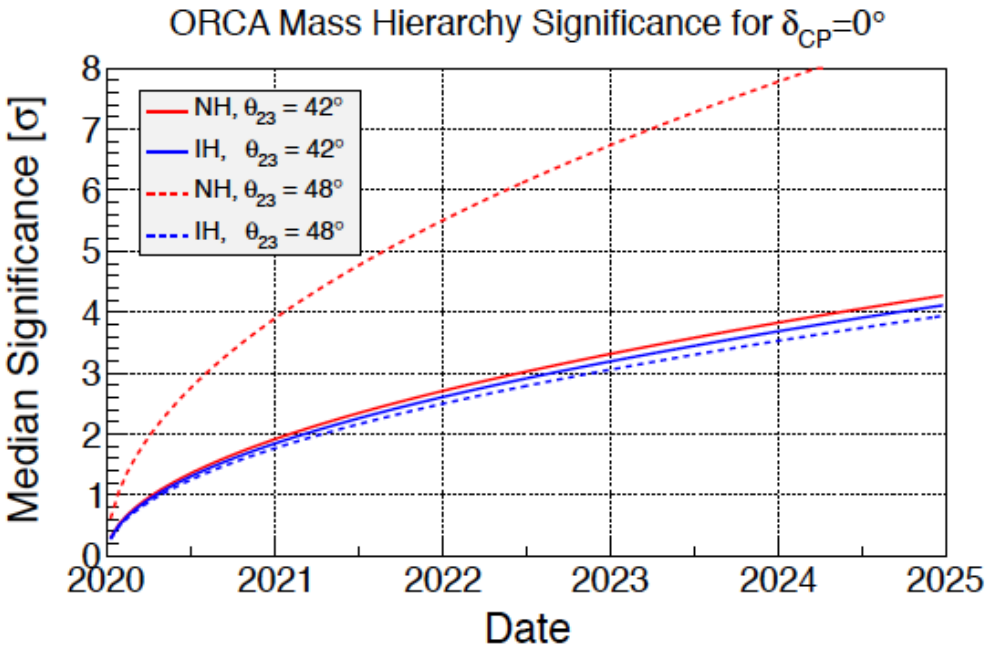
- Flux, cross section, detector related

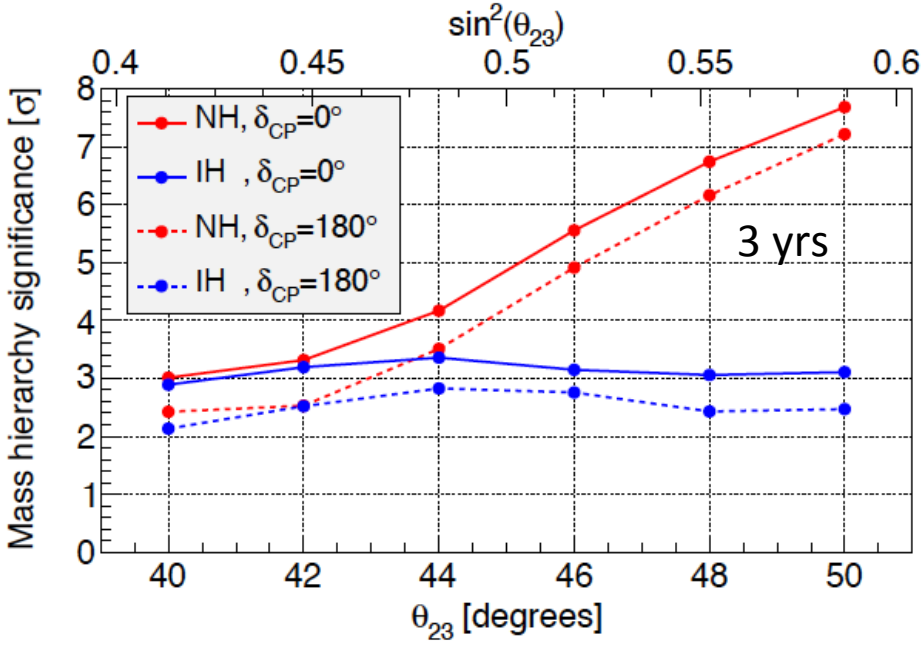
(average fluctuation w.r.t. nominal)

  - 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

Sensitivity to mass hierarchy



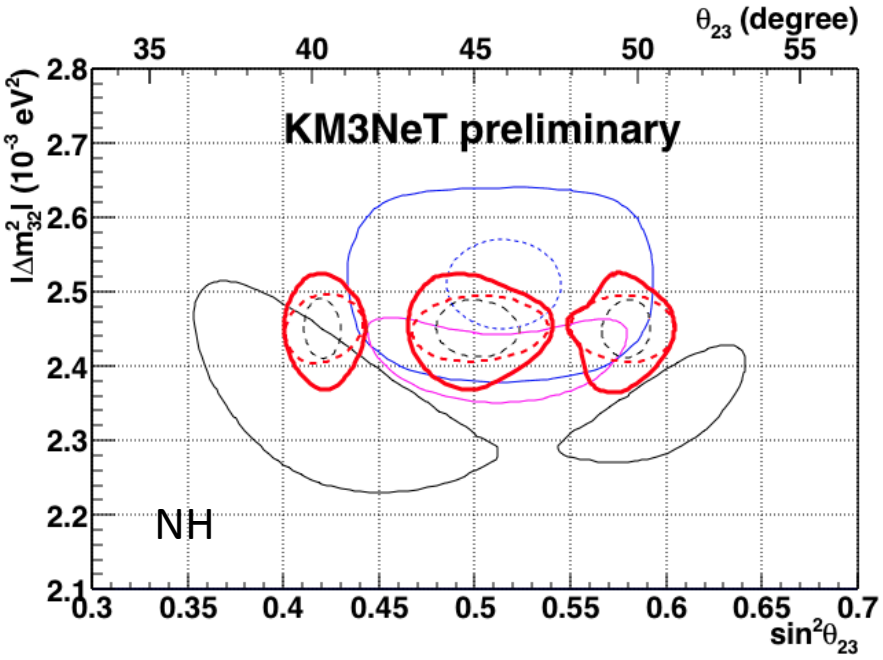


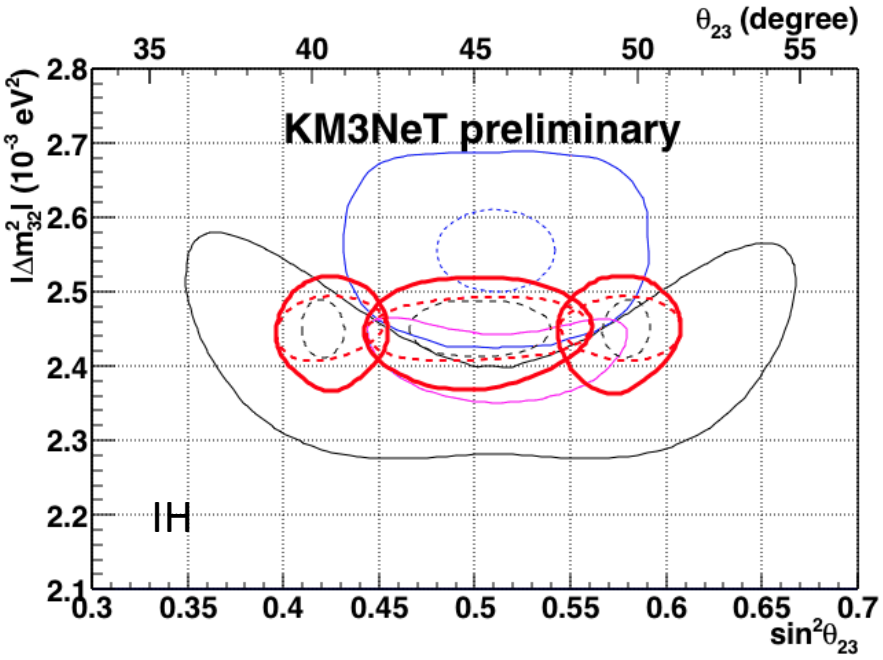
Sensitivity to PMNS parameters

3 year sensitivity to the atmospheric parameters

ORCA: red ellipses (solid/dashed=with/wo Ev scale)

1 σ contour: 3% in ΔM^2, 4-10% in $\sin^2\theta_{23}$





ORCA, MINOS, T2K, NovA 2020

Additional ORCA physics topics

- Indirect Search for Dark Matter

- Earth tomography and composition

  📖 Gonzales-Garcia et al.,Phys.Rev.Lett.100:061802,2008,
  📖 Agarwalla et al., arXiv:1212.2238v1

- Test NSI, sterile and other exotic physics

  📖 Ohlsson et al, Phys. Rev. D 88 (2013) 013001
  📖 Gonzales-Garcia et al., Phys.Rev. D71 (2005) 093010

- Supernovae monitoring (takes advantage of new DOM features)

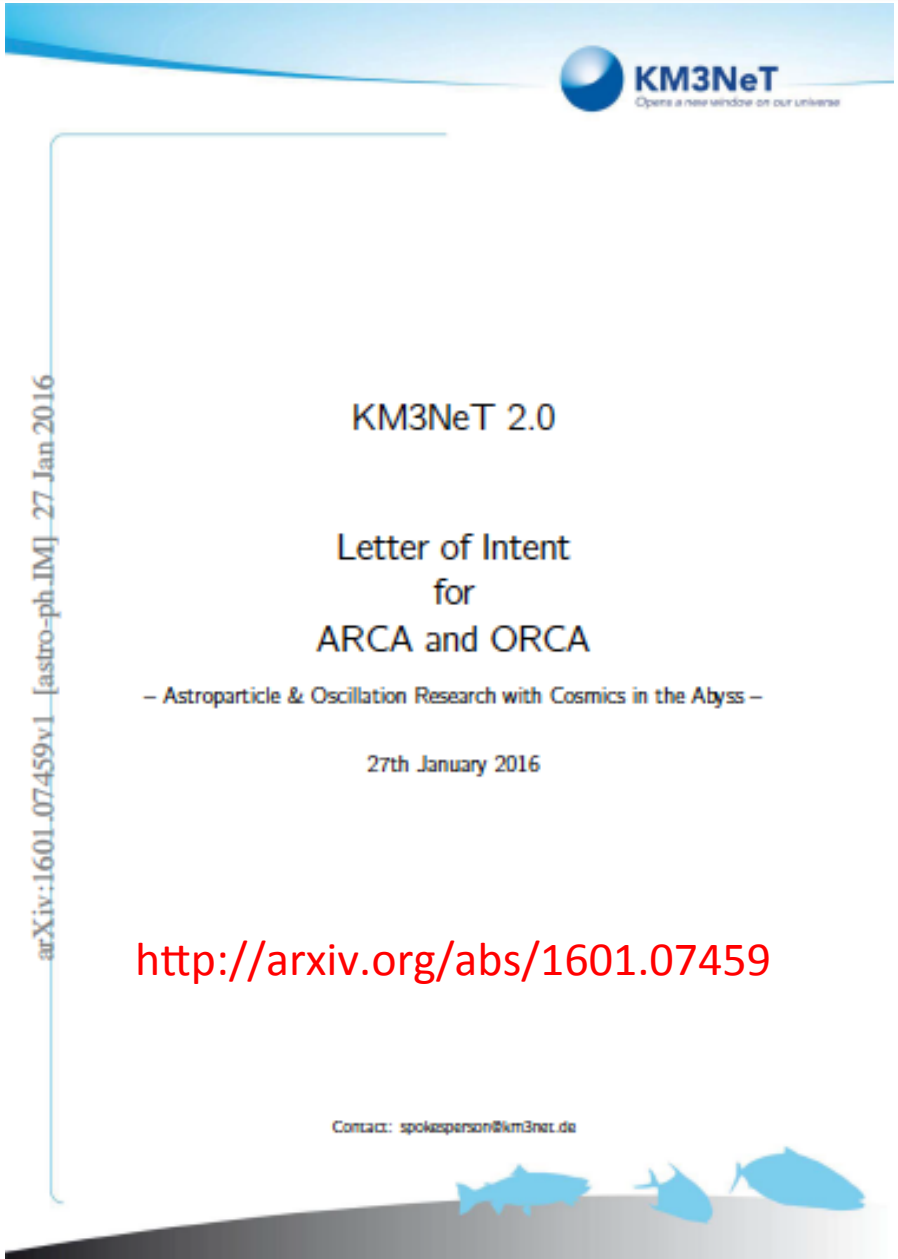
- Low Energy Neutrino Astrophysics
  - Gamma-ray bursts, Colliding Wind Binaries

  📖 J. Becker Tjus, arXiv:1405.0471 ...

- A Neutrino beam from Protvino to ORCA (NMH and CP phase)

  📖 Lujan-Peschard et al, Eur. Phys. J. C (2013) 73:2439
  📖 Tang & Winter, JHEP 1202 (2012) 028
  📖 J. Brunner, AHEP, Volume 2013 (2013), Article ID 782538.

KM3NeT 2.0: Letter of Intent



The main objectives of the KM3NeT Collaboration are i) the discovery and subsequent observation of high-energy neutrino sources in the Universe and ii) the determination of the mass hierarchy of neutrinos. These objectives are strongly motivated by two recent important discoveries, namely: 1) The high-energy astrophysical neutrino signal reported by IceCube and 2) the sizable contribution of electron neutrinos to the third neutrino mass eigenstate as reported by Daya Bay, Reno and others. To meet these objectives, the KM3NeT Collaboration plans to build a new Research Infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea. A phased and distributed implementation is pursued which maximises the access to regional funds, the availability of human resources and the synergetic opportunities for the earth and sea sciences community. Three suitable deep-sea sites are identified, namely off-shore Toulon (France), Capo Passero (Italy) and Pylos (Greece). The infrastructure will consist of three so-called building blocks. A building block comprises 115 strings, each string comprises 18 optical modules and each optical module comprises 31 photo-multiplier tubes. Each building block thus constitutes a 3-dimensional array of photo sensors that can be used to detect the Cherenkov light produced by relativistic particles emerging from neutrino interactions. Two building blocks will be configured to fully explore the IceCube signal with different methodology, improved resolution and complementary field of view, including the Galactic plane. One building block will be configured to precisely measure atmospheric neutrino oscillations.

KM3NeT Collaboration

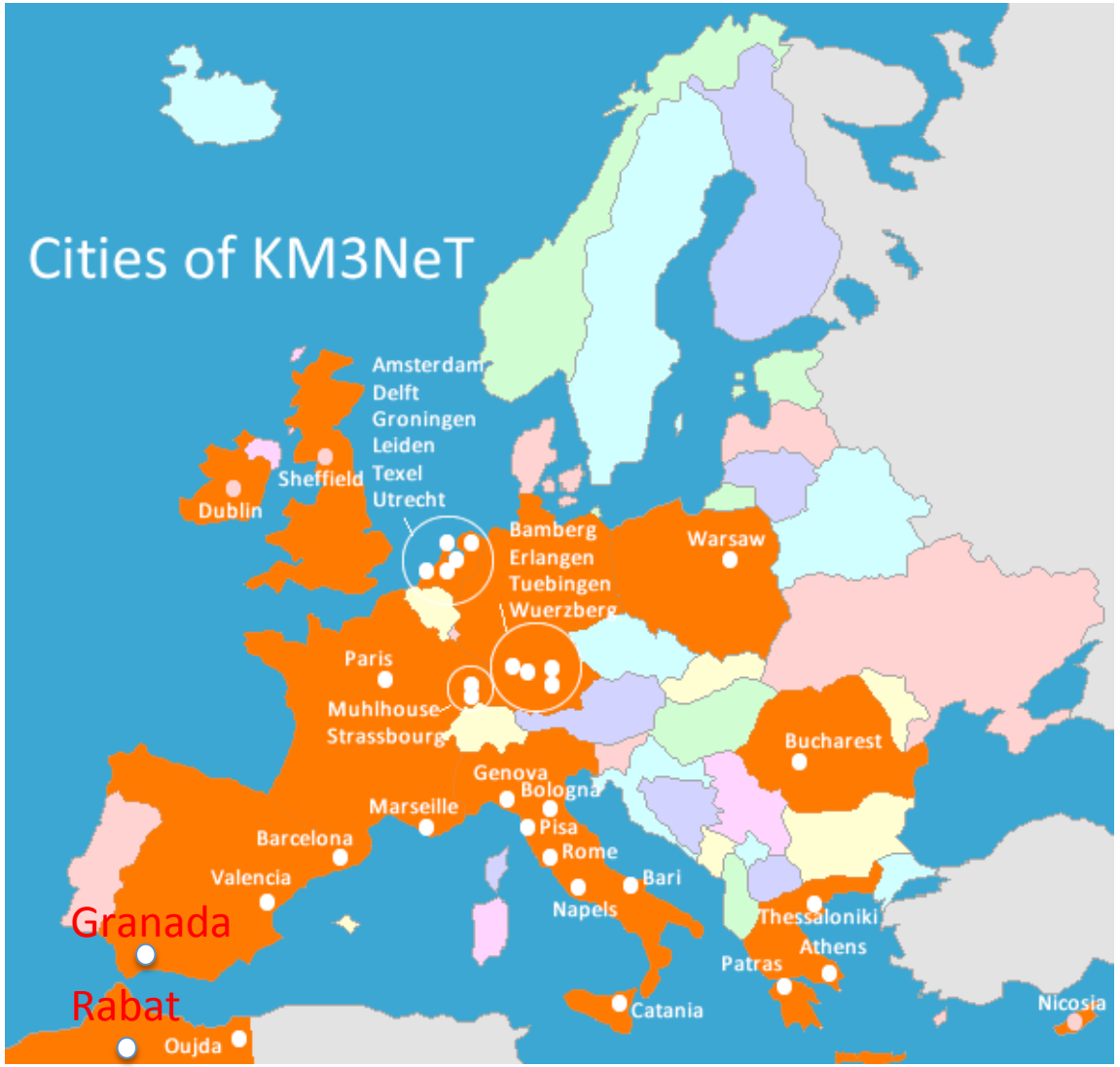
12 Countries
42 Institutes
225 Scientists

APC
- Calibration Unit base
- PMT studies

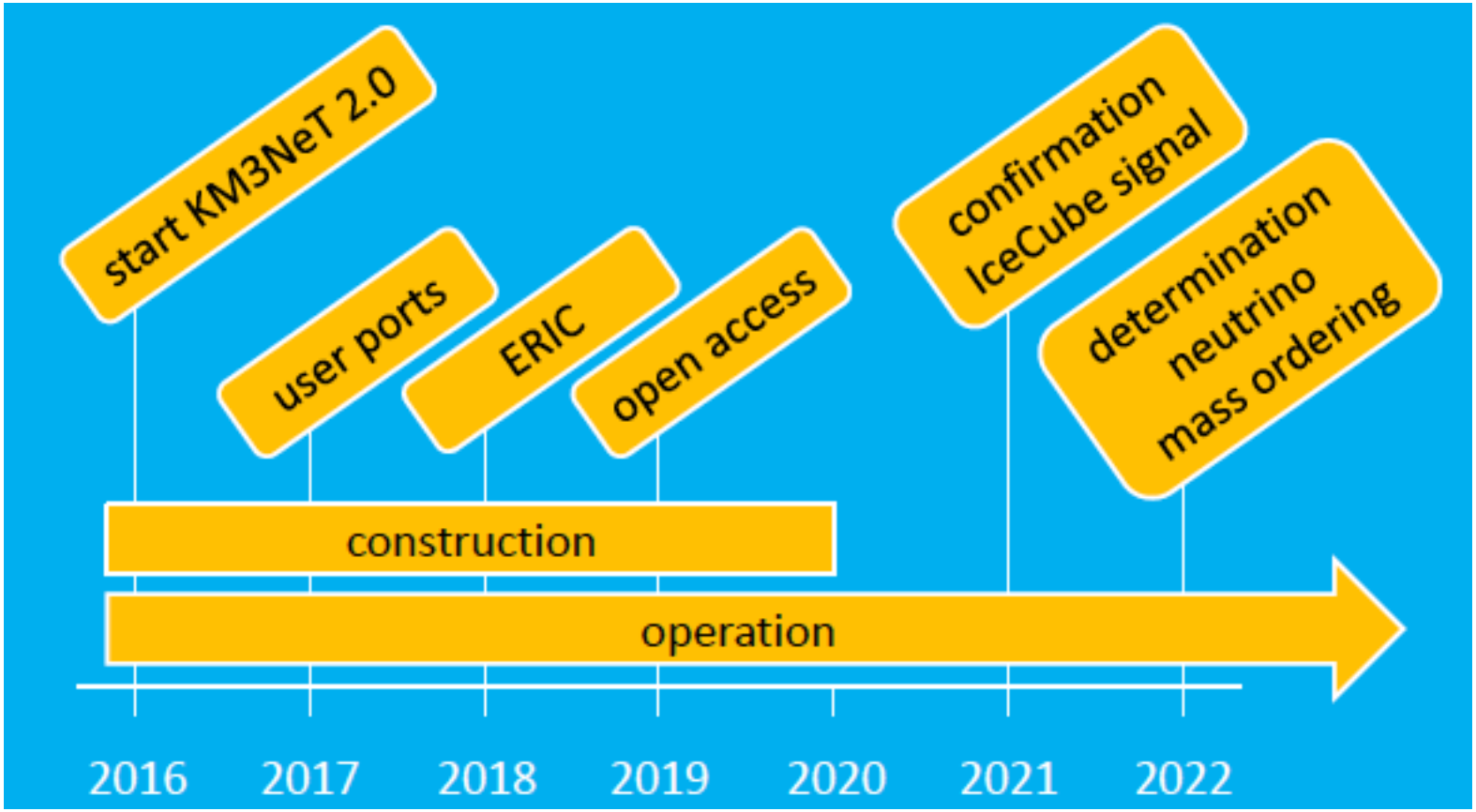
CPPM
- seafloor infrastructure
- base and anchor
- string integration+deployment
- shore station

IPHC+Mulhouse
- DOM integration

Nantes, Clermont Ferrand, Grenoble, CEA, …
- in discussion



KM3NeT Timeline



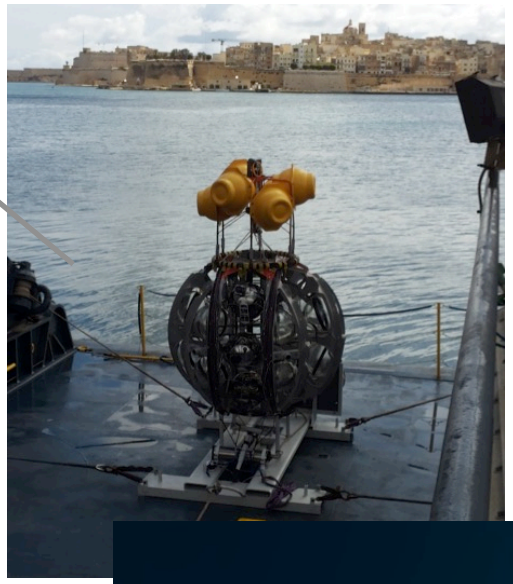
KM3NeT Design

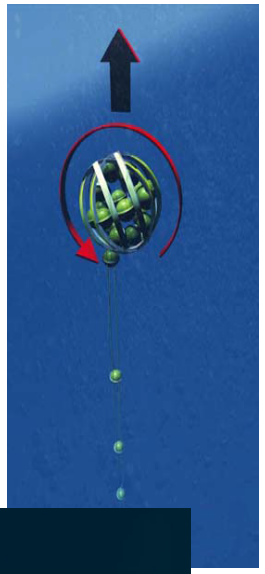
String

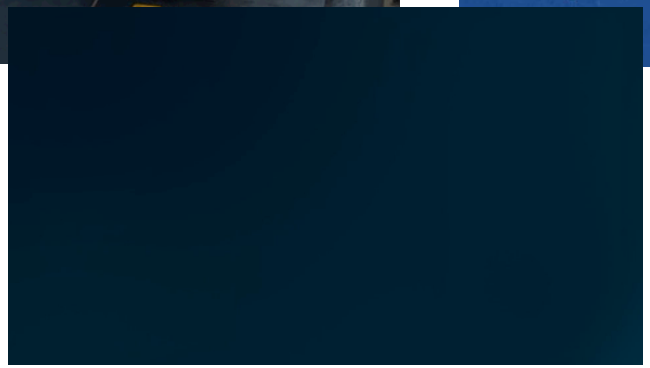
Launcher Vehicle

Digital Optical Module

17”





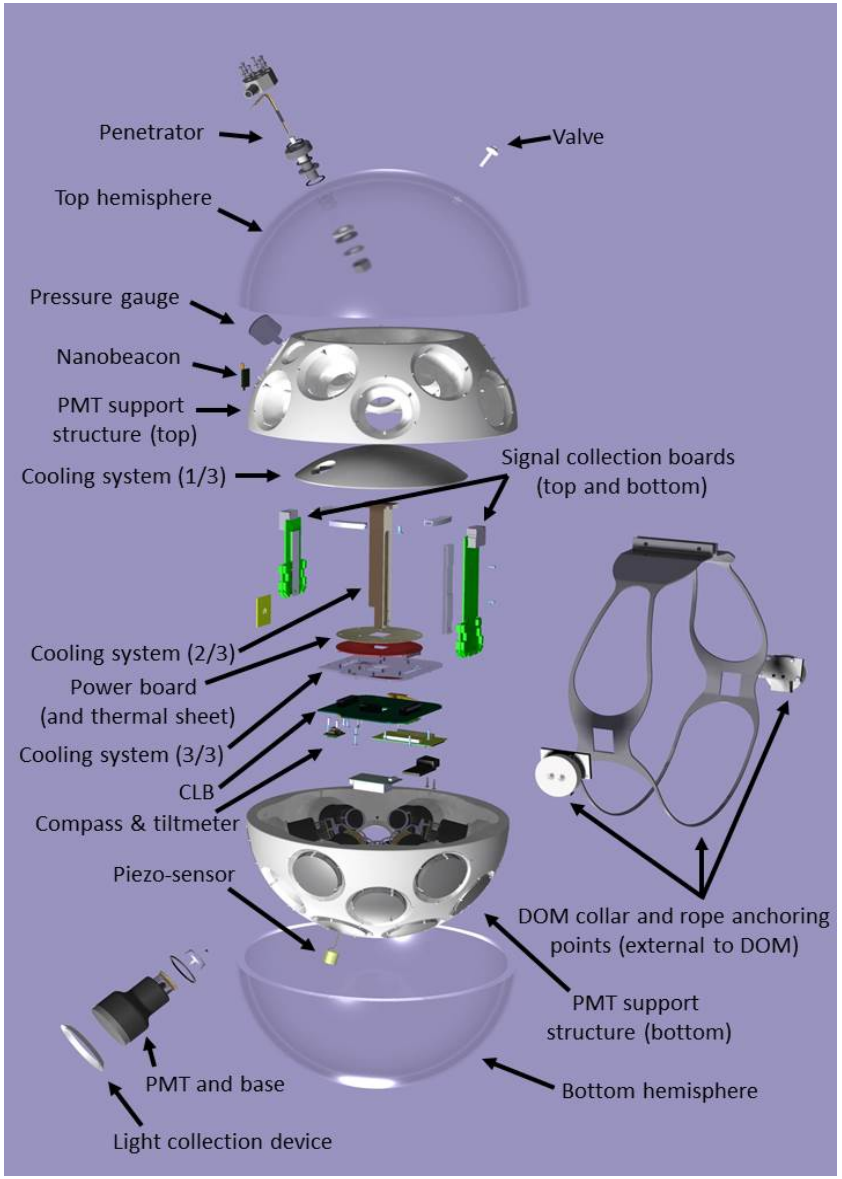


- *31 x 3” PMTs*
- *LED & acoustic piezo inside*
- *Uniform angular coverage*
- *Directional information*
- *Photon counting*
- *Background rejection*
- *Low ageing*
- *Low drag*

- *Rapid deployment*
- *Compact*
- *Autonomous unfurling*
- *Recoverable*

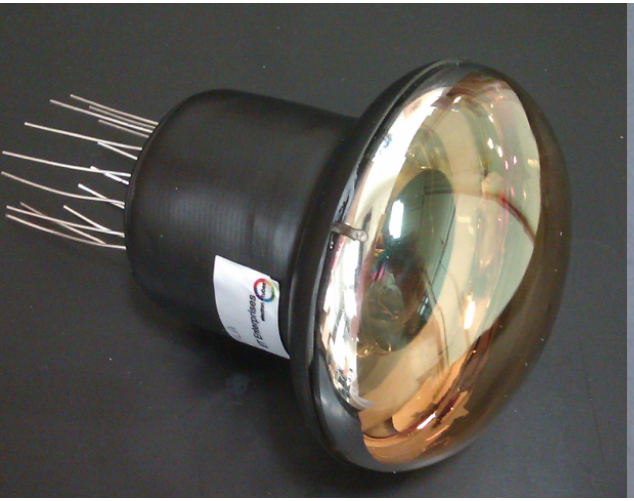
KM3NeT Digital Optical Module

- 31 x 3” PMTs
- Reflective rings around PMTs (+27% light detection, JINST 8 (2013) T03006)
- PMTs supported by plastic structure produced by 3D-printing
- Electronics components attached to cooling mushroom
- One single penetrator for connection to vertical cable
- Optical fibre data transmission
  - DWDM with 80 wavelengths
  - Gb/s readout
- FPGA readout
  - 1 ns time stamp
  - Time over threshold
- Modified White Rabbit time synchronisation
- Calibration: piezo-acoustic sensor, compass + tiltmeter, nano-LED beacon
- Low power (7W per DOM)



3 Inch PMT Suppliers

ETEL D792



Fulfil specifications;
15,000 items ordered for Phase1

Hamamatsu R12199

HZC XP53B20

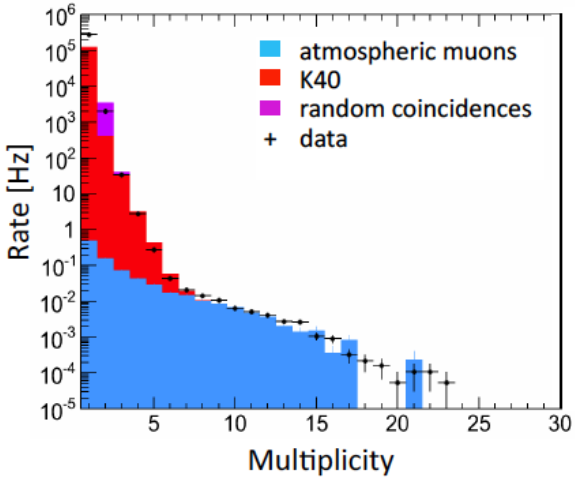
First prototype not yet compliant with specifications (gain, dark rate, afterpulses, …).
New prototype expected in June.

Note: In all cases price/photocathode area < 10-inch tubes

Phase2: +175,000 PMTs

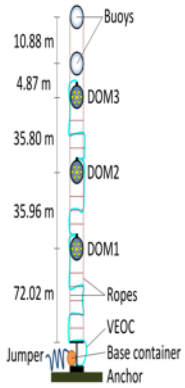
KM3NeT Prototypes

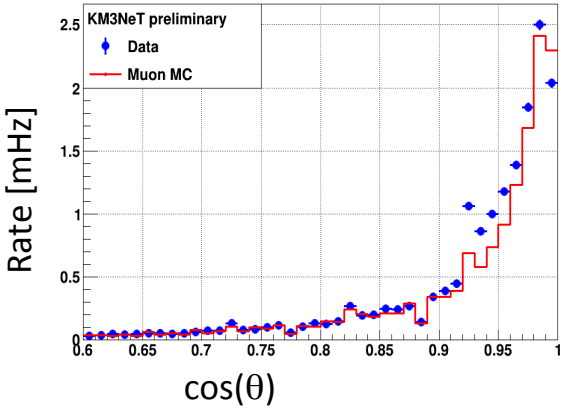
1) Optical Module deployed at Antares, April 2013 (2500 m)



Eur. Phys. J.
C (2014) 74:3056

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

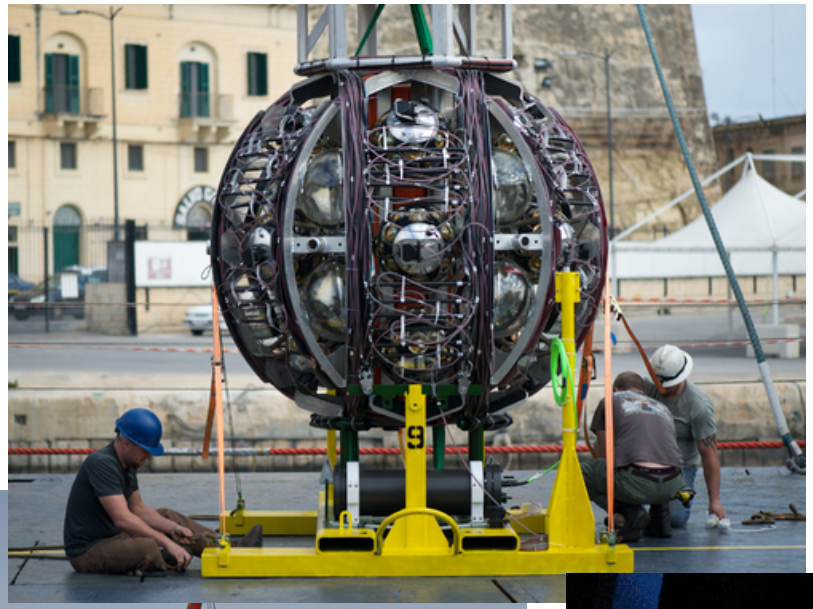


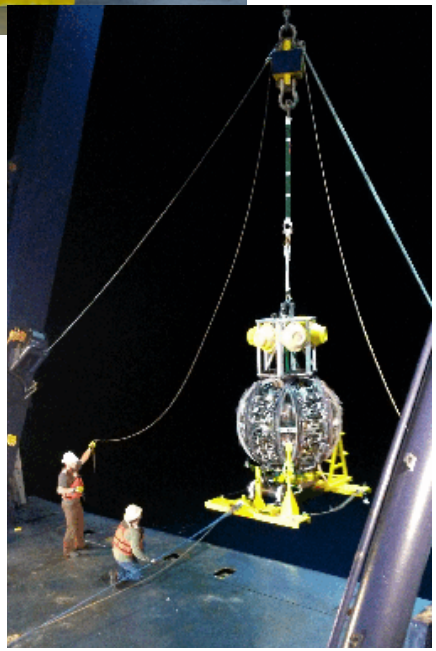


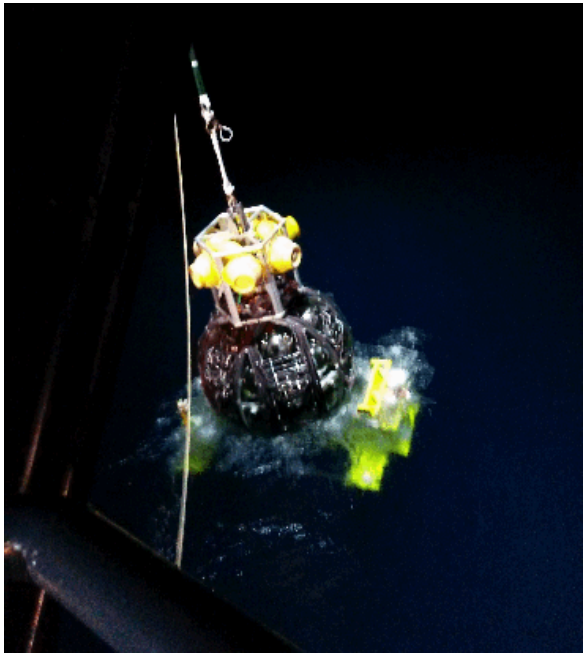
arXiv:1510.01561
Accepted by
Eur. Phys. J. C

The first KM3NeT String: construction

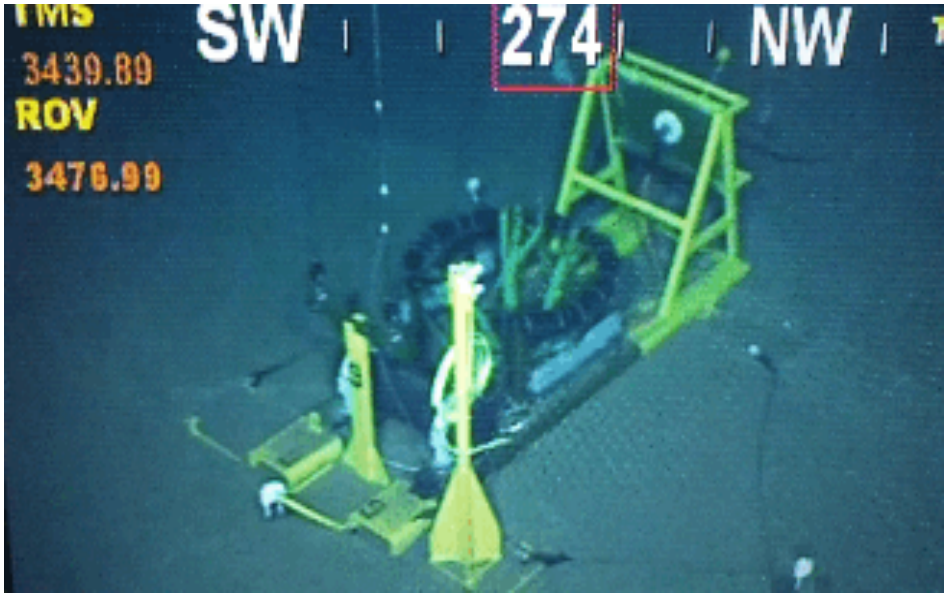
The first KM3NeT String: deployment

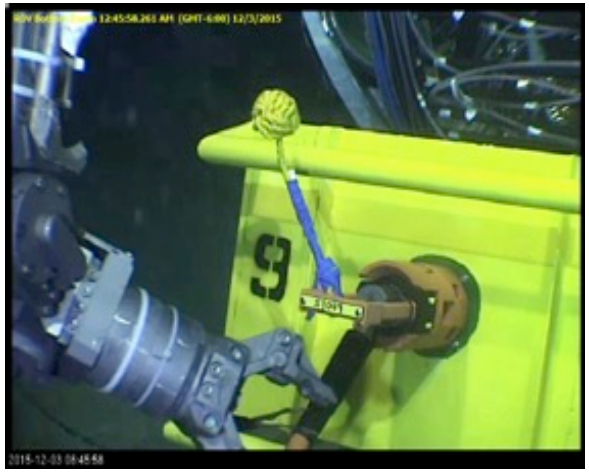






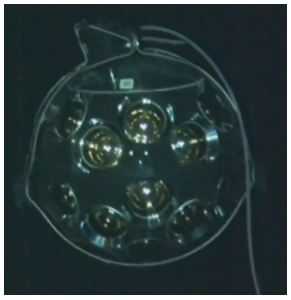
KM3NeT string connection (3rd Dec 2015)

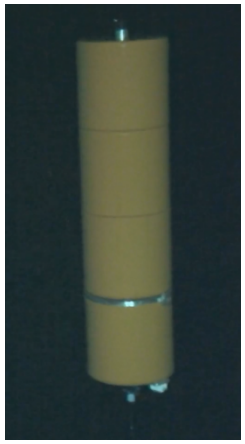


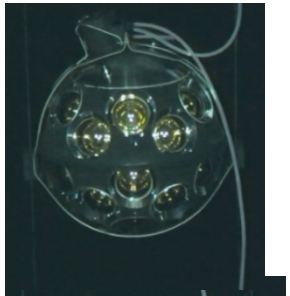


The first KM3NeT String

KM3NeT





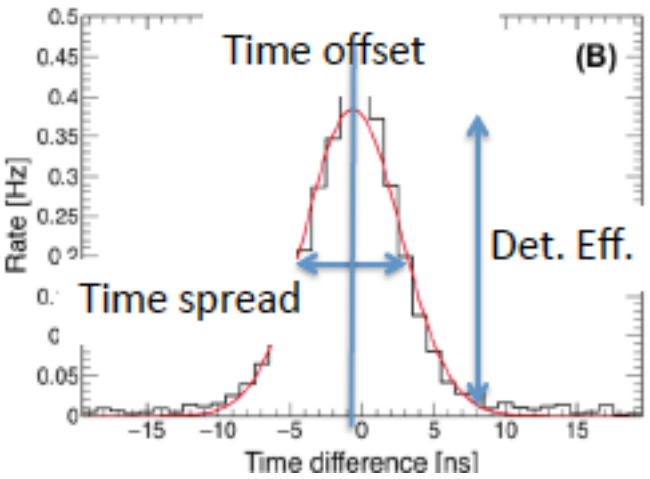


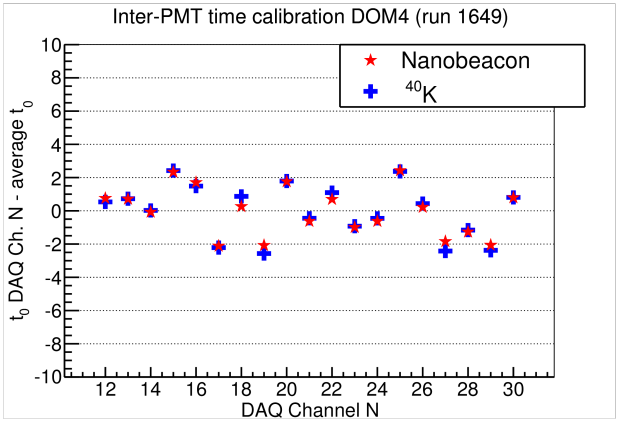
K40 Inter-PMT Calibration

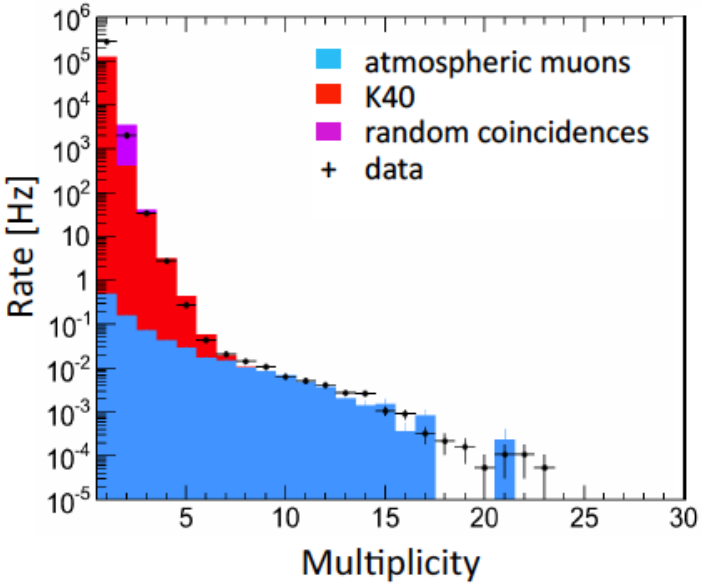
^{40}K e^- (β decay)

^{40}Ca

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

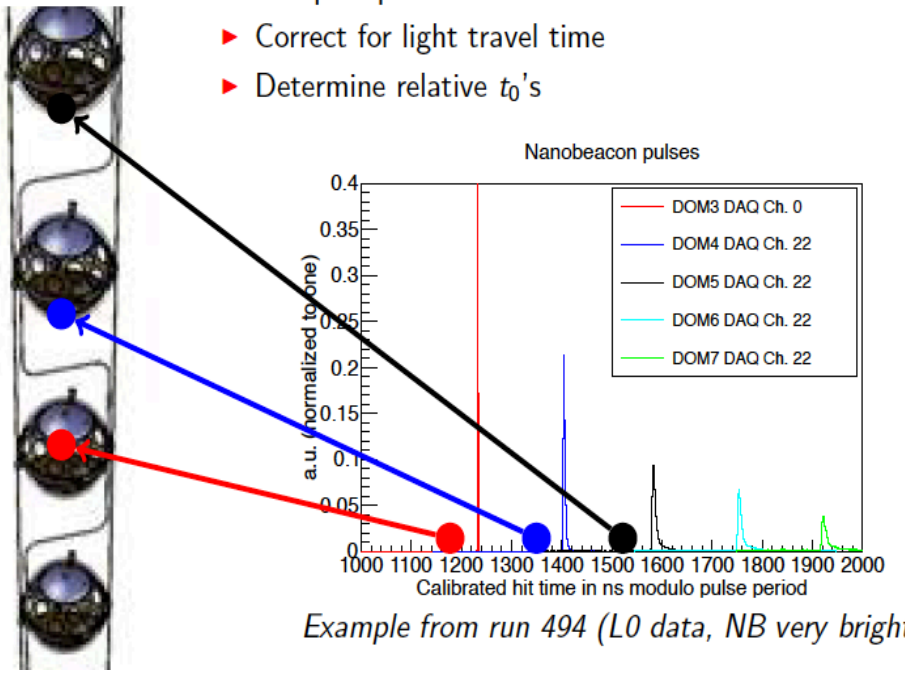






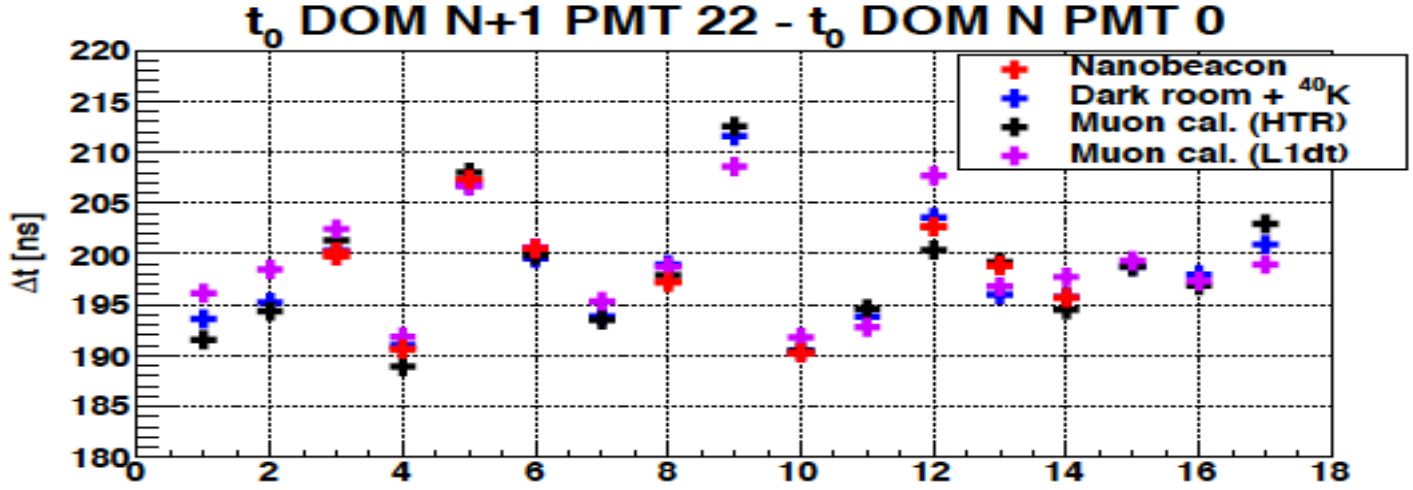
Inter-DOM calibration

- Compare pulse arrival time
- Correct for light travel time
- Determine relative t_0's

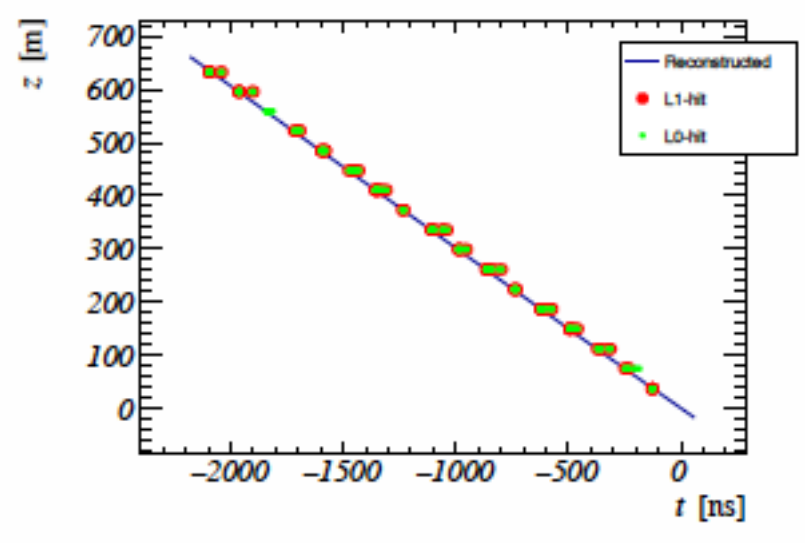


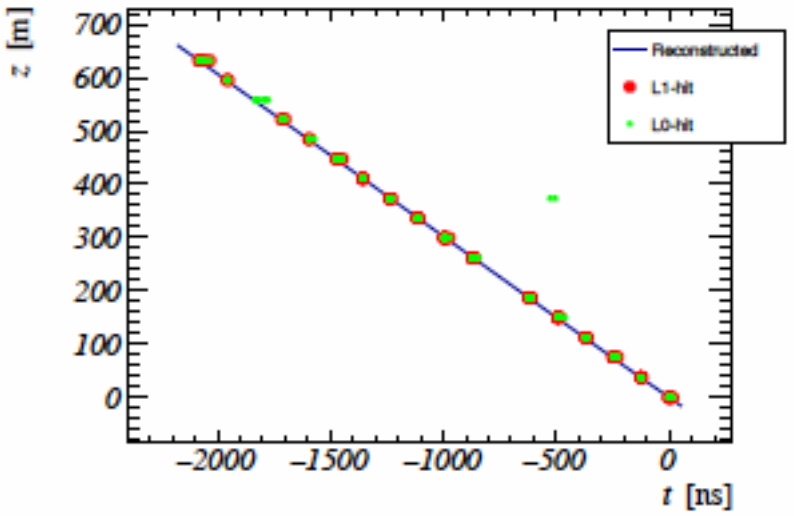
Example from run 494 (L0 data, NB very bright)

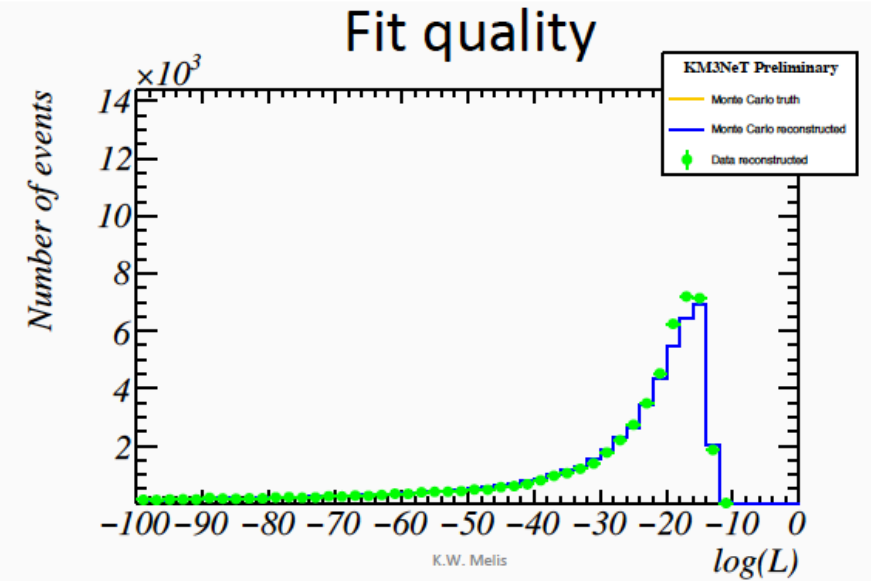
- Method 2:
- Hit time residual excluding one DOM
- Triggered events ≥ 6 DOMs hit

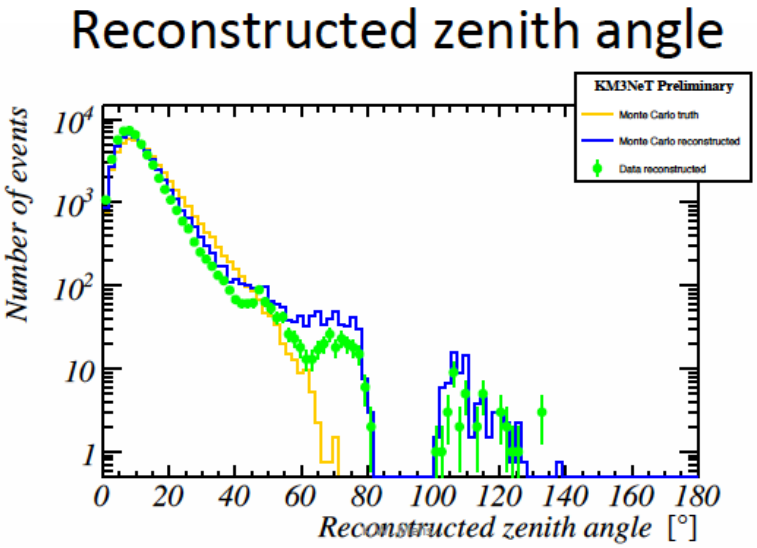


Atmos Muon Reconstruction



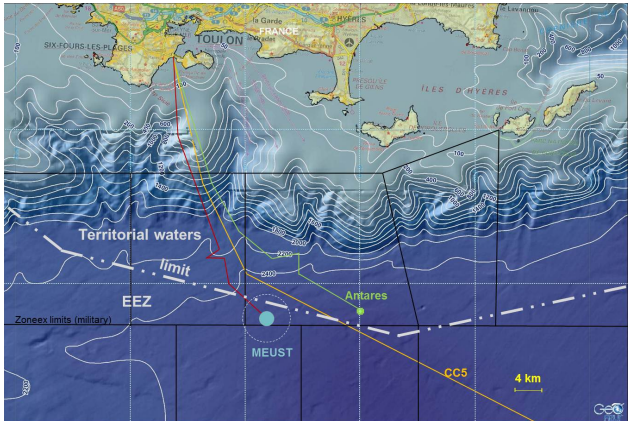




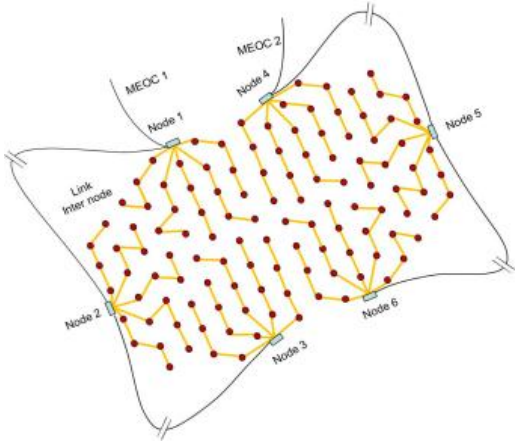


ORCA Construction

Phase 1 (funded- 11M€) : deploy a 7 string array
In the ORCA configuration to demonstrate detection methods in the GeV range.



Phase 2 (+40 M€): deploy 1 building block
115 strings at KM3NeT-Fr site, Completion in 2020
Funds: 9M€ (France)+6M€(Netherlands)+…



Main cable: Dec 2015

1st node: May 2016

1st ORCA string: June 2016

Summary and perspectives (I)

- KM3NeT: phased approach to next-generation neutrino telescope
  - Capo Passero (KM3NeT-It) → **ARCA for HE neutrino astronomy**
  - Toulon (KM3NeT-Fr) → **ORCA for measurement of NMH**
  - First string performing well
  - Letter of Intent published
  - Selected for new ESFRI roadmap

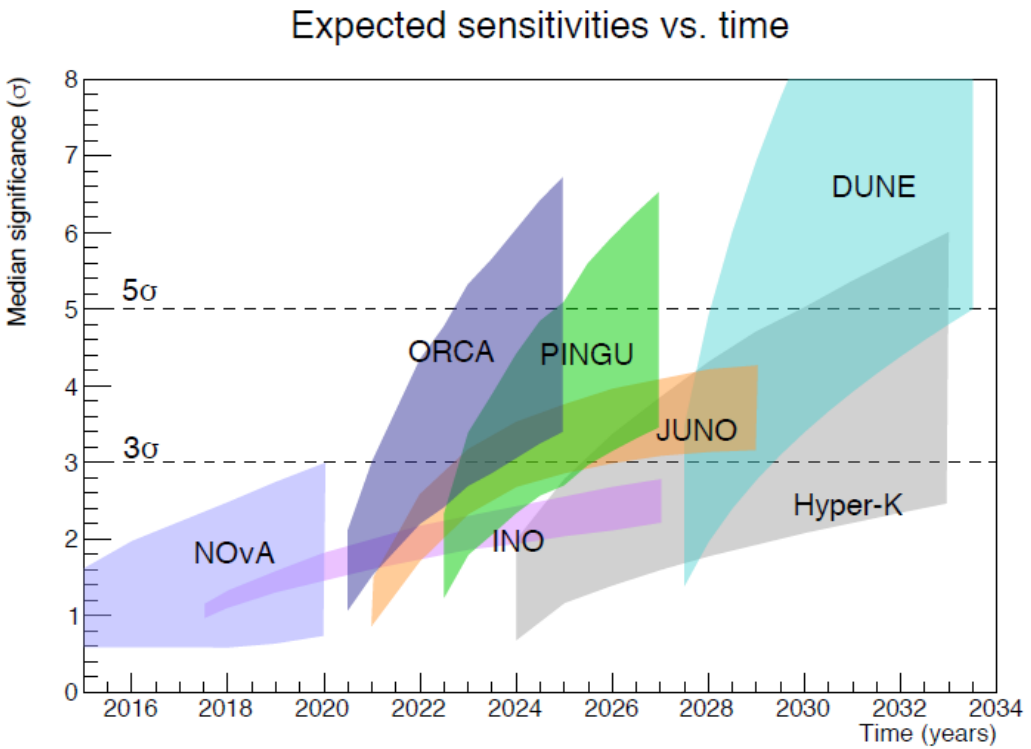
KM3NeT selected for the 2016 ESFRI Roadmap

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

- Diffuse flux of cosmics neutrinos observed by IceCube (ANTARES)
- higher level of hadronic activity in the non-thermal universe than previously thought
- Sources remain to be identified

Summary and perspectives (II)

- Atmospheric Neutrinos still have a major role to play for precision neutrino measurements
- Low energy (GeV) extensions of Neutrino Telescopes offer prospect of rapid and cost-effective measurement of NMH and PMNS parameters
- Preliminary ORCA sensitivities are very promising and expected to improve
- New collaborators very welcome



(adopted from Blennow)

KM3NeT site in China?

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Published online 26 January 2011 | *Nature* **469**, 460-461 (2011) | doi:10.1038/469460a

News Feature

Marine science: China's unsinkable scientist

After years of struggle on behalf of ocean science, Wang Pinxian is taking a key role in China's plans to expand marine research.

Jane Qiu

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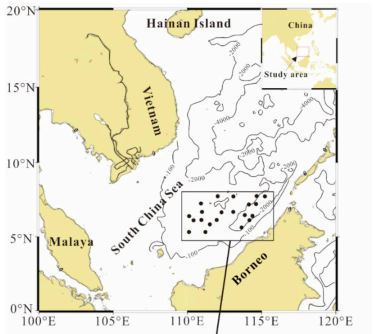
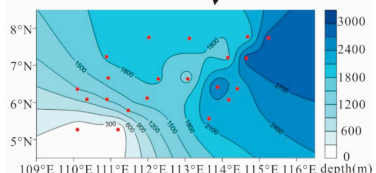




http://www.tongji.edu.cn/english/index.php?classid=61&newsid=33301&t=show

With the influx of funding and interest from the Chinese government, Wang has big plans for the future. Beyond the eight-year South China Sea project, his team is working with the government to establish a sea-floor observatory off the coast of Xiaoqu Shan, an island southeast of Shanghai. The observatory will record important features of the ocean, including temperature, salinity and sedimentation rates. Wang would ultimately like to build a network of ocean-floor observatories in the South China Sea similar to those off the coasts of the United States and Canada. "This is the only way we can truly understand the oceans," he says.

In these projects, Tongji University is responsible for the project management, the systematic research of scientific cabled observatories, the system design and test of the experimental observatory prototype, and the instrumentation of the CPAS, including the development of a novel underwater ion chromatography (UIC) unit; Zhejiang University is responsible for developing the junction box and the DVCS; and China Ocean University is responsible for developing the HEMS. In addition, Zhejiang University and Tongji University are both working on HV undersea stations, of different design schemes but similar functionality. Tongji University's first HV undersea station is being developed for an experimental multi-node cabled seafloor observatory which will be deployed in East China Sea around 2013, with a backbone cable of at least 50km.

Synergies JUNO/ORCA

Complementary paths to neutrino mass hierarchy determination

ORCA- via mass effects
JUNO- via vacuum oscillations

Complementary access to PMNS parameters

	ORCA	JUNO
Theta23:	yes	no
DM32:	yes	yes
Theta12:	no	yes
DM12:	no	yes

(In)consistency of DM32 result important cross-check of correct NMH

Require large numbers of 3 inch PMTs- possibly from Chinese supplier

Underwater connectivity

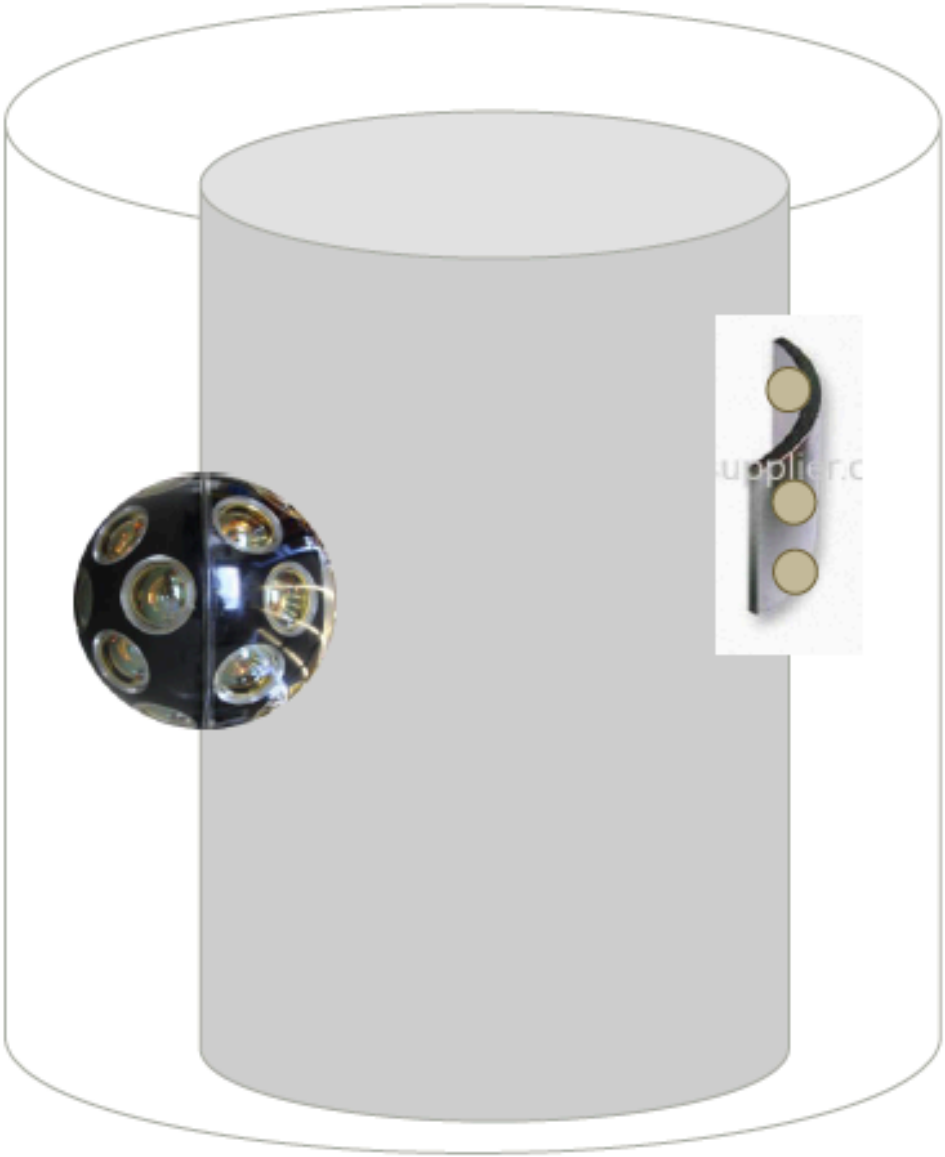
MultiPMT in HyperK

ID/OD DOM

→ part of DOM looking at inner detector, part looking at outer detector

(or even strings in the centre of the volume)

MoU KM3NeT/HyperK signed
Workshop in July 2016



G.De Rosa, T. Feusels