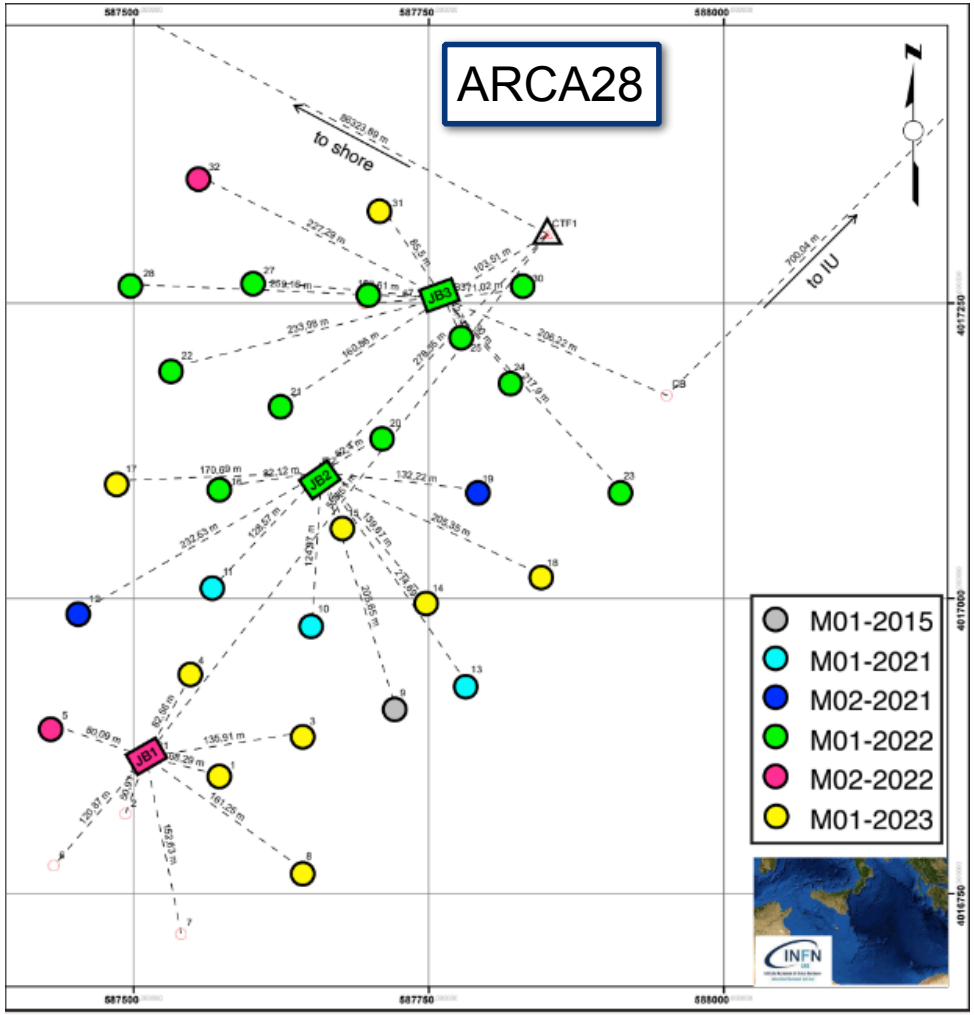
PHYSICS RESULTS AND PERSPECTIVES

R. Coniglione - INFN-LNS for the KM3NeT collaboration

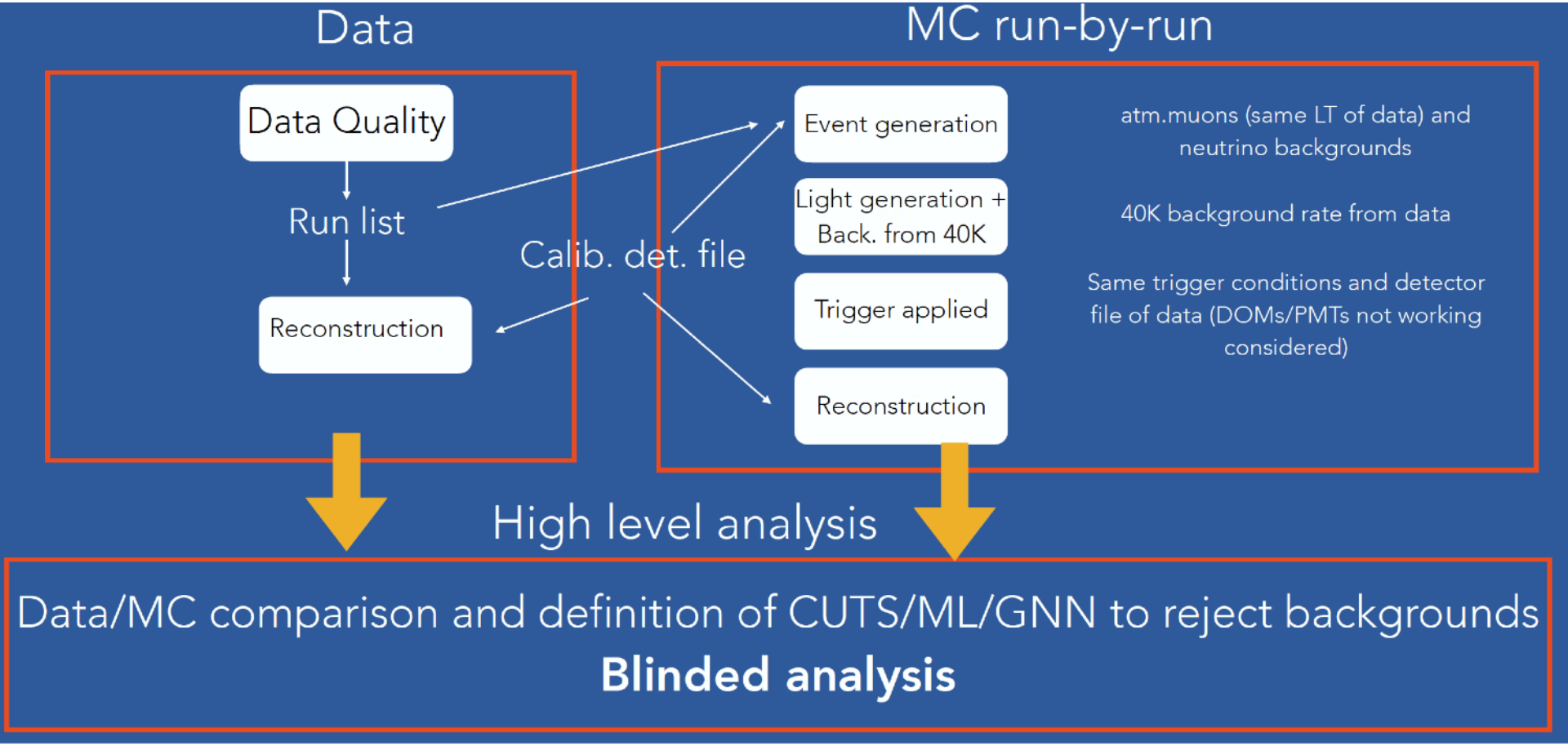
ARCA detector: status



	Livetime (days)	Data taking period
ARCA006	114	12 May 2021 10 sept 2021
ARCA008	235	26 Sep 2021 01 Jun 2022
ARCA020	53	13 Jul 2022 07 Sep 2022
ARCA021	308	22 Sep 2022 11 Sep 2023
ARCA028	156	05 Oct 2023 Today
Total	866	12 May 2021 Today

In total ~ 850 days of live time with detector in different configurations

Analysis work flow



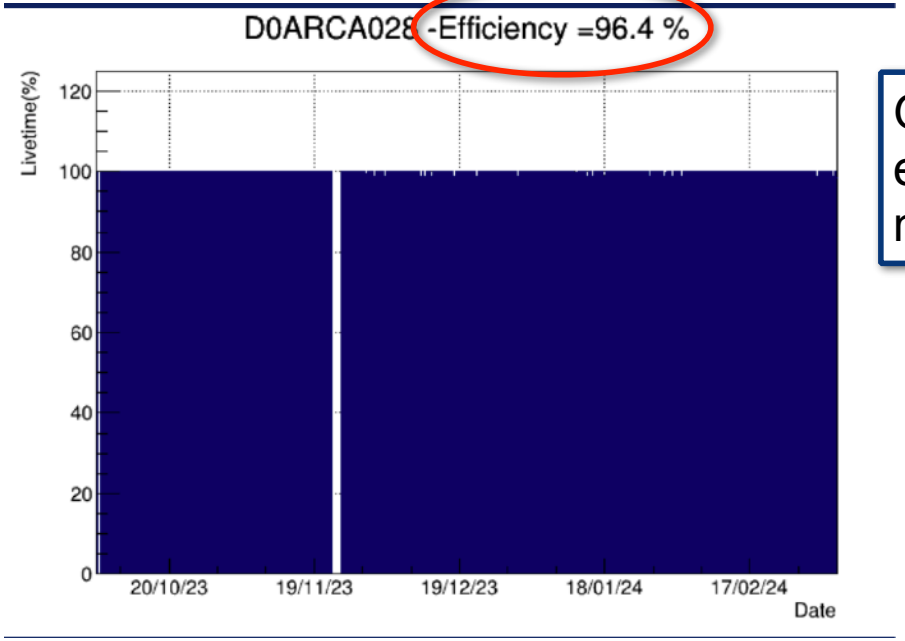
Processing for Data reconstruction and MC now also at CNAF

Data quality

From the data quality analysis

	Livetime (days)	Golden run	Silver runs	Bronze runs
ARCA008	235	93.4%	1.1%	5.5%
ARCA020	53	88.5%	1.4%	10.2%
ARCA021	308	77.7%	17.6%	3.5%
ARCA028	152			

Golden and silver runs are good for data analysis



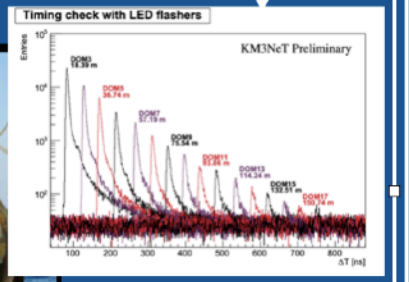
Good data quality and stable data taking especially after the implementation of the new firmware (end of 2023)

Calibration

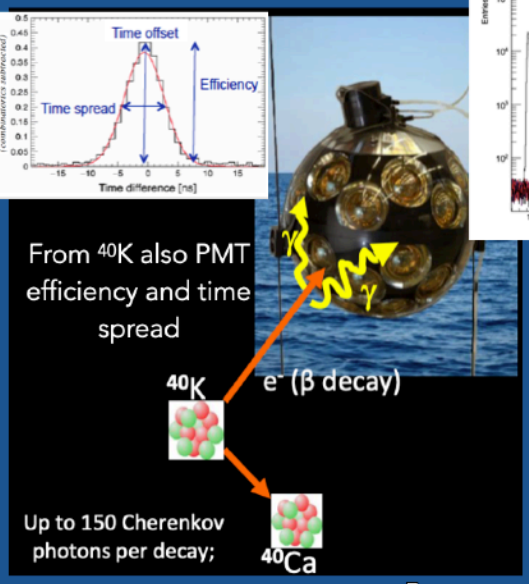
Time calibration

Time offsets:

- Intra DOM PMT time offset 👉 K40
- Inter DOM time offset 👉 LED beacon
- Inter Line time offset 👉 White Rabbit based + laser beacon



ICRC2023 PoS 1067

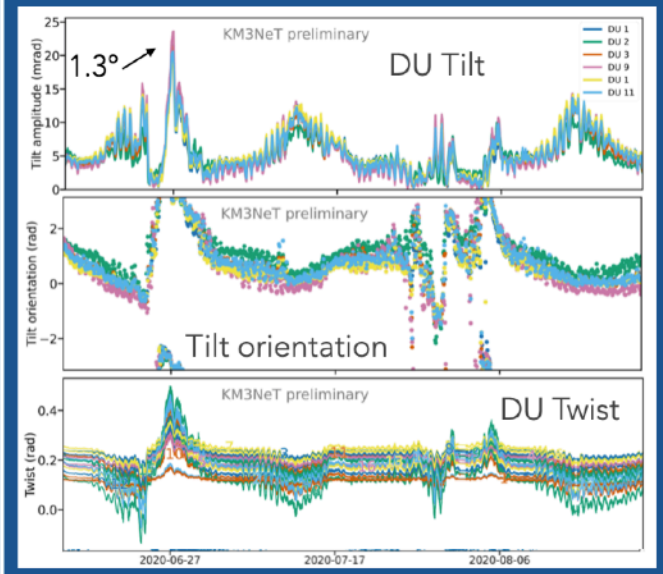


Positioning

Based on the acoustic positioning system

Receivers are located in each DOM (Piezo-electric acoustic sensors)
Emitters are located in autonomous tripod and JB and some DUs (Beacon)

ORCA 4 months — A measurement each 10 minutes



Dynamic positioning taken into account in the event reconstruction

DU Twist with compasses

ICRC2023 PoS 1033

Dynamic positioning taken into account in the event reconstruction

Ongoing analyses

		Analysis
Ongoing	Paper prep.	ARCA19/21 PS analysis
Ongoing		Double bang tau neutrino reconstruction
Ongoing		Improving shower reconstruction
	Paper prep.	Full ARCA sensitivity
Stopped		PS likelihood analysis
Stalled		Galactic extended source likelihood analysis with full ARCA
Stopped		Diffuse likelihood analysis
Ongoing	Paper prep.	Starburst Diffuse and PS analysis
Stalled		IC diffuse analysis (full ARCA)
	Paper finished	Combined gamma-ray/neutrino likelihood analysis
Stalled		Quiescent Blazars analysis
	Paper prep.	ARCA6+8 PS likelihood analysis
Ongoing		ARCA6+8+ANTARES PS likelihood analysis
	Paper prep.	Diffuse analysis + Galactic ridge ARCA6
Ongoing		Stacked point source analysis
Ongoing		IC neutrino alert - blazar's flare associations (PKS 0735, PKS 1741...) with ARCA8 and ORCA10
	Paper prep.	GRB 221009A analyses
Ongoing		HAWC template analysis with ARCA data
Stalled		GRB likelihood analysis (ORCA)
Stopped		GRB binned analysis
Stalled		Transient binned analysis
Ongoing		Triggered flaring analysis
Ongoing		Untriggered flaring analysis
	Paper prep.	Transient likelihood analysis (microquasar)
Ongoing		Periodic sources (pulsar) in VLE data
	Paper prep.	GW O3 analysis
Ongoing		FRB analysis
Stopped		Preliminary GeV neutrino analysis (ORCA/ARCA)
Ongoing		Advanced GeV neutrino analysis (ORCA/ARCA)
Ongoing		CCSN analysis
Ongoing		CCSN analysis (online)
Ongoing		Online ORCA/ARCA analysis
Ongoing		GNN

Priorities for 2024

ARCA6-21 / ORCA6-18 analyses:

- Include full ARCA 21 in PS/diffuse/GR analyses
- ARCA 6-21 / ORCA6-18 transient analyses (triggered/untriggered searches)
- ARCA 6-21 stacking analysis
- ARCA 6-21 tau neutrino search
- Include showers in all astro analyses

Astronomy WG
17 analyses ongoing

Ongoing analyses

Dark matter & exotic WG
10 analyses ongoing

1. Search for WIMP annihilating in the Galactic Centre with ARCA19+21
2. Combined dark matter search $\nu + \gamma$
3. Dark matter decay?
4. Search for dark matter with ARCA230 using the `aanet` framework
5. Search for light WIMPs with ORCA6
6. Non-WIMP scenarios: signature of boosted dark matter in ORCA115
7. Search for dark matter in the Sun with ORCA-6
8. Dark matter search towards the Sun
9. Signatures of very massive nuclearites in ARCA230 and ORCA-115
10. Search for ultra-relativistic magnetic monopoles with ORCA

Ongoing analyses

Cosmic rays WG
7 analyses ongoing

Topic	Status
Prompt muon analysis	Completed
Stopping Muons	Ongoing
Muon Decays	Ongoing
Mupage and CORSIKA studies	Completed
Mupage tuning on ORCA6	Completed
Cosmic ray anisotropy and variation of the muon flux analyses	Ongoing
Seasonal variations and Kaon/Pion ratio	Completed
In-DOM muon detector	Completed
Muon bundle reconstruction and Cosmic Ray compostion	Completed
Atmospheric neutrino flux	Ongoing
CORSIKA production on Grid	Ongoing
GNN muon bundle regression (ARCA)	Ongoing
Cosmic Ray anisotropy with ARCA	Ongoing

Ongoing analyses

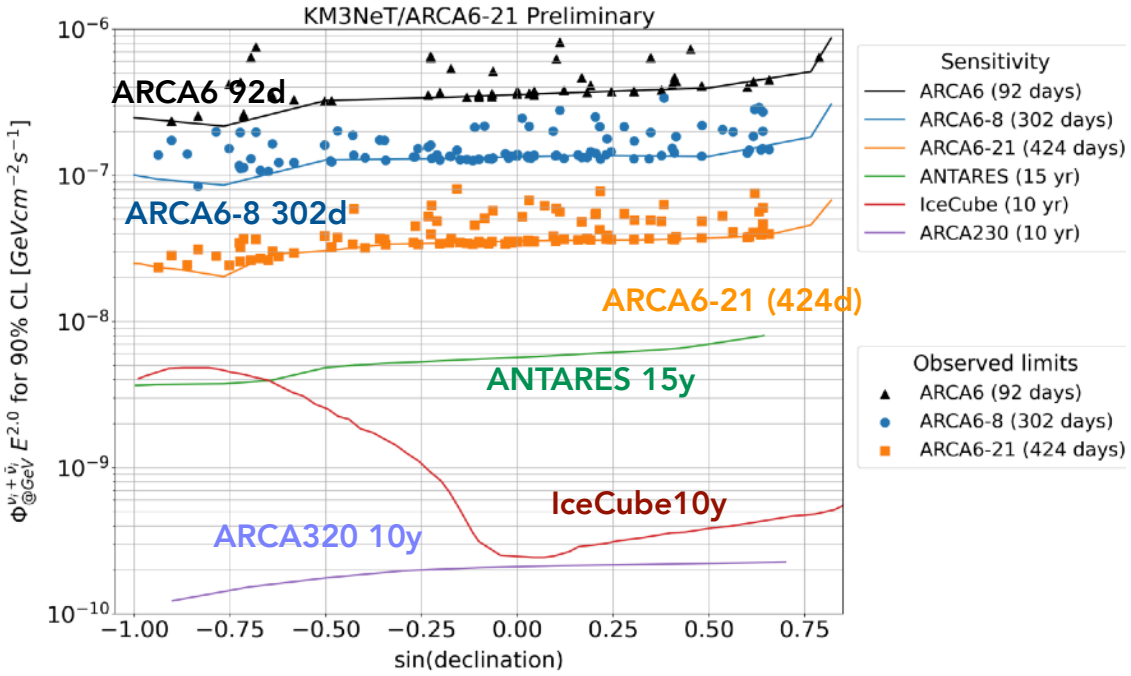
Oscillation WG
10 analyses ongoing

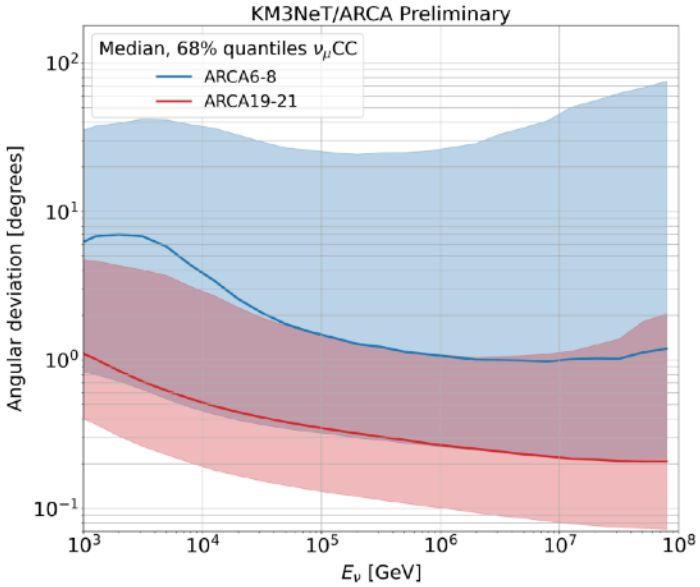
Analysis	Status
Sterile Neutrinos with ARCA	restarting
NSI with ORCA115	stalled
Tau Appearance with ORCA115	restarting
Sterile Neutrinos with ORCA6 433 kt-yr	in progress
Non-unitary neutrino mixing with ORCA6 433 kt-yr	in progress
Lorentz invariance violation with ORCA	in progress
LIV with ORCA6 433 kt-yr	in progress
QD with ORCA6 433 kt-yr	in progress
Nu decay with ORCA6 433 kt-yr	in progress
NSI with ORCA6 433 kt-yr	in progress
Tau App with ORCA6 433 kt-yr	in progress
Std Oscillation with ORCA6 433 kt-yr	in progress
Neutrino Tagging	in progress
Neutrino Decay Sensitivity ORCA 115	published
Combined analysis ORCA 115 with JUNO	published
Sterile Neutrinos ORCA 115	published
Neutrino Mass Hierarchy ORCA 115	published
Tau Appearance ORCA 115	published
P2O and Super-ORCA	published

Search for point-like sources

ARCA6 & ARCA8 & ARCA19 fully analyzed
ARCA21 partially analyzed (until December 2022)

101 candidate sources





Main contributors: R. Muller (PhD student at Nikhef now in Bologna)

@neutrino 2024 conference

Add more data 👉 ARCA21 full period (until sept 2023)

PS search

Full sky search

Joint analysis with ANTARES

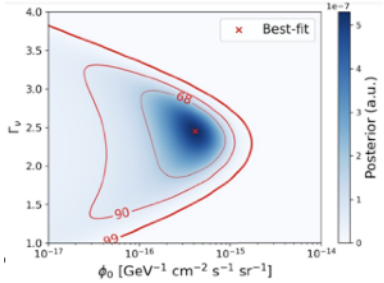
Diffuse from the galactic plane

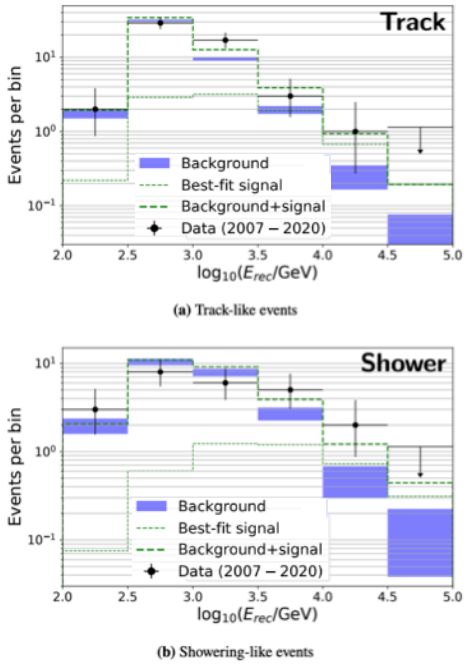
Phys. Lett. B 841 (2023), p. 137951

ANTARES 2007-2020 data

2σ excess in tracks and showers → hint for Galactic signal

ICRC2023 PoS 1103





For E_ν>1 TeV

21 track events observed -> 11.7±0.6 back. expected

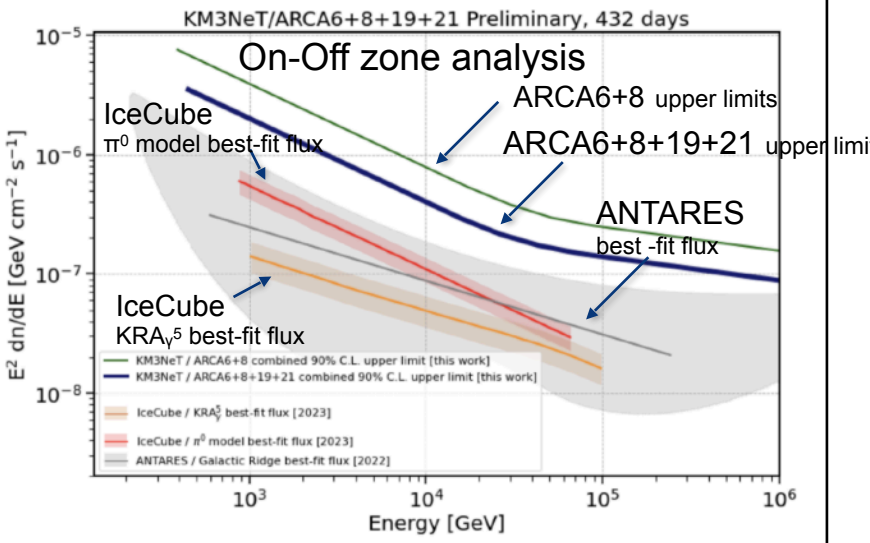
13 shower events observed -> 11.2±0.9 back. expected

ARCA6 & ARCA8 & ARCA19 fully analyzed
ARCA21 partially analyzed (until December 2022)

ICRC2023
PoS 1190

KM3NeT

|l| < 31° and |b| < 5° for KM3NeT/ARCA6-8 and
|l| < 31° and |b| < 4° for KM3NeT/ARCA19-21



Next step for the Neutrino 2024 conference

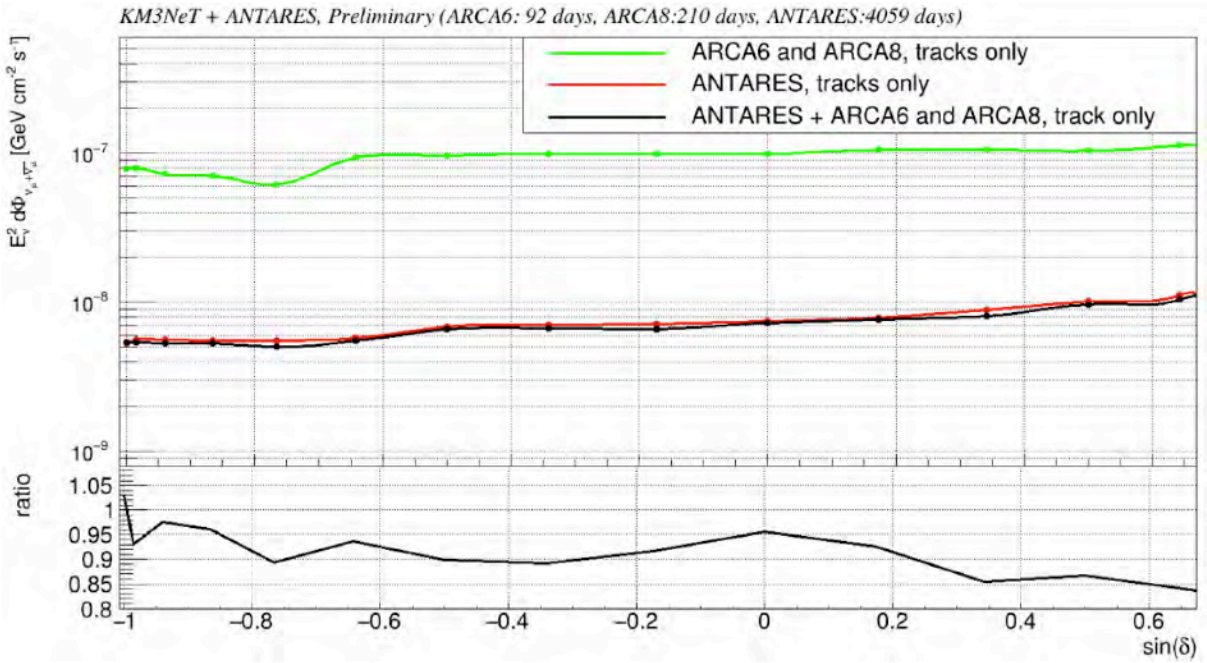
Add more data 👉 ARCA21 full period

Joint analysis with ANTARES (?)

Main contributors: F. Filippini (Bo) and L. Fusco (Salerno)

ANTARES-ARCA Joint analysis

ARCA6 & ARCA8 ≈300 days
ANTARES 11 years



ICRC2023
PoS 1147

Main contributors: B. Caiffi (Ge), V. Kulikovskiy (Ge) & Genova group

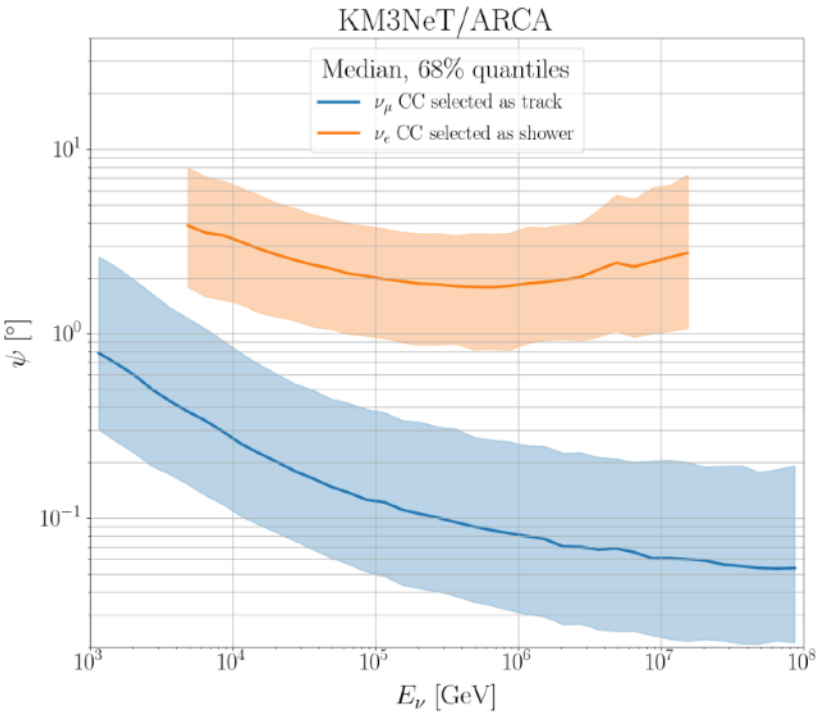
All the machinery for the joint analysis is ready

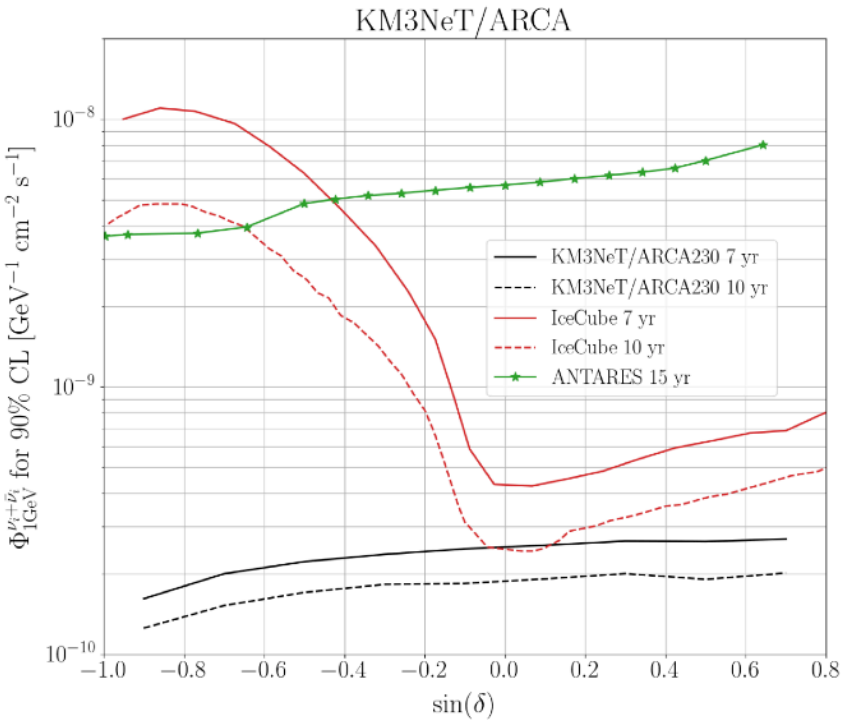
At moment only 10% improvement
Important in the next years

ARCA 230 DU

From the latest prediction published (2019) https://doi.org/10.1016/j.astropartphys.2019.04.002:

- Improved the track and shower reconstructions
- Improved neutrino selection
- Added shower events





The sensitivity and discovery potential for point-like sources have improved by 5-15%

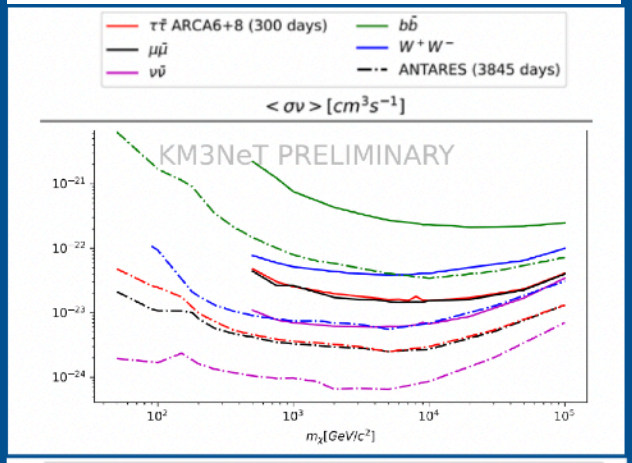
Just submitted on EPJC and on ArXiV
https://arxiv.org/pdf/2402.08363.pdf

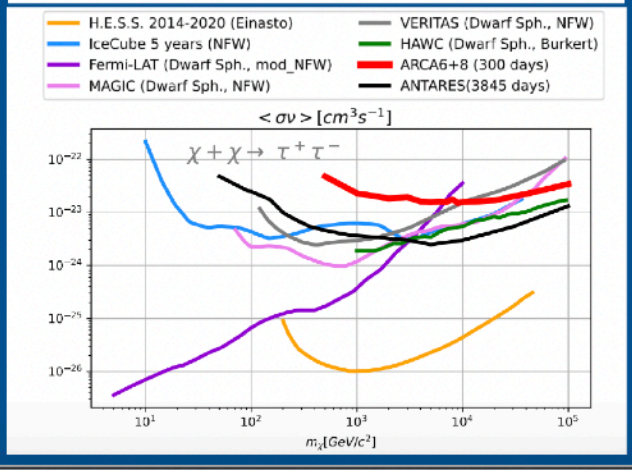
Main contributors: Thijs (Nikhef) & R. Muller (Nikhef now in Bologna)

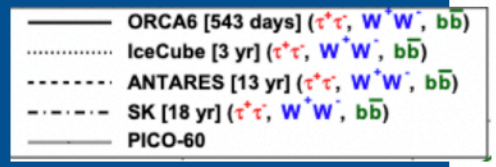
Dark Matter

ICRC2023
PoS 1377

From the Galactic Center
ARCA6 & ARCA8



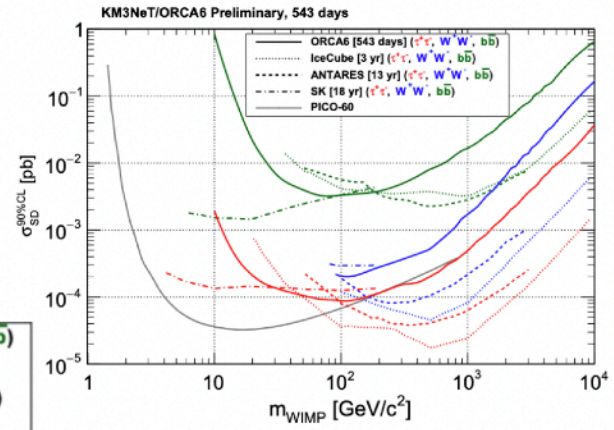


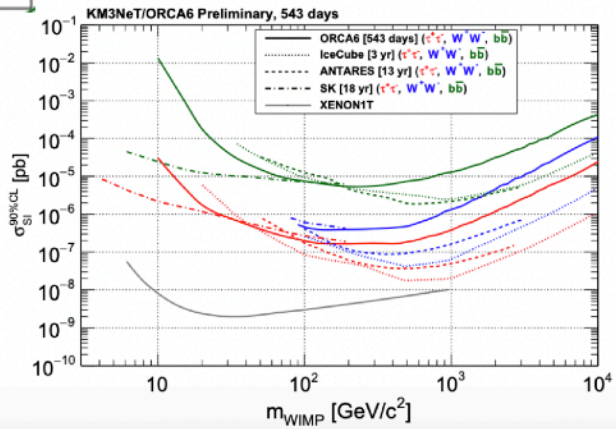


KM3NeT quickly reaching the ANTARES limits

From the Sun
ORCA6

ICRC2023
PoS 1406

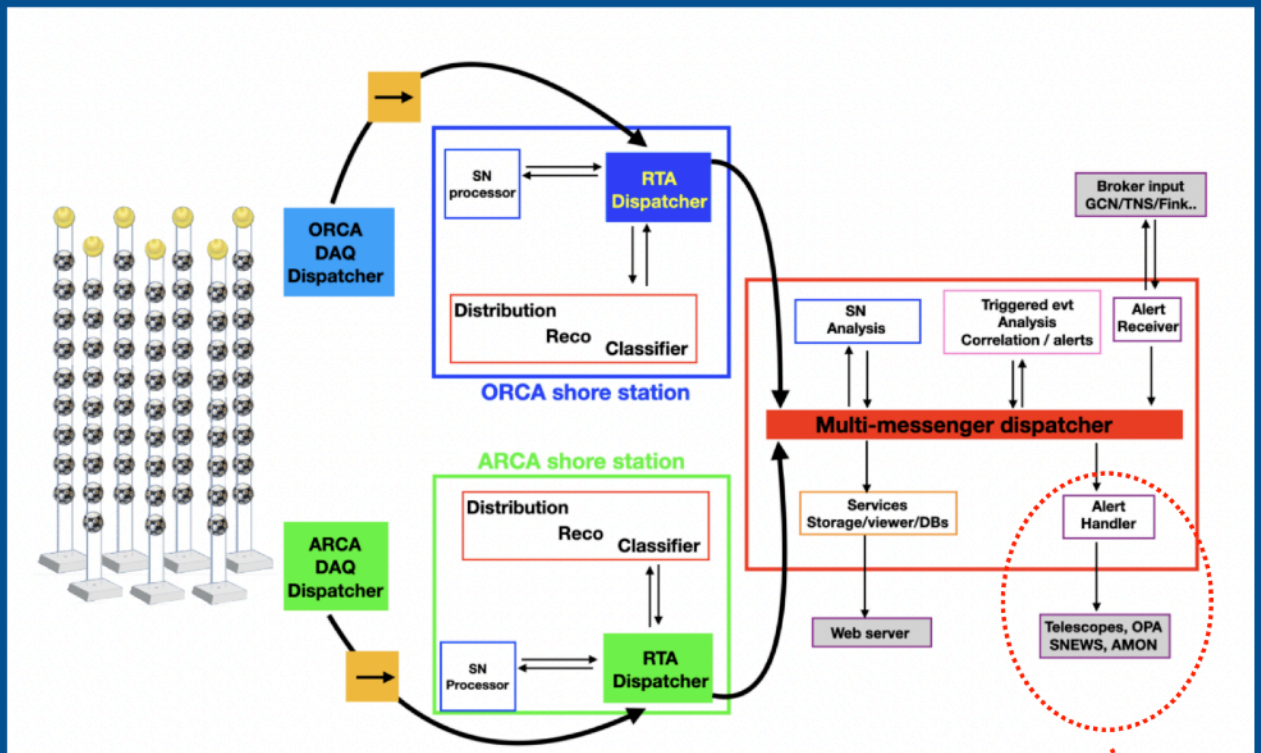




Next step for the Neutrino 2024 conference
Add ARCA19-21 data

Multimessenger

ICRC2023 PoS 1125 and PoS 1521



- Event processing done separately for ORCA and ARCA at each shore station
- Data from each detector are transferred to a common dispatcher (MM dispatcher), where analysis pipelines are also activated
- Events reconstructed in real-time (both as track and shower) and classified (μ/ν) via machine learning algorithms

Not yet implemented
Work on-going

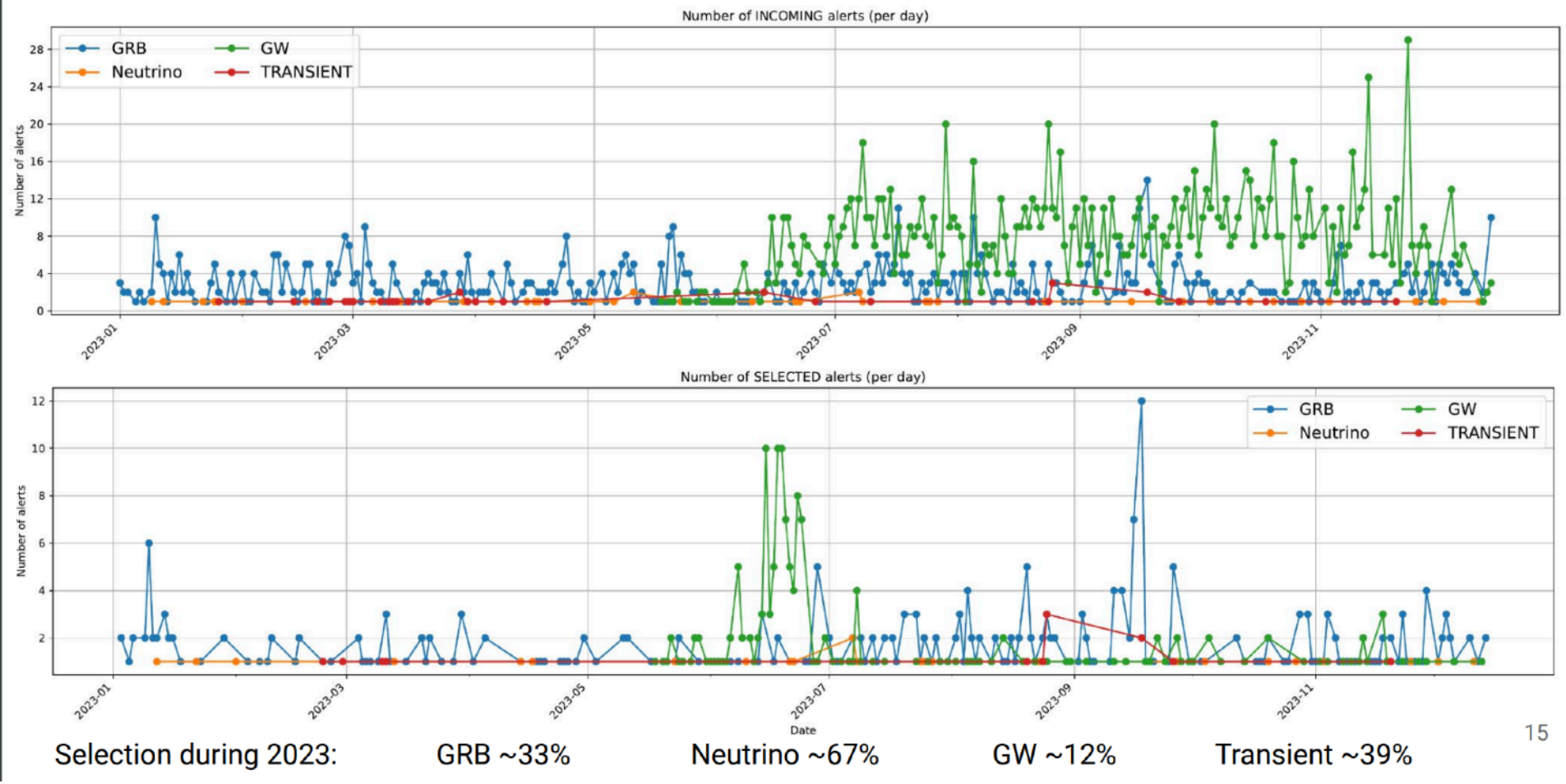
What are we currently receiving?

- INTEGRAL (GRB)
- FERMI_GBM (GRB / Transient)
- FERMI_LAT (Transient)
- SWIFT_BAT_GRB (GRB / Transient)
- SWIFT_XRT (GRB / Transient)
- SWIFT_BAT_TRAN (Transient)
- MAXI (Transient)
- HAWC (Transient)
- IceCube (Neutrino)
- LVK (GW)
- SNEWS (CCSN)
- SK_SN (CCSN)

Big contribution from Roma1

Multimessenger

ICRC2023 PoS 1125 and PoS 1521



15

External alerts trigger the Real Time Analysis system

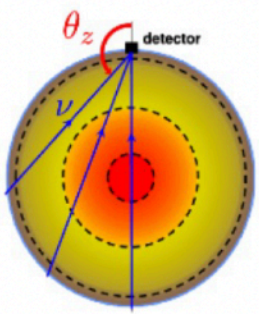
👉 events satisfying the following criteria are selected:

- temporal and spatial coincidences
- visibility in KM3NeT for up-going tracks
- Reported false alarm rate

No significant excess has been found so far

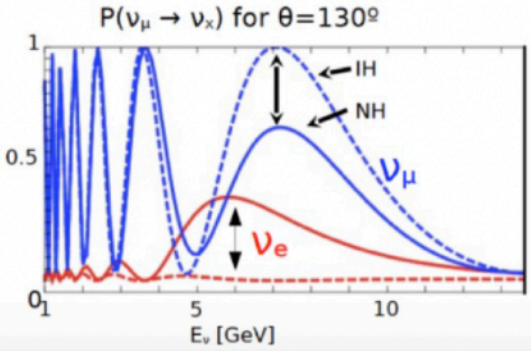
Neutrino oscillation with ORCA

Baseline from 50 to 12800 km

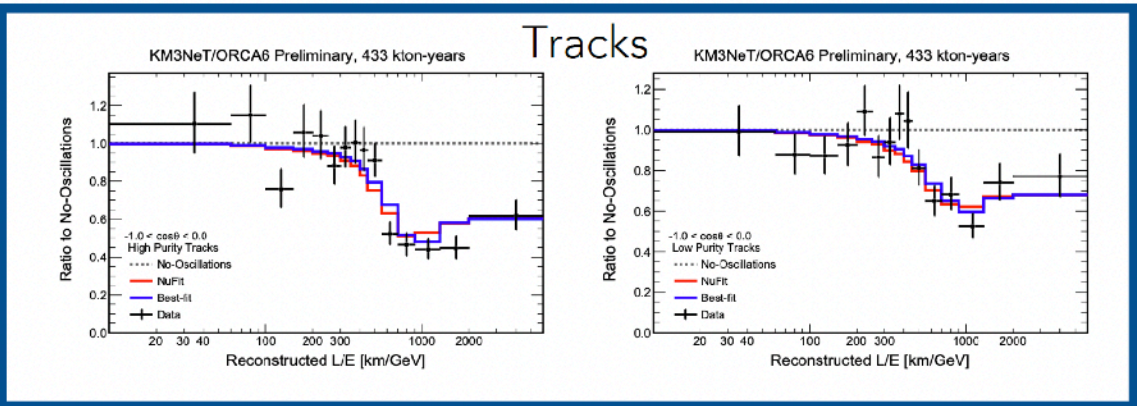


Neutrino Mass Ordering measuring atmospheric neutrinos crossing the Earth

Energy range of interest 5-15 GeV

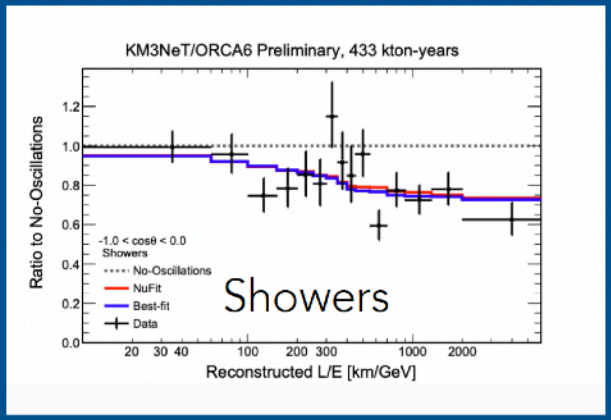


Tracks



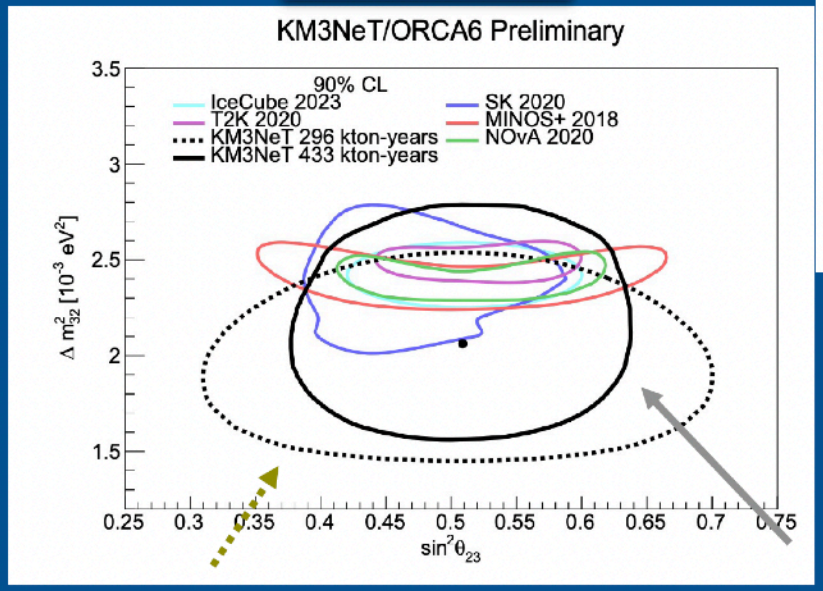
ORCA6 data

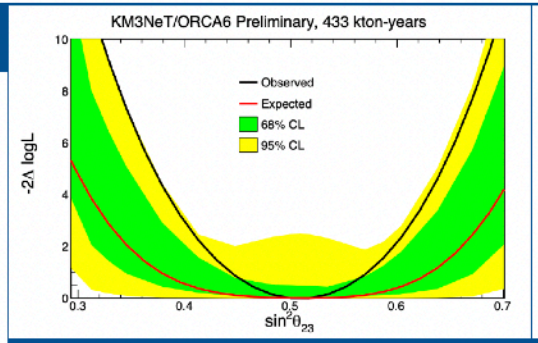
Oscillation clearly seen both in track and shower events

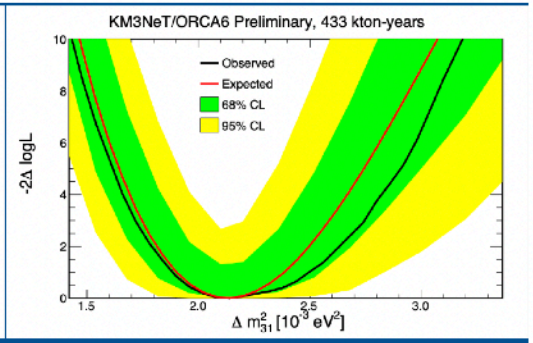


Neutrino oscillation with ORCA

Δm^2_{32} vs $\sin^2\theta_{23}$







ORCA6 DUs 354days

ORCA 6 DUs 510days

With respect to Neutrino 2022 conference 👇

Increased event sample of a factor 5:

- Better selection track/shower 👉 ICRC2023 PoS 1191
- Added showers
- Livetime + 40%

KM3NeT/ORCA competitive

Inclusion of data of ORCA10-11 on going

Papers in the past year

Probing invisible neutrino decay with KM3NeT-ORCA	*https://doi.org/10.1007/JHEP04(2023)090*
Prospects for combined analyses of hadronic emission from γ-ray sources in the Milky Way with CTA and KM3NeT	*https://doi.org/10.1140/epjc/s10052-023-12279-z*
Embedded Software of the KM3NeT Central Logic Board	*https://doi.org/10.1016/j.cpc.2023.109036*
First search for neutrino counterparts from gravitational waves from the run O3 with KM3NeT	*Accepted for publication on JCAP https://arxiv.org/abs/2311.03804*
Astronomy potential of KM3NeT/ARCA	*Submitted to EPJC - arXiv:2402.08363*
KM3NeT/ARCA Differential Sensitivity for Diffuse and Point-Like Emissions: Probing Starburst Galaxies Emissions	*Submitted to Astropart. Phys. arXiv:2402.09088*
Search for Neutrino Emission from GRB 221009A using the KM3NeT ARCA and ORCA detectors	*To be submitted soon to Astrophysical Journal Letters*
Atmospheric muons measured with the KM3NeT detectors in comparison with modern numeric predictions	*To be submitted soon to XXX*

Napoli group

Genova group

@Neutrino 2024 conference

ANTARES+KM3NeT

- Search for point sources with KM3NeT/ARCA and ANTARES
- Search for neutrino emission from gamma-ray flaring blazars with ANTARES and KM3NeT detectors
- Search for a diffuse flux of cosmic neutrinos combining the ANTARES and KM3NeT/ARCA datasets
- Untriggered neutrino flares search with the ANTARES and KM3NeT/ARCA neutrino telescopes
- Model-Dependent and Independent Stacking Search for Seyfert Neutrino Emission with the KM3NeT/ARCA and ANTARES Detectors
- Search for Lorentz invariance violation with ANTARES and KM3NeT/ORCA6

ANTARES

- Indirect dark matter searches towards the Sun using the full ANTARES data set
- Searches for point-like and extended sources of cosmic neutrinos with the complete ANTARES dataset
- Enhanced classification and reconstruction of low-energy events in ANTARES neutrino tele
- Search for a diffuse flux of cosmic neutrinos with the complete ANTARES dataset
- Search for high-energy Galactic neutrinos: An ANTARES legacy

KM3NeT

- Diffuse astrophysical neutrino flux search with KM3NeT/ARCA6-8-19-21 data
- WIMP dark matter searches in the Galactic Centre with KM3NeT
- Dark matter sensitvity with the full KM3NeT/ARCA detector
- Time-integrated search for astrophysical neutrino emission with 2 years of KM3NeT/ARCA data
- Advanced Quantum Efficiency Measurement Setup for Characterization of 3-Inch PMTs in the KM3NeT Neutrino Telescope
- Neutrino alerts from the KM3NeT detectors
- The KM3NeT real-time analysis framework
- Search for high energy neutrinos in KM3NeT in coincidence with Fast Radio Bursts
- Stacking Search for Ultra-Luminous Infrared Galaxies with KM3NeT/ARCA Detector
- Results of the follow-up of external triggers with KM3NeT
- Machine-Learning methods to improve the sensitivity of KM3NeT to MeV-GeV neutrinos using multi-PMT optical modules
- Searches for diffuse astrophysical neutrino flux from the Galactic Ridge with KM3NeT/ARCA data
- GNNs applications for neutrino selection in KM3NeT-ARCA
- KM3NeT's sensitivity to the next core-collapse supernova
- First measurement of light sterile neutrino mixing parameters with KM3NeT/ORCA
- Non unitarity neutrino mixing test with KM3NeT/ORCA
- Introducing a Simultaneous Track+Shower Reconstruction Algorithm, dedicated for KM3NeT/ORCA
- Measurement of the atmospheric muon neutrino flux with KM3NeT/ORCA6
- Data reconstruction with Graph Neural Networks in KM3NeT/ARCA
- Updated measurement of atmospheric neutrino oscillation parameters with KM3NeT/ORCA

Summary

KM3NeT present status: ARCA 28 DUs (12% of the full detector) and ORCA 18DUs (14% of the full detector)

- Latest official results presented at ICRC2023 👉 about 40 contributions (https://arxiv.org/abs/2309.05016)
- Submitted more than 30 abstracts at the Neutrino 2024 conference

👇

KM3NeT upper limits are rapidly approaching the ANTARES limits
Online multi-messenger analysis framework already operative

👇

Exciting results expected in a few years especially in the exploration of the southern sky

Promising results also in the neutrino oscillation 👉 KM3NeT/ORCA in the race for the mass hierarchy

We are building two underwater laboratories 👉 unique multidisciplinary opportunities and many activities already ongoing

Ongoing analyses

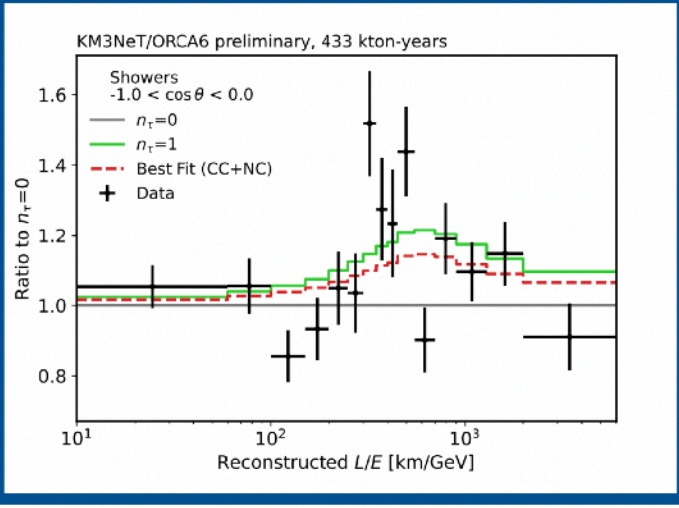
Topic	Detector Conf.	Publication
Search for nuclearites with KM3NeT	ORCA-115 and ARCA-230	In draft
Galactic Centre WIMPs	ARCA-6	--
Galactic Centre WIMPs	ARCA-8	In draft together with DM in the Sun
Galactic Centre WIMPs	ARCA-19/21	In draft together with DM in the Sun (?)
WIMPs from the Sun	ORCA-6	In draft together with GC
WIMPs from the Sun with ARCA	ARCA-6/8/19/21	
Search for magnetic monopoles with KM3NeT	ORCA-115	
Combined analysis	Combined DM search with neutrinos and	
Galactic Centre WIMPs	ARCA-230	
Galactic Centre WIMPs	ORCA-115	
Double-cascade events from new physics in ORCA	ORCA-115	
DM lines with ARCA	ARCA-230	
Deep learning for single-line reconstruction	ANTARES	
WIMP annihilations in the Galactic Centre	ANTARES	In draft

Dark matter & exotic WG
10 analyses ongoing

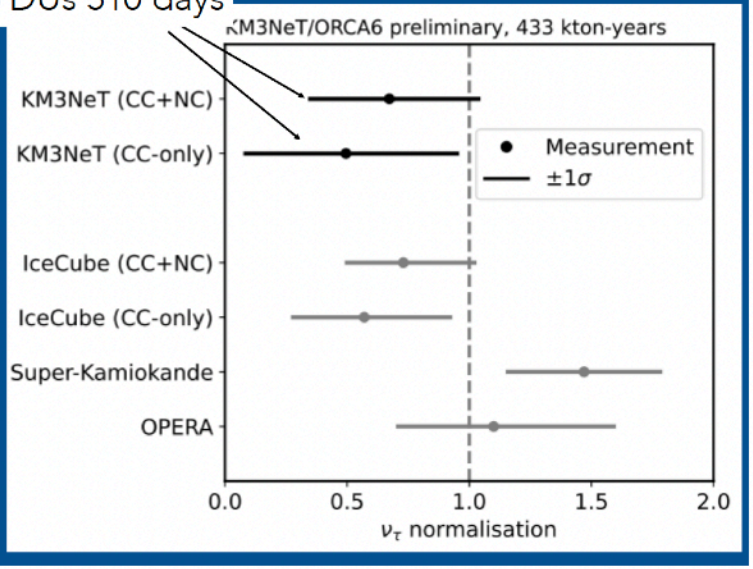
Neutrino oscillation with ORCA

ν_τ appearance

ν_μ -> ν_τ 👉 search for a statistical excess of shower-like events



ORCA6 DUs 510 days



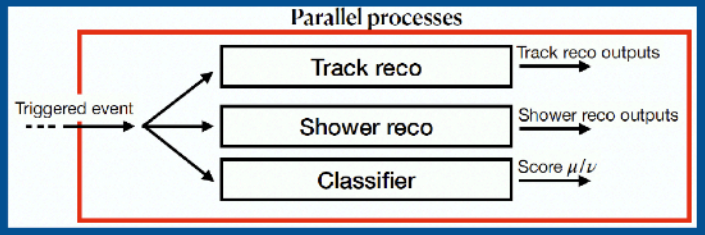
Also competitive results in:

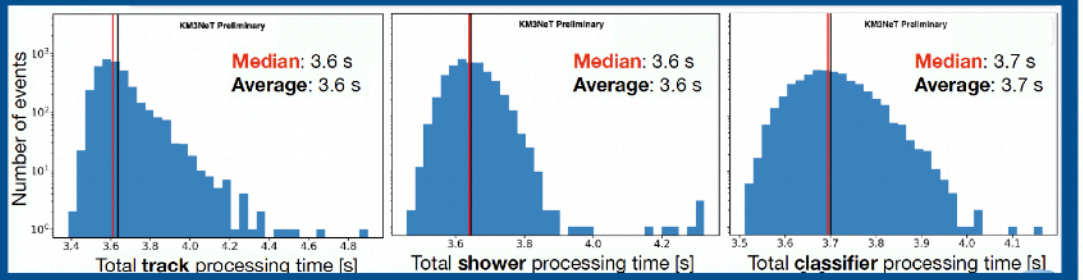
- Non standard interactions 👉 ICRC2023 PoS 998
- Neutrino decay 👉 ICRC2023 PoS 997
- Lorentz invariance violation 👉 ICRC2023 PoS 1086

Inclusion of data of ORCA10-11 on going

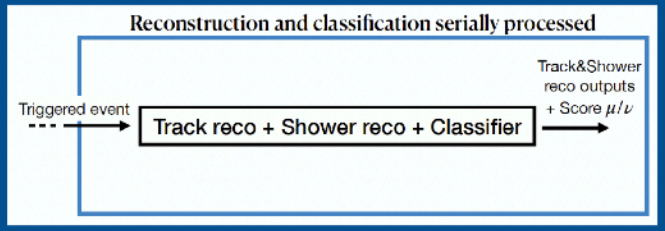
MULTI-MESSENGER: ONLINE PROCESSING TIME

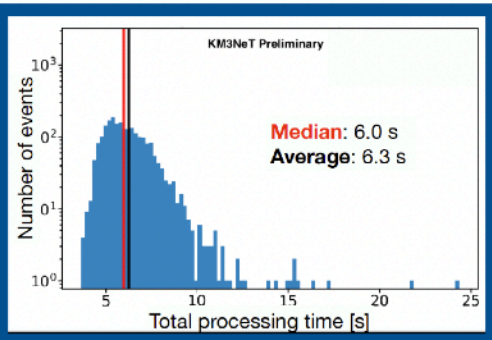
19





On average ~4 seconds to reconstruct and classify ARCA events

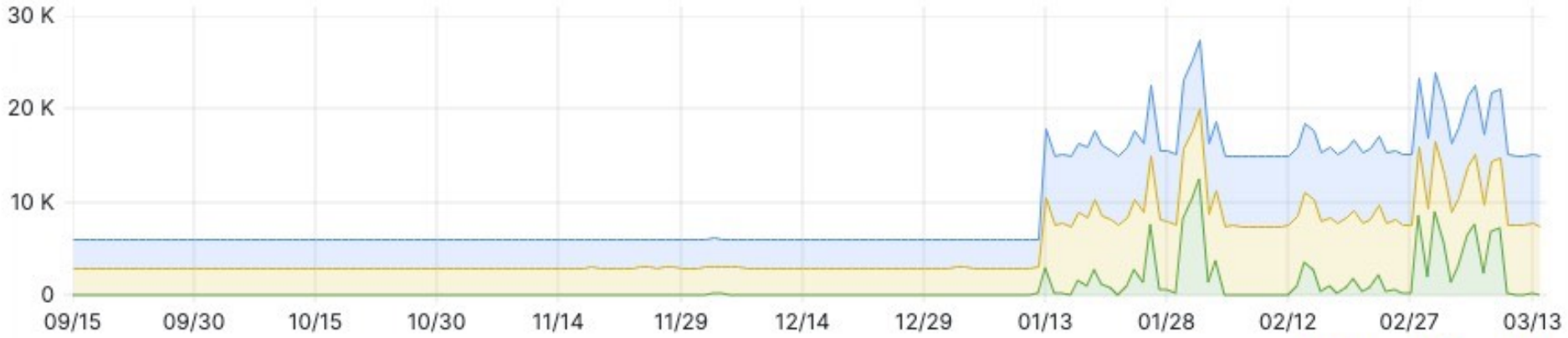




On average ~6 seconds to reconstruct and classify ORCA events

Farm HTC

HS06 KM3



	Mean	Min	Max
used	1.65 K	0.0199	12.5 K
pledge	4.53 K	3 K	7.50 K
assigned	4.53 K	3 K	7.50 K