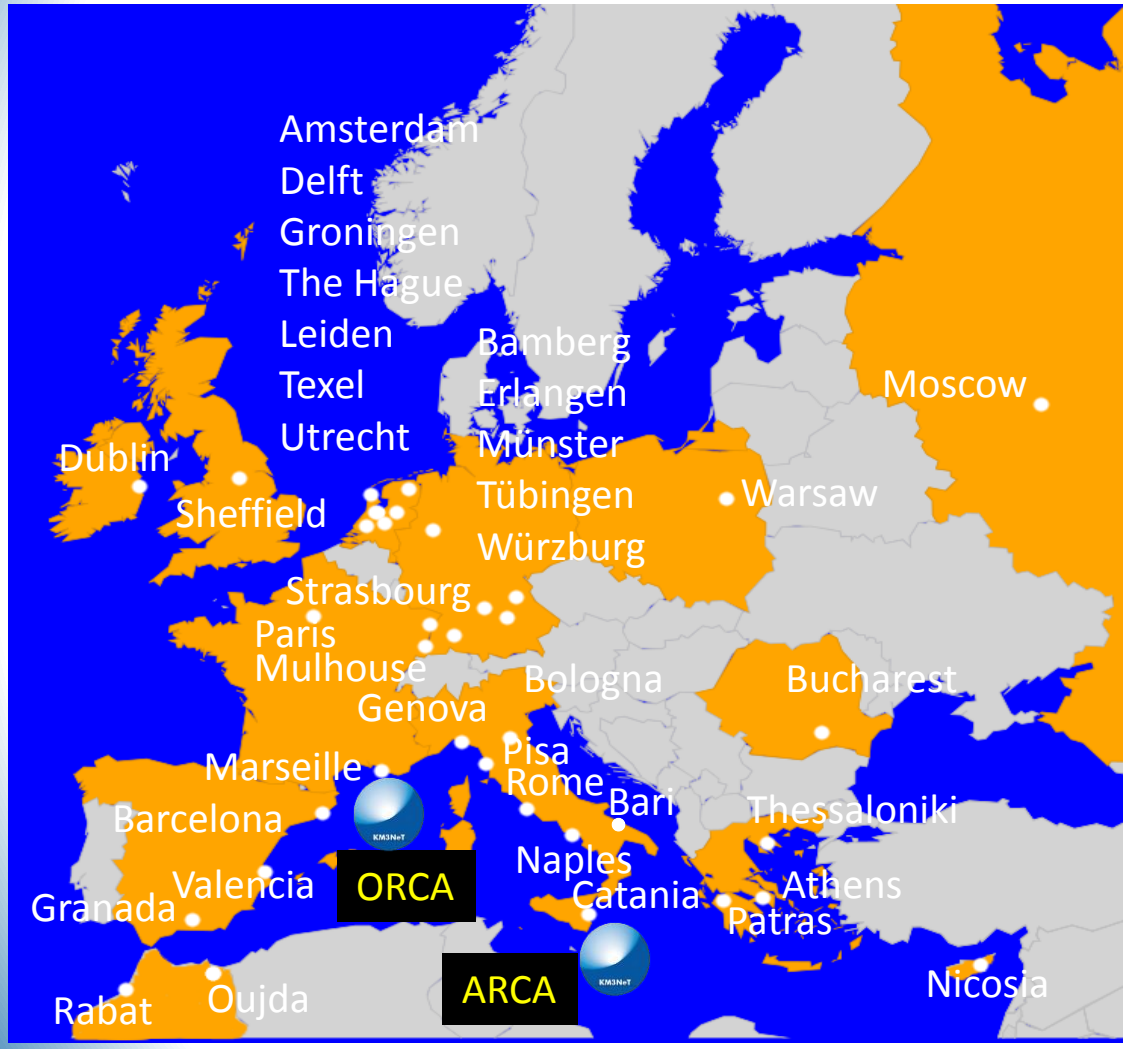
Astroparticle and neutrino oscillation research with KM3NeT

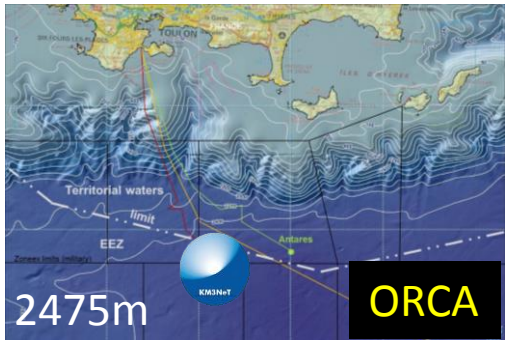
M. Circella (INFN Bari)

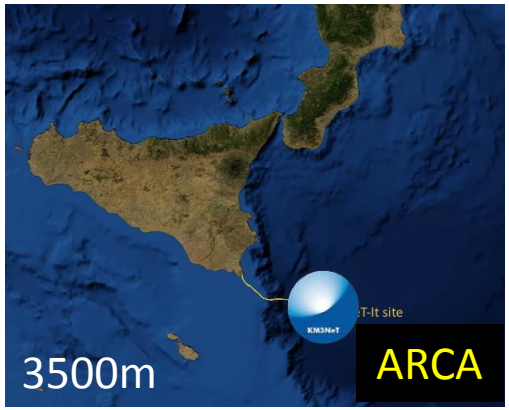
on behalf of the KM3NeT Collaboration

KM3NeT

Multi-site, deep-sea, next generation neutrino research infrastructure

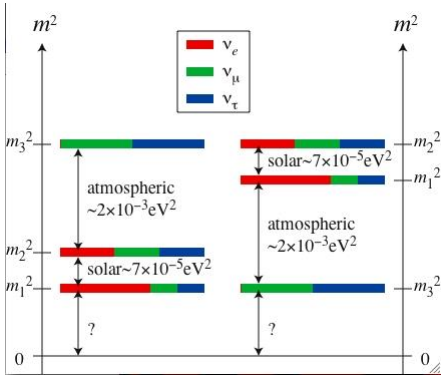


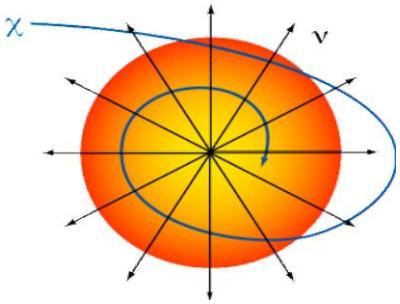


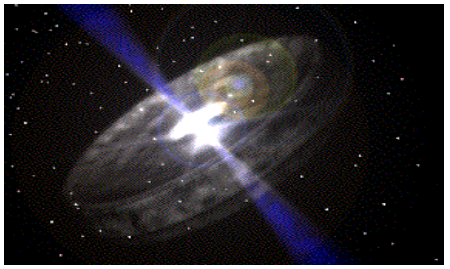


Single Collaboration, Single Technology

Objectives







Low Energy	Medium Energy	High Energy
3 GeV < E_ν < 50 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV
ν Oscillations ν Mass Hierarchy	Dark Matter search + Exotic searches	ν from extra-terrestrial sources Origin and production mechanism of HE CR

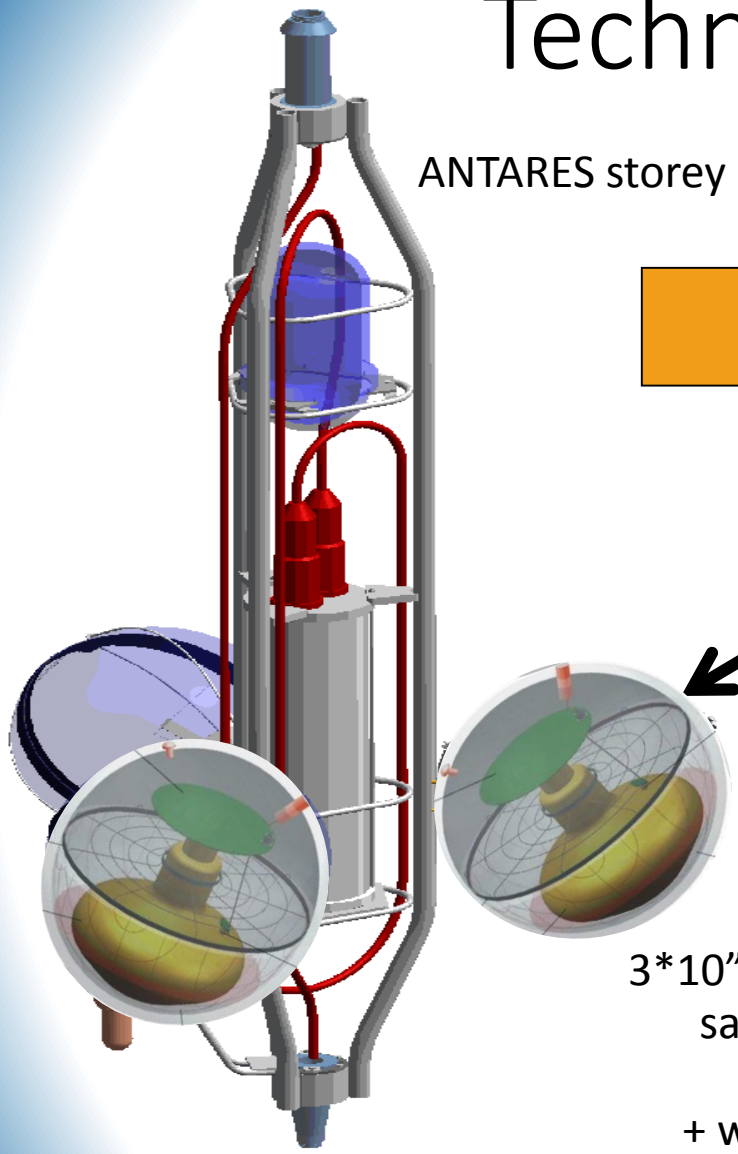
KM3NeT-ORCA — ANTARES (operating) — KM3NeT-ARCA

Oscillation Research with Cosmics in the Abyss (ORCA)

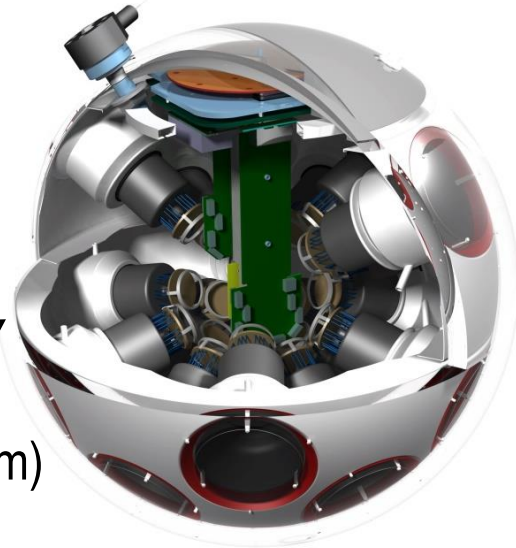
Astroparticle Research with Cosmics in the Abyss (ARCA)

Technologies

ANTARES storey

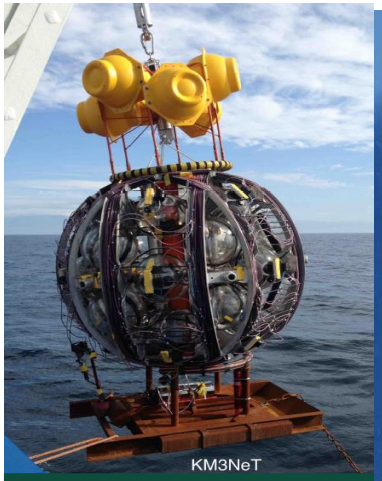


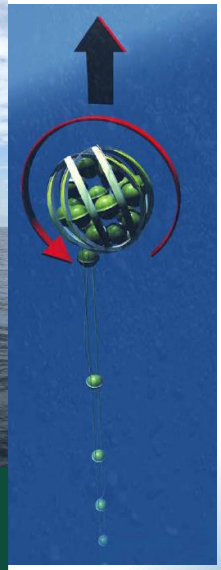
KM3NeT DOM
(Digital Optical Module)



Same size (43cm)

3*10” PMTs -> 31*3” PMTs
same sensitive area
+ compactness
+ wider angle of view
+ directional information
+ digital photon counting
+ cost reduction



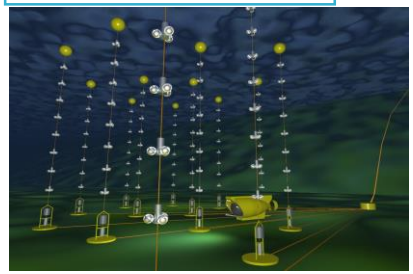


The DU (Detection Unit):
rapid deployment
autonomous unfurling
launcher vehicle recoverable

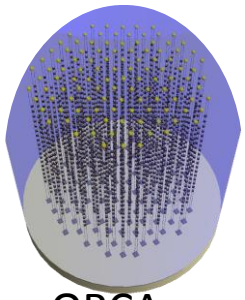
Detector sizes

	ANTARES	ORCA (denser)	ARCA (larger)
Eff. Mass	10 Mt	5.7 Mt	1 Gt
Line length	350 m	200 m	650 m
Interline distance	70 m	20 m	90 m

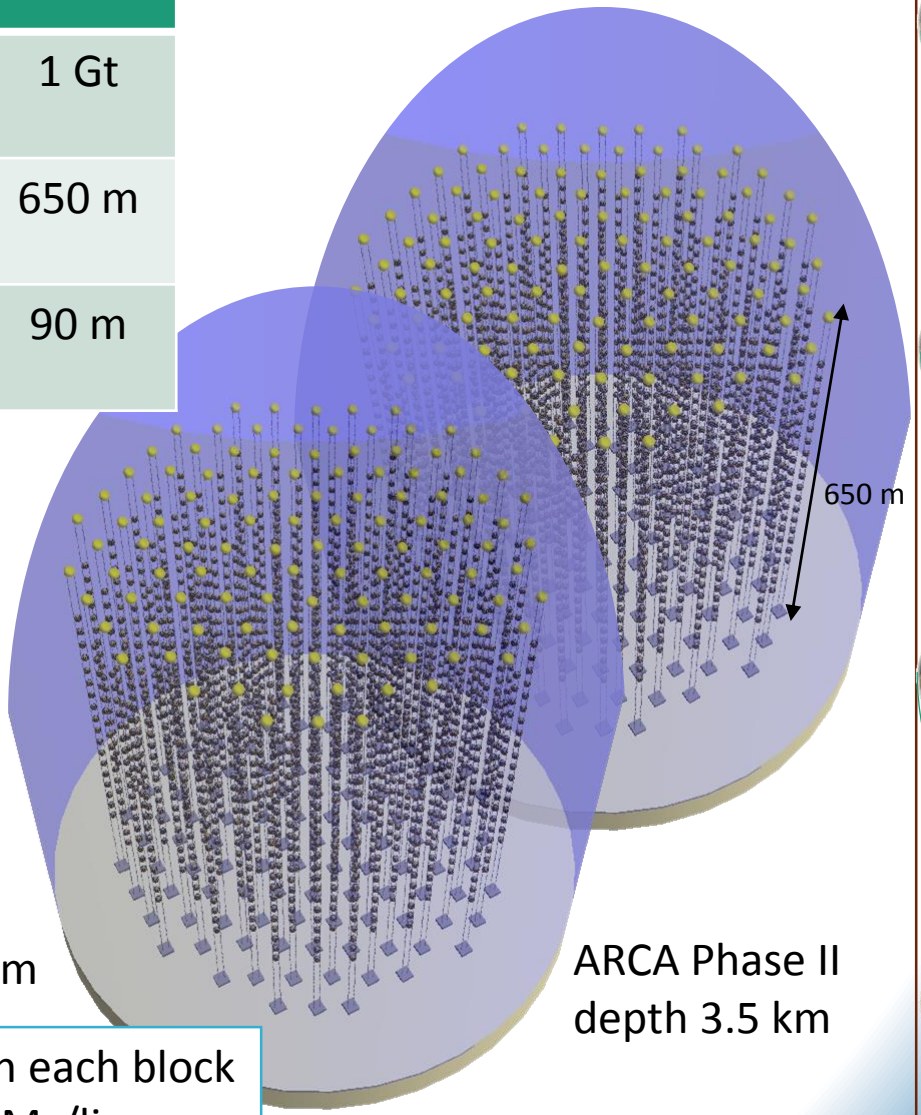
12 lines
25 sectors/line



ANTARES
depth 2.5 km



ORCA
depth 2.5 km



ARCA Phase II
depth 3.5 km

115 lines in each block
18 DOMs/line

Phase-1 vs. Phase-2 (ARCA+ORCA)

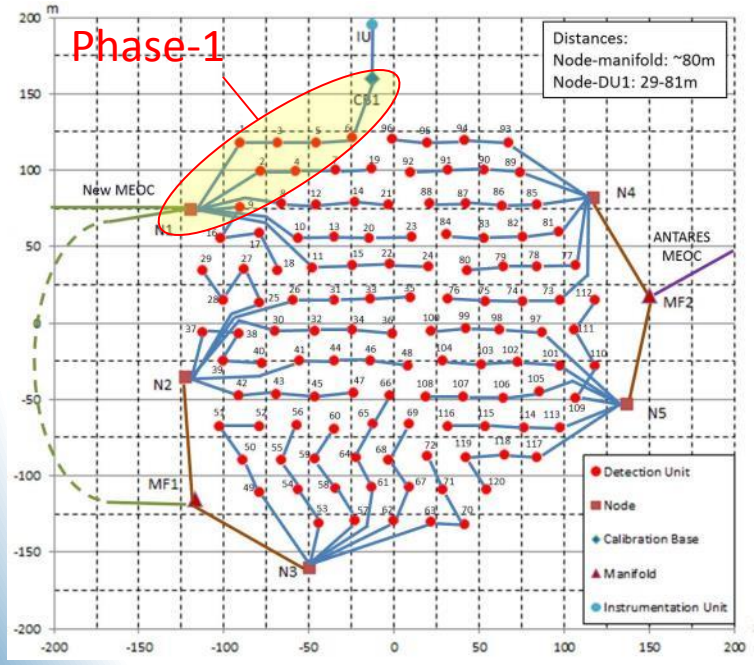
Phase-1 (ongoing):

- **24 ARCA DUs at KM3NeT-It (ARCA)**
- **6 ORCA DUs at KM3NeT-Fr (ORCA)**

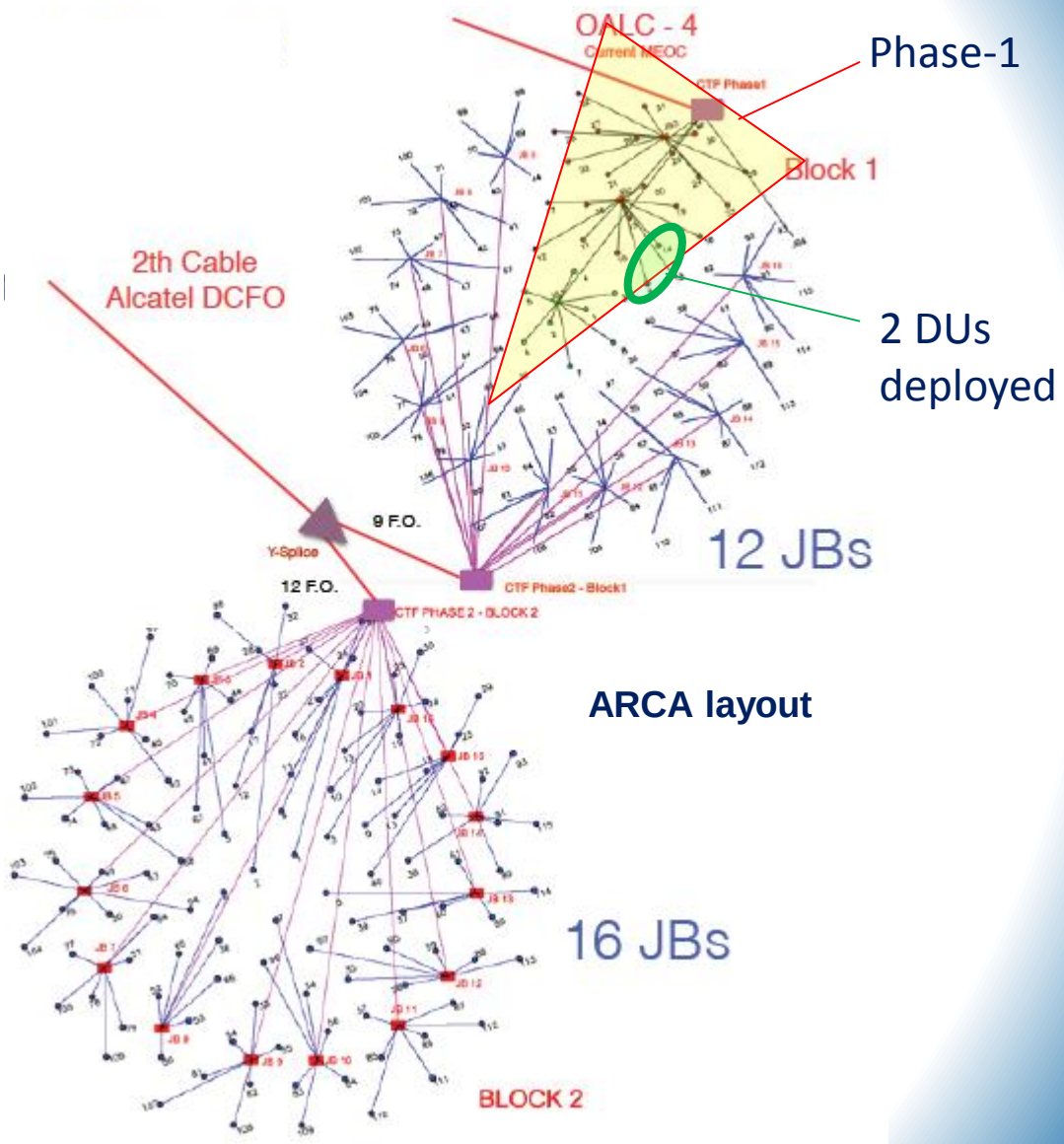
Phase-2 (coming up possibly soon!):

- **2 ARCA blocks at KM3NeT-It**
- **1 ORCA block at KM3NeT-Fr**

(1 block = 115 DUs)



ORCA layout



ARCA layout

Status of infrastructures

ORCA (Toulon, France, 2500 m depth)

- **Main electro-optical cable and submarine node of Phase-1 installed**
- **Onshore station up and running**

i.e.: infrastructure ready to accept first detection units!

Deployment of the ORCA long-distance cable

Deployment of the ORCA node

Power station ORCA (side by side to ANTARES…)

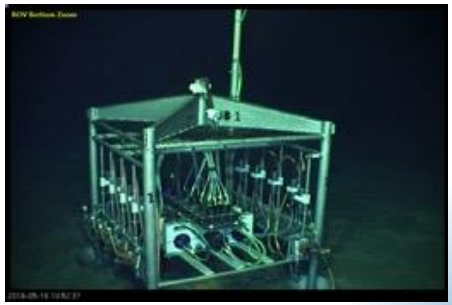
ARCA (Capo Passero, Italy, 3500 m depth)

- **Shore station operating**
- **First Junction Box of Phase-1 submarine infrastructure installed**
- **Two detection units in operation**

i.e.: infrastructure up and running, data taking ongoing!

Shore station of ARCA

Cable Termination Frame (above) and first Junction Box (below) of ARCA

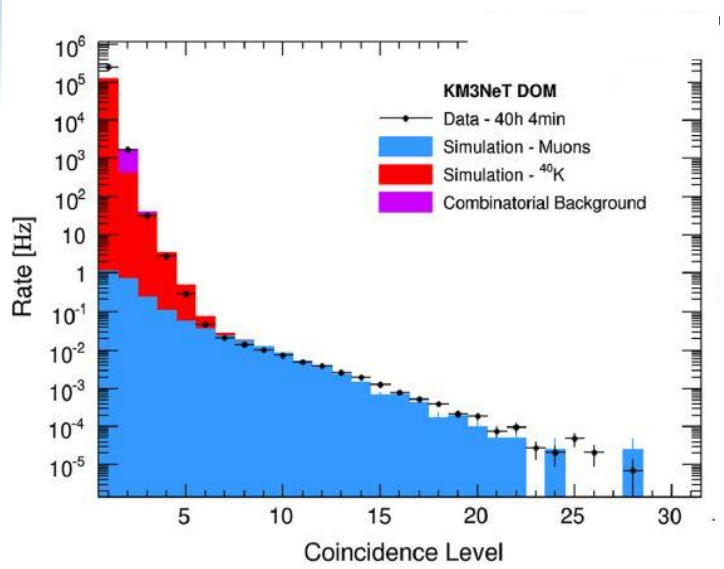


A bit more about DOMs (Digital Optical Modules)

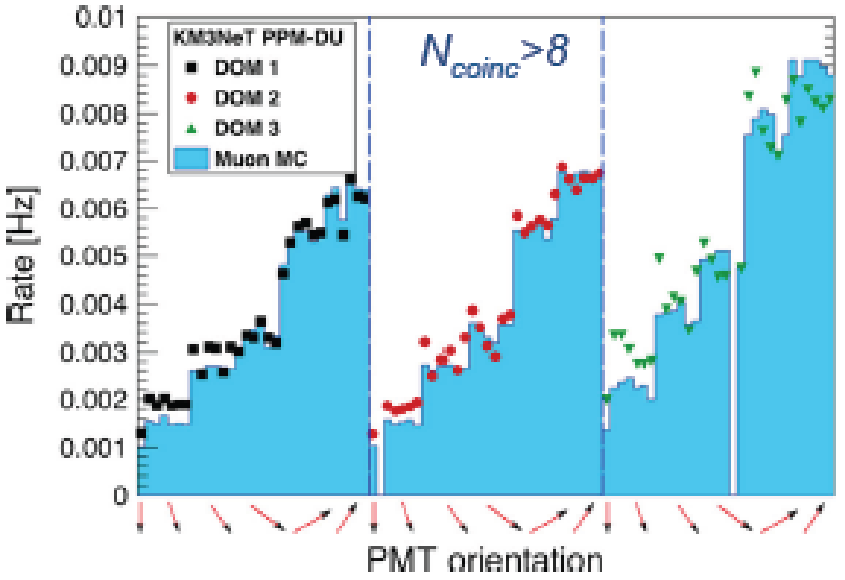
- **31 PMTs of 3” photocathode in a 17” glass sphere**
- **Optical gel coupling between PMTs and glass**
- **Reflection rings around the PMTs to increase detection surface**
- **Electronics, optics for long-range communications and calibration devices (including: ‘nanobeacon’ LED pulser, compass/tiltmeter, and piezo-sensor for acoustic measurements) installed inside the sphere – each DOM acting as an individual, autonomous detection node**
- **Connection to the rest of the apparatus requires two conductors (+12 V power) and one optical fibre through a single penetrator**

See presentations by Ronald Bruijn (DOM) and Salvo Viola (calibrations) yesterday

About DOM performance

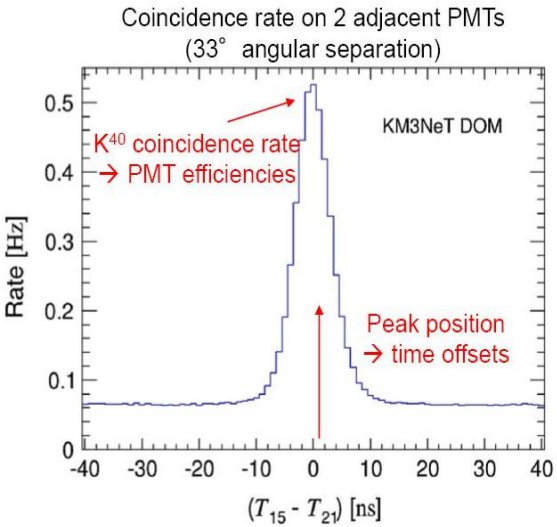


A cut on multiplicity allow to select particle hits, background-free

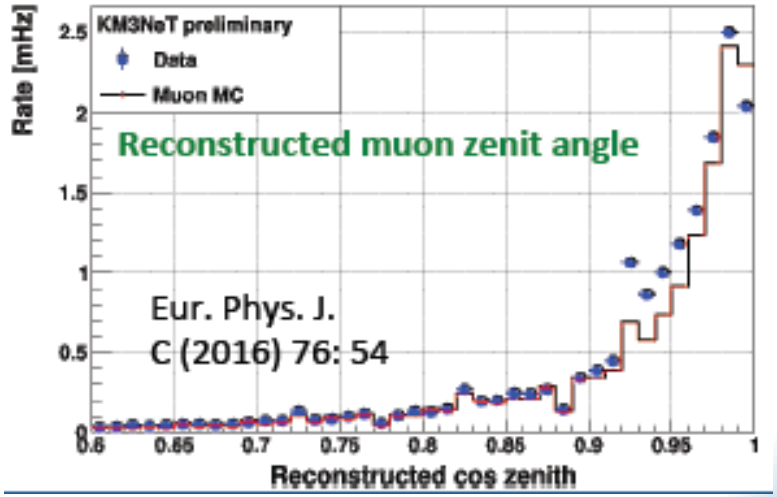


Directionality response in the 3 DOMs of prototype PPM-DU

Coincidences (due to ^{40}K) help for detector calibration



Eur.Phys.J. C74 (2014) 3056



A bit more about DUs (Detection Units)

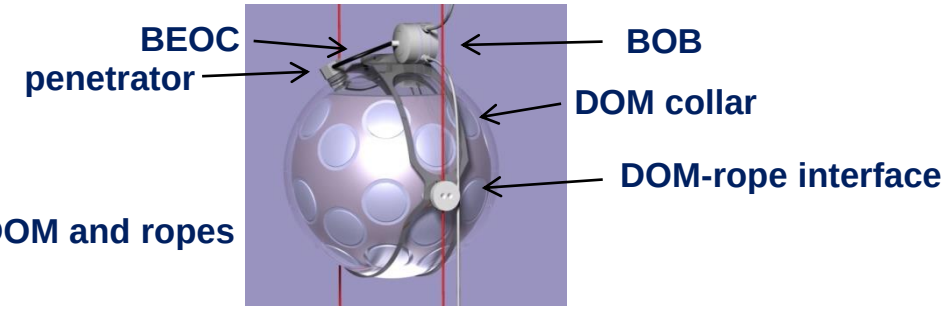
- **Mechanical structure of the string based on two dyneema ropes, anchored on sea floor and kept taut by a (commercial) top buoy (plus DOM buoyancy)**
  - **Slender arrangement**
  - **DOMs keep the correct attitude**
  - **String dynamics under control (but requires positioning calibration!)**

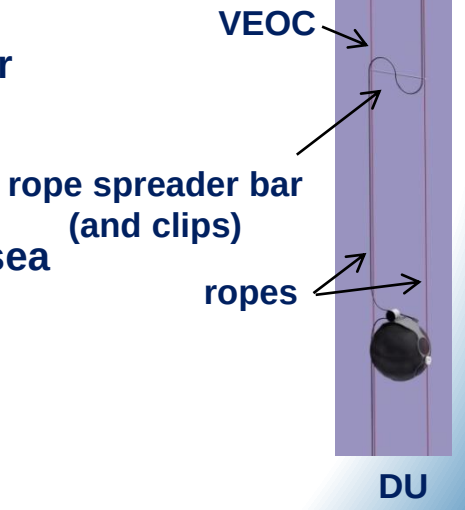
- **DOM collars keep the DOMs in their positions**

- **the VEOC (Vertical Electrical-Optical Cable) connects all DOMs to the DU base – the VEOC is an oil-filled pressure-balanced hose equipped with 18 optical fibres (one for each DOM)**

- **A Break-out-box (BOB) is the interface between a DOM and the VEOC**
  - **Very simple structure hosting fibre splices and a DC/DC converter**
  - **A short cable (BEOC – BOB Electrical-Optical Cable) connects the BOB to the DOM penetrator**

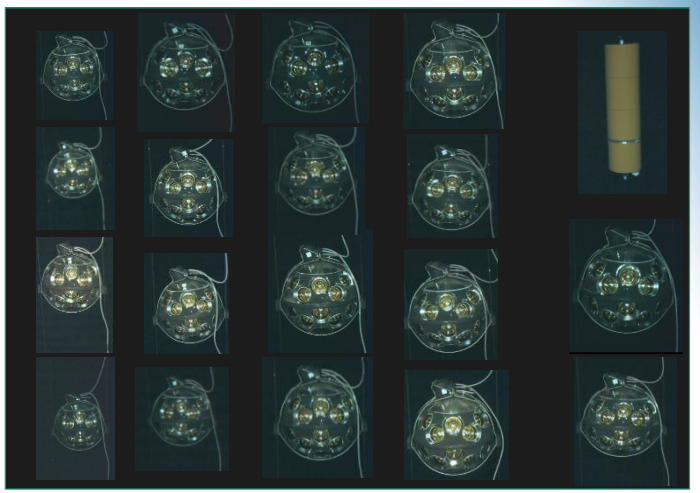
An anchor equipped with a base module allows connection to undersea network



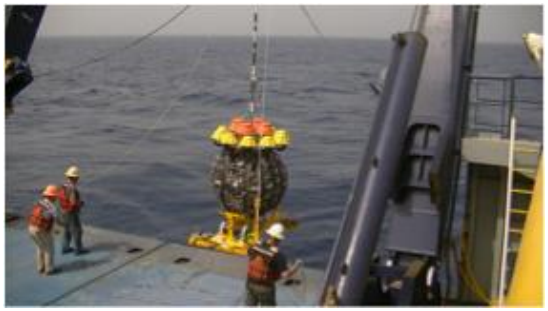


Detection unit installation

- The detection unit is packed on a launcher vehicle (LOM) and installed on an anchor
- After deployment on sea bed, unfurling is launched by operating a (ROV-operable or acoustic) release
- LOM (and acoustic release) is recovered after operation

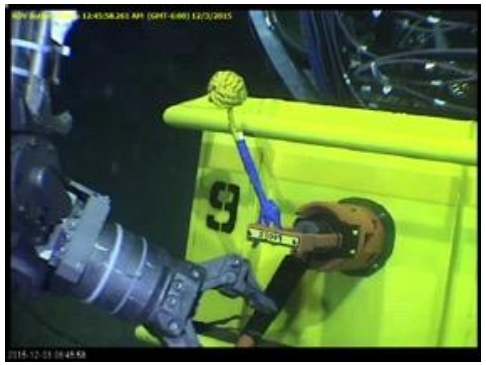


ROV inspection of an unfurled DU

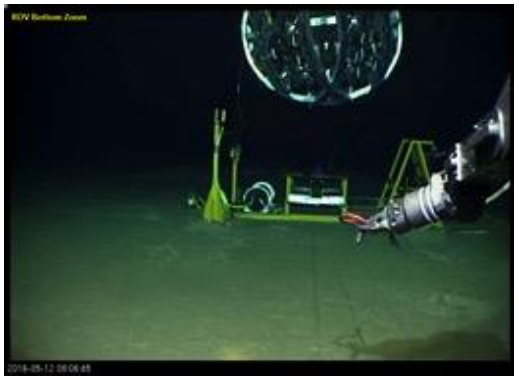


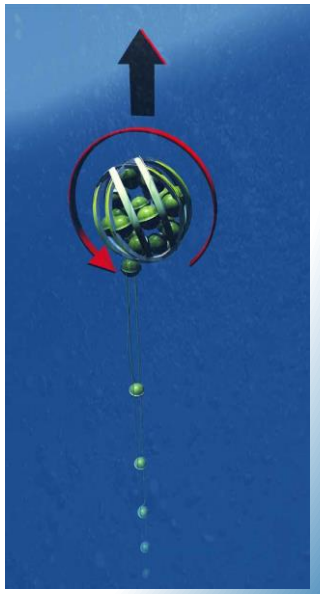
Overboard

Ready to deployment!



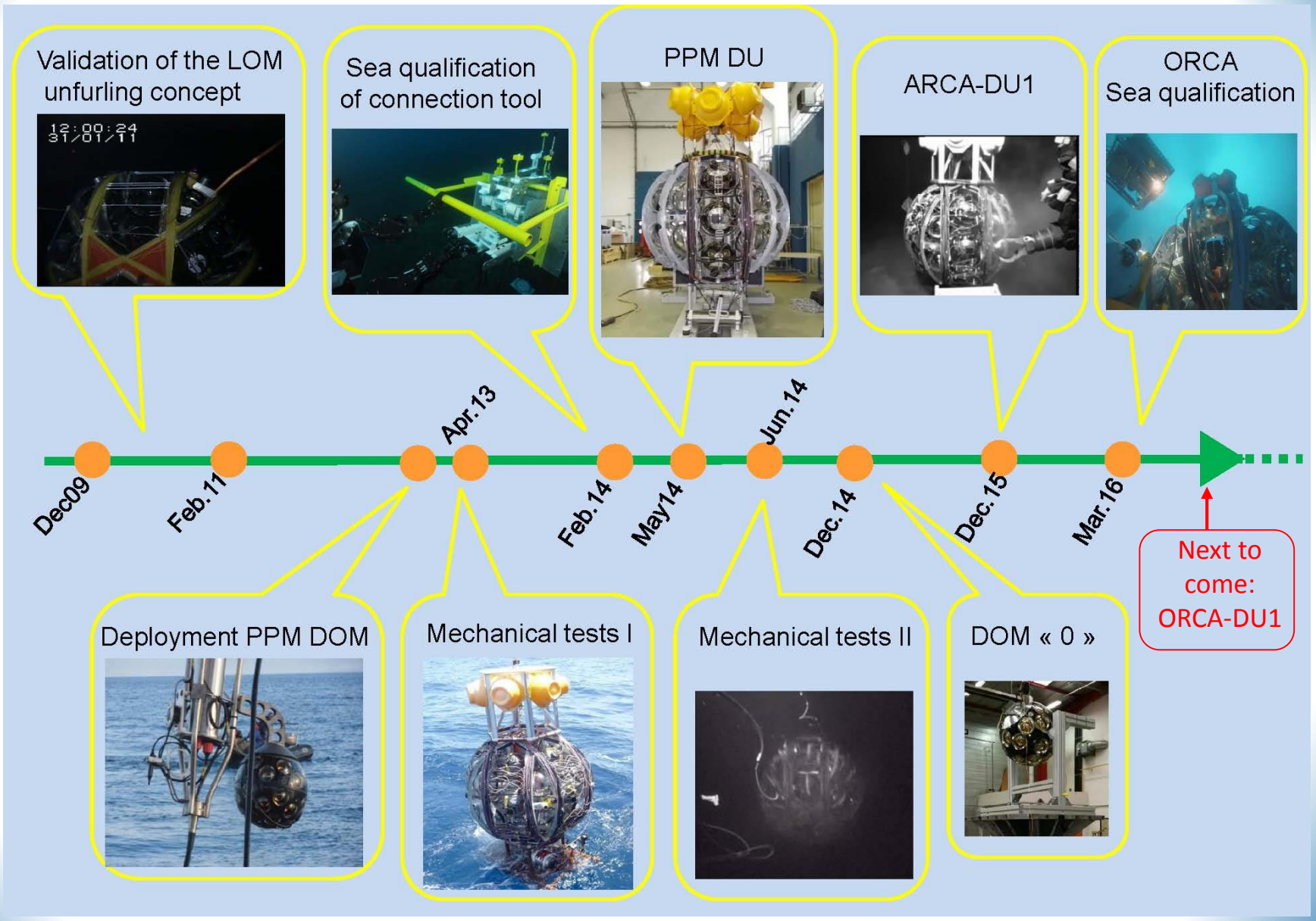
Connection to undersea infrastructure



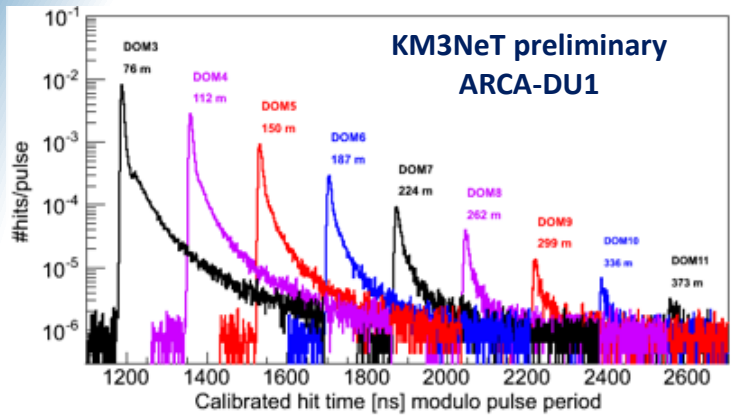


Unfurling!

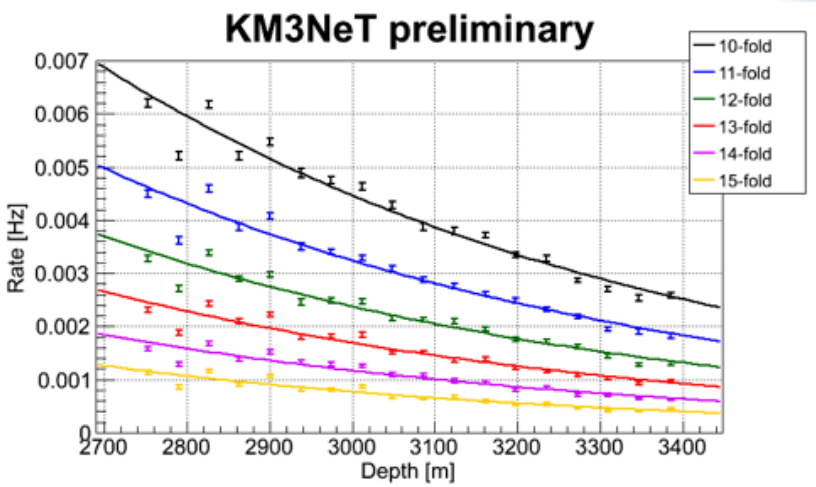
Development plan



Selected results from ARCA-DU1&2

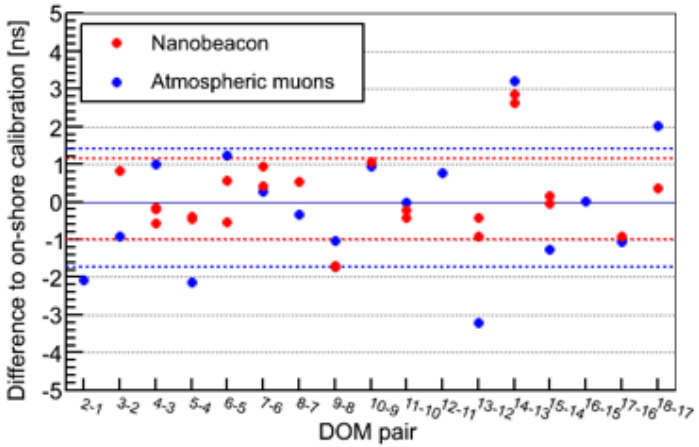


Nanobeacon-induced hits in DOMs (light emitted from DOM1 upwards)



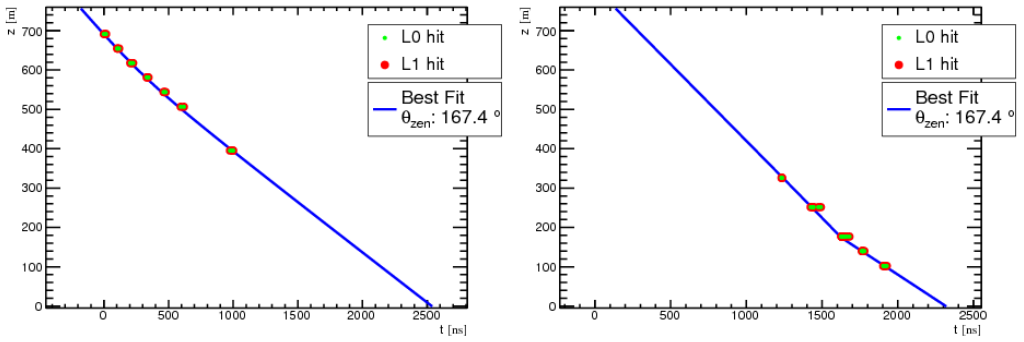
Depth dependence of multiple-hit coincidence rates

KM3NeT preliminary
Inter-DOM time offsets in ARCA-DU1



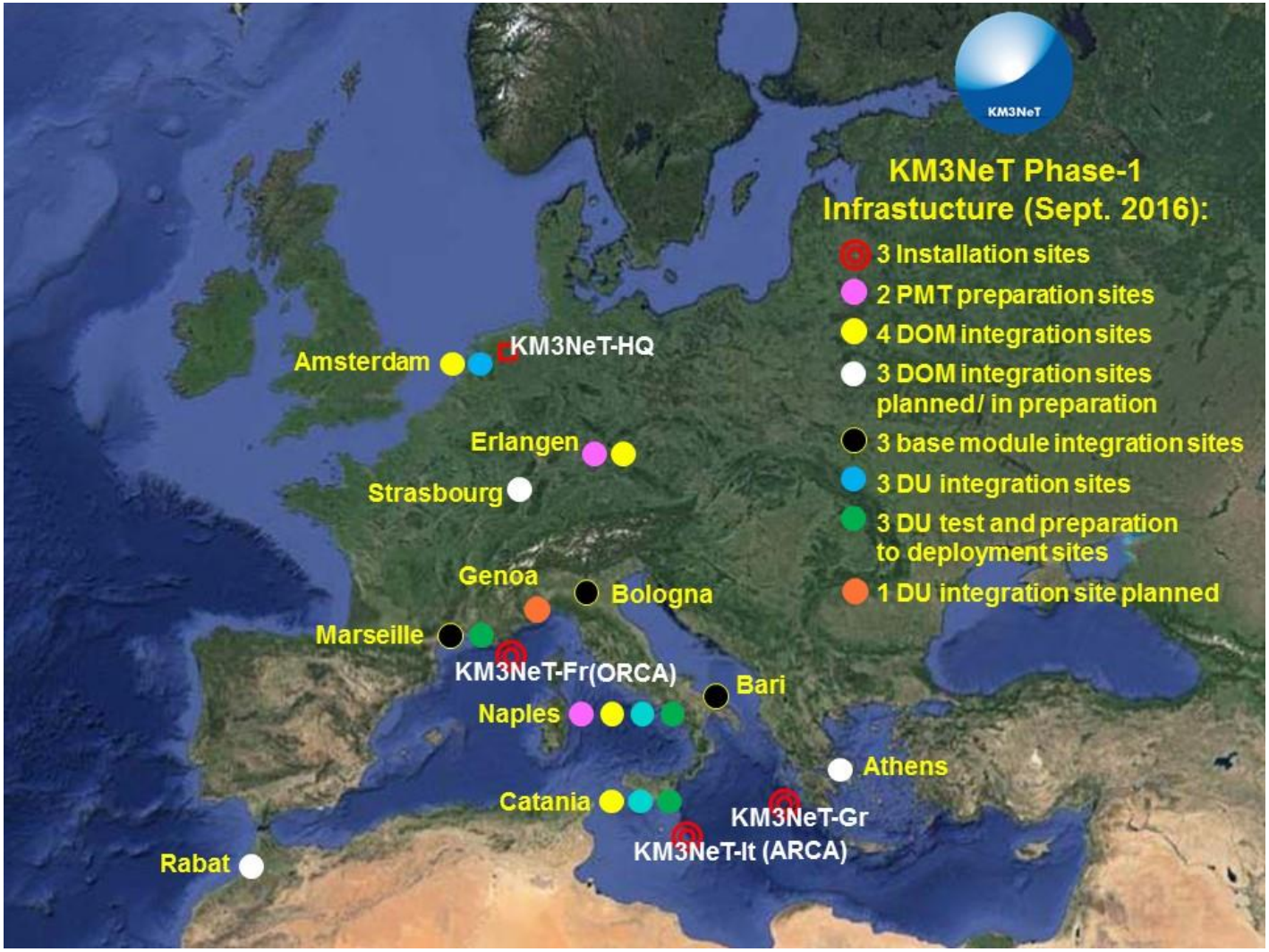
Comparison of time offsets determined with different methods

KM3NeT preliminary



A muon track detected by the two DUs

Preparation of mass production

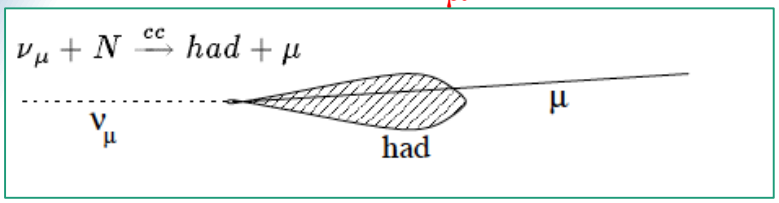


DOM production: 1 DOM/day/site (ongoing)
DU production: 1 DU/month/site

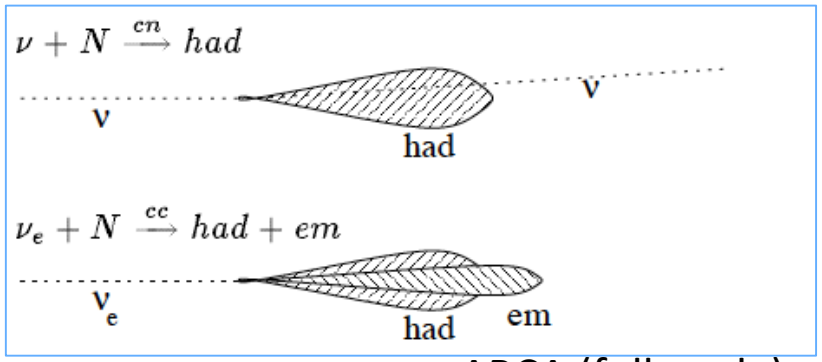
At full speed, it will be possible to mount up to 3 DUs/month (for Phase-1; to be increased for Phase-2)

Event topologies

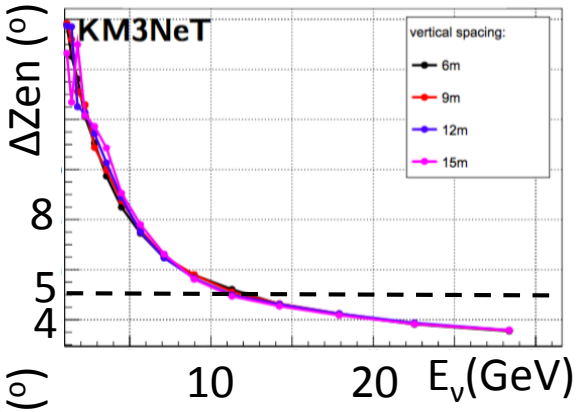
Track-like (ν_μ CC)

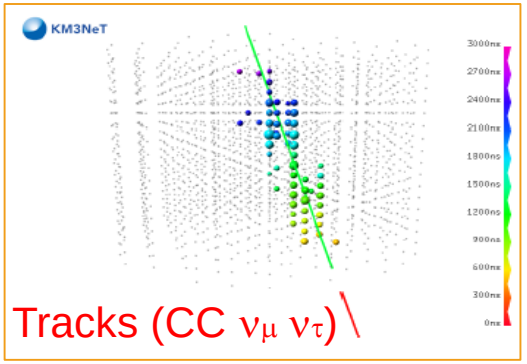


shower-like (ν NC, ν_e CC)

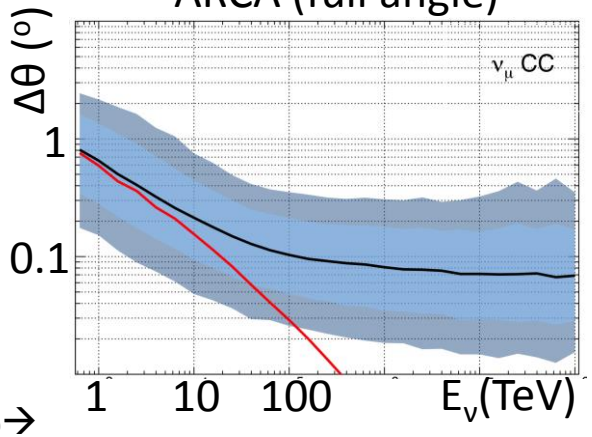


ORCA (zenith)

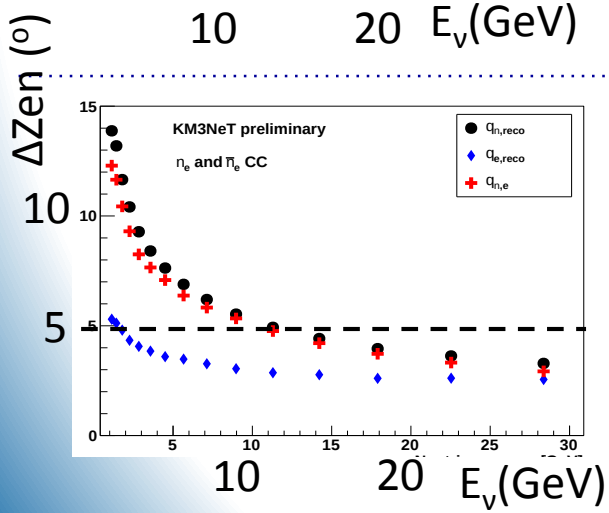


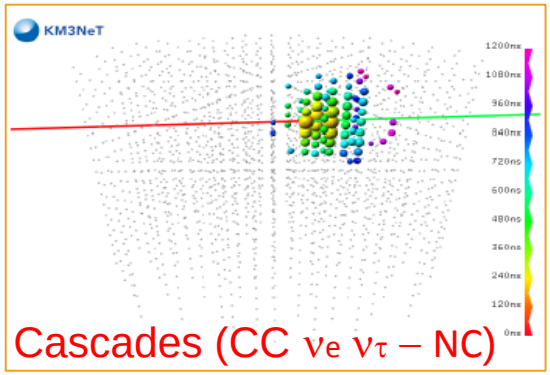


ARCA (full angle)

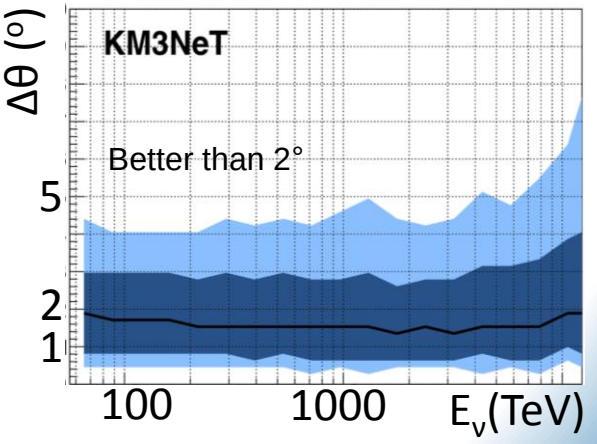


←<30% E_ν Resolution E_μ <27%→



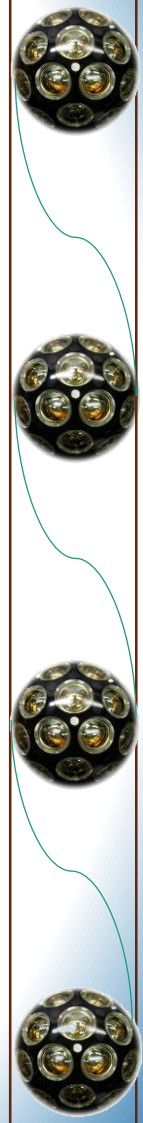


←26% Energy Resolution 5%→



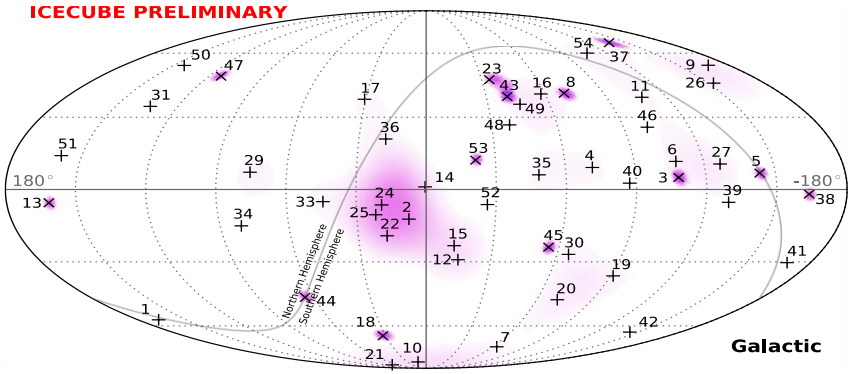
ARCA

Astroparticle Research with Cosmics in the Abyss



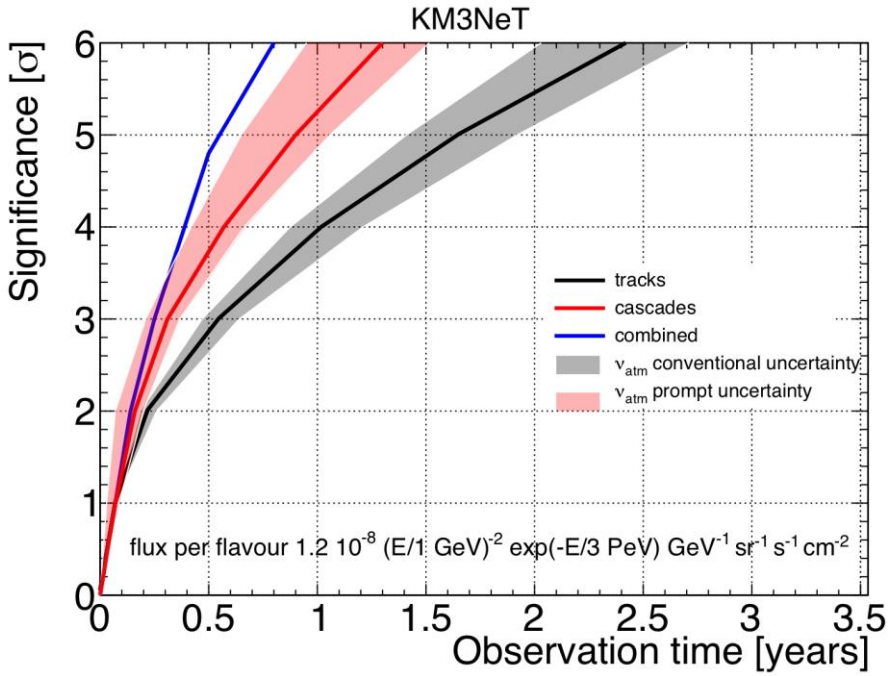
Diffuse flux searches

IceCube confirmed existence of cosmic neutrino diffuse flux
The search for sources is launched!



- **Track channel**

Analysis for up-going events based on maximum likelihood
Pre-cuts on θ_{zen} >80°, reconstruction quality parameter and N_{hit} (proxy for muon energy)



- **Cascade channel**

Containment cut on reconstructed vertex to remove atmospheric muons (excludes upper 100 m layer)
All sky analysis based on BDT and maximum likelihood.

- **Reduced search windows**

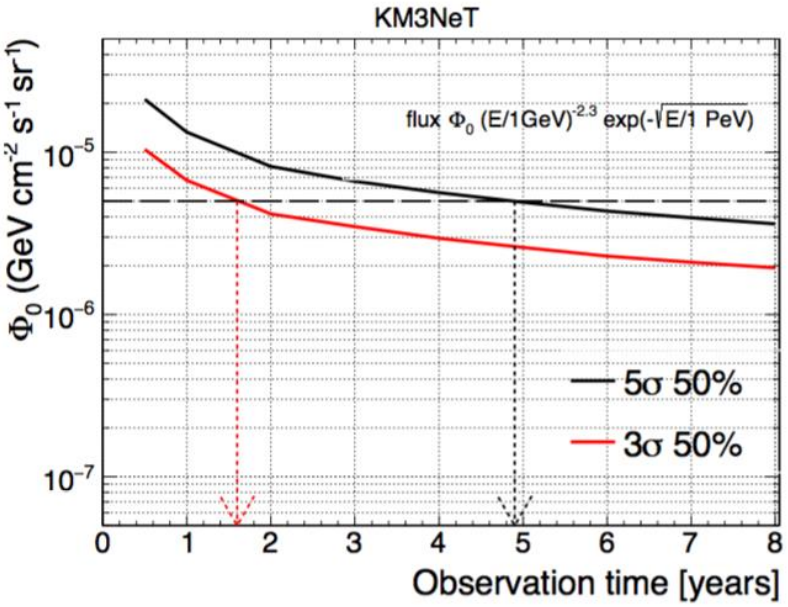
Mediterranean is best location for dedicated search to Galactic Ridge, Fermi Bubbles, etc.

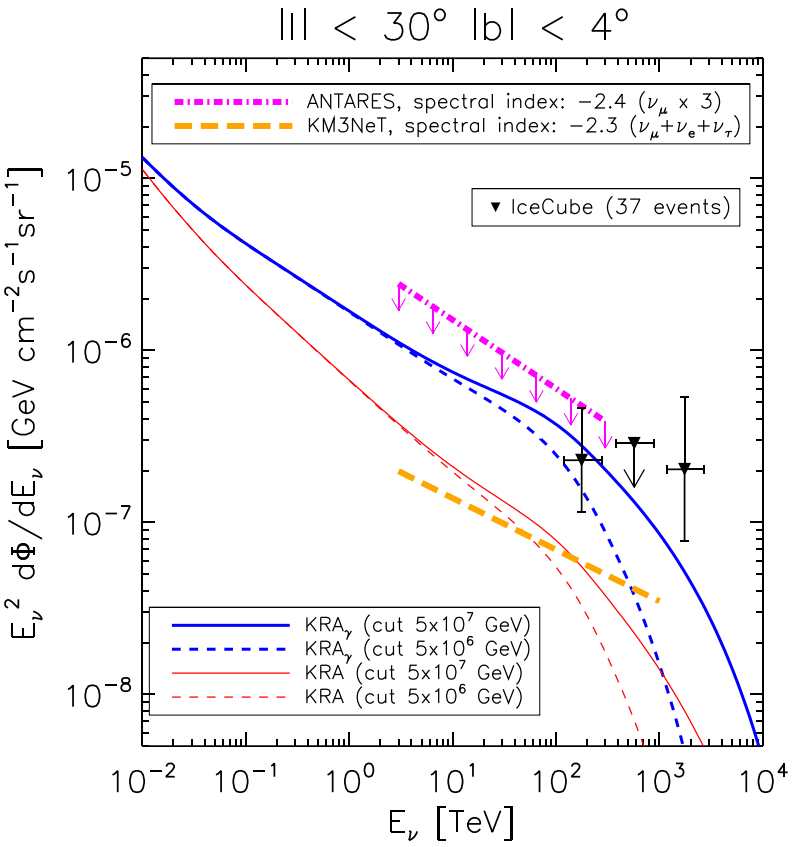
Inner Galactic plane

ANTARES upper limits for 1500 days

📖 Phys lett. B2016.06.0511504.00227

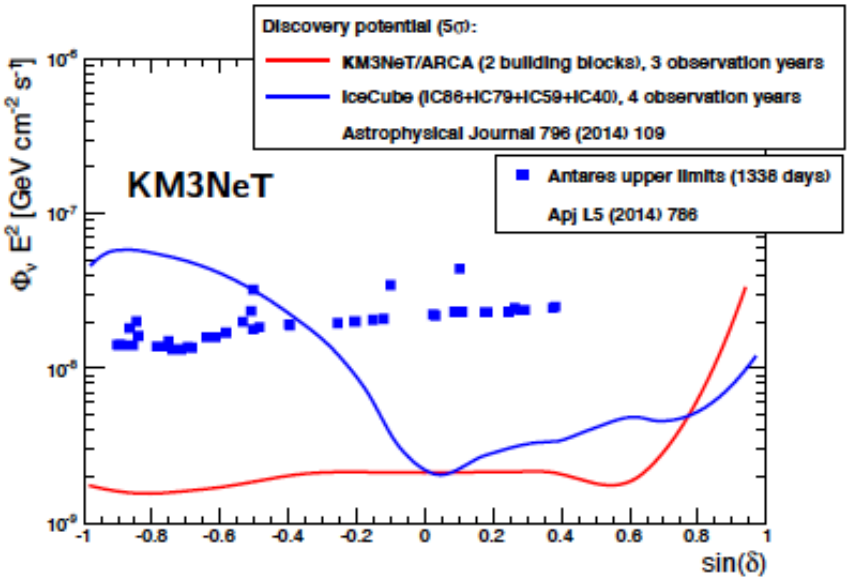
KM3NeT/ARCA 5 discovery potential (track events only) for this region considering 1500 days.
Improved analysis is ongoing.

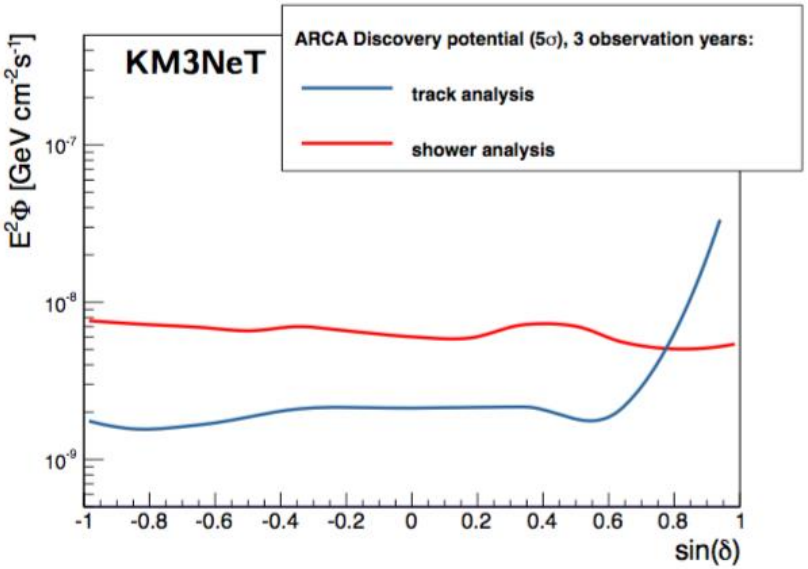




Updated version of the plot from: ICRC2015 Arxiv:1508.03681 (Antonio Marinelli)

Point-like sources

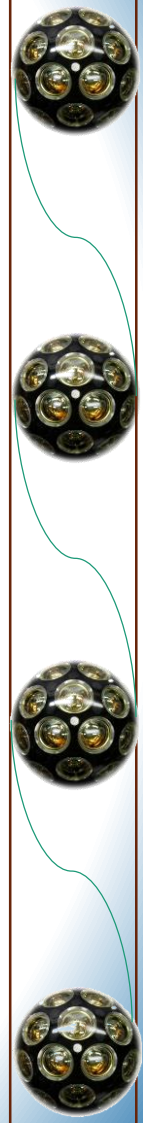




- KM3NeT sensitivity for point-like sources with unbroken E^{-2} spectrum.
- Shower channel is also promising
- The sensitivity may be increased for transient/periodic sources if the time information is provided (from gamma, GW, radio detectors…). Source stacking for the candidate lists.

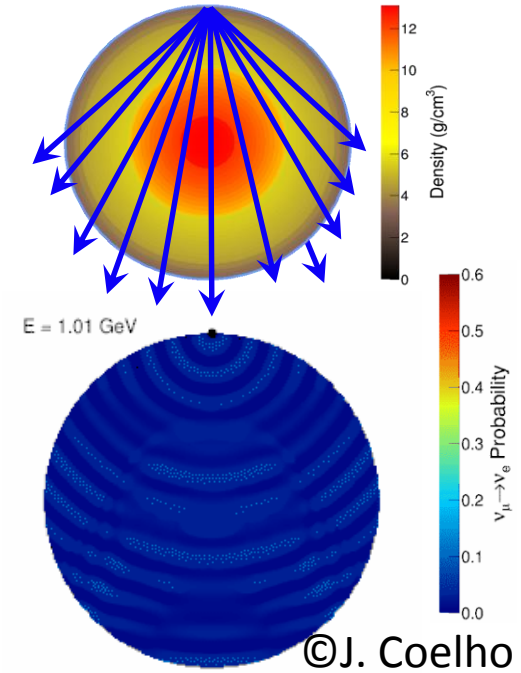
ORCA

Oscillation Research with Cosmics in the Abyss



Measuring NMH 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 vs NH at
  - $\theta=130^\circ$ (7645 km) and $E\nu$ = 7 GeV
- Opposite effect on anti-neutrinos: IH(ν)≈NH(anti-ν)
- BUT differences in flux and cross-section:
- Φatm(ν) ≈ 1.3 x Φatm(anti-ν)
- σ(ν) ≈ 2σ(anti-ν) at low energies



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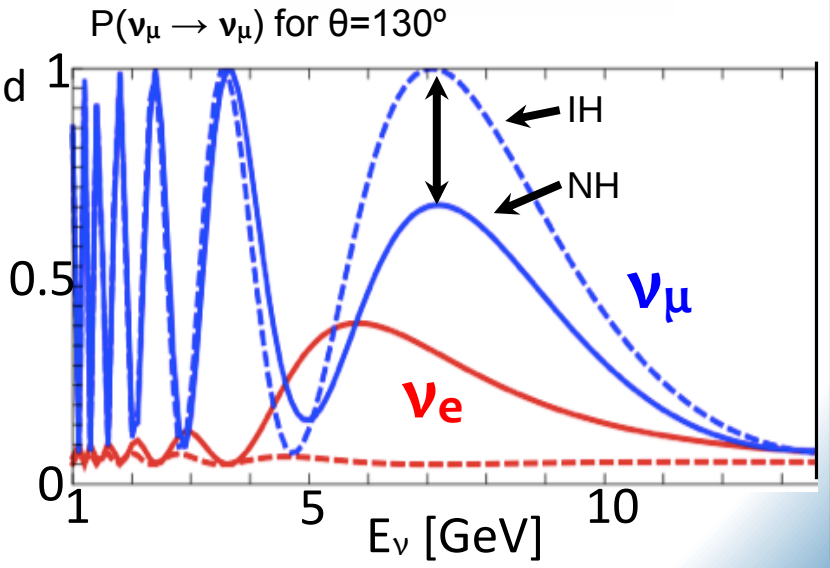
- Measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos, identify and count muon and electron channel events

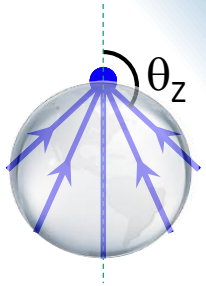
- Careful treatment of systematics mandatory



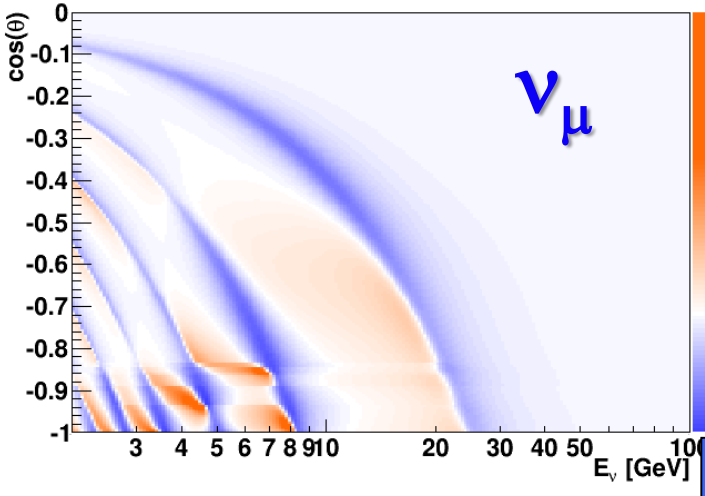
NMH Experimental Signature

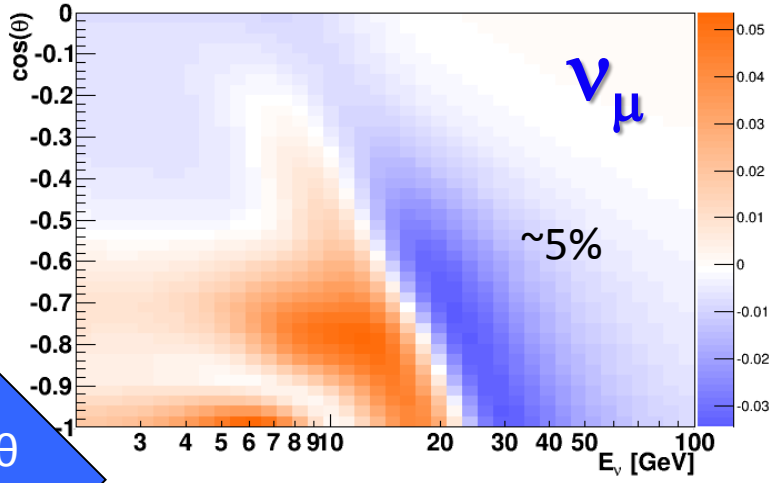
Both muon and electron channels contribute to hierarchy asymmetry

Electron channel more robust against detector resolution effects

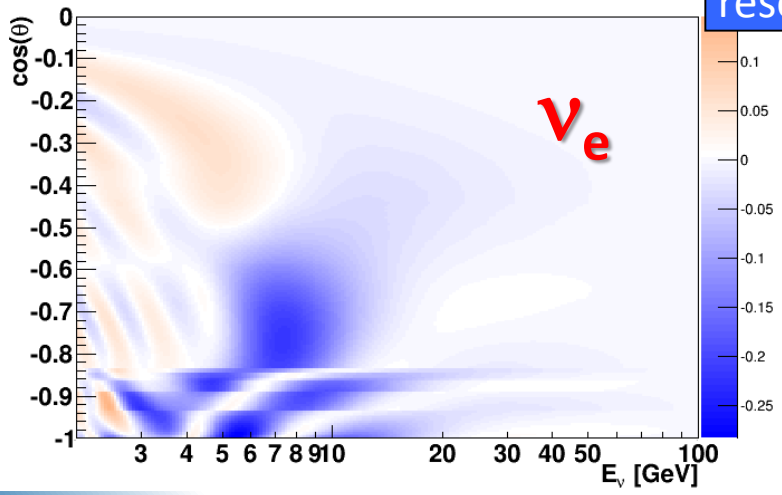


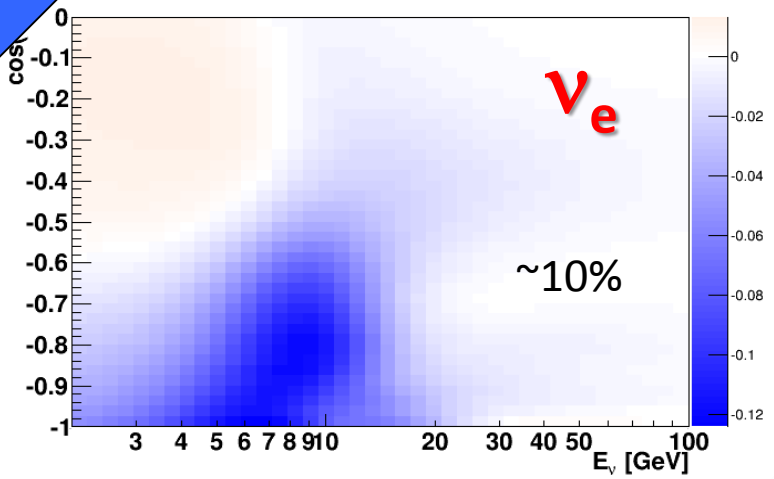
$(N_{IH}-N_{NH})/N_{NH}$





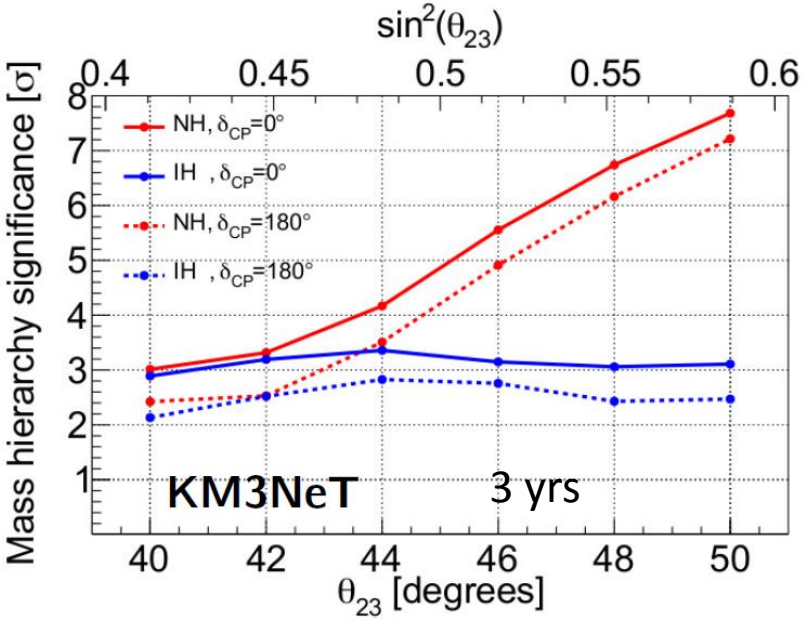
ORCA E,θ resolutions

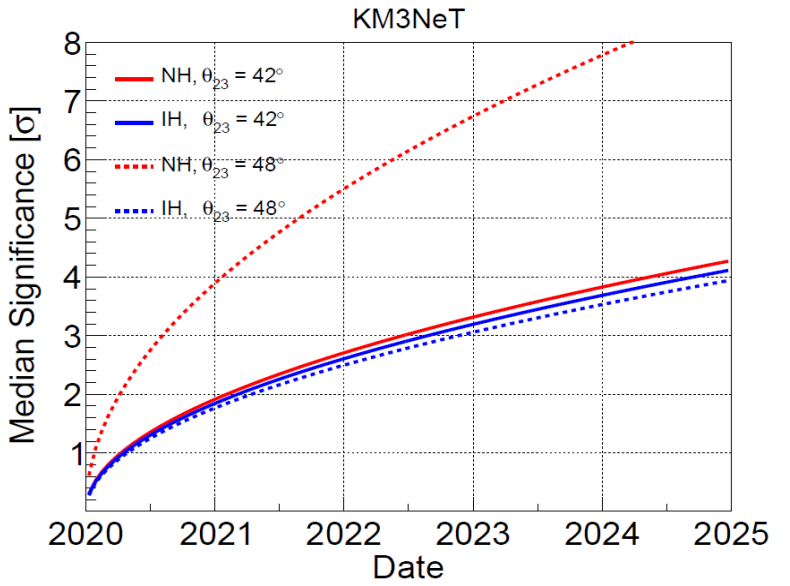




Sensitivity to Mass Hierarchy

- **~3σ** MH sensitivity **in 3 years**
- The combination of **NH and upper octant** of θ_{23} would significantly improve sensitivity (**5σ in 3 years**)
- For IH, sensitivity is essentially independent of θ_{23}
- The value of δ_{cp} has small but non-negligible impact on sensitivity

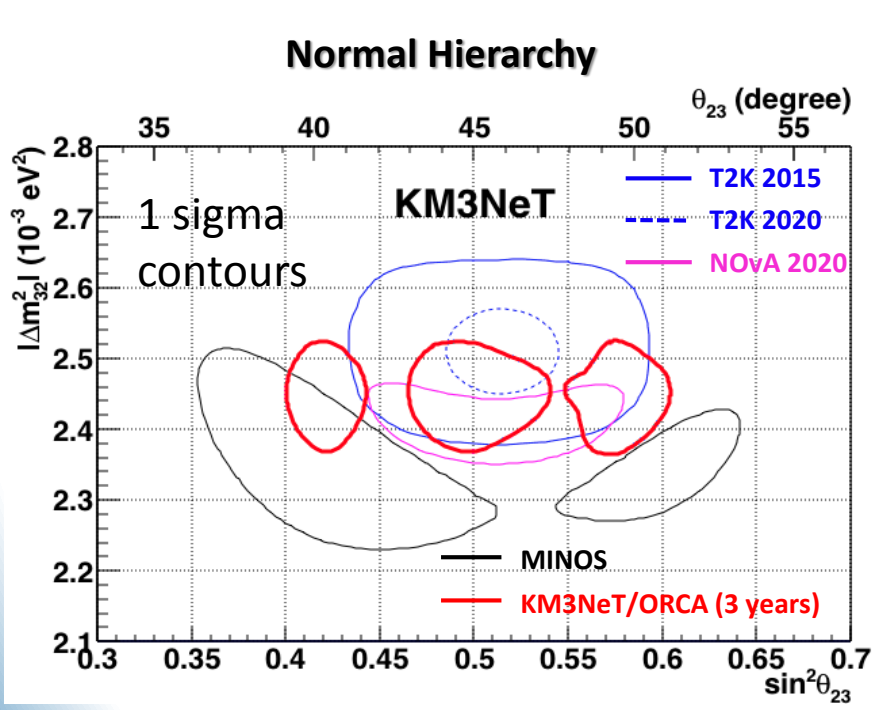


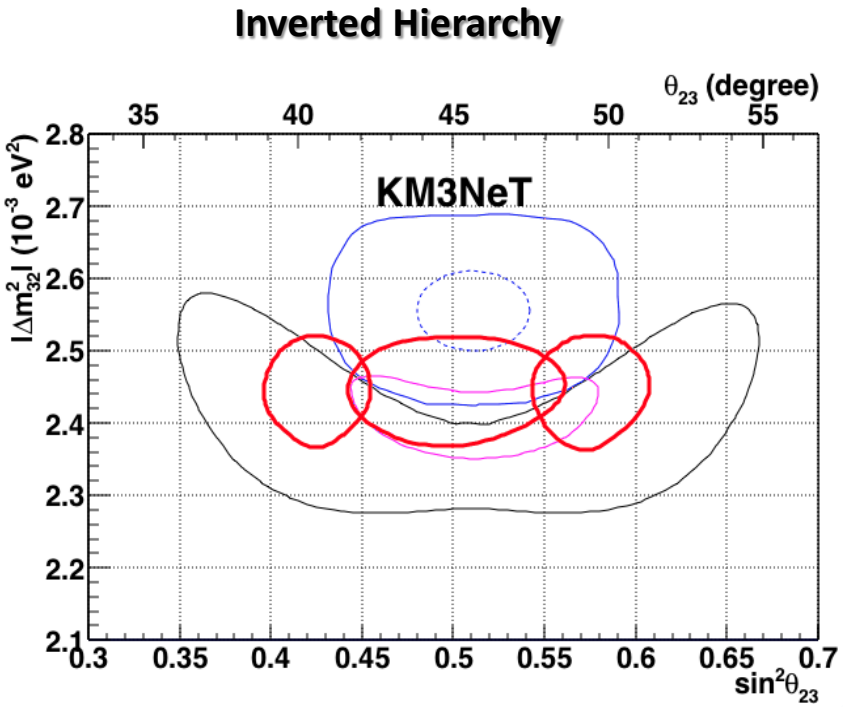


- **Best case** scenario (NH and θ_{23}=48°) could achieve **>5σ by mid 2021** (1.5 years)

Measurement of Δm^2_{32} and $\sin^2\theta_{23}$

- High statistics and excellent resolution → Measure Δm^2_{32} and $\sin^2\theta_{23}$
- Competitive with NOvA and T2K projected sensitivity in 2020
- Achieve 2-3% precision in Δm^2_{32} and 4-10% in $\sin^2\theta_{23}$



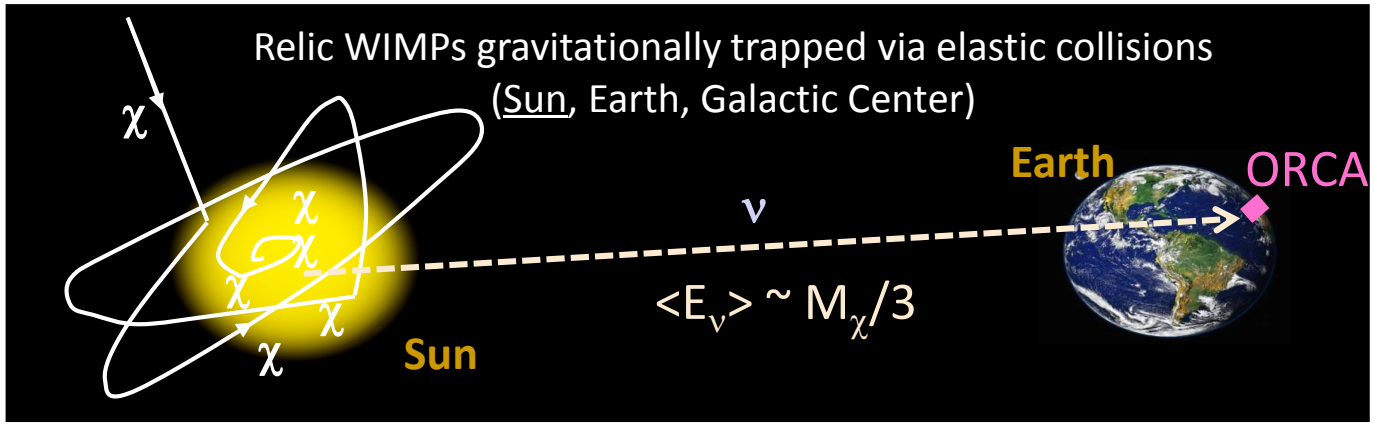


Additional ORCA Physics Topics

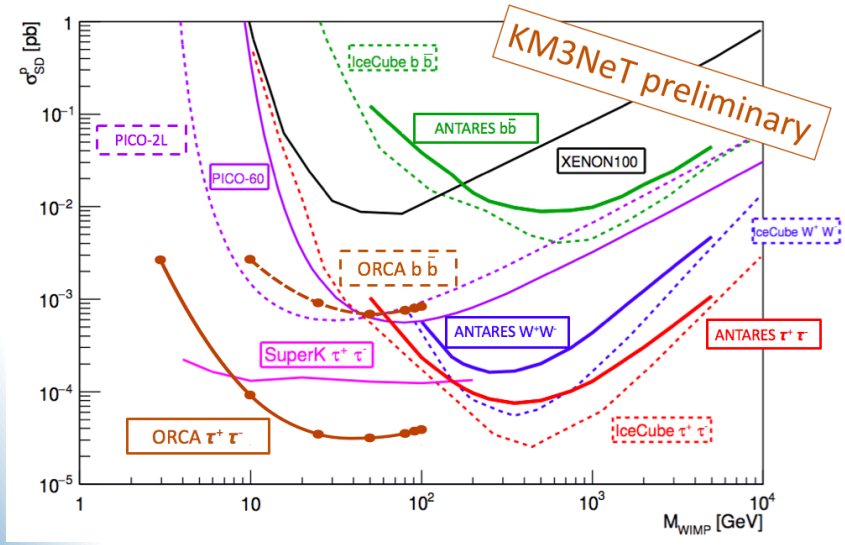
- Test NSI, sterile and other exotic physics — 🕮 J. Coelho, P2.026 Neutrino 2016
- **Indirect Search for Dark Matter**
- Earth tomography and composition — 🕮 W. Winter, arXiv:1511.05154
  - Low energy neutrino astrophysics
    - Gamma-ray bursts, Colliding Wind Binaries,.. — 🕮 J. Becker Tjus, arXiv:1405.0471 ...
  - A neutrino beam from Protvino to ORCA — 🕮 J. Brunner, AHEP, Volume 2013 (2013), Article ID 782538.
    - NMH and CP phase
  - **Supernova monitoring**

+ (common to ARCA): Earth and Sea sciences - oceanography, seismology, bioacoustics, bioluminescence, ...

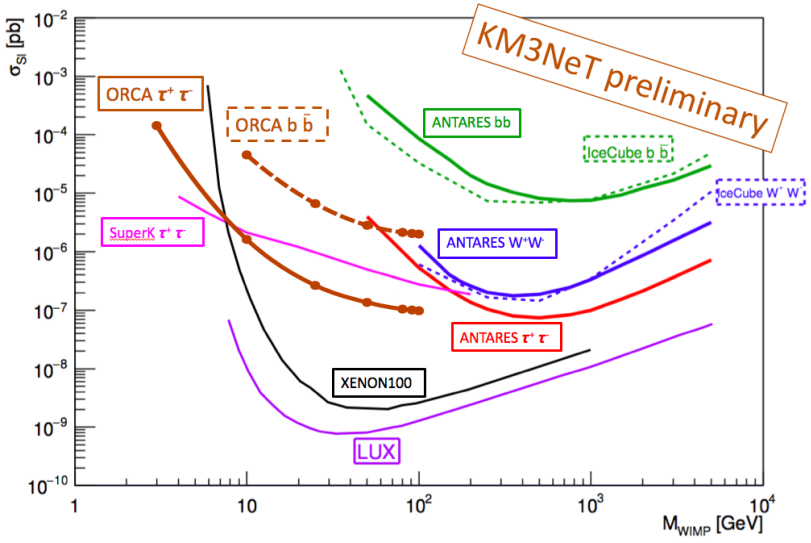
Indirect Detection of Dark Matter



Spin Dependent



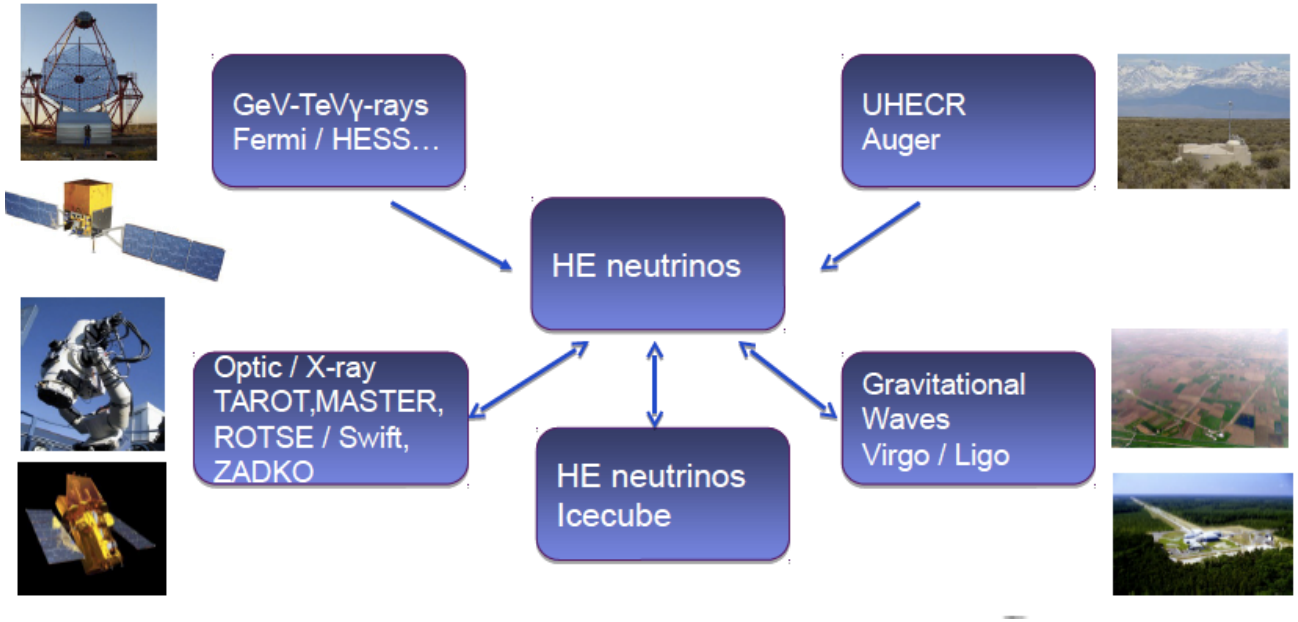
Spin Independent



ORCA 3 years - tracks+showers

Future multi-messenger programs

following ANTARES



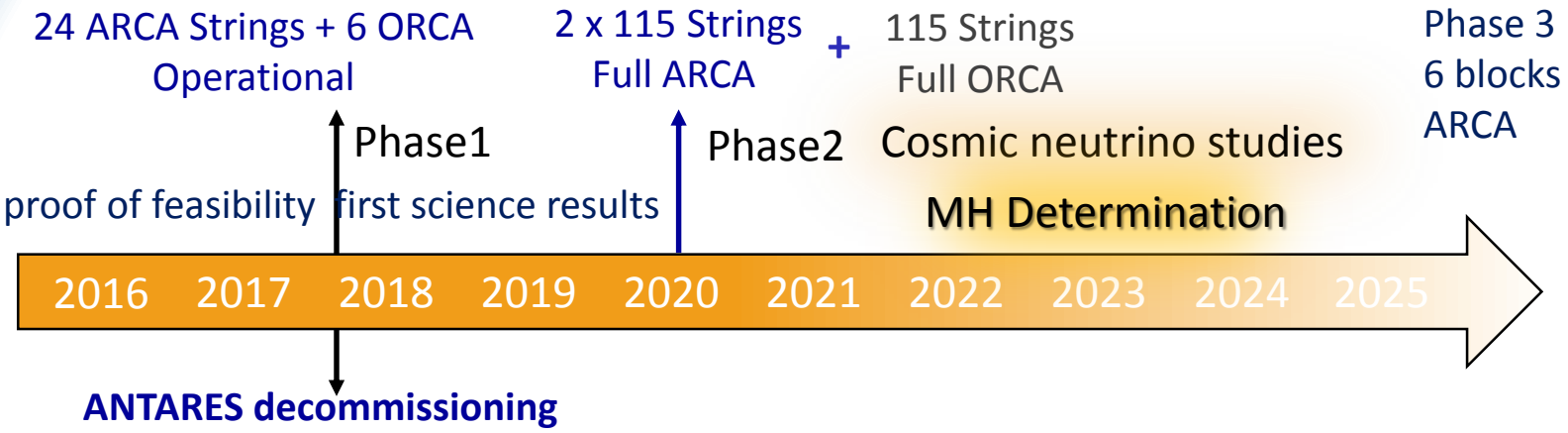
Astronomy ESFRI & Research Infrastructure Cluster

Bringing together the astronomy, astrophysics and particle astrophysics communities.

SNEWS

+SNEWS (low energy neutrinos). Both ORCA and ARCA are promising for supernova detection in our Galaxy (measured by optical rate increase in the detector)

Achieved and planned goals



- DOM prototype tested in situ (2500 m) 🕮 Eur. Phys. J. C (2014) 74:3056
- DU prototype tested (3 DOMs) in situ (3500 m) 🕮 Eur. Phys. J. C (2016) 76: 54
- Detector geometries defined
- Letter Of Intent is published 🕮 J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001
- Data taking at ARCA is ongoing with two DUs
- Preparing to deploy first ORCA DU
- Mass production of the DUs is in preparation (for ARCA and ORCA)
- KM3NeT 2.0 is in ESFRI Roadmap 2016 – launch of Phase-2 expected soon!

Summary and Perspectives

- KM3NeT: phased construction of a next-generation neutrino telescope (ARCA-high energy + ORCA-low energy)
- ORCA
  - Neutrino Telescope optimised for low energy (GeV) atmospheric neutrinos offers prospect of rapid and cost-effective measurement of NMH
  - Worst case scenario (IH, NH/first octant) can determine NMH at 3 sigma level in 3 years. Much quicker if NH/second octant
  - Competitive measurements of Δm^2_{32} and $sin^2\theta_{23}$ parameters, sterile neutrinos, NSI, low mass dark matter,…
- ARCA
  - It will provide soon complementary measurement of IC flux
  - Great capabilities for point-like search (angular resolution <0.2 deg, effective for E>1 TeV) for track events
  - Checks neutrino emission from:
    - Galactic plane (3 sigma in 1.3 years)
    - RXJ1713 (3 sigma in 4 years), Vela X (in 2 years)
    - GC (<4 years to rule out the recent model)
    - Other point and extended candidates from gamma-rays (stacking)
  - Search for unknown sources (extragalactic/optically thick)
- Multimessenger searches
- Multidisciplinary (bio-, geo-physics)
- Developed novel and performant multi-PMT technology (it may be of interest for other experiments as well)