Conference on Recent Developments in High Energy Physics and Cosmology
25–28 April 2013, University of the Aegean, Chios, Greece

The KM3NeT Project

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FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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The plan for the next 40 minutes:

- Neutrino telescopes
- What is KM3NeT?
- Physics prospects with KM3NeT
- Recent achievements
- Studying low-energy neutrinos: The ORCA option
- Summary

Sincere thanks to all colleagues who allowed me to use their material

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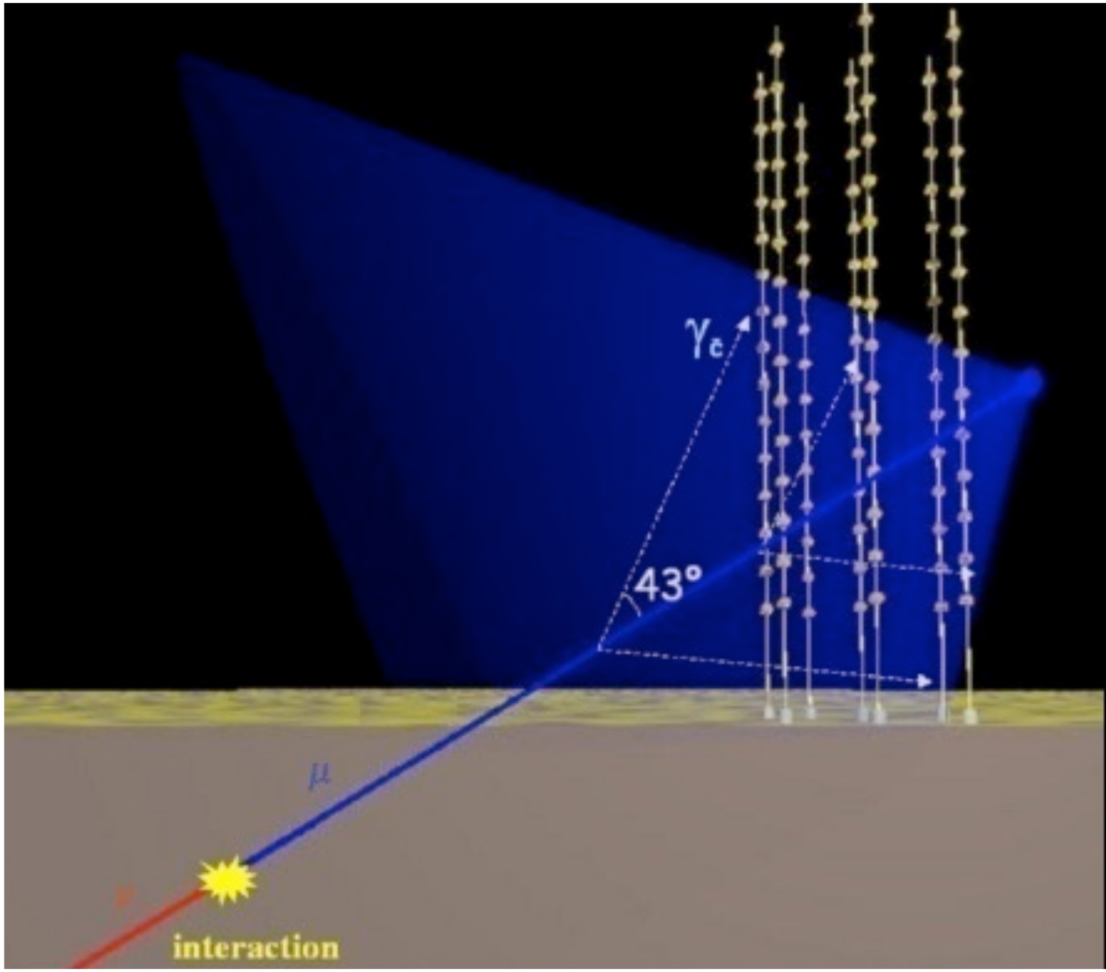
Neutrino telescopes

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
- Most important channel: $\nu_\mu + N \rightarrow \mu + X$
- Energy range : 10(0) GeV – some PeV



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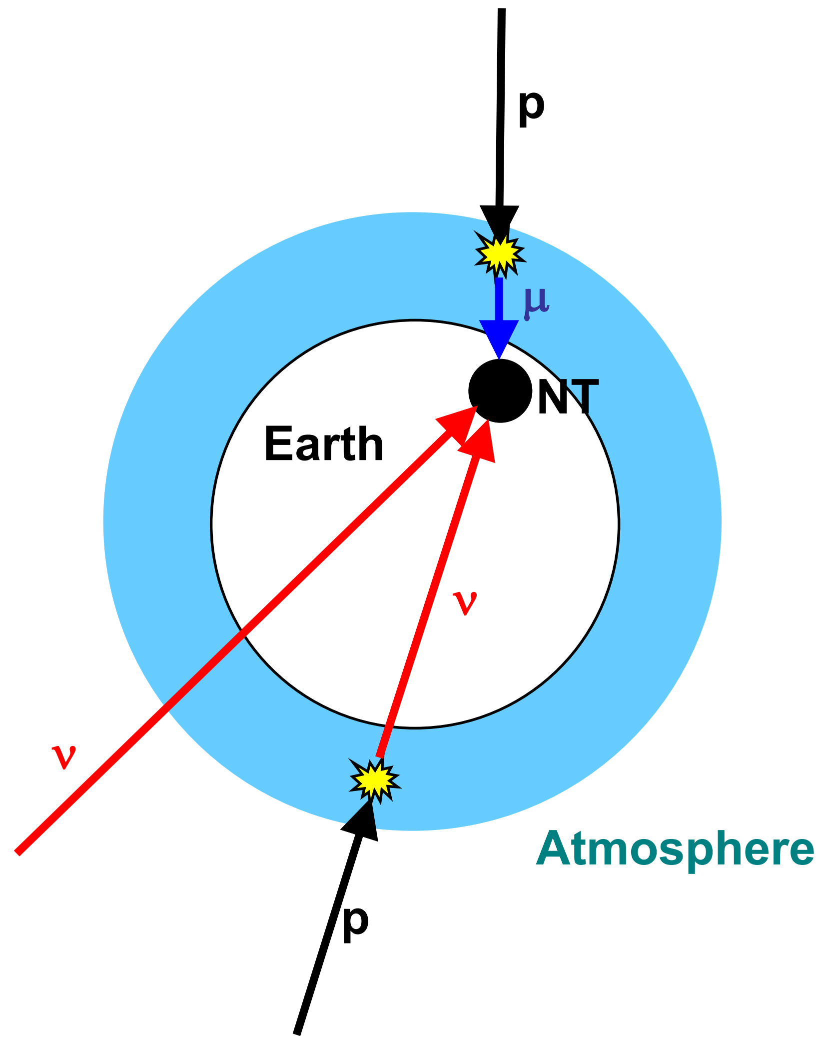
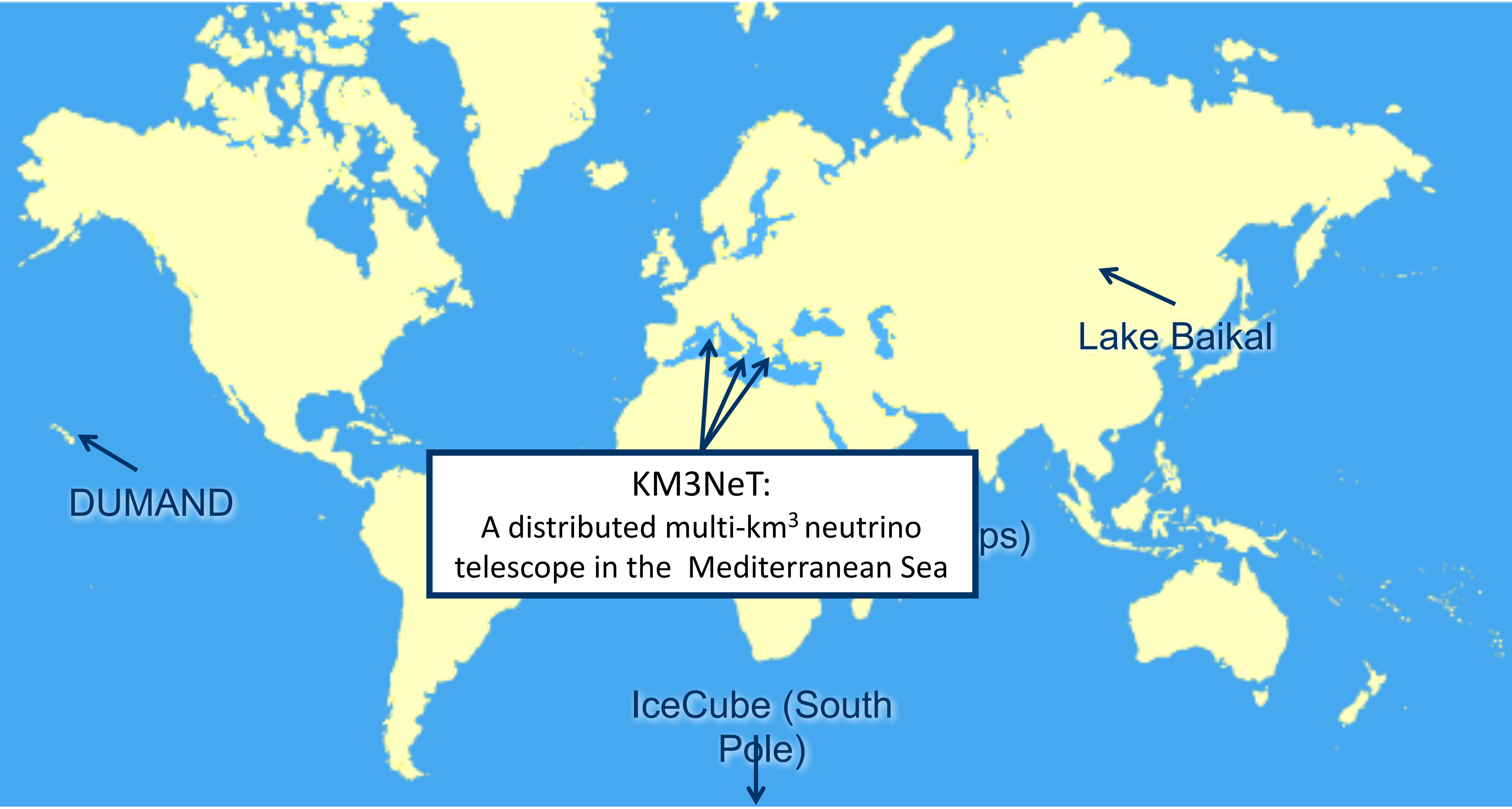
Backgrounds, or maybe not

- Atmospheric neutrinos from cosmic-ray interactions in atmosphere
  - irreducible
  - important calibration source
  - allow for oscillation studies
- 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 neutrino telescope world map



KM3NeT:
A distributed multi-km^3 neutrino telescope in the Mediterranean Sea

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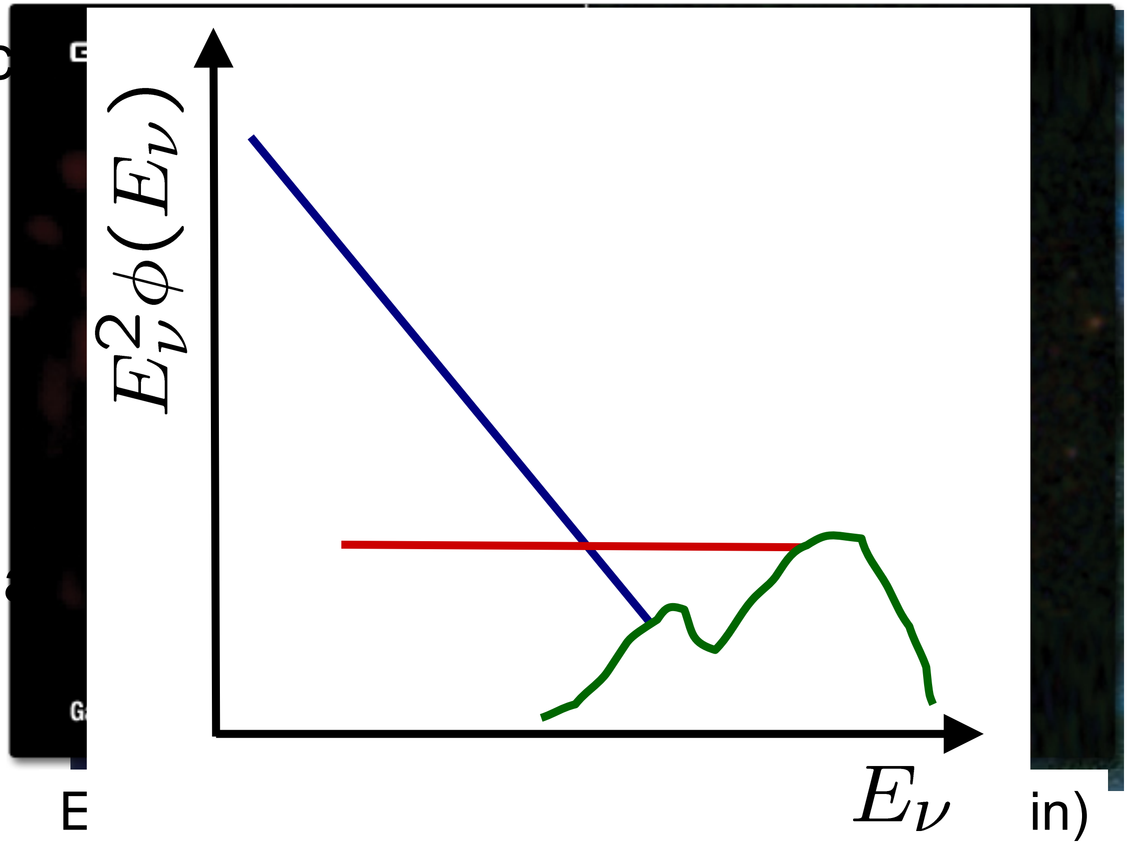
Example targets of neutrino astronomy

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



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

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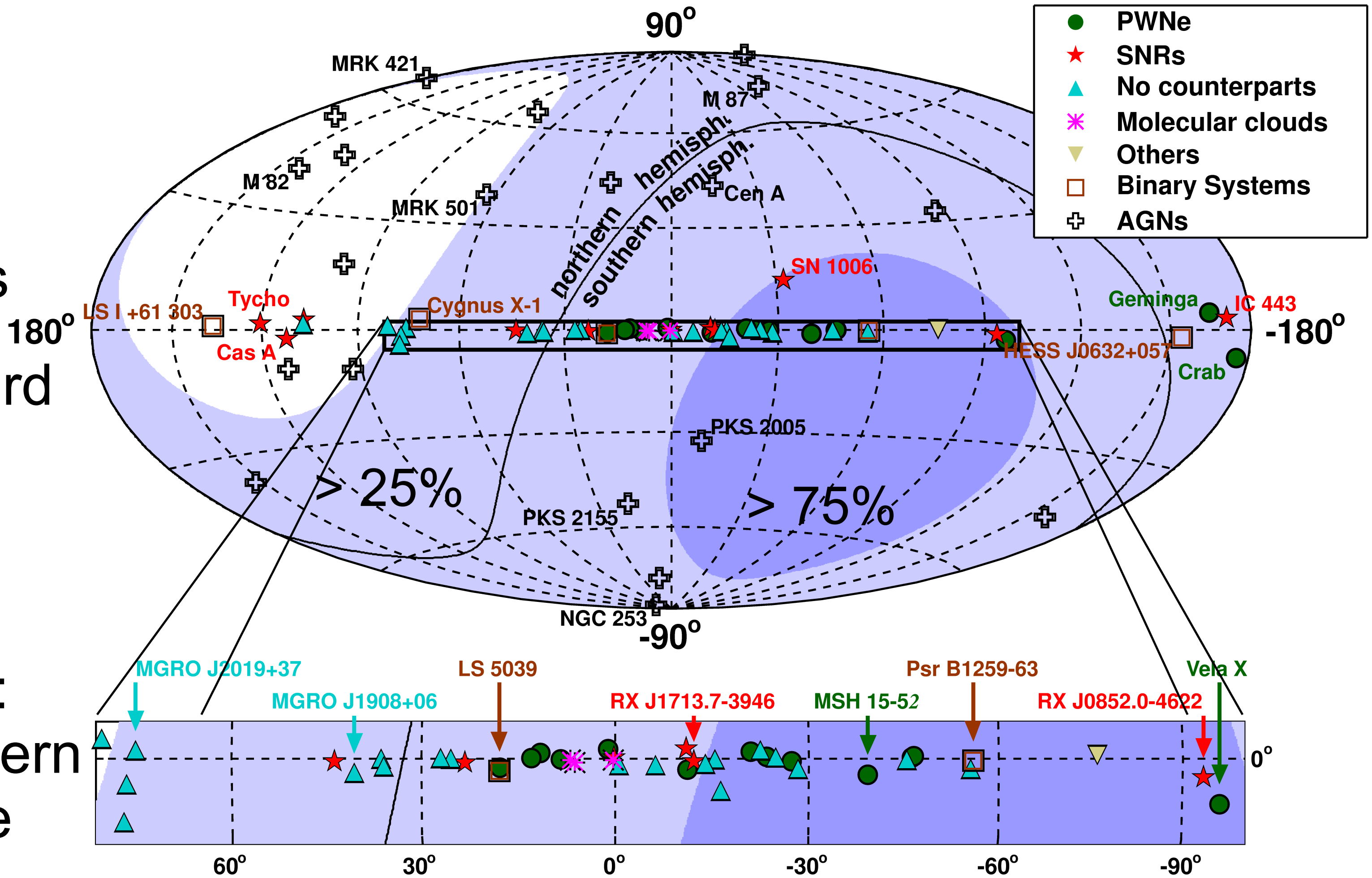
South Pole and Mediterranean fields of view

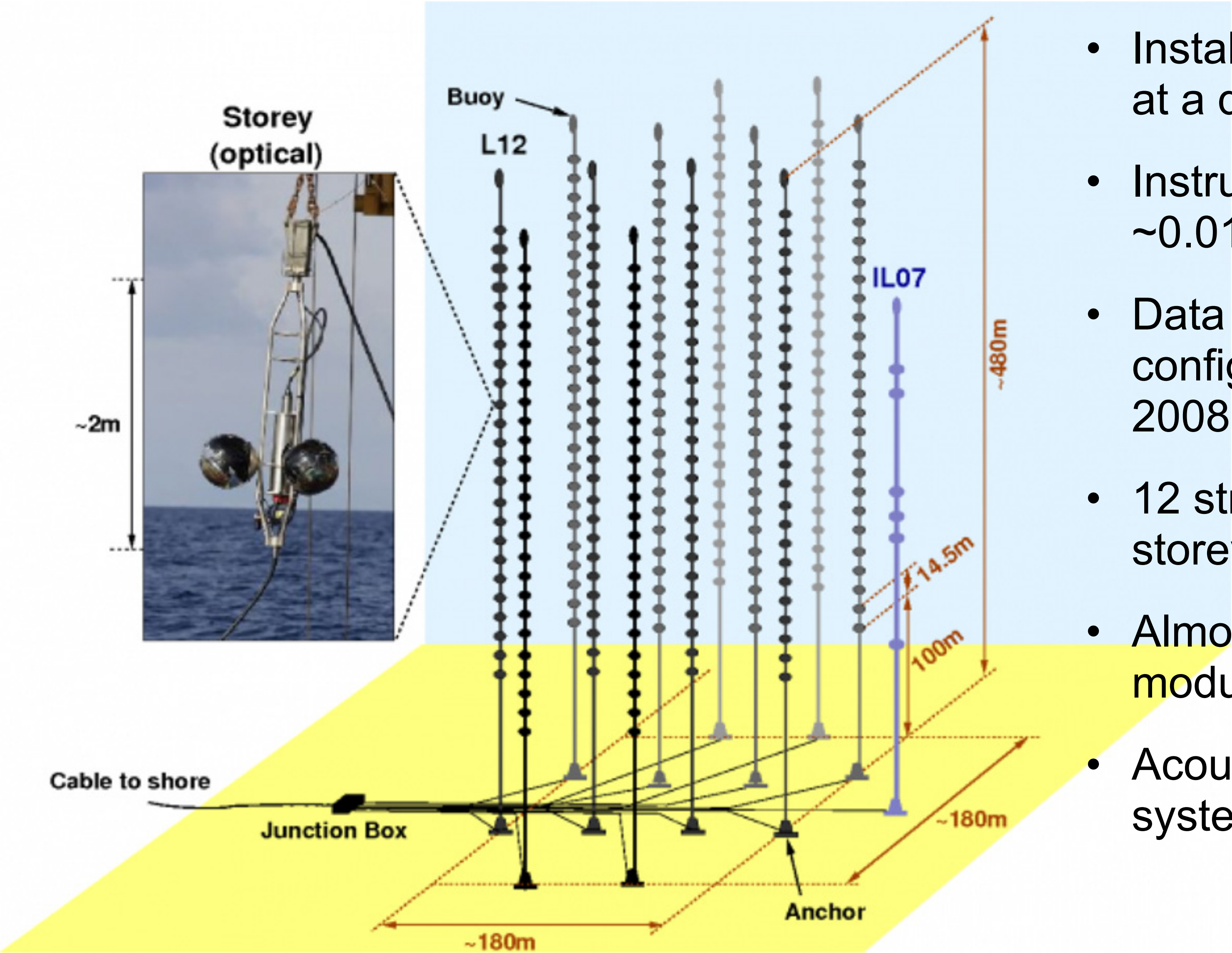
Galactic coordinates

2π downward sensitivity assumed

IceCube @ South Pole: Sees Northern hemisphere



ANTARES: The first NT in the deep sea



- Installed near Toulon at a depth of 2475m
- Instrumented volume ~0.01km^3
- Data taking in full configuration since 2008
- 12 strings with 25 storeys each
- Almost 900 optical modules
- Acoustic sensor system

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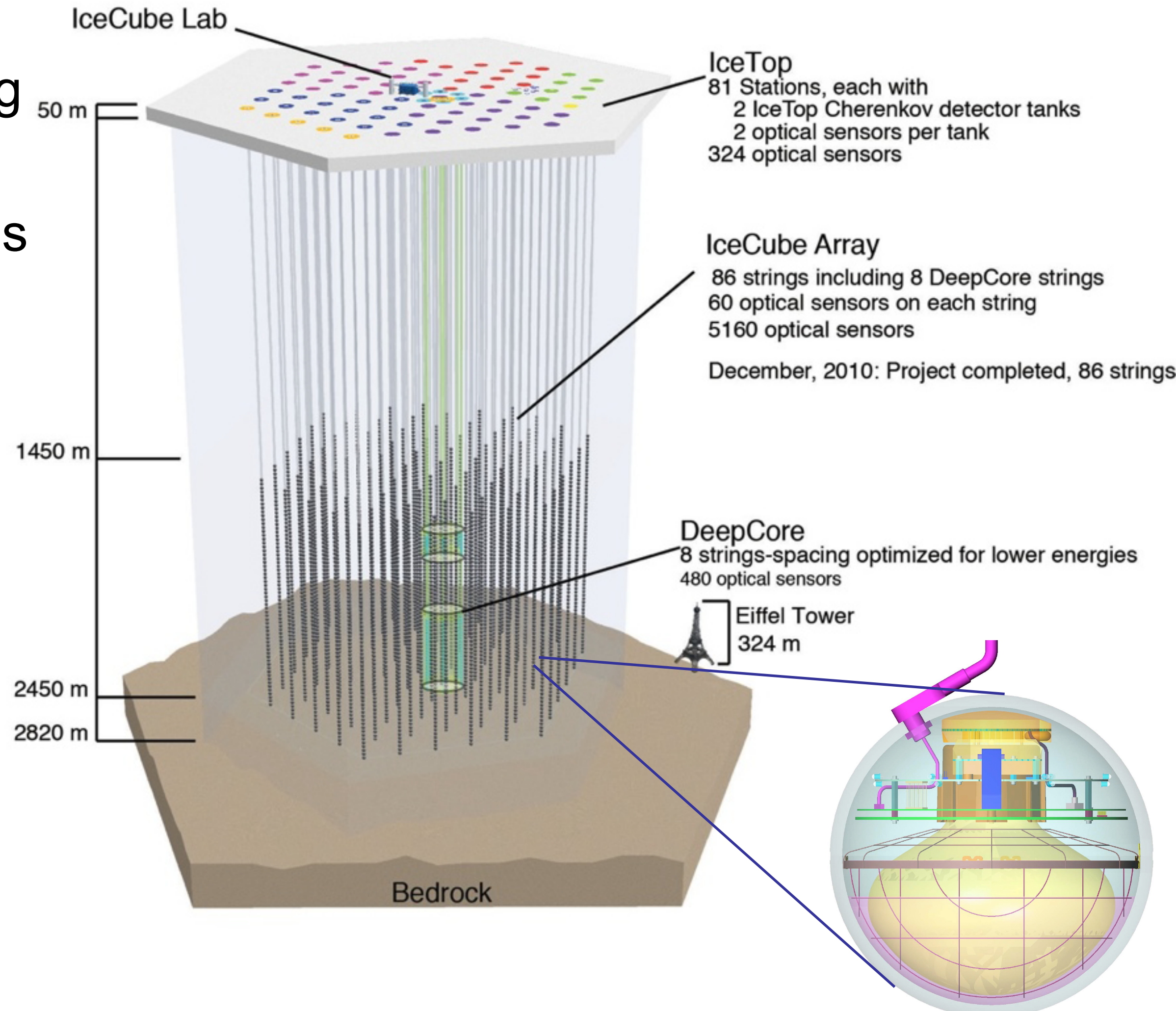
IceCube: Completed in December 2010

- 86 strings altogether
  - 125 m horizontal spacing
  - 17 m vertical distance between Optical Modules
  - 1 km^3 instrumented volume, depth 2450m
- Deep Core
  - densely instrumented region in clearest ice
  - atmospheric muon veto by IceCube
  - first Deep Core results
- Plan for future low-energy extension (PINGU)



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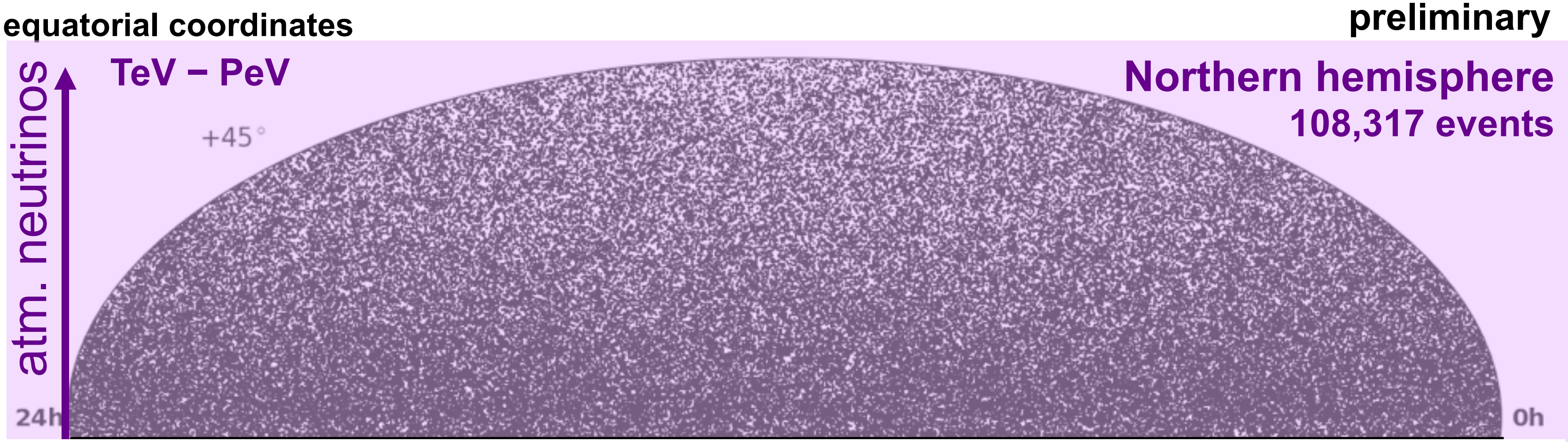
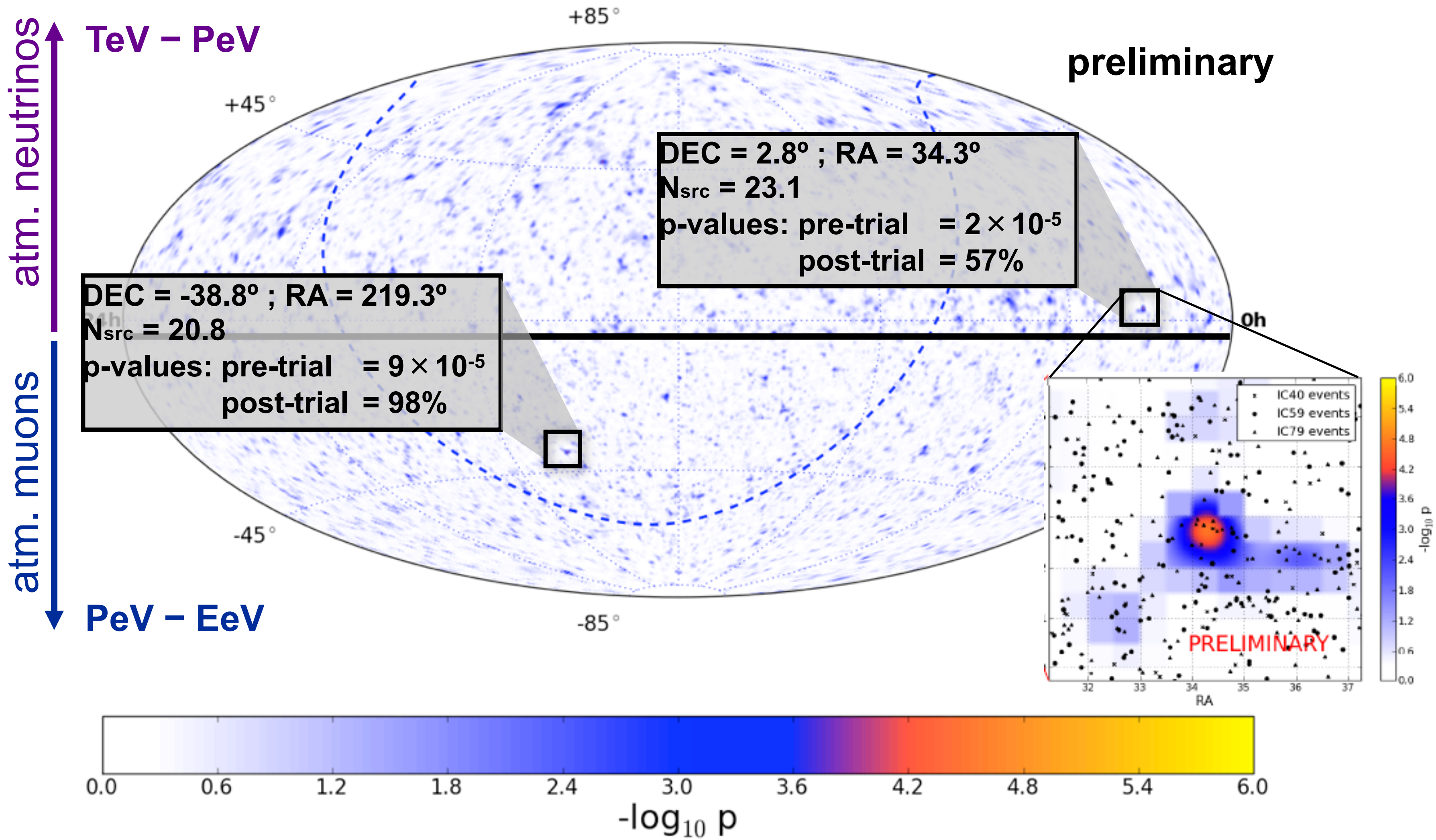
IceCube: Event skymap (IC40+59+79)



IceCube: Significance map (IC40+59+79)



What is KM3NeT?

The KM3NeT project

- Multi-km^3 NT in Mediterranean Sea, exceeding IceCube substantially in sensitivity
- Central physics goals (by priority):
  - Galactic neutrino “point” sources (energy 1-100 TeV)
  - Extragalactic sources
  - High-energy diffuse neutrino flux
- EU-funded Design Study and Preparatory Phase
- Decisions taken:
  - Technology: Strings with 18 multi-PMT optical modules
  - Multi-site installation (France, Greece, Italy)
  - 6 building blocks of ~115 strings each
- Collaboration established

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KM3NeT implementation parameters

- Staged implementation:
  Phase-1 in progress, 40 M€ available.
- Science potential from very early stage of construction on.
- Overall investment ~220 M€.
- Operational costs of full detector 4-6 M€ per year (2-3% of capital investment), including electricity, maintenance, computing, data centre and management.
- Node for deep-sea research of earth and sea sciences.

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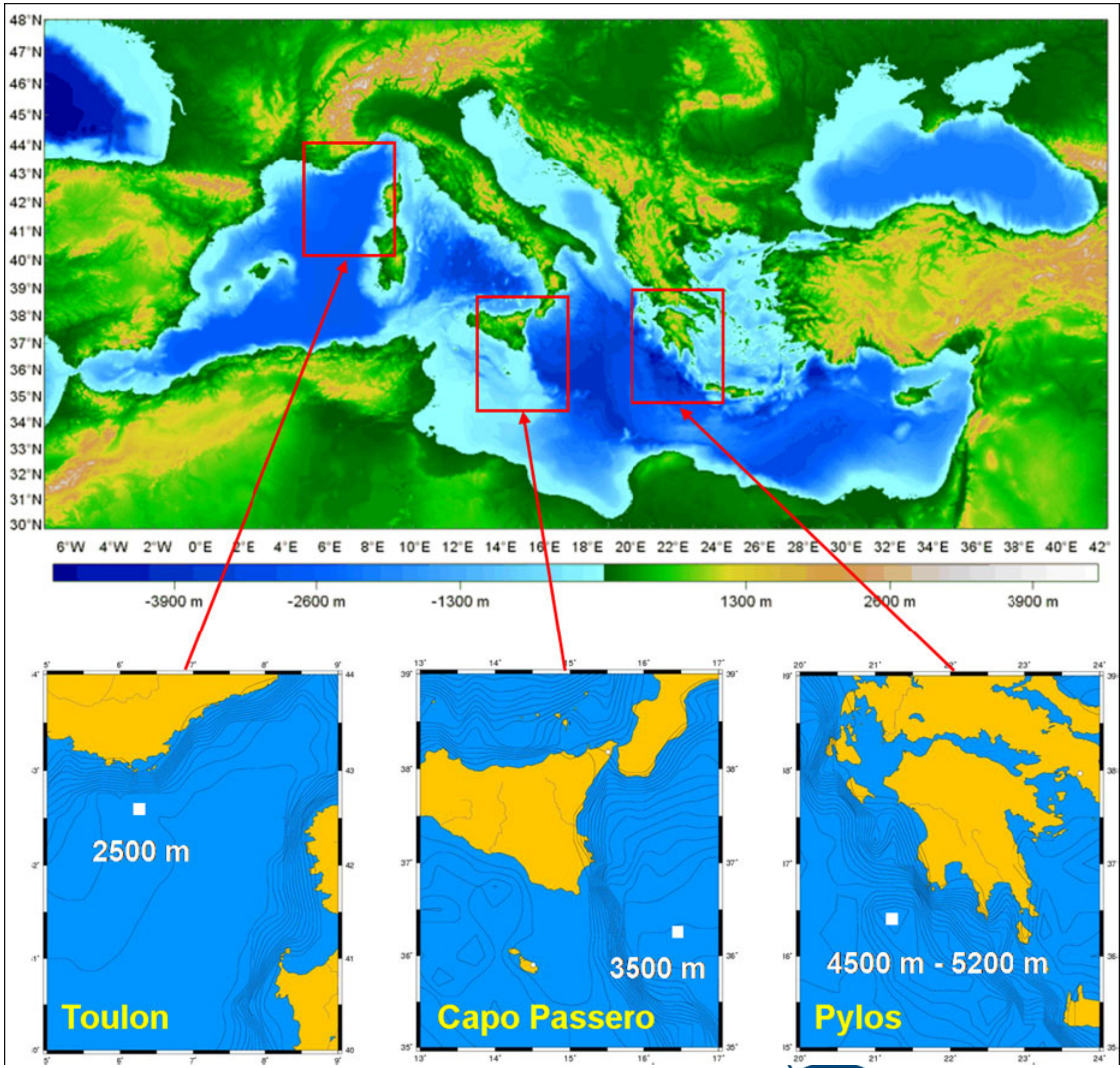
Installation Sites

- Locations of the three pilot projects:
  - ANTARES: Toulon
  - NEMO: Capo Passero
  - NESTOR: Pylos
- Long-term site characterisation measurements performed
- Political and funding constraints
- Solution: networked, distributed implementation



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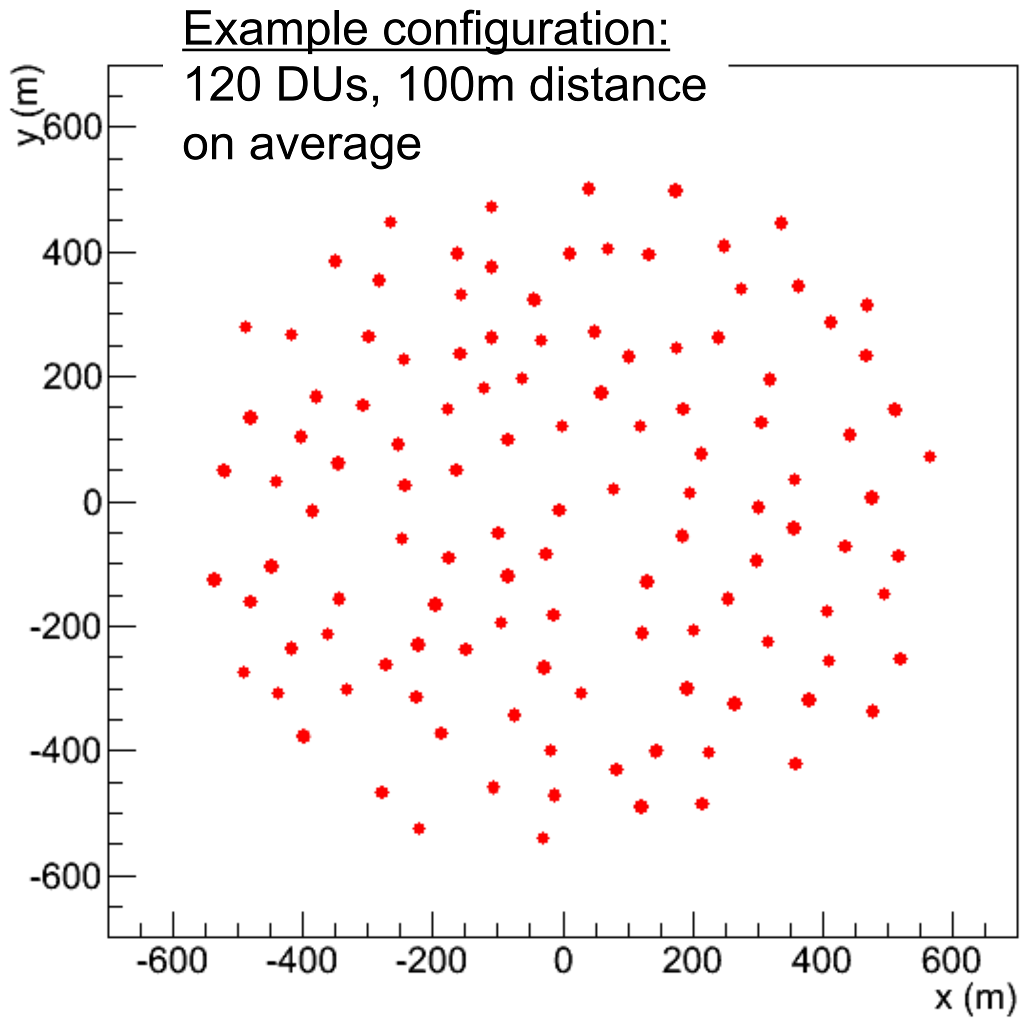
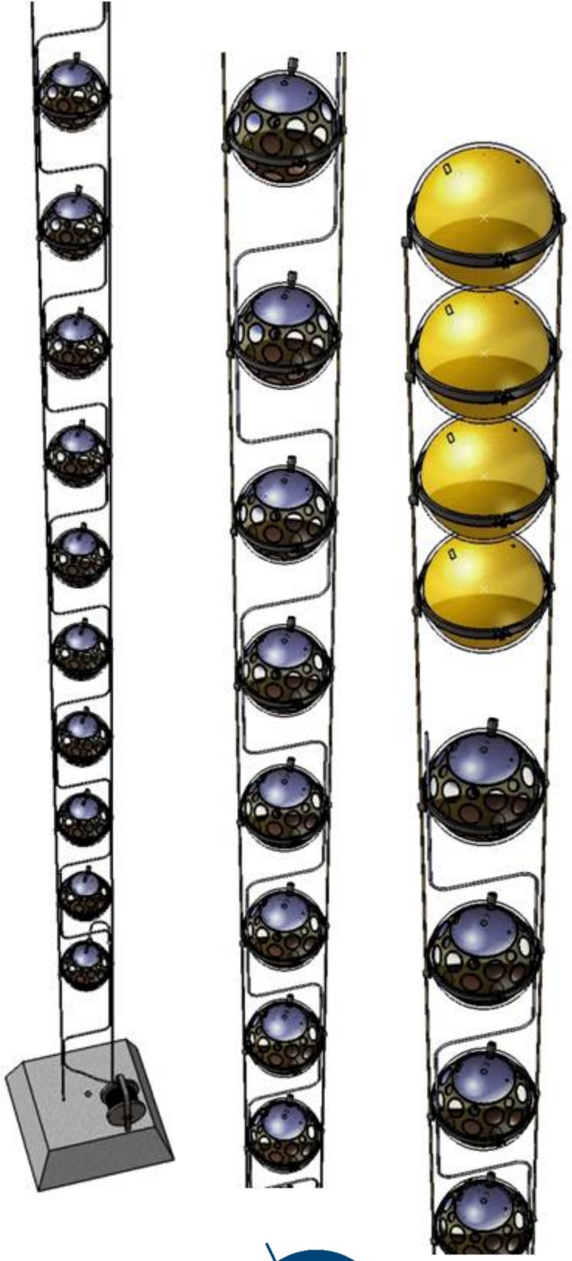
The building block concept

- Building block:
  - 115 detection units
  - Segmentation enforced by technical reasons
  - Sensitivity for muons independent of block size above ~75 strings
  - One block ~ one IceCube
- Geometry parameters optimised for galactic sources (E cut-off)
- Final optimisation in progress



Detection units: Strings

- Mooring line:
  - Buoy (probably syntactic foam)
  - 2 Dyneema© ropes (4 mm diameter)
  - 18 storeys (one OM each),
    30-36m distance, 100m anchor-first storey
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - fibres and copper wires
  - At each storey:
    connection to 1 fibre+2 wires
  - Break out box with fuses at each storey:
    One single pressure transition



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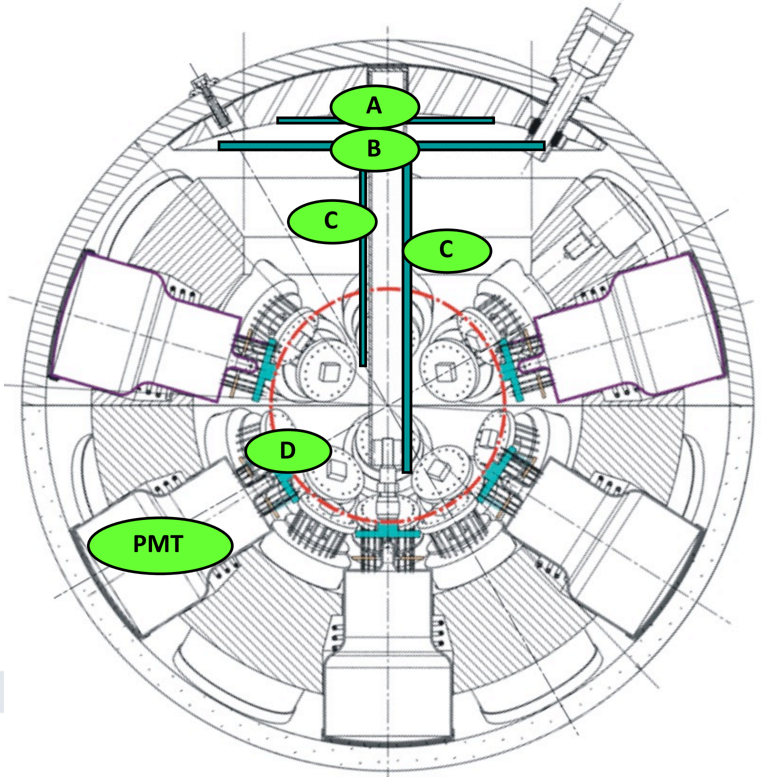
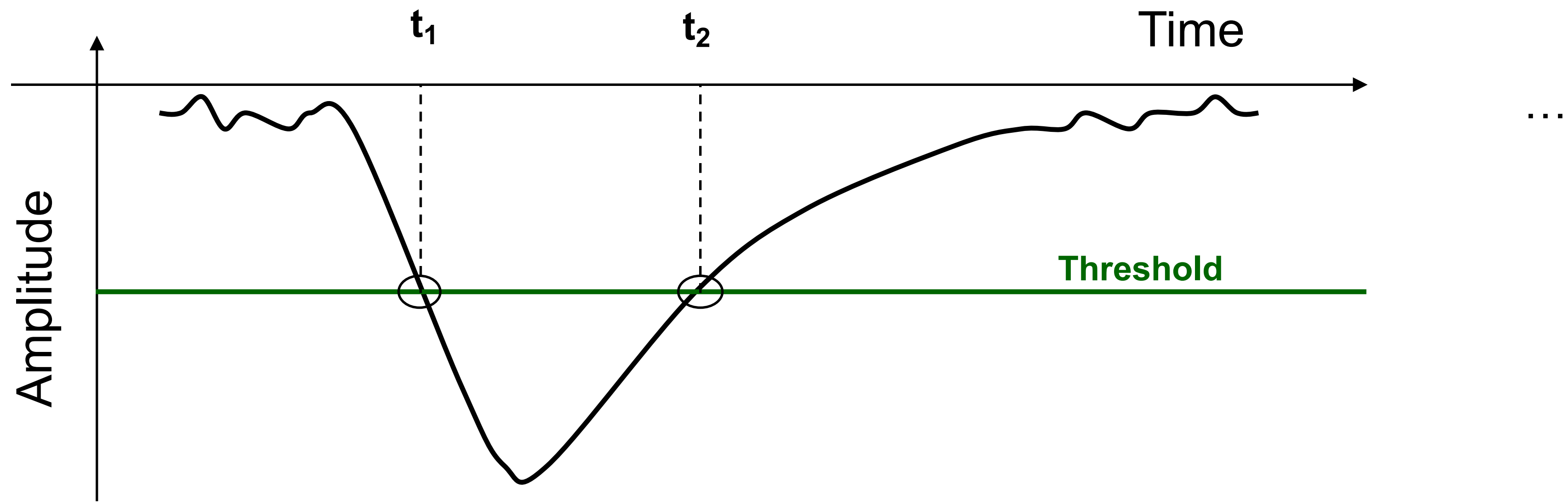
OM with many small PMTs

- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10” 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
- 2mm optical gel
- Advantages:
  - increased photocathode area
  - 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - directionality



Readout: time-over-threshold

From the analogue signal to time stamped digital data:



- Implemented through FPGA on central logic board contained in optical module
- All data to shore via optical fibres driven by lasers on shore
- Time synchronisation and slow control

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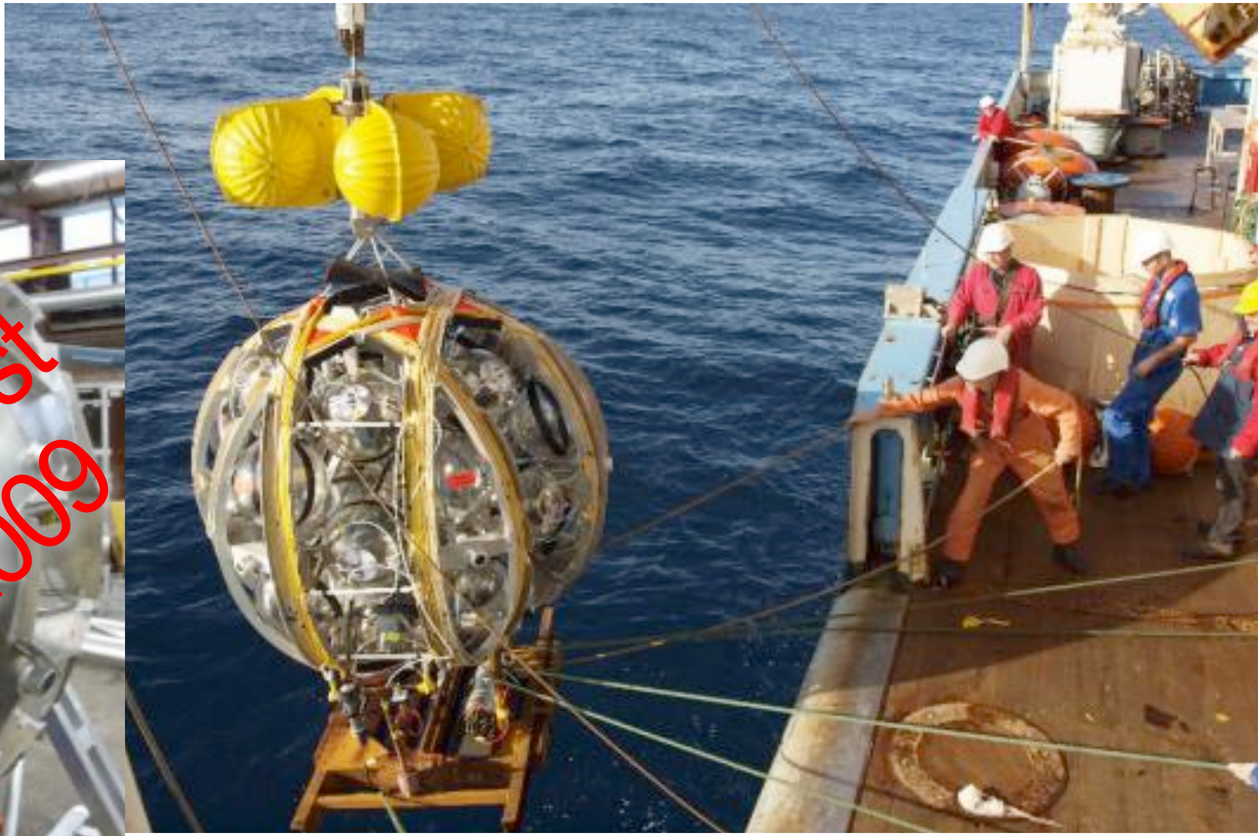
Deployment Strategy

- Compact package – deployment – self-unfurling
  - Eases logistics
    (in particular in case of several assembly lines)
  - Speeds up and eases deployment;
    several units can be deployed in one operation
  - Self-unfurling concepts is being thoroughly tested and verified
- Connection to seabed network by ROV

Compactifying Strings

String rolled up for self-unfurling:



Physics prospects with KM3NeT

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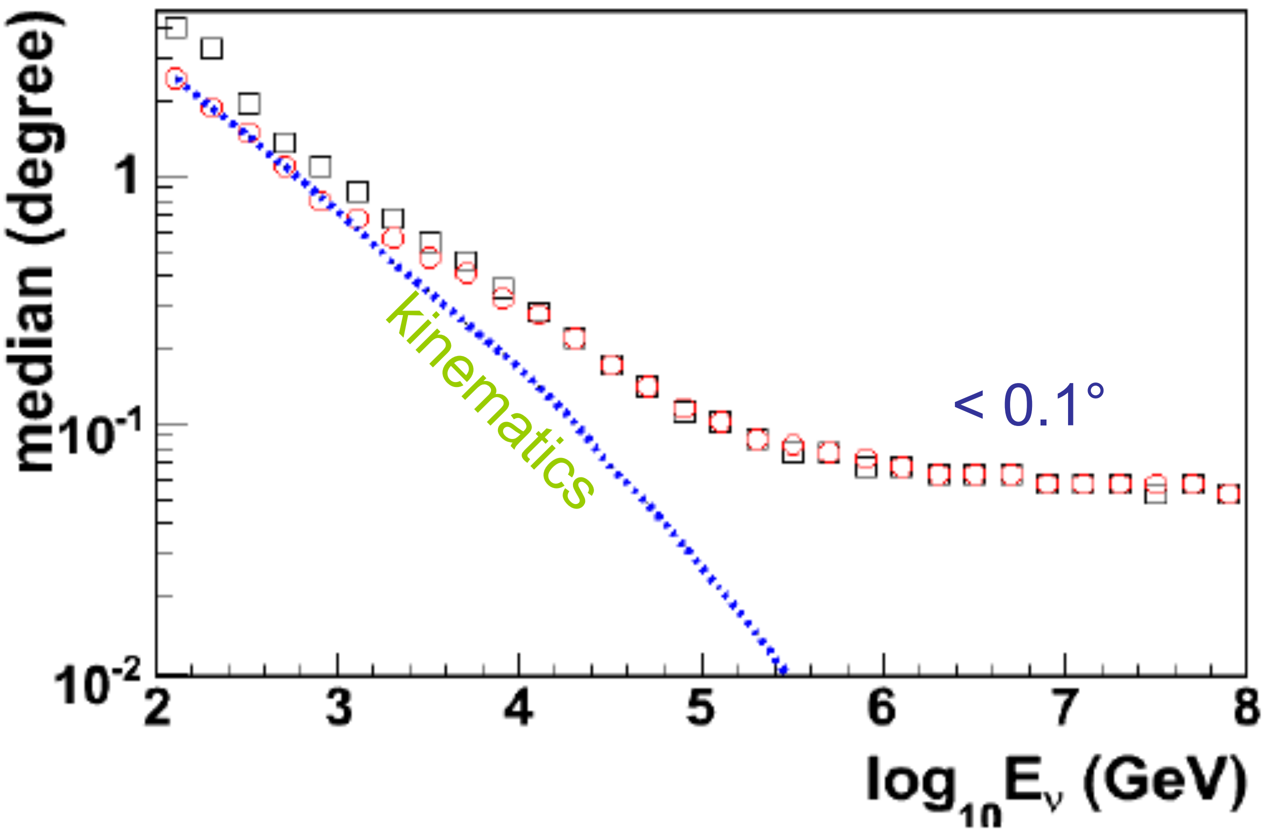
Angular resolution

- Investigate distribution of angle between incoming neutrino and reconstructed muon
- Dominated by kinematics up to ~1TeV
- Energy resolution ~0.3 in $\log_{10}(E_\nu)$ if E_μ>1 TeV



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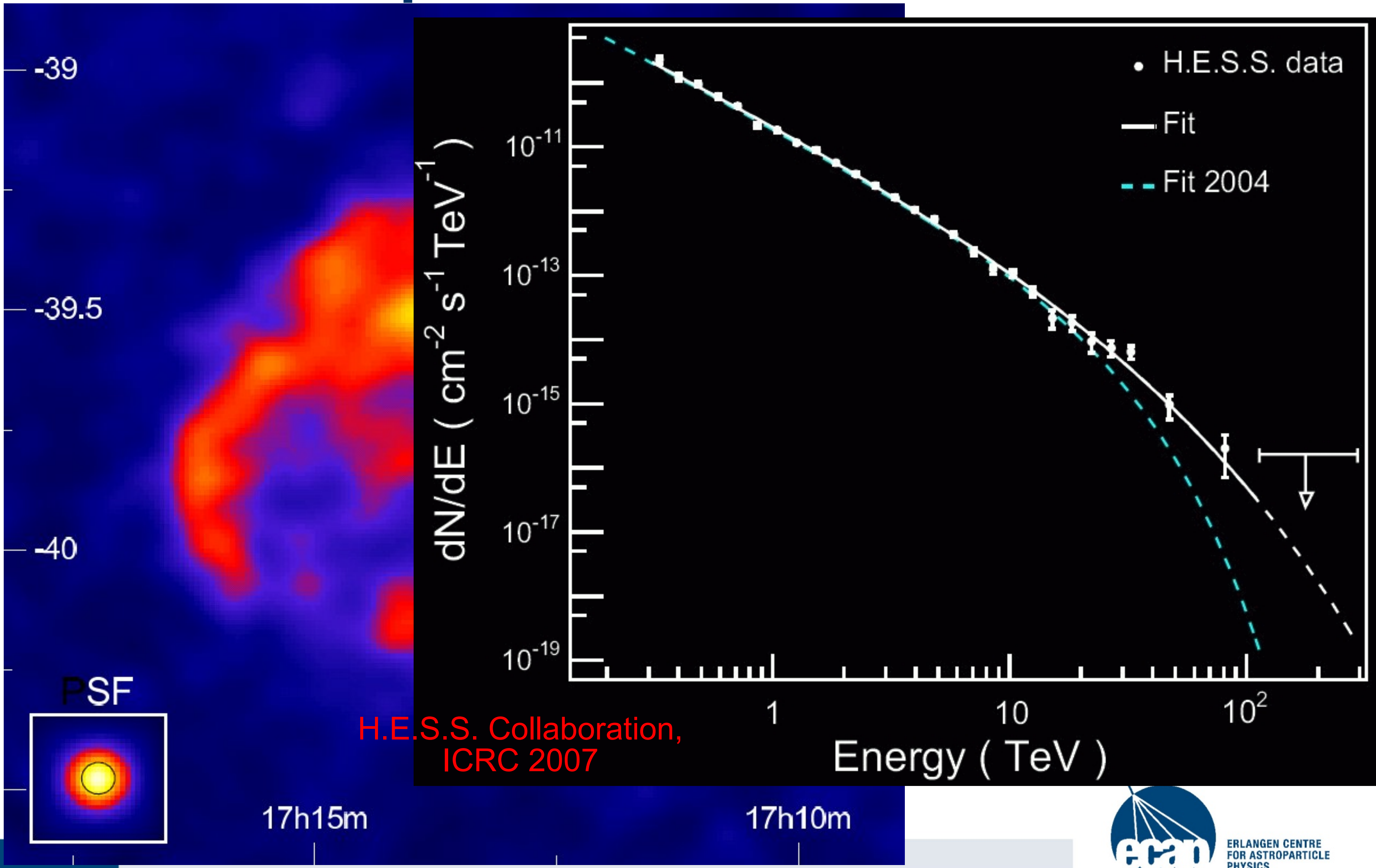
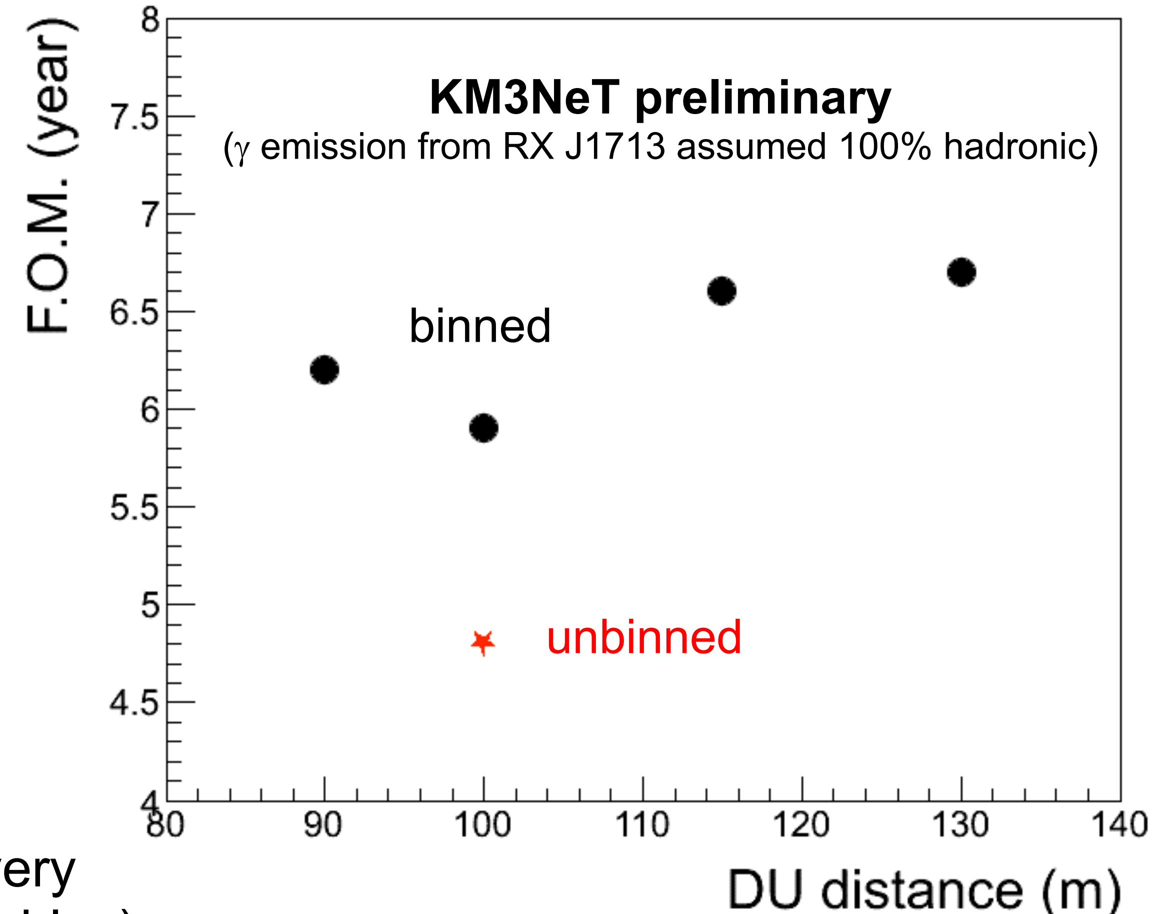
RX J1713: A prime candidate source



H.E.S.S. Collaboration, ICRC 2007

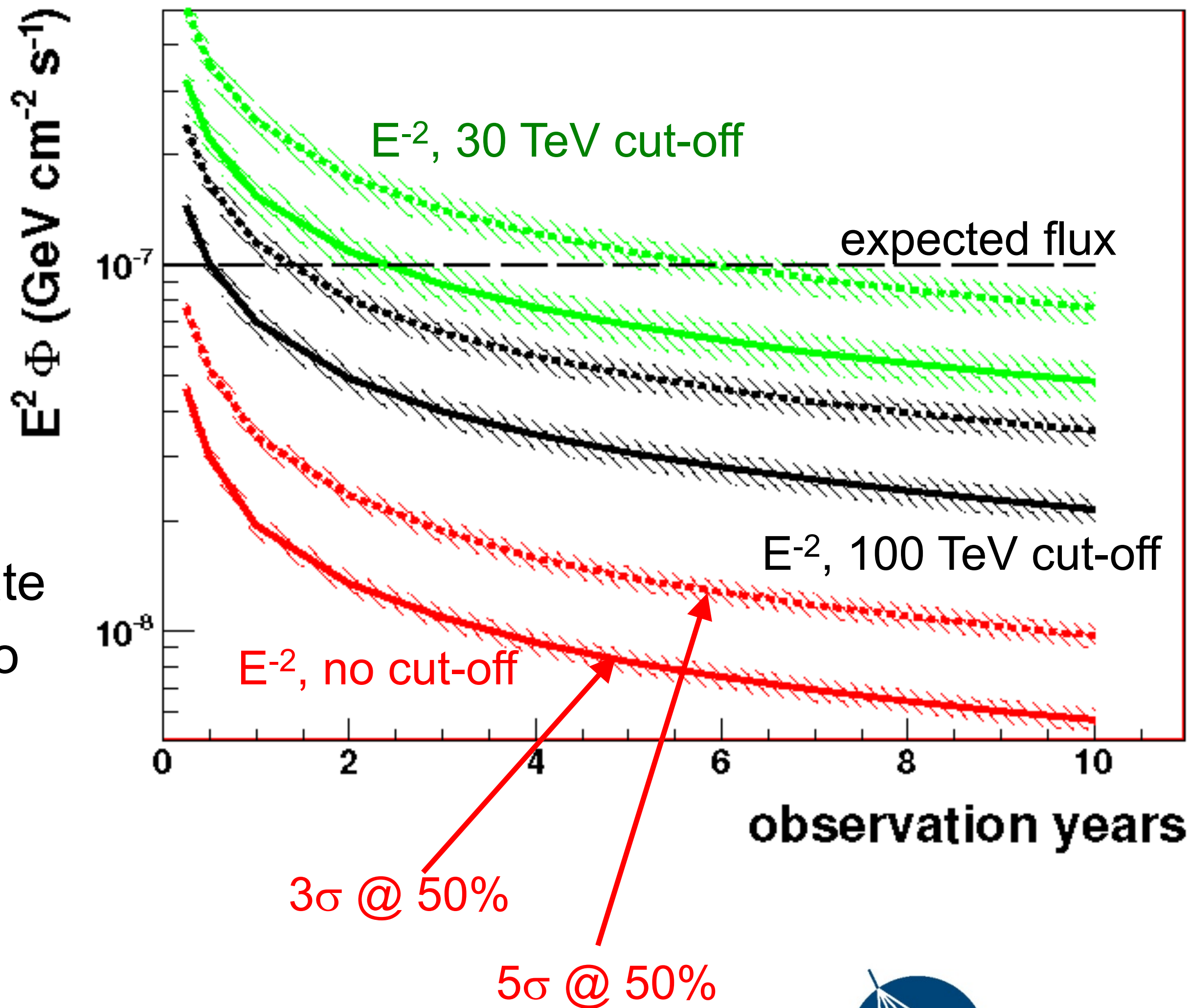
RX J1713: A prime candidate source

- Figure of merit (FOM): time to make an observation at 5σ with 50% probability
- KM3NeT analysis very conservative; ~20% improvement by unbinned analysis
- Clear (but flat) optimum in horizontal distance between DUs
- Further candidate sources with similar or better discovery chances (Vela X, Fermi Bubbles)



The Fermi bubbles

- Two extended regions above/below centre of Galactic plane
- Fermi detected hard γ emission (E^{-2}) up to 100 GeV
- Origin and acceleration mechanisms under debate – if hadronic, hot neutrino source candidate
- Could be first source detected by KM3NeT



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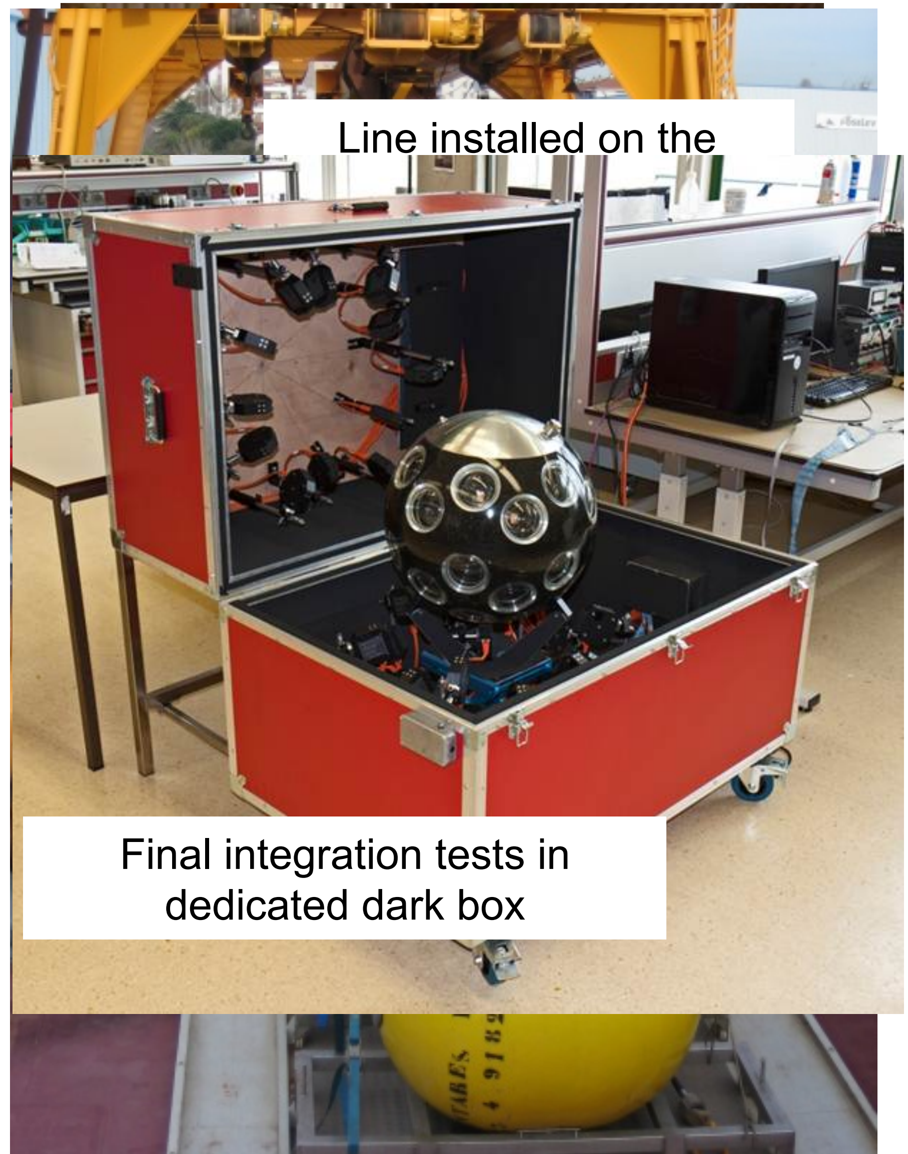
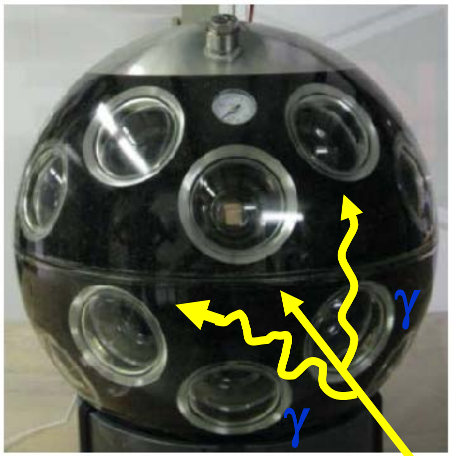
Recent achievements

The preproduction optical module (PPM-DOM)

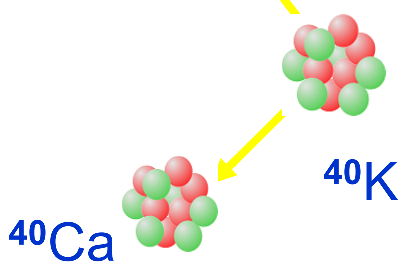
- Fully equipped DOM (31 PMTs + acoustic positioning sensors + time calibration LED beacon)
- Mounted on the instrumentation line of ANTARES
- Instrumentation line installed and connected on 16 April 2013
- PPM-DOM fully operational and working correctly

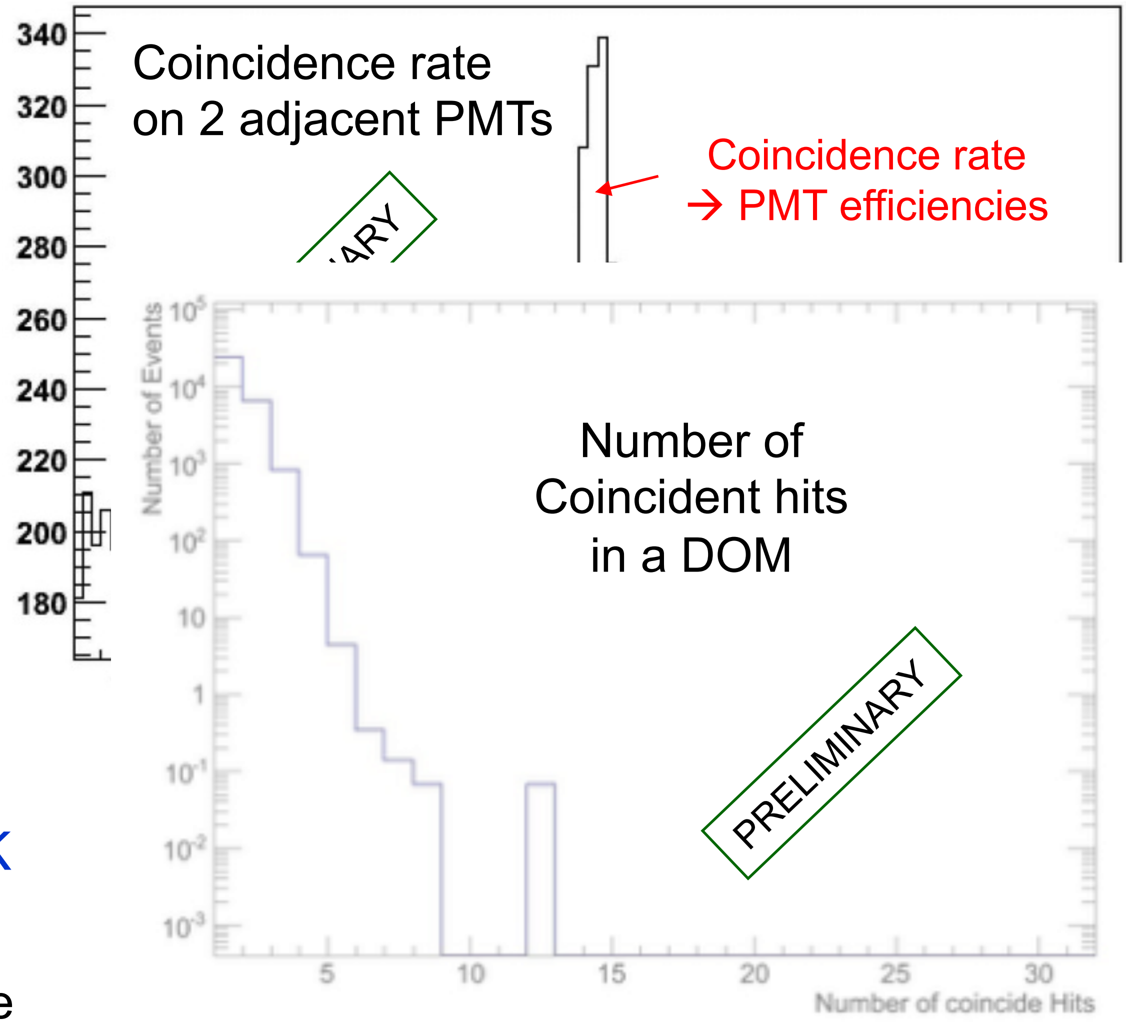


First PPM-DOM data from the deep sea



Up to 150 Cherenkov photons per decay





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

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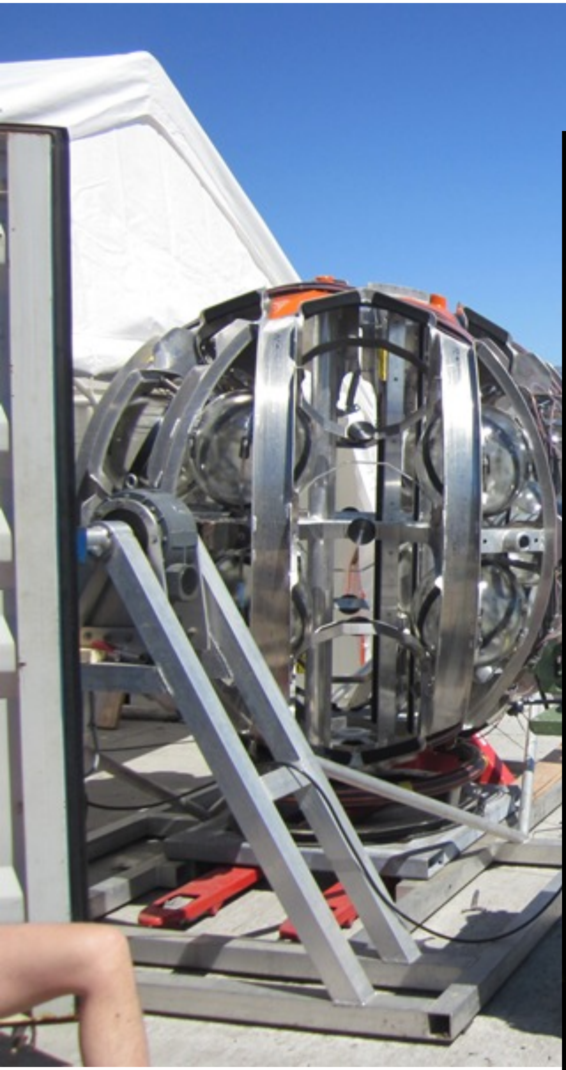
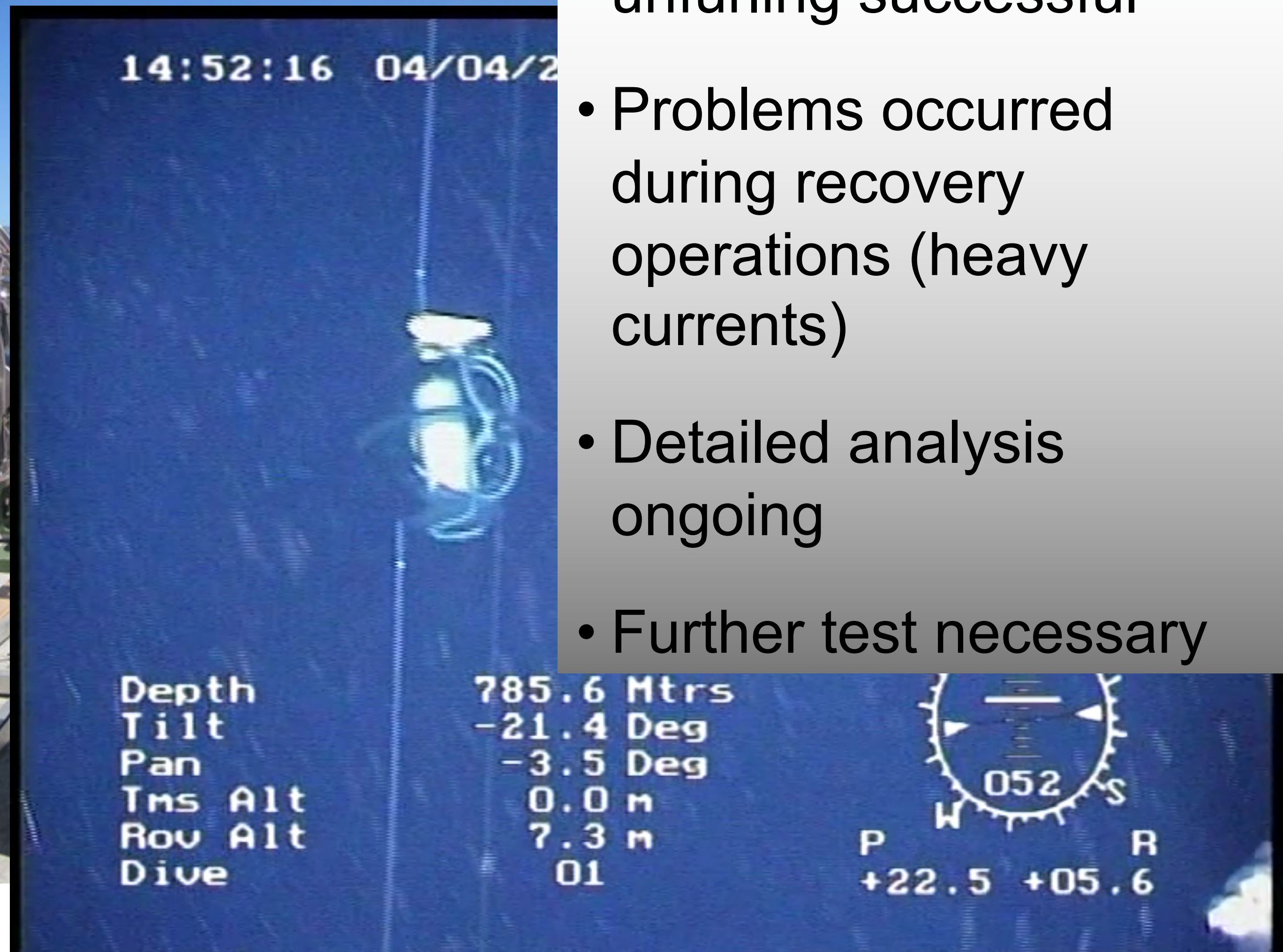
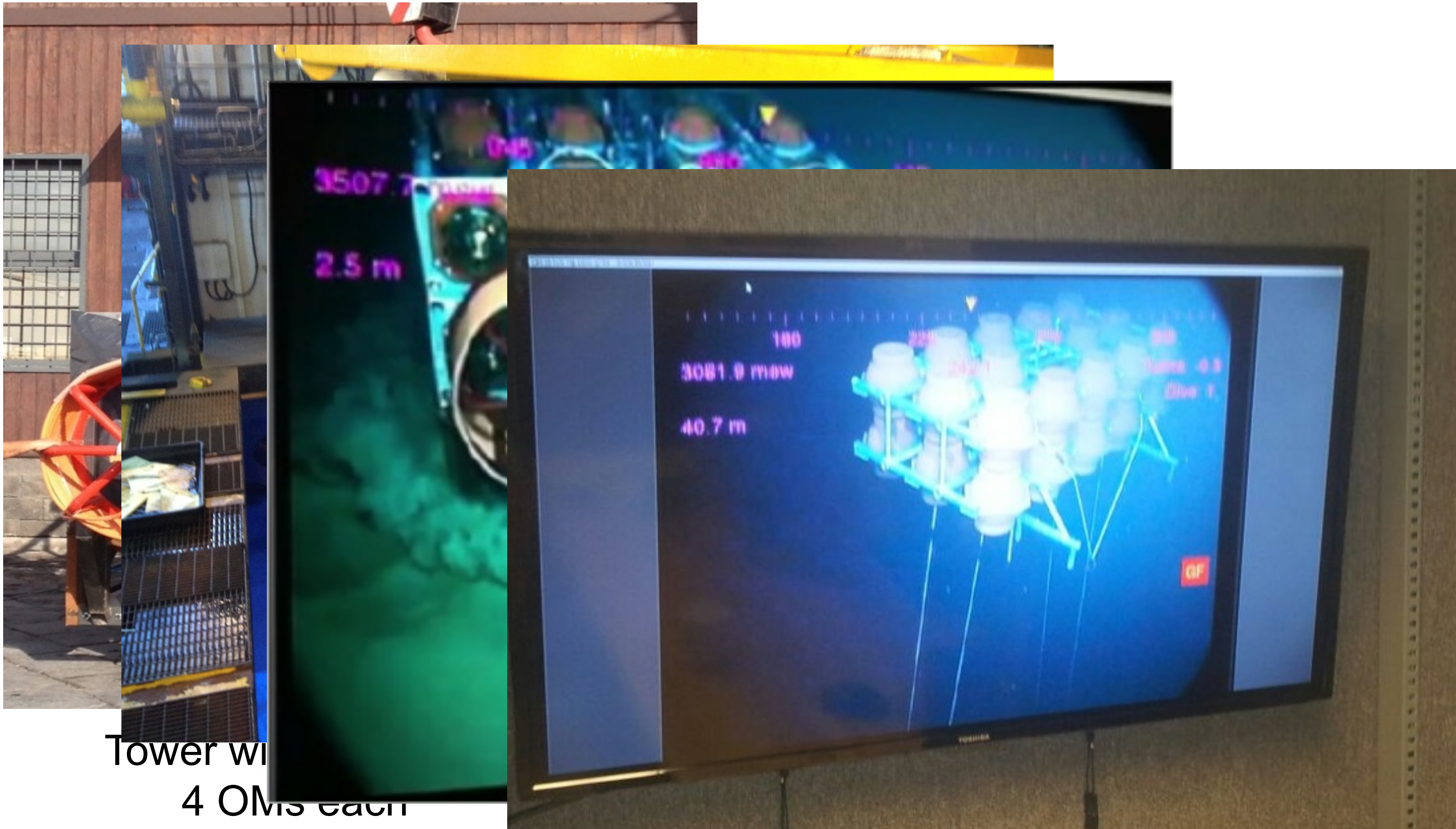
String deployment tests, April 2013





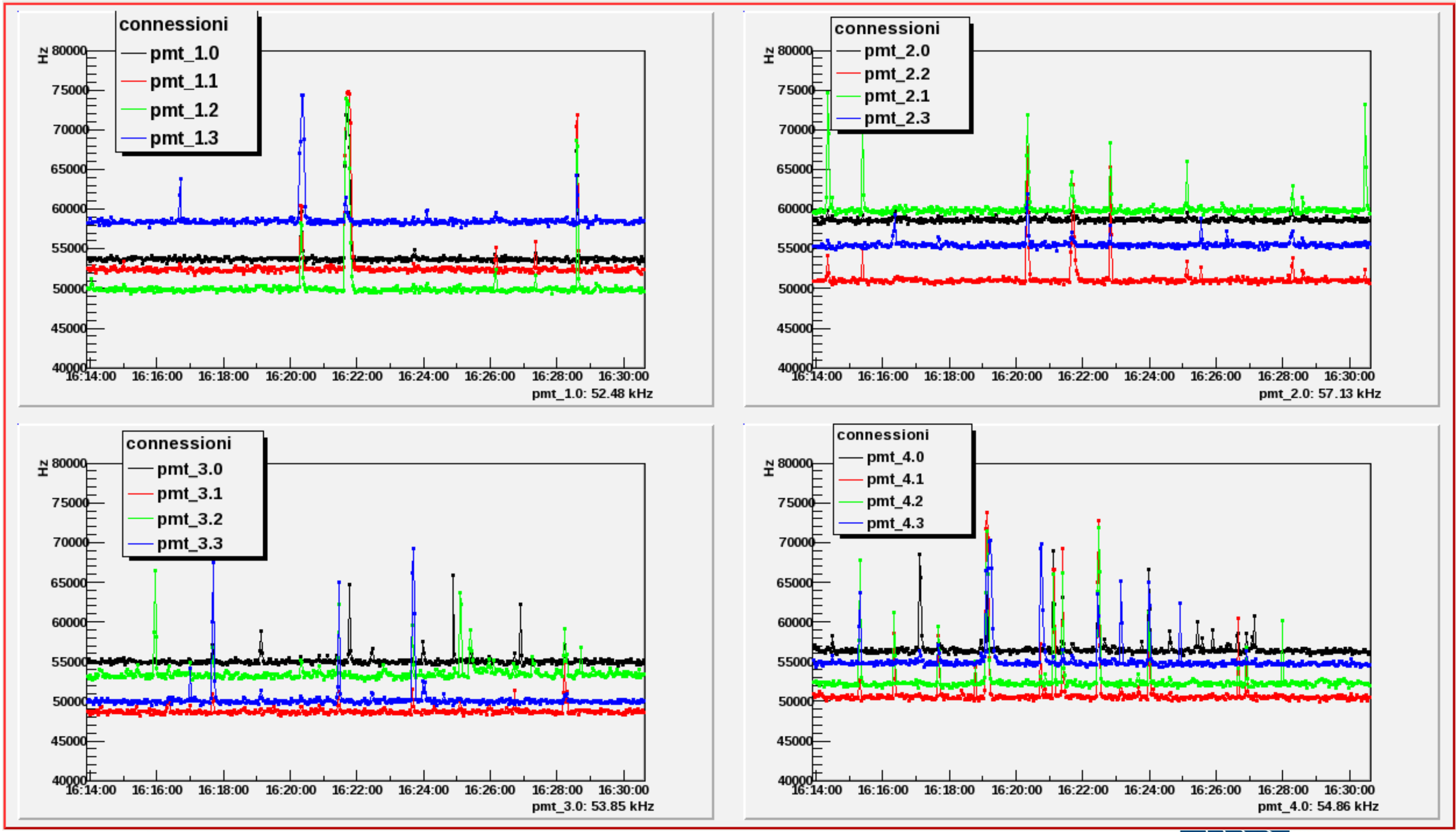
- Deployment and unfurling successful
- Problems occurred during recovery operations (heavy currents)
- Detailed analysis ongoing
- Further test necessary

Tower deployment, Capo Passero, April 2013



Tower wi
4 OMs each
(one 10‘-inch PMT per DOM`)

First data: PMT rates



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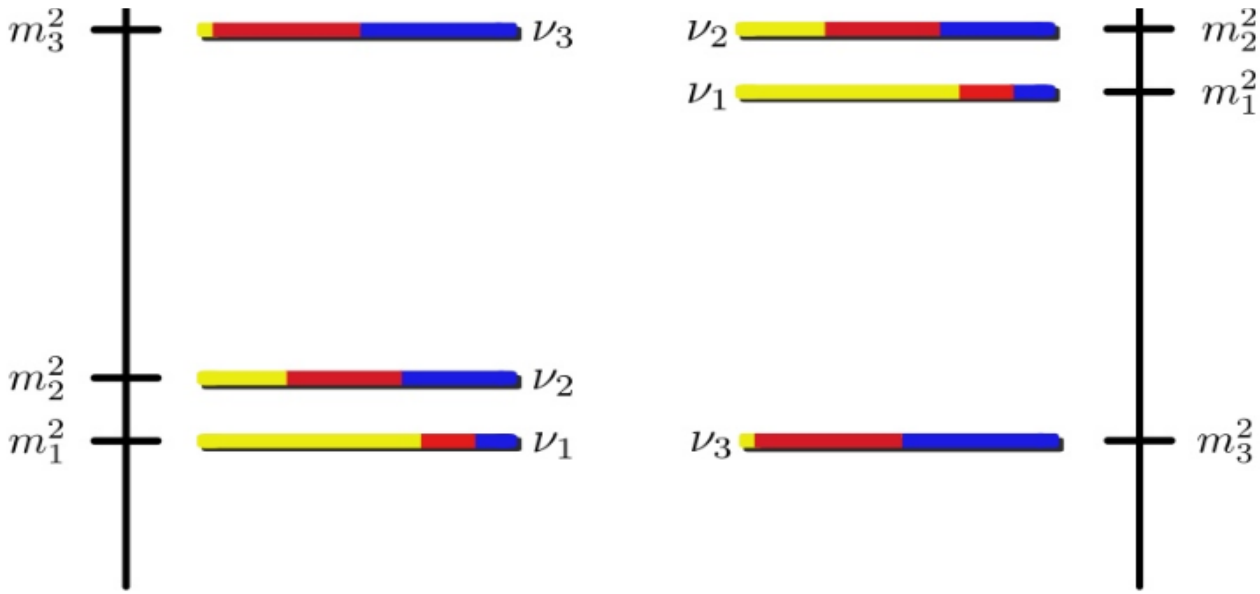
Studying low-energy neutrinos: The ORCA option

Neutrino mass hierarchy

- Depending on sign of Δm^2_{23} :
  "normal hierarchy" or "inverted hierarchy"
  (NH) (IH)



- A fundamental parameter of particle physics!

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Mass hierarchy and atmospheric neutrinos

- Determining the sign of Δm^2_{23} requires matter effect. Oscillation of ν_e and/or $\overline{\nu}_e$ must be involved.
- 3-flavour oscillations of $\nu_e \leftrightarrow \nu_\mu$ in matter:

$$P_{e\to\mu} \approx P_{\mu\to e} \approx \sin^2\theta_{23}\sin^2(2\theta_{13}^{\text{eff}})\sin^2\left(\frac{\Delta_{13}^{\text{eff}}L}{2}\right)$$

$$\Delta_{13} = \frac{\Delta m^2_{13}}{2E_\nu} \qquad \sin^2(2\theta_{13}^{\text{eff}}) = \frac{\Delta_{13}^2\sin^2(2\theta_{13})}{\Delta_{13}^{\text{eff}}L}$$

$$\Delta_{13}^{\text{eff}} = \sqrt{[\Delta_{13}\cos(2\theta_{13}) - A]^2 + \Delta_{13}^2\sin^2(2\theta_{13})}$$

$$A = \sqrt{2}G_F N_e \text{ for } \nu \text{ and } A = -\sqrt{2}G_F N_e \text{ for } \overline{\nu}$$

- “Matter resonance” for $A = \Delta_{13}\cos(2\theta_{23})$ (maximal mixing, minimal oscillation frequency). This is the case for $E_\nu \approx 30\,\text{GeV}/\rho[\text{g cm}^{-3}]$

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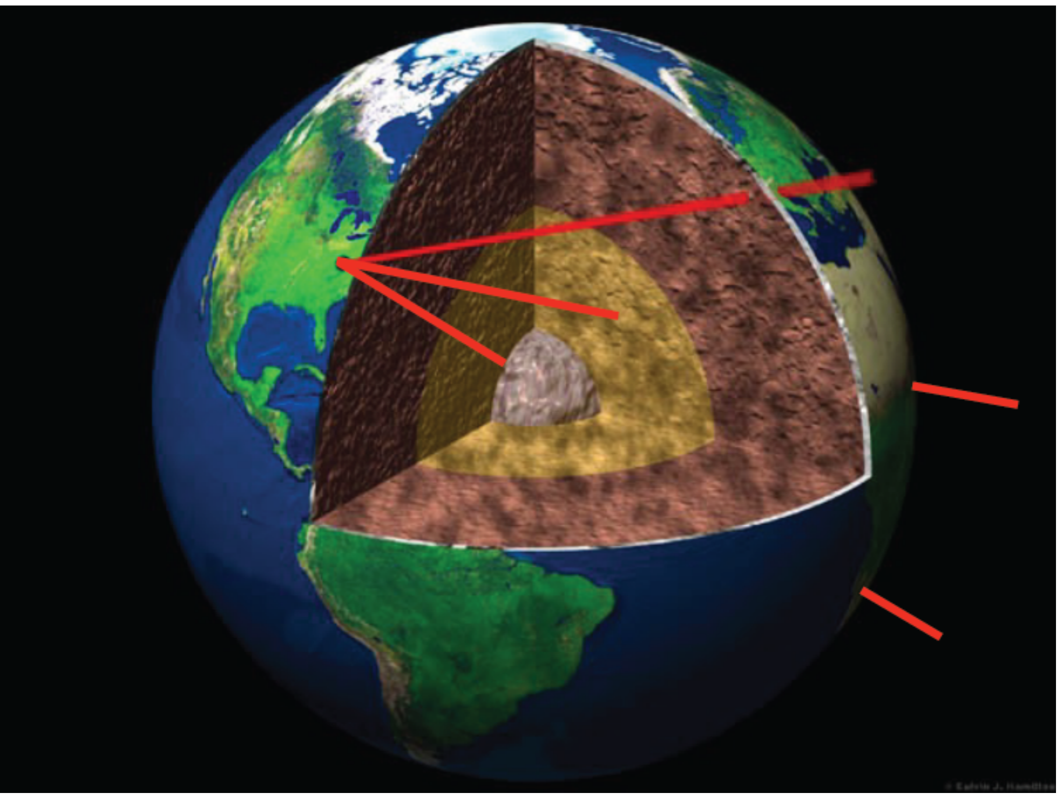
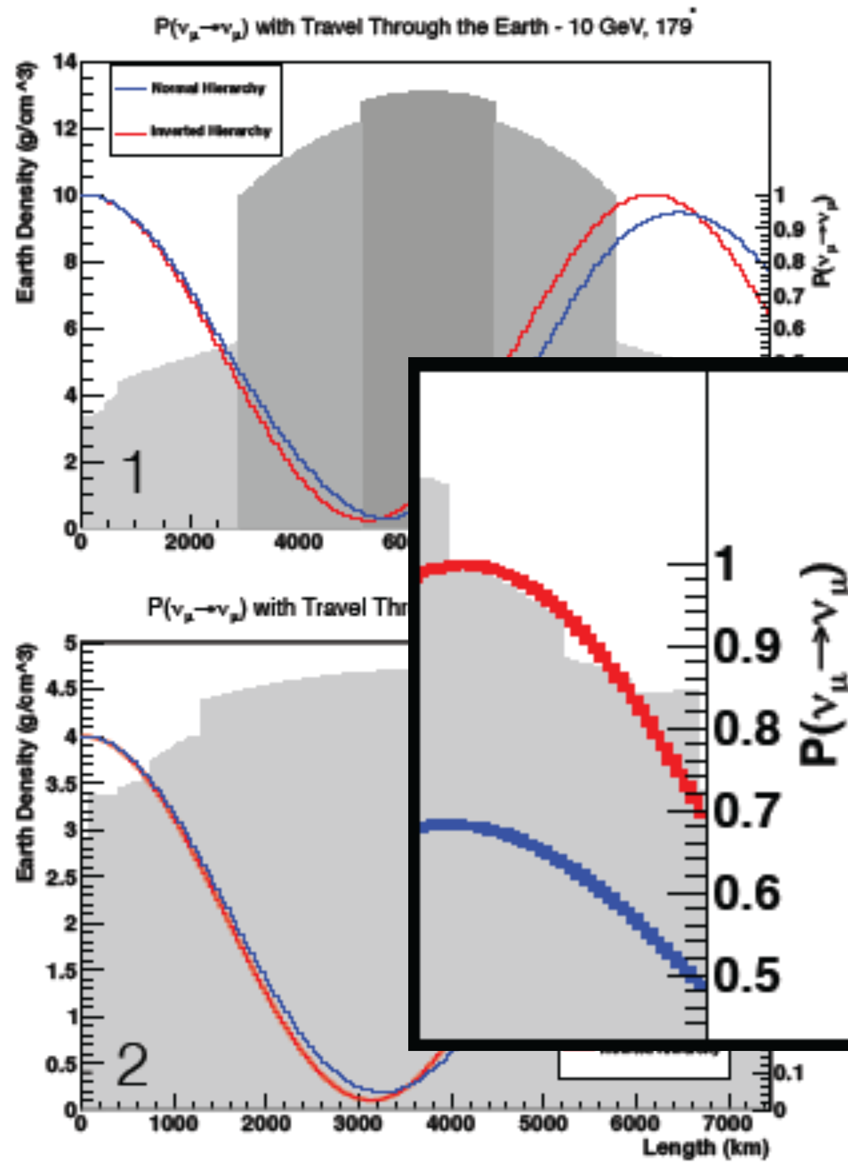
Neutrino oscillations in Earth

- Earth density 4-13 g/cm^3
- Relevant: $E_\nu \sim 3\text{–}10\,\text{GeV}$



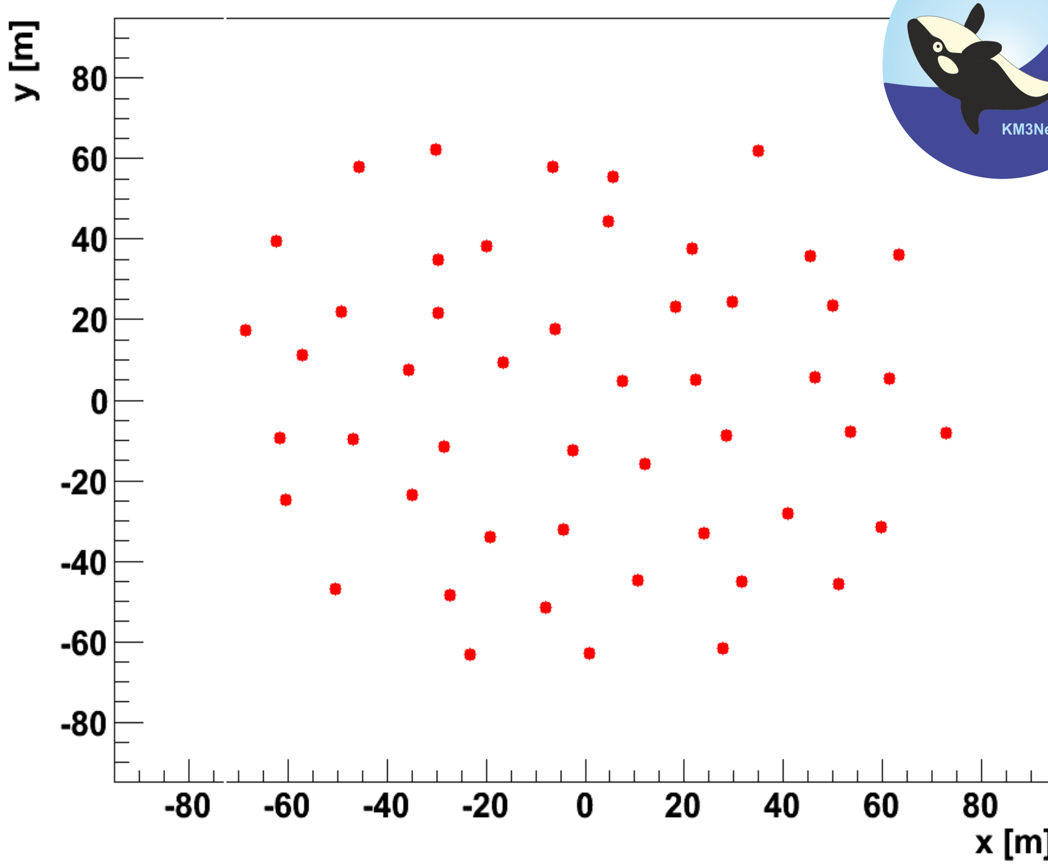


FOR ASTROPARTICLE PHYSICS

ORCA: A case study for KM3NeT

- Investigated: 50 strings, 20 OMs each
- KM3NeT design: 31 3-inch PMTs / OM
- 20 m horizontal distance
- 6 m vertical distance
- Instrumented volume: 1.75 Mton water

Note: This is just a (scalable) example configuration



ORCA: Hardware and construction issues

- Use agreed KM3NeT technology;
  no major modifications required,
  but cable lengths etc. to be adapted
- String length restricted to avoid entanglement
  due to deep-sea currents
- Deployment requires care and studies
  (operation of deep-sea submersibles (ROVs) between deployed strings is impossible)
- New deployment scheme proposed
  (several strings in one sea operation)
- Very tight time constraints due to funding situation

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The major experimental questions

- What are the trigger/event selection efficiencies?
- How and how efficiently can we separ… …ferent event classes?
- How can we reconstruct th… …d what resolutions can we reach on E_ν and…
- How can we cont… …grounds?
- What are t… …systematic effects and how can we control them…
- What precision of calibration is needed and how can it be achieved?

Questions under investigation,
no firm conclusions yet

A proposal requires knowing the answers!

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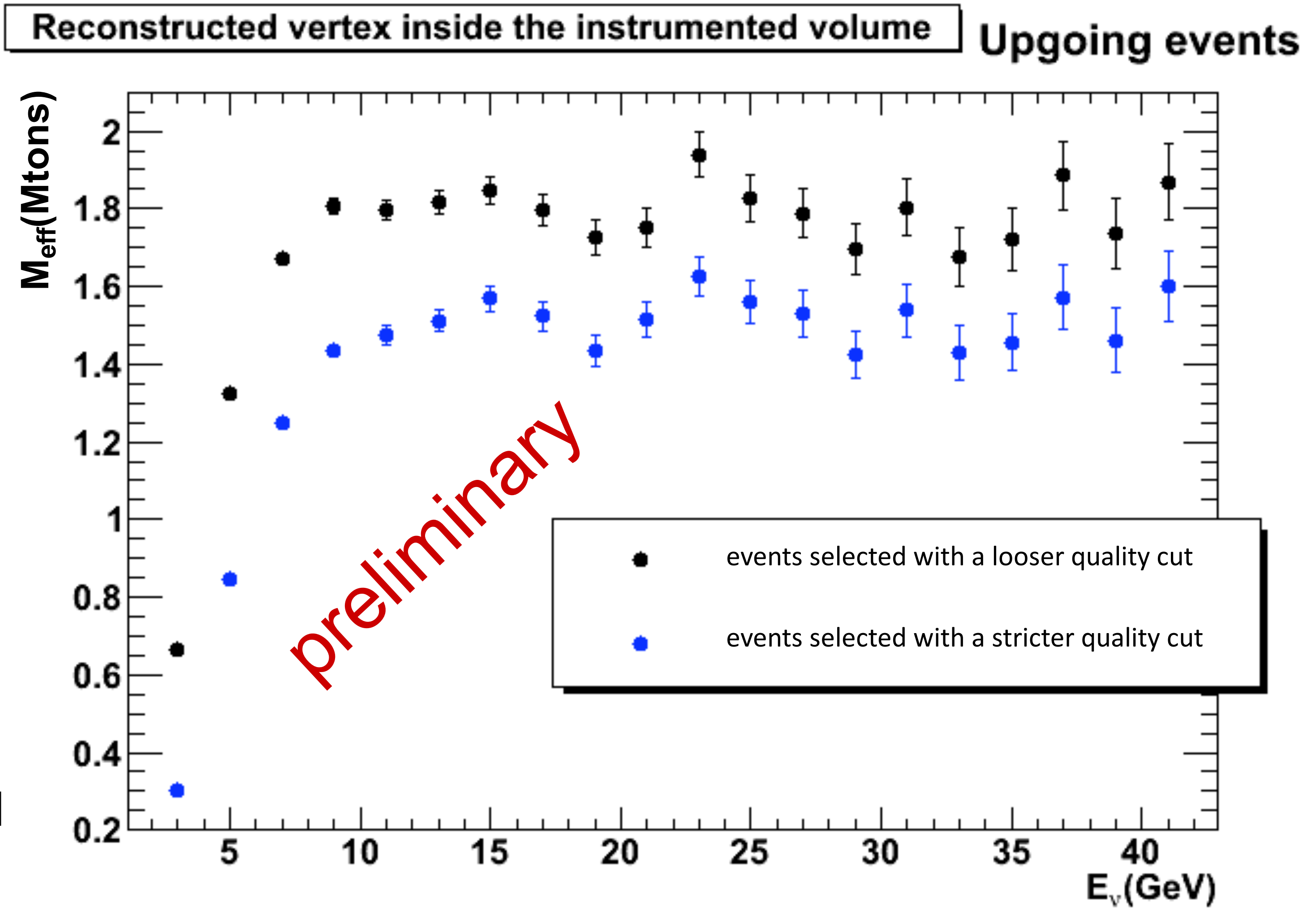
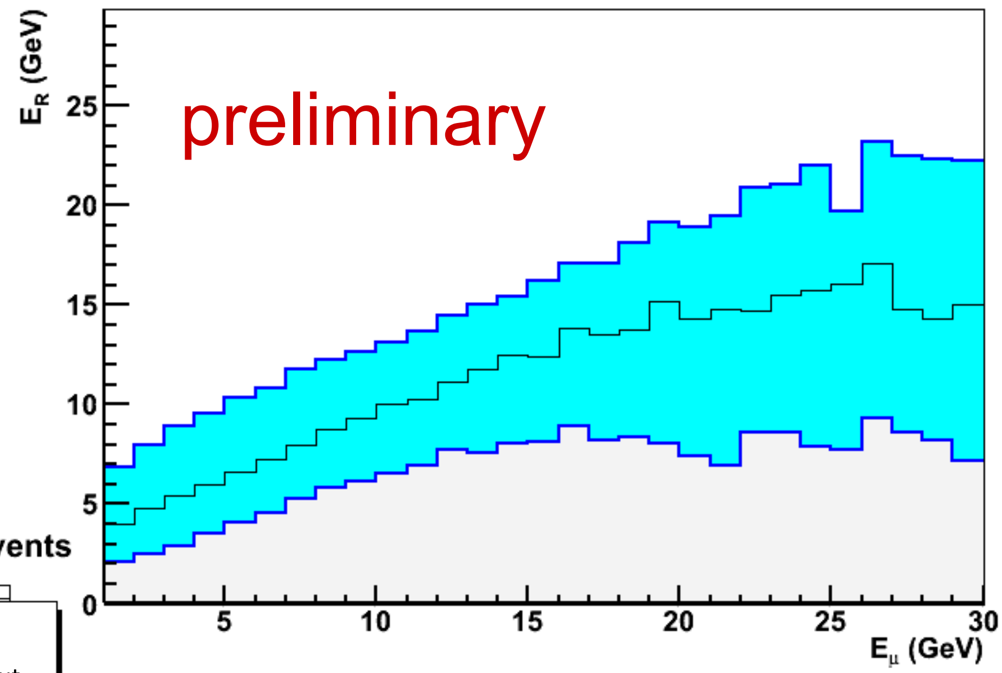
ORCA reconstruction efficiency

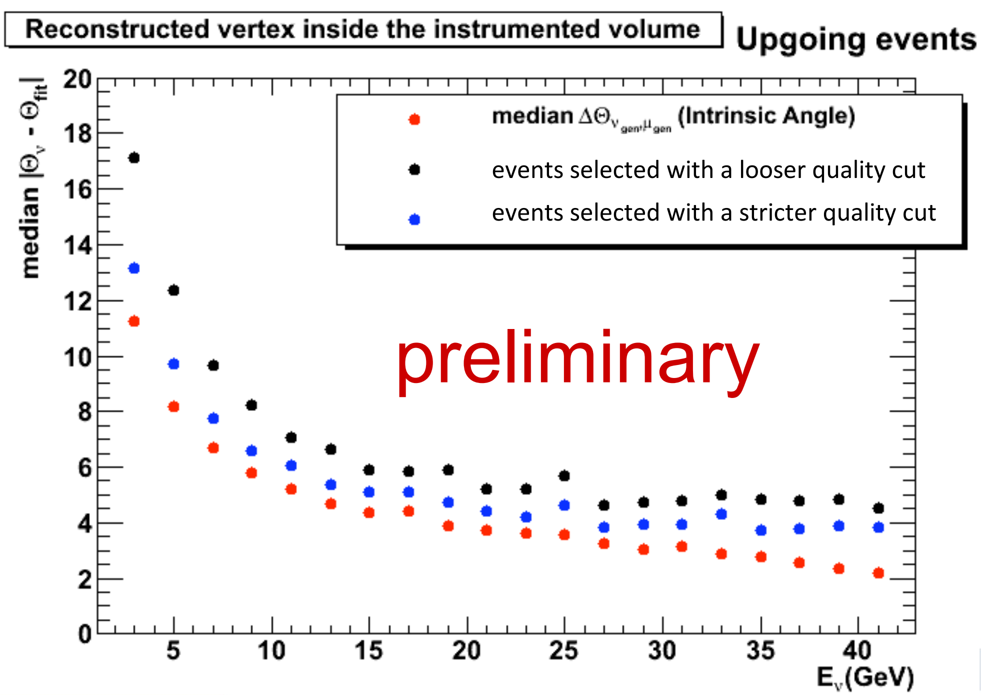
- Isotropic ν_μ CC events generated
- Event must be reconstructed as up-going with vertex in instrumented volume
- Efficiencies determined for two levels of quality cuts
- No background rejection



ORCA energy and zenith resolutions

- E_μ reconstructed from μ track length
- Shaded region: 16% and 84% quantiles as function of E_μ^{true}
- $\Delta E_\nu \overset{?}{\approx} 1\ \text{GeV}|_\mu + 0.2 E_{\text{shower}}$





- Median of zenith angle difference ν – rec. μ

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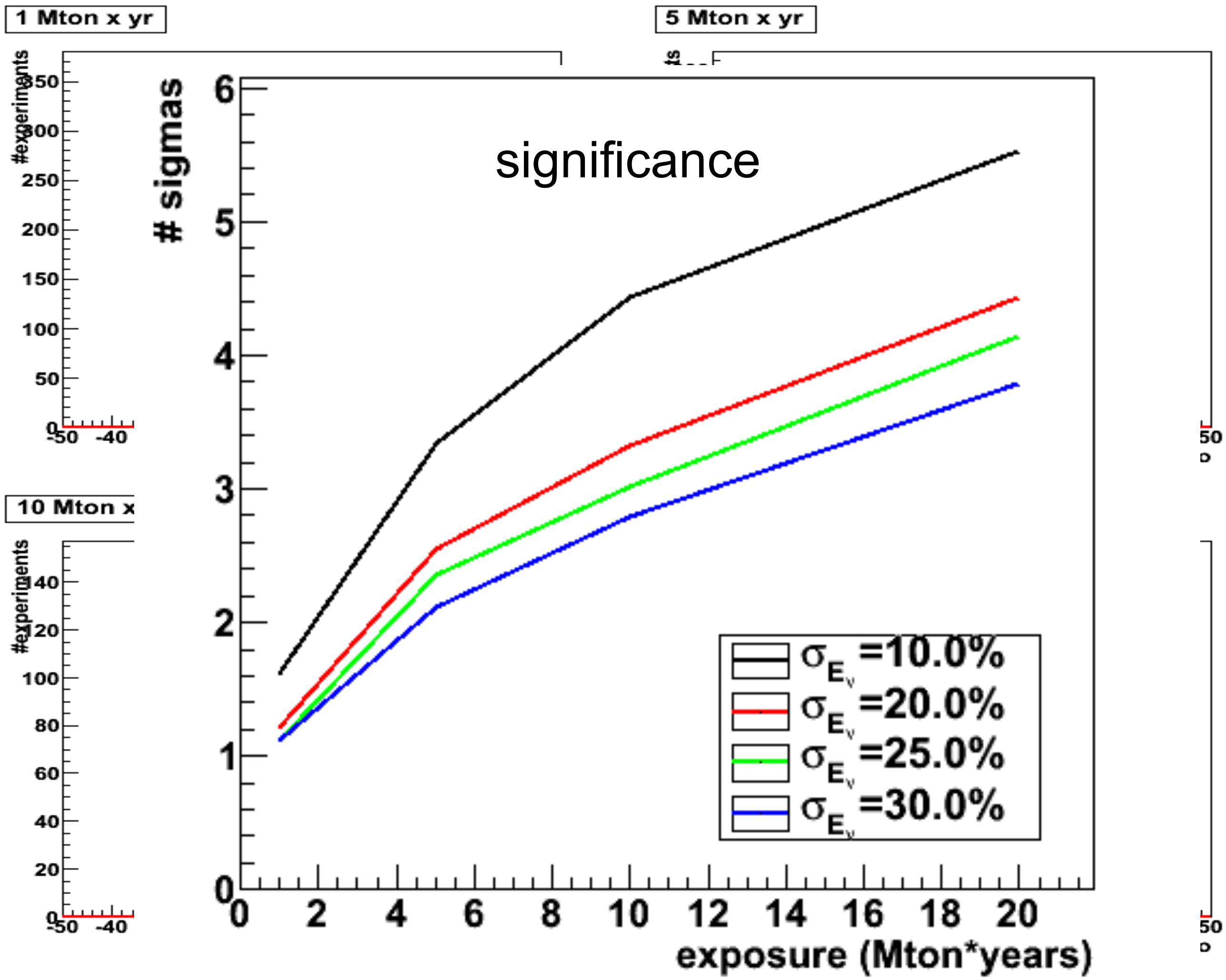
Results of toy analysis:

- Experimental determination of mass hierarchy at 4-5σ level requires ~20 Mton-years
- Improved determination of Δm^2_{23} and θ_{23} seems possible



Summary and outlook

- ANTARES has demonstrated the feasibility of a deep-sea neutrino telescope.
- KM3NeT will provide a multi-km^3 installation in the Mediterranean Sea sensitive enough to detect Galactic sources and more.
- The design process has concluded in an agreed technology (strings with multi-PMT digital OMs).
- KM3NeT will be a multi-site installation (France, Greece, Italy).
- It will provide nodes for earth/sea sciences.
- A first construction phase in underway.
- A low-energy option (ORCA) is under investigation.