KM3NeT - Status and perspectives

J. Brunner
On behalf of the KM3NeT collaboration

RICAP , 24 June 2016

KM3NeT

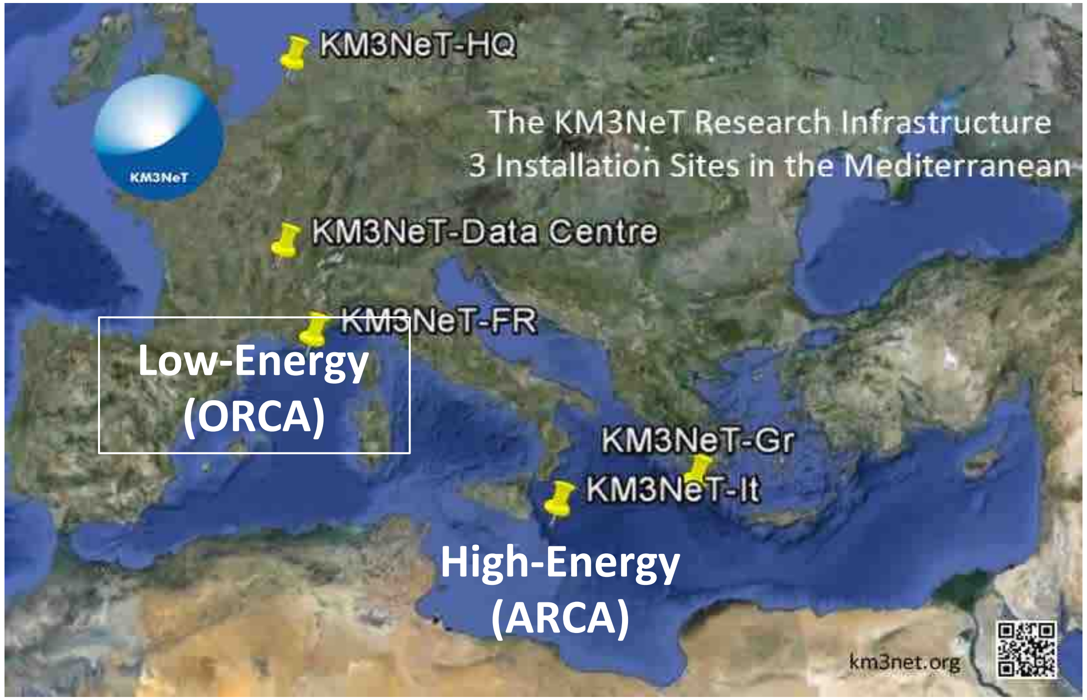
KM3NeT is a research infrastructure with 2 main physics topics:

- 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

Single Management

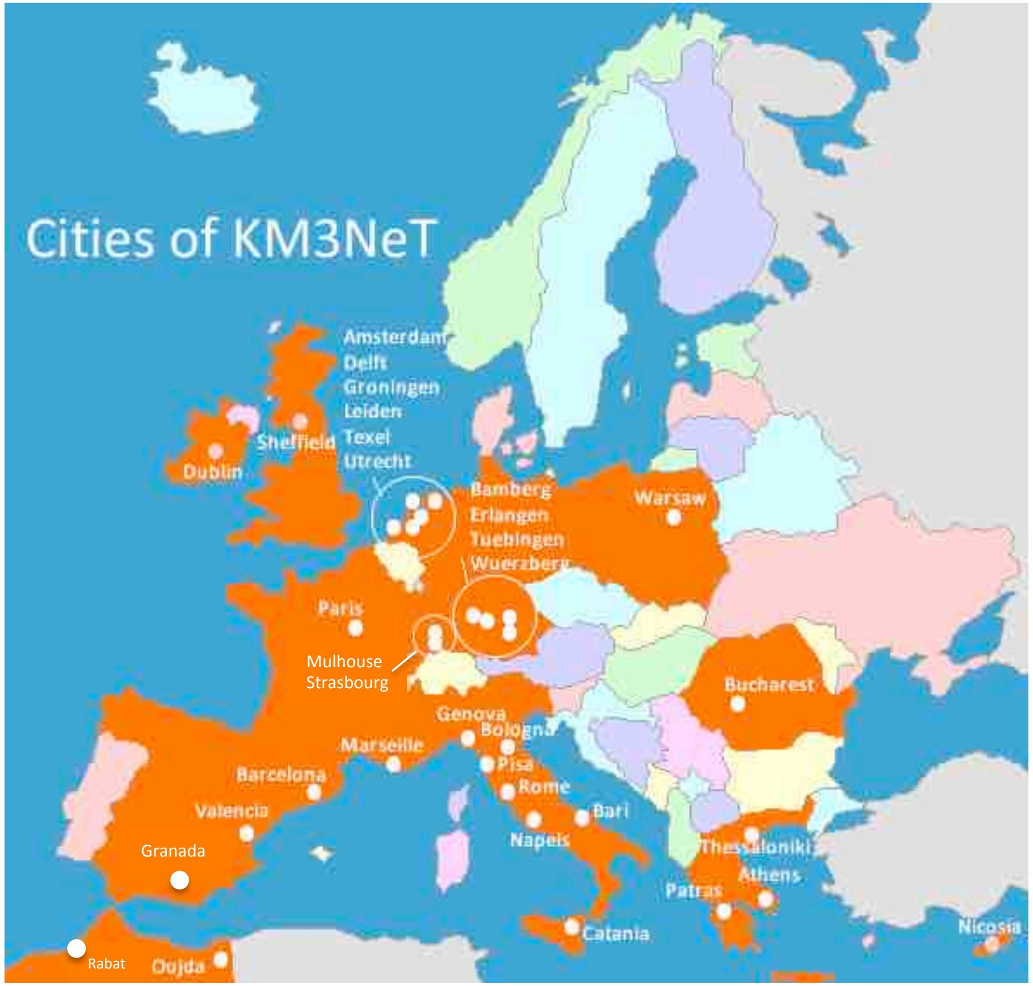


ARCA- Astroparticle Research with Cosmics in the Abyss

ORCA- Oscillation Research with Cosmics in the Abyss

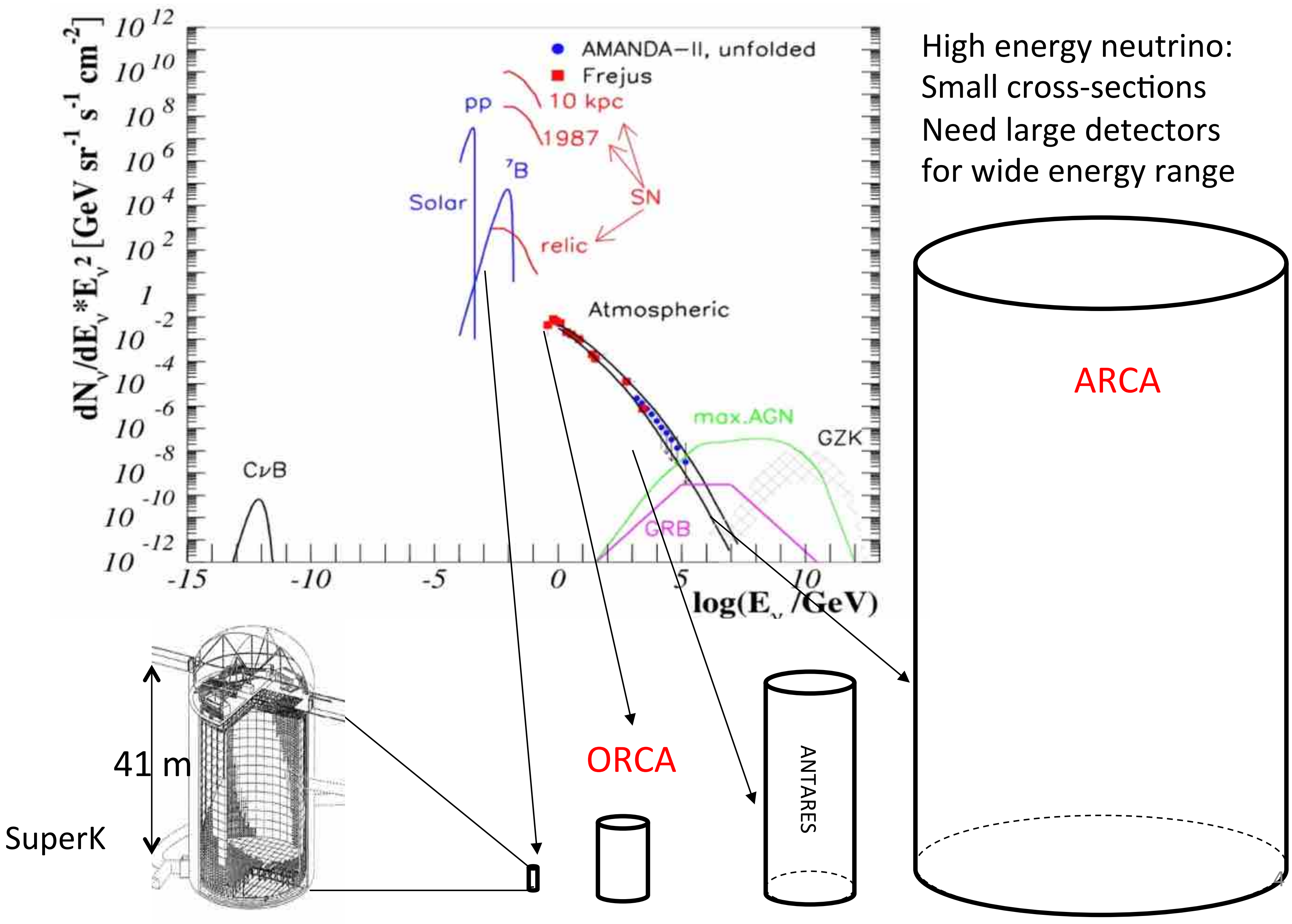
KM3NeT Collaboration

12 Countries
>40 Institutes
>220 Scientists



From MeV ν to PeV ν

High energy neutrino:
Small cross-sections
Need large detectors
for wide energy range



KM3NeT Technology

Optical module

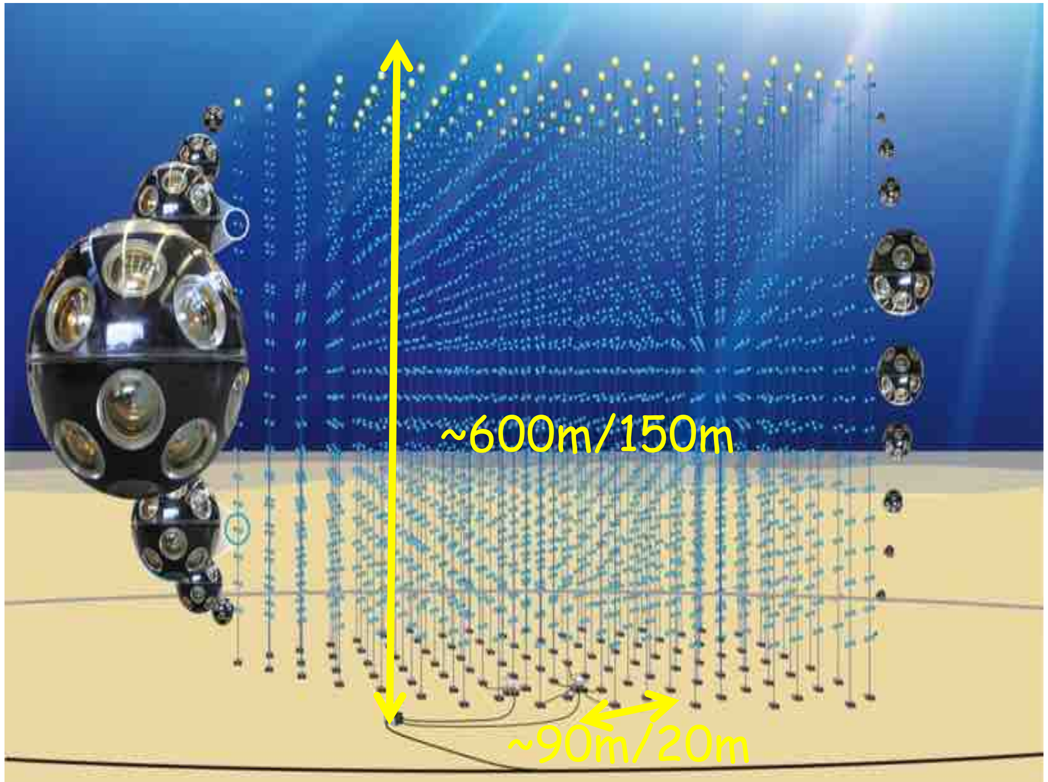
17”

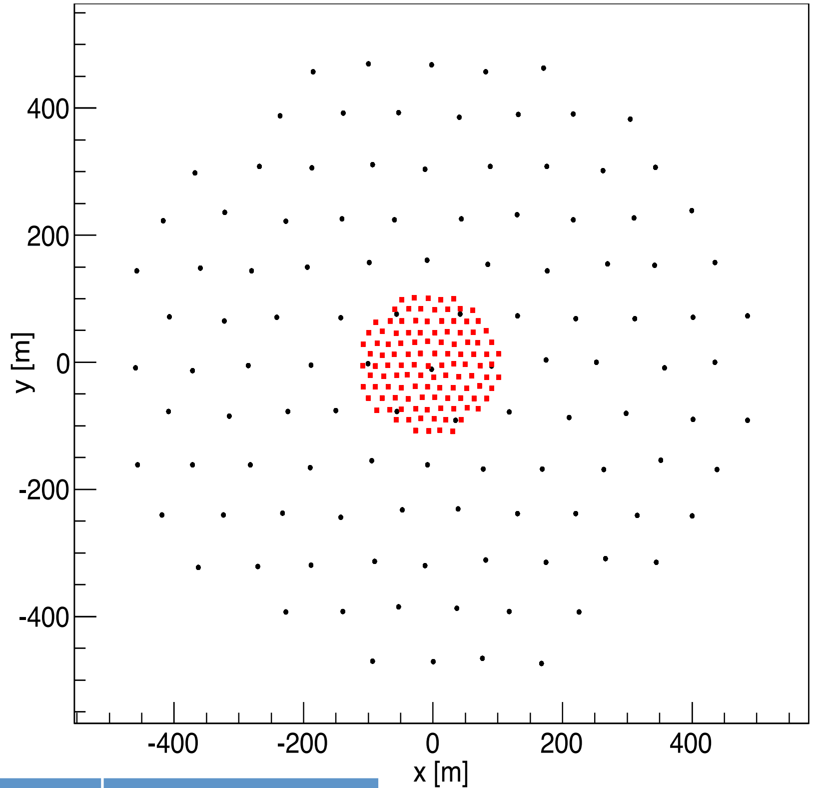
31 x 3” PMTs
PMT HV
LED & piezo inside
FPGA readout
Photon counting
Directional information

Launcher vehicle

rapid deployment
autonomous unfurling
recoverable

KM3NeT Building Block (115 detector lines)





	ARCA	ORCA
Location	Italy	France
Detector line distance	90 m	20 m
DOM spacing	36 m	9 m
Intrumented mass	500 Mton	5.7 Mton

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

December 2015 : KM3NeT confirmed on ESFRI Roadmap

KM3Net 2.0 LoI Published

arXiv.org > astro-ph > arXiv:1601.07459

Search or

Astrophysics > Instrumentation and Methods for Astrophysics

Letter of Intent for KM3NeT2.0

S. Adrián-Martínez, M. Ageron, F. Aharonian, S. Aiello, A. Albert, F. Ameli, E. Anassontzis, M. Andre, G. Androulakis, M. Anghinolfi, G. Anton, M. Ardid, T. Avgitas, G. Barbarino, E. Barbarito, B. Baret, J. Barrios-Martí, B. Belhorma, A. Belias, E. Berbee, A. van den Berg, V. Bertin, S. Beurthey, V. van Beveren, N. Beverini, S. Biagi, A. Biagioni, M. Billault, R. Bormuth, B. Bouhadef, G. Bourlis, S. Bourret, C. Boutonnet, M. Bouwhuis, C. Bozza, R. Bruijn, J. Brunner, E. Buis, J. Busto, G. Cacopardo, L. Caillat, M. Calamai, D. Calvo, A. Capone, L. Caramete, S. Cecchini, S. Celli, C. Champion, R. Cherkaoui El Moursli, S. Cherubini, T. Chiarusi, M. Circella, L. Classen, R. Cocimano, J. A. B. Coelho, A. Coleiro, S. Colonges, R. Coniglione, M. Cordelli, A. Cosquer, P. Coyle, A. Creusot, et al. (182 additional authors not shown)

(Submitted on 27 Jan 2016)

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

Accepted for publication in J. Phys. G

Mass Production

DOM Integration Sites

Nikhef, Erlangen, Naples, Catania, Strasbourg, Athens, Rabat

5 DOMs/week/site

Detector Line Integration Sites

LNS, CPPM, Nikhef, Naples

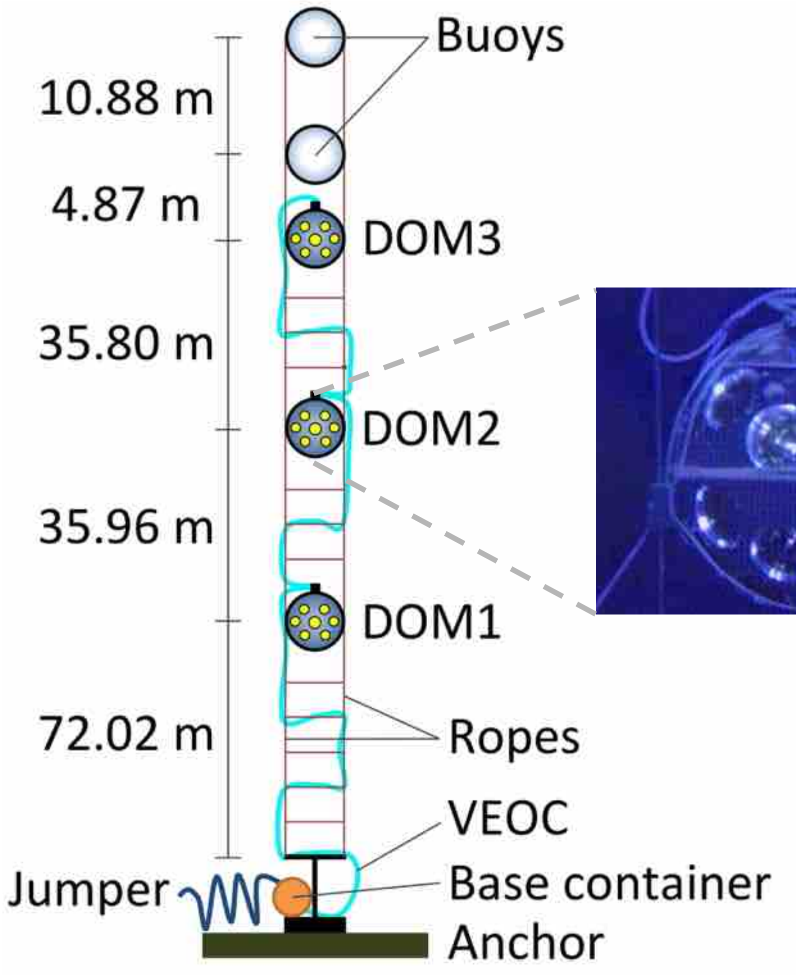
1 line/1.3 week/site

Deployment Sites

LNS, CPPM

4 lines/sea operation/site

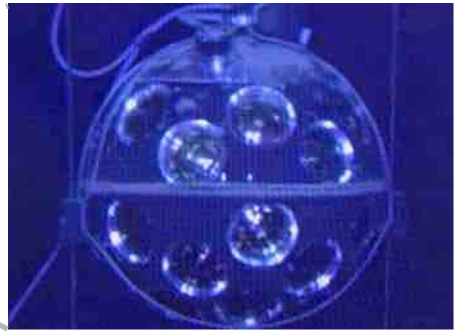
Detector Line prototype



Prototype Line with three DOMs

Deployed at the KM3NeT-It site at 3500m depth

Followed successful operation of prototype DOM at the ANTARES site



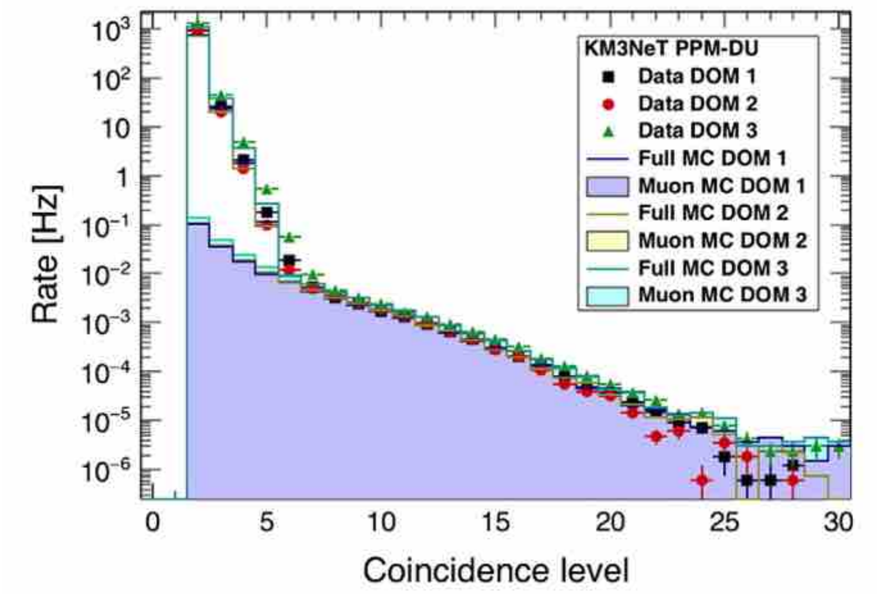
Operational from May 2014 to July 2015

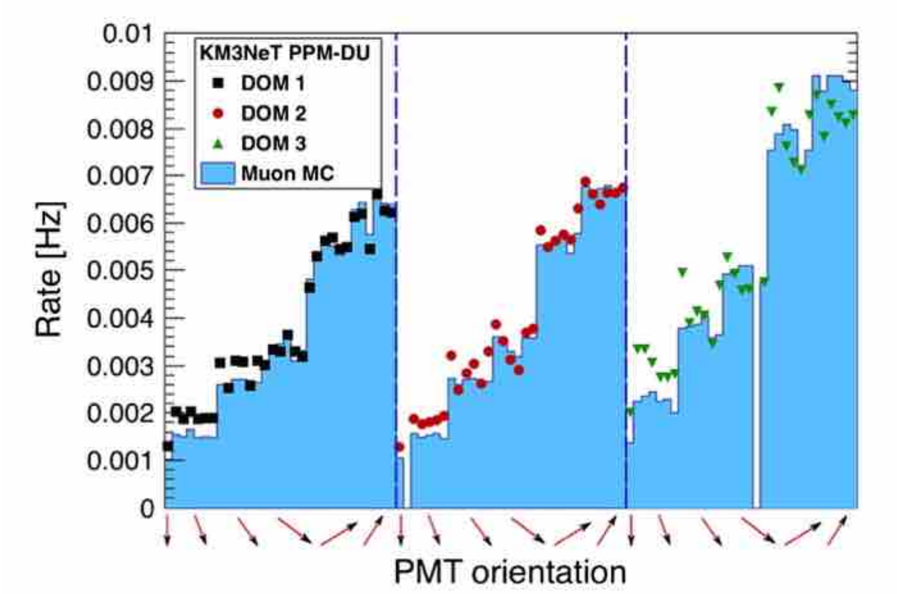
Proof of concept functionality

Test of readout, DAQ, connection, intra-DOM and inter-DOM synchronization

DOM prototype results

arXiv:1510.01561
Eur. Phys. J. C (2016) 76:54





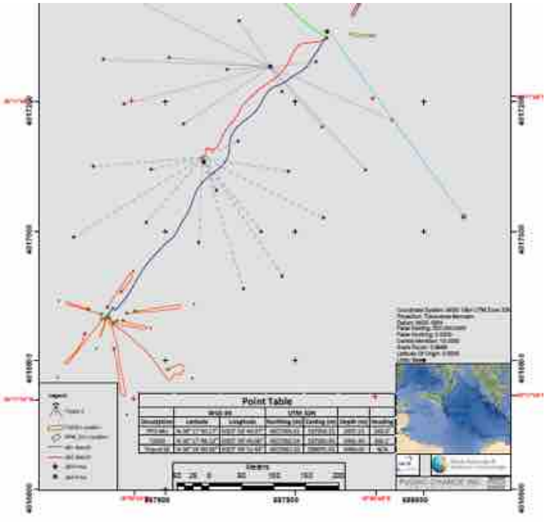
Photon counting

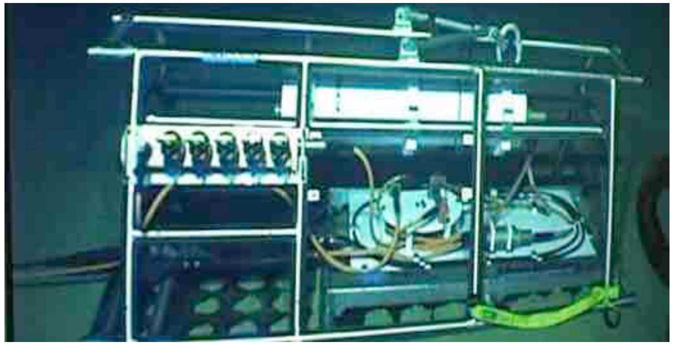
Directional sensitivity

High level coincidences cleanly select muon events

Muon events (coincidence level > 7)

ARCA Installation Progress





July 2015

- Replacement of cable termination frame
- Deployment & connection of 2 junction boxes
- Upgrade of the shore station

December 2015

- Deployment of first complete detector line

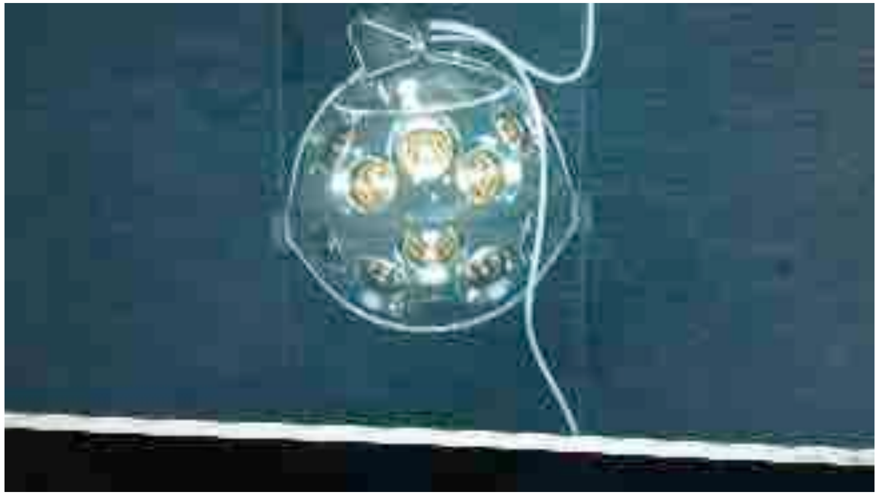
May 2016

- Deployment of additional detector lines

Installation of first Line Dec 2015

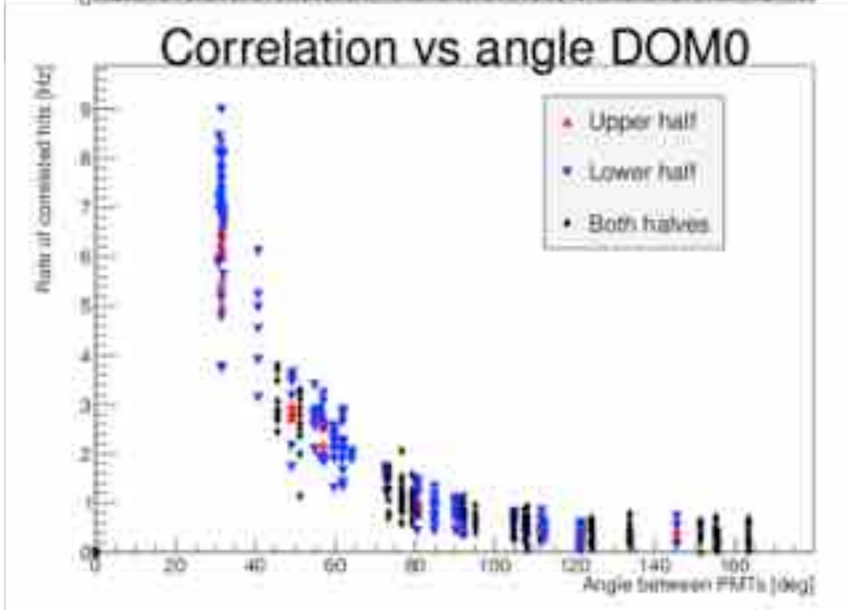
- First full detector line installed in Capo Passero in December 2015
- Functional and operating since then

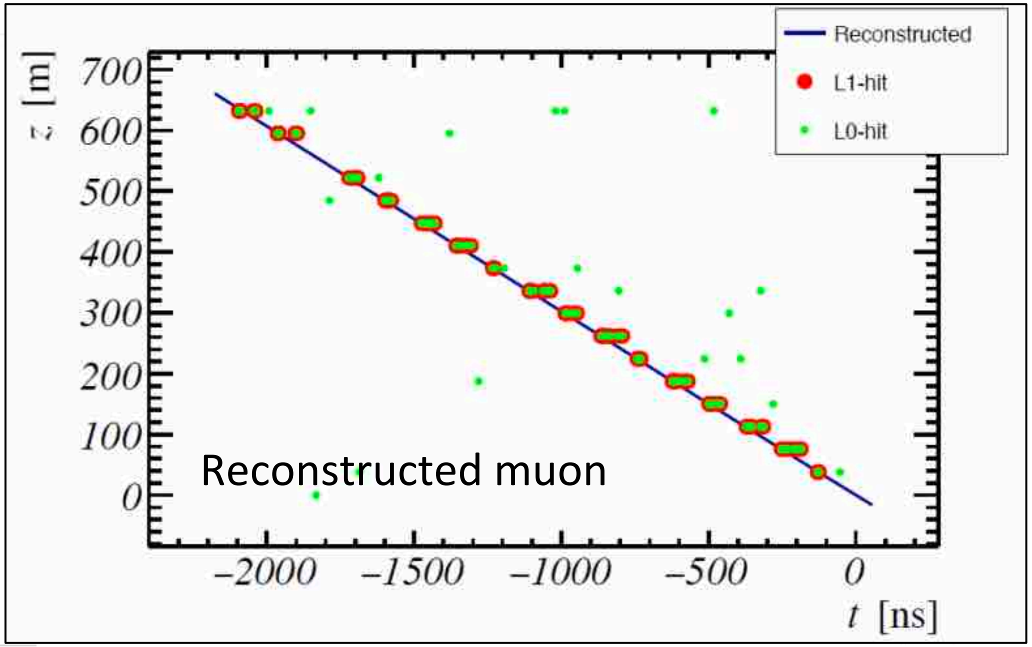
Line after successful unfurling



Early Results

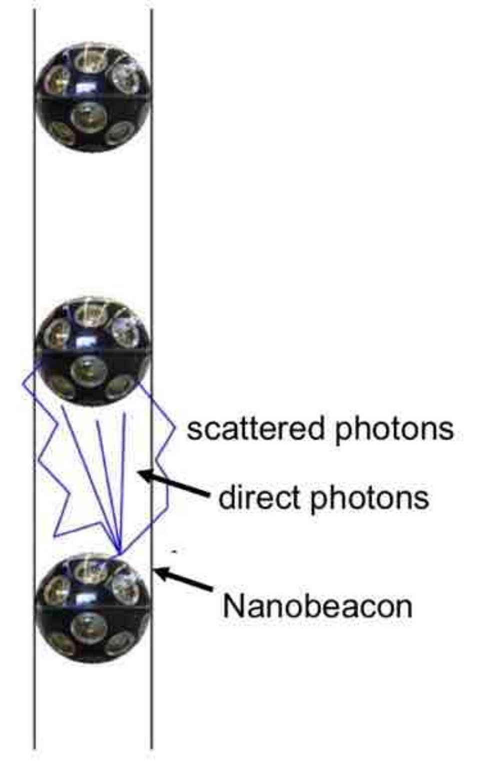
All 18 DOMs work
All 31x18 PMTs work

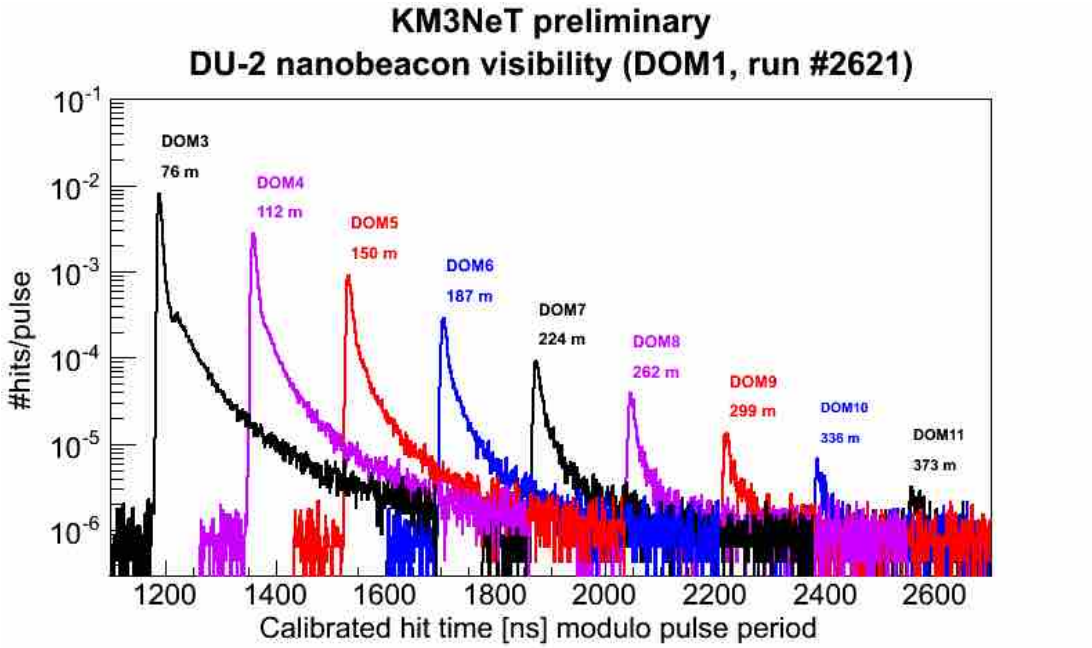




First Line preliminary results

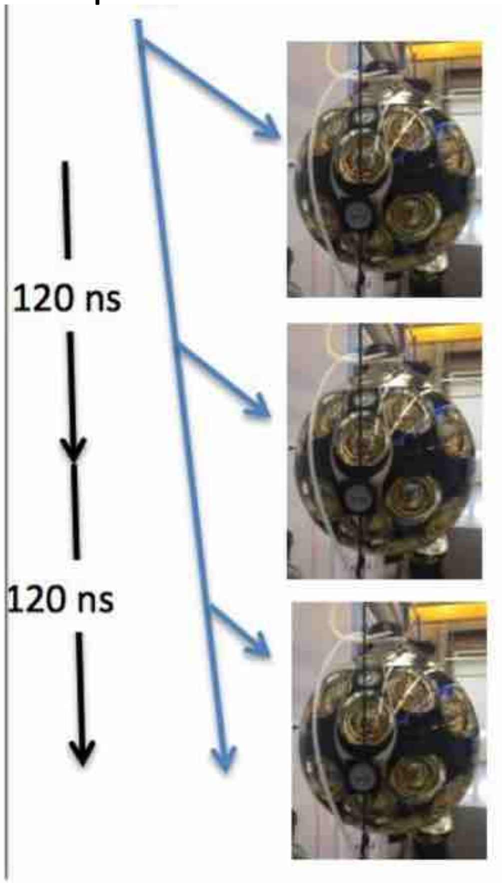
Time calibration with LED nanobeacons

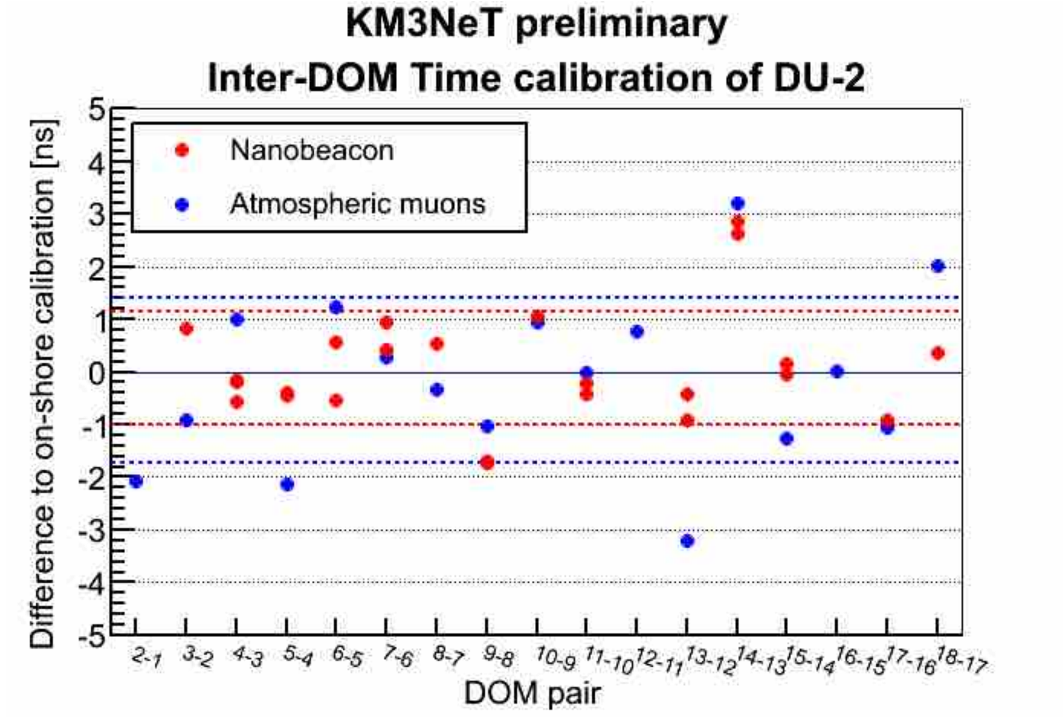




First Line preliminary results

Comparison of calibration with LED nanobeacons and atmospheric muons





Growing up

- 2 more Detector Lines installed in May 2016
- One NEMO tower installed in the same operation

KM3NeT/ARCA: Physics goals

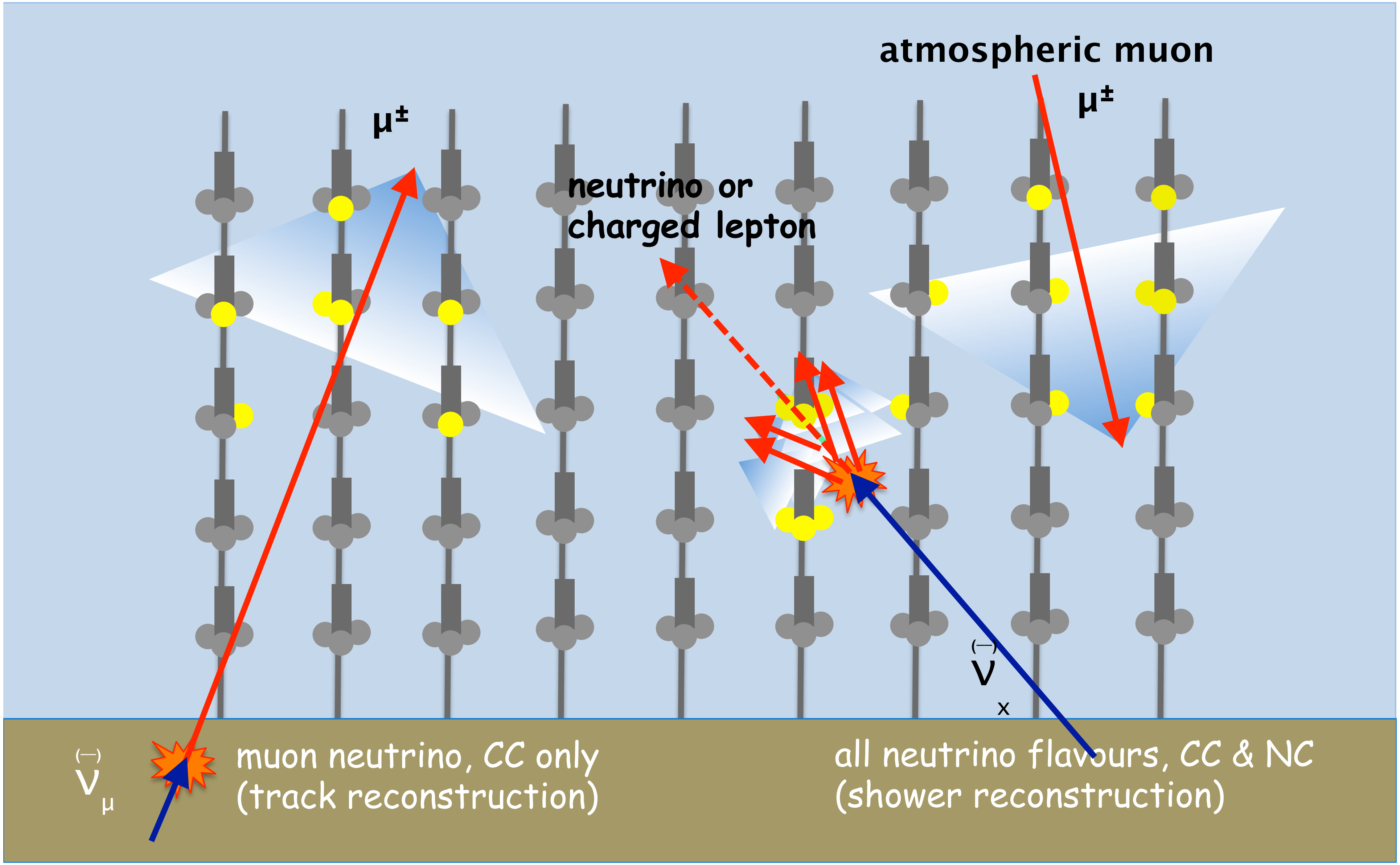
- Diffuse high-energy neutrino fluxes
  - Benchmark: the IceCube flux (assumed isotropic, flavour symmetric)

$$\Phi(E) = 1.2 \cdot 10^{-8} \left(E/1\ \mathrm{GeV}\right)^{-2} \exp\left(-E/3\ \mathrm{PeV}\right)\ \ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

M.G. Aartsen et al., Science 342 (2013) 1242856

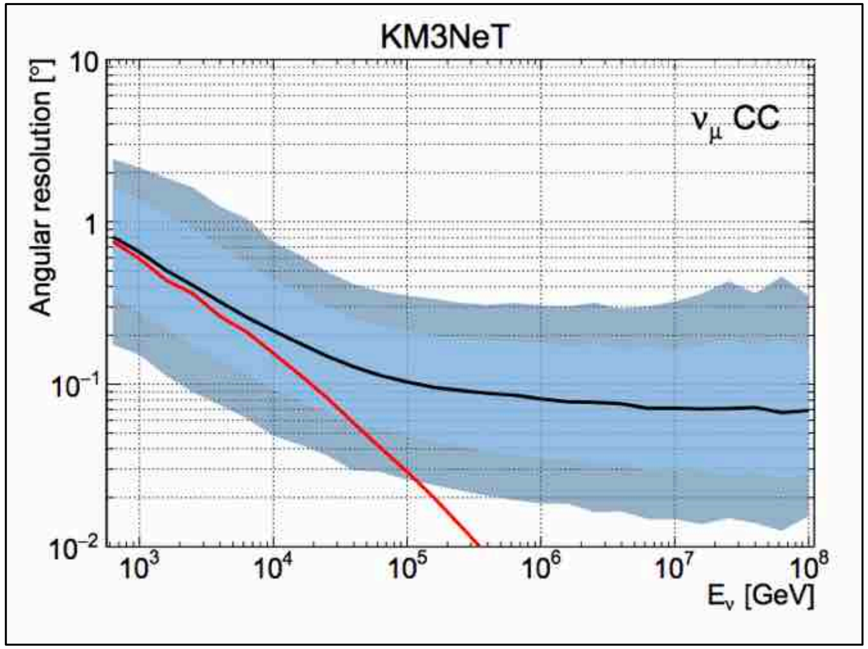
- Neutrino point-like sources
  - Benchmark: intense galactic TeV gamma sources

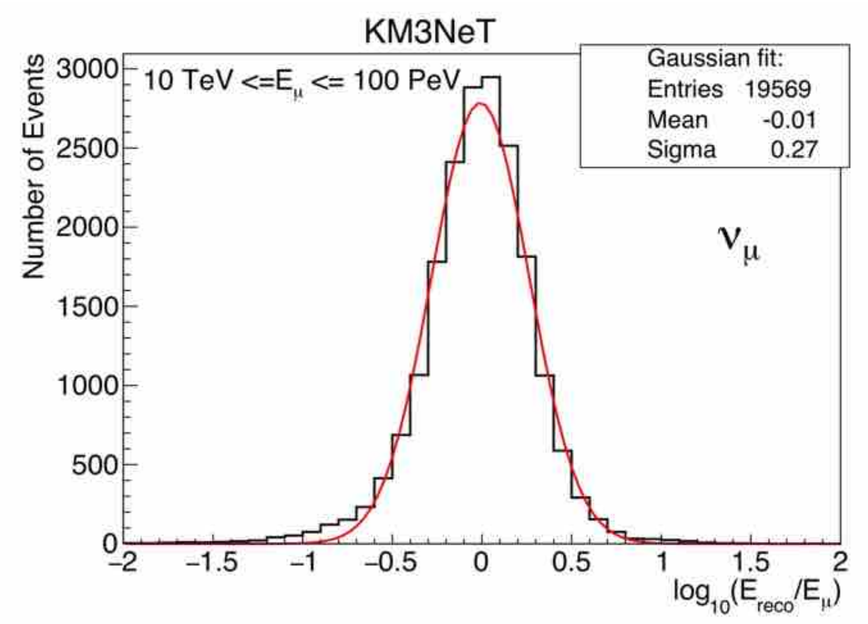
High Energy Neutrino Signatures



KM3NeT/ARCA performance
Tracks

After cuts optimized for track reconstruction



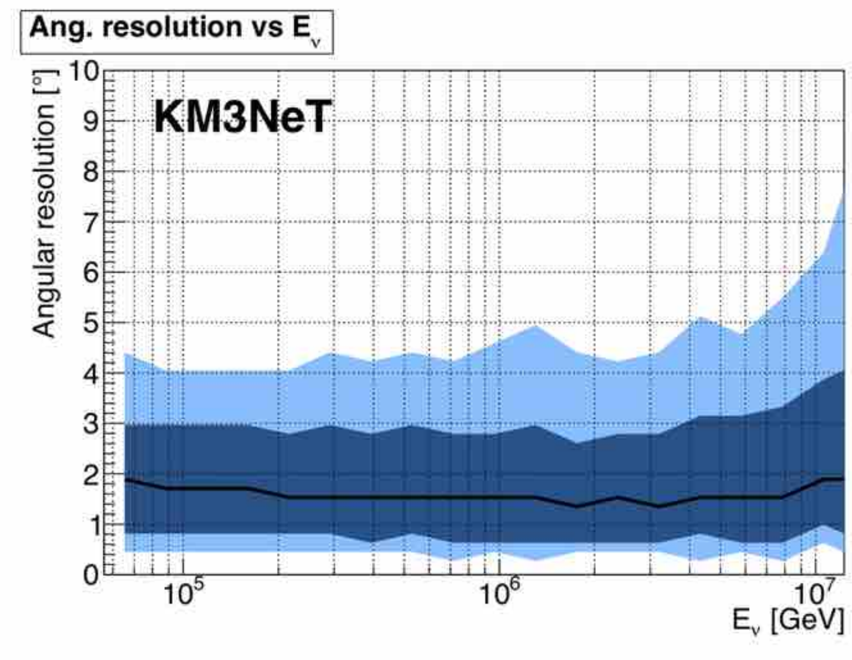


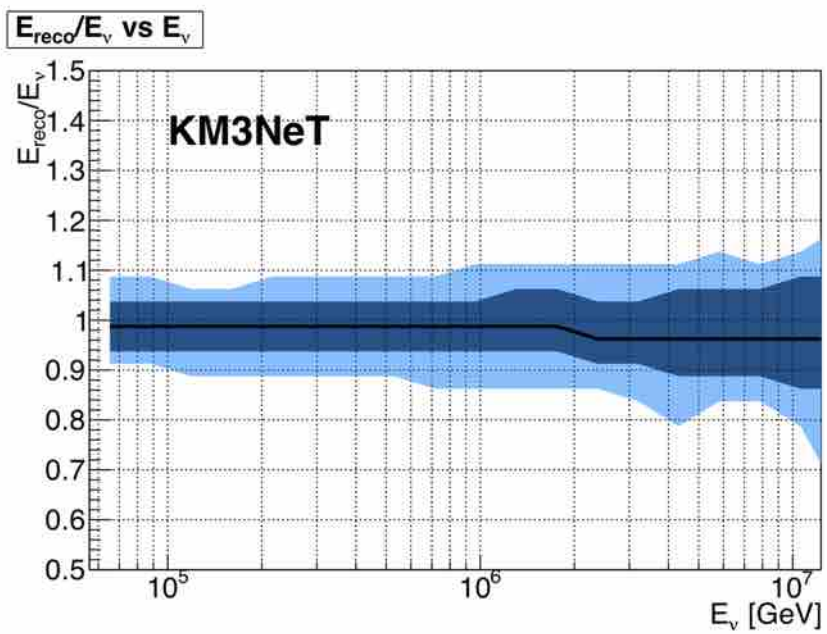
Angular resolution
about 0.1° (E_ν>10 TeV)

Energy resolution
0.27 in $\log E_\mu$
(1 TeV < E_ν < 100 PeV)

KM3NeT/ARCA performance
Cascades

Angular and energy resolution for the event sample after the final cuts of the diffuse cascade analysis





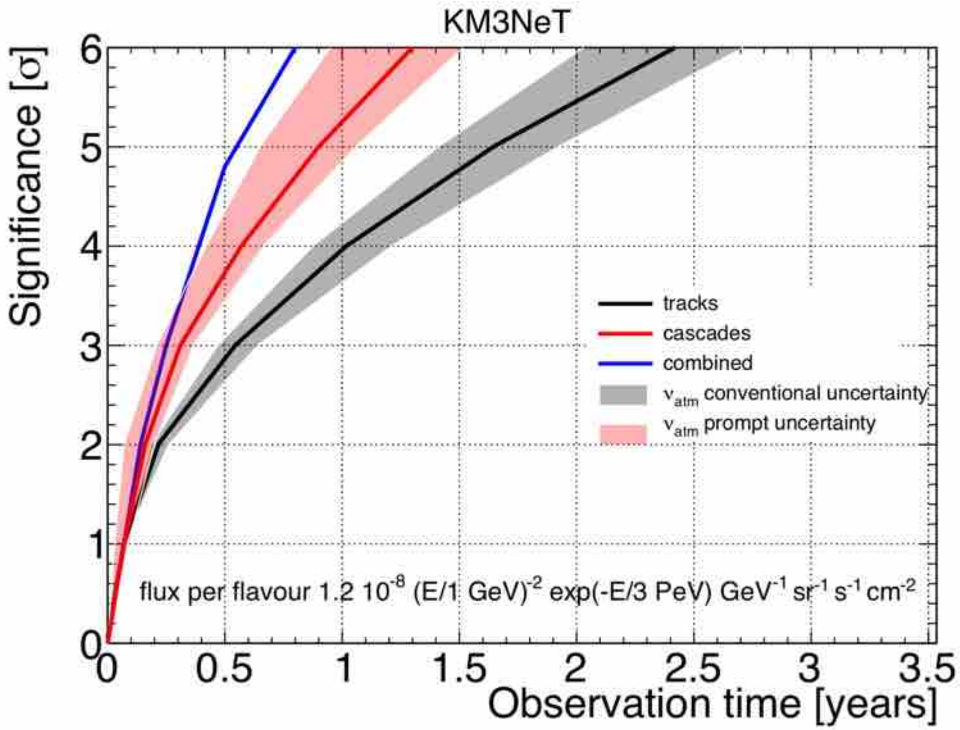
Angular resolution better than 2°

Energy resolution < 10%

KM3NeT/ARCA
Sensitivity to neutrino diffuse flux

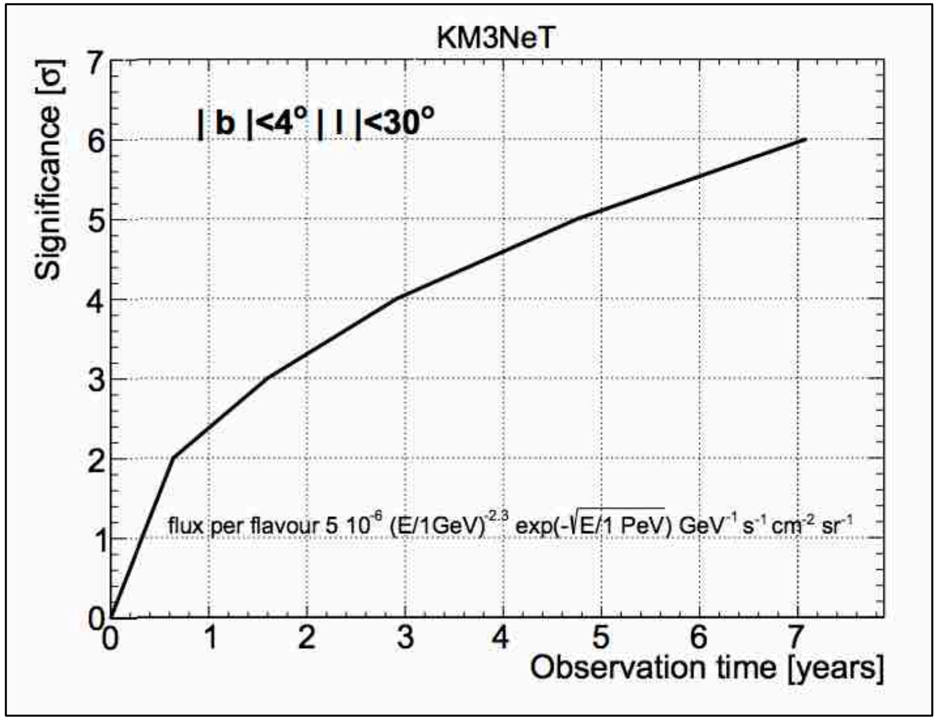
Analysis for the track events:

- **Track channel:** analysis for up-going events based on Max. likelihood
  Pre-Cuts on θ_{zen} >80°, Λ (reconstruction quality parameter), N_{hit} (number of hits -> parameter related to the muon energy)



Discovery at 5σ significance (50% probability) in less than one year

KM3NeT/ARCA
Diffuse flux around the Galactic Center



Significance estimation over time for the assumed spectra.

- Galactic Plane as potential region of diffuse astrophysical source.
  - D. Gaggero et al.,
  - arXiv:1508.03681 (2015)
- Only muon-track events added
- Events selected within the region: |l|<30°, |b|<4°
- 5σ discovery to be achieved after 5 years of operation.

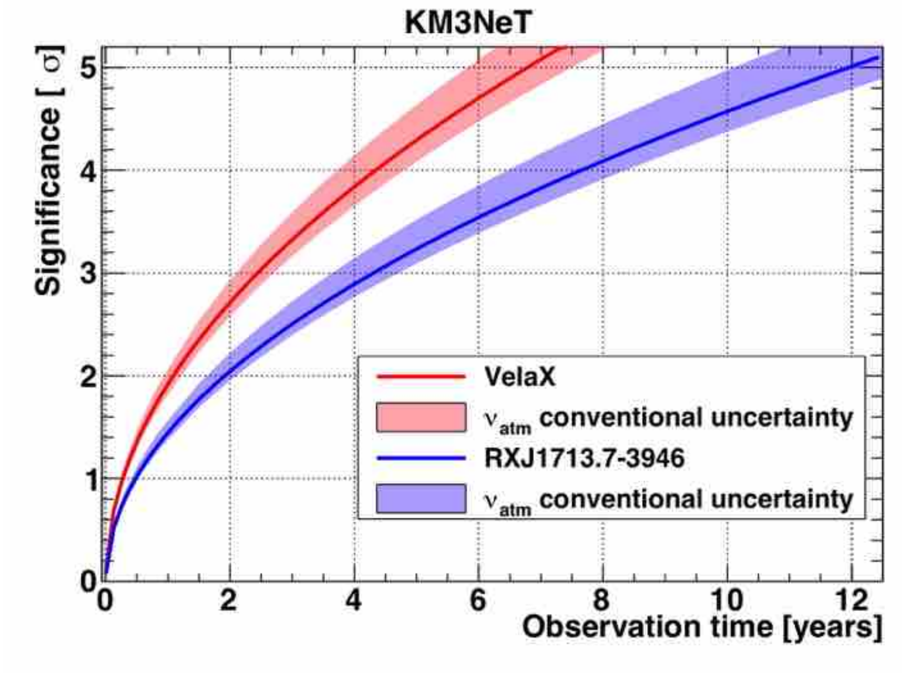
KM3NeT/ARCA
Galactic sources

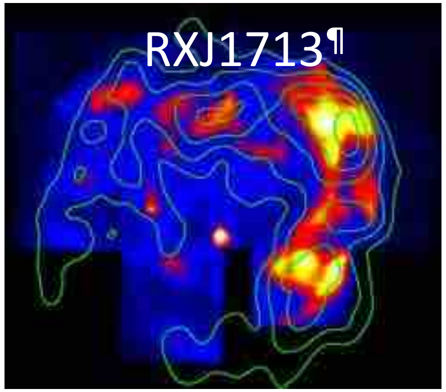
HE gamma emission observed by HESS in SNRs
Neutrino spectra predicted using gamma spectra

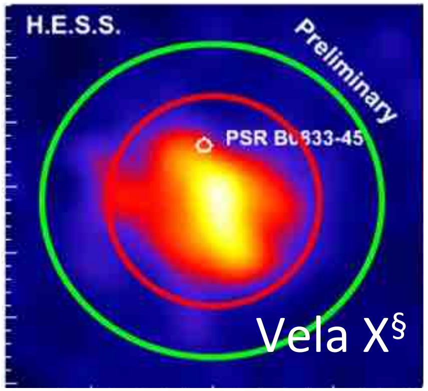
¶ S.R. Kelner, *et al.*, PRD 74 (2006) 034018

§ F.L. Villante and F. Vissani, PRD 78 (2008) 103007

Hypotheses: 100% hadronic emission and transparent source



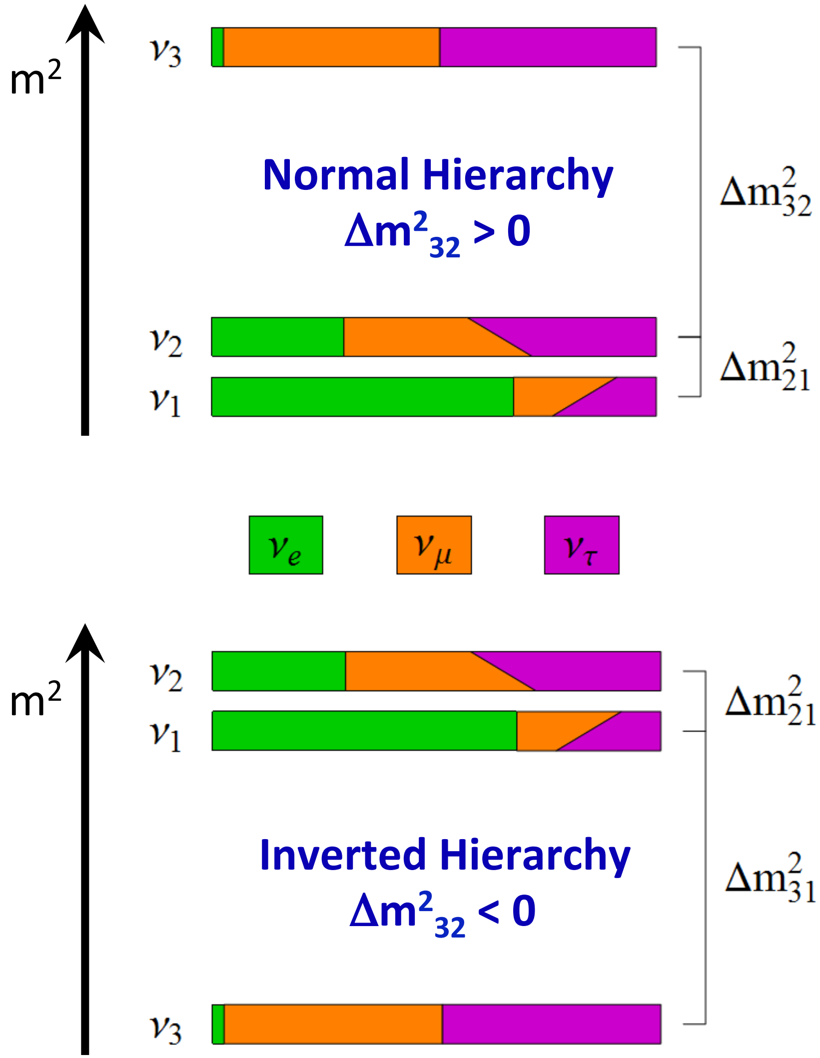




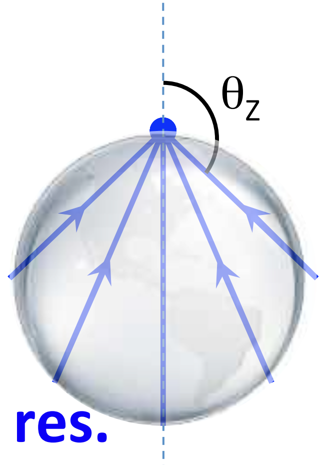
Vela X: 3σ in about 2 years
RXJ1713: 3σ in about 4 years

KM3NeT/ORCA Physics Goals

- Determine the **Neutrino Mass Hierarchy (NMH)**
- Precise Measurement of atmospheric Neutrino parameters
- Indirect dark matter search

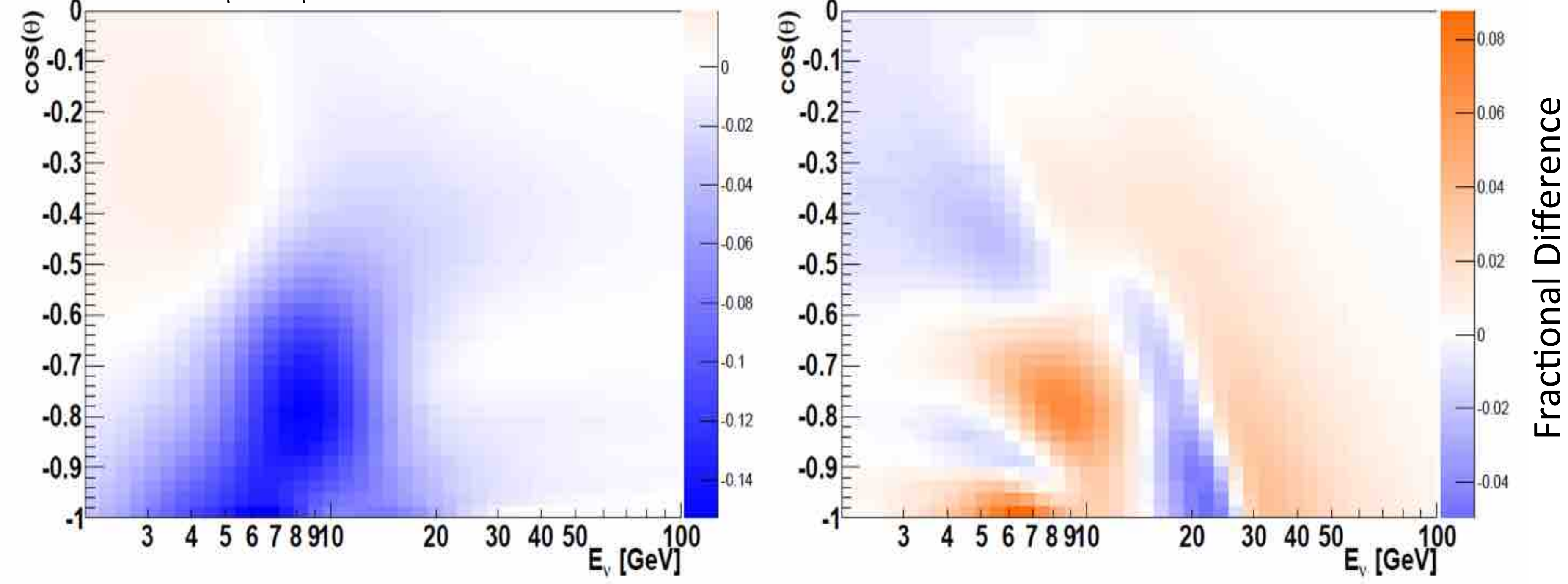


How to Measure NMH



- Measure neutrino direction and energy
- Search for **oscillation patterns** from **matter effects**
- Requires **large statistics** and good **energy and direction res.**

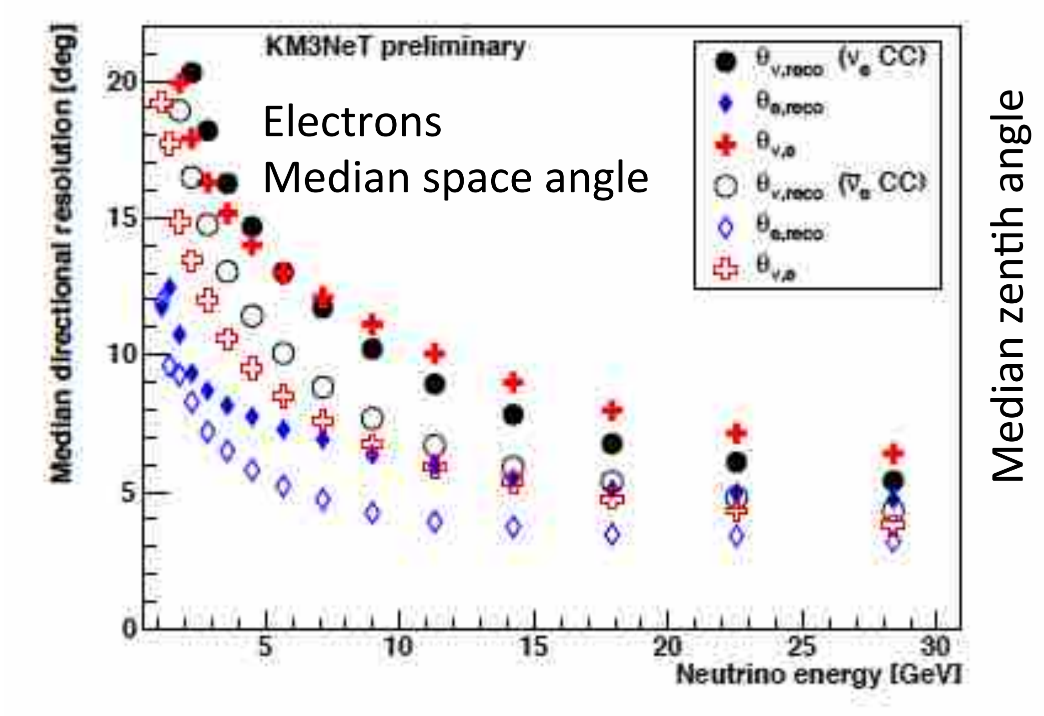
$\nu_\mu + \bar{\nu}_\mu$ (NH - IH) / NH $\qquad$ $\nu_e + \bar{\nu}_e$ (NH - IH) / NH

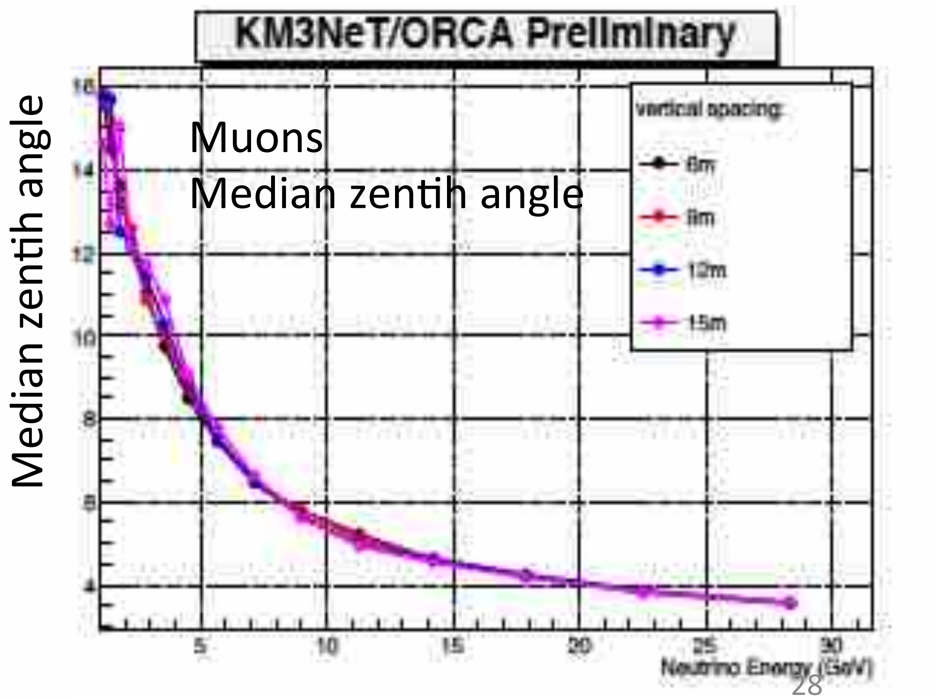


$E_{resol} = 25\%$ $\quad$ $\theta_{resol} = (m_p/E)^{1/2}$

KM3NeT/ORCA
Angular Resolution

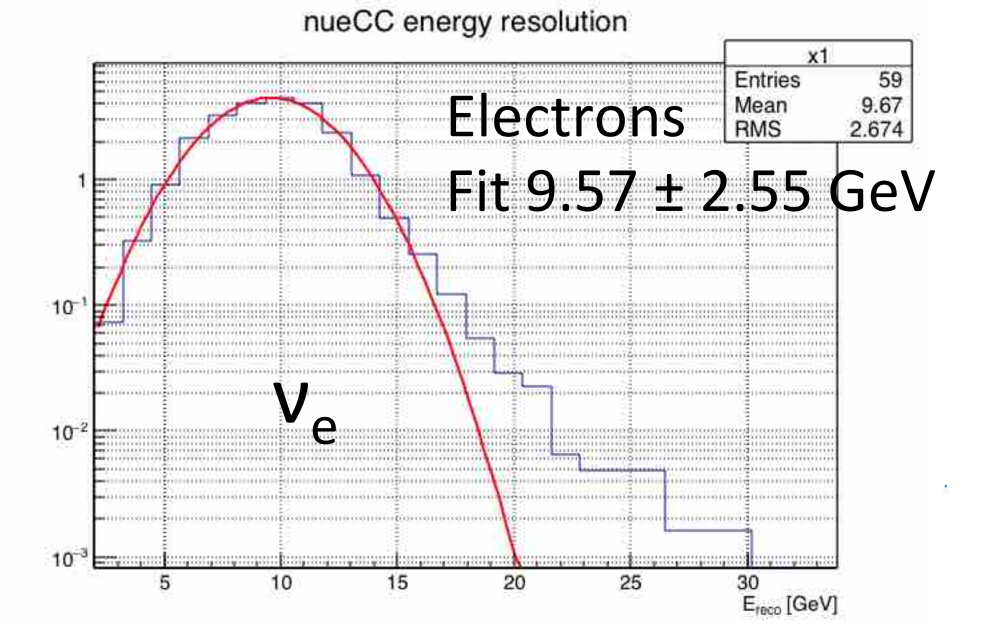
- For both electron/muon channel resolution dominated by kinematics
- Largely independent from spacing

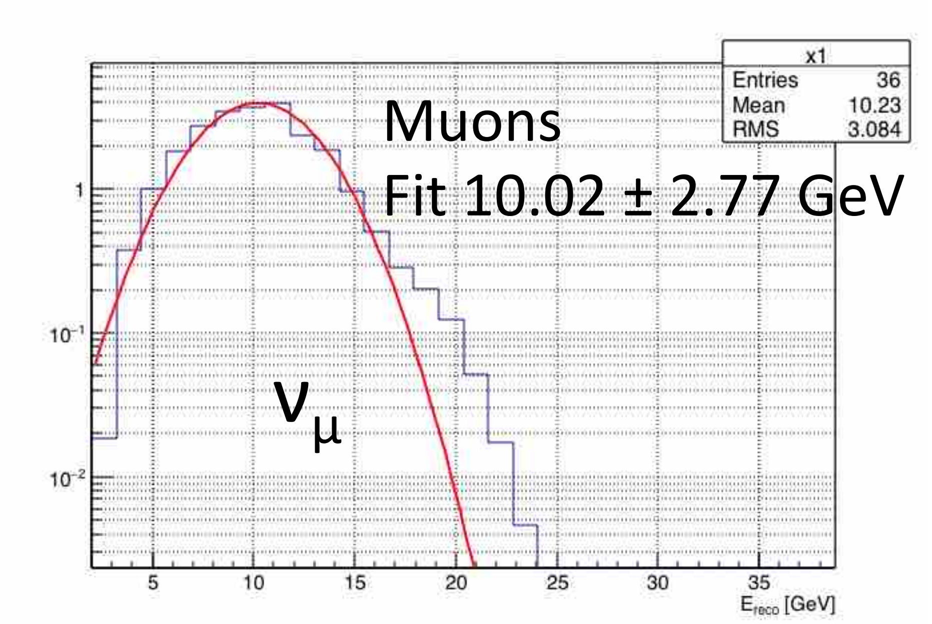




KM3NeT/ORCA
Energy Resolution

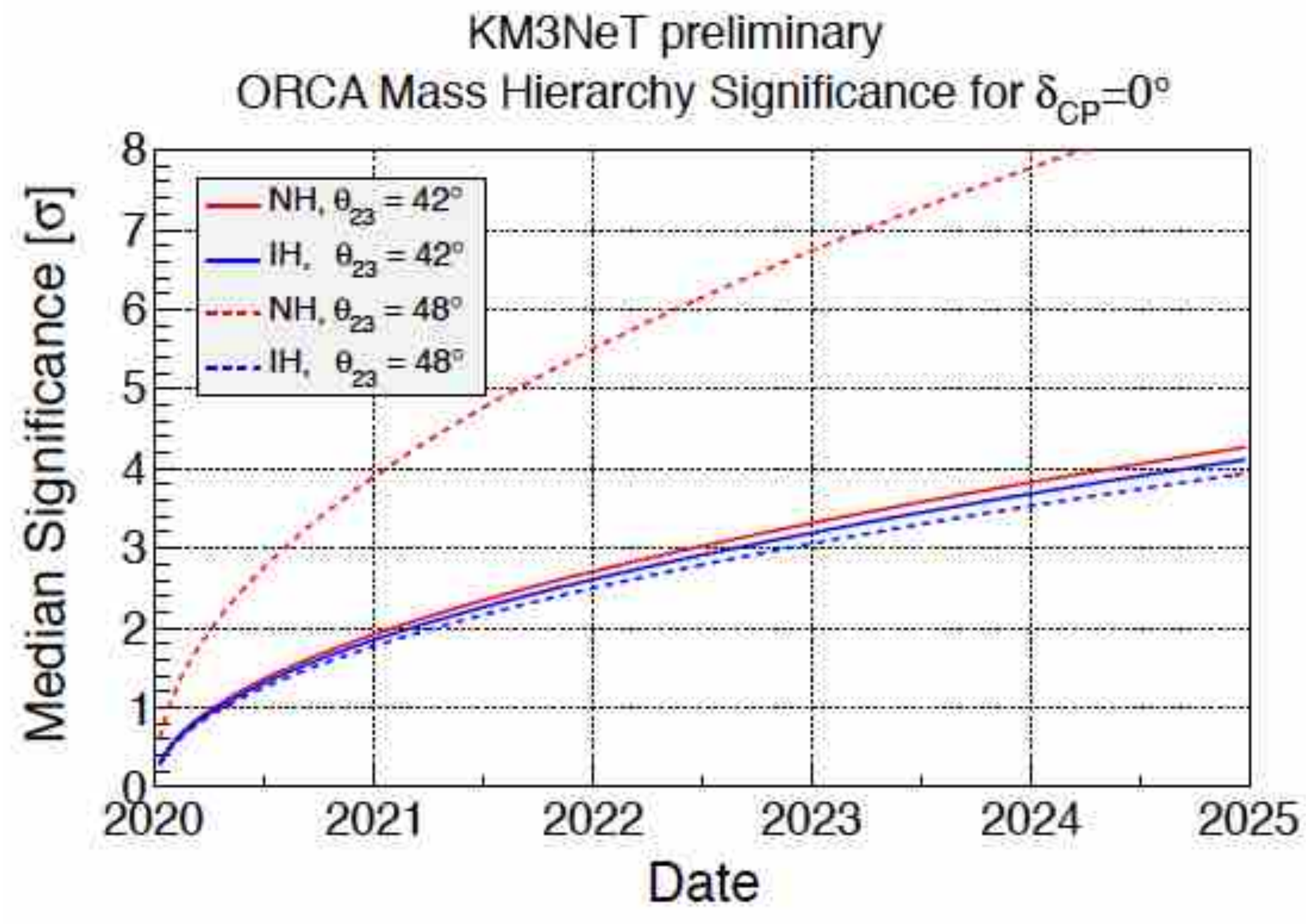
- Almost Gaussian response for both channels
- Example : E_{reco} distribution for $E_\nu \approx 10$ GeV





KM3Net/ORCA
Neutrino Mass Hierarchy

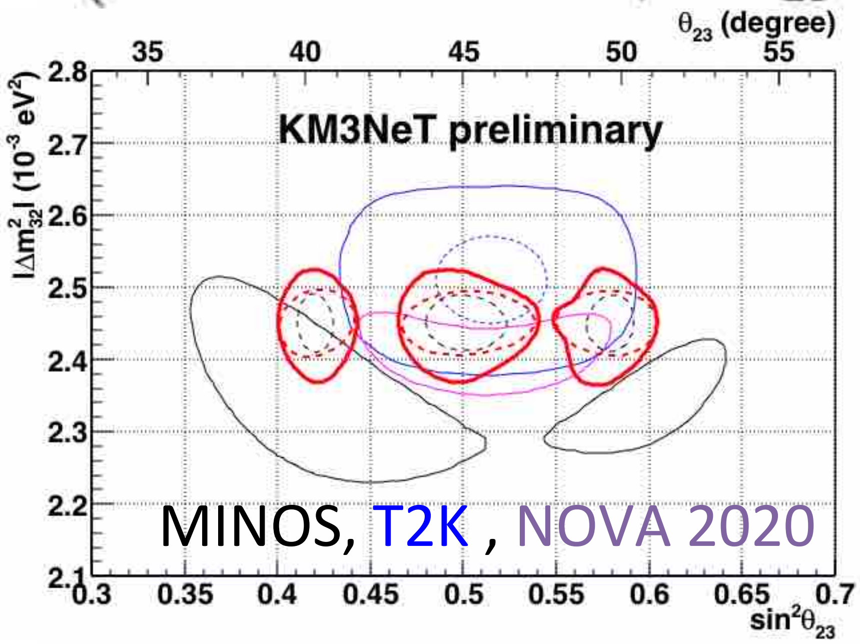
- Time dependence of sensitivity

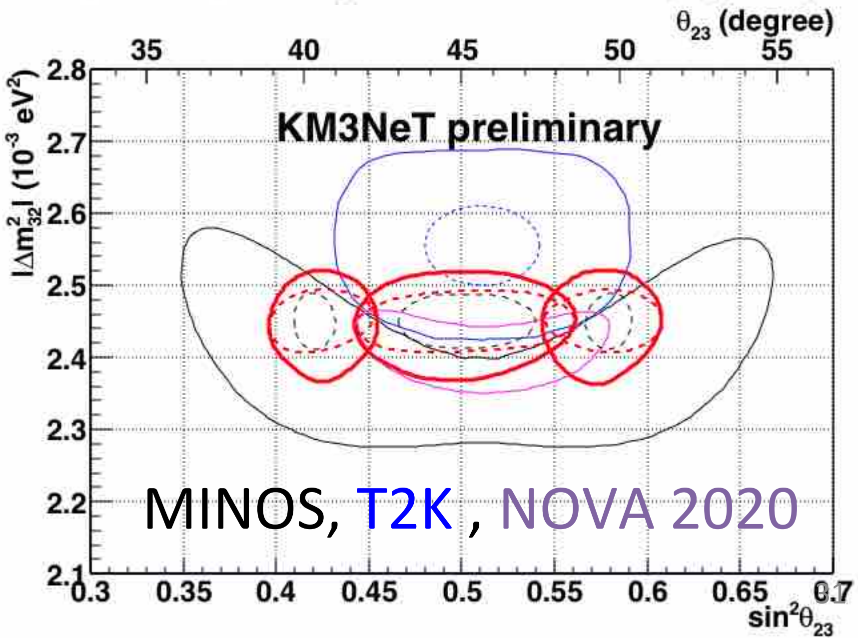


Measurement of oscillation parameters

- Reachable precision with 3 years data taking
- Competitive results also when compared to future reach of T2K and NOVA
- ORCA : red ellipses (solid/dashed = with/wo E_ν scale)
- All contours at 1-σ 3% in ΔM^2, 4-10% in $\sin^2\theta_{23}$

$(\Delta M^2 = 2.45\ 10^{-3}\mathrm{eV}^2, \sin^2\theta_{23} = 0.42, 0.50, 0.58)$





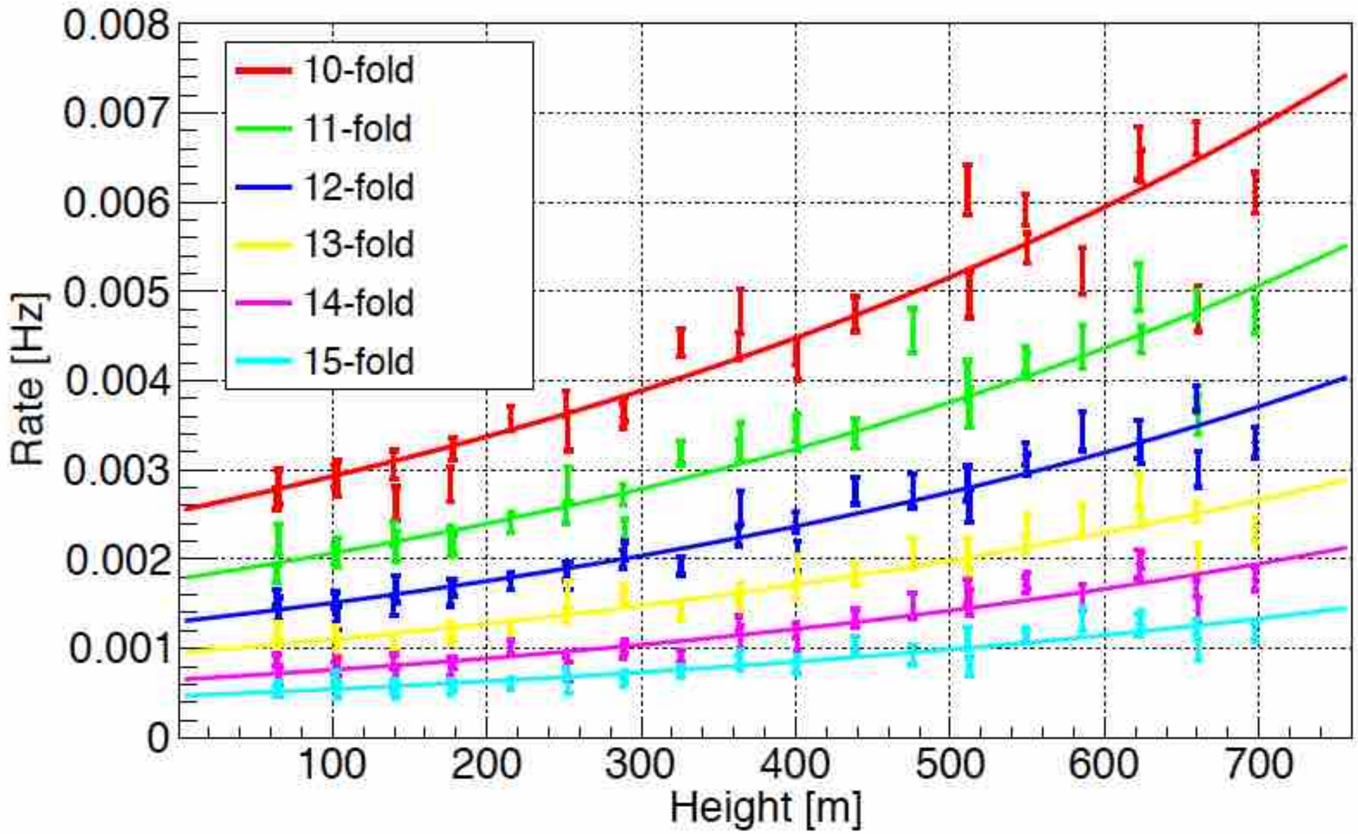
Conclusion

- KM3NeT
  - Mass production of DOMs started
  - First ARCA detector lines have been deployed
  - First results obtained
- KM3NeT/ARCA
  - Verify IceCube diffuse flux within few months
  - Strong potential to detect Galactic CR sources
- KM3NeT / ORCA
  - Neutrino Mass Hierarchy measurement on unequalled time scale
  - Competitive measurement of oscillation parameters

Backup

First Line preliminary results

- Depth dependence of atmospheric muon flux



Global Funding

Investment [M€]				
country	Phase-1 (spent)		KM3NeT 2.0 (anticipated)	
	total	Region	total	Region
Italy	16.0	16.0	70	70
France	7.0	3.5	8.7	4
Netherlands	8.8		10	
Spain	0.2		?	?
Germany	0.2		?	?
Greece	0.1		?	?
others			?	?
total	31.0	19.5	88.7	74

KM3NeT stays on ESFRI roadmap

KM3NeT Timeline

KM3NeT Technical Design Report[¶]

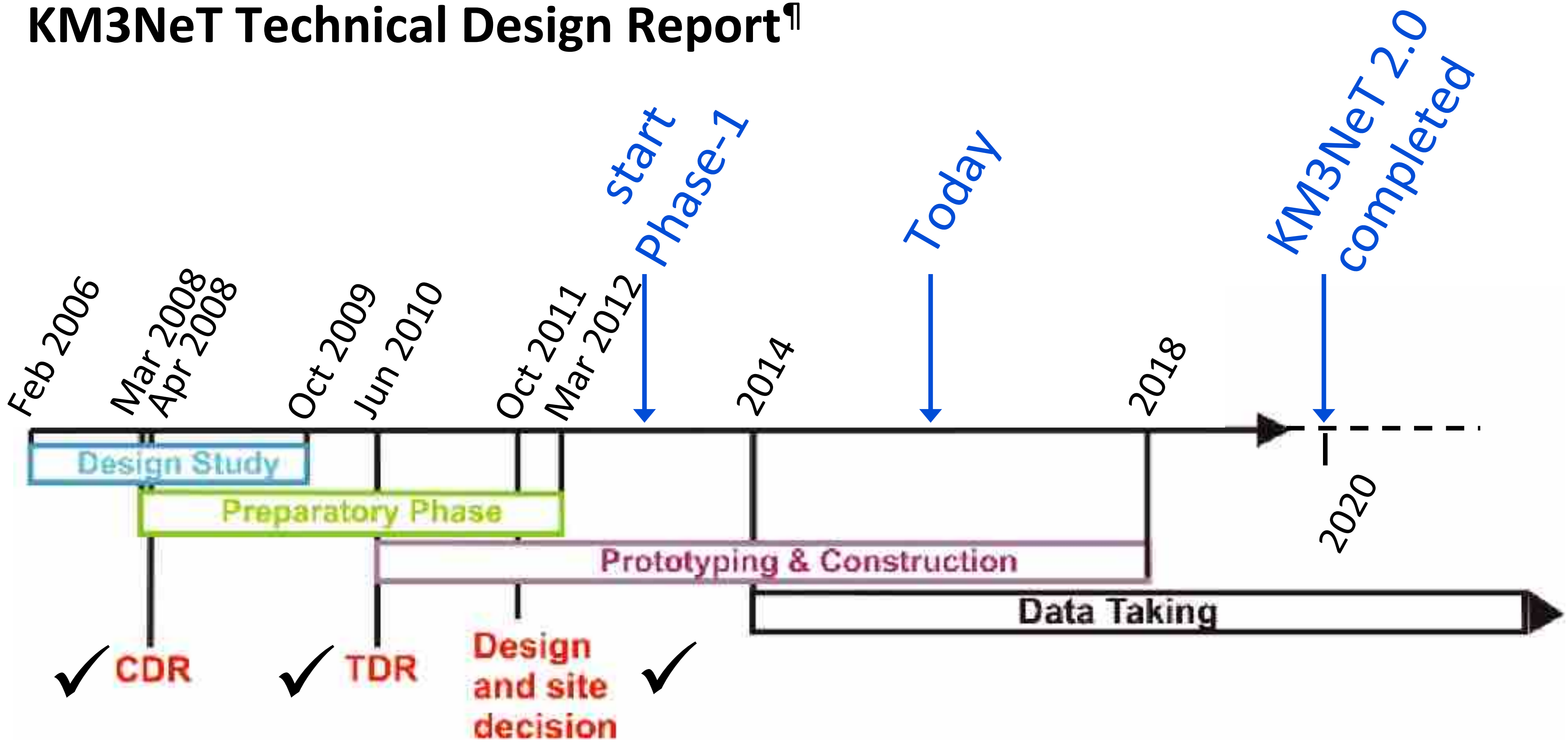
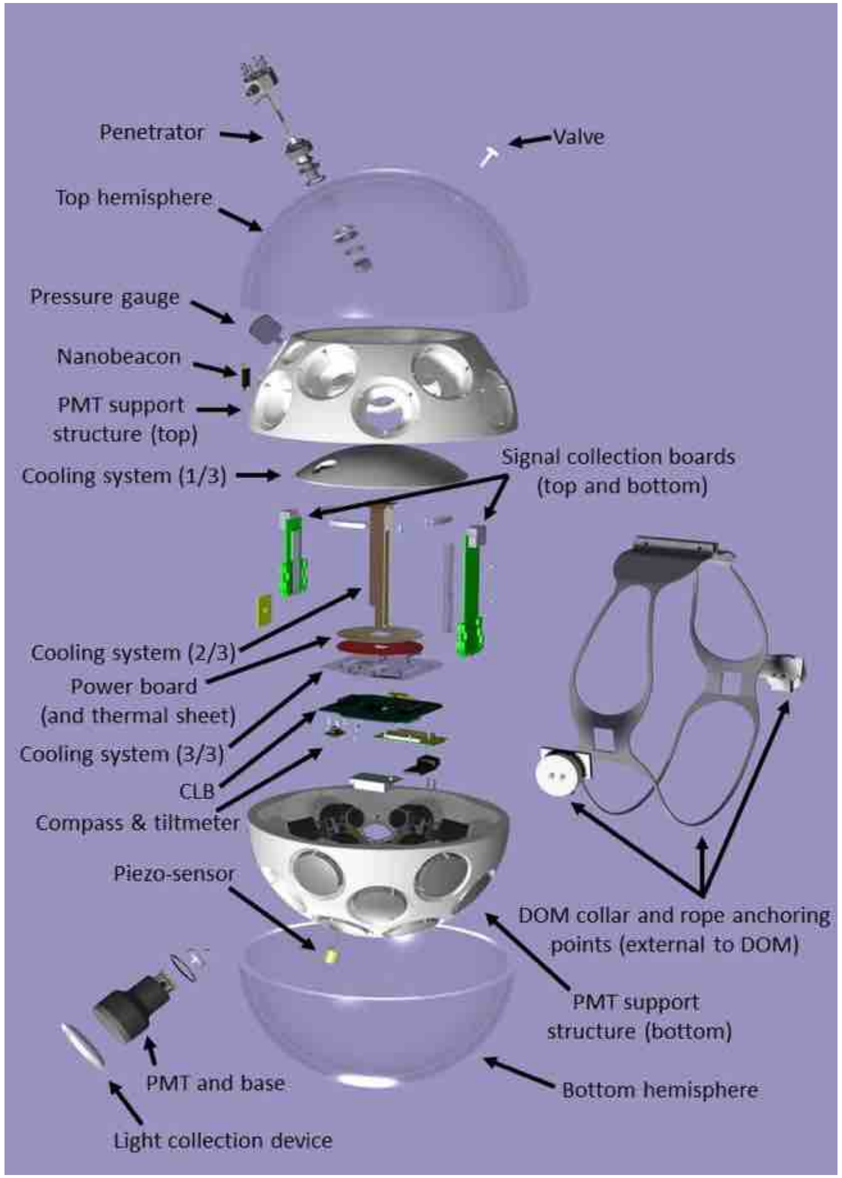


Figure 10-1: Overall time schedule of the KM3NeT project.

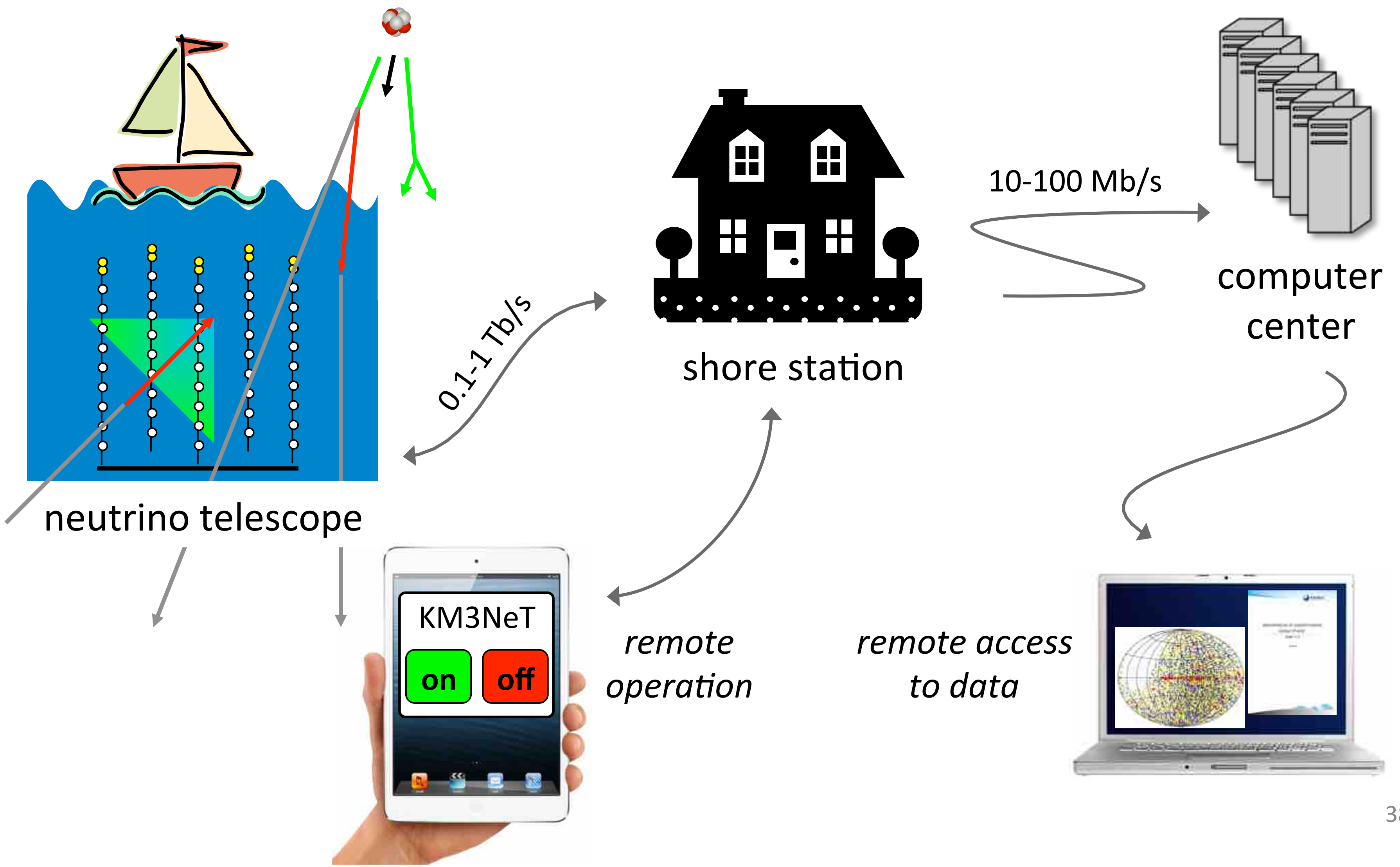
[¶] Deliverable of EU-funded Design Study.

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 structure
- 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)

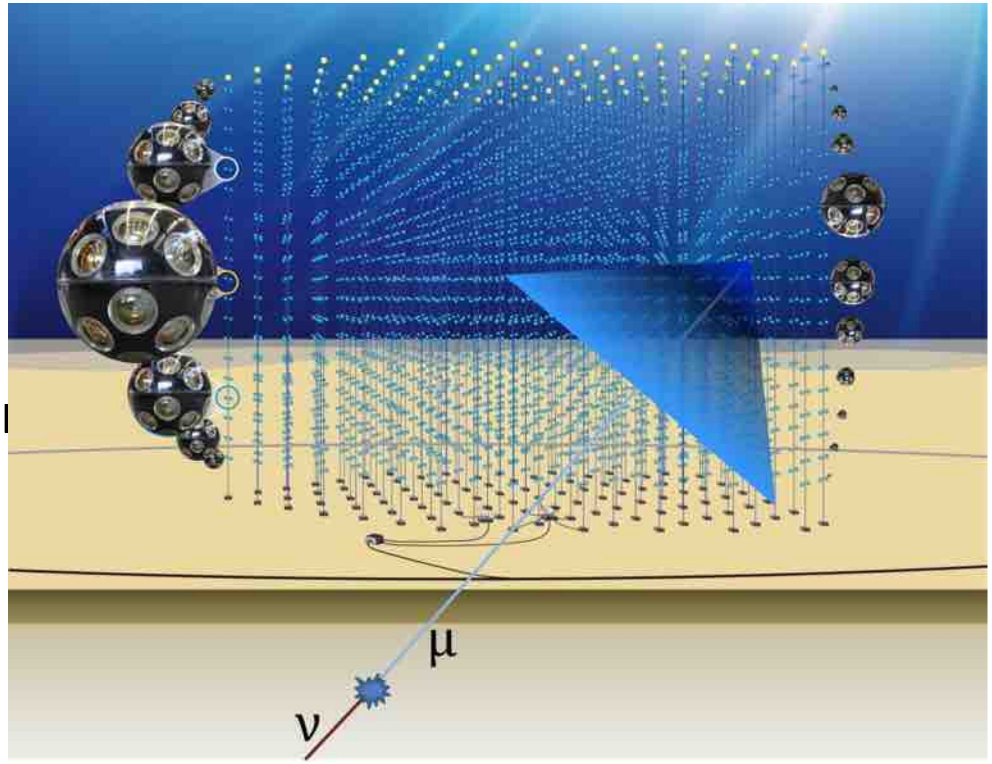


The KM3NeT architecture

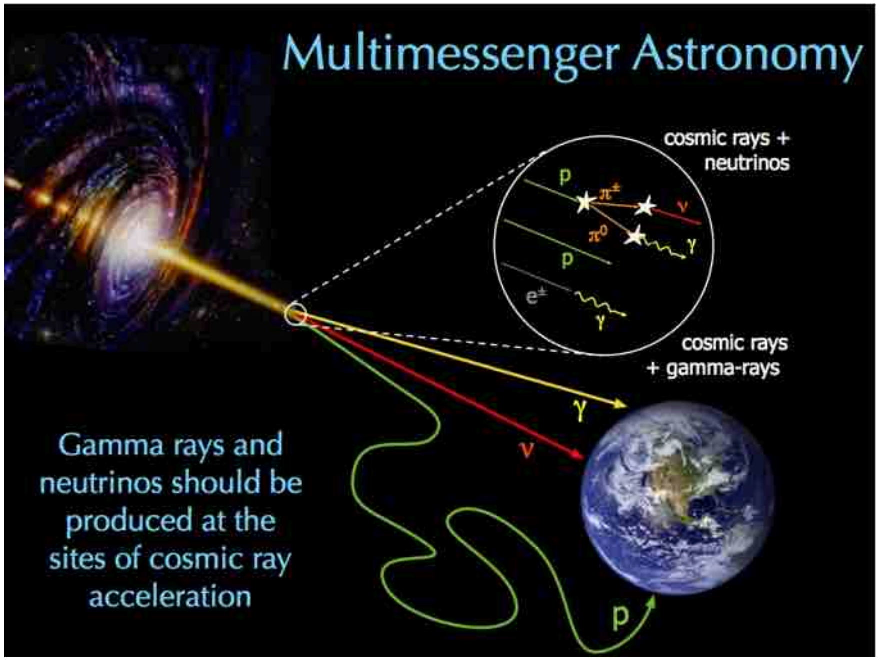


The KM3NeT design

- Detection unit (DU) – vertical slender string with multi-PMT digital optical modules (DOMs)
- Power and data distributed by a single backbone cable with breakouts at DOMs
- Building blocks of 115 DUs each, allow for a distributed detector
- Multi-site infrastructure
  - High-energy neutrino astronomy at the KM3NeT-It site
  - Low-energy neutrino physics (NMI at the KM3NeT-Fr site
- KM3NeT 2.0 selected by ESFRI for the next roadmap



Physics with high-energy neutrinos



Neutrinos can provide unperturbed information on the sources

Charged Cosmic Rays
☺ copiously produced
☹ directions scrambled by magnetic fields

UltraHigh Energy Cosmic Rays
☺ not strongly deflected by magnetic field
☹ limited by GZK cut-off

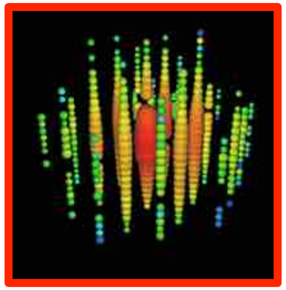
High Energy Gamma Rays
☺ copiously produced both by hadronic and leptonic mechanisms
☹ absorbed on dust and radiation

Neutrinos
☺ produced only by hadronic mechanisms
☺ not affected by magnetic fields and radiation
☹ very low $\sigma_{interaction}$

… and Gravitational Waves too

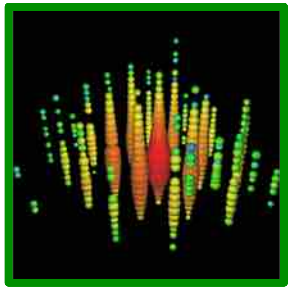
The IceCube signal

“Bert”



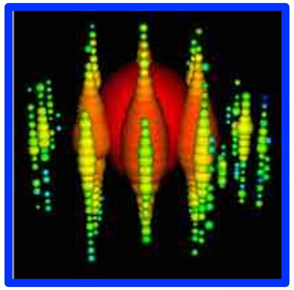
$\Delta\theta = 13.2^{\circ}$

“Ernie”

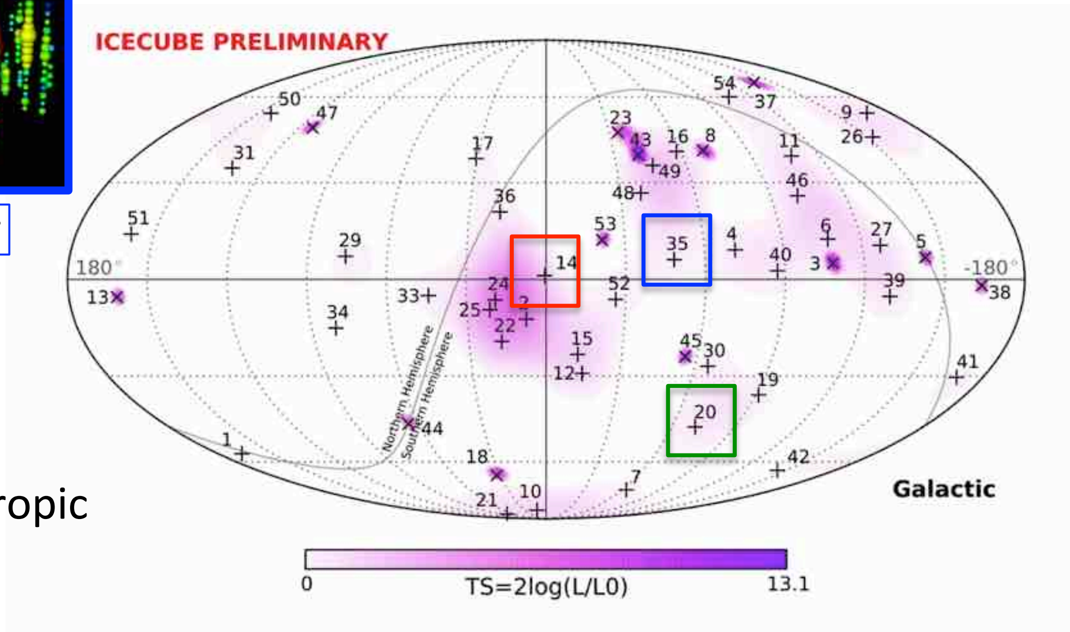


$\Delta\theta = 10.7^{\circ}$

“BigBird”



$\Delta\theta = 15.9^{\circ}$

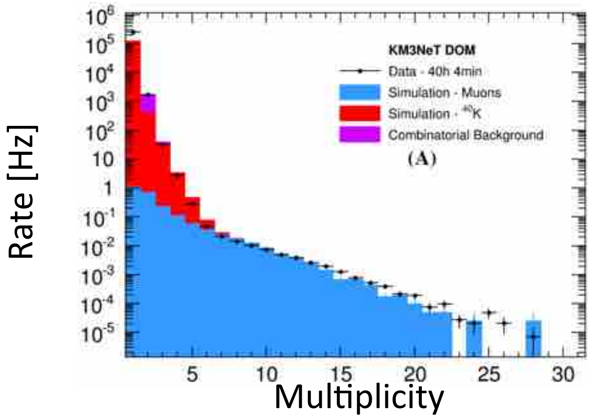


Consistent with flavour-uniform isotropic diffuse flux

$$\Phi_{\nu} = 6.7 \cdot 10^{-18} \left(\frac{E}{100\ \mathrm{TeV}} \right)^{-2.5} \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

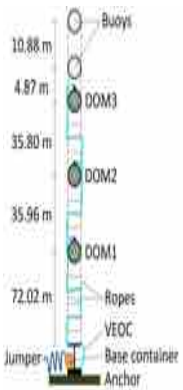
Prototypes

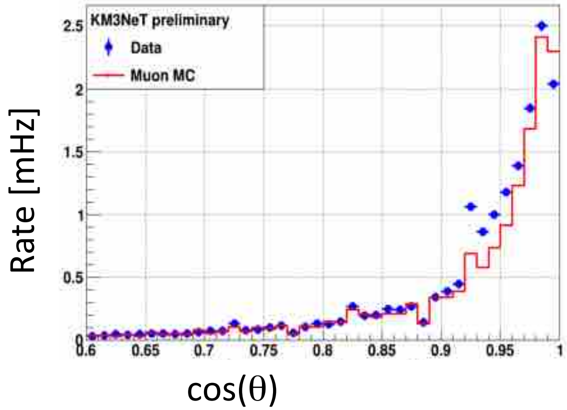
1) Optical Module deployed at Antares, April 2013 (2500 m)



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

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



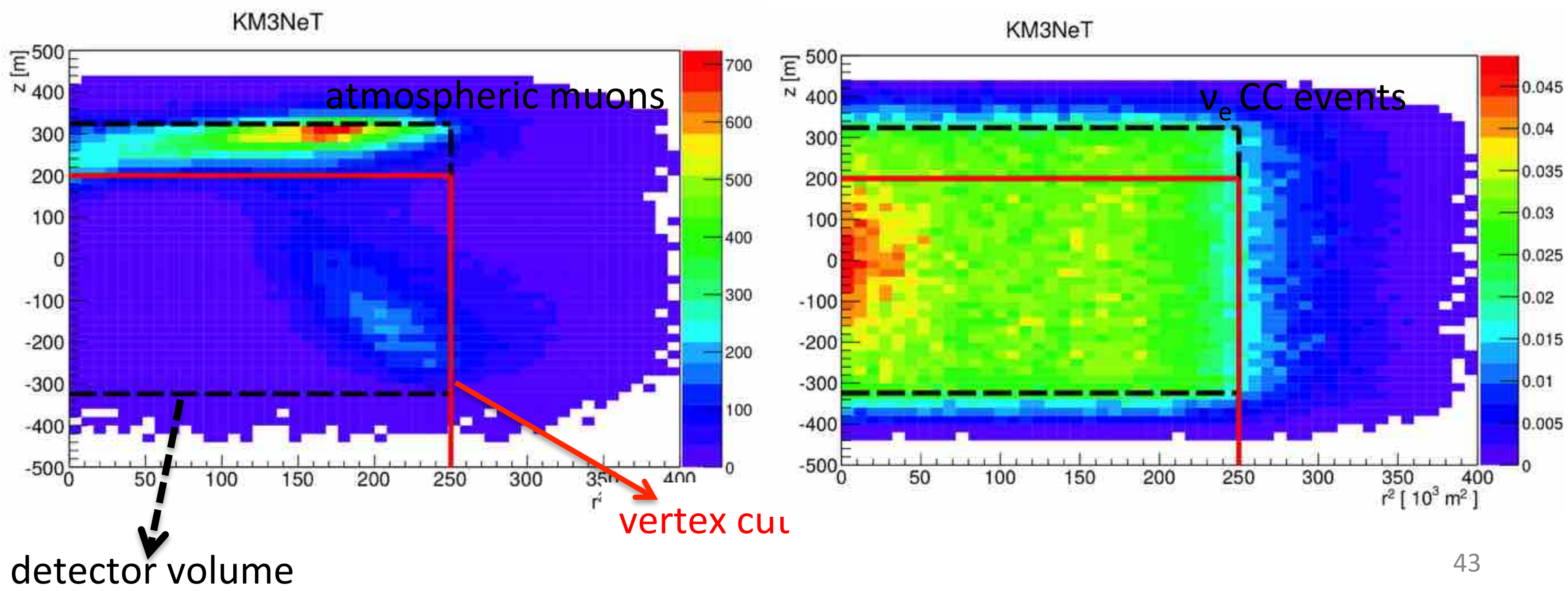


Eur. Phys. J. C (2016) 76:54

Diffuse flux: cascade event selection

All neutrino flavour MC simulation and 3 years of live time for high energy atmospheric muons

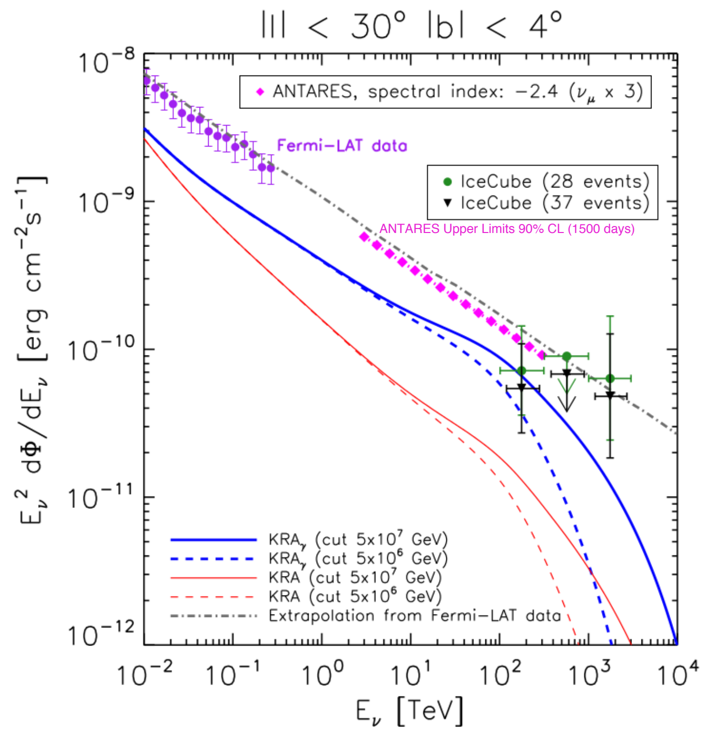
- Event pre-selection: reject most of the atmospheric muons on the reconstructed cascade vertex
  - **Online triggering**: ≥ 5 coincidences between PMTs in the same OM in Δt=10ns
  - **Vertex cut**: cut on the position of the reconstructed vertex to get rid of atmospheric muons (z<200m AND r<500m)
  - **Energy cut**: cut on the total ToT of the event (ToT>12 μs)
- Full sky analysis based on BDT and Max. likelihood.

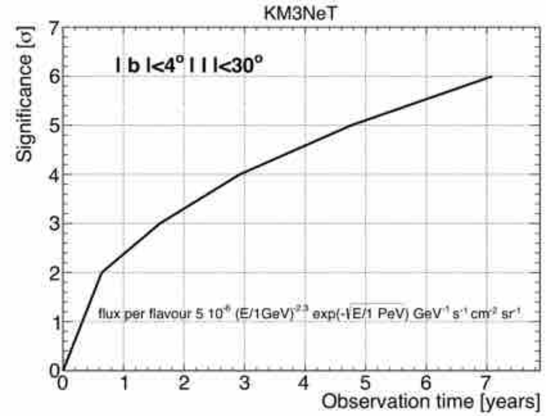


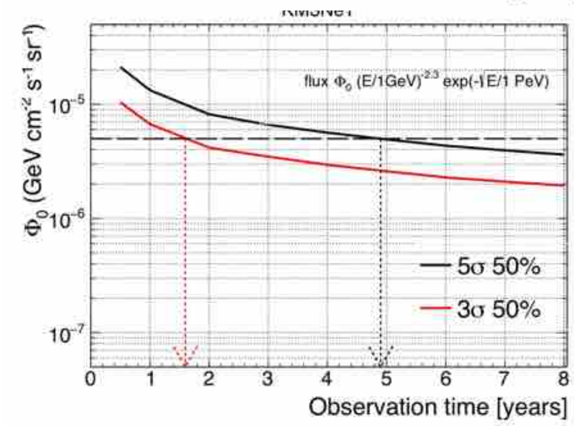
Diffuse flux from the galactic plane

ARCA performance to a flux from a region of the Galactic Plane near the Galactic Center
Evaluation of the neutrino flux based on a radially-dependent cosmic-ray transport properties

D. Gaggero et al., proceedings ICRC2015



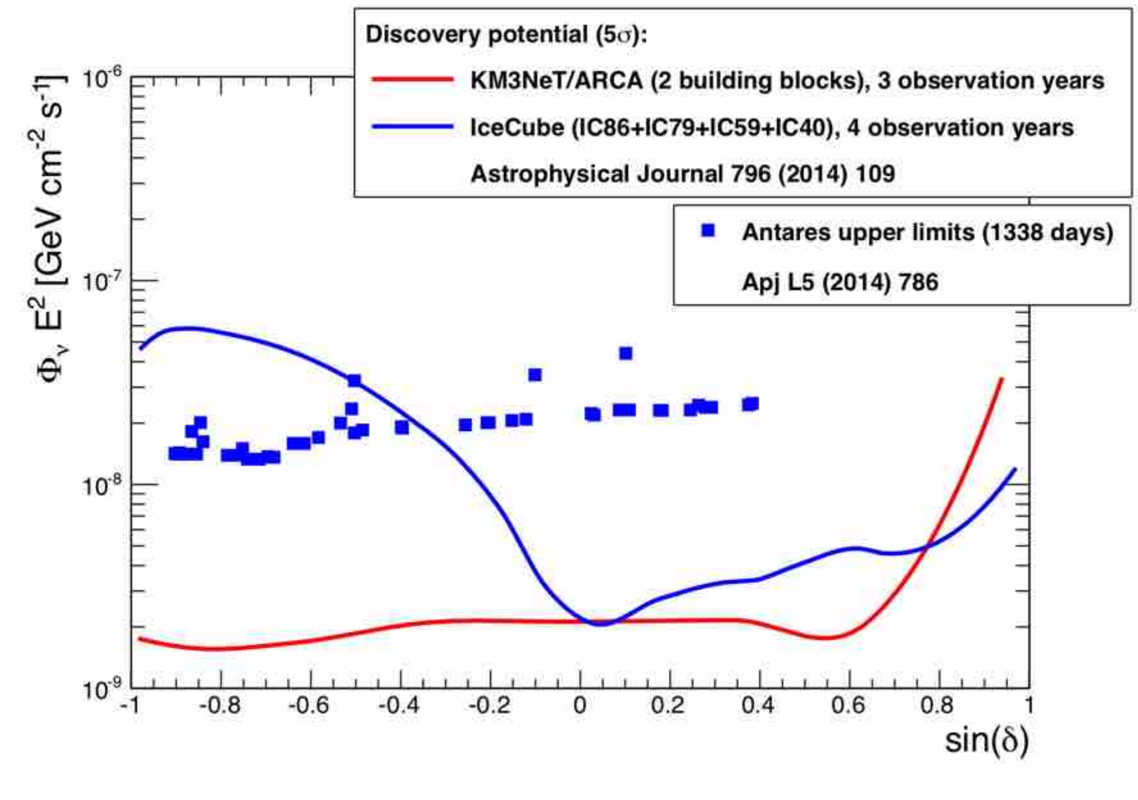




Discovery at 5σ significance (50% probability) in about 5 years

E^{-2} sources spectra

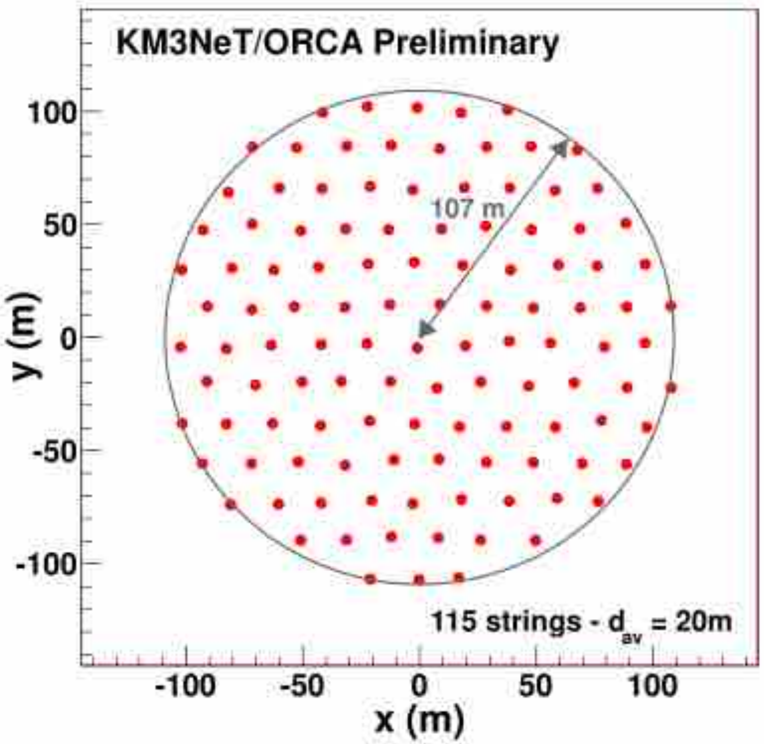
ARCA discovery potential for E^{-2} sources



Better sensitivity (for equivalent exposure) and better sky coverage than IceCube

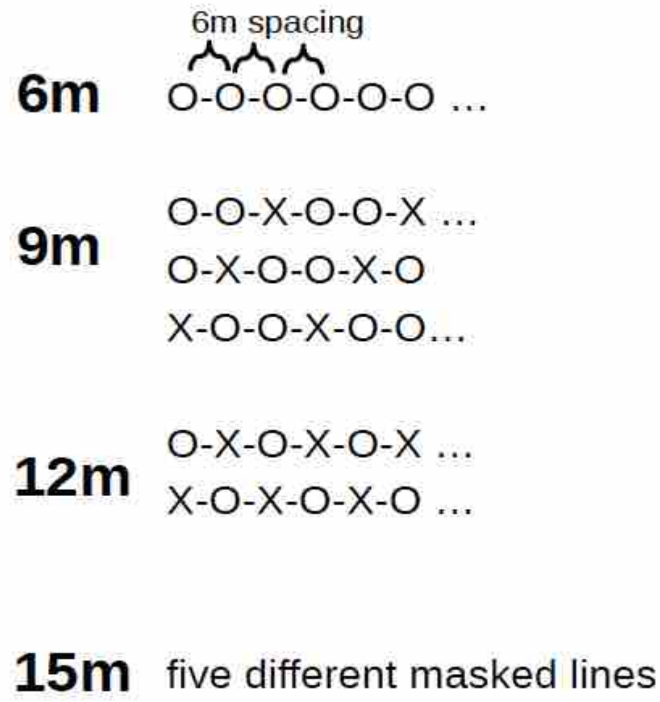
ORCA Simulations

Simulations are performed for this new configuration



115 lines, 20m spaced,
18 OM/line 6m spaced default
Instrumented volume ~3.8 Mt, 2070 OM

Apply OM masking for vertical spacing studies

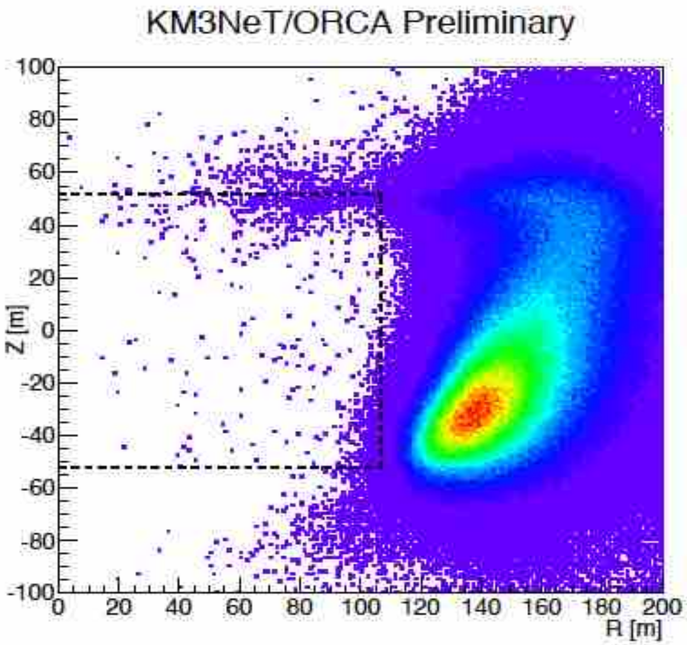


Scale factor 1/1.5/2/2.5

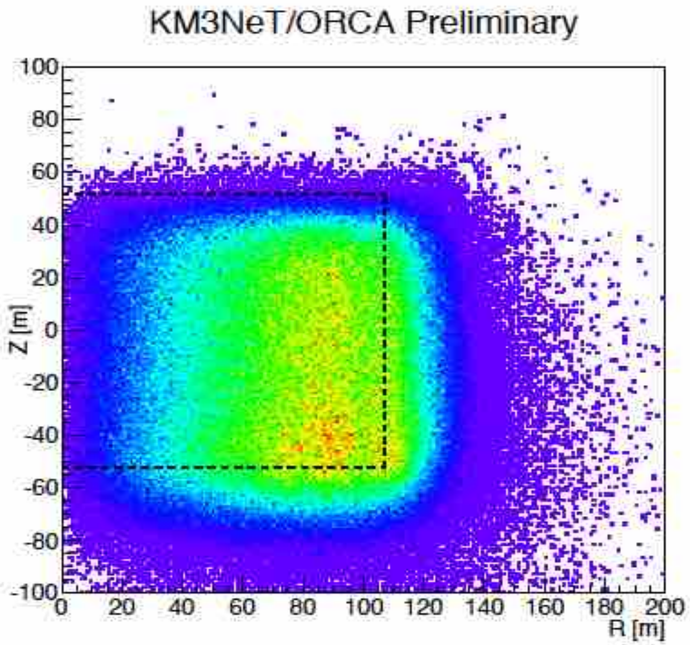
10 kHz/ PMT
500 Hz ^{40}K coincidence

Atmospheric Muon Rejection

- Preselection :
  - upward going reconstructed tracks or showers
  - Topological cuts
- Use of a Random Decision Forest → 1%-3% contamination



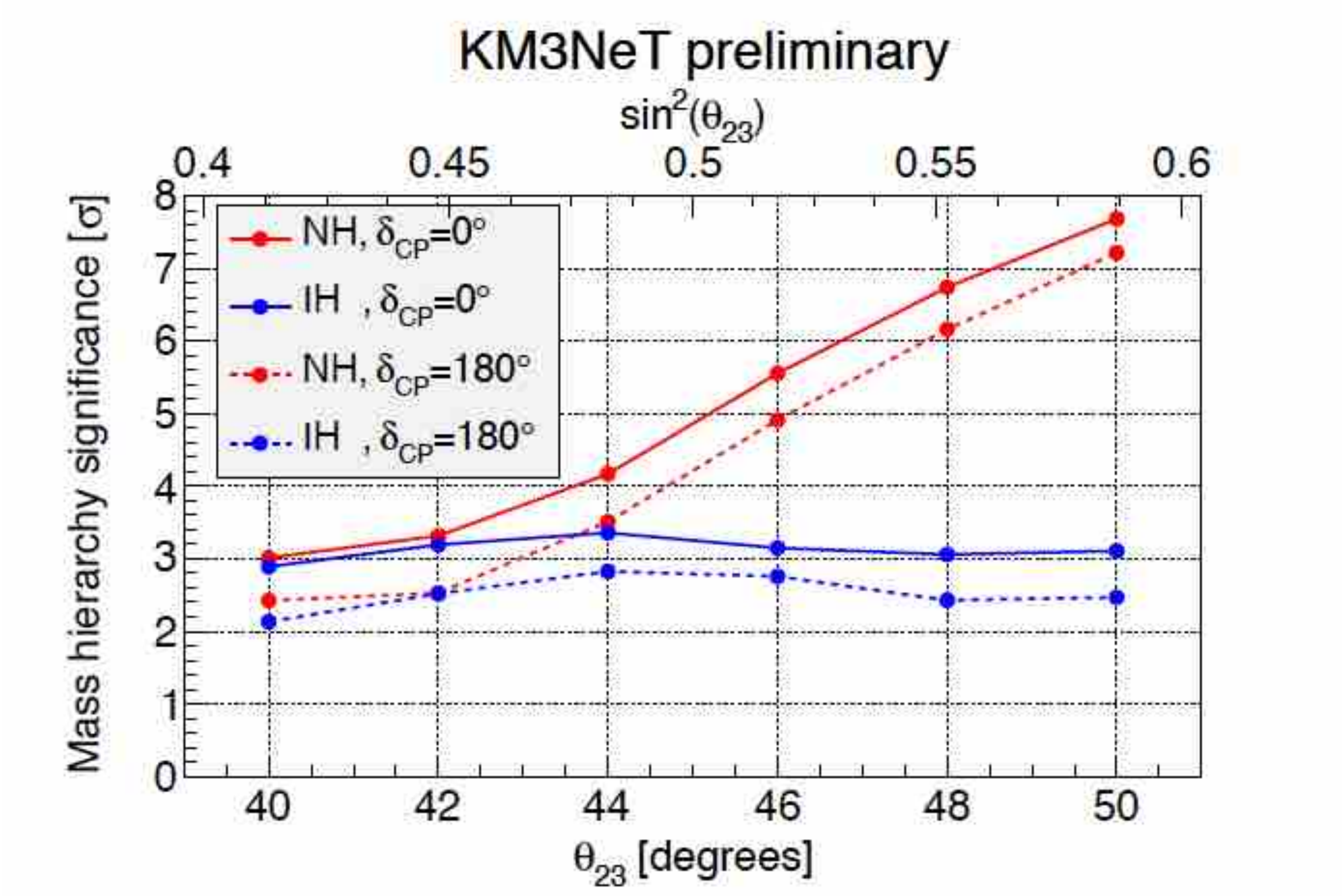
(a) Atmospheric muons



(b) Atmospheric neutrinos - below 20 GeV

Neutrino Mass Hierarchy

- Reachable sensitivity with 3 years data taking as function of θ_{23} and δ_{CP}



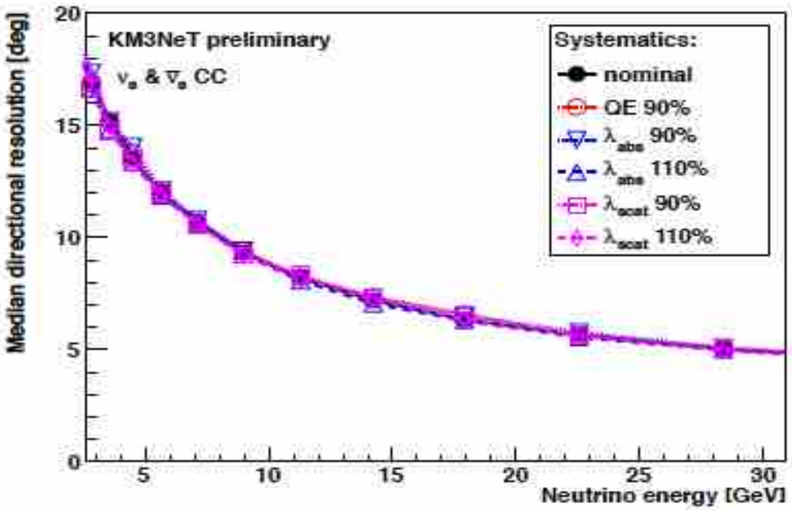
Systematic Effects

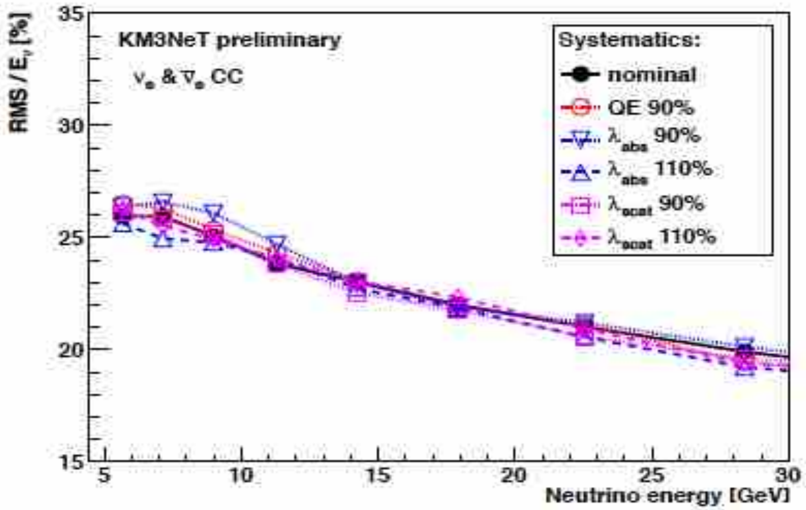
- Oscillation parameters fitted in conjunction with neutrino mass hierarchy
- Various Nuisance parameters are left free as well
- Global fit of 8 to 9 parameters

parameter	*true value distr.*	*initial value distr.*	*treatment*	*prior*
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
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

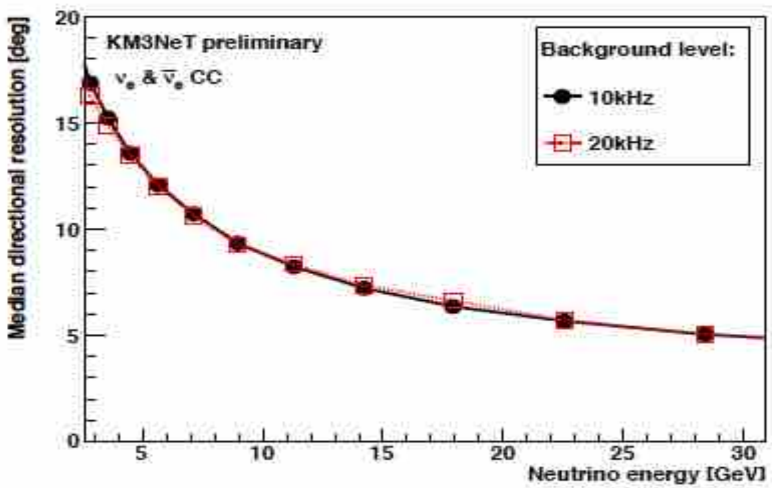
Additional Systematics Studies

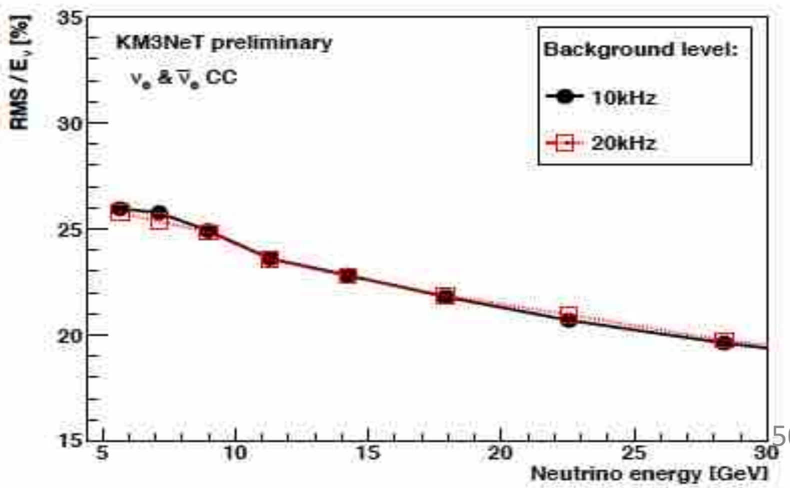
- QE of PMTs, absorption/scattering length → tiny effect





- Optical background [10 kHz conservative, 20 kHz unrealistic]





Simple χ^2 Analysis

- 9m spacing achieves best sensitivity