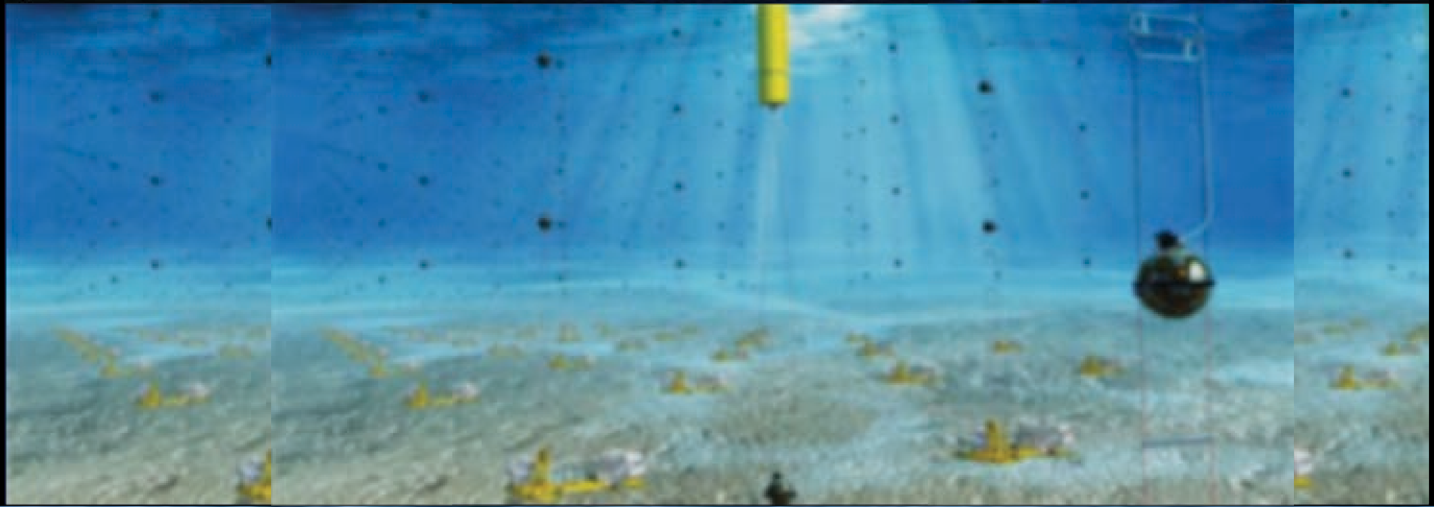
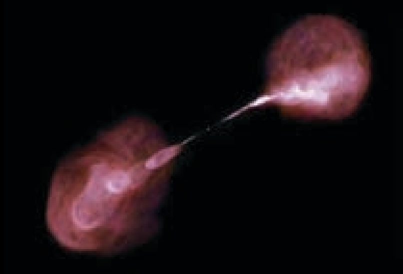
Calibration of the KM3NeT detector



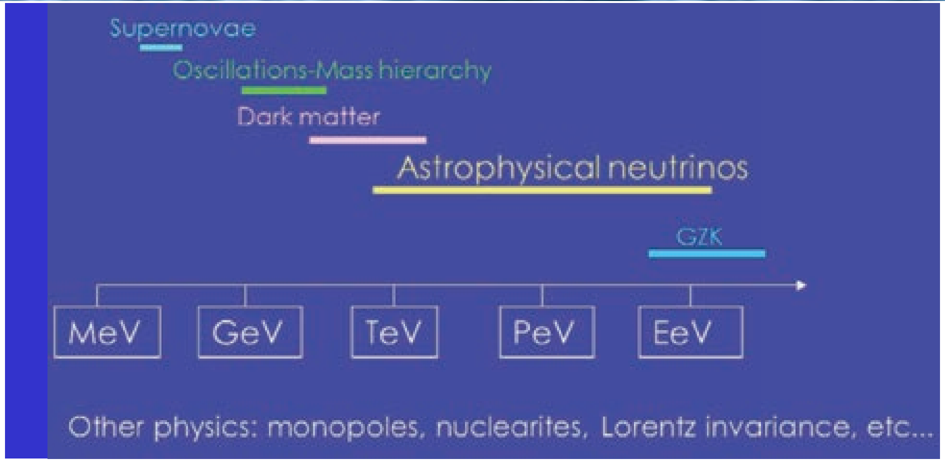


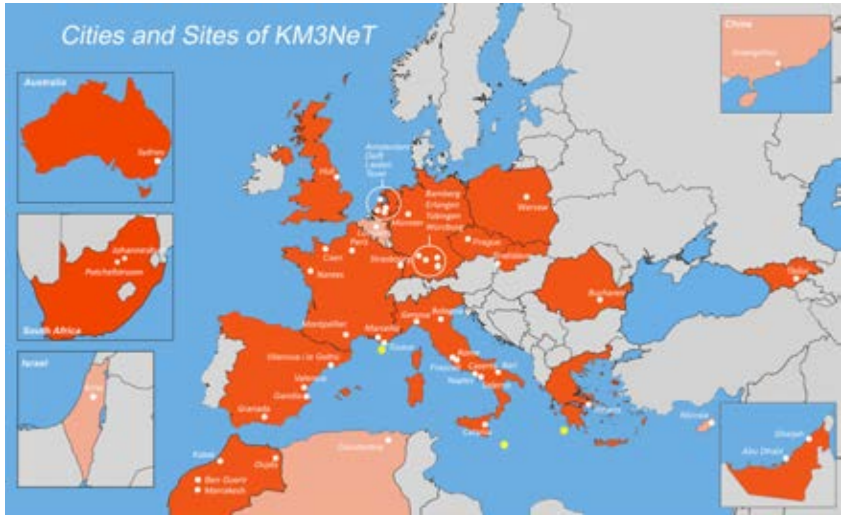
G. Riccobene INFN-LNS

KM3NeT: the giant underwater HE ν telescope

Large volume of transparent medium surveyed by photodetectors

- Deep Sea water
- Long light absorption length (70 m)
- Very small light scattering (good angular resolution)
- Natural backgrounds (^{40}K and bioluminescence) can be handled
- Northern terrestrial hemisphere:
- Complementary to IceCube
- Upgoing tracks from Southern sky sources. Milky-Way optimised





Volume (ARCA + ORCA) ≈ 1 km^3

more sensors (circa 180000) more photocathode area than IC

better optical properties in sea than in the ice

→ improved sensitivity

→ identification of neutrino sources and study of neutrino properties

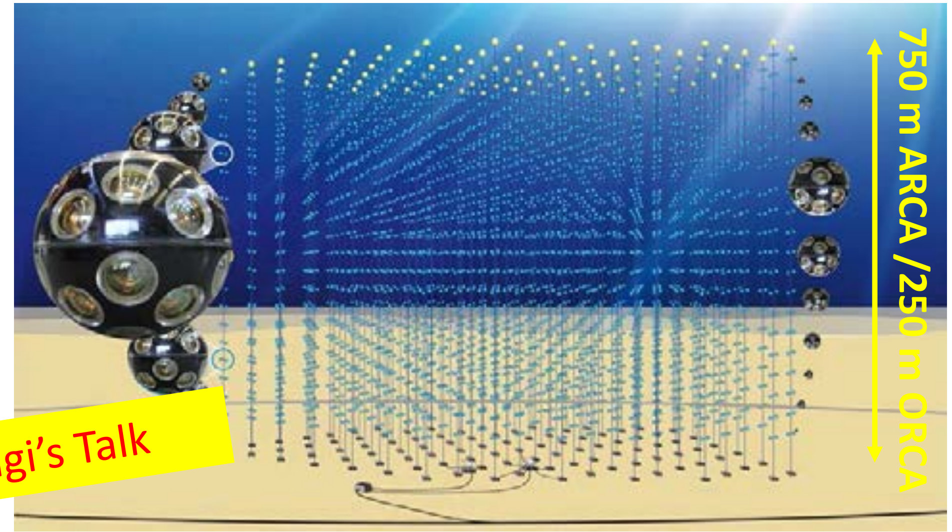
Still growing!

See R. Coniglione's Talk

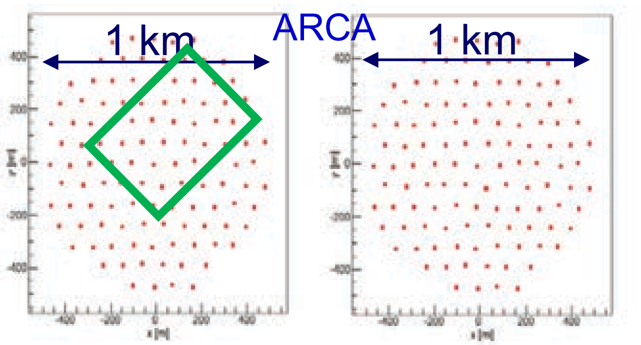
KM3NeT: the giant underwater HE ν telescope

Astronomy: ARCA @ Capo Passero 3500 m wd
2 building blocks (few km among the blocks)
115 Detection Units(DU) / block
18 DOMs (36 m inter-DOM), 90 m inter-DU distance
1 km^3 volume

Oscillations and Mass Hierarchy: ORCA @ Toulon 2500 m wd
1 building block
115 detection Units
18 DOMs (9 m inter-DOM), 23 m inter-DU distance
8 Mton volume

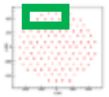


See S. Biagi's Talk



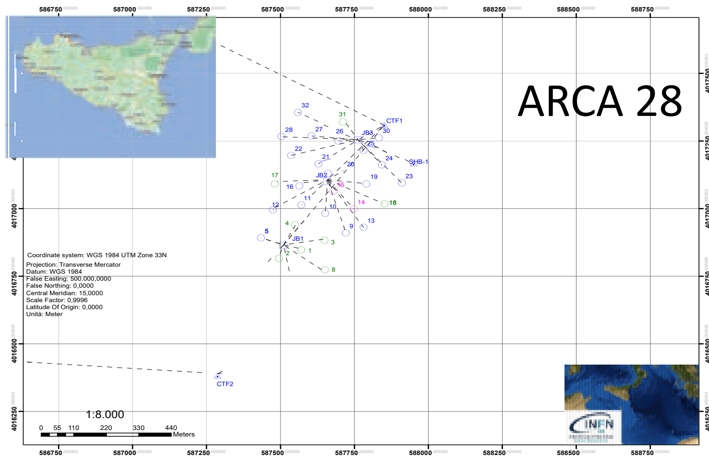
ORCA

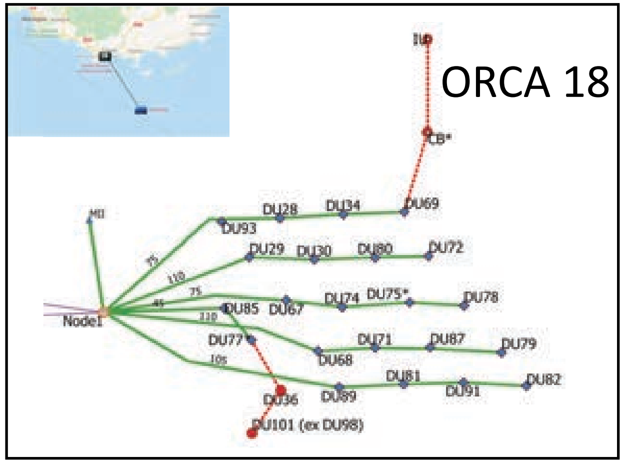
200 m



Phase 1: COMPLETE !

KM3NeT 2.0





KM3NeT: detector elements

Digital Optical Module (DOM)
A fly's eye light detector Inside a 17'' glass sphere

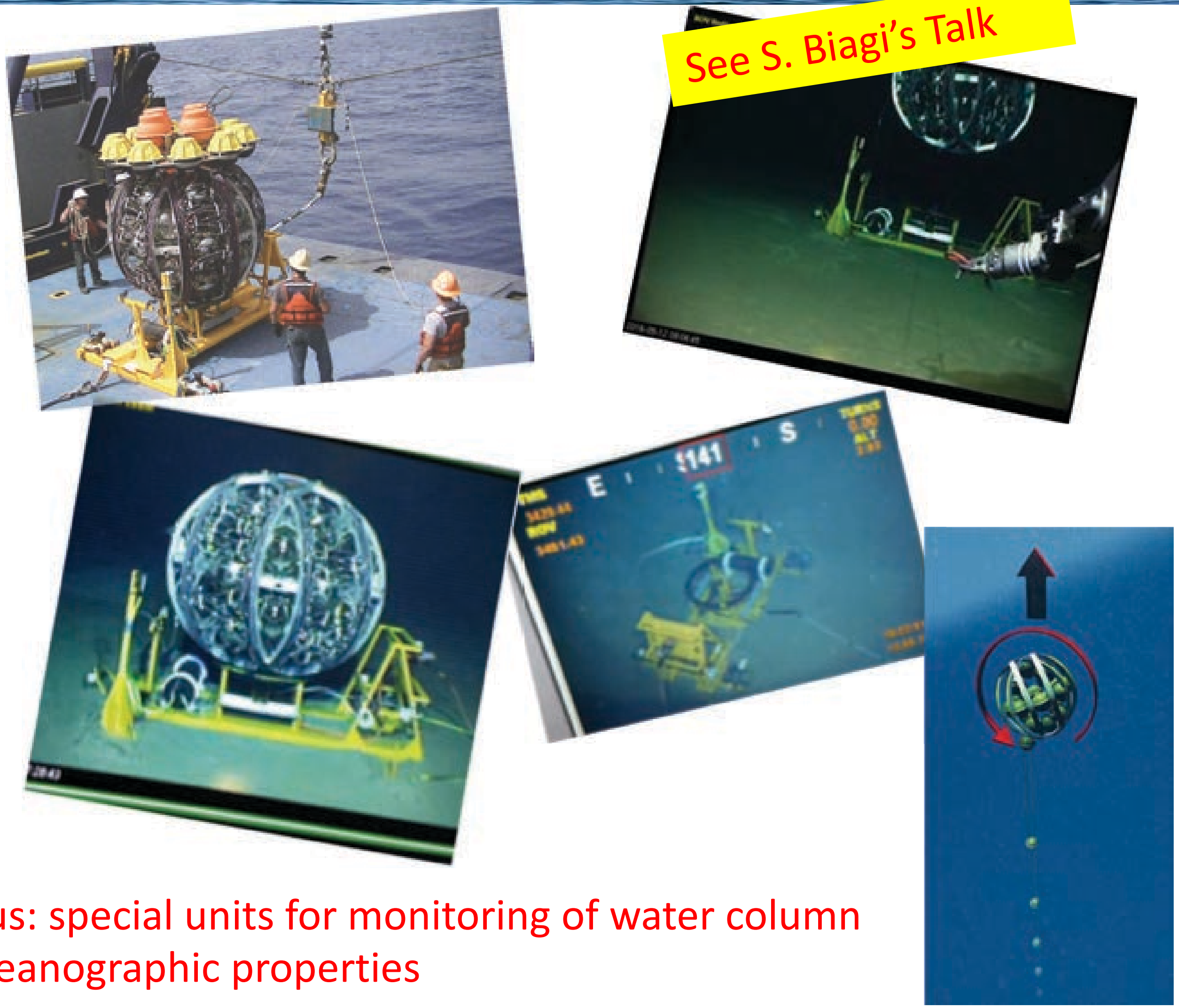
Plus:
compass, acoustic sensor, front-end and data transmission electronics

1 hydrophone at each Detection Unit base

Detection Unit
a vertical string with 18 DOMs

power: 260 W

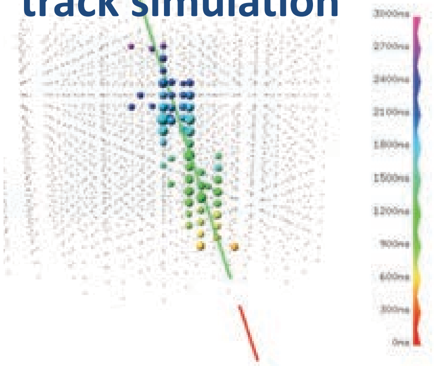
See S. Biagi's Talk



Plus: special units for monitoring of water column oceanographic properties

KM3NeT: angular resolution vs. time calibration

track simulation

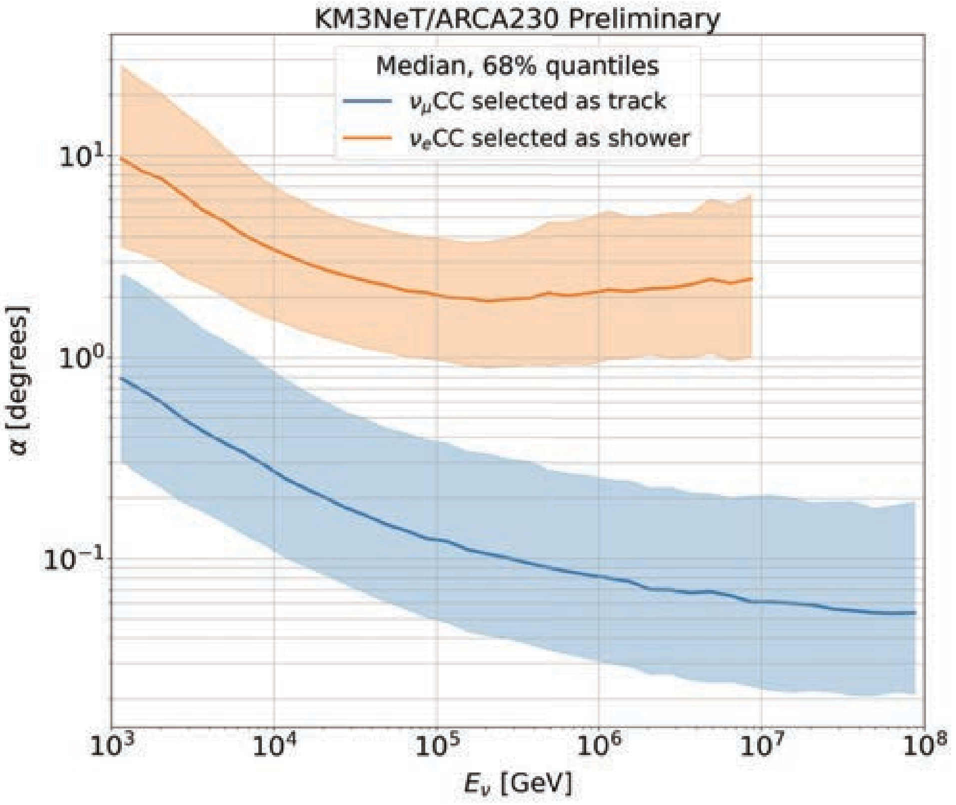


shower simulation

See S. Biagi's and R.Coniglione's Talks

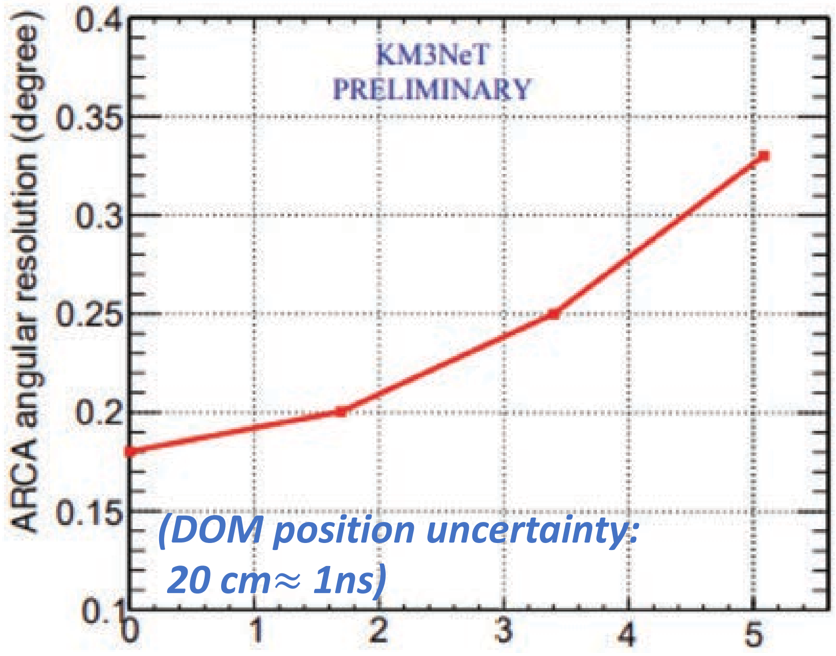
Photon hit information:
- Hit Time (T0)
- Hit Charge (Q → ToT, Time over threshold)

Angular resolution (in ARCA):
- Rejection of atmospheric muons
- Source identification



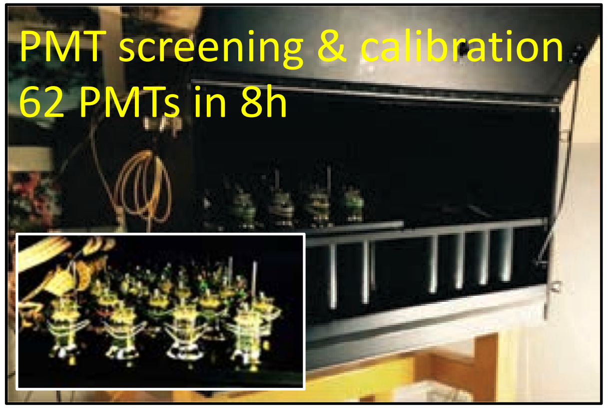
T.J. Van Eeden for KM3NeT PoS(ICRC2023)1075

Time Synchronisation and DOM position calibration is the key parameter to optimise angular resolution

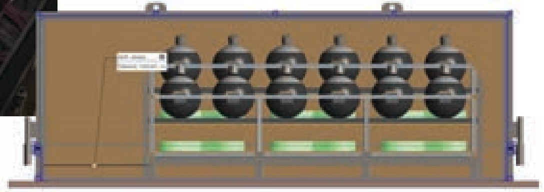


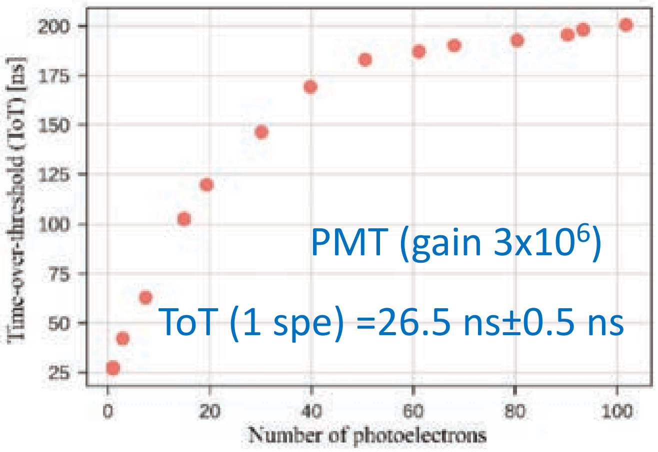
time synchronisation smearing (ns)

KM3NeT calibration: PMT gain equalisation



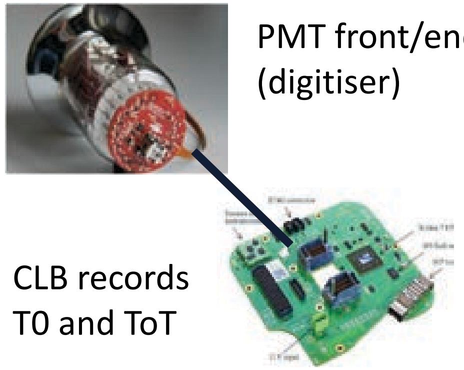
PMT signal digitised:
Time over threshold (ToT)
proxy of charge
(threshold 0.3 spe)

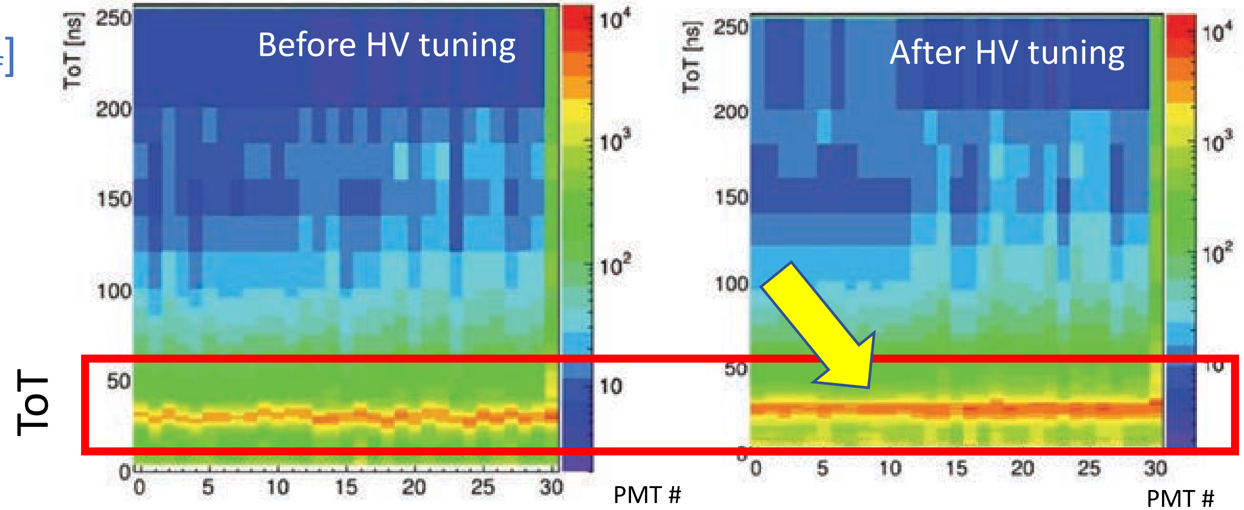


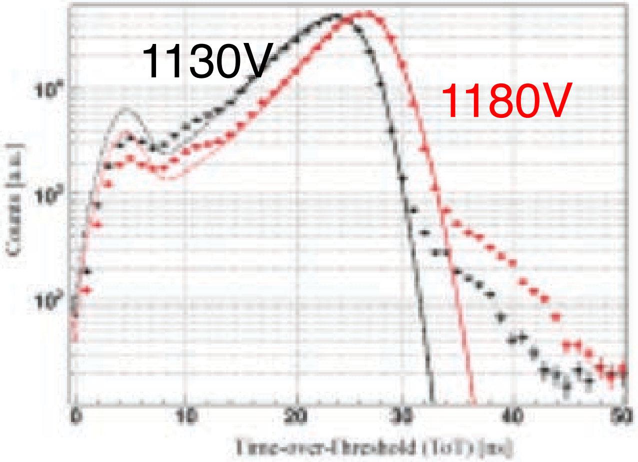


S. Aiello *et al.* 2022 *JINST* 17 P07038

Gain ~HV
HV tuning in darkroom:
[-125 V+V_{Ref}]:[+125 V +V_{Ref}]







HV retuning in situ

KM3NeT calibration: time calibration

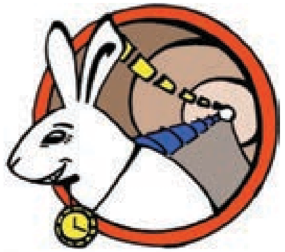
Time synchronisation in KM3NeT mostly based on the White Rabbit CERN project

Determination of the relative time offsets:

- between the PMTs in the DOM (intra-DOM, in darkroom / in situ)
- between DOMs in the same DU (inter-DOM, in darkroom) [White rabbit topology (slightly) dependent]
- between different DUs (inter-DU, in situ) [White rabbit topology dependent]

In situ checks:

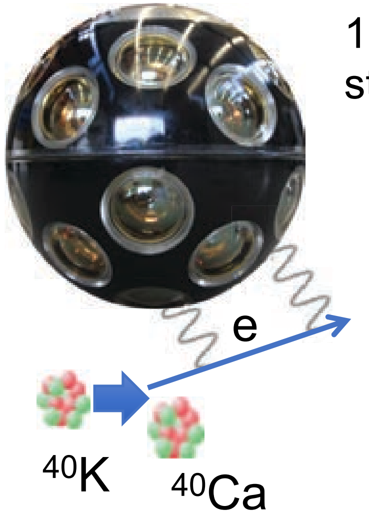
- nano-beacons
- laser beacons
- atmospheric muons (& neutrinos)
- CR shadow (Moon & Sun shadow)



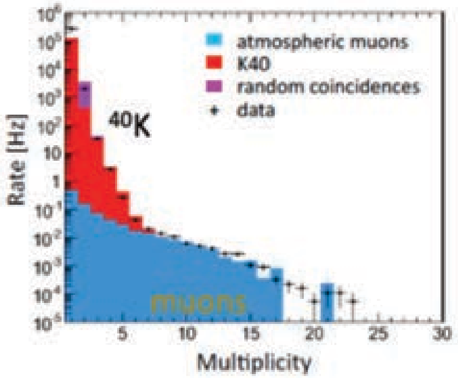
first time over multi 10km cables!

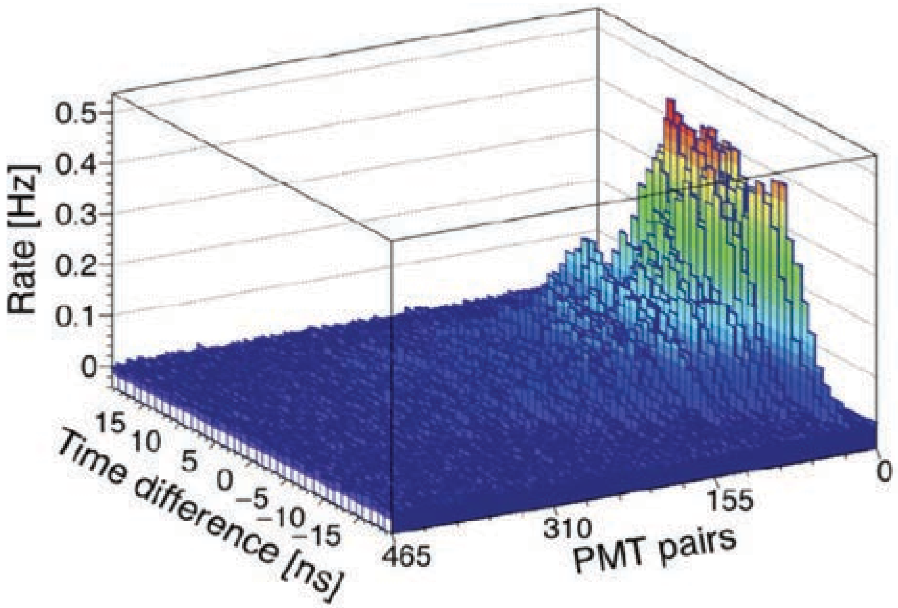
KM3NeT calibration: intra-DOM time calibration

Use photons resulting from the β⁻ decay of ^{40}K naturally present in seawater or in the glass-sphere of each DOM



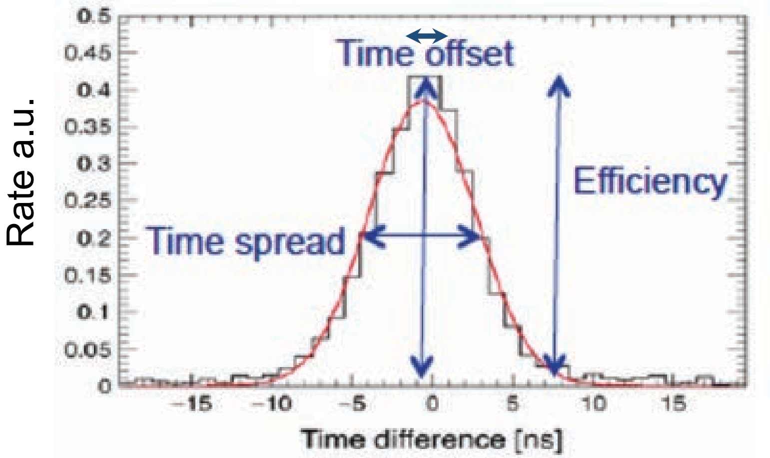
150 Cherenkov photons per decay
stable ^{40}K concentration in seawater





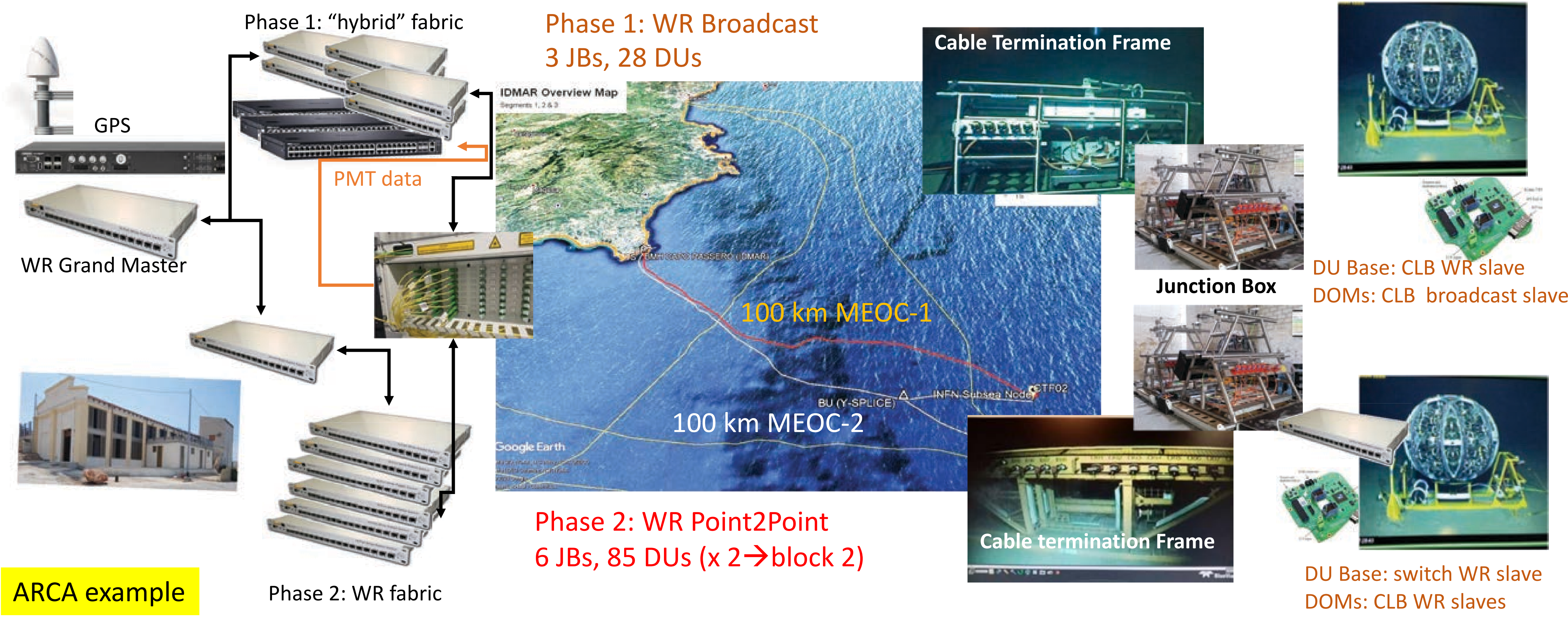
Hit time difference between PMT pairs

2-fold PMT coincidences in a DOM



KM3NeT time calibration: White Rabbit network

WR Master-Slave time synchronisation through signal “round-trip time” measurement



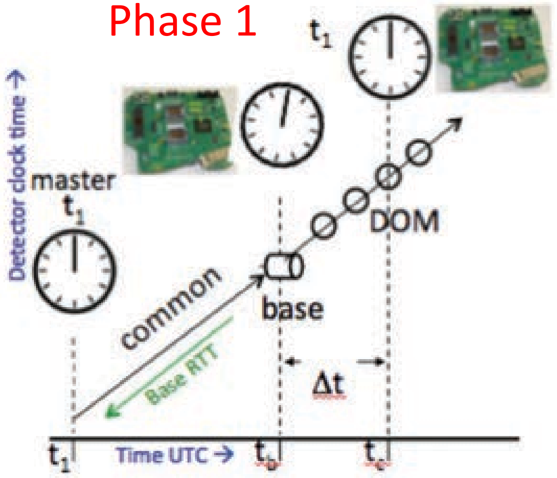
KM3NeT time calibration: inter-DOM

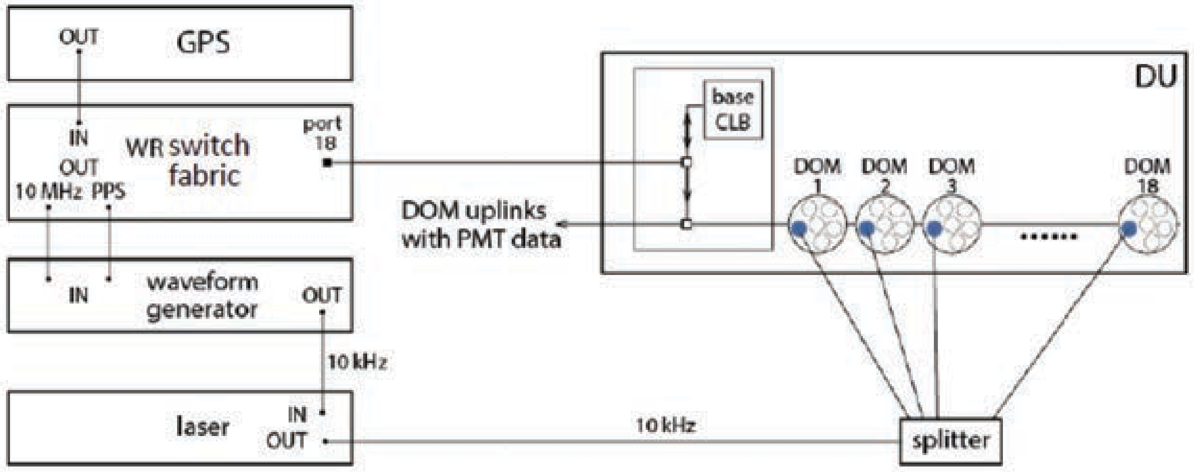
A single laser source illuminates simultaneously 2 PMTs in each DOM

"Phase 1": time delays take into account all latencies from PMT surface to the DU base

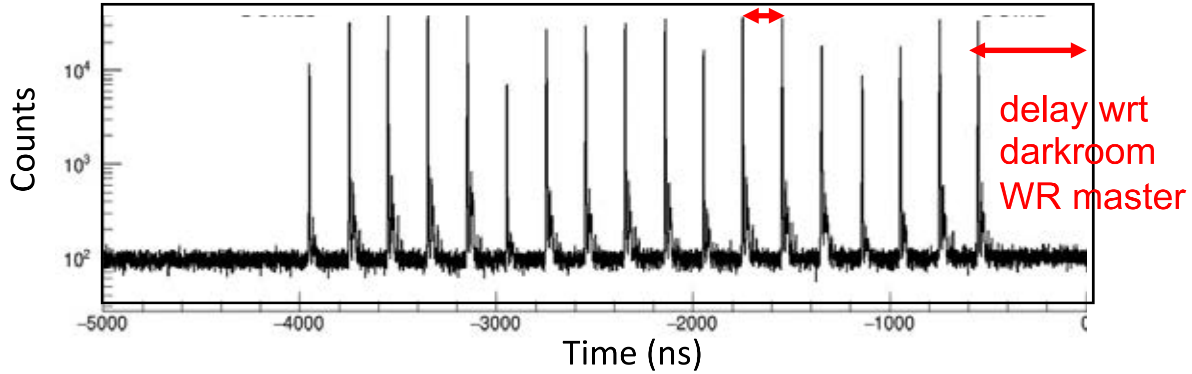
"Phase 2": time delays take into account only latencies in DOMs (all CLB synchronised)

Phase 1



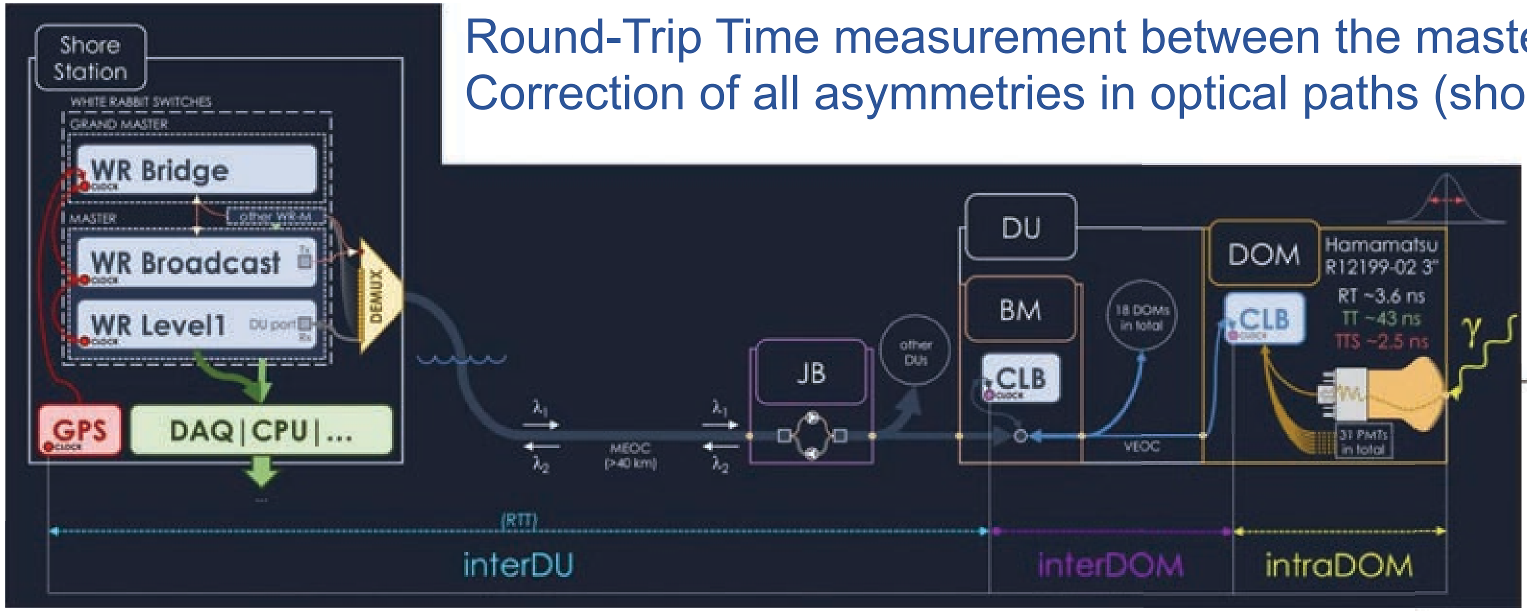


inter DOM ≈200ns



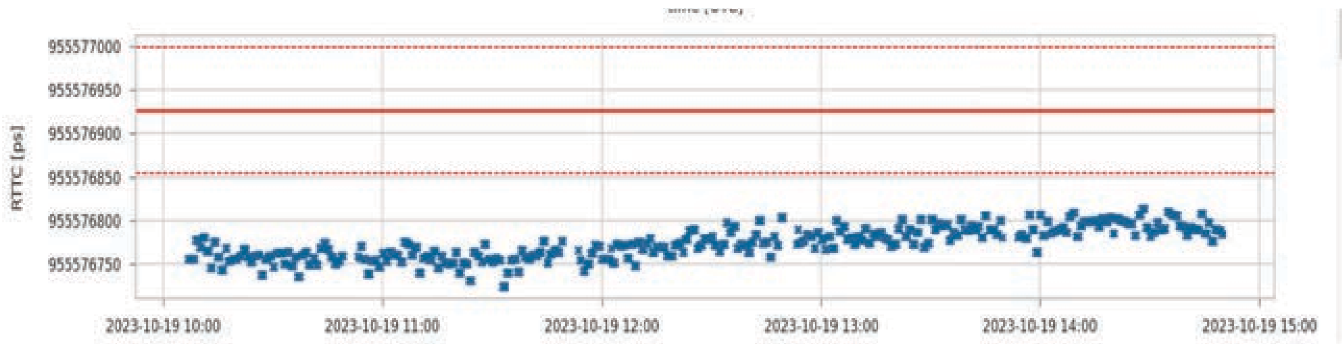
Phase 1: 200 ns fiber delay from floor to floor (40 m fiber length)

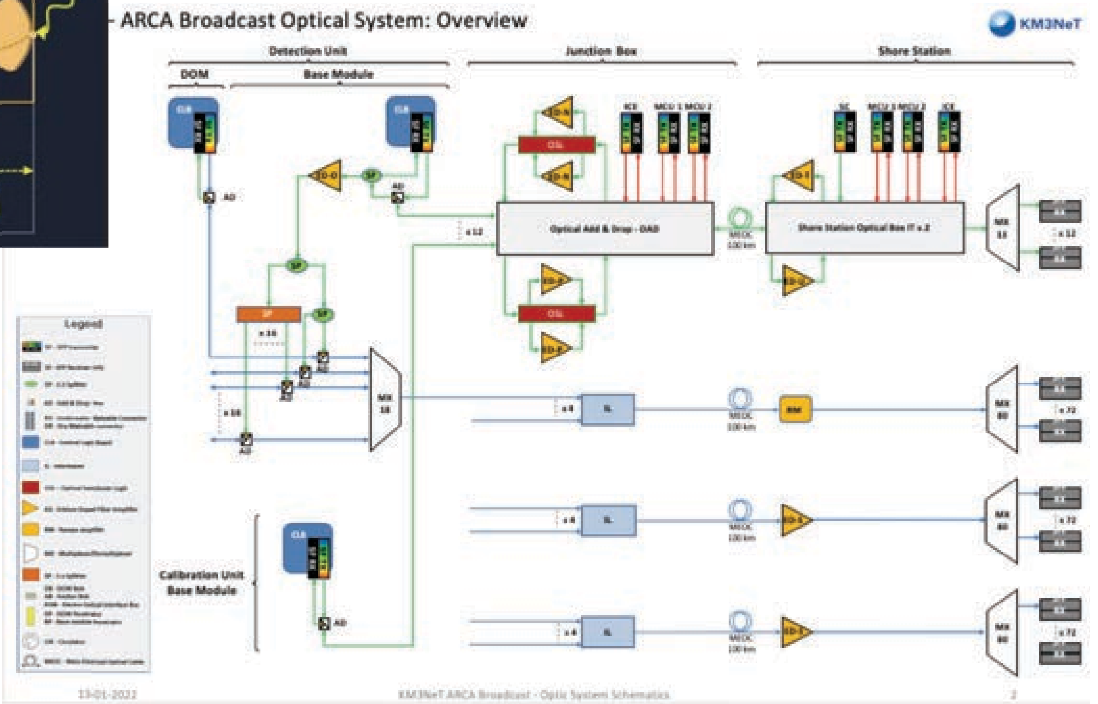
KM3NeT time calibration: inter-DU (Phase 1)



Round-Trip Time measurement between the master clock (on shore) and each DU base (slave)
Correction of all asymmetries in optical paths (shore/sea – sea/shore):
not handled by White Rabbit (applied offline)

DOM time distributed through broadcast communication





KM3NeT time calibration: inter-DU (Phase 1)

$$\Delta T^{sea}_{DOM} = \Delta T^{SS}_{GPS-WRB} + \Delta T^{DR}_{DOM} + \frac{1}{2}\left[RTTC^{*sea}_{BASE} - RTTC^{*DR}_{BASE} + ASY^{SS} + ASY^{MEOC} + \Sigma_i ASY^{JB_i} - ASY^{TS} - ASY^{Jum}\right] + TxM^{SS} - TxM^{TS} + \Delta RxS^{sea-DR} = \Omega_{DU} - \delta t^{DR:Laser}_{DOM}$$

$$\Omega_{DU} = \Delta T^{SS}_{GPS-WRB} + LC^{DR}_{Laser} + \Delta T^{DR}_{LCE} + \frac{1}{2}\left[RTTC^{*sea}_{BASE} - RTTC^{*DR}_{BASE} + ASY^{SS} + ASY^{MEOC} + \Sigma_i ASY^{JB_i} - ASY^{TS} - ASY^{Jum}\right] + TxM^{SS} - TxM^{TS} + \Delta RxS^{sea-DR}$$

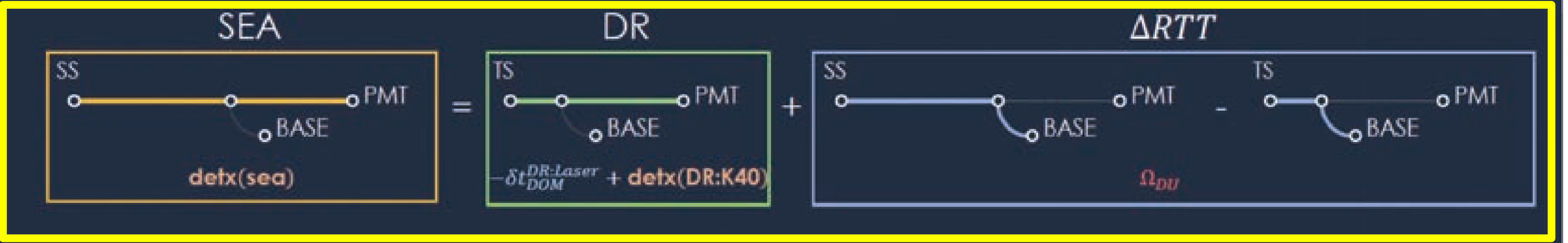
$\Delta T^{DR}_{DOM} = \Delta T^{DR}_{Laser} - \delta t^{DR:Laser}_{DOM}$

- $\Delta T^{DR}_{Laser} = LC^{DR}_{Laser} + \Delta T^{DR}_{LCE}$ → Laser path on the Test Station used for the interDOM calibration, including the laser controller emission time (ΔT^{DR}_{LCE})
- $-\delta t^{DR:Laser}_{DOM}$ → **The anticipation time to apply to each DOM from the laser DR interDOM calibration**

$\Delta T^{SS}_{GPS-WRB}$ → Delay of the GPS PPS on the Shore Station WR-Broadcast (*)

$RTTC^{*DR}_{BASE}$ → Mesurable RTTC (TxS=RxS=0, but bitslide≠0) with the DU base on the DR (§)
$RTTC^{*sea}_{BASE}$ → Mesurable RTTC (TxS=RxS=0, but bitslide≠0) with the DU base on the sea (a priori a theoric value)

ASY^{SS} → Shore Station asymetry (SC-DC)
ASY^{TS} → Test Station asymetry
ASY^{MEOC} → Cromatic asymetry on MEOC
ASY^{Jum} → Cromatic asymetry on Jumper (negligible)
ASY^{JB_i} → Node asymetries



TxM^{SS} → Shore Station WR-Broadcast Tx (*)
TxM^{TS} → Test Station WR-Broadcast Tx (§)
ΔRxS^{sea-DR} → DU base CLB Rx sea-DR differences (theoretically null)

(*) Just a global detector offset → time precission with astronomical events
(§) To be measured during the DU calibration

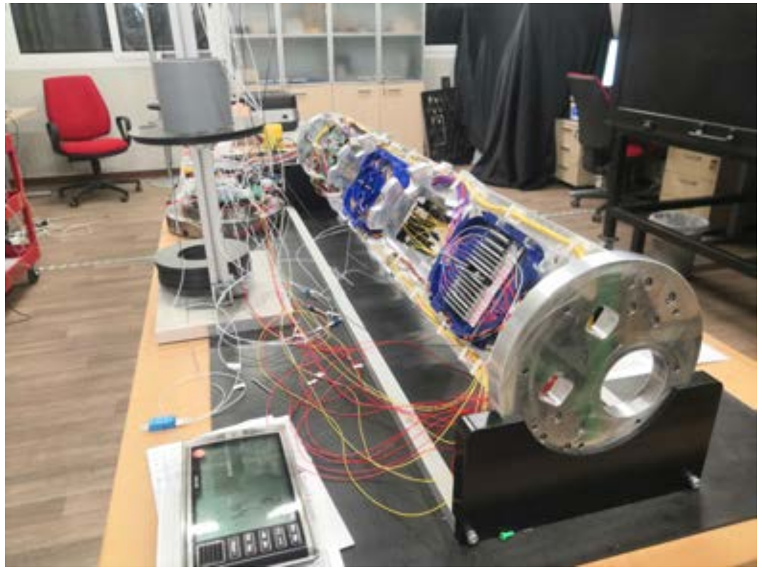
detx(sea) = $\Omega_{DU} - \delta t^{DR:Laser}_{DOM}$ + detx(DR:K40)
detx DR:K40 → **The .detx base from the K40 DR intraDOM calibration**

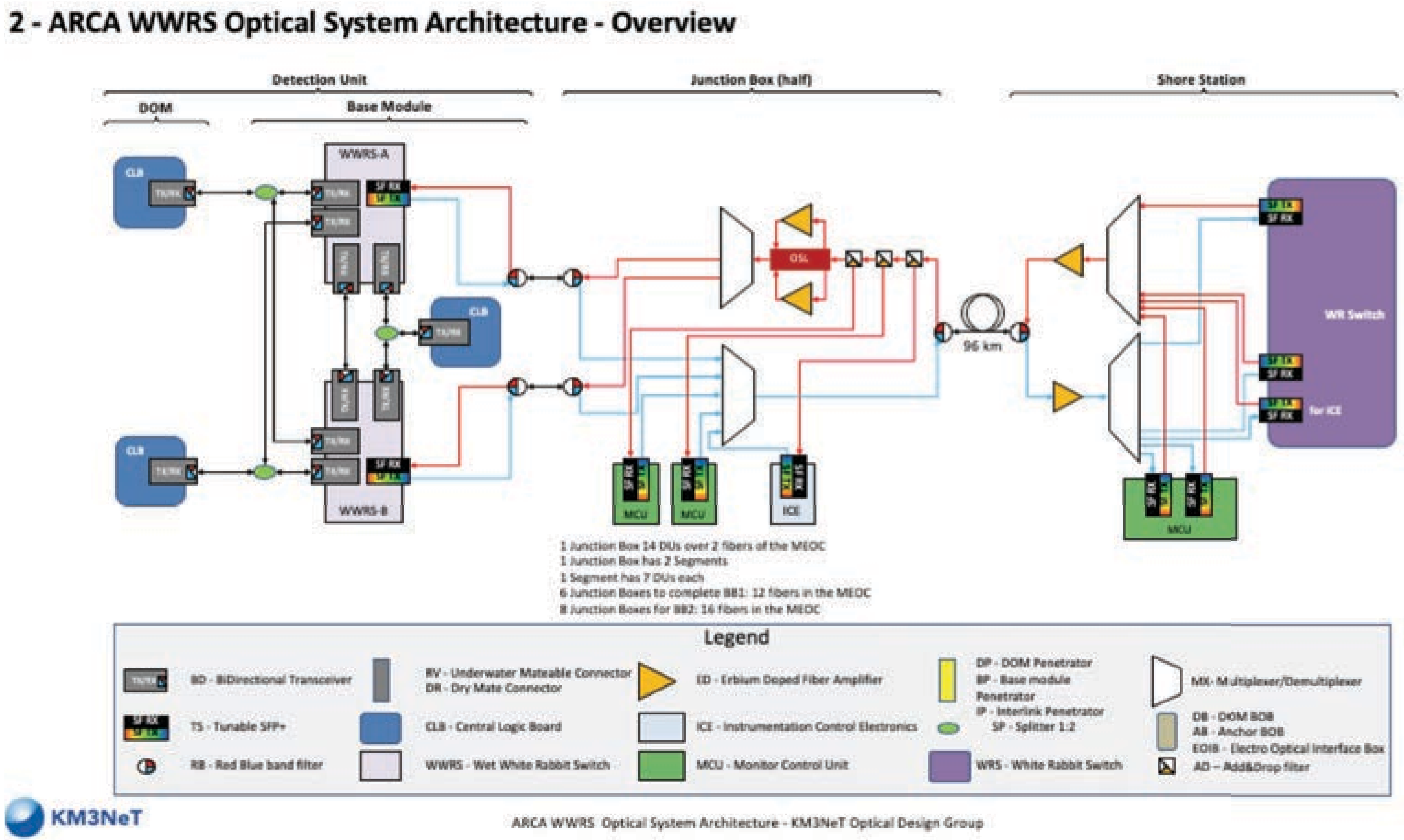
Time offsets corrections applied "offline" using the values measured before the deployment and round trip time in situ

KM3NeT calibration: inter-DU (Phase 2)

WR synchronisation: Round-Trip Time between the master clock (on shore) and each slave DOM/DU Base
Correction of all asymmetries in optical paths (shore/sea – sea/shore): applied offline [symmetrisation of optical link]

the new Base Module hosts subsea WR switch for the DU

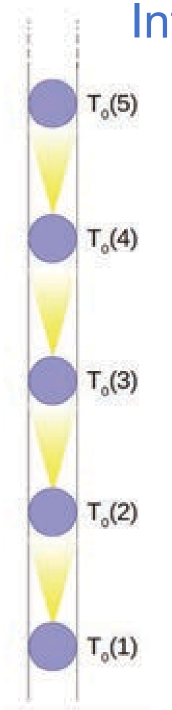


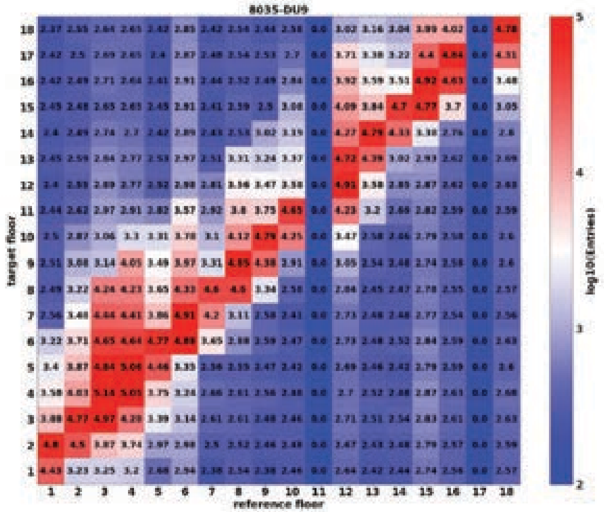


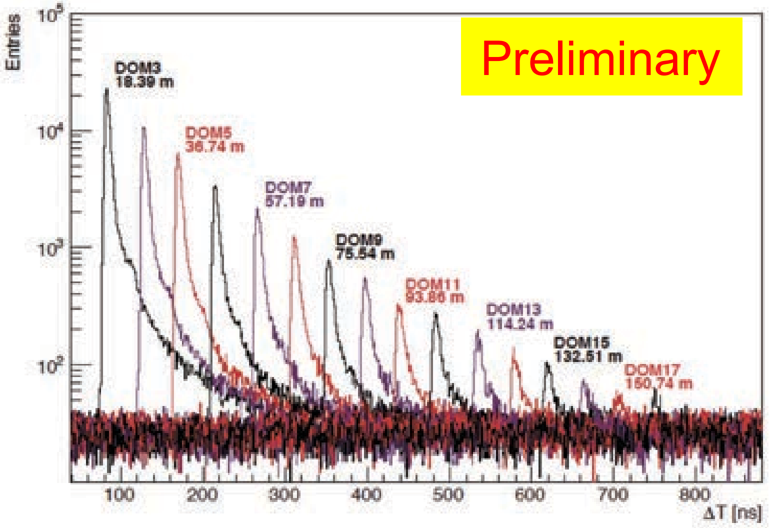
DU inter-DOM “laser calibration”:
PMT photocathode is still the “time-reference plane”

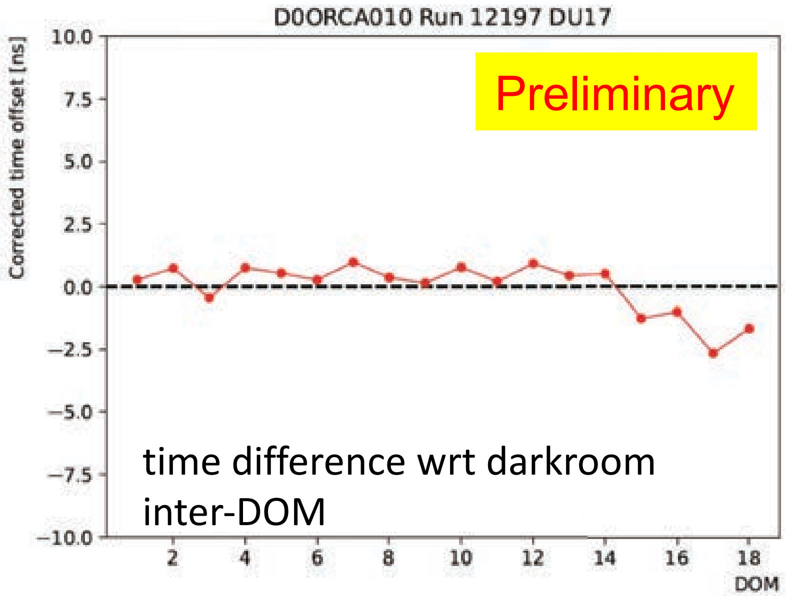
KM3NeT calibration in situ: nanobeacons

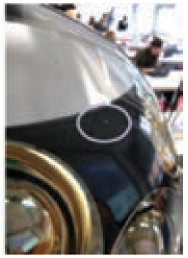
Inter-DOM time calibration check











DOM-DOM time delay in situ
nanobeacons flashed sequentially with a
delay of 3520 ns between one DOM and the following

Dual use:
measurement of seawater optical properties
simulation of shower in situ

additional systematics:

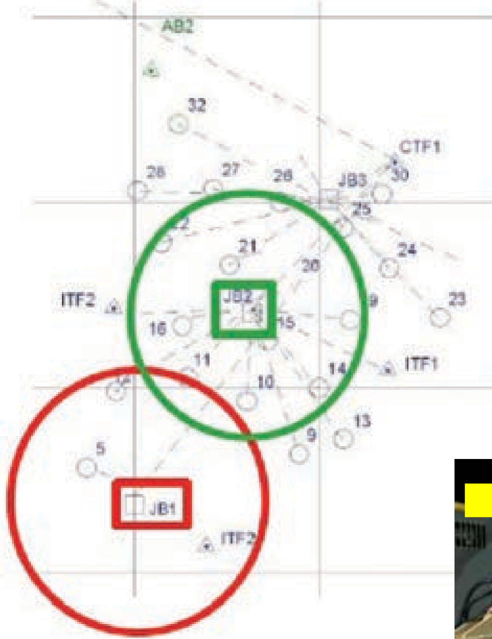
- position of the DOMs
- light propagation speed

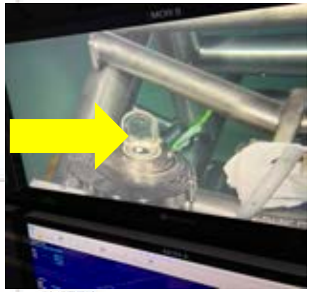
A. Sanchez-Losa et al, ICRC 2023

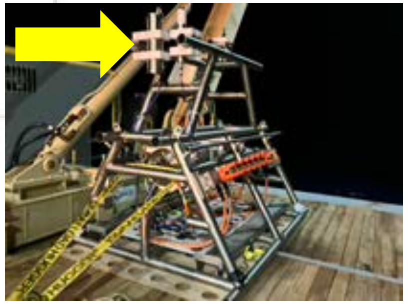
S. Aiello et al – NIM A 1040 (2022) 167132

KM3NeT calibration in situ: laser beacon

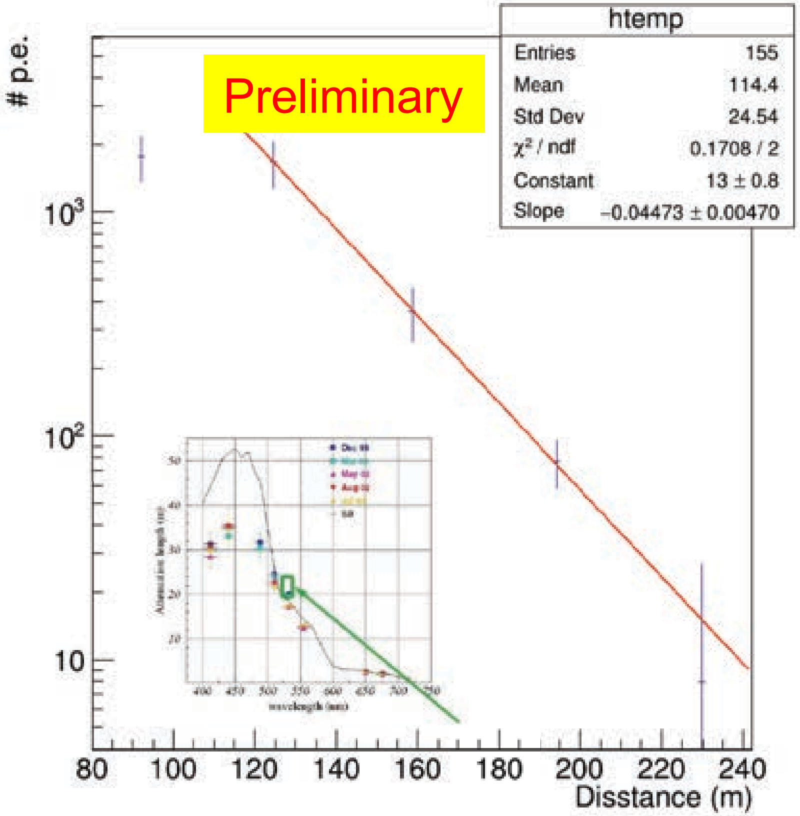
Inter-DU time calibration check





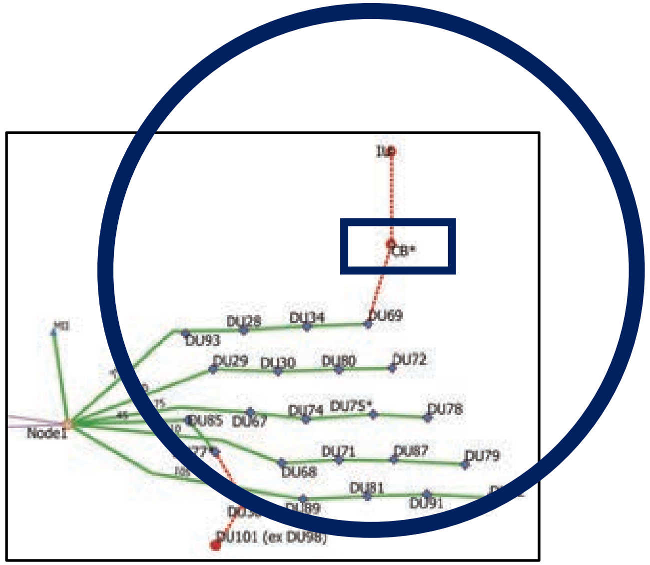


lasers in ARCA in JB



Laser signal clearly visible in time difference distributions

Illumination range ~150m
Npe received well in agreement with optical properties in situ

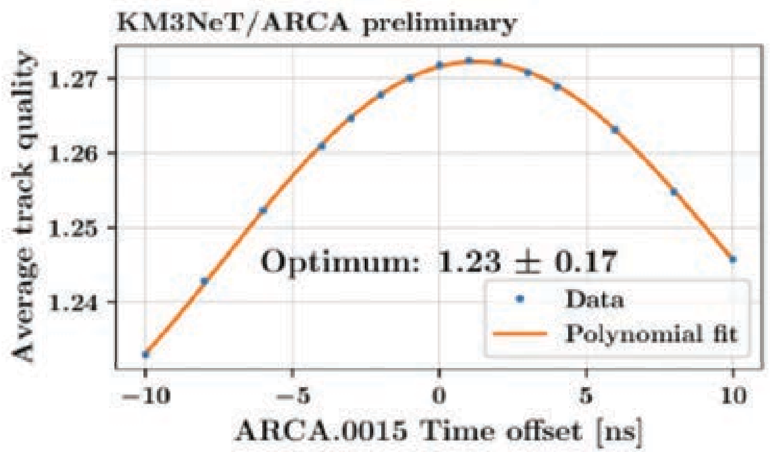


laser in ORCA in CU

Dual use:
measurement of seawater optical properties
simulation of shower in situ

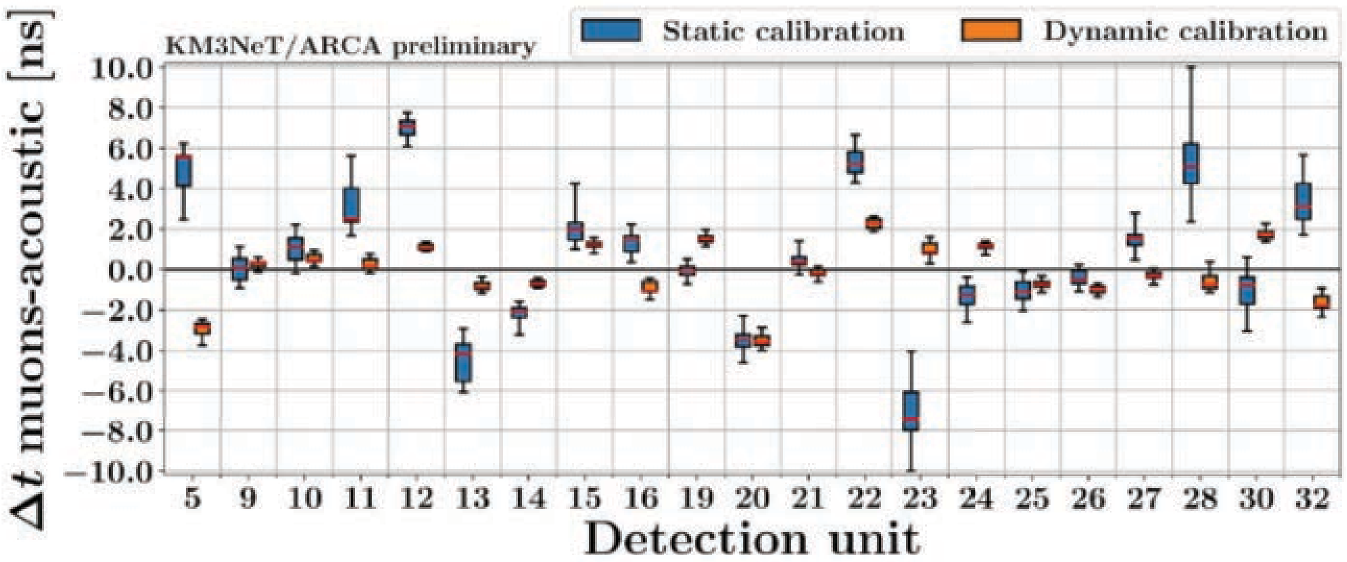
KM3NeT calibration in situ: atmospheric muons

Track quality as function of time offset



L. Bailly-Salins at ICRC23 - PoS(ICRC2023)218

Evaluated time offsets



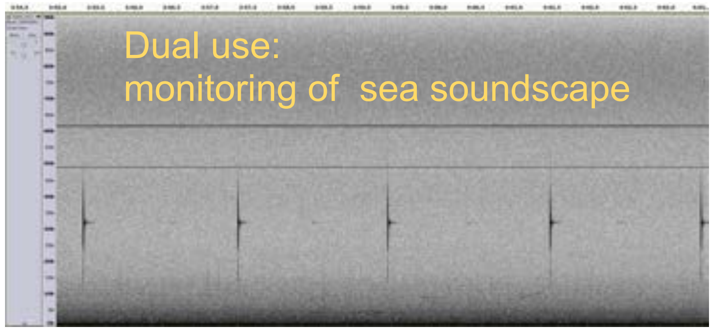
0.3ns uncertainty

caveat: interplay between timing & positioning accuracy !

At later stage atmospheric neutrinos could be also used

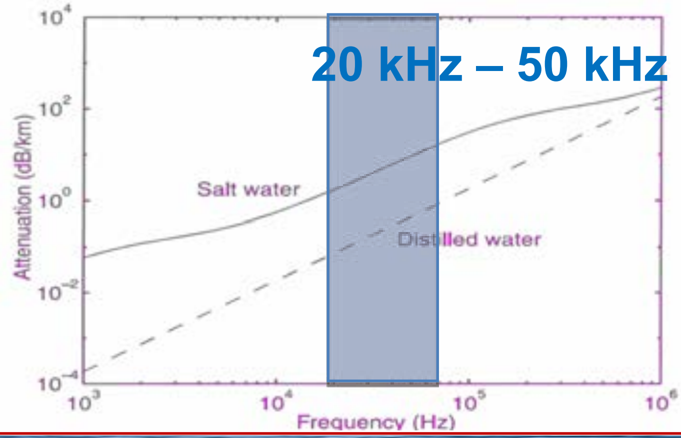
KM3NeT: acoustic positioning system

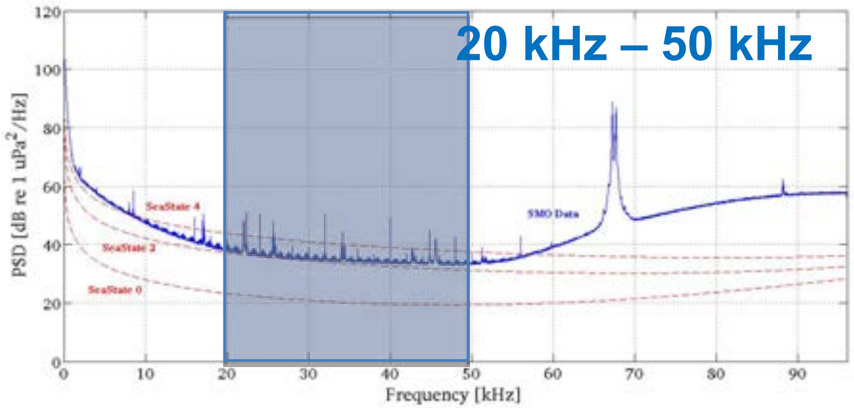
Navigation and absolute acoustic positioning system (NAAPS) - commercial
Used during sea operations to geo-reference the field asset
Long Base-Line (LBL) of acoustic transducers (commercial).
Ship (GPS reference) with main transducer



Relative acoustic positioning system (RAPS) - custom KM3NeT
Continuous monitoring of the DOMs positions
Long Base-Line (LBL) of acoustic transmitters (beacons) and receivers, located at known positions on seabed
Phased array of digital acoustic receivers (piezo) in each DOM

Acoustic emitter signals must be detected up to distances of 1 km





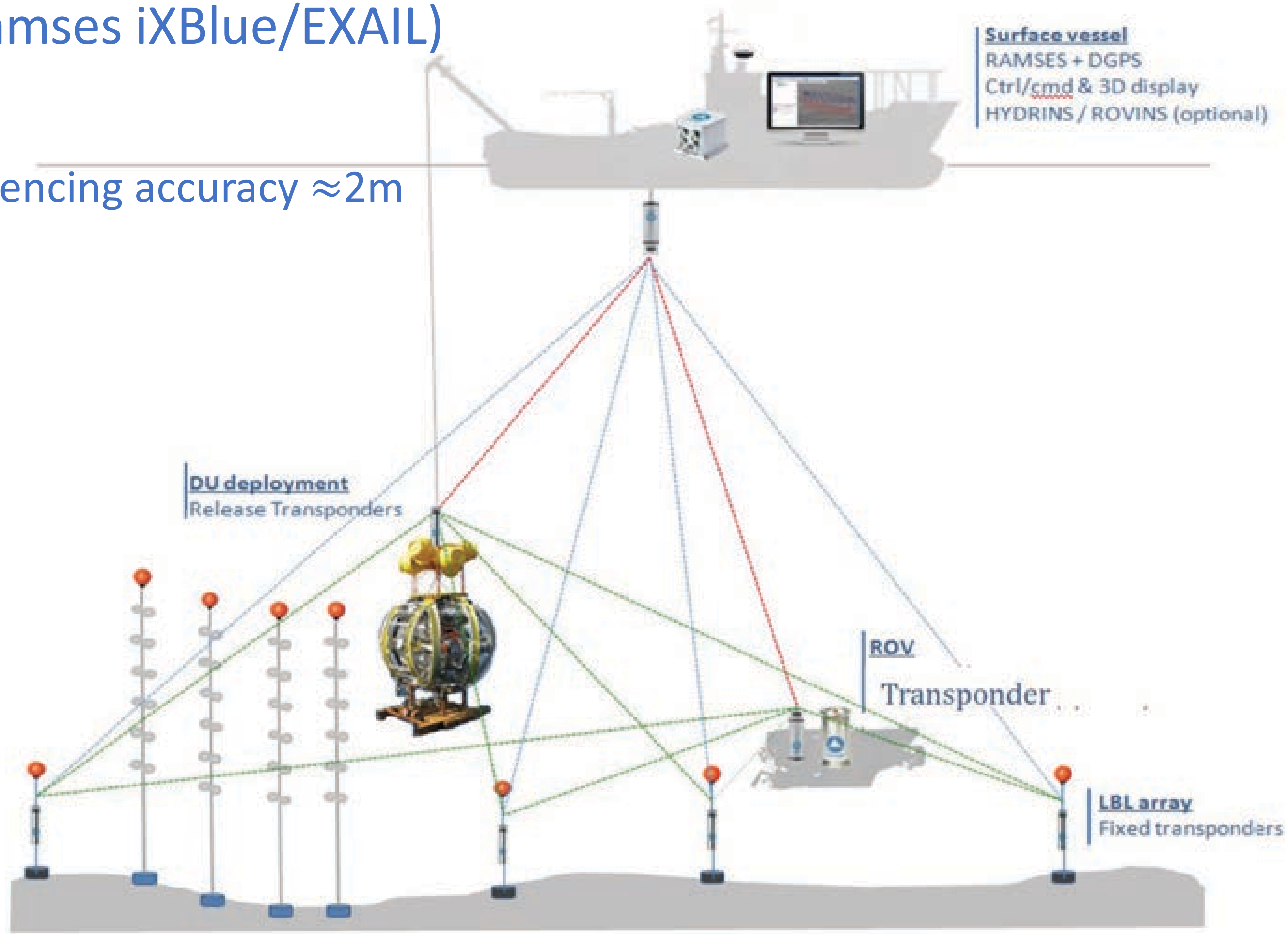
Suitable frequency range:
20 kHz-50 kHz
Lowest level of PSD:
~40 dB re 1 uPa²/Hz
Attenuation:
1-10 dB/km

KM3NeT: NAAPS

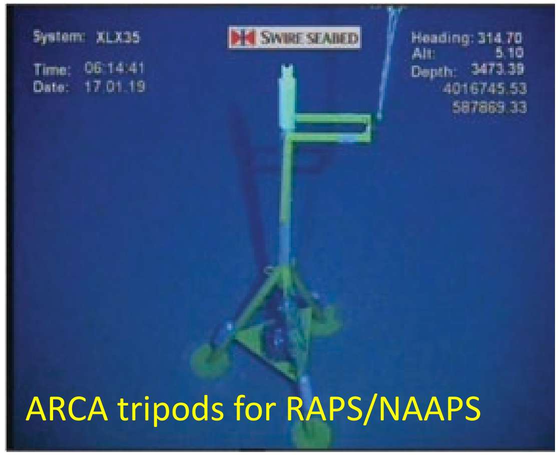
ORCA (and soon also in ARCA)

LBL (Ramses iXBlue/EXAIL)

Geo-referencing accuracy ≈2m



Subsea Tripods for LBL NAAPS/RAPS elements



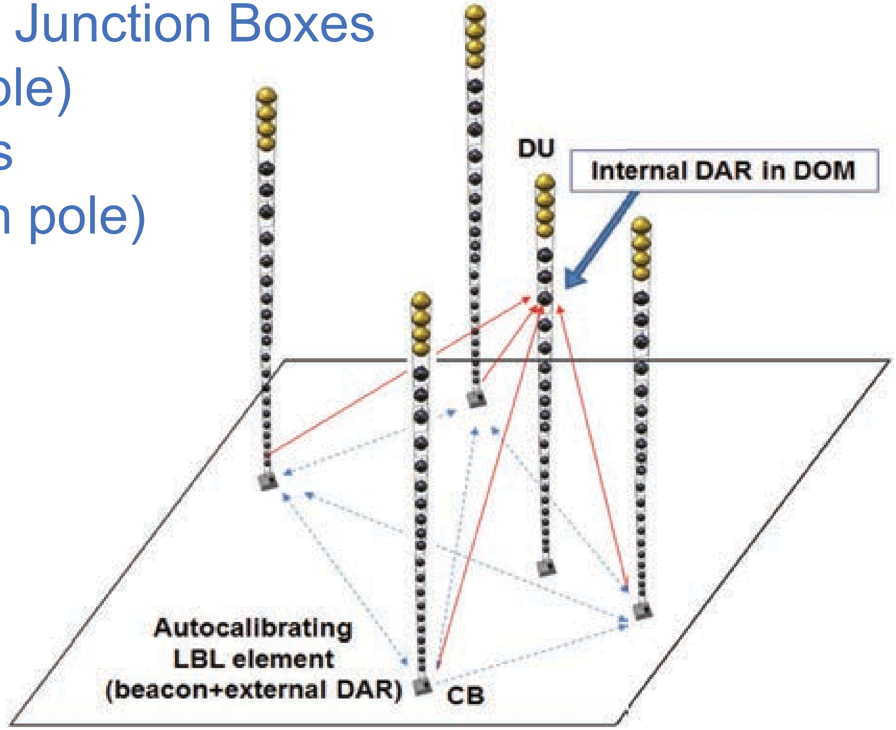
RAPS acoustic beacon

KM3NeT: RAPS

Digital acoustic receivers (192 kHz/24 bits) synchronised with detector master clock (<1 μs)
All data to shore in real time
→ the largest (scientific) phased array of acoustic receivers subsea

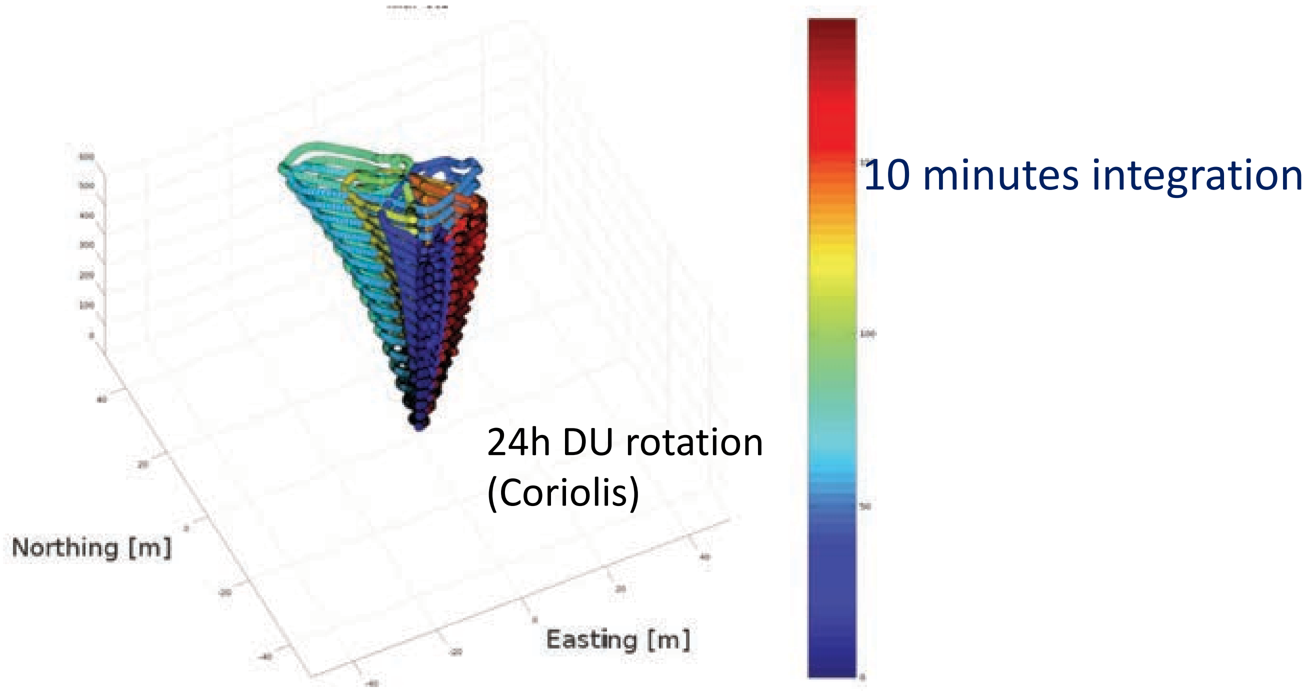
Long baseline of acoustic emitters and receivers

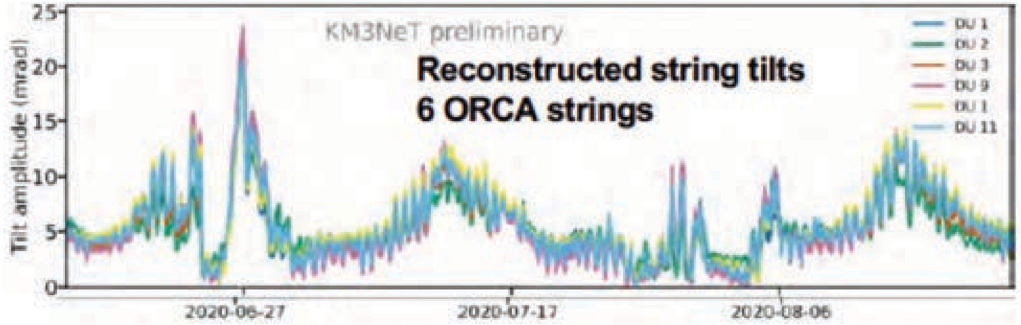
- reconfigurable beacons on selected DU bases and (in ARCA) on Junction Boxes
- autonomous beacons on tripods at the subsea field rim (retrievable)
- hydrophones on each DU base and (in ARCA) on Junction boxes
- acoustic sensors glued to the inside of each DOM (close to south pole)

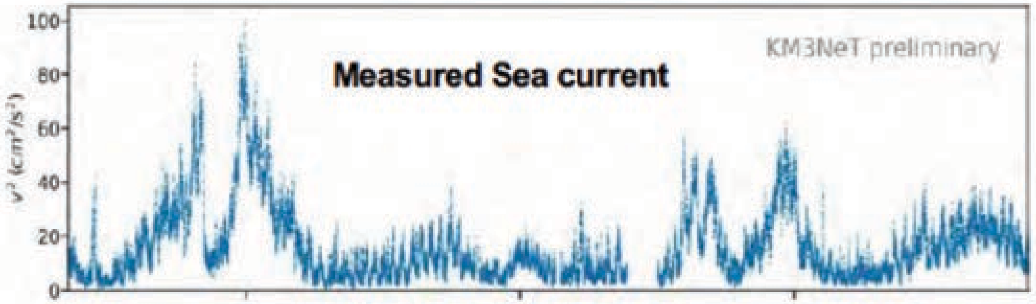


KM3NeT: RAPS

Goal 20 cm accuracy (1ns / DOM radius)
Two reconstruction methods in action:
1) Measurement of time of emission (ToE, beacon/hydro) and Time of arrival (ToA, beacon/piezo) plus multi-lateration; independent measurement of DOM position
2) Global fit of ToAs (only DOM receivers) [used at present for data analysis for ARCA and ORCA]







C. Galtius at ICRC23 - PoS(ICRC2023)1033

Work in progress: DU mechanical fit, on-line monitoring of sound speed and sea current in situ

KM3NeT: test of acoustic positioning system

Sun & Moon shadow to cosmic rays: pointing accuracy (offset) and resolution (smearing)

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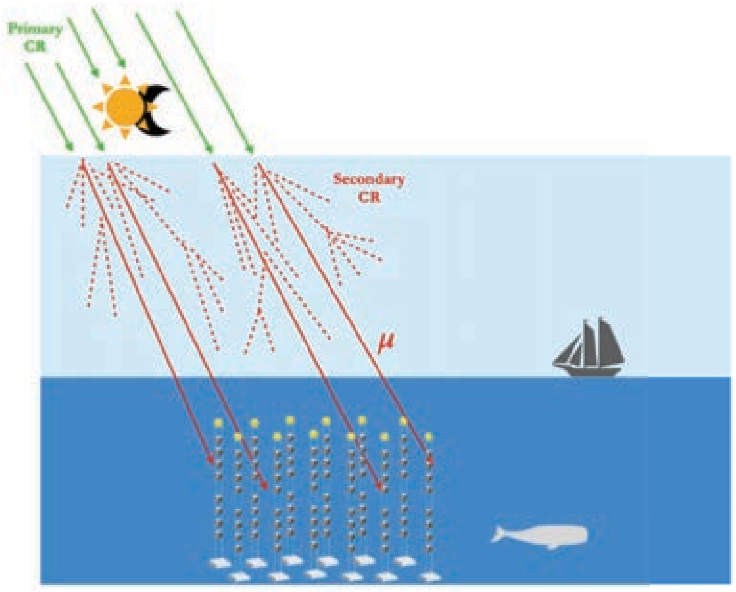
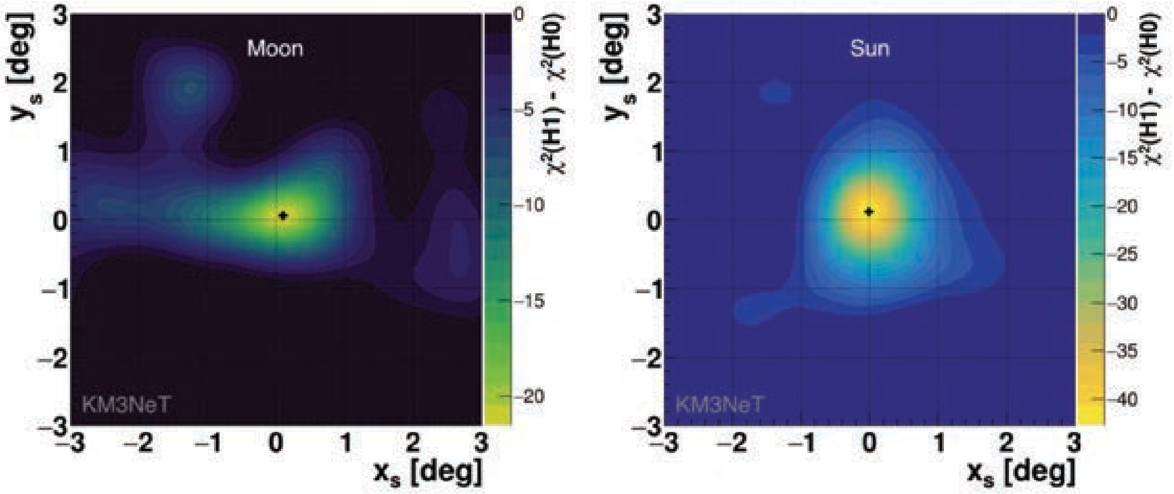


ORCA6 - 500 days



4.2 σ - res. 0.49±0.15°

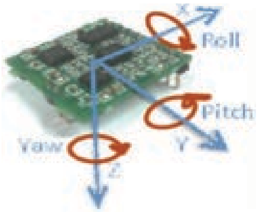
6.2 σ - res. 0.65±0.13°

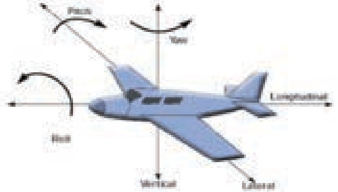
Sun+Moon with ARCA 19+21 (positioning method 2):
Result compatible with perfect orientation only at 3σ level.
Not constraining better than ~0.5°
Analysis on-going to extend the statistics

KM3NeT DOM orientation: AHRS boards

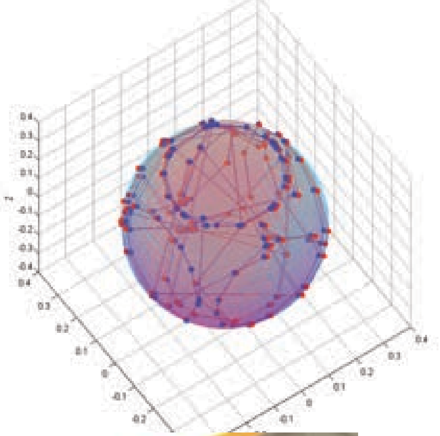
DOM orientation/tilt constantly monitored by 3D compass + 3D accelerometers board

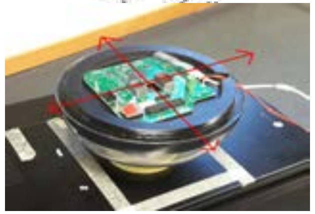
- 3D orientation reconstruction of the DOM: (yaw, pitch, roll)
- Continuous data flow

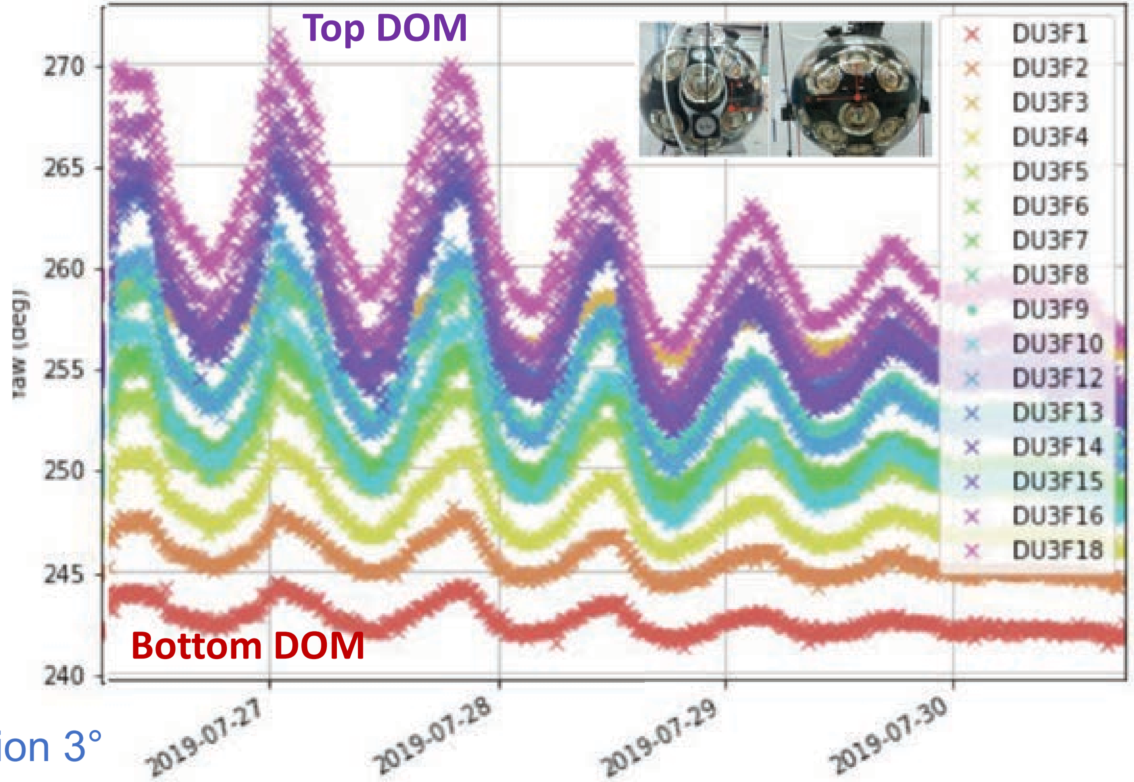




3D CLB "wobbling"
→calibration of "hard iron" effects of compass
→ accelerometers calibration





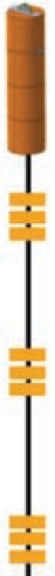


target resolution 3°

KM3NeT: calibration unit

Allow streaming of water column oceanographic properties

Sound Velocity
Water Current (Doppler acoustic sensor)
Conductivity, Temperature, Depth, Oxygen Probe (CTD)
Absolute Pressure (bottom)



inductive cable technology
(no connectors, up to 100 instruments)

Retrievable unit: re-calibration/re-configuration of instruments

Installed far at the rim of the detector footprint
for safe multiple recovery/deployment

R. Le Breton JINST 16-C09004, 2021

Summary and Outlook

Upon completion, the KM3NeT detector will be one of the largest tracker and calorimeter ever designed
Angular resolution (and overall sensitivity) is strongly dependent on DOM timing and position accuracy

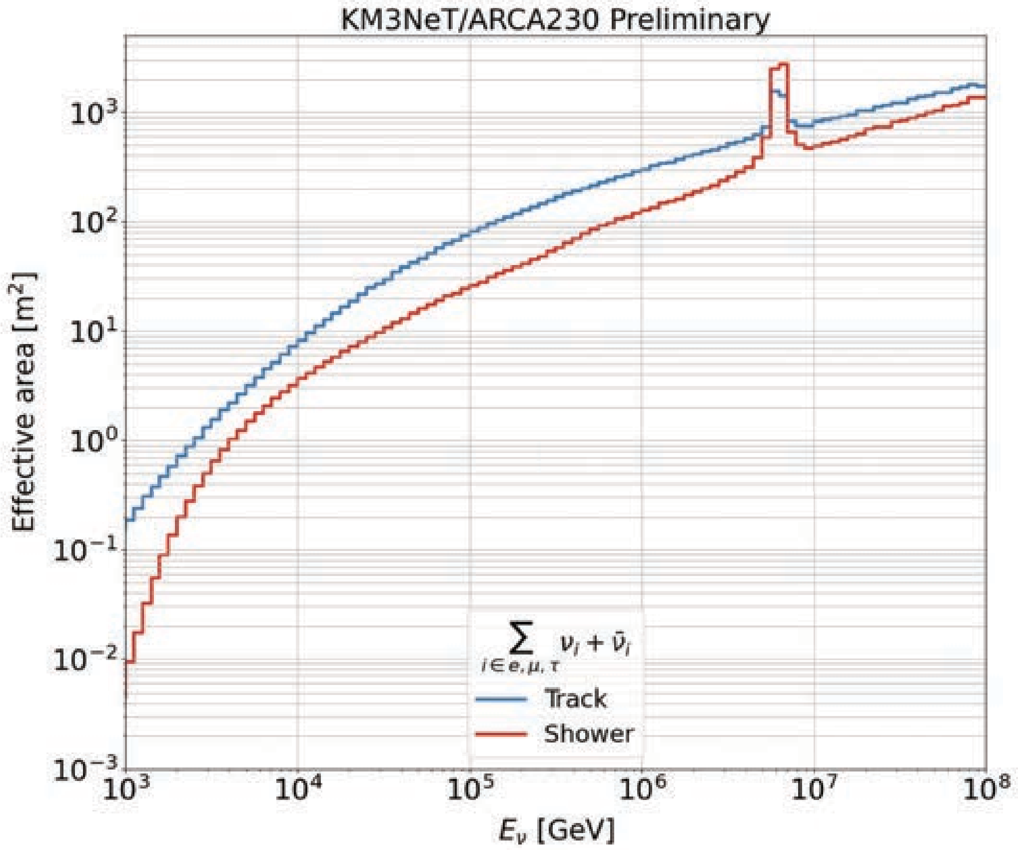
Calibration of KM3NeT (Focal points)

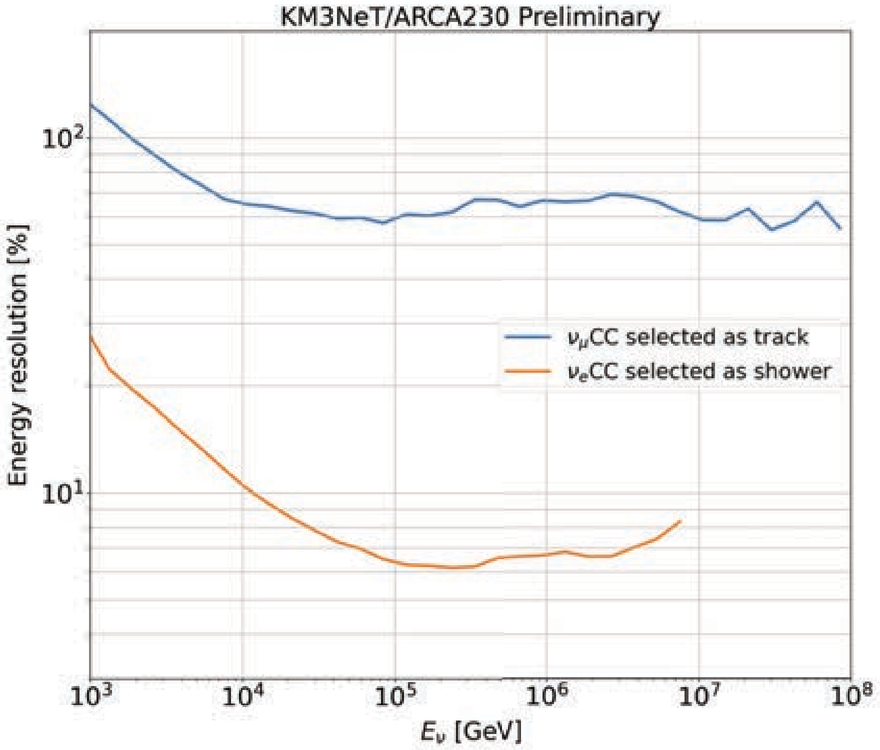
- timing (ns accuracy required) – based on CERN White Rabbit paradigm (first time over multi 10km cables)
  - Phase 1- Broadcast timing solution
    - a lot of effort needed for calibration (asymmetries corrections, interoperability of dark-rooms), not supported by the WR community (firmware branch specifically developed for KM3NeT, abandoned).
    - in-situ methods excellent tools to check and correct mis-calibrated time offsets
    - DUs well time calibrated so-far (ns accuracy reached)
  - Phase 2- White Rabbit Standard
    - under construction and test now

- Acoustic positioning (20 cm accuracy needed)
  - Innovative Acoustic Positioning System designed and operated. The largest acoustic phased array in sea
  - actual accuracy dominated by absolute positioning uncertainties of emitters
  - Improved NAAPS, operation of more beacons and improved signal analysis should reduce soon the uncertainties

Cross fertilization with Earth and Sea Science well established

Backup





T.J. Van Eeden for KM3NeT, PoS(ICRC2023)1075