KM3NeT

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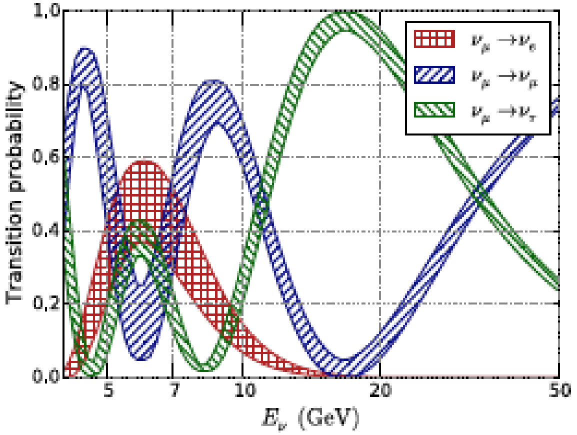
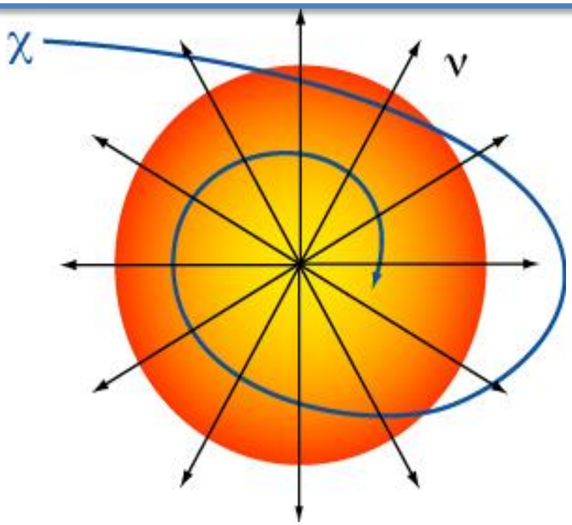
on behalf of the KM3NeT Collaboration

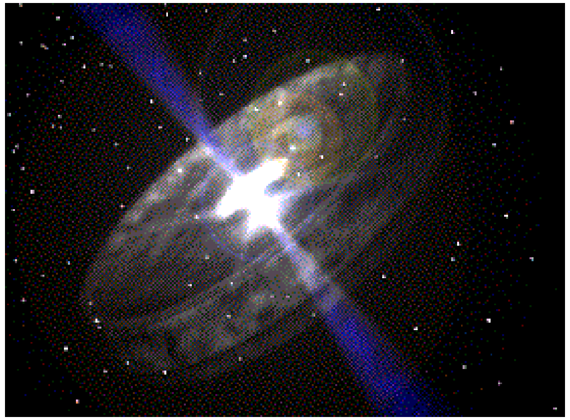
EuCAPT 2024, Prague
21/08/24

Neutrino telescopes: science

MeV to PeV energies







Supernova
Solar flares

Atmos neutrinos
ν oscillations
ν mass ordering
Sterile, NSI, …

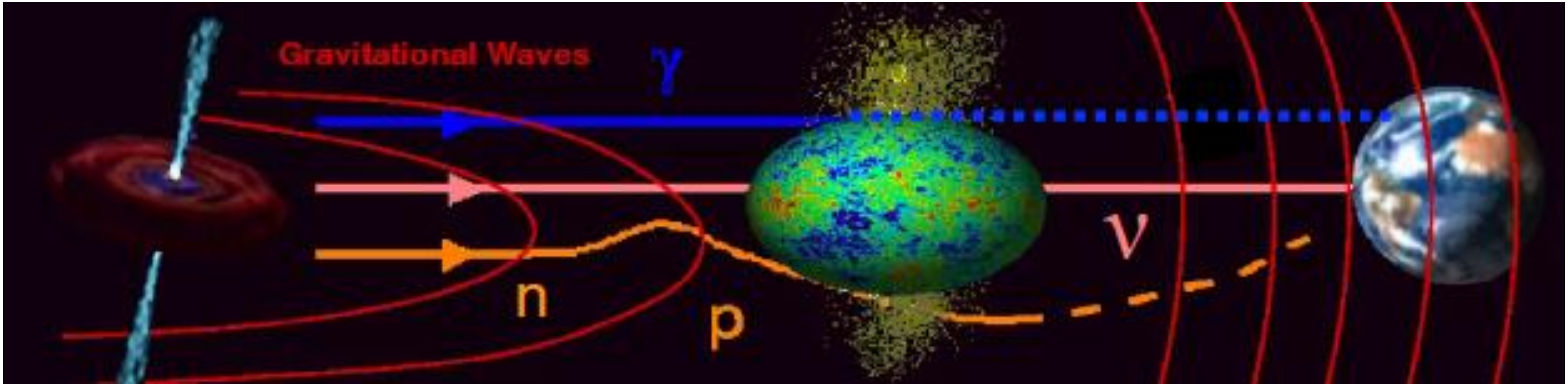
Dark matter
Monopoles,
Nuclearites,…

Cosmic neutrinos
Cosmic rays
Origin and production mechanism of HE CR

KM3NeT-ORCA ANTARES KM3NeT-ARCA

+ oceanography, biology, bioacoustics, seismology,…

Neutrinos: cosmic messengers



Neutrinos: neutral, stable, weakly interacting

- not absorbed by background light/CMB ➒ access to cosmological distances
- not absorbed by matter ➒ access to dense environments
- not deviated by magnetic fields ➒ astronomy over full energy range

'Smoking gun' signature for hadronic processes

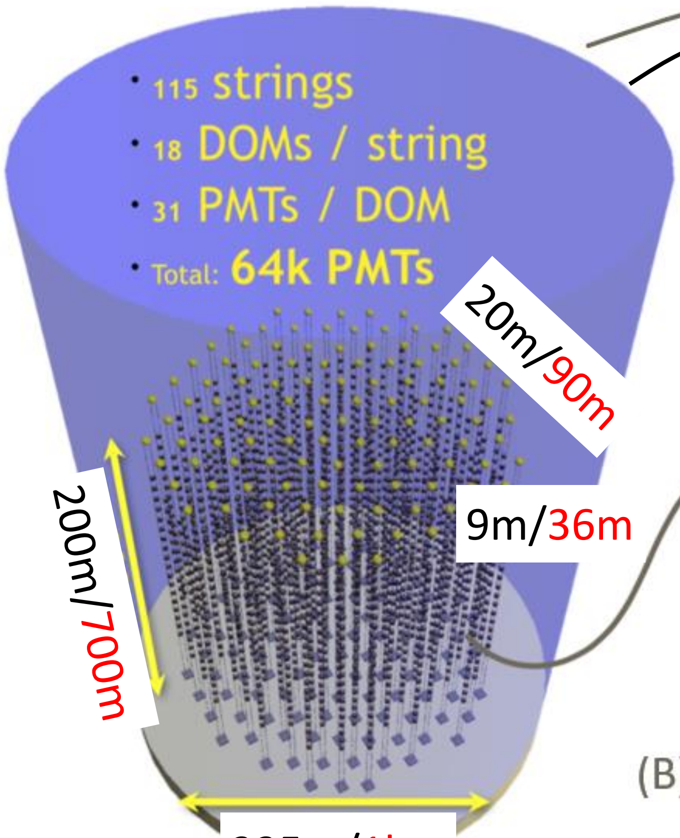
Correlated in time/direction with electromagnetic and gravitational waves

New window of observation on the Universe

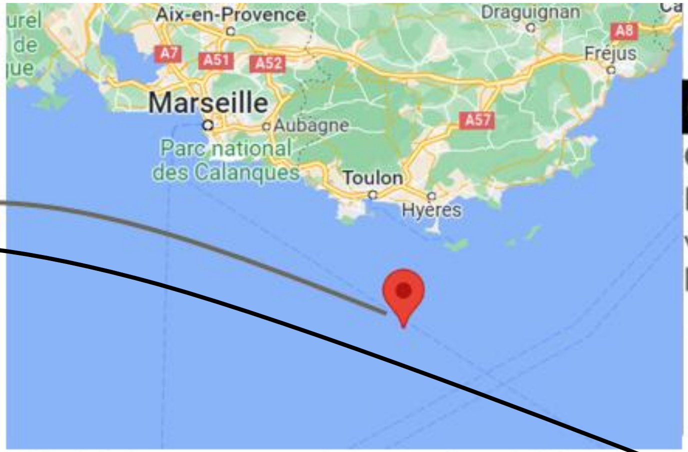
KM3NeT ORCA/ARCA: neutrino telescope concept

1 for ORCA and 2 for ARCA

(C) Total Instrumented Volume ~ 8 Mton



(D) Site



ORCA : -2450m
Oscillation **R**esearch with **C**osmics In the **A**byss

ORCA: Low energy physics ~ few GeV (Neutrino Oscillations)

Astroparticle **R**esearches with **C**osmics In the **A**byss

ARCA 3400m

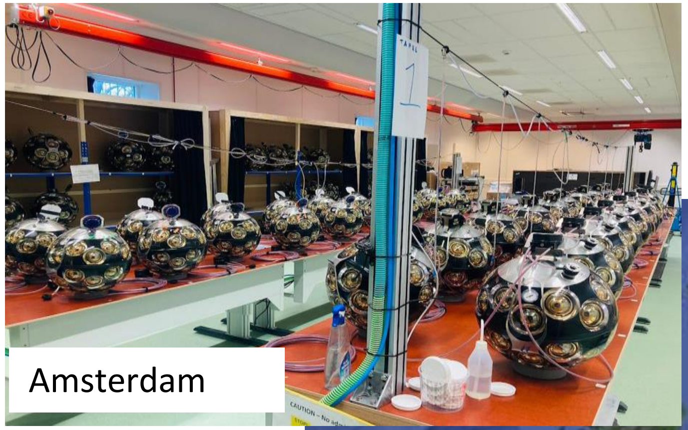
(B) Detection Unit (DU)

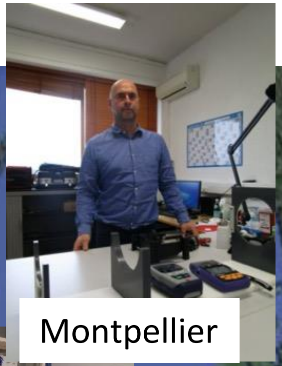
(A) The KM3NeT DOM housing 31 3" PMTs

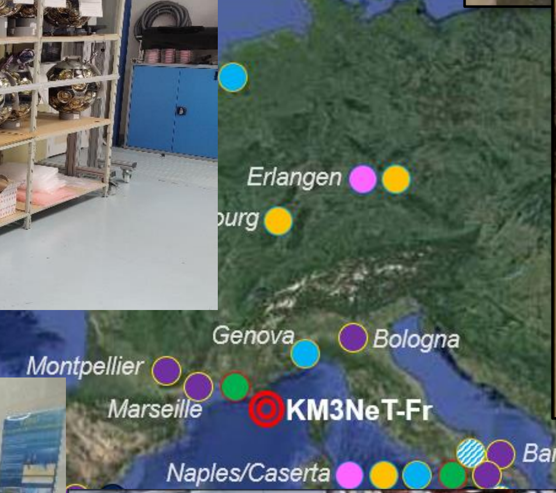
- All data to shore: Gbit/s optical fibre
- White Rabbit time synchronisation
- LED flasher & acoustic piezo
- Tiltmeter/compass

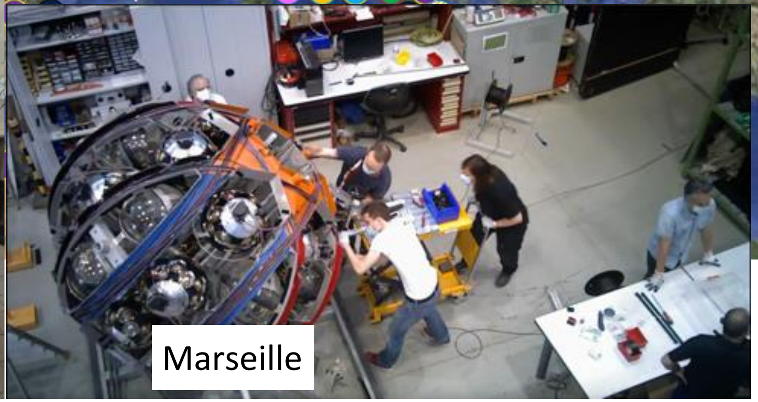
[KM3NeT 2.0: Letter of Intent](http://dx.doi.org/10.1088/0954-3899/43/8/084001)
http://dx.doi.org/10.1088/0954-3899/43/8/084001
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

Detector construction



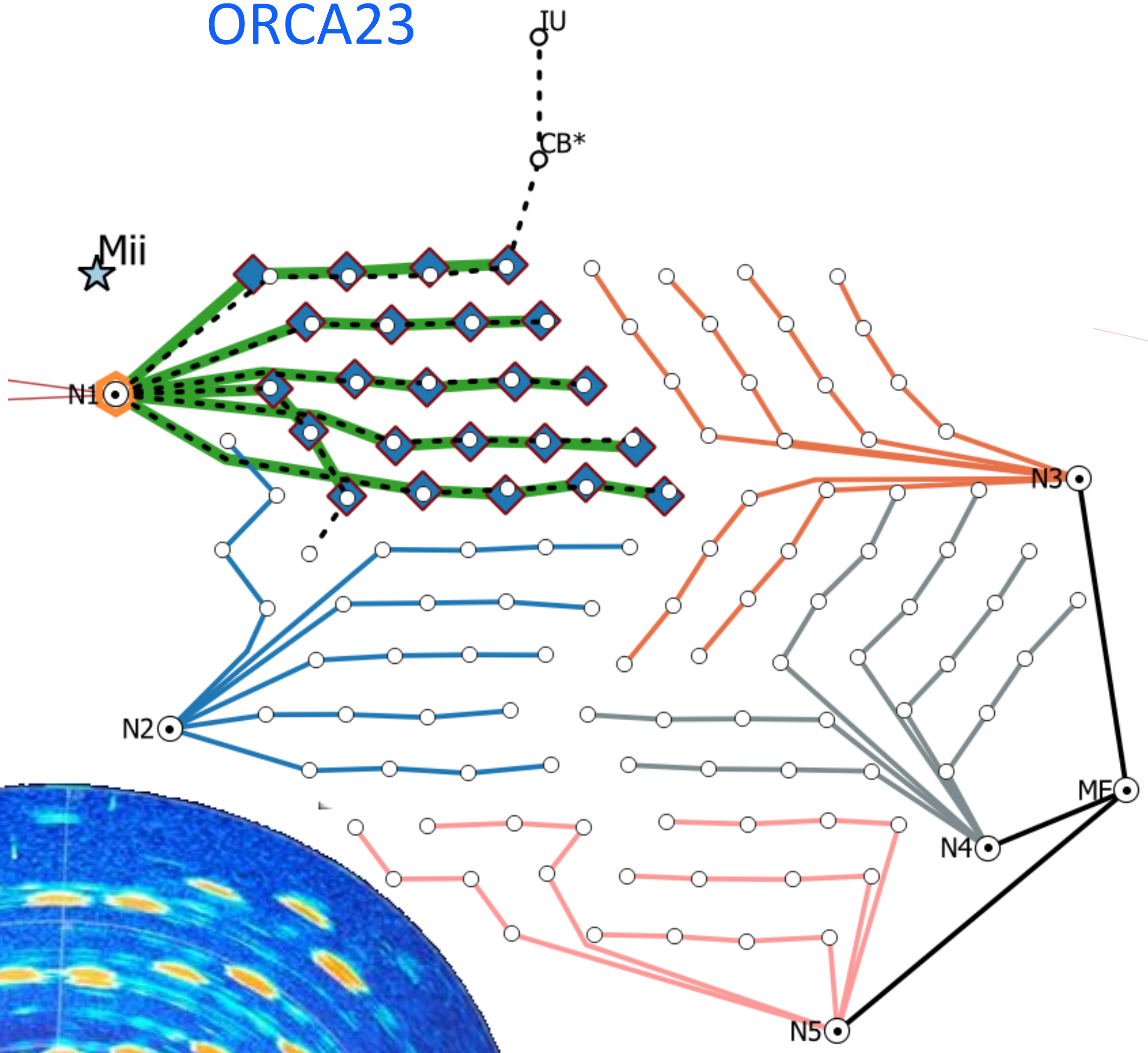




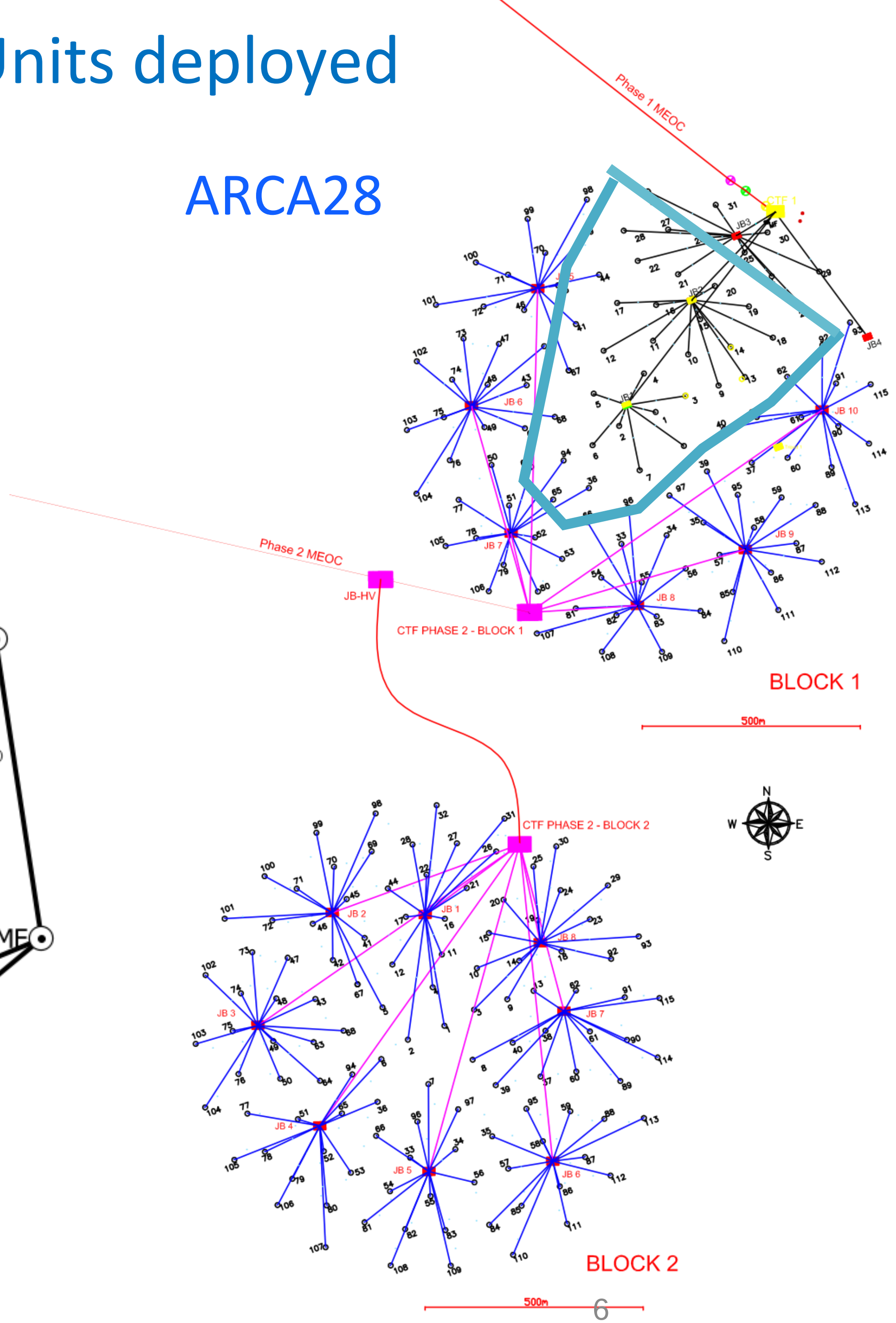


Current Status: 51 Detection Units deployed

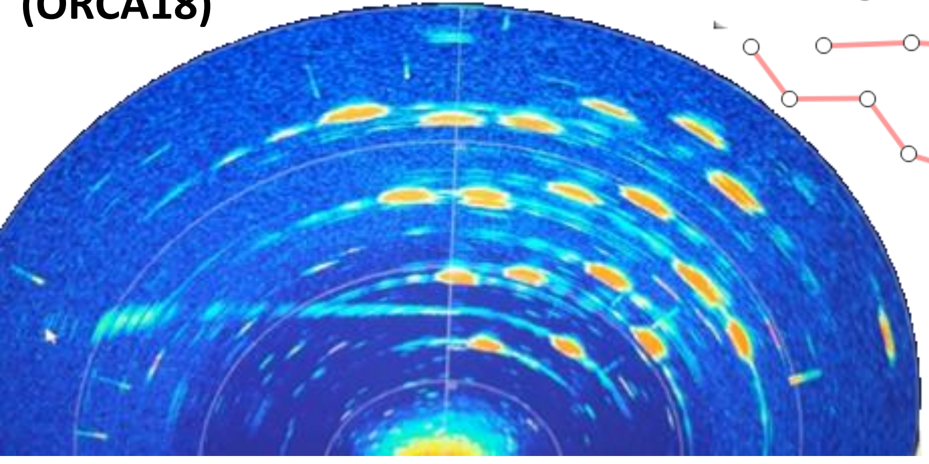
ORCA23



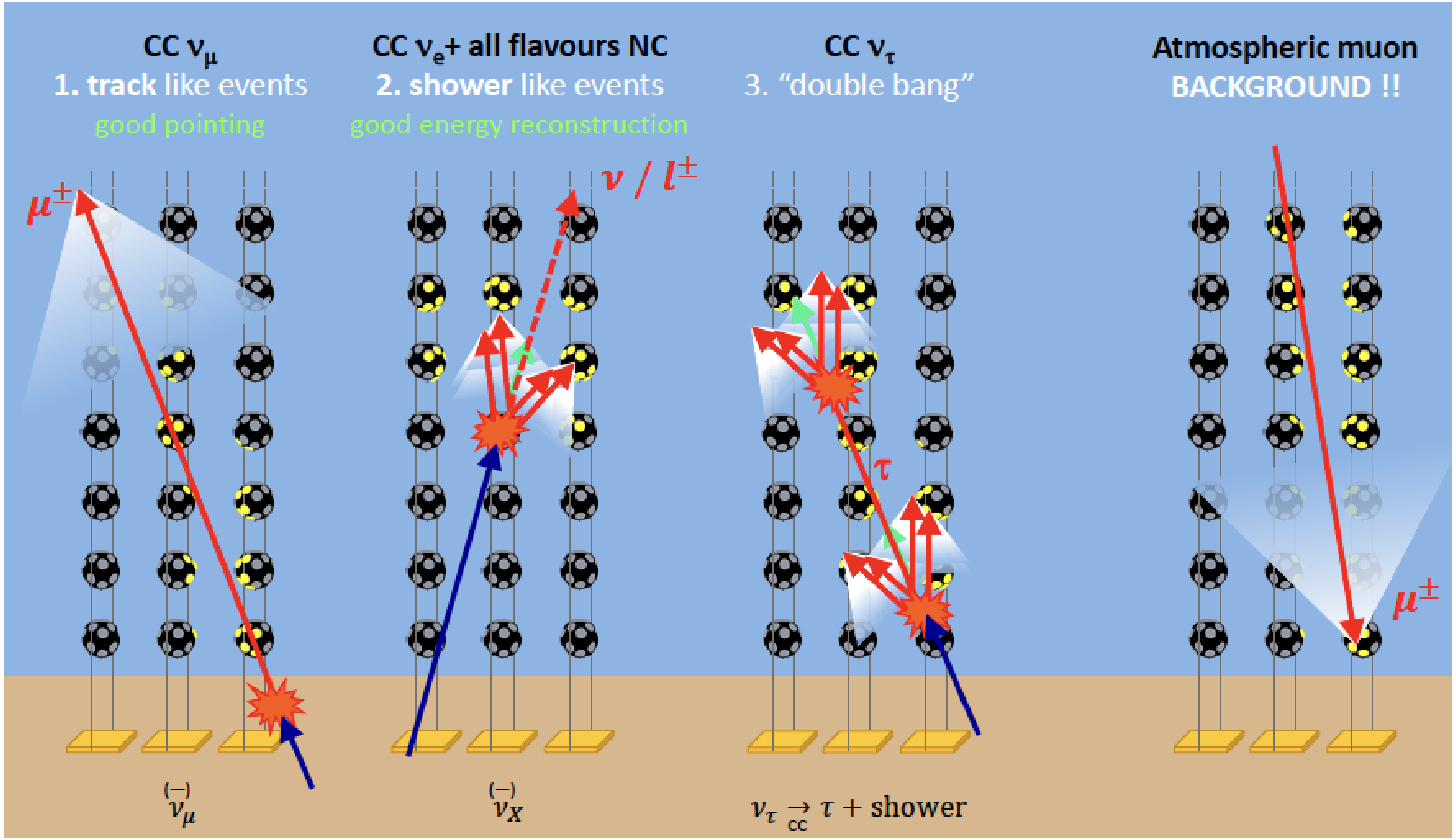
ARCA28



Sonar scan (ORCA18)



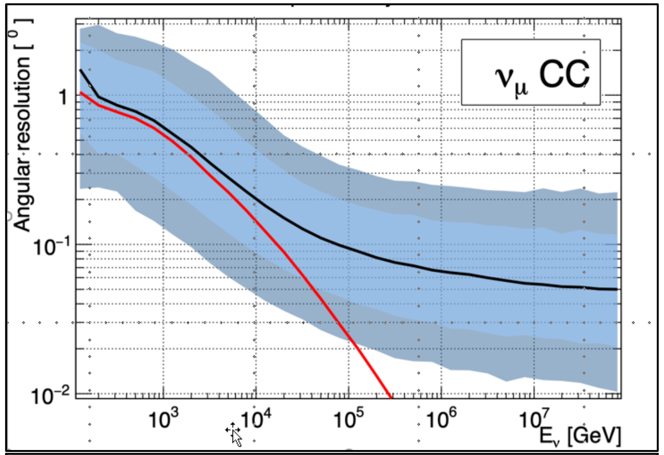
Event Topologies



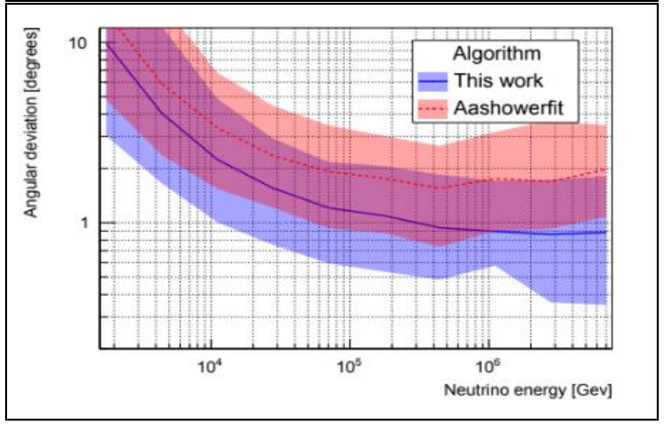
Tracks @E_ν>100 TeV Ang. res. below 0.1° - Energy res. ~ factor 2
Shower @E_ν>100 TeV Ang. res. below 2° - Energy res. ~6%

Angular Resolutions

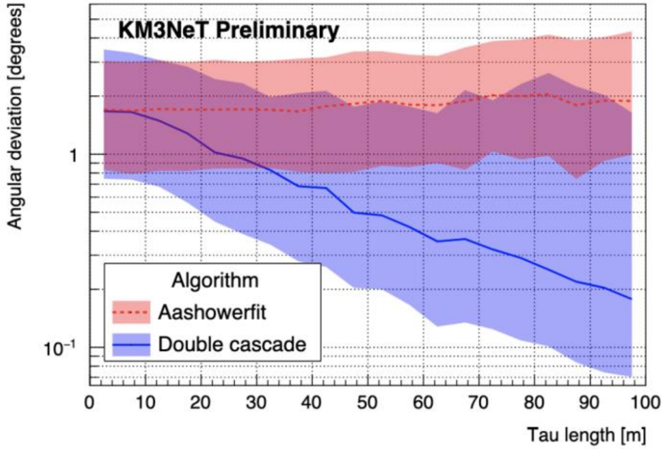
Tracks
Better than 0.1° > 20 TeV



Showers
Better than 1° > 30 TeV



Taus
Better than 1° for tau track length > 22 m



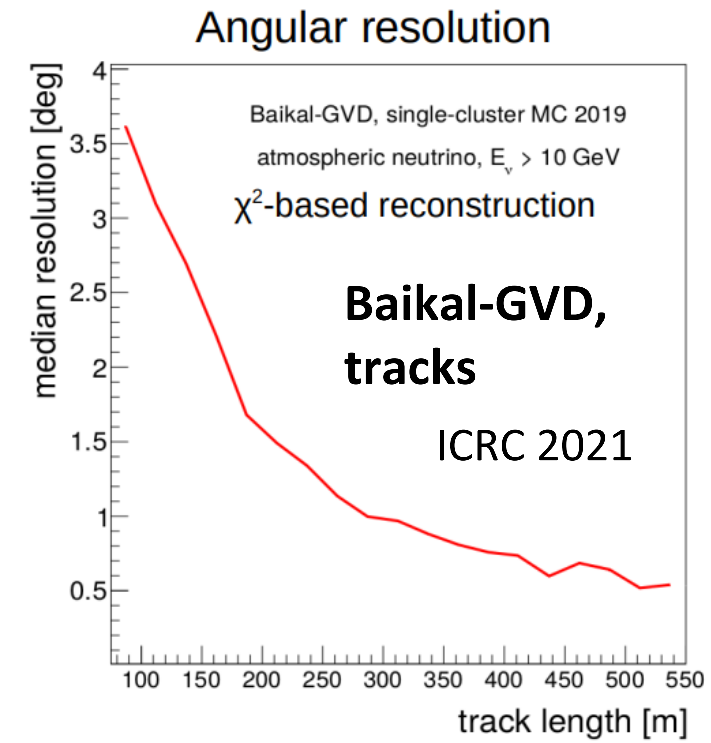
Angular resolution vs different NTs

	TRACK*	CASCADE*
ANTARES	0.3°	3°
KM3NET	0.1°	1.5°
ICECUBE	0.3°	7°-8°
BAIKAL -GVD	0.25°	3° - 3.5°

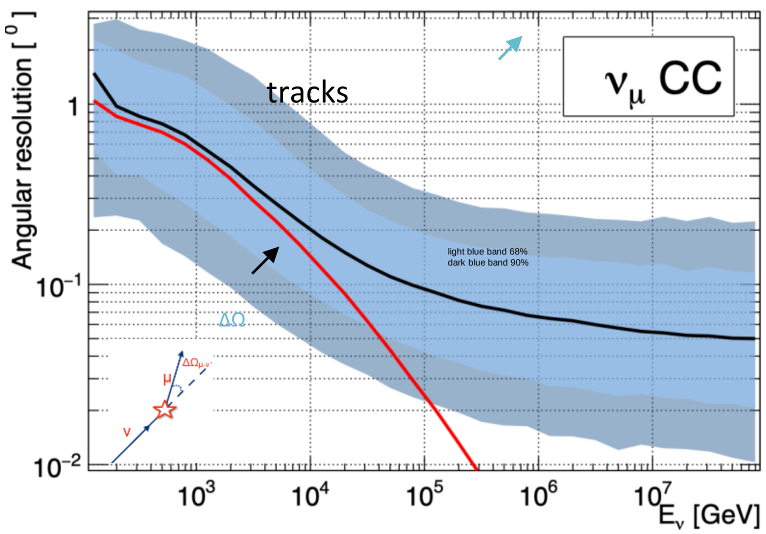
*Resolution at 100 TeV

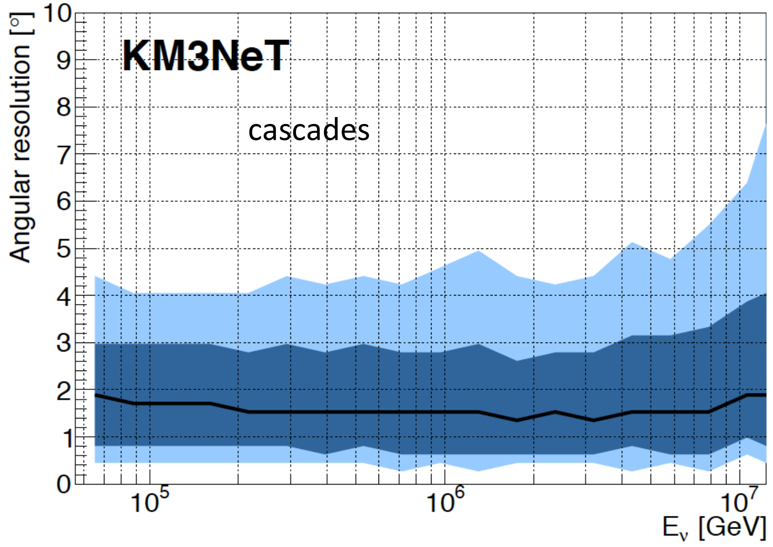
Tracks: very long path (Eμ>1TeV several km)
Big lever arm
- Good angular resolution

Cascades: small path (Ecasc >1TeV some tens of meters)
- Modest angular resolution

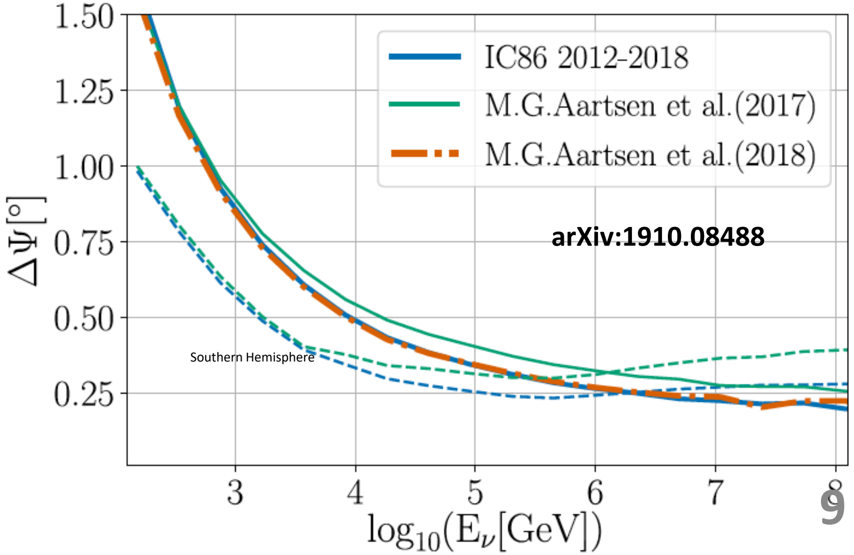


KM3NeT





IC, tracks

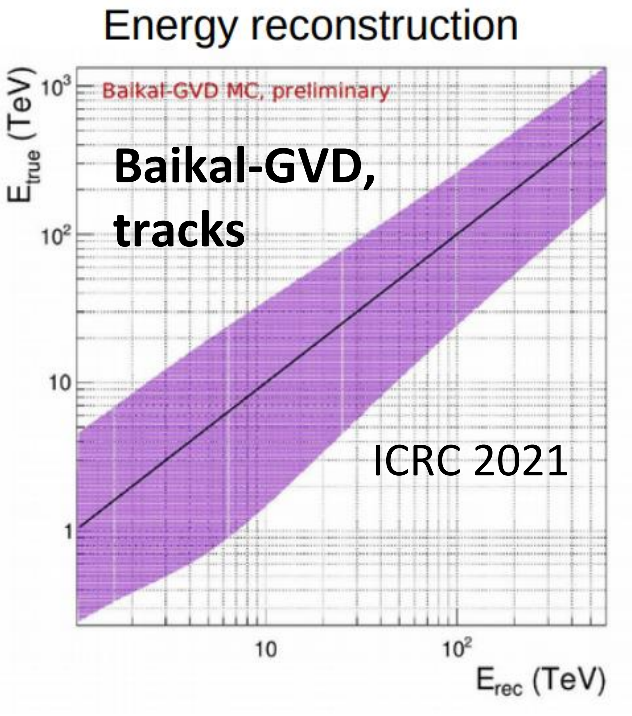


Energy resolution vs different NTs

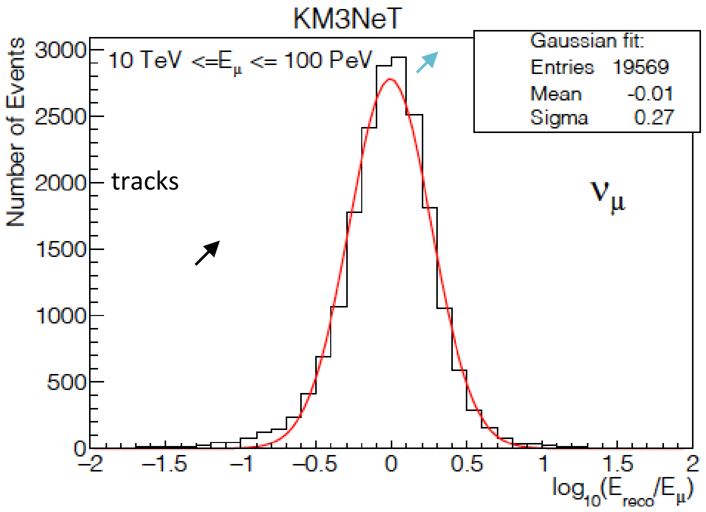
	TRACK IN LOG(E)	CASCADE
ANTARES	35%	5%
KM3NET	27%	5%
ICECUBE	~30%	10%
BAIKAL -GVD		10-30%

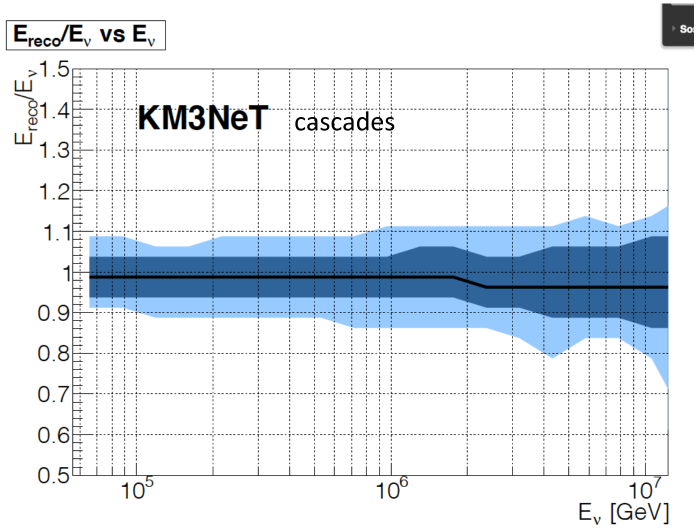
Tracks: very long path (Eμ>1TeV several km)
Neutrino interaction vertex far from the detector
- **Modest energy resolution**

Cascades: small path (E_{casc} >1TeV some tens of meters)
All the energy released inside the detector
- **Good energy resolution**

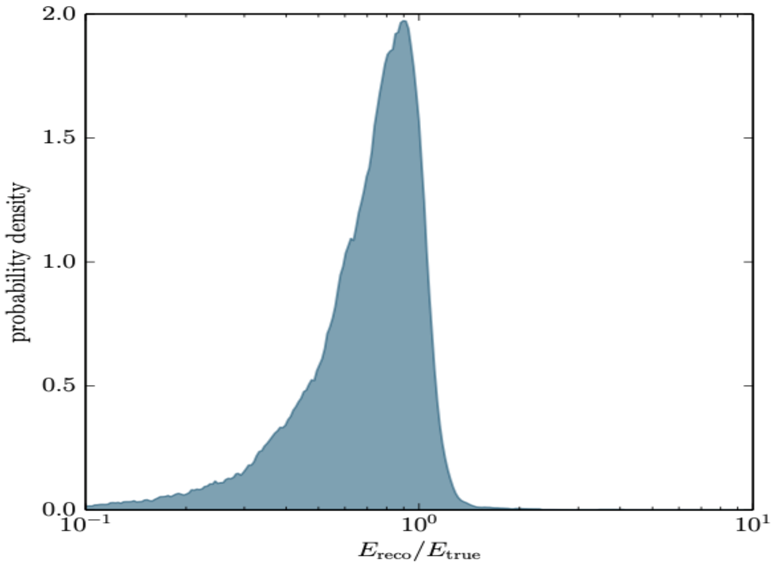


KM3NeT

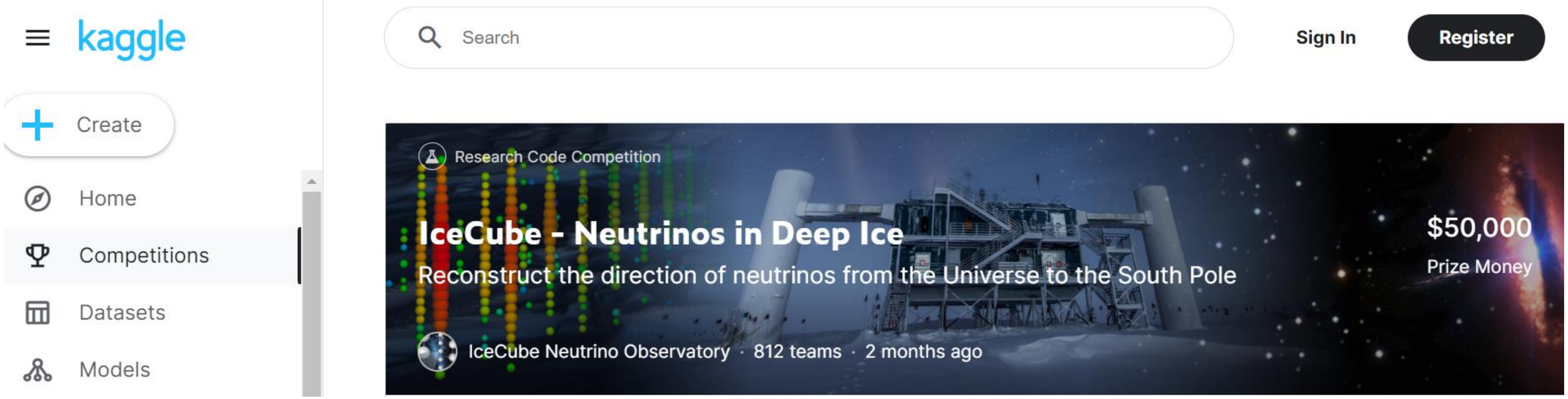




IIC energy resolution for cascades



KM3NeT: AI-driven tracking algos



The kaggle competition IceCube - Neutrinos in Deep Ice ended on April 19 2023, with over 11,000 entries by 901 participants. During the three months competition phase this project attracted active participants from 74 countries, and overall counted 6460 registrants.

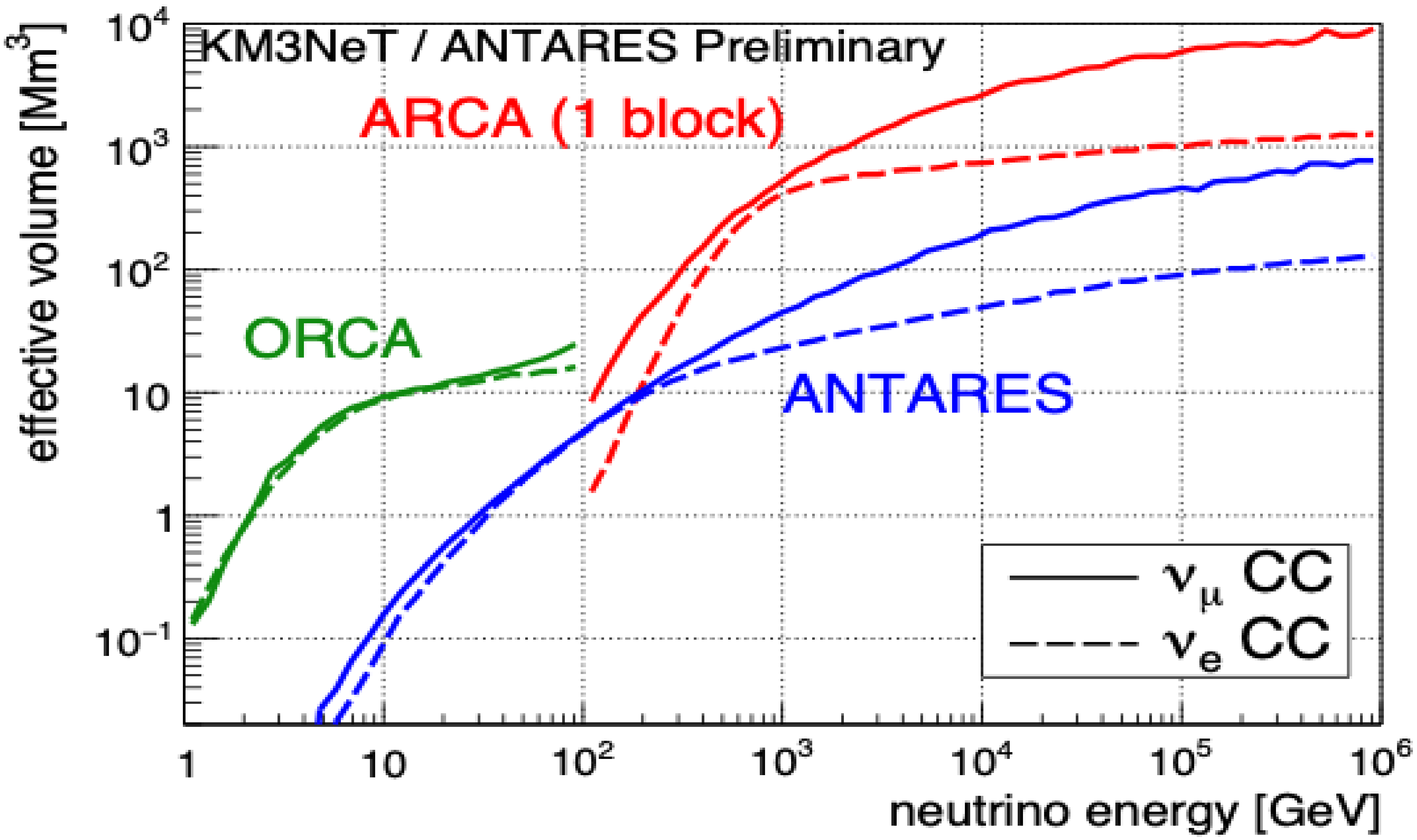
- 1st Place, winner of $18k: Team "Tito"
- 2nd Place, winners of $12k: Team "IceMix" (drhabib,iafoss)
- 3rd Place, winner of $10k: Team "GPUs on Ice"

The Early Sharing Prize ($5k) is awarded to "Datasaurus", and 5x $1k are awarded to the best solution write-ups

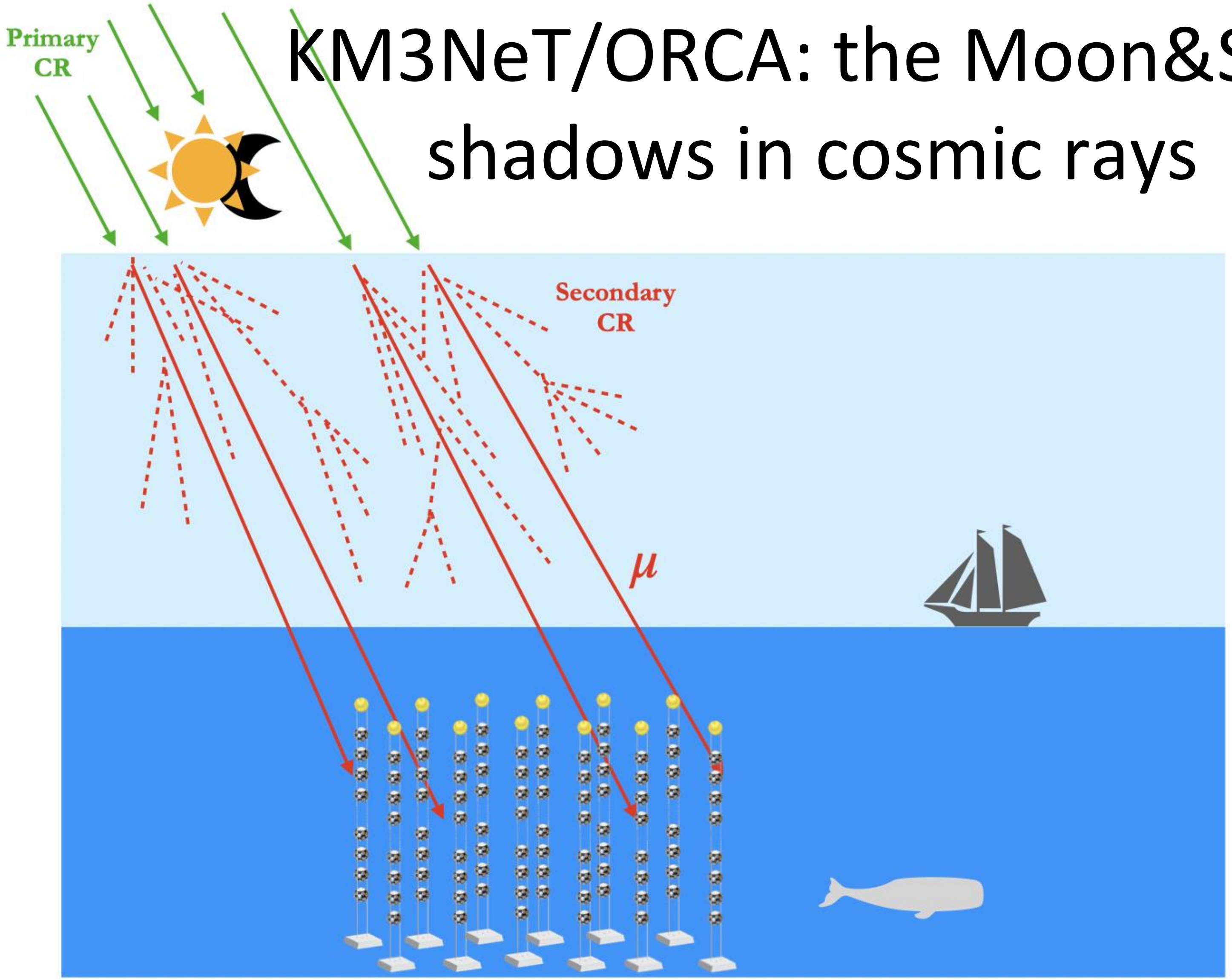
- The top 3 placements share in common, that they all apply so-called "transformers", which is the same architectures that powers the latest generation of large language models such as chatGPT.
- This is a new technique used on IceCube data, and surpasses the quality of previous machine learning based reconstructions significantly.
- All top 3 solutions are able to reconstruct the direction of "track" events (neutrino events that contain an elongated signature caused by a muon from the interaction) to sub-degree resolution.
- This likely opens new possibilities to apply these algorithms to vast numbers of events, if not the entire IceCube data stream at once. Such high precision was until now reserved for select neutrino event candidates that needed to be processed with computationally intensive methods, taking easily minutes to hours per event.
- In contrast, the methods developed during this kaggle competition are blazing fast, and can be applied for all dataset.

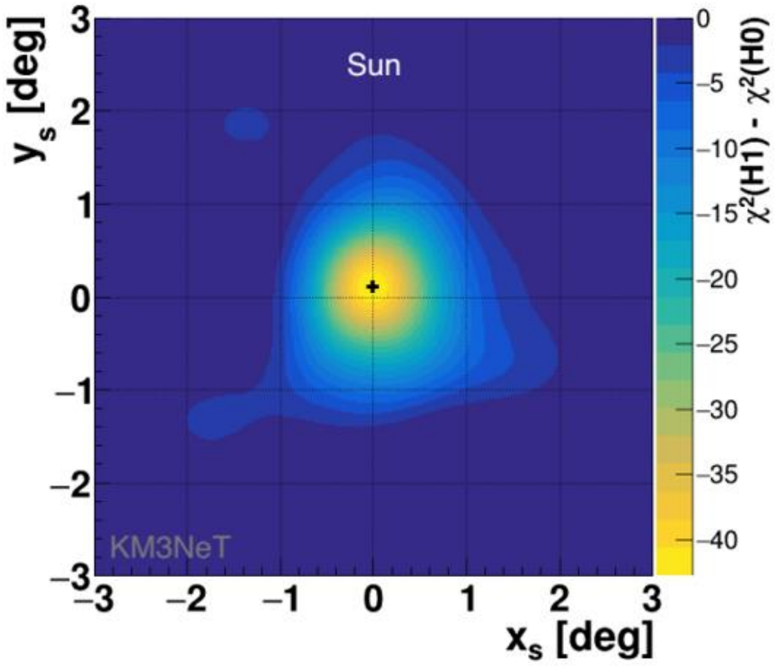
This is future of data analysis and amazing opportunity for students!

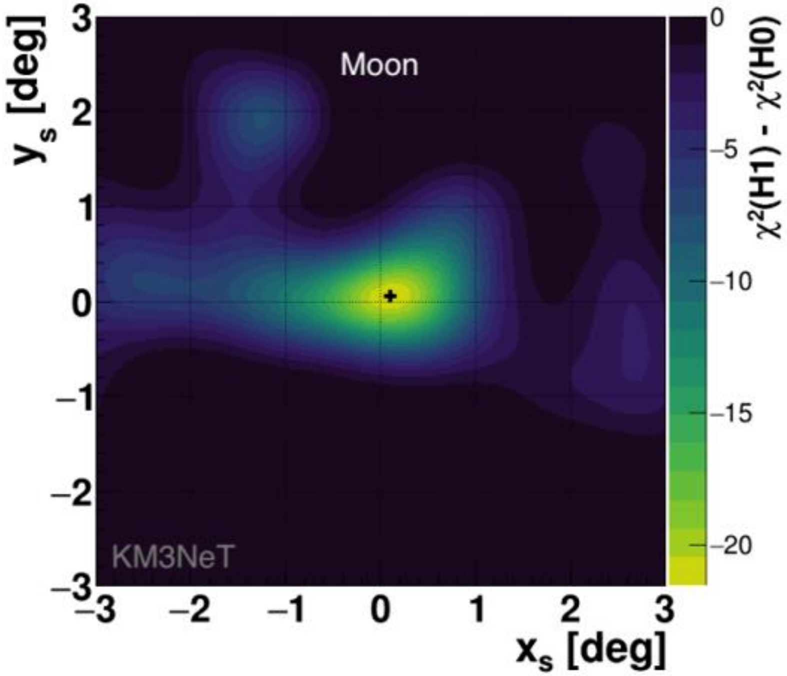
Effective areas: KM3NeT vs ANTARES



KM3NeT/ORCA: the Moon&Sun shadows in cosmic rays

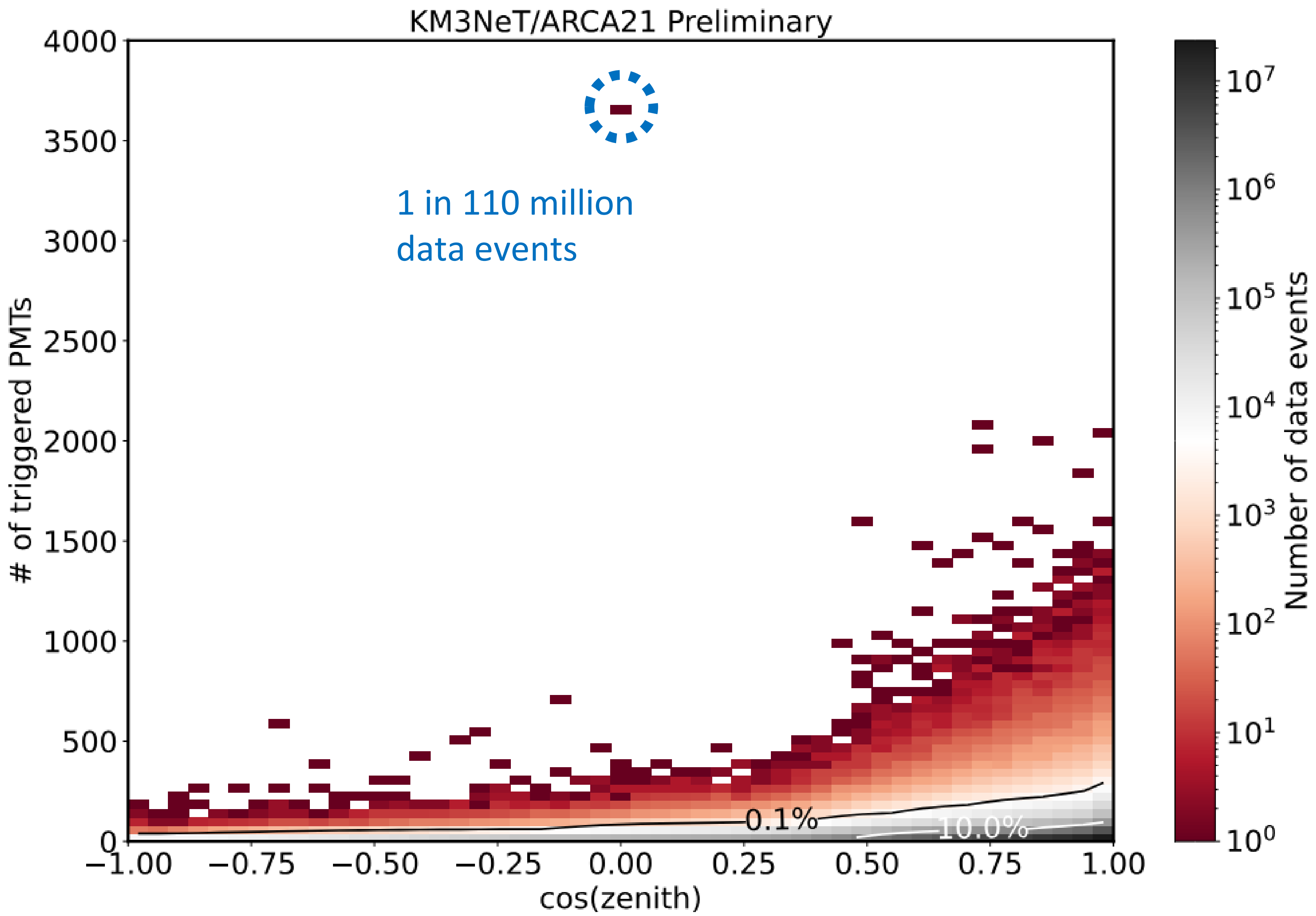






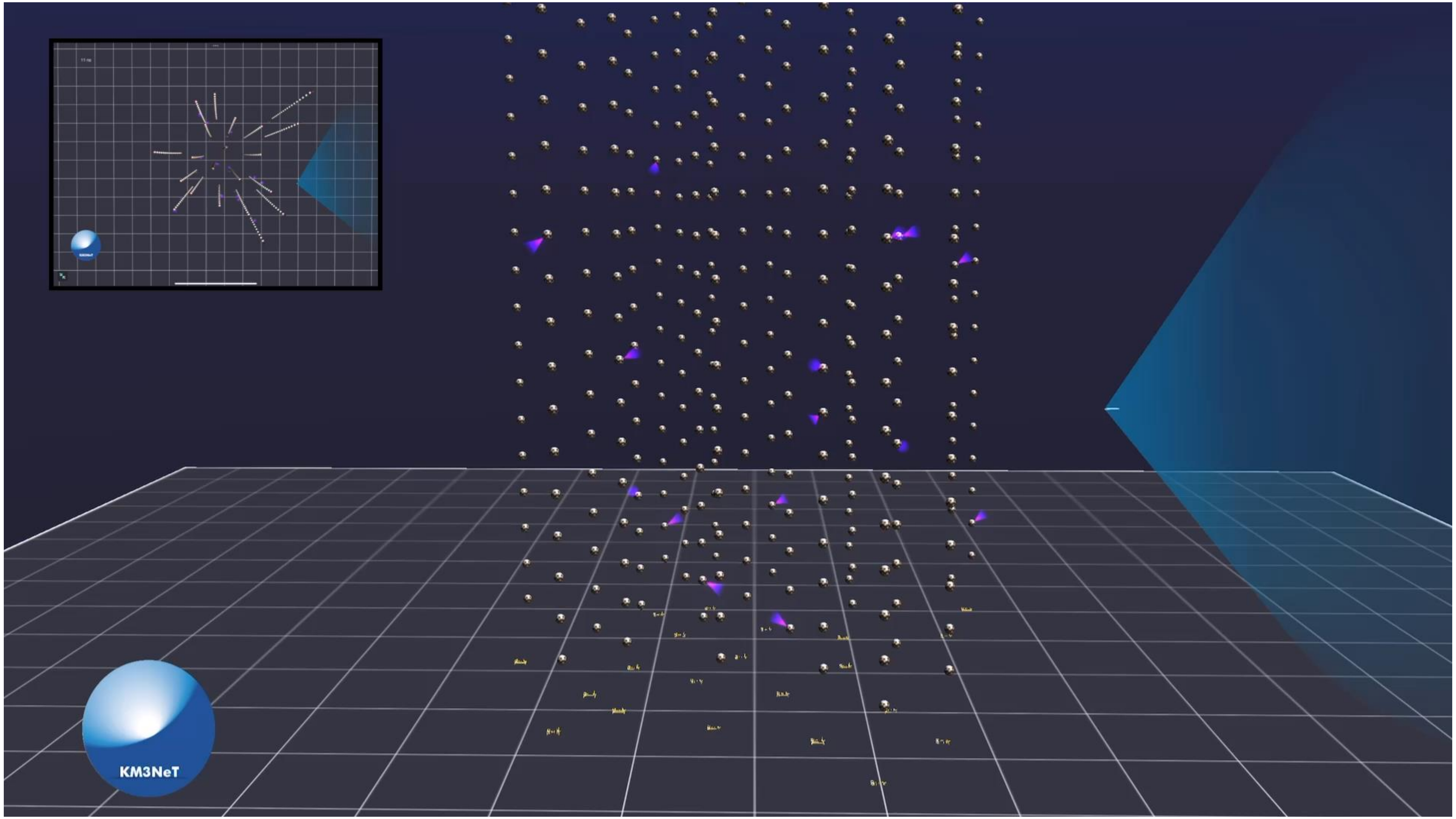
- The Moon and the Sun shadows in the sky distribution of cosmic-ray induced muons measured by the KM3NeT/ORCA detector

Detection of an exceptional event



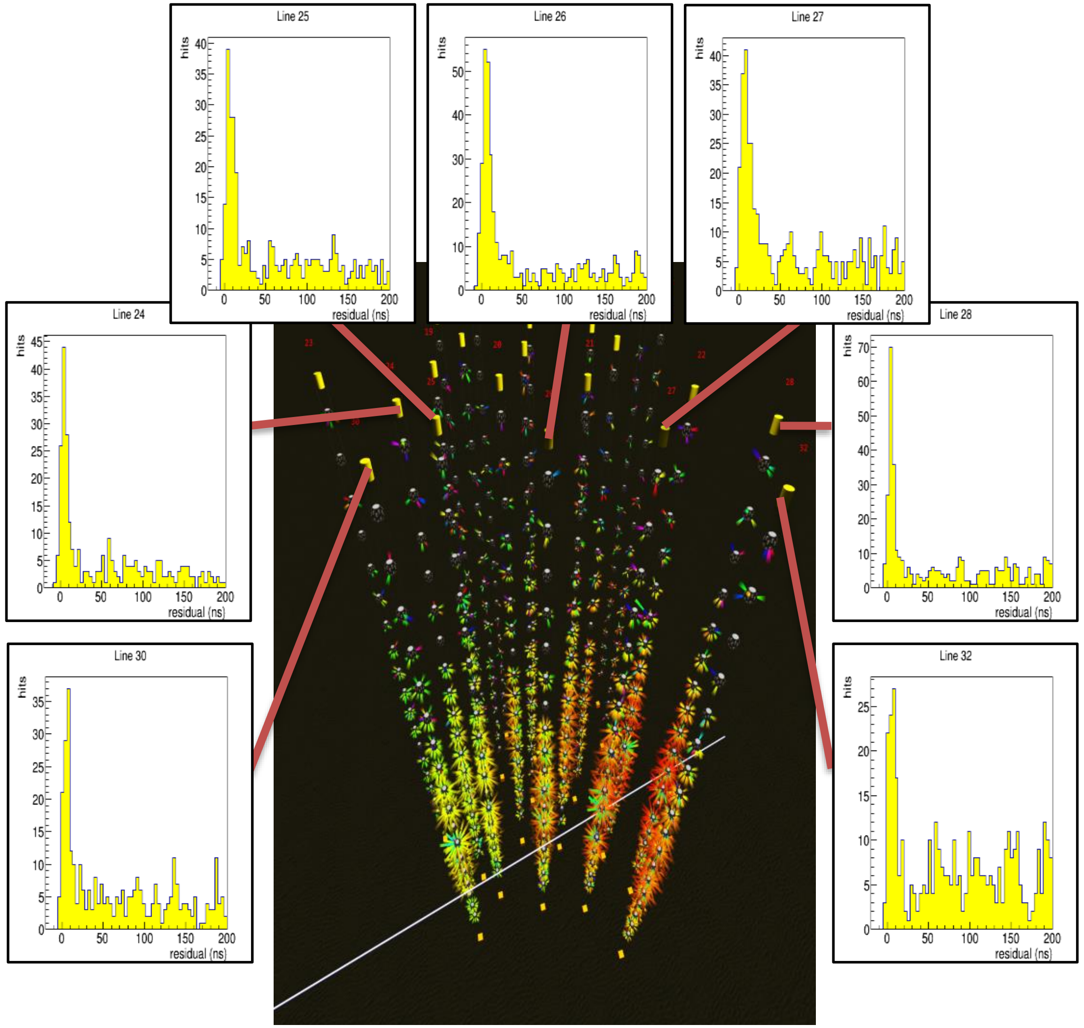
- **Significant event observed with huge amount of light**
- Horizontal event (1° above horizon)
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV

VHE event display

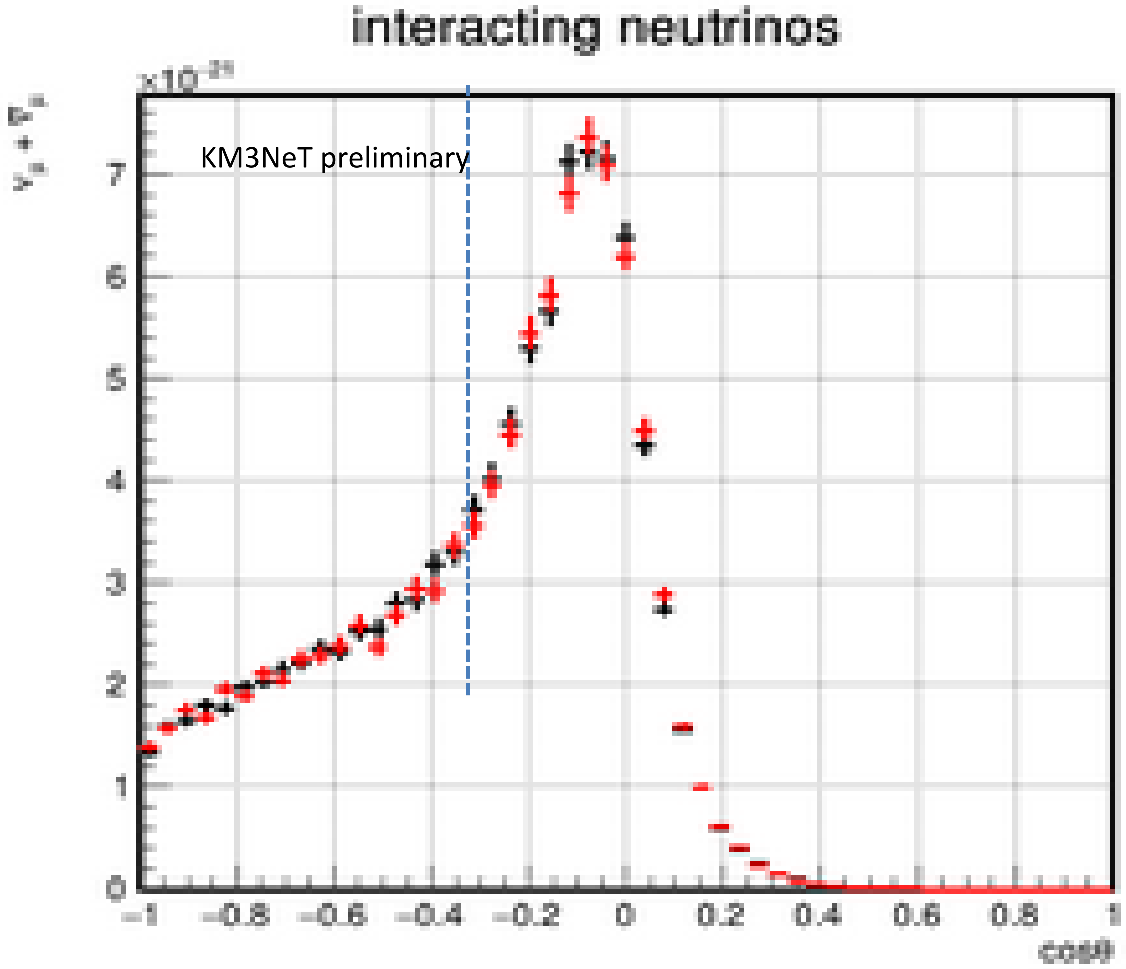


Consistent with muon neutrino

Event is well reconstructed as a high energy muon crossing entire ARCA21 detector

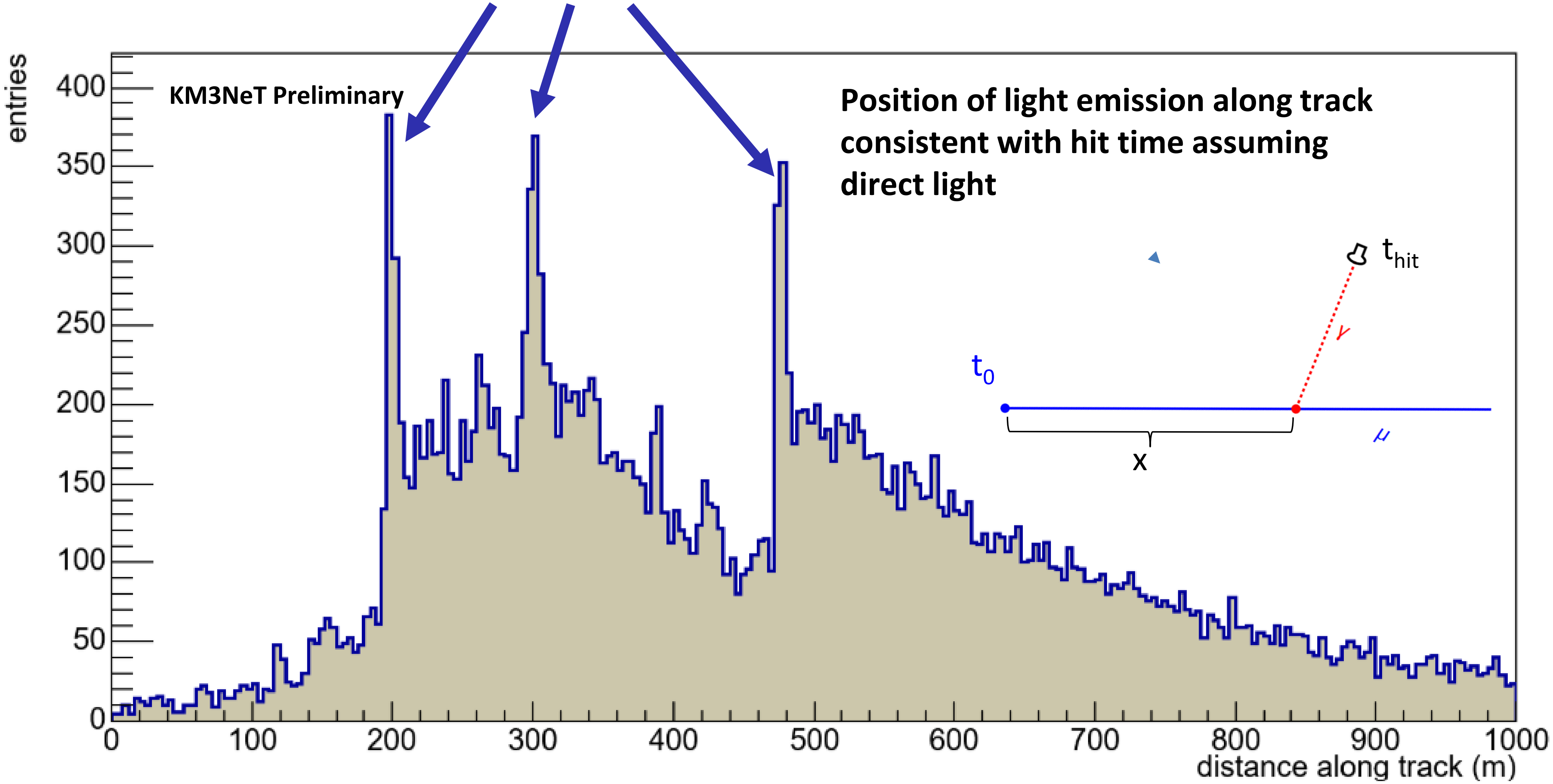


Expected zenith distribution for 100 PeV neutrinos

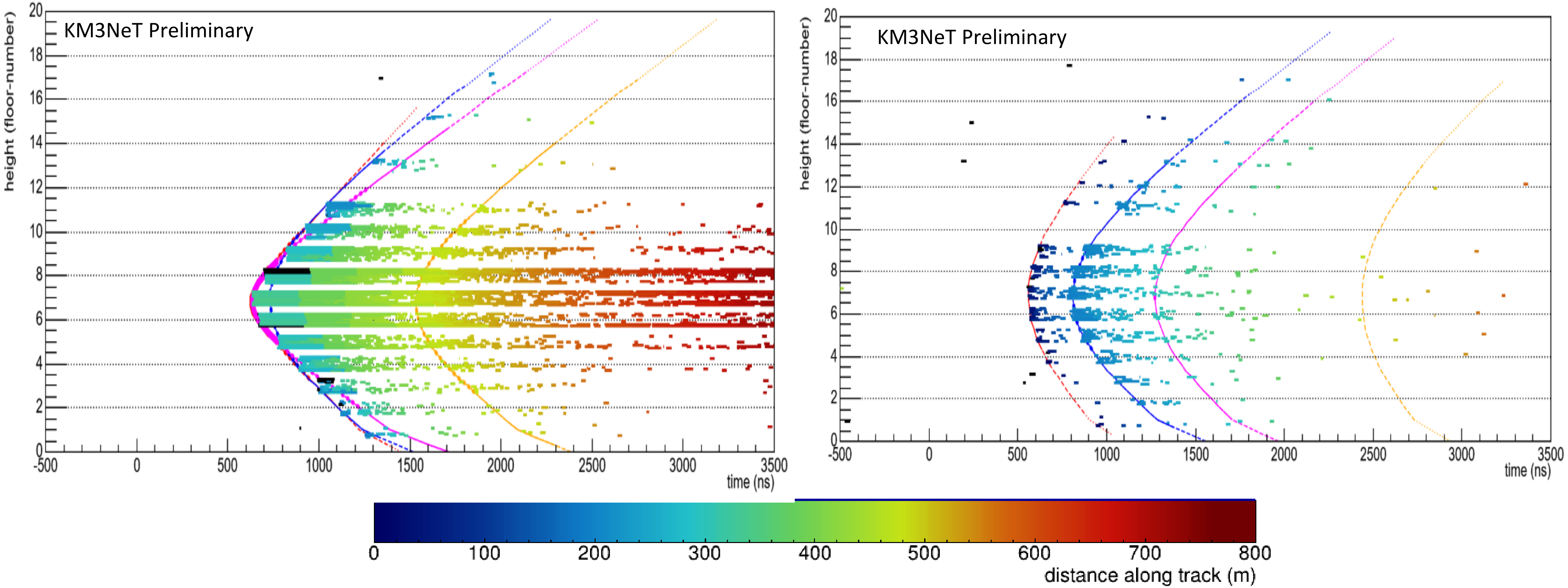


Rich detail

- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons

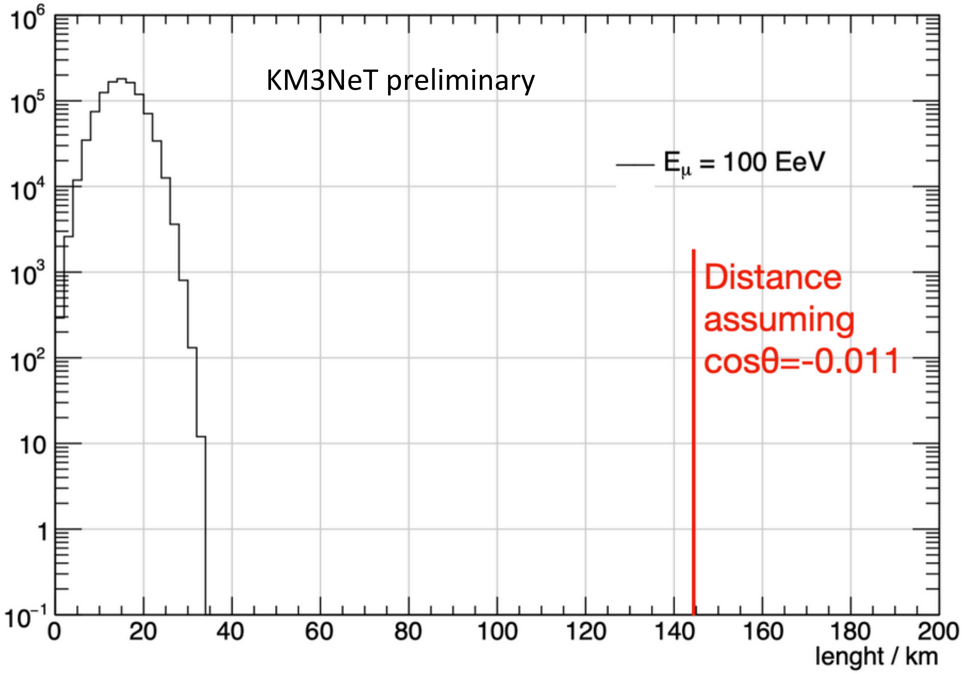


Rich detail

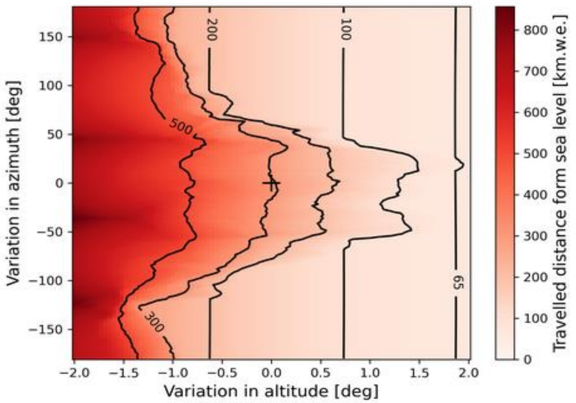


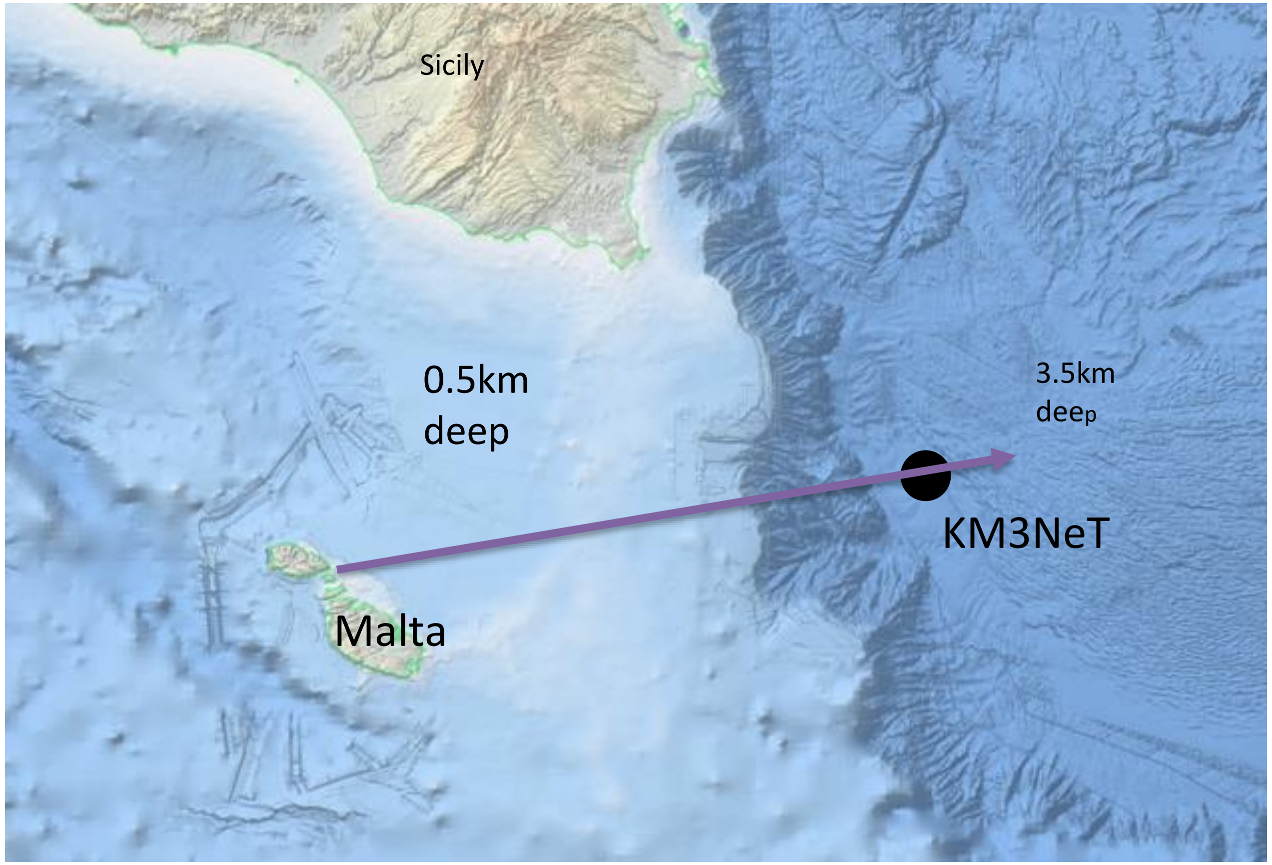
- **Light profile consistent with at least 3 large energy depositions along the muon track**
- **Characteristic of stochastic losses from very high energy muons**
- **Space-time distribution of light consistent with shower hypothesis associated with these energy depositions**
- **Low scattering is key to observing this richness of detail**

Not an atmospheric muon



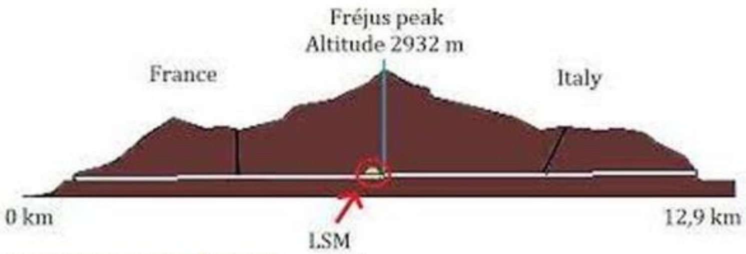
Range in sea water (km)

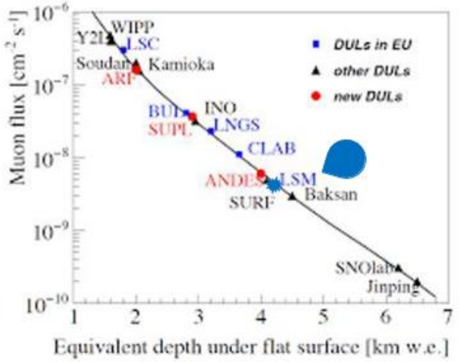




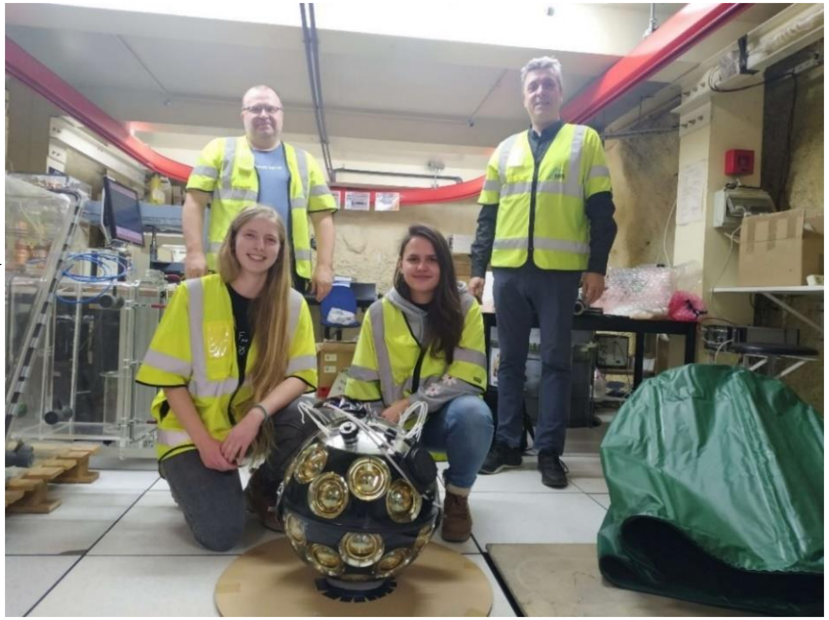
Passes through continental shelf/Malta actual amount of matter is even larger…

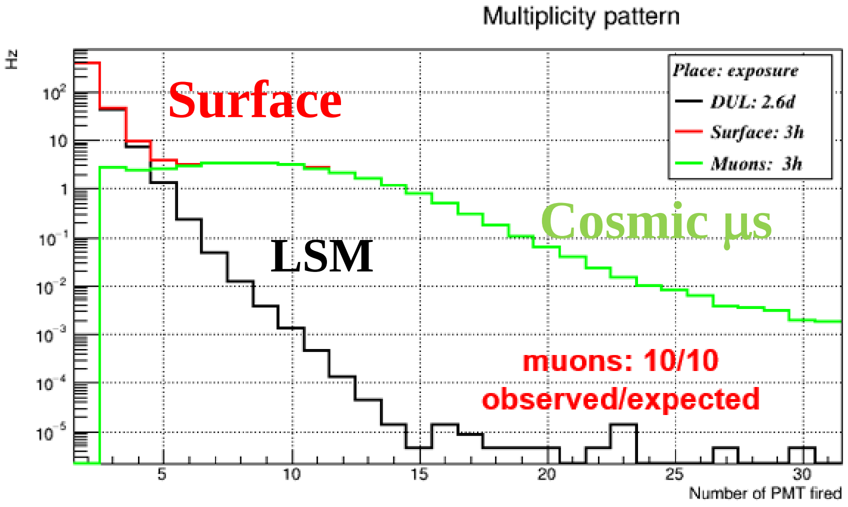
CZ/SK activities in KM3NeT: 1) DOM tests @ LSM





- Our (CZ/SK groups) contribution are radioactivity studies of the digital optic module (DOM).
- **Test measurements in a cosmic-free environment @ LSM provide valuable information for data analysis, model improvement and systematic errors.**
- Two dry tests were carried out (Dec 2023/Mar 2024), unique data on the pure radioactive background DOM without cosmics were obtained, data analysis is in progress.



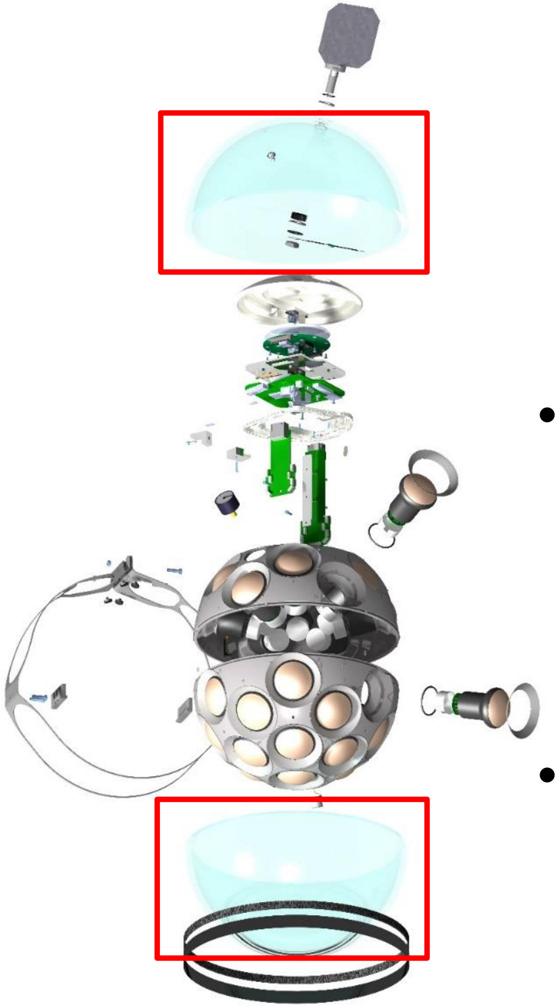


DOM hit multiplicity spectrum

Future plans:

- **Second half of 2024: systematic measurements of new DOMs** and their subsequent tracking.
- **2025:** creation and launch of a facility for conducting **water DOM tests** @ LSM.

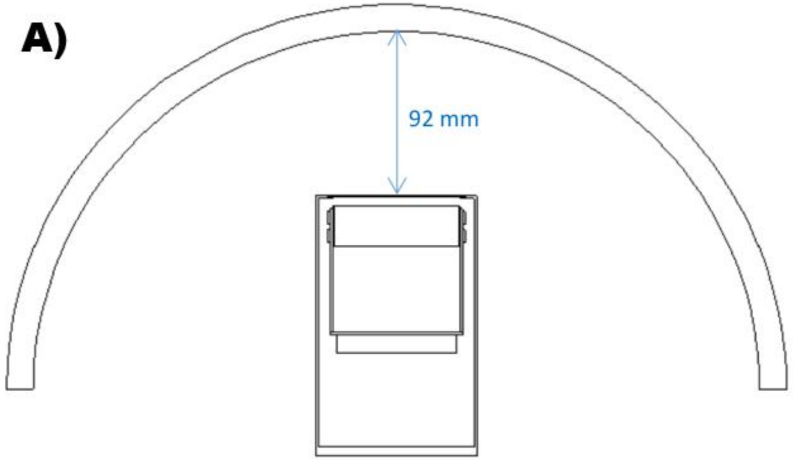
CZ/SK activities in KM3NeT:
2) Screening of DOM components



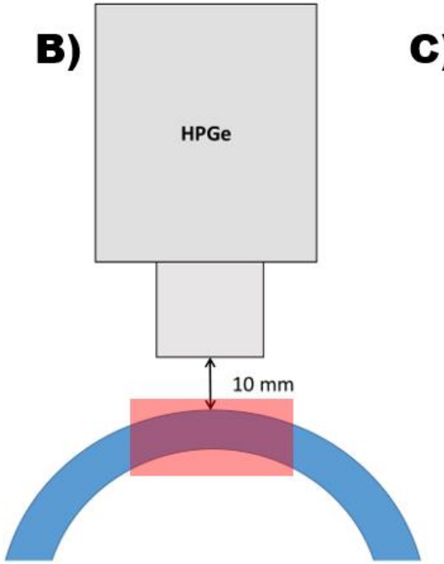
- The DOM is made up of 80+ different components
- Many of them, despite their small size (electronic boards, solder, piezo element, etc.) may contain a noticeable amount of radioactive impurities.
- The goal of the research is to **create a radioactive budget for the DOM** to refine its own background and the accuracy of the simulations.
- In this work, we have measured **several components of the DOM.**

Measurement technique

A)



B)



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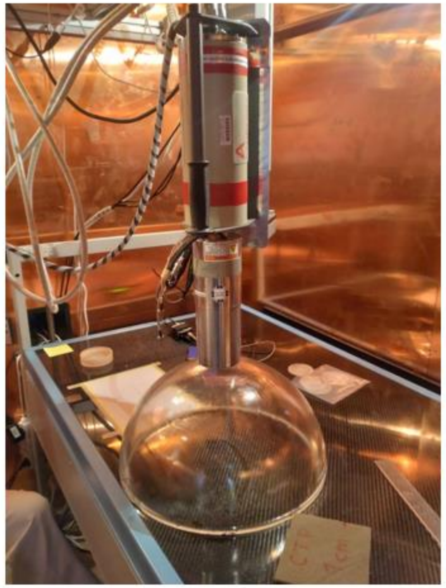
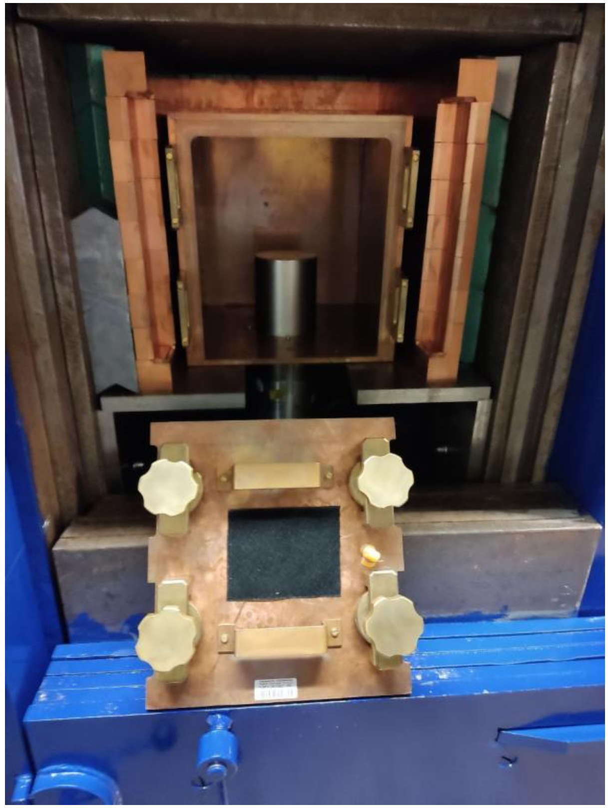
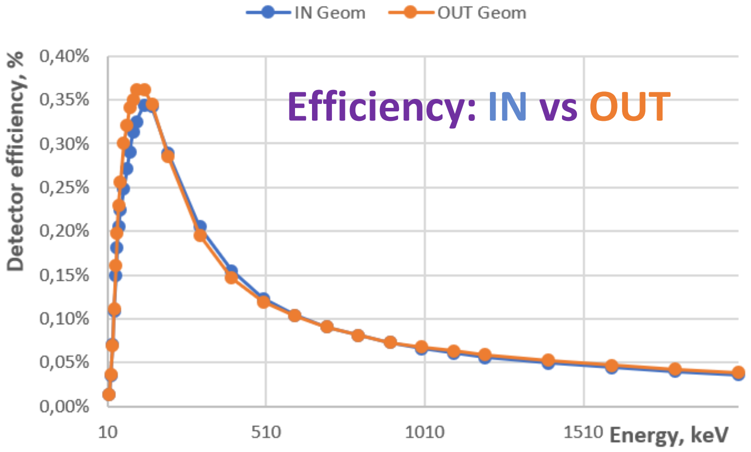






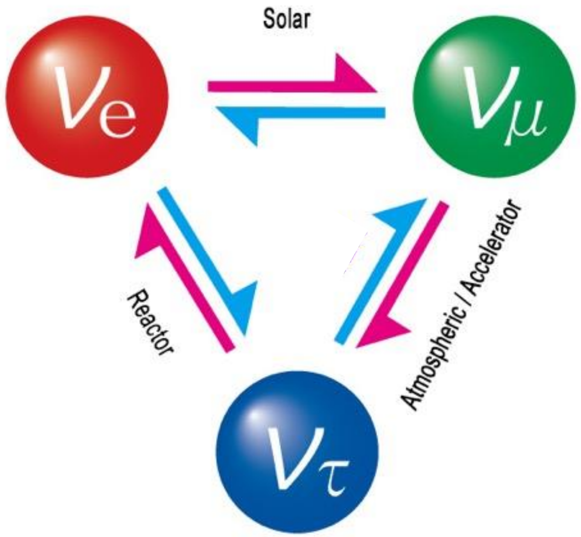
IN vs OUT geometry are close in efficiencies, but GLOBALY vs LOCALY sensitives

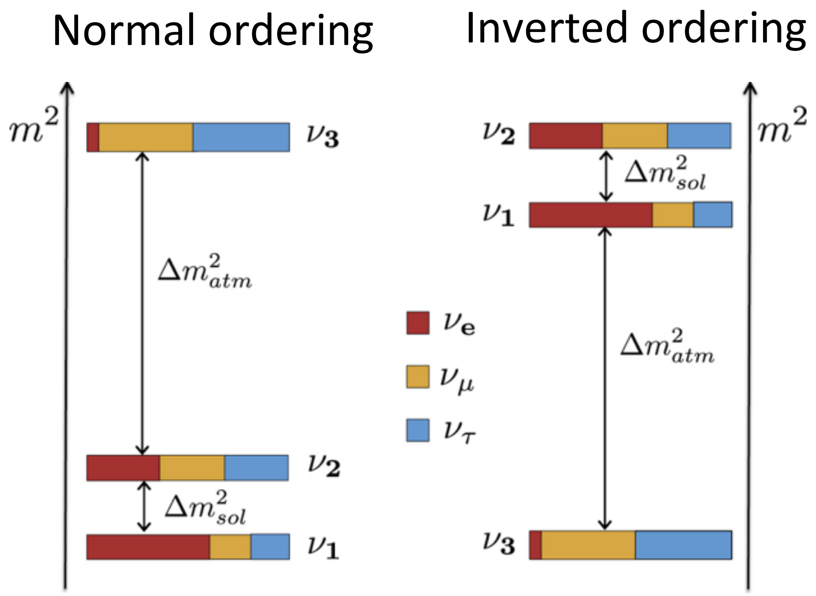
1. All measurements are carried out on special certified installations (HPGe CANBERRA in shielding) in SURO, which carries out standard radiometric measurements on them for government services.
2. The largest sample that forms the maximum background is the outer glass sphere, for which non-destructive analysis in a body chamber in two geometries (IN and OUT) was proposed.
3. Other, smaller samples were measured in more compact setups.
4. The analysis of the results was carried out by certified software from CANBERRA.

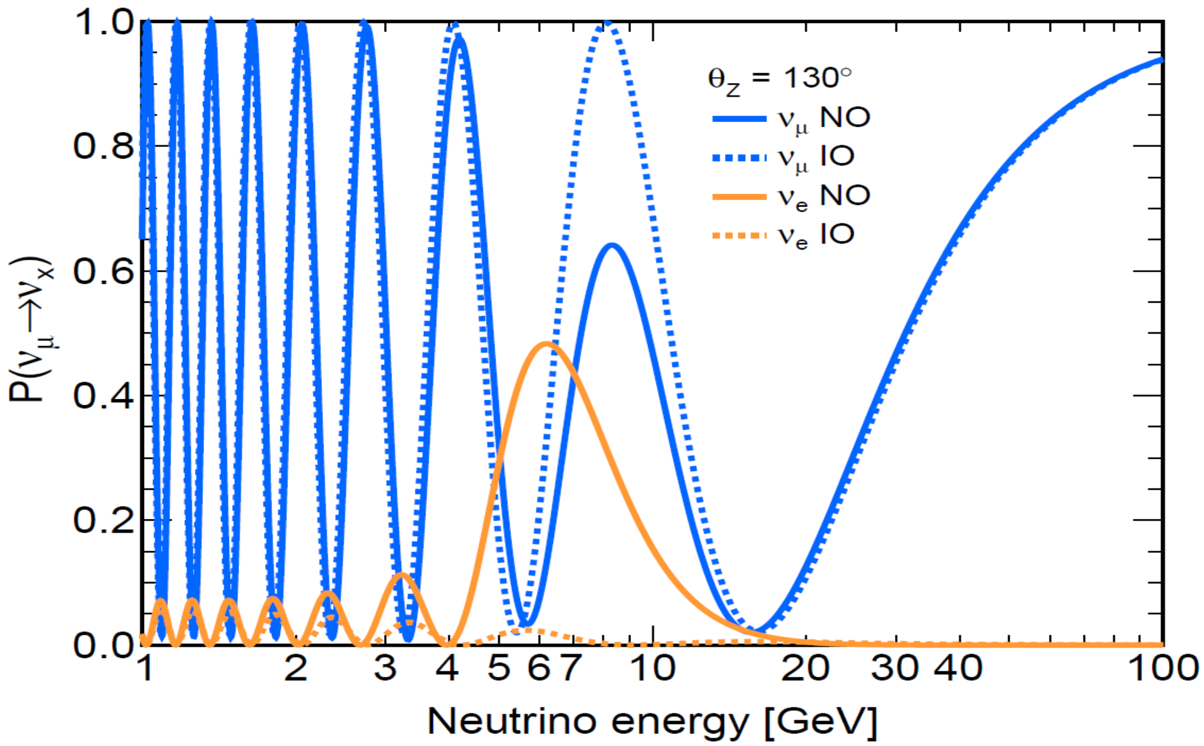
Integrated results and DOM radio budget

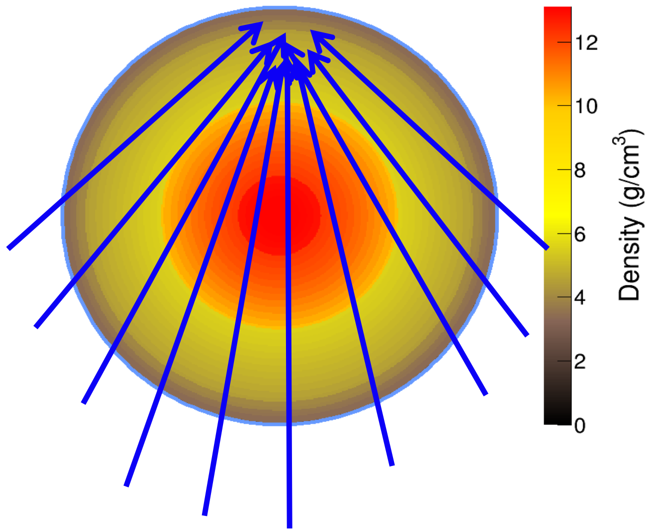
Sample	Activity of chains, Bq per sample								Image/Link
	K40		U238		TH232		U235		
	Val	Err	Val	Err	Val	Err	Val	Err	
11-2024 (PMT KM20835)	2,40	0,13	0,94	0,07	0,25	0,02	0,09	0,01	
12-2024 (PMT KM59654)	2,48	0,13	0,88	0,07	0,36	0,04	0,20	0,01	
PMT average	2,44	0,13	0,91	0,07	0,30	0,03	0,14	0,01	
31 PMT (DOM)	**75,59**	**4,00**	**28,26**	**2,18**	**9,32**	**1,06**	**4,49**	**0,26**	
14-2024 (Power Board)	1,17	0,06	0,53	0,04	0,84	0,08	0,06	0,00	
15-2024 (CLB)	1,08	0,06	0,52	0,01	0,92	0,01	0,06	0,00	
16-2024 (OCTO-L radiator)			0,03	0,02	0,02	0,00	0,01	0,00	
17-2024 (OCTO-L Board)	5,08	0,11	0,91	0,19	1,32	0,11	0,14	0,00	
Glass1 IN	1020,18	7,75	21,55	1,04	8,72	0,27	2,85	0,10	
Glass2 OUT	996,59	11,48	19,89	1,41	9,12	1,96	2,24	0,16	
Glass average x 2	**2016,78**	**19,23**	**41,44**	**2,45**	**17,84**	**2,23**	**5,09**	**0,26**	
Total per DOM	**2099,70**	**23,46**	**71,68**	**4,88**	**30,26**	**3,48**	**9,85**	**0,54**	

Neutrino oscillations with atmospheric neutrinos

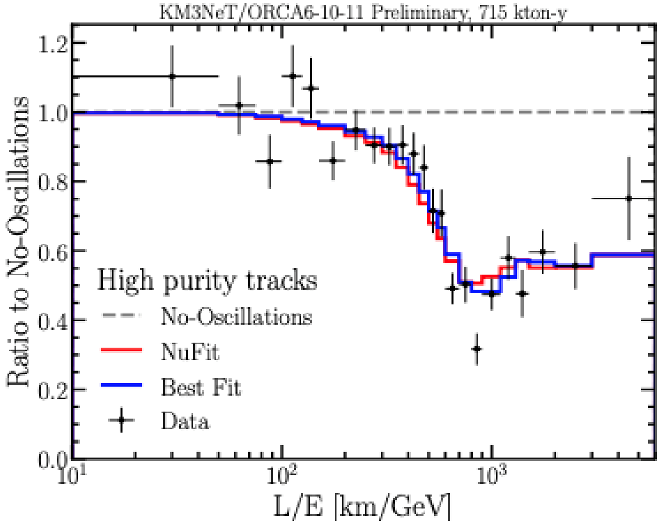


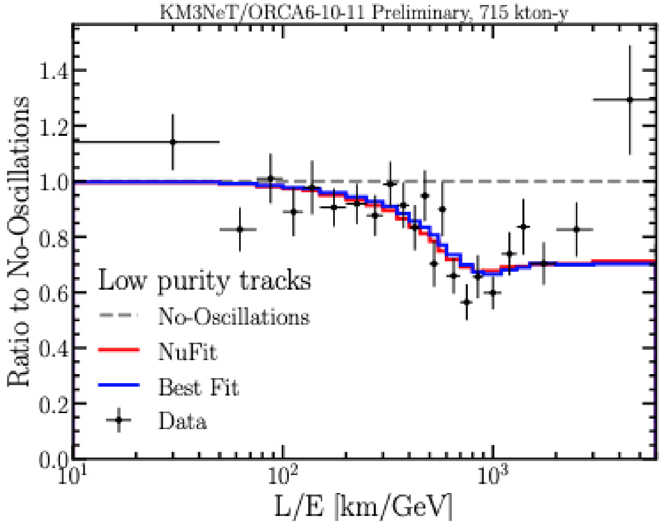


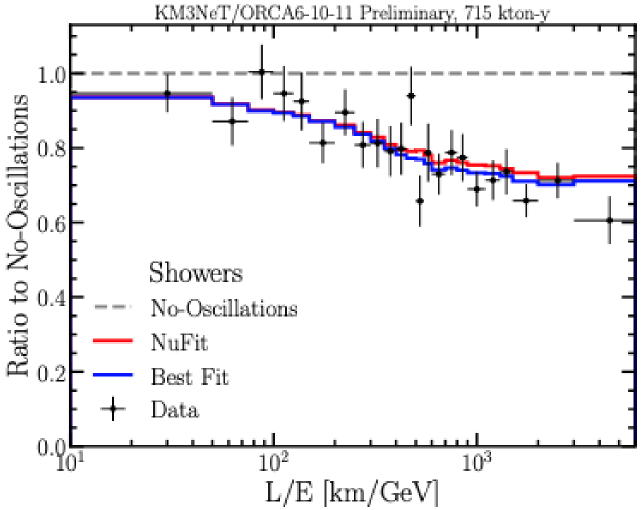


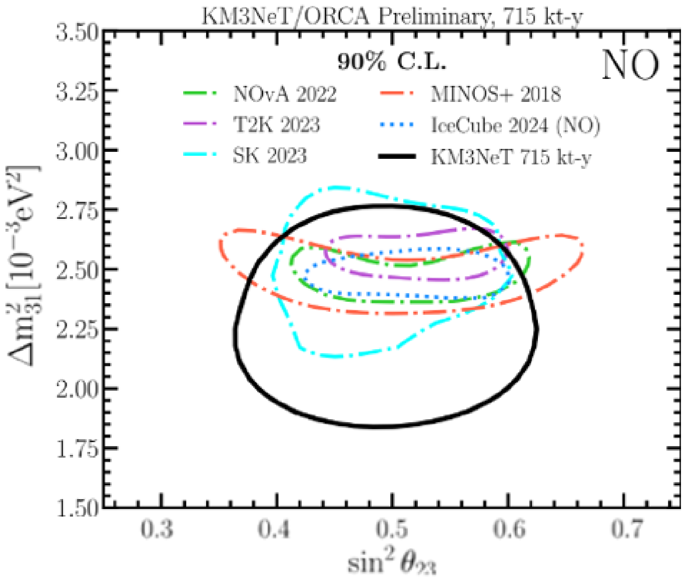


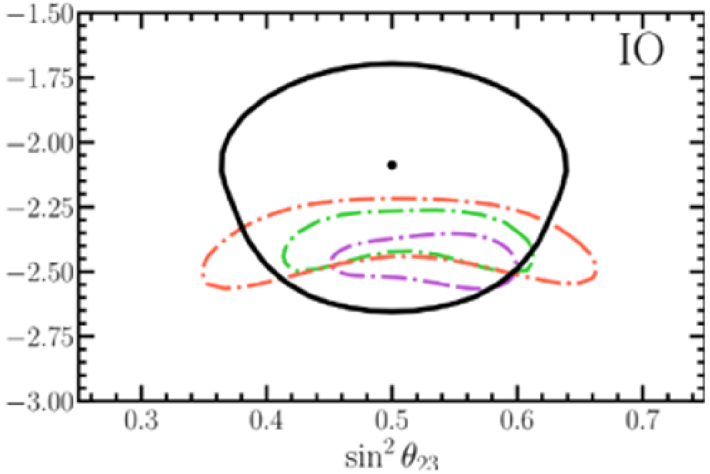
Oscillation results with ORCA6-11











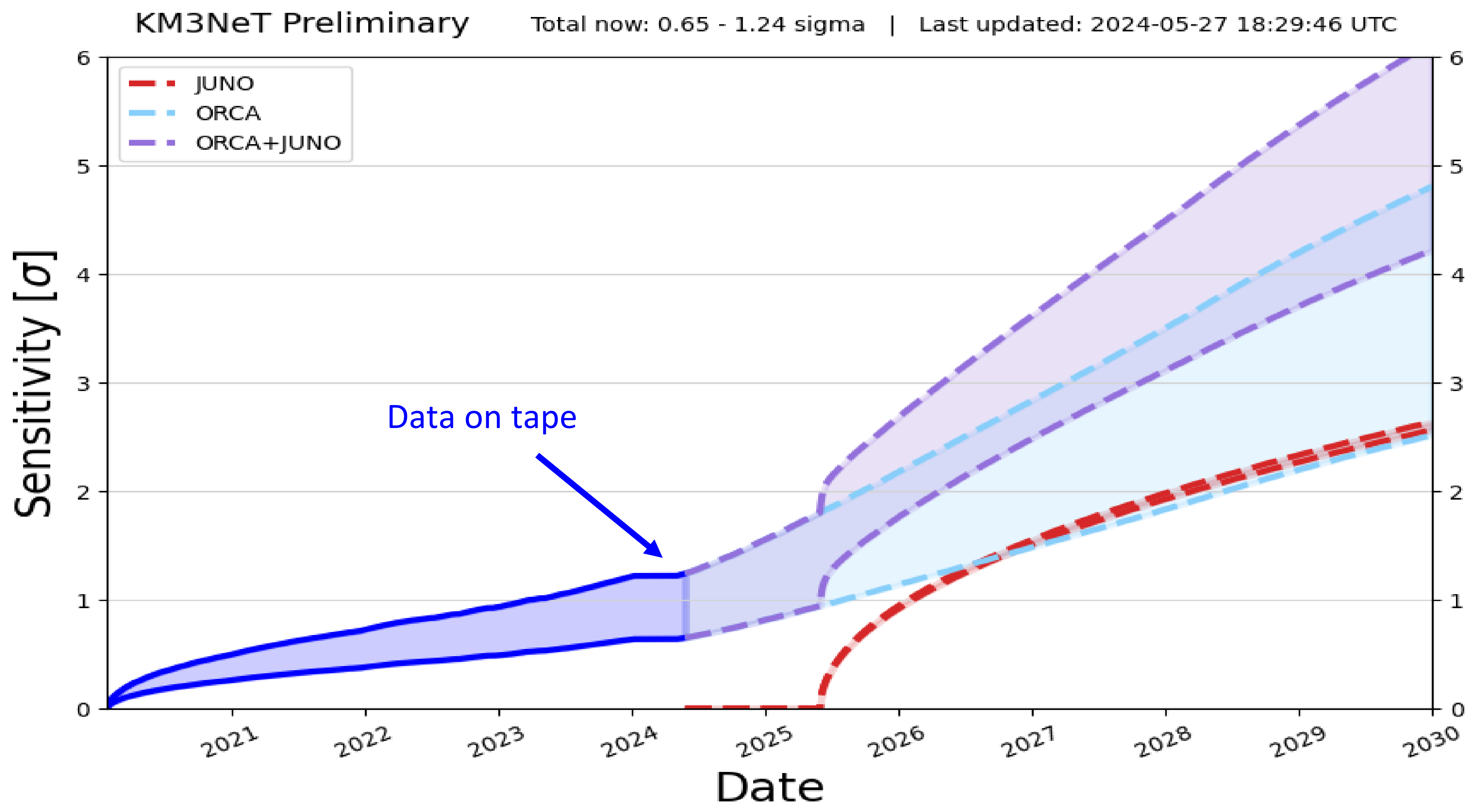
$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\text{eV}^2, & \text{IO} \\ [2.10, 2.37] \times 10^{-3}\text{eV}^2, & \text{NO} \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$

$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$

Slight preference for IO, but not significant

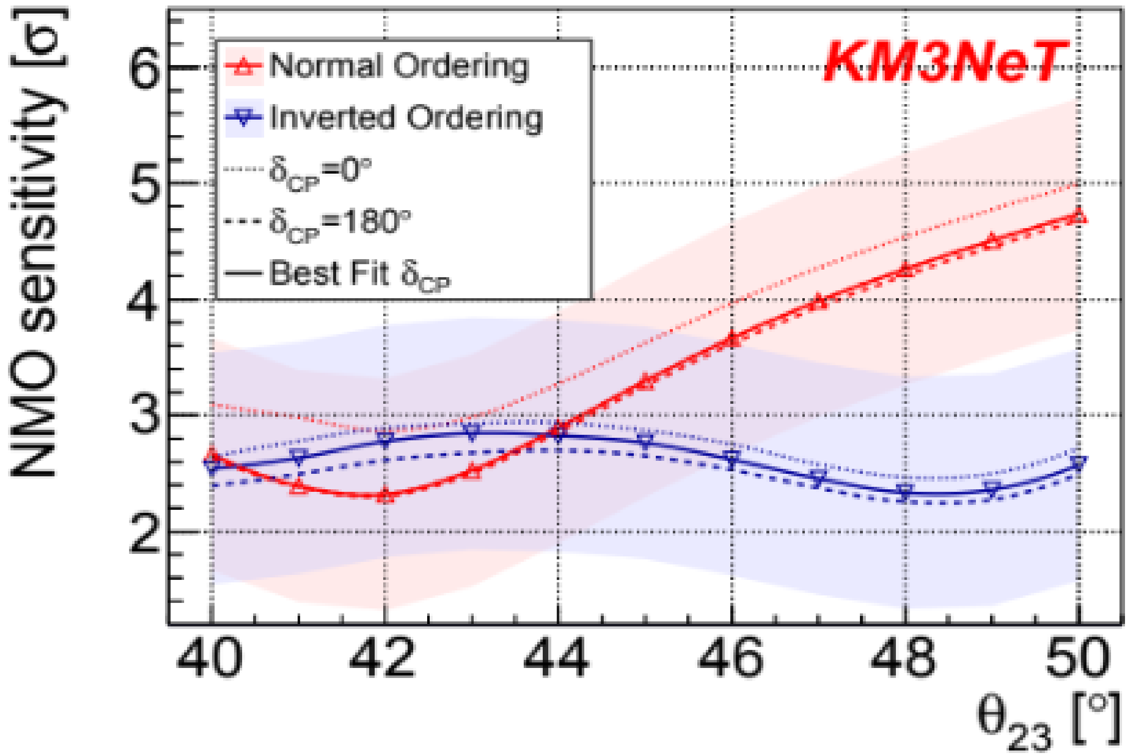
Prospects for neutrino mass ordering



Projections including detector construction schedule show 5σ NMO determination in reach within this decade (with JUNO)

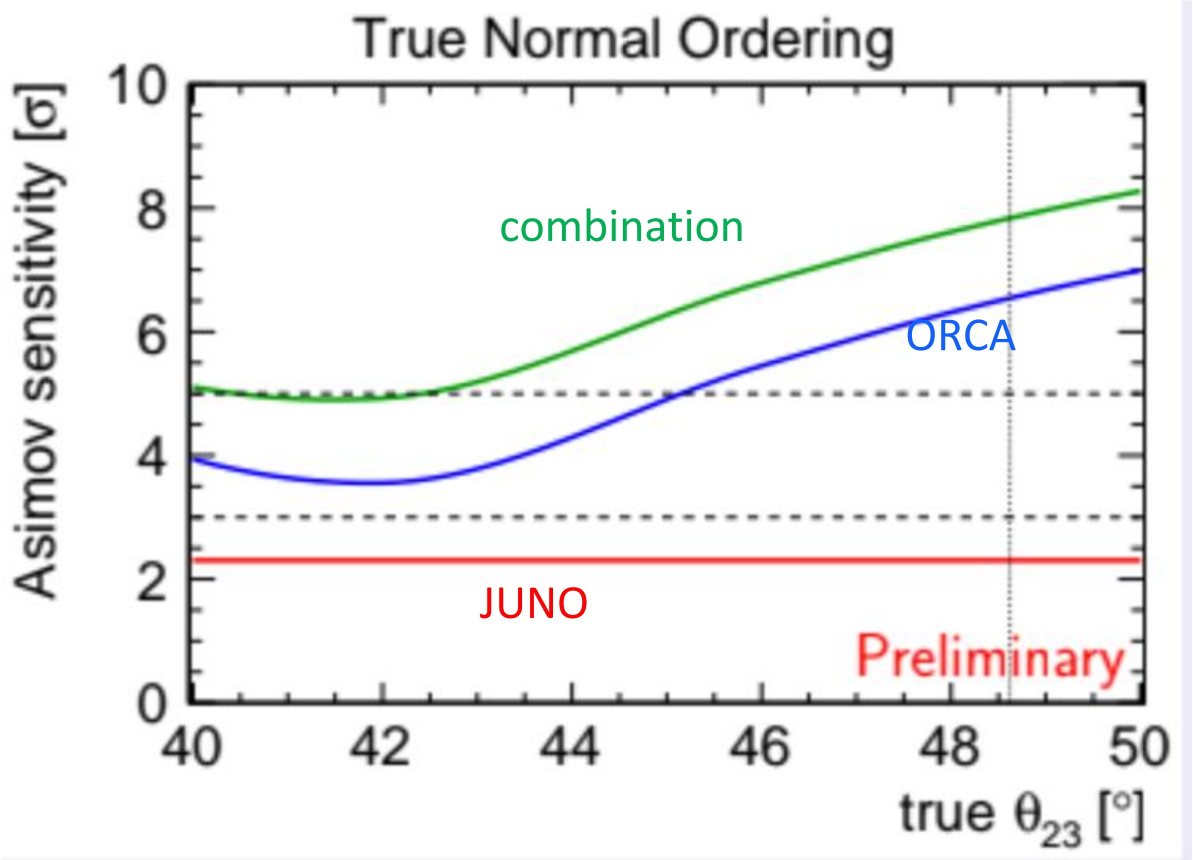
ORCA115: neutrino mass ordering

3 years



2.5-5σ determination of Neutrino Mass Ordering possible in 3 years

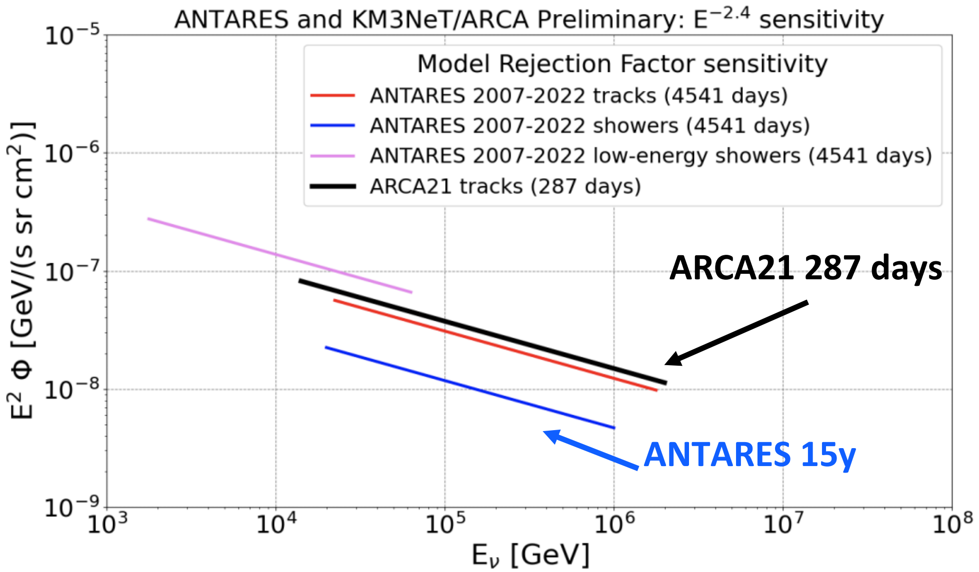
6 yrs & combination with JUNO

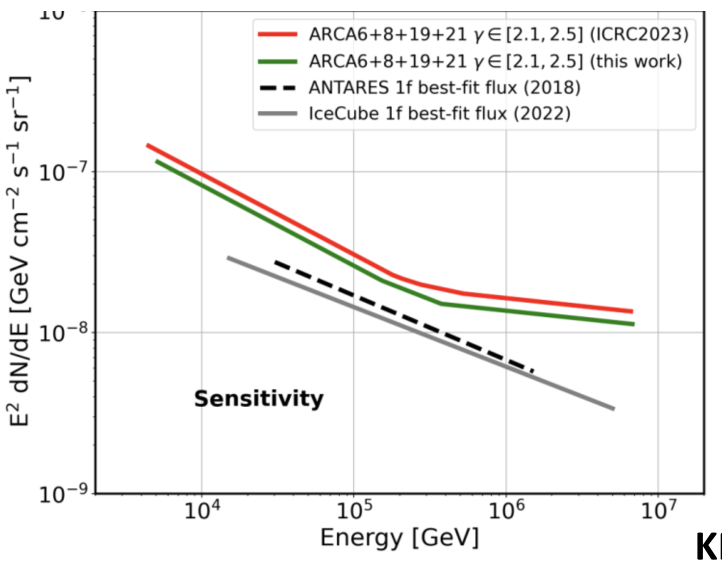


Combination power relies on tension between best-fit of Δm^2_{31}

KM3NeT searches for diffuse fluxes

Full sky

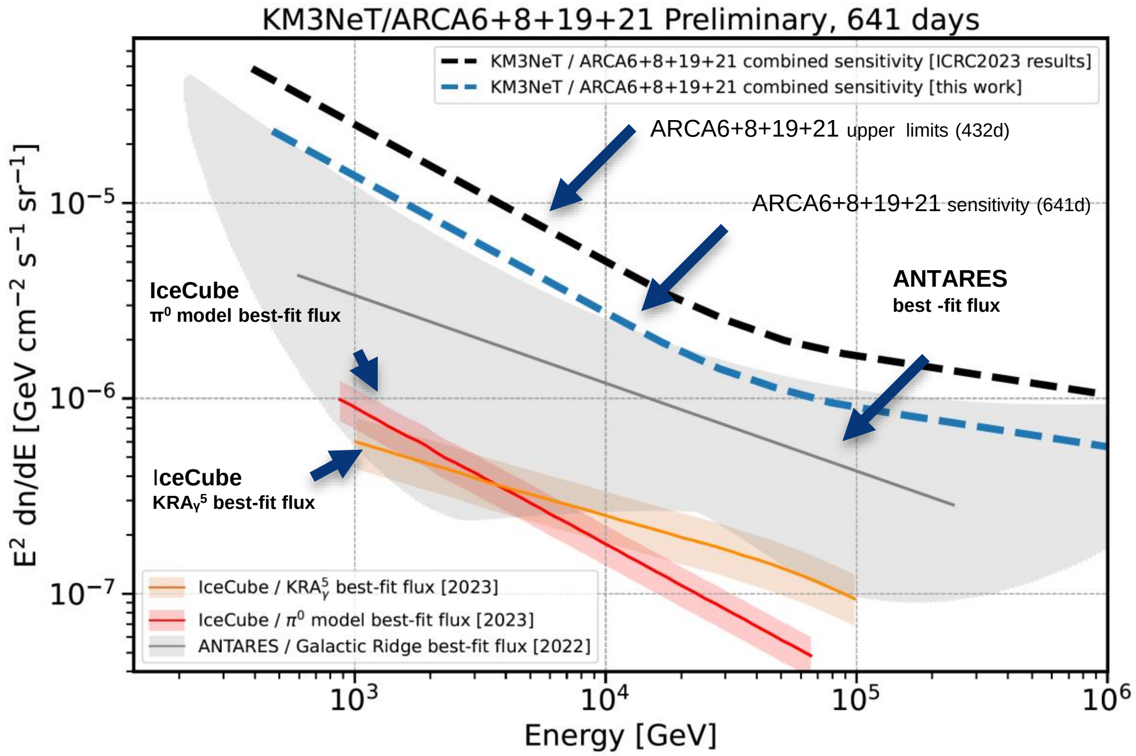




With the data collected until Sept. 2023 same sensitivity as ANTARES 15 years of data for track events

Galactic plane

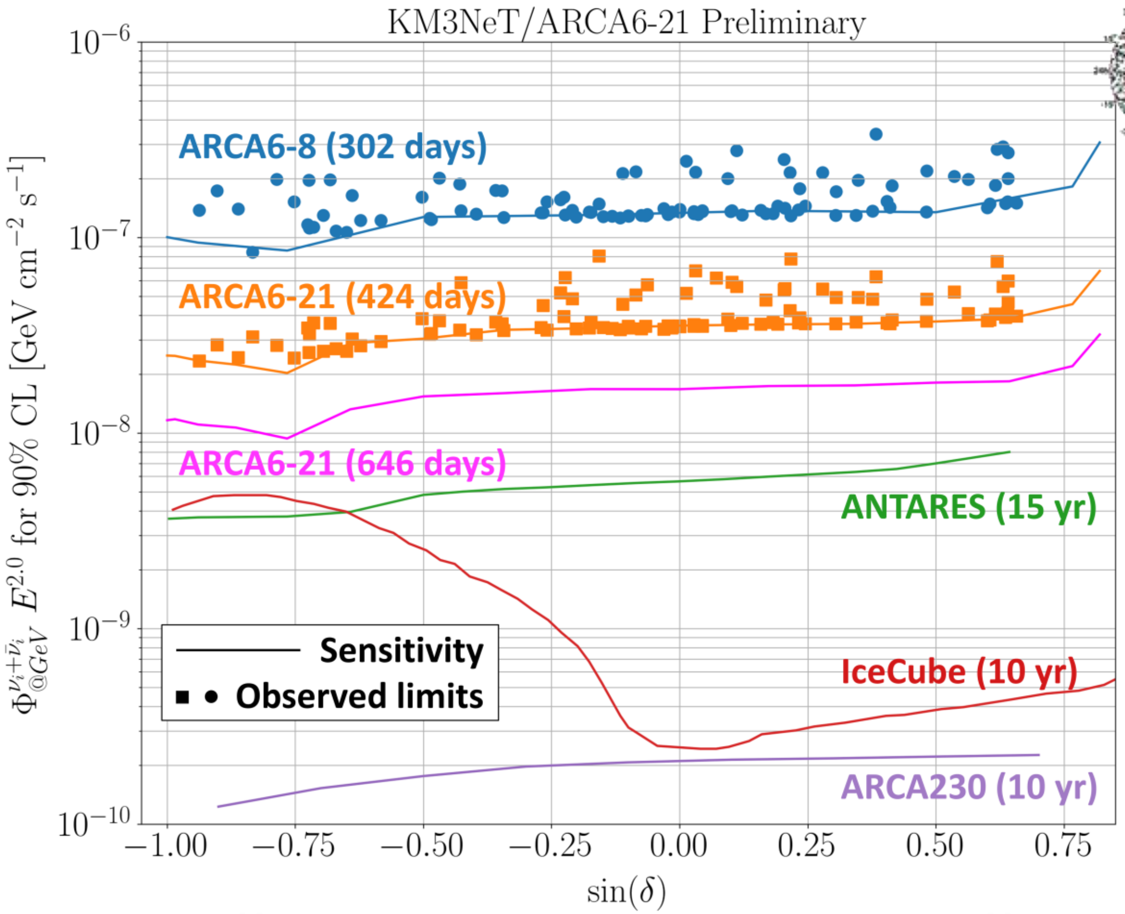
On-Off zone analysis

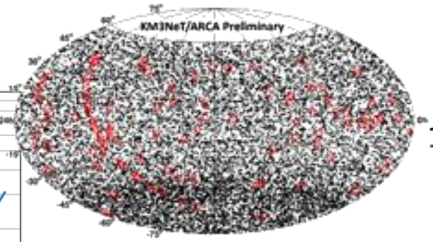


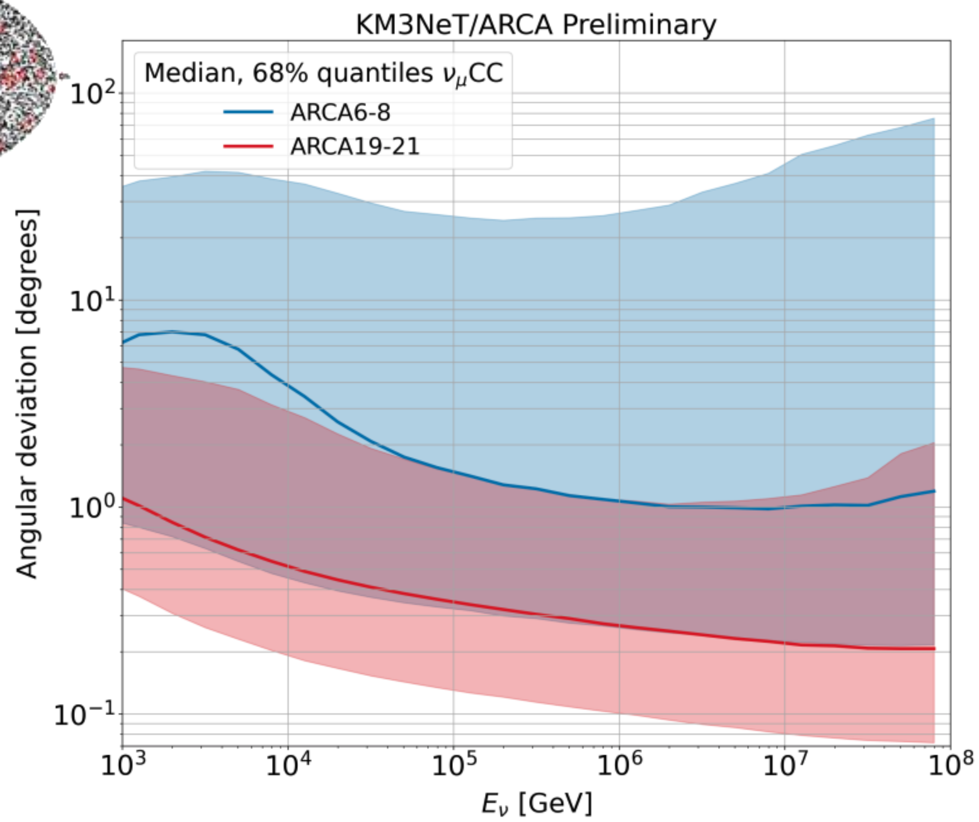
|l| < 31° and |b| < 5° for KM3NeT/ARCA6-8 and
|l| < 31° and |b| < 4° for KM3NeT/ARCA19-21

KM3NeT/ARCA rapidly approaching ANTARES/IceCube sensitivities

KM3NeT point source searches







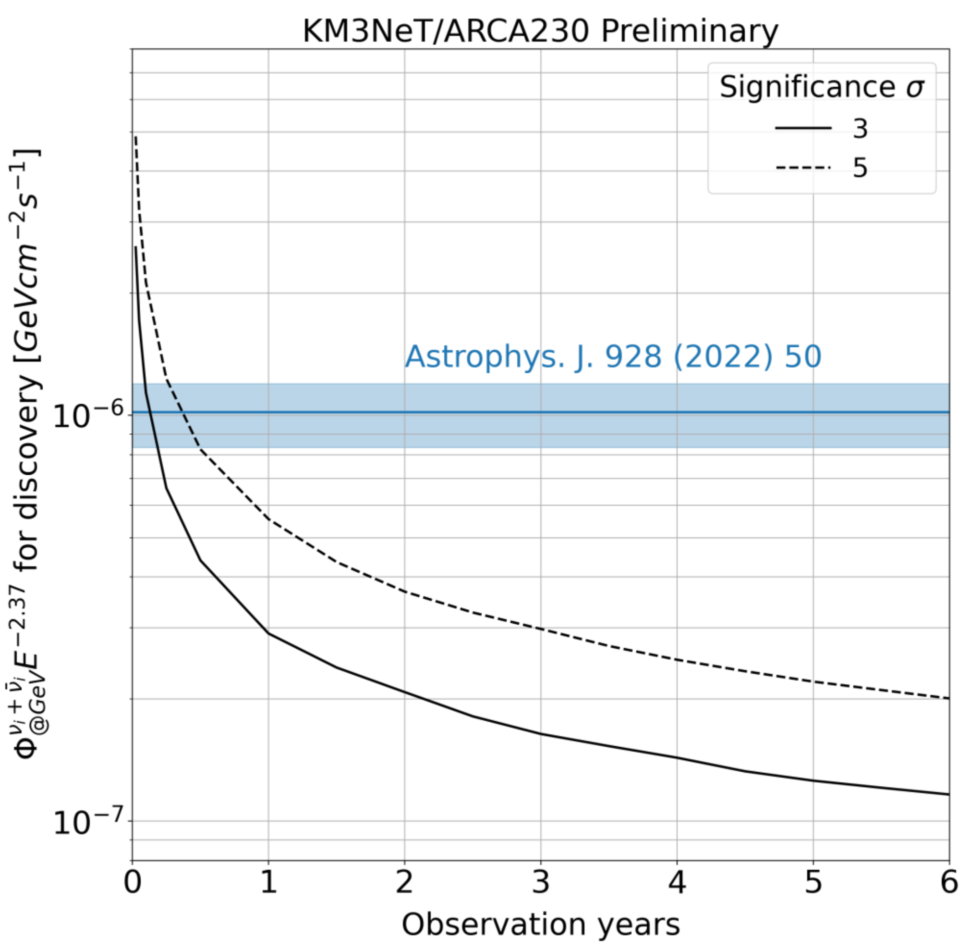
Angular resolution (tracks)

KM3NeT upper limits are quickly reaching the ANTARES 15 year limits

Angular resolution improves as detector grows

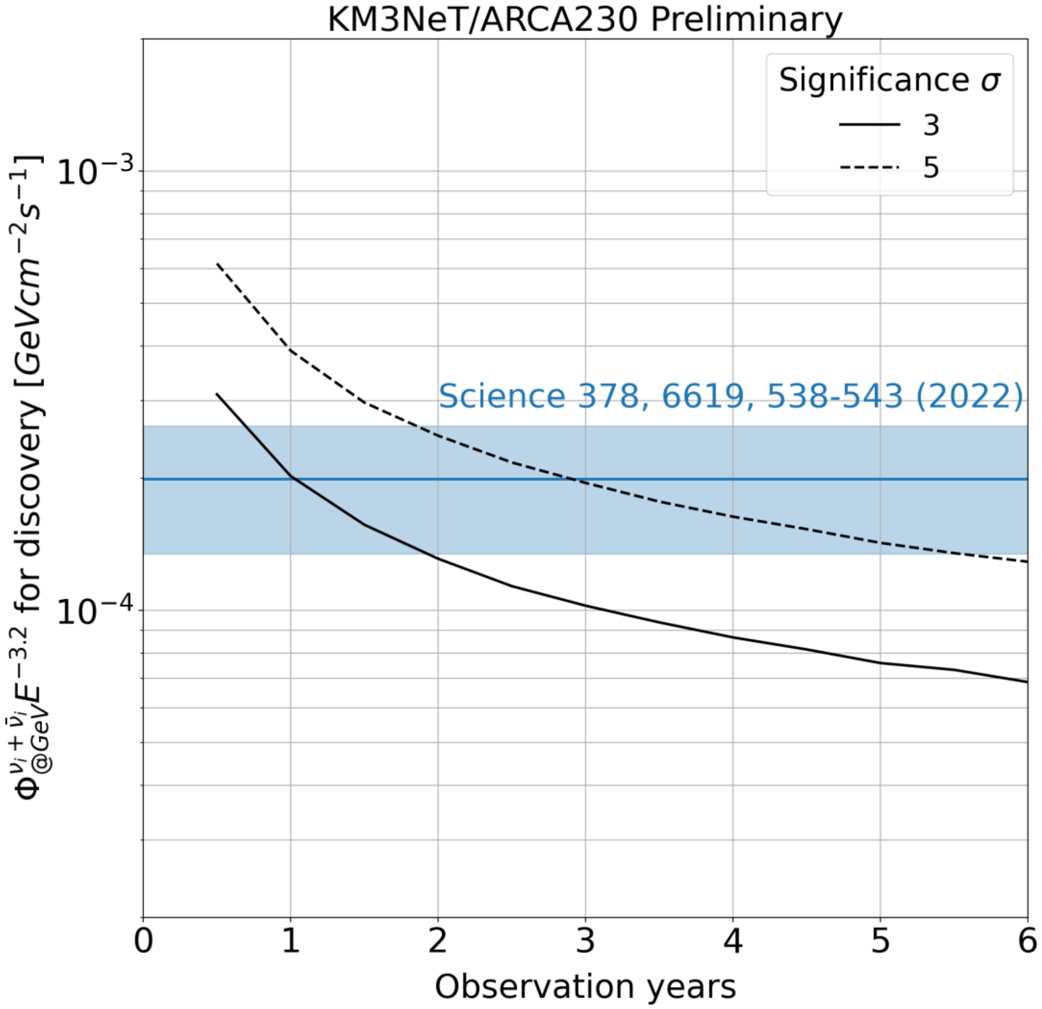
ARCA23 expected sensitivities

Diffuse flux



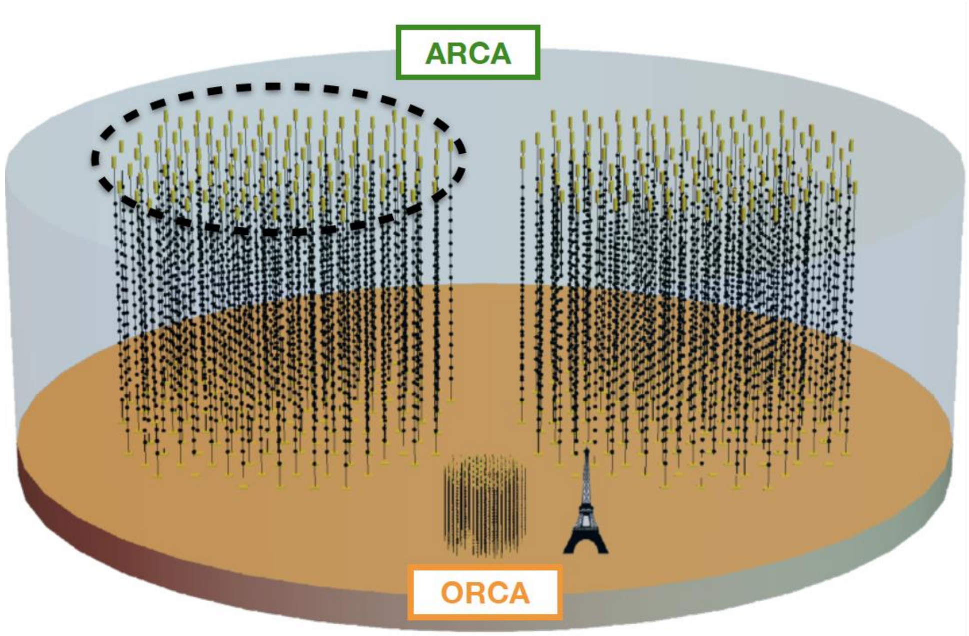
5σ in ~ 0.5 year

NGC1068 (M77) AGN



3σ in one year

Multi-messenger program



Send neutrino alerts to external communities

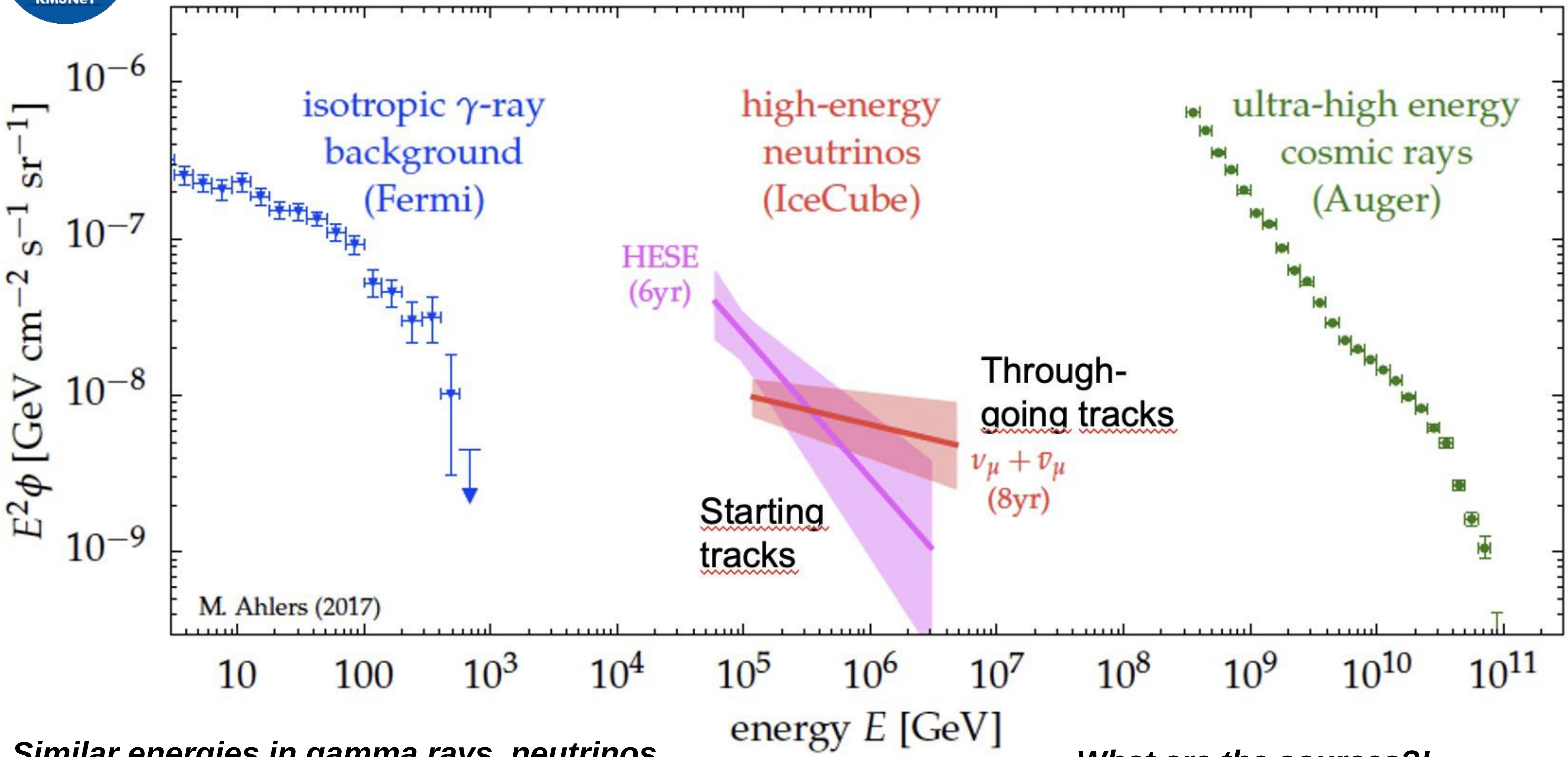
Receive alerts from external communities

Main followers

Receiving alert system operative ☞
Real Time Analysis platform already active from Nov 2022 in ARCA/ORCA

Sending alert system under test ☞
High-energy neutrino alerts will be sent in real-time (<20 s) by end of 2024.

Multi-messenger diffuse flux



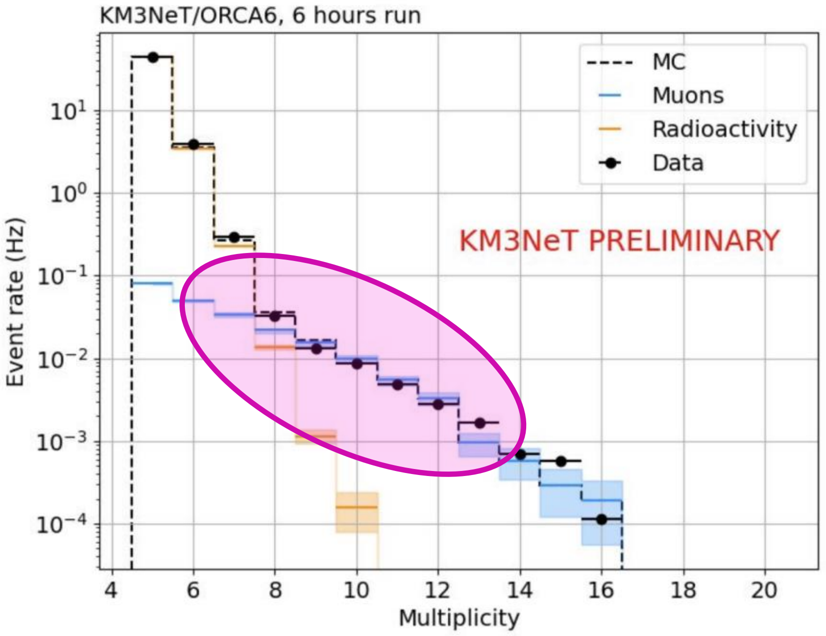
Similar energies in gamma rays, neutrinos & cosmic rays injected into our Universe

What are the sources?!

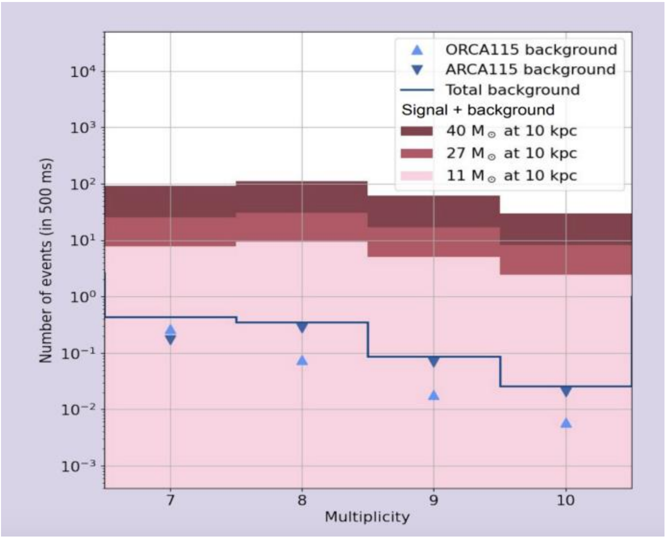
Single DOMs -> Supernova detection

- 7 kHz random background, mostly from ^{40}K decays
- Constant natural source to calibrate the charge and timing of PMTs
- Can use single DOM variables to search for supernova neutrino bursts

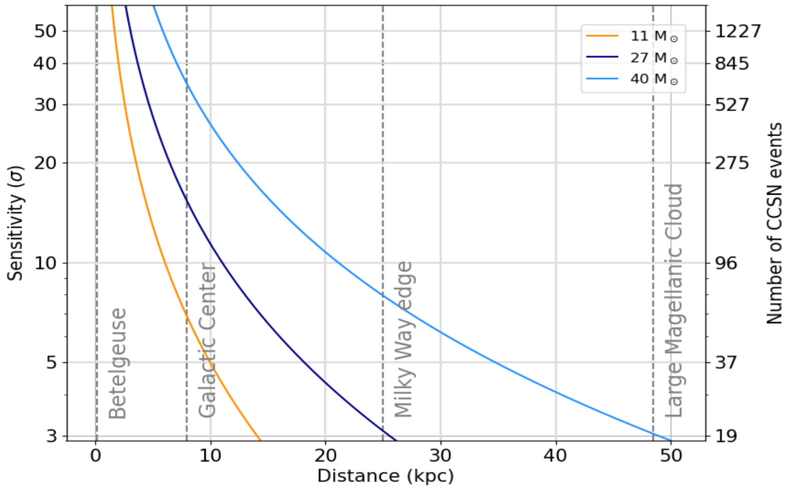
PMT multiplicity plot



SN signal above background



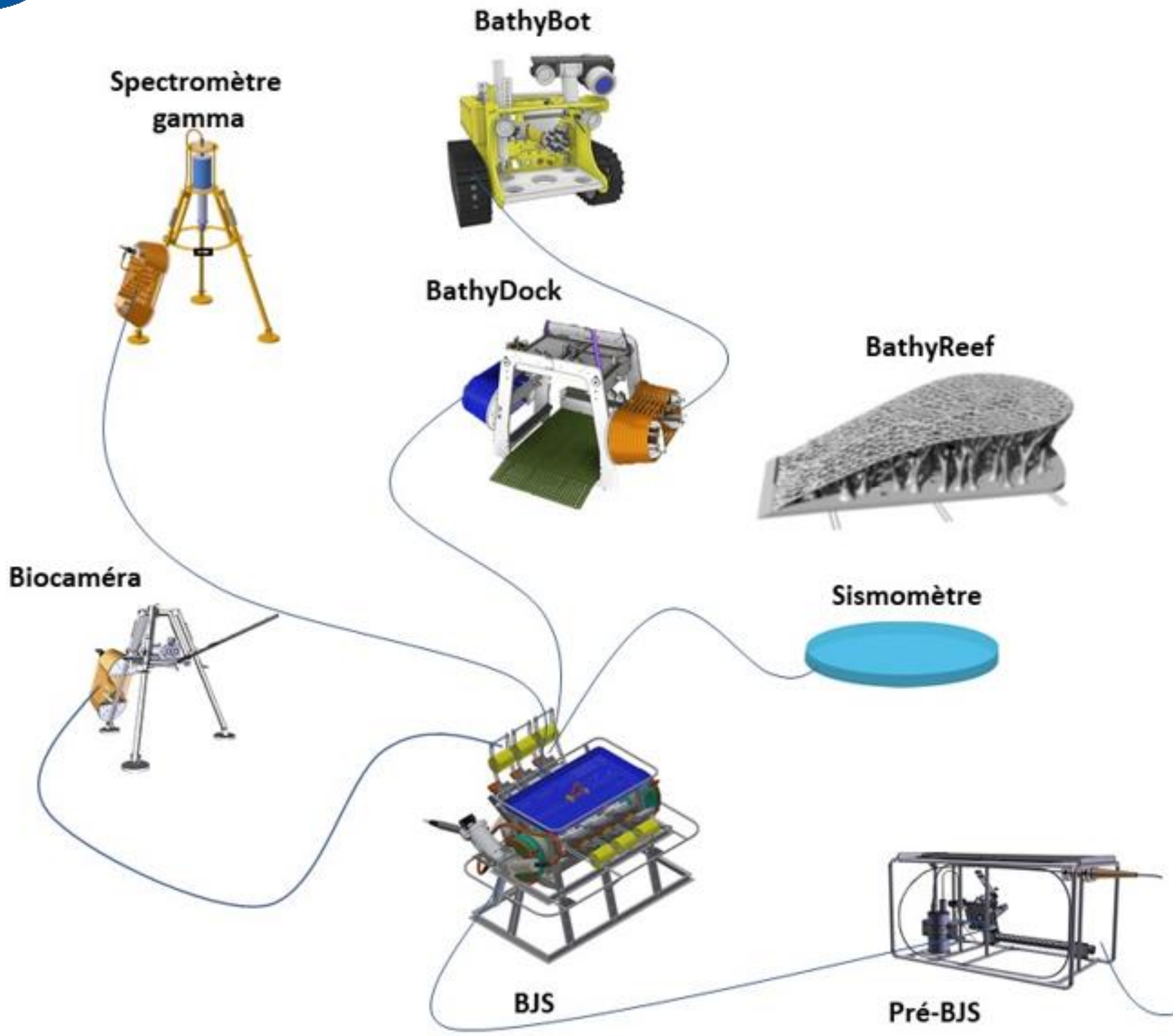
Significance



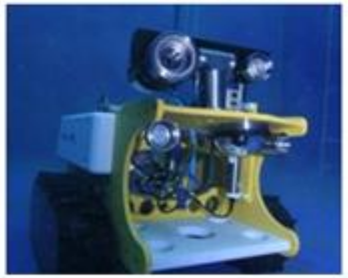
Full KM3NeT: >5σ for ARCA+ORCA for 27M⊙ at a distance <50 kpc

An on-line alert system for CCSN already implemented
Integrated in SNEWS

Marine science instrumentation

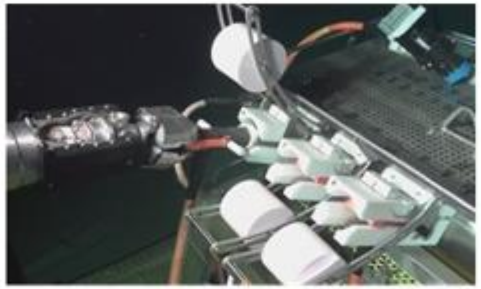


BathyBot



BathyReef

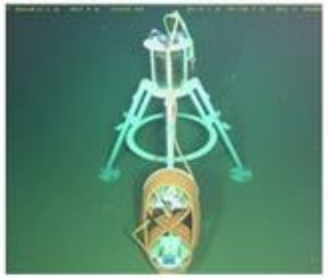
BJS



Biocaméra

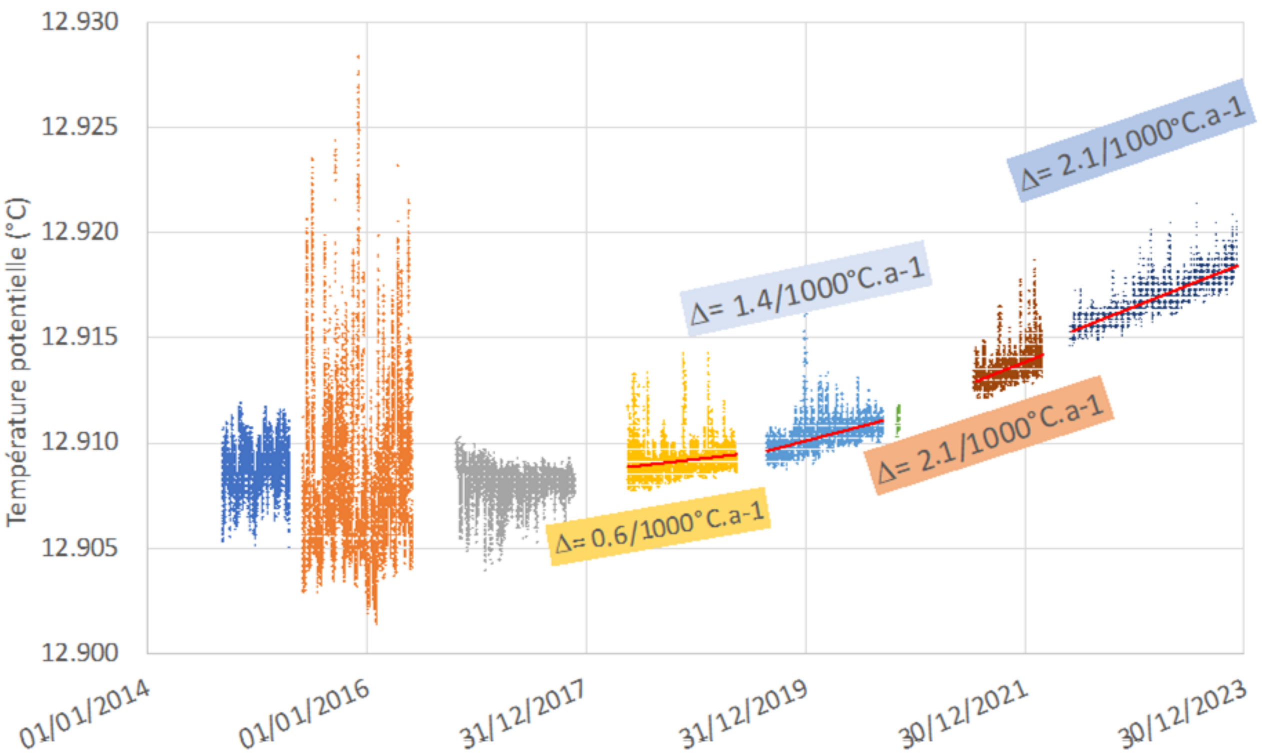
Sismomètre

Spectromètre gamma

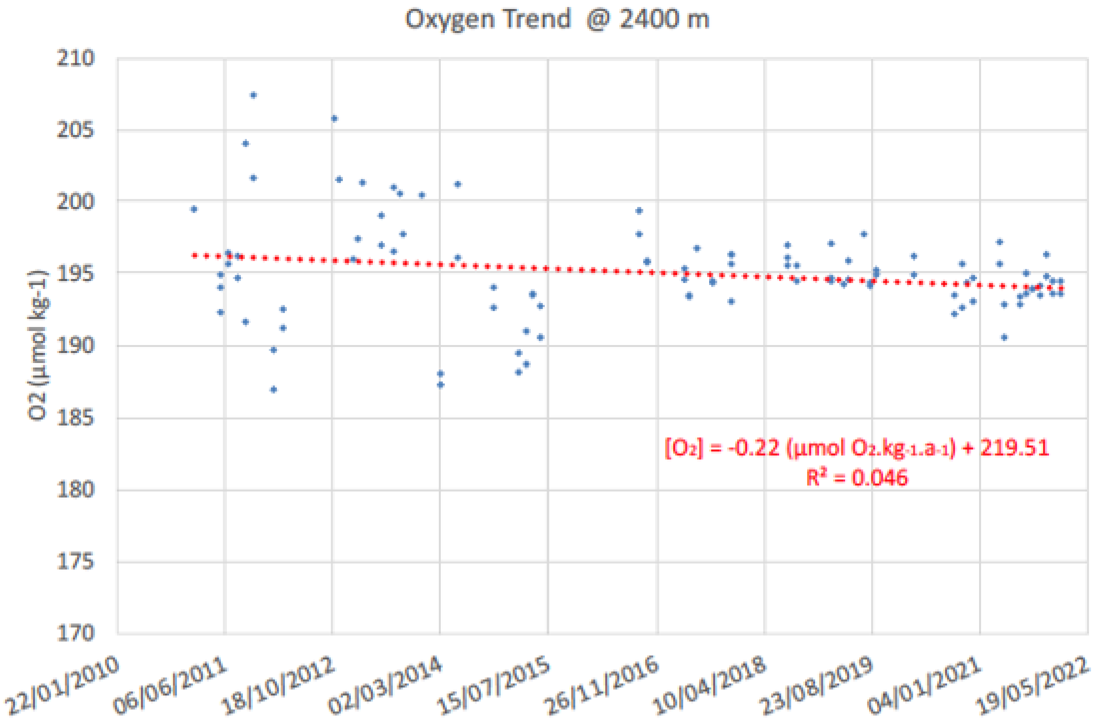


Climate change in the deep sea (ORCA)

Temperature



Oxygen



Summary

Water based neutrino telescopes:

- all sky
- angular resolution -> precision multi-flavour astronomy
- location -> galactic + extra-galactic sources
- ARCA/ORCA -> full energy range
- marine observatory for environmental sciences

KM3NeT taking data and growing rapidly:

- competitive measurement of neutrino oscillation parameters
- First point source limits, ATELs reacting to external alerts
- completion 2028

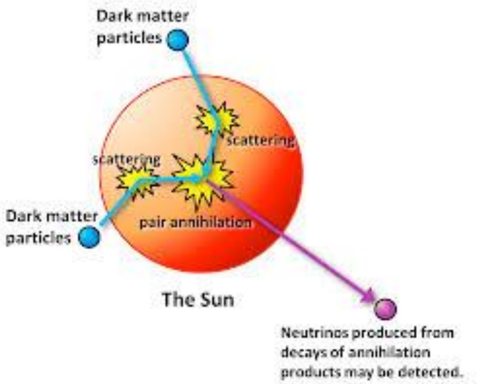
Exceptional >10 PeV energy event detected-stay tuned

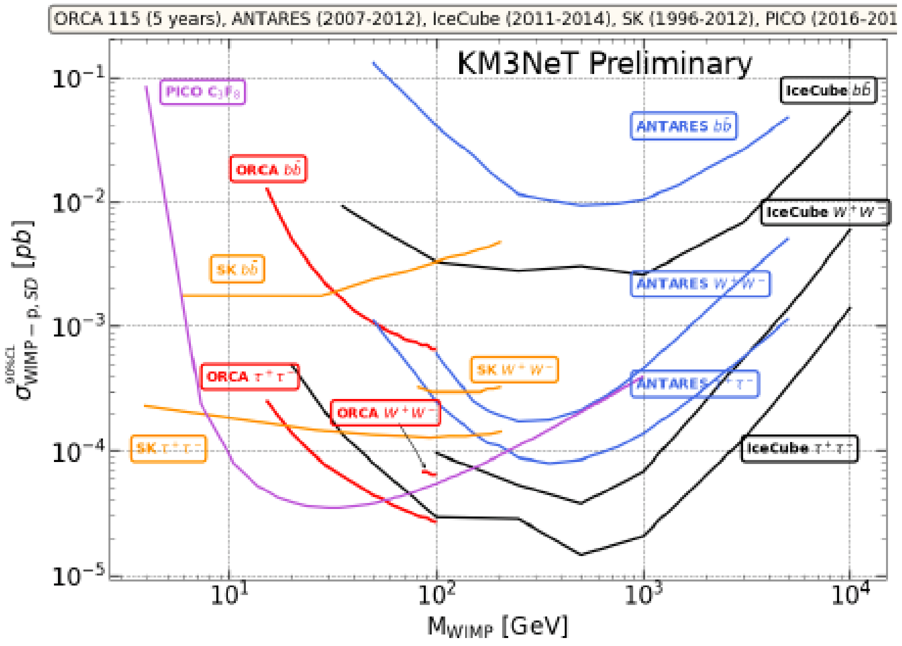
New collaborators very welcome- come and join the adventure!

BACK UP

Dark matter-indirect detection

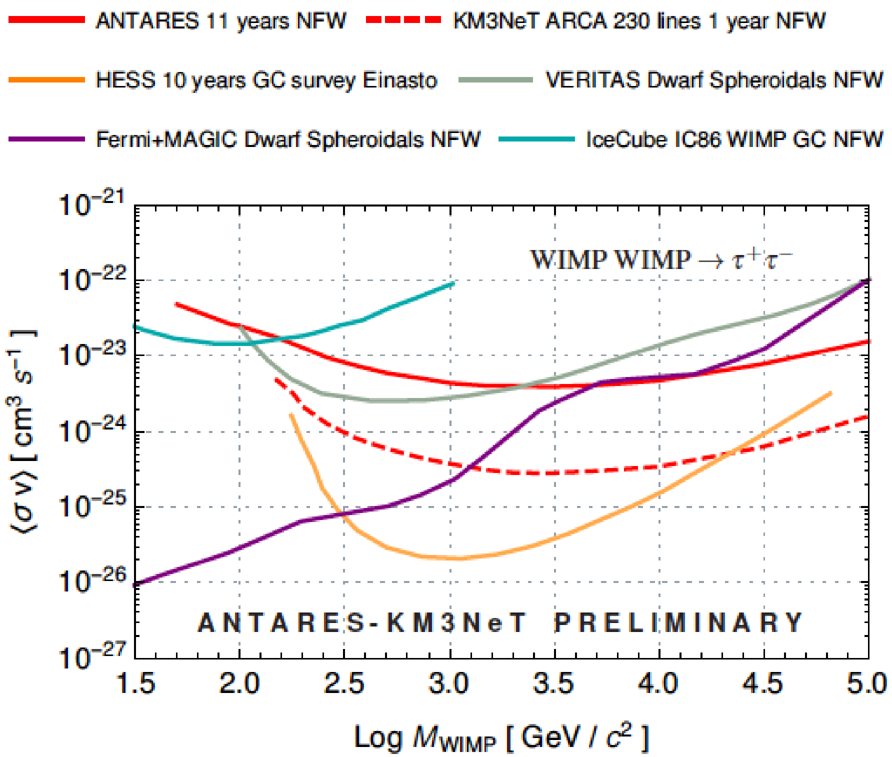
Sun





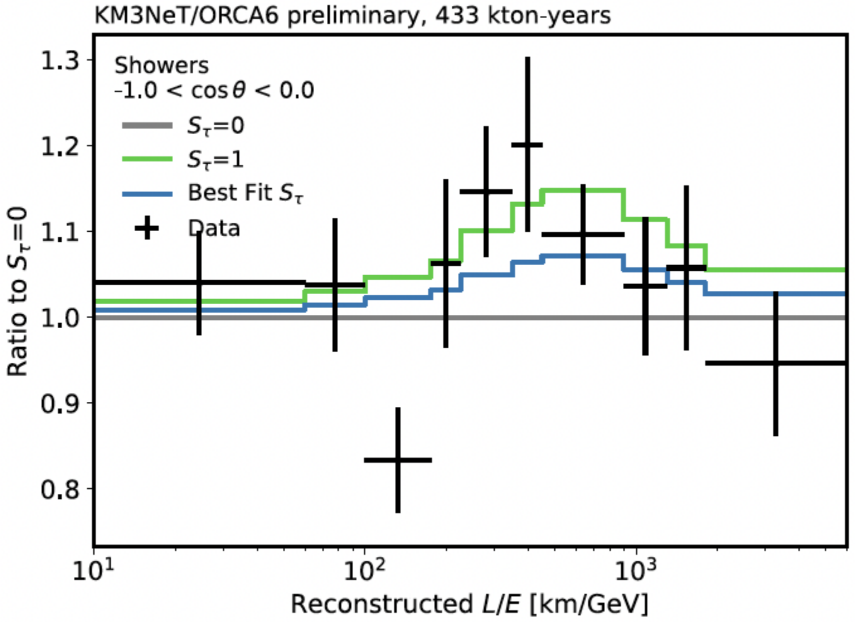
Phys.Lett. B759 2016

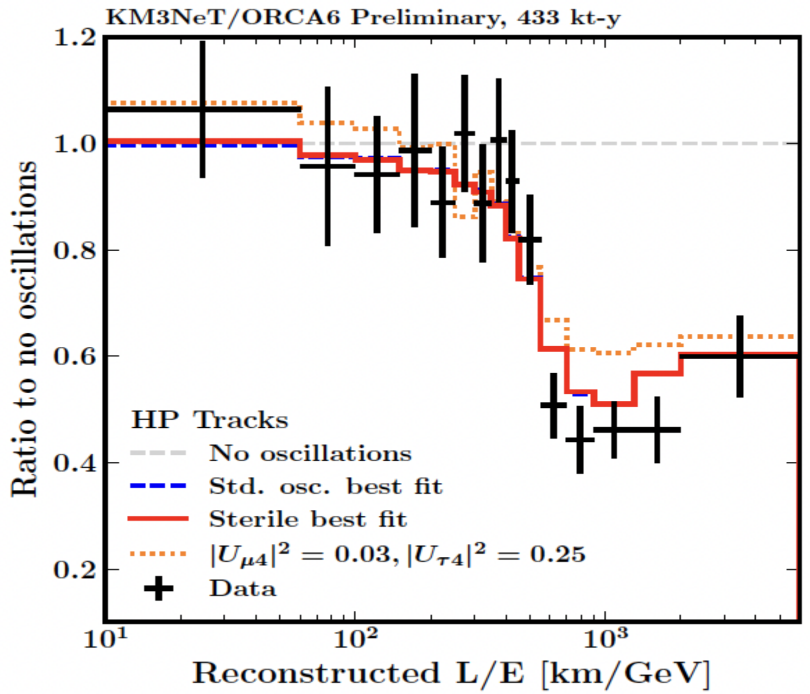
Galactic Centre

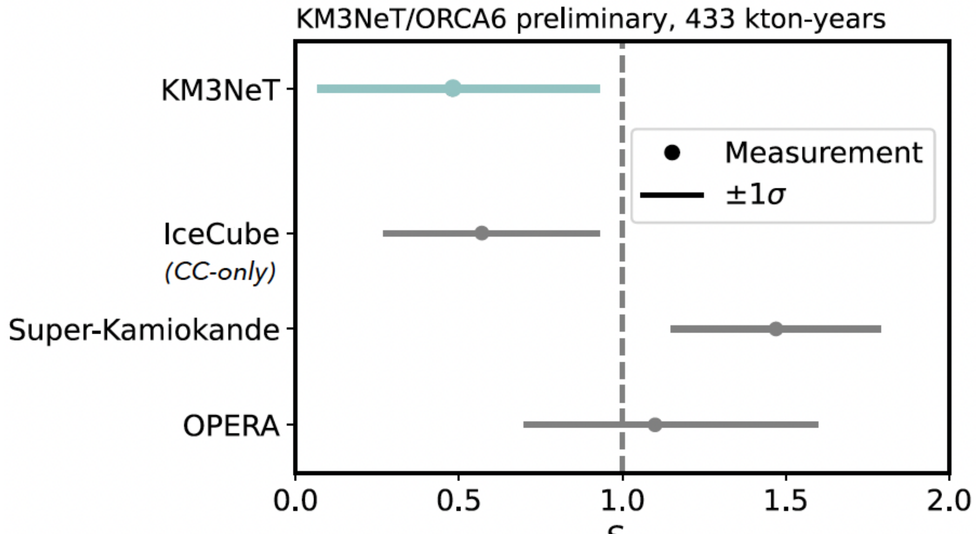


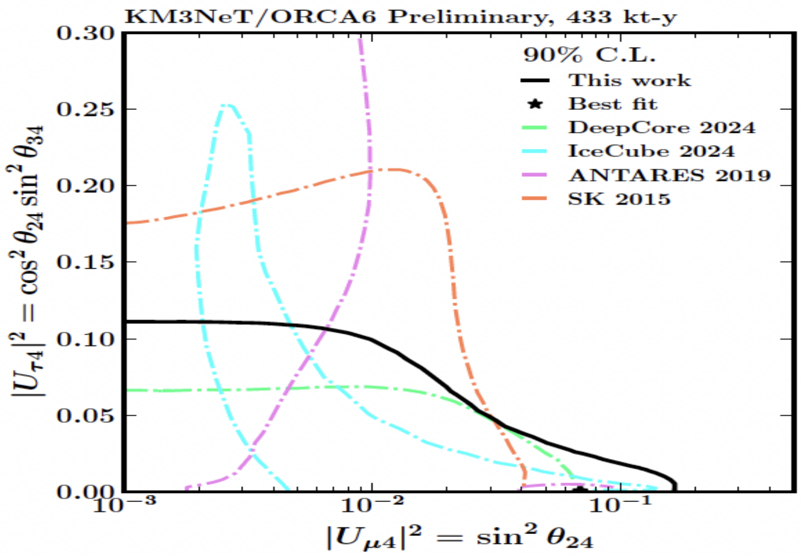
Phys. Lett. B 805 135439 (2020)

τ–appearance / Sterile ν-s









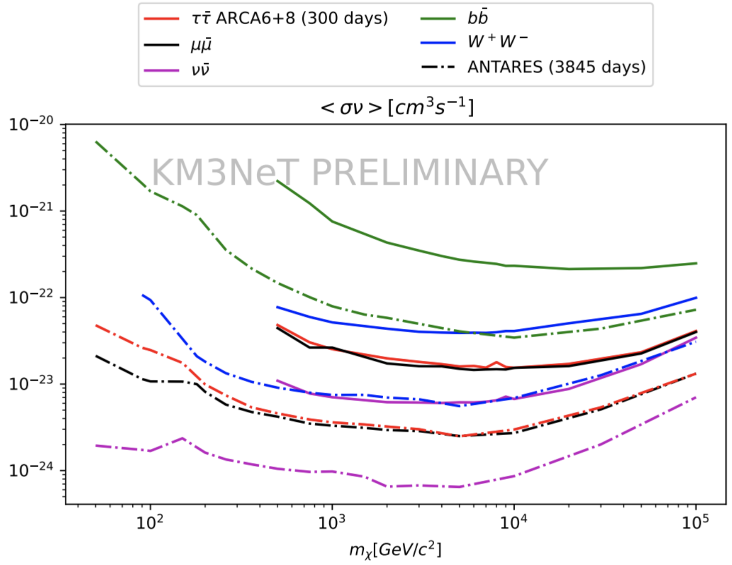
DeepCore: [arXiv:2407.01314] ANTARES: J. HEP 2019, 113
IceCube: [arXiv:2406.00905] SK: Phys. Rev. D 91, 052019

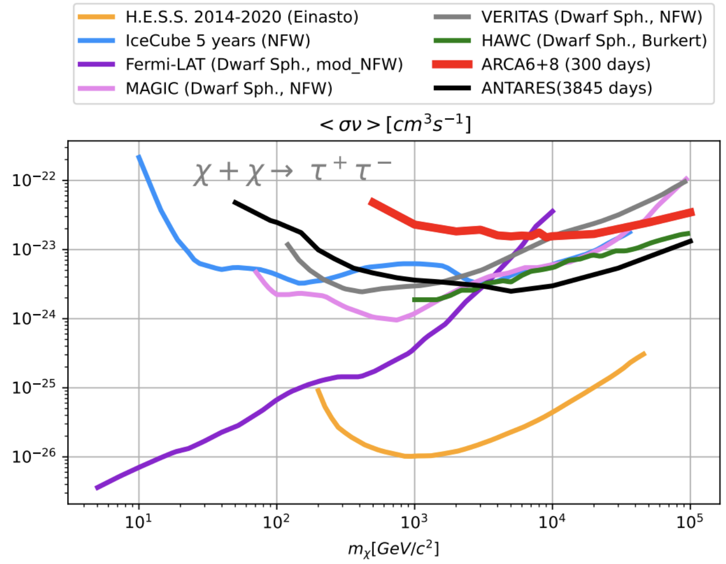
Dark Matter

Galactic Centre

ARCA6 + ARCA8

ICRC2023 PoS 1377

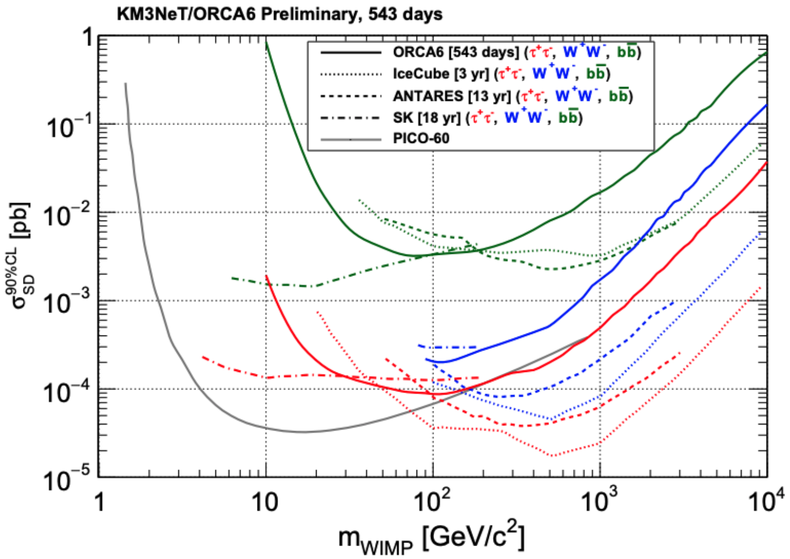




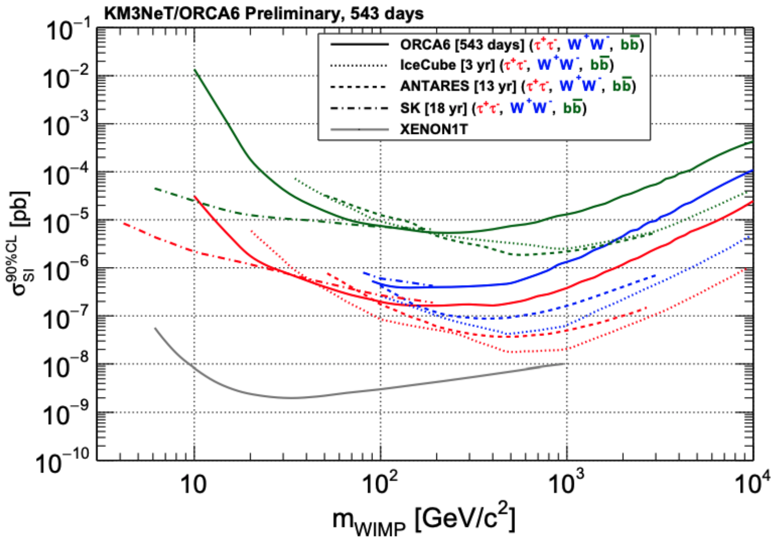
The Sun

ORCA6

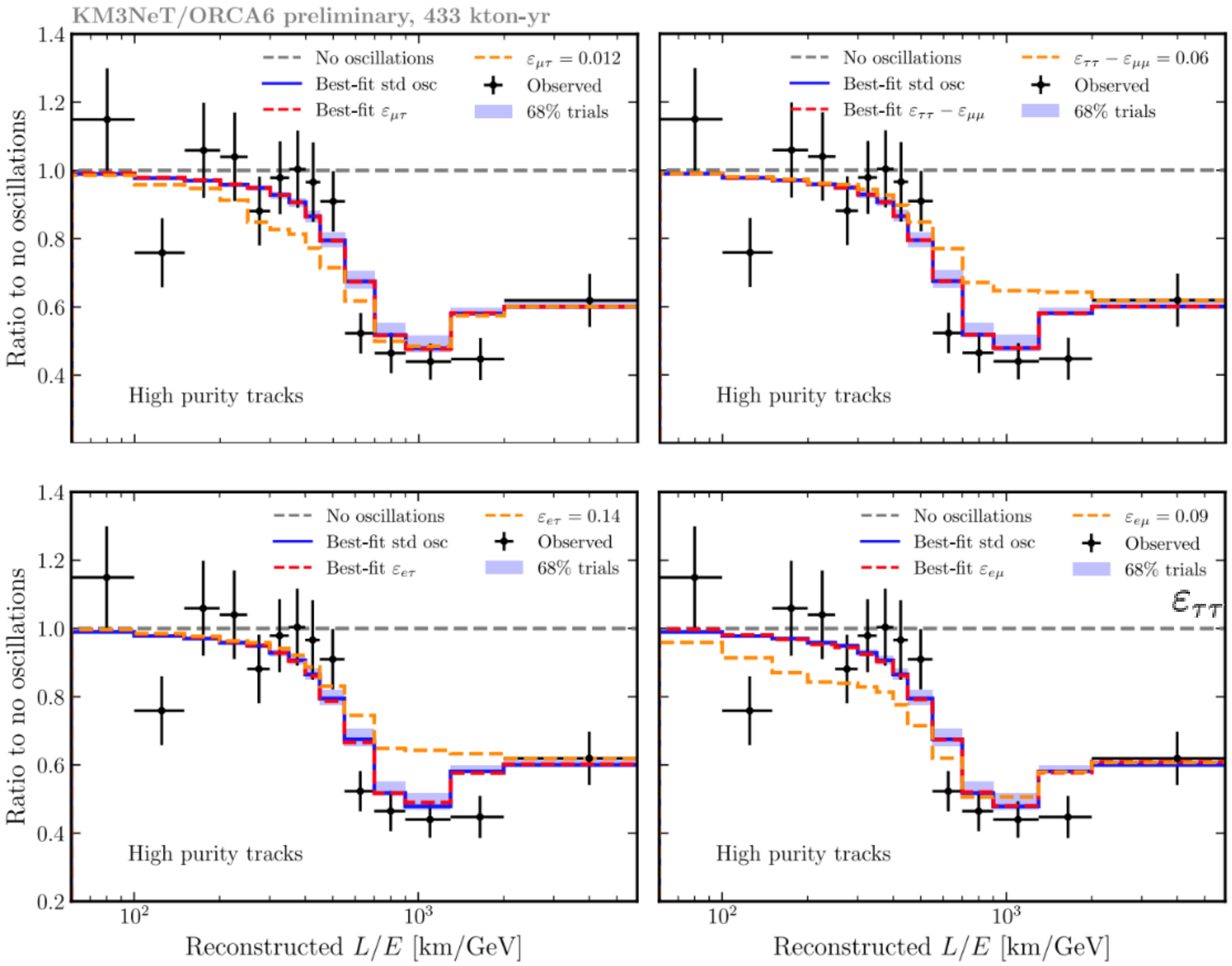
ICRC2023 PoS 1406

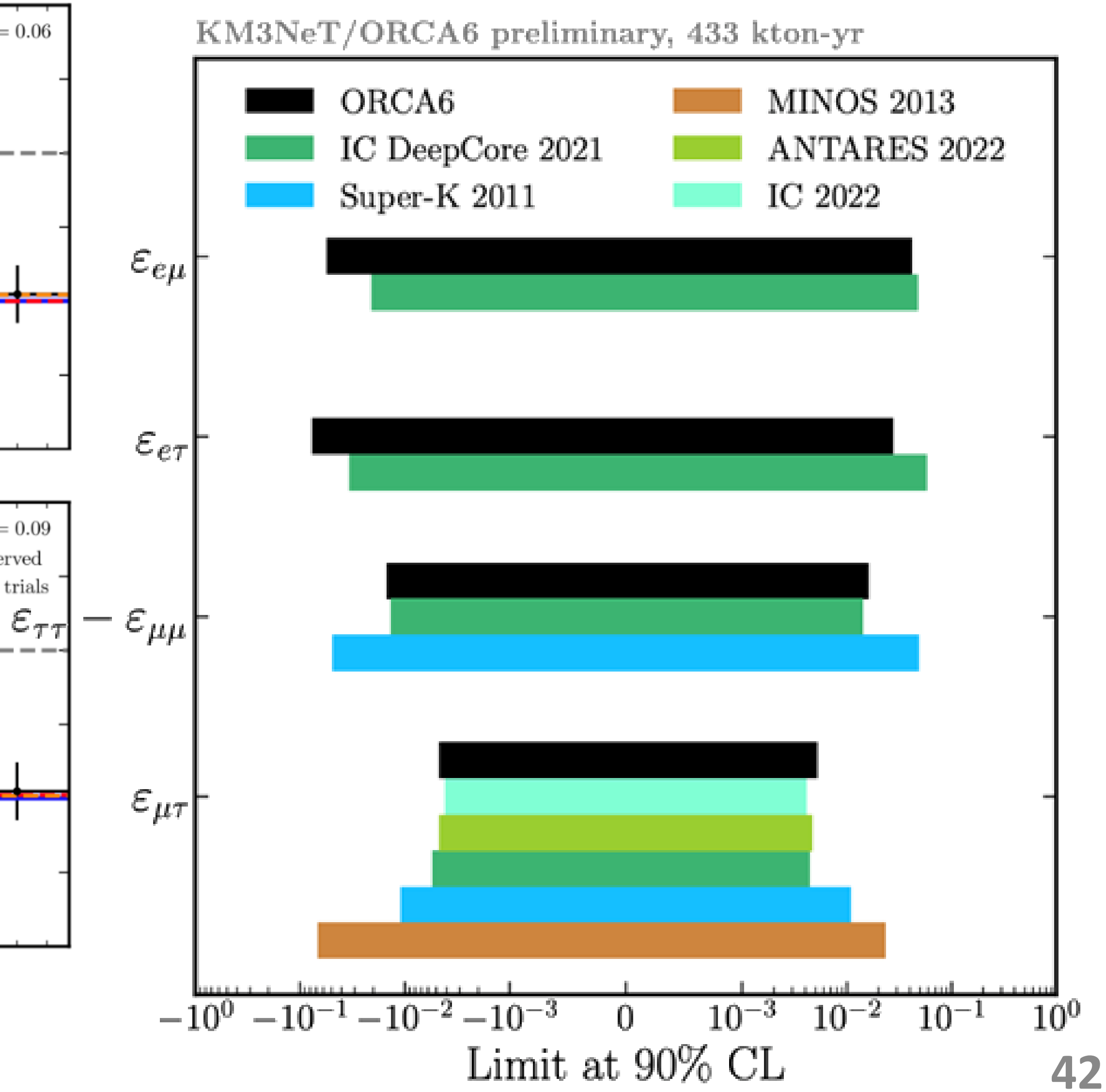


KM3NeT quickly reaching the ANTARES limits



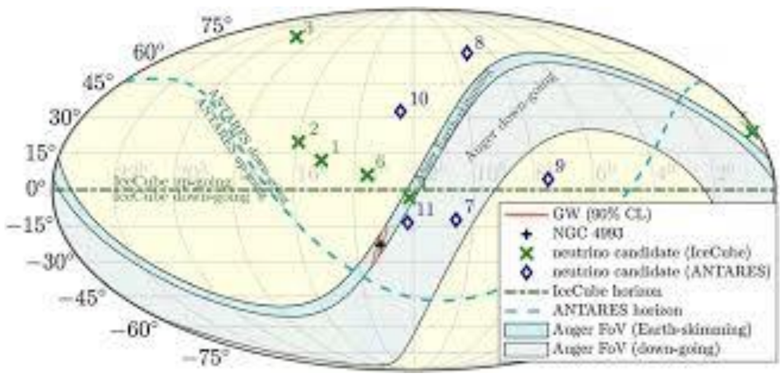
Non-Standard Interactions





Multi-messenger example: Kilonova GWs

Neutrinos: all sky detection, precise location



BNS merger or NS-BH: looking for a short GRB signal (kilonova produced too low energy neutrinos) or the remaining potential magnetar

BBH merger: either looking for BBH happening in dense environment or with large mass difference between the 2 progenitors (remaining accretion disk)