The KM3NeT Neutrino Telescope: Results from First Data

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KM3NeT

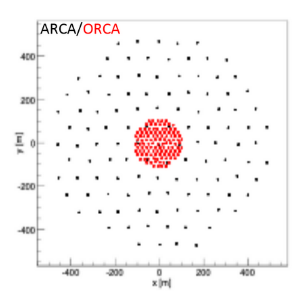
Underwater astronomy and high-exposure accumulator of atmospheric neutrinos using an instrumented portion of the Mediterranean Sea as a detector medium.

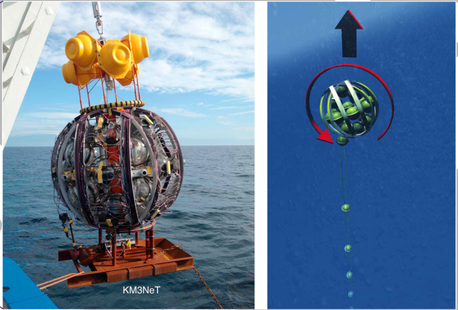
[*J.Phys.G:Nucl.Part.Phys.* **43** 084001 (2016)]

KM3NeT: layout

KM3NeT/ORCA

ex ANTARES site

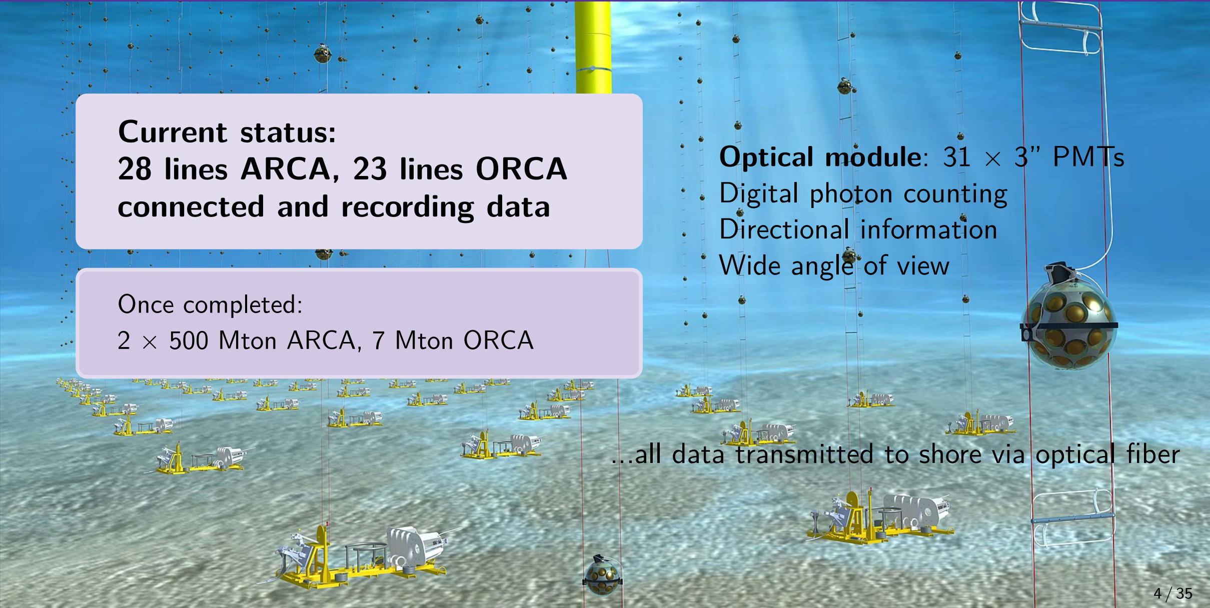




KM3NeT/ARCA

ORCA (spacing 23×9 m): **high statistics** of atmospheric ν	
ARCA (spacing 90×36 m): **rare fluxes** of extraterrestrial ν	

KM3NeT: layout



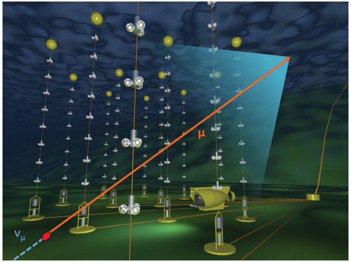
Current status:
28 lines ARCA, 23 lines ORCA connected and recording data

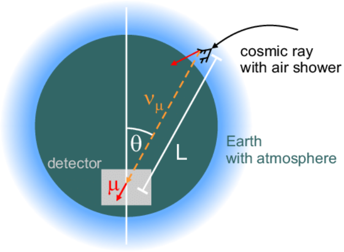
Once completed:
2 × 500 Mton ARCA, 7 Mton ORCA

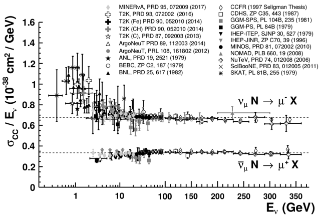
Optical module: 31 × 3" PMTs
- Digital photon counting
- Directional information
- Wide angle of view

...all data transmitted to shore via optical fiber

Very-large volume Cherenkov neutrino detector

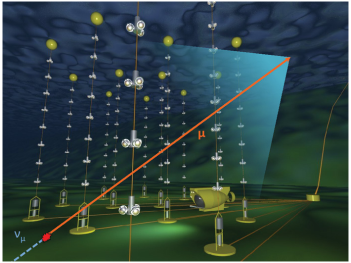


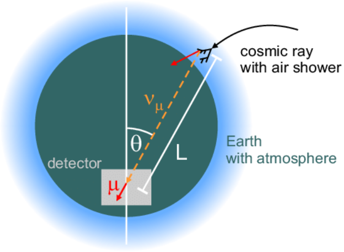


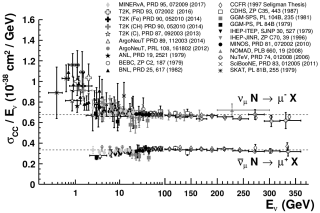


Look through the Earth for leptons from $\nu \to$ lepton conversion.
$\sigma_{\nu \to l} \sim 10^{-38}$ cm^2 at 1 GeV! Low rate $\to$ very large (natural) reservoirs of transparent medium. Scattering length influences pointing precision.

Very-large volume Cherenkov neutrino detector **data**

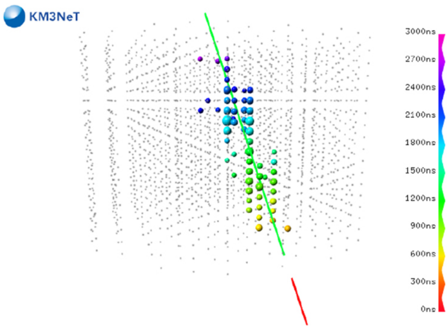


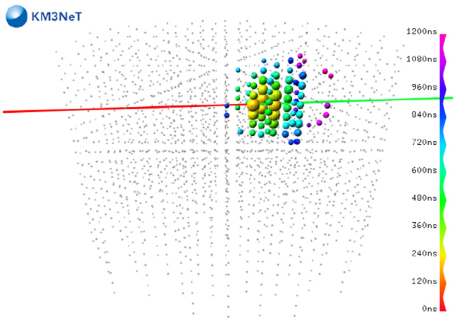




Times, positions of hit PMTs	$\rightarrow$	arrival direction coordinates
Number of hit PMTs	$\rightarrow$	energy
Shape	$\rightarrow$	flavour of associated lepton

Performance: pointing





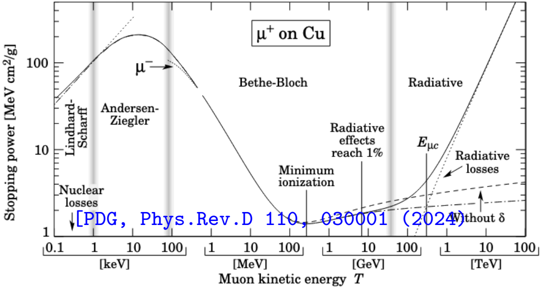
KM3NeT reconstructs two classes of events:

Tracks: predominantly $\nu_\mu CC$; angular resolution down to 0.1° at 1 PeV - fly-through

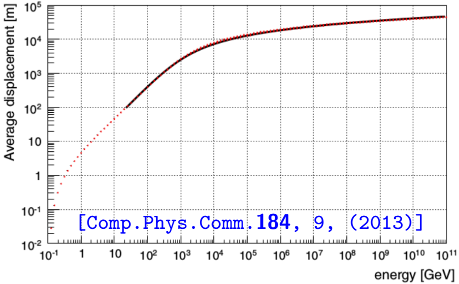
Showers: predominantly ν_e CC or any NC; angular resolution 1° at 1 PeV - contained

Performance: particle identification

Tracks and showers are not univocally discriminated depending on their energy



[PDG, Phys.Rev.D 110, 030001 (2024)]



[Comp.Phys.Comm.**184**, 9, (2013)]

Example: 1 GeV muon leaves a track of a few metres in water. ORCA granularity: 23×9 m

Water over ice?

Larger scattering length: direct photons → better **pointing** and **particle identification capability**. Noise from radioactive ^{40}K decays, natural luminescence in sea easily identifiable.

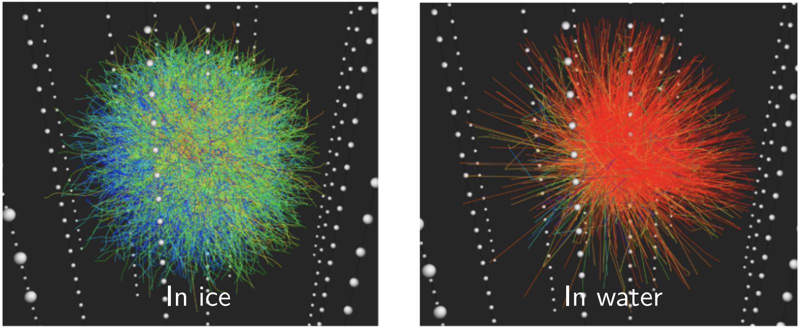
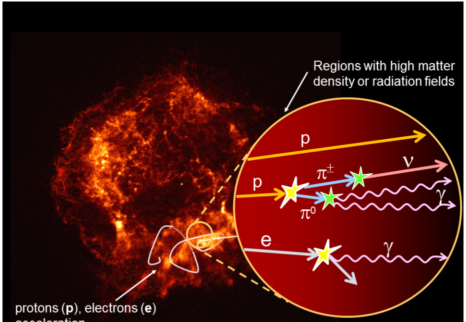


Figure: Simulation of light from a 10 TeV cascade in ice (left) and water (right).

Physics case 1: extraterrestrial neutrinos

High-energy neutrinos are expected from collisions yielding particles such as $\pi^{\pm}$ and $\mu^{\pm}$, through pp and $p\gamma$ scattering, taking place in different environments, steady or with flares

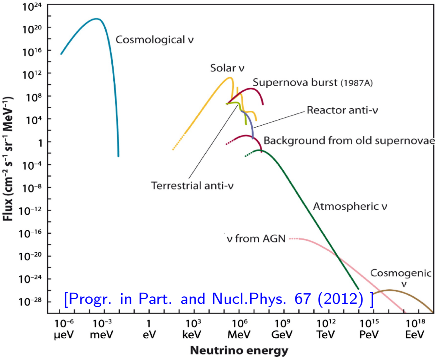


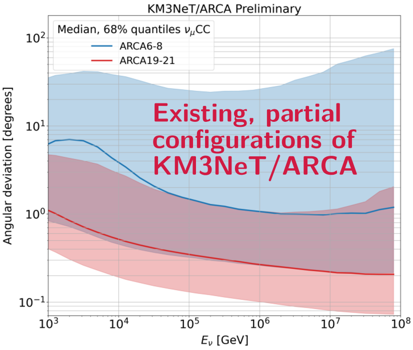
[Fig. from Universe 2020, 6(2), 30]

- Neutrino astronomy: backtracking sources
  1. As a **correlation** with underlying catalogue
     1. Jets of active galactic nuclei (AGNs)
     2. Starburst galaxies, star-forming galaxies
     3. Expanding front of supernova remnants
     4. Gamma-ray bursts
     5. IceCube HE events
  2. As **autocorrelation** or clusters in space (-time)
- Search for a diffuse excess and measurement of its energy spectrum. Accelerator properties.
- Search for prompt multimessenger coincidences

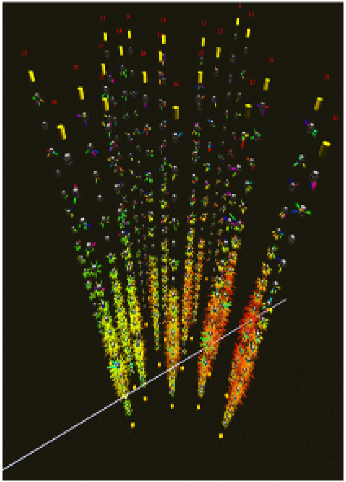
Neutrino astronomy *in the making*: experimental challenge

Astrophysical neutrinos: atmospheric neutrinos: atmospheric muons $= 1{:}10^4 : 10^{10}$

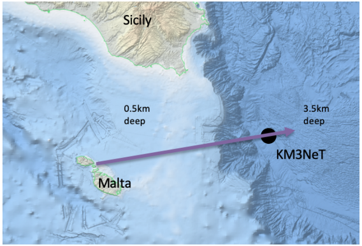


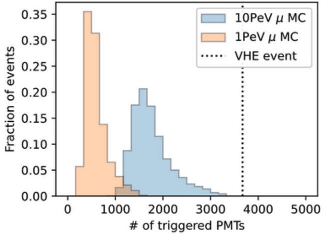


Observation of an ultra-high-energy cosmic ν with KM3NeT



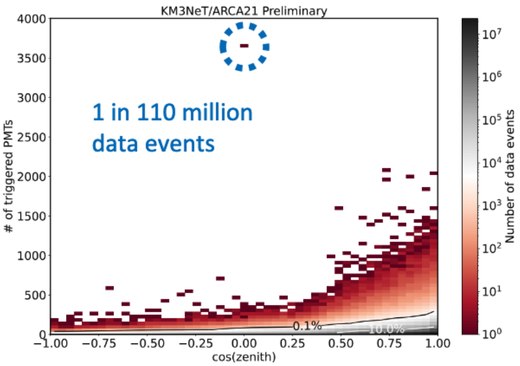
- Recorded with 21-line configuration of KM3NeT/ARCA
- Huge light deposit: 35% of the detector (3672 photomultipliers) triggered; likely multiple tens of PeV
- Consistent with neutrino signal, horizontally crossing the detector traversing continental shelf: not an atmospheric muon



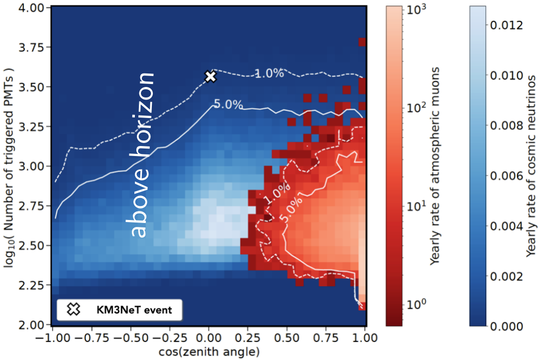


Observation of an ultra-high-energy cosmic ν with KM3NeT

Really a unique event or *beginners' luck* when compared with expected yearly rate of atmospheric muons + cosmic neutrinos.

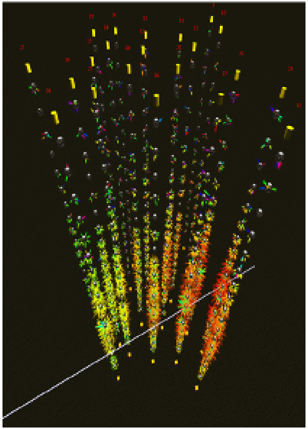


Data: $cos(\theta) : N_{PMT}$



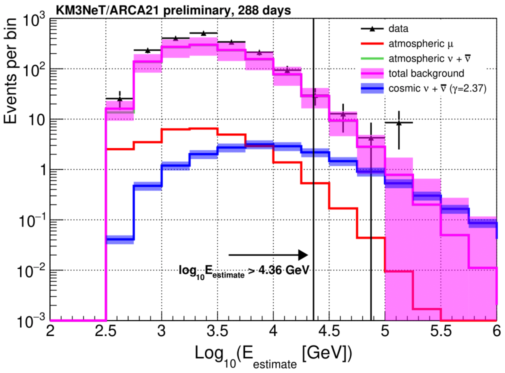
Monte Carlo simulation $cos(\theta) : N_{PMT}$

Observation of an ultra-high-energy cosmic ν with KM3NeT

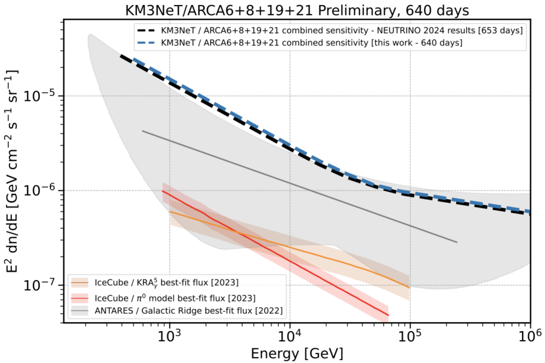


Search for a cosmic component in the ν energy spectrum

Analysis wishes to identify high-energy excess over the atmospheric ν, diffuse over full sky or from the region of the Galactic Plane.



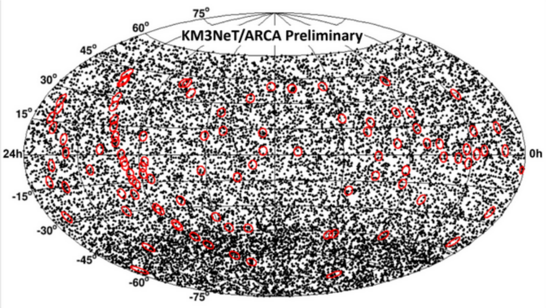
Diffuse, full sky



Galactic ridge region

Search for point sources (all-sky)

Assuming ν flux $\propto E^{-2}$, KM3NeT/ARCA will reach comparable level to IceCube for the Northern Hemisphere, and improve by almost a factor 2 for the Southern Hemisphere



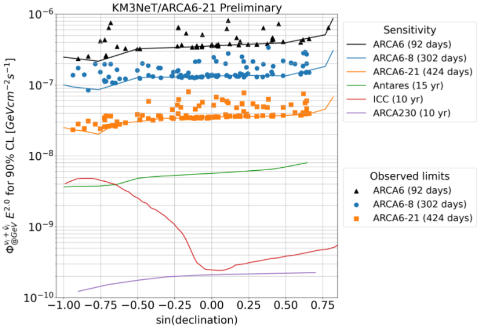
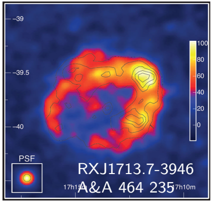


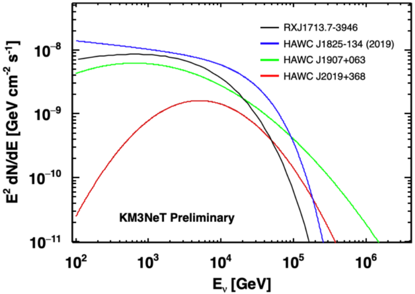
Figure: Upper limits at 90% C.L. reached with KM3NeT/ARCA [PoS(ICRC2023)1018]. Red circles are 2.5° around the candidate source positions.

Sensitivity to strongest Galactic sources

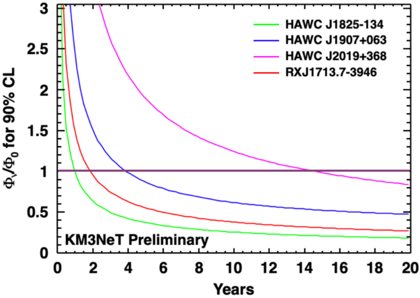
In hypothesis of hadronic emission, computing ν flux from γ-ray flux, several **extended Galactic sources** will be observable in a few years of operation.



Example of γ-ray emission as seen by H.E.S.S.



Expected ν fluxes
(assumed 100% hadronic scenario)



Sensitivity at 90% CL as a function of the observation time

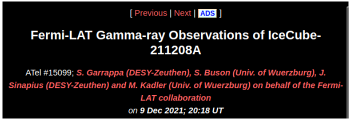
Multi-messenger networking

Flares, transients and other sources with time variability (GRBs, gravitational waves, SN)

Example: flares caused by hadronic emission on top of quiescent state → Prompt alerting system associated with rapid online analysis and pointing directions for telescopes

KM3NeT is getting ready to send and receive alerts in multi-messenger network

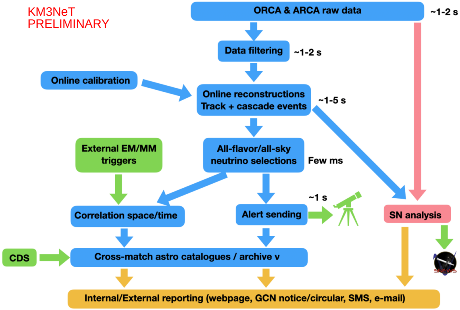
1. SN pipeline already active for real-time analysis
2. KM3NeT will replace ANTARES in follow up of alerts (ATel, GCN via AMON)


[Previous | Next | ADS]

Fermi-LAT Gamma-ray Observations of IceCube-211208A

ATel #15099; *S. Garrappa (DESY-Zeuthen), S. Buson (Univ. of Wuerzburg), J. Sinapius (DESY-Zeuthen) and M. Kadler (Univ. of Wuerzburg) on behalf of the Fermi-LAT collaboration*

on 9 Dec 2021; 20:18 UT

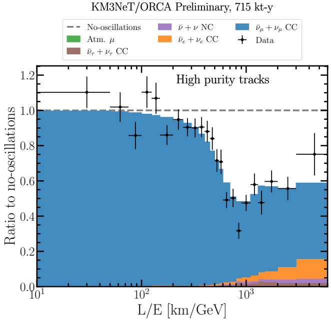


Oscillations, mass ordering and related observables

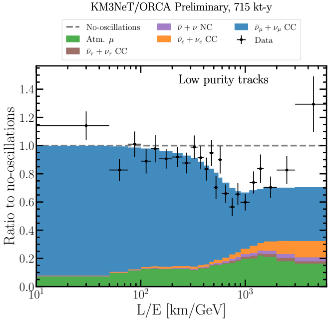
Flavour-related observables require particle identification in detector (e, μ, τ lepton?). Ideal region for search is GeV and just above, at the first disappearance peak.

Evidence for atmospheric neutrino oscillations

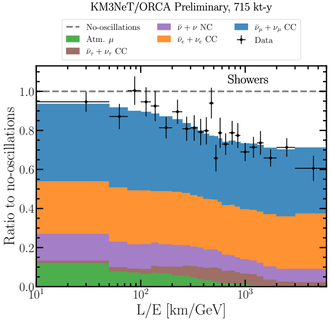
Oscillations are seen with significance $> 6\sigma$ in L/E distributions through ν_μ **disappearance** with KM3NeT/ORCA 715 kton-years data set (6+10+11 detector lines).



High-purity tracks



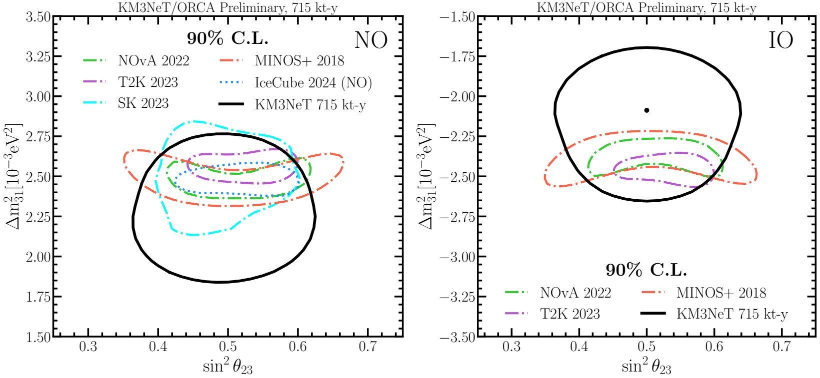
Low-purity tracks



Showers

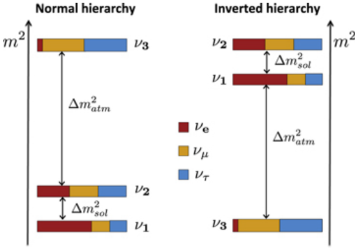
Measurement of atmospheric oscillation parameters

Best fit: $\sin^2\theta_{23} = 0.50^{+0.07}_{-0.07}$ $\Delta m^2_{31} = -2.09^{+0.17}_{-0.21} \cdot 10^{-3}\text{eV}^2$. Data display a slight preference for inverted ordering. 1.6 Mton-y of data awaiting.



Neutrino mass ordering

Matter resonance at 5 GeV affects: ν if normal ordering (NO), $\bar{\nu}$ if inverted ordering (IO).



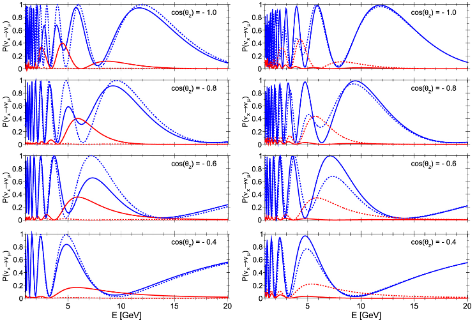
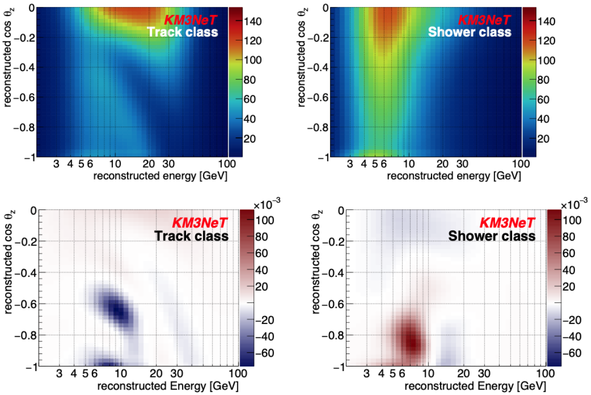


Figure: Right: oscillation probabilities $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_\mu$ for different energies and baselines. The solid (dashed) lines are for NO (IO), ν (left) and $\bar{\nu}$ (right).

Neutrino mass ordering

Matter resonance at 5 GeV affects: ν if normal ordering (NO), $\bar{\nu}$ if inverted ordering (IO). Sensitivity due to ν-$\bar{\nu}$ asymmetry in flux and cross section. Both μ- and e-channels contribute.



Expected sensitivity: number of expected events with normal/inverted hierarchy $(N_{IH} - N_{NH})/N_{NH}$

and relative χ^2. Left: muons; right: electrons. Electron channel is more robust against detector resolution.

Physics case 3: indirect searches for *new physics* signatures

Neutrino telescopes are versatile instruments! Exploiting two features

1. At 1-100 GeV energies: effects that alter oscillations of atmospheric neutrinos, which are measured with **high statistics**
2. At TeV-PeV energies: limits from cosmic neutrinos: effects that **scale with energy** or **accumulate along large distances**

- Non-standard interactions (NSI)
- Neutrino quantum decoherence
- Neutrino decay
- Sterile neutrinos
- Violation of Lorentz Invariance with effects on oscillations
- Neutrinos from annihilation of dark matter particles
- Heavy Neutral Leptons via double cascades at low energy

Summary

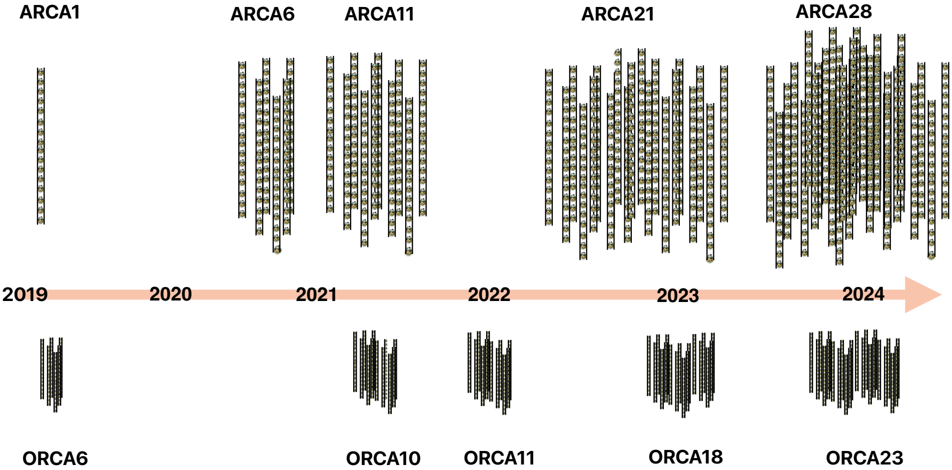
KM3NeT/ARCA - current status: 28 lines, outperforming predecessor ANTARES

1. exceptional **multi-PeV event recorded** ...publication coming out soon.
2. able to detect the **diffuse flux** observed by IceCube with **5σ** significance in **half a year**
3. sensitivity to **astrophysical sources** in the Southern Hemisphere improves by almost 2 orders of magnitude with respect to IceCube

KM3NeT/ORCA - current status: 23 detection line, 1.6 Mton-year recorded data

1. Measurement of **neutrino oscillations** and best fit of oscillation parameters
2. Seach for new physics: ν_τ normalization factor, NSI, quantum decoherence, violation of Lorentz invariance, neutrino decay, dark matter through indirect detection

KM3NeT: building roadmap



Backup

ANTARES decommissioning

ANTARES decommissioning

ANTARES decommissioning

Core-collapse supernova ν

Produced in stellar core collapse at the end of stellar evolution like SN1987A. Real-time search for simoultaneous rate raise in DOMs [PoS(ICRC2021)941]

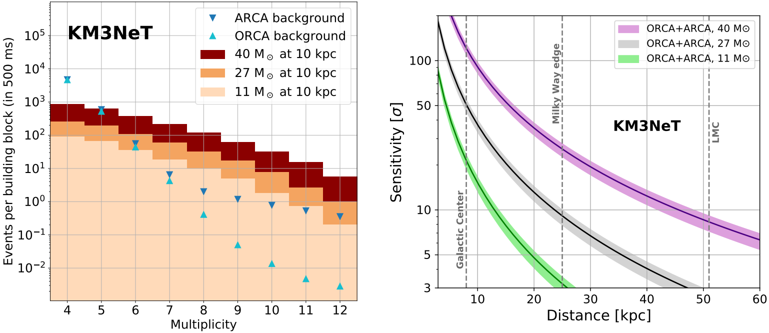
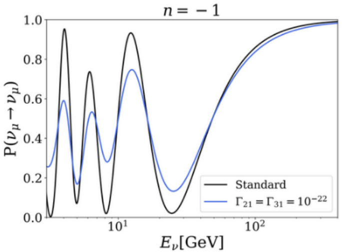
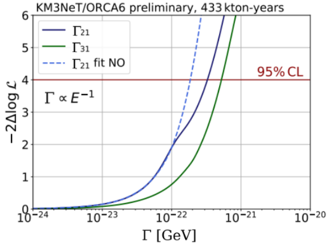


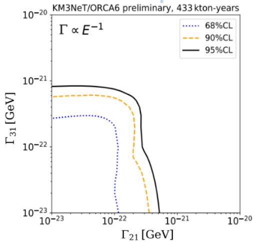
Figure: Left: SN events expected from 3 simulated progenitors at ORCA and ARCA as a function of different multiplicity values compared with BG rates. Right: Sensitivity as a function of distance.

Neutrino quantum decoherence

Neutrino mass eigenstates lose their coherent superposition due to interactions with the environment → oscillation amplitude is suppressed [https://doi.org/10.22323/1.444.1025]







Non-standard interactions of neutrinos (NSI)

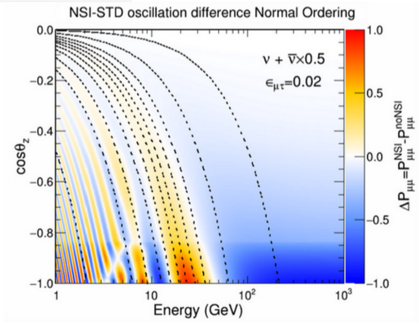
LHC has detected **no new particles** $\Rightarrow$ interest turns towards possible **new operators** that can be constructed: modifications of the Standard Model that manifest themselves indirectly.

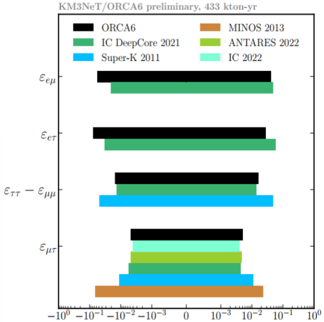
SM effective theory (SMEFT) = SM + dimension 6 operators + ...

All dimension-4 operators that observe Lorenz invariance and gauge symmetry are already contained in the SM. Next possible trial is dimension 6 $\Rightarrow$ this brings in new terms in the Hamiltonian $\Rightarrow$ new vertex $\Rightarrow$ modified interaction.

Non-standard interactions of neutrinos (NSI)

Neutral current forward scattering of neutrinos inside the Earth is modified $\rightarrow$ Flavour-dependent matter effects alter neutrino oscillations inside the Earth. [https://doi.org/10.22323/1.444.0998]





Motivation: (3+1) models with $\Delta m^2_{41} \sim 1$ eV^2 might explain short baseline anomalies. KM3NeT is sensitive to mixing angles $\Theta_{24} and \Theta_{34}$.