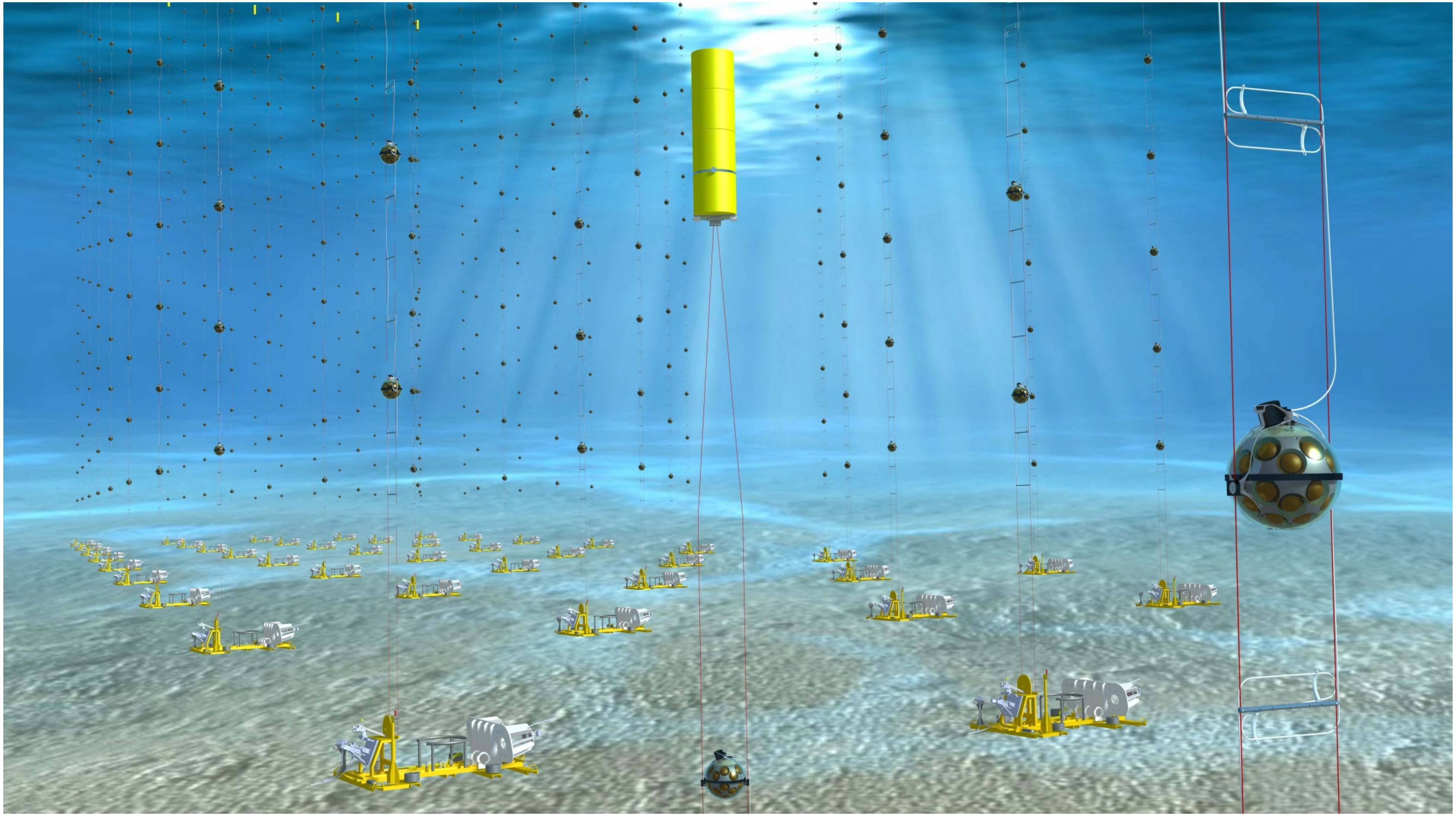
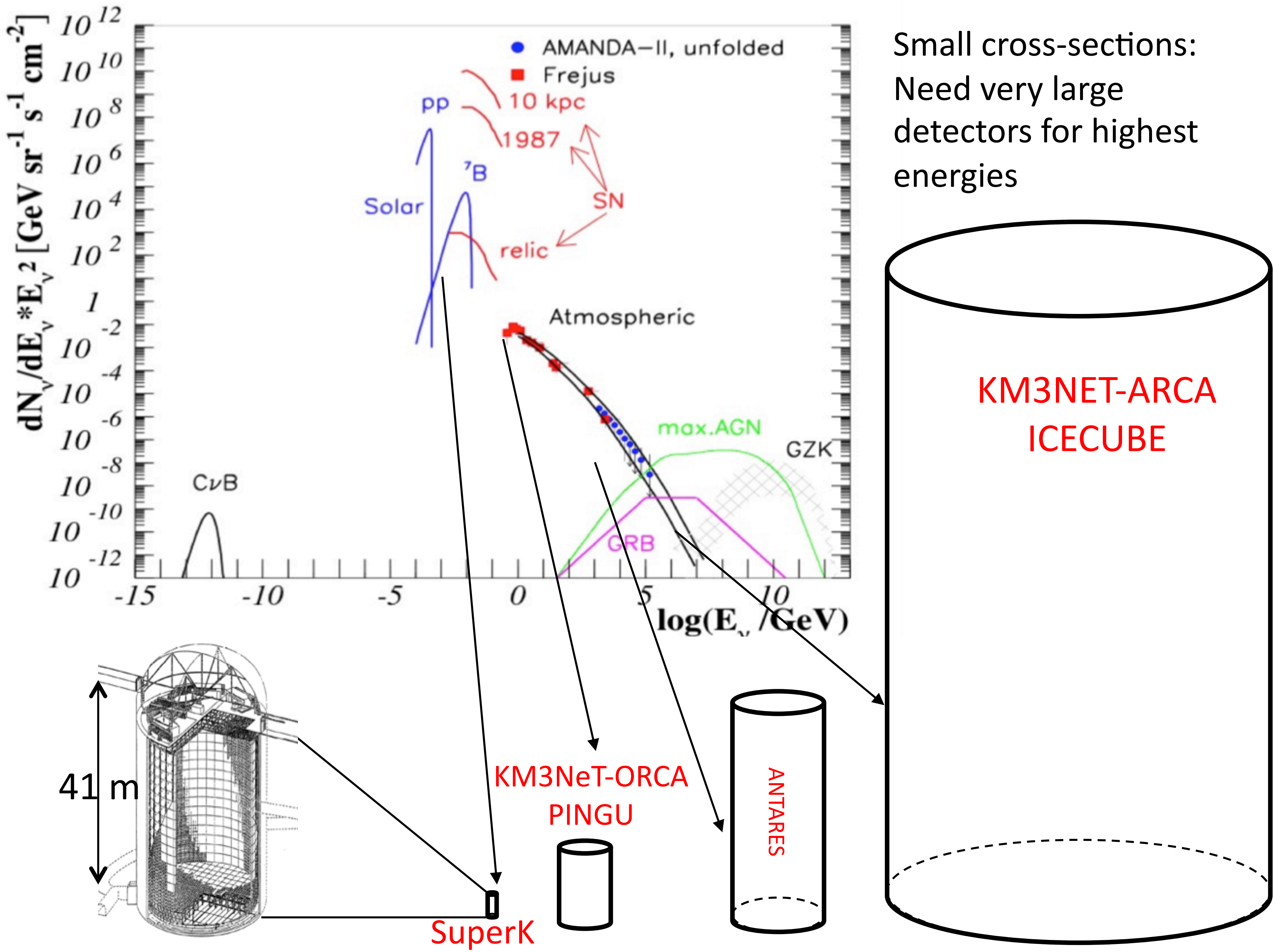
KM3NeT ARCA/ORCA

(Astroparticle and Oscillation Research in the Abyss)



Neutrinos From MeV to PeV

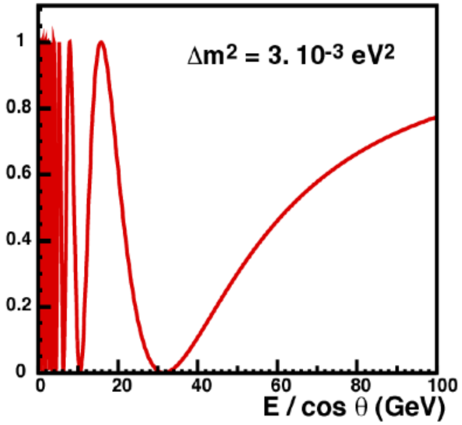
Small cross-sections:
Need very large detectors for highest energies

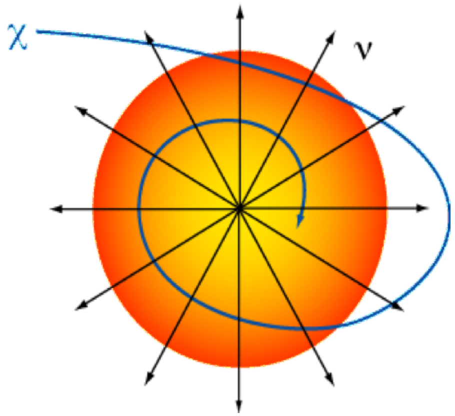


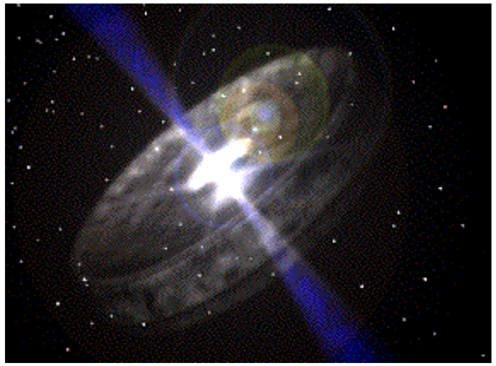
Neutrino telescopes: science scope

2012-3: Two breaking news

- IceCube discovered extra-terrestrial neutrinos
- DayaBay measured the oscillation angle theta13 (large value)







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

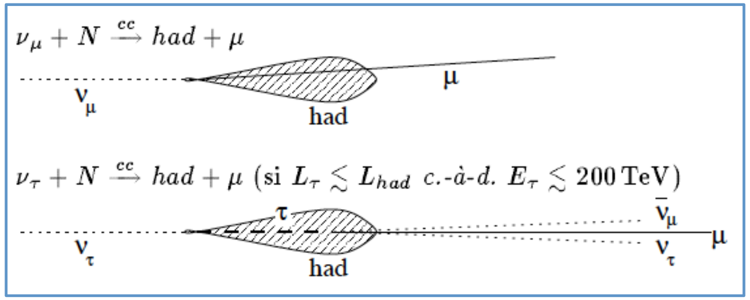
ν from extra-terrestrial sources

Origin and production mechanism of HE CR

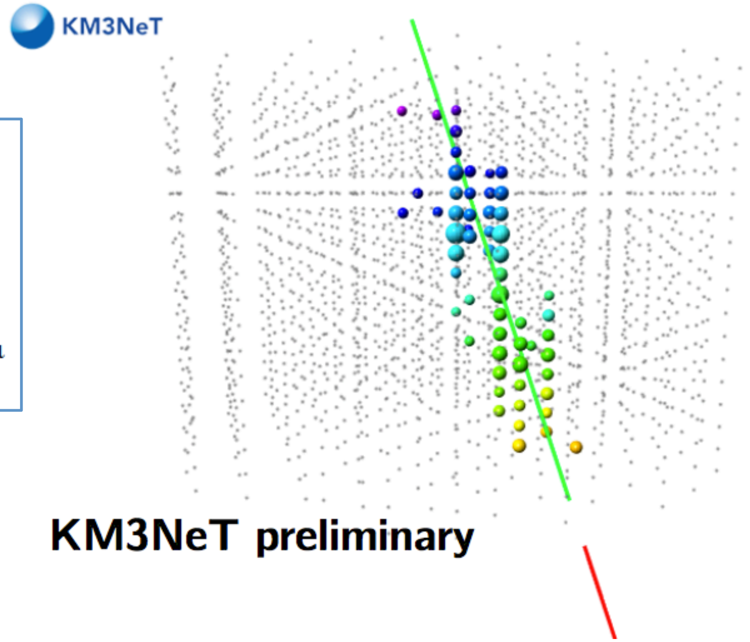
oceanography, biology, seismology,…

Event Topologies

Track-like



Track-like contains both a cascade and one track

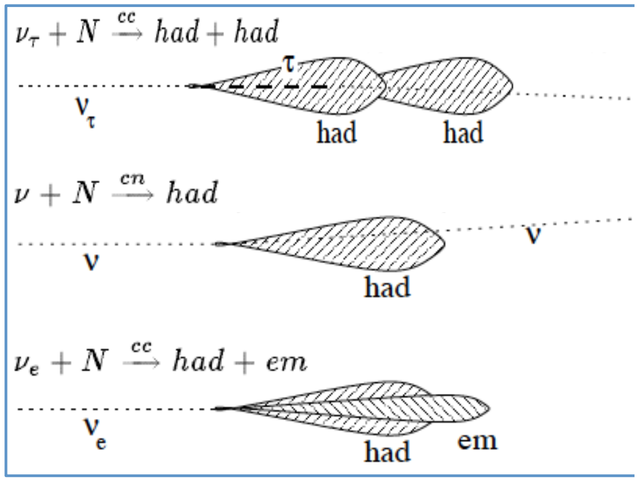


Muon track from CC muon neutrinos

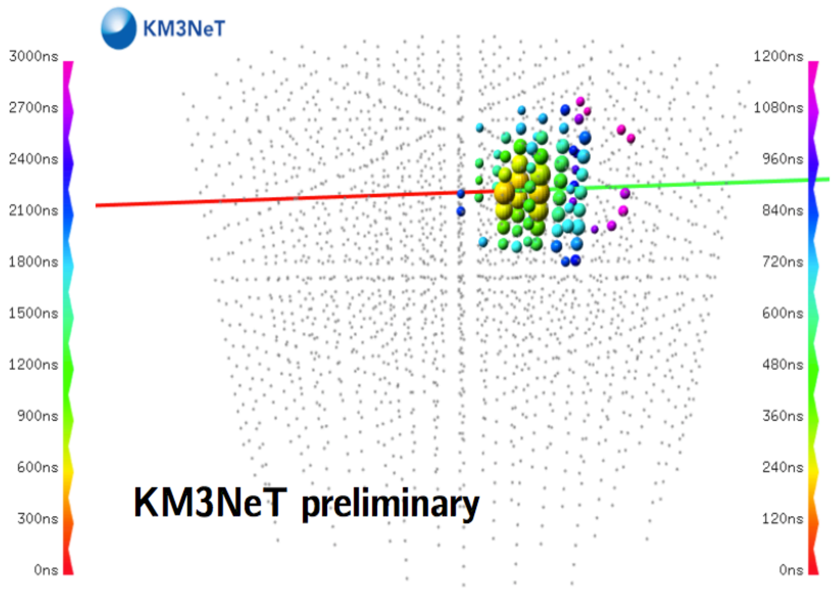
Angular resolution 0.5°/0.1° for ice/water

dE/dx resolution factor 2-3

Not to scale Shower-like



No track is identified



CC electron/tau and NC all flavour

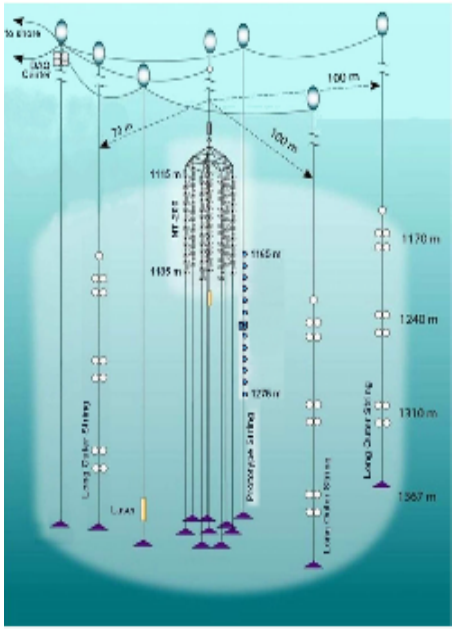
80% of all nu interactions

Angular resolution 10°/1° at 100 TeV for ice/water

Energy resolution ~ 10%

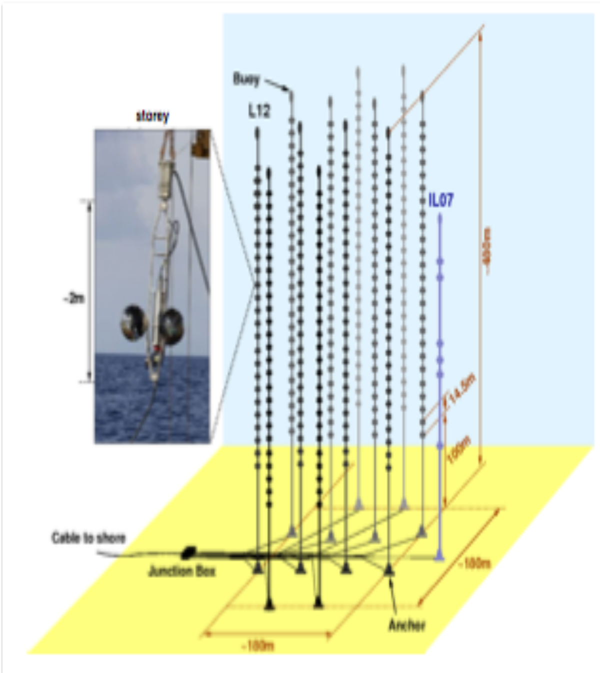
Current Neutrino Telescopes

NT-200+



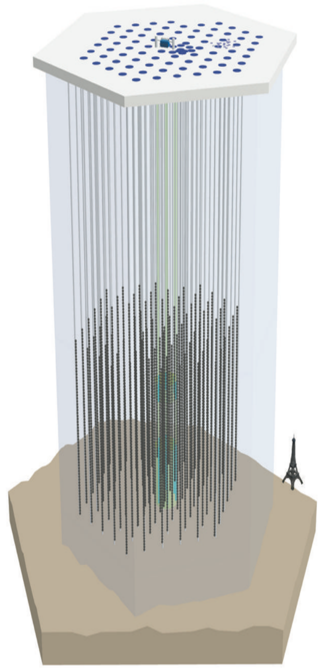
Lake Baikal
1/2000 km3
228 PMTs

Antares



Mediterranean Sea
1/100 km3
885 PMTs

IceCube



South Pole glacier
1 km3
5160 PMTs

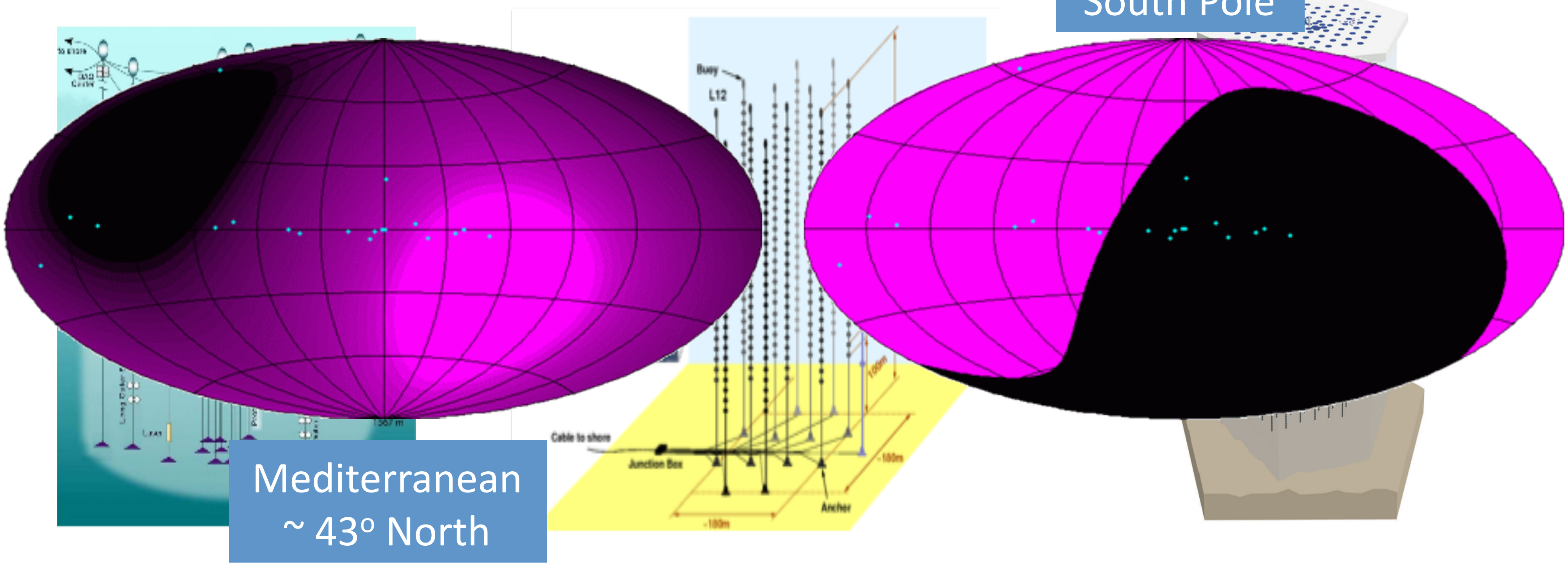
Larger, sparser

Current Neutrino Telescopes

NT-200+

Antares

IceCube



Lake Baikal
1/2000 km3
228 PMTs

Mediterranean Sea
1/100 km3
885 PMTs

South Pole glacier
1 km3
5160 PMTs

Larger, sparser

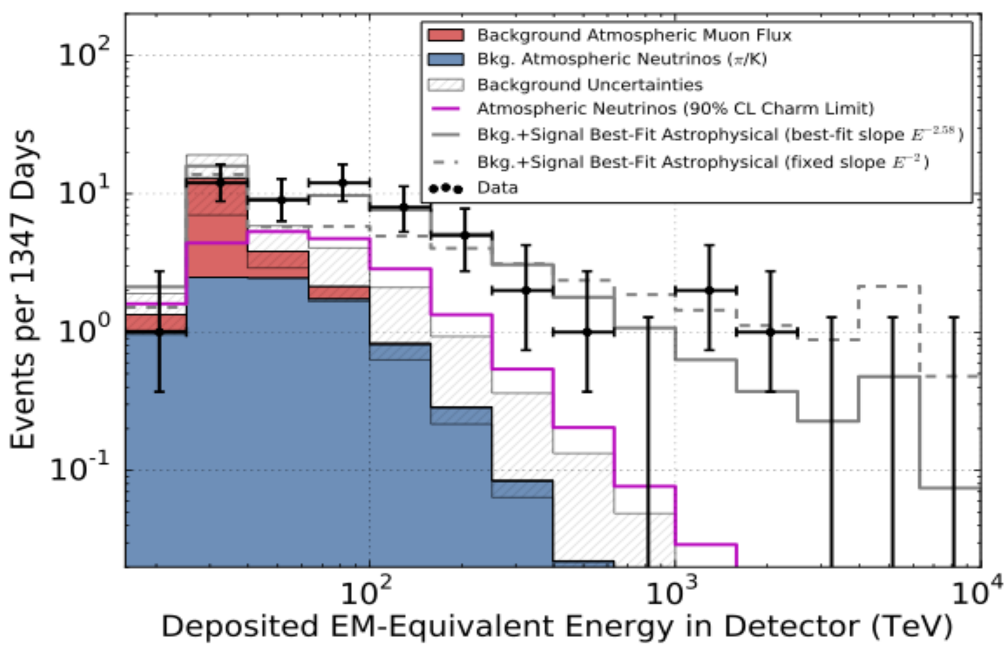
IceCube Diffuse Flux Signal

4 year HESE analysis
ICRC 2015

53 events

5.7 sigma
Ethreshold: 60 TeV

Best fit spectral index: -2.58

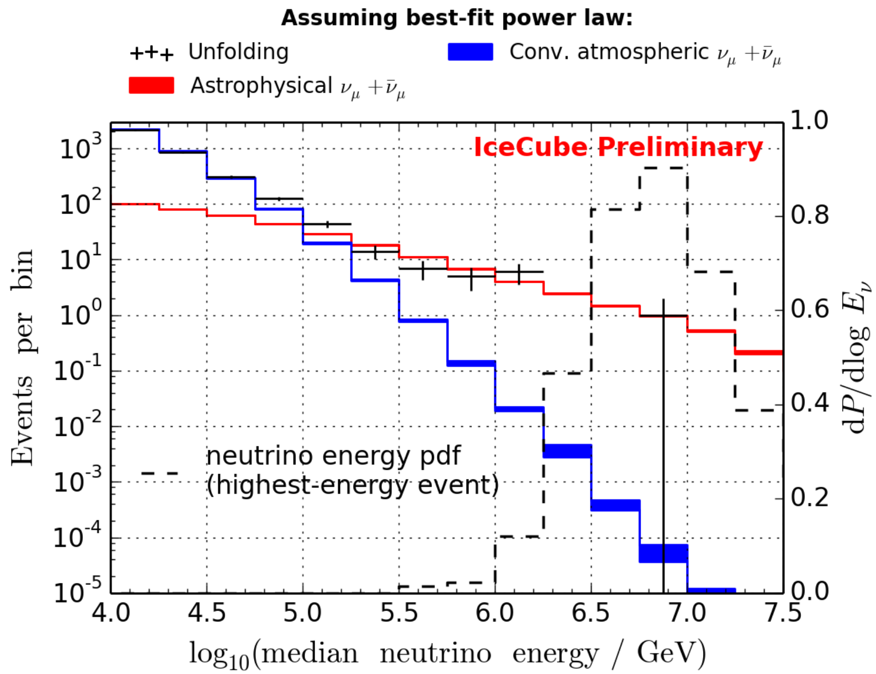


Unfolded upgoing muon spectrum
TEVPA 2015

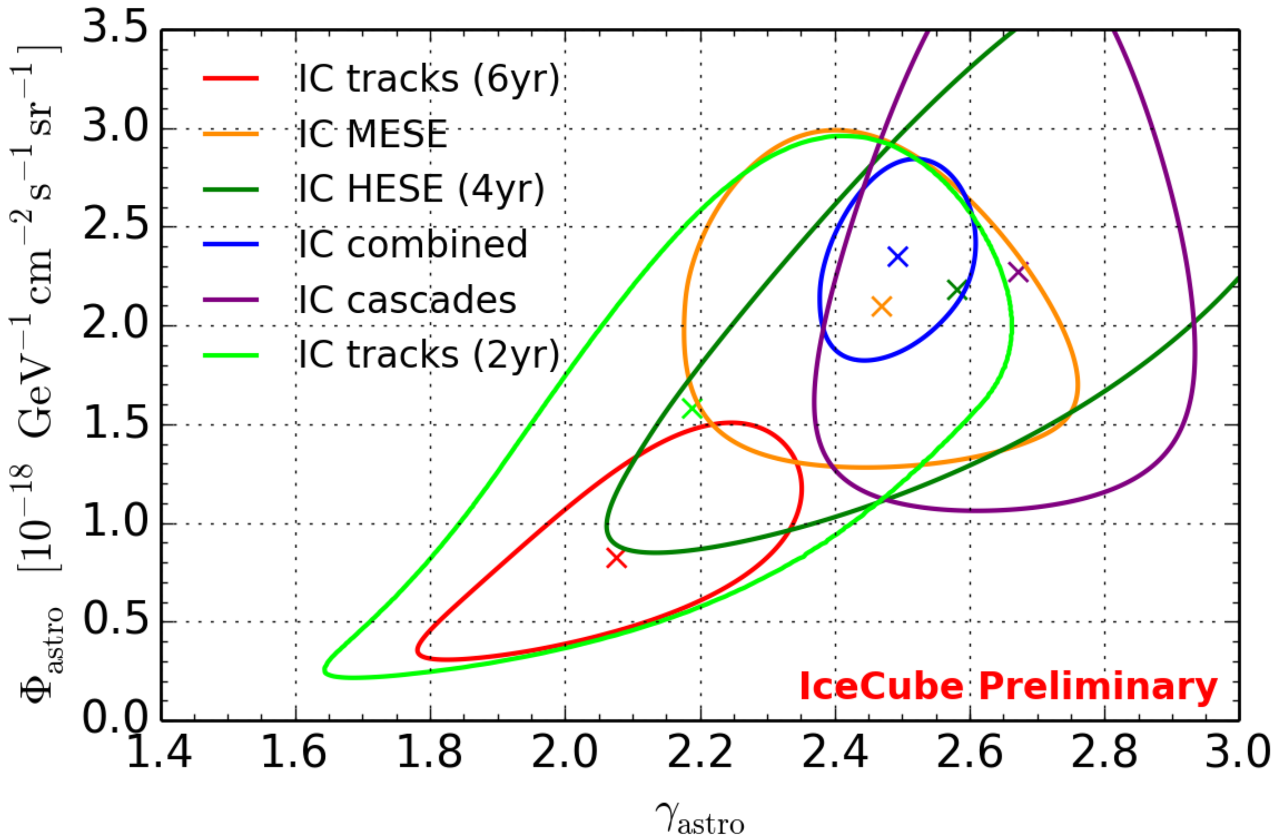
6 yr data

5.9 sigma
Ethreshold: 200 TeV

Best fit spectral index: -2.03+-0.13



Flux Characteristics



90% CL contours

Results of IC tracks(6yr) and IC combined not compatible at > 3.6σ level

Indication of spectral break (different energy thresholds) ??

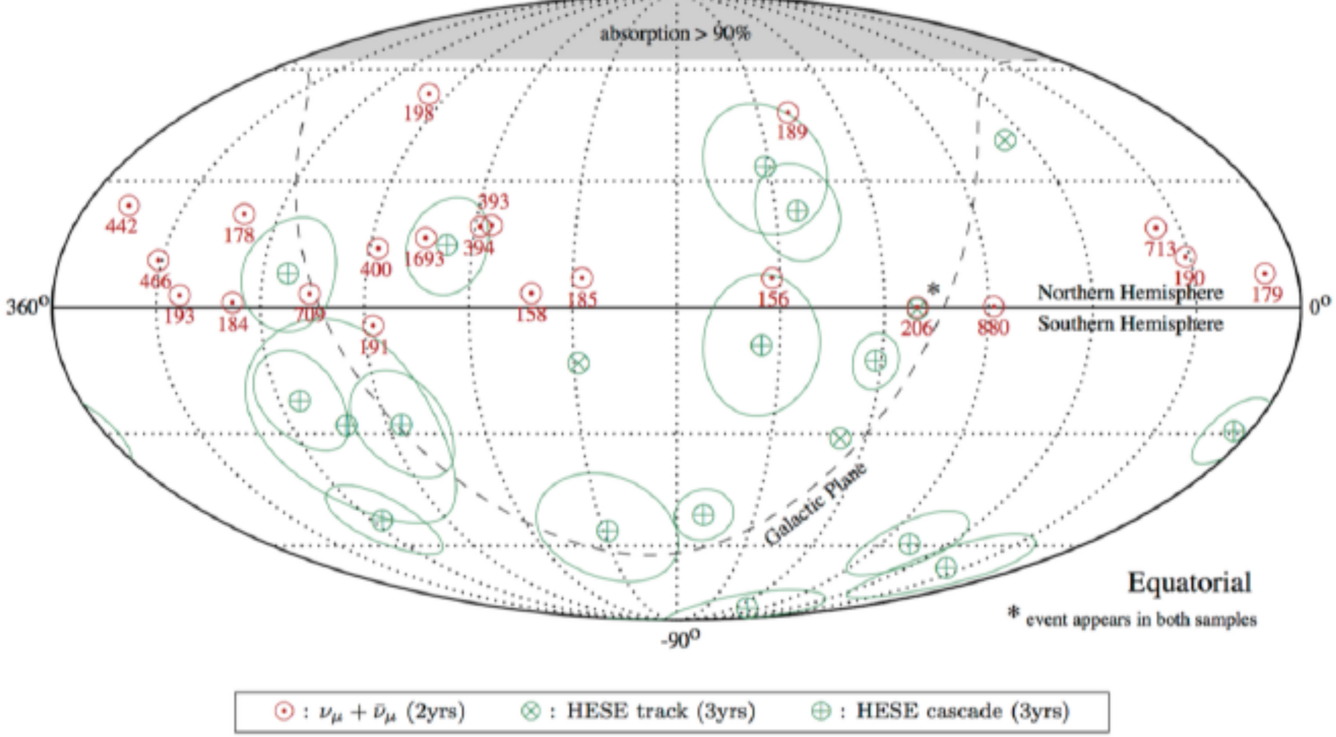
Indication of galactic and extra-galactic contributions (different hemispheres) ??

Origin of Astrophysical Neutrinos?

Only highest energy events are shown.

Most of these events are of astrophysical origin.

http://icecube.wisc.edu/news/view/348



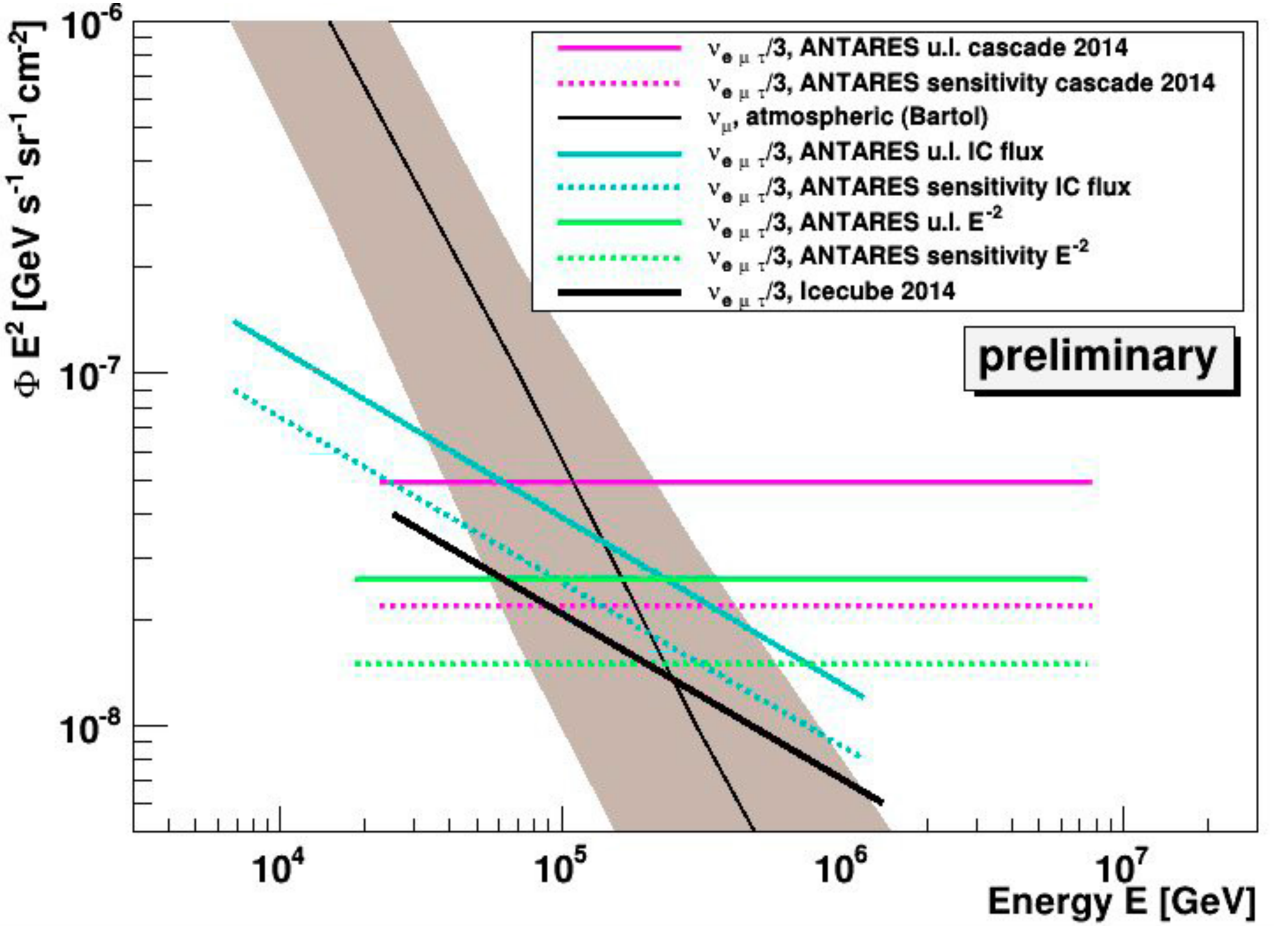
Cascade resolution 10-15° - mainly Southern hemisphere

Muon resolution 0.5° - only Northern hemisphere

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

Indications of Galactic and extra-galactic contributions ??

ANTARES Diffuse flux



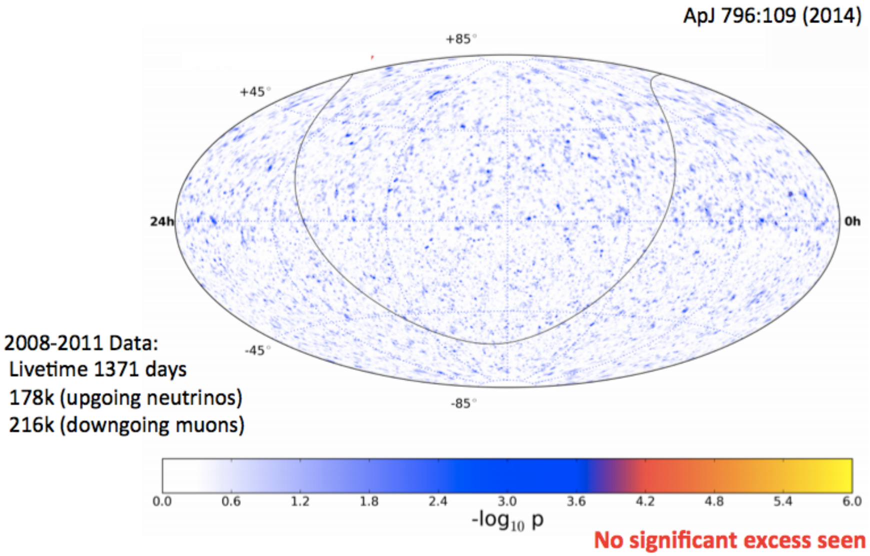
Expected:
9.5 ± 2.5 bkgd
5.0 ± 1.1 IC flux

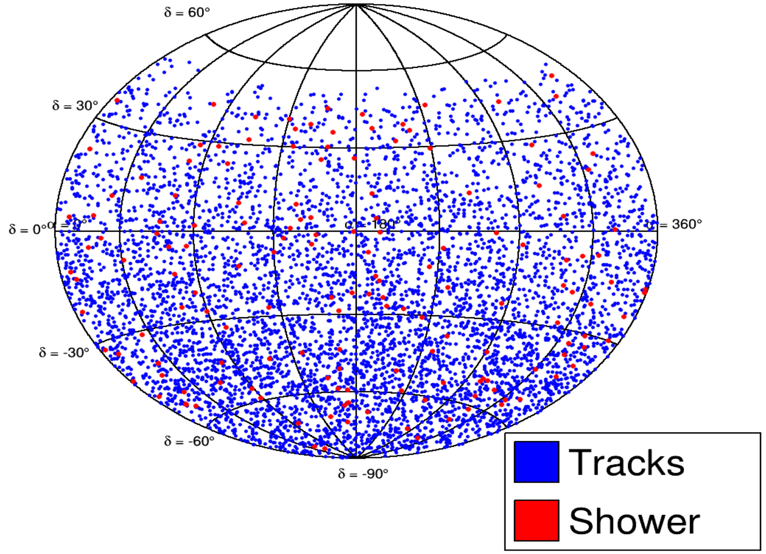
Observed:
12 events

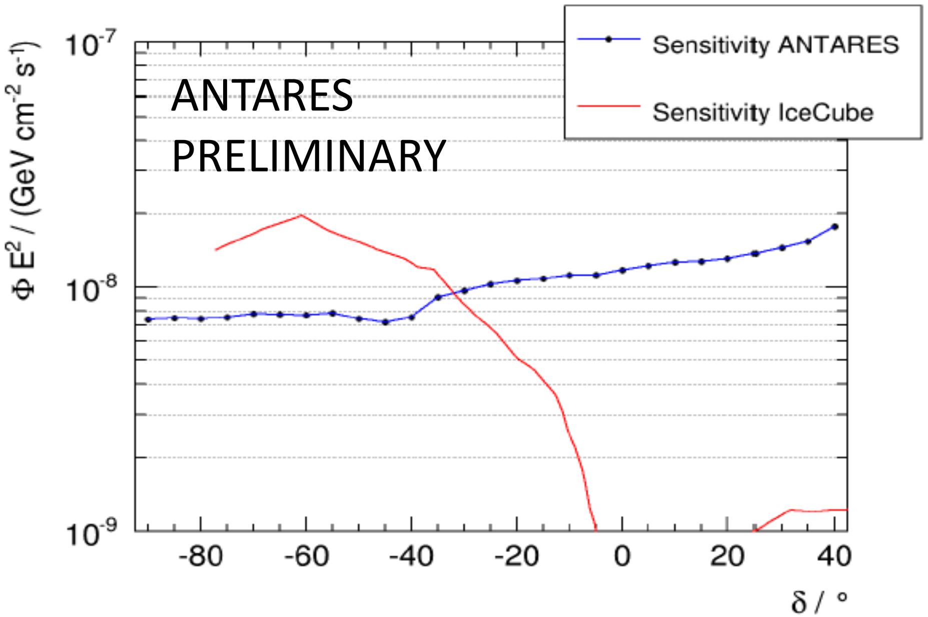
1.75σ excess

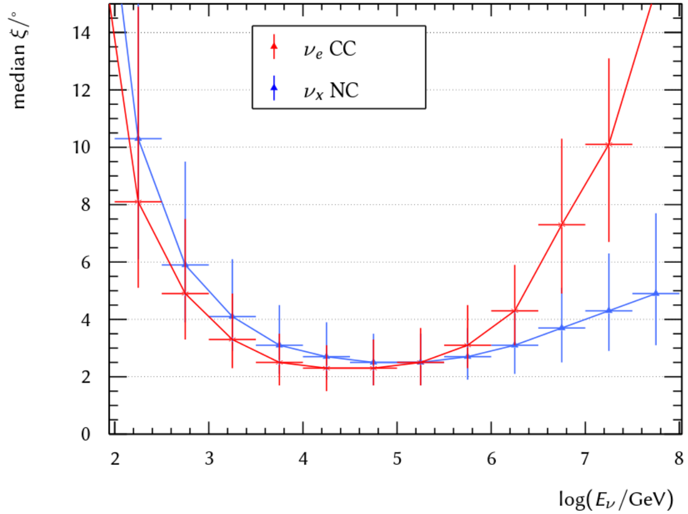
Consistent with bkgd
Consistent with IC

No Point Source Found (yet)







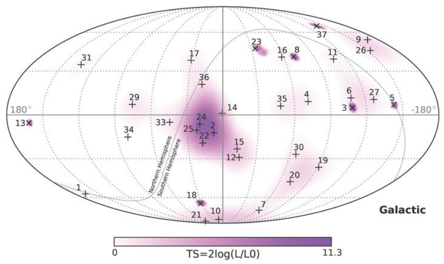


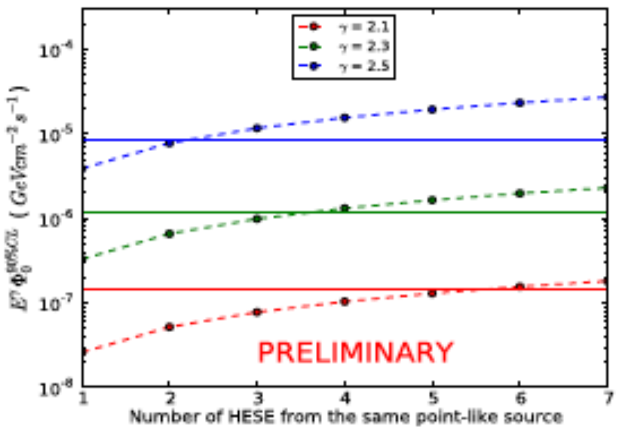
Cascade resolution <4°

30% improvement adding cascades

ANTARES: Some Galactic Searches

IC hot spot

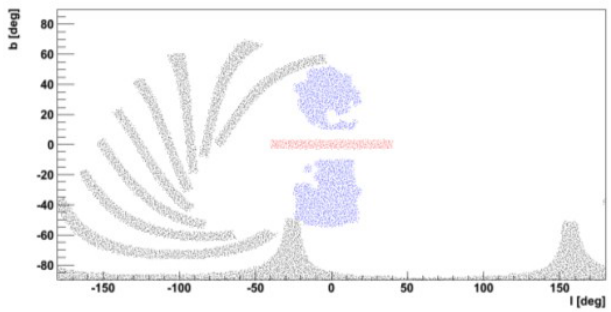


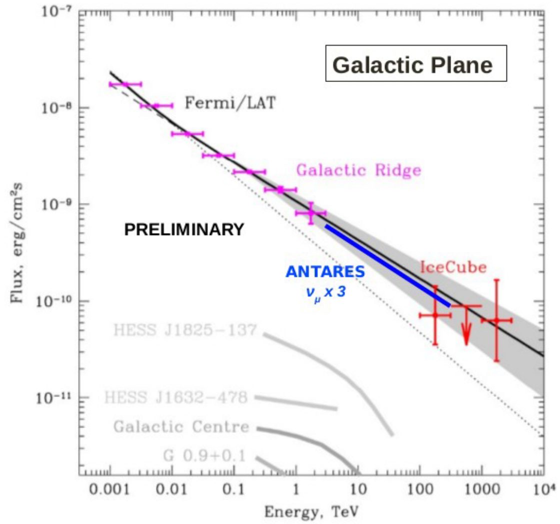


No signifcant cluster found within 20° of IC hotspot

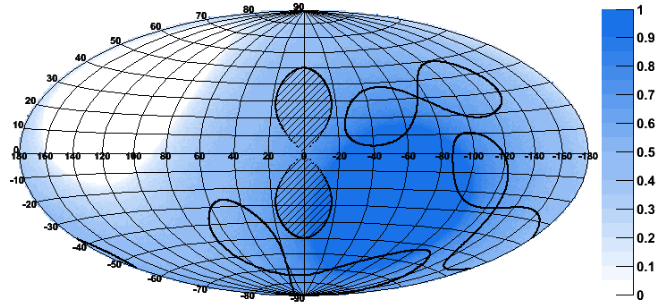
Exclude more than 2 HESE events for index=2.5

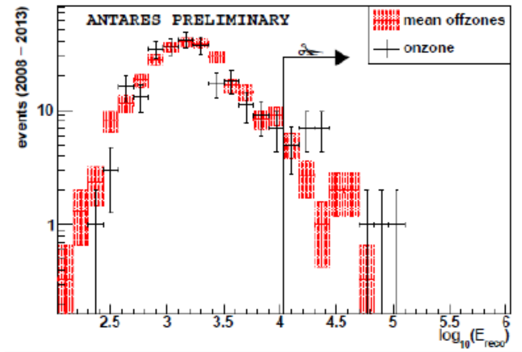
Galactic plane: molecular clouds





Fermi Bubbles



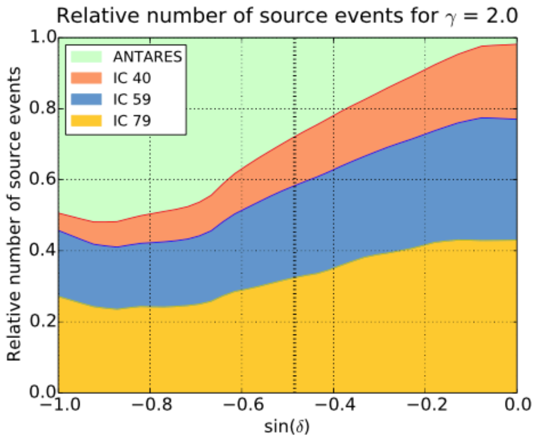


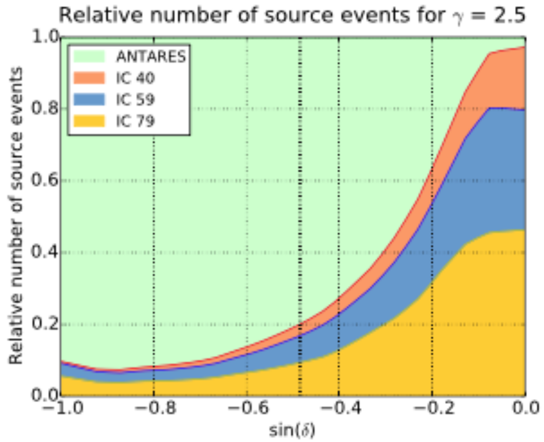
Expected: 12
Observed: 22

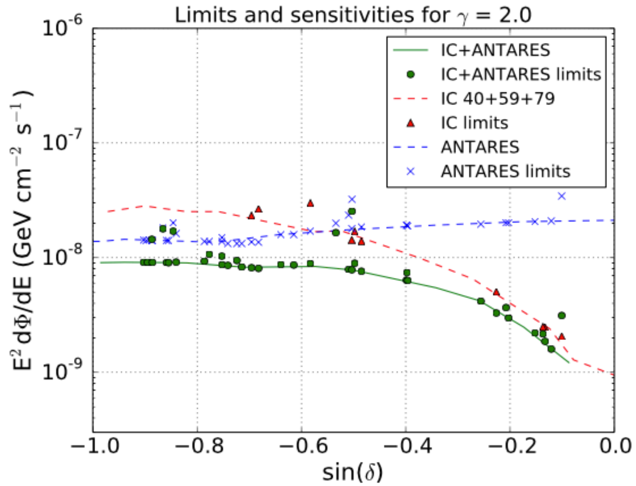
1.9 σ excess

ANTARES: multi-messenger programs

Joint ANTARES/IceCube analysis







* **TAToO:** multi wavelength follow-up of neutrinos

Radio	Visible	X-ray	GeV-ray	TeV-ray	TeV-ray
MWA	TAROT ZADKO MASTER	Swift	Fermi	HESS	HAWC
(12/yr)	(30 alerts/yr)	(6 alerts/yr)	(Offline)	(1+1 alert/yr)	(10 alerts/yr)

\+ advanced Ligo (Virgo)

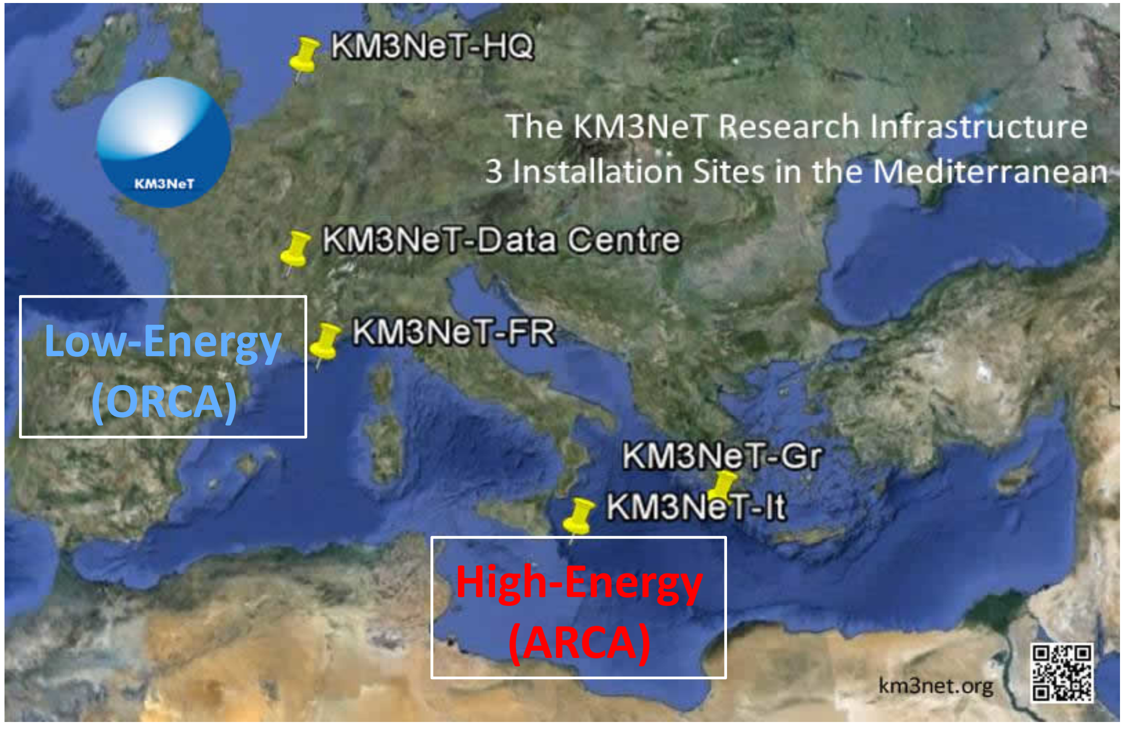
KM3NeT

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 Collaboration

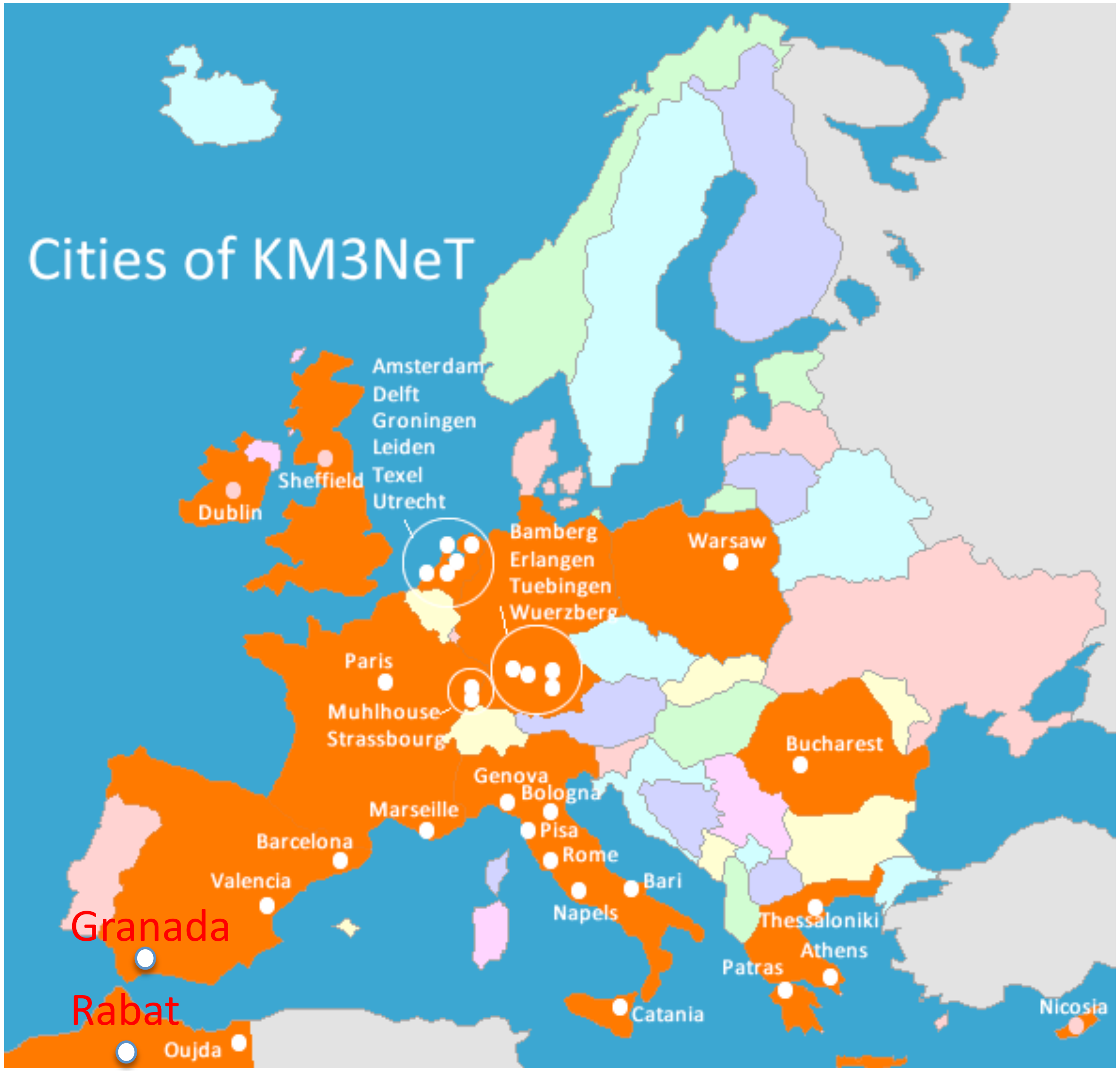
12 Countries
42 Institutes
225 Scientists

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 Technical Design Report¶

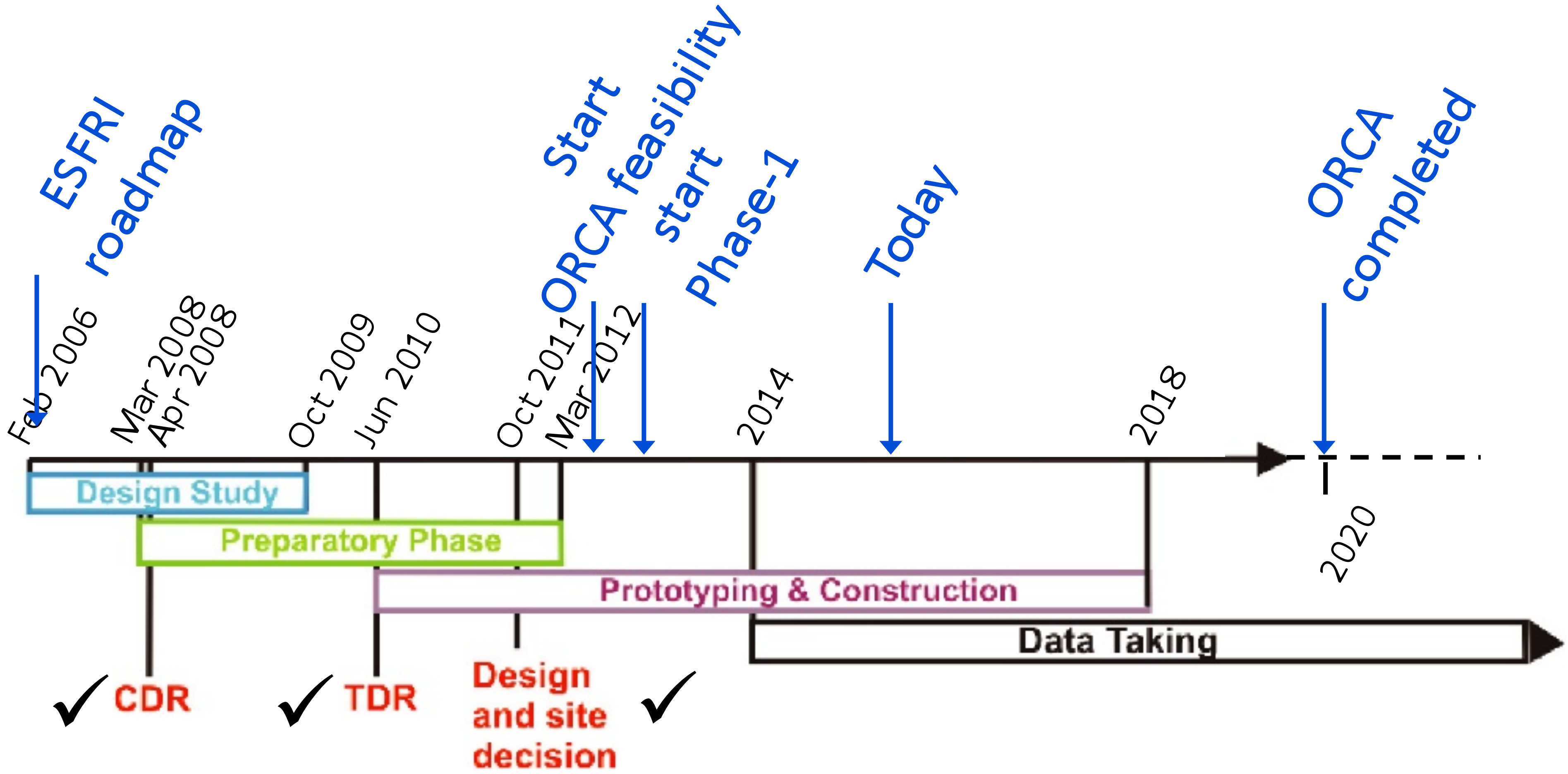
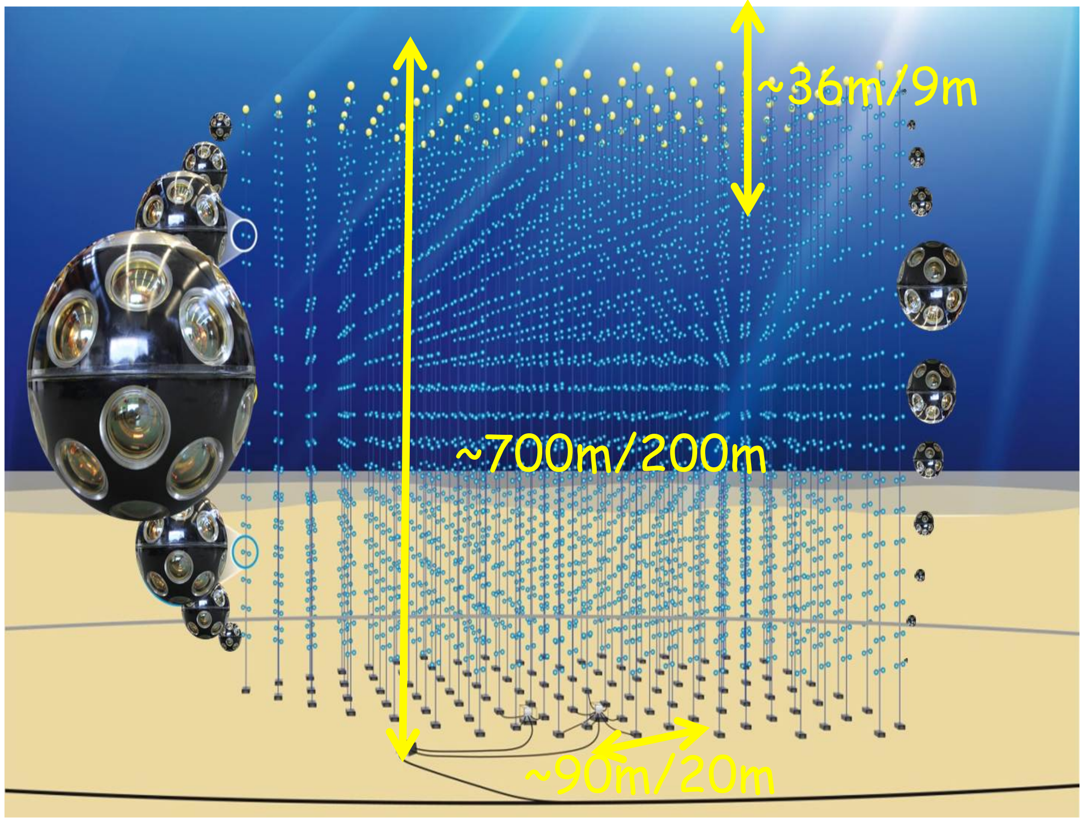
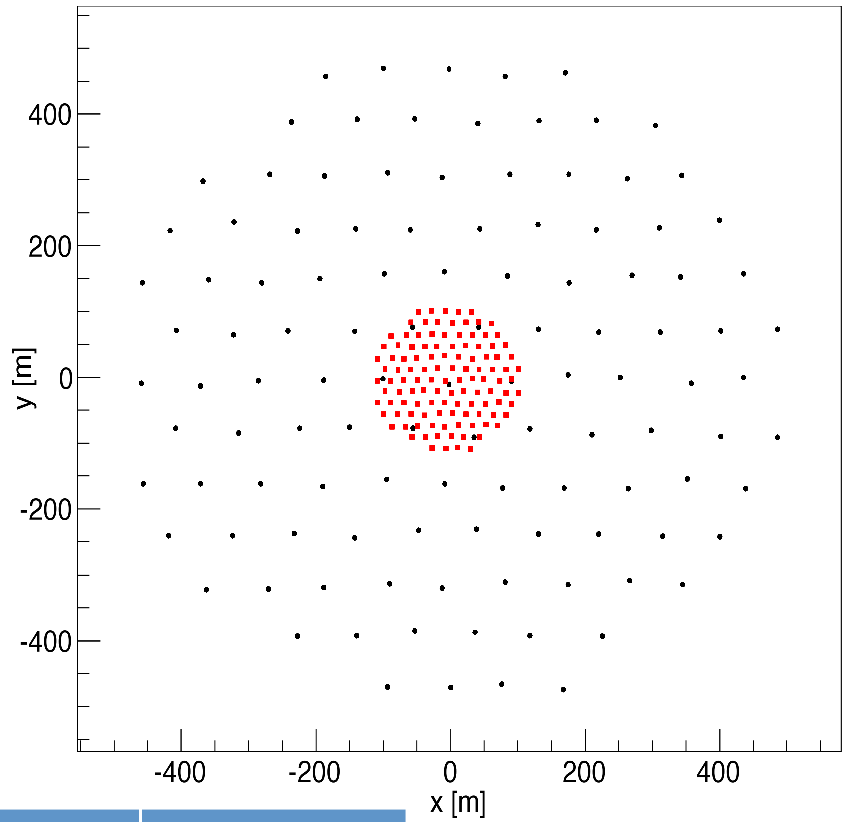


Figure 10-1: Overall time schedule of the KM3NeT project.

¶ Deliverable of EU-funded Design Study.

KM3NeT Building Block (115 strings)



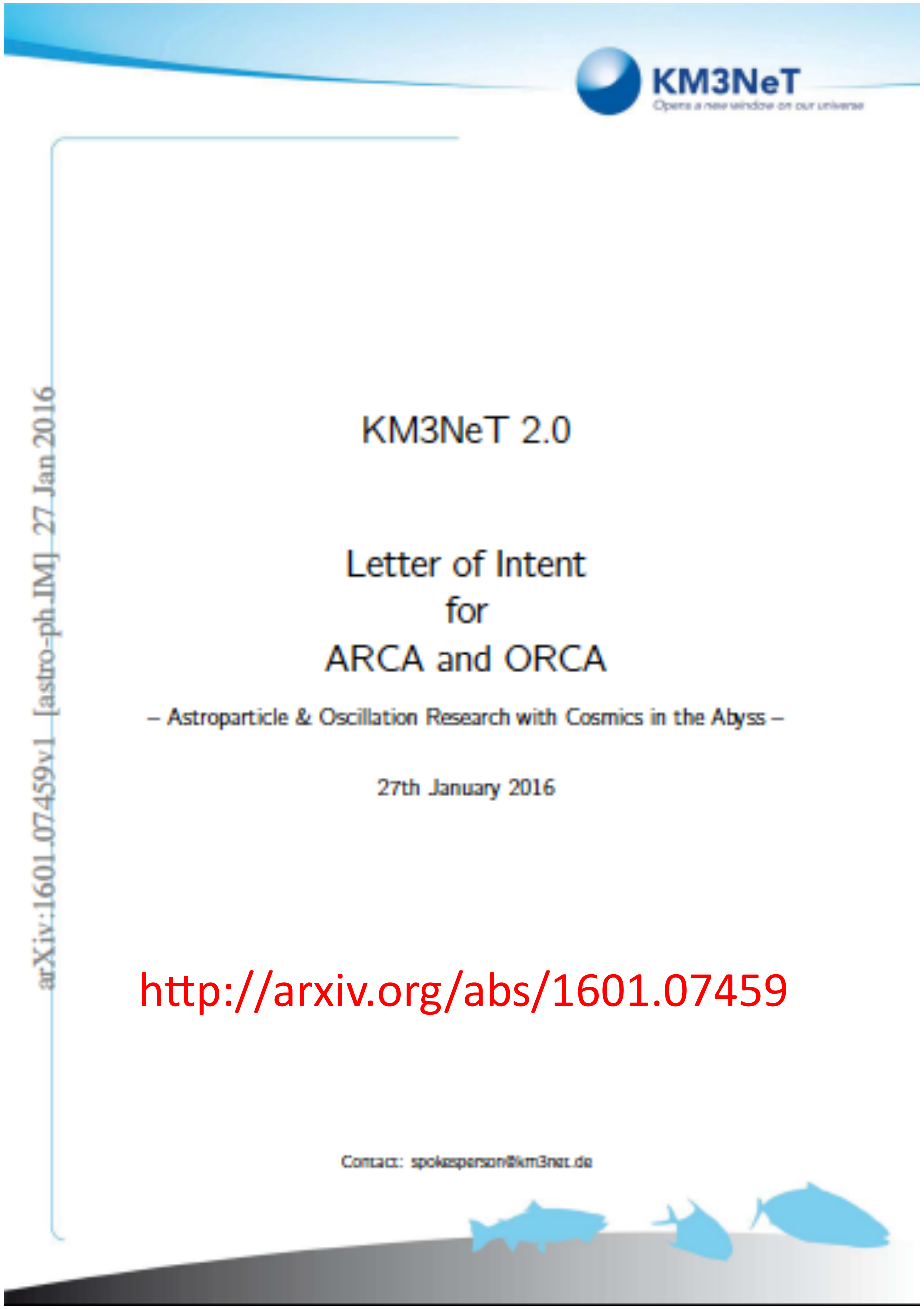


	ARCA	ORCA
Location	Italy	France
String distance (m)	90	20
DOM spacing (m)	36	9
Volume (MTon)	500*2	3.8

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

KM3NeT 2.0: Letter of Intent


KM3NeT
Opens a new window on our universe

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

KM3NeT 2.0

Letter of Intent
for
ARCA and ORCA

– Astroparticle & Oscillation Research with Cosmics in the Abyss –

27th January 2016

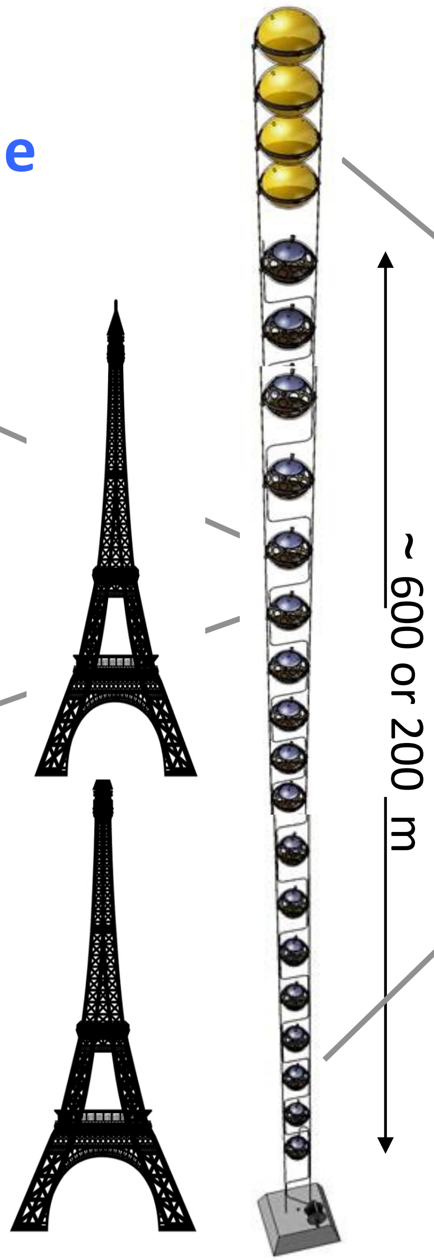
Contact: spokesperson@km3net.de

http://arxiv.org/abs/1601.07459

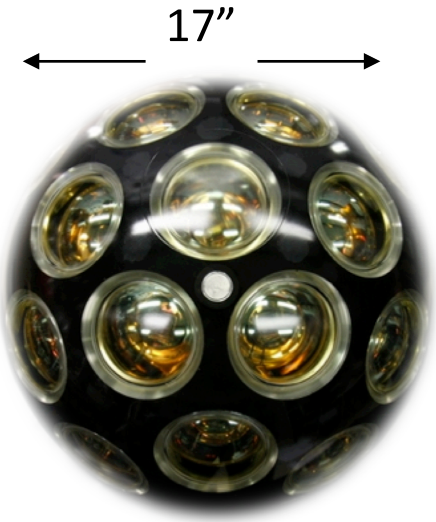
The main objectives of the KM3NeT Collaboration are i) the discovery and subsequent observation of high-energy neutrino sources in the Universe and ii) the determination of the mass hierarchy of neutrinos. These objectives are strongly motivated by two recent important discoveries, namely: 1) The high-energy 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 Design

String

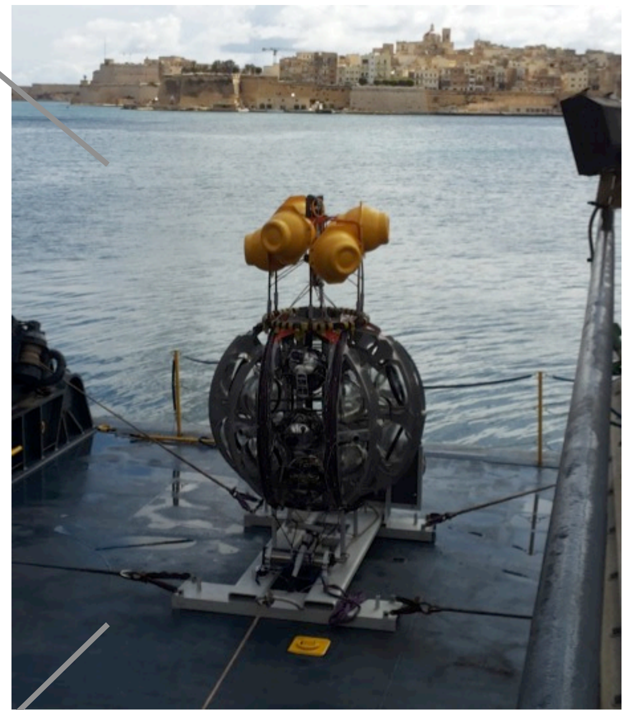


Digital Optical Module



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

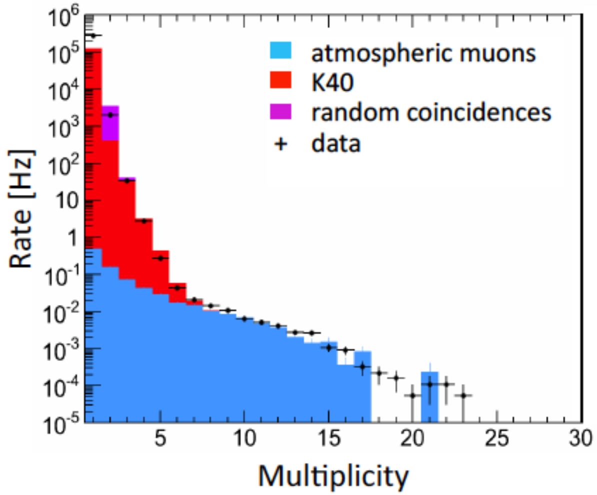
Launcher Vehicle



- Rapid deployment
- Compact
- Autonomous unfurling
- Recoverable

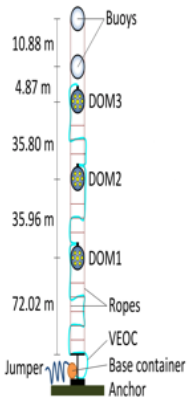
KM3NeT Prototypes

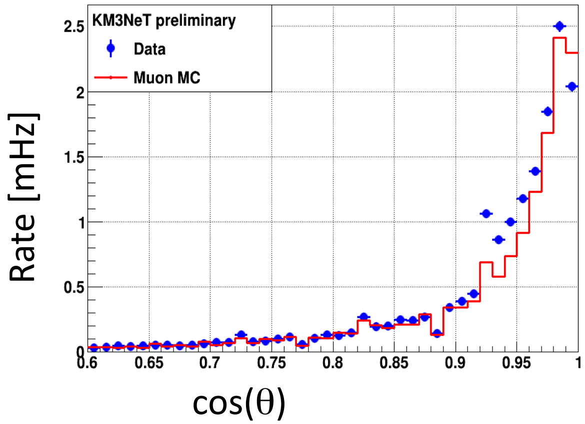
1) Optical Module deployed at Antares, April 2013 (2500 m)



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

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

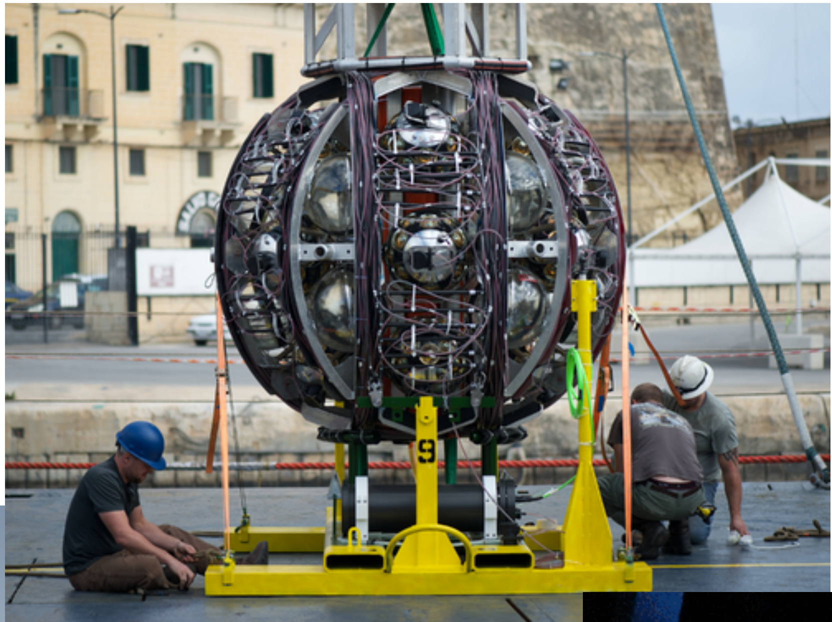


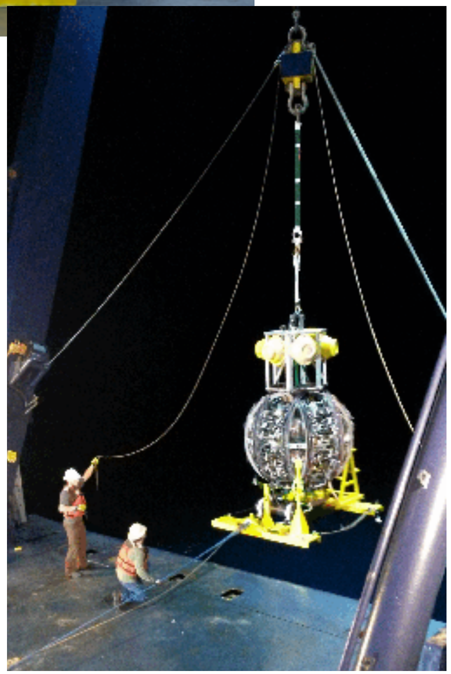


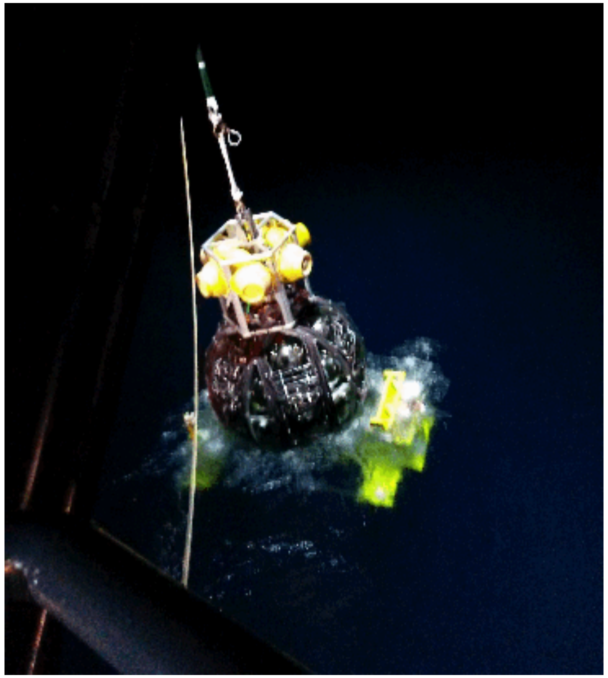
arXiv:1510.01561
Accepted by
Eur. Phys. J. C

The first KM3NeT String: construction

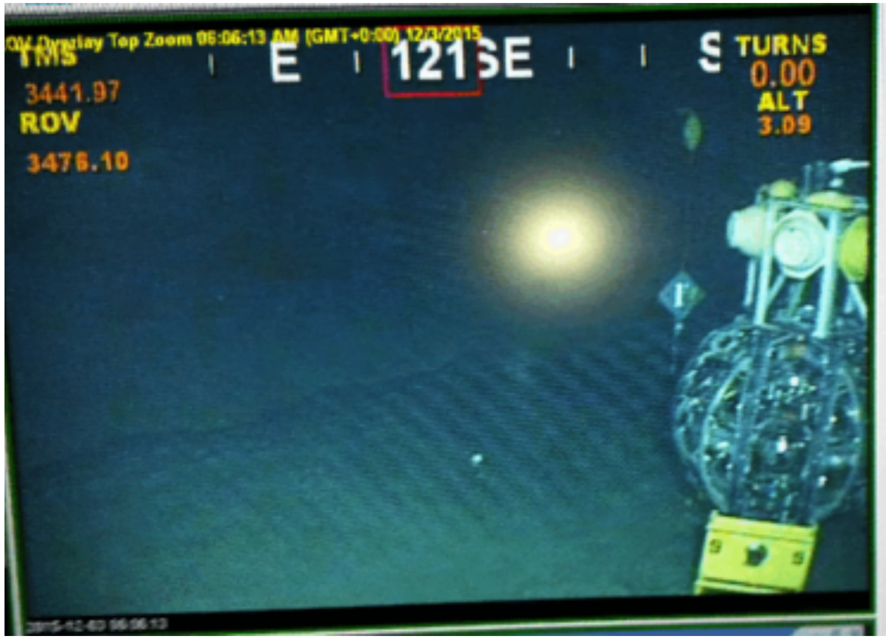
The first KM3NeT String: deployment

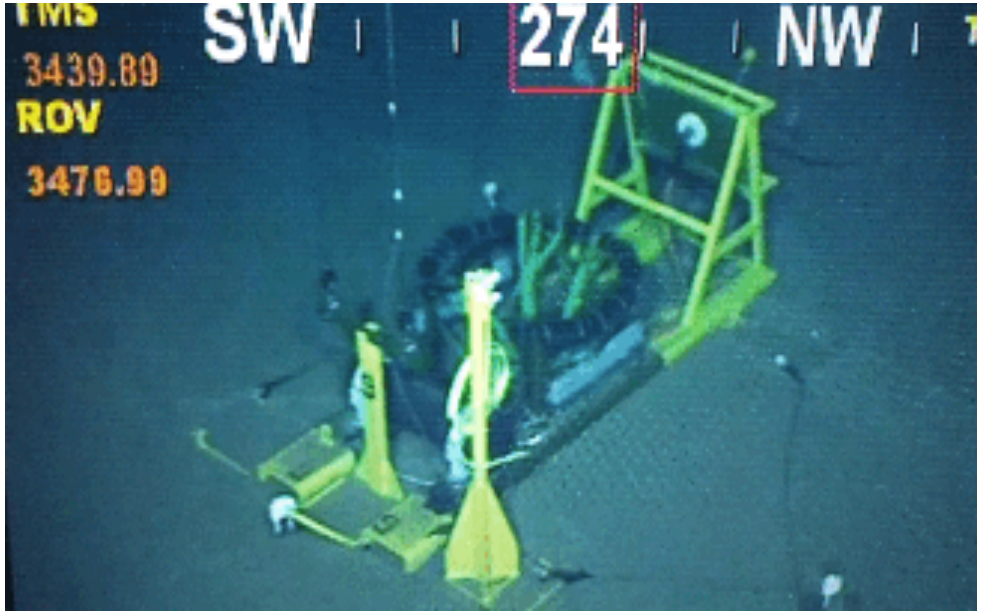


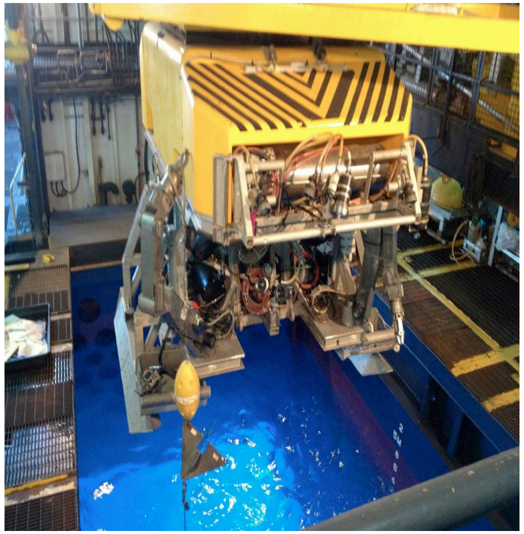


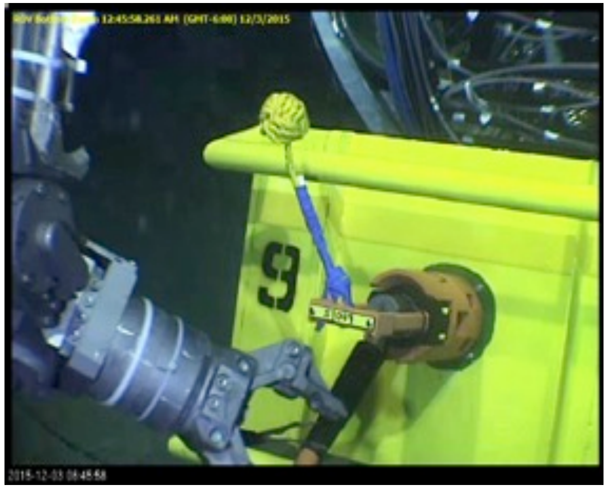


KM3NeT string connection (3rd Dec 2015)

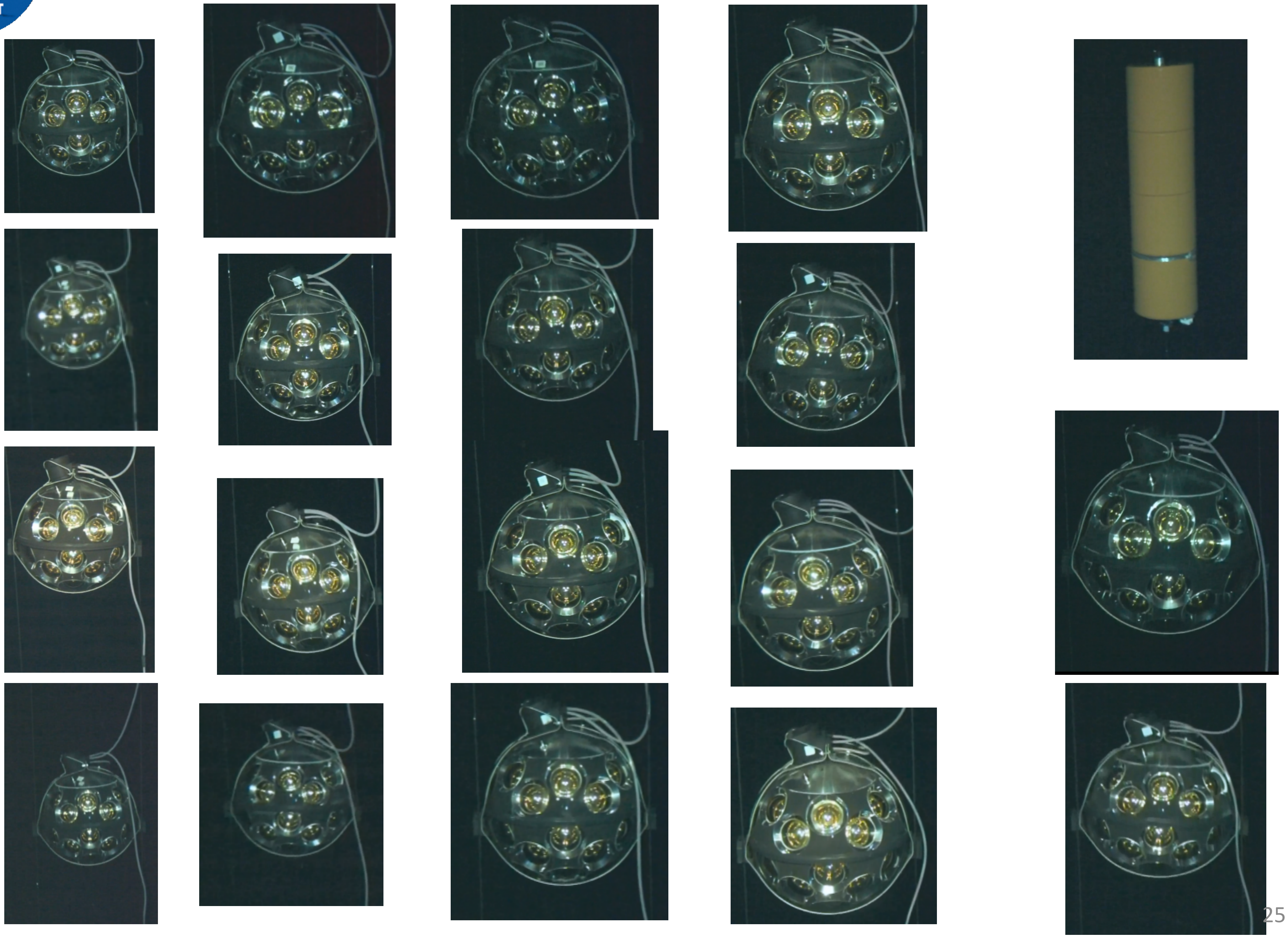






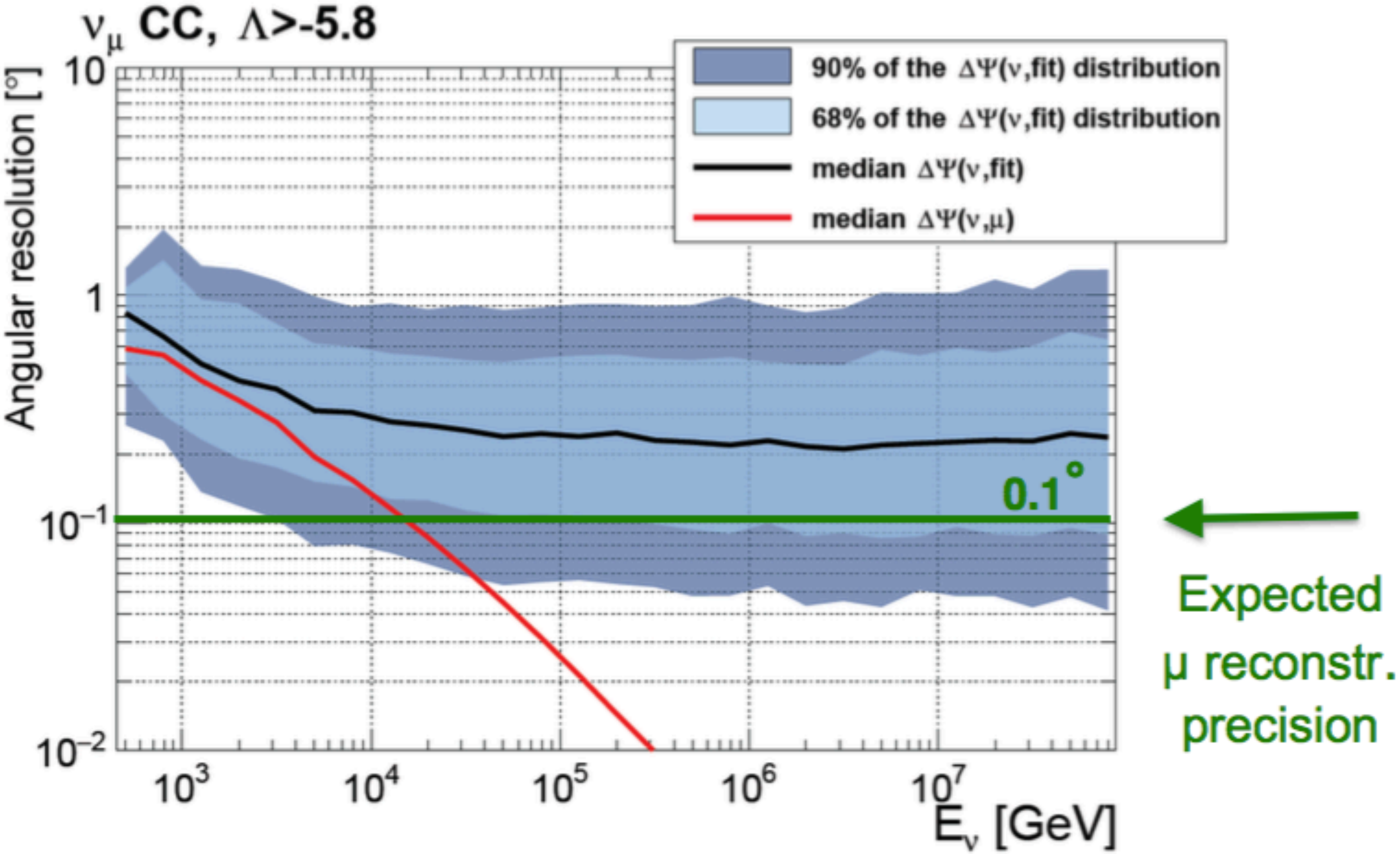


The first KM3NeT String

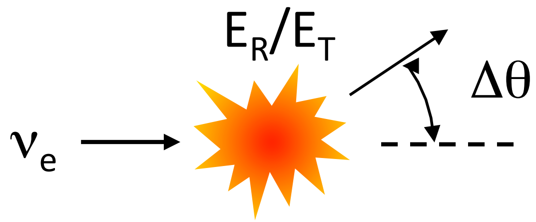


KM3NET ARCA: Performances

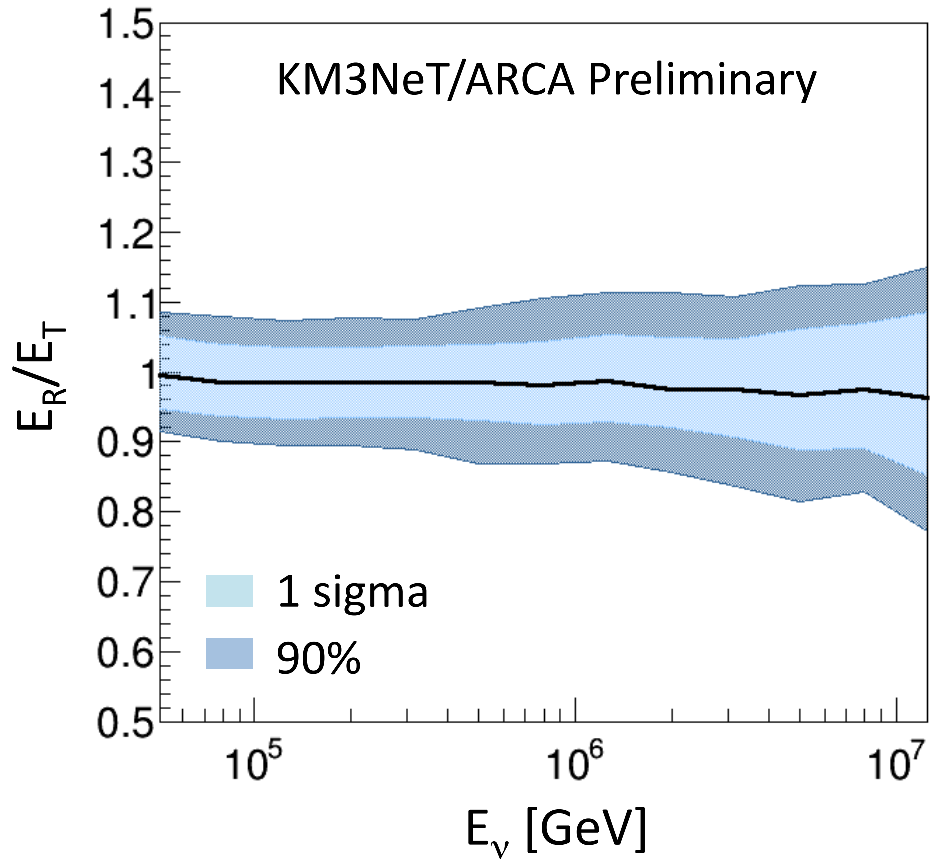
- Reconstruction using new PMT response simulation:
Median of angle $\Delta\Omega$ between reconstructed μ and true ν direction



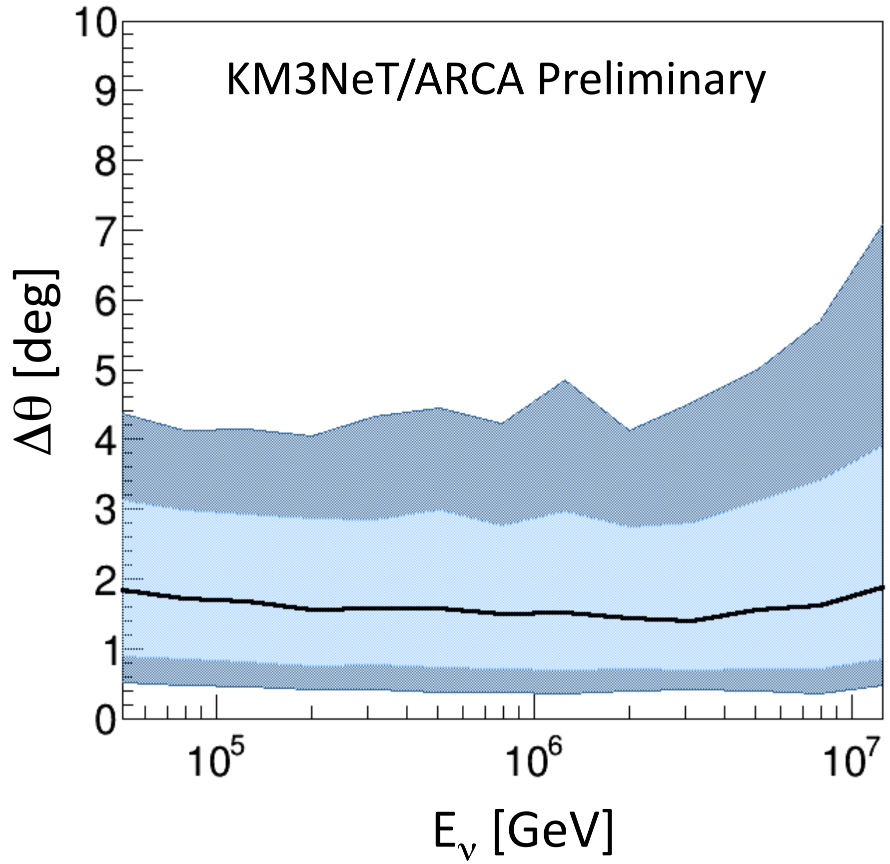
KM3NET ARCA: Performances



Energy



Direction



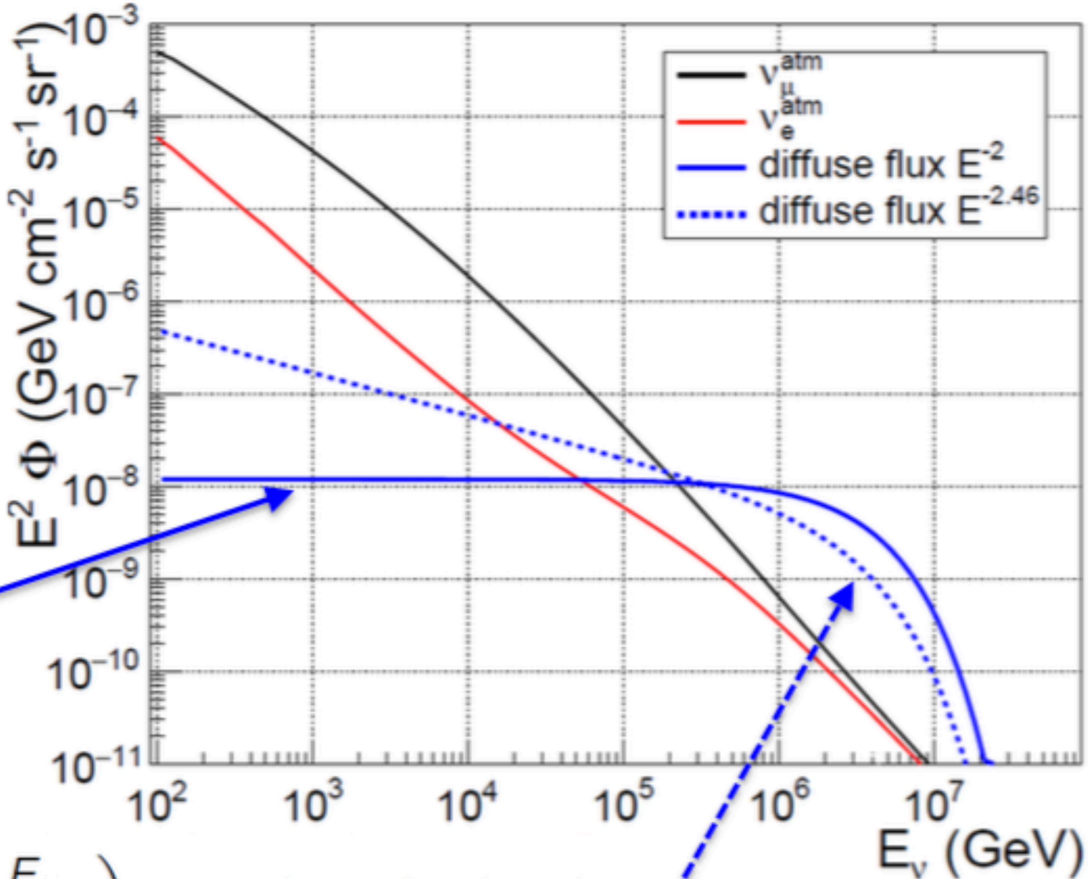
5%

<2°

KM3NET: diffuse flux

Assumptions:

1. Flavour-symmetric
2. Isotropic
3. Energy spectrum consistent with IceCube findings

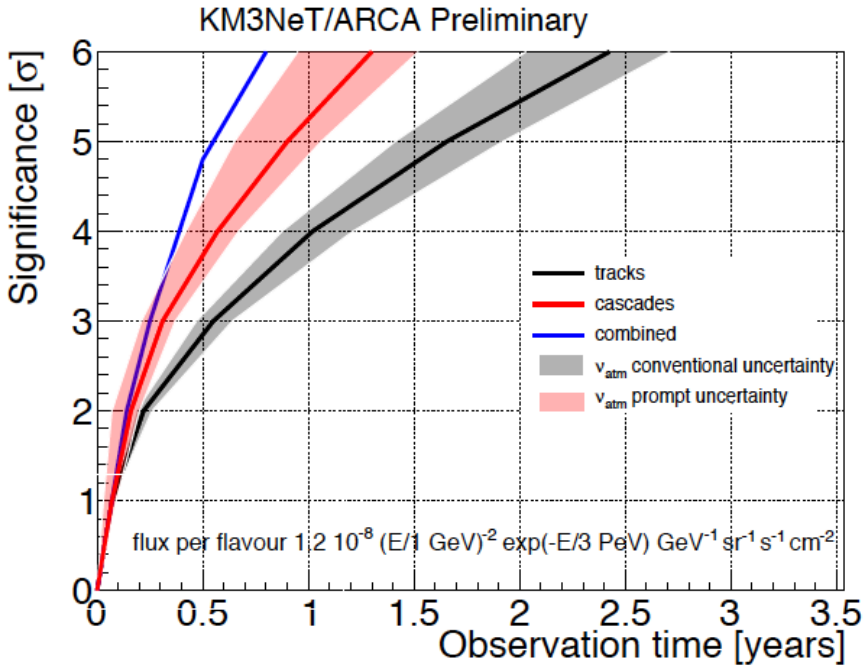


$$\Phi(E_\nu) = 1.2 \times 10^{-8} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right)\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

$$\Phi(E_\nu) = 4.11 \times 10^{-6} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2.46} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right)\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

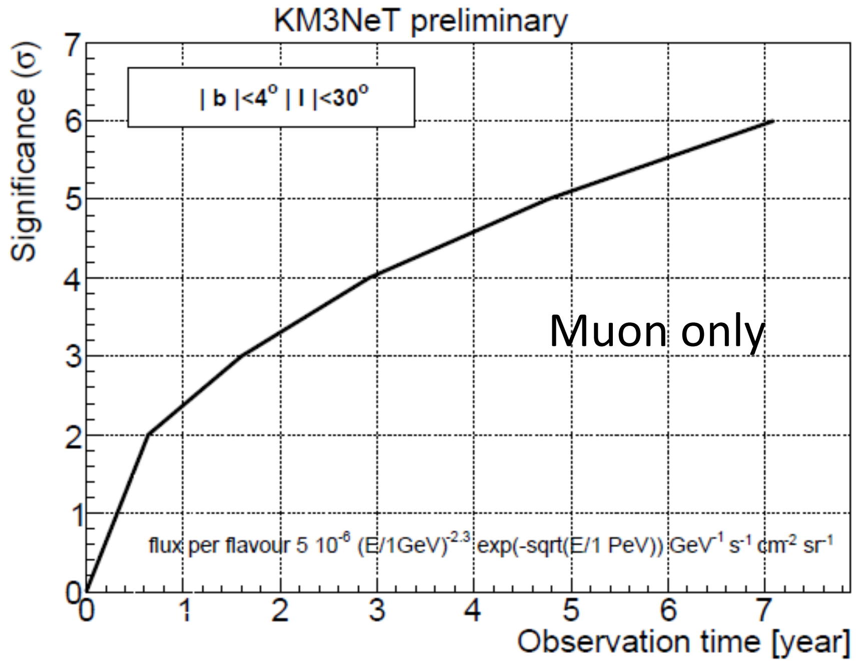
KM3NET: Diffuse Flux

IC Diffuse flux



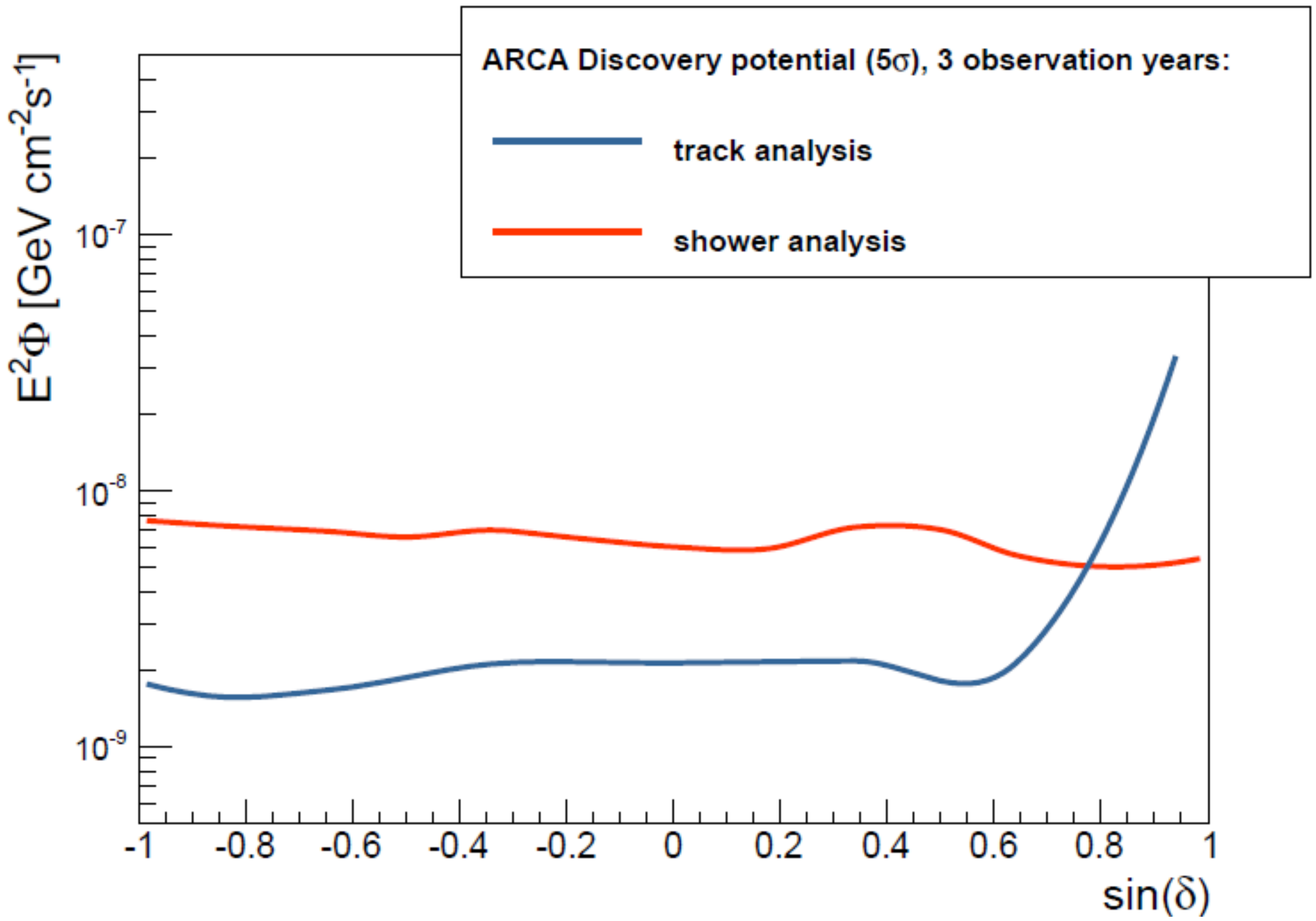
KRAγ Model

radially dependent diffusion coefficient for Galactic cosmic rays



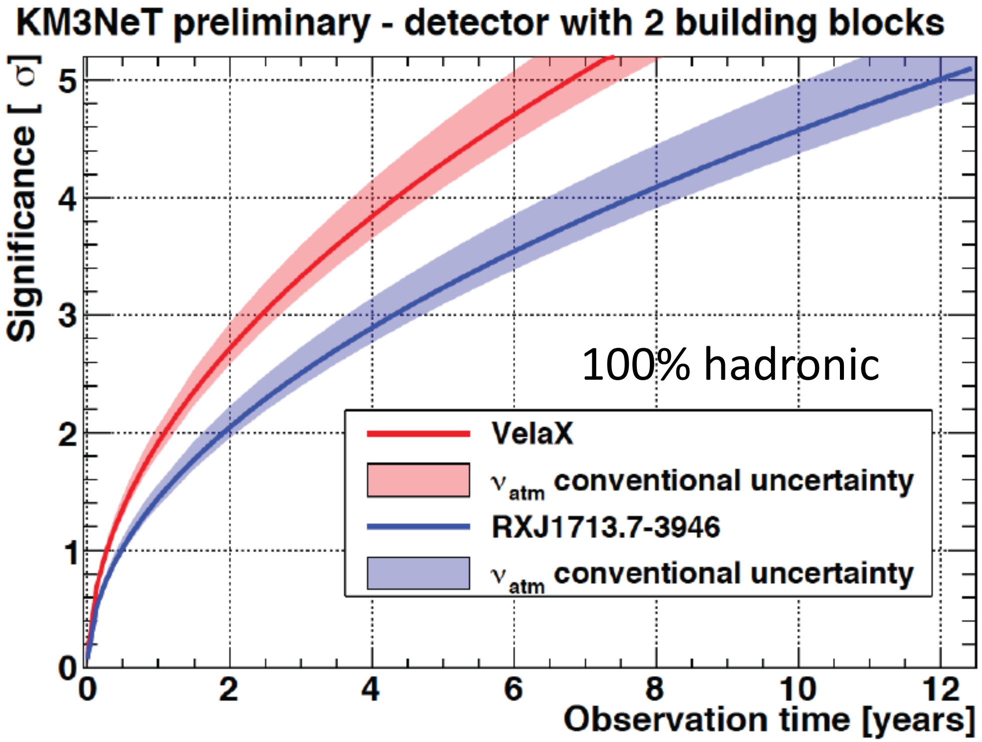
	muon	cascade
Angular resolution	0.1°	2°
Energy resolution	300%	5%

KM3NET: Point Sources

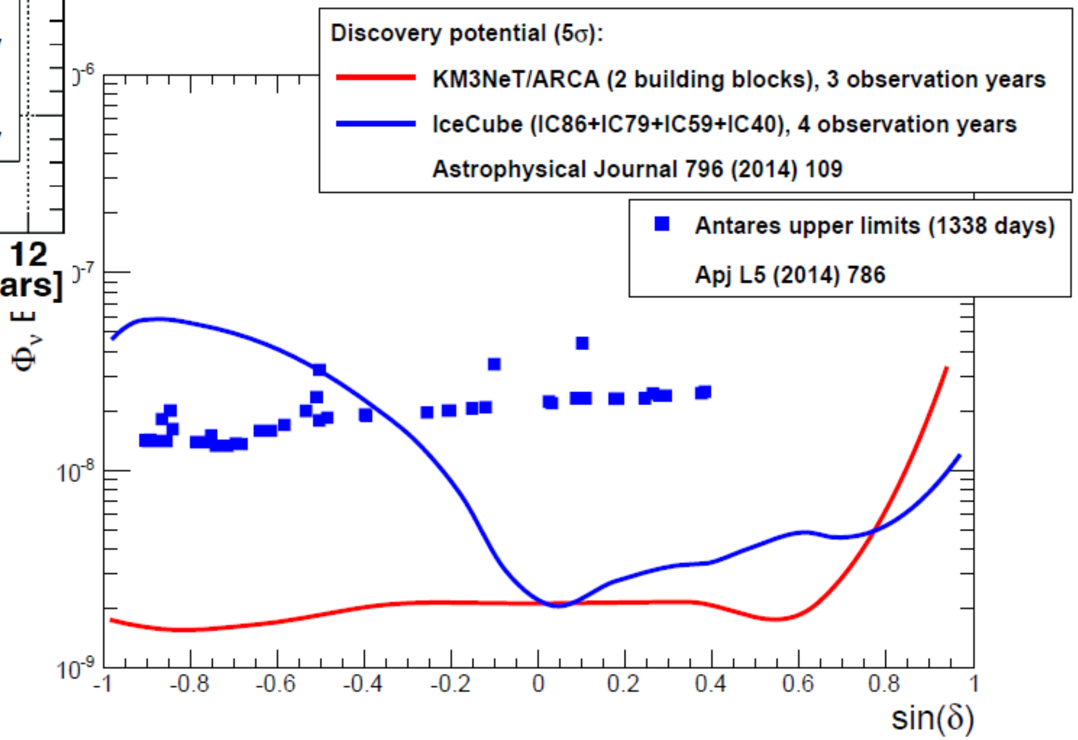


- Results are “rather preliminary”
- Important: Provides cascade event sample for source candidates
- Closes visibility gap

KM3NET: Point Sources



- Galactic sources in reach

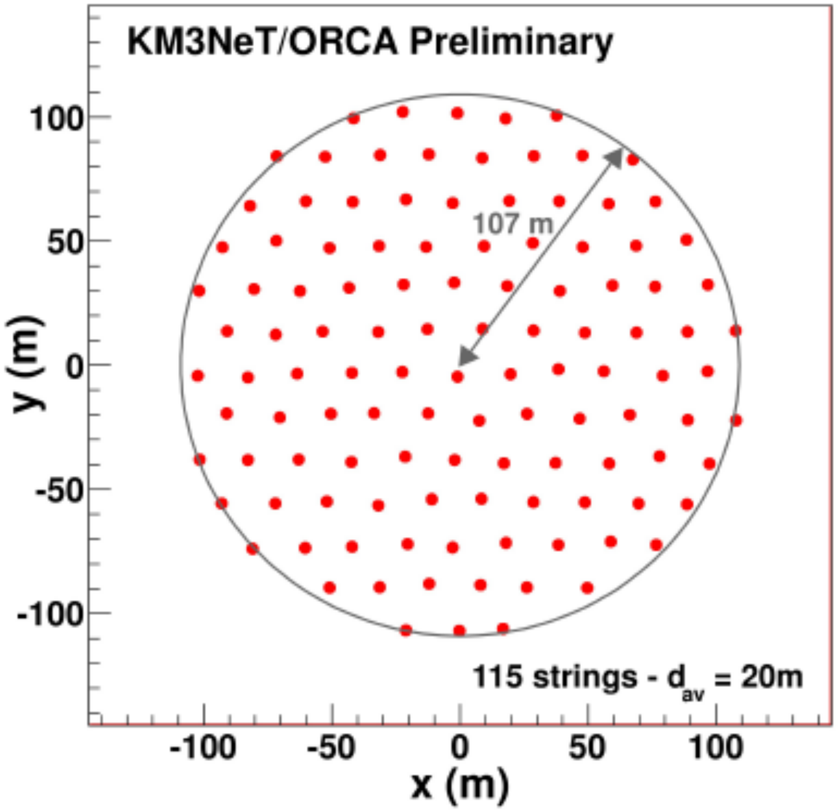


- Significant discovery potential for extragalactic sources

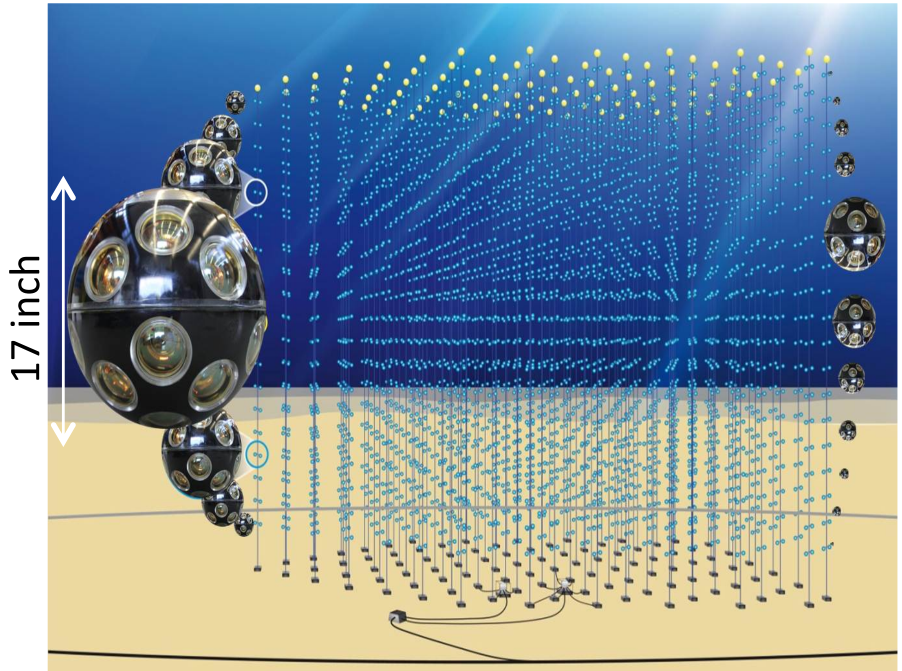
31

The ORCA benchmark design

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



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



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

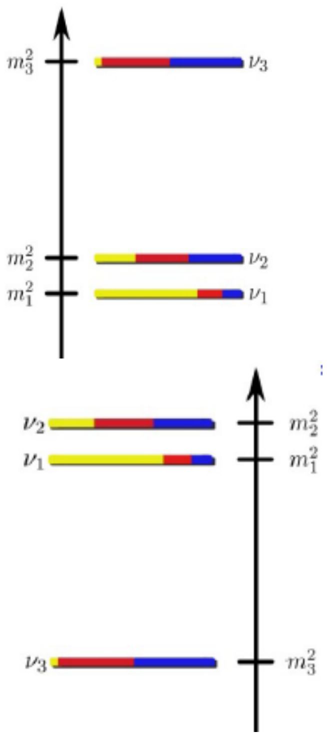
↓

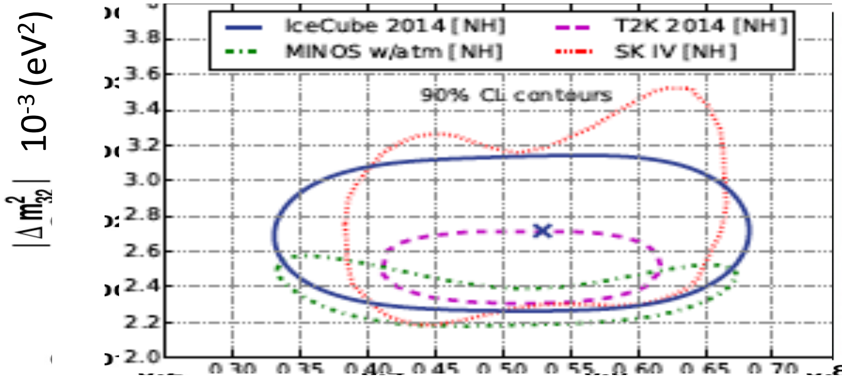
CP violating phase δ_{CP}

$$m_1^2 < m_2^2$$

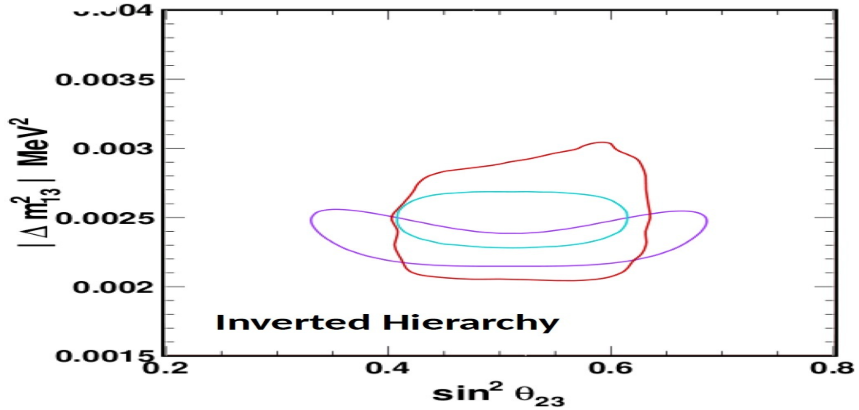
$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

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





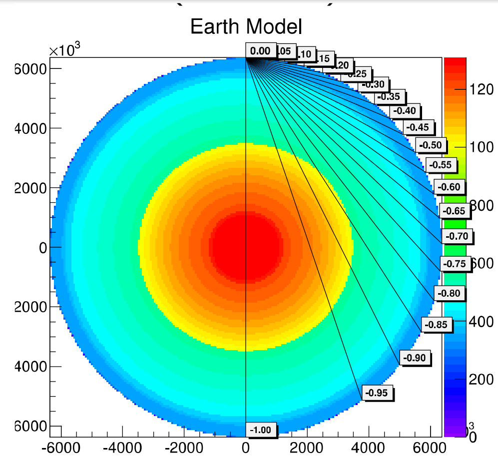
arXiv:1410.7227

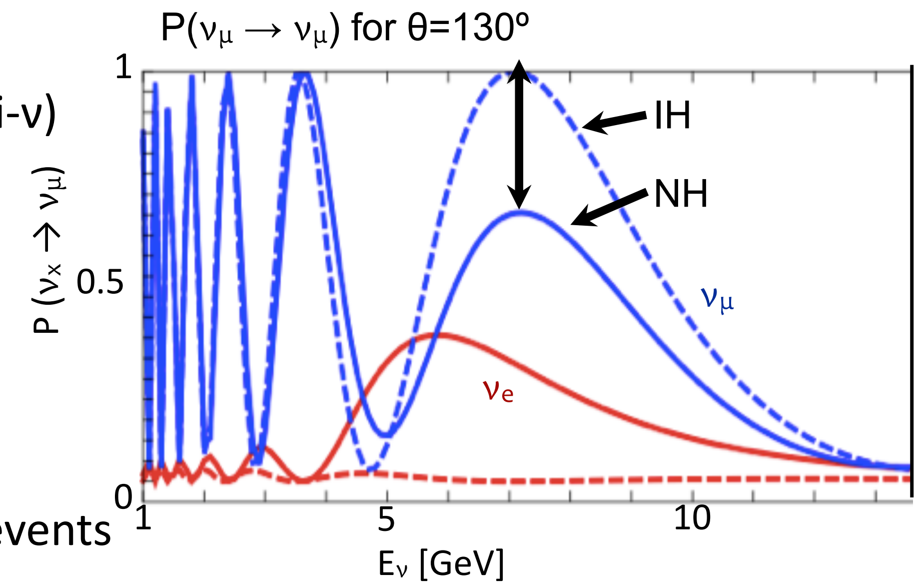


Measuring the neutrino mass hierarchy with atmospheric neutrinos

- 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





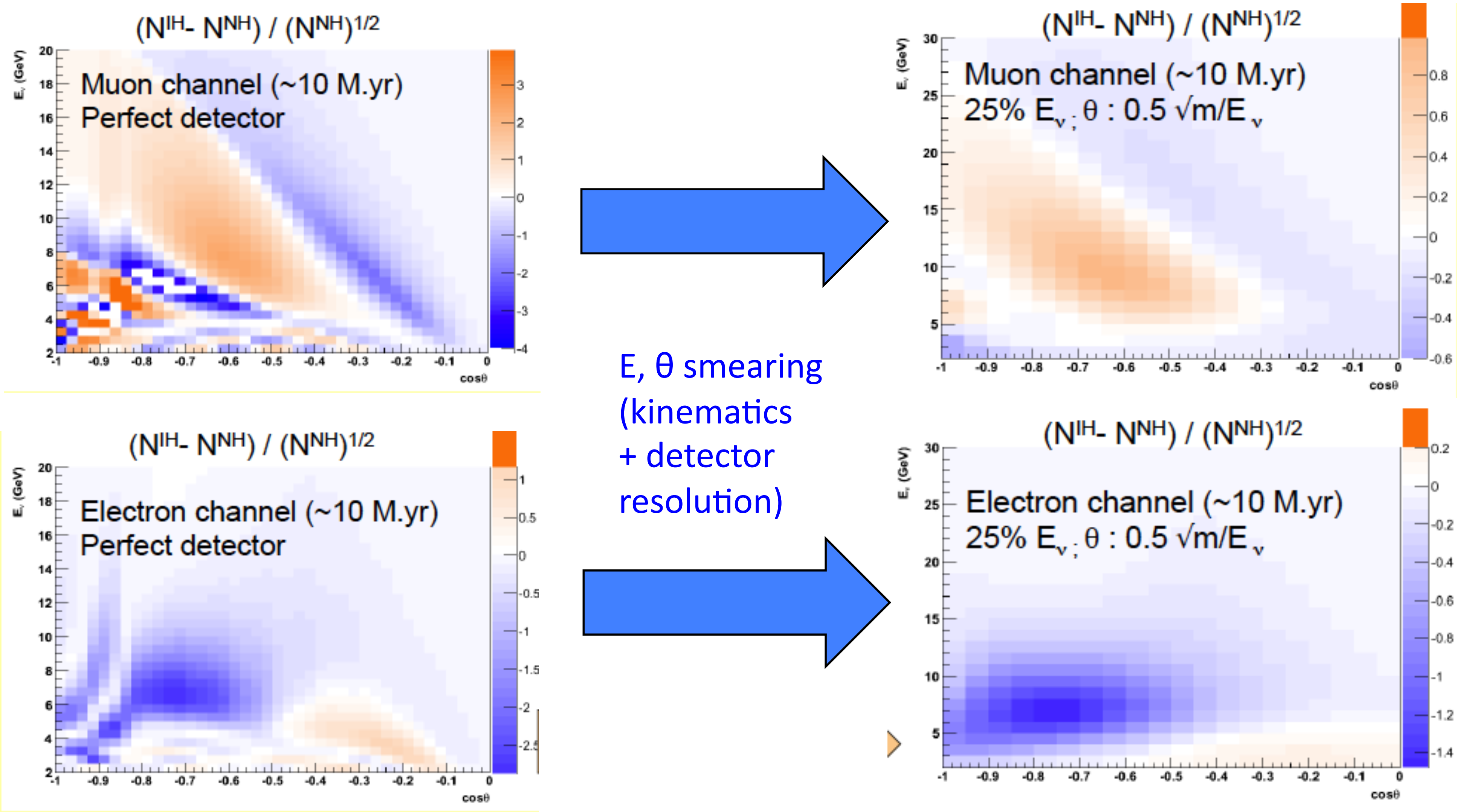
- opposite effect on anti-neutrinos: IH(ν)≈NH(anti-ν)
  BUT differences in flux and cross-section:
  $\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\text{anti-}\nu)$
  $\sigma(\nu) \approx 2\sigma(\text{anti-}\nu)$ at low energies
- measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos,
  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

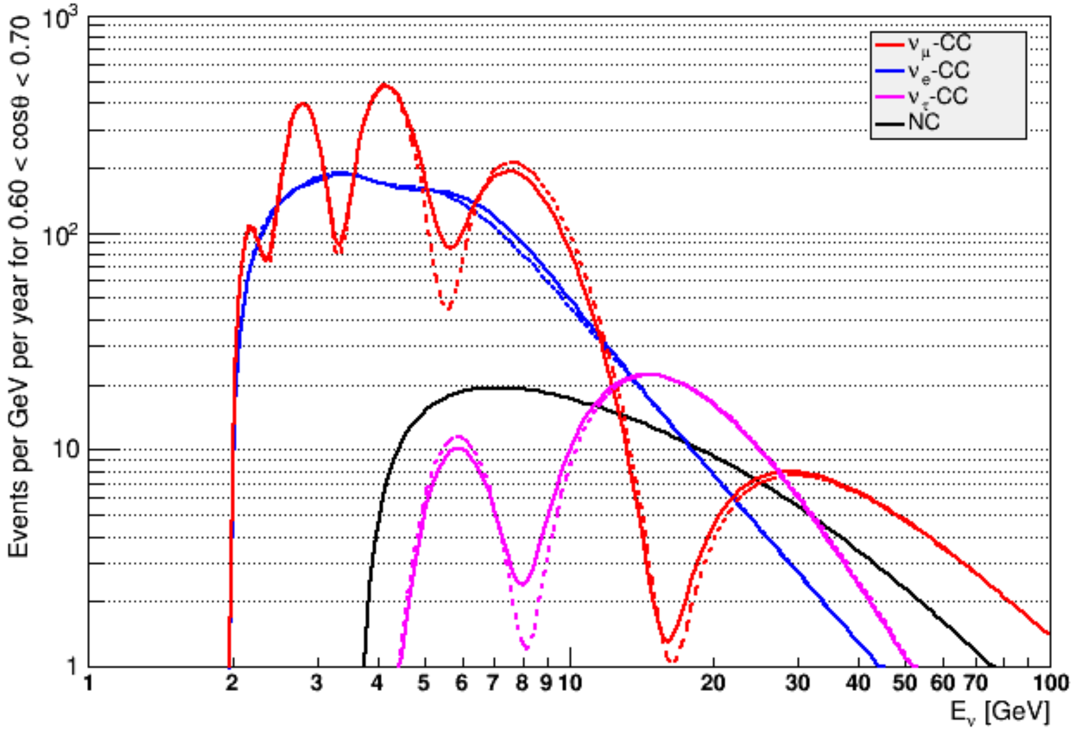
Both muon- and electron-channels contribute to net hierarchy asymmetry

electron channel more robust against detector resolution effects:



Event rate in ORCA (9m)

- Events per year per GeV
- No resolutions, no PID
- One example bin in cosθ (width 0.1 at 45°)



For all angles:

ν_μ CC 24,800

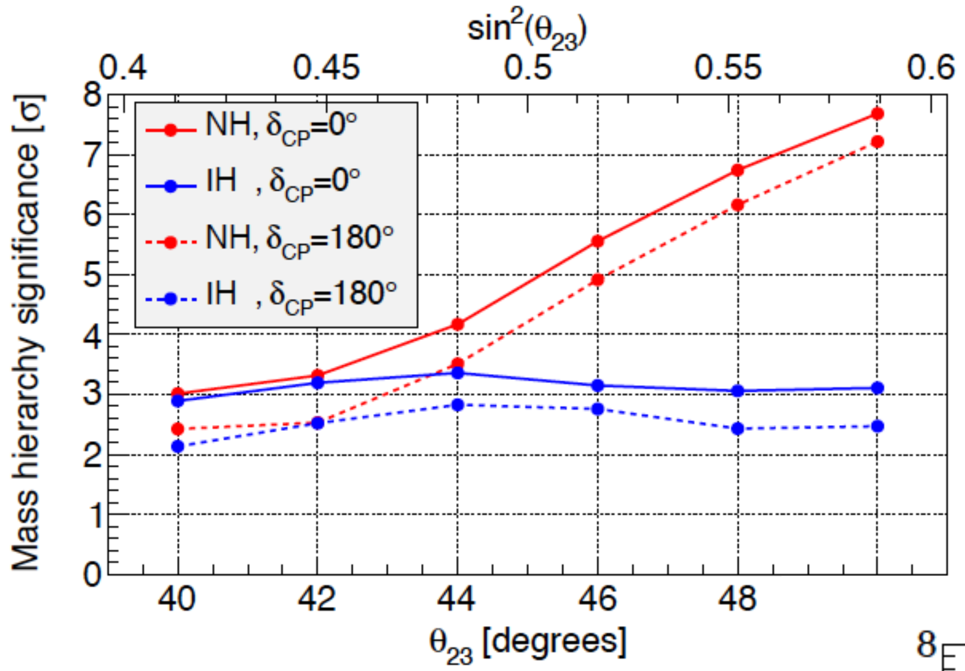
ν_e CC 17,300

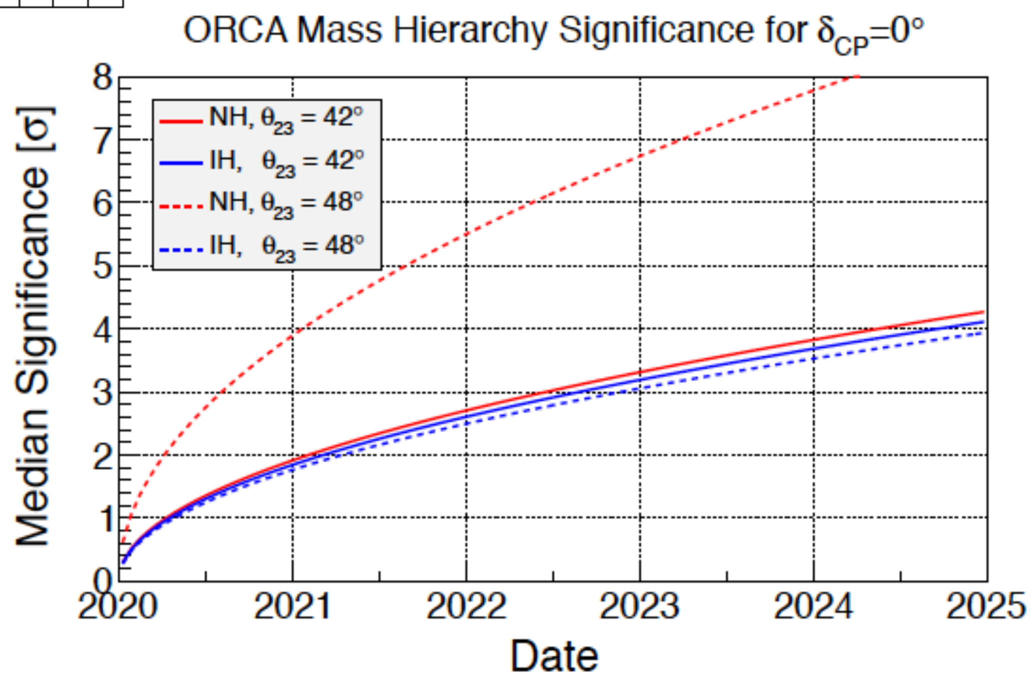
ν_τ CC 3,100

NC 5,300

28

Sensitivity to mass hierarchy



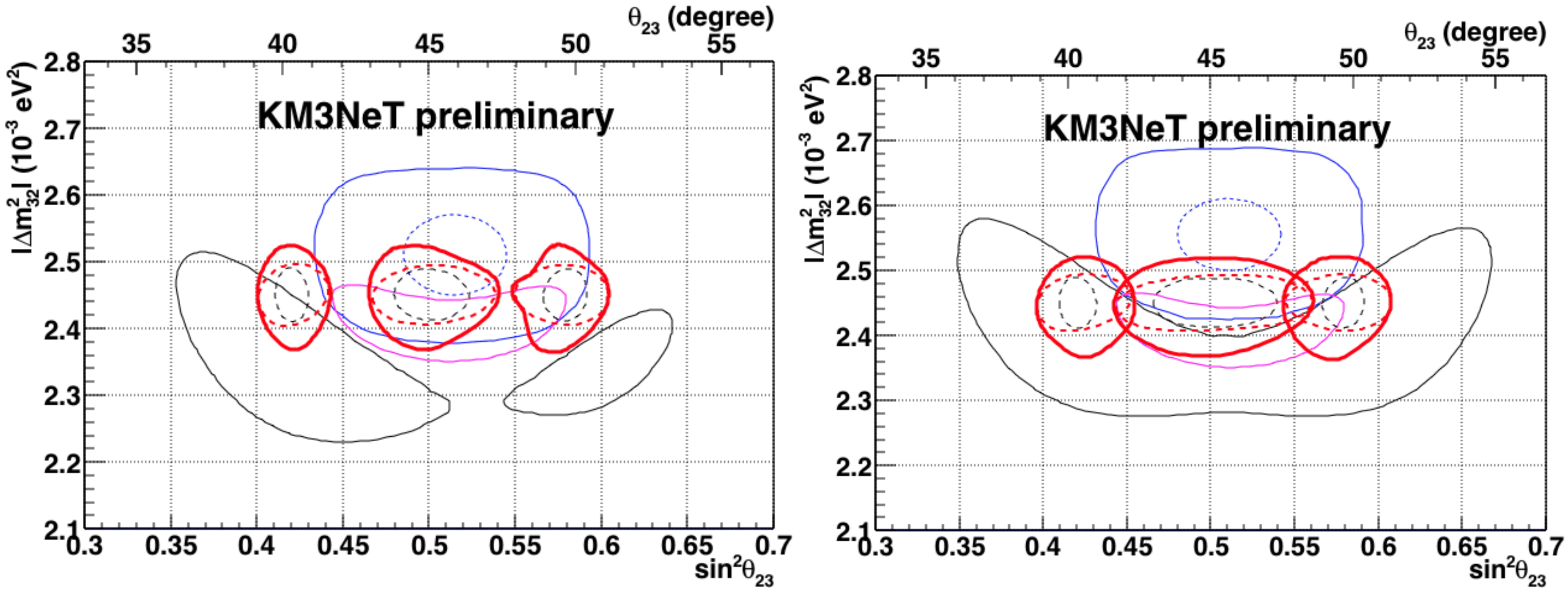


Sensitivity to PMNS parameters

3 year sensitivity to the atmospheric parameters

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

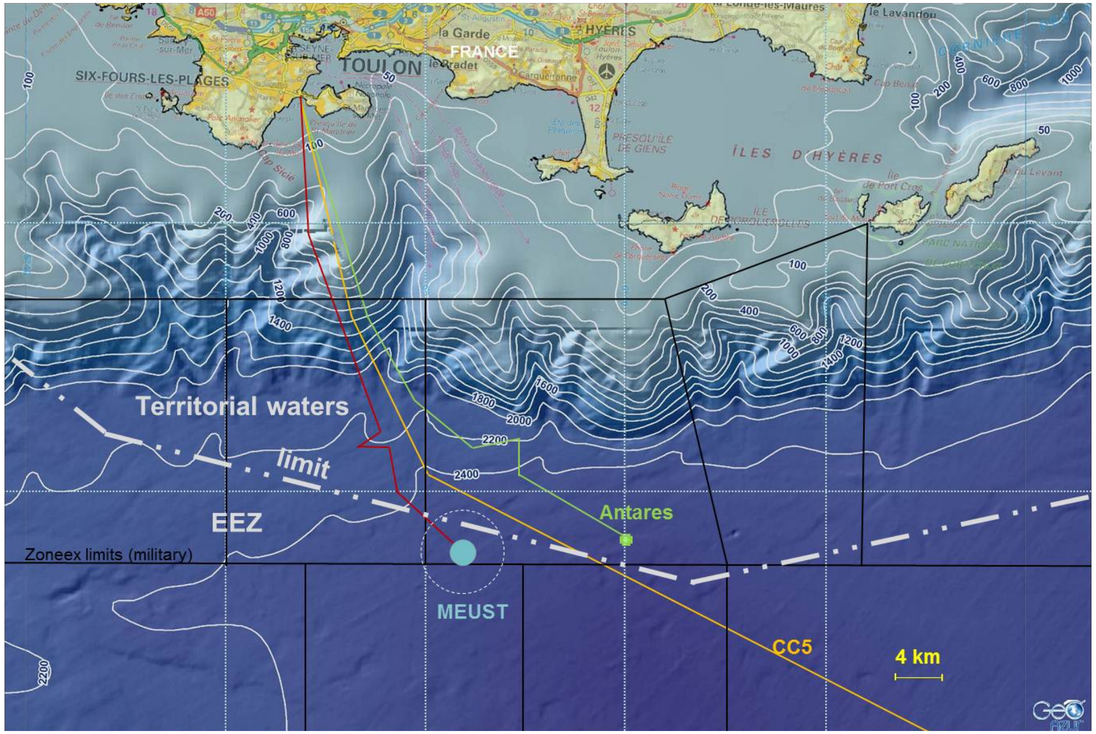
1 σ contour: 3% in ΔM^2, 4-10% in $\sin^2\theta_{23}$



ORCA, MINOS, T2K, NovA 2020

ORCA Construction

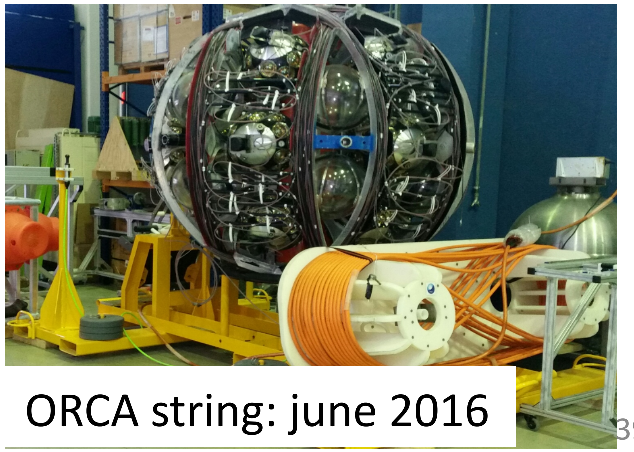
Phase 1 (funded- 11M€) : deploy a 6-7 string array
In the ORCA configuration to demonstrate
detection method in the GeV range.



Phase 2 (+40 M€): deploy 1 building block
115 strings in French KM3NeT site
Completion in 2020
Funds: 9M€ (France)+5M€(Netherlands)+…


Main cable: dec 2015


node: april 2016


ORCA string: june 2016

Summary and perspectives (I)

- Diffuse flux of cosmic neutrinos observed
- Higher level of hadronic activity in the non-thermal universe than previously thought → Exciting times ahead !
- Sources remain to be identified

- ANTARES: first undersea Cherenkov detector
  - Excellent angular resolution, view of Southern sky
  - Competitive sensitivities (Galactic neutrino component, Dark matter searches)
  - Improvements still to come: include showers in all analyses
  - Taking data until superseded by KM3NeT circa mid of 2017

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

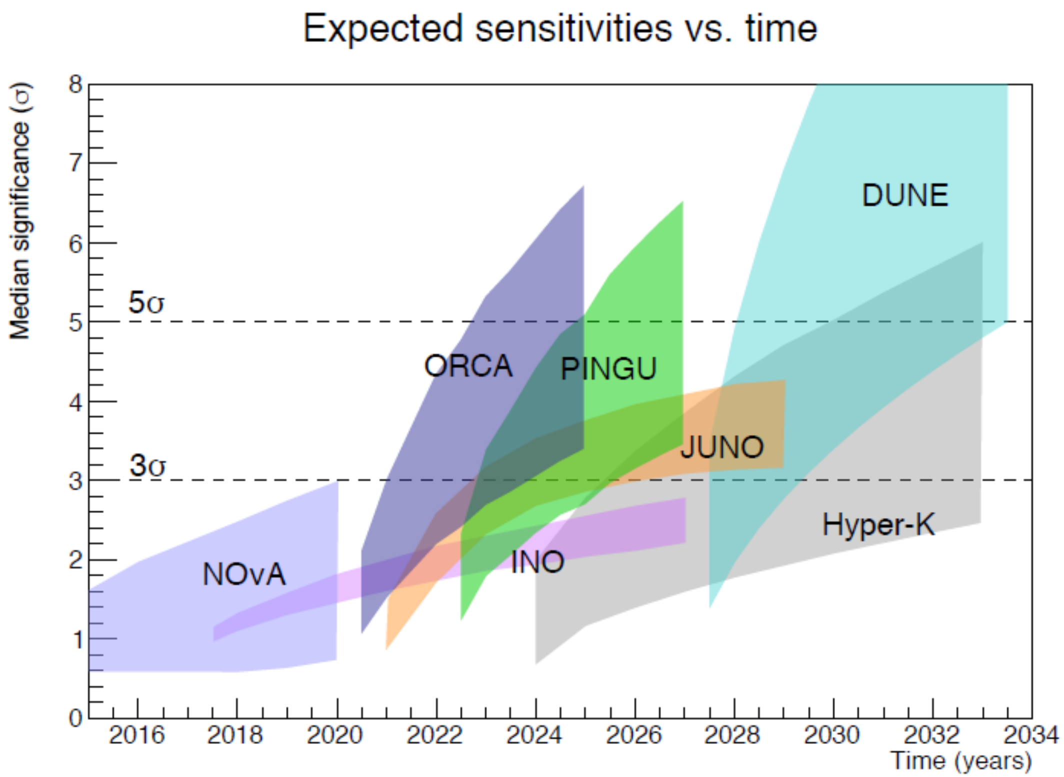
Summary and perspectives (II)

- Atmospheric Neutrinos still have a major role to play for precision measurements and determination of unknown parameters such as the mass hierarchy and the search for exotic phenomena

- Low energy (GeV) extensions of Neutrino Telescopes faster and cheaper than other alternatives…

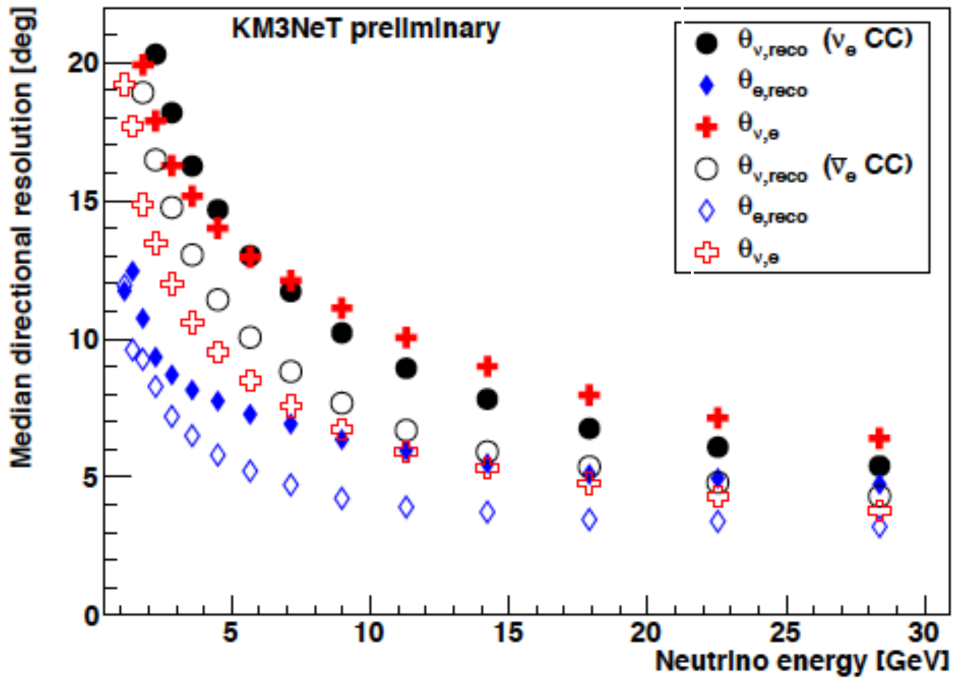
- …but challenging, as systematics must be carefully controlled

- Preliminary ORCA sensitivities are very promising and expected to improve

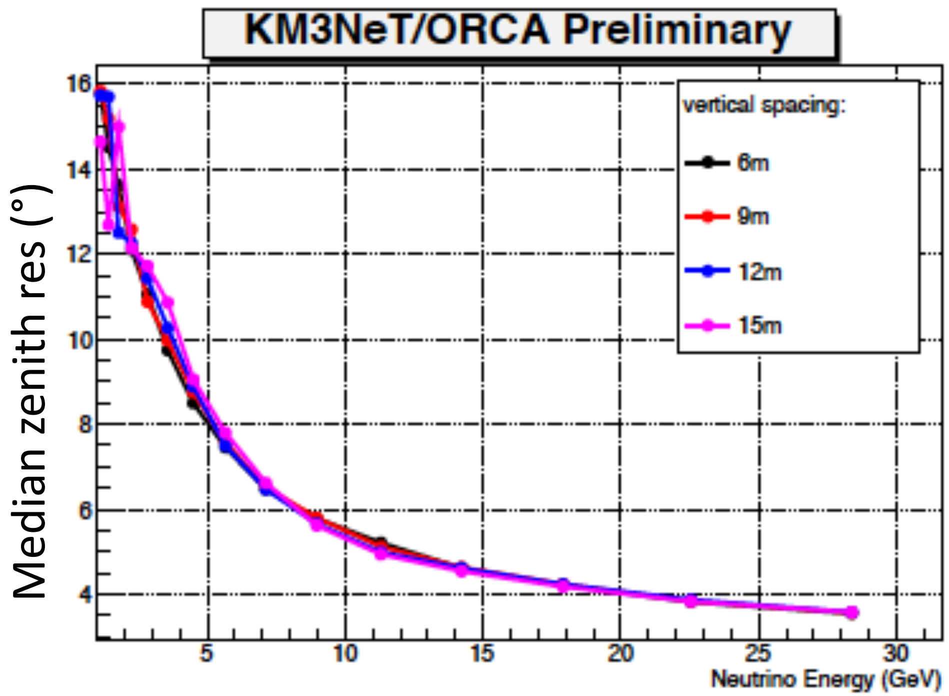


Angular Resolutions

cascade



track



Excellent angular resolution

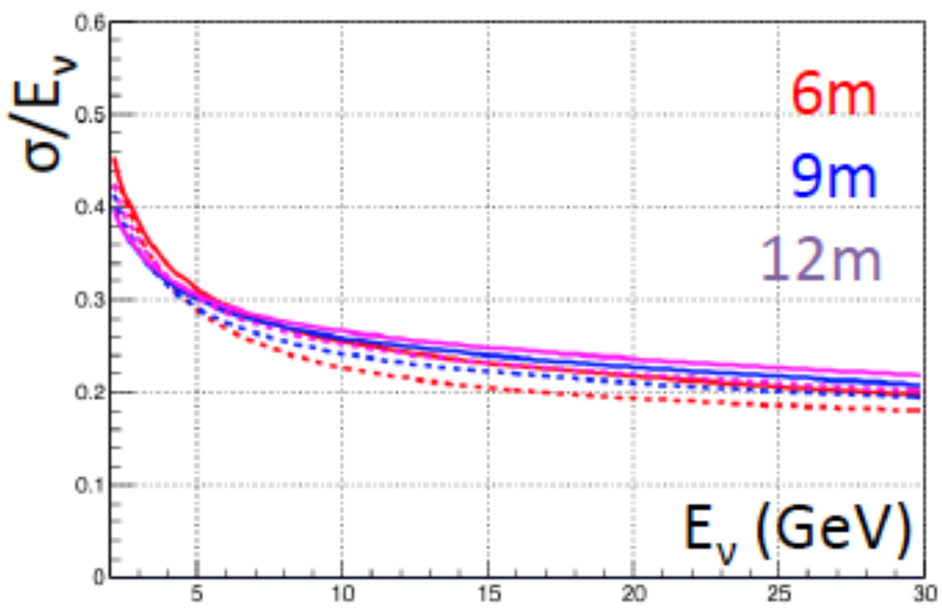
Dominated by kinematics

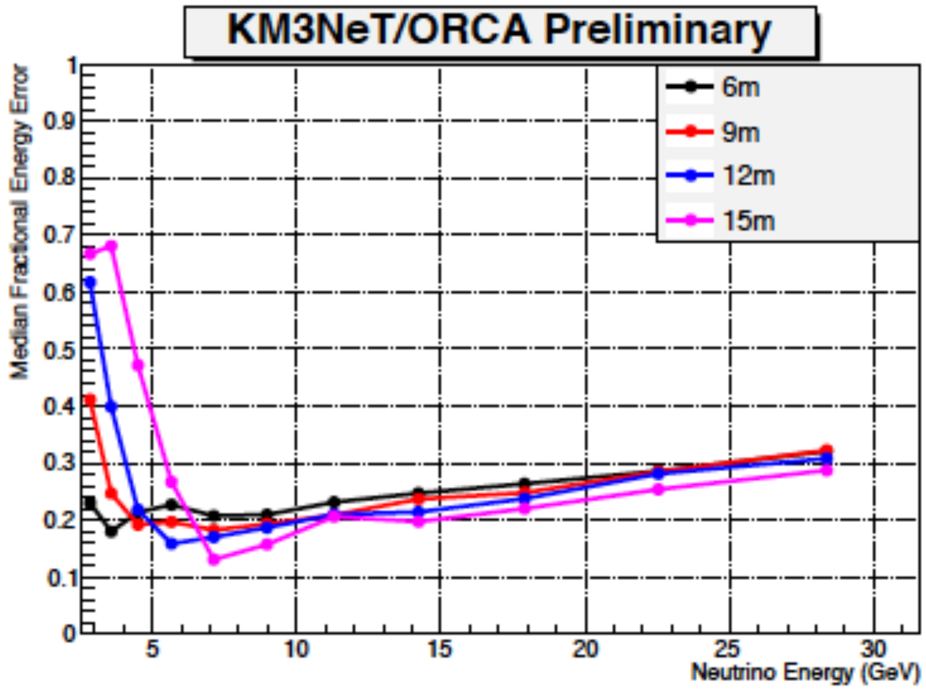
Largely independent of vertical spacing

Energy Resolutions

cascade

track

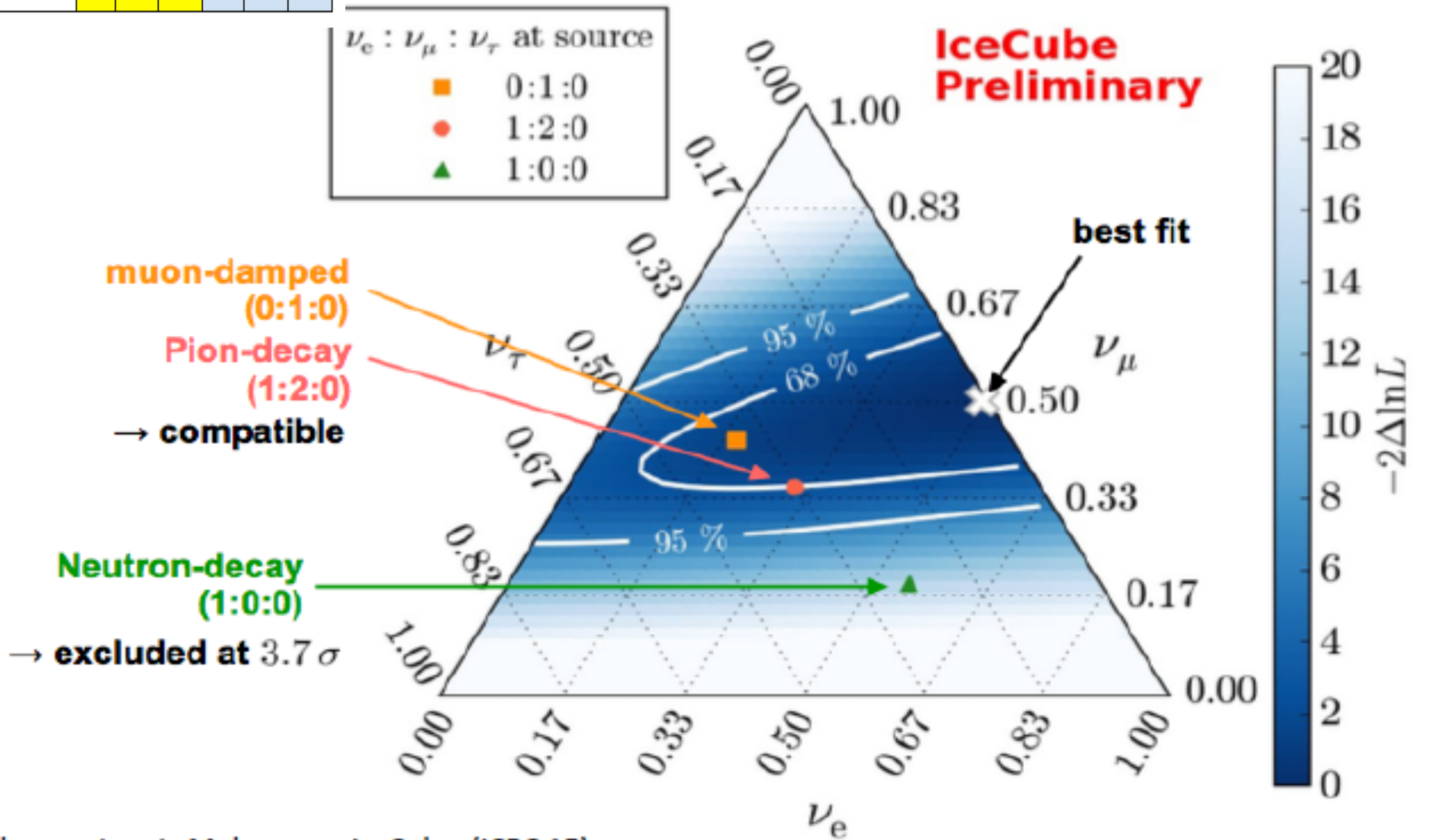




Energy resolution better than 25% in relevant range
– close to Gaussian

Flavour Ratios

	At source			At Earth		
	ν_e	ν_μ	ν_τ	ν_e	ν_μ	ν_τ
Pion decay	1	2	0	1	1	1
Muon-damped	0	1	0	0.2	.39	.39
Neutron-decay	1	0	0	.56	.22	.22



Slide: courtesy L. Mohrmann, IceCube (ICRC 15)