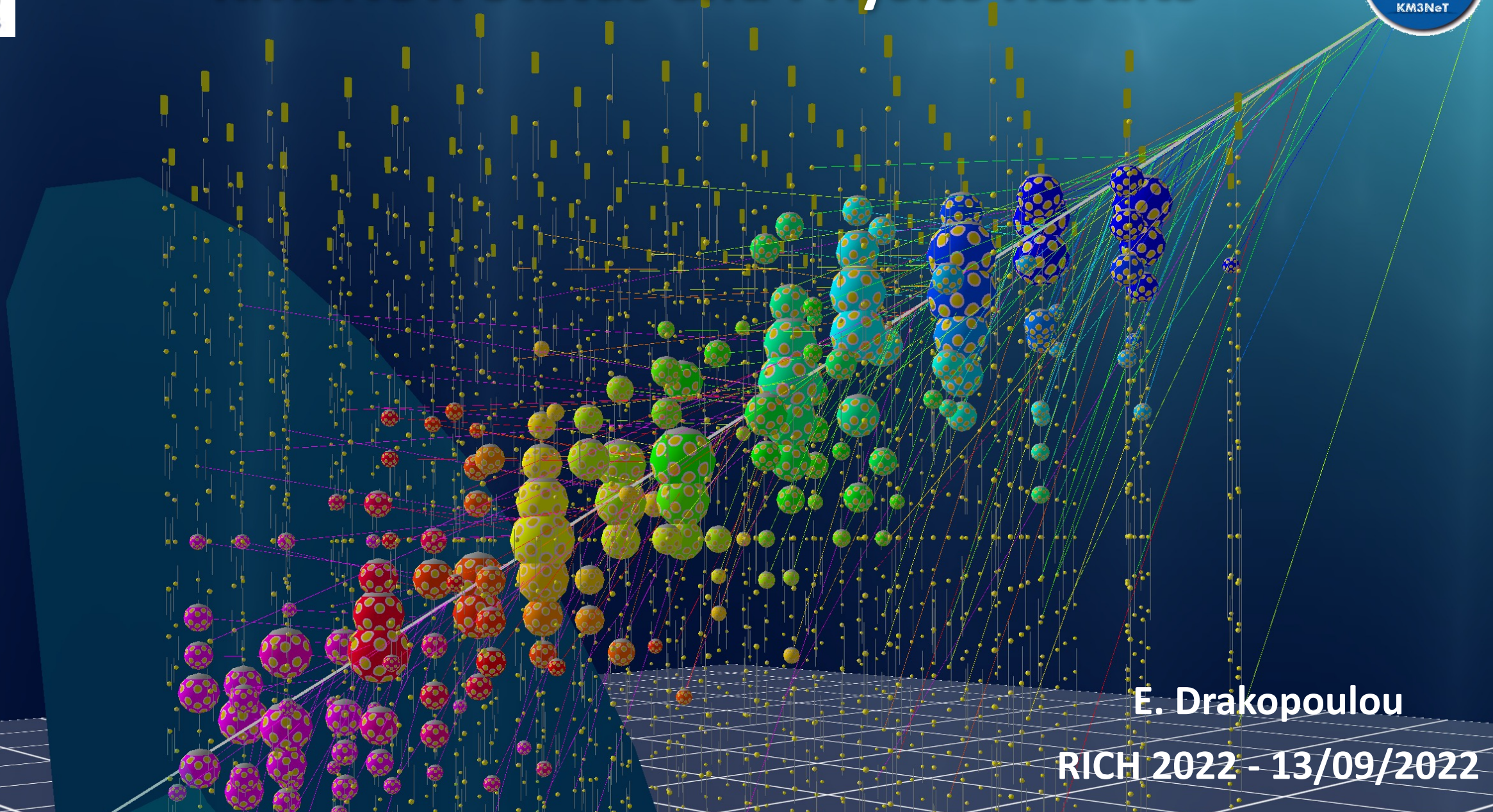
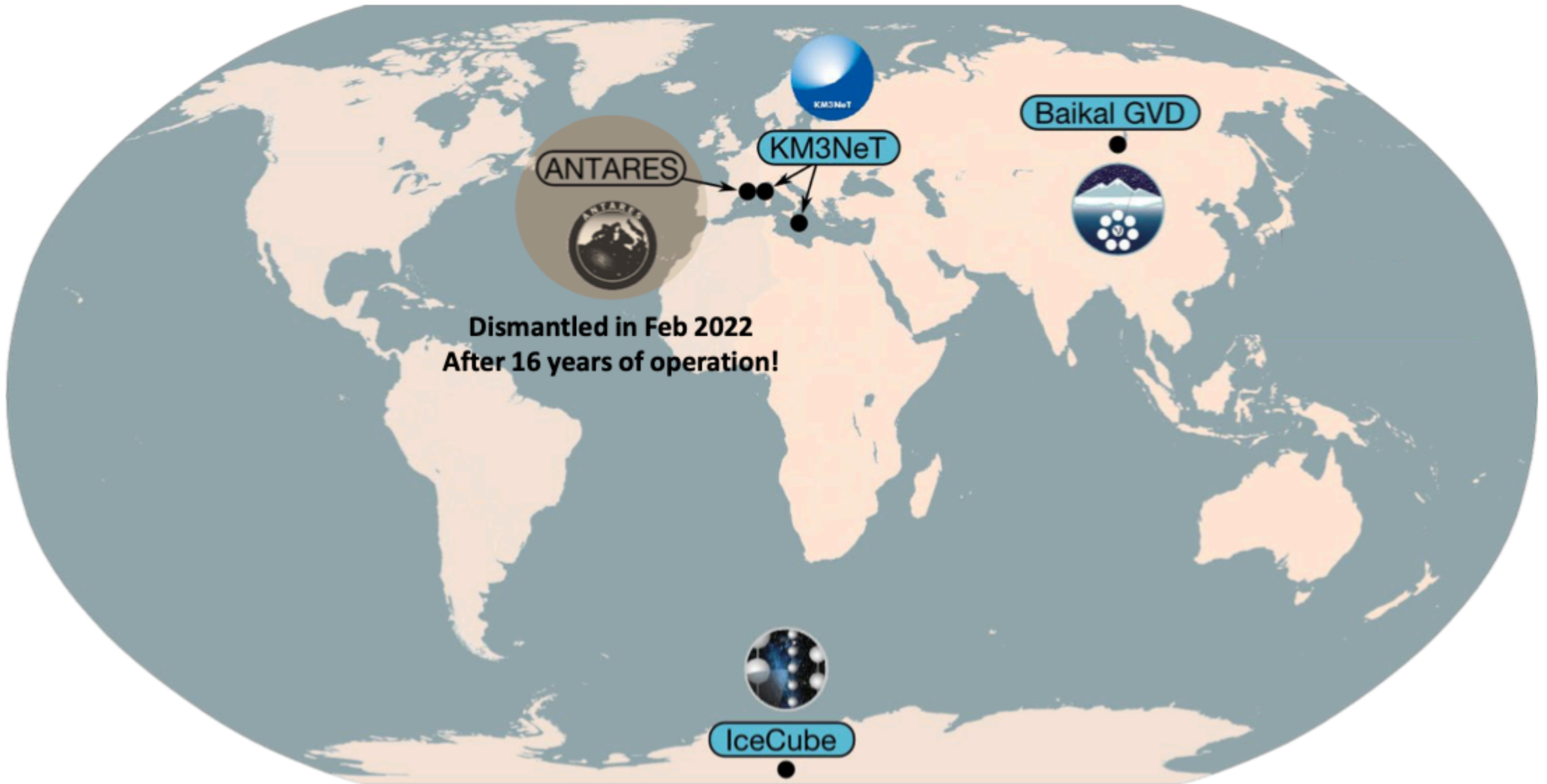
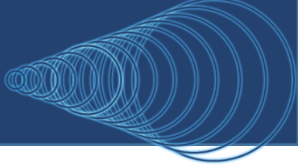


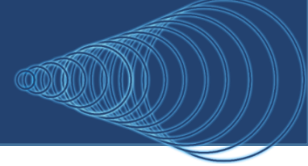
KM3NeT: Status and Physics Results



E. Drakopoulou

RICH 2022 - 13/09/2022





Lol: [arXiv:1601.07459](https://arxiv.org/abs/1601.07459) [astro-ph.IM]

Cities and Sites of KM3NeT

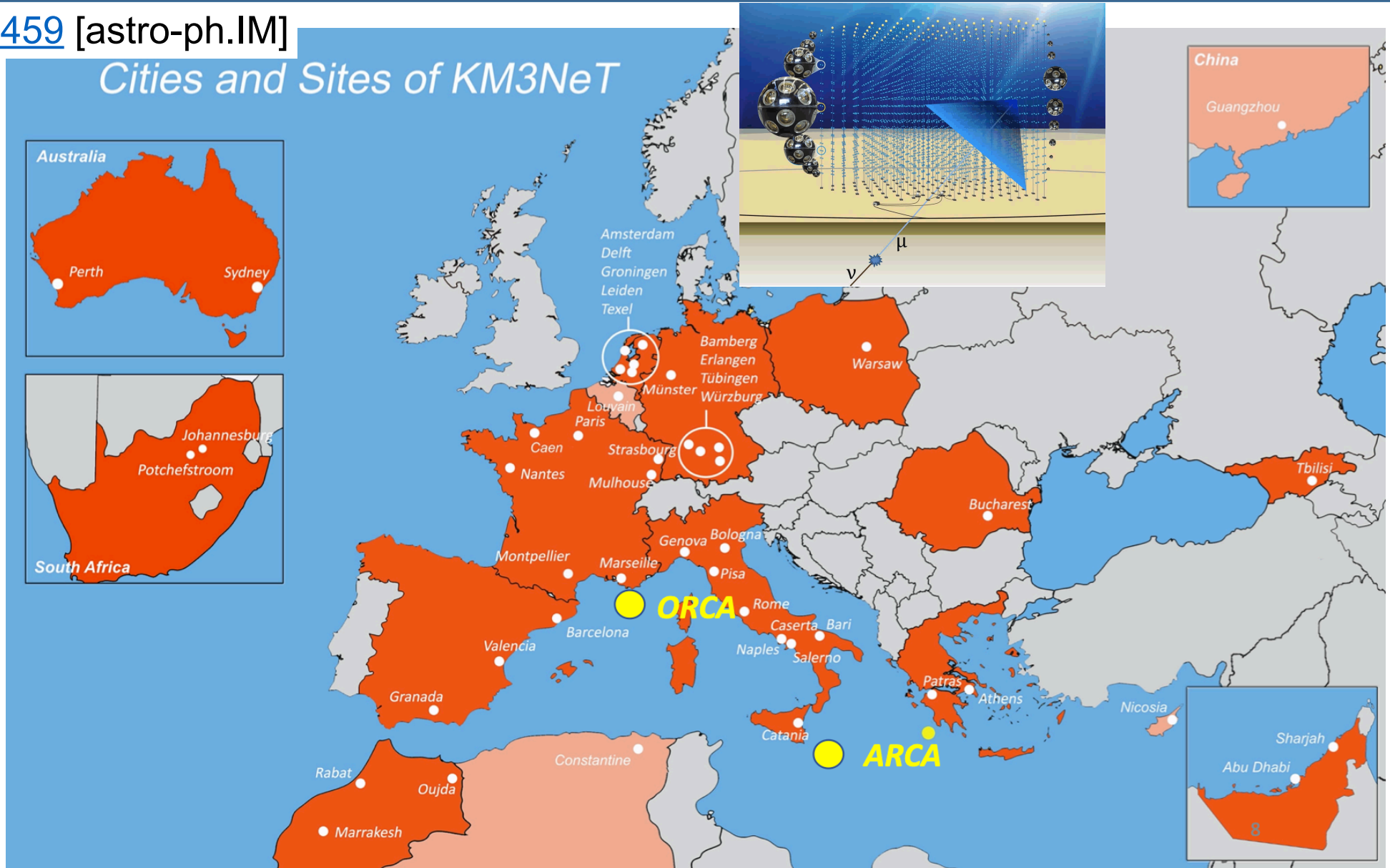
Numbers:

- 55 groups
- 16 countries
- 4 continents
- 2 detectors

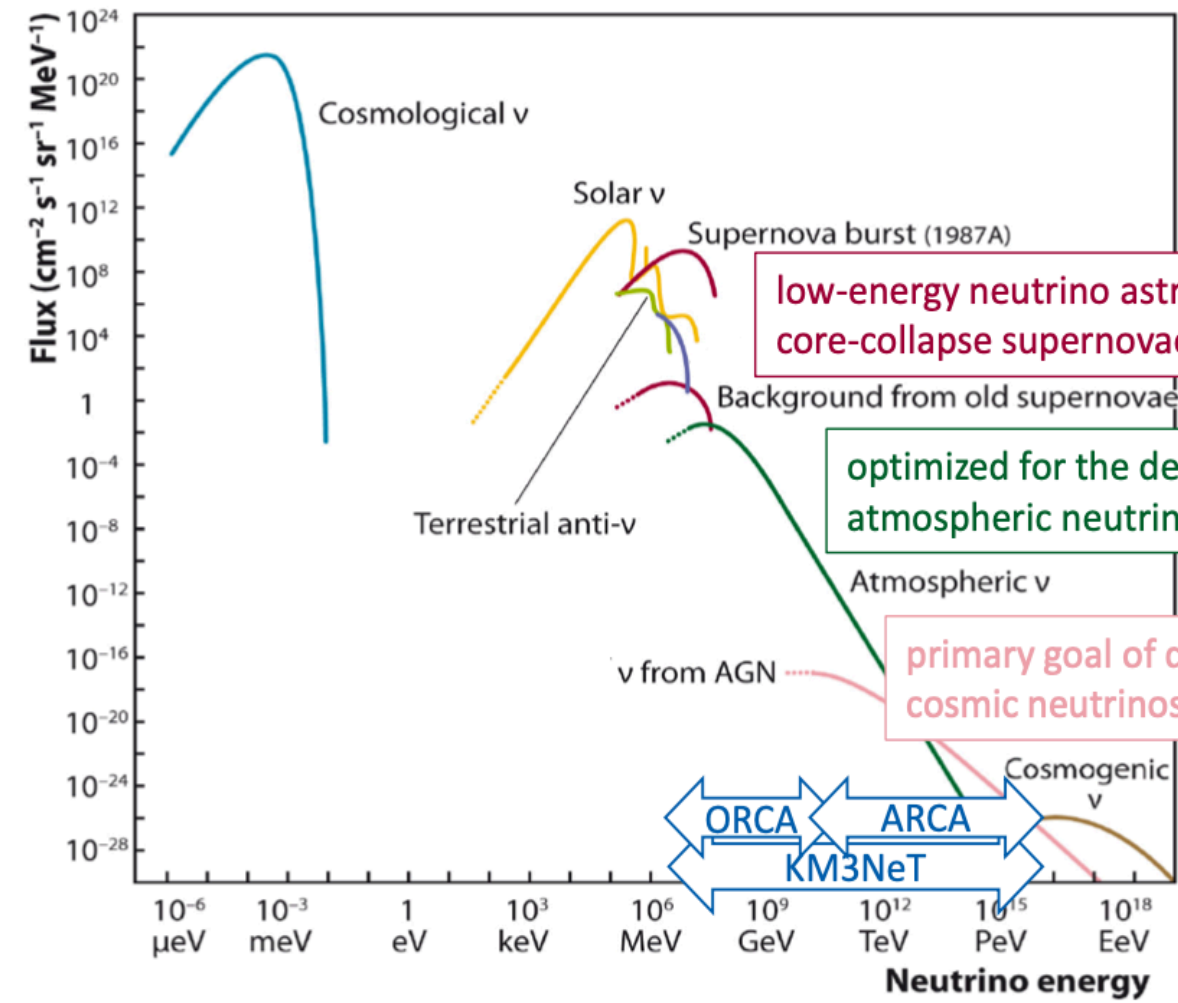
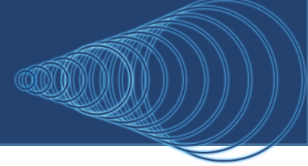
ORCA/ARCA

Legend:

- group
- observer
- member



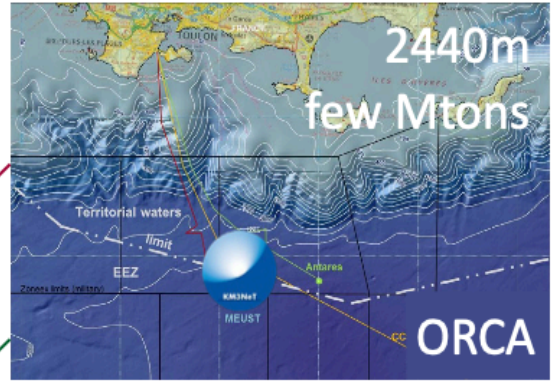
Neutrino Sources



low-energy neutrino astronomy like core-collapse supernovae

optimized for the detection of atmospheric neutrinos

primary goal of detecting cosmic neutrinos

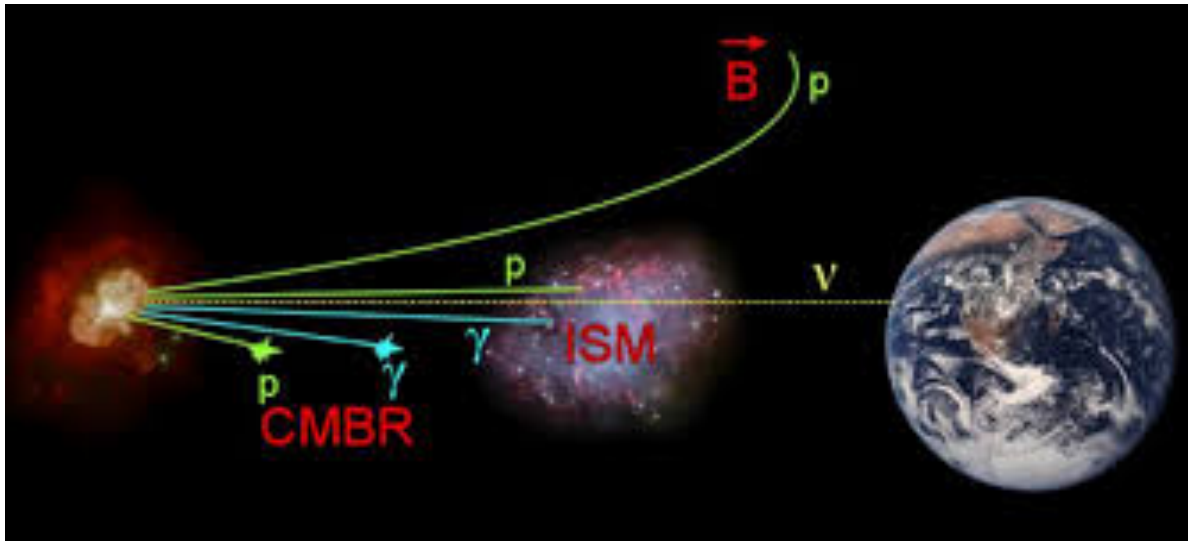


KM3NeT/ORCA
Oscillation Research with Cosmics In the Abyss



KM3NeT/ARCA
Astroparticle Research with Cosmics In the Abyss

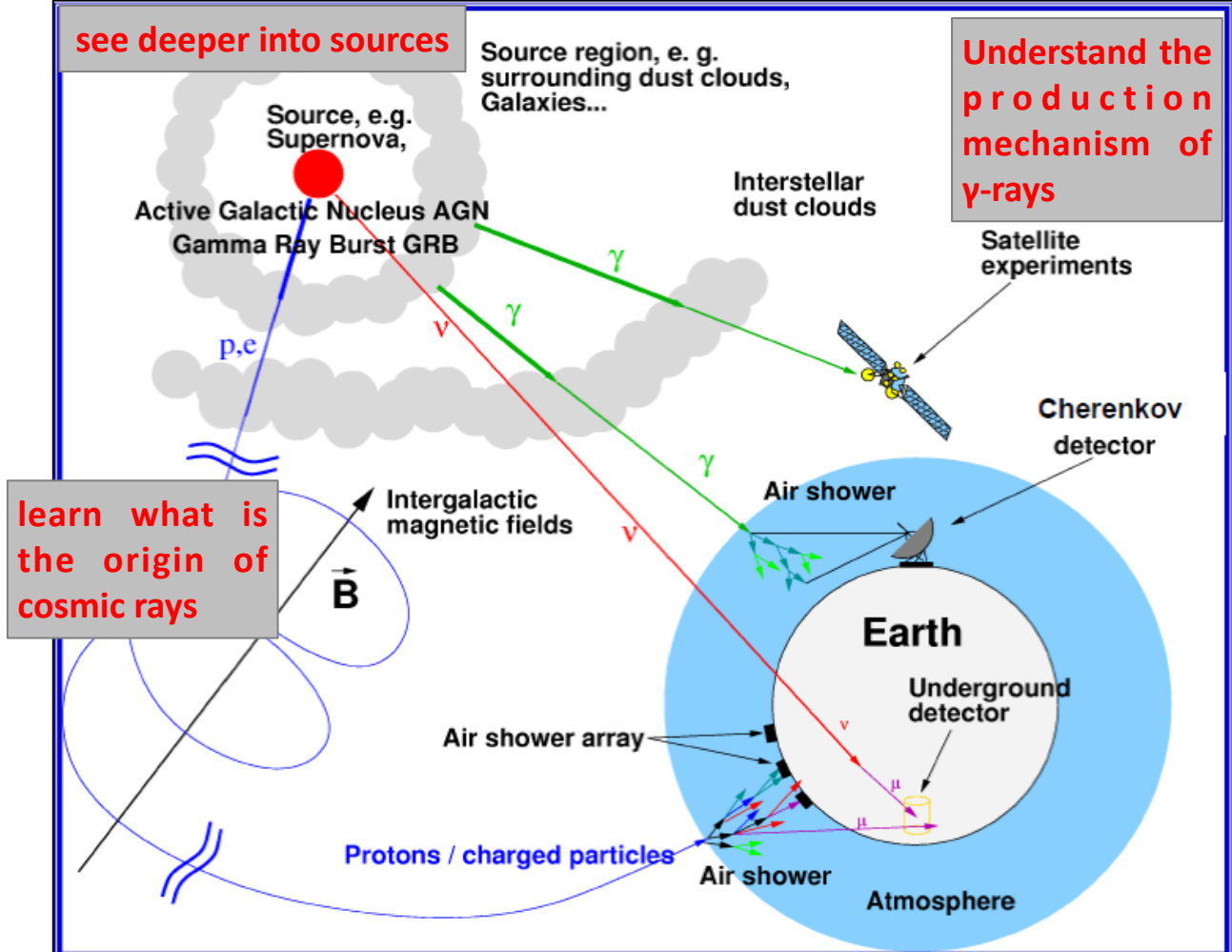
Position in the Northern Hemisphere: optimal view of the Southern sky, including the Galactic Center



Neutrinos: straight trajectories, practically no absorption.
Sources: powerful cosmic hadronic accelerators

KM3NeT/ARCA: Exploring the High Energy Universe

- observe high energy (>TeV energy regime) neutrinos from astrophysical sources
- measure the diffuse flux of astrophysical neutrinos



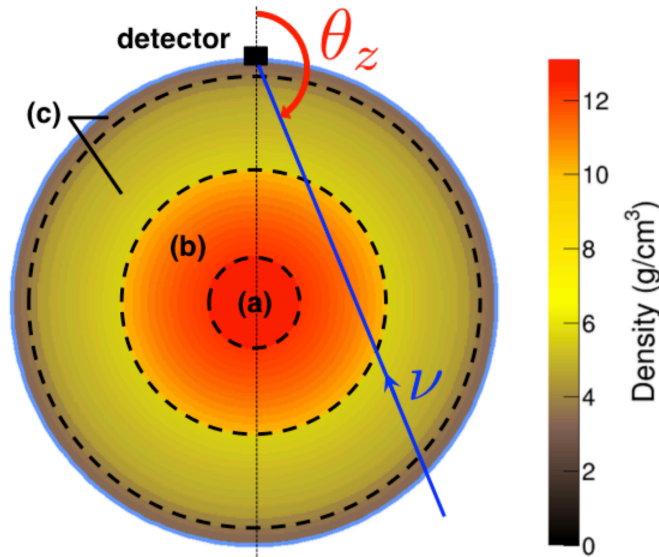
learn what is the origin of cosmic rays

see deeper into sources

Source region, e.g. surrounding dust clouds, Galaxies...

Understand the production mechanism of γ -rays

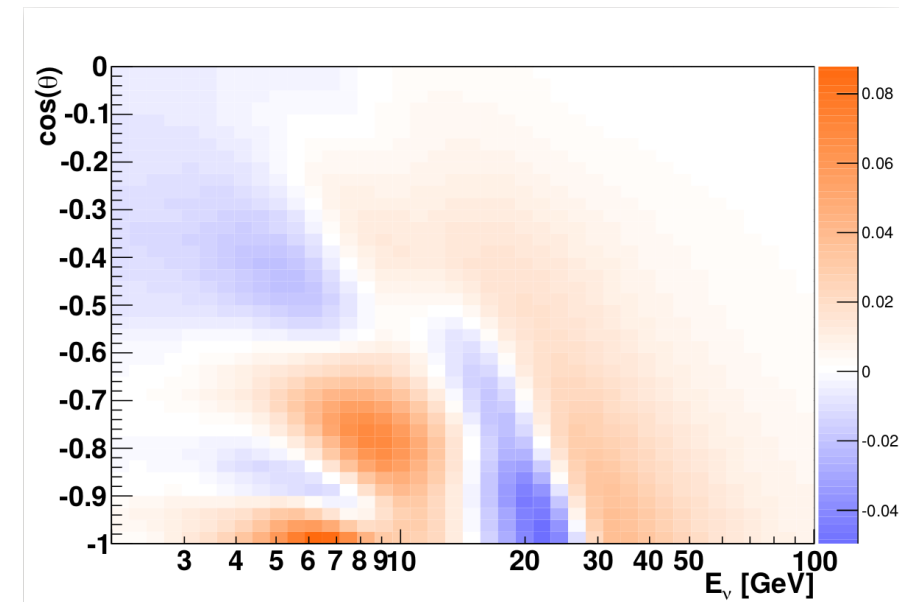
Multi-messenger astronomy combine ν , γ -rays, other EM waves, gravitational waves, charged cosmic rays

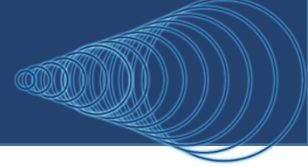


- Neutrino properties through oscillation studies
 - neutrino mass hierarchy
 - measure atm. mixing parameters
 - **New physics** (sterile neutrinos, NSI & other)
- Characteristic patterns of neutrino appearance/disappearance at different energies/path length

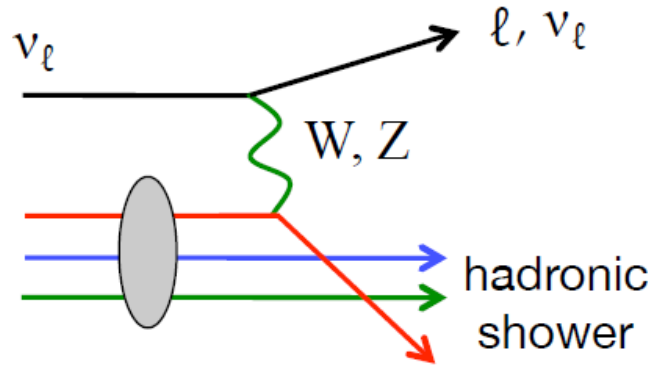
KM3NeT/ORCA: Determine the neutrino mass ordering

- study atmospheric neutrino (\sim few GeV energy regime) oscillations
- Oscillation pattern distorted by Earth matter effects. Allows for determination of mass ordering because of different behaviour of neutrinos/antineutrinos.
- KM3NeT: no event-by-event $\nu/\bar{\nu}$ separation, but differences in flux/kinematics/cross-section.



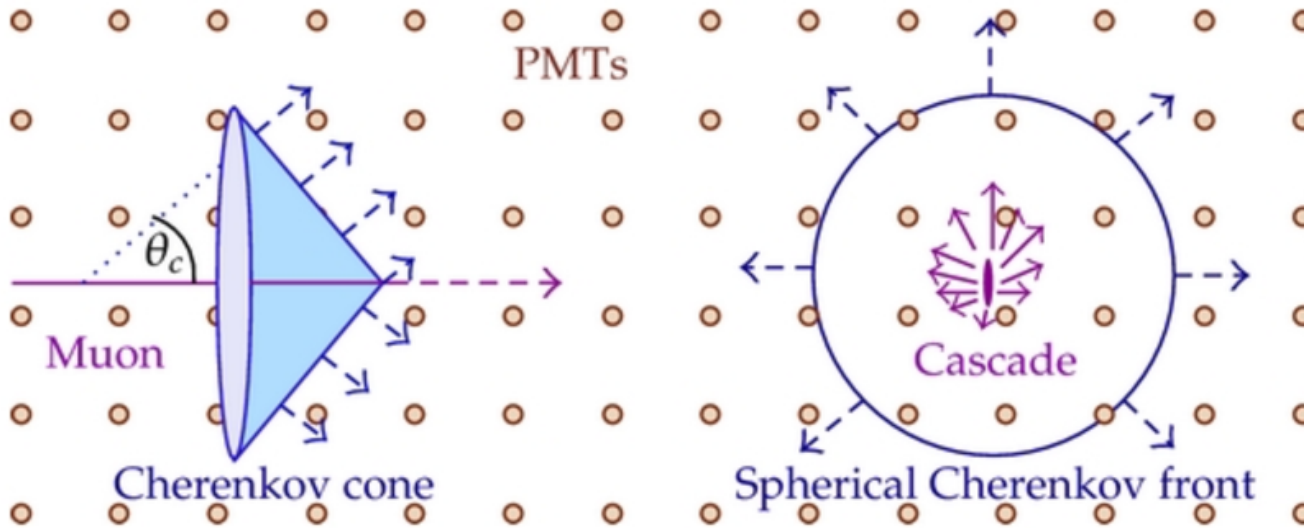


Charged Current (CC) /
Neutral Current (NC)
interactions



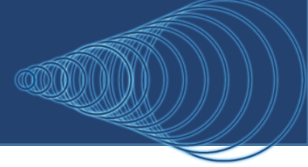
Neutrino detection:

- Cherenkov radiation allows directional reconstruction
- radiative processes allows energy reconstruction



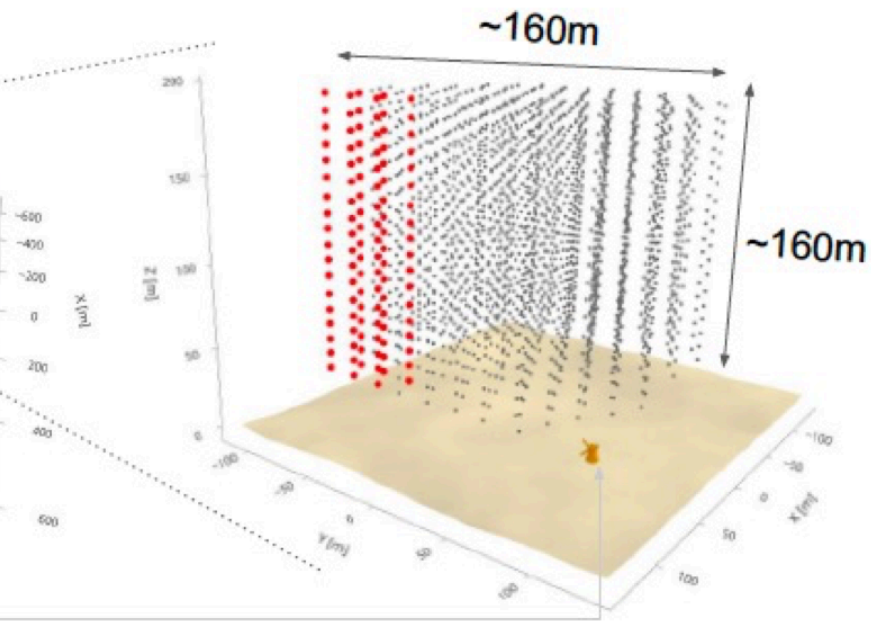
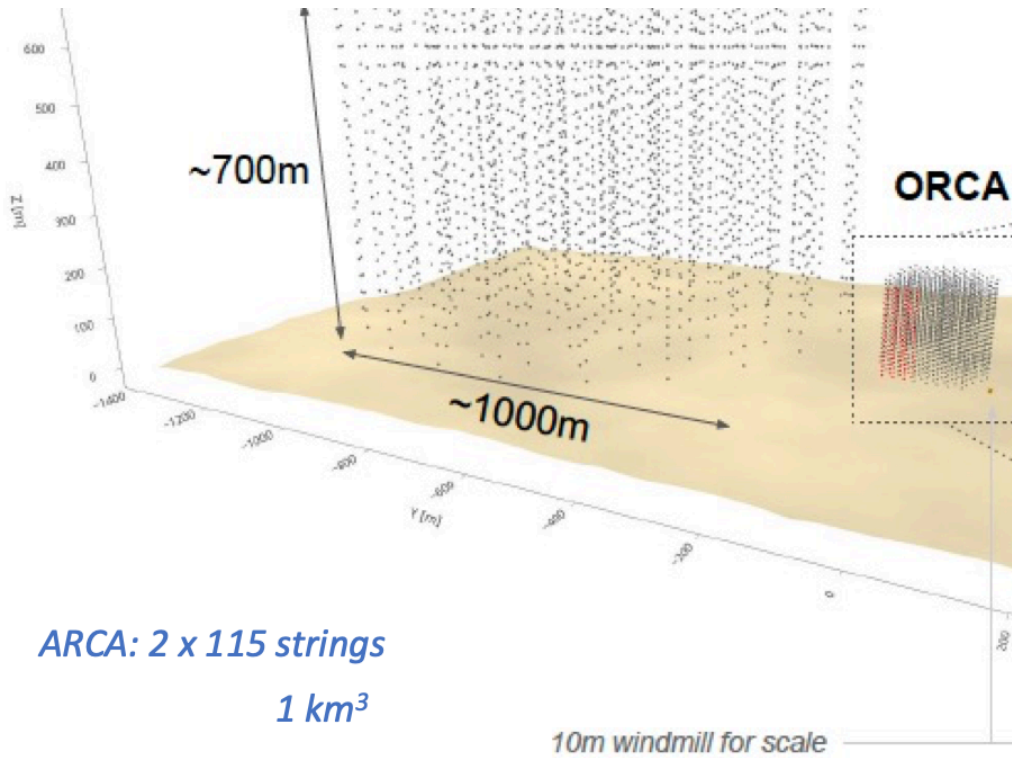
Detector properties:

- Transparent medium
- Deep underground to shield backgrounds (atmospheric muons)
- Huge detector volumes
- Direction Resolutions:
 - track channel: better than 0.1° for $E > 100 \text{ TeV}$
 - cascade channel: better than 2°



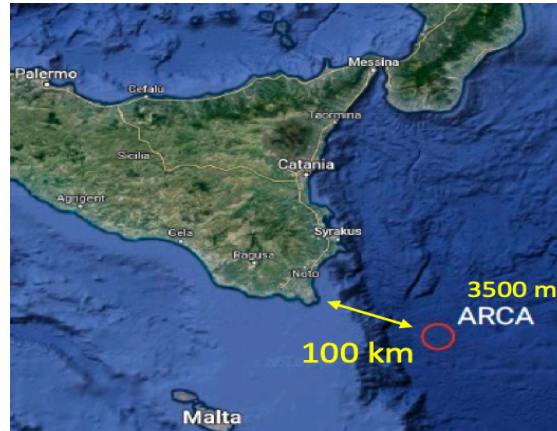
ARCA: Astroparticle Research with Cosmics in the Abyss

ORCA: Oscillation Research with Cosmics in the Abyss



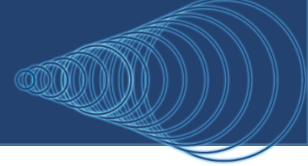
ARCA: 2 x 115 strings
1 km³

ARCA:
cosmic ν , $E > 1$ TeV



ORCA:
atm ν oscillations, 1-100 GeV



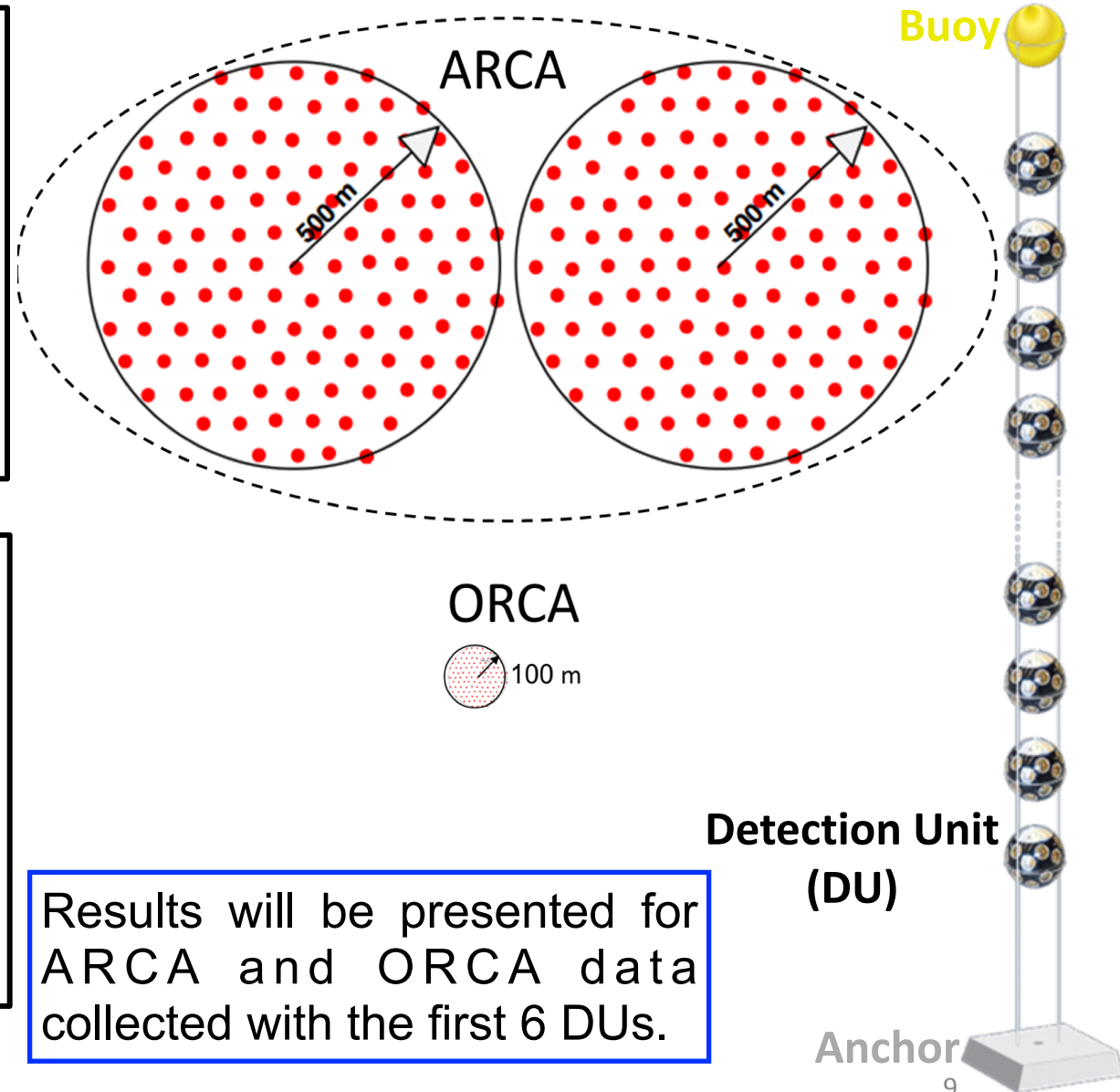


ARCA: Astroparticle Research with Cosmics in the Abyss

- ✓ Astrophysical Neutrinos (TeV-PeV Energies).
- ✓ 2 blocks of 115 DUs each: Volume $(0.5 * 2) \text{ km}^3 \approx 1 \text{ Gton}$.
- ✓ Each DU is about 700 m in height, with DOMs 36 m vertically spaced; The DU horizontal spacing is about 90 m.
- ✓ Sparsely instrumented
- ✓ **Currently 19 DUs deployed**

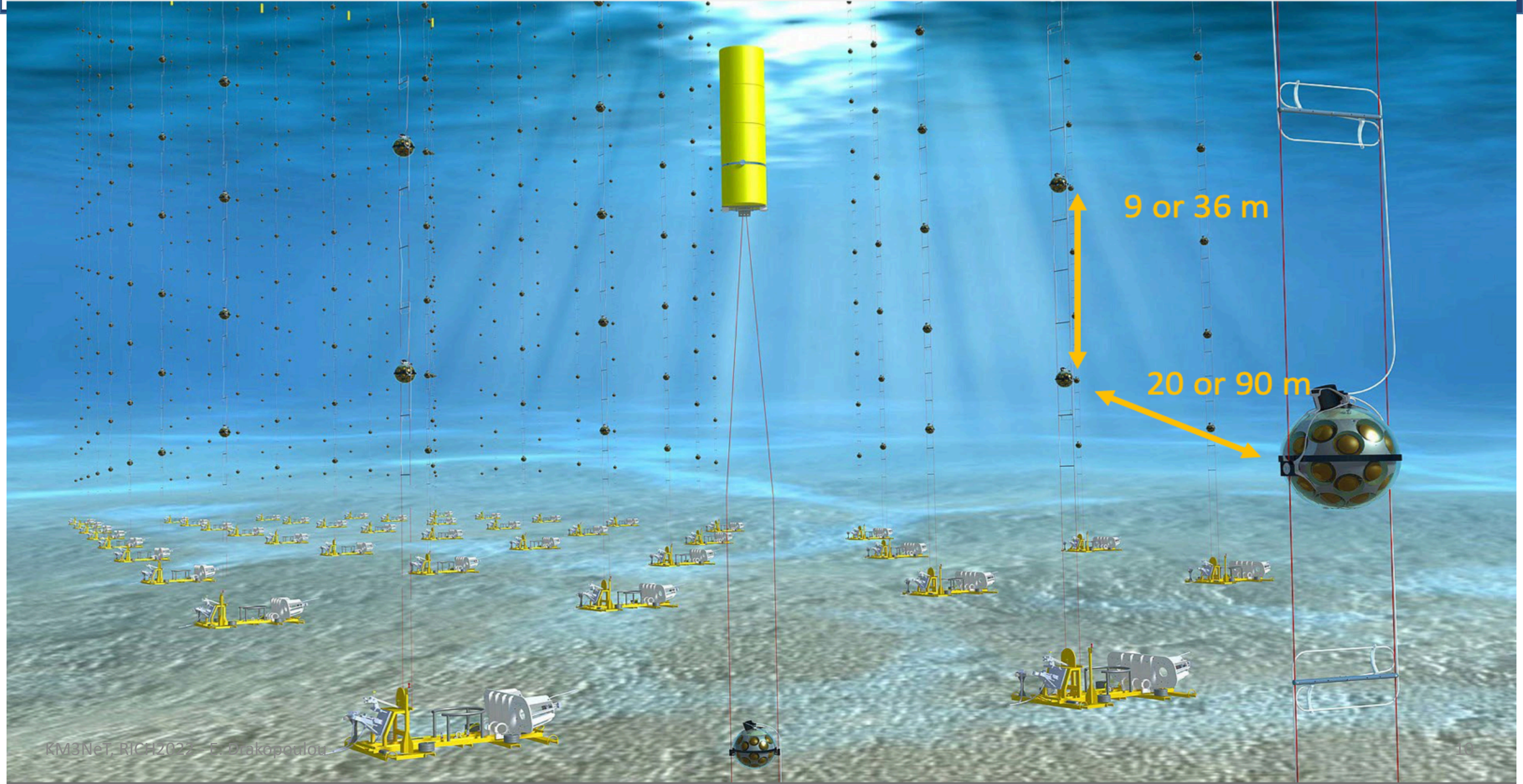
ORCA: Oscillations Research with Cosmics in the Abyss

- ✓ Atmospheric neutrinos (GeV Energies).
- ✓ 1 block of 115 DUs : Volume $\approx 8 \text{ Mton}$.
- ✓ Each DU is 200 m in height with DOMs vertically spaced 9 m. The DU horizontal spacing is about 20 m.
- ✓ More densely instrumented.
- ✓ **Currently 10 DUs deployed**

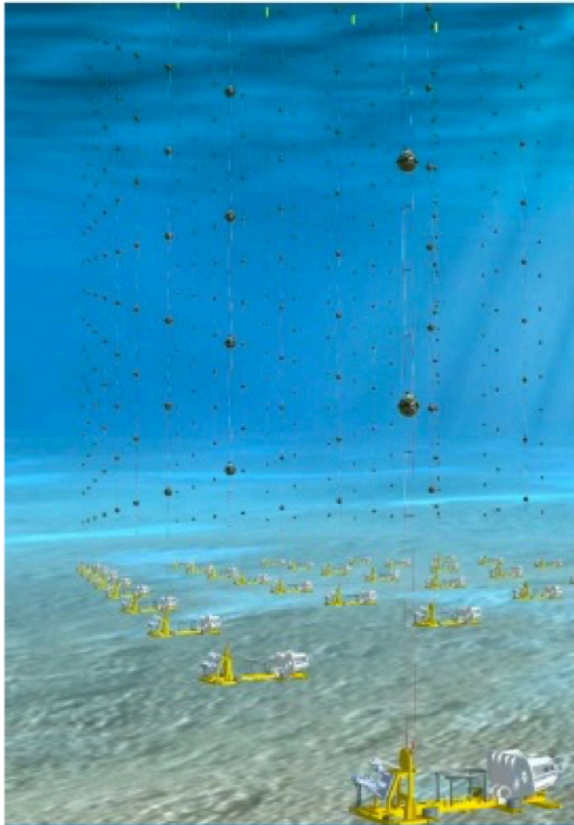
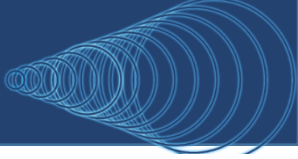


Results will be presented for ARCA and ORCA data collected with the first 6 DUs.

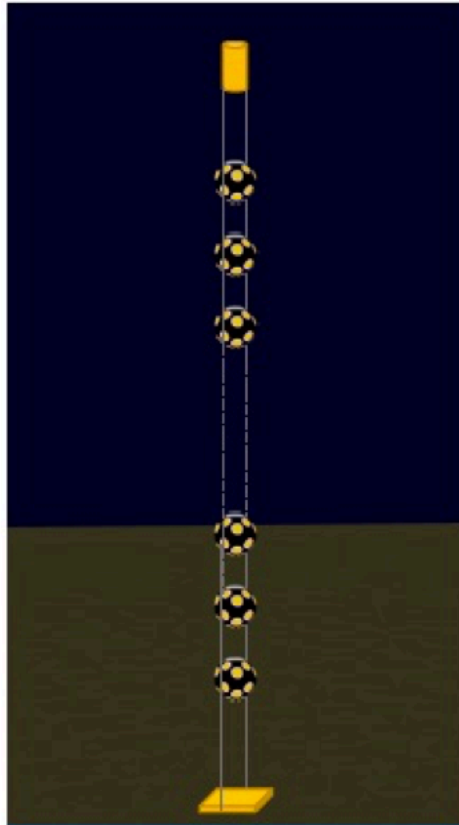
The KM3NeT Detectors



KM3NeT Components



1 building block =
115 lines



1 line =
18 optical modules



1 optical module =
31 photomultiplier tubes



71 unique components
(in solid or liquid phase)

Rasa Muller

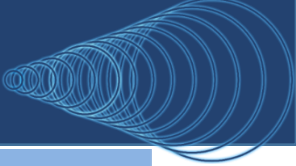
“detection unit (DU)”

“digital optical module (DOM)”
31 3” photomultiplier tubes

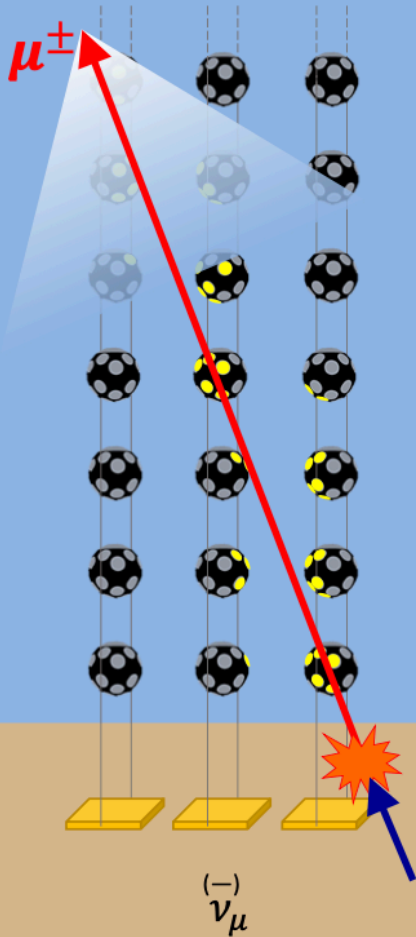
JINST 17 (2022) 07, P07038

Identical for ARCA and ORCA

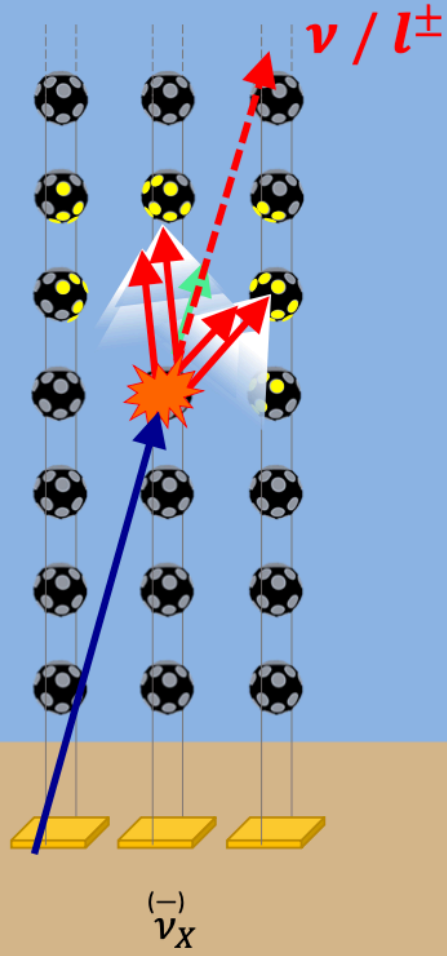
Event Signatures



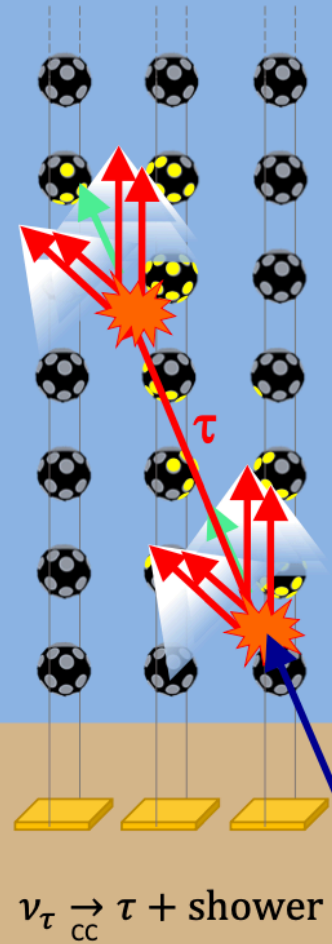
CC ν_μ
 1. track like events
 good pointing



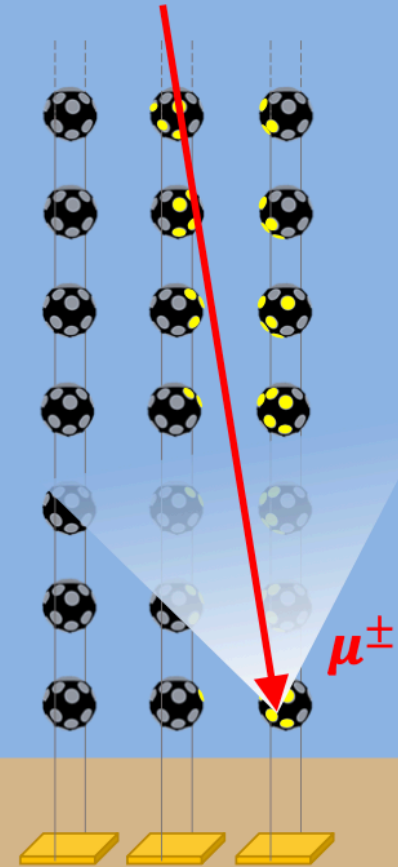
CC ν_e + all flavours NC
 2. shower like events
 good energy reconstruction

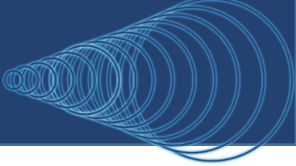


CC ν_τ
 3. "double bang"



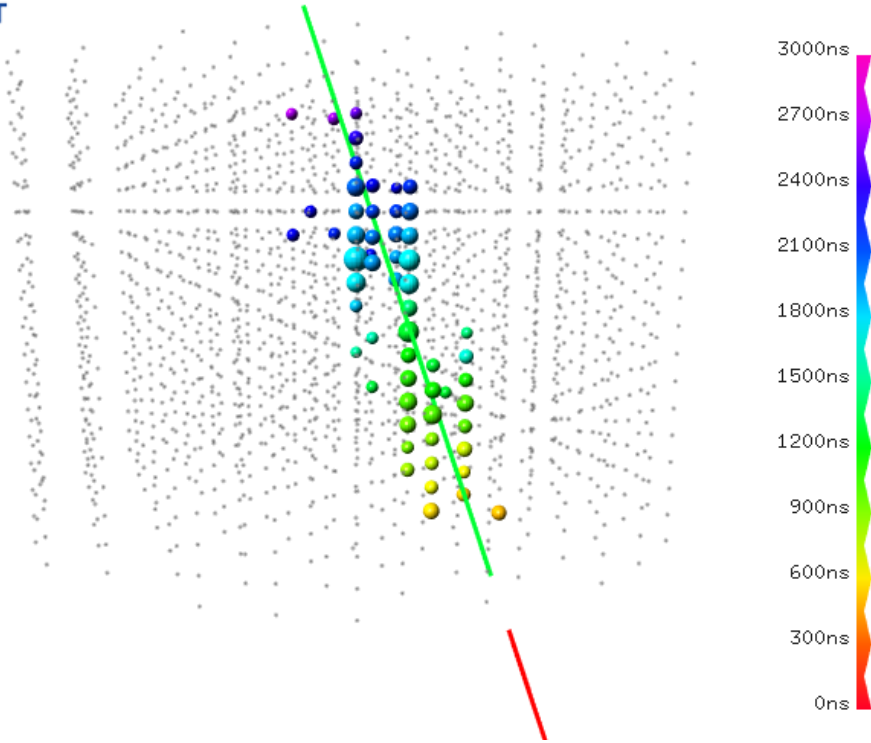
Atmospheric muon
BACKGROUND !!





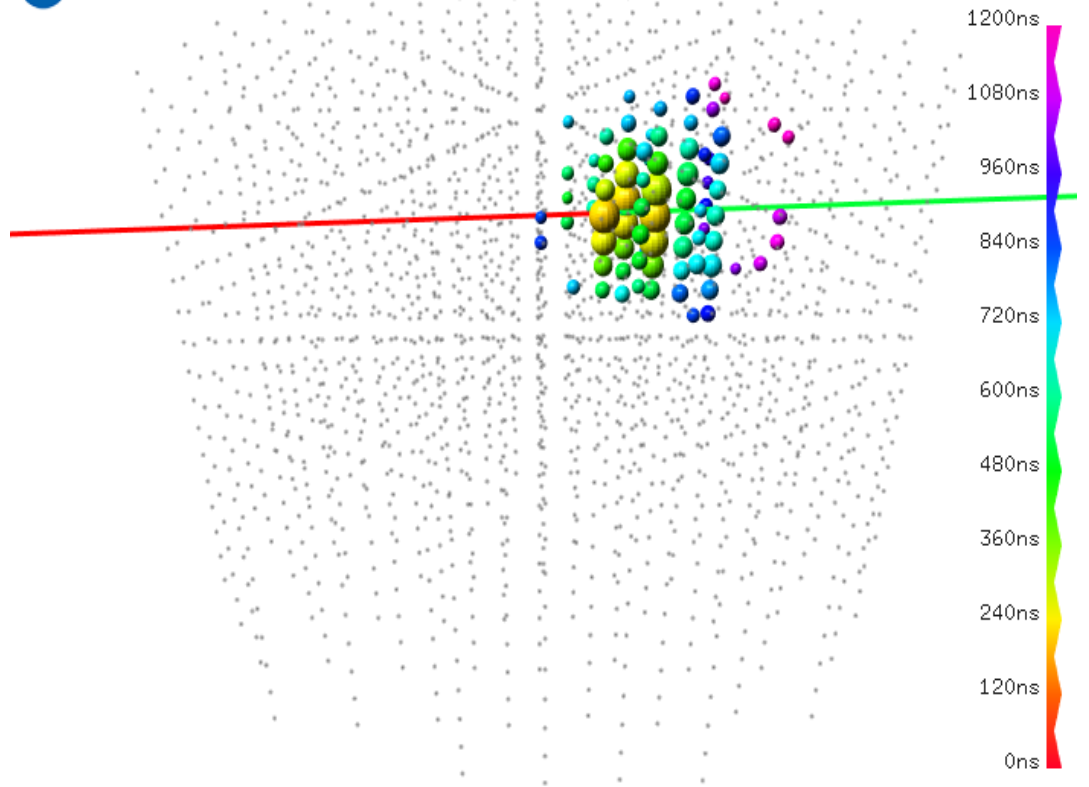
KM3NeT

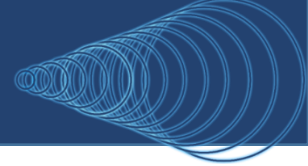
Track-like event



KM3NeT

Shower-like event





Timing Calibration:

- LED pulsers (nanobeacon) for inter-DOM calibration
[arXiv:2111.00223](https://arxiv.org/abs/2111.00223) [astro-ph.IM]
- < 1ns precision for relative timing between DOMs

Position Calibration:

Lines move with the sea current. Needs dynamic position calibration.

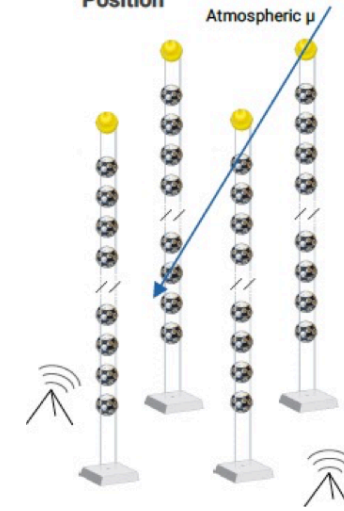
- Acoustic system for dynamic alignment
- Precision O(10 cm)
- Checked with atmospheric muons

Orientation

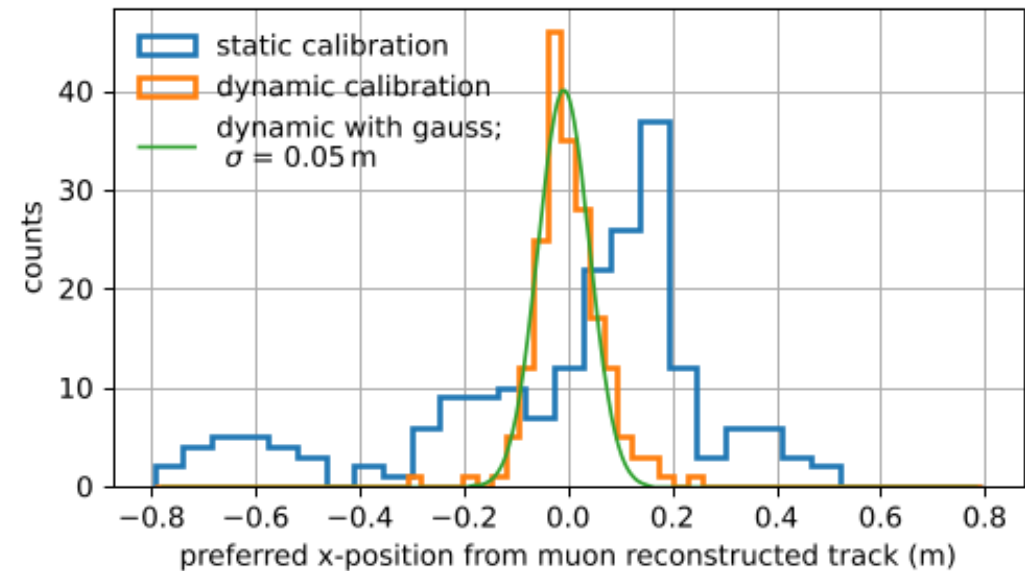


compass in DOMs

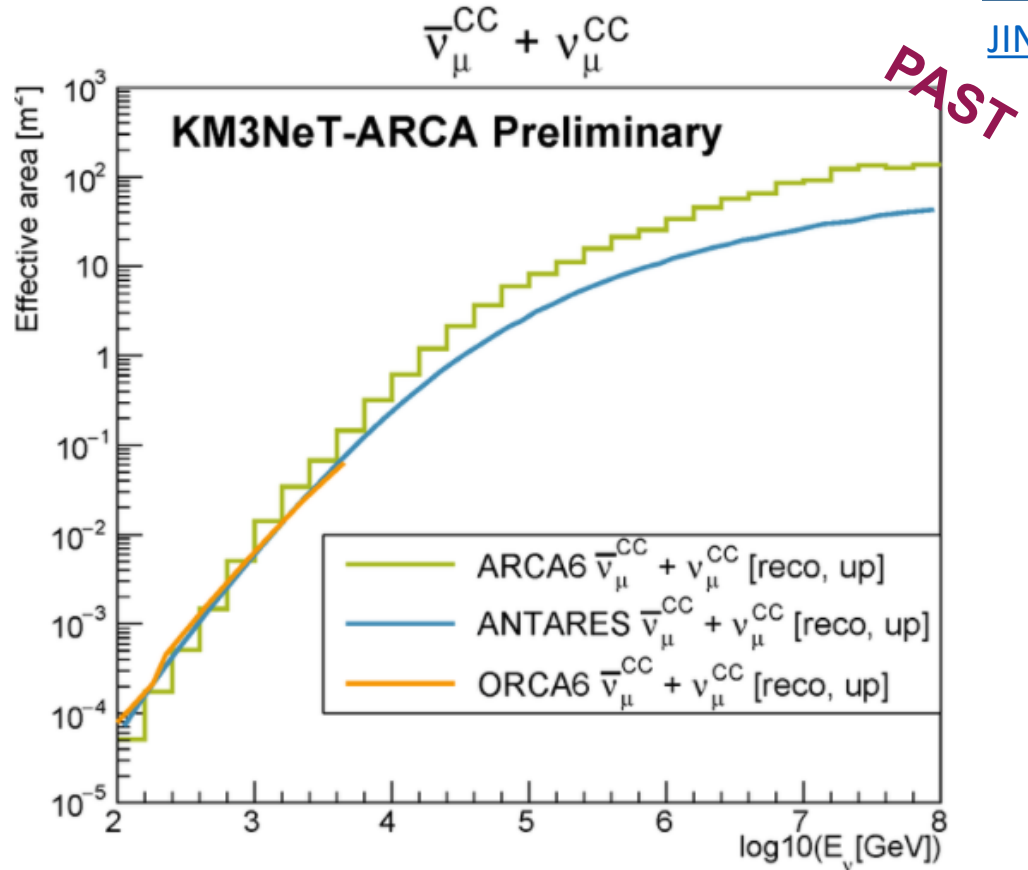
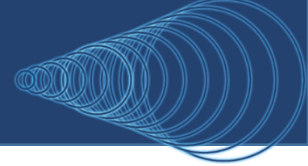
Position



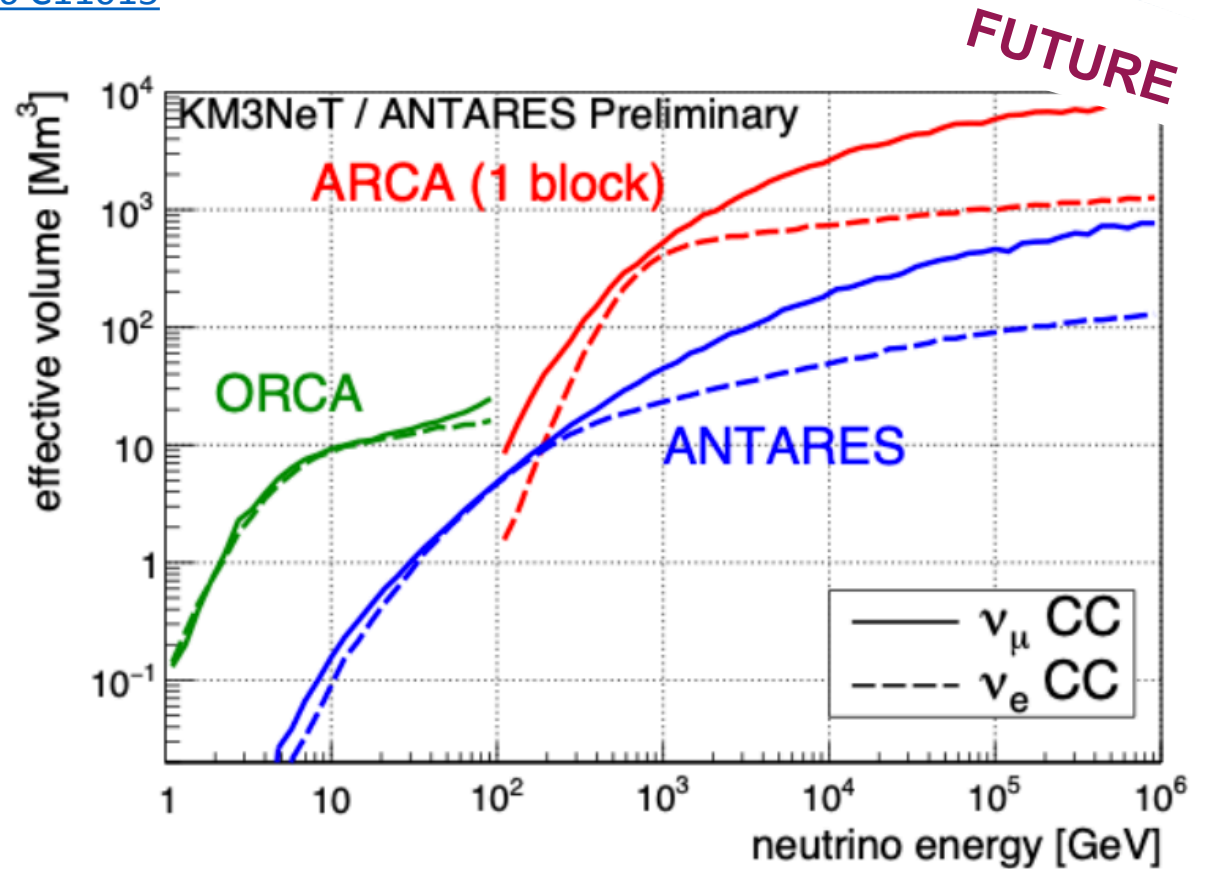
acoustic emitters,
hydrophones, piezo sensors



Detector Performance



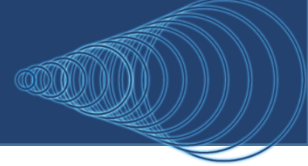
JINST 16 C11015



- ARCA6, ORCA6 and ANTARES have comparable effective areas for low energies.
- For $E > 10$ TeV, ARCA6 has significantly higher effective area.

- Effective volume for ARCA (1BB) and ORCA compared to ANTARES.

ARCA6: ARCA with 6 DUs

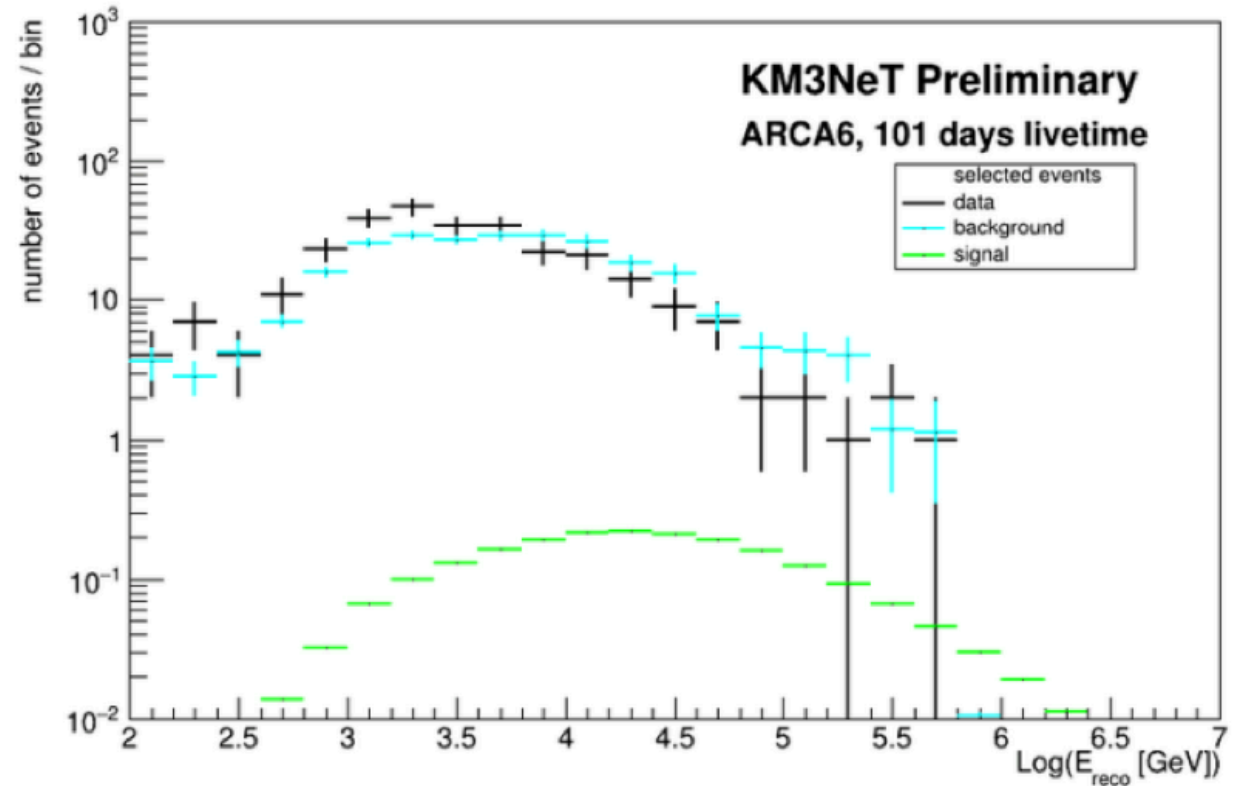


The detection of a diffuse flux of cosmic neutrinos provides:

- information on the production mechanisms composition and acceleration of Cosmic Rays
- Signal from faint sources that are difficult to detect individually

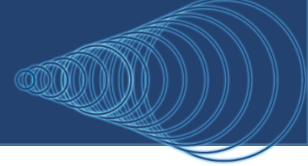
100 days ARCA 6

- Sample dominated by muons
- No high-E excess due to neutrinos
- Results compatible with background

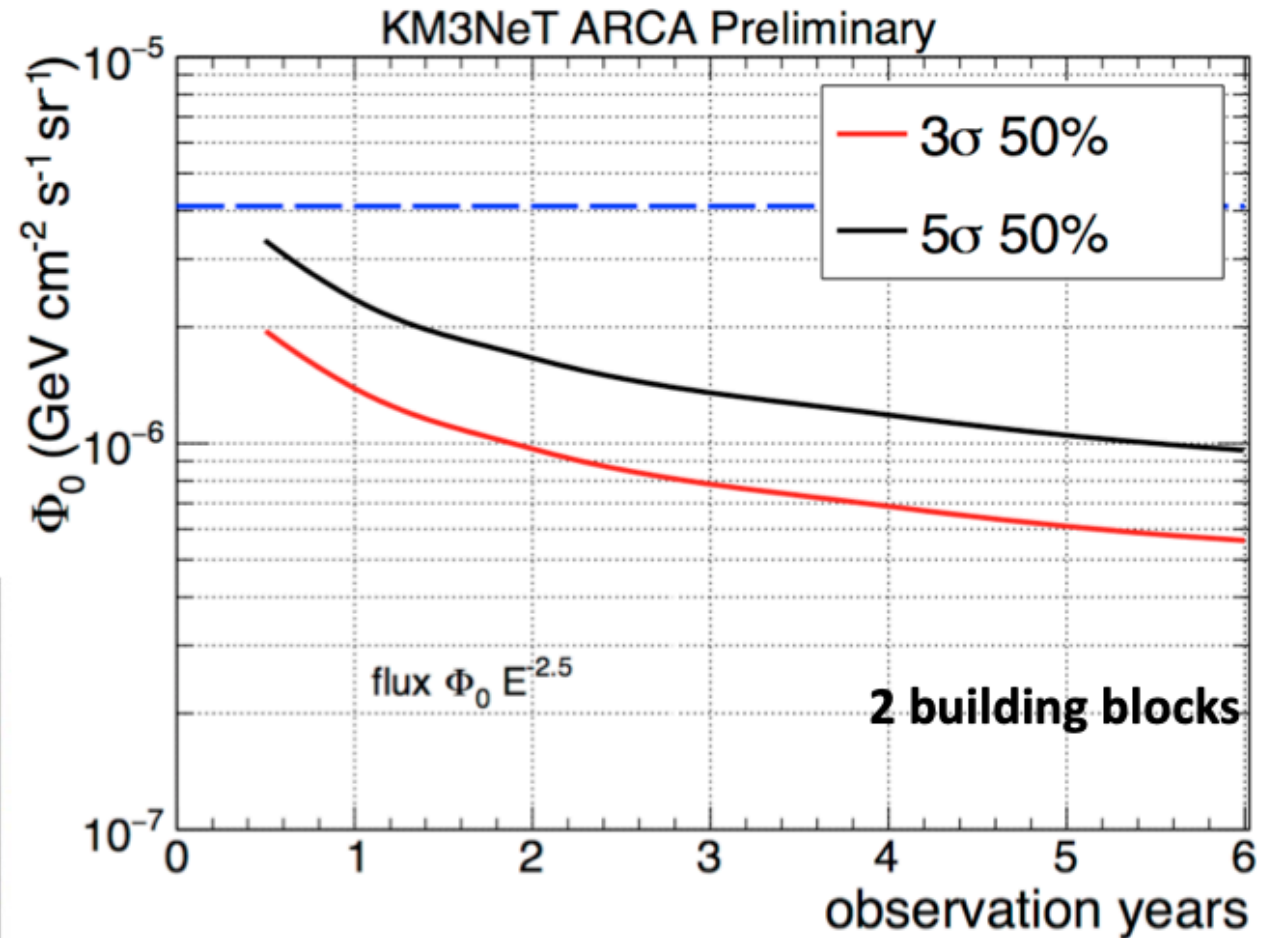
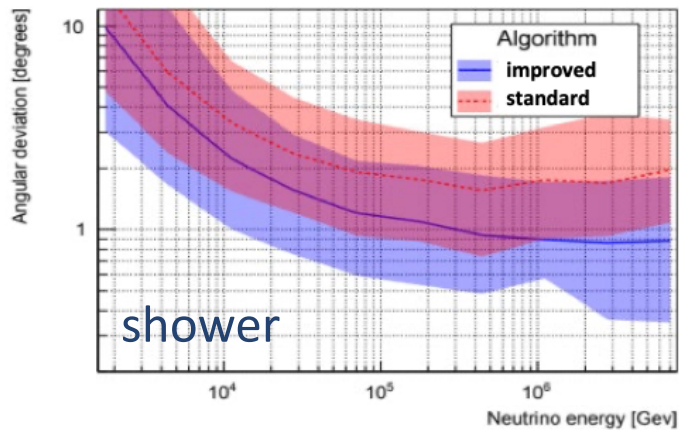
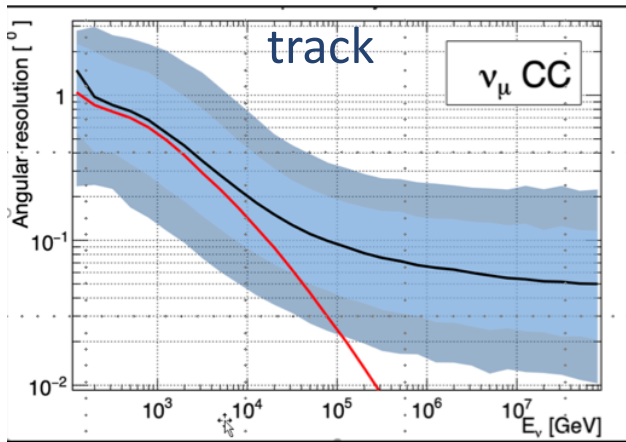


For the diffuse cosmic neutrino flux of [2]: $1.44 \times 10^{-18} (E/100\text{TeV})^{-2.28} [\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$		Number of events
$\Phi_{90\%CL} [\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$	$\Phi_{5\sigma} [\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$	$N_{\text{atm.mu}\&\text{nu}} = 68.4$
17.3×10^{-18}	51.4×10^{-18}	$N_{\text{cosmic nu}} = 1.3$

zenodo.org/record/6767724



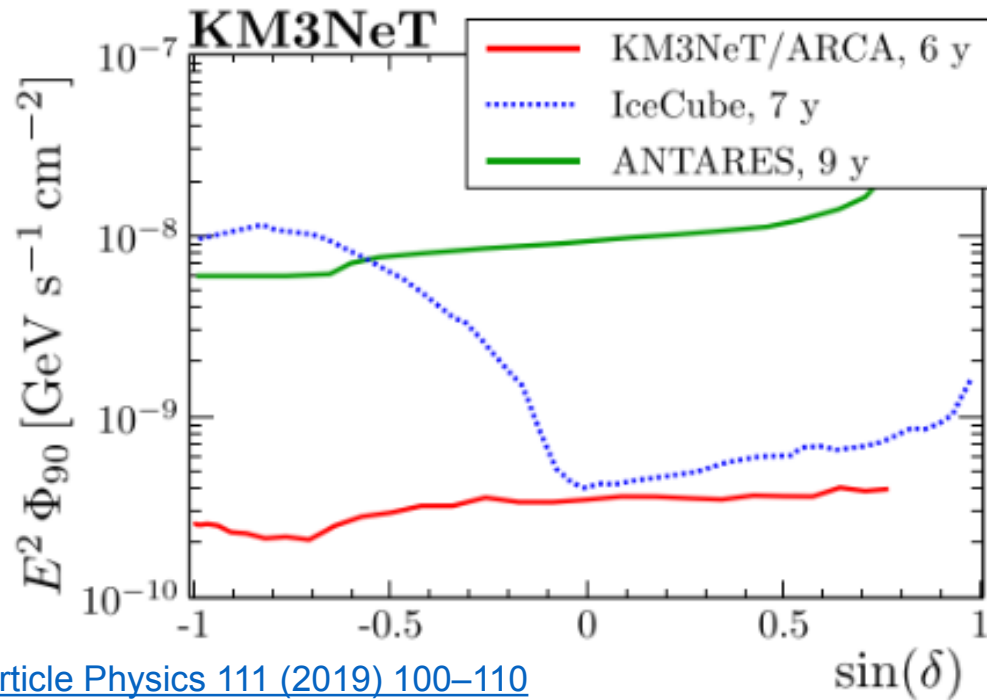
When ARCA is completed (2BB), it will be able to confirm the IceCube flux within within 1 year of data



There are sources of High Energy Cosmic Rays in the galactic center; CR + interstellar medium $\rightarrow \nu$'s!

Unblinded 'pilot (on/off-zone) analysis', **100 days ARCA 6** \rightarrow no signal as expected

FULL ARCA: Observation with 3σ significance possible in about six years of operation for most intense sources

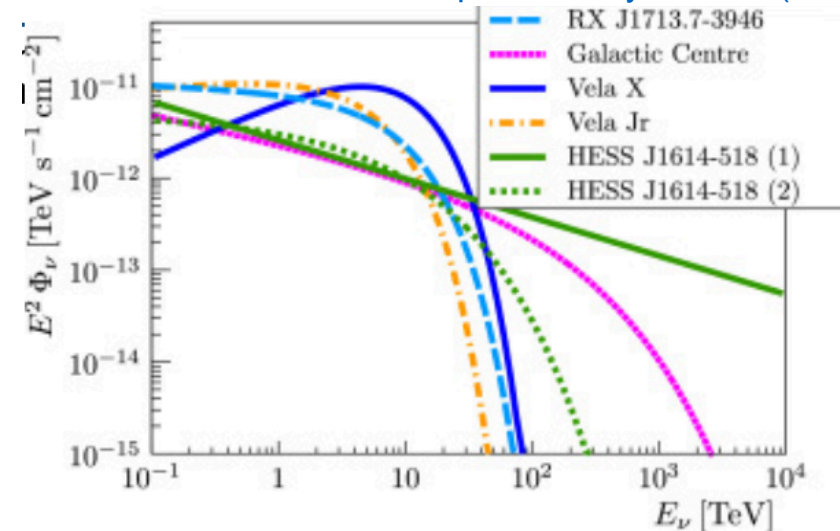


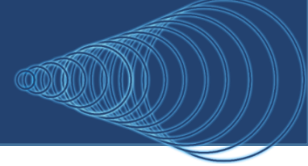
[Astroparticle Physics 111 \(2019\) 100–110](#)

Simulated signal flux $1.2 \times 10^{-8} (E/1\text{GeV})^{-2.4} [\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$	
MC simulated signal in ON region	1.81×10^{-4}
Background events: mean over 9 OFF regions (sum)	4.3 (39)
ON region events:	8

Neutrino flux from potential astrophysical neutrino sources

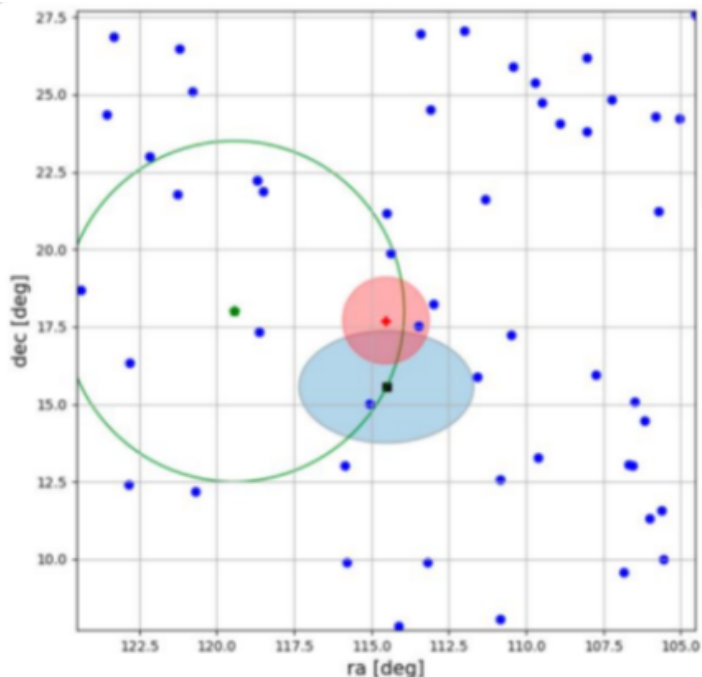
[Astroparticle Physics 111 \(2019\) 100–110](#)





Method: ON/OFF technique

- **ON region**: cone centered on the source position
- **OFF region**: declination band centered at the source's position (but with ON region subtracted).
The solid angle is rescaled to be able to compare with the ON region.
- Example for PKS 0735+17 blazar:

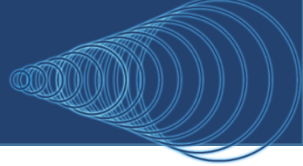


+ Fermi PKS 0735+17 position
 ■ IceCube-211208A alert, 90% containment
 ● Baikal shower event, 50% containment
 ○ 1.4° cone, ON Zone
 ● KM3NeT/Arca data
 Atm muon contamination 99%
 Median E^{-2} cosmic neutrino angular resolution = 1.7°

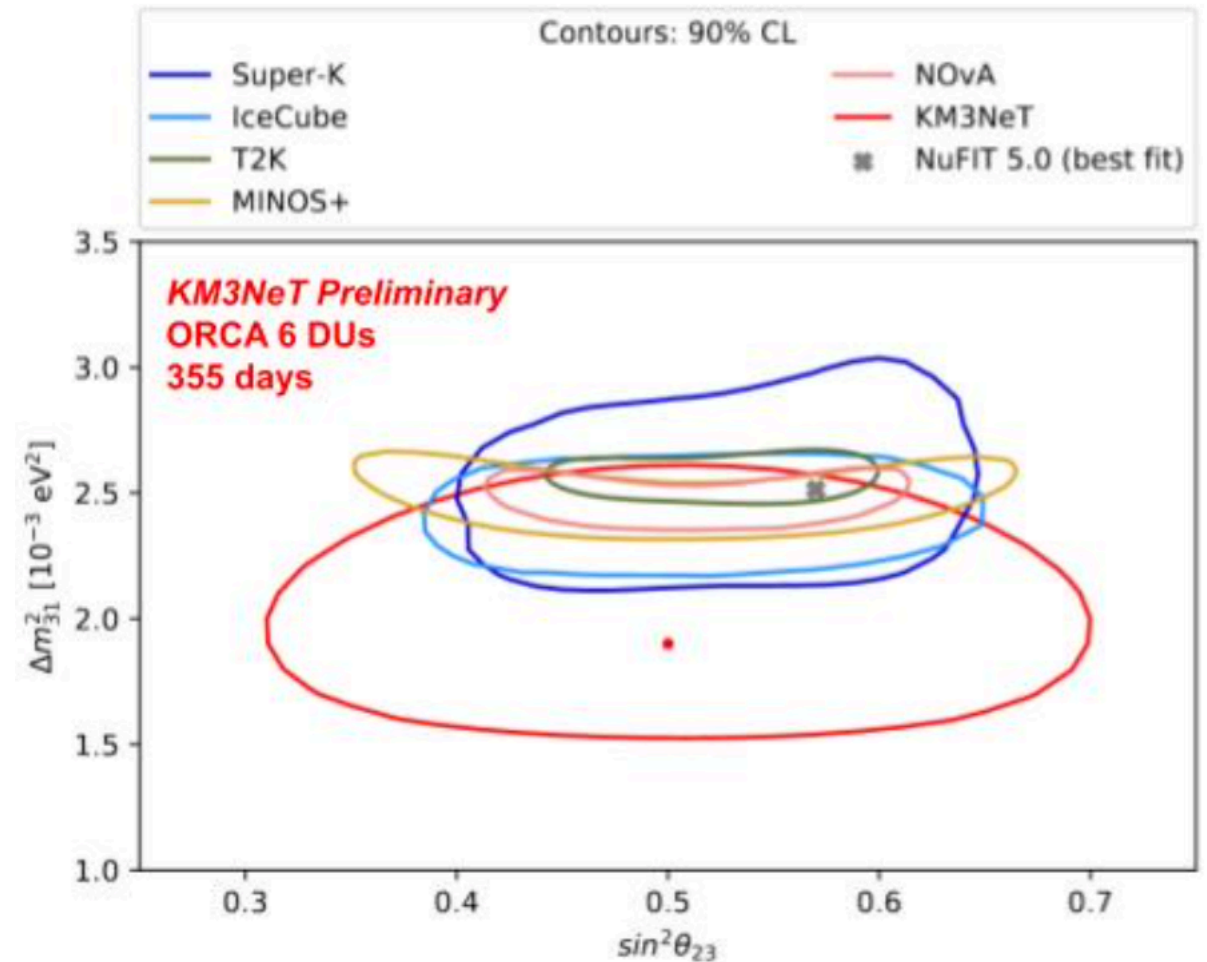
Alert	IC211208A		IC220205B
Associated blazar	PKS 0735+17		PKS 1741-03
Time window	±1 day	1 month	±1 day
Radius of Interest	1.4°	1.4°	1.9°
Expected signal	$8.9 \cdot 10^{-3}$	$1.2 \cdot 10^{-1}$	$9.7 \cdot 10^{-3}$
Expected bgd (MC)	$4.9 \cdot 10^{-2}$	$6.7 \cdot 10^{-1}$	$5.2 \cdot 10^{-2}$
Expected bgd (data)	$(4.7 \pm 0.7) \cdot 10^{-2}$	$(6.6 \pm 0.3) \cdot 10^{-1}$	$(4.9 \pm 0.9) \cdot 10^{-2}$
Events in ON region for 3σ	2	5	2
Measured events in ON region	0	1	0

No significant discovery, only 1 ν_μ candidate with $E \sim 18 \text{ TeV}$ ($p = 0.14$)

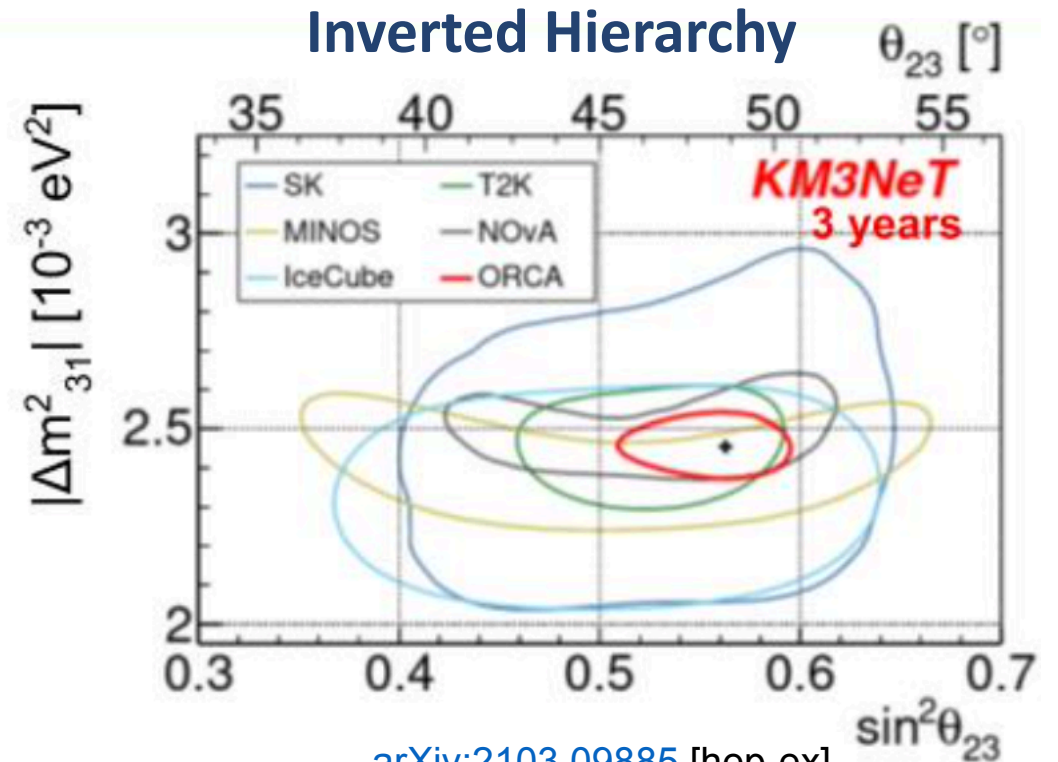
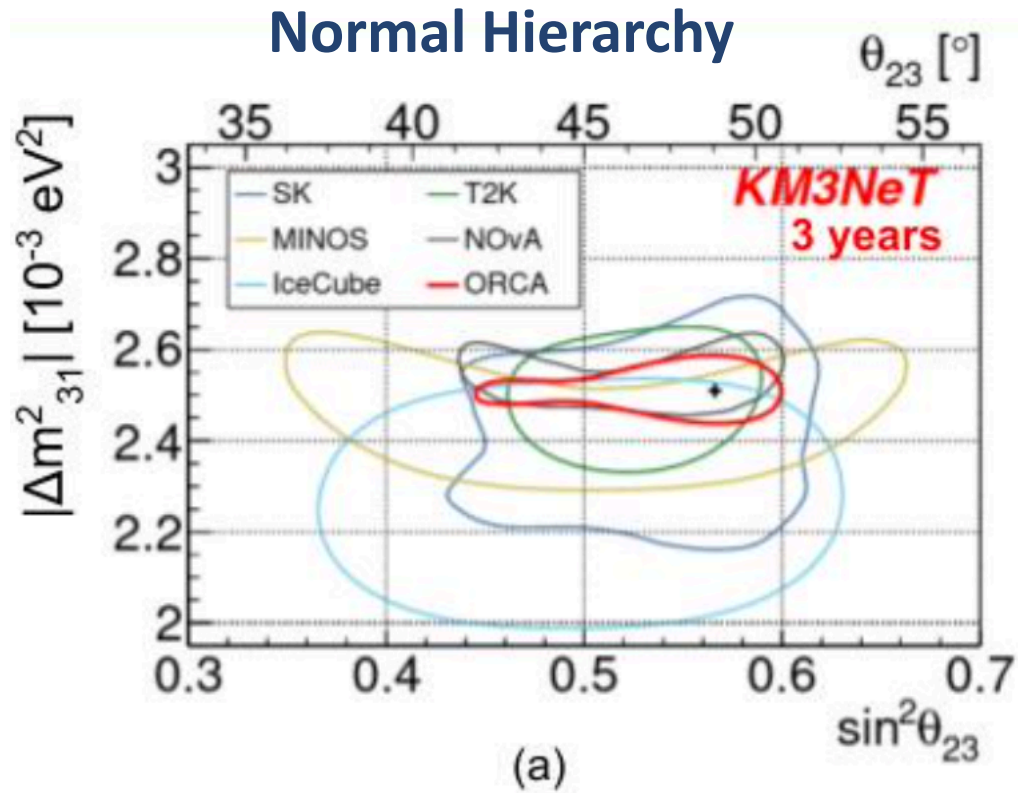
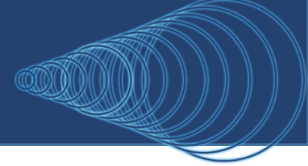
zenodo.org/record/6805372



- Measurement of Δm_{31}^2 and θ_{23} with ORCA6 DUs for about a year of data taking.
- This measurement was conducted using only track-like events and demonstrates the potential for early oscillation measurements with this detector.



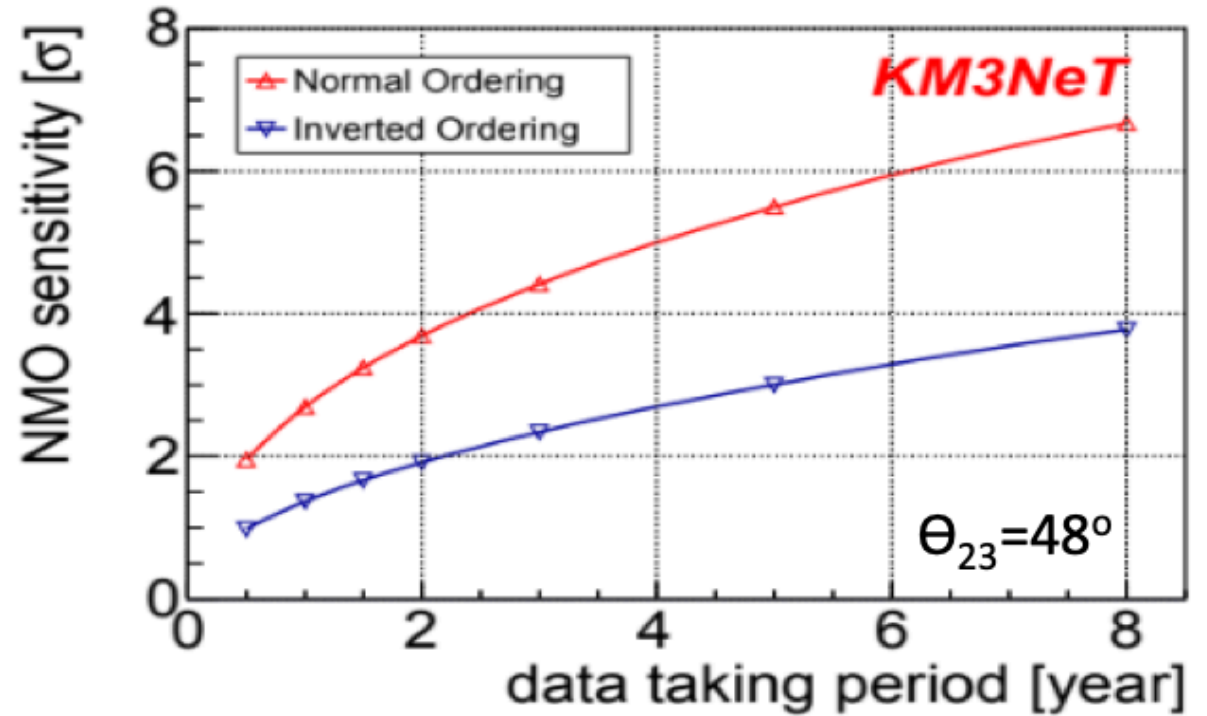
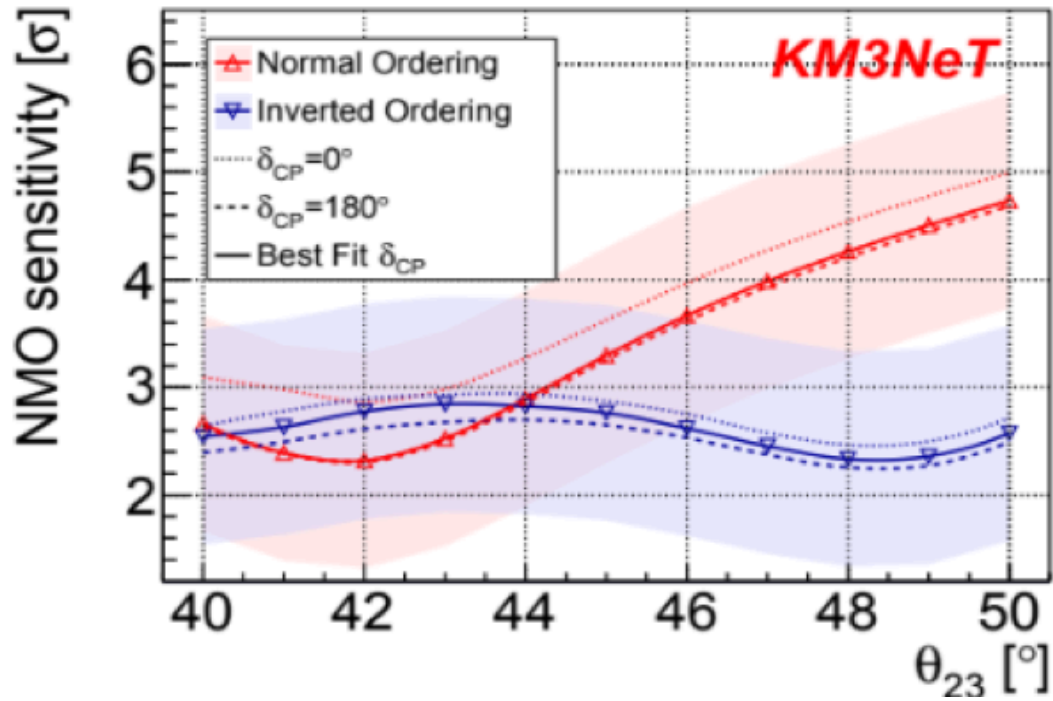
zenodo.org/record/6785279



[arXiv:2103.09885](https://arxiv.org/abs/2103.09885) [hep-ex]
zenodo.org/record/6785279

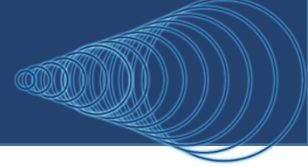
Expected measurement precision after 3 years of data taking at 90% confidence level:

- precision to measure Δm_{31}^2 : $85 \cdot 10^{-6} \text{ eV}^2$ (normal), $75 \cdot 10^{-6} \text{ eV}^2$ (inverted) ordering and θ_{23} : $[-3.1, +1.9]^\circ$ (normal), $[-7.0, +2.0]^\circ$ (inverted) ordering.



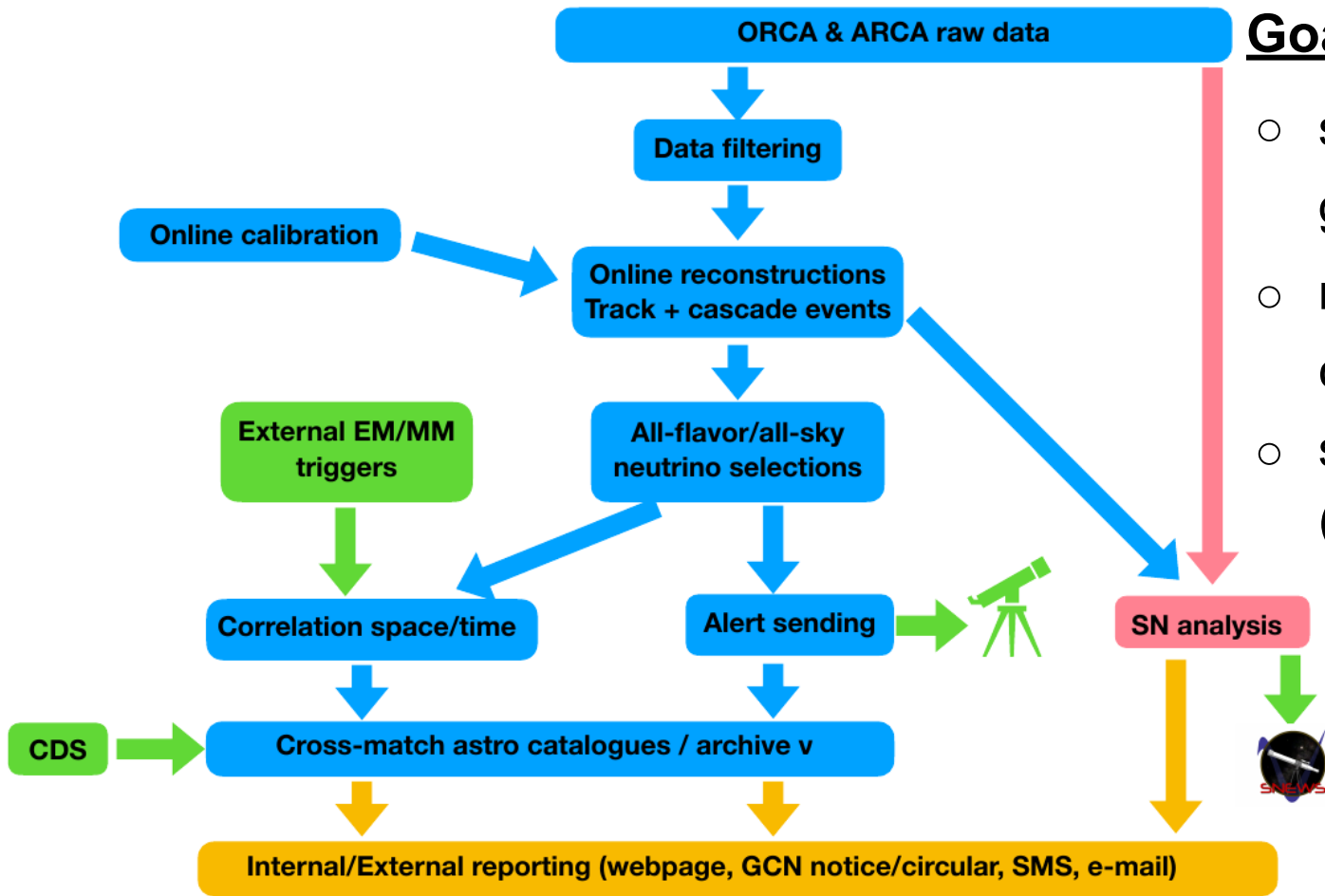
zenodo.org/record/6785279

- The sensitivity to Neutrino Mass Ordering (NMO) after 3 years of data taking is 4.4σ for normal and 2.3σ for inverted hierarchy.
- The NMO can be determined at 3σ level after 1.3 (5.0) years if the true NMO is normal (inverted).



Goal: To identify neutrino candidates in real-time

- supernova monitoring for prompt alerts, generation latency < 20 s
- receive external EM/GW/ ν alerts; search for correlated ν
- send all flavor, all-sky ν alerts (multiplets & HE (GeV - PeV)) to external observatories

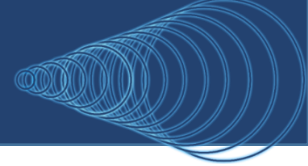


Two pipelines:

- MeV Supernova alert
- GeV - PeV Neutrino alert

zenodo.org/record/6805417

ARCA - Many more topics...

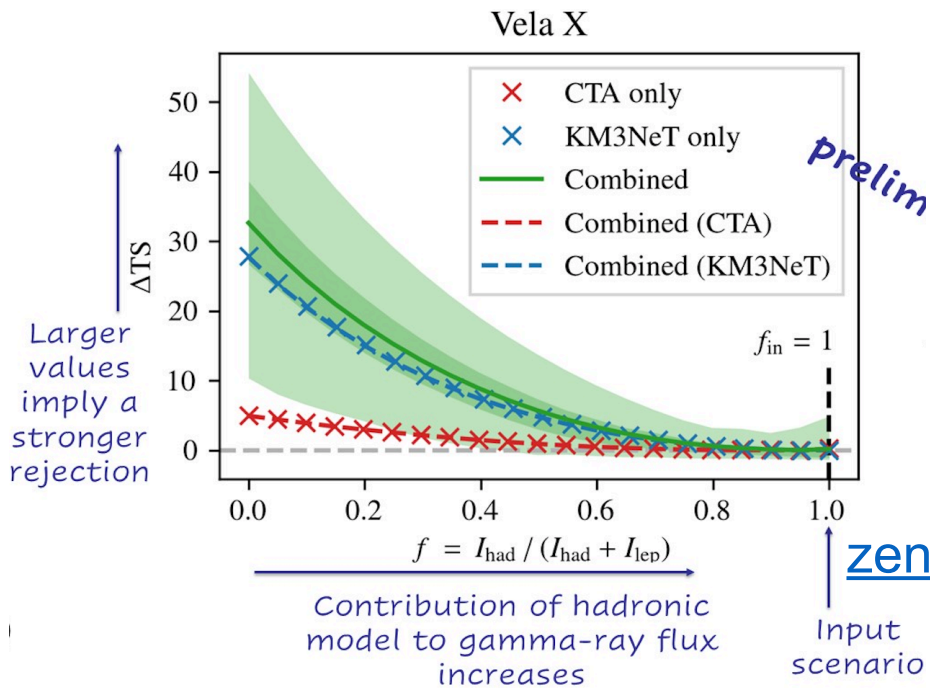


- Starburst Galaxies
- Supernovae
- KM3NeT + CTA
- Cosmic Rays
- Dark matter & exotics

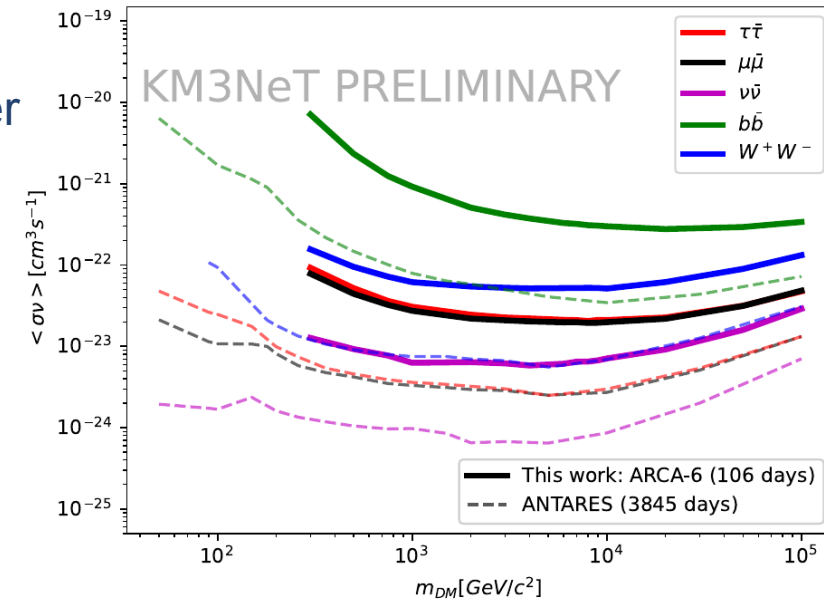
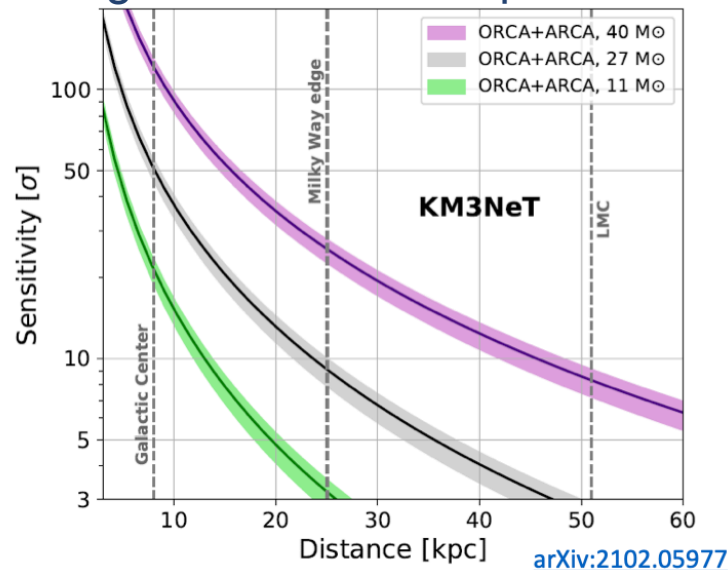
sources with WIMP accumulation

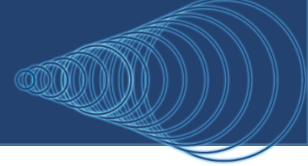
- galactic center (zenodo.org/record/6785348)
- solar core (zenodo.org/record/6775092)

Currently (ORCA6) would trigger on e.g. $27 M_{\odot}$ at ~ 10 kpc

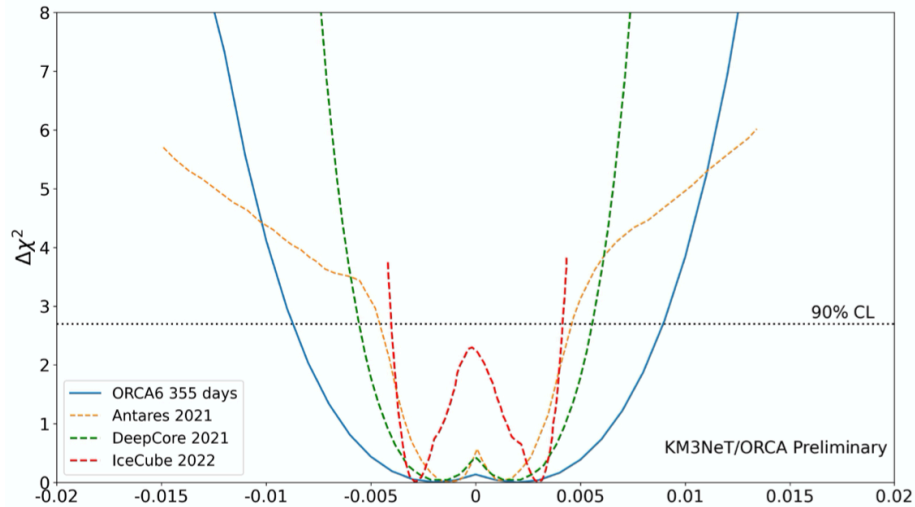


zenodo.org/record/6785242

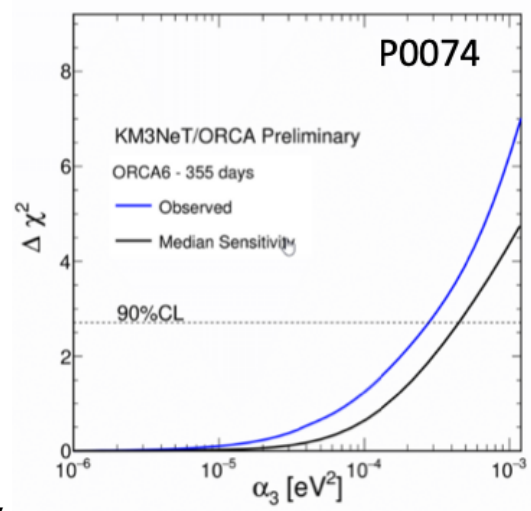




- probing neutrino invisible decay (neutrino mass state ν_3 decays into a sterile neutrino) (zenodo.org/record/6758959)
- sterile neutrino searches: active-sterile mixing with mass squared differences Δm_{41}^2 between 10^{-5} and 10 eV² (zenodo.org/record/6804567)
- non-standard interactions: sub-dominant effects in the oscillation patterns (zenodo.org/record/6785232)
- quantum decoherence from quantum gravity (zenodo.org/record/6781033)



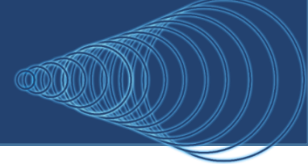
Non-standard interactions: 1 year ORCA6 already starting to become competitive with similar experiments



Neutrino decay / lifetime

- Proof of principle
- Full ORCA detector will be world-leading

Experiment	L.L.(90%CL) (ps/eV)
ORCA6	2.4
ORCA115 (10y)	180
T2K, NOvA	1.5
T2K, MINOS	2.8
K2K, MINOS, SK I+II	290

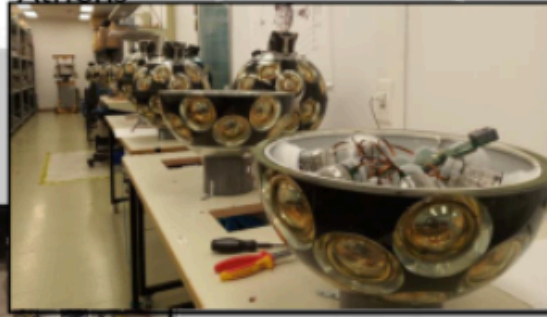


Production ongoing

Amsterdam



Athens



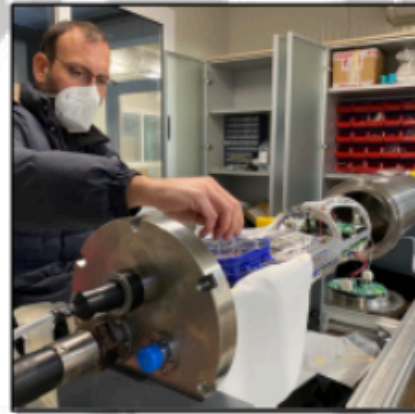
Genova



Nantes



Erlangen

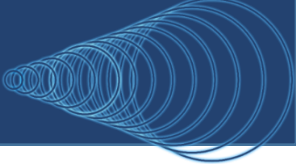


Bologna

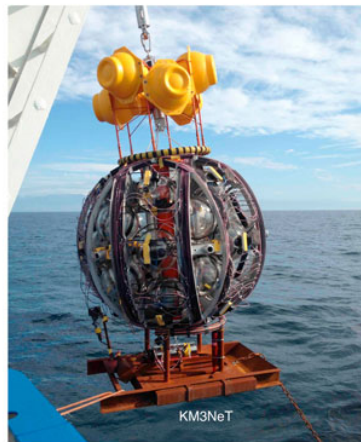
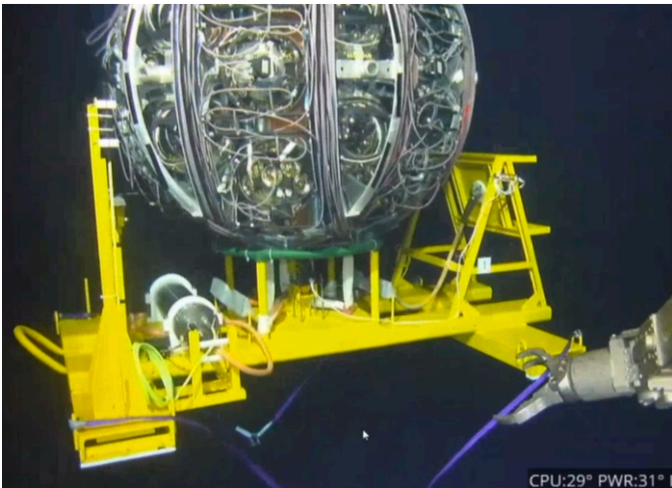
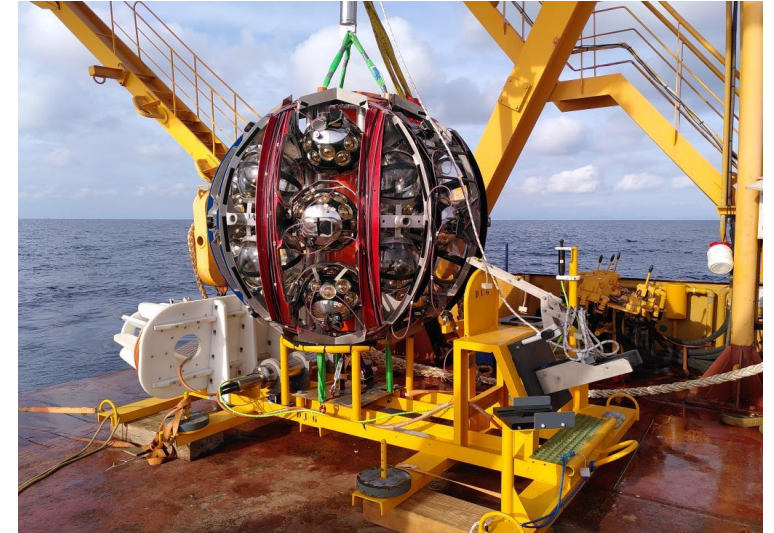
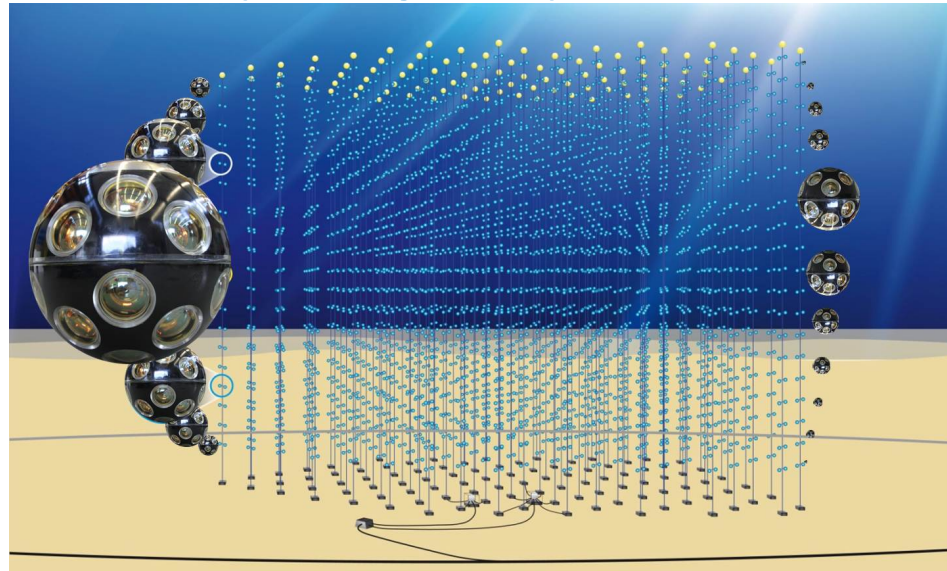


Catania

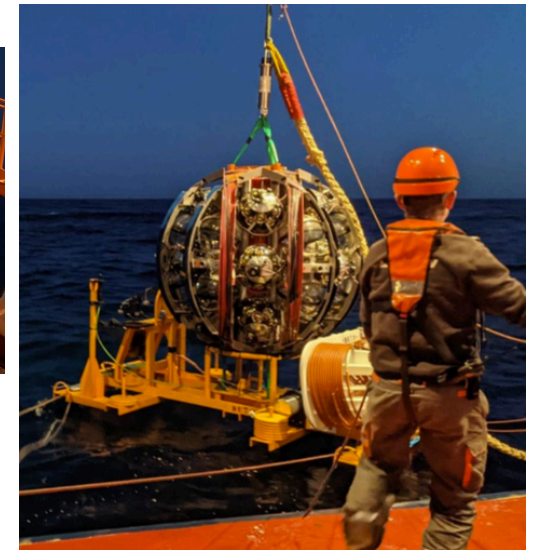


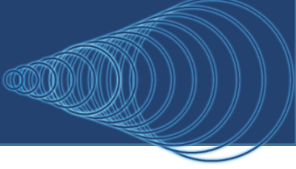


Thank you for your attention!



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Backup

Neutrino Astronomy: the reality!

- Signal: Neutrinos from astrophysical sources
- Background: atmospheric neutrinos
atmospheric muons

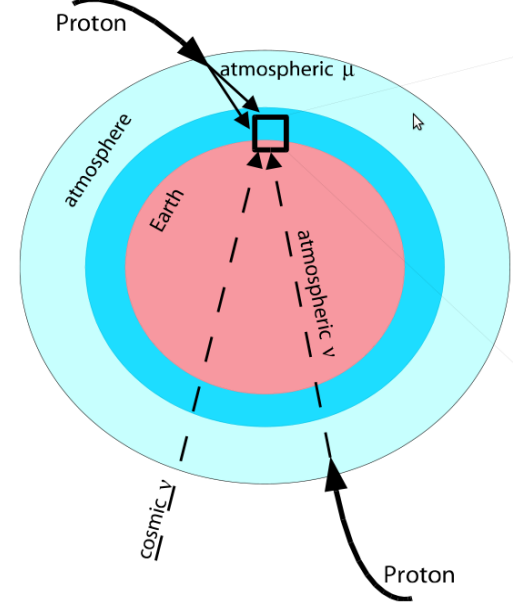
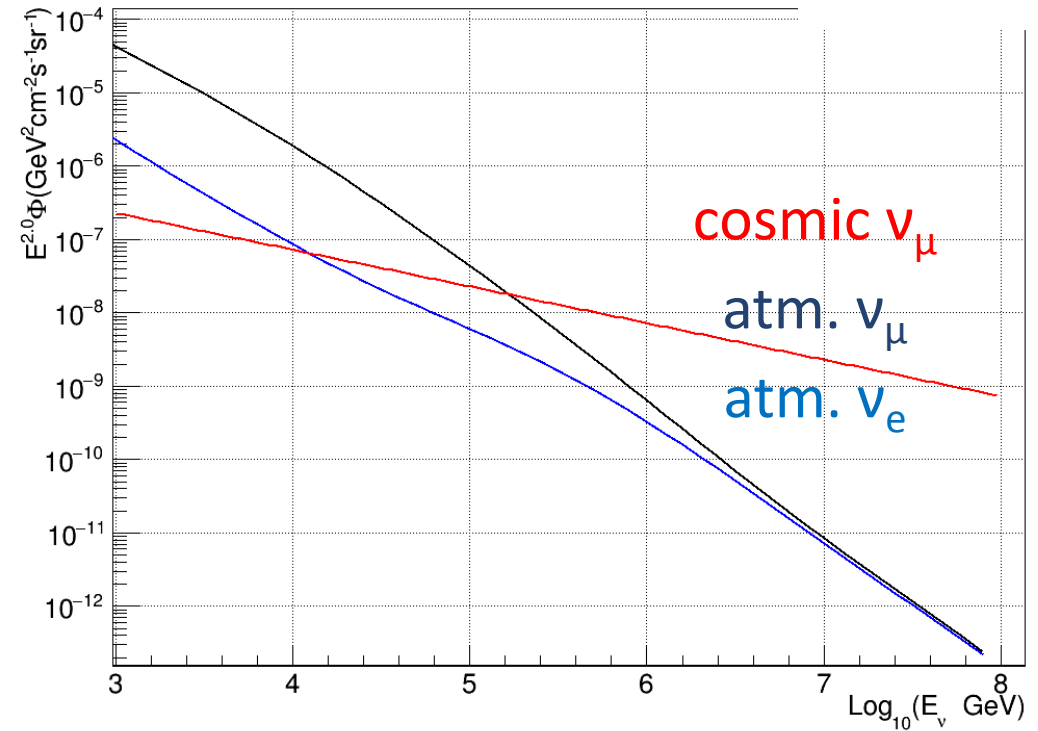
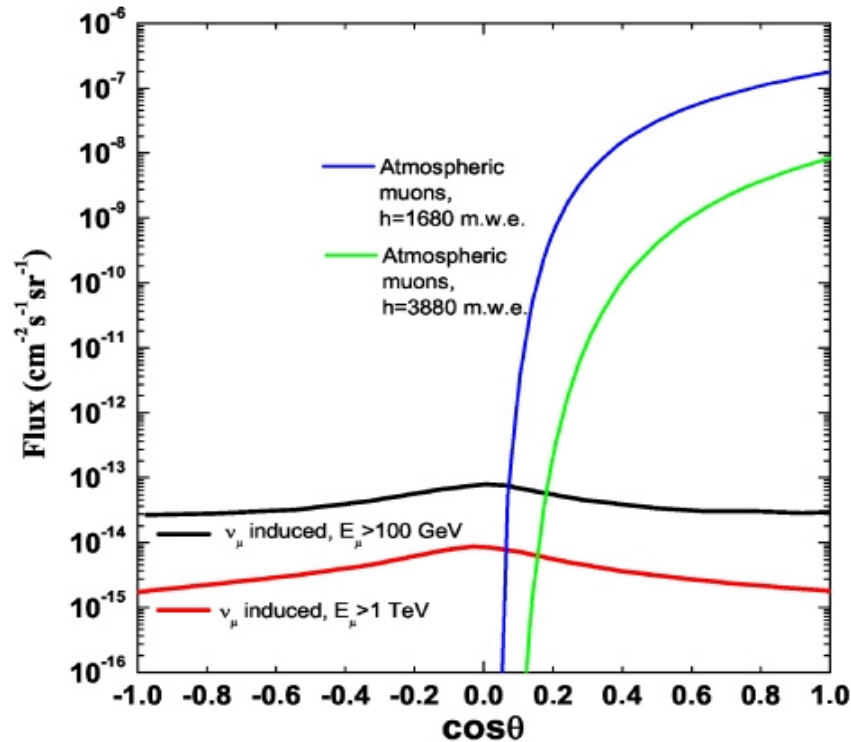
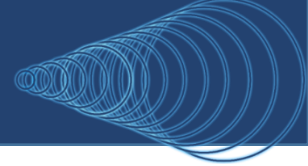
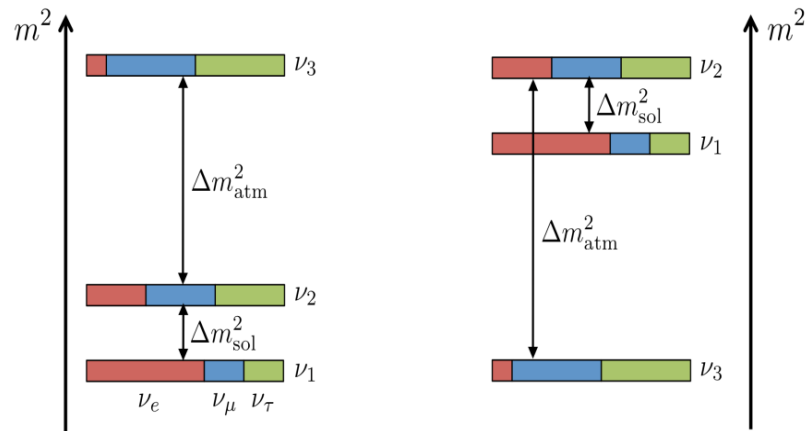


Figure 12 from High-energy neutrino astronomy: detection methods and first achievements B Baret and V Van Elewyck 2011 Rep. Prog. Phys. 74 046902





normal ordering (NO) inverted ordering (IO)



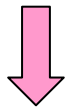
Atmospheric neutrinos:
 "free beam" of known composition (ν_e, ν_μ)

Oscillation pattern distorted by Earth matter effects
 maximum difference for $\theta=130^\circ$ (7645 km) and $E_\nu = 7$ GeV

KM3NeT-ORCA: Oscillation Research with Cosmics in the Abyss



Measure θ and E_ν for upgoing atmospheric neutrinos (GeV scale)



Treatment of systematics is important

measuring the neutrino mass ordering (MC Simulation)

