KM3NeT – The next-generation neutrino telescope in the Mediterranean Sea

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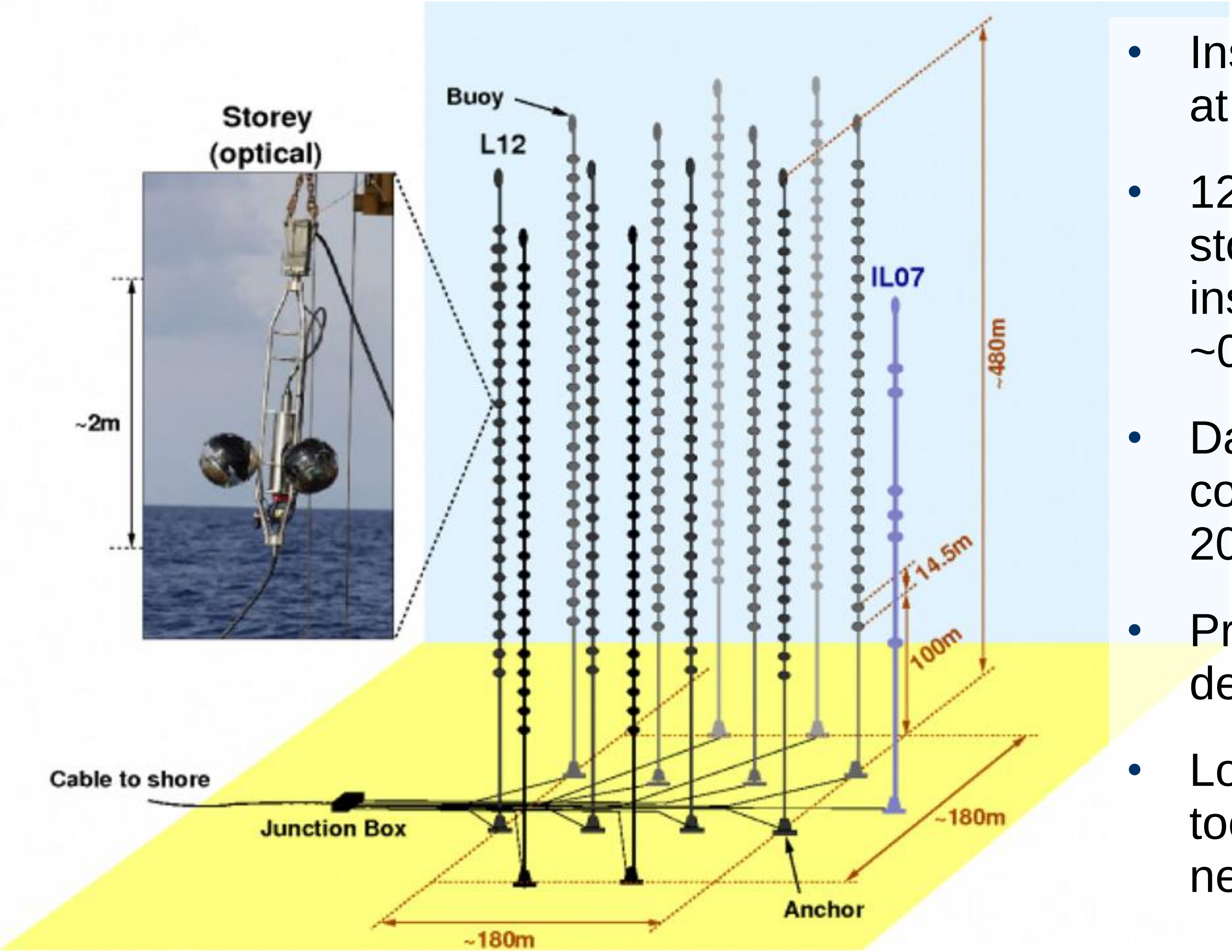
The plan for the next 30 minutes

- The KM3NeT project: Concept and design
- ARCA and ORCA
- Results from prototypes and the first string
- Neutrino astronomy: Selected sensitivity studies
- Summary

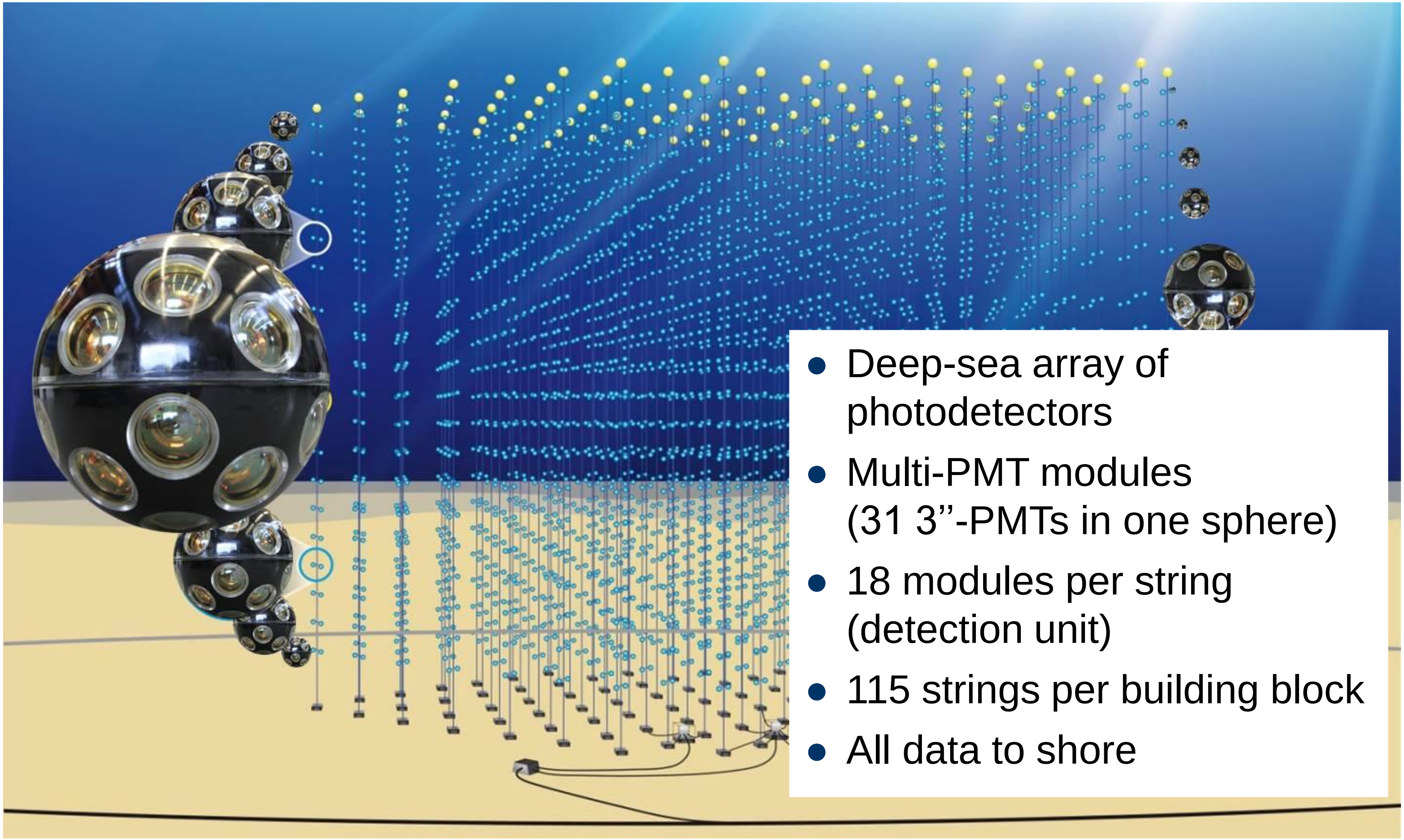
The KM3NeT project: Concept and design

ANTARES:
The first deep-sea ν telescope



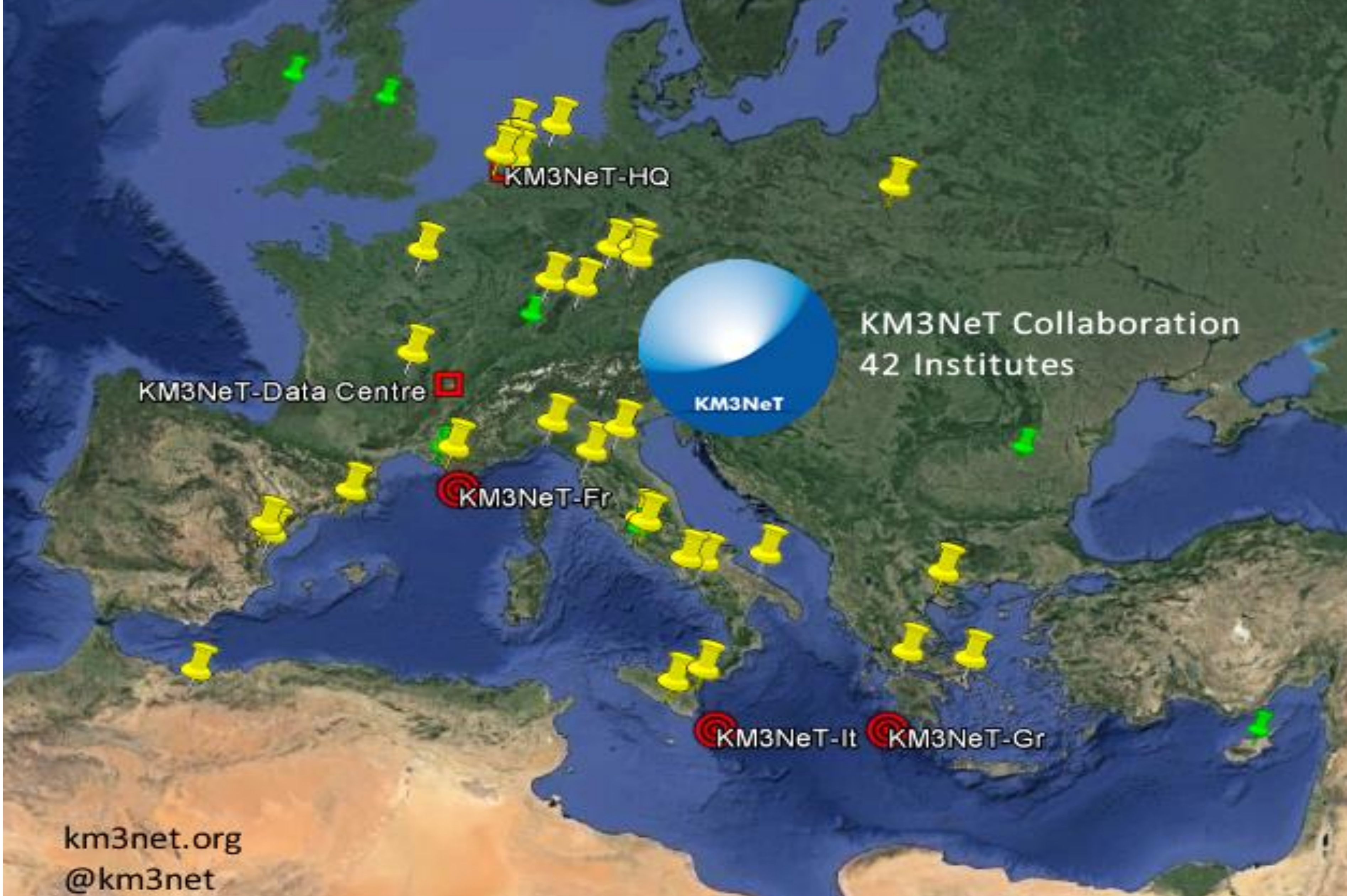
- Installed near Toulon at a depth of 2475m
- 12 strings with 25 storeys each, instrumented volume ~0.01km^3
- Data taking in full configuration since 2008
- Proof of principle of deep-sea ν telescope
- Lots of results – but too small for cosmic neutrinos

The KM3NeT concept



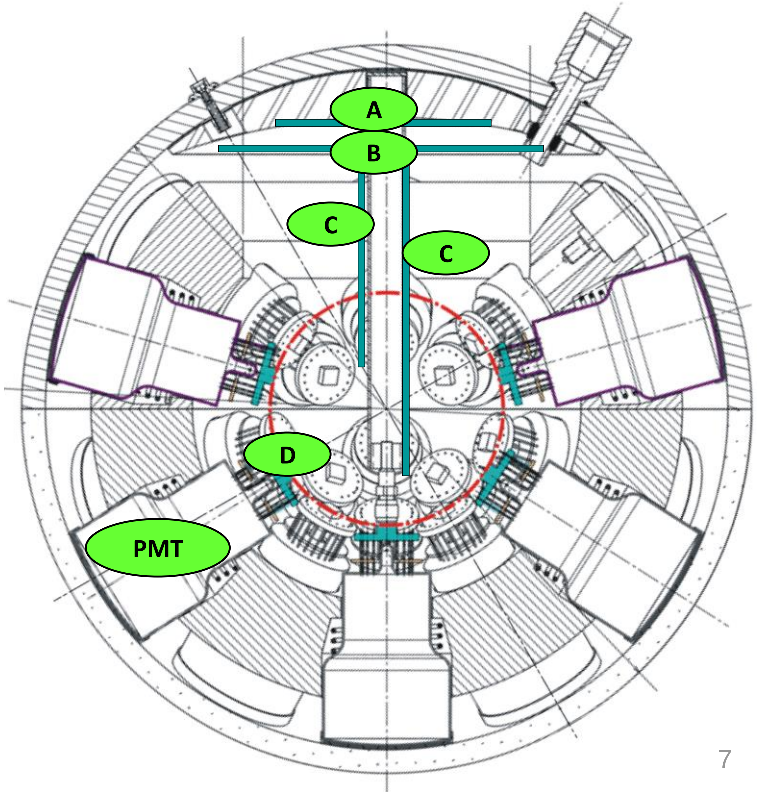
- Deep-sea array of photodetectors
- Multi-PMT modules (31 3''-PMTs in one sphere)
- 18 modules per string (detection unit)
- 115 strings per building block
- All data to shore

The KM3NeT Collaboration



The KM3NeT DOM

- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10-inch PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by plastic structure
- 31 PMT bases (total ~140 mW) (D)
- Front-end electronics (B,C)
- Al cooling shield and stem (A)
- Single penetrator
- Advantages:
  - Increased photocathode area
  - 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - Directionality
  - Cost / photocathode area
  - Minimal number of penetrations → reduced risk



PMT specifications

Parameter	Requirement
Photocathode diameter	> 72 mm
Nominal Voltage for Gain 3×10^6	900 – 1300 V
Gain slope = $\log_{10}(\text{gain})/\log_{10}(\text{HV})$	6.5 – 8.0
QE at 404 nm	> 23 %
QE at 470 nm	> 18 %
TTS (FWHM)	< 5 ns
Dark count rate (0.3 p.e. threshold)	< 2 kHz
Pre-pulses	< 1 %
Delayed pulses	< 3.5 %
Early afterpulses	< 2 %
Late afterpulses	< 10 %

PMTs available

+MELZ …

ETEL D792	Hamamatsu R12199	HZC XP53B20
		

Fulfil specifications; orders placed / expected

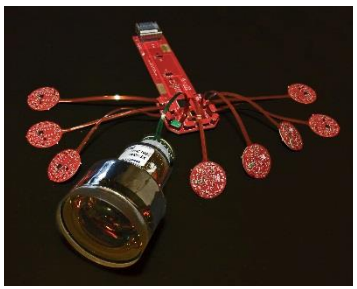
First prototype not yet compliant with specifications (gain, dark rate, afterpulses, …), further development under way

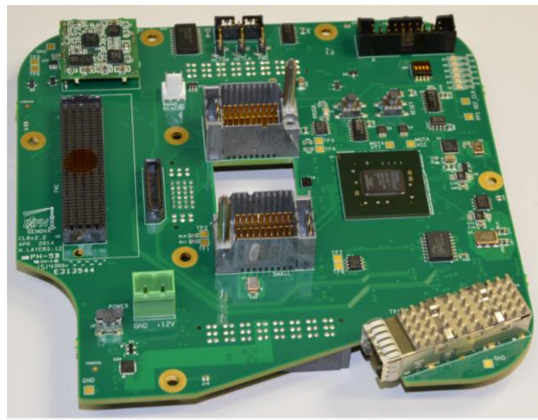
Note: In all cases price/photocathode area < 10-inch tubes (MELZ?)

KM3NeT readout

Power board

31 PMTs + bases
2 octopus boards





Central Logic Board (CLB)

All data to shore (optical fibres) → Online filter on shore

HV for PMTs

Discrimination w.r.t. predefined threshold

Signal collection

FPGA for TDC (time & time over threshold), time stamping (1 ns precision);

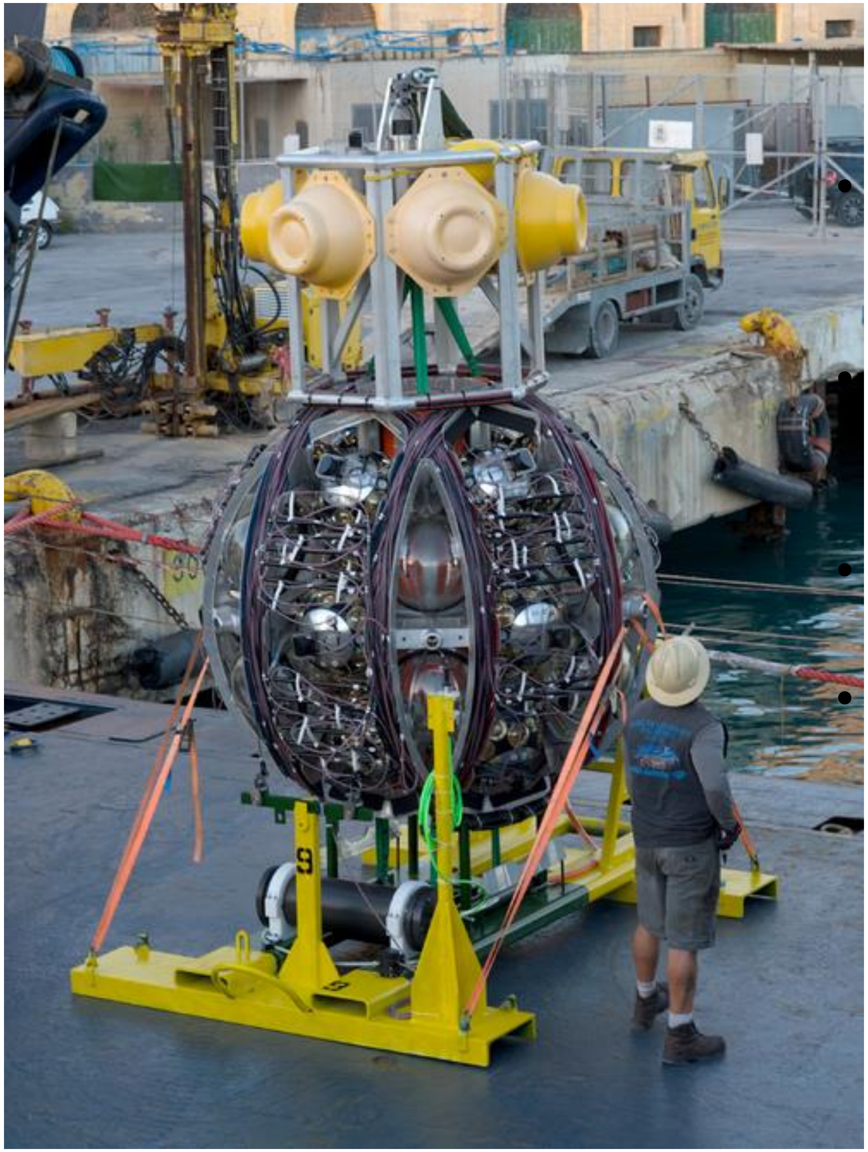
Interface for time synchronisation:

Control of calibration devices;
Communication;

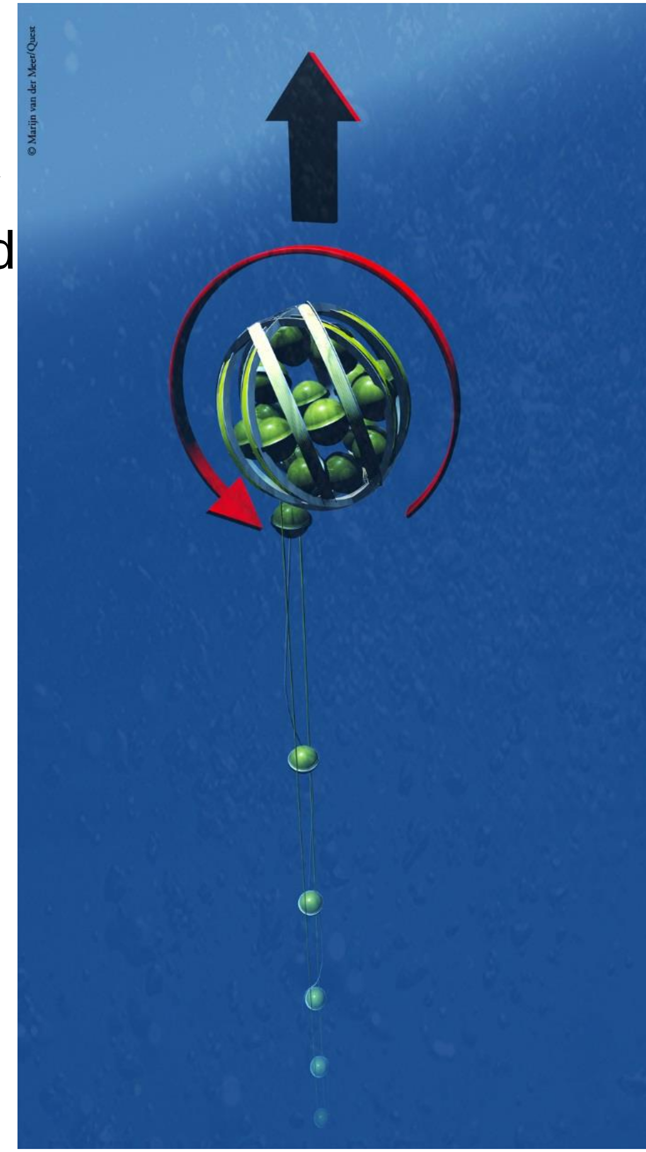
KM3NeT detection units (DUs)

- Mooring line:
  - Buoy (syntactic foam or empty spheres)
  - 2 pre-stretched Dyneema© ropes (4 mm diameter)
  - 18 storeys (one DOM each)
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - Optical fibres and copper wires
  - At each storey: Break-out box for connection to 1 fibre + 2 wires (one single pressure transition)
  - Point-to-point connection DOM-shore for each DOM

Deployment



- ← Deploy to sea bed
- Acoustic release
- Unfurl →
- Collect frame



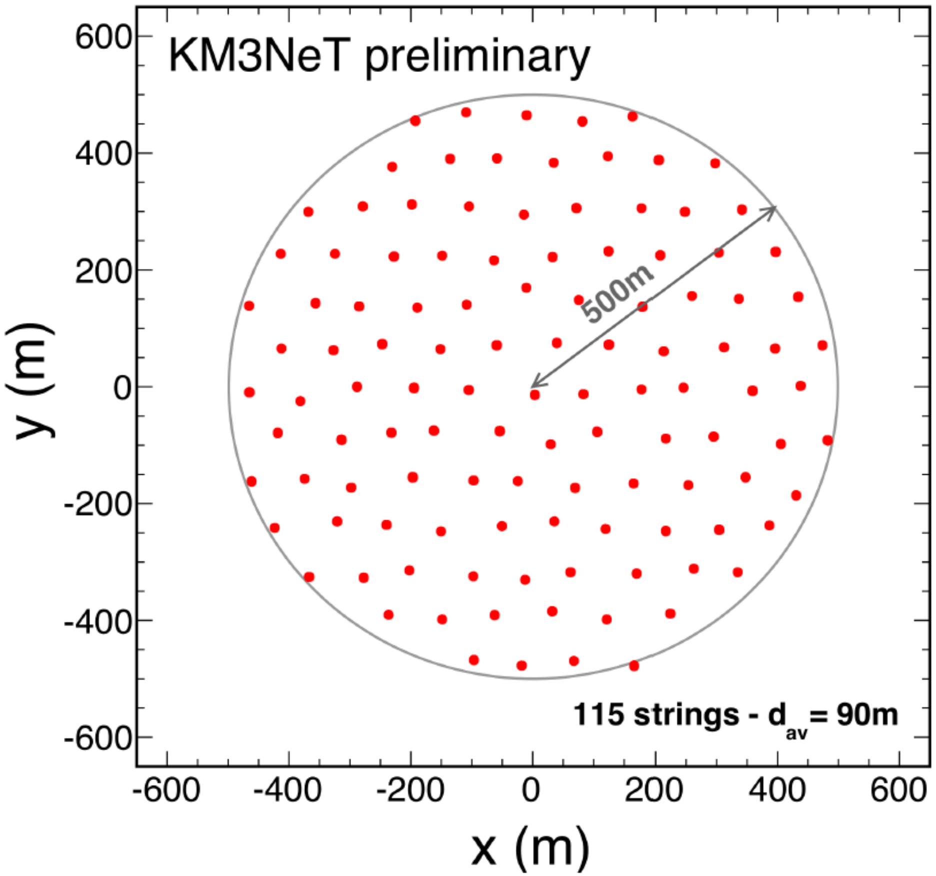
ARCA and ORCA

– Astroparticle and Oscillation Research with Cosmics in the Abyss –

The building block concept

- Building block:
  - 115 detection units
  - Segmentation enforced by technical reasons
- Large block (neutrino astronomy)
  - Sensitivity per string for muons independent of block size above ~75 strings
  - One block ~ half IceCube
- Small block (neutrino oscillations)
  - Precision measurement of atmospheric neutrinos
  - One block ~ 6 Mtons
- Allows for staged, block-wise, multi-site installation

DU distance adjusted to scientific objective:
90-120 m for neutrino astronomy /
20 m for oscillation research



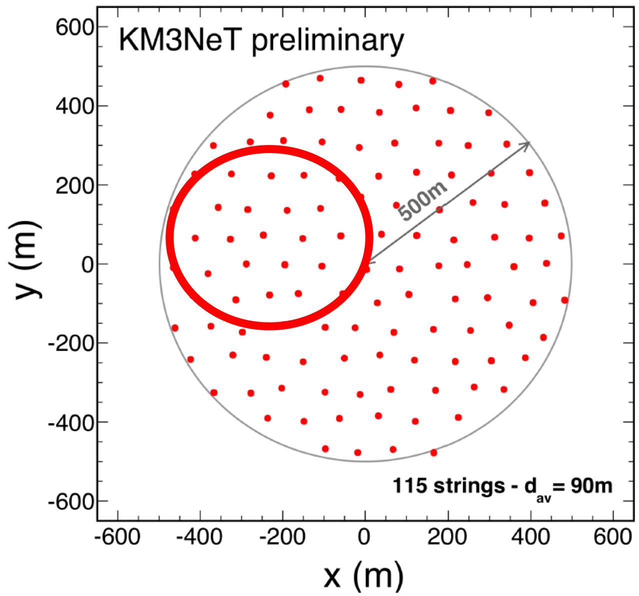
KM3NeT development

Phase	Blocks/ strings	Primary deliverables / site(s)	Funding Construction
1	0.2/31	Proof of feasibility and first science results; KM3NeT-Fr + KM3NeT-It sites	Fully funded 2015-17
2.0	2/230	Measurement of neutrino signal reported by IceCube; All-flavor neutrino astronomy; KM3NeT-It site	Applications pending 2017-2020
	1/115	Neutrino mass hierarchy; KM3NeT-Fr site	
3	6+1/805	Neutrino astronomy including Galactic sources; Multiple sites	t.b.d. ?

KM3NeT Phase-1 = 31 DUs

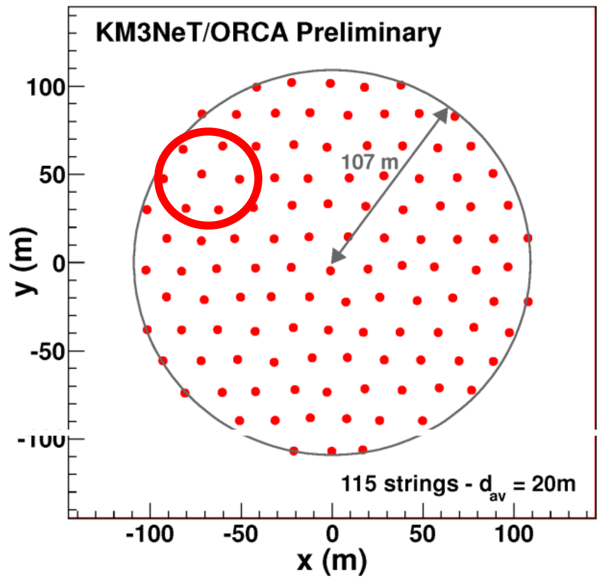
ARCA =

Astroparticle Research with Cosmics in the Abyss



Vertical OM distance = 36 m
3 times ANTARES

ORCA =
Oscillation Research with Cosmics in the Abyss

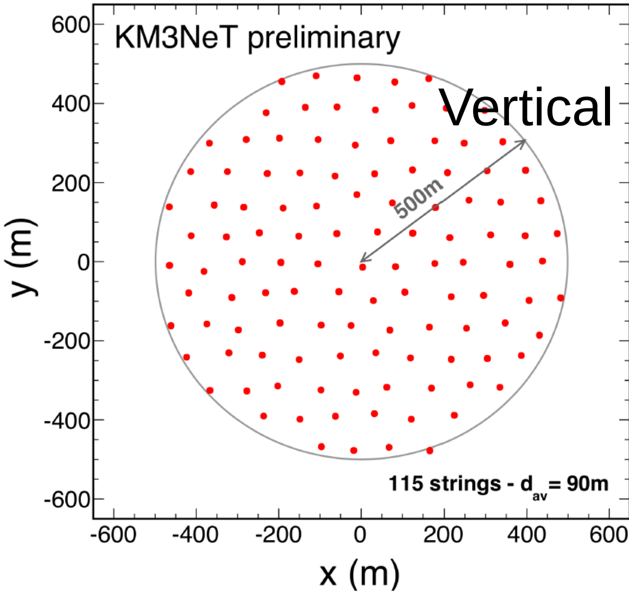


Vertical OM distance = 9 m

KM3NeT 2.0 = ARCA and ORCA

ARCA =

Astroparticle Research with Cosmics in the Abyss



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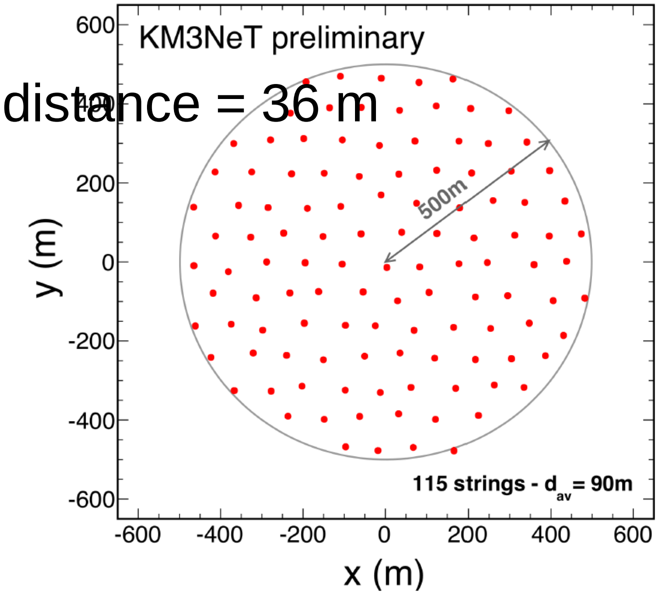
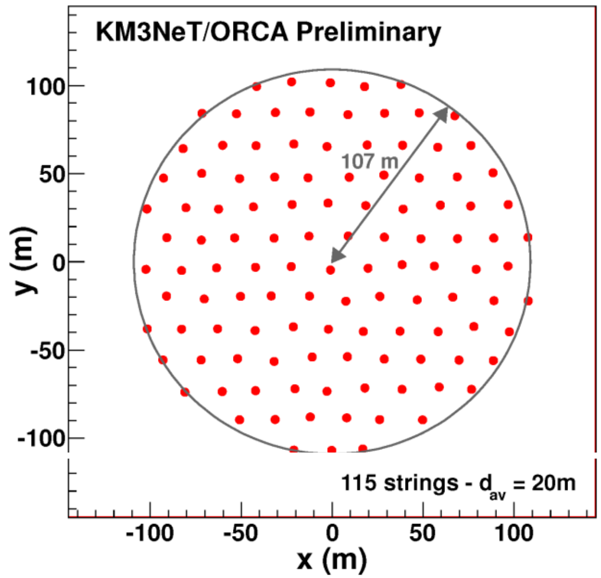


Vertical OM distance = 36 m

ORCA =

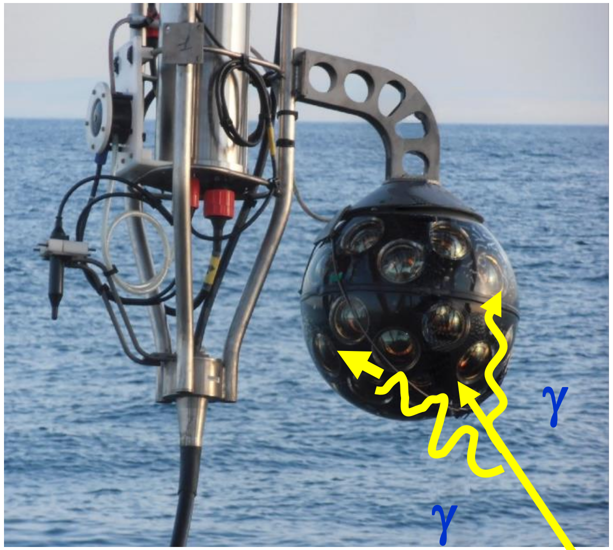
Oscillation Research with Cosmics in the Abyss



Vertical OM distance = 9 m

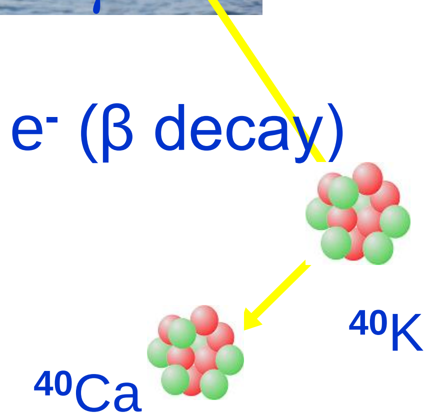
Results from prototypes and first string

DOM prototype (PPM-DOM)

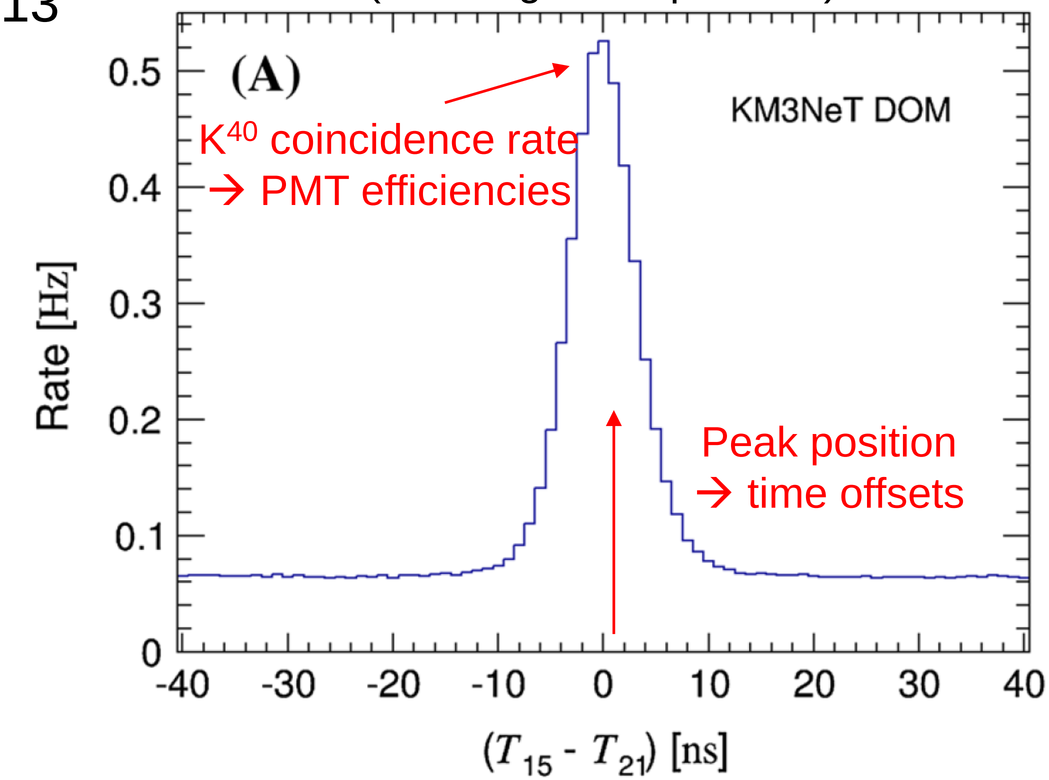


Deployed at ANTARES in April 2013

Up to 150 Cherenkov photons per decay



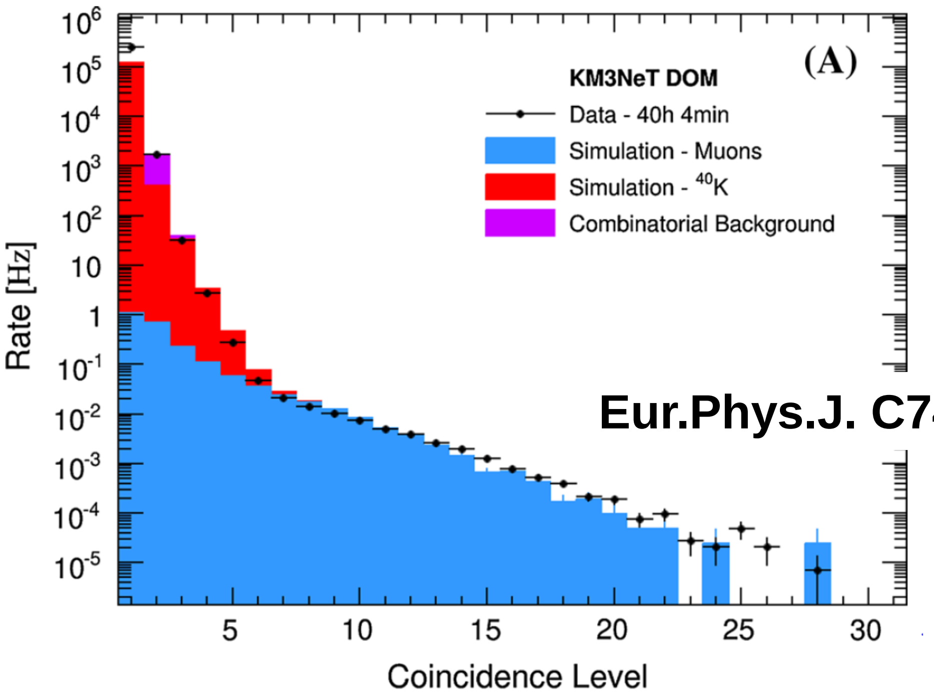
Coincidence rate on 2 adjacent PMTs (33° angular separation)



Eur.Phys.J. C74 (2014) 3056

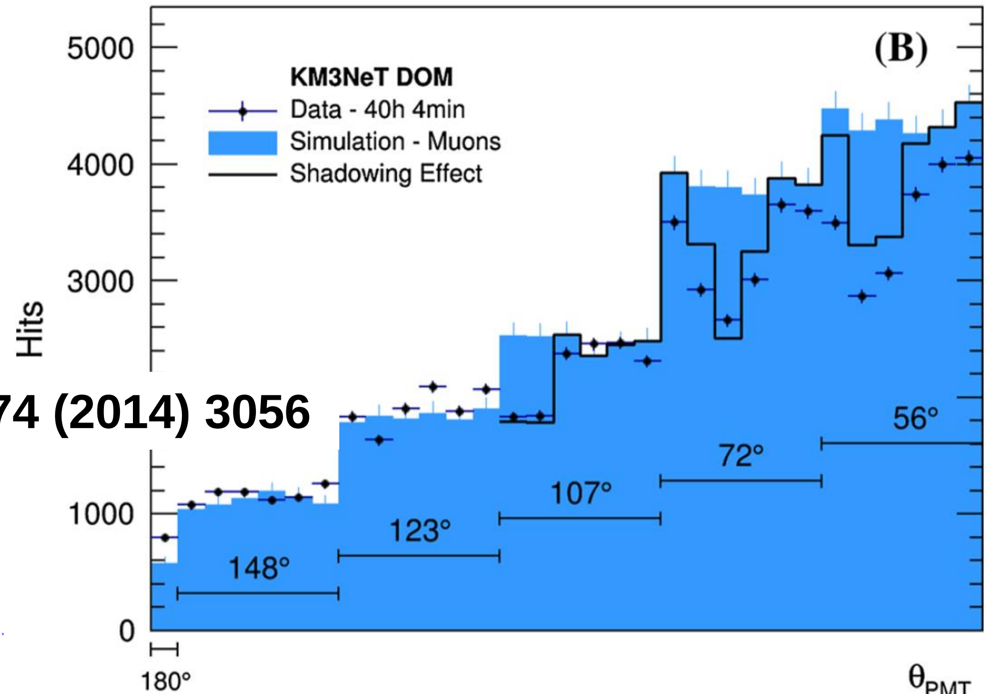
Concentration of ^{40}K is stable
(coincidence rate ~5 Hz on adjacent PMTs)

PPM-DOM: Atmospheric Muons



Number of coincident hits in a DOM

Eur.Phys.J. C74 (2014) 3056

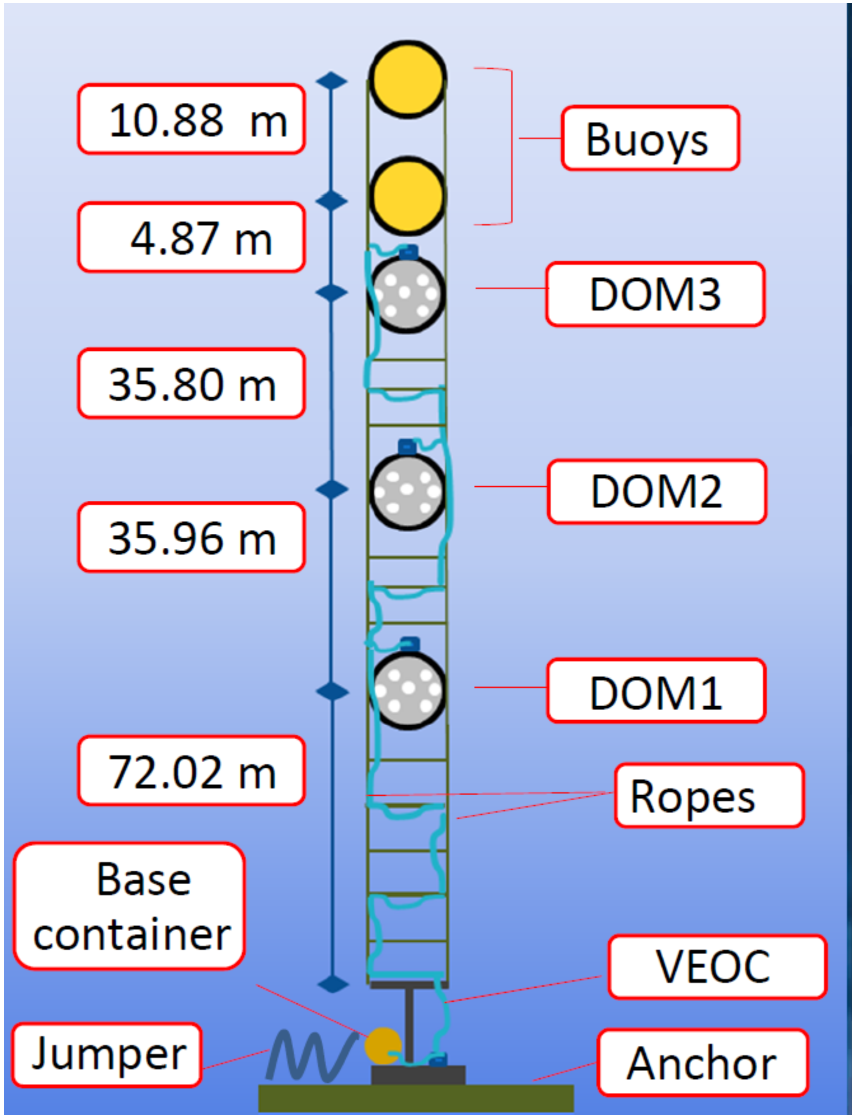


Zenith angle of hit PMTs in events with more than 7 coincident hits

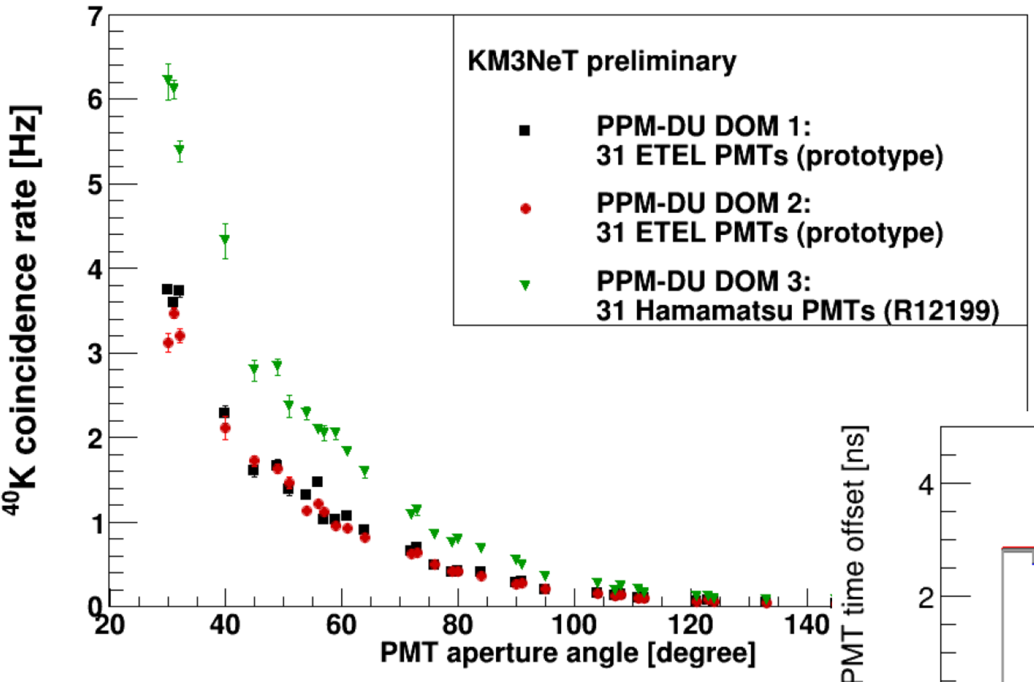
>5 coincidences within 20ns ⇒ reduced K40 contribution, dominated by atmospheric muons

More upper PMTs in multi-hit events ⇒ directional information from single storey

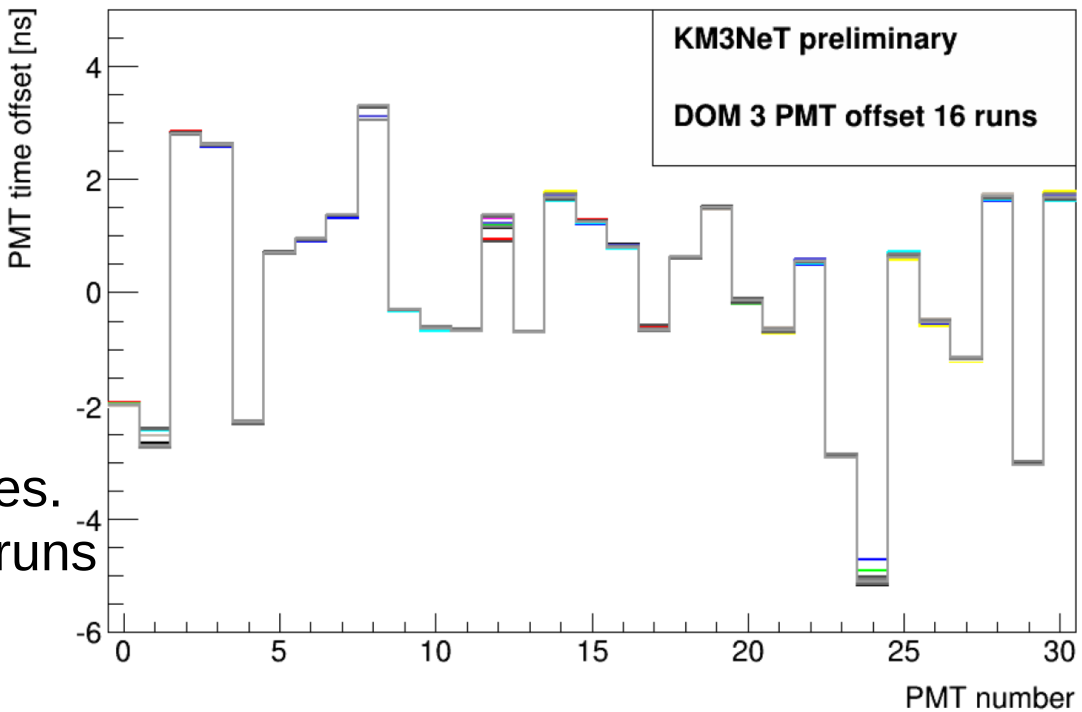
DU prototype (PPM-DU): 3 DOMs



PPM-DU: Intra-DOM timing



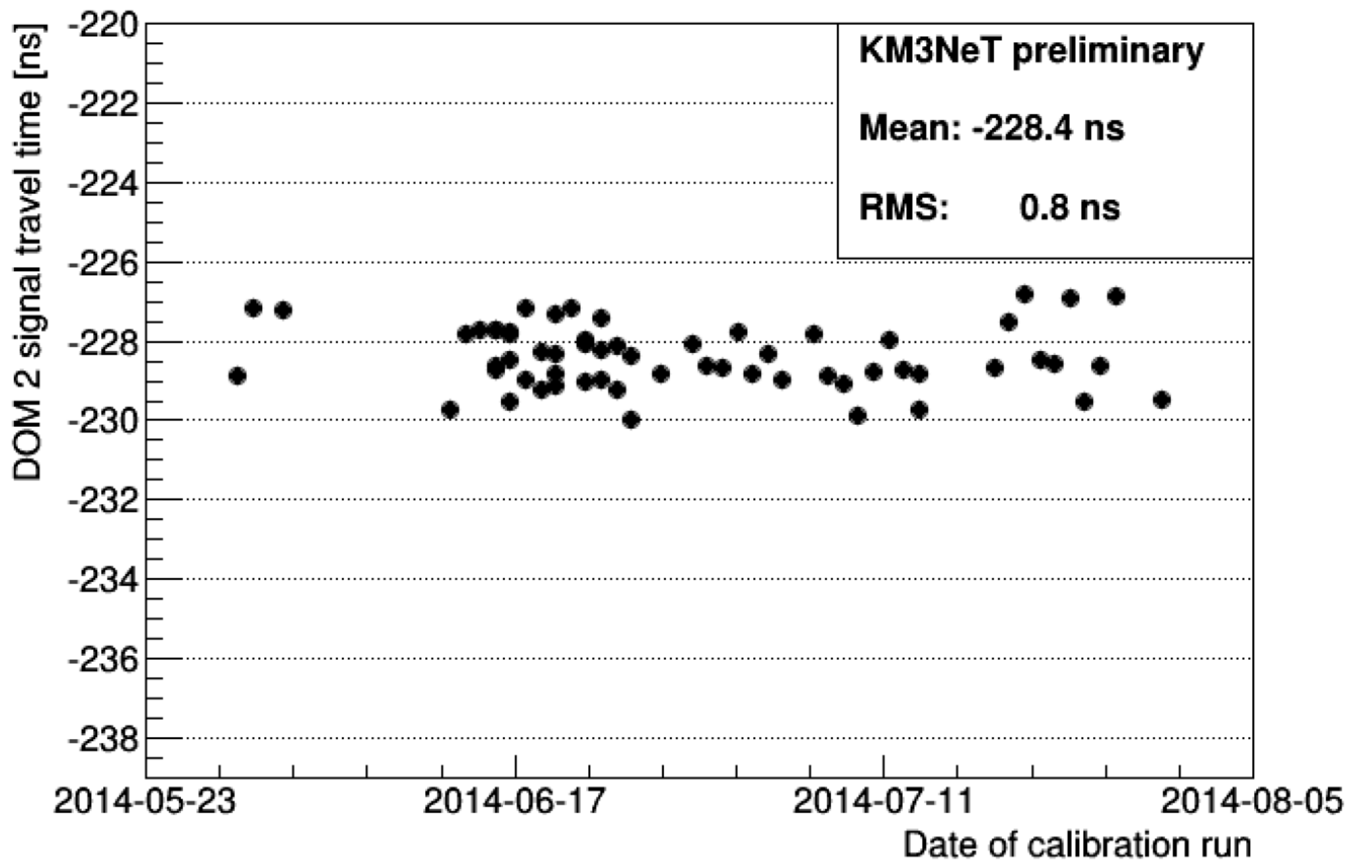
K40 coincidence rate as a function of the angle between PMTs.
Note: Different PMT types!



Relative timing calibration of 31 PMTs in DOM using coincidences.
Note: Extremely stable over many runs

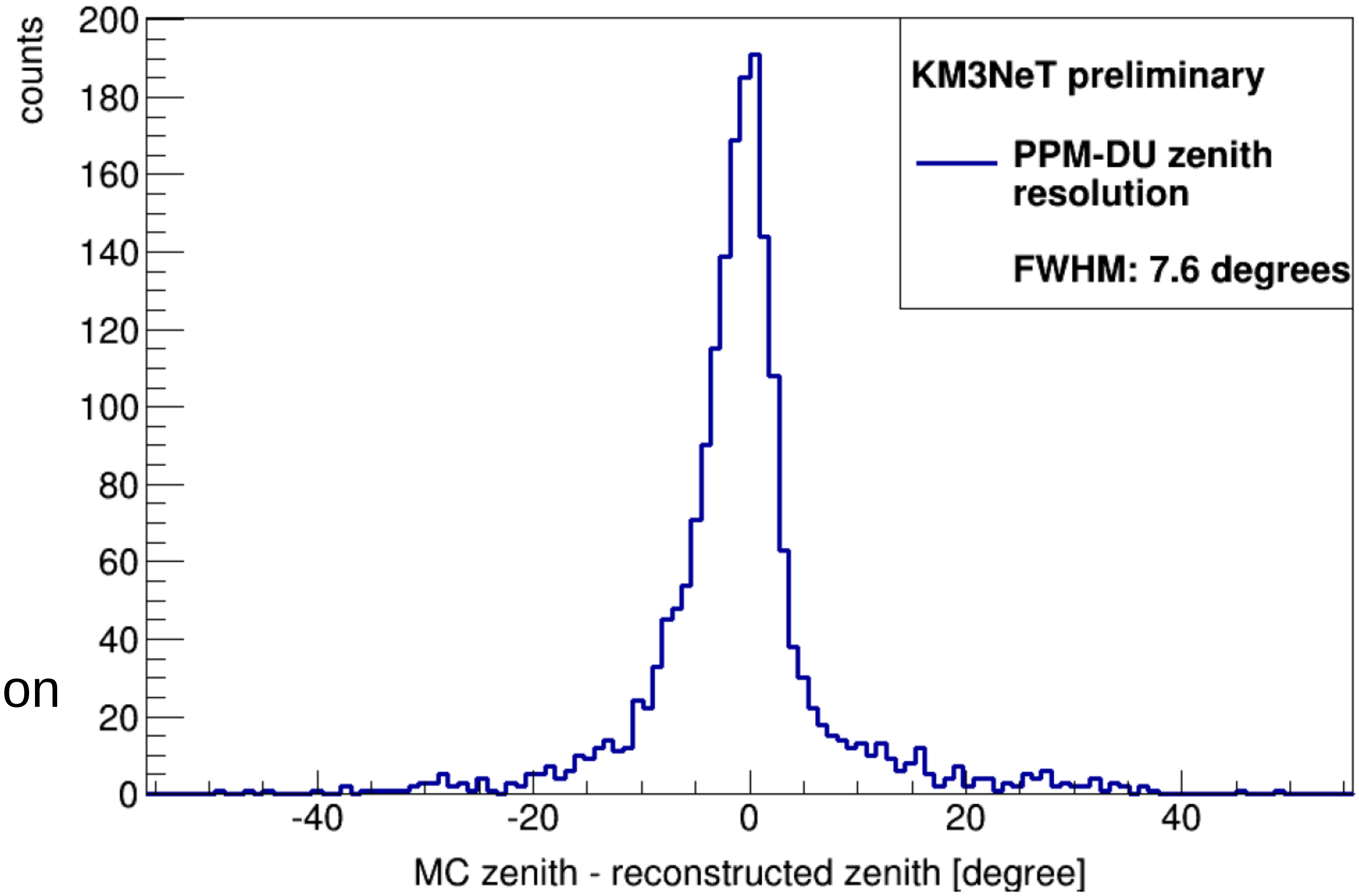
PPM-DU: Inter-DOM timing

- Calibration with pulsed LED
- Time difference – light travel time = Signal travel time
- Result very stable over several months, RMS of jitter < 1 ns



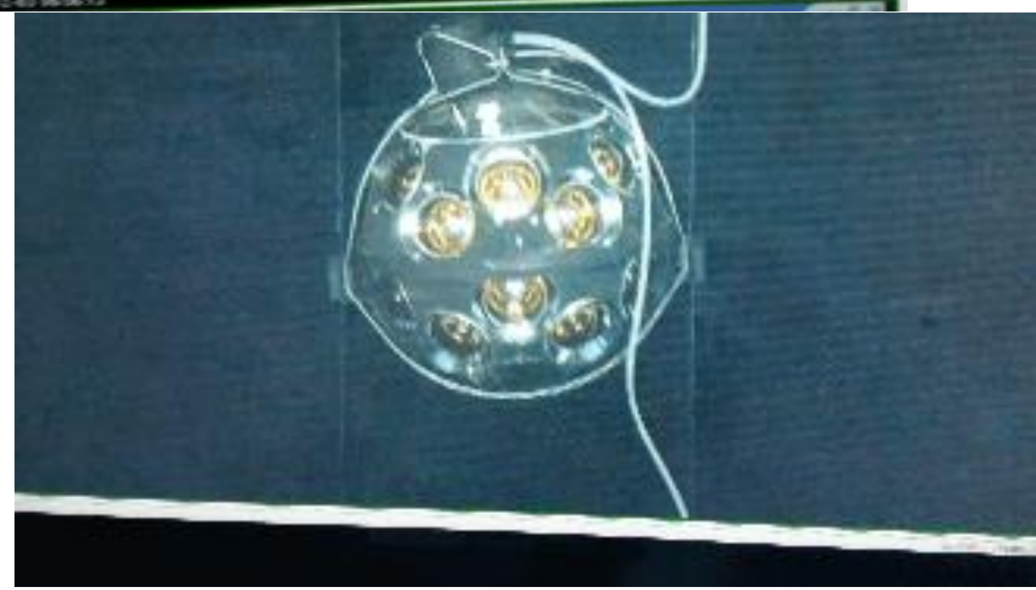
PPM-DU: Muon reconstruction

- Reconstruct muon trajectory from hits on 3 DOMs
- Ambiguities can be reduced by cuts on time differences
- 7° FWHM resolution achieved



First string deployed on 3 Dec 2015

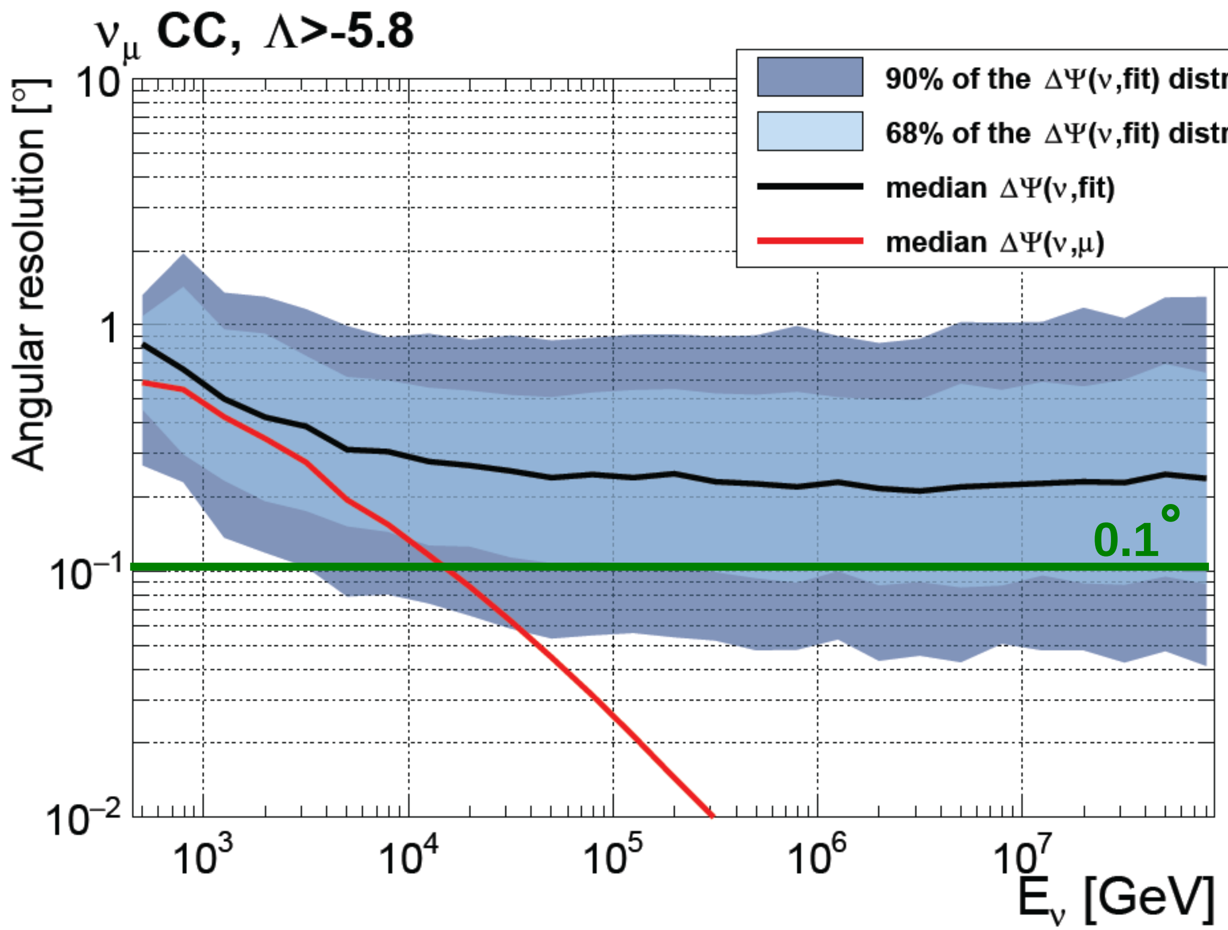
- Smooth operation
- All 18 DOMs alive and functional
- First muons reconstructed within hours after switch-on
- Data taking in progress
- Breaking news: Very first neutrino candidate on 5 Jan 2016



Neutrino astronomy: Selected sensitivity studies

Muon angular reconstruction

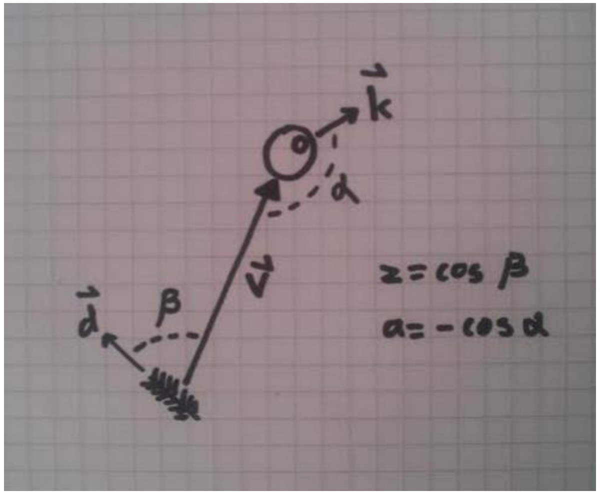
- Reconstruction using new PMT response simulation:
  Median of angle ΔΩ between reconstructed μ and true ν direction

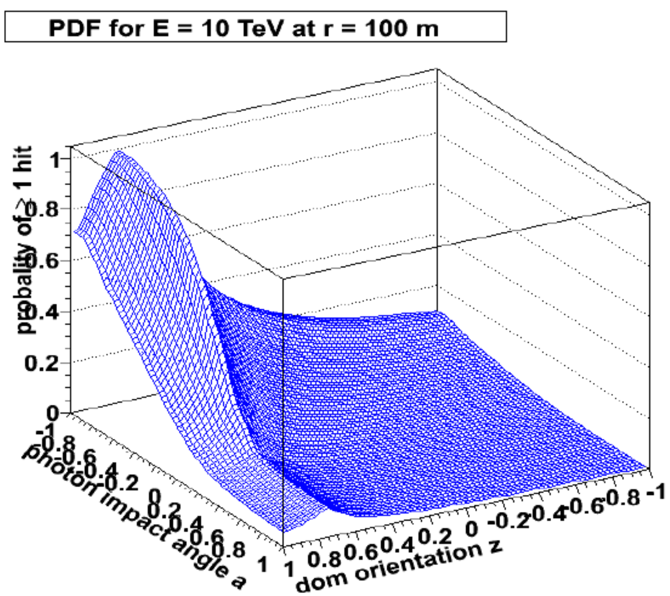


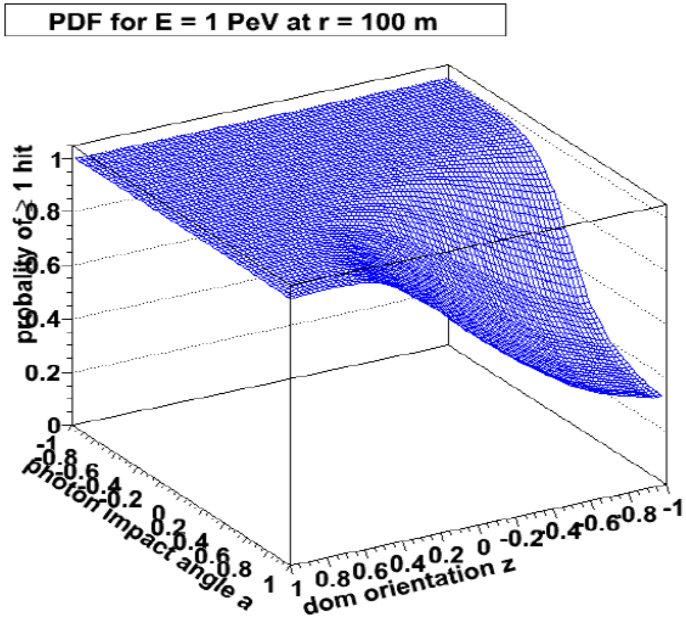
Expected μ reconstr. precision

Shower reconstruction: Method

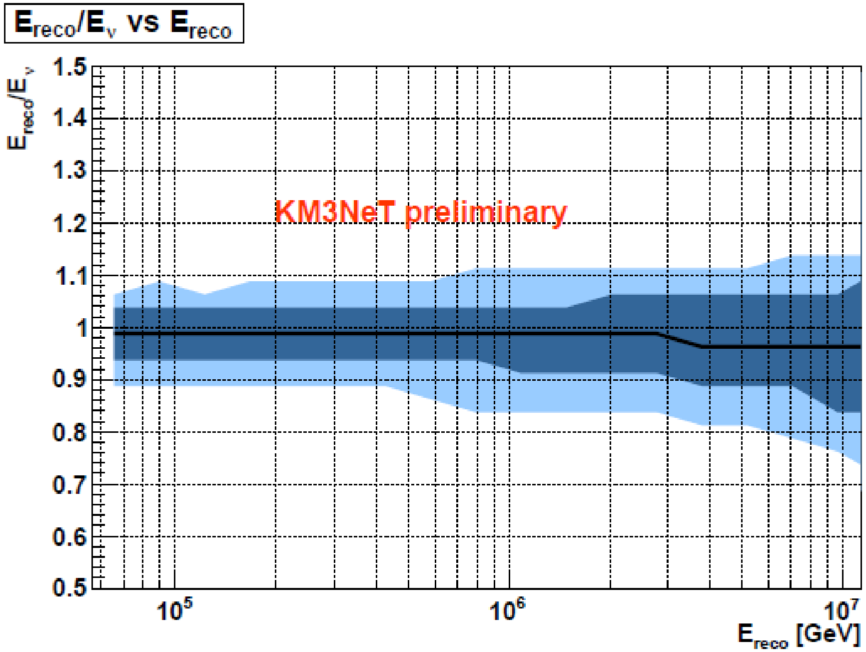
- Vertex fit: Suitable hit selection, fit uses timing; result used for containment requirement
- Direction and energy: Uses PDF depending on
  - Distance vertex – DOM
  - Angle between shower direction and DOM
  - Orientation of PMTs
- Hit information used: yes/no

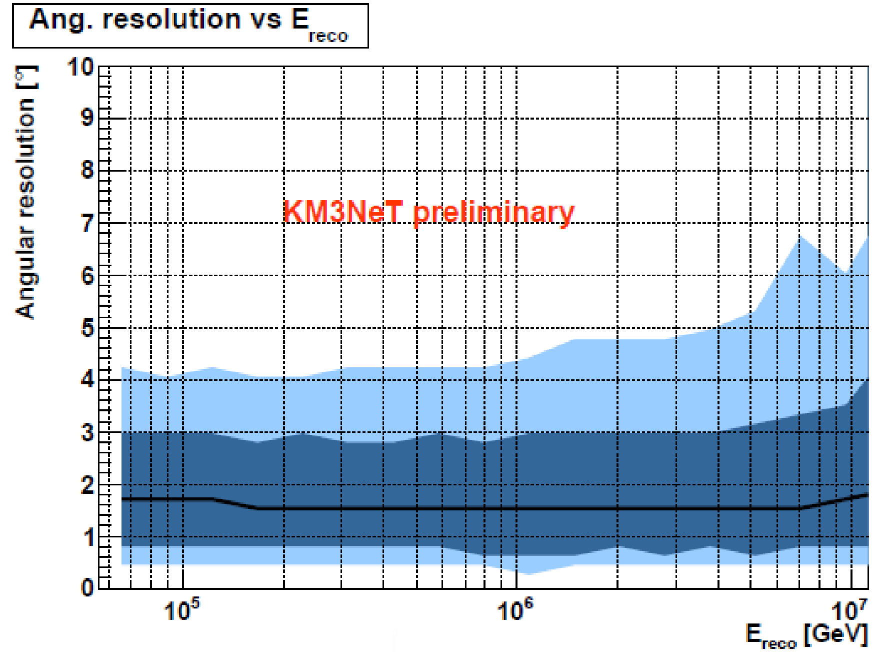






Shower reconstruction: θ, E





- For contained ν_e CC events
- Event sample after selection cuts
- ~10% in E, better than 2° in direction
- Systematic effects very small

Analysis scheme

- All analyses proceed through 4 consecutive steps:
  1. Preselection (e.g. quality cuts or cuts on reconstructed zenith or N_{hit})
  2. Further background rejection by Boosted Decision Tree
  3. 'Cut-and-count' significance analysis
  4. Maximum-likelihood analysis using likelihood ratio

$$\mathrm{LR} = \sum_{k=1}^{n} \log \frac{\frac{n_{\mathrm{sig}}}{n} \cdot P_{\mathrm{sig}}(X_k) + \left(1 - \frac{n_{\mathrm{sig}}}{n}\right) \cdot P_{\mathrm{back}}(X_k)}{P_{\mathrm{back}}(X_k)}$$

Significance determined by generating pseudo-experiments

Note: All detector information is in the probability density functions P(X), where the event variables X depend on the type of analysis.

- Main results:

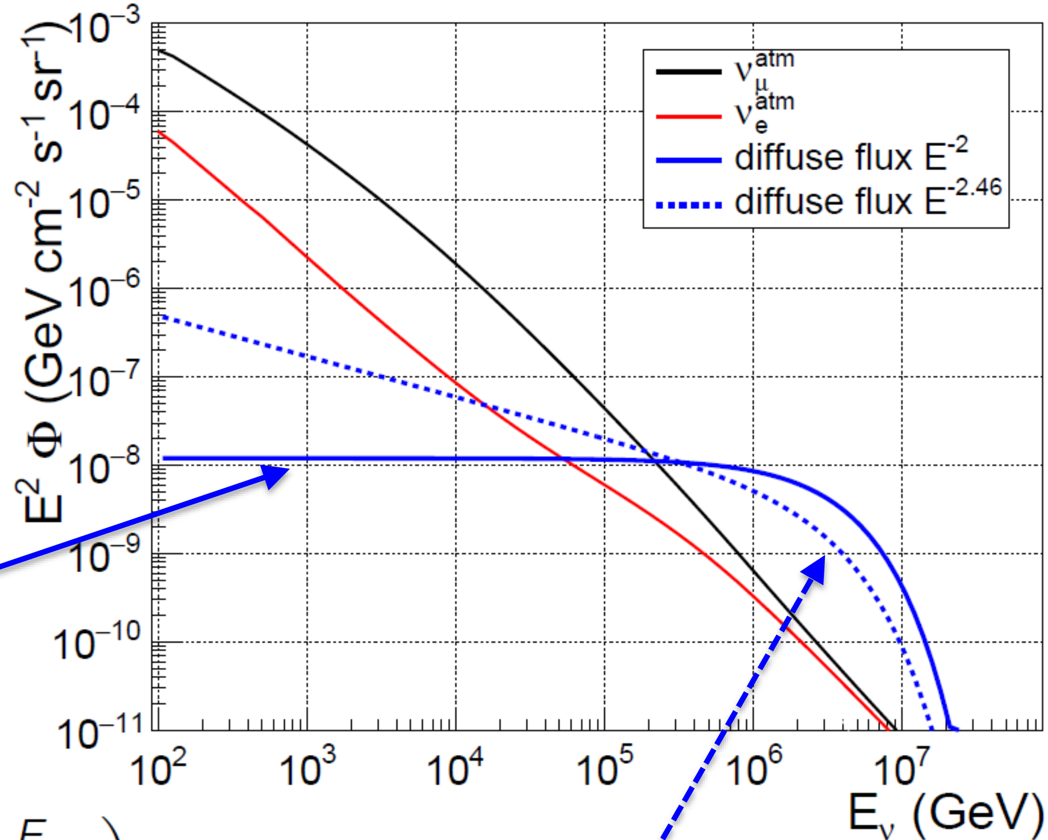
→ Event samples with high signal content from step (3)

→ Optimised sensitivities from step (4)

Diffuse extragalactic neutrino flux

Assumptions:

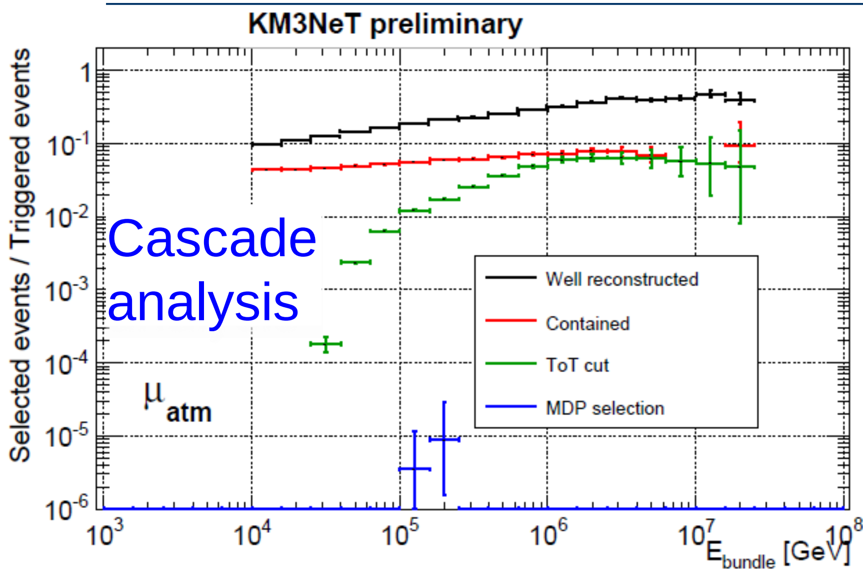
1. Flavour-symmetric
2. Isotropic
3. Energy spectrum consistent with IceCube findings

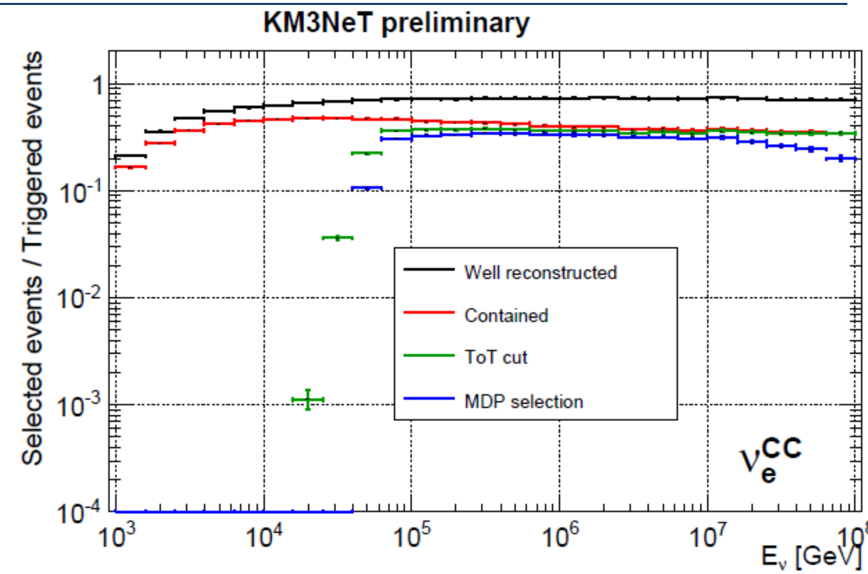


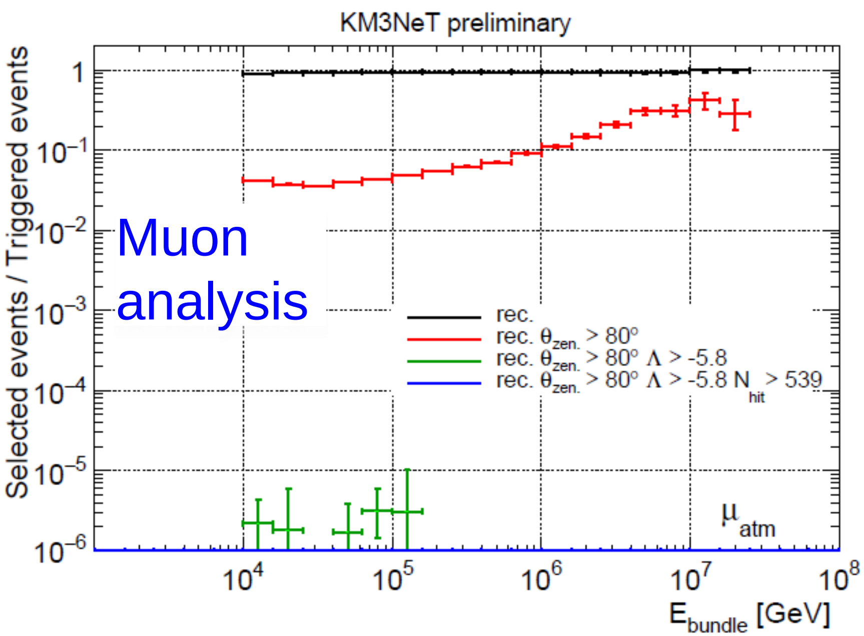
$$\Phi(E_\nu) = 1.2 \times 10^{-8} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right) \quad \mathrm{GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

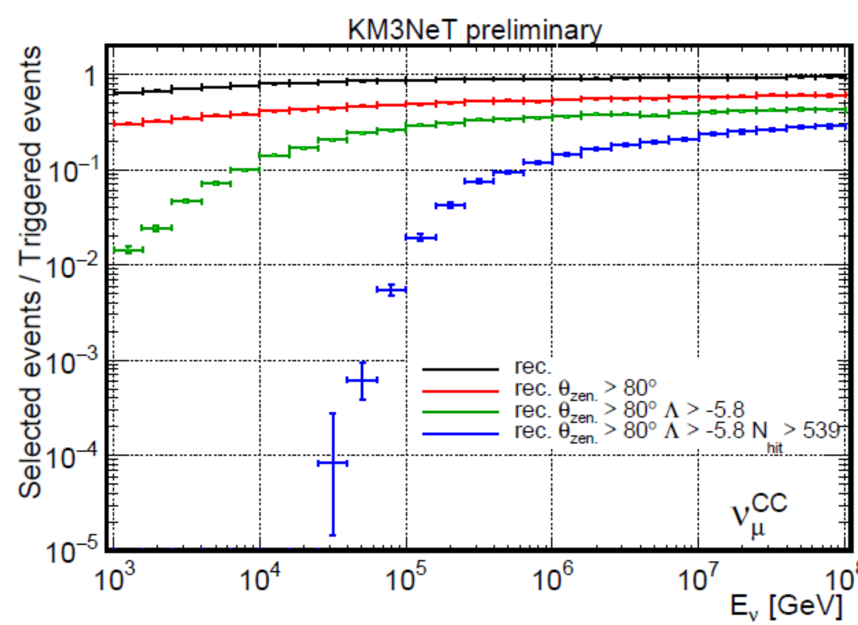
$$\Phi(E_\nu) = 4.11 \times 10^{-6} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2.46} \cdot \exp\left(-\frac{E_\nu}{3\,\mathrm{PeV}}\right) \quad \mathrm{GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Signal/background separation

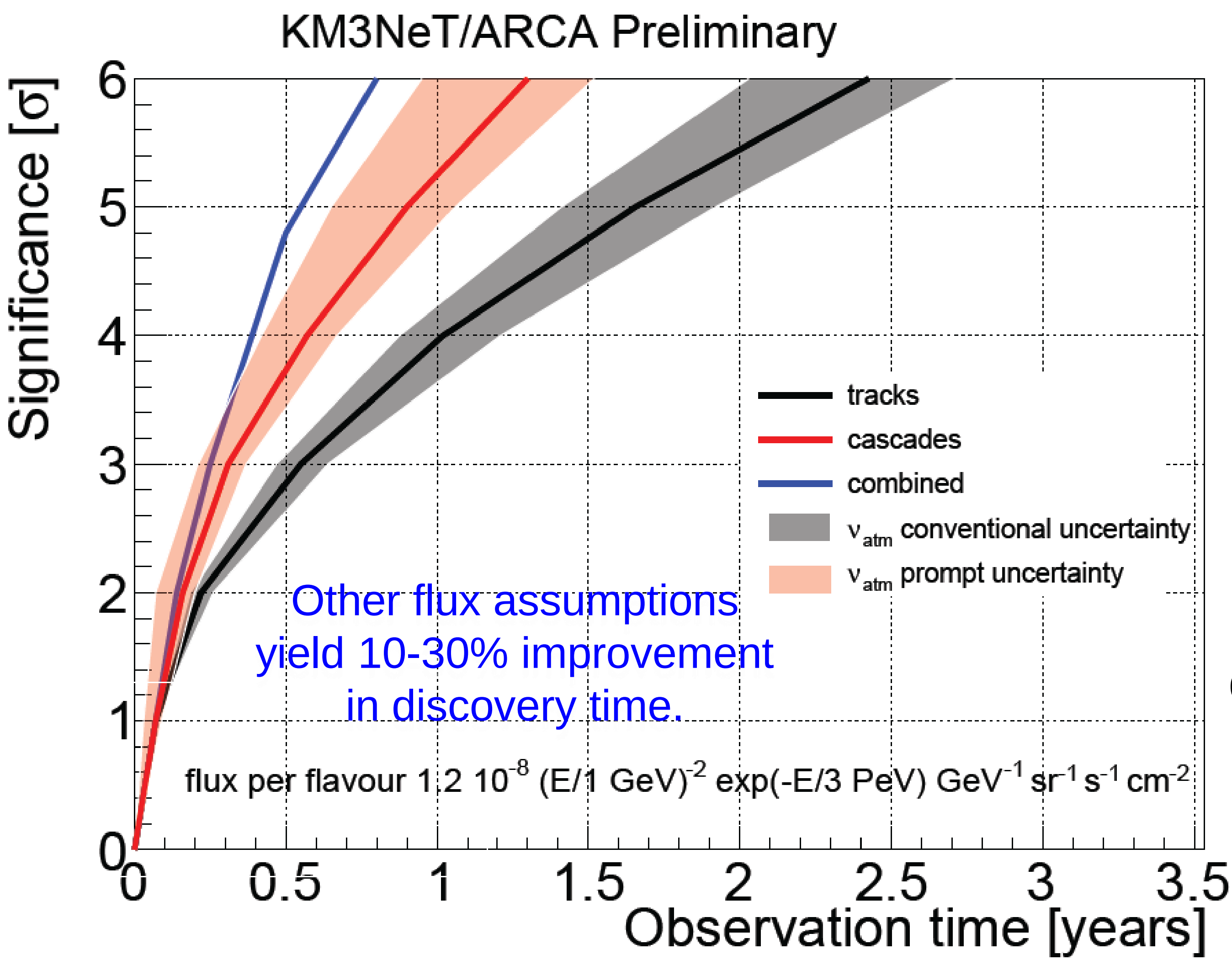








Diffuse flux results (max. liklihood)



Event numbers (cut&count):

16/9 cascades

7.5/5 track-like

(signal/background per ARCA year)

Note:

For each energy, direction and flavour, KM3NeT is complementary to IceCube

Diffuse flux from galactic plane

- New model by D. Gaggero at al.
(spatially dependent diffusion coefficient in galactic centre/plane)

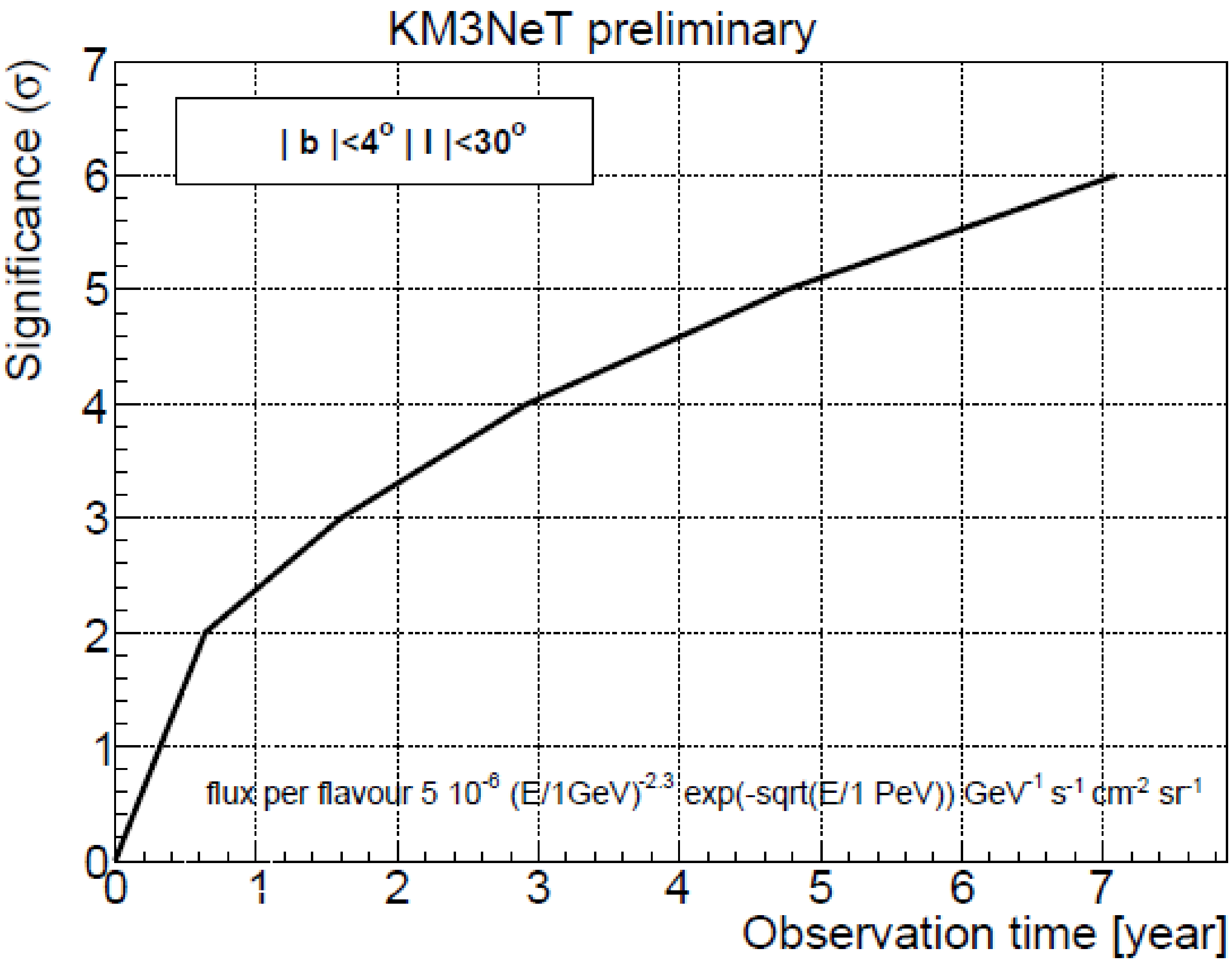
- Neutrino flux prediction for central part of Galaxy
(longitude |l| < 30° and latitude |b| > 4°):

$$\frac{\mathrm{d}\phi}{\mathrm{d}E_\nu} = 5 \times 10^{-6} \left(\frac{E_\nu}{1\,\mathrm{GeV}}\right)^{-2.3} \cdot \exp\left(-\sqrt{\frac{E_\nu}{1\,\mathrm{PeV}}}\right) \quad \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

per flavour (small region but much higher flux than extragalactic)

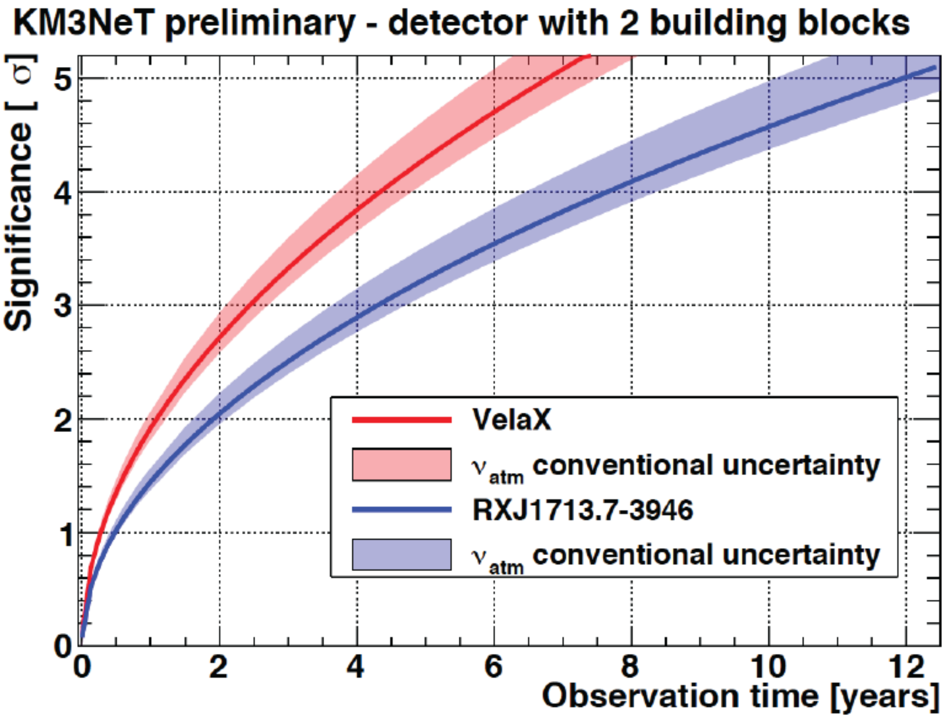
- Region very well visible for KM3NeT for up-going events
→ First analysis in muon channel

Galactic plane: First results



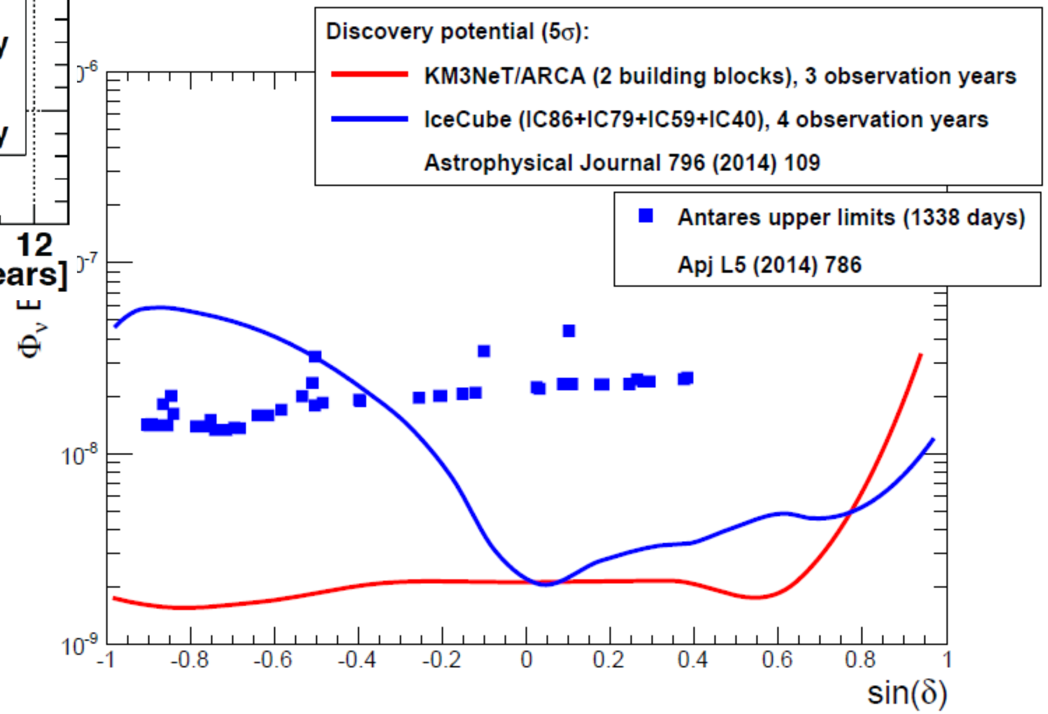
- Discovery in 4-5 years
- Inclusion of cascade channel will improve this result
- Confirmation of this flux: major breakthrough in astrophysics

Point-source results

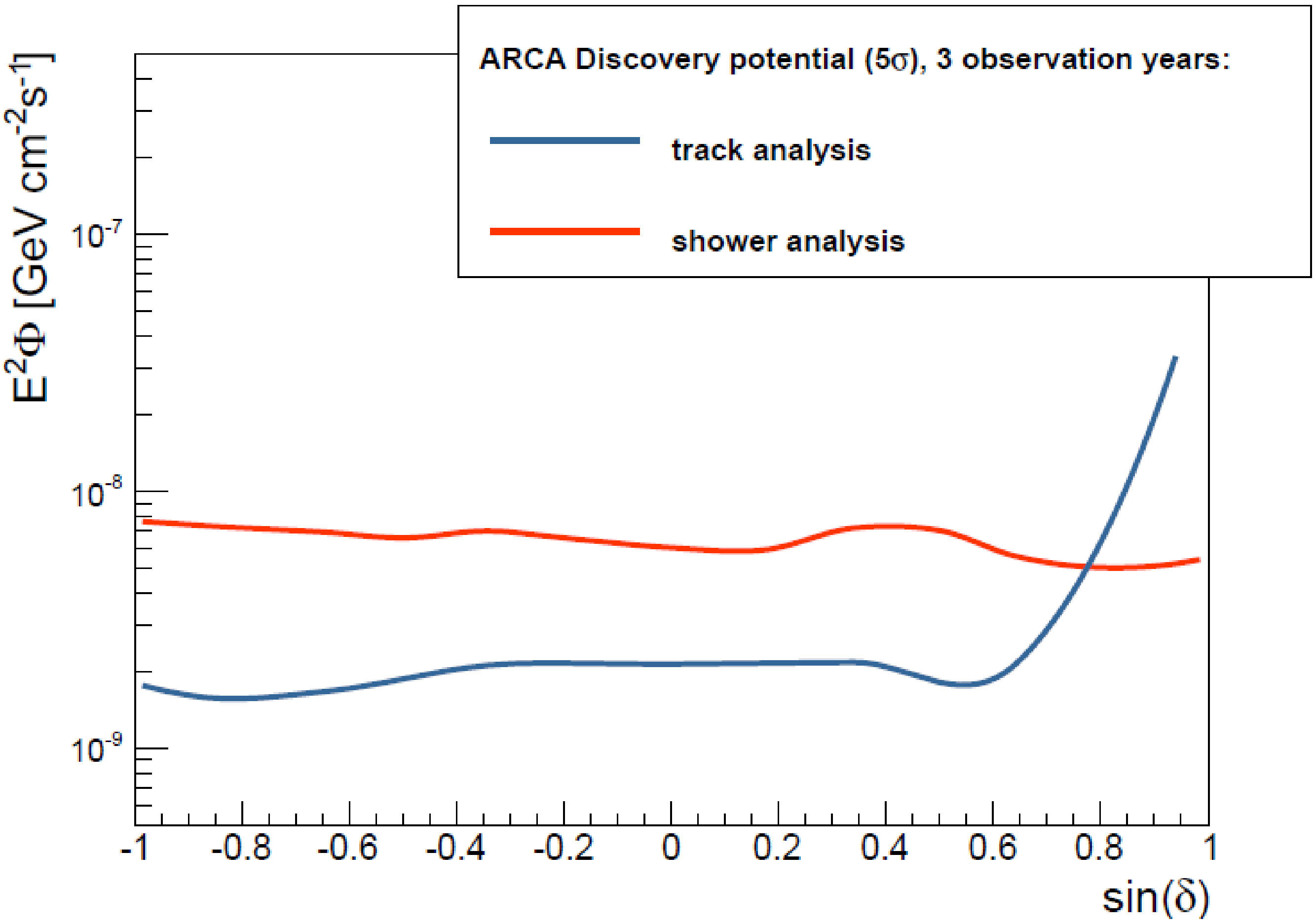


- Galactic sources in reach

- Significant discovery potential for extragalactic sources



Point-source search with cascades



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

… concluding

Summary and outlook

- The KM3NeT neutrino telescope has entered its first construction phase
- Results from prototypes and first string very encouraging
- ARCA & ORCA to follow in 2016-20, sensitivity complementary to IceCube
- Priority science goals:
  - All-flavour neutrino astronomy
  - Measurement of the neutrino mass hierarchy

Stay tuned!