

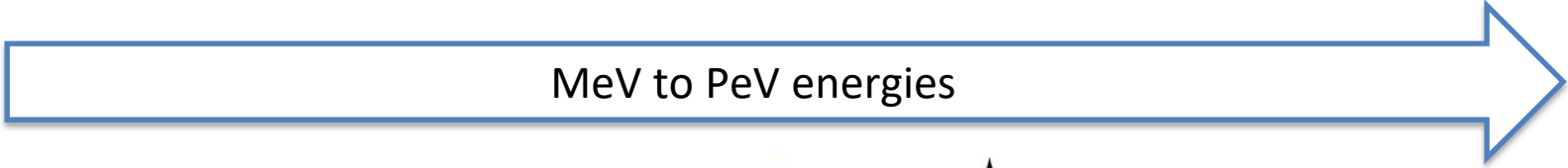
Status of KM3NeT the kilometre cube neutrino telescope

Paschal Coyle (CPPM)
on behalf of the KM3NeT Collaboration

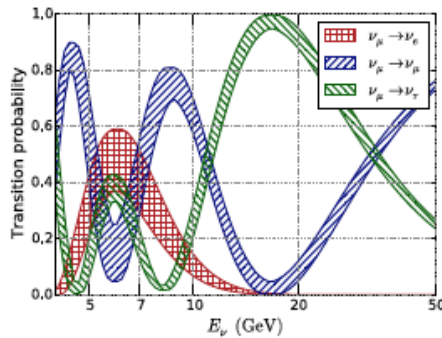
ICHEP 2024, Prague
19/7/24



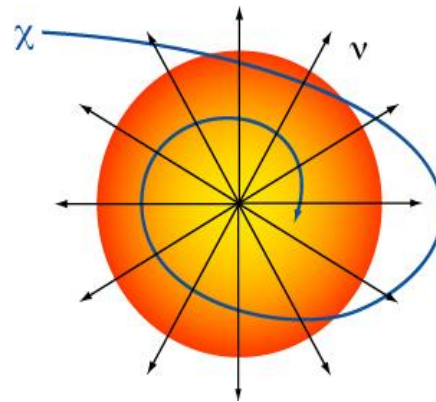
Neutrino telescopes: science



Supernova
Solar flares



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



Dark matter
Monopoles,
Nuclearites,...

A. Saina Dark matter searches with KM3NeT

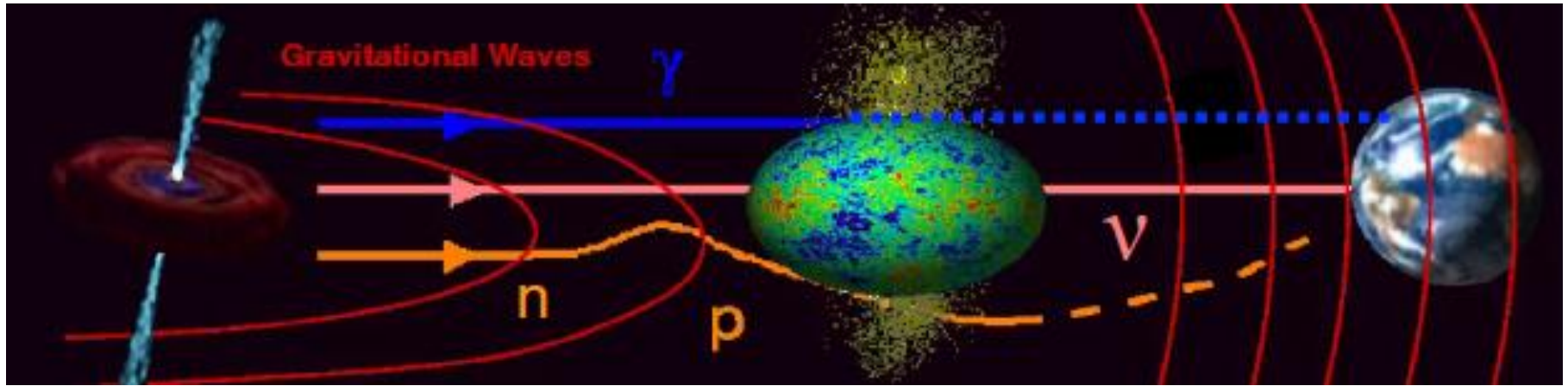


Cosmic neutrinos
Cosmic rays
Origin and production mechanism of HE CR



+ oceanography, biology, bioacoustics, seismology,...

Neutrinos: cosmic messengers



Neutrinos: neutral, stable, weakly interacting

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

‘Smoking gun’ signature for hadronic processes

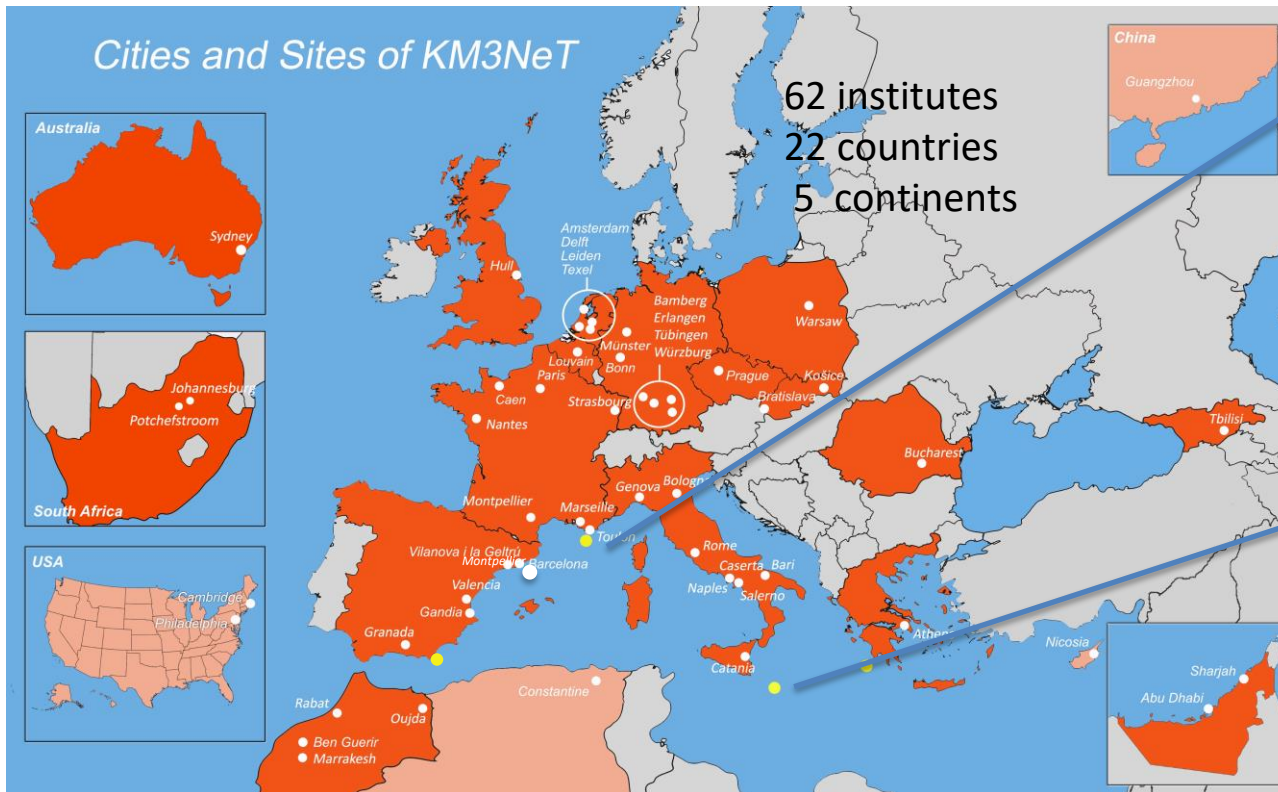
Correlated in time/direction with electromagnetic and gravitational waves

New window of observation on the Universe



KM3NeT

Multi-site, deep-sea infrastructure
 Single collaboration, single technology
 Selected for ESFRI roadmap 2016



**Oscillation Research
 with Cosmics In the Abyss**



**Astroparticle Research
 with Cosmics In the Abyss**

[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



Connection nodes of

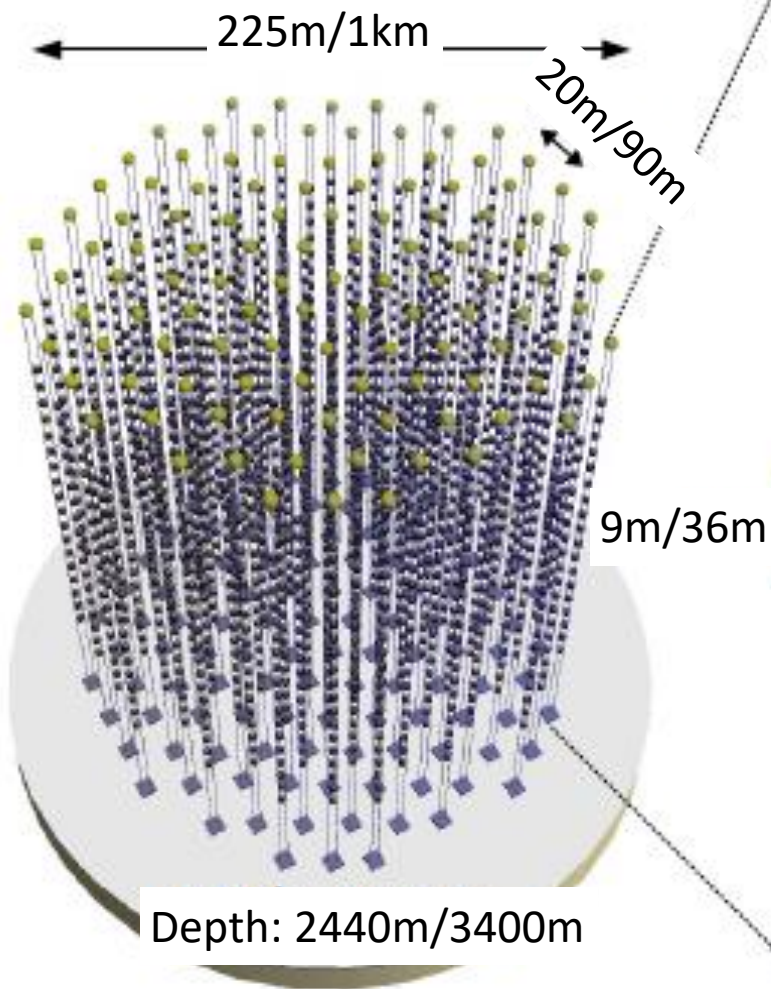
European
 multidisciplinary
 seafloor & water column
 observatory

emso



KM3NeT building block

115 strings
18 DOMs / string



- 31 x 3" PMTs
- All data to shore: Gbit/s optical fibre
- White Rabbit time synchronisation
- LED flasher & acoustic piezo
- Tiltmeter/compass
- Low drag

See:

I. C. Rea (poster)

The multi-PMT DOM of KM3NeT

Instrumented mass 7 Mton 500*2 Mton



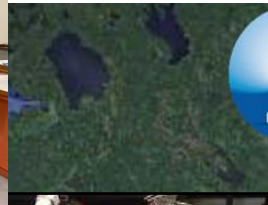
Detector construction



Amsterdam



Strasbourg



Bologna



ated
bench



Nantes



Erlangen

- 9 integration sites



Caen

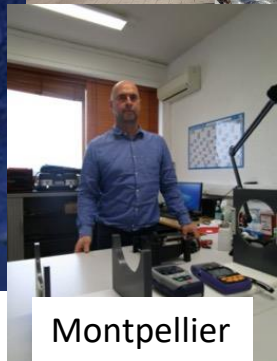


Athens

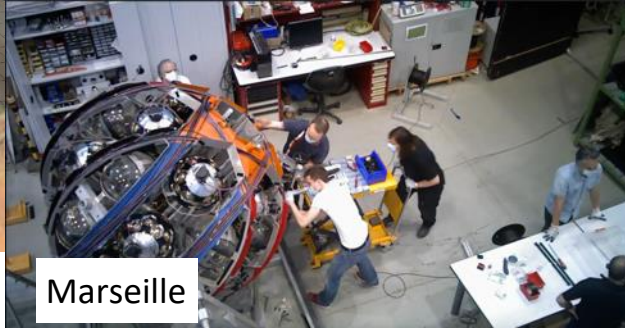


Caserta

ated
bench



Montpellier



Marseille



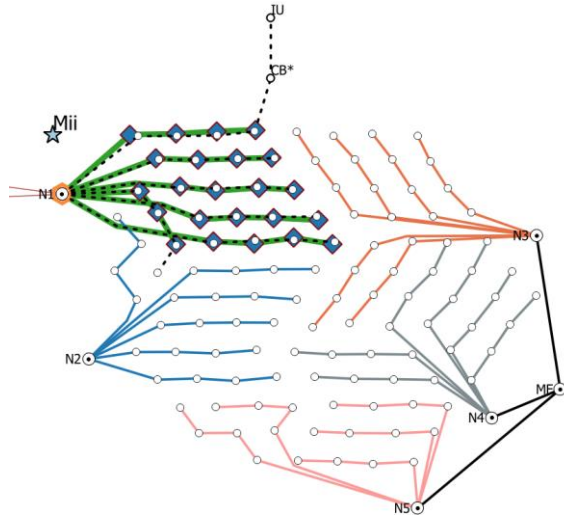
Catania

sites
ated

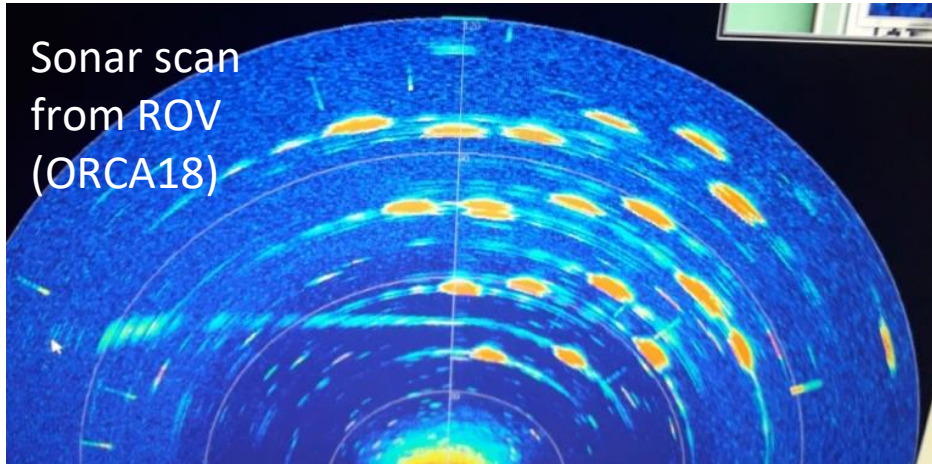
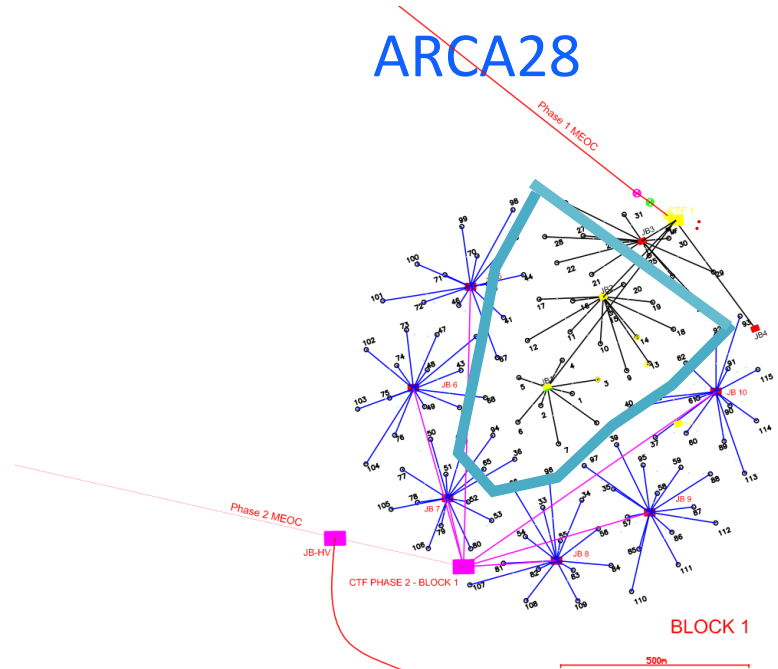


Current Status: 51 Dection Units deployed

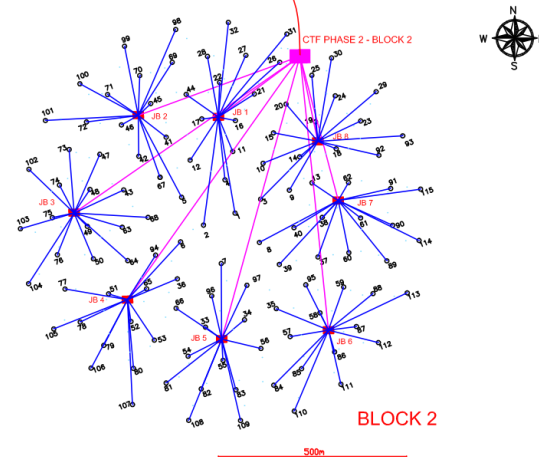
ORCA23



ARCA28

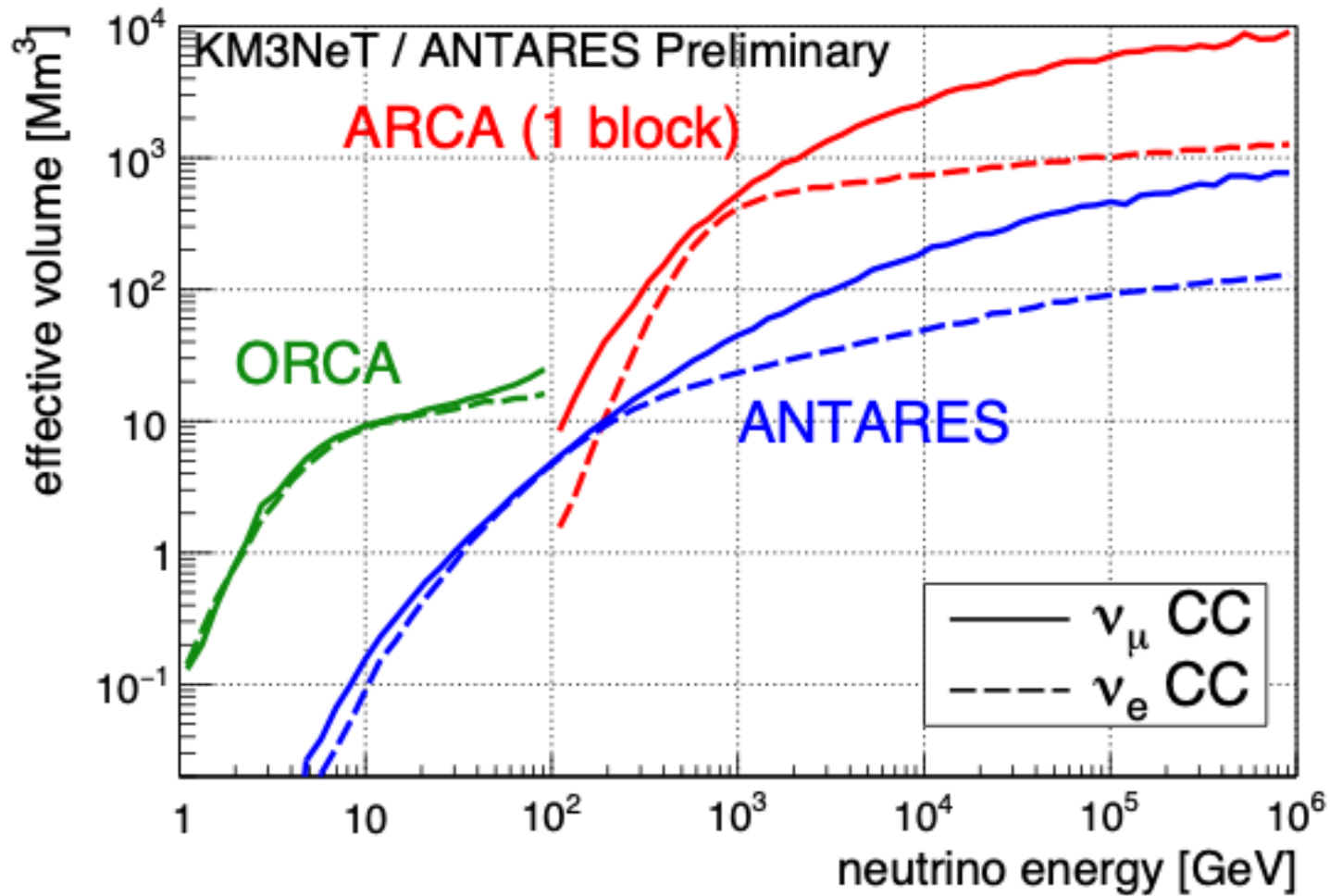


Sonar scan from ROV (ORCA18)

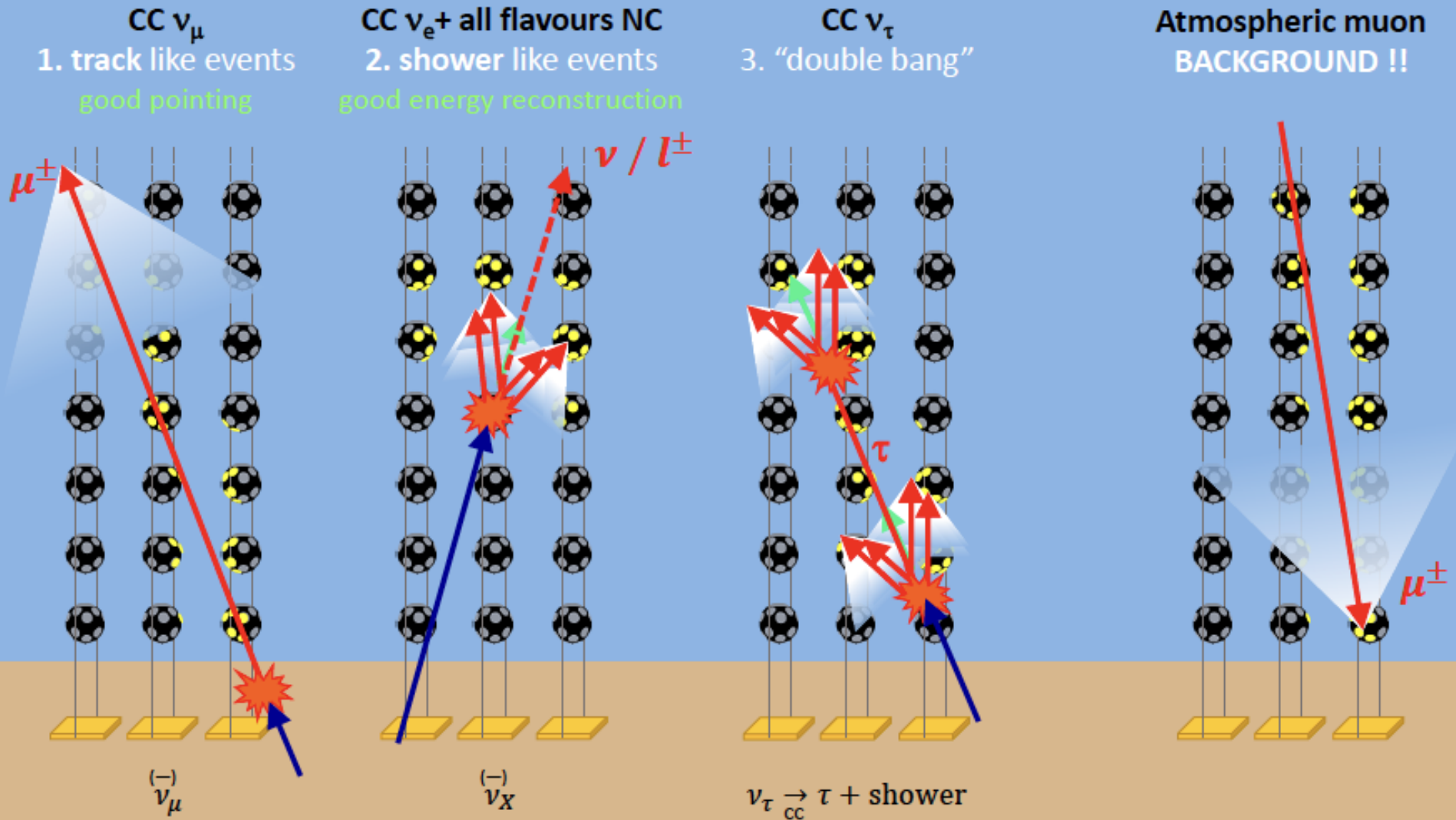




Effective areas: KM3NeT vs ANTARES

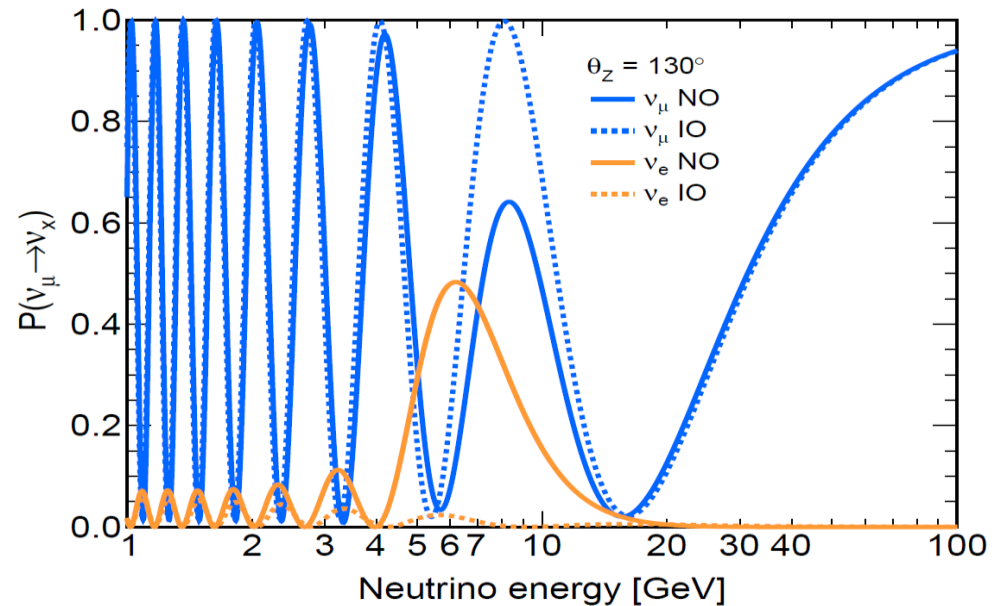
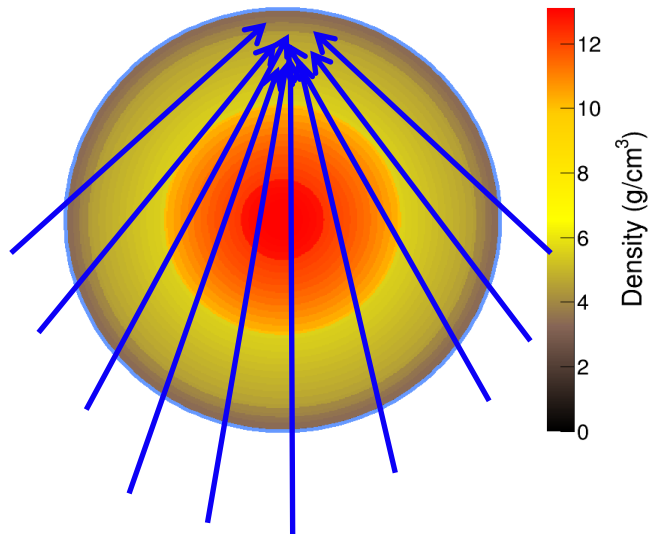
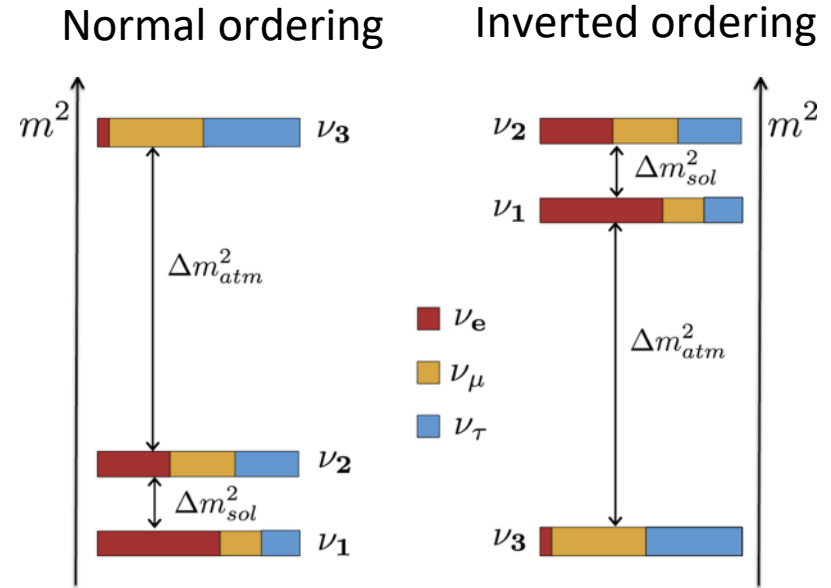
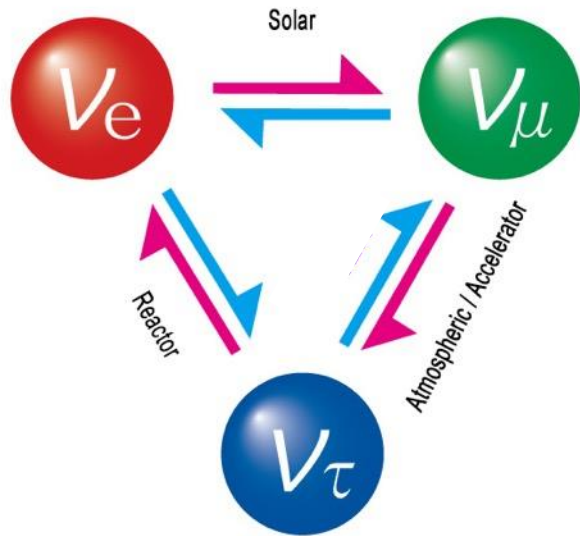


Event Topologies



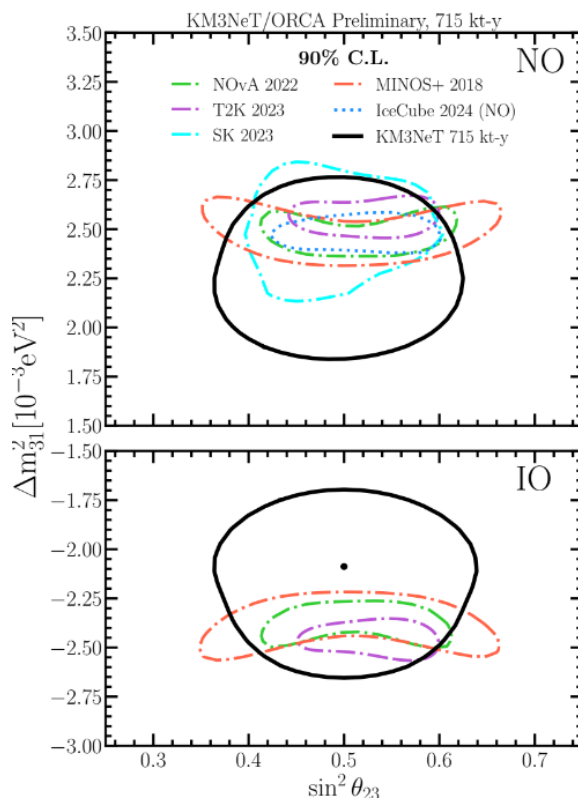
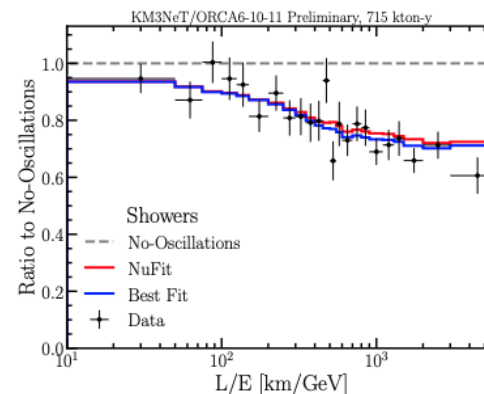
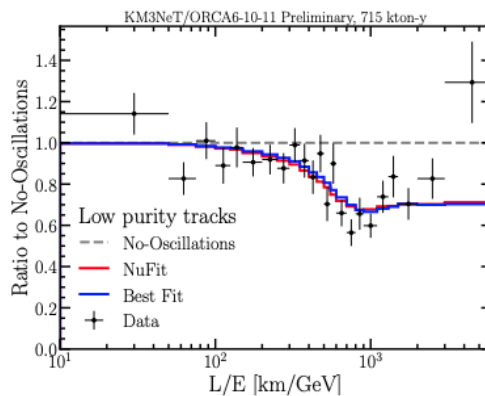
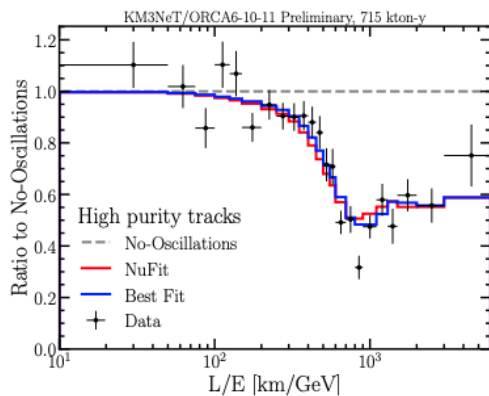
Tracks @ $E_\nu > 100$ TeV Ang. res. below 0.1° - Energy res. \sim factor 2
 Shower @ $E_\nu > 100$ TeV Ang. res. below 2° - Energy res. $\sim 6\%$

Neutrino oscillations with atmospheric neutrinos





Oscillation results with ORCA6-11



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

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

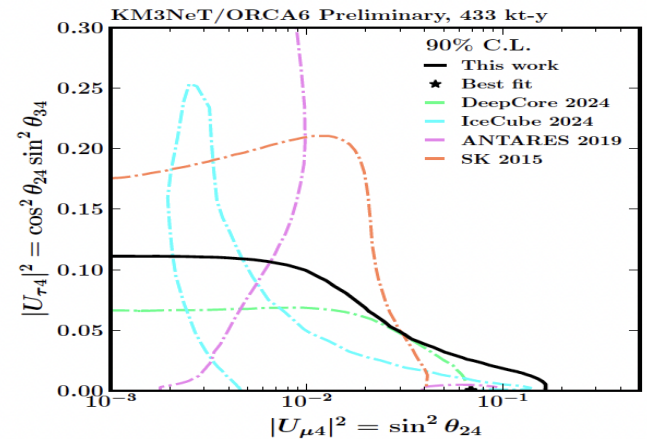
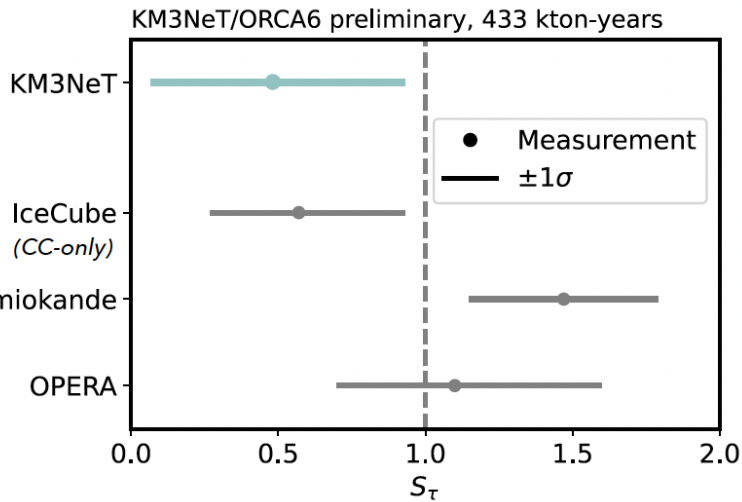
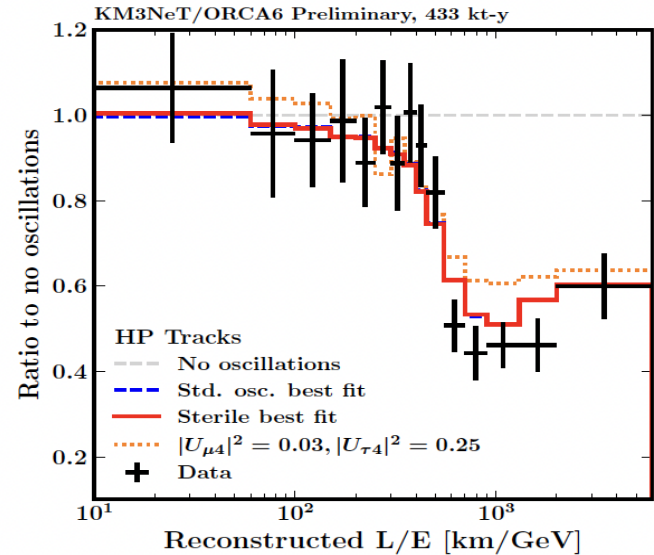
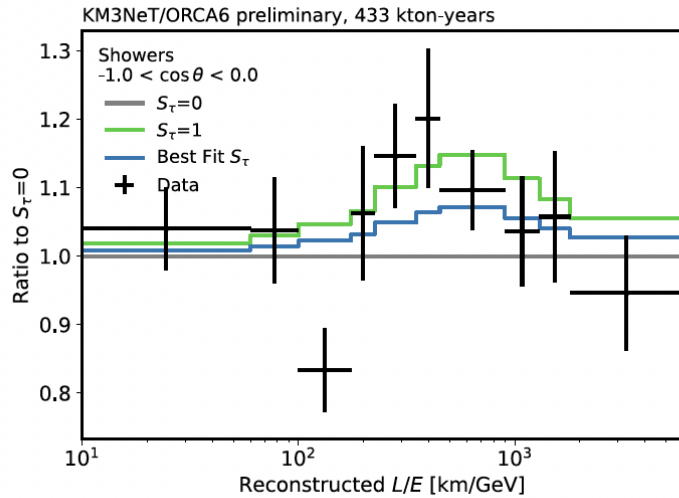
$$2 \log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$

Slight preference for IO, but not significant

A. Lazo Pedrajas Atmospheric neutrino oscillations



Tau appearance / Sterile neutrinos



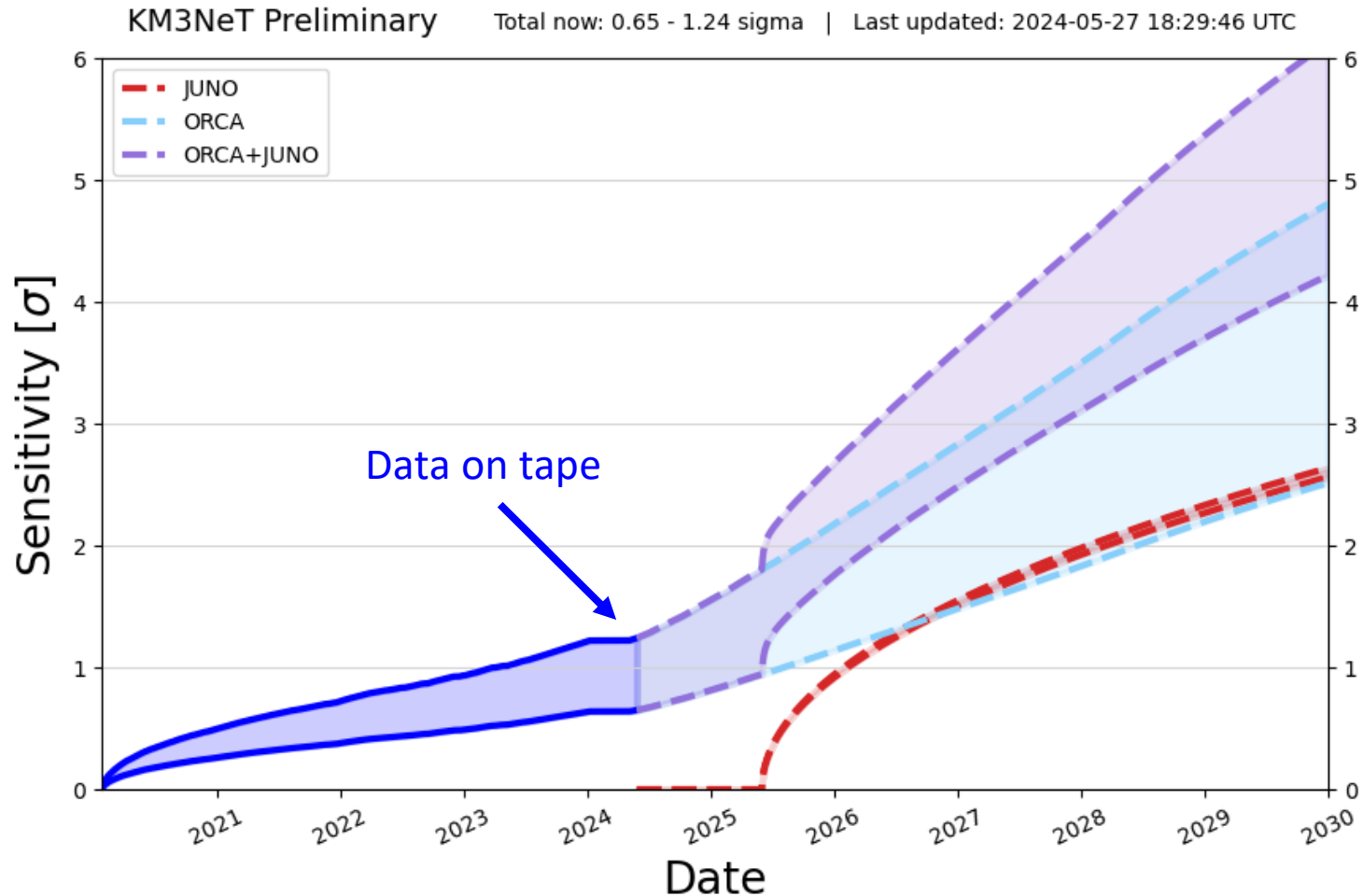
DeepCore: [arXiv:2407.01314]
 IceCube: [arXiv:2406.00905]

ANTARES: J. HEP 2019, 113
 SK: Phys. Rev. D 91, 052019



Prospects for neutrino mass ordering

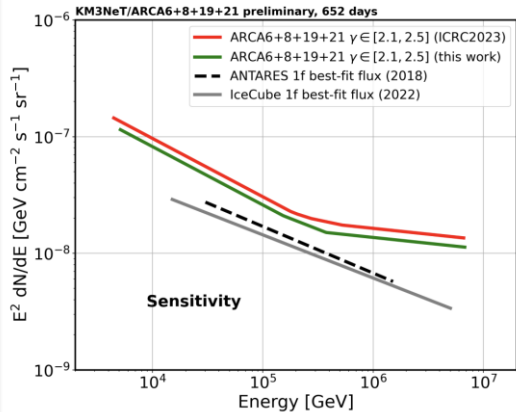
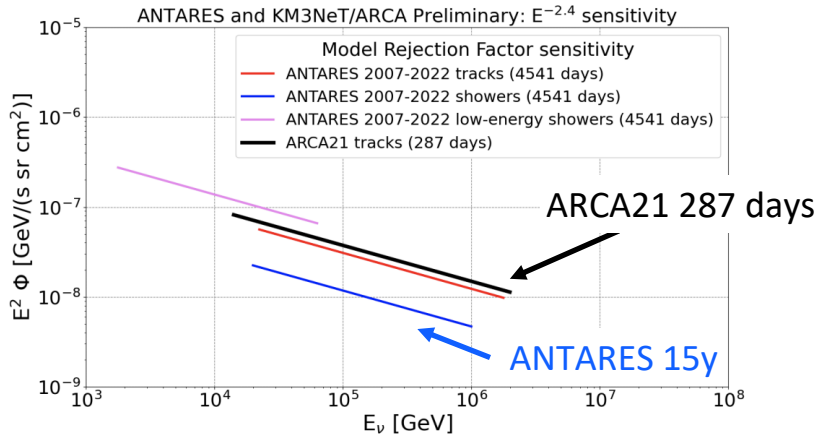
projections including detector construction schedule show 5σ NMO determination in reach within this decade when combined with JUNO





KM3NeT searches for diffuse fluxes

Full sky

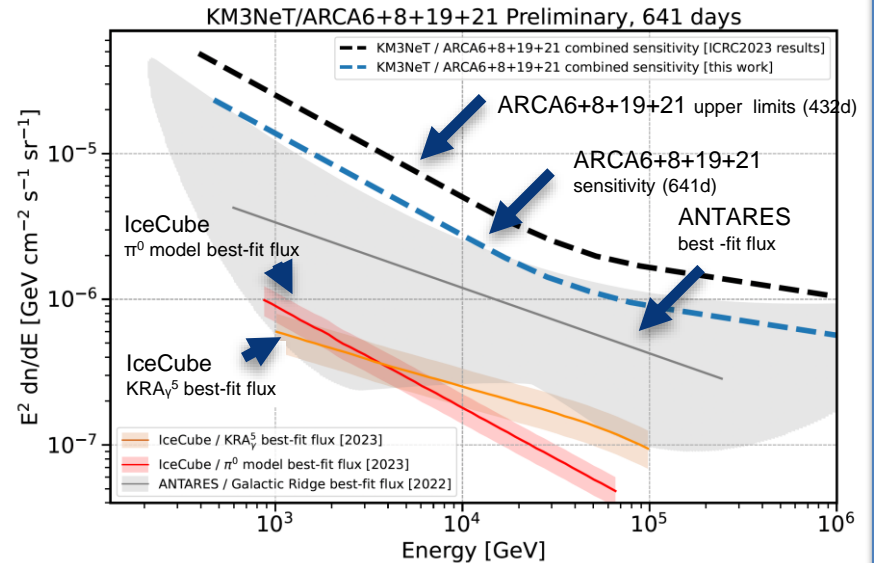


With the data collected until Sept. 2023 same sensitivity as ANTARES 15 years of data for track events

Galactic plane

On-Off zone analysis

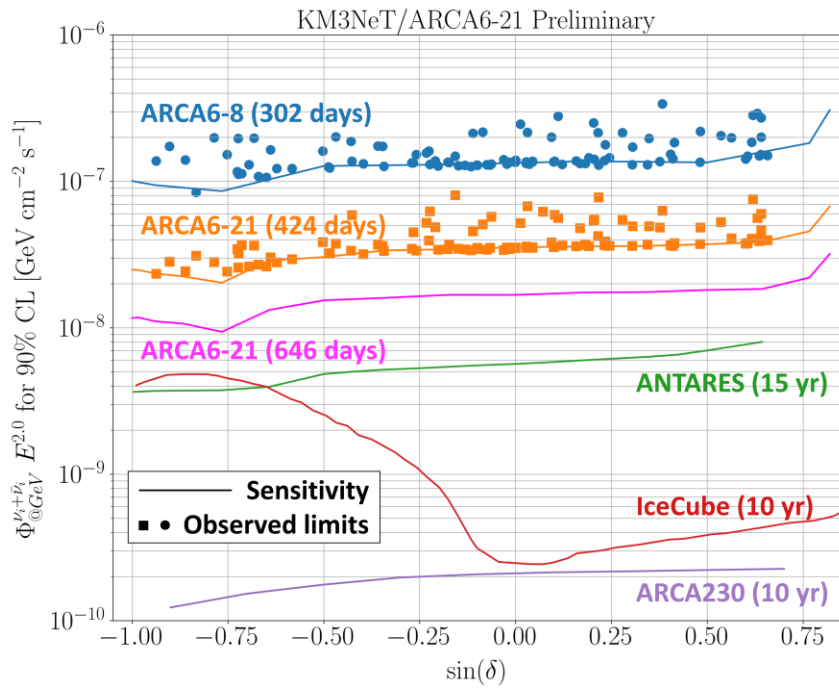
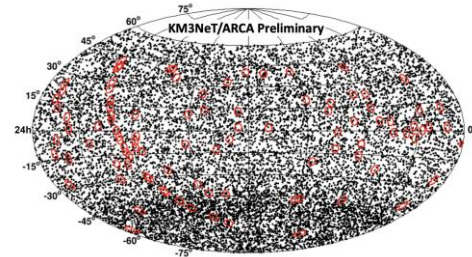
$|| < 31^\circ$ and $|b| < 5^\circ$ for KM3NeT/ARCA6-8 and
 $|| < 31^\circ$ and $|b| < 4^\circ$ for KM3NeT/ARCA19-21



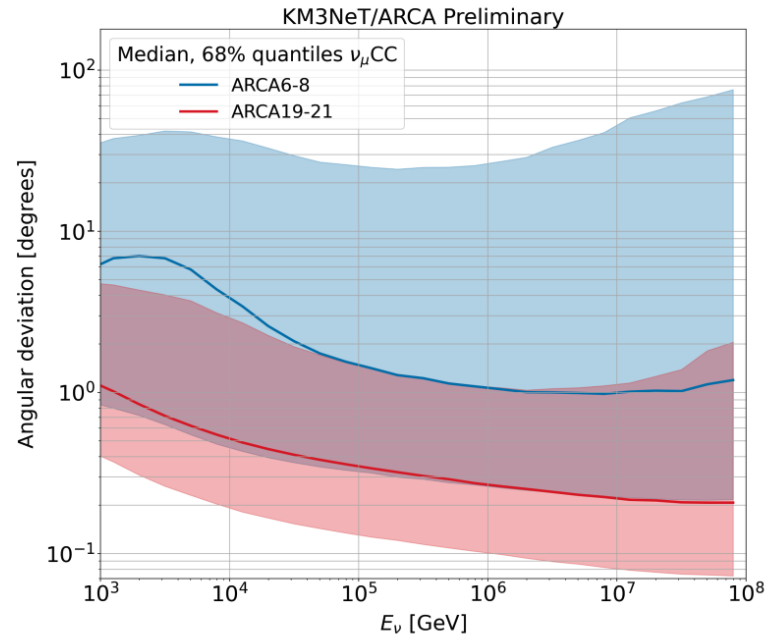
KM3NeT/ARCA rapidly approaching ANTARES/IceCube sensitivities



KM3NeT point source searches



Angular resolution (tracks)



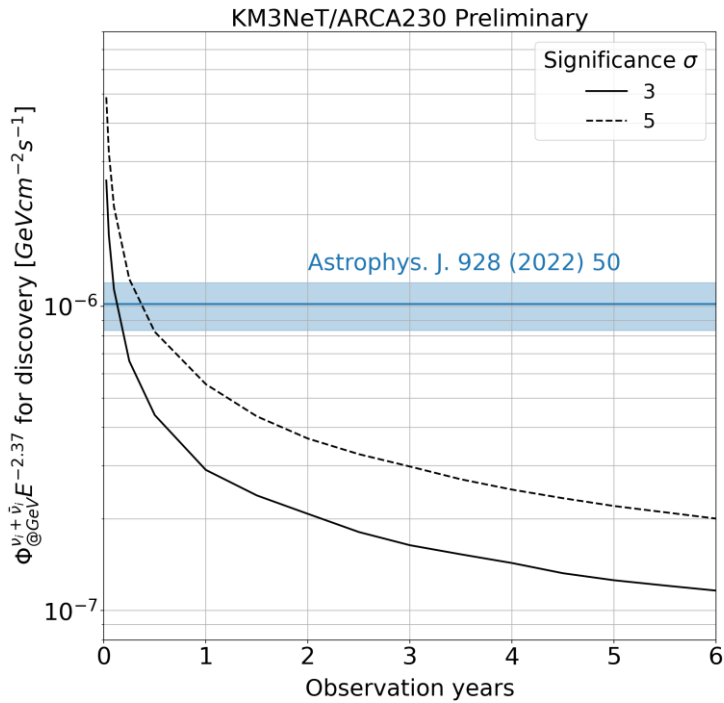
KM3NeT upper limits are quickly reaching the ANTARES 15 year limits

Angular resolution improves as detector grows



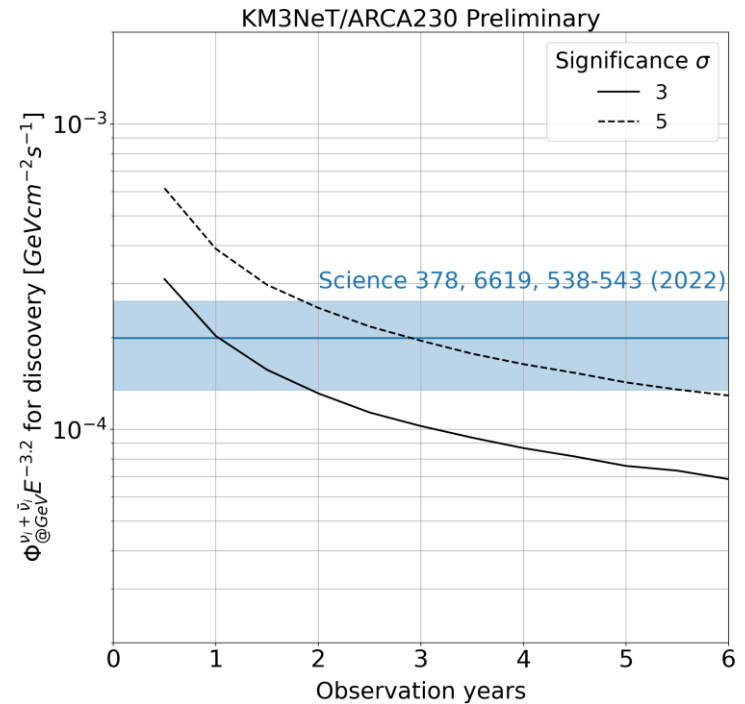
ARCA230 expected sensitivities

Diffuse flux



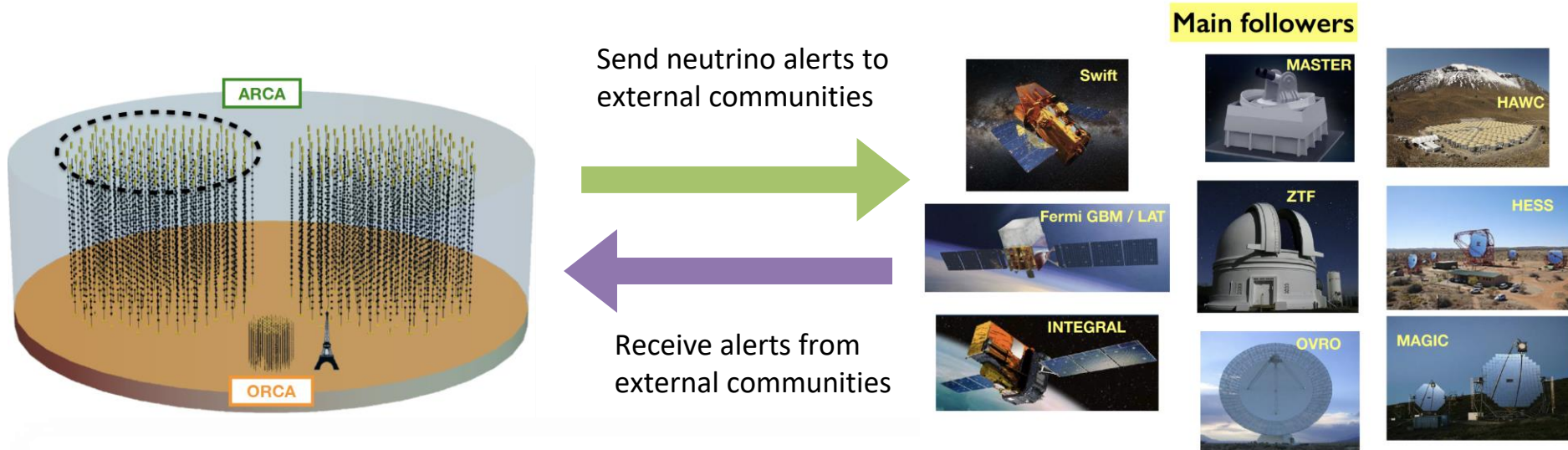
5 σ in ~ 0.5 year

NGC1068



3 σ in one year

Multi-messenger program



Receiving alert system operative 🖱

Real Time Analysis platform already active from Nov 2022 in ARCA/ORCA

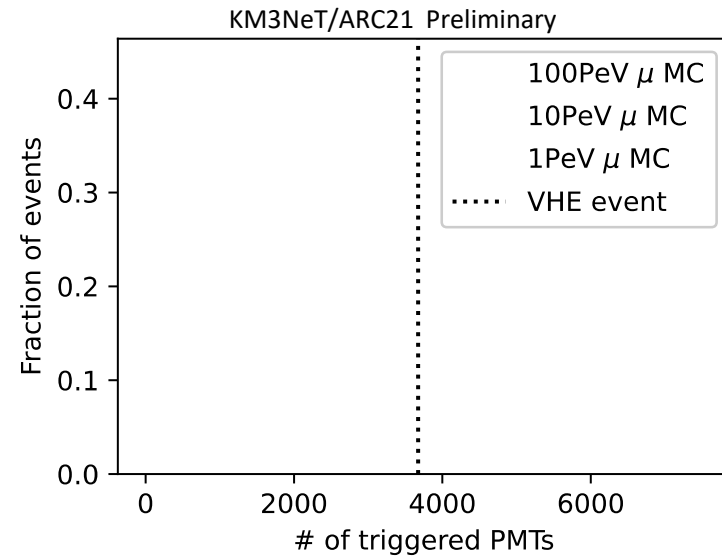
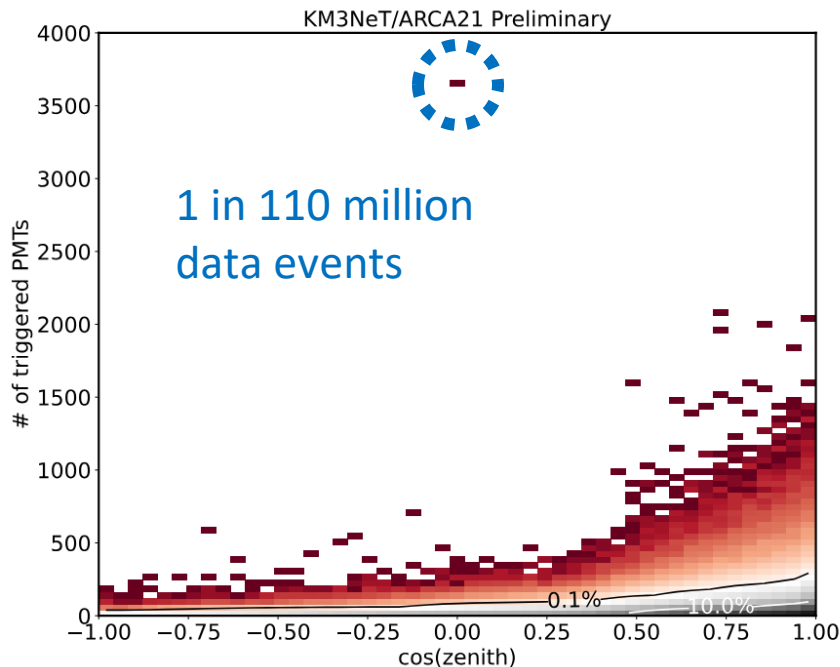
Sending alert system under test 🖱

High-energy neutrino alerts will be sent in real-time (<20 s) by end of 2024.



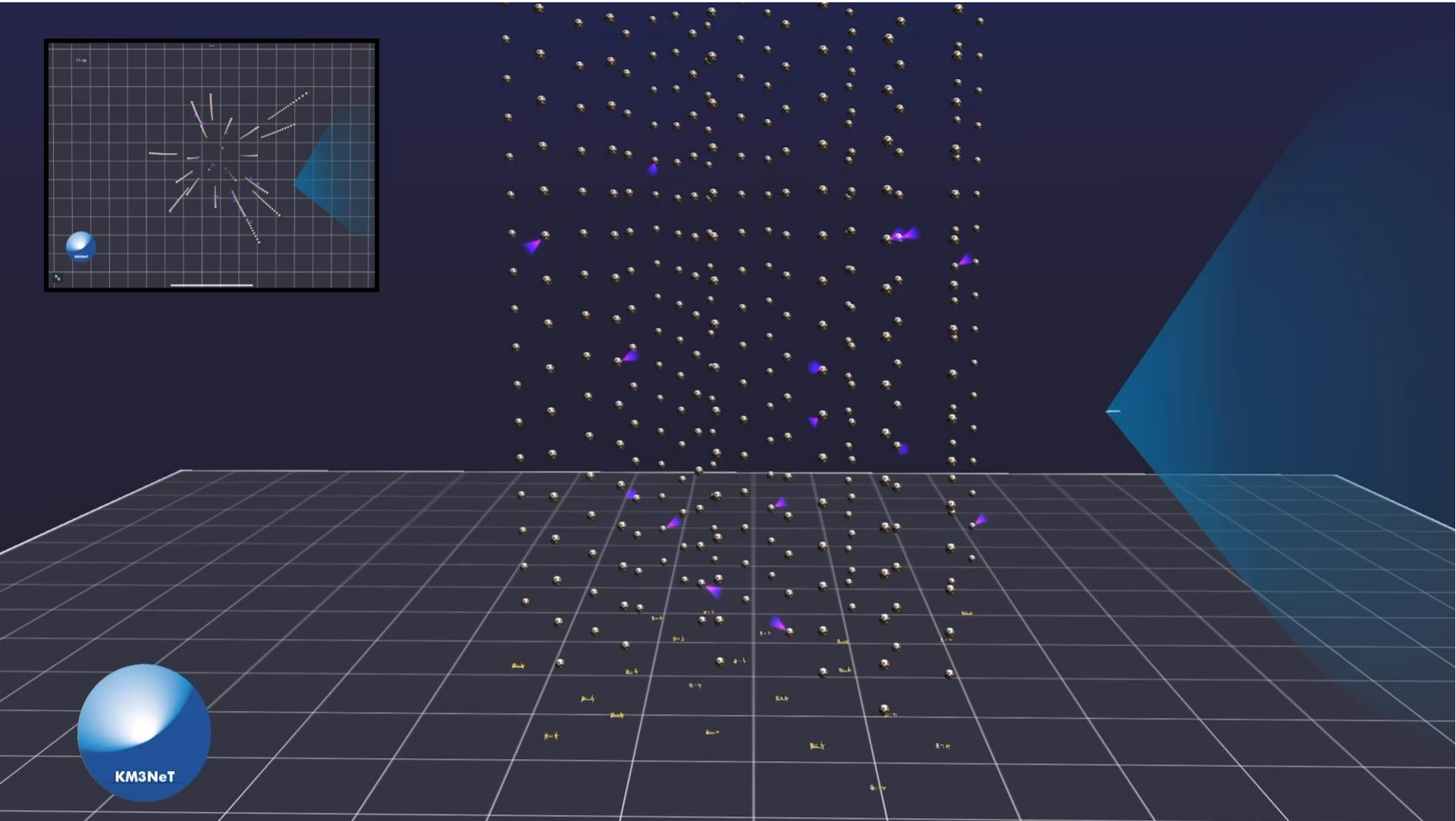
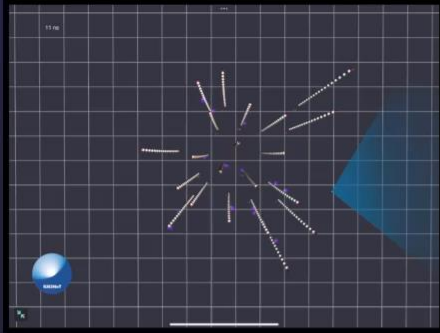
Detection of an exceptional event

- 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





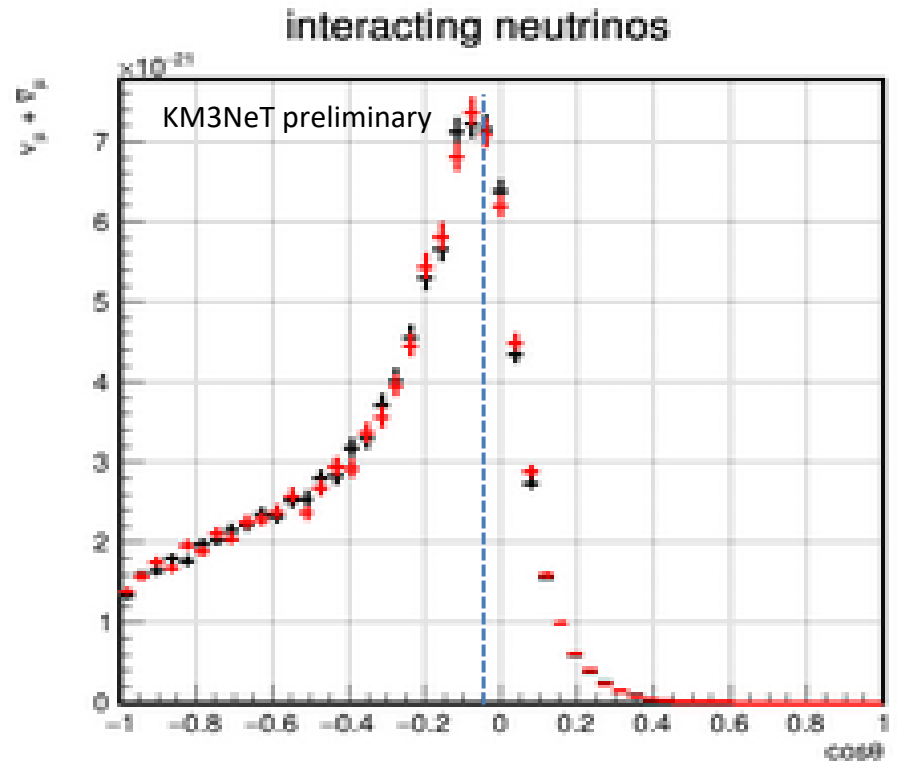
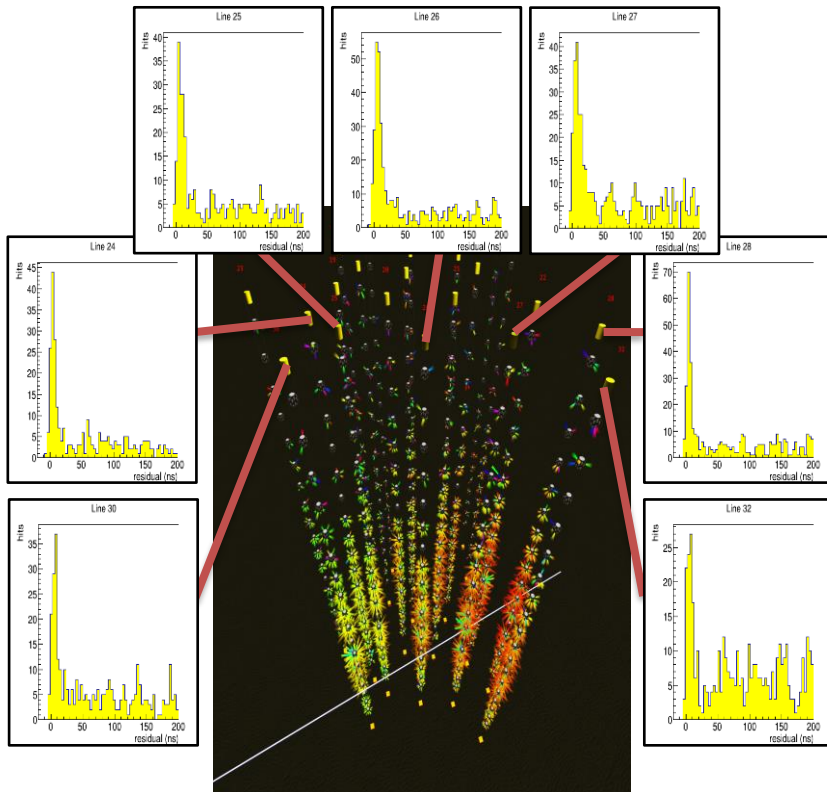
VHE event display



Consistent with muon neutrino

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

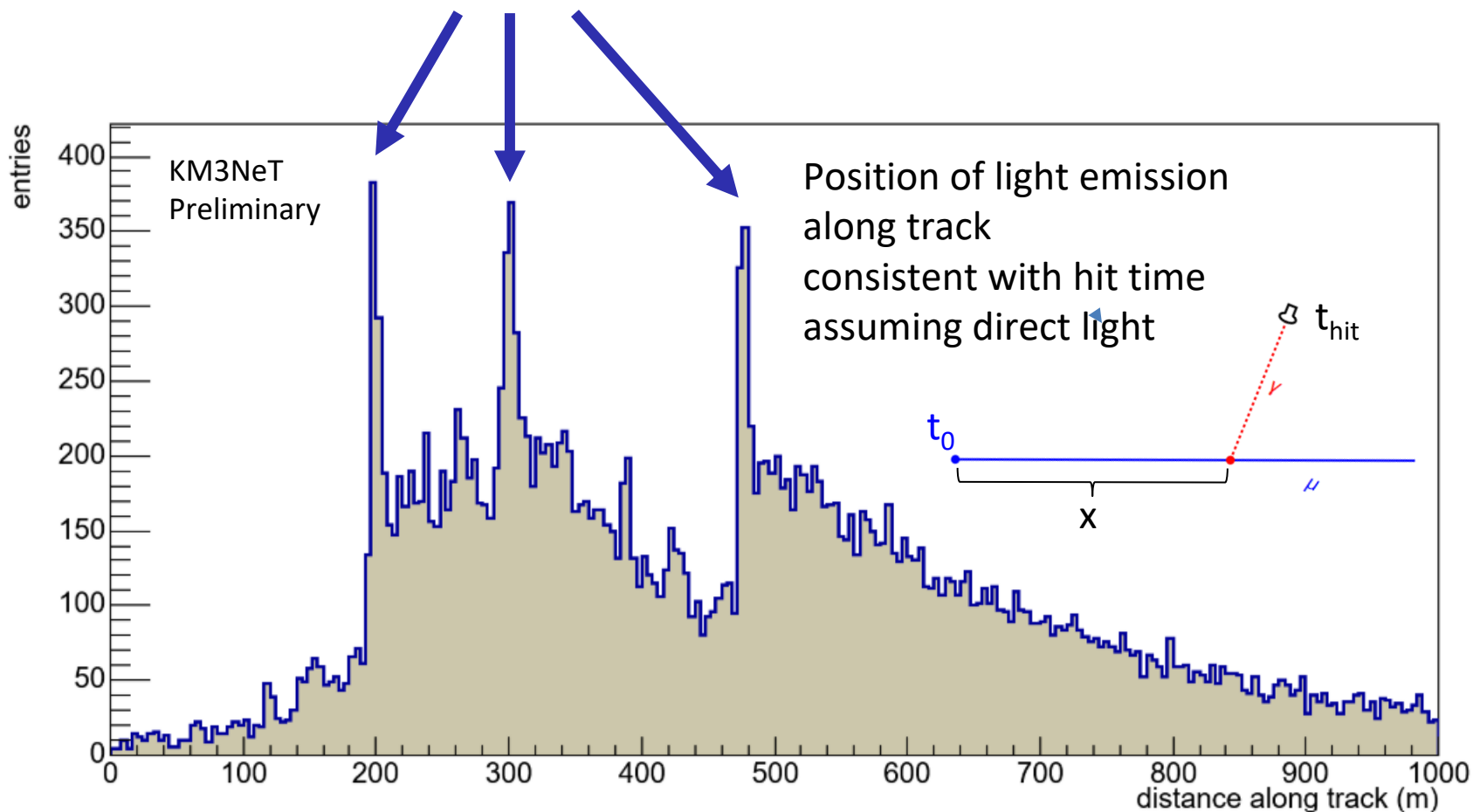
Expected zenith distribution for 100 PeV neutrinos





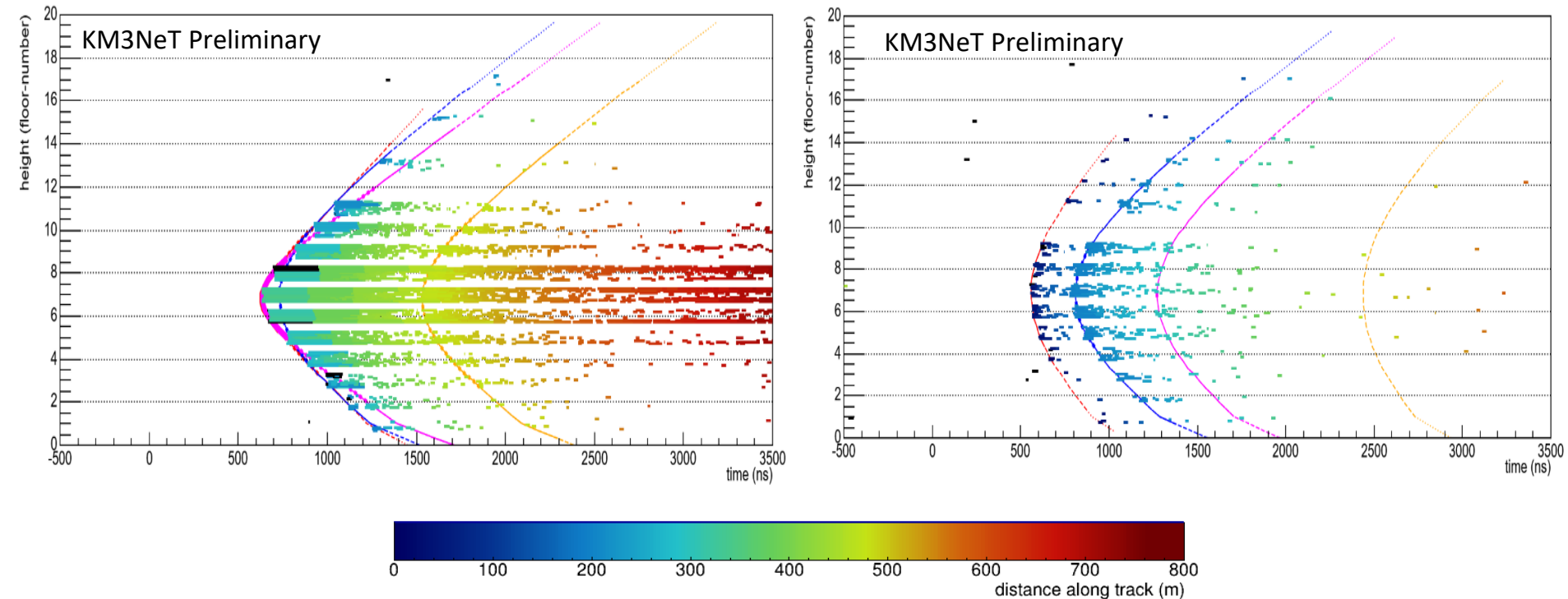
Rich detail

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

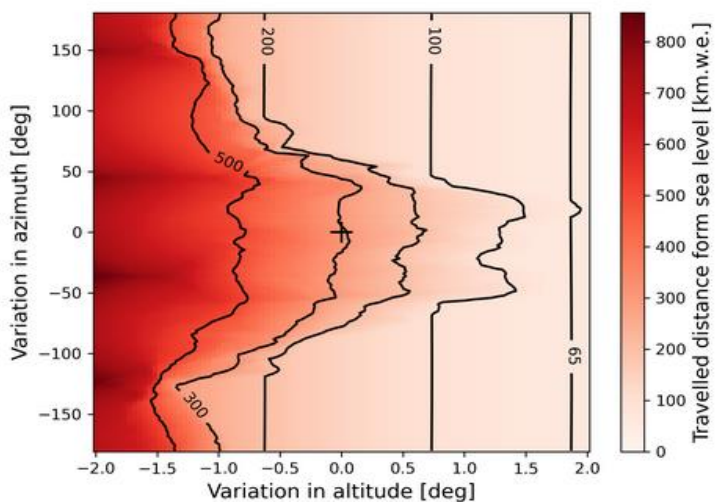
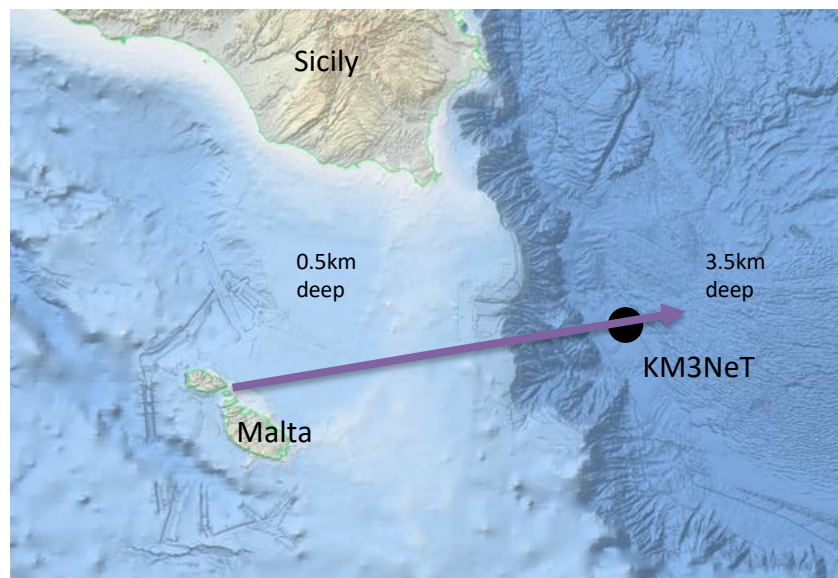
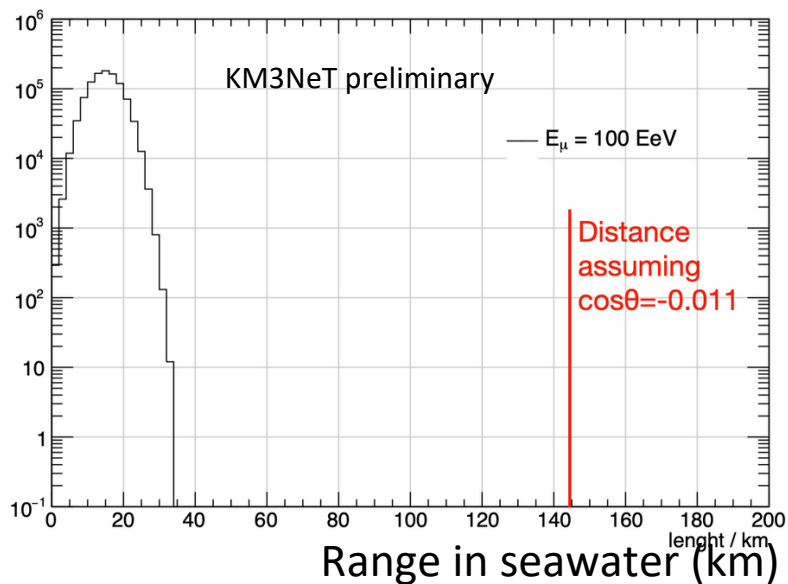


Rich detail

- 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



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



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, ATEs reacting to external alerts
- completion 2028

Exceptional >10 PeV energy event detected-stay tuned

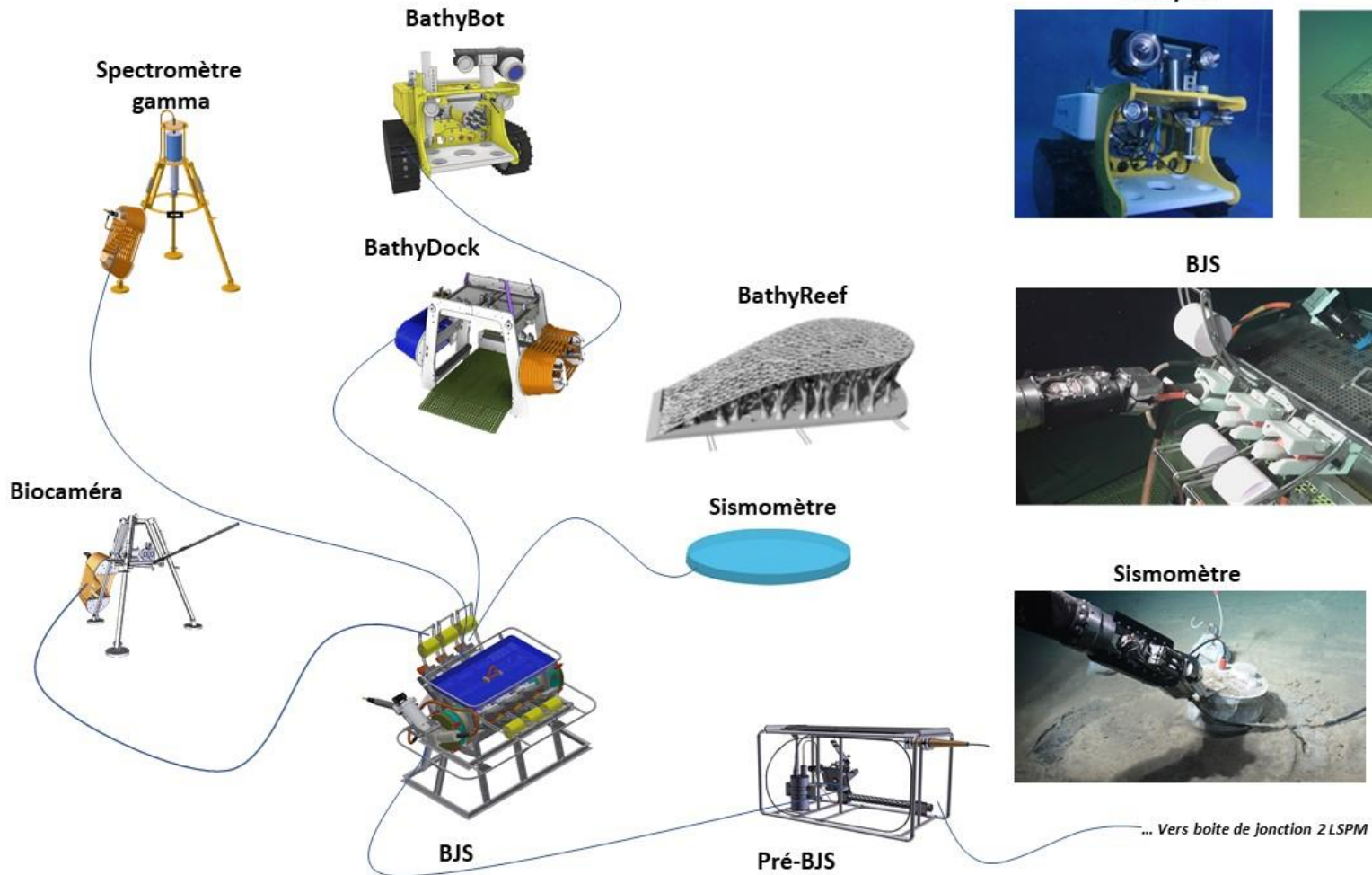
New collaborators very welcome- come and join the adventure!



KM3NeT @ ICHEP

P. Coyle	Status of the KM3NeT neutrino telescope
C. Lastoria	Exploring tau appearance measurements in KM3NeT/ORCA
J. Palacios Gonzalez	Multi-messenger results of the KM3Net real time analysis
A. Lazo Pedrajas	Measurement of atmospheric neutrino oscillations with KM3NeT/ORCA
L. Bailly-Salins	Sterile neutrinos
A. Saina	Dark matter searches with the KM3neT neutrino telescope
V. Kulikovskiy	Joint search for neutrino point-like and diffuse sources with KM3NeT/ANTARES
I. C. Rea (poster)	The multi-PMT optical module of KM3NeT

BACK UP



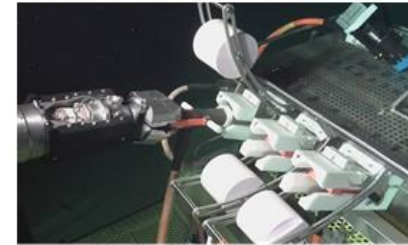
BathyBot



BathyReef



BJS



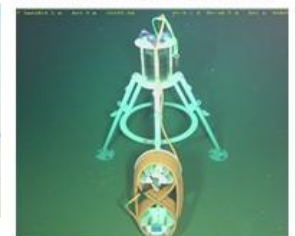
Biocaméra



Sismomètre

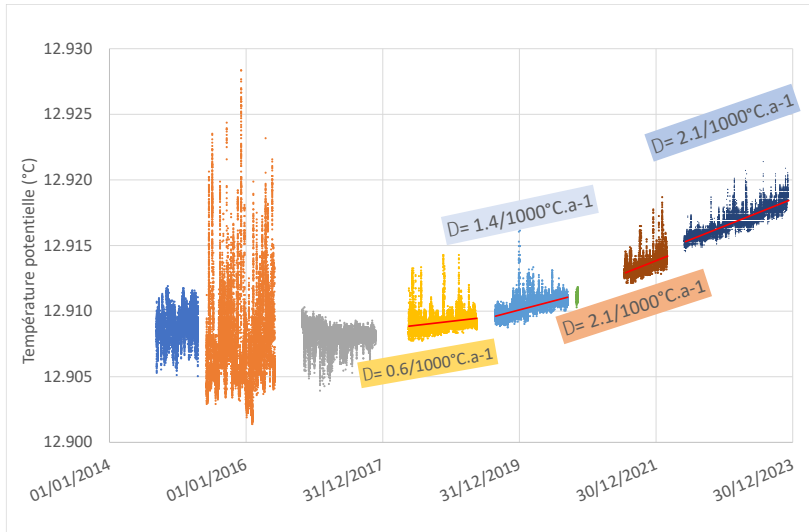


Spectromètre gamma

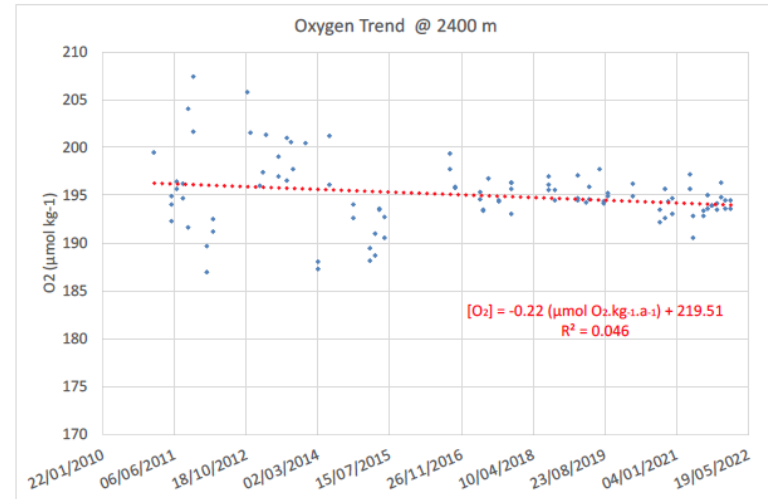


... Vers boîte de jonction 2LSPM

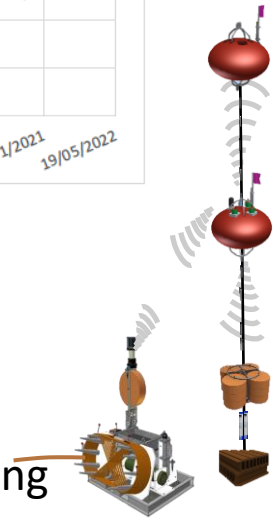
Temperature



Oxygen

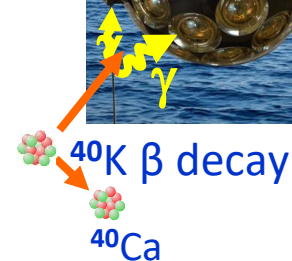


Albatross
autonomous
Acoustic mooring



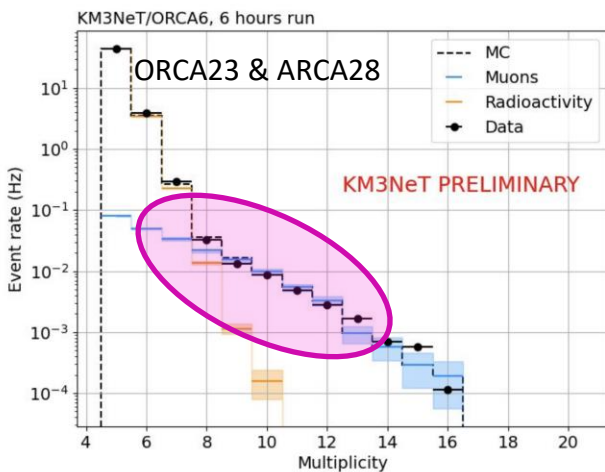


Single DOMs -> Supernova detection

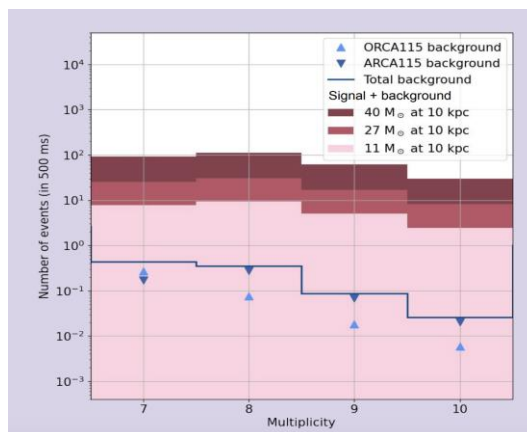


- 7 kHz random background, mostly from ^{40}K decays
- Constant natural source to calibrate the charge and timing of PMTs
- Can use single DOM variables to search for supernova neutrino bursts

PMT multiplicity plot

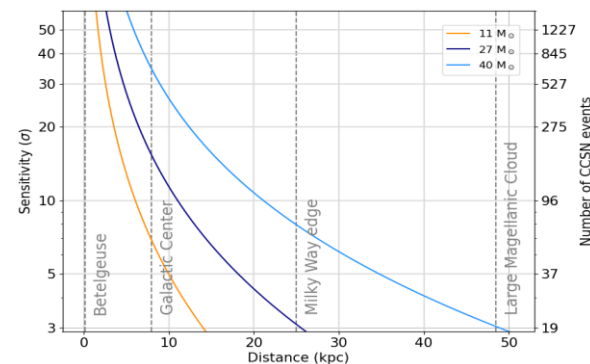


SN signal above background



Significance

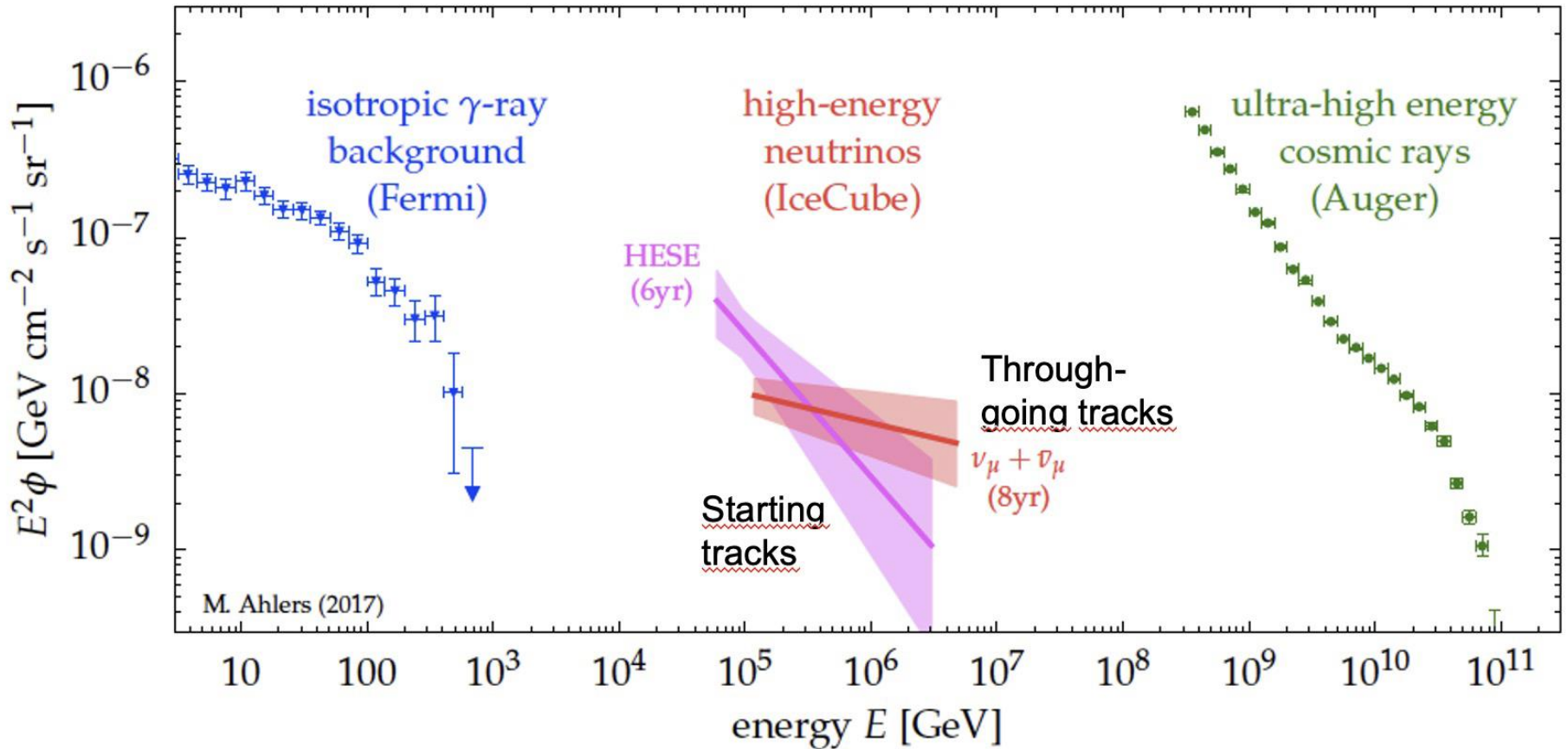
ARCA28+ORCA23



Full KM3NeT: $>5\sigma$ for ARCA+ORCA for $27M_{\odot}$ at a distance <50 kpc

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

Multi-messenger diffuse flux

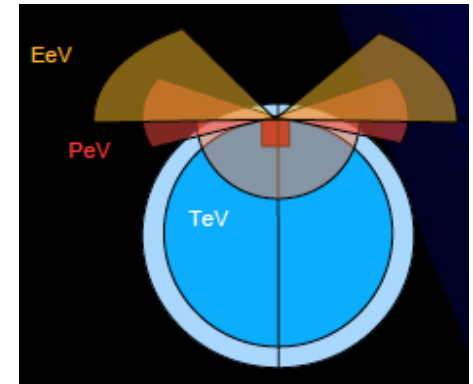


Similar energies in gamma rays,
neutrinos & cosmic rays
injected into our Universe

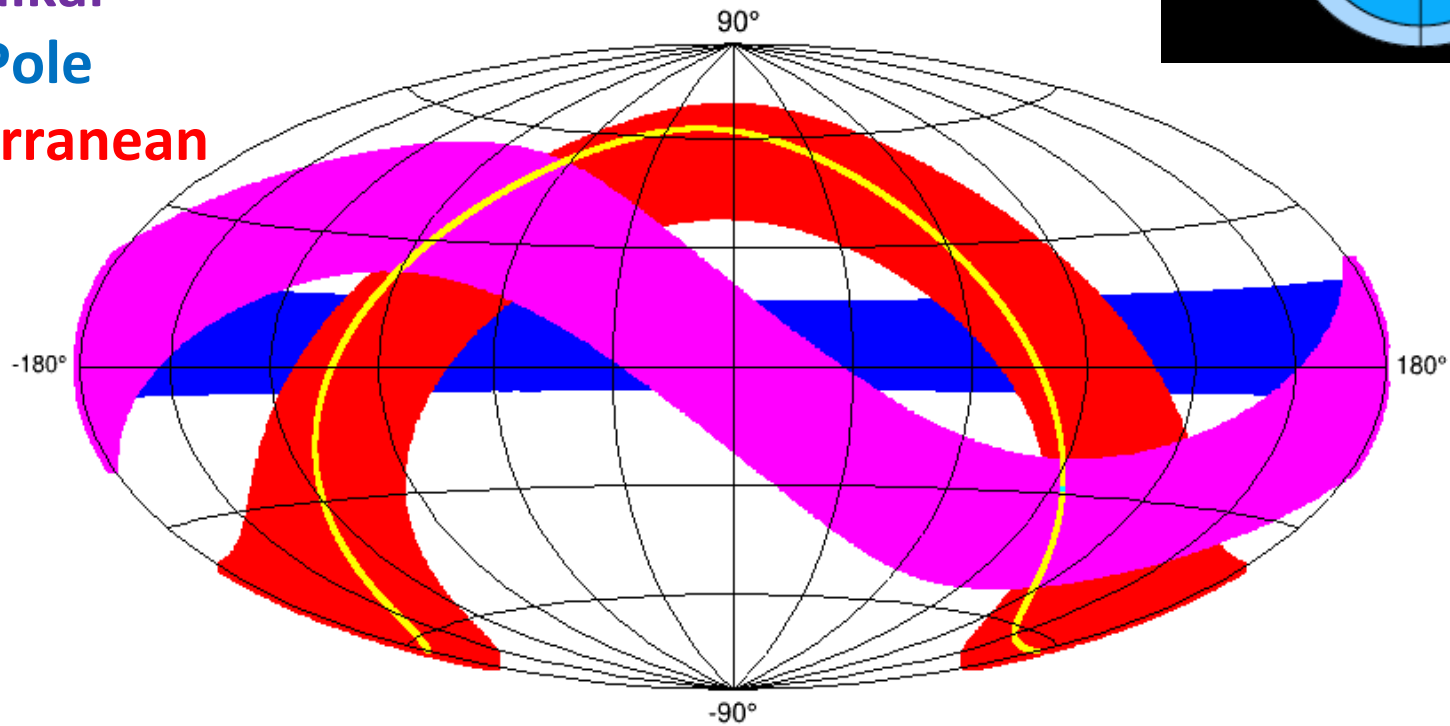
What are the sources?!

Instantaneous fields of view at PeV energies

At highest energies, neutrinos don't make it through the Earth: horizontal tracks are golden channel



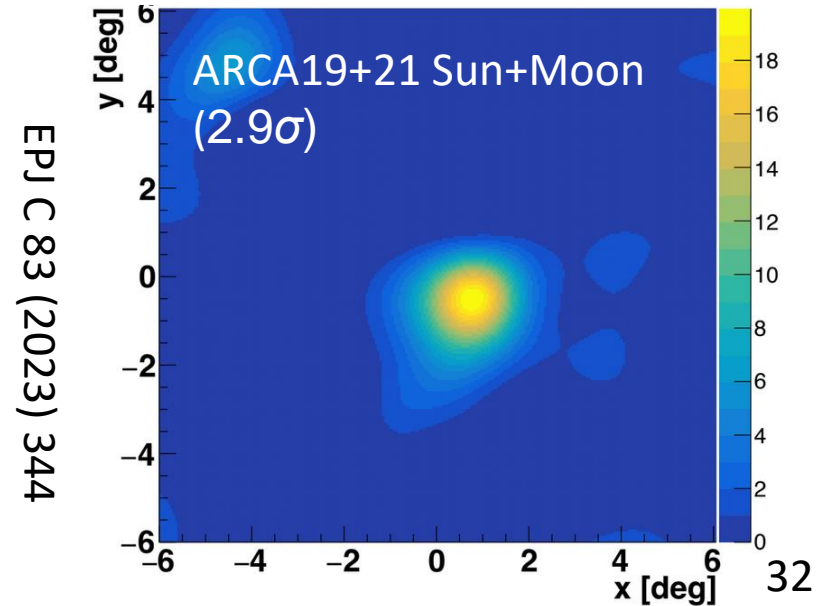
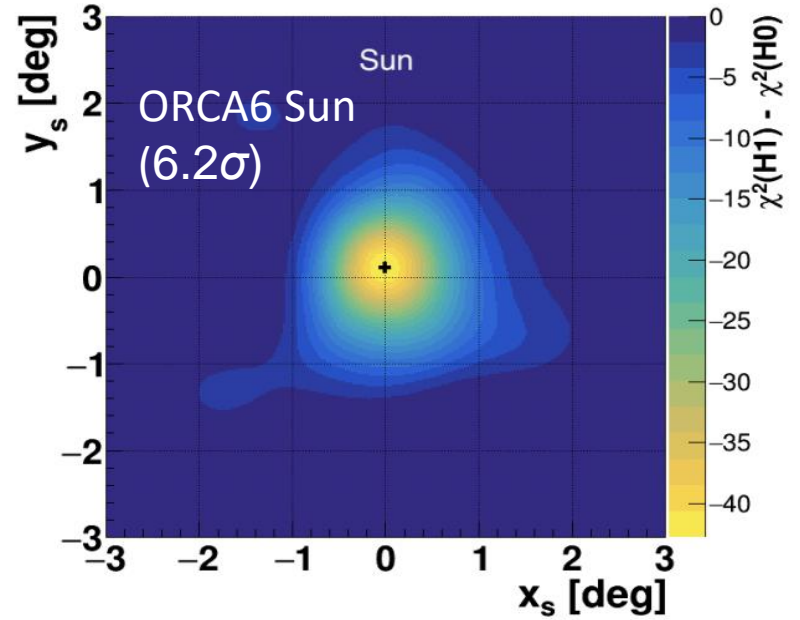
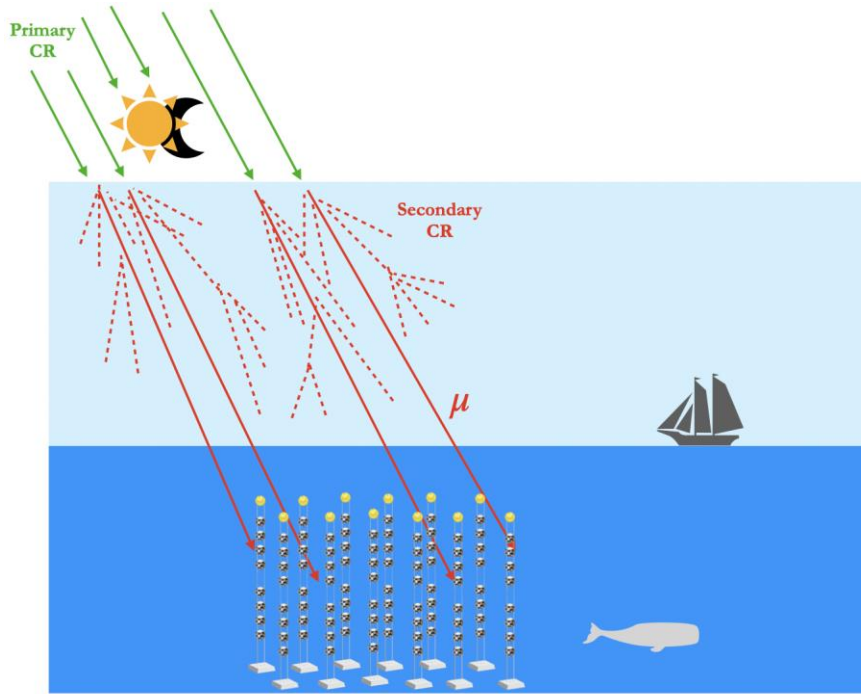
Lake Baikal
South Pole
Mediterranean



Instantaneous field of view with horizontal tracks



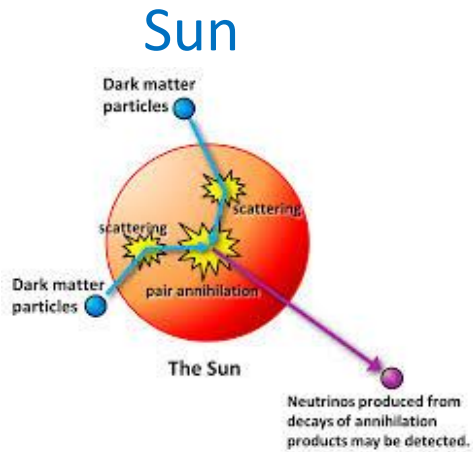
Absolute pointing calibration with Moon/Sun Shadow



EPJ C 83 (2023) 344



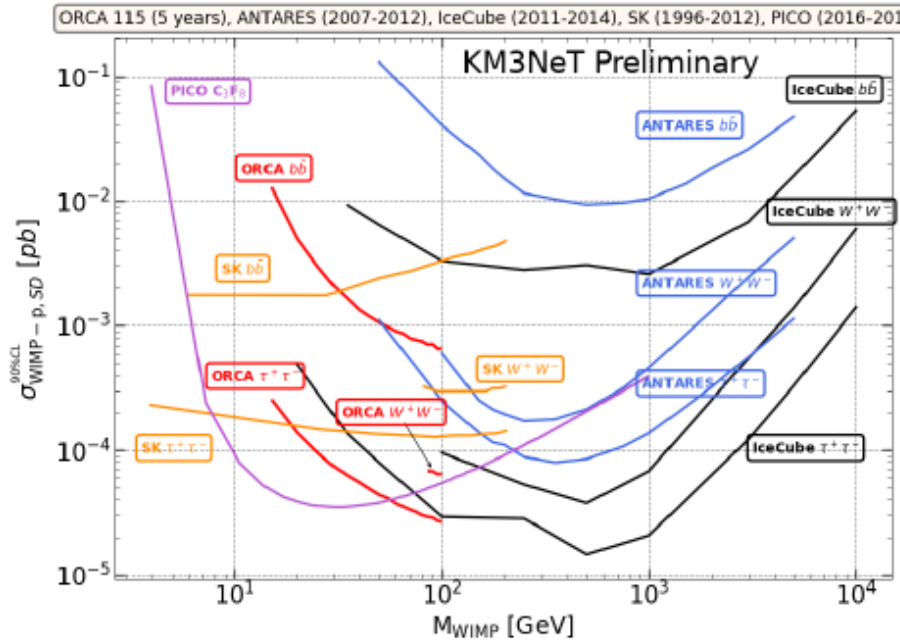
Dark matter-indirect detection



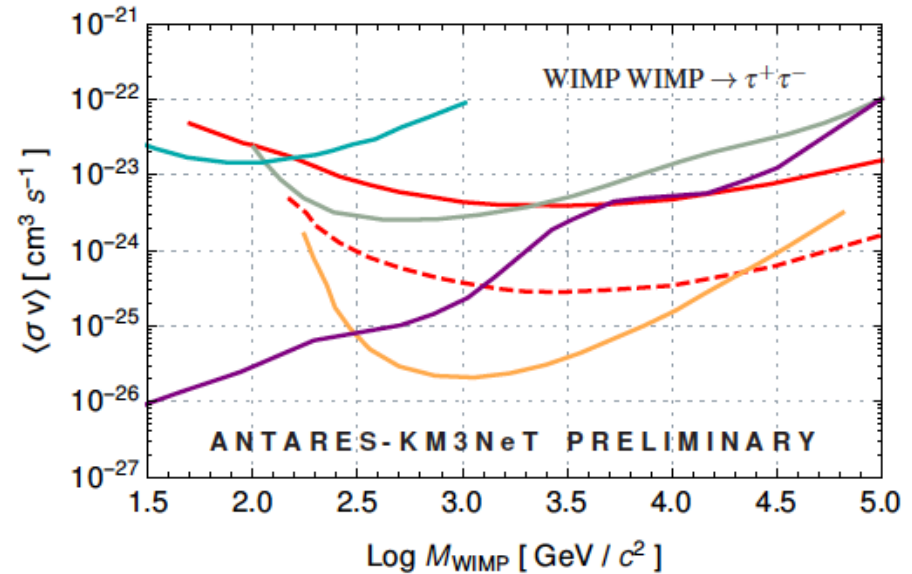
Galactic Centre



- ANTARES 11 years NFW - - - KM3NeT ARCA 230 lines 1 year NFW
- HESS 10 years GC survey Einasto — VERITAS Dwarf Spheroidals NFW
- Fermi+MAGIC Dwarf Spheroidals NFW — IceCube IC86 WIMP GC NFW



Phys.Lett. B759 2016



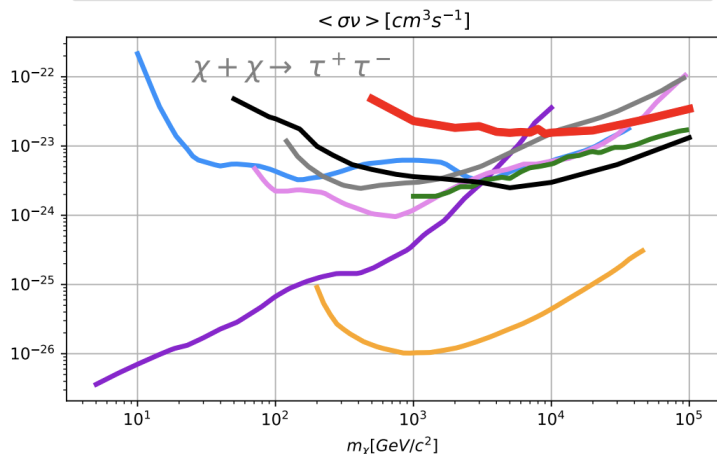
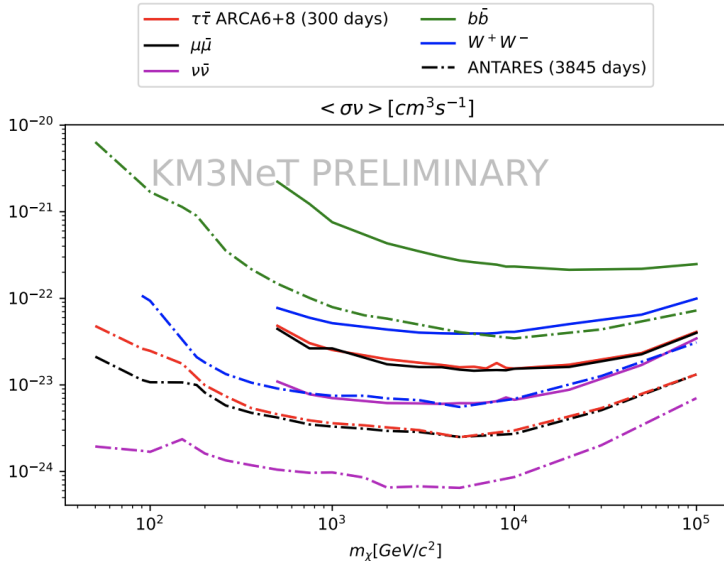
Phys. Lett. B 805 135439 (2020)



Dark Matter

Galactic Centre

ARCA6 + ARCA8 ICRC2023 PoS 1377

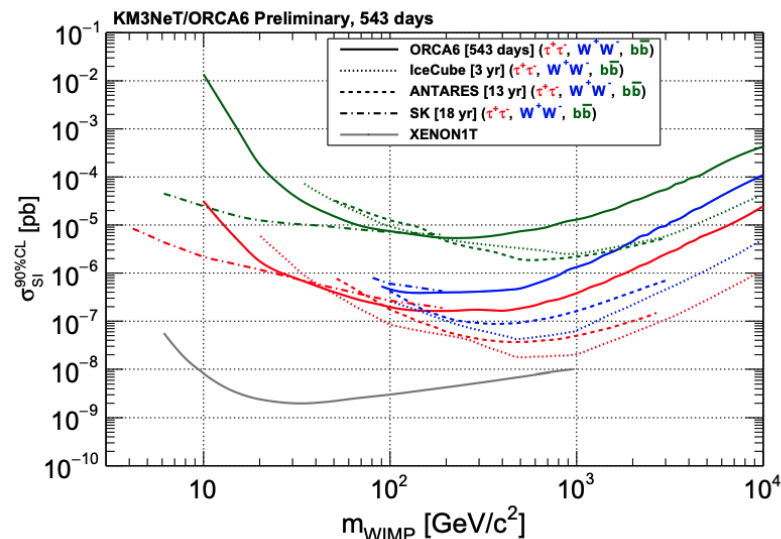
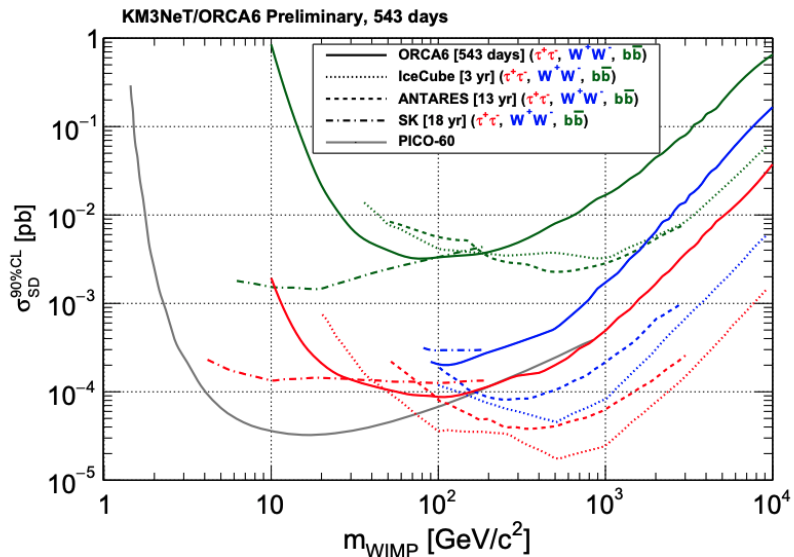


KM3NeT quickly reaching the ANTARES limits

The Sun

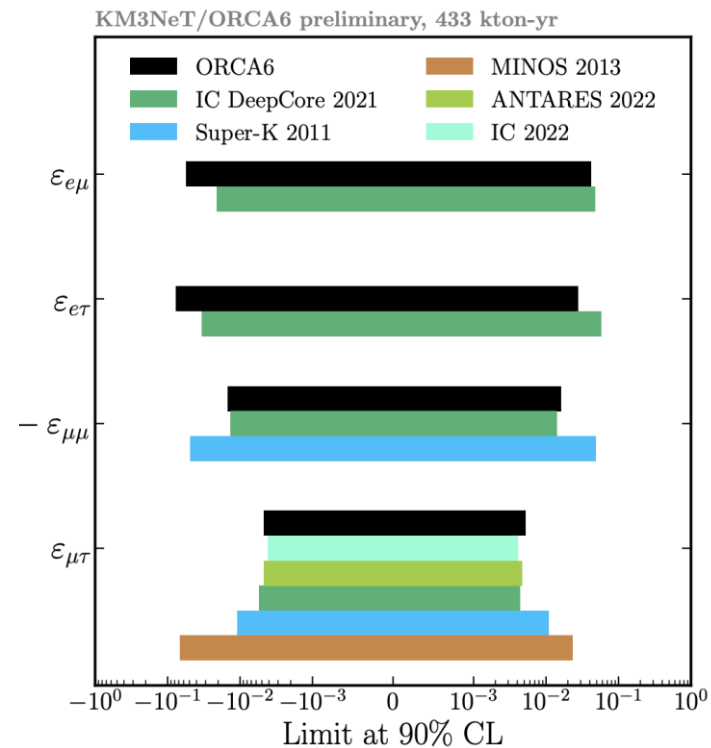
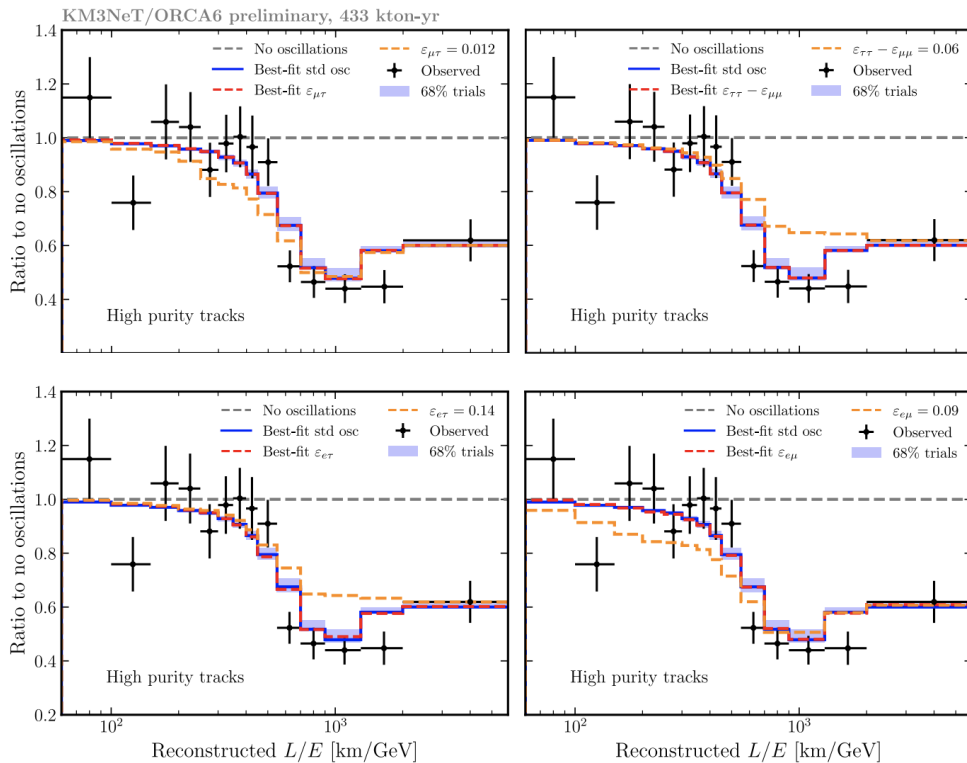
ORCA6

ICRC2023 PoS 1406





Non-Standard Interactions





Angular Resolutions

Tracks

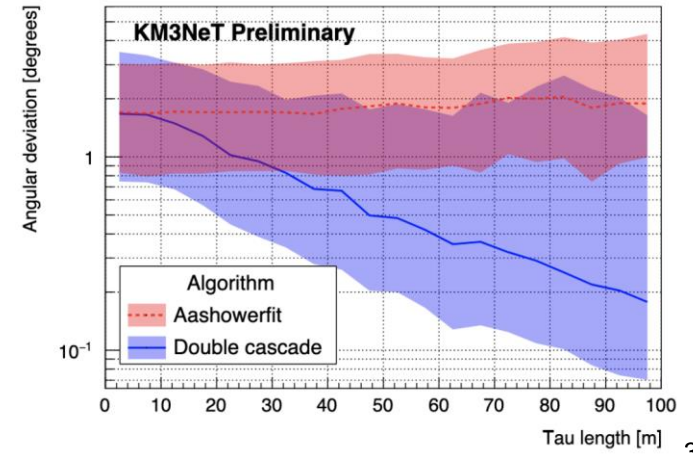
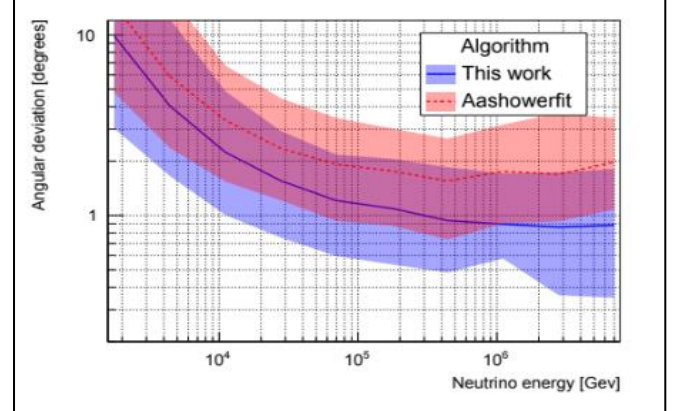
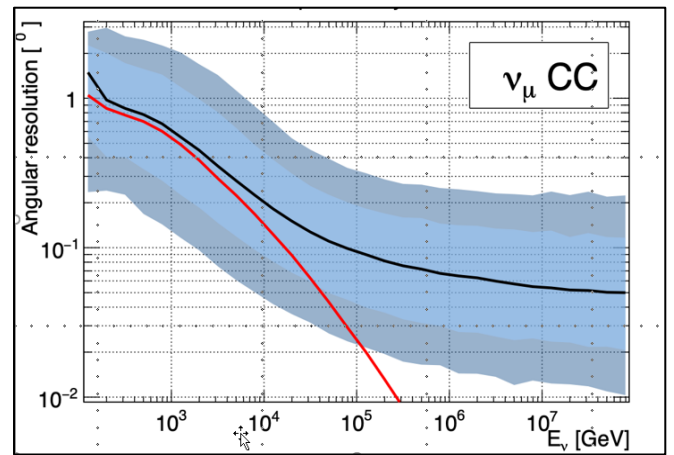
Better than $0.1^\circ > 20 \text{ TeV}$

Showers

Better than $1^\circ > 30 \text{ TeV}$

Taus

Better than 1° for tau track length $> 22 \text{ m}$

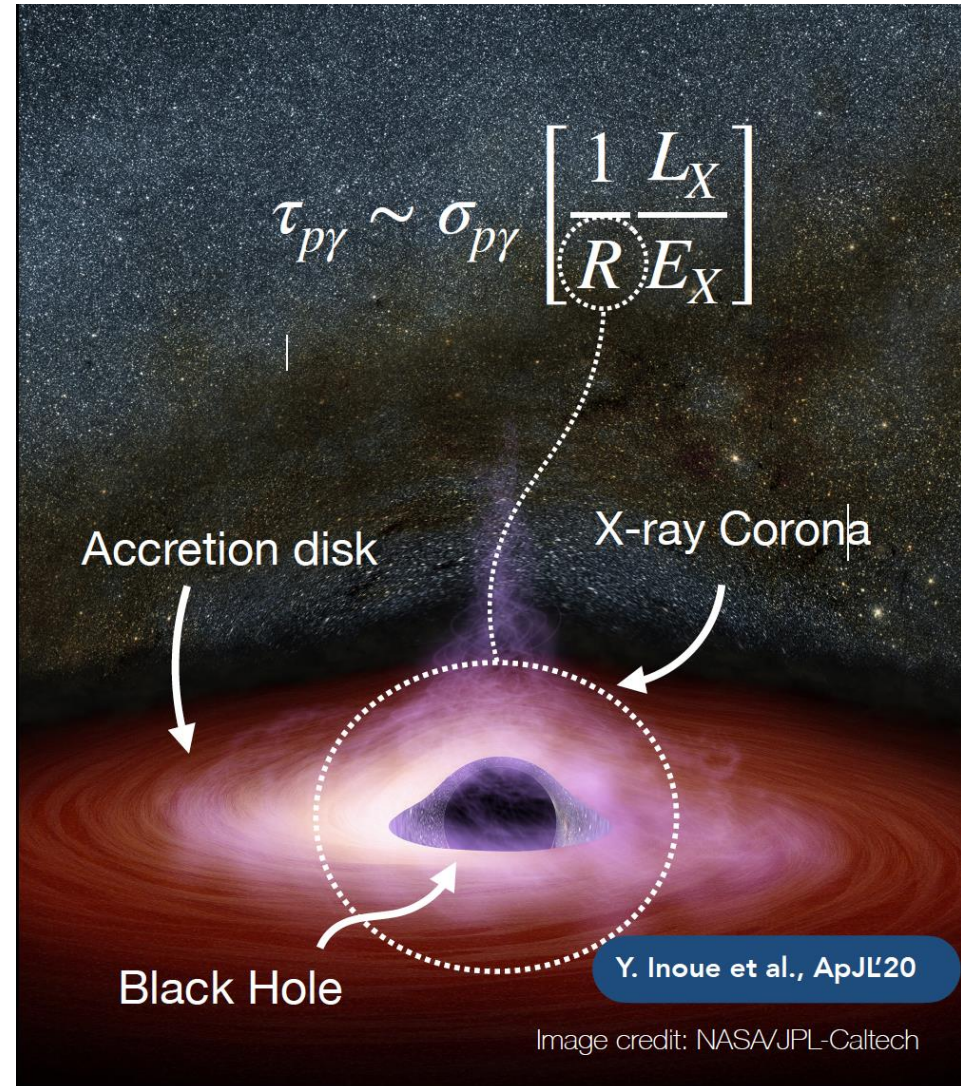


NGC 1068: The Disk Corona model

- AGN powered by a SMBH with mass $\sim 10^7 - 10^8$ solar masses
- It is close! ~ 14.4 Mpc
- Intrinsically the brightest Seyfert in the X-ray band

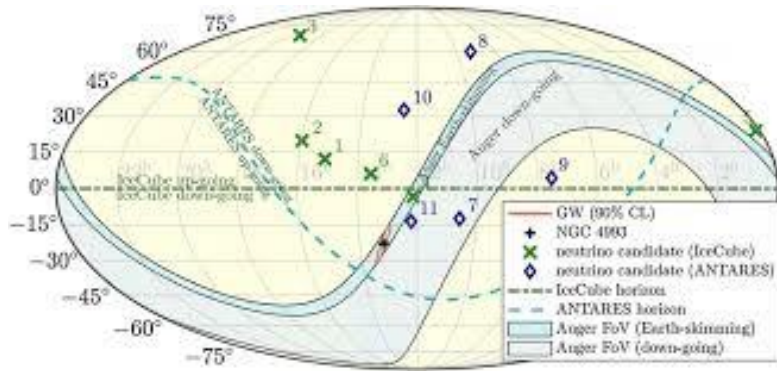
Electron and protons are accelerated in the high field regions associated with the black hole and the accretion disk

- They produce neutrinos in the optical thick corona
- **Gamma-rays are absorbed**



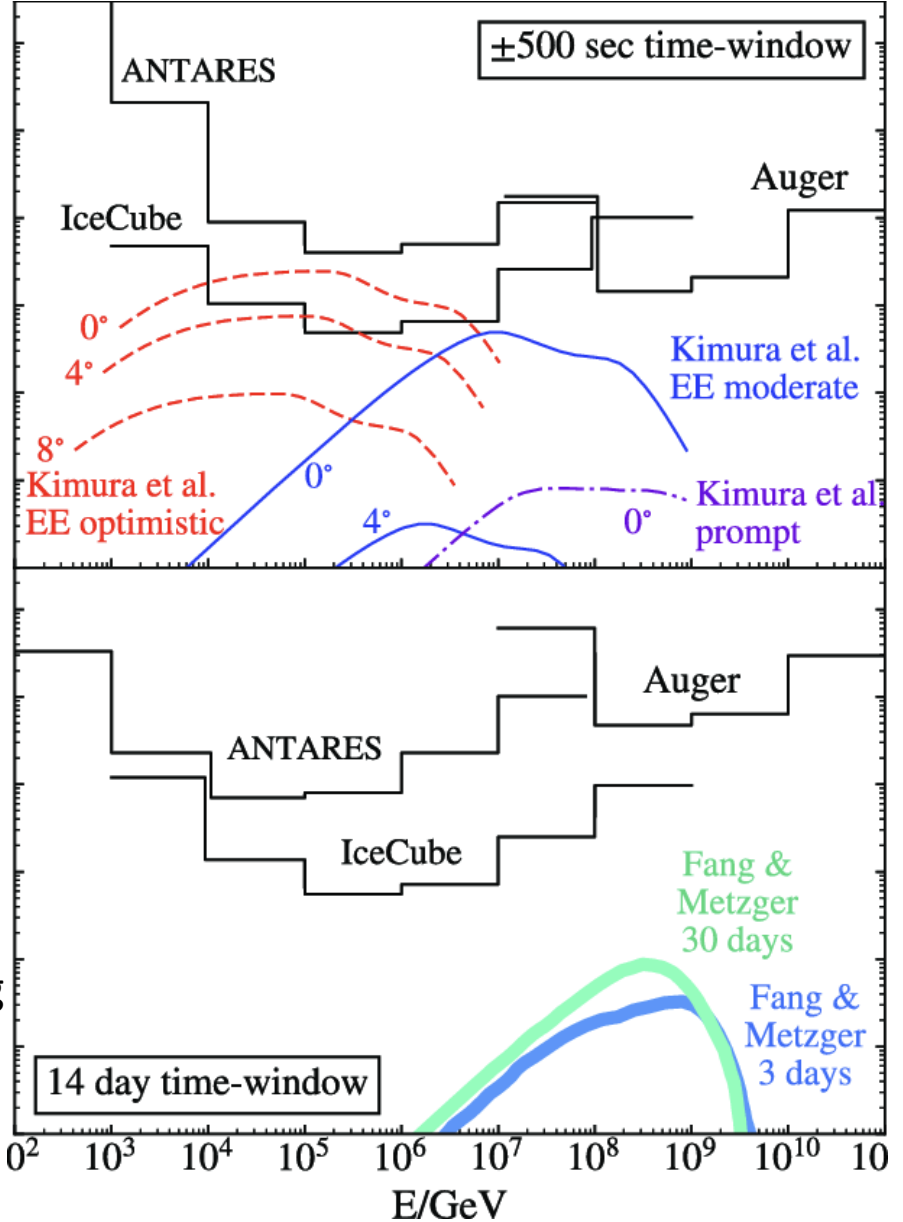
Multi-messenger example: Kilonova GWs

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

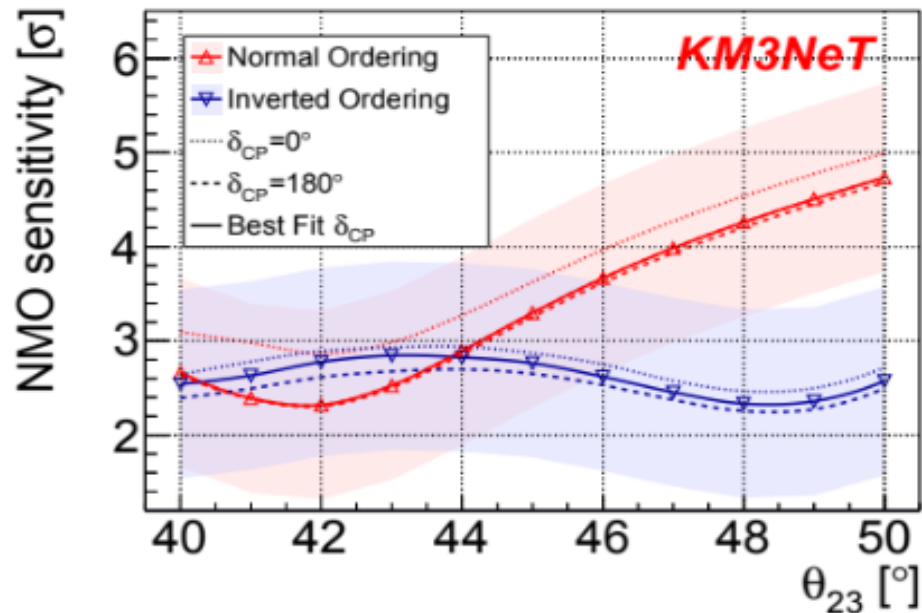
BBH merger: either looking for BBH happening in dense environment or with large mass difference between the 2 progenitors (remaining accretion disk)





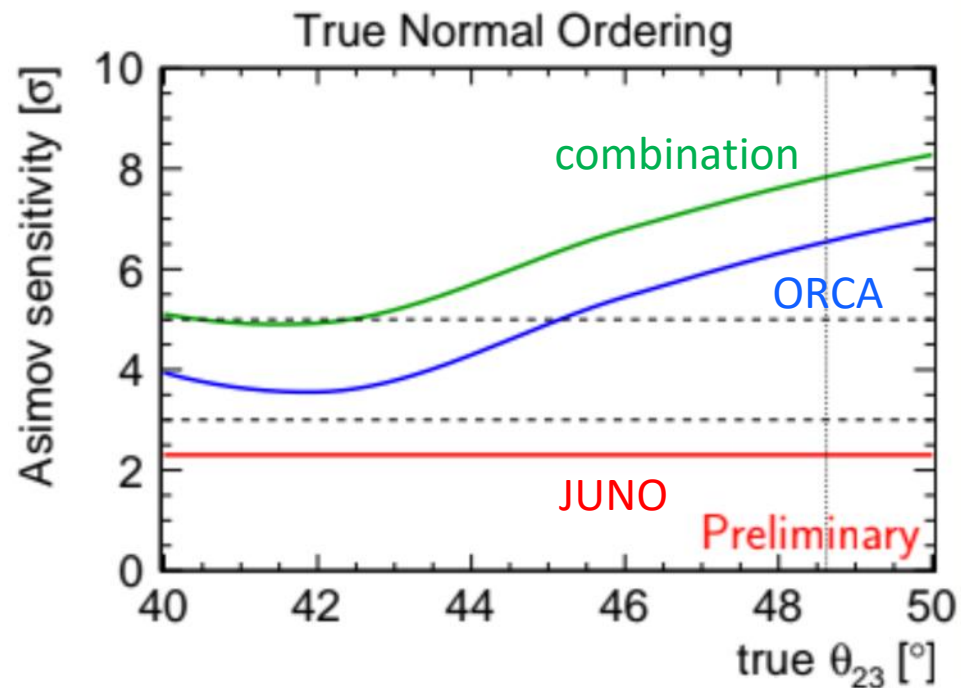
ORCA115: neutrino mass ordering

3 years



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

6 yrs & combination with JUNO



Combination power relies on tension between best-fit of Δm_{31}^2 in “wrong ordering” between JUNO and ORCA

EVENT TYPE AND ANGULAR RESOLUTION

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

Tracks: very long path ($E_\mu > 1\text{TeV}$ several km)

Big lever arm

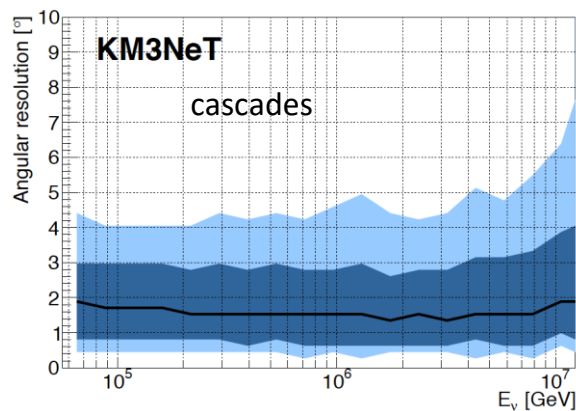
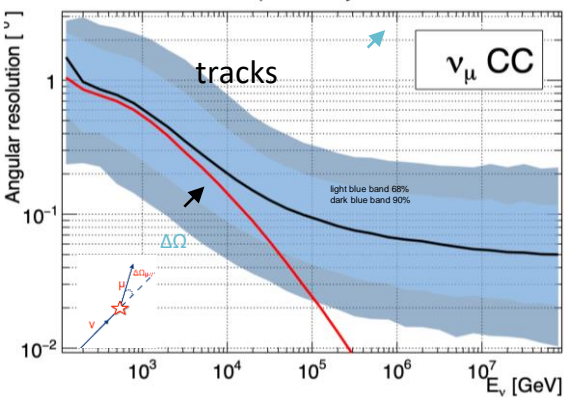
- Good angular resolution

Cascades: small path ($E_{\text{casc}} > 1\text{TeV}$ some tens of meters)

- Modest angular resolution

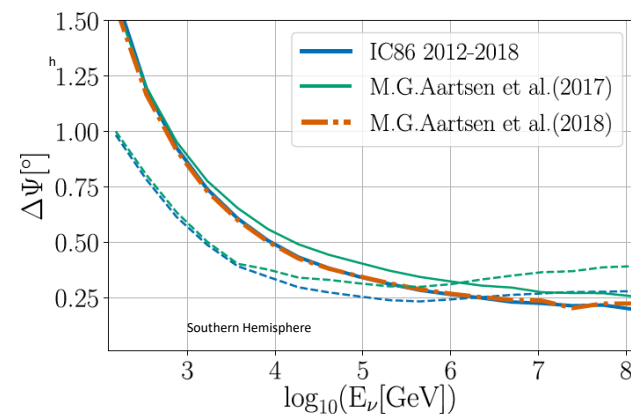
•Resolution at 100 TeV

KM3NeT



IC resolution for tracks

from arXiv:1910.08488, 15 October 2019



EVENT TYPE AND ENERGY RESOLUTION

Tracks: very long path ($E_{\mu} > 1\text{TeV}$ several km)
 Neutrino interaction vertex far from the detector

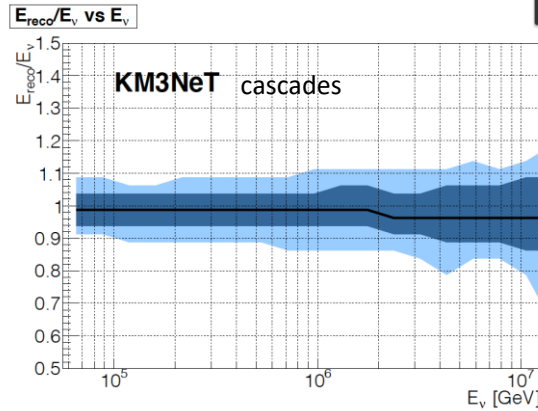
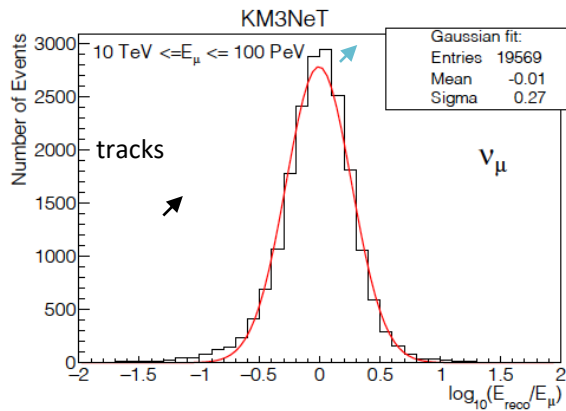
- Modest energy resolution

Cascades: small path ($E_{\text{casc}} > 1\text{TeV}$ some tens of meters)
 All the energy released inside the detector

- Good energy resolution

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

KM3NeT



IIC energy resolution for cascades

