Neutrino Astronomy and Oscillations with KM3NeT

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Astroteilchen-Seminar DESY Zeuthten

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KM3NeT

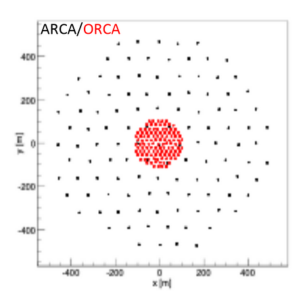
Underwater astronomy and high-exposure accumulator of atmospheric neutrinos using an instrumented portion of the Mediterranean Sea as a detector medium.

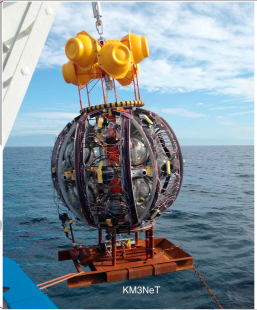
[*J.Phys.G:Nucl.Part.Phys.* **43** 084001 (2016)]

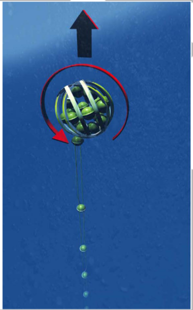
KM3NeT: layout

KM3NeT/ORCA

ex ANTARES site





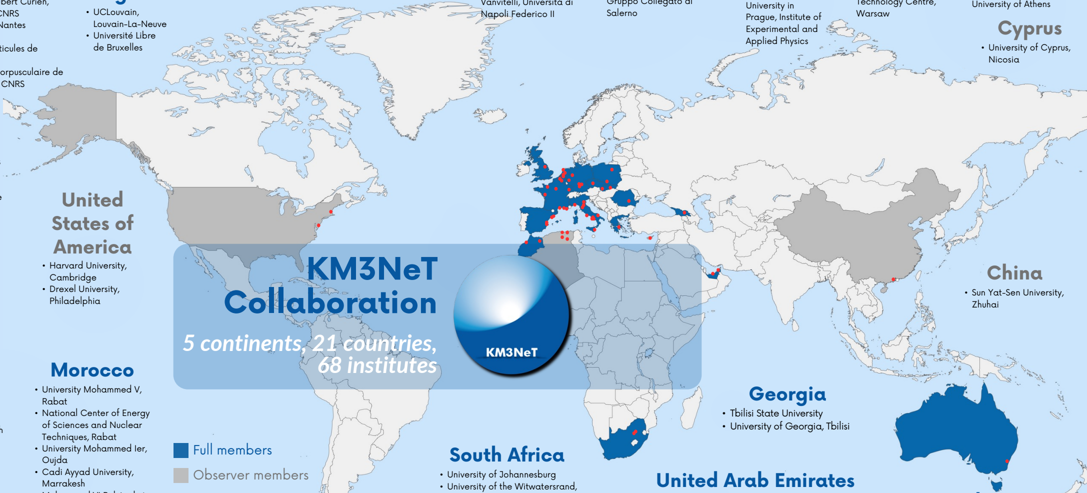


KM3NeT/ARCA

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

KM3NeT Collaboration

5 continents, 21 countries, 68 institutes



France
- CNRS Nucléaire et Particules
- Astroparticle and Cosmology Laboratory, Université Paris Cité, CNRS
- Centre for Particle Physics of Marseille, Aix-Marseille Université, CNRS
- Laboratoire d'Astrophysique de Marseille
- Mediterranean Institute of Oceanography, CNRS Terre et Univers, Marseille
- Université de Toulon
- Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, CNRS
- Subatech, IMT Atlantique, Nantes Université
- Laboratoire Univers et Particules de Montpellier
- Laboratoire de Physique Corpusculaire de Caen, Université de Caen, CNRS

United Kingdom
- University of Hull

The Netherlands
- NWO-I, Nikhef, Amsterdam
- Universiteit van Amsterdam
- Universiteit Leiden
- NIOZ, Texel
- TNO, Technical Sciences, Delft

Germany
- Friedrich-Alexander-Universität Erlangen-Nürnberg
- Max-Planck-Institut für Radioastronomie, Bonn
- Universität Würzburg
- Universität Erlangen, Remeis Sternwarte, Bamberg
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- Slovenská akadémia vied, Kosice

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- AGH University of Krakow
- NCBJ - National Centre for Nuclear Research, Warsaw
- Nicolaus Copernicus Astronomical Center, Particle Astrophysics Science and Technology Centre, Warsaw

Romania
- Institute of Space Science - INFLPR Subsidiary, Magurele

Belgium
- UCLouvain, Louvain-La-Neuve
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- Czech Technical University in Prague, Institute of Experimental and Applied Physics

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- University of Cyprus, Nicosia

Spain
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- Instituto de Física Corpuscular, Universitat de València, CSIC
- Universitat Politècnica de València, IGIC, Gandia, València
- Universidad de Granada
- Centro Oceanográfico de Murcia (IEO-CSIC)
- Laboratori d'Aplicacions Bioacústiques, Universitat Politècnica de Catalunya, Vilanova i la Geltrú
- Instituto de Ciencias del Mar, CSIC, Barcelona

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- University of Georgia, Tbilisi

South Africa
- University of Johannesburg
- University of the Witwatersrand, Johannesburg
- North-West University, Potchefstroom

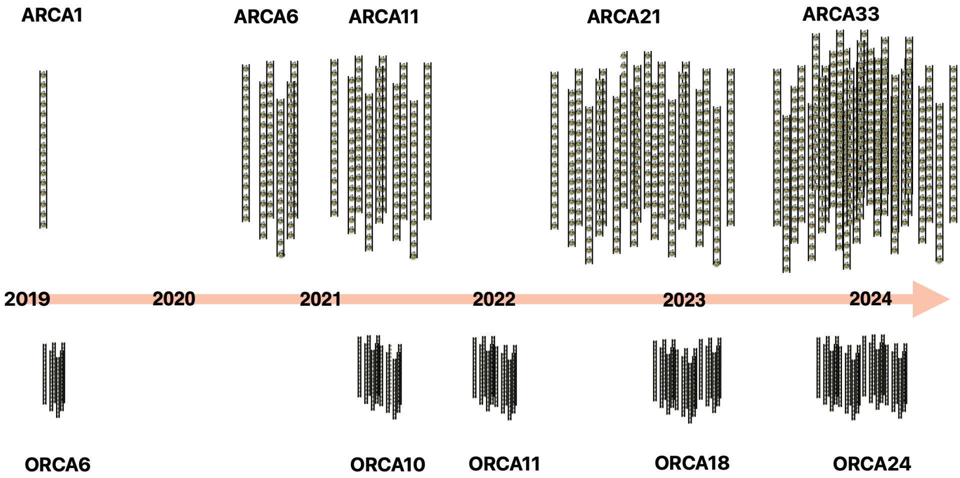
United Arab Emirates
- University of Sharjah
- Khalifa University of Science and Technology, Abu Dhabi

Australia
- Western Sydney University

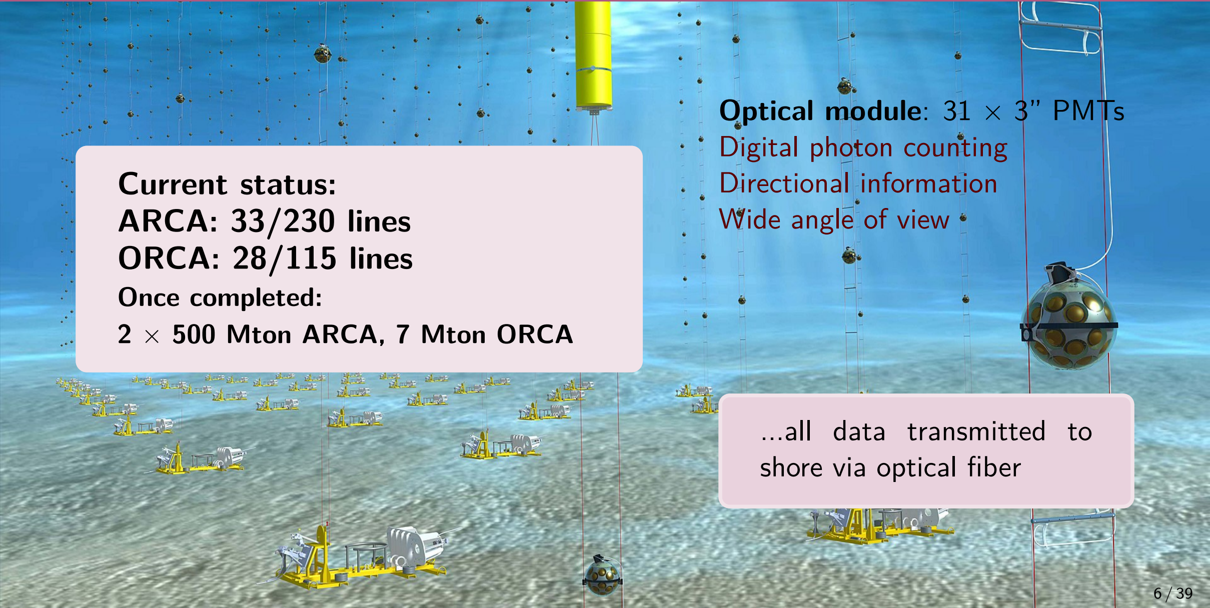
Full members

Observer members

KM3NeT: building roadmap



KM3NeT: layout

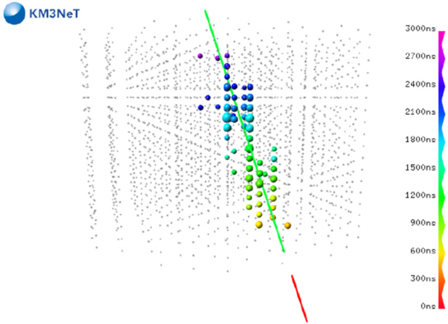


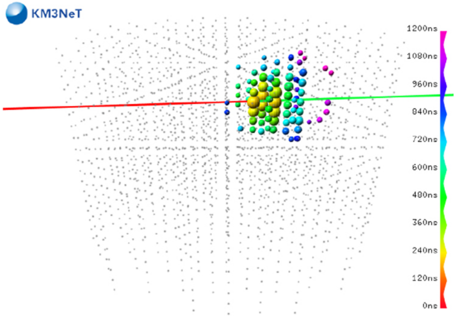
Current status:
ARCA: 33/230 lines
ORCA: 28/115 lines
Once completed:
2 $\times$ 500 Mton ARCA, 7 Mton ORCA

Optical module: 31 $\times$ 3" PMTs
Digital photon counting
Directional information
Wide angle of view

...all data transmitted to shore via optical fiber

Performance: pointing





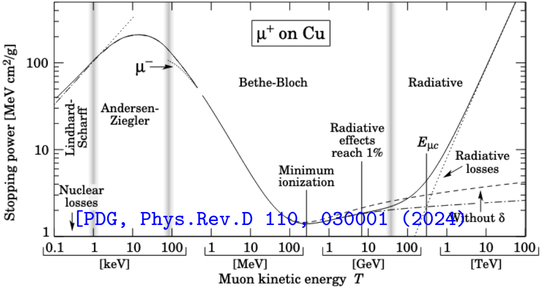
KM3NeT reconstructs two classes of events:

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

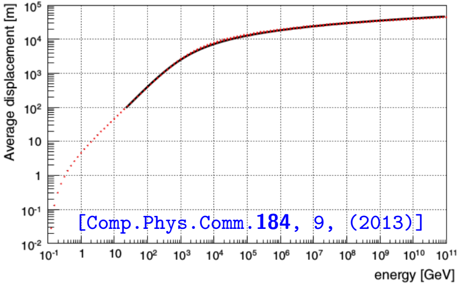
Showers: predominantly ν_e CC or any NC; angular resolution 1° at 1 PeV - contained

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.

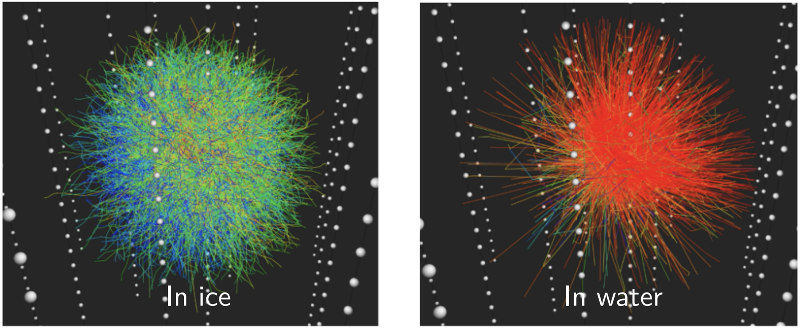
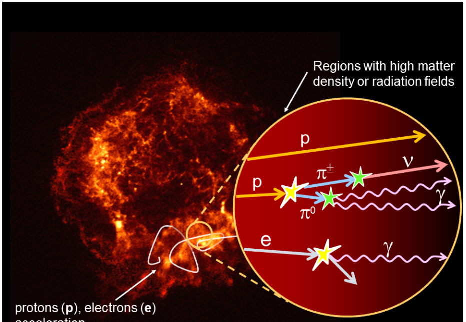


Figure: Simulation of light from a 10 TeV cascade in ice (left) and water (right).

Physics case 1: extraterrestrial neutrinos

High-energy cosmic ν 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

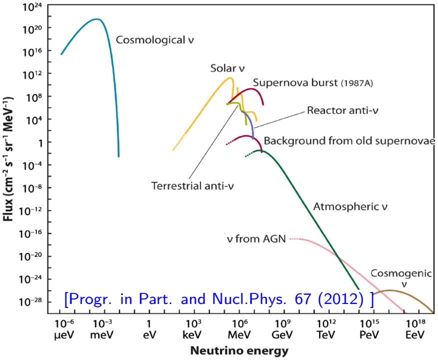


[Fig. from Universe 2020, 6(2), 30]

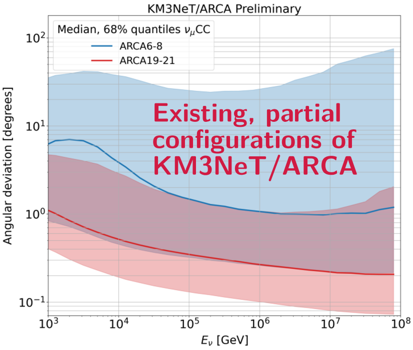
- Neutrino astronomy: backtracking sources
  1. As a **correlation** with underlying catalogue
     1. Jets of active galactic nuclei (AGNs)
     2. Starburst galaxies, star-forming galaxies
     3. Expanding front of supernova remnants
     4. Gamma-ray bursts
     5. IceCube HE events
  2. As **autocorrelation** 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 $= 1{:}10^4 : 10^{10}$



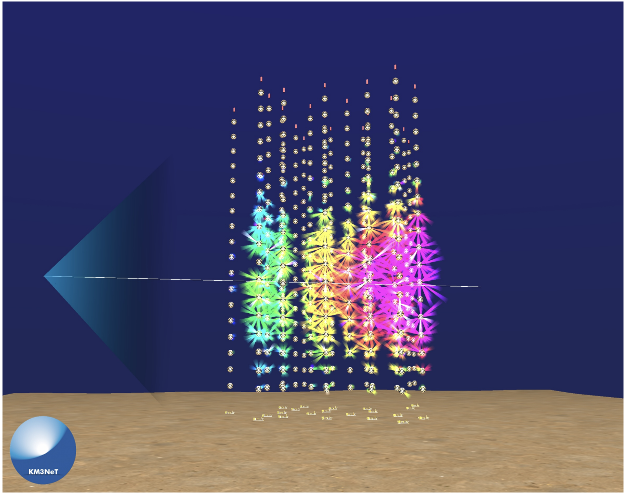
[Progr. in Part. and Nucl.Phys. 67 (2012)]



Existing, partial configurations of KM3NeT/ARCA

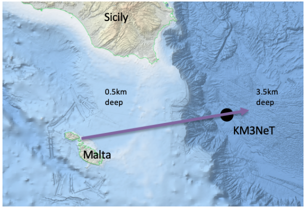
[Pic. credits: J Coelho]

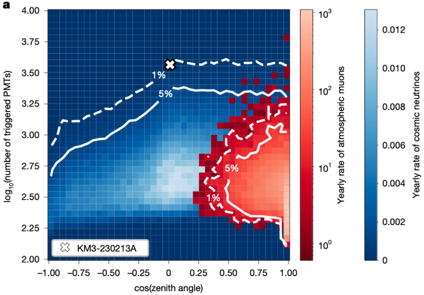
Observation of an ultra-high-energy cosmic ν with KM3NeT

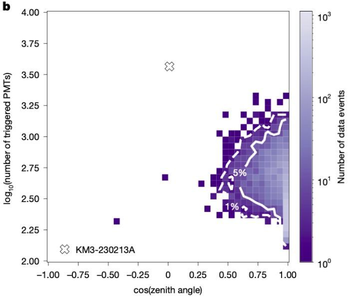


Observation of an ultra-high-energy cosmic ν with KM3NeT

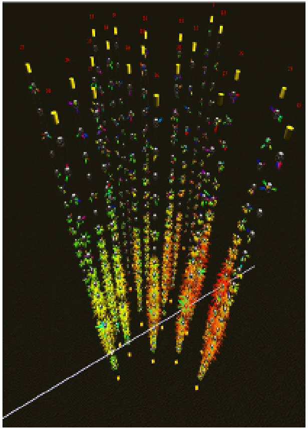
- Observed with 21-line configuration of KM3NeT/ARCA **[Nature 638, 376–382 (2025)]**
- Horizontally crossing the detector traversing continental shelf: not an atmospheric muon
- 35% of the detector (3672 photomultipliers) triggered



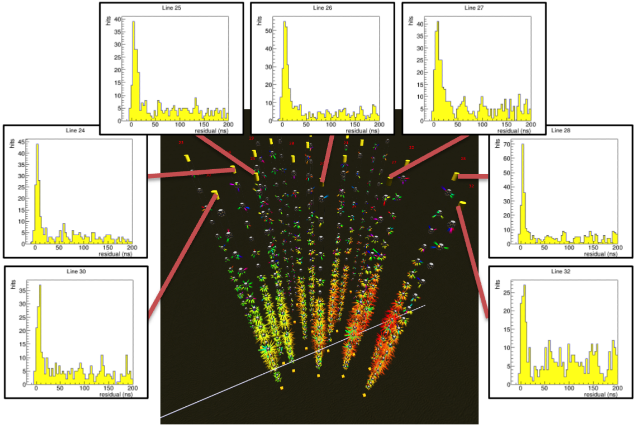




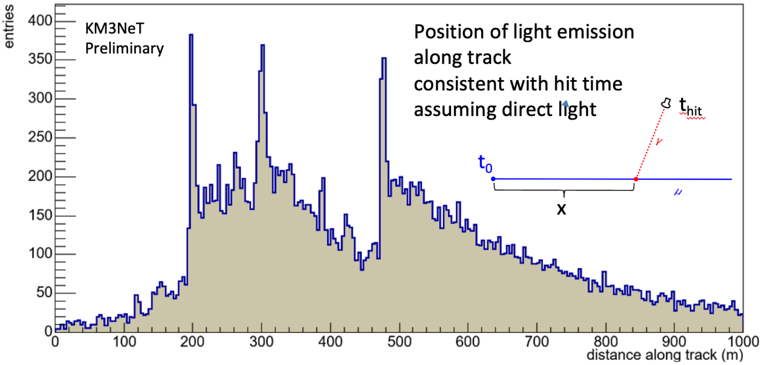
Observation of an ultra-high-energy cosmic ν with KM3NeT



Arrival time residuals of photons at photomultipliers well understood.

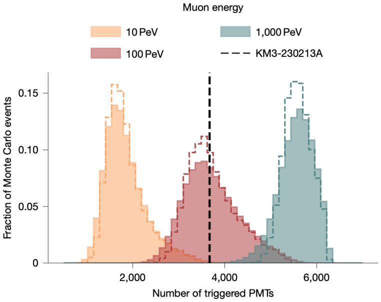


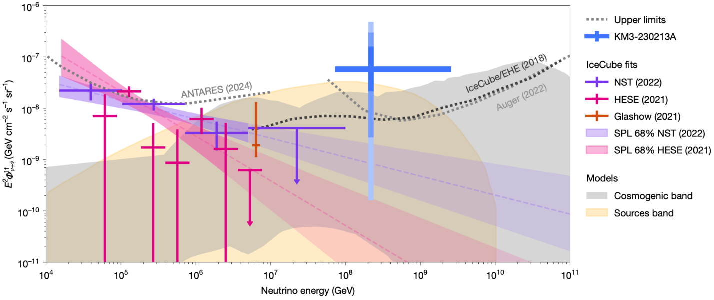
Light profile consistent with at least 3 large energy depositions along the muon track: characteristic of stochastic losses of very high energy muons



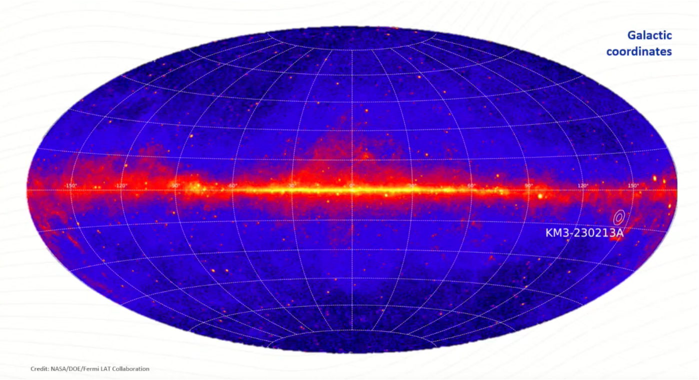
Muon energy: 120^{+110}_{-60} PeV, based on Monte Carlo simulation. The measured muon energy serves as a lower limit on the incoming neutrino energy.

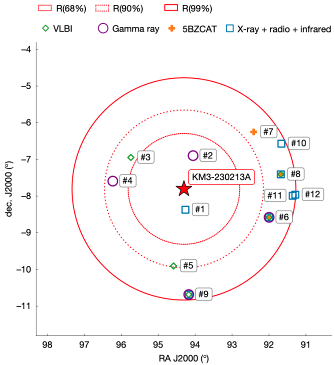
Neutrino energy: 220^{+570}_{-100} PeV, 110–790 PeV (68%), 72 PeV–2.6 EeV (90%), under the assumption of a E^{-2} spectrum.





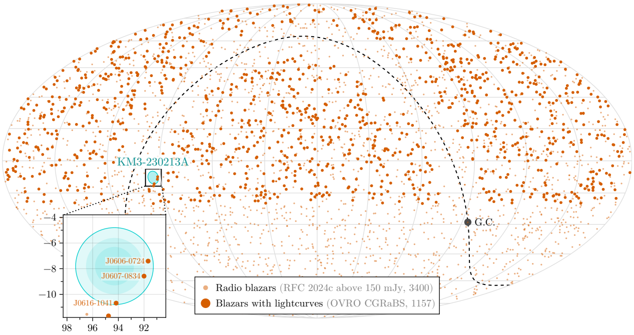
Celestial coordinates: $RA = 94.3°$, $dec = -7.8°$, with $1.5°$ uncertainty





Ultra-high-energy cosmic ν with KM3NeT: search for counterparts

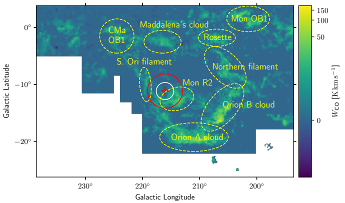
Candidate blazars selected through multi-wavelength properties. Correlation non conclusive.



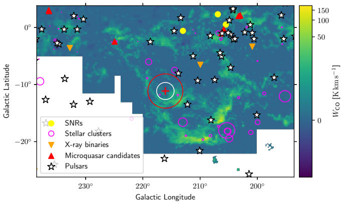
[https://arxiv.org/abs/2502.08484]

Ultra-high-energy cosmic ν with KM3NeT: search for counterparts

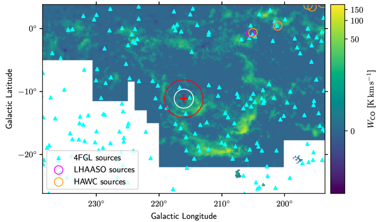
Lack of a nearby potential Galactic particle accelerator in the direction of the event. Low fluxes of the Galactic diffuse emission at event's energies. **Unlikely of Galactic origin**.



Map of CO clouds



Known potential CR accelerators

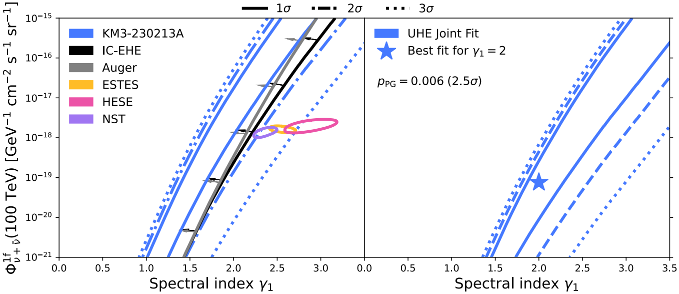


γ-ray sources from 4FGL-DR4 3HWC, LHAASO.

[https://arxiv.org/pdf/2502.08387]

Ultra-high-energy cosmic ν with KM3NeT: search for counterparts

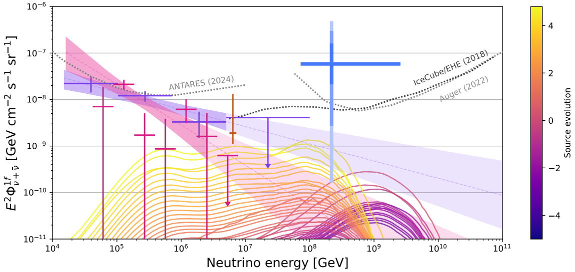
Null observations above tens of PeV from the IceCube and Pierre Auger observatories ⇒ joint fit performed, under the assumption of an isotropic E^{-2} flux.



[https://arxiv.org/pdf/2502.08173]

Ultra-high-energy cosmic ν with KM3NeT: search for counterparts

Light tension with the standard cosmogenic neutrino predictions. Observation can be reconciled with limits by Pierre Auger and Telescope Array by extending up to a redshift of $z \simeq 6$ and assuming a subdominant fraction of protons in UHE cosmic-ray flux.



[https://arxiv.org/abs/2502.08508]

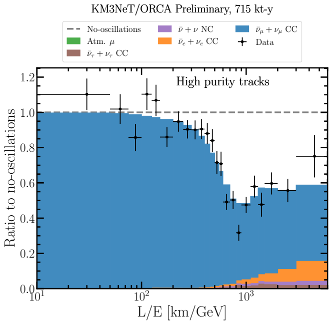
Physics case 2: fundamental neutrino properties

Oscillations, mass ordering and related observables

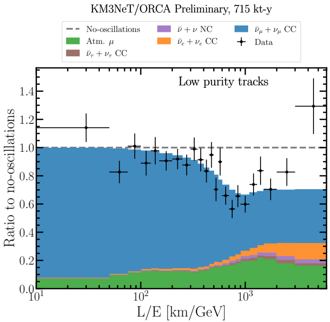
Flavour-related observables require particle identification in detector (e, μ, τ lepton?). Ideal region for search is GeV and just above, at the first disappearance peak.

Evidence for atmospheric neutrino oscillations

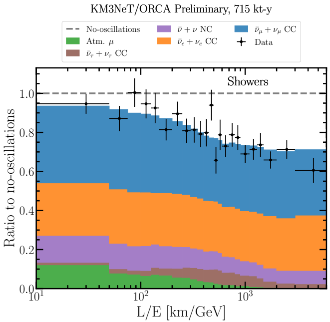
Oscillations are seen with significance $> 6\sigma$ in L/E distributions through ν_μ **disappearance** with KM3NeT/ORCA 715 kton-years data set (6+10+11 detector lines).



High-purity tracks



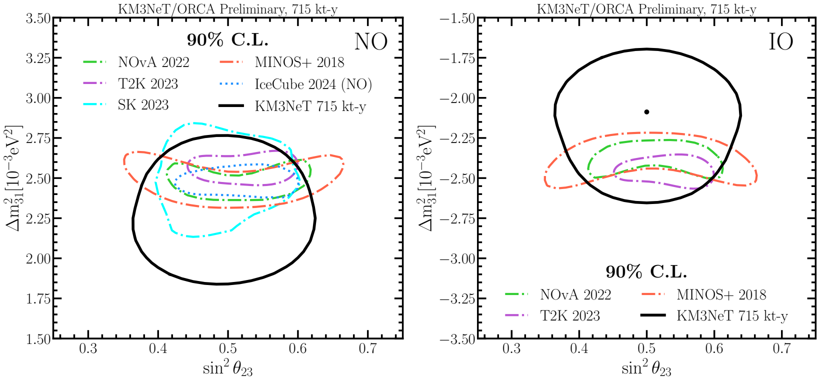
Low-purity tracks



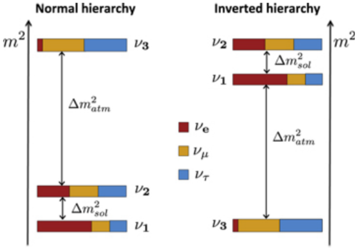
Showers

Measurement of atmospheric oscillation parameters

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



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



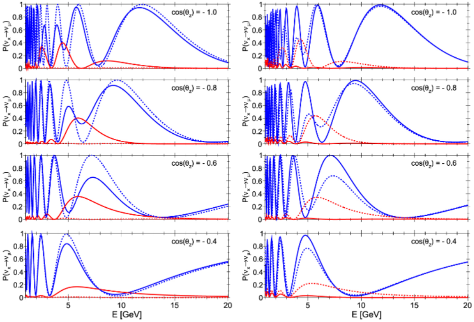
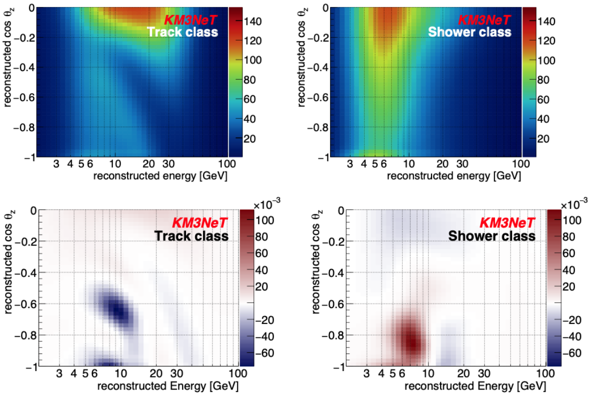


Figure: Right: oscillation probabilities $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_\mu$ for different energies and baselines. The solid (dashed) lines are for NO (IO), ν (left) and $\bar{\nu}$ (right).

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**

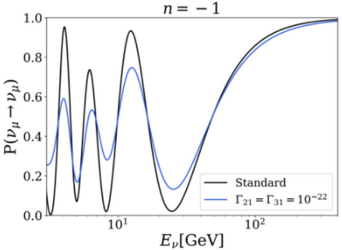
Neutrino quantum decoherence

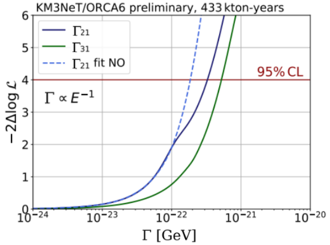
Example case: quantum space-time with a *foamy* structure in which Planck length size black holes form and evaporate on the Planck time scale

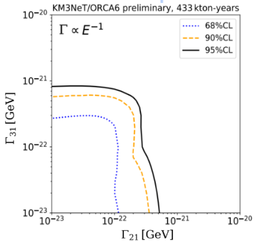
$\rightarrow$ loss of quantum information across their event horizons, providing an *environment* that can induce decoherence of apparently isolated matter systems **[Phys.Rev.D 72 (2005)]**.

Neutrino quantum decoherence

Neutrino mass eigenstates lose their coherent superposition due to interactions with the environment $\rightarrow$ oscillation amplitude is suppressed [https://arxiv.org/abs/2410.01388]







Non-standard interactions of neutrinos (NSI)

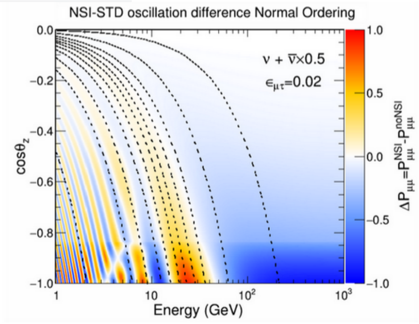
LHC has detected **no new particles** $\Rightarrow$ interest turns towards possible **new operators** that can be constructed: modifications of the Standard Model that manifest themselves indirectly.

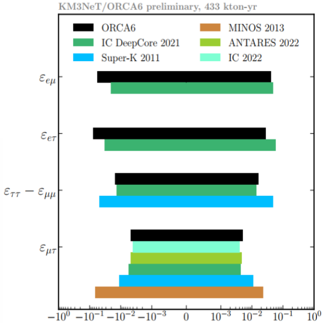
SM effective theory (SMEFT) $=$ SM $+$ dimension 6 operators $+ \ldots$

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.

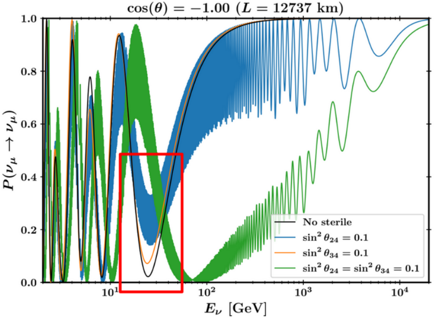
Non-standard interactions of neutrinos (NSI)

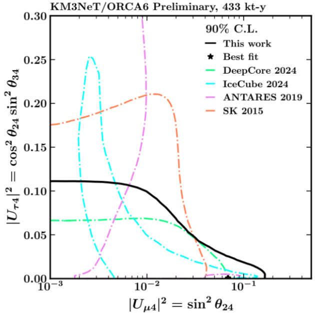
Neutral current forward scattering of neutrinos inside the Earth is modified $\rightarrow$ Flavour-dependent matter effects alter neutrino oscillations inside the Earth. [https://arxiv.org/abs/2411.19078]





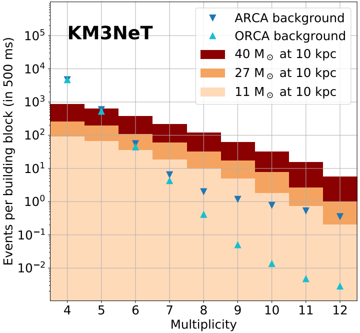
Motivation: (3+1) models with $\Delta m^2_{41} \sim 1\ \mathrm{eV}^2$ might explain short baseline anomalies.
KM3NeT is sensitive to mixing angles $\Theta_{24} and \Theta_{34}$.





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]



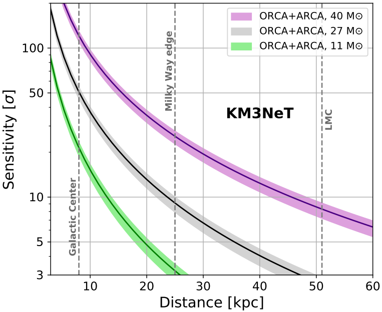


Figure: Left: SN events expected from 3 simulated progenitors at ORCA and ARCA as a function of different multiplicity values compared with BG rates. Right: Sensitivity as a function of distance.

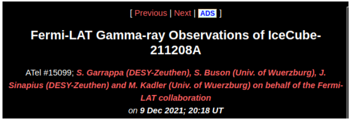
Multi-messenger networking

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

Example: flares caused by hadronic emission on top of quiescent state $\rightarrow$ 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

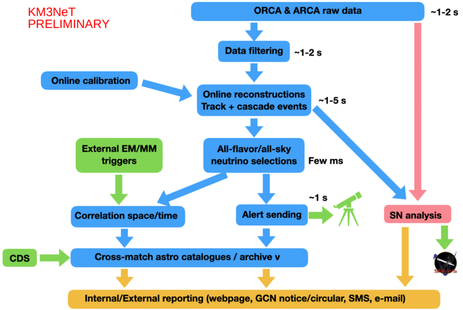
1. SN pipeline already active for real-time analysis
2. KM3NeT will replace ANTARES in follow up of alerts (ATel, GCN via AMON)


[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



Conclusions

KM3NeT has recorded 715 kton-year (ORCA) and 332 days (ARCA) of **high-quality data**

- Rare UHE event observed with E = 220 PeV, likely extragalactic origin, however no conclusive evidence of candidate source associated
- Multi-messenger program ongoing: real-time monitoring of astrophysical transient, IceCube neutrinos, gravitational waves
- Flavour oscillations measured through ν_μ disappearance with more than 6σ
- Indirect tests of physics beyond the Standard Model expectations through effects on oscillation probabilities, indirect dark matter searches

The most exciting phrase to hear in science [...] is not '*Eureka!*' but 'That's funny...' [Isaac Asimov]

ANTARES decommissioning

ANTARES decommissioning

ANTARES decommissioning