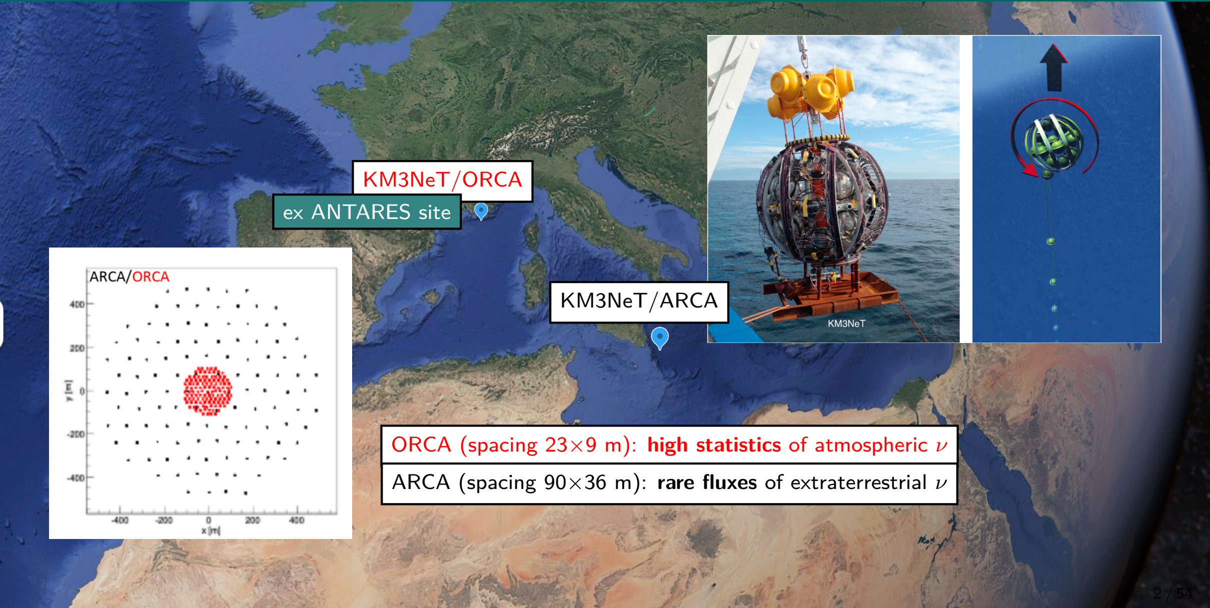
Neutrino Astronomy and Oscillations with KM3NeT

Sara Rebecca Gozzini for the KM3NeT Collaboration

LGNS Seminar

April 3, 2025

KM3NeT: layout [*J.Phys.G:Nucl.Part.Phys.* **43** 084001 (2016)]

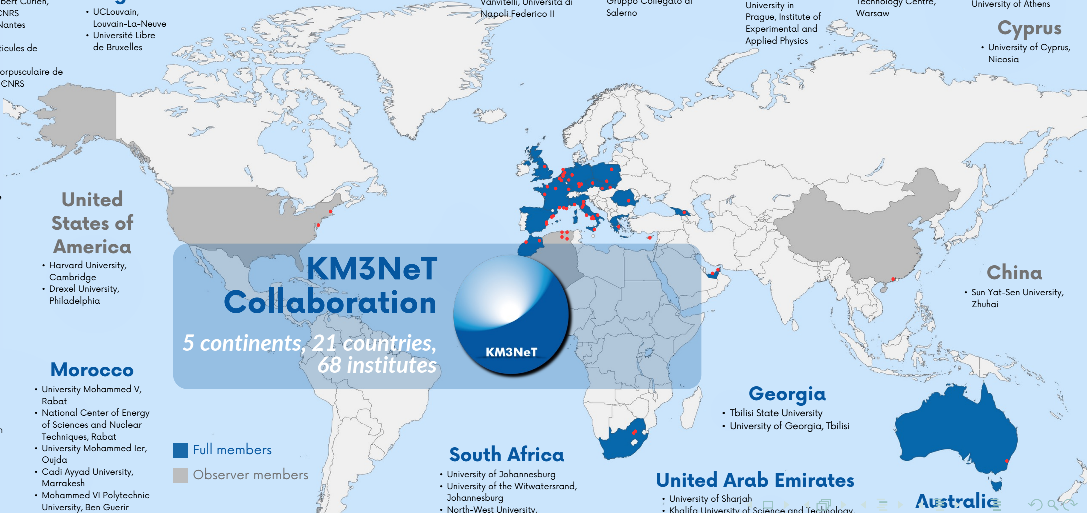


ORCA (spacing 23×9 m): **high statistics** of atmospheric ν

ARCA (spacing 90×36 m): **rare fluxes** of extraterrestrial ν

KM3NeT Collaboration

5 continents, 21 countries, 68 institutes



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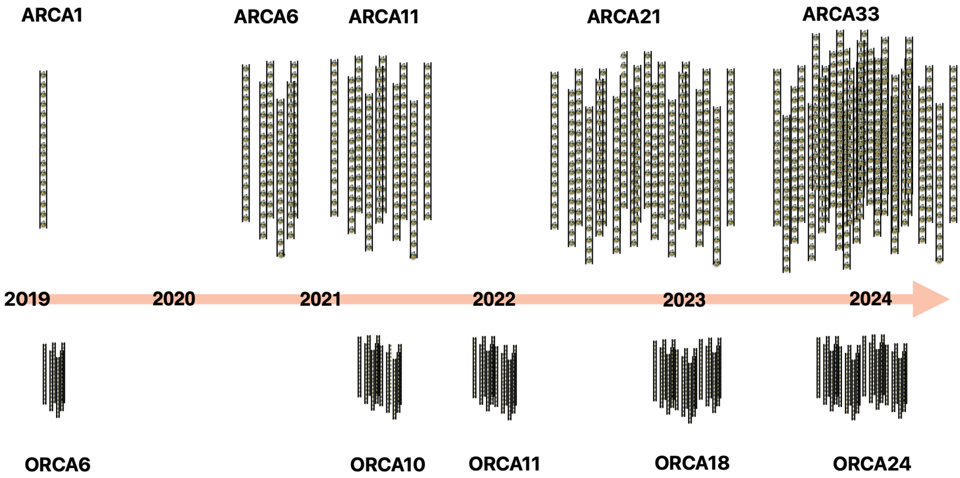
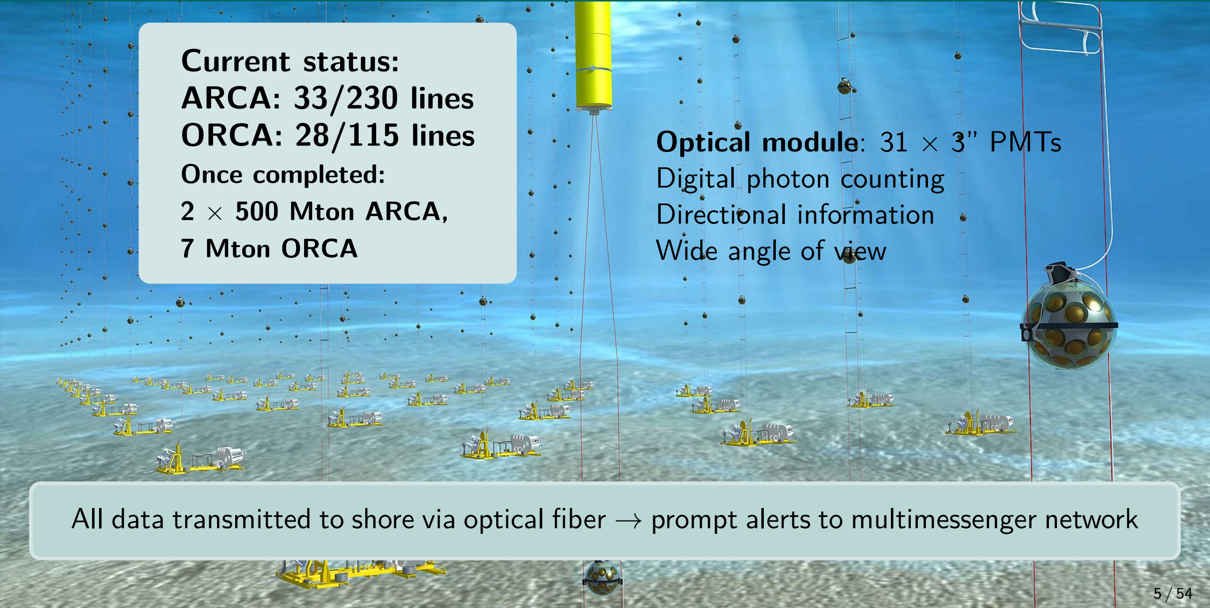
KM3NeT: building roadmap



KM3NeT: layout



Current status:
ARCA: 33/230 lines
ORCA: 28/115 lines

Once completed:

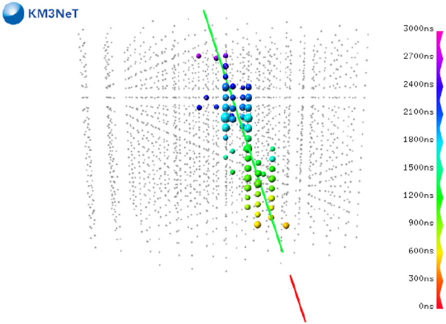
2 × 500 Mton ARCA,

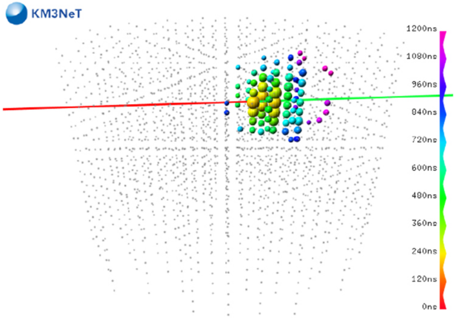
7 Mton ORCA

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

All data transmitted to shore via optical fiber → prompt alerts to multimessenger network

Performance: pointing





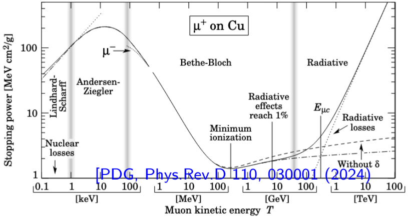
KM3NeT reconstructs two classes of events:

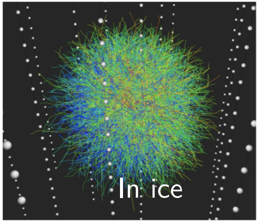
Tracks: predominantly $\nu_\mu CC$; angular resolution down to 0.1° at 1 PeV - fly-through

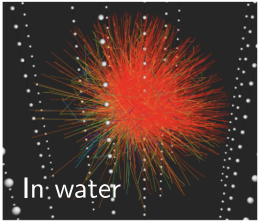
Showers: predominantly ν_e CC or any NC; angular resolution 1° at 1 PeV - contained

Performance: particle identification

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





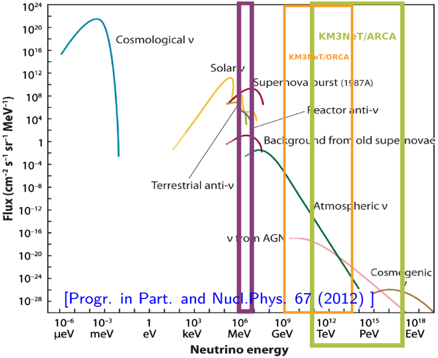


Simulation of light from a 10 TeV cascade in ice (left) and water (right).

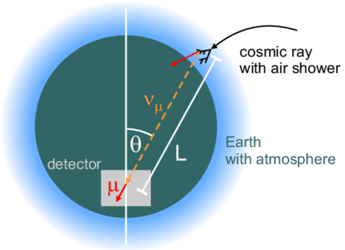
Larger scattering length: direct photons → better **pointing** and **particle identification**.

Neutrino astronomy *in the making*: experimental challenge

Preserve source information thanks to very weak interaction: large enough detector volume + a good filter (the Earth). Astrophysical ν: atmospheric ν: atmospheric μ = 1:10^4 :10^{10}.



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

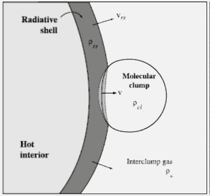


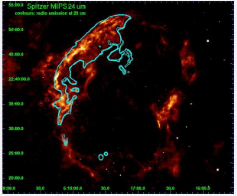
The neutrino-gamma connection: hadron acceleration

All sites where proton or nuclei are accelerated radiate γ and ν

1. $pN \rightarrow \pi^0, \pi^\pm, \eta^0 + X$ like in SNR with molecular clouds
2. $p\gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$ or $p + \pi^0 ... + X$ like in jets of active galactic nuclei

In Galactic sources surrounded by clouds, with steady emission: $p - N$ of protons on molecular gas

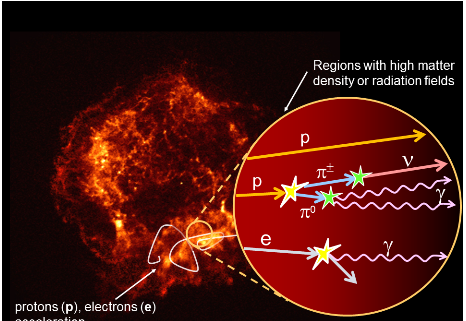




In extragalactic sources surrounded by high photon density, exhibiting flares: $p - \gamma$ of protons on AGN jets

Physics case 1: extraterrestrial neutrinos

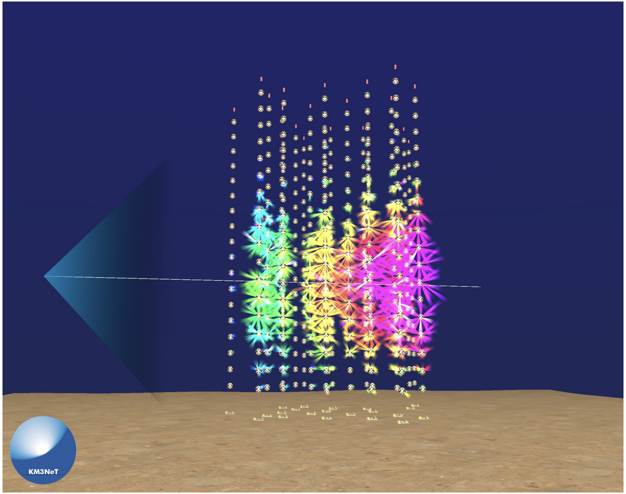
High-energy cosmic ν are expected from collisions yielding particles such as $\pi^{\pm}$ and $\mu^{\pm}$, through *pp* and $p\gamma$ scattering, taking place in different environments, steady or with flares



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

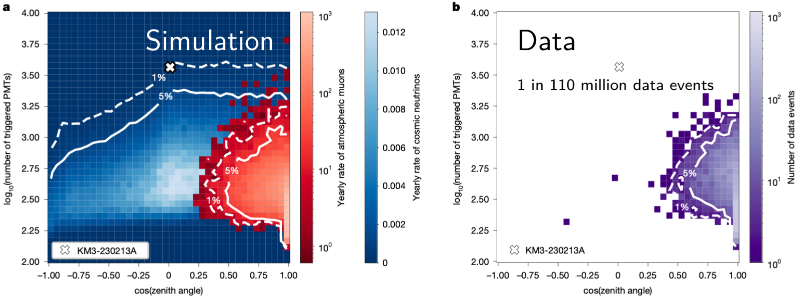
- Neutrino astronomy: backtracking sources
  1. As a **correlation** with underlying catalogue
     1. Jets of active galactic nuclei (AGNs)
     2. Starburst galaxies, star-forming galaxies
     3. Expanding front of supernova remnants
     4. Gamma-ray bursts
     5. IceCube HE events
  2. As **autocorrelation**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

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

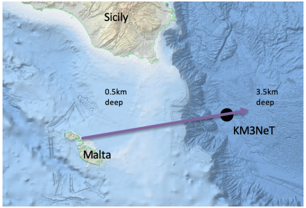


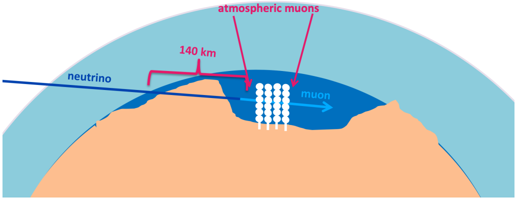
Observation of an ultra-high-energy cosmic ν with KM3NeT

- 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

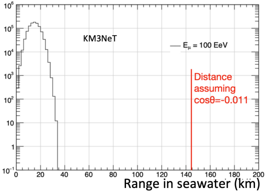


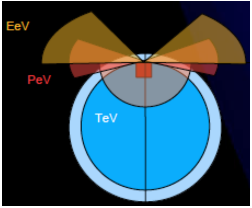
KM3-230213A: horizontal muon from ν_μ



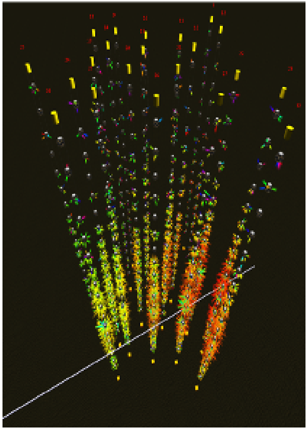


Actual water equivalent distance even larger due to continental shelf $\rightarrow$ not an atmospheric μ.



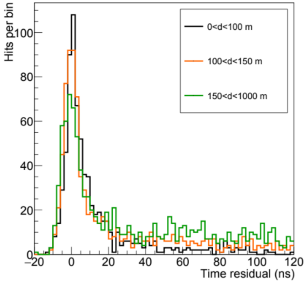


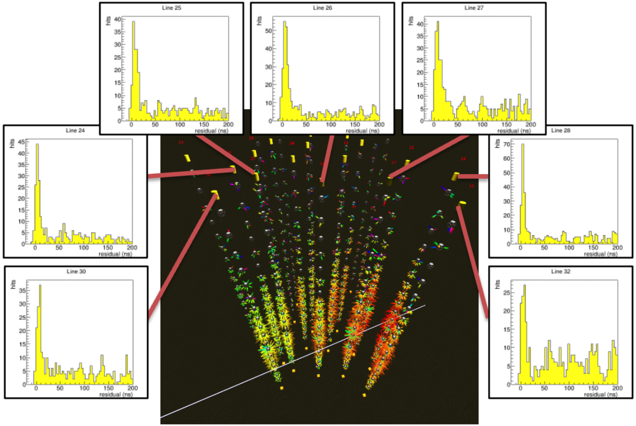
Observation of an ultra-high-energy cosmic ν with KM3NeT



Reconstruction of the muon track

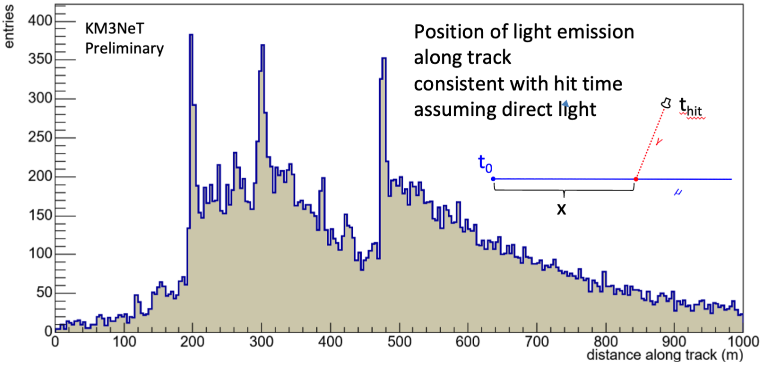
Arrival time residuals of photons at photomultipliers well understood.





Rich detail of the muon track

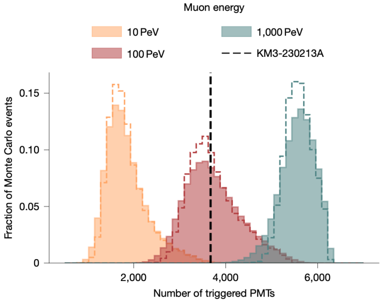
Light profile consistent with at least 3 large energy depositions along the muon track: characteristic of stochastic losses of very high energy muons.

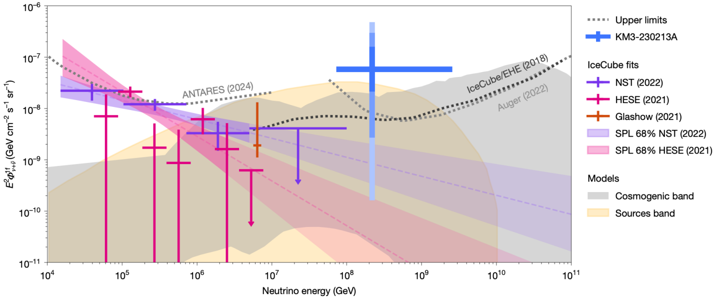


Ultra-high-energy cosmic ν with KM3NeT: energy

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.

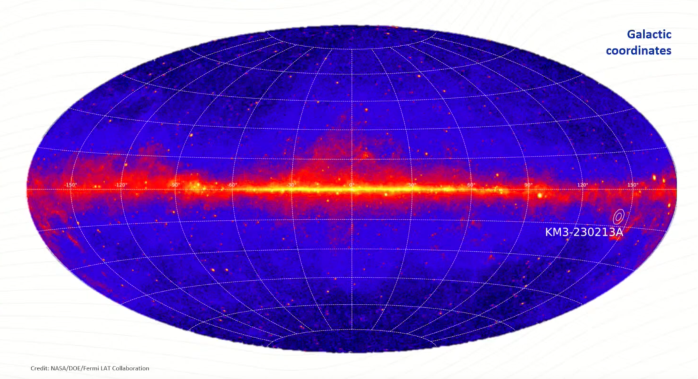
Neutrino energy: 220^{+570}_{-100} PeV, 110–790 PeV (68%), 72 PeV–2.6 EeV (90%), under the assumption of a E^{-2} spectrum.





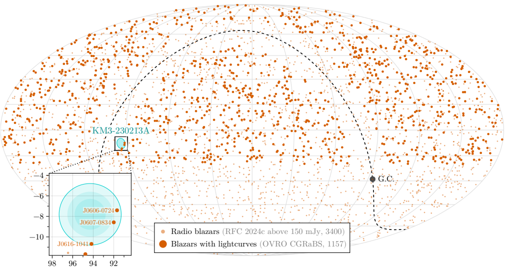
Ultra-high-energy cosmic ν with KM3NeT: arrival direction

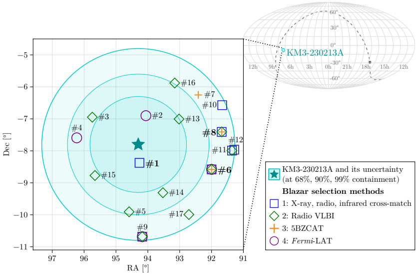
Celestial coordinates: $RA = 94.3°$, $dec = -7.8°$, with $1.5°$ uncertainty. Region-of-interest (cut/count) based searches will improve significance with more restrictive uncertainty radius.



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

Candidate blazars selected through multi-wavelength properties with dedicated proposals. (1) radio flare on neutrino arrival time (pre-trial $p = 0.26\%$); (2) rising trend in the X-ray flux in a one-year window around the event; (3) γ-ray flare. Correlation non conclusive.

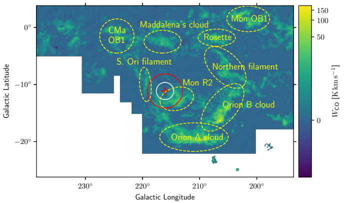




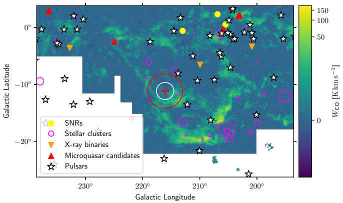
[https://arxiv.org/abs/2502.08484]

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

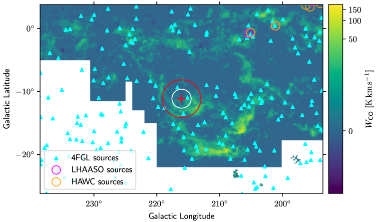
Lack of a nearby potential Galactic particle accelerator in the direction of the event. Low fluxes of the Galactic diffuse emission at event's energies. **Unlikely of Galactic origin**.



Map of CO clouds



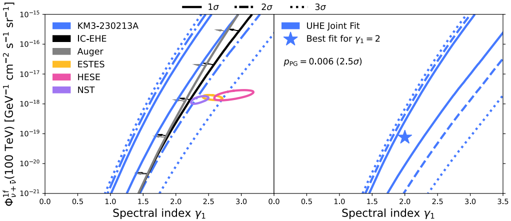
Known potential CR accelerators

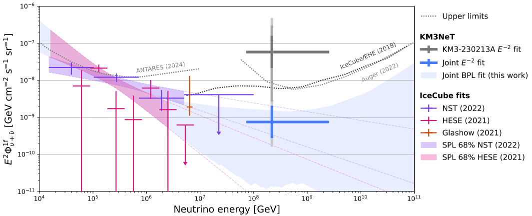


γ-ray sources from 4FGL-DR4 3HWC, LHAASO.

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

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.

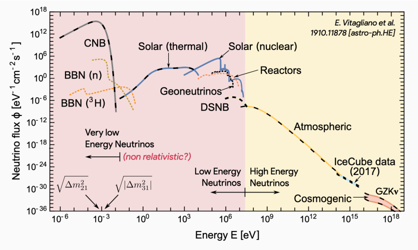


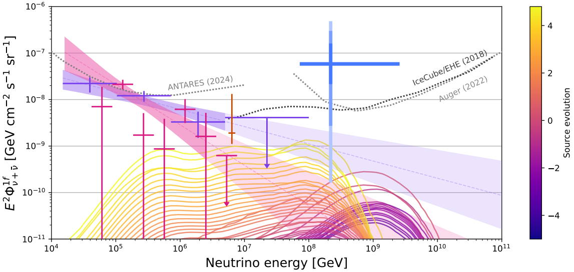


[https://arxiv.org/pdf/2502.08173]

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.



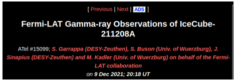


[https://arxiv.org/abs/2502.08508]

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

1. SNEWS pipeline active for real-time analysis
2. KM3NeT replaces 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*

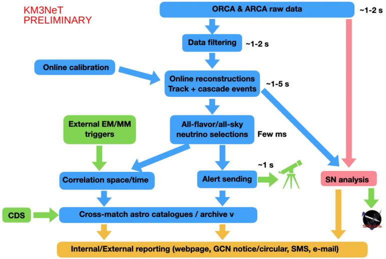
on 9 Dec 2021; 20:18 UT

GCN Circular 32741

Subject GRB 221009A: search for neutrinos with KM3NeT
Date 2022-10-13T18:57:37Z (2 years ago)
From Damien Dornic at CPPM,France <dornic@cppm.in2p3.fr>

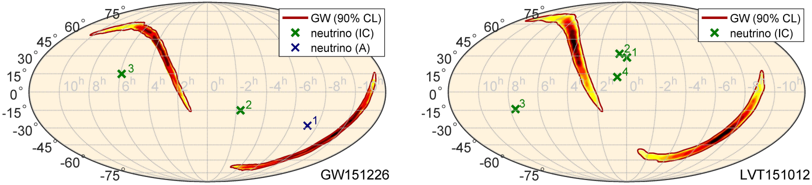
The KM3NeT Collaboration (https://www.km3net.org/) reports:

Using the data from the online fast processing chain, the KM3NeT Collaboration has performed a dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A (Dichiara et al. GCN 32632 (Swift); Veres et al. GCN 32636 (Fermi-GBM)). The search covers the time range of [T0-50s, T0+5000s], with T0 being the trigger time reported by Fermi-GBM (T0=2022-10-09 13:16:59.00 UTC), during which both KM3NeT detectors were collecting good quality data. However, the GRB location was above the



Neutrino coincidence with gravitational waves

Multi-messenger alert network for flares, transients and other sources with time variability (GRBs, gravitational waves, supernovae)



Offline analysis of event rate alerts in O3 run of VIRGO/LIGO - 190 of 900 alerts were inside the field of view of KM3NeT. Real-time follow-up of O4 alerts.

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(ICRC2023)1160]

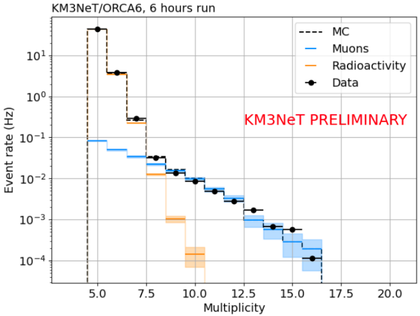


Figure: Left: image of a DOM with 4 out of the 31 PMTs highlighted. Right: Multiplicity distribution for a 6 hour period of ORCA6 (full black) compared to simulations.

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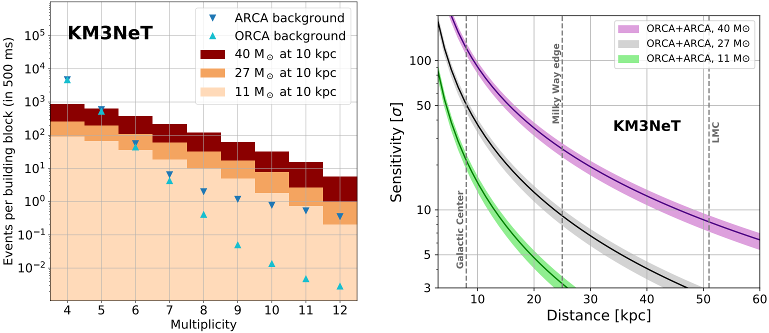
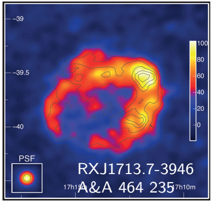


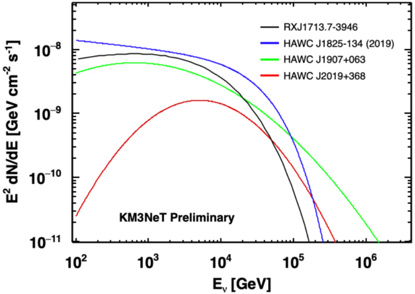
Figure: Left: SN events expected from 3 simulated progenitors at ORCA and ARCA as a function of different multiplicity values compared with BG rates. Right: Sensitivity as a function of distance.

Sensitivity to strongest Galactic sources

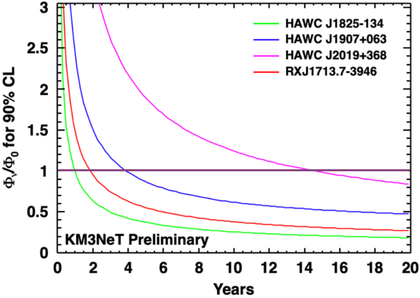
In hypothesis of hadronic emission, computing ν flux from γ-ray flux, several **extended Galactic sources** will be observable in a few years of operation.



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

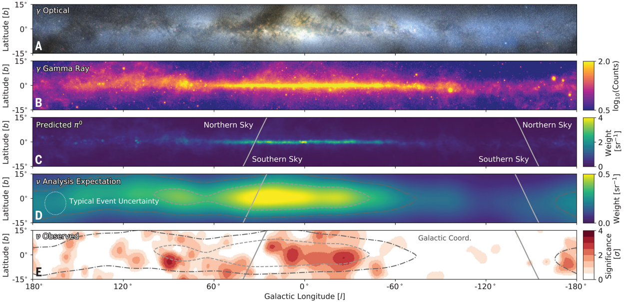


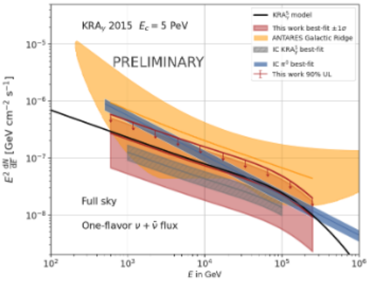
Expected ν fluxes (assumed 100% hadronic scenario)



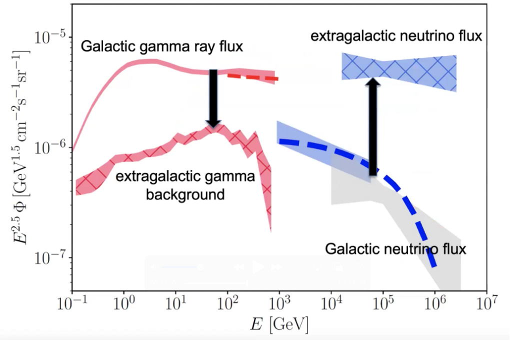
Sensitivity at 90% CL as a function of the observation time

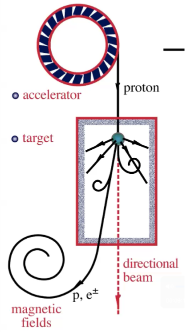
Characterize and identify sources with KM3NeT in model-independent way (ON/OFF method) or template fit (from γ rays, KRA, CRINGE). Small excess seen by ANTARES with $1.5 - 1.8\ \sigma$. IceCube: only template method (Pole does not rotate)





Galactic diffuse emission: message





Neutrino astronomy is particle physics at all effects! Moreover

> *Powerful accelerators operate in other galaxies that do not exist in our own.*

Physics case 2: fundamental neutrino properties

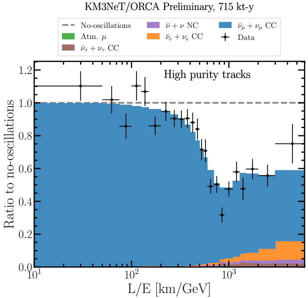
Oscillations, mass ordering and related observables

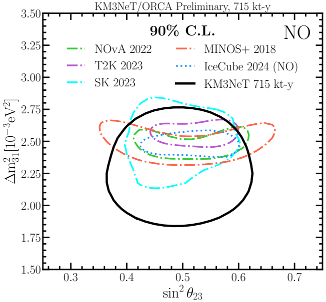
Flavour-related observables require particle identification in detector (e, μ, τ lepton?). Ideal region for search is GeV and just above, at the first disappearance peak.

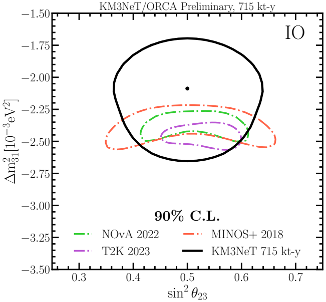
Measurement of atmospheric oscillation parameters with KM3NeT

Oscillations are seen in KM3NeT/ORCA through ν_μ **disappearance** with significance $> 6\sigma$

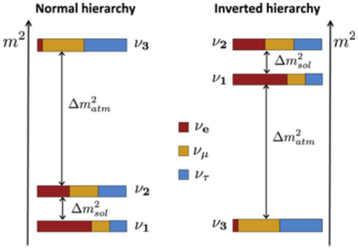
- Data set: 715 kton-years (6+10+11 detector lines). 1.6 Mton-y of data awaiting.
- Best fit: $\sin^2\theta_{23} = 0.50^{+0.07}_{-0.07}$ $\Delta m^2_{31} = -2.09^{+0.17}_{-0.21} \cdot 10^{-3}\mathrm{eV}^2$.
- Data display a slight preference for inverted ordering.







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



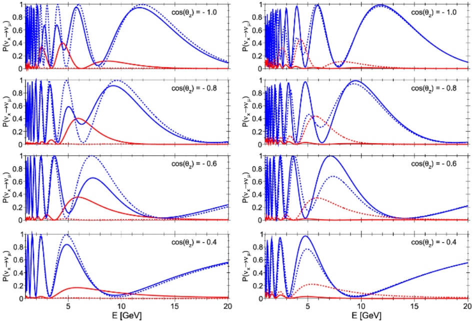
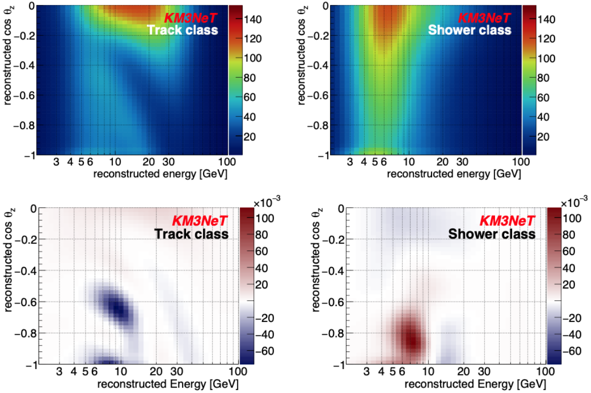


Figure: Right: oscillation probabilities $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_\mu$ for different energies and baselines. The solid (dashed) lines are for NO (IO), ν (left) and $\bar{\nu}$ (right).

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.

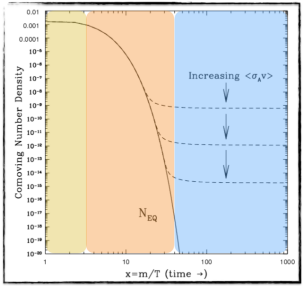
Physics case 3: indirect searches for *new physics* signatures

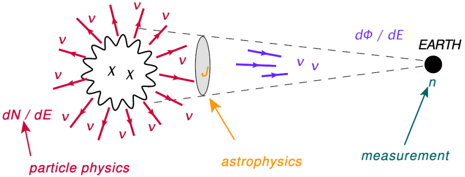
Neutrino telescopes are versatile instruments!

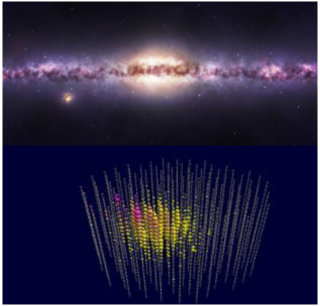
1. Indirect dark matter searches (rather unconstrained par. space, both ORCA and ARCA)
2. Effects that alter oscillations of **atmospheric neutrinos**, which are measured with **high statistics** (ORCA)
3. At TeV-PeV energies: limits from cosmic neutrinos: effects that **scale with energy** or **accumulate along large distances** (ARCA)

Dark matter as a thermal relic

Particularly symptomatic candidates (WIMPs: correct relic density in a freeze-out scenario) give rise to sizeable fluxes of high-energy ν. Overdensity regions of dark matter in Galactic haloes. Characterize energy distribution and source morphology.



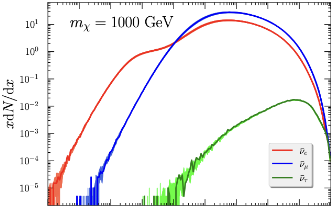


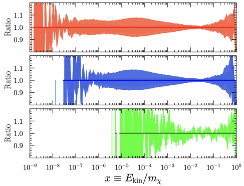


The extra trouble with indirect searches: external input

Indirect searches are unavoidably affected by **large uncertainties**. This also means that these searches alone can hardly make a univocal claim for detection.

(I) Energy feature

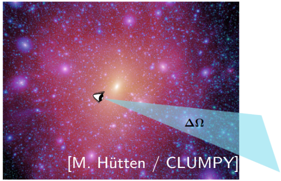




$x = E_{kin}/m_\chi$

Affected both by energy rec. of the detector (20% – 5%) and by theoretical uncertainties (10% – 30%) mostly on hadronization model [JCAP03(2024)035]

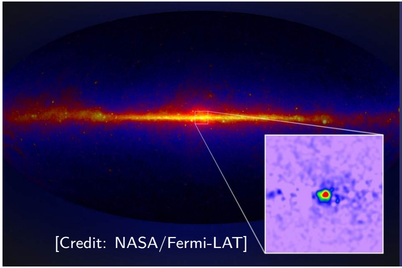
(II) Ambient

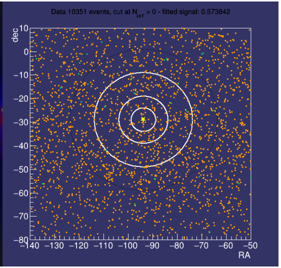


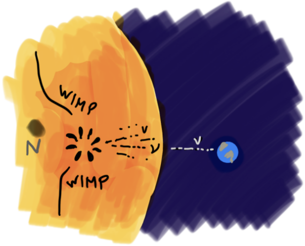
Dominated by astrophysical input for modelling haloes

Indirect dark matter searches with ANTARES and KM3NeT

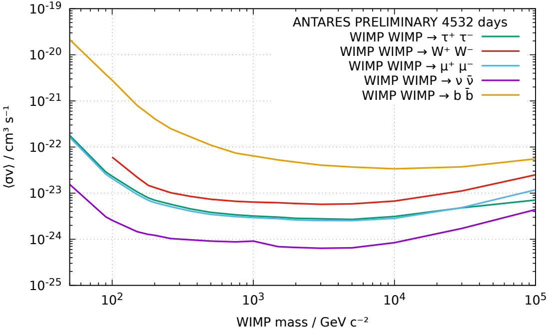
Search for a signal of neutrinos from the annihilation of WIMP dark matter in the Galactic Centre and the Sun, using maximum likelihood algorithm.

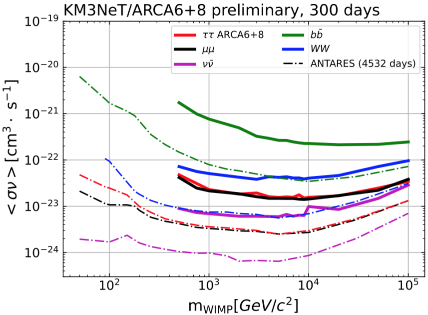






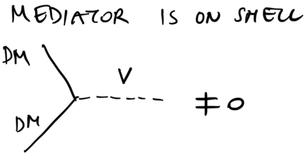
Galactic Centre visible for about 70% of the time in regular data taking mode, using the Earth as a filter. Data from ANTARES (2007 to 2022) and partial configuration of KM3NeT/ARCA is found consistent with background for all combinations of WIMP parameters **[Phys. Lett. B 805 (2020)] [JCAP03(2025)058]**

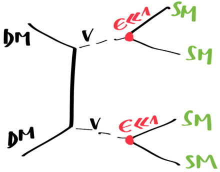


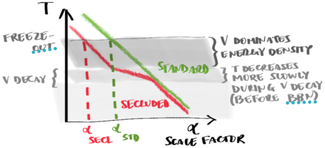


3. Test of novel dark matter scenarios

Above 10-100 TeV, in line with recent interest for BSM physics in heavy sectors at colliders.





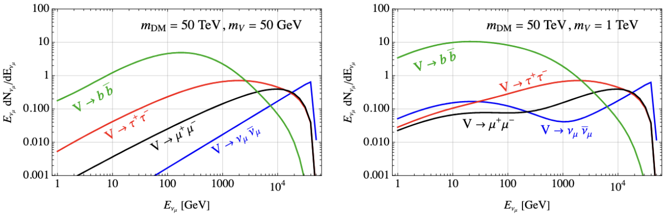


Modified cosmological evolution: universe at freeze-out is smaller $\Rightarrow$ the same amount of DM is later more diluted $\Rightarrow$ σv(DM DM $\rightarrow$ VV) smaller $\Rightarrow$ DM can be **heavier**

(I) Unitarity bound on the dark matter mass naturally evaded with a modified cosmology.

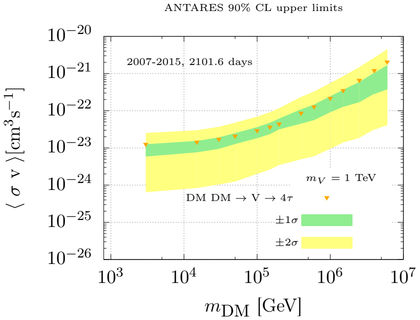
(II) $\mathrm{DM\,DM} \to 4\mathrm{SM}$ leaving the Galactic Centre as neutrinos. Spectra of relevance for experiments are computed from *boosted* PPPC4DMID **[JCAP02(2019)014]**.

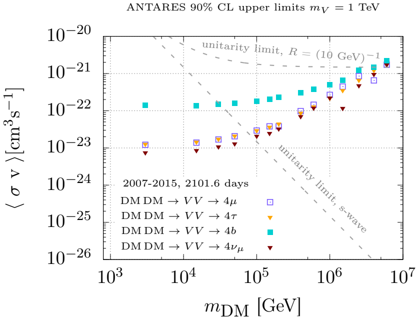
The relevant energy scale is not the heavy DM mass (that would demand a resummation of EW radiation for $m_{\mathrm{DM}} > 10$ TeV), but rather the sub-TeV mediator mass, where the first order treatment of EW corrections included in PPPC4DMID is under control.



Test of novel dark matter scenarios

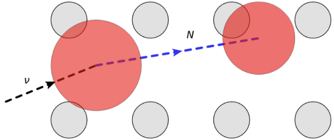
Search explores for the first time parameter space regions at high energies / large masses up to 6 PeV **[JCAP06(2022)028]**.





Heavy neutral leptons: new physics with atmospheric neutrinos

Heavy neutral lepton (HNL) such as 4th sterile ν with mass around the GeV could leave a signal in KM3NeT/ORCA **[JHEP05 030(2009)]**, **[PRL 119(2017)]**, that could become competitive with its future larger-volume configurations, and can already search in data.



HNL mass: in keV range: dark matter candidate, in $\mathcal{O}(1-100)$ GeV can generate the matter-antimatter asymmetry (*baryogenesis from ν oscillations*) **[arXiv:1606.06719]**

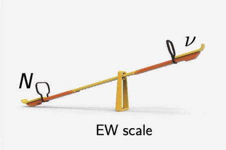
Heavy neutral leptons: context

Problem of hierarchy in fundamental scales $\rightarrow$ ν **masses are tiny.** How built?

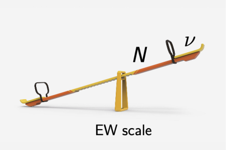
1. Tiny Yukawa couplings. Tuned by hand
2. See-saw mechanism. Masses of active ν are kept small by large M.

$$\mathcal{L}^{\text{mass}}_{\text{see-saw}} = -\frac{1}{2}(\bar{\Phi}_L, \bar{\Phi}_R)\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \Phi_L \\ \Phi_R \end{pmatrix}$$

Diagonalizing mass matrix: $m_{\text{light}} \simeq \dfrac{m_D^2}{M}$, $m_{heavy} \simeq M$



Type-1 see-saw.
Heavy N can hardly be tested

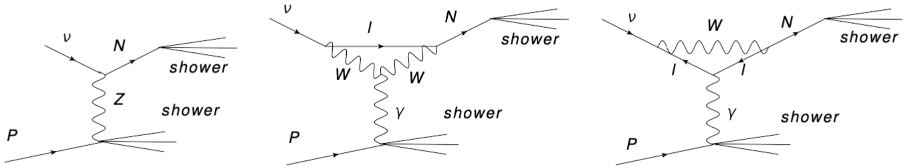


HNL search with KM3NeT.
Light N weakly interacting.

Search for heavy neutral lepton signatures

Signature: double cascade events at low energy. Active ν is atmospheric, after oscillations.

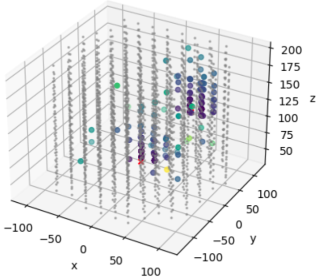
1. HNL production via neutral current + mixing in final state. $|U_{\tau 4}|^2$ is the least constrained. Separation between vertices (decay length) depends on MN and on $|U_{\tau 4}|^2$.
2. HNL production via a transition magnetic moment: NC + W loop + mixing in final state



1) NC scattering with mixing

2) transition magnetic moment: W-loop and mixing in final state

Dedicated simulation of HNLs with the lepton injector of SIREN **[arXiv:2406.01745]**.
Machine learning regression (`dynedge`) to discriminate and reconstruct distance and energy.



Background?

1. Random coincidences of two uncorrelated muons: about $3{\cdot}10^{-9}$: negligible
2. Stochastic electromagnetic showers along the track: only relevant for μ, not for e
3. ν_τ: completely negligible. At GeV energies the two cascades are μm apart: completely overlayed.

The signature with two cascades separated by a long distance is characteristic fingerprint of something **new** outside the Standard Model

New physics in flavour oscillations: quantum decoherence

Wave packet separation

Interaction with environment

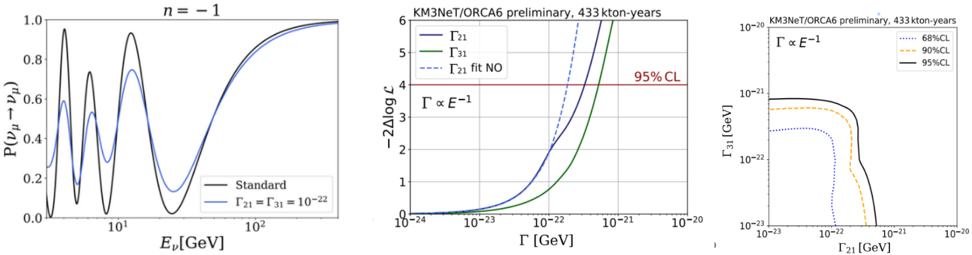
Here in the case: non-closed quantum system (ν) in interaction with enviroment.

> Neutrino + environment represented as a quantum system (mixture of states, ρ) with *dissipative* term $\mathcal{D}$ (decoherence) that damps the oscillation probabilities.

$$\frac{d\rho(t)}{dt} = -i[H, \rho(t)] + \mathcal{D}[\rho(t)]$$

Neutrino quantum decoherence

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



Non-standard interactions of neutrinos (NSI)

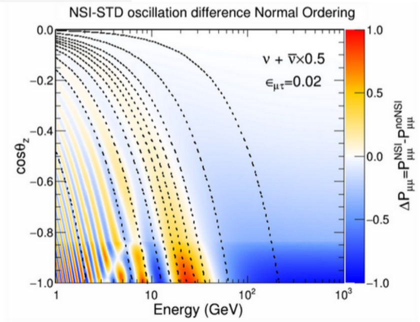
LHC has detected **no new particles** $\Rightarrow$ interest turns towards possible **new operators** that can be constructed: modifications of the Standard Model that manifest themselves indirectly.

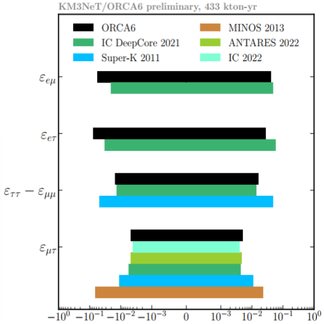
SM effective theory (SMEFT) = SM + dimension 6 operators + ...

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)

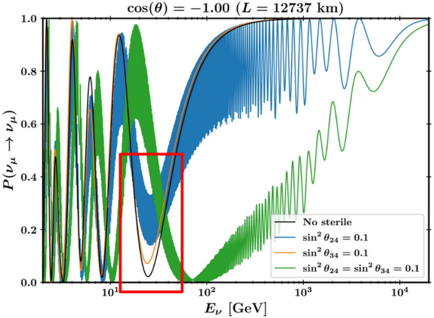
Neutral current forward scattering of neutrinos inside the Earth is modified $\rightarrow$ Flavour-dependent matter effects alter neutrino oscillations inside the Earth. [https://arxiv.org/abs/2411.19078]

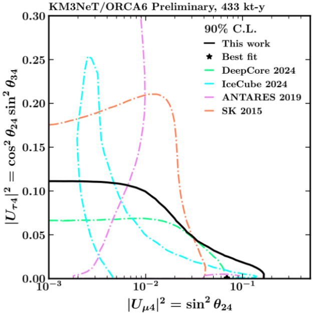




Sterile neutrinos

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





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