The KM3NeT Neutrino Experiment

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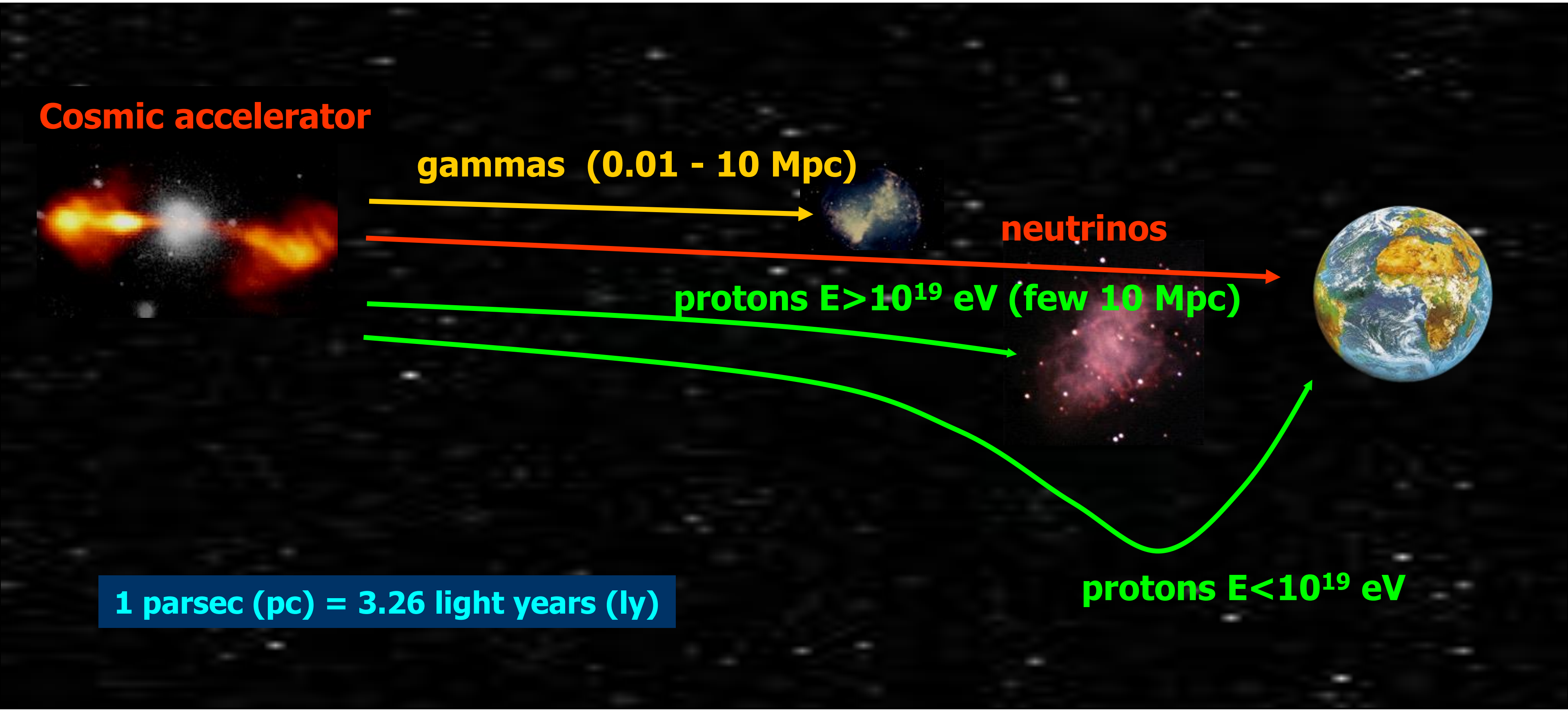
Overview

- Introductory remarks
- Neutrino astronomy: Where are we?
- KM3NeT: Design and prospects
- KM3NeT: Status
- Neutrino telescopes and neutrino physics

Neutrino Astronomy

High-energy particle propagation in Universe



Photons: absorbed on dust and radiation;
Protons/nuclei: deviated by magnetic fields, reactions with radiation (CMB)

Neutrino production mechanism

- Neutrinos are produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \to \pi^{\pm}(K^{\pm}\ldots) + Y \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) + Y$$

$$\downarrow$$

$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_\mu(\nu_\mu)$$

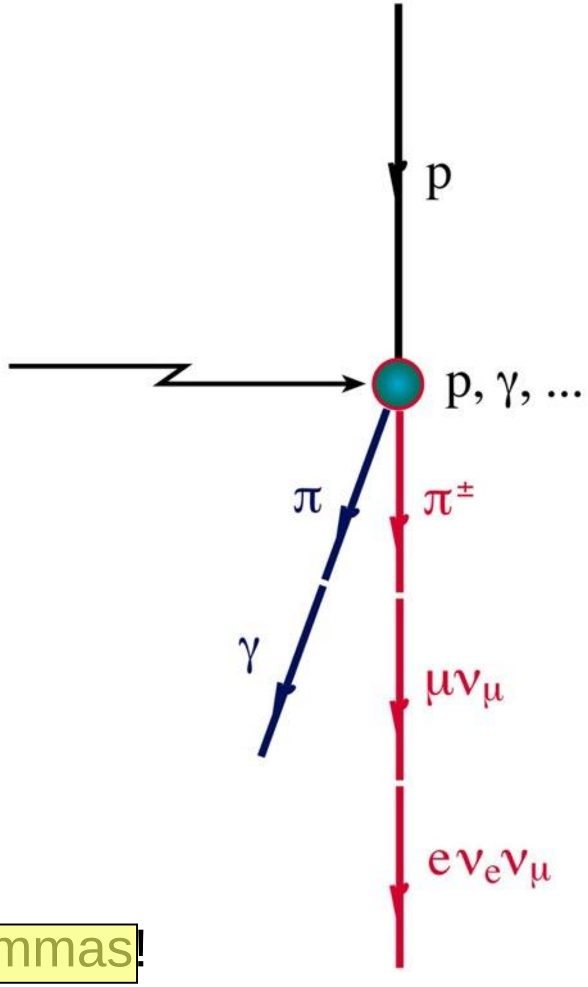
Cosmic rays

- Simultaneously, gamma production takes place:

$$N + X \to \pi^0 + Y \to \gamma\ \gamma + Y$$

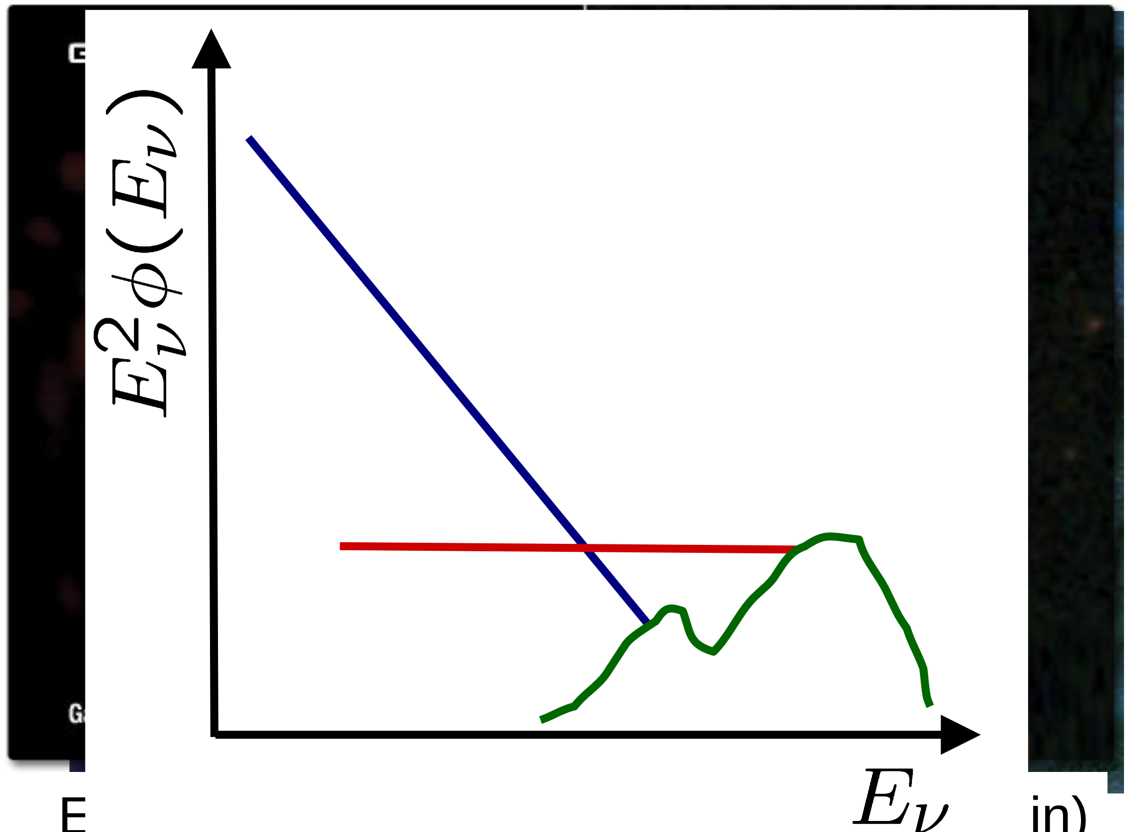
Cosmic rays

- Cosmic ray acceleration yields neutrinos and gammas!
- … but gammas also from purely leptonic processes



Example targets of ν astronomy

- Galactic neutrino sources
- Extragalactic sources
- Transient sources
- Diffuse neutrino flux
- Neutrinos from Dark Matter annihilations
- Particle physics with atmospheric neutrinos
- Search for exotics (monopoles, nuclearites,…)



E in)

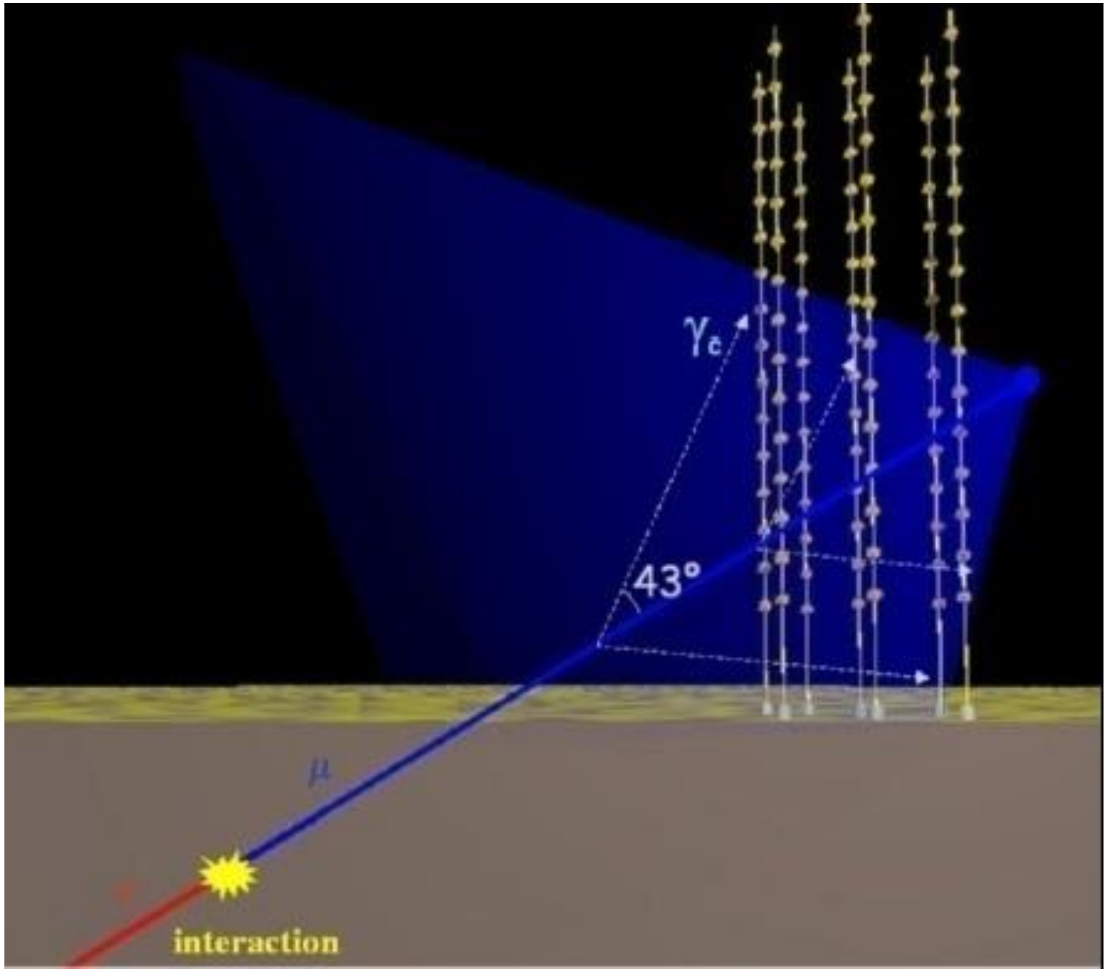
. xy

Isotropic high-energy neutrino flux above atmospheric neutrino background from unresolved astrophysical sources or of cosmogenic origin (GZK)

Neutrino Telescopes

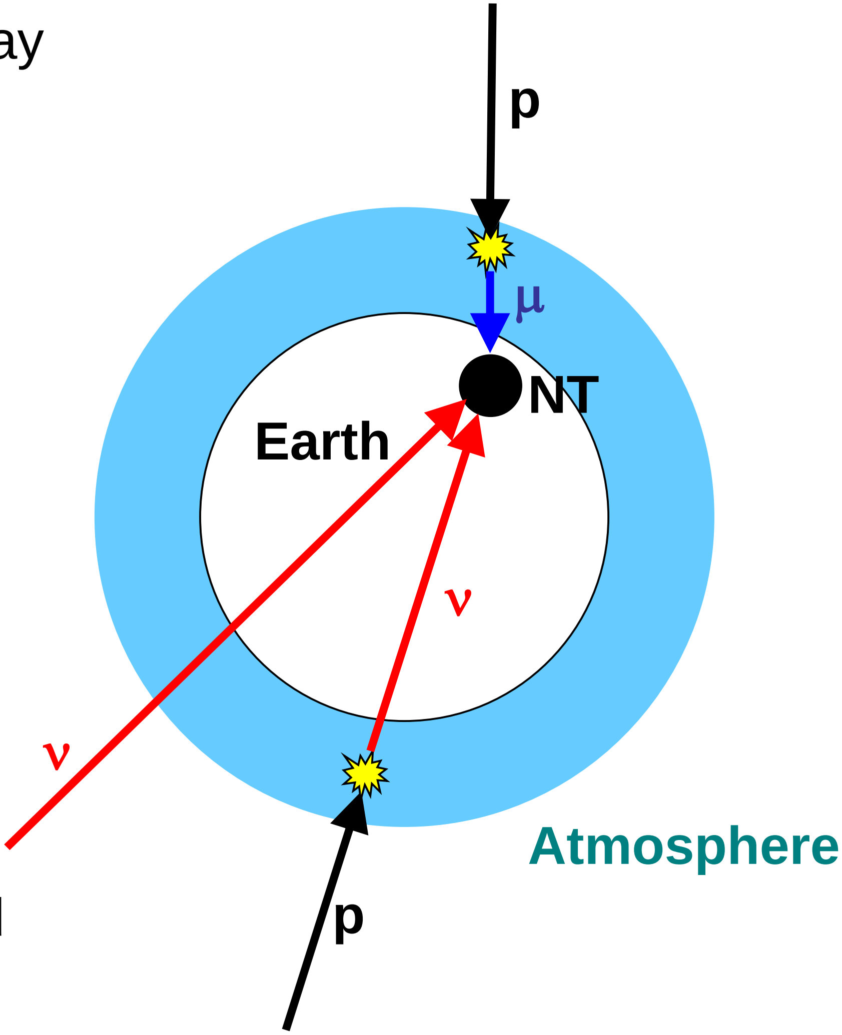
How does a neutrino telescope work?

- Neutrino interacts in the (vicinity of the) telescope
- Charged secondaries cross the detector volume (water or ice) and stimulate Cherenkov emission
- Recorded by a 3D-array of photo-sensors
- "Traditional" channel: $\nu_\mu + N \rightarrow \mu + X$
- Energy range : 10(0) GeV – some PeV

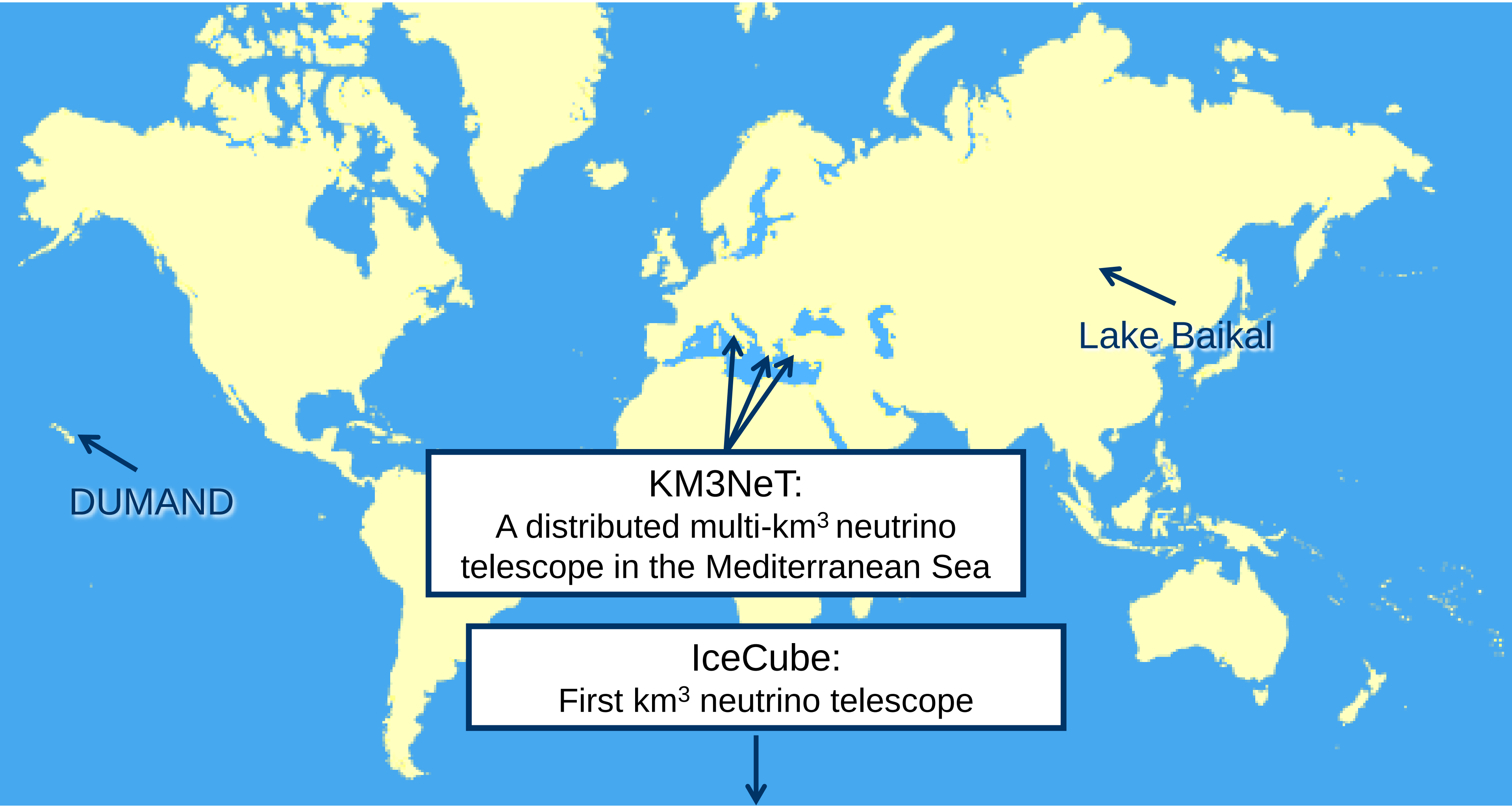


Backgrounds, or maybe not

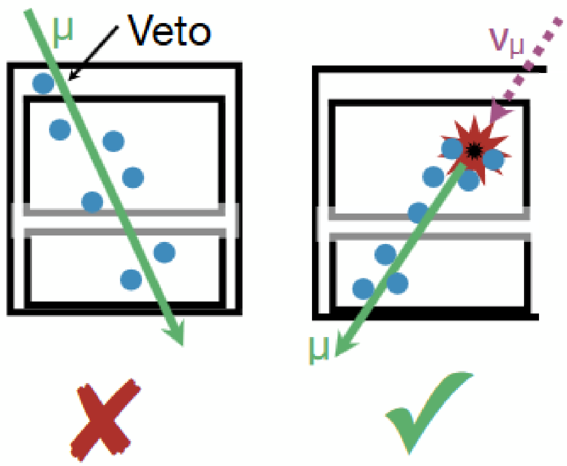
- Atmospheric neutrinos from cosmic-ray interactions in atmosphere
  - irreducible
  - important calibration source
  - allow us to study oscillations
- Atmospheric muons from cosmic-ray interactions in atmosphere above NT
  - penetrate to NT
  - exceed neutrino event rate by several orders of magnitude
- Sea water: light from K40 decays and bioluminescence



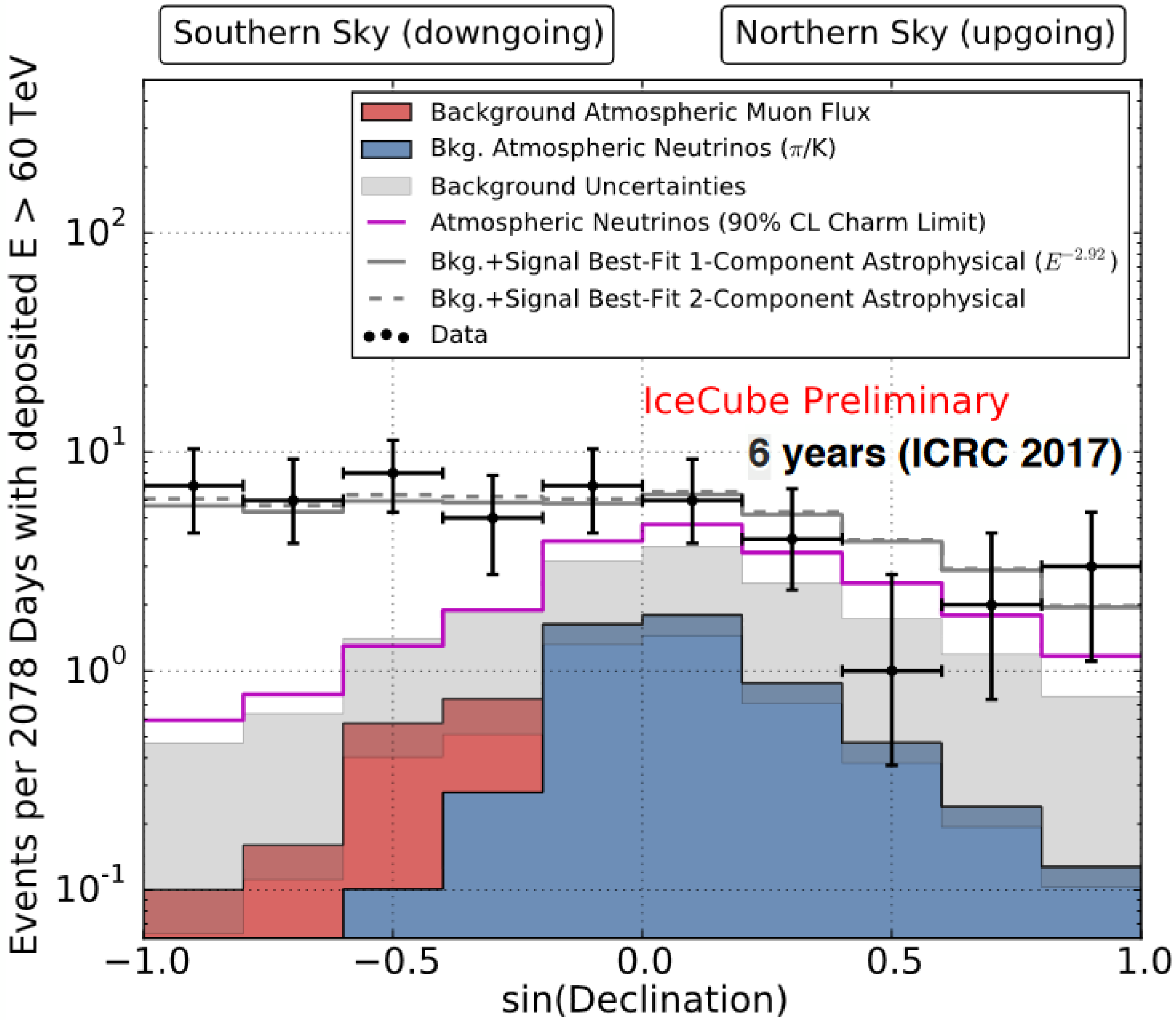
The ν telescope world map



IceCube: Cosmic neutrinos



- Selected events that start in IceCube volume
- **82 events in 6 years** (54 in 4 years)



Jakob van Santen, ICRC2017

And now?

- More and full-sky data needed to draw firm conclusions!
- Future projects: KM3NeT and IceCube-Gen2

KM3NeT:

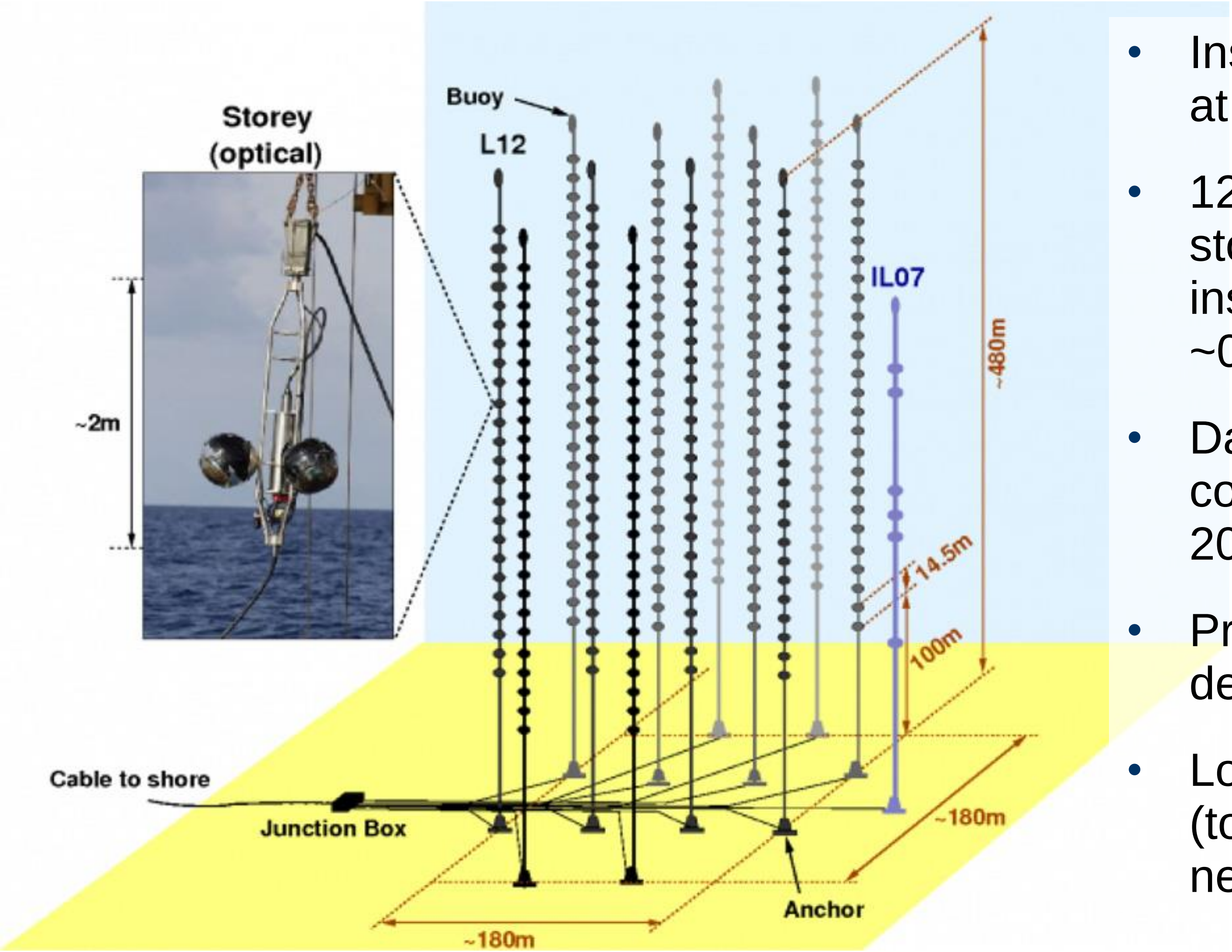
- KM3NeT-ORCA:
  Dense array, ν physics
  Construction 2018-
- KM3NeT-ARCA:
  High-energy ν telescope
  Construction 2018-

IceCube-Gen2:

- Phase 1 proposal:
  Dense array with 7 strings,
  R&D and ν/DM physics
  Construction 2021-
- Gen2:
  High-energy ν telescope
  Surface array
  Radio array ?
  PINGU?
  Construction ?

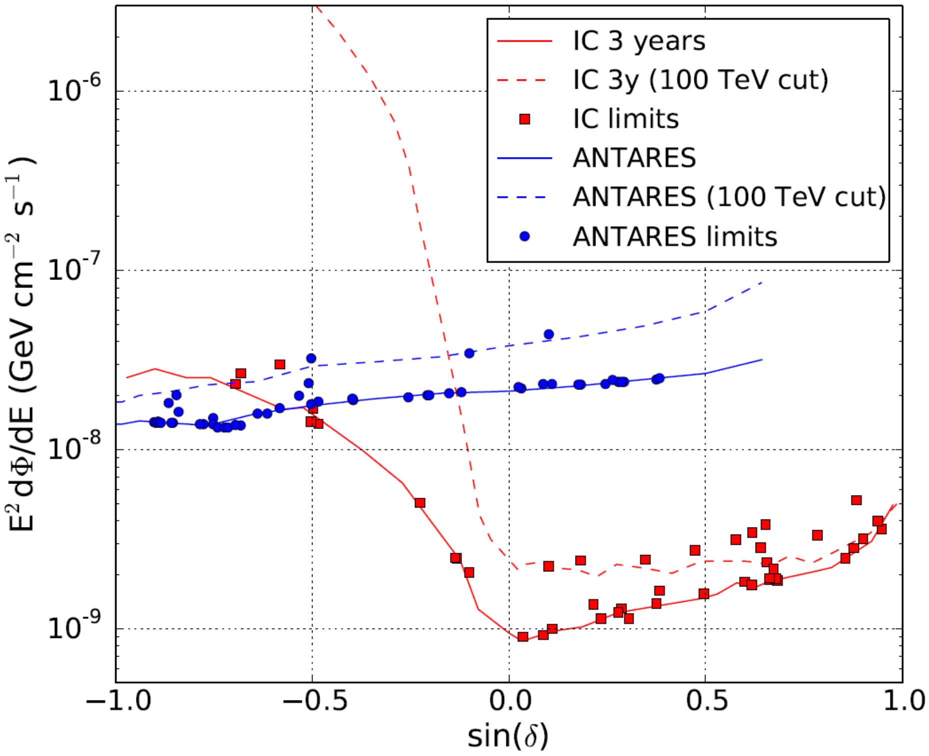
- And also: GVD in Lake Baikal

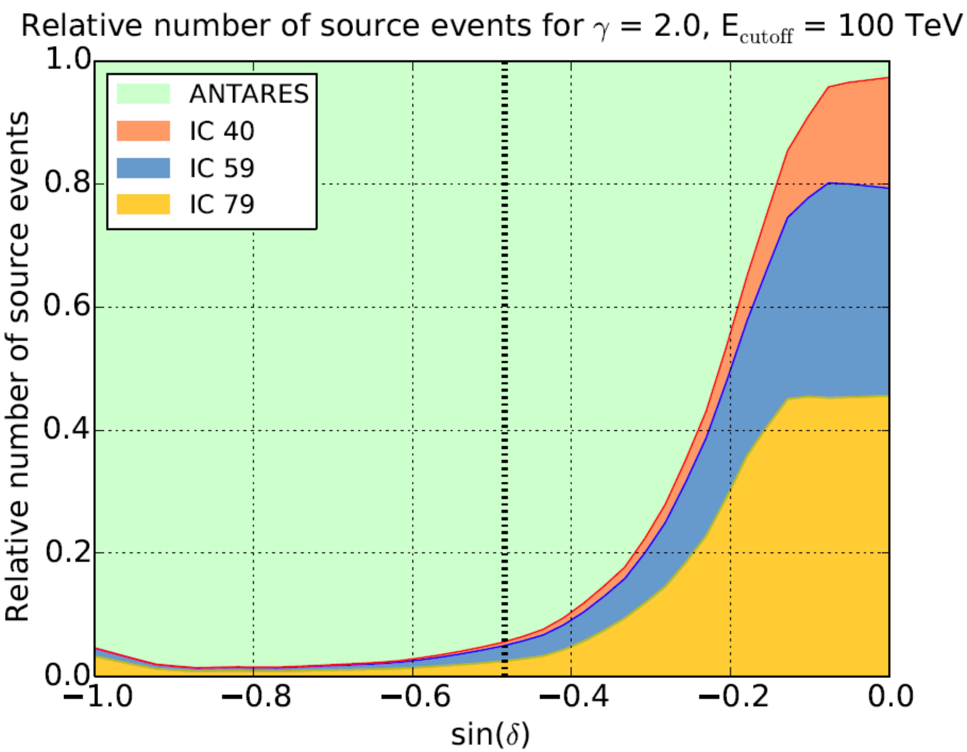
ANTARES: The first deep-sea ν telescope



- 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

ANTARES and IceCube: Combined analysis

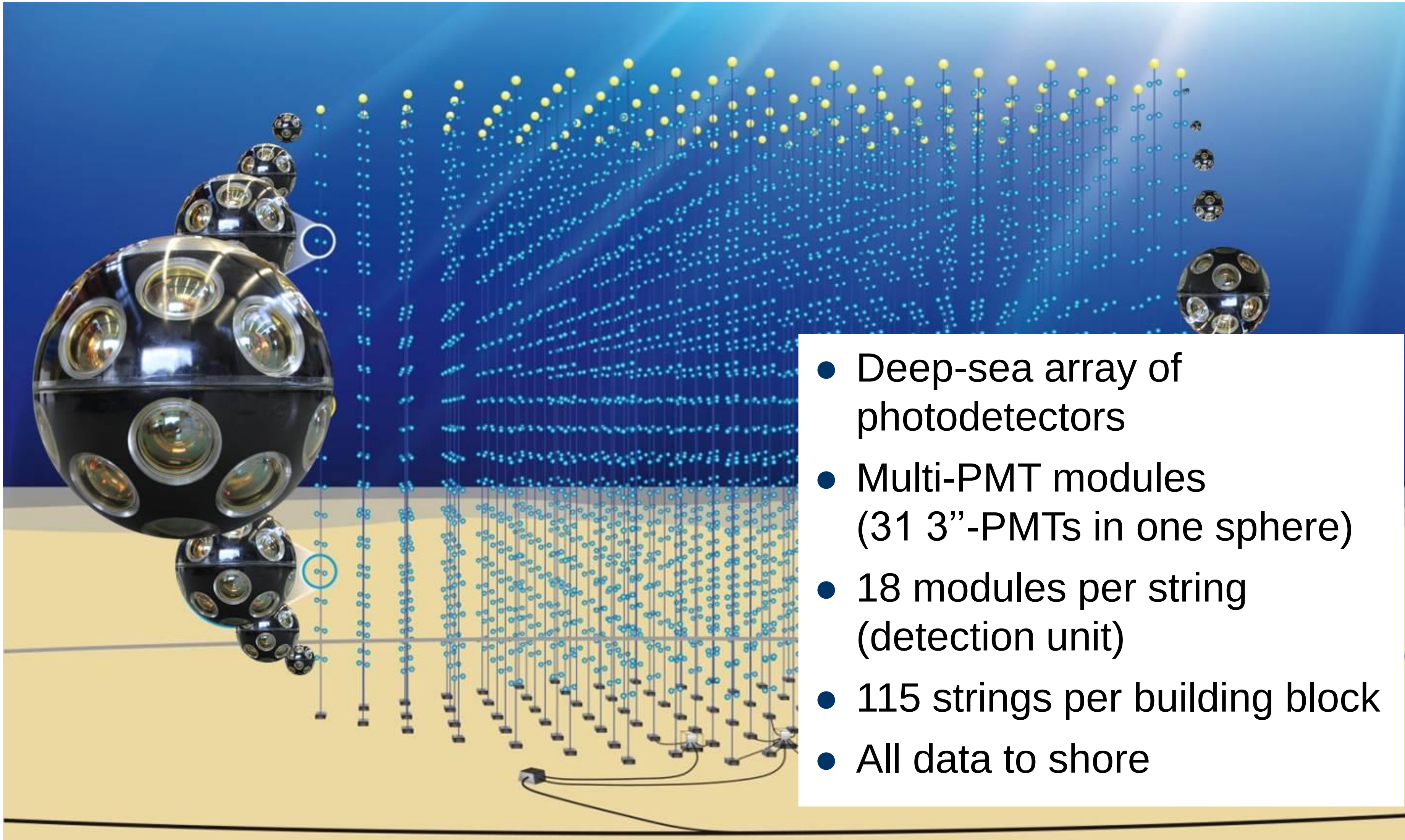




- Common analysis of ANTARES and IceCube data
- Search for point-like neutrino sources, spectrum ~ $E^{-\gamma}$ x cutoff(E_{cutoff})
- Substantial contribution from ANTARES for spectra with E_{cutoff} ~ 100 TeV

KM3NeT

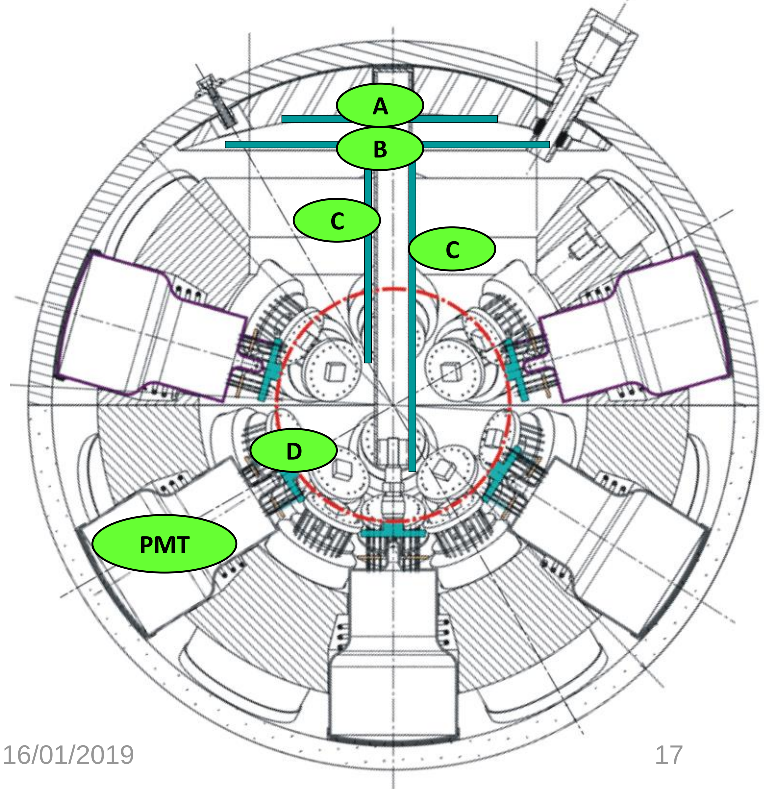
The KM3NeT concept



- 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 Digital Optical Module

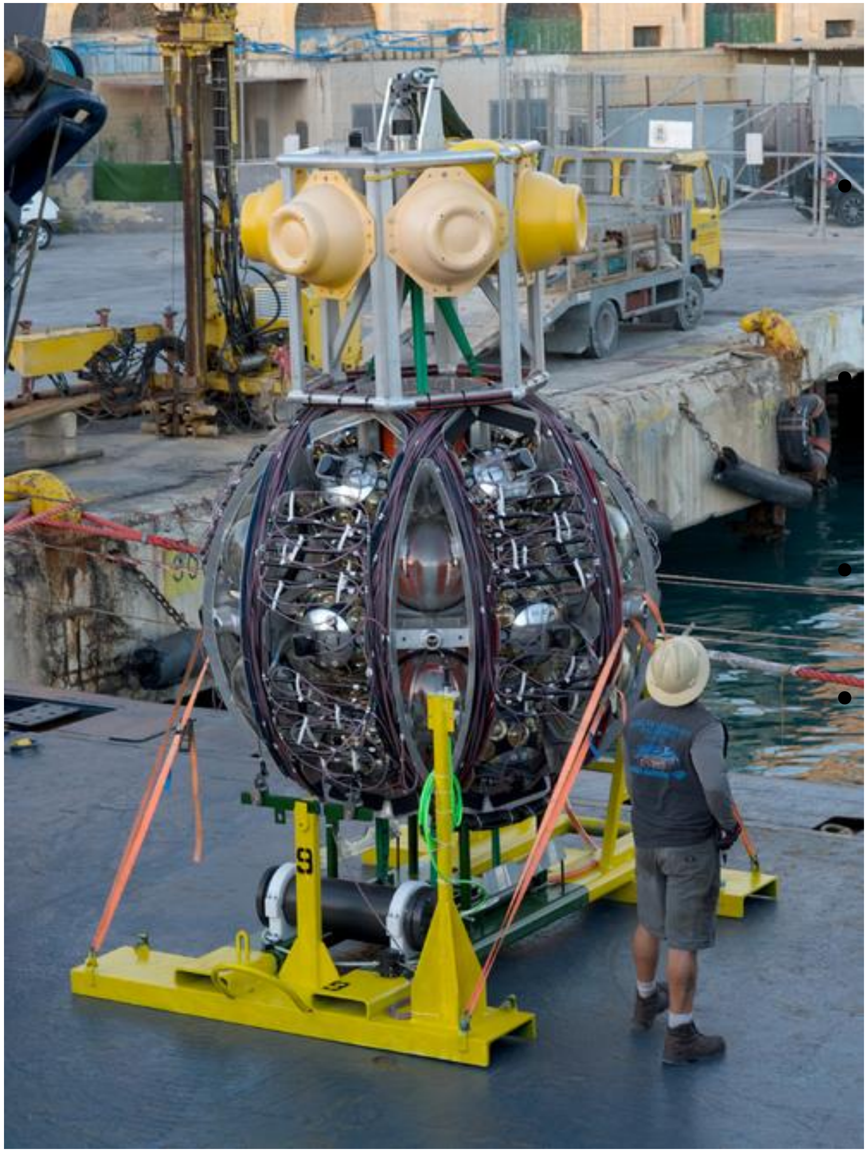
- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10-inch PMTs)
    - 19 in lower, 12 in upper hemisphere
    - Suspended by plastic structure
- 31 PMT bases (total ~140 mW) (D)
- Front-end electronics (B,C)
- Al cooling shield and stem (A)
- Single penetrator
- Advantages:
    - Increased photocathode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



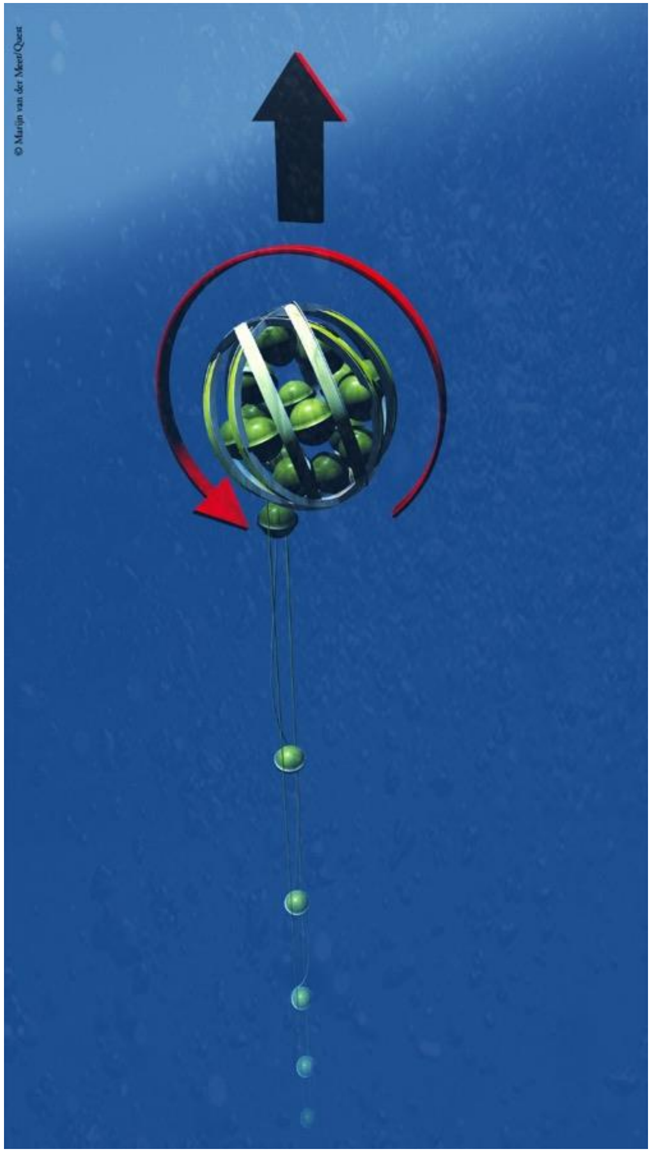
The KM3NeT detection unit (DU)

- Mooring line:
  - Buoy (empty spheres)
  - 2 pre-stretched Dyneema© ropes (4 mm diameter)
  - 18 storeys (one DOM each)
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 7mm 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)

Deployment



- ← Deploy to sea bed
- Release by ROV
- Unfurl →
- Collect frame

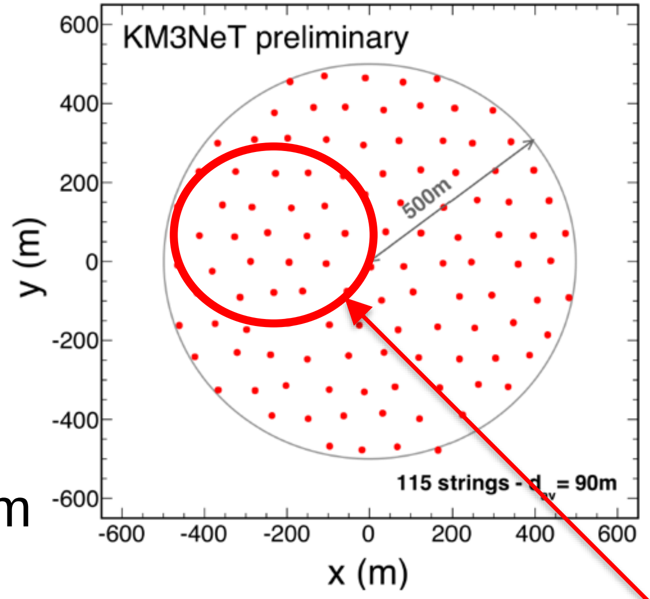


KM3NeT 2.0 = ARCA and ORCA

ARCA =

Astroparticle Research with Cosmics in the Abyss

Vertical DOM distance = 36 m



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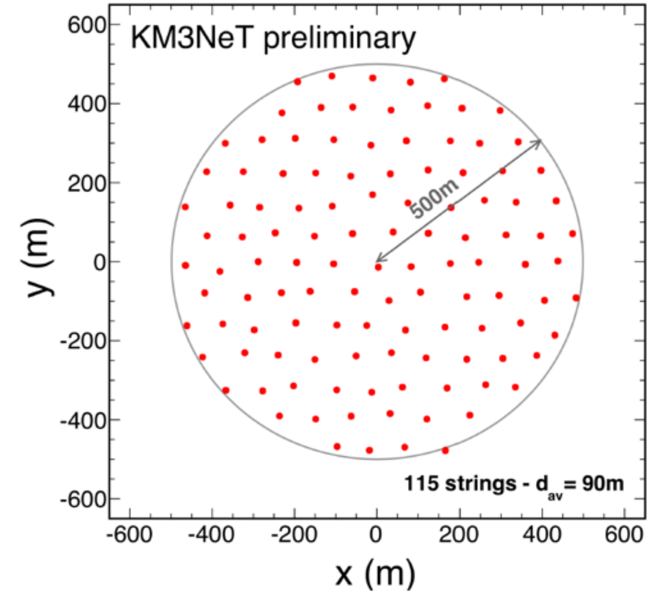
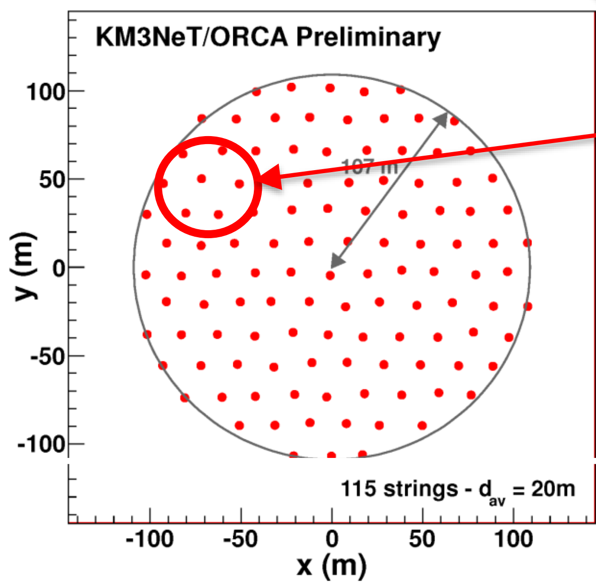


Phase1 (fully funded)

ORCA =
Oscillation Research with Cosmics in the Abyss

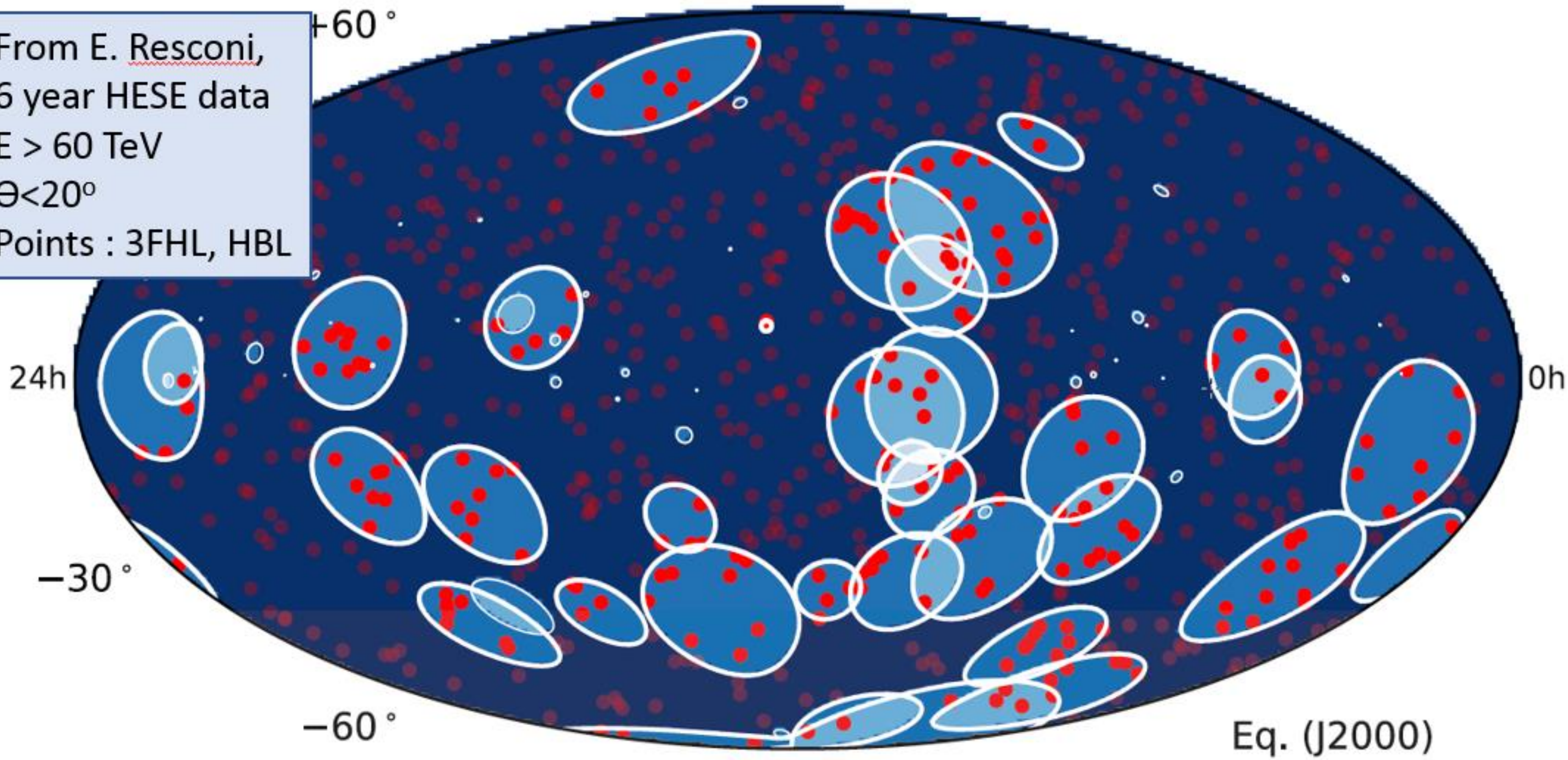
Vertical DOM distance = 9 m



KM3NeT 2.0 Letter of Intent:
arXiv:1601.07459 and
J.Phys. G43 (2016) 084001

Angular resolutions

From E. Resconi,
6 year HESE data
E > 60 TeV
$\Theta<20^{o}$
Points : 3FHL, HBL



Aart Heijboer, ICRC2017

Resolution for ν_e
ANTARES
KM3NeT

Resolution for ν_μ
ANTARES
KM3NeT

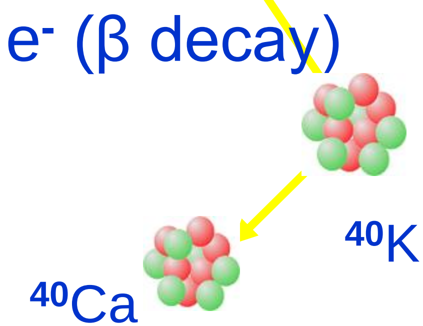
Resolution of key importance
for catalogue searchers

The KM3NeT Collaboration

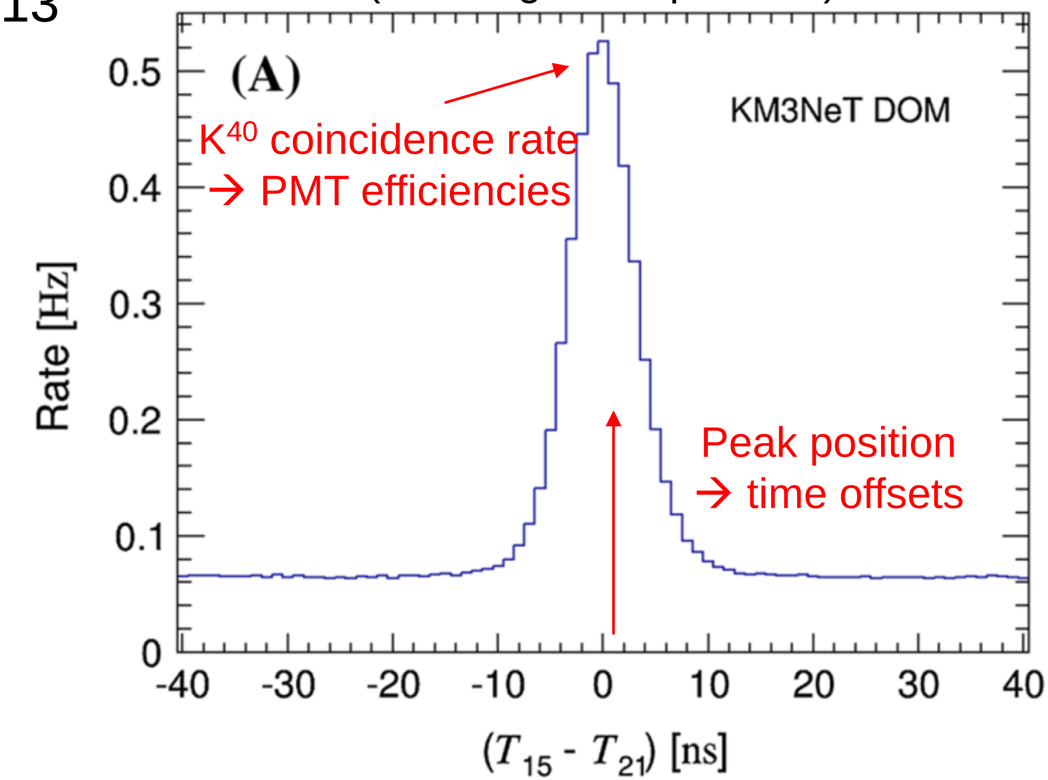
DOM prototype (PPM-DOM)

Deployed at ANTARES in April 2013

Up to 150 Cherenkov photons per decay



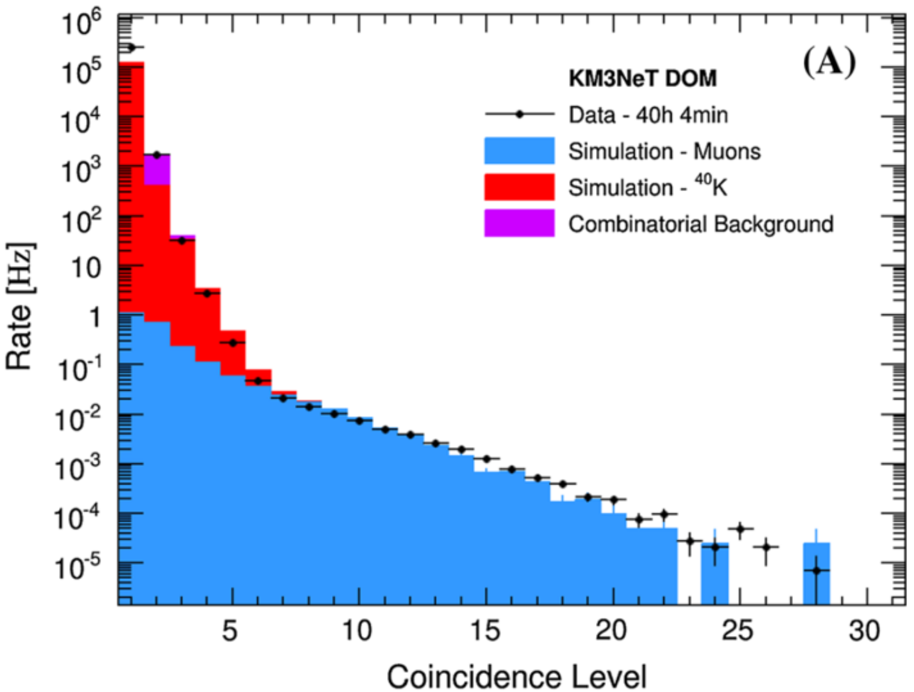
Coincidence rate on 2 adjacent PMTs (33° angular separation)



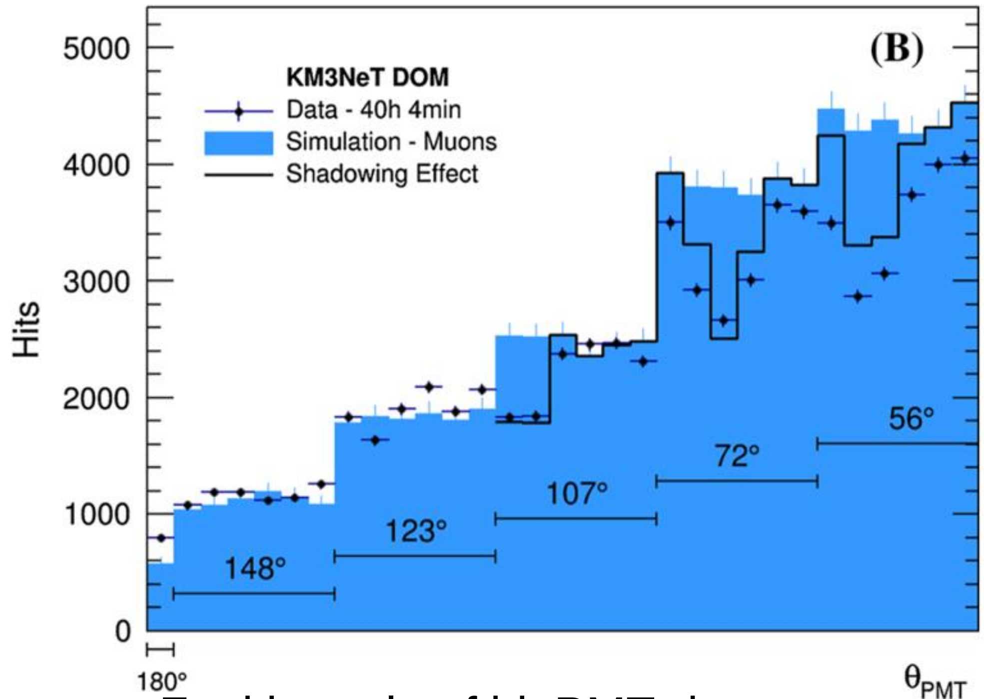
Concentration of ^{40}K is stable
(coincidence rate ~5 Hz on adjacent PMTs)

Eur.Phys.J. C74 (2014) 3056

PPM-DOM: Atmospheric muons



Number of coincident hits in a DOM

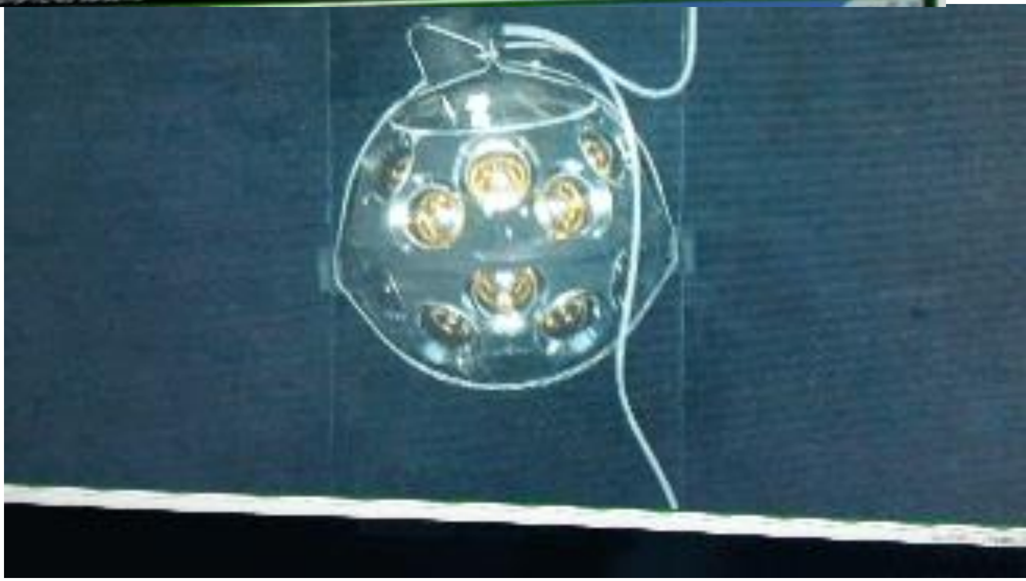


Zenith angle of hit PMTs in events with more than 7 coincident hits

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

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

First KM3NeT-ARCA strings deployed



First string (Dec 2015)

- Smooth operation
- All 18 DOMs alive and functional
- First muons reconstructed within hours after switch-on
- Data taking in progress

Strings #2 and #3 (May 2016)

- String #2: 16/18 DOMs work, data taking in progress
- String #3: Short in power system, not operational
- String recovered in July 2016

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 2015-18
2.0	2/230	Measurement of neutrino signal reported by IceCube; All-flavor neutrino astronomy; KM3NeT-It site	Applications granted/pending 2018-2021
	1/115	Neutrino mass hierarchy; KM3NeT-Fr site	
3	6+1/805	Neutrino astronomy including Galactic sources; Multiple sites	t.b.d. ?

Data Analysis

Typical Analysis Scheme

- 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 machine learning, e.g. 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

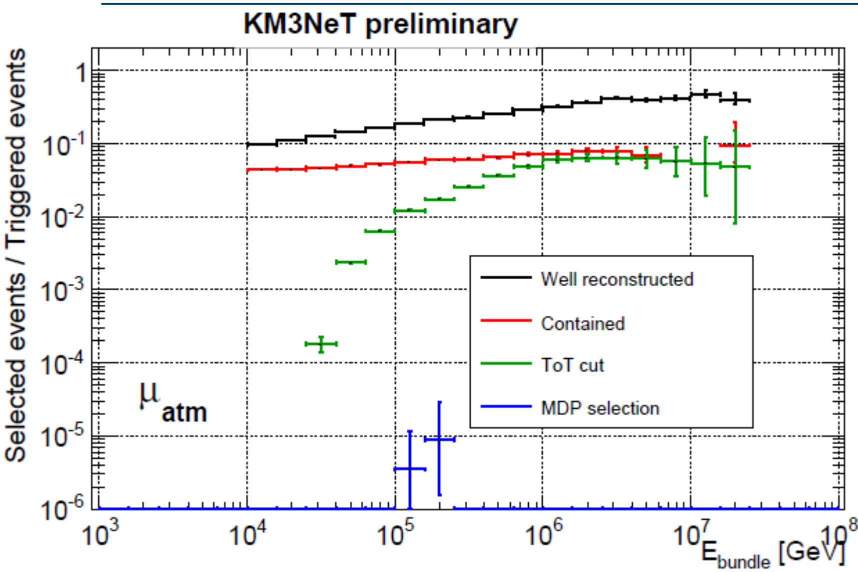
Note: All detector information is in the probability density functions P(X), where the event variables X depend on the type of analysis.

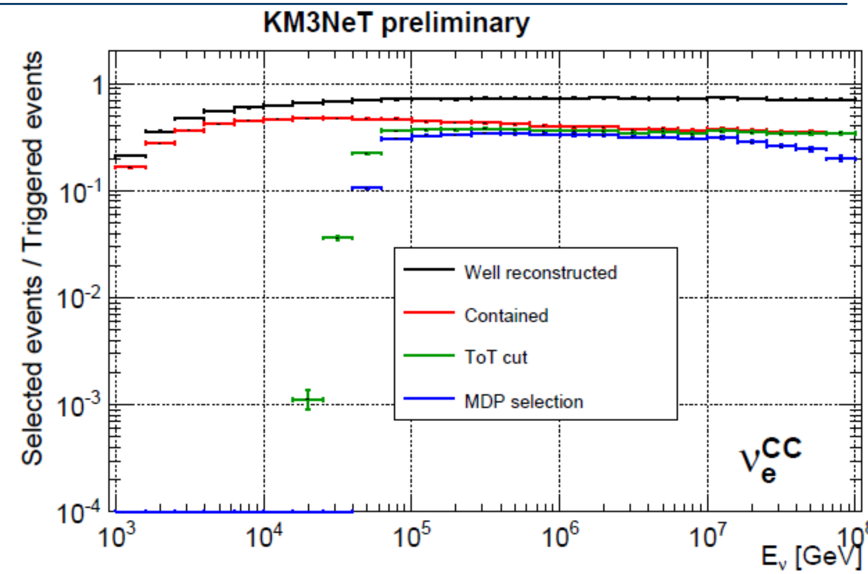
- Main results:

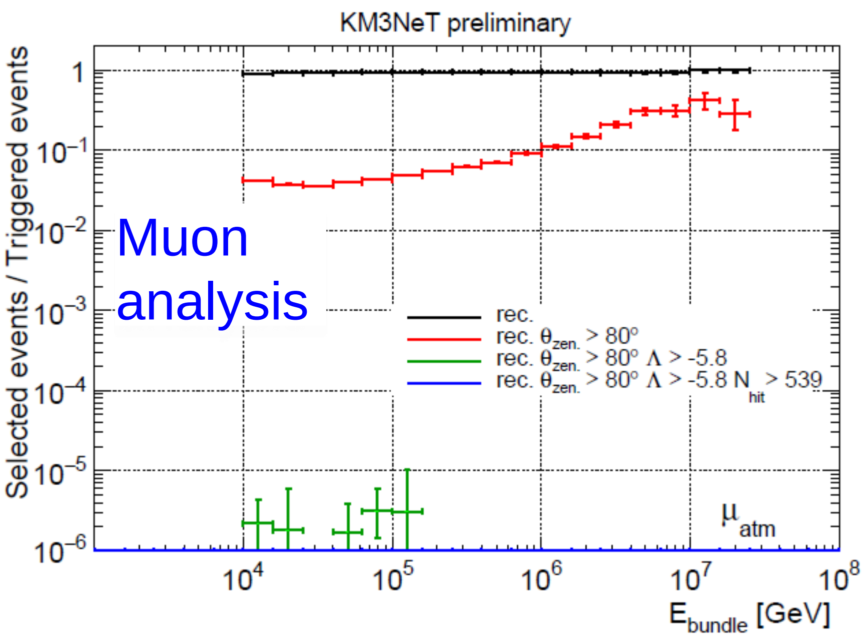
→ Event samples with high signal content from step (3)

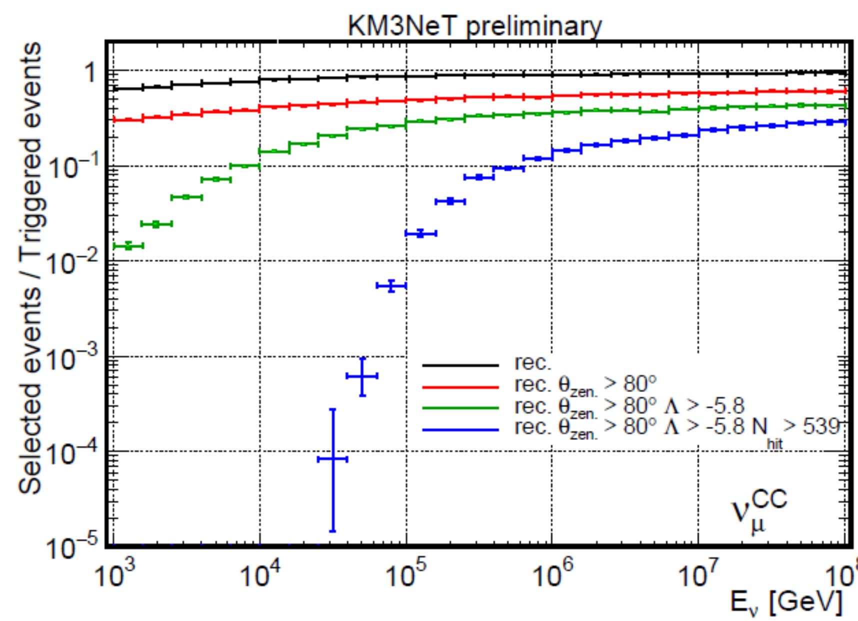
→ Optimised sensitivities from step (4)

Signal/background separation





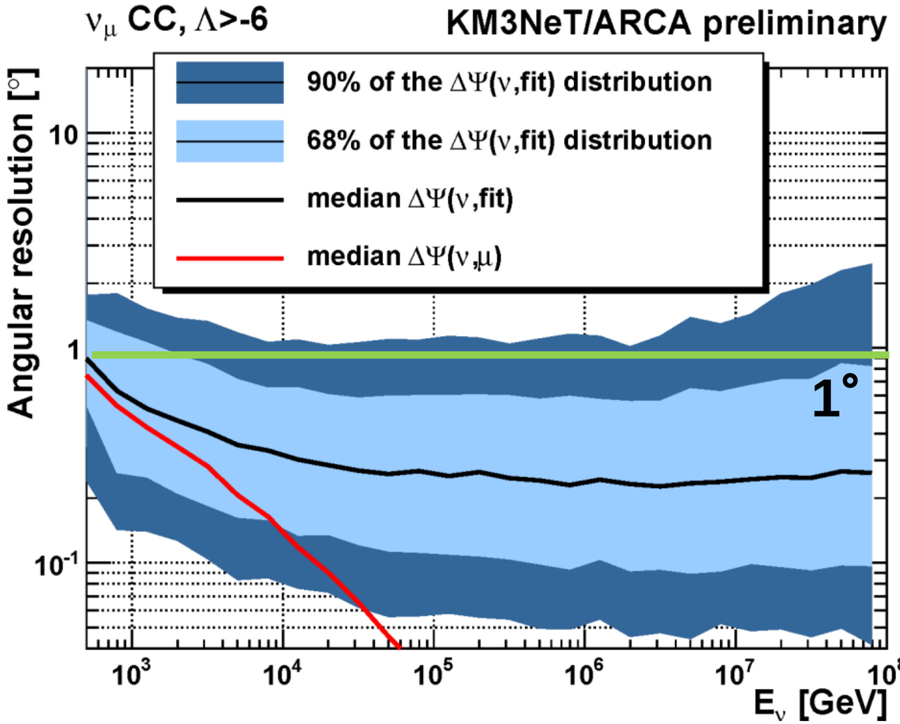




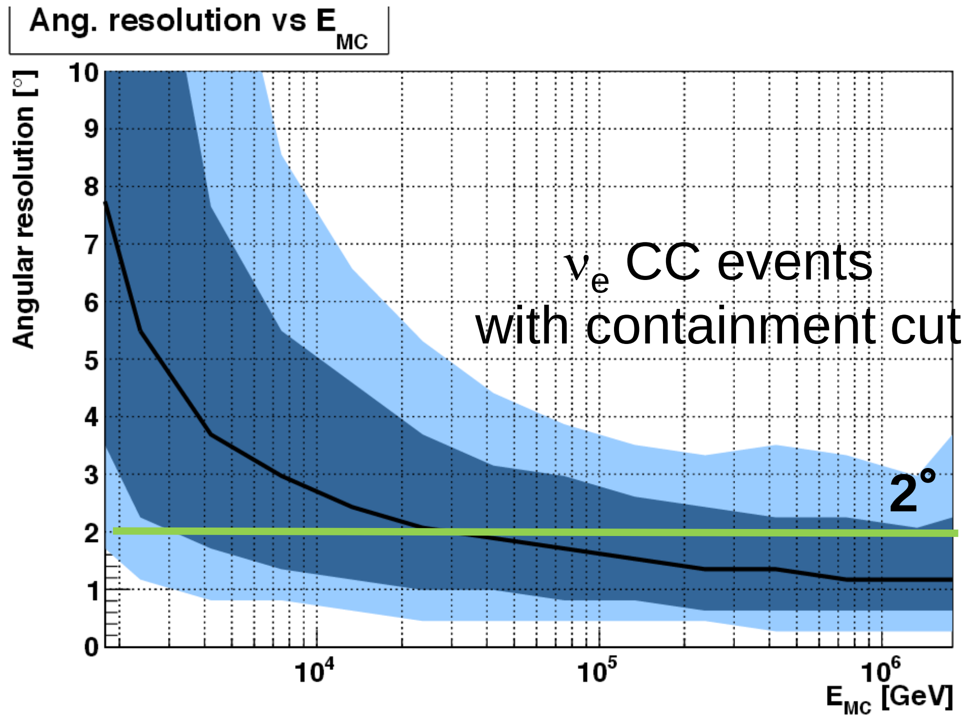
KM3NeT-ARCA Sensitivities

KM3NeT resolutions

Track-like events:

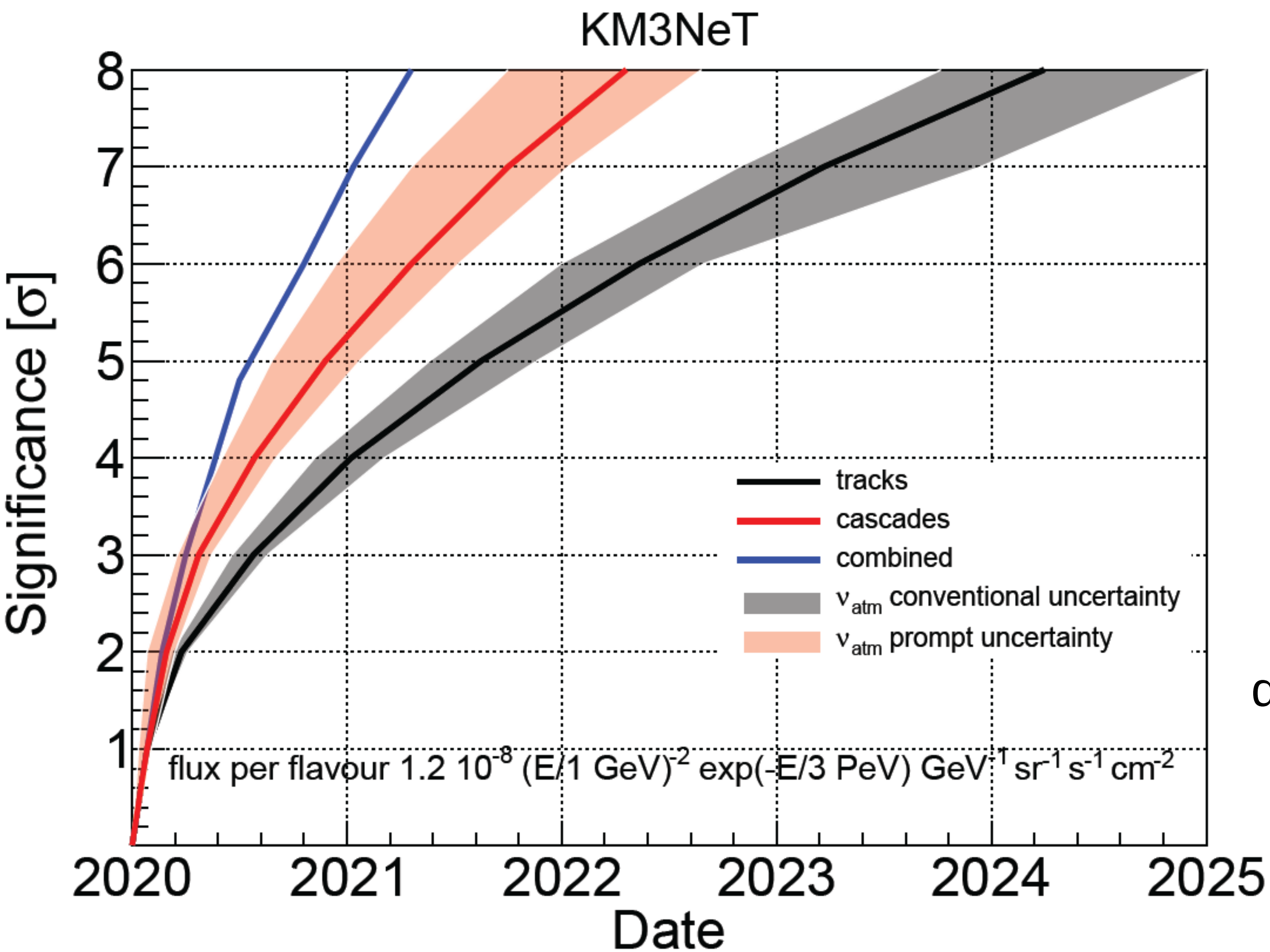


Cascades:



- Muon energy: d(log10 E)=0.25-0.3 at E > 10 TeV
- Cascade energy: 5-10% at E > some 10 TeV
- All-flavour neutrino astronomy in reach

Diffuse flux results (max. liklihood)



Event numbers (cut&count):

16/9 cascades

7.5/5 track-like

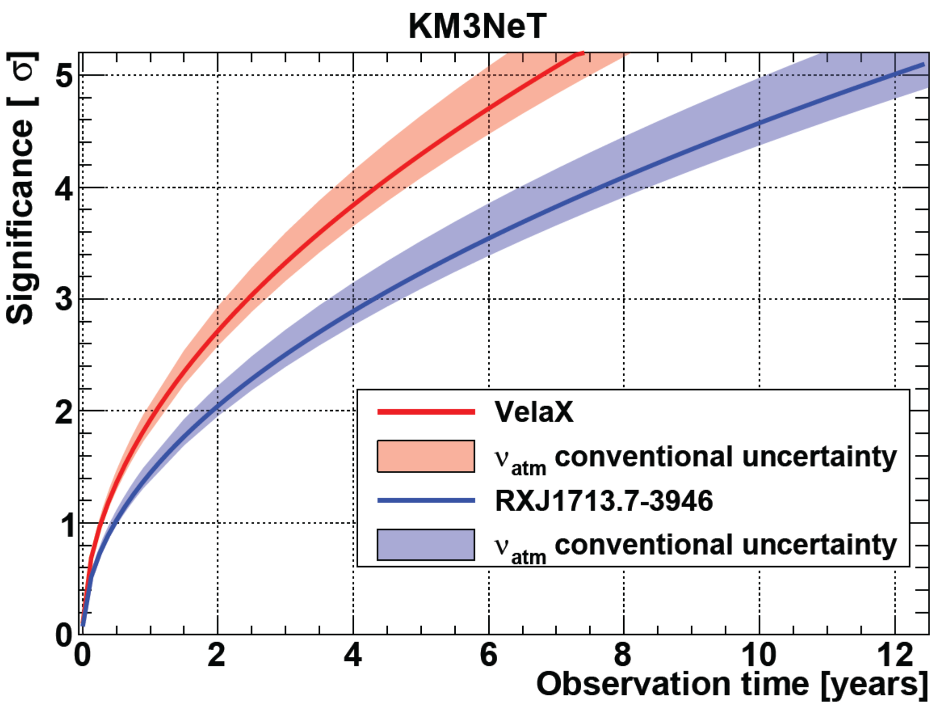
(signal/background per ARCA year)

Note:

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

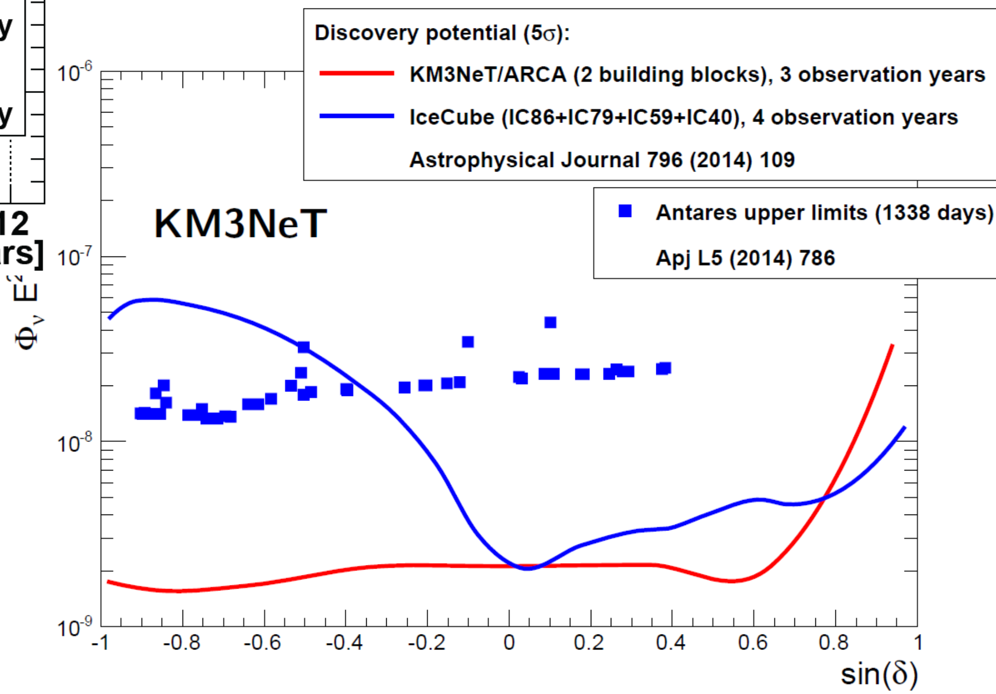
Other flux assumptions yield 10-30% improvement in discovery time.

Point-source results



- Galactic sources in reach

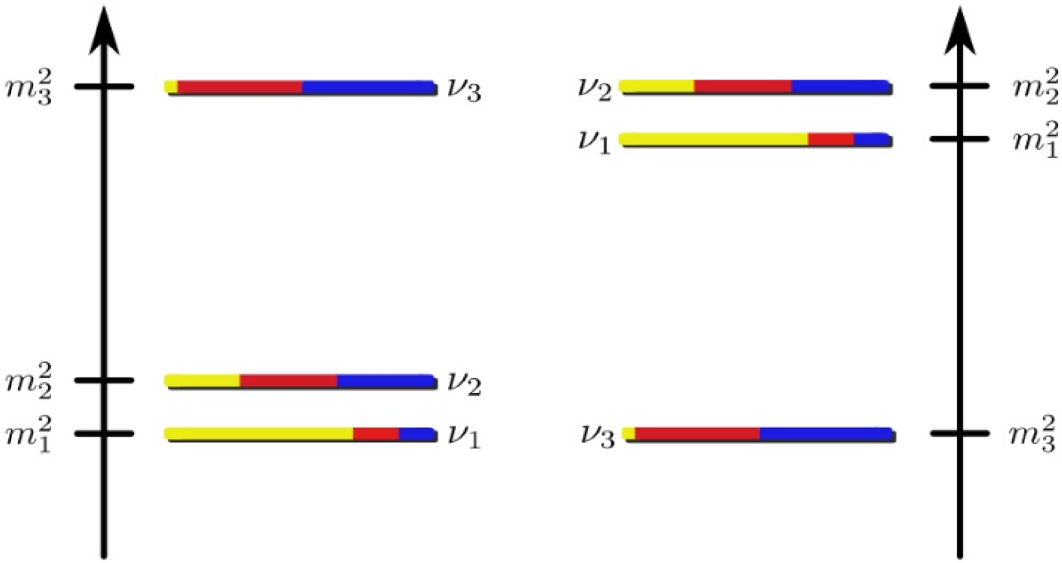
- Significant discovery potential for extragalactic sources



KM3NeT-ORCA Sensitivities

Neutrino physics with atmospheric neutrinos

- Use atmospheric neutrinos for oscillation studies
- Oscillations in Earth: Matter effects induce sensitivity to neutrino mass hierarchy



- Hierarchy and other oscillation parameters in reach of neutrino telescopes – in particular ORCA and PINGU
- Timeline similar to JUNO – completely different systematics
- Future options for ~~CP~~: Extended detectors or ν beams

Measuring the mass hierarchy

- Sensitivity depends on true value of θ_{23} (“the octant”)
- CP phase δ=0 assumed (no strong CP effect)
- 3σ in 3 years for most unfavourable situation
- Similar result for PINGU, but later starting date